

Measurements of the Higgs boson production, fiducial and differential cross-sections in the four lepton decay channel using 164 fb^{-1} of data collected at $\sqrt{s} = 13.6 \text{ TeV}$ with the ATLAS detector



The ATLAS collaboration

Full author list at the end of the paper

E-mail: atlas.publications@cern.ch

ABSTRACT: Inclusive, differential and production-mode cross-section measurements of the Higgs boson are performed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel. The analysis uses proton–proton collision data produced at the Large Hadron Collider at a centre-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$ and recorded with the ATLAS detector, corresponding to an integrated luminosity of 164 fb^{-1} . The inclusive fiducial cross-section for the $H \rightarrow ZZ^* \rightarrow 4\ell$ process is measured to be $\sigma_{\text{fid}} = 3.65^{+0.35}_{-0.33} \text{ fb}$, in agreement with the Standard Model prediction of $\sigma_{\text{fid}}^{\text{SM}} = 3.68 \pm 0.17 \text{ fb}$. Differential cross-sections are measured as a function of key kinematic observables of the Higgs boson and the four-lepton final state. Cross-sections are measured for the main production-modes in several exclusive regions of the Higgs boson production phase space and combined to measure an overall Higgs boson signal strength, defined as the measured cross-section normalised to the SM prediction, of $\mu = 0.99 \pm 0.13$. The results are interpreted in terms of modifications of Higgs boson couplings using the κ framework, within the Standard Model Effective Field Theory, and in scenarios probing the Higgs boson self-coupling. All the results are consistent with Standard Model expectations.

KEYWORDS: Hadron-Hadron Scattering, Higgs Physics

ARXIV EPRINT: [2605.19016](https://arxiv.org/abs/2605.19016)

Contents

1	Introduction	2
2	ATLAS detector	3
3	Signal and background simulation	4
3.1	Data	4
3.2	Simulated event samples	4
4	Event selection	7
4.1	Event reconstruction	7
4.2	Higgs boson candidate formation	9
5	Background estimation	10
5.1	Background process with prompt leptons	10
5.2	Background process with non-prompt leptons	11
6	Analysis overview	13
6.1	Inclusive and differential cross-sections	13
6.2	Production-mode cross-sections	15
6.3	Statistical method	19
7	Systematic uncertainties	20
7.1	Experimental uncertainties	21
7.2	Theoretical uncertainties	21
8	Results	22
8.1	Inclusive fiducial and total cross-sections	22
8.2	Differential cross-sections	24
8.3	Cross-sections per production-mode	29
9	Interpretations of the differential distributions and production cross-sections	35
9.1	Constraints on Higgs boson couplings within the κ -framework	35
9.2	Constraints on CP-even and CP-odd effective field theory operators	35
9.3	Constraints on Higgs boson self-coupling	40
10	Conclusion	41
	The ATLAS collaboration	52

1 Introduction

The observation of the Higgs boson by the ATLAS and CMS Collaborations [1, 2] using proton–proton (pp) collisions at the Large Hadron Collider (LHC) marked a major milestone in the understanding of the electroweak (EW) symmetry-breaking mechanism [3–5]. Subsequent studies of the Higgs boson properties have established the observed particle as a scalar boson consistent with the Standard Model (SM) predictions for a Higgs boson with a mass of $125.09 \pm 0.24 \text{ GeV}$ [6].

The $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel, where $\ell = e, \mu$, provides a particularly clear experimental signature, featuring an excellent signal-to-background ratio and full reconstruction of the final state enabled by the high-precision lepton momentum measurements of the ATLAS detector. Background contributions are small and can be precisely estimated by using data-driven techniques. As a result, this channel has played a central role in precision measurements of Higgs boson properties by both the ATLAS and CMS experiments using the full LHC Run 2 integrated luminosity of 140 fb^{-1} . At a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$, measurements of the Higgs boson production and differential cross-sections [7–13], and derived constraints on couplings, as well as its mass [14–16], tensor structure [17, 18], and width [16, 19], have been performed. More recently, first measurements at $\sqrt{s} = 13.6 \text{ TeV}$ have been reported by ATLAS [20] and CMS [21].

This paper presents measurements of Higgs boson production using $H \rightarrow ZZ^* \rightarrow 4\ell$ decay candidates recorded during Run 3 with the ATLAS experiment in pp collisions at $\sqrt{s} = 13.6 \text{ TeV}$ between the 2022 and 2024 data-taking periods, corresponding to an integrated luminosity of 164 fb^{-1} . Inclusive and differential cross-sections for eight observables sensitive to the production and decay kinematics of the Higgs boson, are measured within a well-defined fiducial phase space. In addition, cross-sections per Higgs boson production-mode are extracted using the Simplified Template cross-section (STXS) framework [22, 23].

The cross-sections are determined using binned likelihood fits to the reconstructed four-lepton invariant mass spectrum for the inclusive and differential cross-sections measurements, and are corrected for detector efficiencies and resolution effects through an unfolding procedure. Neural-network-based (NN) discriminant distributions are used for the production-mode cross-sections measurements.

The measured cross-sections are compared with SM predictions and are further interpreted to constrain possible anomalous Higgs boson couplings. In particular, the differential production cross-sections are interpreted in the context of the Standard Model effective field theory (SMEFT), while the cross-sections per production-mode are interpreted in terms of modified Higgs boson couplings to vector bosons. Constraints on the Higgs boson trilinear self-coupling are derived by exploiting both the Higgs boson transverse momentum spectra and the production-mode cross-sections. Furthermore, a statistical combination of Run 2 and Run 3 data is performed in the context of the coupling-modifier interpretation, significantly improving the precision of the constraints.

Compared with previous results in this analysis channel [8, 9, 20], the results presented in this paper benefit from additional data collected in 2023 and 2024. A new transformer-based [24] machine learning (ML) algorithm is used to identify jets from the hadronisation of b -quarks, providing substantial improvements in background rejection [25] for measuring

the top-quark-associated Higgs production-mode. A data-driven fake-factor method [26] is used to estimate backgrounds with non-prompt leptons, such as those arising from Z +jets, $t\bar{t}$, and WZ processes. The double-differential distribution of the transverse momentum of the four-lepton system as function of the invariant mass of the sub-leading dilepton pair is measured for the first time, owing to its high sensitivity to possible beyond-the-Standard-Model (BSM) effects in Higgs boson couplings. A new neural-network architecture is also employed to construct discriminants that enhance the sensitivity to distinguish between the various Higgs boson production-modes. In addition, the azimuthal angle between the decay planes of the two Z bosons, ϕ , was found to improve sensitivity to SM-BSM interference effects and is reinterpreted in the context of SMEFT for the first time in this channel.

The paper is organised as follows. Section 2 provides a brief description of the ATLAS detector. The data used in the analysis, together with the simulated signal and background samples, is described in section 3. The event selection for Higgs boson candidates is presented in section 4, while the estimation of background contributions is discussed in section 5. An overview of the analysis methodology used to measure inclusive and differential cross-sections in a fiducial phase space, and production-mode cross-sections in the STXS framework, is given in section 6. The experimental and theoretical systematic uncertainties affecting the measurements are summarised in section 7. The cross-section results are presented in section 8, and their interpretation is discussed in section 9. Finally, the conclusions are given in section 10.

2 ATLAS detector

The ATLAS experiment [27, 28] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.¹ It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking (TRT) detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, except in the innermost layer of the

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

end-cap region, where layers of small-strip thin-gap chambers and Micromegas chambers both provide precision tracking in the region $1.3 < |\eta| < 2.7$. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, thin-gap chambers in the endcap regions, and the aforementioned small-strip thin-gap chambers and Micromegas chambers in the innermost layer of the endcap. The luminosity is measured mainly by the LUCID-2 detector which is located close to the beampipe. A two-level trigger system is used to select events [29]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate close to 100 kHz. This is followed by a software-based trigger that reduces the accepted rate of complete events to 3 kHz on average, depending on the data-taking conditions. A software suite [30] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Signal and background simulation

3.1 Data

The measurements presented in this paper are performed using pp collision data recorded with the ATLAS detector between 2022 and 2024, corresponding to an integrated luminosity of 164 fb^{-1} . Data are selected only if all detector components relevant for each analysis channel are in good operating condition. The uncertainty in the integrated luminosity is 1.9% [31], following the methodology described in ref. [32]. The average number of interactions per bunch crossing (pile-up), averaged over all colliding bunch pairs, is about 42 in 2022, increases to about 51 in 2023, and reaches approximately 57 in 2024.

Events used in the measurement are recorded using a combination of single-lepton, dilepton, and trilepton triggers [33, 34]. The electron triggers used for the 2023 and 2024 data-taking periods exploit the new electromagnetic feature extractors deployed for LHC Run 3 [29]. The transverse momentum thresholds of the single-lepton triggers are 24 GeV for muons and 26 GeV for electrons. The dielectron triggers require a minimum transverse momentum of 17 GeV per electron, while the dimuon triggers require at least 14 GeV per muon. Mixed lepton flavour $e\mu$ triggers combine these thresholds, and trilepton triggers allow for lower thresholds in exchange for a higher lepton multiplicity. For simulated Higgs boson candidates produced via the gluon–gluon fusion process, the resulting total trigger efficiency is 98.1% for signal events satisfying the final selection described in section 4.

3.2 Simulated event samples

This analysis uses simulated event samples to model the Higgs boson signal and all relevant background processes, and to derive corrections for detector effects.

3.2.1 Signal modelling

Higgs boson production and decay are simulated for the primary production-modes: gluon–gluon fusion (ggF), vector-boson fusion (VBF), associated production with a vector boson (VH , where $V = W, Z$), top- or bottom-associated production² ($t\bar{t}H$ and $b\bar{b}H$), and associated

² $t\bar{t}H$ and $b\bar{b}H$ are also denoted by ttH and bbH in the figures.

production with a single top quark (t -channel for tH and tHW).³ Hard-scattering matrix-elements (MEs) for the nominal signal samples are generated with the POWHEG BOX v2 [35–37] Monte Carlo (MC) generator. Next-to-leading-order (NLO) accuracy in quantum chromodynamics (QCD) is achieved for the ggF and VH processes with up to one additional parton by employing the MINLO [38–40] approach. In a subsequent step, the ggF simulation is improved to next-to-next-to-leading-order (NNLO) [41, 42] accuracy for inclusive observables by reweighting the Higgs boson rapidity spectrum in HJ-MINLO [38–40] to that obtained with HNNLO [43]. The VBF and $t\bar{t}H$ processes are simulated at NLO accuracy in QCD, while the $b\bar{b}H$ sample is generated in the four-flavour scheme. The loop-induced $gg \rightarrow ZH$ process is generated at leading-order in QCD. tH and tHW processes are generated at NLO using the MADGRAPH5_AMC@NLO generator [44]. All signal samples are generated assuming a Higgs boson mass of 125 GeV and a Higgs boson width of 4.07 MeV. A shift of 90 MeV is applied to the signal parameterisation used in the fit to the data to match the measured Higgs boson mass of 125.09 ± 0.24 GeV [6].

The signal events are then interfaced to a parton-shower generator for showering, hadronisation, modelling of the underlying event and decay of the Higgs boson. All signal samples use the PDF4LHC21 Parton Density Function (PDF) set [45] for the ME calculations. The nominal signal samples are interfaced to PYTHIA 8.309 to simulate the $H \rightarrow ZZ^* \rightarrow 4\ell$ decays and use the A14 tune for the parton shower [46] with the NNPDF2.3LO PDF set [47].

Alternative signal samples are produced to assess uncertainties related to parton-shower and hadronisation modelling. These are obtained by interfacing the same POWHEG events to HERWIG 7 [48] with the H7.1 event tune, using the same PDF setup for the ME calculation. In addition, a simulation of the ggF process is generated using the MADGRAPH5_AMC@NLO generator and showered with PYTHIA 8.312 [49] using the A14 tune with the NNPDF2.3LO PDF set. This sample is accurate to NLO in QCD for up to two additional partons merged using the FxFx [44, 50] merging scheme.

The decays of bottom and charm hadrons are simulated using EVTGEN [51].

3.2.2 Signal normalisation and branching ratios

The signal samples are normalised to state-of-the-art theoretical cross-section predictions [52] interpolated to a centre-of-mass energy of 13.6 TeV [53]. The ggF sample is normalised to a N³LO QCD calculation including NLO EW corrections [54–65]. The VBF and VH samples are normalised to an approximate NNLO QCD cross-section with NLO EW corrections [66–76]. The $b\bar{b}H$ contribution is normalised using a calculation that combines NLO contributions with the resummation of collinear logarithms up to NNLO [77, 78], and is cross-checked using an alternative matching scheme [79, 80]. The $t\bar{t}H$ cross-section is taken from a calculation accurate to NLO in QCD with NLO EW corrections [81–84]. tH and tHW are normalized to cross-sections that are accurate to NLO in QCD [85, 86].

The Standard Model prediction for the $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell = e, \mu$) branching ratio is obtained from PROPHECY4F [87, 88]. This prediction includes the full NLO EW corrections and interference effects that lead to a branching ratio approximately 10% higher for same-

³The t -channel processes tH and tHW are denoted by tH in the figures.

flavour final states (4μ and $4e$) than for different-flavour final states ($2e2\mu$ and $2\mu2e$). The predicted SM branching ratio is $(1.24 \pm 0.03) \times 10^{-4}$ for a Higgs boson mass of 125 GeV.

3.2.3 Background modelling

The dominant background contribution arises from continuum $(Z^{(*)}/\gamma^*)(Z^{(*)}/\gamma^*)$ production, and is denoted by ZZ^* . The quark-initiated process ($qqZZ^*$) is the dominant component, while the corresponding gluon-initiated process ($ggZZ^*$) provides a smaller contribution of the order of 10%. Additional background contributions arise from events with non-prompt or misidentified leptons, including those from Z boson production in association with jets (Z +jets), top-quark pair-production ($t\bar{t}$), and WZ production. Additional minor backgrounds include $t\bar{t} + \ell\ell$ and triboson (WWZ , WZZ , ZZZ) production.

Continuum $ZZ^* \rightarrow 4\ell$ production. The nominal $qqZZ^*$ sample is simulated using the SHERPA 2.2.14 [89] generator, including off-shell effects. Matrix elements for fully leptonic final states are calculated at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional partons. These matrix elements are matched and merged with the SHERPA parton shower, based on Catani–Seymour dipole factorisation [90, 91], using the MEPS@NLO prescription [92–95]. Virtual QCD corrections are provided by the OPENLOOPS library [96–98]. The NNPDF3.0NNLO PDF set [99] is used, together with the dedicated tune.

An alternative $qqZZ^*$ sample is simulated using the MADGRAPH5_AMC@NLO generator with the NNPDF3.0NNLO PDF set, accurate to NLO in QCD for zero and one additional parton merged using the FxFx scheme. In this case, parton showering, hadronisation, and underlying-event modelling are performed with PYTHIA 8.308 using the A14 tune with the NNPDF2.3LO PDF set.

The loop-induced $ggZZ^*$ contribution is simulated at NLO accuracy in QCD matched to a parton shower using the POWHEG approach [100] with the NNPDF3.0NLO PDF set. The NLO calculation includes two-loop virtual corrections and loop-squared real contributions, with heavy-quark mass effects included in the virtual corrections. The real matrix elements retain the full top-quark mass dependence [100].

Production of ZZ^* via electroweak vector-boson-scattering-like topologies is simulated at LO using SHERPA 2.2.14 with NNPDF3.0NNLO PDF set, with Higgs-mediated contributions removed at generation level.

Since the overall normalisation of the ZZ^* background is derived from collision data, the MC predicted cross-sections are used only to determine the relative fraction of the three different processes.

top-quark-associated and triboson backgrounds. Minor background contributions include top-quark-associated multilepton production and triboson processes. The production of tWZ , tZq , $t\bar{t}Z$, and $t\bar{t}VV$ is modelled using the MADGRAPH5_AMC@NLO [44] generator at NLO accuracy with the NNPDF3.0NLO PDF set. The events are interfaced to PYTHIA 8.230 using the A14 tune and the NNPDF2.3LO PDF set. The $t\bar{t}W$ process is simulated using SHERPA 2.2.14 with NNPDF3.0NNLO PDF set. The combination of these processes is referred to as tXX . Triboson processes (WWW , WWZ , WZZ , ZZZ) are

simulated using SHERPA 2.2.16, with matrix elements evaluated at NLO accuracy in QCD for up to one additional jet and at LO accuracy for up to three additional jets, merged with the SHERPA parton shower.

Samples for non-prompt lepton background estimates. Simulated samples of Z +jets, $t\bar{t}$, and WZ production are used exclusively to support the data-driven estimate of backgrounds arising from non-prompt or misidentified leptons. The Z +jets samples are generated with SHERPA 2.2.14 following the setup described in ref. [101]. These samples use the NNPDF3.0NNLO PDF set and are normalised to a NNLO QCD prediction [102].

The $t\bar{t}$ process is simulated using the POWHEG BOX v2 generator at NLO accuracy with the NNPDF3.0NLO PDF set and the h_{damp} ⁴ parameter set to $1.5 m_{\text{top}}$ [103]. Events are interfaced to PYTHIA 8.230 using the A14 tune and the NNPDF2.3LO PDF set. The decays of bottom and charm hadrons are simulated using EVTGEN 2.1.1 [51]. The WZ process is modelled using the SHERPA 2.2.16 generator with the same setup as used for the $qqZZ^*$ sample.

3.2.4 Detector simulation and pile-up modelling

All generated signal and background events are passed through a full simulation of the ATLAS detector based on GEANT4 [104, 105]. Scale factors are applied to the simulation to match the performance of algorithms used to reconstruct physics objects to the one observed in data.

The effects of multiple interactions in the same and neighbouring bunch crossings (pile-up) are modelled by overlaying simulated hard-scattering events with inelastic pp collisions generated using a mixture of EPOS 2.0.1.4 [106] and PYTHIA 8.308 [49]. The EPOS events are generated with the EPOS LHC tune [107], while the PYTHIA events use the A3 tune [108] and the NNPDF2.3LO PDF set. The PYTHIA pile-up events include either a high- p_T jet, a prompt photon, or a lepton from a b -hadron decay, whereas EPOS is used to model the remaining pile-up activity. The individual samples are first reweighted to ensure a smooth transition across jet p_T , and the combined pile-up distribution is subsequently reweighted to match the distribution of the average number of interactions per bunch crossing observed in data.

4 Event selection

Higgs boson candidates are formed by selecting quadruplets of reconstructed and identified charged leptons (electrons and muons). The selection procedure follows that of ref. [20] and is briefly summarised below.

4.1 Event reconstruction

Event reconstruction begins with the formation of tracks in the ID [109] from measurements in the silicon detectors and the TRT, and in the MS from measurements in the muon chambers. ID tracks are reconstructed for $p_T > 500$ MeV and are used to form vertex candidates along the beam line [110, 111]. Candidate events are required to contain at least one vertex reconstructed from at least two ID tracks. Among all reconstructed vertices

⁴The h_{damp} parameter is a resummation damping factor and one of the parameters that controls the matching of POWHEG matrix elements to the parton shower and thus effectively regulates the high- p_T radiation against which the $t\bar{t}$ system recoils.

in an event, the primary interaction vertex is defined as the one with the largest summed p_T^2 of its associated tracks.

Electron candidates are reconstructed by matching electromagnetic calorimeter clusters to ID tracks [112]. A refit of the ID track, allowing for bremsstrahlung energy losses, is performed to improve the impact-parameter⁵ resolution. Electron identification is based on a likelihood discriminant [113], using *loose* criteria that combine track properties, electromagnetic shower-shape variables, and the quality of the track–cluster matching. Electrons are required to satisfy $p_T > 7$ GeV and $|\eta| < 2.47$. The electron energy is calibrated following the procedure described in ref. [112]. Photons are reconstructed from EM calorimeter signals exceeding noise thresholds using dynamic topological clustering, with additional clusters included for photon conversion products when applicable [112]. The photon candidates are calibrated [114] and identified by an algorithm that relies on the shape of the EM showers reconstructed in the calorimeter [113].

Muon candidates are reconstructed in the pseudorapidity range $|\eta| < 2.5$ by matching tracks reconstructed in the MS to ID tracks. In the region $|\eta| < 0.1$, where the MS is only partially instrumented, muons are additionally reconstructed from ID tracks matched either to partial MS track segments or to calorimeter energy deposits consistent with a minimally ionising particle (calorimeter-tagged muons) [115]. Muons are required to have $p_T > 5$ GeV, except for calorimeter-tagged muons, which must satisfy $p_T > 15$ GeV. A set of *Loose* identification criteria is applied to suppress muons from hadron decays and misidentified tracks [115]. The muon momentum is calibrated using the procedure described in ref. [116].

Electron and muon candidates are associated with the primary vertex using their impact parameters. Muon candidates with $|d_0| > 1$ mm are rejected to suppress cosmic-ray background. Both electron and muon candidates are required to satisfy $|z_0 \sin \theta| < 0.5$ mm.

Jet candidates are reconstructed using the particle-flow (PFlow) algorithm [117], which combines calorimeter energy deposits and ID tracks into particle-flow objects that are clustered into jets using the anti- k_t [118] jet algorithm with radius parameter $R = 0.4$. Jets are calibrated using simulation with corrections obtained by using *in situ* techniques in data [119]. After calibration, jets are required to satisfy $p_T > 30$ GeV and $|\eta| < 4.5$. To suppress jets originating from pile-up interactions, a neural-network-based algorithm [120, 121] is used to associate jets with $p_T < 60$ GeV to the primary vertex.

Jets containing b -hadrons are identified (b -tagged) using the GN2 transformer-based neural network algorithm [25]. Compared with previous algorithms, GN2 does not rely on lower-level flavour-tagging algorithms and uses a single training to optimise different downstream tasks, including jet identification. It demonstrates improved background rejection at a given efficiency compared with the previous tagger [25]. Two b -tagging working points are used, one with a b -tagging efficiency of approximately 85% and a tighter working point with an efficiency of about 65%. The corresponding light-jet rejections are approximately 6×10^1 and 3×10^3 , respectively.

⁵The transverse impact parameter d_0 of a charged-particle track is defined in the transverse plane as the distance of closest approach to the beam spot. The longitudinal impact parameter z_0 is defined as the distance along the beam axis between this point and the primary vertex.

Ambiguities are resolved if electron, muon, or jet candidates overlap in geometry or share the same detector information. If the two calorimeter energy clusters from the two electron candidates overlap, the electron with the higher p_T is retained. If a reconstructed electron and muon share the same ID track, the muon is rejected if it is calorimeter-tagged; otherwise the electron is rejected. Reconstructed jets geometrically overlapping in a cone of radial size $\Delta R = 0.1$ (0.2) with a muon (an electron) are also removed.

The missing transverse momentum vector, $\vec{p}_T^{\text{miss}}$, is defined as the negative vector sum of the transverse momenta of all the identified and calibrated leptons and jets and the remaining unclustered energy, where the latter is estimated from low- p_T tracks associated with the primary vertex but not assigned to any lepton, photon, hadronically decaying τ -lepton or jet candidate [122]. The missing transverse momentum (E_T^{miss}) is defined as the magnitude of $\vec{p}_T^{\text{miss}}$.

4.2 Higgs boson candidate formation

Higgs boson candidates are formed from pairs of same-flavour, opposite-charge (SFOC) electron or muon pairs. Each such combination, referred to as a quadruplet, is required to include the leptons that triggered the event, as described in section 3.1. The three highest- p_T leptons in the quadruplet are required to satisfy $p_T > 20, 15$, and 10 GeV, respectively.

Further requirements are imposed on the invariant masses of the SFOC lepton pairs. For each quadruplet, the lepton pair with invariant mass m_{12} closest to the Z -boson mass [123] is defined as the leading pair, while the remaining SFOC pair, with invariant mass m_{34} second-closest to the Z -boson mass, is defined as the subleading pair. On the selected SFOC lepton pairs, additional requirements are applied on the angular separation between leptons, a J/ψ veto, the lepton transverse impact-parameter significance ($|d_0|/\sigma(d_0)$), and the quality of the four-lepton vertex. The four leptons are required to be fitted to a common vertex and to be compatible with originating from the same interaction point. In addition, track- and calorimeter-based isolation requirements are applied on the lepton candidates in the pairs to suppress the non-prompt contributions. Those requirements are detailed in ref. [20]. The full set of requirements is summarised in table 1.

If more than one quadruplet with different lepton-flavour combination in an event satisfies all above selection criteria, the candidates containing the leading lepton pair closest to the Z -boson mass are selected. If more than one quadruplet with the same leading lepton pair but different subleading pairs satisfies this criterion, the quadruplet with the lepton-flavour combination corresponding to the highest total expected selection efficiency, as estimated from simulation, is chosen. The expected efficiencies are approximately 28%, 23%, 14%, and 12% for the 4μ , $2e2\mu$, $2\mu2e$, and $4e$ final states, respectively. The $2e2\mu$ and $2\mu2e$ final states are distinguished by the flavour of the leading lepton pair.

If after this selection, an additional lepton, not used in the quadruplet, with $p_T > 12$ GeV is present in the event, it may originate from leptonic decays of vector bosons and top quarks in VH and $t\bar{t}H$ production-modes. To improve the mass resolution in this scenario, a decay-side ME discriminant is calculated at leading-order using MADGRAPH5 for each quadruplet in the event, with the reconstructed lepton four-momenta used as inputs [8],

Leptons and Jets	
Muons	$p_T > 5 \text{ GeV}, \eta < 2.5$
Electrons	$p_T > 7 \text{ GeV}, \eta < 2.47$
Jets	$p_T > 30 \text{ GeV}, \eta < 4.5$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10 \text{ GeV}$
Leading pair (m_{12})	SFOC lepton pair with smallest $ m_Z - m_{\ell\ell} $
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $ m_Z - m_{\ell\ell} $
Event selection (at most one Higgs boson candidate per event)	
Mass requirements	$50 \text{ GeV} < m_{12} < 106 \text{ GeV}$ and $m_{\text{threshold}} < m_{34} < 115 \text{ GeV}$
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5 \text{ GeV}$ for all SFOC lepton pairs
Impact parameter	$ d_0 /\sigma(d_0) < 5$ (3) for electrons (muons)
Isolation	Track- and calorimeter-based isolation for all four leptons
Vertex selection	$\chi^2/N_{\text{dof}} < 6$ (9) for 4μ (other channels)
If extra lepton with $p_T > 12 \text{ GeV}$	quadruplet with largest matrix-element value

Table 1. Summary of the event selection requirements for leptons and Higgs boson candidates. SFOC lepton pairs are same-flavour opposite-charge lepton pairs. For the subleading lepton-pair mass requirement, $m_{\text{threshold}}$ is 12 GeV for $m_{4\ell} < 140 \text{ GeV}$, and increases linearly to 50 GeV at $m_{4\ell} = 190 \text{ GeV}$, remaining constant after [8].

and the quadruplet with the highest ME value is selected. The improvement in correctly identifying the leptons in the quadruplet is about 50% for these cases.

The selected Higgs boson candidates are further refined by accounting for final-state radiation (FSR) photons, using the procedure described in refs. [8, 9]. For electrons, the reconstruction already includes the recovery of nearby FSR photons within $\Delta R < 0.15$ [124]; therefore, only the recovery of far FSR photons is applied to electron candidates. For muons, both nearby and far FSR photons are explicitly recovered.

5 Background estimation

5.1 Background process with prompt leptons

The dominant background contribution arises from continuum ZZ^* production initiated by quarks or gluons. Unlike the Higgs boson signal, the $m_{4\ell}$ spectrum of the ZZ^* background does not exhibit a resonant structure near the Higgs boson mass, m_H . This feature is exploited to constrain the normalisation of the ZZ^* background directly from data.

The shapes of the $m_{4\ell}$ templates and the differential distributions for the ZZ^* background are taken from the simulation described in section 3. The relative contributions of the individual ZZ^* sub-processes are fixed to their simulated expectations, while the overall normalisation is left free in the statistical model through one or more scale factors defined relative to the MC-predicted yields. The binning of these scale factors differs between the two measurements and is described below.

The ZZ^* normalisation is constrained using signal-depleted sideband regions defined by $105 < m_{4\ell} < 115$ GeV and $130 < m_{4\ell} < 160$ GeV. These regions are representative of the continuum background process under the Higgs boson peak and avoid the resonant $Z \rightarrow 4\ell$ process before 105 GeV and the fully resonant ZZ production after 160 GeV.

For the fiducial cross-section measurements, including differential observables, the full fit is performed over the full mass range $105 < m_{4\ell} < 160$ GeV. For differential measurements, the ZZ^* normalisation is determined independently in each bin of the measured observable. To reduce the impact of statistical fluctuations in categories with low expected event yields, the normalisation parameters of neighbouring bins are combined together. For the production-mode cross-section measurements in the STXS framework, the low and high mass sideband regions are merged together in $m_{4\ell}$ but are further categorised according to the reconstructed jet multiplicity ($N_{\text{jets}} = 0, 1$, and ≥ 2) to reduce theoretical assumptions on extrapolating results between different regions. Signal-region categories with the same jet multiplicity are fitted simultaneously with their corresponding sideband regions, using a common ZZ^* normalisation parameter for each jet-multiplicity category.

This strategy substantially reduces theoretical uncertainties in the ZZ^* background prediction for both measurements, as the statistical model primarily relies on data to constrain the normalisations, leaving only the relative normalisation between the signal and sideband regions and the modelling of the differential shapes dependent on theoretical assumptions.

Top-quark-associated background processes are treated differently in the two measurement strategies. In the fiducial and differential cross-section measurements, their contribution is small and is therefore taken directly from simulation. In the production-mode cross-section measurements analysis, where sensitivity to $t\bar{t}H$ production is enhanced, a dedicated control region is included in the fit to constrain the normalisation of these processes. A single normalisation parameter is determined in a simultaneous fit to the $t\bar{t}H$ signal regions and the control region, defined following the Run 2 analysis strategy described in ref. [8]. In this control region, the upper bound of the $m_{4\ell}$ selection is extended to 350 GeV to improve the statistical precision of the constraint, while avoiding the fully resonant top-associated production.

Contributions from triboson production are taken directly from simulation in all regions considered.

5.2 Background process with non-prompt leptons

A small contribution to the selected 4ℓ sample arises from events with two or three prompt leptons accompanied by additional non-prompt leptons from heavy-flavour hadron decays, light-jet misidentification, or photon conversions (including final-state radiation), primarily from Z +jets, $t\bar{t}$, and WZ production. Non-prompt muons typically originate predominantly from heavy-flavour hadron decays, while non-prompt electrons originate from light-jet misidentification and photon conversions. Such non-prompt leptons are typically produced around or nearby hadronic activity and therefore have a higher probability to fail the isolation and/or impact-parameter requirements used in the signal selection. This background is referred to as *reducible* and is estimated with a data-driven fake-factor method, following approaches used in other four-lepton final-state analyses [125, 126].

The method is based on two nested lepton definitions: *baseline* leptons satisfy the full signal selection described in section 4, except for the isolation and impact-parameter requirements, while *tight* leptons additionally satisfy these requirements. The fake efficiency f is defined as the probability for a non-prompt (fake) baseline lepton to also satisfy the tight requirements, and is measured in data after subtracting the expected prompt-lepton contamination. The fake factor (F) is then defined as

$$F = \frac{f}{1 - f}, \quad (5.1)$$

relating the yield of events with tight fake leptons to the yield of events in which the corresponding leptons fail to satisfy the tight requirements.

The fake factors are measured in two control regions enriched in reducible background: a Z +jets-dominated region (CR_Z) and a $t\bar{t}$ -dominated region (CR_{top}). In both regions, a tight lepton pair is required together with an additional baseline lepton. In CR_Z , the tight pair is required to be same-flavour opposite-sign with an invariant mass close to m_Z , while in CR_{top} the tight pair is required to be an $e\mu$ pair and the event must contain at least one b -tagged jet using the working point with 85% efficiency. Prompt-lepton contamination in the measurement regions is dominated by WZ production. Its contribution is estimated in each CR applying a scale factor (SF) to correct the WZ MC estimate with data. This SF is extracted from a dedicated region (CR_{WZ}) that requires a SFOC tight lepton pair with an invariant mass close to m_Z and one extra tight lepton.

The fake factors are parameterised separately for electrons and muons in a three-dimensional map of the lepton p_T , $|\eta|$, and jet multiplicity. The final fake efficiency in the signal region (SR) is obtained by combining the measurements from CR_Z and CR_{top} with equal weights,

$$f^{\text{SR}} = 0.5 f^{\text{CR}_Z} + 0.5 f^{\text{CR}_{\text{top}}}, \quad (5.2)$$

while for the 0-jet category $f_{0j}^{\text{SR}} = f_{0j}^{\text{CR}_Z}$, since the CR_{top} definition requires the presence of b -tagged jets. While the compositions for the origin of the non-prompt lepton in the signal region are more similar to those observed in CR_{top} , an equal-weighted average is used to ensure a robust estimate as weighting according to the composition increases sensitivity to statistical variation from CR_{top} , which has significantly lower event yields than CR_Z . However, as described in section 7, the full difference between two regions is included as a conservative systematic uncertainty to account for the composition difference. This systematic uncertainty has a negligible impact on the final results.

The reducible-background yield in the signal region is estimated by applying fake-factor event weights to data events that satisfy the nominal quadruplet selection but contain at least one baseline lepton failing to meet the tight requirements, after subtracting residual prompt contributions from simulation.

The procedure is validated in two additional regions that are kinematically close to the signal region but enriched in the reducible background: a same-charge region requiring the leptons of the subleading pair to have the same charge, and an $e\mu$ region requiring one lepton pair to be an $e\mu$ pair, with all other selections identical to the signal region. To

reduce statistical fluctuations in the signal region, a smoothing procedure is applied and the corresponding statistical uncertainty is evaluated using pseudo-datasets.

6 Analysis overview

The analysis performs two complementary measurements of the Higgs boson cross-section in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel. In the first approach, inclusive and differential cross-sections are measured in a fiducial phase space designed to closely mirror the detector-level selection, thereby minimising extrapolation and reducing the dependence on theoretical assumptions. In this measurement, the relative contributions of the different Higgs boson production-modes are fixed to the Standard Model expectation when deriving acceptance and migration corrections. Signal yields are extracted from maximum-likelihood fits to the reconstructed $m_{4\ell}$ spectrum, and detector effects are corrected using a likelihood-based matrix unfolding procedure [9] to obtain particle-level results that are as model independent as possible and sensitive to deviations from the Standard Model.

The second, complementary approach aims to measure the underlying Higgs boson production mechanisms. Production-mode cross-sections are measured using event categories and multivariate discriminants optimised for separation of ggF, VBF, VH , and $t\bar{t}H$ contributions, and are interpreted within the STXS framework. The STXS approach provides a common set of phase-space regions that enables increasingly granular measurements, enhancing sensitivity to differences between production kinematics and potential BSM effects.

The following sections describe these two strategies in detail, first presenting the fiducial inclusive and differential cross-section measurement and then the production-mode measurement in the STXS framework. Although both approaches provide an inclusive Higgs boson production cross-section, they do so using complementary combinations and are impacted by different model dependences. In the fiducial analysis, the inclusive cross-section is obtained by combining measurements performed separately in the four decay final states, and depends on the modelling of the relative effects between the 4μ , $2e2\mu$, $2\mu2e$, and $4e$ channels. In the STXS measurement, the inclusive cross-section is obtained by summing the fitted production-mode contributions across the reconstructed categories, and is sensitive to the modelling of the relative signal composition across jet-multiplicity regions and categories.

6.1 Inclusive and differential cross-sections

6.1.1 Fiducial phase space and observables

The fiducial cross-sections are defined at particle level in a phase space chosen to closely match the detector-level event selection, thereby reducing the size of model-dependent acceptance extrapolations and minimising theoretical and experimental uncertainties associated with the unfolding procedure [9]. The fiducial phase space definition is outlined in table 2. Leptons are defined as final-state electrons and muons that do not originate from hadron or τ -lepton decays, after FSR [127]. Leptons are “dressed” by adding the four-momenta of photons within a cone of $\Delta R = 0.1$ around the lepton direction (excluding photons from hadron decays) to the lepton four-momentum [9] to recover energy lost to FSR. Dressed leptons are required to satisfy $|\eta| < 2.7$ and $p_T > 5$ GeV irrespective of flavour to simplify

Leptons and jets	
Leptons	$p_T > 5 \text{ GeV}, \eta < 2.7$
Jets	$p_T > 30 \text{ GeV}, y < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10 \text{ GeV}$
Leading pair (m_{12})	SFOC lepton pair with smallest $ m_Z - m_{\ell\ell} $
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $ m_Z - m_{\ell\ell} $
Event selection (at most one quadruplet per event)	
Mass requirements	$50 \text{ GeV} < m_{12} < 106 \text{ GeV}$ and $12 \text{ GeV} < m_{34} < 115 \text{ GeV}$
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \text{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5 \text{ GeV}$ for all SFOC lepton pairs
If extra lepton with $p_T > 12 \text{ GeV}$	Quadruplet with largest matrix element value
Mass window	$105 \text{ GeV} < m_{4\ell} < 160 \text{ GeV}$

Table 2. Event selection requirements at particle level defining the fiducial phase space for the cross-section measurement. SFOC lepton pairs are same-flavour opposite-charge lepton pairs.

comparisons with theoretical predictions. Particle-level jets are reconstructed from final state neutral and charged particles using the anti- k_t algorithm with radius parameter $R = 0.4$ and are required to satisfy $p_T > 30 \text{ GeV}$ and $|y| < 4.4$. Overlapping jets are removed if $\Delta R(\ell, \text{jet}) < 0.1$ with any selected lepton [9]. Higgs boson candidates are formed from SFOC lepton pairs using the quadruplet selection described in section 4.2, with the exception of the isolation, impact-parameter, and vertex requirements. Events enter the fiducial phase space if a candidate satisfying the mass and kinematic requirements is reconstructed, including $105 < m_{4\ell} < 160 \text{ GeV}$ [9].

Fiducial production cross-sections are measured inclusively and separately for each $H \rightarrow ZZ^* \rightarrow 4\ell$ final state ($4\mu, 2e2\mu, 2\mu2e, 4e$). Differential fiducial cross-sections are measured for eight observables sensitive to the production and decay kinematics of the Higgs boson. The transverse momentum of the four-lepton system, $p_T^{4\ell}$, provides a stringent test of perturbative QCD calculations and is sensitive to modifications of Higgs boson production dynamics. The rapidity of the four-lepton system, $|y_{4\ell}|$, probes the parton distribution functions of the colliding protons and is also affected by QCD radiative corrections. The invariant masses of the leading and subleading SFOC lepton pairs, m_{12} and m_{34} , are sensitive to higher-order electroweak effects and to the decay kinematics of $H \rightarrow ZZ^* \rightarrow 4\ell$. The decay angle between the two Z bosons, ϕ , is sensitive to the Higgs boson spin and parity and to BSM contributions in the HZZ vertex. Jet activity is characterised by the jet multiplicity, N_{jets} , which is sensitive to QCD radiation and to the relative contributions of different production mechanisms. For events with at least two jets, the azimuthal separation of the two leading jets, $|\Delta\phi_{jj}|$, provides additional sensitivity to production dynamics through the structure of associated QCD radiation. In addition, a double-differential measurement of $p_T^{4\ell}$ versus m_{34} is performed, which enhances sensitivity to BSM couplings effects affecting both the production and decay of the Higgs boson.

6.1.2 Signal extraction and unfolding

The fiducial cross-section σ_j^{fid} in each bin j of a differential distribution (or, for the inclusive measurement, in each decay final state) is obtained from a binned maximum-likelihood fit of signal and background templates to the $m_{4\ell}$ spectrum. The fit is performed simultaneously over all the reconstruction bins i of the corresponding observable. The expected number of events in reconstruction bin i , expressed as a function of $m_{4\ell}$, is given by

$$N_i(m_{4\ell}) = \sum_j \sigma_j^{\text{fid}} \cdot \mathcal{P}_i(m_{4\ell}) \cdot r_{ij} \cdot (1 + f_i^{\text{nonfid}}) \cdot \mathcal{L} + N_i^{\text{bkg}}(m_{4\ell}) \quad (6.1)$$

where $\sigma_j^{\text{fid}} = \sigma_j \cdot a_j \cdot \mathcal{B}$. Here, σ_j is the total production cross-section in particle-level bin j , a_j is the particle-level acceptance of the fiducial selection in that bin, and $\mathcal{B}$ is the branching ratio. The integrated luminosity is denoted by $\mathcal{L}$, and $N_i^{\text{bkg}}(m_{4\ell})$ is the background contribution in reconstruction bin i . The term $\mathcal{P}_i(m_{4\ell})$ is the signal $m_{4\ell}$ template for reconstruction bin i taken from simulation. The response matrix element r_{ij} corresponds to the probability that an event generated in fiducial bin j is reconstructed in bin i . The fiducial leakage factor, f_i^{nonfid} , accounts for the fraction of events produced outside the fiducial phase space that are still reconstructed within the detector-level signal region. The factors a_j , r_{ij} , and f_i^{nonfid} are derived from simulated signal samples, assuming Standard Model production-mode fractions within their associated theoretical uncertainties.

As outlined in section 5, the background contribution $N_i^{\text{bkg}}(m_{4\ell})$ includes the continuum ZZ^* component and smaller prompt and non-prompt backgrounds. To minimise theory dependence, the overall ZZ^* yield is constrained directly from data by including $m_{4\ell}$ sideband regions in the likelihood fit. The remaining prompt and non-prompt contributions are taken from simulation and the data-driven method respectively.

The binning choice mostly follows the previous measurement [9], which was designed to ensure an expected statistical significance per bin of more than two standard deviations for the SM signal process and to minimise migrations between bins. These same criteria are used to define the binning of the new observable $p_{\text{T}}^{4\ell}$ versus m_{34} . In most cases, the bin width is more than twice the experimental resolution. The response matrices for all the variables considered are well-conditioned and therefore no regularisation of the unfolding is applied.

The response matrices for p_{T}^H and N_{jets} are shown in figure 1. The bin-to-bin migrations are quantified by the *purity*, defined as the fraction of reconstructed events in a given bin that originate from the corresponding particle-level bin. The purity is mostly larger than 80% for the observables related to the Higgs decay kinematics, the $p_{\text{T}}^{4\ell}$, $y_{4\ell}$, m_{12} , m_{34} , ϕ and $p_{\text{T}}^{4\ell}$ versus m_{34} . Instead, for the jet-related observables, N_{jets} and $|\Delta\phi_{jj}|$, migrations are larger due to the jet energy resolution and residual pile-up effects, reducing for example the purity in the highest jet-multiplicity bin to 66%. The fiducial leakage mostly ranges from 1% to 2%, depending on the bin of the unfolded observable or the decay final state. Only the first bin of the m_{12} and the last bin of the m_{34} observables reach values of 4% and 6% respectively.

6.2 Production-mode cross-sections

The cross-sections are also probed separately for four different Higgs boson production-modes: gluon–gluon fusion, vector-boson fusion and associated production with vector bosons or top quark pairs.

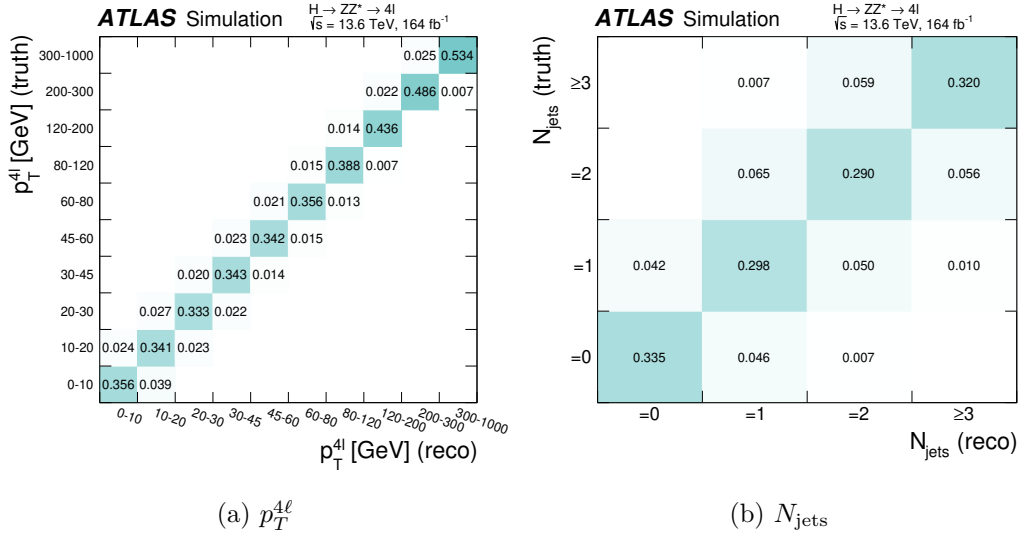


Figure 1. Response matrices, derived from simulation, for (a) the transverse momentum of the four-lepton system $p_T^{4\ell}$ and (b) the jet multiplicity N_{jets} . The response matrix is used in the unfolding procedure (eq. (6.1)). The elements r_{ij} correspond to the probability that an event generated in fiducial bin j is reconstructed in bin i . Only reconstructed events that are matched to particle-level (“truth”) events are included. Bins with values below 0.005 are omitted for clarity.

6.2.1 Simplified template cross-sections

In the STXS framework [22, 23, 128], Higgs boson production cross-sections are measured in exclusive particle-level regions (production bins) designed to minimise the impact of theoretical uncertainties that would otherwise enter through acceptance extrapolations, while retaining sensitivity to production dynamics and potential BSM effects. Two alternative STXS binnings are considered: a production-mode (also referred to as Stage-0) measurement, in which cross-sections are extracted for the four dominant production-modes (ggF, VBF, VH , and $t\bar{t}H$), and a Reduced Stage-1.2 measurement that provides additional kinematic information by subdividing production according to jet activity and Higgs boson kinematics. Bins are merged relative to the full binning where required by the statistical precision. All production bins are defined for Higgs bosons with rapidity $|y_H| < 2.5$, and no requirements are placed on particle-level leptons. Particle-level jets are used for this categorisation and are built using the anti- k_t algorithm with $R = 0.4$ from stable particles (lifetime $c\tau > 10$ mm) and are required to satisfy $p_T > 30$ GeV with no rapidity restriction; Higgs decay products and leptons/neutrinos from leptonic V decays are excluded from the jet clustering, while hadronic V decay products are included [23].

In the production-mode measurement, contributions from $b\bar{b}H$ are included in the ggF bin and contributions from $t\bar{t}H$ are included in the $t\bar{t}H$ bin, with their relative fractions fixed to SM predictions. VH events with hadronic V decays are retained in a dedicated VH bin [22]. For the Reduced Stage-1.2 measurement, the ggF and $gg \rightarrow ZH$ (hadronic Z) contributions are split by p_T^H and jet multiplicity, including a dedicated high- p_T^H bin with $p_T^H \geq 200$ GeV to enhance sensitivity to BSM effects. The electroweak qqH contribution (including VBF and hadronic VH) is further partitioned using p_T^H and the dijet invariant mass m_{jj} , defining

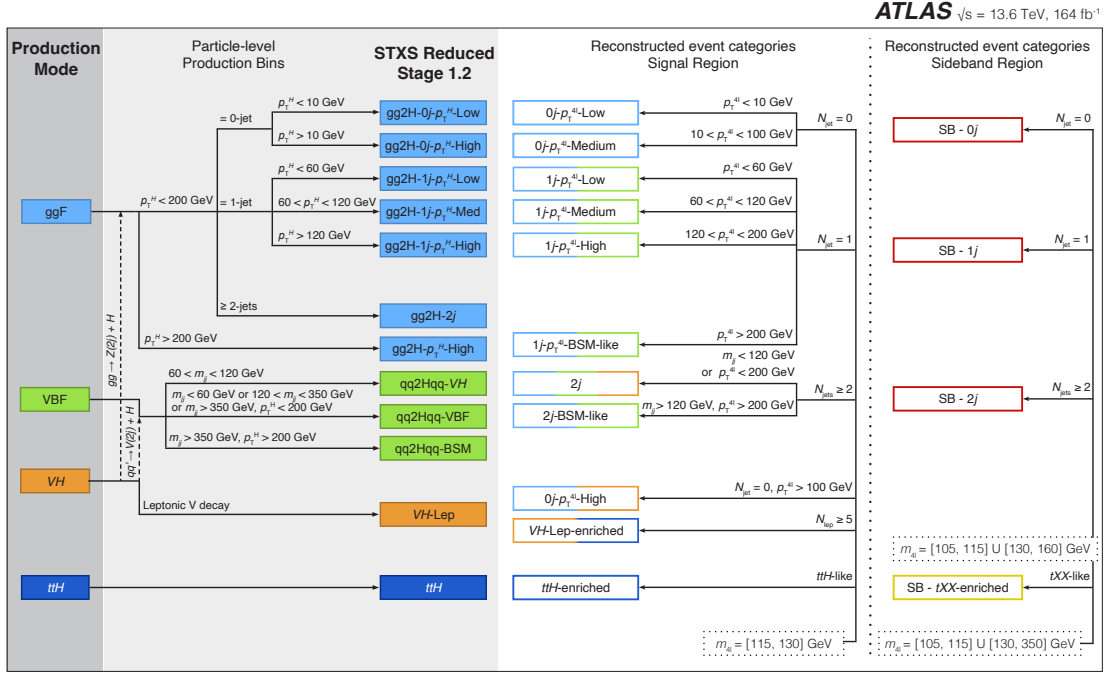


Figure 2. Two sets of exclusive phase-space regions (production bins) are defined at particle level for the measurement of the Higgs boson production cross-sections: the production-mode Stage 0 and the Reduced Stage 1.2 scheme (left and middle-left shaded panels). The corresponding reconstructed event categories are shown for signal (middle-right panel) and sidebands (right panel). The description of the production bins is given in section 6.2.1, while the reconstructed signal-region and sideband event categories are described in section 6.2.2. The $b\bar{b}H$ ($t\bar{t}H$) contribution is included in the ggF ($t\bar{t}H$) production bins. The colours of each reconstructed event-category box indicate the relevant production processes that contribute to the reconstructed category. The reconstructed signal categories are defined sequentially from bottom to top, such that each event is assigned to the first category whose selection criteria are satisfied.

a BSM-sensitive region with $p_T^H \geq 200$ GeV and $m_{jj} > 350$ GeV, a VH -like region with $60 < m_{jj} < 120$ GeV, and a remaining region targeting VBF, while VH with leptonic V decays is treated separately as VH -Lep. The $t\bar{t}H$ production bin definition is unchanged with respect to the production-mode interpretation.

The exact definitions of the STXS production bins and the corresponding labels used in this analysis are shown on the left grayed panel of figure 2.

6.2.2 Event categorisation

Signal-region events with a reconstructed Higgs boson candidate in $115 < m_{4\ell} < 130$ GeV are assigned to mutually exclusive categories sensitive to different production bins in the STXS framework, in a sequential procedure, following the ordering shown in figure 2. Events are first tested against the $t\bar{t}H$ -enriched selection, which targets $t\bar{t}H$ production using requirements on additional leptons and/or high jet and b -tag multiplicities. In particular, events are selected if they contain at least one additional isolated lepton with $p_T > 12$ GeV and satisfy at least

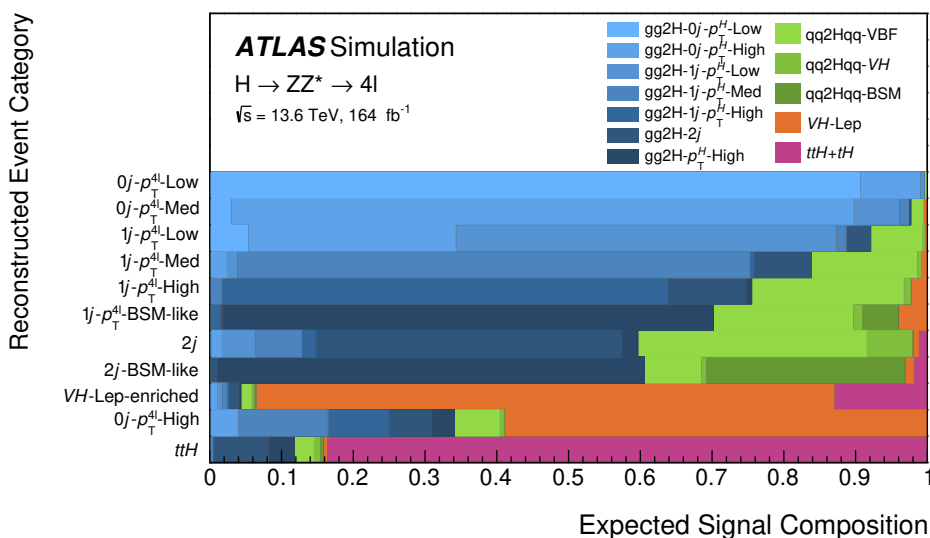


Figure 3. Standard Model signal composition in terms of the Reduced Stage-1.2 production bins in each reconstructed event category. The $b\bar{b}H$ and tH contributions are included in the ggF and ttH production bins, respectively.

one of the following: at least two b -tagged jets at the 85% working point, at least five jets with at least one b -tagged jet at the 85% working point, or at least two jets with at least one b -tagged jet at the 65% working point. Events without an additional isolated lepton can also enter the ttH -enriched selection if they satisfy tighter jet and b -tag requirements, namely at least five jets with at least two b -tagged jets at the 85% working point, or at least four jets with at least one b -tagged jet at the 65% working point.

Events with additional isolated leptons that do not satisfy the ttH -enriched selection define the VH category targeting leptonic vector-boson decays (VH -Lep-enriched). The remaining events are then categorised by jet multiplicity ($N_{\text{jets}} = 0, 1$, or ≥ 2) and further subdivided using p_T^H and, for events with at least two jets, the dijet invariant mass m_{jj} to target specific STXS production bins. Events with at least two jets are separated into a BSM-like category at high p_T^H and large m_{jj} and a complementary category that contains the bulk of the VBF/ VH contributions in addition to ggF. Both the 0-jet and 1-jet regions are further split into low-, medium-, and high- p_T^H intervals.

Sideband categories in $m_{4\ell}$ are defined to constrain the dominant non-resonant ZZ^* background in different jet multiplicity regions (SB-0j, SB-1j, and SB-2j) and the top-quark-associated tXX background (SB- tXX -enriched) as described in section 5.

The definitions of the reconstruction categories and the corresponding names used in this analysis are shown on the right panel of figure 2. The composition of production-modes per reconstructed event category of these categories is shown in figure 3.

6.2.3 Multivariate discriminants and signal extraction

In the STXS measurement, several Higgs boson production mechanisms contribute to each reconstructed event category, together with multiple background processes. To enhance

the separation power beyond the cut-based categorisation, multivariate discriminants are constructed using neural networks (NNs) based on a Set Transformer architecture [129]. The networks are trained independently in each reconstructed category on simulated samples of the relevant Higgs-boson production modes and dominant non-Higgs-boson backgrounds, and are optimised to classify events according to their most likely signal-production or background process. The NN inputs are organised into event-level global observables and sets of reconstructed physics objects. Lepton and jet information is provided as variable-length sets to Set Transformer blocks, which provide permutation-invariant processing through attention mechanisms [24], while global variables are combined with the learned set representations in a classifier head. Each of the NN output nodes is labelled as NN_P , where P refers to one or multiple targeted processes, and is related to the probability of an event originating from that process. The specific feature choices, the corresponding training targets and the output nodes follow the strategy outlined in table 3. Good agreement between data and simulation is observed for the input variables used in the NN training, as illustrated in figure 10. In addition, validation studies are performed in ZZ^* -enriched control regions to verify that the NN outputs are well modelled and that no overtraining or simulation-specific features are learned. In categories with limited statistical power, no NN discriminant is applied and only the observed yield enters the fit.

The STXS cross-sections are obtained from a simultaneous binned likelihood fit to the discriminant distributions across all reconstructed signal categories defined in section 6.2.2, with the dominant background processes constrained as described in section 5. The parameters of interest are collected in a vector $\vec{\sigma}$ and are related to the reconstructed event yields N_{ik} in a histogram bin k of the discriminating observable in reconstructed category i via

$$N_{ik} = \vec{A}_{ik} \cdot \vec{\sigma} \cdot \mathcal{B} \cdot \mathcal{L} + N_{ik}^{\text{bkg}}, \quad (6.2)$$

where $\mathcal{B}$ is the $H \rightarrow ZZ^* \rightarrow 4\ell$ branching ratio, $\mathcal{L}$ is the integrated luminosity, and N_{ik}^{bkg} is the expected background contribution. The vector $\vec{A}_{ik}$ contains the signal selection factors that map particle-level STXS bins to reconstructed categories and discriminant bins, and is determined from MC simulation. In the Stage-0 interpretation, the components of $\vec{\sigma}$ (and thus of $\vec{A}_{ik}$) correspond to the chosen set of production-mode cross-sections, while in the Reduced Stage-1.2 interpretation they correspond to bins defined in section 6.2.1. In both cases, each factor A_{ik}^j is defined as the fraction of generated signal events in STXS bin j that satisfy the reconstruction and event selection and populate histogram bin k of the discriminant observable in reconstructed category i .

6.3 Statistical method

All measurements are performed with a binned profile-likelihood-ratio fit [132]. The likelihood is built as product of Poisson terms for the fitted discriminant distributions in each differential bin or STXS category, and includes nuisance parameters that account for experimental and theoretical systematic uncertainties affecting the normalisation and shapes of the signal and background templates (section 7). The parameters of interest are the cross-sections and the background normalisation factor introduced in sections 6.1 and 6.2 and are extracted by minimising $-2 \ln \lambda$, where λ is the profile likelihood ratio. The asymptotic approximation [132]

Category	Process	Global inputs	Lepton set inputs	Jet set inputs	Discriminant
0j- $p_T^{4\ell}$ -Low 0j- $p_T^{4\ell}$ -Med	ggF, ZZ^*	$\eta_{4\ell}, p_T^{4\ell}, D_{ZZ^*}, m_{12}$ $m_{34}, \cos\theta^*, \cos\theta_1, \phi_{ZZ}$	p_T^ℓ, η_ℓ	–	NN_{ggF}
1j- $p_T^{4\ell}$ -Low 1j- $p_T^{4\ell}$ -Med	ggF, VBF, ZZ^*	$p_T^{4\ell}, p_T^j, \eta_j, D_{ZZ^*}$ $\Delta R_{4\ell,j}, \eta_{4\ell}, E_T^{\text{miss}}$	p_T^ℓ, η_ℓ	–	$NN_{\text{ggF+VBF}}$ for $NN_{ZZ} < 0.2$ NN_{ZZ} for $NN_{ZZ} > 0.2$
1j- $p_T^{4\ell}$ -Med 1j- $p_T^{4\ell}$ -High	ggF, VBF, ZZ^* ggF, VBF	$p_T^{4\ell}, p_T^j, \eta_j, D_{ZZ^*}$ $\Delta R_{4\ell,j}, \eta_{4\ell}, E_T^{\text{miss}}$ $p_T^{4\ell}, p_T^j, \eta_j, D_{ZZ^*}$ $\Delta R_{4\ell,j}, \eta_{4\ell}, E_T^{\text{miss}}$	p_T^ℓ, η_ℓ	–	$NN_{\text{ggF+VBF}}$ for $NN_{ZZ} < 0.2$ NN_{ZZ} for $NN_{ZZ} > 0.2$ NN_{ggF}
2j	ggF, VBF, VH ZZ^*, tXX	$m_{jj}, p_T^{4\ell jj}, \eta_{ZZ}^{\text{zepp}}$	p_T^ℓ, η_ℓ	p_T^j, η_j, m_j	$NN_{\text{ggF+ZZ+tXX}}$ for $NN_{VH} < 0.3, NN_{\text{VBF}} < 0.1$ NN_{VBF} for $NN_{VH} < 0.3, NN_{\text{VBF}} > 0.1$ NN_{VH} for $NN_{VH} > 0.3, NN_{\text{VBF}} < 0.1$
2j-BSM-like	ggF, VBF	$m_{jj}, p_T^{4\ell jj}, \eta_{ZZ}^{\text{zepp}}$	p_T^ℓ, η_ℓ	p_T^j, η_j, m_j	NN_{VBF}

Table 3. Input variables used for the neural-network trainings in the reconstructed STXS categories that use binned NN discriminants. The inputs are grouped into event-level *global* variables and object-level variables provided as variable-length *lepton* and *jet* sets to Set Transformer blocks. Here, $p_T^{4\ell}$ and $\eta_{4\ell}$ are the transverse momentum and pseudo-rapidity of the four-lepton system; m_{12} and m_{34} are the invariant masses of the leading and subleading same-flavour opposite-charge lepton pairs; D_{ZZ^*} denotes the kinematic discriminant against non-resonant ZZ^* production; $\cos\theta^*, \cos\theta_1$, and ϕ_{ZZ} are decay-angle observables defined as in ref. [130]; p_T^j and η_j are the transverse momentum and pseudorapidity of the leading jet; m_{jj} is the dijet invariant mass; $p_T^{4\ell jj}$ is the transverse momentum of the four-lepton plus dijet system; and $\eta_{ZZ}^{\text{zepp}} = |\eta_{4\ell} - \frac{\eta_{j1} + \eta_{j2}}{2}|$ is the Zeppenfeld variable of the four-lepton system relative to the two leading jets [131]. $\Delta R_{4\ell,j}$ is the angular separation between the four-lepton system with respect to the leading jet, while E_T^{miss} is the measured missing transverse momentum.

is validated with pseudo-experiments; where fewer than three events are observed in a bin, the quoted uncertainties are corrected to those obtained from pseudo-experiments.

The compatibility of a measured cross-section and its theoretical prediction is tested by computing a p -value based on the difference between the value of $-2 \ln \lambda$ at the best-fit value and the value obtained by fixing the cross-section in each bin to that predicted by SM theory. These p -values do not include the uncertainties in the theoretical predictions.

7 Systematic uncertainties

The dominant uncertainty in the measurement arises from statistical uncertainty. In addition, many systematic uncertainties are considered. Experimental uncertainties arise from object reconstruction, identification, isolation, energy and momentum scale, resolution, and trigger efficiencies, the determination of the integrated luminosity and the data-driven background estimate. Additional theoretical uncertainties are related to the modelling of the signal and background processes.

7.1 Experimental uncertainties

The uncertainty in the integrated luminosity is 1.9% [31]. This affects the signal and background yields predicted by simulation if no normalisation to data is used. The uncertainty due to pile-up modelling is below 2% in the entire $m_{4\ell}$ range considered.

The reconstruction and identification efficiencies for muons and electrons are determined using the methods described in refs. [112, 115]. For muons, these have associated uncertainties between 0.1% and 1.3%. For electrons with $p_T < 15$ GeV conservative uncertainties up to 17% are included to cover the change in detector conditions between Runs 2 and 3 and updates to the simulation. The isolation efficiency uncertainty is approximately 1% for electrons and 0.5 – 2% for muons.

Lepton energy and momentum scale and resolution are corrected to describe the data using the procedures documented in refs. [114, 116], and the associated uncertainties have an impact at the most of 1 – 1.5% on the measured cross-sections.

Jet energy scale and resolution are calibrated using the procedure described in ref. [119]. An additional uncertainty is assigned to jets in the kinematic region of $|\eta| > 3.2$ to account for an observed mismodelling on the jet energy calibration in the forward calorimeters.

Uncertainties in the b -jet identification efficiency are taken from 2022 and 2023 data and applied also to 2024 data and conservatively increased by ten times to account for differences between different data-taking periods. This is done only in the $t\bar{t}H$ category and tXX sideband, where b -jets are required and the impact is at the level of 1%.

Uncertainties in the lepton trigger efficiency have a negligible impact on the analysis, as does the uncertainty on the measured Higgs boson mass of $m_H = 125.09 \pm 0.24$ GeV [14].

For the data-driven measurement of the reducible background, several sources of uncertainty are considered. The dominant contribution arises from the statistical uncertainty in the region containing a quadruplet with at least one baseline lepton failing to meet the tight requirements, where the fake factors are applied. An additional significant contribution comes from the systematic uncertainty associated with the choice of control regions used to derive the fake factors. This uncertainty reflects the variation of the result when the fake factors are extracted using only CR_Z or only CR_{top} , instead of their nominal combination, as described in section 5. Those uncertainties have an impact that ranges from 1% to 9% both in the differential and in the production cross-section measurements. The statistical uncertainty due to the limited statistics in the CRs is also propagated to the fake factor estimate and has a negligible impact on the final yields. Finally, the uncertainty in the WZ contribution is estimated by varying the fitted normalization within its statistical error and has negligible impact on the estimate.

7.2 Theoretical uncertainties

Uncertainties in the signal prediction due to missing higher-order QCD effects are estimated by using the scheme described in ref. [133]. Parton shower and multiple-parton interaction modelling uncertainties on the acceptance are estimated by using a prediction based on HERWIG7 as alternative parton shower generator and using tune eigenvector variations within the nominal parton shower generator tune, A14. Uncertainties related to the PDF set are evaluated using 40 eigenvector variations of the PDF4LHC21 PDF set. An additional

uncertainty of the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay branching ratio of 2.2% [87, 134] is assigned when extrapolating to the total phase-space. These theory-related uncertainties enter the measurements in different ways. These uncertainties generally have small effects on both cross-section measurements, mainly through acceptance and migration. In contrast, for the global strength measurement and interpretation of the results, the parameters of interest (μ) are defined relative to the SM predictions. In this case the same modelling uncertainties propagate directly to the predicted signal yields and have a larger impact.

Uncertainties in the prediction of the ZZ^* background from missing higher-order QCD effects are taken into account by varying the factorisation and renormalisation scales in the calculation by factors of two and choosing the configuration with the largest impact. PDF-related uncertainties are evaluated using the various PDFs within the NNPDF3.0 PDF set using the method outlined in [99]. A further modelling uncertainty is assigned by comparing the prediction from the nominal SHERPA sample to a simulation in MADGRAPH5_AMC@NLO matched to PYTHIA 8 with the FxFx prescription [44, 50]. As this background contribution is normalised to data, only the change in differential shapes impacts the measurements (1–3%), while the effect in the shapes of the NN discriminants and in the relative contribution of this background between the sidebands and the signal regions for the STXS measurement is negligible. For the tXX process, uncertainties due to PDF and missing higher-order QCD effects are estimated from simulation using a similar procedure as the ZZ^* process.

Finally, unfolding-related systematic uncertainties for the inclusive and differential cross-section measurements arise from uncertainties in the production-mode composition that affect the response matrices. Additional uncertainties come from a potential bias introduced by the unfolding method. This bias is evaluated independently in each bin by comparing the unfolded cross-section in simulation with the expected result when the underlying true cross-sections of the simulated sample are varied within their expected statistical uncertainty. The impact of these uncertainties is negligible.

8 Results

Figure 4 shows the expected and observed four-lepton invariant mass distribution $m_{4\ell}$ for all Higgs boson candidates accepted by the event selection. The observed number of events and the expected signal and background yields in the mass range $115 \text{ GeV} < m_{4\ell} < 130 \text{ GeV}$ are presented in table 4 before fitting to the data (pre-fit). The data agree with predictions.

8.1 Inclusive fiducial and total cross-sections

The inclusive fiducial and total cross-sections of the $H \rightarrow ZZ^* \rightarrow 4\ell$ process are measured by combining the results from the four decay final states assuming the relative SM branching ratio and are summarised in figure 5. A normalisation factor of $N/N_{\text{MC}} = 0.94 \pm 0.08$ is obtained for the ZZ^* background component. The fiducial cross-section is measured as

$$\sigma_{\text{fid}} \equiv \sigma \cdot \mathcal{B}(H \rightarrow ZZ^* \rightarrow 4\ell) = 3.65 \pm 0.30(\text{stat.}) \pm 0.18(\text{sys.}) \text{ fb} = 3.65^{+0.35}_{-0.33} \text{ fb},$$

consistent with the SM prediction of $\sigma_{\text{fid}}^{\text{SM}} = 3.68 \pm 0.17 \text{ fb}$. The resulting total cross-section is

$$\sigma_{\text{total}} = 59.3 \pm 4.8(\text{stat.}) \pm 3.1(\text{sys.}) \text{ pb} = 59.3 \pm 5.7 \text{ pb},$$

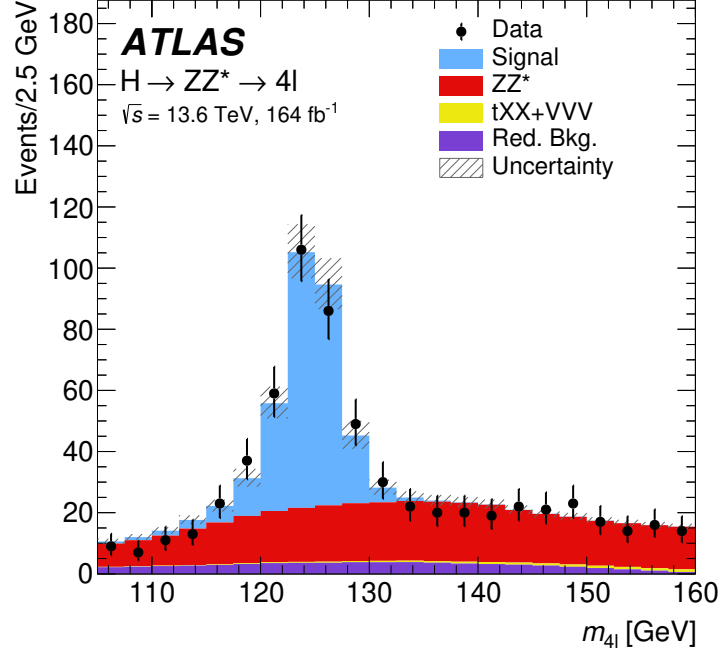


Figure 4. The observed and expected (pre-fit) inclusive four-lepton invariant mass distributions for the selected Higgs boson candidates. The uncertainty in the predictions is shown by the hatched band, which includes the theoretical uncertainties of the SM cross-section for the signal and the background processes.

Final state	Signal	ZZ^*	Other Backgrounds	Total SM	Observed
4μ	90.5 ± 5.3	41.2 ± 1.6	4.5 ± 0.3	136 ± 6	136
$2e2\mu$	63.4 ± 4.0	30.0 ± 1.3	4.7 ± 0.5	98 ± 5	98
$2\mu 2e$	40.7 ± 9.1	15.6 ± 4.4	5.6 ± 0.2	62 ± 13	67
$4e$	36.5 ± 9.2	14.1 ± 4.3	5.3 ± 0.3	56 ± 13	59
Total	231 ± 23	101 ± 10	20.1 ± 1.3	352 ± 32	360

Table 4. Expected (pre-fit) and observed numbers of events in the four decay final states after the event selection, in the mass range $115 \text{ GeV} < m_{4\ell} < 130 \text{ GeV}$. The column ‘Other Backgrounds’ includes the reducible background and other minor sources discussed in section 5. The sum of the expected number of SM Higgs boson events and the estimated background yield is compared with the data. Combined statistical and systematic uncertainties are included for the predictions (see section 7).

consistent with the SM value of $\sigma_{\text{total}}^{\text{SM}} = 59.9 \pm 3.0 \text{ pb}$. The systematic uncertainty in the measurement is dominated by lepton reconstruction and isolation efficiencies. Larger uncertainties in decay channels with electrons in the subleading lepton pair reflect the conservative estimates of uncertainties on electron reconstruction efficiency. In combination with other final states, the impact of this systematic uncertainty is reduced in the inclusive fiducial measurement. The probability of compatibility of the measured fiducial cross-section

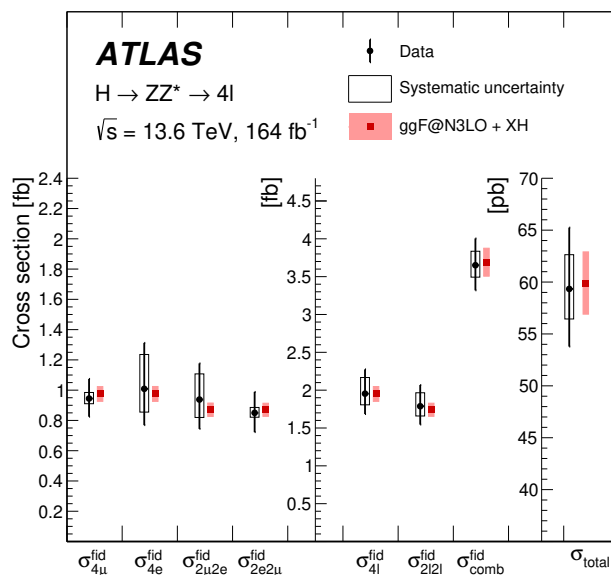


Figure 5. Measured fiducial and total cross-sections: (left panel) fiducial cross-sections for the four individual final states; (middle panel) inclusive fiducial cross-section obtained by combining same-flavour, different-flavour, and all final states assuming relative SM branching ratios; (right panel) total cross-section obtained after accounting for the branching ratio of the Higgs boson into four leptons and the fiducial acceptance as determined from the simulated SM Higgs boson samples. The measurement in data is shown as black circular markers with error bands indicating the total error and boxes indicating the systematic uncertainty. The measurements are compared to theoretical predictions with their associated uncertainties.

and the SM expectation is 92% and for the individual channels it ranges from 75% for $2\mu 2e$ to 90% for $4e$ final states.

8.2 Differential cross-sections

Figure 6 and figure 7 show the expected (pre-fit) and observed distributions of the $p_{\text{T}}^{4\ell}$, $y_{4\ell}$, m_{12} , m_{34} , N_{jets} , $\Delta\phi_{jj}$, ϕ observables used for the differential cross-section measurements, and the $p_{\text{T}}^{4\ell}$ vs. m_{34} distribution used for the double-differential cross-section measurement. The data are found to be largely in agreement with the prediction.

The corresponding measured differential cross-sections obtained from these distributions using the procedure discussed in section 6.1 and the corresponding normalisation factors for the background, N/N_{MC} , are depicted in figure 8 and figure 9. Uncertainties are statistically dominated, and the subdominant systematic component arises primarily from lepton efficiency and (for jet-related observables) jet energy calibration uncertainties. The data are compared with SM expectations constructed from the ggF predictions provided by POWHEG and MADGRAPH5_AMC@NLO, which are normalised to N³LO cross-section as described in section 3.2.2, with k-factors of 1.1 and 1.5 respectively. The uncertainty for POWHEG predictions is estimated from the procedure described in section 7, while those for MADGRAPH5_AMC@NLO are estimated from varying factorisation and renormalisation scales. The probability of compatibility of the measured differential cross-section and the SM

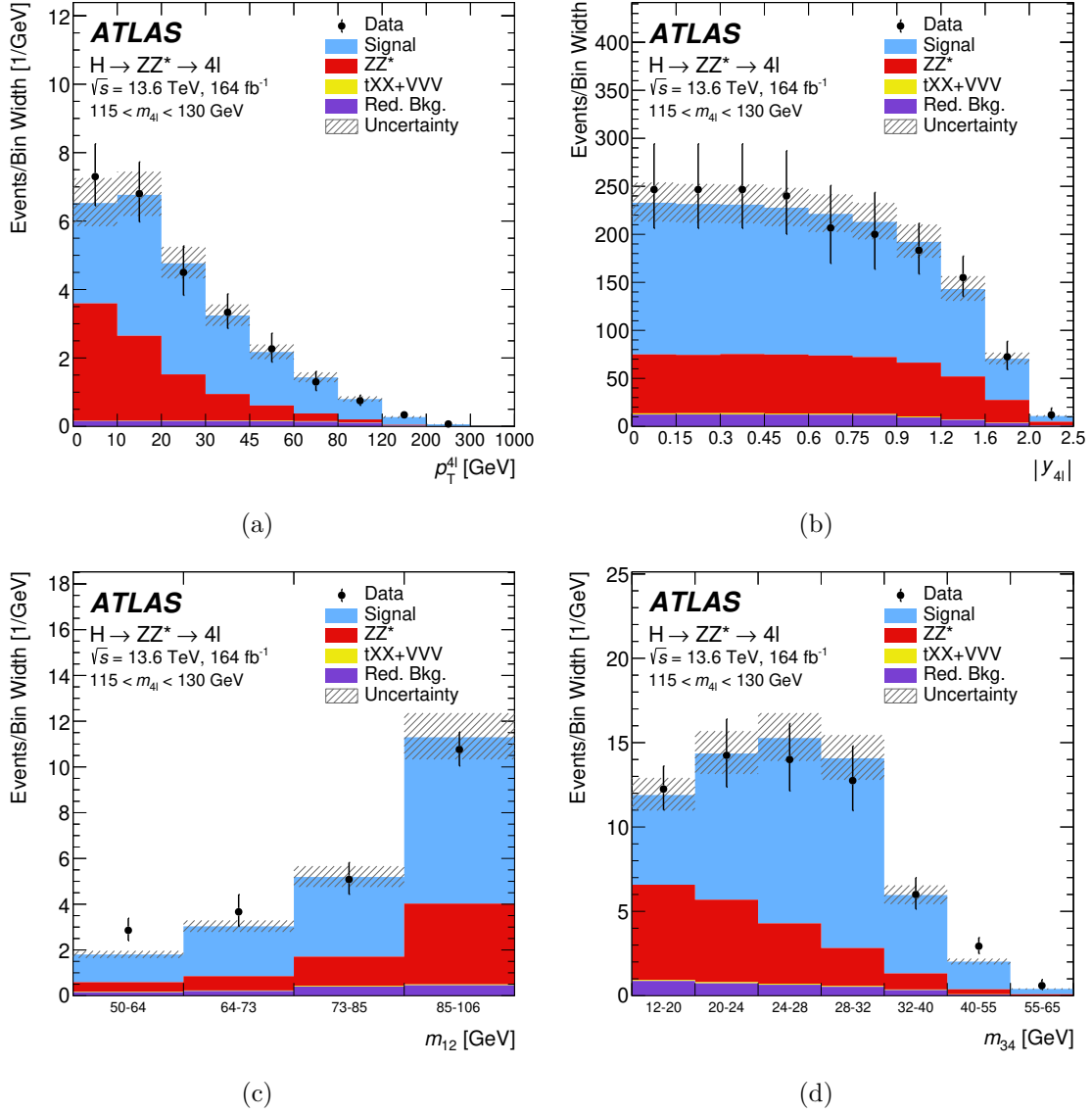


Figure 6. The observed and expected (pre-fit) distributions of (a) $p_T^{4\ell}$, (b) $|y_{4\ell}|$, (c) m_{12} , and (d) m_{34} observables, after the event selection in the mass range $115 \text{ GeV} < m_{4\ell} < 130 \text{ GeV}$. The uncertainty in the predictions is shown by the hatched band, which includes the theoretical uncertainties of the SM cross-section for the signal and the background processes.

expectation ranges from 5% to approximately 100%, with the m_{12} being the least compatible with SM predictions due to a fluctuation in the first bin of the distribution.

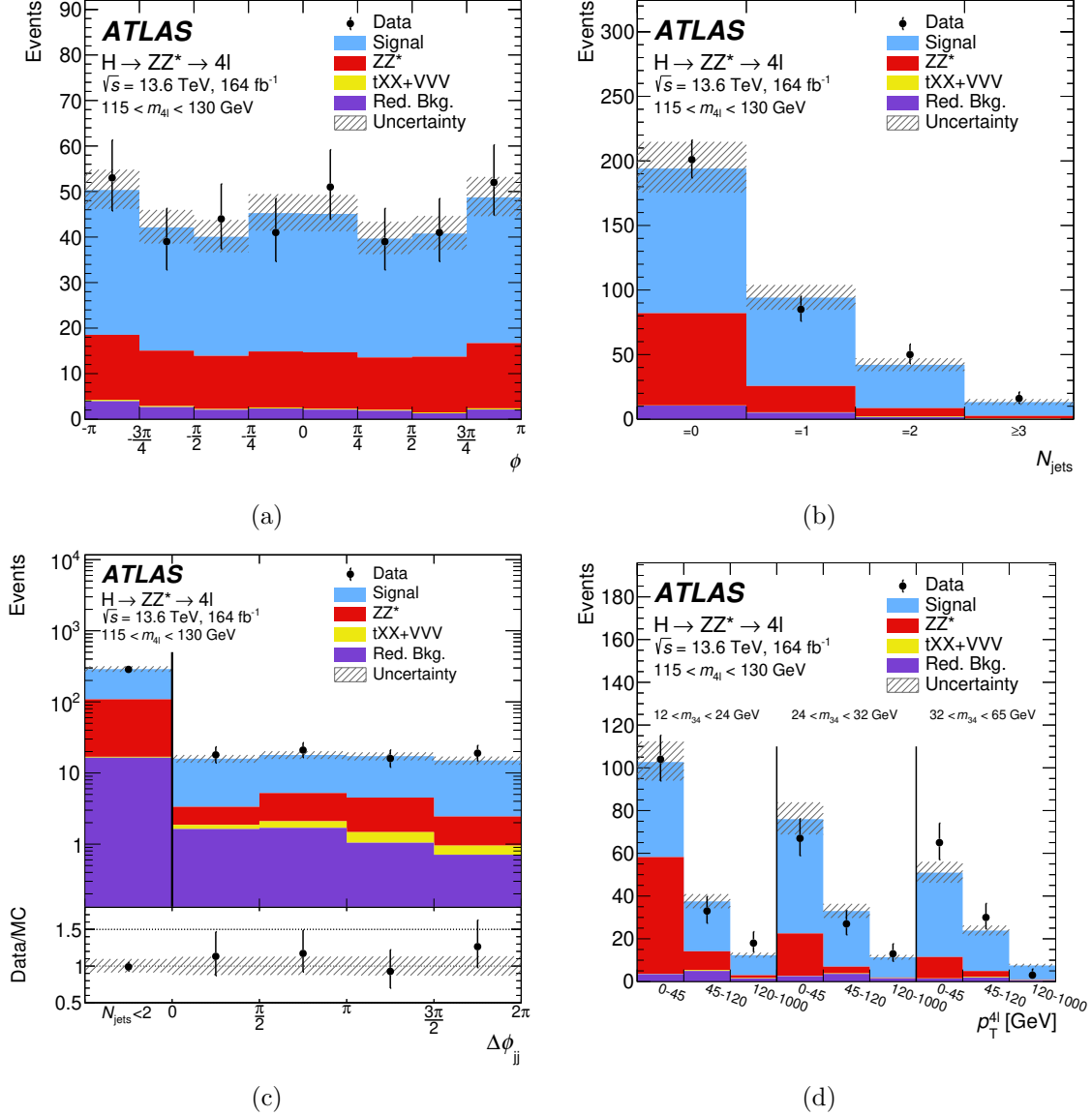


Figure 7. The observed and expected (pre-fit) distributions of (a) ϕ , (b) N_{jets} , (c) $\Delta\phi_{jj}$ and (d) $p_{\text{T}}^{4\ell}$ vs. m_{34} observables, after the event selection in the mass range $115 \text{ GeV} < m_{4\ell} < 130 \text{ GeV}$. The uncertainty in the predictions is shown by the hatched band, which includes the theoretical uncertainties of the SM cross-section for the signal and the background processes.

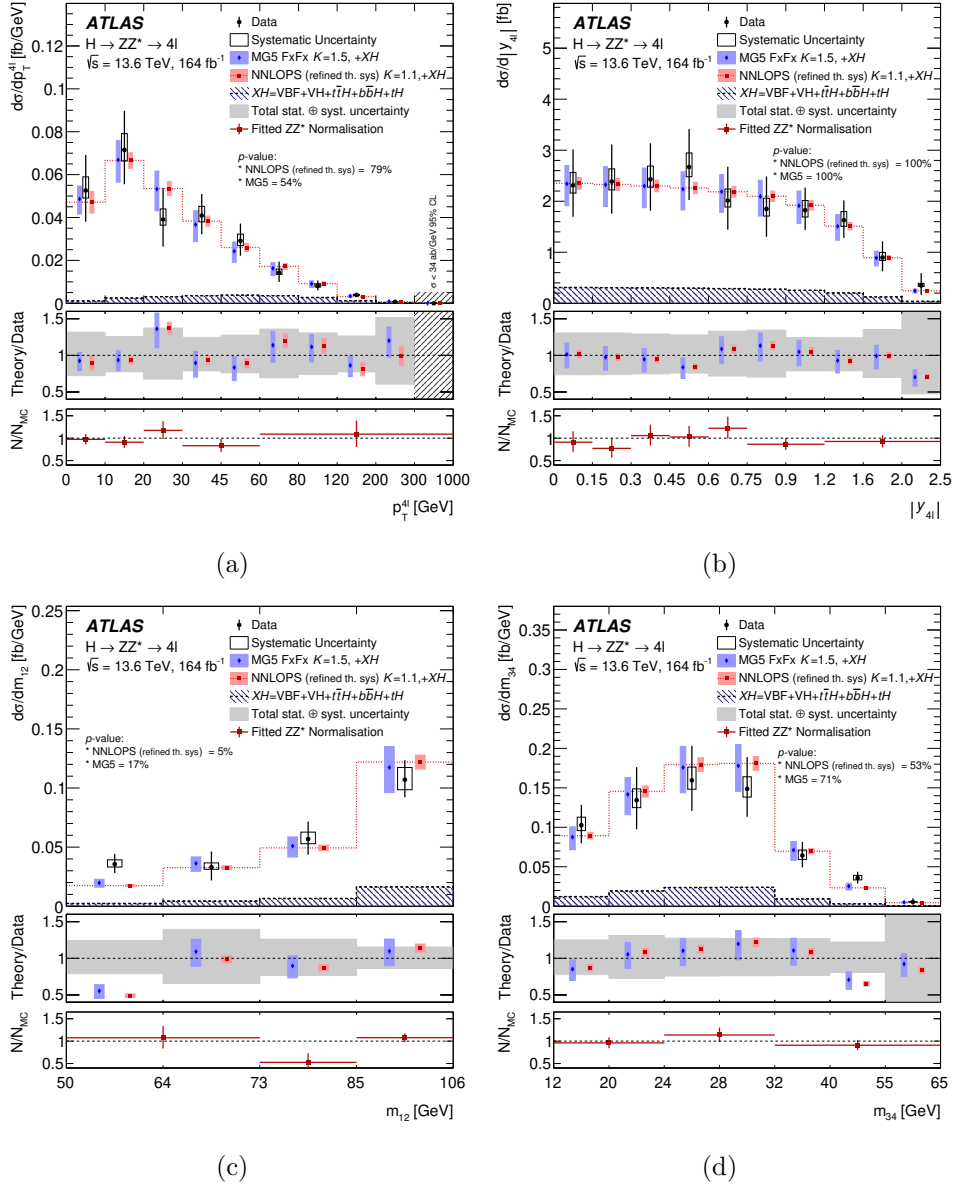


Figure 8. Differential fiducial cross-sections as a function of (a) $p_T^{4\ell}$, (b) $|y_{4\ell}|$, (c) m_{12} , and (d) m_{34} . The upper panel shows the measured cross-sections, compared with ggF predictions by POWHEG (NNLOPS) and MADGRAPH5_AMC@NLO (MG5), which are normalised to the N³LO total cross-section with the listed K -factors. The shaded bands on the expected cross-sections indicate the PDF and scale systematic uncertainties, in particular the ones for NNLOPS are calculated as described in ref. [133], while for MG5 are estimated from varying factorisation and renormalisation scales. The markers denoting the simulation are horizontally displaced relative to the measurement in data to improve readability. MC-based predictions for all other Higgs boson production-modes XH are normalised to the SM predictions. The error bars on the data points show the total uncertainties, while the systematic uncertainties are indicated by the boxes. The middle panel shows the ratio of different predictions to the data, and the grey shaded area represents the total uncertainty of the measurement. The bottom panel shows the ratios of the fitted values of the ZZ^* normalisation factors to the predictions from MC simulation. No data candidates are observed in the final bin of the $p_T^{4\ell}$ distribution in (a), and a 95% CL limit on the cross-section is set as indicated by the hatched lines.

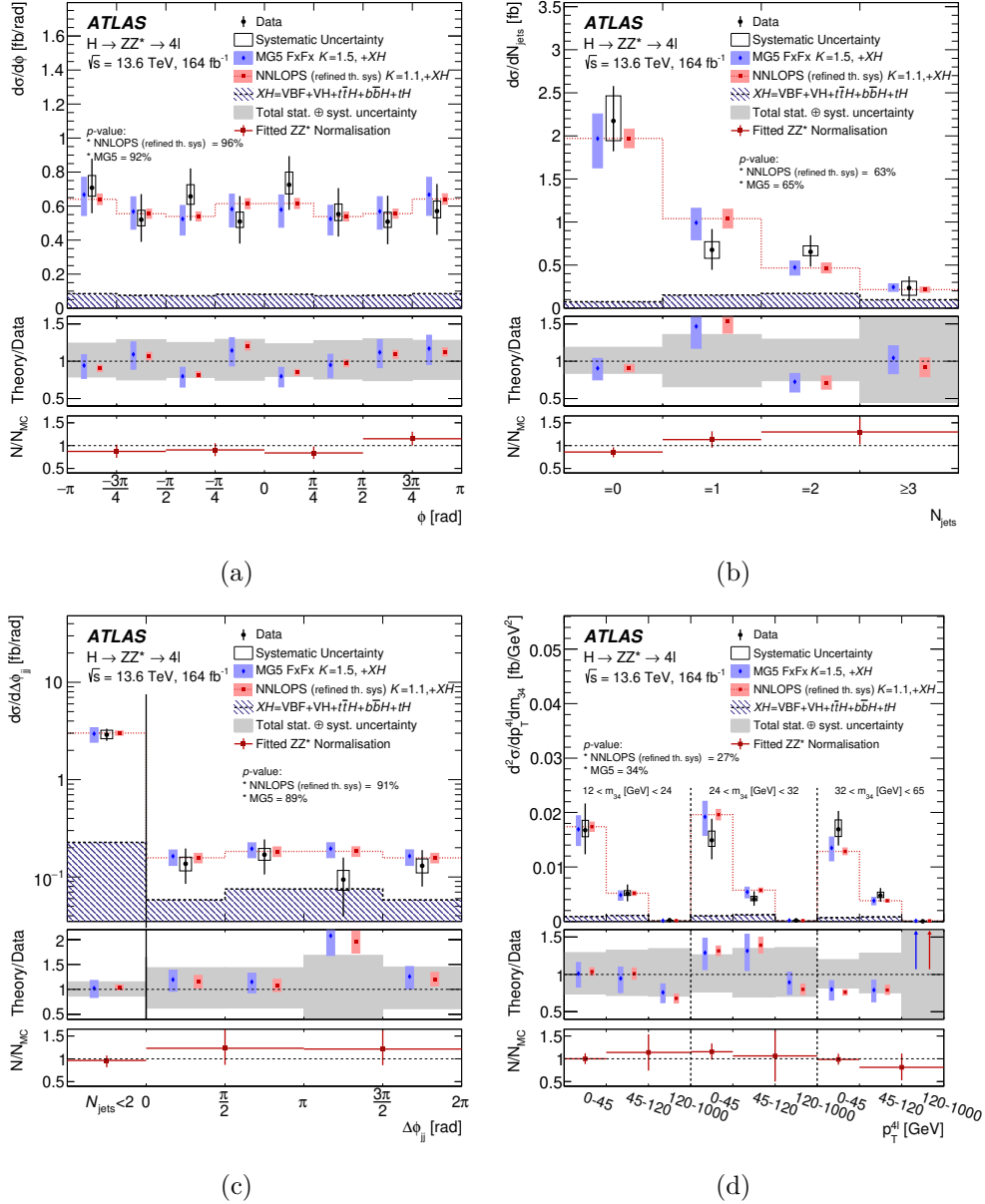


Figure 9. Differential fiducial cross-sections as a function of (a) ϕ , (b) N_{jets} , (c) $\Delta\phi_{jj}$ and (d) $p_T^{4\ell}$ vs. m_{34} . The upper panel shows the measured cross-sections, compared with ggF predictions by POWHEG (NNLOPS) and MADGRAPH5_AMC@NLO (MG5), which are normalised to the N³LO total cross-section with the listed K -factors. The shaded bands on the expected cross-sections indicate the PDF and scale systematic uncertainties, in particular the ones for NNLOPS are calculated as described in ref. [133], while for MG5 are estimated from varying factorisation and renormalisation scales. The markers denoting the simulation are horizontally displaced relative to the measurement in data to improve readability. MC-based predictions for all other Higgs boson production-modes XH are normalised to the SM predictions. The error bars on the data points show the total uncertainties, while the systematic uncertainties are indicated by the boxes. The middle panel shows the ratio of different predictions to the data, and the grey shaded area represents the total uncertainty of the measurement. The bottom panel shows the ratios of the fitted values of the ZZ^* normalisation factors to the predictions from MC simulation.

8.3 Cross-sections per production-mode

For the production cross-section measurement, the expected numbers of signal and background events in each reconstructed event category are shown in table 5 together with the corresponding observed number of events. They are in good agreement. The observed and expected (pre-fit) distributions of the transverse momentum of the leading lepton, the kinematic discriminant D_{ZZ^*} , the transverse momentum of the leading jet and the angular separation between the four lepton system and the leading jet $\Delta R_{4\ell,j}$, which are used as inputs variables for the NN training in the reconstructed categories, are shown in figure 10 and are in good agreement as well.

The observed and expected (post-fit) distributions of the NN discriminants are shown in figure 11 and figure 12. The $1j$ - $p_T^{4\ell}$ -Low category is additionally split into two sub-categories with NN_{ZZ} greater or smaller than 0.2 to target different sub-processes as defined in table 3. Similarly, the $2j$ is divided into three sub-categories with $(NN_{VH} < 0.3, NN_{VBF} < 0.1)$, $(NN_{VH} < 0.3, NN_{VBF} > 0.1)$ and $(NN_{VH} > 0.3, NN_{VBF} < 0.1)$ to target the ggF, VBF and VH processes. In addition, figure 12(e) and figure 12(f) show the observed and expected yields in the categories where no NN discriminant is used and in the mass sidebands used to constrain the ZZ^* and tXX background, respectively. All distributions are in good agreement with the data.

The observed values of $\sigma_{|y_H|<2.5} \cdot \mathcal{B}(H \rightarrow ZZ^*)$ in the Higgs boson rapidity range of $|y_H| < 2.5$, the corresponding expected SM cross-sections, and their ratios are shown in figure 13 for the inclusive production and for the individual production-modes as defined in section 6.2. Similarly, the results for the Reduced Stage 1.2 bins are shown in figure 14. The branching ratio for the $ZZ^* \rightarrow 4\ell$ decay is fixed to the SM prediction, such that $\mathcal{B}(H \rightarrow ZZ^*) = 2.62 \times 10^{-2}$ [22]. In the ratio calculation, uncertainties on the SM expectation are presented separately and not included in the systematics. An inclusive cross-section of

$$\sigma_{|y_H|<2.5} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 1.42 \pm 0.11(\text{stat.}) \pm 0.12(\text{sys.}) \text{ pb} = 1.42 \pm 0.16 \text{ pb}$$

is measured, in agreement with the SM prediction of $\sigma_{|y_H|<2.5}^{\text{SM}} \cdot \mathcal{B}^{\text{SM}}(H \rightarrow ZZ^*) = 1.44 \pm 0.08 \text{ pb}$. Normalisation factors for the ZZ^* continuum background of $N_{ZZ}^{\text{SB-}0j}/N_{\text{MC}} = 0.82 \pm 0.14$, $N_{ZZ}^{\text{SB-}1j}/N_{\text{MC}} = 1.18^{+0.22}_{-0.19}$, and $N_{ZZ}^{\text{SB-}2j}/N_{\text{MC}} = 1.53^{+0.46}_{-0.37}$ are obtained from the sidebands, separately for the three event categories with different jet multiplicities, while the one for the tXX backgrounds from the specific category $N_{tXX}^{\text{SB-}tXX}/N_{\text{MC}} = 2.5^{+0.9}_{-0.7}$.

The data are also interpreted in terms of the global signal strength, where the theoretical uncertainties in the SM cross-section predictions are included in the measurement, yielding

$$\mu = 0.99 \pm 0.08(\text{stat.}) \pm 0.10(\text{sys.}) = 0.99 \pm 0.13$$

The dominant systematic uncertainty in inclusive cross-section measurement is the experimental uncertainty in the lepton efficiency and the integrated luminosity measurements. For the global signal strength measurement theoretical uncertainties in the ggF prediction are dominant.

The dominant contribution to the measurement uncertainty in the ggF production-mode originates from the same sources as in the inclusive measurement and in the Reduced Stage

Reconstructed event category	Signal	ZZ^* background	tXX background	Other backgrounds	Total expected	Observed
Signal	$115 < m_{4\ell} < 130$ GeV					
$0j\text{-}p_{\text{T}}^{4\ell}\text{-Low}$	26 ± 5	31.4 ± 3.2	—	1.750 ± 0.035	59 ± 7	64
$0j\text{-}p_{\text{T}}^{4\ell}\text{-Med}$	85 ± 11	40 ± 4	—	5.86 ± 0.26	131 ± 15	135
$0j\text{-}p_{\text{T}}^{4\ell}\text{-High}$	0.38 ± 0.05	0.041 ± 0.007	0.0243 ± 0.0019	0.149 ± 0.014	0.60 ± 0.06	1
$1j\text{-}p_{\text{T}}^{4\ell}\text{-Low}$	38 ± 5	15.3 ± 2.1	0.112 ± 0.015	3.21 ± 0.33	57 ± 7	54
$1j\text{-}p_{\text{T}}^{4\ell}\text{-Med}$	23.2 ± 3.4	4.3 ± 0.4	0.138 ± 0.019	1.69 ± 0.18	29 ± 4	24
$1j\text{-}p_{\text{T}}^{4\ell}\text{-High}$	5.4 ± 0.9	0.56 ± 0.05	0.047 ± 0.007	0.2861 ± 0.0013	6.3 ± 0.9	7
$1j\text{-}p_{\text{T}}^{4\ell}\text{-BSM-Like}$	1.4 ± 0.4	0.083 ± 0.007	0.0076 ± 0.0010	0.030 ± 0.009	1.5 ± 0.4	0
$2j$	44 ± 7	8.9 ± 1.4	0.96 ± 0.14	4.07 ± 0.33	58 ± 8	67
$2j\text{-BSM-like}$	4.1 ± 0.8	0.197 ± 0.013	0.033 ± 0.004	0.58 ± 0.06	4.9 ± 0.8	4
$VH\text{-Lep-enriched}$	1.42 ± 0.12	0.256 ± 0.029	0.059 ± 0.006	0.365 ± 0.018	2.10 ± 0.15	2
$t\bar{t}H\text{-enriched}$	1.68 ± 0.20	0.037 ± 0.008	0.29 ± 0.04	0.301 ± 0.027	2.31 ± 0.21	2
Sideband	$105 < m_{4\ell} < 115$ GeV or $130 < m_{4\ell} < 160$ GeV					
SB- $0j$	5.9 ± 1.0	161 ± 15	—	21.06 ± 0.35	189 ± 16	153
SB- $1j$	3.8 ± 0.6	53 ± 5	1.64 ± 0.021	12.9 ± 0.4	71 ± 6	74
SB- $2j$	3.0 ± 0.5	26 ± 4	4.4 ± 0.6	7.237 ± 0.020	40 ± 4	48
	$105 < m_{4\ell} < 115$ GeV or $130 < m_{4\ell} < 350$ GeV					
SB- $tXX\text{-enriched}$	0.096 ± 0.012	0.27 ± 0.07	5.3 ± 0.8	2.29 ± 0.14	7.9 ± 0.8	15

Table 5. The expected (pre-fit) and observed numbers of events are shown for an integrated luminosity of 164fb^{-1} at $\sqrt{s} = 13.6$ TeV. Results are presented for the signal region $115 < m_{4\ell} < 130$ GeV and the sideband regions $105 < m_{4\ell} < 115$ GeV and $130 < m_{4\ell} < 160$ GeV (350 GeV for $tXX\text{-enriched}$) in each reconstructed event category, assuming a SM Higgs boson signal with a mass $m_H = 125$ GeV. The sum of the expected SM Higgs boson signal and the estimated background yields is compared with the data. Combined statistical and systematic uncertainties are included for the predictions. Expected contributions below 0.2% of the total yield in each reconstructed event category are not shown and are replaced by ‘—’.

1.2 bins with zero jets. For the VBF production bin, the theoretical systematic uncertainties related to missing higher-order QCD corrections for both VBF and ggF predictions and experimental uncertainties related to the jet energy scale and resolution become relevant. For VH and $t\bar{t}H$ production-modes, theoretical uncertainties in the ggF prediction and those experiment ones on jet flavour tagging are dominant. For the Reduced Stage 1.2 bins with higher jet multiplicity, the dominant uncertainties on the cross-sections are the jet energy scale and resolution, and missing higher-order corrections. The probability of compatibility of the measured production-mode (Reduced Stage 1.2) measurement and the SM Higgs boson expectation is 51% (68%).

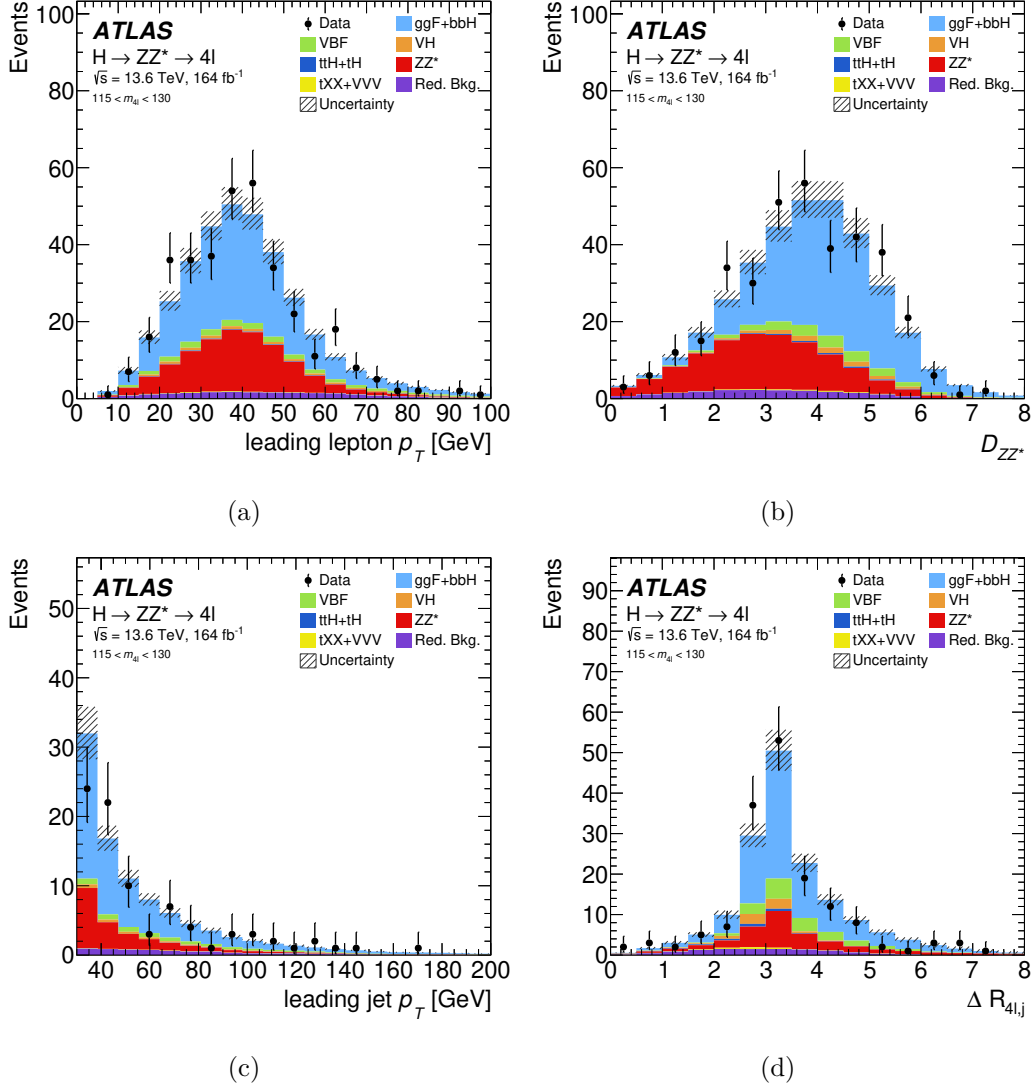


Figure 10. The observed and expected distributions (pre-fit) of (a) the transverse momenta of the leading lepton (b) the kinematic discriminant D_{ZZ^*} (c) the transverse momenta of the leading jet and (d) angular separation between the four lepton system and the leading jet $\Delta R_{4l,j}$. The SM Higgs boson signal is assumed to have a mass $m_H = 125$ GeV. The uncertainty in the prediction is shown by the hatched band, calculated as described in section 7.

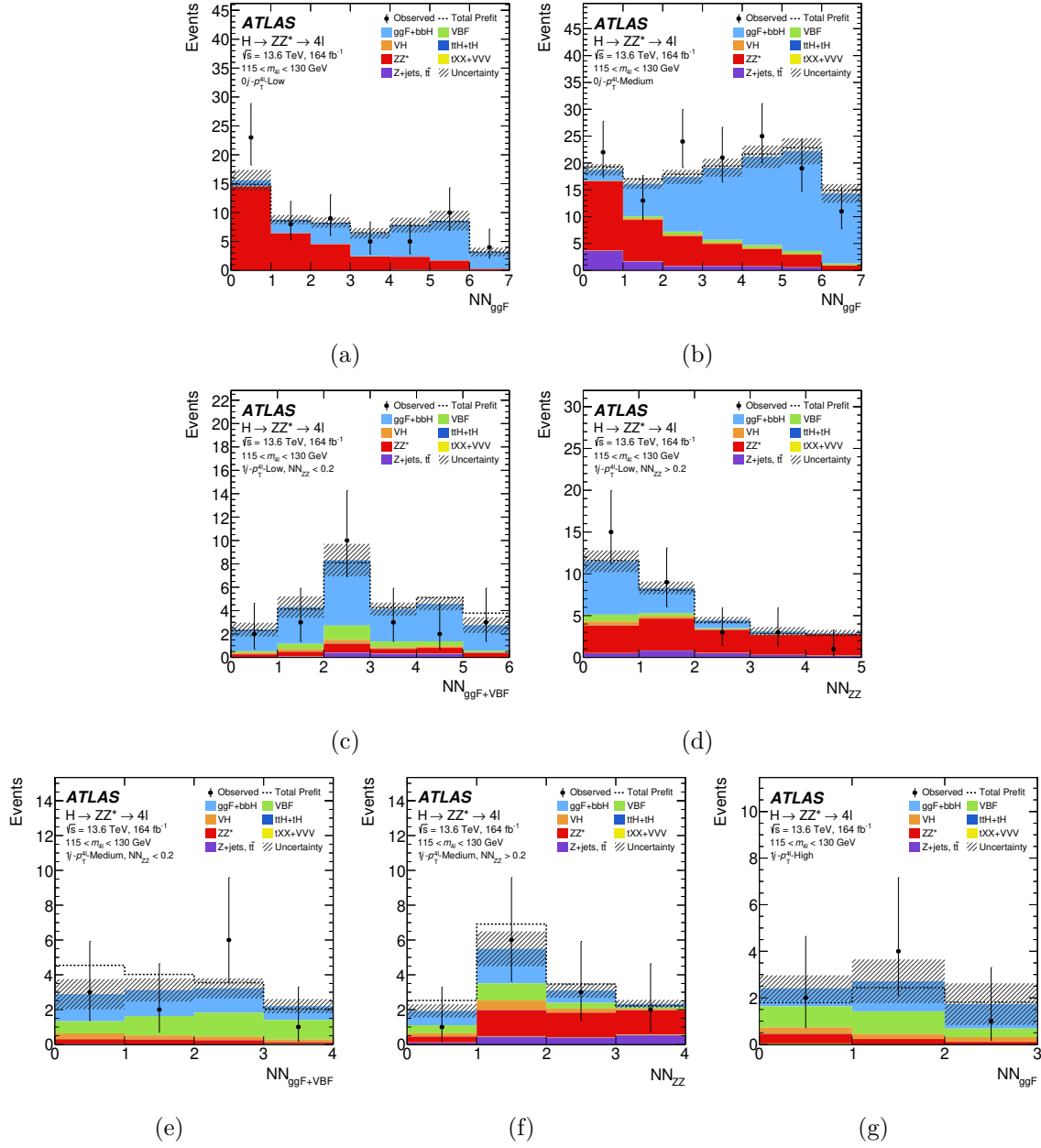


Figure 11. The observed and expected neural network output (post-fit) distributions for an integrated luminosity of 164 fb^{-1} at $\sqrt{s} = 13.6\text{ TeV}$ in the different reconstructed event categories: (a) NN_{ggF} in $0j\text{-}p_{\text{T}}^{4\ell}\text{-Low}$, (b) NN_{ggF} in $0j\text{-}p_{\text{T}}^{4\ell}\text{-Med}$, (c) $\text{NN}_{\text{ggF}+\text{VBF}}$ and (d) NN_{ZZ} in $1j\text{-}p_{\text{T}}^{4\ell}\text{-Low}$ for low and high NN_{ZZ} , respectively, (e) $\text{NN}_{\text{ggF}+\text{VBF}}$ and (f) NN_{ZZ} in $1j\text{-}p_{\text{T}}^{4\ell}\text{-Med}$ for low and high NN_{ZZ} , respectively and (g) NN_{ggF} in $1j\text{-}p_{\text{T}}^{4\ell}\text{-High}$. The total post-fit distribution is shown as a stacked histogram, while the total pre-fit distribution is shown with dotted black line for comparison. The uncertainty in the prediction, corresponding to the total error associated with the post-fit signal cross-sections and background normalization factors, is shown by the hatched band. The bin boundaries are chosen to maximise the significance of the targeted signal in each category. The individual bins do not map linearly to discriminant values.

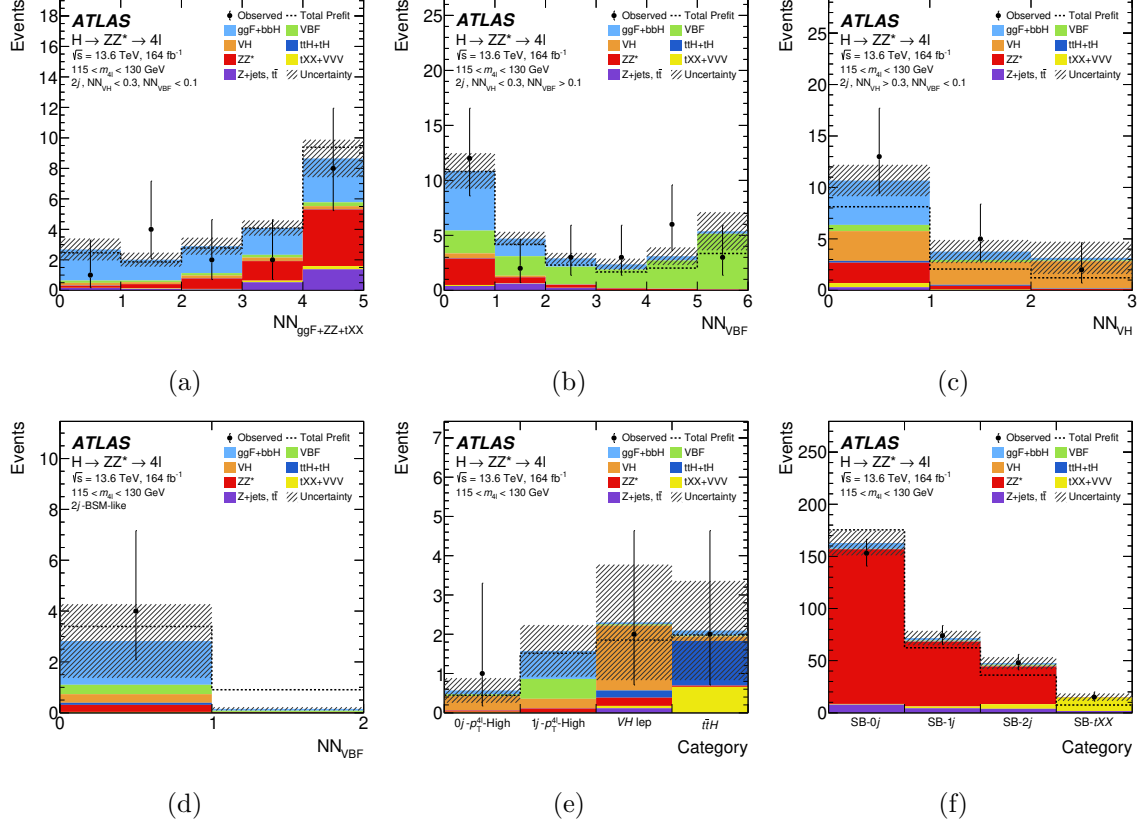


Figure 12. The observed and expected neural network output (post-fit) distributions for an integrated luminosity of 164 fb^{-1} at $\sqrt{s} = 13.6 \text{ TeV}$ in the different reconstructed event categories: (a) $\text{NN}_{\text{ggF+ZZ+ttXX}}$ (b) NN_{VBF} and (c) NN_{VH} with the different selection on NN_{VBF} and NN_{VH} in 2j categories, (d) NN_{VBF} in 2j-BSM-like. (e) Shows the categories where no NN discriminant is used while (f) shows the sidebands used to constrain the ZZ^* and $t\text{XX}$ backgrounds. The total post-fit distribution is shown as a stacked histogram, while the total pre-fit distribution is shown with dotted black line for comparison. The uncertainty in the prediction, corresponding to the total error associated with the post-fit signal cross-sections and background normalization factors, is shown by the hatched band. The bin boundaries are chosen to maximise the significance of the targeted signal in each category. The individual bins do not map linearly to discriminant values.

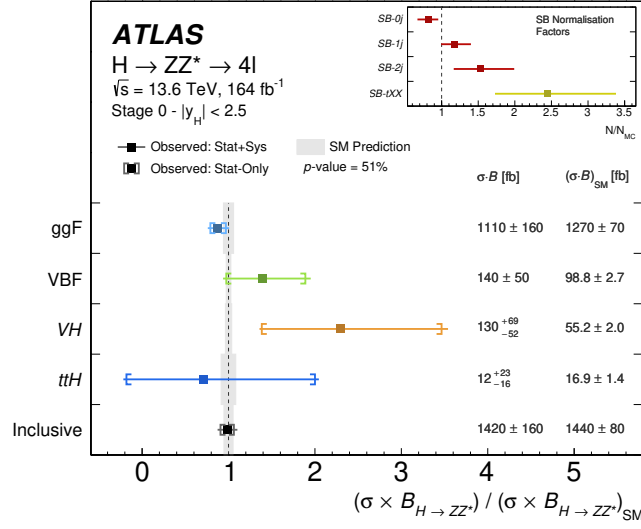


Figure 13. The observed and expected SM values of the inclusive and individual production-mode cross-sections $\sigma_{|y_H| < 2.5} \cdot \mathcal{B}(H \rightarrow ZZ^*)$ normalised by the SM expectation for an integrated luminosity of 164 fb^{-1} at $\sqrt{s} = 13.6$ TeV. The branching ratio for the $ZZ^* \rightarrow 4\ell$ decay is assumed to be given by the SM prediction. The horizontal bands around the expected SM result indicate the theoretical uncertainty in the prediction.

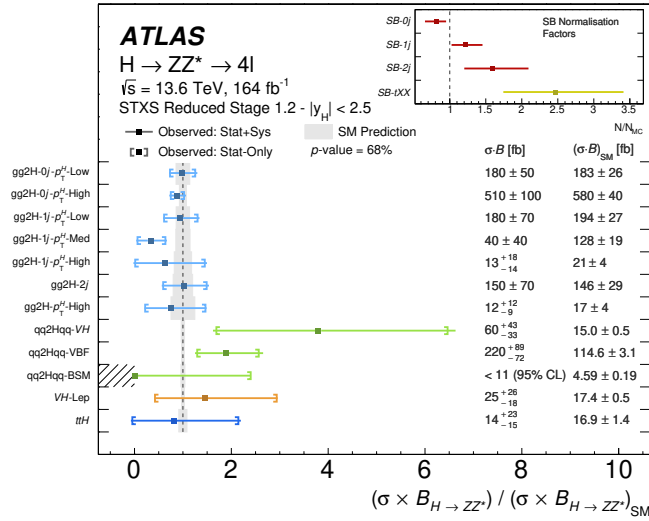


Figure 14. The observed and expected SM values of the inclusive and individual production-mode cross-sections $\sigma_{|y_H| < 2.5} \cdot \mathcal{B}(H \rightarrow ZZ^*)$ normalised by the SM expectation for an integrated luminosity of 164 fb^{-1} at $\sqrt{s} = 13.6$ TeV. The branching ratio for the $ZZ^* \rightarrow 4\ell$ decay is assumed to be given by the SM prediction. The horizontal bands around the expected SM result indicate the theoretical uncertainty in the prediction. Due to zero observed events in the bins with highest sensitivity, an upper limit at 95%CL for the qq2Hqq-BSM bin is set. The hatched area indicates that the qq2Hqq-BSM parameter of interest is constrained to positive values in the fit.

9 Interpretations of the differential distributions and production cross-sections

9.1 Constraints on Higgs boson couplings within the κ -framework

To probe physics beyond the SM, the measured production-mode cross-sections are interpreted in the κ framework [135], which parameterises possible deviations of Higgs boson couplings from their SM values using coupling-strength modifiers $\vec{\kappa}$. Under the narrow-width approximation, Higgs production and decay factorise, and $\sigma \cdot \mathcal{B}$ can be expressed in terms of modified Higgs production cross-sections and partial widths. The $\vec{\kappa}$ dependence at $\sqrt{s} = 13.6$ TeV is obtained by linear interpolation between the corresponding terms at 13 and 14 TeV [41].

The interpretation is performed in a benchmark scenario with two universal modifiers: $\kappa_V = \kappa_W = \kappa_Z$ for Higgs-to-vector-boson couplings and $\kappa_f = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_\mu$ for Higgs-to-fermion couplings, assuming a single Higgs boson state that is even under the combined charge-parity (CP) transformation, with the SM tensor structure and no undetected or invisible decays. For loop-induced processes, the resolved treatment is adopted, in which the effective loop couplings are expressed in terms of the modified couplings to the massive SM particles.

The results are statistically combined with the corresponding measurements performed with the full Run 2 data set [8], accounting for the systematic uncertainties described in section 7. The following experimental uncertainties are treated as correlated between Run 2 and Run 3 results: the muon momentum scale and reconstruction efficiency; the electron energy scale and energy resolution; and the jet energy scale and resolution, except for Run 3-specific components. Other experimental uncertainties are treated as uncorrelated. Theoretical uncertainties from missing higher-order corrections affecting the Higgs boson signal cross-sections in exclusive kinematic regions, the Higgs boson mass uncertainty, and uncertainties in background estimates are treated as correlated. All other theoretical uncertainties, including PDF and parton shower uncertainties, are treated as uncorrelated.

The likelihood contours and best-fit values in the (κ_f, κ_V) plane are shown in figure 15. Only the quadrant with $\kappa_f > 0$ and $\kappa_V > 0$ is displayed, as the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel has limited sensitivity to the relative sign of the two modifiers. The combined measurements improves on the previous result [8] by about 40% (25%) on κ_V (κ_f). The compatibility of the combined measurement with the SM expectation corresponds to a p -value of 29%.

9.2 Constraints on CP-even and CP-odd effective field theory operators

The κ -framework assumes that the tensor structure of the Higgs boson couplings is the same as in the SM. To probe possible non-SM tensor structures, selected unfolded differential measurements are interpreted in an effective field theory (EFT) approach. In this approach, the BSM interactions are introduced via additional higher-dimensional operators $\mathcal{O}_i^{(d)}$ of dimension d , supplementing the SM Lagrangian $\mathcal{L}_{\text{SM}}$,

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)} \quad \text{for } d > 4,$$

where $C_i^{(d)}$ are the Wilson coefficients and Λ denotes the characteristic scale of new physics. In this analysis, only dimension-six operators are considered. Dimension-five and dimension-

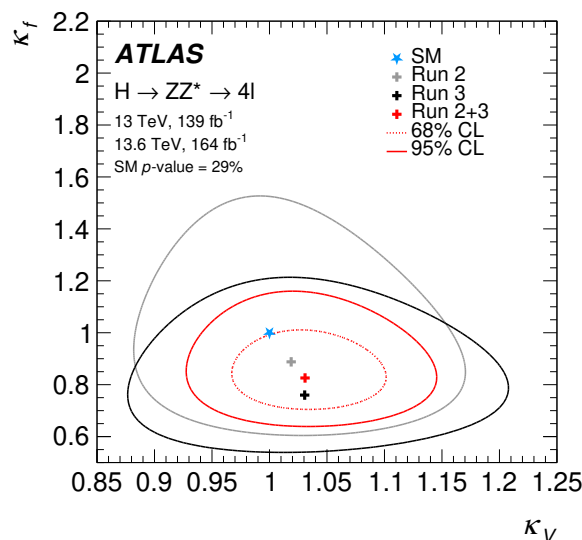


Figure 15. Likelihood contours in the (κ_f, κ_V) plane comparing the current results with those obtained in Run 2. The statistical combination of the two measurements is also presented. The area outside the solid (dashed) contours is excluded at 95% (68%) confidence level. The best-fit point (solid cross) is shown together with the SM prediction (star).

seven operators are not included, as they violate lepton or baryon number conservation and are therefore not relevant in the present context. Although dimension-eight operators can interfere with the SM amplitudes at a same order as the quadratic contributions from dimension-six operators, their effect is not considered. The data are sensitive only to the combinations $c_i = C_i^{(d=6)}/\Lambda^2$, which are the quantities constrained in this analysis.

Constraints are derived within the Standard Model EFT (SMEFT) formalism [136] in the Warsaw basis [137]. Given the sensitivity in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel, only three CP-even and three CP-odd operators modifying Higgs boson interactions with electroweak gauge bosons are probed as summarised in table 6. Operators affecting only double-Higgs boson production, as well as operators modifying Higgs couplings to quarks and leptons, are not considered. The impact of these operators on the total Higgs boson width is neglected.

The EFT interpretation is performed using observables selected to enhance sensitivity to the targeted operators and to retain discrimination between the interference (linear) and BSM-squared (quadratic) contributions. The two-dimensional $(p_T^{4\ell}, m_{34})$ measurement is used to constrain c_{HW} , since it simultaneously probes production- and decay-side effects: $p_T^{4\ell}$ is sensitive to modifications of the production kinematics, while m_{34} provides sensitivity to changes in the decay matrix element in $H \rightarrow ZZ^* \rightarrow 4\ell$. The sensitivity of this approach depends on the chosen binning in m_{34} as the balance between statistical precision and shape sensitivity is required to be optimised.

For the remaining CP-even operators, the angular observable ϕ provides improved sensitivity compared with $(p_T^{4\ell}, m_{34})$. This improvement arises as the linear SMEFT contribution exhibits sign changes as a function of ϕ , leading to a periodic modulation that cancels when integrated over the full phase space. Consequently, the SM-BSM interference is suppressed in ϕ -inclusive observables, similarly to those observed in non-Higgs boson decays [138, 139].

Operator	Structure	Coeff.
$\mathcal{O}_{HW}$	$HH^\dagger W_{\mu\nu}^l W^{\mu\nu l}$	c_{HW}
$\mathcal{O}_{HB}$	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}
$\mathcal{O}_{HWB}$	$HH^\dagger \tau^l W_{\mu\nu}^l B^{\mu\nu}$	c_{HWB}
$\mathcal{O}_{H\tilde{W}}$	$HH^\dagger \tilde{W}_{\mu\nu}^l W^{\mu\nu l}$	$c_{H\tilde{W}}$
$\mathcal{O}_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$
$\mathcal{O}_{H\tilde{W}B}$	$HH^\dagger \tau^l \tilde{W}_{\mu\nu}^l B^{\mu\nu}$	$c_{H\tilde{W}B}$

Table 6. Summary of CP-even and CP-odd EFT operators in the SMEFT formalism probed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel. The corresponding tensor structure in terms of the SM fields from ref. [136] is shown together with the associated Wilson coefficients and the affected interaction vertices. $V_{\mu\nu}$ is the field-strength tensor for a given gauge field $V = W, B$.

Although ϕ is a CP-even observable, it also exhibits sensitivity to CP-odd operators, with the interference term showing an analogous behaviour to the CP-even case but with different periodicity. The $\Delta\phi_{jj}$ observable is also studied for CP-odd operators, but it does not provide discrimination between CP-even and CP-odd operators in the present dataset due to the dominant dependence on quadratic EFT terms.

The Wilson coefficients are constrained by first parametrizing the unfolded signal cross-section in each bin of the chosen distribution to the SMEFT expectation, with the expected cross-section and acceptance using a matrix-element-based procedure [140] and refitting the data. For a bin j of a given observable, the expected cross-section is written as

$$\sigma_{pp \rightarrow H \rightarrow 4\ell, j}^{\text{SMEFT}}(c_i) = \sigma_{pp \rightarrow H \rightarrow 4\ell, j}^{\text{SM}} \cdot \sum_p \left(1 + \sum_i \alpha_i^{(p, j)} c_i + \sum_{i, k \geq i} \beta_{ik}^{(p, j)} c_i c_k \right) \cdot \frac{\left(1 + \sum_i \alpha_i^{(\Gamma_{4\ell, j})} c_i + \sum_{i, k \geq i} \beta_{ik}^{(\Gamma_{4\ell, j})} c_i c_k \right)}{\left(1 + \sum_i \alpha_i^{(\Gamma_{\text{tot}, j})} c_i + \sum_{i, k \geq i} \beta_{ik}^{(\Gamma_{\text{tot}, j})} c_i c_k \right)}, \quad (9.1)$$

where p labels Higgs boson production processes, and $\Gamma_{4\ell}$ and Γ_{tot} denote the partial width to four leptons and the total width, respectively. The terms linear in c_i encode SM–EFT interference, while the quadratic terms represent the pure dimension-six contribution. The coefficients α and β are obtained from matrix elements computed using dedicated simulated samples generated at LO in QCD with MADGRAPH5_AMC@NLO and the NNPDF23lo PDF set. The SMEFT contributions to VBF production and the HZZ decay vertex are modelled using SMEFTSIM [136, 141]. The SMEFT impact on VH production is neglected, as it has a negligible effect on the considered distributions.

Since the measurements do not provide sufficient sensitivity to constrain the full set of coefficients simultaneously, fits are performed for one coefficient at a time, with all others set to zero. Two treatments of the SMEFT expansion are presented: a *linear-only* interpretation retaining only the interference term, and a *linear+quadratic* interpretation including both interference and BSM-squared terms. Quadratic terms typically increase sensitivity through additional changes in total cross-section, and a comparison of the two treatments provides information on the impact of higher-order contributions and the possible onset of perturbative breakdown as quadratic effects become dominant. For each probed coefficient, one-dimensional likelihood scans are performed using the observable providing the best expected sensitivity: $(p_T^{4\ell}, m_{34})$ for c_{HW} and ϕ for the other Wilson coefficients. The observed and expected

	Expected 95% CL [TeV ⁻²]		Observed 95% CL [TeV ⁻²]		Best fit [TeV ⁻²]	
	Linear	Linear + Quadratic	Linear	Linear + Quadratic	Linear	Linear + Quadratic
c_{HW}	[-3.8, 3.2]	[-1.8, 1.8]	[-4.3, 2.9]	[-2.0, 1.8]	-0.40	-0.08
c_{HB}	[-0.63, 0.59]	[-0.54, 1.2]	[-0.58, 0.64]	[-0.49, 1.25]	0.05	0.05
c_{HWB}	[-1.5, 1.4]	[-0.42, 0.48]	[-1.6, 1.3]	[-0.40, 0.45]	-0.08	-0.02
$c_{H\tilde{W}}$	[-3.0, 3.0]	[-1.6, 1.6]	[-2.1, 3.9]	[-1.3, 1.6]	0.88	0.38
$c_{H\tilde{B}}$	[-1.5, 1.5]	[-1.0, 0.96]	[-1.1, 1.6]	[-0.80, 0.96]	0.39	0.20
$c_{H\tilde{W}B}$	[-2.3, 2.3]	[-0.45, 0.45]	[-3.1, 1.5]	[-0.44, 0.41]	-0.80	-0.09

Table 7. Expected and observed 95% confidence intervals (CL) on the CP-even and CP-odd SMEFT Wilson coefficients for an integrated luminosity of 164 fb⁻¹ at $\sqrt{s} = 13.6$ TeV, assuming $\Lambda = 1$ TeV. Only one Wilson coefficient is fitted at a time while all others are set to zero. For each coefficient, results obtained in the linear-only and linear+quadratic SMEFT treatments are presented. ($p_T^{4\ell}, m_{34}$) observable is used for c_{HW} results, while ϕ is used for the other operators.

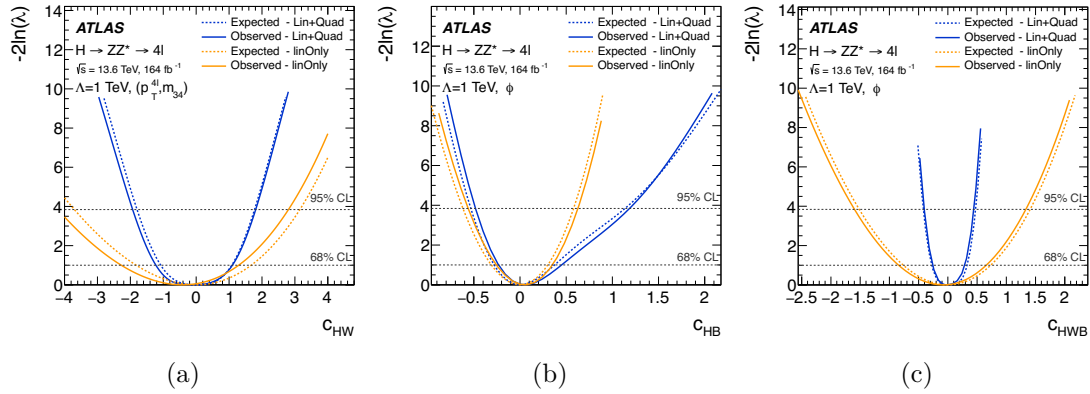


Figure 16. One-dimensional likelihood scans for the CP-even SMEFT Wilson coefficients, comparing the linear-only and linear+quadratic SMEFT treatments. The c_{HW} scan uses the unfolded ($p_T^{4\ell}, m_{34}$) measurement, while the other scans use the unfolded ϕ measurement. A new physics scale of $\Lambda = 1$ TeV is assumed.

confidence intervals (CL) are summarised in table 7, and the corresponding likelihood scans comparing the linear-only and linear+quadratic treatments are shown for the CP-even Wilson Coefficients in figure 16. Additional results where combinations of two EFT operators are simultaneously probed are in shown in figure 17. For each combination, the scans are obtained from the observable that provides the best expected sensitivity. Two-dimensional EFT scans are not used to derive limits, as the likelihood exhibits poorly constrained directions in parameter space, leading to degeneracies and flat directions.

The corresponding limits on the new physics scale Λ for benchmark coefficient values are shown in figure 18.

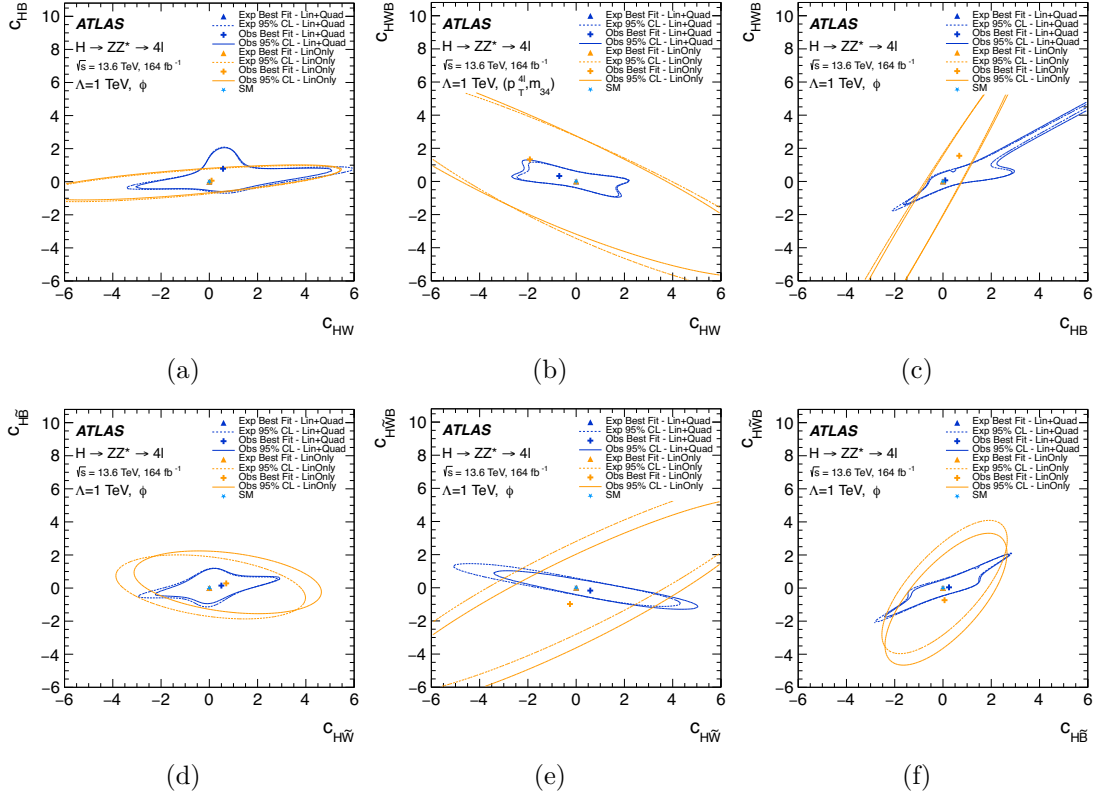


Figure 17. Expected (dashed line) and observed (full line) two-dimensional likelihood scans for the SMEFT Wilson coefficients, comparing the linear-only and linear+quadratic SMEFT treatments. Coupling values outside the solid lines are excluded at 95% confidence level (CL). The best fit to the data (solid cross) and the SM prediction (triangle) are also indicated. A new physics scale of $\Lambda = 1$ TeV is assumed. Except for the two fitted Wilson coefficients, all others are set to zero. The CP-even C_{HW} vs C_{HWB} scan uses the unfolded $(p_T^{4\ell}, m_{34})$ measurement, while the other scans use the unfolded ϕ measurement.

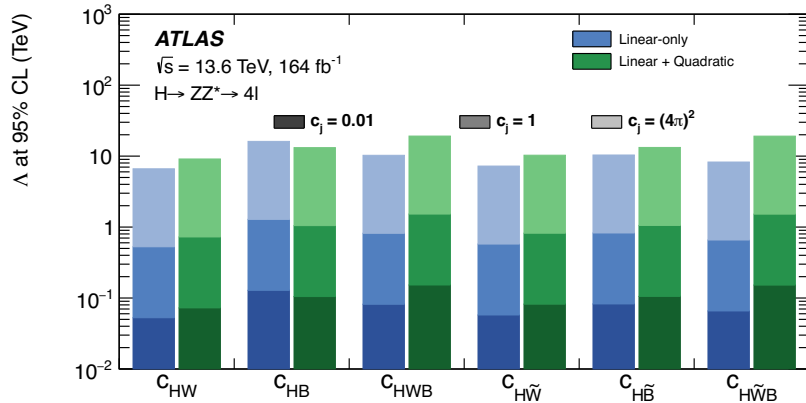


Figure 18. Observed lower limits at 95% confidence intervals (CL) on the new physics scale Λ for the indicated benchmark values of a given Wilson coefficient, assuming all others are set to zero. Asymmetric uncertainties are symmetrised using the root mean square. With the sensitivity of the current results, the constraints for $c_j = 0.01$ are outside the validity of the EFT approach.

9.3 Constraints on Higgs boson self-coupling

The trilinear Higgs self-coupling, λ_3 , enters single-Higgs production and decay at the one-loop level through electroweak corrections, and can therefore be constrained using precision measurements of single-Higgs observables. These effects modify both the overall rate and, in particular, the shape of kinematic distributions that probe hard radiation, making the Higgs boson transverse-momentum spectrum especially sensitive to λ_3 [142]. For this reason, both the differential measurement of $p_T^{4\ell}$ in the fiducial phase space and the STXS measurements, which rely on different event categorisations and modelling assumptions, can be used to probe the effects of the self-coupling, allowing a comparison of the sensitivity achieved by the two complementary approaches.

The interpretation is performed in the κ -framework by introducing the modifier $\kappa_\lambda \equiv \lambda_3/\lambda_3^{\text{SM}}$, with $\kappa_\lambda = 1$ corresponding to the SM expectation and setting all other couplings to their SM expectations.

The dependence of an observable Σ on the trilinear Higgs self-coupling is parametrised following ref. [142] as

$$\Sigma_{\lambda_3}^{\text{BSM}}(\kappa_\lambda) = Z_H^{\text{BSM}} \Sigma_{\text{LO}} (1 + \kappa_\lambda C_1(\{p_n\}) + \delta Z_H), \quad (9.2)$$

where Σ_{LO} denotes the leading-order prediction, including factorisable higher-order QCD corrections. The factor Z_H^{BSM} represents the universal Higgs wave-function renormalisation, which accounts for corrections induced by the modified self-coupling. The coefficient $C_1(\{p_n\})$ encodes the finite one-loop contribution arising from the modified trilinear interaction and depends on the kinematics of the process, denoted collectively by $\{p_n\}$. The factor Z_H^{BSM} is expressed in terms of δZ_H and represents the NLO term [142], as

$$Z_H^{\text{BSM}} = \frac{1}{1 - (\kappa_\lambda^2 - 1) \delta Z_H}. \quad (9.3)$$

In this interpretation, all other coupling modifiers are fixed to their SM values, and the κ_λ dependence is implemented as a reweighting of the expected signal yields in each analysis bin, using C_1 values evaluated in the relevant fiducial or STXS phase space. The C_1 coefficients are obtained with the automated reweighting procedure of ref. [142] for all production-modes supported by the tool, and supplemented for ggF using the dedicated calculation at $\sqrt{s} = 13.6$ TeV [143]. The Higgs boson decay contribution is taken to be weakly dependent on kinematics [142], and the corresponding total-width contribution is taken from ref. [144]. The range of the validity for the given C_1 and δZ_H is $|\kappa_\lambda| < 20$.

Complementary constraints on κ_λ are derived from the differential $p_T^{4\ell}$ and the STXS production-mode measurements. The corresponding likelihood scans are compared in figure 19, yielding observed 95% CL intervals of $[-8.8, 19.9]$ and $[-9.0, 20.9]$, respectively, compatible with expected 95% CL intervals of $[-8.8, 19.9]$. The double-minimum structure of the likelihood arises from the quadratic dependence of the cross-section on κ_λ . The observed limit from the STXS measurement is slightly weaker than that obtained from the differential $p_T^{4\ell}$ measurement. This difference is driven by the strong sensitivity of the κ_λ interpretation to the ggF production mode and by the fact that the observed ggF signal strength in the STXS measurement is lower than the inclusive signal strength.

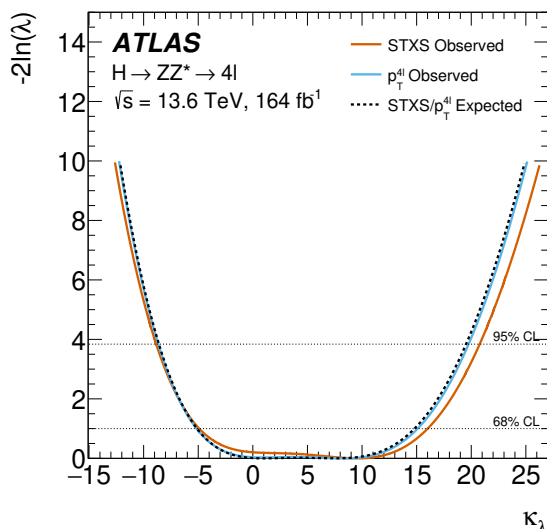


Figure 19. Observed negative-log-likelihood scan as a function of the trilinear Higgs self-coupling modifier κ_λ , comparing the constraints obtained from the STXS production-mode measurement (orange line) and from the fiducial differential measurement based on $p_T^{4\ell}$ (light blue line). The expected results are plotted together for measurements due to their similar sensitivity (black dashed line). The curves are shown relative to their respective minima. The Standard Model prediction corresponds to $\kappa_\lambda = 1$.

10 Conclusion

A measurement of inclusive and differential Higgs boson production cross-sections in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel is presented using 164 fb^{-1} of $\sqrt{s} = 13.6 \text{ TeV}$ pp collision data recorded by the ATLAS detector at the LHC between 2022 and 2024. These results constitute the most comprehensive ATLAS measurements of Higgs boson production in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel at $\sqrt{s} = 13.6 \text{ TeV}$ to date, with a precision already comparable to that obtained using the full Run 2 dataset at $\sqrt{s} = 13 \text{ TeV}$. The analysis exploits the data using improved analysis and ML techniques in two complementary frameworks, measuring fiducial cross-sections with minimal theoretical assumptions and production-mode and STXS cross-sections to separate the contributions from different Higgs boson production mechanisms. The inclusive fiducial cross-section is measured to be $\sigma_{\text{fid}} = 3.65^{+0.35}_{-0.33} \text{ fb}$, in agreement with the Standard Model prediction of $\sigma_{\text{fid}}^{\text{SM}} = 3.68 \pm 0.17 \text{ fb}$, and is extrapolated to a total cross-section of $\sigma_{\text{total}} = 59.3 \pm 5.7 \text{ pb}$, also consistent with the Standard Model and previous results. Differential cross-sections are measured as a function of several Higgs boson production and decay observables and are found to be in agreement with state-of-the-art SM predictions. Higgs boson candidate events are categorised into regions sensitive to different production mechanisms and are used to measure production-mode cross-sections and a Reduced STXS Stage 1.2 scheme. A product of inclusive production cross-section and branching ratio into ZZ^* of $\sigma_{|y_H| < 2.5} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 1.42 \pm 0.16 \text{ pb}$ is obtained for Higgs boson rapidities below 2.5, consistent with the Standard Model prediction of $\sigma_{|y_H| < 2.5}^{\text{SM}} \cdot \mathcal{B}^{\text{SM}}(H \rightarrow ZZ^*) = 1.44 \pm 0.08 \text{ pb}$. The precision of both the differential and STXS measurements is comparable to that achieved by ATLAS at $\sqrt{s} = 13 \text{ TeV}$ with Run 2 data [8, 9], and improves by approximately a factor of

two relative to the first ATLAS results at $\sqrt{s} = 13.6$ TeV in this channel [20]. The differential measurements as a function of ϕ and $p_T^{4\ell}$ vs. m_{34} are used to constrain effective field theory operators and are found to be compatible with SM expectations. The production-mode results are further interpreted in the κ framework and combined with Run 2 measurements [8], yielding best-fit values consistent with Run 2 and about 40% (25%) improvement on κ_V (κ_f) limits. Limits are also derived on the trilinear Higgs self-coupling, and are consistent with the Standard Model.

Acknowledgments

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [145].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMFWF and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST, NSFC and FRFCU, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRf and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMFTR, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ICHEP and Academy of Sciences and Humanities, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA and AGAUR programs from Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom; Eric and Wendy Schmidt Fund for Strategic Innovation, United States of America.

In addition, individual members wish to acknowledge support from Chile: Agencia Nacional de Investigación y Desarrollo (ANID FONDECYT reg. 1230987, FONDECYT 1230812, FONDECYT 1240864, Fondecyt 3240661, Fondecyt Regular 1240721);

China: Fundamental Research Funds for the Central Universities (010-63263105), Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), National Natural Science Foundation of China (NSFC 12275265, NSFC-W2543005); Czech Republic: Czech Science Foundation (GACR – 24-11373S), Ministry of Education Youth and Sports (ERC-CZ-LL2327, FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC – 101002463); European Union: European Research Council (BARD No. 101116429, ERC – 101219398, ERC – 948254, ERC 101089007), European Regional Development Fund (HE COFUND GA No.101081355, ERDF), Marie Skłodowska-Curie Actions (GAP-101168829); France: Agence Nationale de la Recherche (ANR-21-CE31-0013, ANR-22-EDIR-0002, ANR-24-CE31-0504-01); Germany: Deutsche Forschungsgemeinschaft (DFG – 469666862); China: Research Grants Council (GRF); Italy: Istituto Nazionale di Fisica Nucleare (LHC-MIUR – 28003/2025), Ministero dell’Università e della Ricerca (NextGenEU I53D23001490006 M4C2.1.1, NextGenEU I53D23000820006 M4C2.1.1, NextGenEU I53D23001490006 M4C2.1.1, SOE2024_0000023); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP25H0063, JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP24K23939, JSPS KAKENHI JP24KK0251, JSPS KAKENHI JP25H00650, JSPS KAKENHI JP25H01291, JSPS KAKENHI JP25K01011, JSPS KAKENHI JP25K01023); Poland: Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920, UMO-2024/53/N/ST2/00869); Spain: Agència de Gestió d’Ajuts Universitaris i de Recerca. (AGAUR – 2023 BP 00141), Ministry of Science and Innovation (RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I), Ministerio de Ciencia, Innovación y Universidades/Agencia Estatal de Investigación (EU NextGenerationEU (PRTR-C17.I1), PID2022-142604OB-C22); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2021-03651, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR 2024-05451, VR 2025-05940), Knut and Alice Wallenberg Foundation (KAW 2023.0366); Switzerland: Swiss National Science Foundation (SNSF – PCEFP2_194658); United Kingdom: The Binks Trust, Royal Society (NIF-R1-231091); United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), John Templeton Foundation (John Templeton Foundation 63206), Neubauer Family Foundation.

Data Availability Statement. This article has no associated data or the data will not be deposited.

Code Availability Statement. This article has no associated code or the code will not be deposited.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [[arXiv:1207.7214](#)] [[INSPIRE](#)].
- [2] CMS collaboration, *Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [[arXiv:1207.7235](#)] [[INSPIRE](#)].
- [3] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, *Phys. Rev. Lett.* **13** (1964) 321 [[INSPIRE](#)].
- [4] P.W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, *Phys. Rev. Lett.* **13** (1964) 508 [[INSPIRE](#)].
- [5] G.S. Guralnik, C.R. Hagen and T.W.B. Kibble, *Global Conservation Laws and Massless Particles*, *Phys. Rev. Lett.* **13** (1964) 585 [[INSPIRE](#)].
- [6] ATLAS and CMS collaborations, *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments*, *Phys. Rev. Lett.* **114** (2015) 191803 [[arXiv:1503.07589](#)] [[INSPIRE](#)].
- [7] ATLAS collaboration, *Fiducial and differential cross sections of Higgs boson production measured in the four-lepton decay channel in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *Phys. Lett. B* **738** (2014) 234 [[arXiv:1408.3226](#)] [[INSPIRE](#)].
- [8] ATLAS collaboration, *Higgs boson production cross-section measurements and their EFT interpretation in the 4ℓ decay channel at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **80** (2020) 957 [Erratum *ibid.* **81** (2021) 29] [[arXiv:2004.03447](#)] [[INSPIRE](#)].
- [9] ATLAS collaboration, *Measurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **80** (2020) 942 [[arXiv:2004.03969](#)] [[INSPIRE](#)].
- [10] ATLAS collaboration, *Measurement of the total and differential Higgs boson production cross-sections at $\sqrt{s} = 13$ TeV with the ATLAS detector by combining the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ decay channels*, *JHEP* **05** (2023) 028 [[arXiv:2207.08615](#)] [[INSPIRE](#)].
- [11] CMS collaboration, *Measurement of differential and integrated fiducial cross sections for Higgs boson production in the four-lepton decay channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV*, *JHEP* **04** (2016) 005 [[arXiv:1512.08377](#)] [[INSPIRE](#)].
- [12] CMS collaboration, *Measurements of inclusive and differential cross sections for the Higgs boson production and decay to four-leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **08** (2023) 040 [[arXiv:2305.07532](#)] [[INSPIRE](#)].
- [13] CMS collaboration, *Measurements of production cross sections of the Higgs boson in the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **81** (2021) 488 [[arXiv:2103.04956](#)] [[INSPIRE](#)].
- [14] ATLAS collaboration, *Measurement of the Higgs boson mass in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel using 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions recorded by the ATLAS detector at the LHC*, *Phys. Lett. B* **843** (2023) 137880 [[arXiv:2207.00320](#)] [[INSPIRE](#)].
- [15] ATLAS collaboration, *Combined measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels with the ATLAS detector using $\sqrt{s} = 7, 8$ and 13 TeV pp collision data*, *Phys. Rev. Lett.* **131** (2023) 251802 [[arXiv:2308.04775](#)] [[INSPIRE](#)].
- [16] CMS collaboration, *Measurement of the Higgs boson mass and width using the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. D* **111** (2025) 092014 [[arXiv:2409.13663](#)] [[INSPIRE](#)].

- [17] ATLAS collaboration, *Test of CP-invariance of the Higgs boson in vector-boson fusion production and in its decay into four leptons*, *JHEP* **05** (2024) 105 [[arXiv:2304.09612](#)] [[INSPIRE](#)].
- [18] CMS collaboration, *Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state*, *Phys. Rev. D* **104** (2021) 052004 [[arXiv:2104.12152](#)] [[INSPIRE](#)].
- [19] ATLAS collaboration, *Measurement of off-shell Higgs boson production in the $H^* \rightarrow ZZ \rightarrow 4\ell$ decay channel using a neural simulation-based inference technique in 13 TeV pp collisions with the ATLAS detector*, *Rept. Prog. Phys.* **88** (2025) 057803 [[arXiv:2412.01548](#)] [[INSPIRE](#)].
- [20] ATLAS collaboration, *Measurement of the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ cross-sections in pp collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **84** (2024) 78 [[arXiv:2306.11379](#)] [[INSPIRE](#)].
- [21] CMS collaboration, *Measurements of the Higgs boson production cross section in the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13.6$ TeV*, *JHEP* **05** (2025) 079 [[arXiv:2501.14849](#)] [[INSPIRE](#)].
- [22] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, *Simplified template cross sections* [LHCHXSWG-DRAFT-INT-2016-006](#).
- [23] N. Berger et al., *Simplified template cross sections — Stage 1.1 and 1.2*, [arXiv:1906.02754](#) [[DOI:10.21468/SciPostPhysCommRep.15](#)] [[INSPIRE](#)].
- [24] A. Vaswani et al., *Attention Is All You Need*, in the proceedings of the *31st International Conference on Neural Information Processing Systems*, Long Beach, U.S.A., 04–09 December 2017 [[arXiv:1706.03762](#)] [[INSPIRE](#)].
- [25] ATLAS collaboration, *Transforming jet flavour tagging at ATLAS*, *Nature Commun.* **17** (2026) 541 [[arXiv:2505.19689](#)] [[INSPIRE](#)].
- [26] ATLAS collaboration, *Tools for estimating fake/non-prompt lepton backgrounds with the ATLAS detector at the LHC*, *2023 JINST* **18** T11004 [[arXiv:2211.16178](#)] [[INSPIRE](#)].
- [27] ATLAS collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *2008 JINST* **3** S08003 [[INSPIRE](#)].
- [28] ATLAS collaboration, *The ATLAS experiment at the CERN Large Hadron Collider: a description of the detector configuration for Run 3*, *2024 JINST* **19** P05063 [[arXiv:2305.16623](#)] [[INSPIRE](#)].
- [29] ATLAS collaboration, *The ATLAS trigger system for LHC Run 3 and trigger performance in 2022*, *2024 JINST* **19** P06029 [[arXiv:2401.06630](#)] [[INSPIRE](#)].
- [30] ATLAS collaboration, *Software and computing for Run 3 of the ATLAS experiment at the LHC*, *Eur. Phys. J. C* **85** (2025) 234 [[arXiv:2404.06335](#)] [[INSPIRE](#)].
- [31] ATLAS collaboration, *Preliminary luminosity calibration of the ATLAS 13.6 TeV data recorded in 2024 and combination with the 2022 and 2023 measurements*, [ATL-DAPR-PUB-2025-001](#) (2025) [[INSPIRE](#)].
- [32] ATLAS collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C* **83** (2023) 982 [[arXiv:2212.09379](#)] [[INSPIRE](#)].
- [33] ATLAS collaboration, *Performance of the ATLAS muon triggers in Run 2*, *2020 JINST* **15** P09015 [[arXiv:2004.13447](#)] [[INSPIRE](#)].
- [34] ATLAS collaboration, *Performance of electron and photon triggers in ATLAS during LHC Run 2*, *Eur. Phys. J. C* **80** (2020) 47 [[arXiv:1909.00761](#)] [[INSPIRE](#)].

- [35] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [[arXiv:1002.2581](#)] [[INSPIRE](#)].
- [36] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [[hep-ph/0409146](#)] [[INSPIRE](#)].
- [37] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [[arXiv:0709.2092](#)] [[INSPIRE](#)].
- [38] K. Hamilton, P. Nason and G. Zanderighi, *MINLO: Multi-Scale Improved NLO*, *JHEP* **10** (2012) 155 [[arXiv:1206.3572](#)] [[INSPIRE](#)].
- [39] J.M. Campbell et al., *NLO Higgs Boson Production Plus One and Two Jets Using the POWHEG BOX, MadGraph4 and MCFM*, *JHEP* **07** (2012) 092 [[arXiv:1202.5475](#)] [[INSPIRE](#)].
- [40] K. Hamilton, P. Nason, C. Oleari and G. Zanderighi, *Merging $H/W/Z + 0$ and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching*, *JHEP* **05** (2013) 082 [[arXiv:1212.4504](#)] [[INSPIRE](#)].
- [41] K. Hamilton, P. Nason, E. Re and G. Zanderighi, *NNLOPS simulation of Higgs boson production*, *JHEP* **10** (2013) 222 [[arXiv:1309.0017](#)] [[INSPIRE](#)].
- [42] K. Hamilton, P. Nason and G. Zanderighi, *Finite quark-mass effects in the NNLOPS POWHEG+MiNLO Higgs generator*, *JHEP* **05** (2015) 140 [[arXiv:1501.04637](#)] [[INSPIRE](#)].
- [43] S. Catani and M. Grazzini, *Next-to-Next-to-Leading-Order Subtraction Formalism in Hadron Collisions and its Application to Higgs-Boson Production at the Large Hadron Collider*, *Phys. Rev. Lett.* **98** (2007) 222002 [[hep-ph/0703012](#)] [[INSPIRE](#)].
- [44] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [45] PDF4LHC WORKING GROUP collaboration, *The PDF4LHC21 combination of global PDF fits for the LHC Run III*, *J. Phys. G* **49** (2022) 080501 [[arXiv:2203.05506](#)] [[INSPIRE](#)].
- [46] ATLAS collaboration, *ATLAS Pythia 8 tunes to 7 TeV data*, *ATL-PHYS-PUB-2014-021* (2014) [[INSPIRE](#)].
- [47] R.D. Ball et al., *Parton distributions with LHC data*, *Nucl. Phys. B* **867** (2013) 244 [[arXiv:1207.1303](#)] [[INSPIRE](#)].
- [48] J. Bellm et al., *Herwig 7.1 Release Note*, [arXiv:1705.06919](#) [[INSPIRE](#)].
- [49] C. Bierlich et al., *A comprehensive guide to the physics and usage of PYTHIA 8.3*, *SciPost Phys. Codeb.* **2022** (2022) 8 [[arXiv:2203.11601](#)] [[INSPIRE](#)].
- [50] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061 [[arXiv:1209.6215](#)] [[INSPIRE](#)].
- [51] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [[INSPIRE](#)].
- [52] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, *CERN Yellow Rep. Monogr.* **2** (2017) 1 [[arXiv:1610.07922](#)] [[INSPIRE](#)].
- [53] A. Karlberg et al., *Ad interim recommendations for the Higgs boson production cross sections at $\sqrt{s} = 13.6$ TeV*, [arXiv:2402.09955](#) [[INSPIRE](#)].
- [54] U. Aglietti, R. Bonciani, G. Degrandi and A. Vicini, *Two-loop light fermion contribution to Higgs production and decays*, *Phys. Lett. B* **595** (2004) 432 [[hep-ph/0404071](#)] [[INSPIRE](#)].

- [55] S. Actis, G. Passarino, C. Sturm and S. Uccirati, *NLO Electroweak Corrections to Higgs Boson Production at Hadron Colliders*, *Phys. Lett. B* **670** (2008) 12 [[arXiv:0809.1301](#)] [[INSPIRE](#)].
- [56] S. Actis, G. Passarino, C. Sturm and S. Uccirati, *NNLO computational techniques: The cases $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$* , *Nucl. Phys. B* **811** (2009) 182 [[arXiv:0809.3667](#)] [[INSPIRE](#)].
- [57] C. Anastasiou, R. Boughezal and F. Petriello, *Mixed QCD-electroweak corrections to Higgs boson production in gluon fusion*, *JHEP* **04** (2009) 003 [[arXiv:0811.3458](#)] [[INSPIRE](#)].
- [58] A. Pak, M. Rogal and M. Steinhauser, *Finite top quark mass effects in NNLO Higgs boson production at LHC*, *JHEP* **02** (2010) 025 [[arXiv:0911.4662](#)] [[INSPIRE](#)].
- [59] R.V. Harlander and K.J. Ozeren, *Top mass effects in Higgs production at next-to-next-to-leading order QCD: Virtual corrections*, *Phys. Lett. B* **679** (2009) 467 [[arXiv:0907.2997](#)] [[INSPIRE](#)].
- [60] R.V. Harlander and K.J. Ozeren, *Finite top mass effects for hadronic Higgs production at next-to-next-to-leading order*, *JHEP* **11** (2009) 088 [[arXiv:0909.3420](#)] [[INSPIRE](#)].
- [61] R.V. Harlander, H. Mantler, S. Marzani and K.J. Ozeren, *Higgs production in gluon fusion at next-to-next-to-leading order QCD for finite top mass*, *Eur. Phys. J. C* **66** (2010) 359 [[arXiv:0912.2104](#)] [[INSPIRE](#)].
- [62] C. Anastasiou et al., *Higgs Boson Gluon-Fusion Production in QCD at Three Loops*, *Phys. Rev. Lett.* **114** (2015) 212001 [[arXiv:1503.06056](#)] [[INSPIRE](#)].
- [63] C. Anastasiou et al., *High precision determination of the gluon fusion Higgs boson cross-section at the LHC*, *JHEP* **05** (2016) 058 [[arXiv:1602.00695](#)] [[INSPIRE](#)].
- [64] F. Dulat, A. Lazopoulos and B. Mistlberger, *iHiggs 2 — Inclusive Higgs cross sections*, *Comput. Phys. Commun.* **233** (2018) 243 [[arXiv:1802.00827](#)] [[INSPIRE](#)].
- [65] M. Bonetti, K. Melnikov and L. Tancredi, *Higher order corrections to mixed QCD-EW contributions to Higgs boson production in gluon fusion*, *Phys. Rev. D* **97** (2018) 056017 [Erratum *ibid.* **97** (2018) 099906] [[arXiv:1801.10403](#)] [[INSPIRE](#)].
- [66] M. Ciccolini, A. Denner and S. Dittmaier, *Strong and Electroweak Corrections to the Production of a Higgs Boson + 2 Jets via Weak Interactions at the Large Hadron Collider*, *Phys. Rev. Lett.* **99** (2007) 161803 [[arXiv:0707.0381](#)] [[INSPIRE](#)].
- [67] M. Ciccolini, A. Denner and S. Dittmaier, *Electroweak and QCD corrections to Higgs production via vector-boson fusion at the CERN LHC*, *Phys. Rev. D* **77** (2008) 013002 [[arXiv:0710.4749](#)] [[INSPIRE](#)].
- [68] P. Bolzoni, F. Maltoni, S.-O. Moch and M. Zaro, *Higgs Boson Production via Vector-Boson Fusion at Next-to-Next-to-Leading Order in QCD*, *Phys. Rev. Lett.* **105** (2010) 011801 [[arXiv:1003.4451](#)] [[INSPIRE](#)].
- [69] M.L. Ciccolini, S. Dittmaier and M. Krämer, *Electroweak radiative corrections to associated WH and ZH production at hadron colliders*, *Phys. Rev. D* **68** (2003) 073003 [[hep-ph/0306234](#)] [[INSPIRE](#)].
- [70] O. Brein, A. Djouadi and R. Harlander, *NNLO QCD corrections to the Higgs-strahlung processes at hadron colliders*, *Phys. Lett. B* **579** (2004) 149 [[hep-ph/0307206](#)] [[INSPIRE](#)].
- [71] O. Brein, R. Harlander, M. Wiesemann and T. Zirke, *Top-Quark Mediated Effects in Hadronic Higgs-Strahlung*, *Eur. Phys. J. C* **72** (2012) 1868 [[arXiv:1111.0761](#)] [[INSPIRE](#)].
- [72] L. Altenkamp et al., *Gluon-induced Higgs-strahlung at next-to-leading order QCD*, *JHEP* **02** (2013) 078 [[arXiv:1211.5015](#)] [[INSPIRE](#)].
- [73] A. Denner, S. Dittmaier, S. Kallweit and A. Mück, *HAWK 2.0: A Monte Carlo program for Higgs production in vector-boson fusion and Higgs strahlung at hadron colliders*, *Comput. Phys. Commun.* **195** (2015) 161 [[arXiv:1412.5390](#)] [[INSPIRE](#)].

- [74] O. Brein, R.V. Harlander and T.J.E. Zirke, *vh@nnlo — Higgs Strahlung at hadron colliders*, *Comput. Phys. Commun.* **184** (2013) 998 [[arXiv:1210.5347](#)] [[INSPIRE](#)].
- [75] R.V. Harlander, A. Kulesza, V. Theeuwes and T. Zirke, *Soft gluon resummation for gluon-induced Higgs Strahlung*, *JHEP* **11** (2014) 082 [[arXiv:1410.0217](#)] [[INSPIRE](#)].
- [76] R.V. Harlander, J. Klappert, S. Liebler and L. Simon, *vh@nnlo-v2: New physics in Higgs Strahlung*, *JHEP* **05** (2018) 089 [[arXiv:1802.04817](#)] [[INSPIRE](#)].
- [77] M. Bonvini, A.S. Papanastasiou and F.J. Tackmann, *Resummation and matching of b-quark mass effects in $b\bar{b}H$ production*, *JHEP* **11** (2015) 196 [[arXiv:1508.03288](#)] [[INSPIRE](#)].
- [78] M. Bonvini, A.S. Papanastasiou and F.J. Tackmann, *Matched predictions for the $b\bar{b}H$ cross section at the 13 TeV LHC*, *JHEP* **10** (2016) 053 [[arXiv:1605.01733](#)] [[INSPIRE](#)].
- [79] S. Forte, D. Napoletano and M. Ubiali, *Higgs production in bottom-quark fusion in a matched scheme*, *Phys. Lett. B* **751** (2015) 331 [[arXiv:1508.01529](#)] [[INSPIRE](#)].
- [80] S. Forte, D. Napoletano and M. Ubiali, *Higgs production in bottom-quark fusion: matching beyond leading order*, *Phys. Lett. B* **763** (2016) 190 [[arXiv:1607.00389](#)] [[INSPIRE](#)].
- [81] W. Beenakker et al., *NLO QCD corrections to $t\bar{t}H$ production in hadron collisions*, *Nucl. Phys. B* **653** (2003) 151 [[hep-ph/0211352](#)] [[INSPIRE](#)].
- [82] S. Dawson et al., *Associated Higgs boson production with top quarks at the CERN Large Hadron Collider: NLO QCD corrections*, *Phys. Rev. D* **68** (2003) 034022 [[hep-ph/0305087](#)] [[INSPIRE](#)].
- [83] Y. Zhang et al., *QCD NLO and EW NLO corrections to $t\bar{t}H$ production with top quark decays at hadron collider*, *Phys. Lett. B* **738** (2014) 1 [[arXiv:1407.1110](#)] [[INSPIRE](#)].
- [84] S. Frixione et al., *Electroweak and QCD corrections to top-pair hadroproduction in association with heavy bosons*, *JHEP* **06** (2015) 184 [[arXiv:1504.03446](#)] [[INSPIRE](#)].
- [85] F. Demartin, F. Maltoni, K. Mawatari and M. Zaro, *Higgs production in association with a single top quark at the LHC*, *Eur. Phys. J. C* **75** (2015) 267 [[arXiv:1504.00611](#)] [[INSPIRE](#)].
- [86] F. Demartin et al., *tWH associated production at the LHC*, *Eur. Phys. J. C* **77** (2017) 34 [[arXiv:1607.05862](#)] [[INSPIRE](#)].
- [87] A. Bredenstein, A. Denner, S. Dittmaier and M.M. Weber, *Precise predictions for the Higgs-boson decay $H \rightarrow WW/ZZ \rightarrow 4$ leptons*, *Phys. Rev. D* **74** (2006) 013004 [[hep-ph/0604011](#)] [[INSPIRE](#)].
- [88] A. Bredenstein, A. Denner, S. Dittmaier and M.M. Weber, *Precision calculations for the Higgs decays $H \rightarrow ZZ/WW \rightarrow 4$ leptons*, *Nucl. Phys. B Proc. Suppl.* **160** (2006) 131 [[hep-ph/0607060](#)] [[INSPIRE](#)].
- [89] SHERPA collaboration, *Event Generation with Sherpa 2.2*, *SciPost Phys.* **7** (2019) 034 [[arXiv:1905.09127](#)] [[INSPIRE](#)].
- [90] T. Gleisberg and S. Hoeche, *Comix, a new matrix element generator*, *JHEP* **12** (2008) 039 [[arXiv:0808.3674](#)] [[INSPIRE](#)].
- [91] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani–Seymour dipole factorisation*, *JHEP* **03** (2008) 038 [[arXiv:0709.1027](#)] [[INSPIRE](#)].
- [92] S. Hoeche, F. Krauss, M. Schönherr and F. Siegert, *A critical appraisal of NLO+PS matching methods*, *JHEP* **09** (2012) 049 [[arXiv:1111.1220](#)] [[INSPIRE](#)].
- [93] S. Hoeche, F. Krauss, M. Schönherr and F. Siegert, *QCD matrix elements + parton showers: The NLO case*, *JHEP* **04** (2013) 027 [[arXiv:1207.5030](#)] [[INSPIRE](#)].
- [94] S. Catani, F. Krauss, R. Kuhn and B.R. Webber, *QCD matrix elements + parton showers*, *JHEP* **11** (2001) 063 [[hep-ph/0109231](#)] [[INSPIRE](#)].

- [95] S. Hoeche, F. Krauss, S. Schumann and F. Siegert, *QCD matrix elements and truncated showers*, *JHEP* **05** (2009) 053 [[arXiv:0903.1219](#)] [[INSPIRE](#)].
- [96] F. Buccioni et al., *OpenLoops 2*, *Eur. Phys. J. C* **79** (2019) 866 [[arXiv:1907.13071](#)] [[INSPIRE](#)].
- [97] F. Cascioli, P. Maierhöfer and S. Pozzorini, *Scattering Amplitudes with Open Loops*, *Phys. Rev. Lett.* **108** (2012) 111601 [[arXiv:1111.5206](#)] [[INSPIRE](#)].
- [98] A. Denner, S. Dittmaier and L. Hofer, *COLLIER: a fortran-based Complex One-Loop Library in Extended Regularizations*, *Comput. Phys. Commun.* **212** (2017) 220 [[arXiv:1604.06792](#)] [[INSPIRE](#)].
- [99] NNPDF collaboration, *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [[INSPIRE](#)].
- [100] S. Alioli, S. Ferrario Ravasio, J.M. Lindert and R. Röntsch, *Four-lepton production in gluon fusion at NLO matched to parton showers*, *Eur. Phys. J. C* **81** (2021) 687 [[arXiv:2102.07783](#)] [[INSPIRE](#)].
- [101] ATLAS collaboration, *Modelling and computational improvements to the simulation of single vector-boson plus jet processes for the ATLAS experiment*, *JHEP* **08** (2022) 089 [[arXiv:2112.09588](#)] [[INSPIRE](#)].
- [102] C. Anastasiou, L.J. Dixon, K. Melnikov and F. Petriello, *High-precision QCD at hadron colliders: Electroweak gauge boson rapidity distributions at next-to-next-to leading order*, *Phys. Rev. D* **69** (2004) 094008 [[hep-ph/0312266](#)] [[INSPIRE](#)].
- [103] ATLAS collaboration, *Studies on top-quark Monte Carlo modelling for Top2016*, *ATL-PHYS-PUB-2016-020* (2016) [[INSPIRE](#)].
- [104] GEANT4 collaboration, *GEANT4 — A Simulation Toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [105] ATLAS collaboration, *The ATLAS Simulation Infrastructure*, *Eur. Phys. J. C* **70** (2010) 823 [[arXiv:1005.4568](#)] [[INSPIRE](#)].
- [106] K. Werner, F.-M. Liu and T. Pierog, *Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron–gold collisions at the BNL Relativistic Heavy Ion Collider*, *Phys. Rev. C* **74** (2006) 044902 [[hep-ph/0506232](#)] [[INSPIRE](#)].
- [107] T. Pierog et al., *EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider*, *Phys. Rev. C* **92** (2015) 034906 [[arXiv:1306.0121](#)] [[INSPIRE](#)].
- [108] ATLAS collaboration, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie-Landshoff diffractive model*, *ATL-PHYS-PUB-2016-017* (2016) [[INSPIRE](#)].
- [109] ATLAS collaboration, *Software Performance of the ATLAS Track Reconstruction for LHC Run 3*, *Comput. Softw. Big Sci.* **8** (2024) 9 [[arXiv:2308.09471](#)] [[INSPIRE](#)].
- [110] ATLAS collaboration, *Development of ATLAS Primary Vertex Reconstruction for LHC Run 3*, *ATL-PHYS-PUB-2019-015* (2019) [[INSPIRE](#)].
- [111] ATLAS collaboration, *Reconstruction of primary vertices at the ATLAS experiment in Run 1 proton–proton collisions at the LHC*, *Eur. Phys. J. C* **77** (2017) 332 [[arXiv:1611.10235](#)] [[INSPIRE](#)].
- [112] ATLAS collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton-proton collision data*, *2019 JINST* **14** P12006 [[arXiv:1908.00005](#)] [[INSPIRE](#)].
- [113] ATLAS collaboration, *Electron and photon efficiencies in LHC Run 2 with the ATLAS experiment*, *JHEP* **05** (2024) 162 [[arXiv:2308.13362](#)] [[INSPIRE](#)].

- [114] ATLAS collaboration, *Electron and photon energy calibration with the ATLAS detector using LHC Run 2 data*, [2024 JINST 19 P02009](#) [[arXiv:2309.05471](#)] [[INSPIRE](#)].
- [115] ATLAS collaboration, *Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **81** (2021) 578 [[arXiv:2012.00578](#)] [[INSPIRE](#)].
- [116] ATLAS collaboration, *Studies of the muon momentum calibration and performance of the ATLAS detector with pp collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **83** (2023) 686 [[arXiv:2212.07338](#)] [[INSPIRE](#)].
- [117] ATLAS collaboration, *Jet reconstruction and performance using particle flow with the ATLAS Detector*, *Eur. Phys. J. C* **77** (2017) 466 [[arXiv:1703.10485](#)] [[INSPIRE](#)].
- [118] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [119] ATLAS collaboration, *Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **81** (2021) 689 [[arXiv:2007.02645](#)] [[INSPIRE](#)].
- [120] ATLAS collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 581 [[arXiv:1510.03823](#)] [[INSPIRE](#)].
- [121] ATLAS collaboration, *Forward jet vertex tagging using the particle flow algorithm*, [ATL-PHYS-PUB-2019-026](#) (2019) [[INSPIRE](#)].
- [122] ATLAS collaboration, *The performance of missing transverse momentum reconstruction and its significance with the ATLAS detector using 140 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions*, *Eur. Phys. J. C* **85** (2025) 606 [[arXiv:2402.05858](#)] [[INSPIRE](#)].
- [123] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *PTEP* **2020** (2020) 083C01 [[INSPIRE](#)].
- [124] ATLAS collaboration, *Electron and photon reconstruction and performance in ATLAS using a dynamical, topological cell clustering-based approach*, [ATL-PHYS-PUB-2017-022](#) (2017) [[INSPIRE](#)].
- [125] ATLAS collaboration, *Evidence of pair production of longitudinally polarised vector bosons and study of CP properties in $ZZ \rightarrow 4\ell$ events with the ATLAS detector at $\sqrt{s} = 13$ TeV*, *JHEP* **12** (2023) 107 [[arXiv:2310.04350](#)] [[INSPIRE](#)].
- [126] ATLAS collaboration, *Differential cross-section measurements of the production of four charged leptons in association with two jets using the ATLAS detector*, *JHEP* **01** (2024) 004 [[arXiv:2308.12324](#)] [[INSPIRE](#)].
- [127] ATLAS collaboration, *Proposal for particle-level object and observable definitions for use in physics measurements at the LHC*, [ATL-PHYS-PUB-2015-013](#) (2015) [[INSPIRE](#)].
- [128] J.R. Andersen et al., *Les Houches 2017: Physics at TeV Colliders Standard Model Working Group Report*, [arXiv:1803.07977](#) [[INSPIRE](#)].
- [129] J. Lee, Y. Lee, J. Kim, A.R. Kosiorek, S. Choi and Y.W. Teh, *Set Transformer*, [arXiv:1810.00825](#).
- [130] Y. Gao et al., *Spin Determination of Single-Produced Resonances at Hadron Colliders*, *Phys. Rev. D* **81** (2010) 075022 [[arXiv:1001.3396](#)] [[INSPIRE](#)].
- [131] D.L. Rainwater, R. Szalapski and D. Zeppenfeld, *Probing color-singlet exchange in $Z+2$ -jet events at the CERN LHC*, *Phys. Rev. D* **54** (1996) 6680 [[hep-ph/9605444](#)] [[INSPIRE](#)].

- [132] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [Erratum *ibid.* **73** (2013) 2501] [[arXiv:1007.1727](#)] [[INSPIRE](#)].
- [133] ATLAS collaboration, *Evaluation of QCD uncertainties for Higgs boson production through gluon fusion and in association with two top quarks for simplified template cross-section measurements*, *ATL-PHYS-PUB-2023-031* (2023) [[INSPIRE](#)].
- [134] A. Bredenstein, A. Denner, S. Dittmaier and M.M. Weber, *Radiative corrections to the semileptonic and hadronic Higgs-boson decays $H \rightarrow WW/ZZ \rightarrow 4$ fermions*, *JHEP* **02** (2007) 080 [[hep-ph/0611234](#)] [[INSPIRE](#)].
- [135] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, [arXiv:1307.1347](#) [[DOI:10.5170/CERN-2013-004](#)] [[INSPIRE](#)].
- [136] I. Brivio, Y. Jiang and M. Trott, *The SMEFTsim package, theory and tools*, *JHEP* **12** (2017) 070 [[arXiv:1709.06492](#)] [[INSPIRE](#)].
- [137] B. Grzadkowski, M. Iskrzyński, M. Misiak and J. Rosiek, *Dimension-Six Terms in the Standard Model Lagrangian*, *JHEP* **10** (2010) 085 [[arXiv:1008.4884](#)] [[INSPIRE](#)].
- [138] A. Azatov, R. Contino, C.S. Machado and F. Riva, *Helicity selection rules and noninterference for BSM amplitudes*, *Phys. Rev. D* **95** (2017) 065014 [[arXiv:1607.05236](#)] [[INSPIRE](#)].
- [139] G. Panico, F. Riva and A. Wulzer, *Diboson interference resurrection*, *Phys. Lett. B* **776** (2018) 473 [[arXiv:1708.07823](#)] [[INSPIRE](#)].
- [140] ATLAS collaboration, *Interpretations of the ATLAS measurements of Higgs boson production and decay rates and differential cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **11** (2024) 097 [[arXiv:2402.05742](#)] [[INSPIRE](#)].
- [141] J. Aebischer et al., *WCxf: an exchange format for Wilson coefficients beyond the Standard Model*, *Comput. Phys. Commun.* **232** (2018) 71 [[arXiv:1712.05298](#)] [[INSPIRE](#)].
- [142] F. Maltoni, D. Pagani, A. Shivaji and X. Zhao, *Trilinear Higgs coupling determination via single-Higgs differential measurements at the LHC*, *Eur. Phys. J. C* **77** (2017) 887 [[arXiv:1709.08649](#)] [[INSPIRE](#)].
- [143] U. Haisch and M. Niggetiedt, *Exact two-loop amplitudes for Higgs plus jet production with a cubic Higgs self-coupling*, *JHEP* **10** (2024) 236 [[arXiv:2408.13186](#)] [[INSPIRE](#)].
- [144] G. Degrandi, P.P. Giardino, F. Maltoni and D. Pagani, *Probing the Higgs self coupling via single Higgs production at the LHC*, *JHEP* **12** (2016) 080 [[arXiv:1607.04251](#)] [[INSPIRE](#)].
- [145] ATLAS collaboration, *ATLAS Computing Acknowledgements*, *ATL-SOFT-PUB-2026-001* (2026).

The ATLAS collaboration

G. Aad [ID](#)¹⁰², E. Aakvaag [ID](#)¹⁷, B. Abbott [ID](#)¹²¹, S. Abdelhameed [ID](#)^{83b}, K. Abeling [ID](#)⁵⁴, N.J. Abicht [ID](#)⁴⁸, S.H. Abidi [ID](#)³⁰, M. Aboelela [ID](#)⁴⁴, A. Aboulhorma [ID](#)^{36e}, H. Abramowicz [ID](#)¹⁵⁴, B.S. Acharya [ID](#)^{68a,68b,a}, A. Ackermann [ID](#)^{62a}, C. Adam Bourdarios [ID](#)⁴, L. Adamczyk [ID](#)^{85a}, S.V. Addepalli [ID](#)¹⁴⁶, M. J. Addison [ID](#)¹⁰¹, J. Adelman [ID](#)¹¹⁷, A. Adiguzel [ID](#)^{22c}, T. Adye [ID](#)¹³⁵, A.A. Affolder [ID](#)¹³⁷, Y. Afik [ID](#)³⁹, M.N. Agaras [ID](#)¹³, A. Aggarwal [ID](#)¹⁰⁰, C. Agheorghiesei [ID](#)^{28c}, A. Ahmad [ID](#)^{83a}, F. Ahmadov [ID](#)^{38,b}, S. Ahuja [ID](#)⁹⁵, S. Ahuja [ID](#)¹⁶⁵, X. Ai [ID](#)^{113c}, G. Aielli [ID](#)^{75a,75b}, A. Aikot [ID](#)¹⁶⁵, M. Ait Tamlihat [ID](#)^{36e}, T.P.A. Åkesson [ID](#)⁹⁸, D. Akiyama [ID](#)¹⁷⁰, N.N. Akolkar [ID](#)²⁵, S. Aktas [ID](#)¹⁶⁸, G.L. Alberghi [ID](#)^{24b}, J. Albert [ID](#)¹⁶⁷, U. Alberti [ID](#)²⁰, P. Albicocco [ID](#)⁵², S. Alderweireldt [ID](#)⁵¹, Z.L. Alegria [ID](#)¹²², M. Aleksa [ID](#)³⁷, I.N. Aleksandrov [ID](#)³⁸, C. Alexa [ID](#)^{28b}, T. Alexopoulos [ID](#)¹⁰, F. Alfonsi [ID](#)^{24b}, M. Algren [ID](#)⁵⁵, M. Alhroob [ID](#)¹⁶⁹, B. Ali [ID](#)¹³³, H. M. J. Ali [ID](#)^{91,c}, S. Ali [ID](#)³², S.W. Alibocus [ID](#)⁹², M. Aliev [ID](#)^{34c}, G. Alimonti [ID](#)^{70a}, C. Allaire [ID](#)⁶⁵, B.M.M. Allbrooke [ID](#)¹⁴⁹, D. R. Allen [ID](#)¹²², J. S. Allen [ID](#)¹⁰¹, J.F. Allen [ID](#)⁵¹, C.S. Alley [ID](#)¹, E.R. Almazan [ID](#)¹³⁷, A. Aloisio [ID](#)^{71a,71b}, F. Alonso [ID](#)⁹⁰, C. Alpigiani [ID](#)¹⁴⁰, A. Alvarez Fernandez [ID](#)¹⁰⁰, M. Alves Cardoso [ID](#)⁵⁵, M.G. Alviggi [ID](#)^{71a,71b}, M. Aly [ID](#)¹⁰¹, Y. Amaral Coutinho [ID](#)^{81b}, C. Amelung [ID](#)³⁷, M. Amerl [ID](#)¹⁰¹, T. Amezza [ID](#)¹²⁸, B. Amini [ID](#)⁵³, K. Amirie [ID](#)¹⁵⁸, A. Amirkhanov [ID](#)³⁸, D. Amperiadou [ID](#)¹⁵⁵, S. An [ID](#)⁸², C. Anastopoulos [ID](#)¹⁴², T. Andeen [ID](#)¹¹, J.K. Anders [ID](#)⁹², A. C. Anderson [ID](#)⁵⁸, A. Andreatza [ID](#)^{70a,70b}, S. Angelidakis [ID](#)⁹, A. Angerami [ID](#)⁴¹, A.V. Anisenkov [ID](#)³⁸, A. Annovi [ID](#)^{73a}, C. Antel [ID](#)³⁷, E. Antipov [ID](#)¹⁴⁸, M. Antonelli [ID](#)⁵², F. Anulli [ID](#)^{74a}, M. Aoki [ID](#)⁸², T. Aoki [ID](#)¹⁵⁶, M.A. Aparo [ID](#)¹³, L. Aperio Bella [ID](#)⁴⁷, M. Apicella [ID](#)³¹, C. Appelt [ID](#)¹⁵⁴, A. Apyan [ID](#)²⁷, M. Arampatzi [ID](#)¹⁰, S. J. Arbiol Val [ID](#)⁸⁶, C. Arcangeletti [ID](#)⁵², A.T.H. Arce [ID](#)⁵⁰, M. Arcuri [ID](#)^{43b,43a}, J-F. Arguin [ID](#)¹⁰⁸, S. Argyropoulos [ID](#)¹⁵⁵, J.-H. Arling [ID](#)⁴⁷, O. Arnaez [ID](#)⁴, H. Arnold [ID](#)¹⁴⁸, G. Artoni [ID](#)^{74a,74b}, H. Asada [ID](#)¹¹¹, S. Asatryan [ID](#)¹⁷⁵, N.A. Asbah [ID](#)³⁷, R. A. Ashby Pickering [ID](#)¹⁶⁹, A. M. Aslam [ID](#)⁹⁵, J. Assahsah [ID](#)^{36d}, K. Assamagan [ID](#)³⁰, R. Astalos [ID](#)^{29a}, K. S. V. Astrand [ID](#)⁹⁸, S. Atashi [ID](#)¹⁶², R.J. Atkin [ID](#)^{34a}, H. Atmani [ID](#)^{36f}, P.A. Atmasiddha [ID](#)¹²⁹, K. Augsten [ID](#)¹³³, A.D. Auriol [ID](#)⁴⁰, V.A. Austrup [ID](#)¹⁰¹, A.S. Avad [ID](#)⁹⁴, G. Avolio [ID](#)³⁷, A. Azzam [ID](#)¹³, D. Babal [ID](#)^{29b}, H. Bachacou [ID](#)¹³⁶, K. Bachas [ID](#)^{155,d}, A. Bachi [ID](#)³⁵, E. Bachmann [ID](#)⁴⁹, M. J. Backes [ID](#)^{62a}, A. Badea [ID](#)³⁹, T.M. Baer [ID](#)¹⁰⁶, M. Bahmani [ID](#)¹⁹, D. Bahner [ID](#)⁵³, K. Bai [ID](#)¹²⁴, L. Baines [ID](#)⁹⁴, O.K. Baker [ID](#)¹⁷⁴, D. Bakshi Gupta [ID](#)⁸, L.E. Balabram Filho [ID](#)^{81b}, V. Balakrishnan [ID](#)¹²¹, R. Balasubramanian [ID](#)⁴, P. Balek [ID](#)^{85a}, E. Ballabene [ID](#)^{24b,24a}, F. Balli [ID](#)¹³⁶, L.M. Baltes [ID](#)^{62a}, W.K. Balunas [ID](#)¹²⁷, I. Bamwidhi [ID](#)^{83c}, E. Banas [ID](#)⁸⁶, M. Bandieramonte [ID](#)¹³⁰, A. Bandyopadhyay [ID](#)²⁵, S. Bansal [ID](#)²⁵, L. Barak [ID](#)¹⁵⁴, M. Barakat [ID](#)⁴⁷, E.L. Barberio [ID](#)¹⁰⁵, D. Barberis [ID](#)^{18b}, M. Barbero [ID](#)¹⁰², M. Z. Barel [ID](#)¹¹⁶, T. Barillari [ID](#)¹¹⁰, M-S. Barisits [ID](#)³⁷, T. Barklow [ID](#)¹⁴⁶, P. Baron [ID](#)¹³⁴, D.A. Baron Moreno [ID](#)¹⁰¹, A. Baroncelli [ID](#)⁶¹, A.J. Barr [ID](#)¹²⁷, J.D. Barr [ID](#)⁹⁶, F. Barreiro [ID](#)⁹⁹, J. Barreiro Guimarães da Costa [ID](#)¹⁴, M.G. Barros Teixeira [ID](#)^{131a}, F. Bartels [ID](#)^{62a}, R. Bartoldus [ID](#)¹⁴⁶, A.E. Barton [ID](#)⁹¹, P. Bartos [ID](#)^{29a}, M. Baselga [ID](#)⁴⁸, S. Bashiri [ID](#)⁸⁶, A. Bassalat [ID](#)^{65,e}, M.J. Basso [ID](#)^{159a}, S. Bataju [ID](#)⁴⁴, R. Bate [ID](#)¹⁶⁶, R.L. Bates [ID](#)⁵⁸, S. Batlamous [ID](#)⁹⁹, M. Battaglia [ID](#)¹³⁷, D. Battulga [ID](#)¹⁹, M. Bause [ID](#)^{74a,74b}, L. Bauckhage [ID](#)⁴⁷, P. Bauer [ID](#)²⁵, L. T. Bayer [ID](#)⁴⁷, L.T. Bazzano Hurrell [ID](#)³¹, T. Beau [ID](#)¹²⁸, J.Y. Beaucamp [ID](#)⁹⁰, S. Beauceron [ID](#)¹²⁸, P.H. Beauchemin [ID](#)¹⁶¹, P. Bechtel [ID](#)²⁵, H.P. Beck [ID](#)^{20,f}, K. Becker [ID](#)¹⁶⁹, A.J. Beddall [ID](#)⁸⁰, V.A. Bednyakov [ID](#)³⁸, C.P. Bee [ID](#)¹⁴⁸, L.J. Beemster [ID](#)¹⁶, M. Begalli [ID](#)^{81d}, M. Begel [ID](#)³⁰, J.K. Behr [ID](#)⁴⁷, J.F. Beirer [ID](#)³⁷, F. Beisiegel [ID](#)²⁵, M. Belfkir [ID](#)^{83c}, G. Bella [ID](#)¹⁵⁴, L. Bellagamba [ID](#)^{24b}, A. Bellerive [ID](#)³⁵, C.D. Bellgraph [ID](#)⁶⁷, P. Bellos [ID](#)²¹, I. Benaoumeur [ID](#)²¹, D. Benckekroun [ID](#)^{36a}, F. Bendebba [ID](#)^{36a},

Y. Benhammou [ID](#)¹⁵⁴, K.C. Benkendorfer [ID](#)¹⁶⁷, L. Beresford [ID](#)⁴⁷, M. Beretta [ID](#)⁵²,
E. Bergeaas Kuutmann [ID](#)¹⁶³, N. Berger [ID](#)⁴, B. Bergmann [ID](#)¹³³, J. Beringer [ID](#)^{18a}, M. Berkat [ID](#)¹³⁶,
G. Bernardi [ID](#)⁵, C. Bernius [ID](#)¹⁴⁶, F.U. Bernlochner [ID](#)²⁵, A. Berrocal Guardia [ID](#)¹³, T. Berry [ID](#)⁹⁵,
P. Berta [ID](#)¹³⁴, A. Berti [ID](#)^{131a}, R. Bertrand [ID](#)¹⁰², S. Bethke [ID](#)¹¹⁰, A. Betti [ID](#)^{74a,74b}, T.F. Beumker [ID](#)¹⁷³,
A.J. Bevan [ID](#)⁹⁴, L. Bezio [ID](#)⁵⁵, N.K. Bhalla [ID](#)⁵³, S. Bharthuar [ID](#)¹¹⁰, S. Bhatta [ID](#)¹⁴⁸, P. Bhattarai [ID](#)¹⁴⁶,
Z.M. Bhatti [ID](#)¹¹⁸, K. D. Bhide [ID](#)¹⁶⁴, V.S. Bhopatkar [ID](#)¹²², R.M. Bianchi [ID](#)¹³⁰, G. Bianco [ID](#)^{24b,24a},
O. Biebel [ID](#)¹⁰⁹, M. Biglietti [ID](#)^{76a}, P. Bijl [ID](#)⁵³, C. S. Billingsley [ID](#)⁴⁴, Y. Bimgdi [ID](#)^{36f}, M. Bindi [ID](#)⁵⁴,
A. Bingham [ID](#)¹⁷³, A. Bingul [ID](#)^{22b}, C. Bini [ID](#)^{74a,74b}, G.A. Bird [ID](#)³³, M. Biros [ID](#)¹³⁴, S. Biryukov [ID](#)¹⁴⁹,
T. Bisanz [ID](#)⁴⁸, E. Bisceglie [ID](#)^{24b,24a}, J.P. Biswal [ID](#)¹³⁵, D. Biswas [ID](#)¹⁴⁴, M. Biyabi [ID](#)¹⁴, I. Bloch [ID](#)⁴⁷,
A. Blue [ID](#)⁵⁸, U. Blumenschein [ID](#)⁹⁴, V.S. Bobrovnikov [ID](#)³⁸, L. Boccardo [ID](#)^{56b,56a}, M. Boehler [ID](#)⁵³,
B. Boehm [ID](#)¹⁶⁸, D. Bogavac [ID](#)¹³, L. S. Boggia [ID](#)¹²⁸, V. Boisvert [ID](#)⁹⁵, P. Bokan [ID](#)¹⁶³, T. Bold [ID](#)^{85a},
M. Bomben [ID](#)⁵, M. Bona [ID](#)⁹⁴, M. Boonekamp [ID](#)¹³⁶, A.G. Borbély [ID](#)⁵⁸, G. Borissov [ID](#)⁹¹,
A. Borkar [ID](#)¹⁶⁸, D. Bortoletto [ID](#)¹²⁷, M. Borysova [ID](#)¹⁷¹, D. Boscherini [ID](#)^{24b}, M. Bosman [ID](#)¹³,
K. Bouaouda [ID](#)^{36a}, L. Boudet [ID](#)¹³⁶, J. Boudreau [ID](#)¹³⁰, E.V. Bouhova-Thacker [ID](#)⁹¹,
D. Boumediene [ID](#)⁴⁰, R. Bouquet [ID](#)^{56b,56a}, A. Boveia [ID](#)¹²⁰, D. Boye [ID](#)³⁰, I.R. Boyko [ID](#)³⁸,
L. Bozianu [ID](#)⁵⁵, J. Bracinik [ID](#)²¹, N. Brahimi [ID](#)⁴, G. Brandt [ID](#)¹⁷³, O. Brandt [ID](#)³³, B. Brau [ID](#)¹⁰³,
R. Brenner [ID](#)¹⁷¹, L. Brenner [ID](#)¹¹⁶, R. Brenner [ID](#)¹⁶³, S. Bressler [ID](#)¹⁷¹, M. Brettell [ID](#)⁹⁶, G. Brianti [ID](#)¹¹⁶,
D. Britton [ID](#)⁵⁸, D. Britzger [ID](#)¹¹⁰, I. Brock [ID](#)²⁵, R. Brock [ID](#)¹⁰⁷, H. Bronson [ID](#)¹²⁹, G. Brooijmans [ID](#)⁴¹,
A.J. Brooks [ID](#)⁶⁷, E. M. Brooks [ID](#)^{159b}, E. Brost [ID](#)³⁰, L.M. Brown [ID](#)^{167,159a}, L.E. Bruce [ID](#)⁶⁰,
T.L. Bruckler [ID](#)¹²⁷, P.A. Bruckman de Renstrom [ID](#)⁸⁶, B. Brüers [ID](#)⁴⁷, A. Bruni [ID](#)^{24b}, G. Bruni [ID](#)^{24b},
D. Brunner [ID](#)^{46a,46b}, M. Bruschi [ID](#)^{24b}, N. Bruscino [ID](#)^{74a,74b}, T. Buanes [ID](#)¹⁷, Q. Buat [ID](#)¹⁴⁰,
D. Buchin [ID](#)¹¹⁰, A.G. Buckley [ID](#)⁵⁸, J. Bucko [ID](#)¹³⁴, M. Bühring [ID](#)⁴⁹, O. Bulekov [ID](#)⁸⁰,
B.A. Bullard [ID](#)¹⁴⁶, T. O. Buratovich [ID](#)⁹⁰, S. Burdin [ID](#)⁹², C.D. Burgard [ID](#)⁴⁸, A.M. Burger [ID](#)⁸⁹,
B. Burghgrave [ID](#)⁸, O. Burlayenko [ID](#)⁵³, J. Burleson [ID](#)¹⁶⁴, J.C. Burzynski [ID](#)¹²¹, V. Büscher [ID](#)¹⁰⁰,
P.J. Bussey [ID](#)⁵⁸, O. But [ID](#)²⁵, J.M. Butler [ID](#)²⁶, C.M. Buttar [ID](#)⁵⁸, J.M. Butterworth [ID](#)⁹⁶, P. Butti [ID](#)³⁷,
W. Buttinger [ID](#)¹³⁵, C.J. Buxo Vazquez [ID](#)¹⁰⁷, A.R. Buzykaev [ID](#)³⁸, S. Cabrera Urbán [ID](#)¹⁶⁵,
L. Cadamuro [ID](#)⁶⁵, H. Cai [ID](#)³⁷, Y. Cai [ID](#)^{24b,112c,24a}, Y. Cai [ID](#)^{112a}, M.A. Cairo [ID](#)¹²⁹, V.M.M. Cairo [ID](#)³⁷,
O. Cakir [ID](#)^{3a}, N. Calace [ID](#)³⁷, P. Calafiura [ID](#)^{18a}, G. Calderini [ID](#)¹²⁸, P. Calfayan [ID](#)³⁵, L. Calic [ID](#)⁹⁸,
G. Callea [ID](#)⁵⁸, L.P. Caloba [ID](#)^{81b}, D. Calvet [ID](#)⁴⁰, S. Calvet [ID](#)⁴⁰, R. Camacho Toro [ID](#)¹²⁸, S. Camarda [ID](#)³⁷,
D. Camarero Munoz [ID](#)²⁷, P. Camarri [ID](#)^{75a,75b}, C. Camincher [ID](#)³⁷, M. Campanelli [ID](#)⁹⁶,
A. Camplani [ID](#)⁴², V. Canale [ID](#)^{71a,71b}, A.C. Canbay [ID](#)^{3a}, E. Canonero [ID](#)⁹⁵, J. Cantero [ID](#)¹⁶⁵,
F. Capocasa [ID](#)²⁷, P. Cappelli [ID](#)²⁷, M. Capua [ID](#)^{43b,43a}, A. Carbone [ID](#)^{70a,70b}, R. Cardarelli [ID](#)^{75a},
J.C.J. Cardenas [ID](#)⁸, M. P. Cardiff [ID](#)²⁷, G. Carducci [ID](#)^{43b,43a}, T. Carli [ID](#)³⁷, G. Carlino [ID](#)^{71a},
J.I. Carlotta [ID](#)¹³, B.T. Carlson [ID](#)^{130,g}, E.M. Carlson [ID](#)¹⁶⁷, L. Carminati [ID](#)^{70a,70b}, A. Carnelli [ID](#)⁴,
M. Carnesale [ID](#)³⁷, S. Caron [ID](#)¹¹⁵, E. Carquin [ID](#)^{138g}, I.B. Carr [ID](#)¹⁰⁵, S. Carrà [ID](#)^{72a,72b},
G. Carratta [ID](#)^{24b,24a}, C. Carrion Martinez [ID](#)¹⁶⁵, A.M. Carroll [ID](#)¹²⁴, N. Cartalade [ID](#)⁴⁰,
M.P. Casado [ID](#)^{13,h}, P. Casolaro [ID](#)^{71a,71b}, M. Caspar [ID](#)⁴⁷, F. Cassinese [ID](#)⁹⁰, W.R. Castiglioni [ID](#)³⁹,
F.L. Castillo [ID](#)⁴, V. Castillo Gimenez [ID](#)¹⁶⁵, N.F. Castro [ID](#)^{131a,131e}, A. Catinaccio [ID](#)³⁷,
J.R. Catmore [ID](#)¹²⁶, T. Cavaliere [ID](#)⁴, V. Cavaliere [ID](#)³⁰, E. Celebi [ID](#)⁸⁰, S. Cella [ID](#)³⁰, V. Cepaitis [ID](#)⁵⁵,
K. Cerny [ID](#)¹²³, A.S. Cerqueira [ID](#)^{81a}, A. Cerri [ID](#)^{73a,i}, L. Cerrito [ID](#)^{75a,75b}, F. Cerutti [ID](#)^{18a},
B. Cervato [ID](#)^{70a,70b}, A. Cervelli [ID](#)^{24b}, G. Cesarini [ID](#)⁵², S.A. Cetin [ID](#)⁸⁰, V. C. Chabalala [ID](#)^{34j},
P.M. Chabrilat [ID](#)¹²⁸, R. Chakkappai [ID](#)⁶⁵, S. Chakraborty [ID](#)¹⁶⁹, A. Chambers [ID](#)⁶⁰, J. Chan [ID](#)^{18a},
J.D. Chapman [ID](#)³³, E. Chapon [ID](#)¹³⁶, D.G. Charlton [ID](#)²¹, C. Chauhan [ID](#)¹³², Y. Che [ID](#)^{112a},

S. Chekanov [ID](#)⁶, G.A. Chelkov [ID](#)^{38,j}, H. Chen [ID](#)³⁰, J. Chen [ID](#)^{141a}, J. Chen [ID](#)¹⁴⁵, M. Chen [ID](#)⁵⁹, S. Chen [ID](#)⁸⁷, S.J. Chen [ID](#)^{112a}, X. Chen [ID](#)^{141a}, X. Chen [ID](#)^{15,k}, Z. Chen [ID](#)⁶¹, C.L. Cheng [ID](#)¹⁴⁶, H.C. Cheng [ID](#)^{63a}, S. Cheong [ID](#)¹⁴⁶, A. Cheplakov [ID](#)³⁸, E. Cherepanova [ID](#)¹¹⁶, E. Cheu [ID](#)⁷, K. Cheung [ID](#)⁶⁴, L. Chevalier [ID](#)¹³⁶, G. Chiarelli [ID](#)^{73a}, G. Chiodini [ID](#)^{69a}, A.S. Chisholm [ID](#)²¹, J. L. Chisholm [ID](#)¹⁶⁶, A. Chitan [ID](#)^{28b}, M. Chitishvili [ID](#)¹⁶⁵, M.V. Chizhov [ID](#)^{38,l}, K. Chmiel [ID](#)^{76a,76b}, K. Choi [ID](#)¹¹, Y. Chou [ID](#)¹⁴⁰, E.Y.S. Chow [ID](#)¹¹⁵, G. Christou [ID](#)⁵¹, K.L. Chu [ID](#)¹⁷¹, M.C. Chu [ID](#)^{63a}, Z. Chubinidze [ID](#)⁵², J. Chudoba [ID](#)¹³², J.J. Chwastowski [ID](#)⁸⁶, D. Cieri [ID](#)¹¹⁰, K.M. Ciesla [ID](#)^{85a}, V. Cindro [ID](#)⁹³, A. Ciocio [ID](#)^{18a}, F. Ciotto [ID](#)^{71a,71b}, Z.H. Citron [ID](#)¹⁷¹, M. Citterio [ID](#)^{70a}, D.A. Ciubotaru [ID](#)^{28b}, A. Clark [ID](#)⁵⁵, P.J. Clark [ID](#)⁵¹, N. Clarke Hall [ID](#)⁹⁶, C. Clarry [ID](#)¹⁵⁸, S.E. Clawson [ID](#)⁴⁷, C. Clement [ID](#)^{46a,46b}, L. Clissa [ID](#)^{24b,24a}, Y. Coadou [ID](#)¹⁰², M. Cobal [ID](#)^{68a,68c}, A. Coccaro [ID](#)^{56b}, M. G. Cochran Branson [ID](#)¹⁴⁰, R.F. Coelho Barrue [ID](#)^{131a}, R. Coelho Lopes De Sa [ID](#)¹⁰³, S. Coelli [ID](#)^{70a}, M.M. Cohen [ID](#)¹²⁹, L. S. Colangeli [ID](#)¹⁵⁸, B. Cole [ID](#)⁴¹, P. Collado Soto [ID](#)⁹⁹, J. Collot [ID](#)⁵⁹, M.R. Coluccia [ID](#)^{69a}, I. Combes [ID](#)⁶⁵, P. Conde Muiño [ID](#)^{131a,131g}, L.H.J. Condren [ID](#)¹⁶², M.P. Connell [ID](#)^{34c}, S.H. Connell [ID](#)^{34c}, E.I. Conroy [ID](#)¹²⁷, M. Contreras Cossio [ID](#)¹¹, F. Conventi [ID](#)^{71a,m}, A.M. Cooper-Sarkar [ID](#)¹²⁷, L. Corazzina [ID](#)^{74a,74b}, F. A. Corchia [ID](#)^{24b,24a}, A. Cordeiro Oudot Choi [ID](#)¹⁴⁰, L.D. Corpe [ID](#)⁴⁰, M. Corradi [ID](#)^{74a,74b}, F. Corriveau [ID](#)^{104,n}, A. Cortes-Gonzalez [ID](#)¹⁵⁶, M.J. Costa [ID](#)¹⁶⁵, F. Costanza [ID](#)⁴, D. Costanzo [ID](#)¹⁴², J. Couthures [ID](#)⁴, G. Cowan [ID](#)⁹⁵, K. Cranmer [ID](#)¹⁷², L. Cremer [ID](#)⁴⁸, D. Cremonini [ID](#)^{24b,24a}, S. Crépé-Renaudin [ID](#)⁵⁹, F. Crescioli [ID](#)¹²⁸, T. Cresta [ID](#)^{72a,72b}, M. Cristinziani [ID](#)¹⁴⁴, M. Cristoforetti [ID](#)^{77a,77b}, T. M. Critchley [ID](#)⁵⁵, E. Critelli [ID](#)⁹⁶, A. Cueto [ID](#)⁹⁹, H. Cui [ID](#)⁹⁶, Z. Cui [ID](#)⁷, B.M. Cunnett [ID](#)¹⁴⁹, W.R. Cunningham [ID](#)⁵⁸, E. Cuppini [ID](#)¹¹⁰, F. Curcio [ID](#)¹⁶⁵, J. R. Curran [ID](#)⁵¹, G. D’amen [ID](#)³⁰, V. D’Amico [ID](#)¹⁰⁹, M. D’Andrea [ID](#)^{56b,56a}, G. D’anniballe [ID](#)^{73a,73b}, S. D’Auria [ID](#)^{70a,70b}, A. D’Avanzo [ID](#)^{71a,71b}, L. D’Eramo [ID](#)⁴⁰, A. D’Onofrio [ID](#)^{71a,71b}, M. D’Onofrio [ID](#)⁹², M. D’uffizi [ID](#)¹⁰¹, M.J. Da Cunha Sargedass De Sousa [ID](#)^{56b,56a}, J.V. Da Fonseca Pinto [ID](#)^{81b}, C. Da Via [ID](#)¹⁰¹, W. Dabrowski [ID](#)^{85a}, T. Dado [ID](#)³⁷, S. Dahbi [ID](#)¹⁵¹, T. Dai [ID](#)¹⁰⁶, D. Dal Santo [ID](#)²⁰, C. Dallapiccola [ID](#)¹⁰³, M. Dam [ID](#)⁴², J.R. Dandoy [ID](#)³⁵, D. Dannheim [ID](#)³⁷, M. Danninger [ID](#)¹⁴⁵, V. Dao [ID](#)¹⁴⁸, G. Darbo [ID](#)^{56b}, F. Dattola [ID](#)⁴⁷, T. Davidek [ID](#)¹³⁴, J. Davidson [ID](#)¹⁶⁹, I. Dawson [ID](#)⁹⁴, K. De [ID](#)⁸, C. De Almeida Rossi [ID](#)¹⁵⁸, N. De Biase [ID](#)⁴⁷, S. De Castro [ID](#)^{24b,24a}, N. De Groot [ID](#)¹¹⁵, P. de Jong [ID](#)¹¹⁶, H. De la Torre [ID](#)¹¹⁷, A. De Maria [ID](#)^{112a}, S. De Miranda Rimes [ID](#)^{81d}, A. De Salvo [ID](#)^{74a}, U. De Sanctis [ID](#)^{75a,75b}, F. De Santis [ID](#)^{69a,69b}, A. De Santo [ID](#)¹⁴⁹, J.B. De Vivie De Regie [ID](#)⁵⁹, K.G. De Vries [ID](#)¹¹⁶, J. Debevc [ID](#)⁹³, D.V. Dedovich [ID](#)³⁸, J. Degens [ID](#)⁹², A.M. Deiana [ID](#)⁴⁴, J. Del Peso [ID](#)⁹⁹, L. Delagrangé [ID](#)²⁷, F. Deliot [ID](#)¹³⁶, C.M. Delitzsch [ID](#)⁴⁸, A. Dell’Acqua [ID](#)³⁷, L. Dell’Asta [ID](#)^{70a,70b}, M. Della Pietra [ID](#)^{71a,71b}, D. Della Volpe [ID](#)⁵⁵, M. Delmastro [ID](#)⁴, C.C. Delogu [ID](#)^{56b,56a}, P.A. Delsart [ID](#)⁵⁹, S. Demers [ID](#)¹⁷⁴, M. Demichev [ID](#)³⁸, H. Denizli [ID](#)^{22a,o}, M.G. Depala [ID](#)⁹², D. Derendarz [ID](#)⁸⁶, L. Derin [ID](#)^{56b,56a}, F. Derue [ID](#)¹²⁸, P. Dervan [ID](#)^{92,†}, A. M. Desai [ID](#)¹, K. Desch [ID](#)²⁵, F.A. Di Bello [ID](#)^{73a,73b}, A. Di Ciaccio [ID](#)^{75a,75b}, L. Di Ciaccio [ID](#)⁴, D. Di Croce [ID](#)³⁷, C. Di Donato [ID](#)^{71a,71b}, A. Di Girolamo [ID](#)³⁷, G. Di Gregorio [ID](#)⁶⁵, A. Di Luca [ID](#)^{77a,77b}, B. Di Micco [ID](#)^{76a,76b}, R. Di Nardo [ID](#)^{76a,76b}, K.F. Di Petrillo [ID](#)³⁹, M. Diamantopoulou [ID](#)³⁵, F.A. Dias [ID](#)¹¹⁶, M.A. Diaz [ID](#)^{138a,138b}, A. R. Didenko [ID](#)³⁸, M. Didenko [ID](#)¹⁶⁵, S.D. Diefenbacher [ID](#)^{18a}, E.B. Diehl [ID](#)¹⁰⁶, S. Díez Cornell [ID](#)⁴⁷, C. Díez Pardos [ID](#)¹⁴⁴, C. Dimitriadi [ID](#)¹⁴⁷, A. Dimitrievska [ID](#)²¹, A. Dimri [ID](#)¹⁴⁸, Y. Ding [ID](#)⁶¹, J. Dingfelder [ID](#)²⁵, T. Dingley [ID](#)¹²⁷, I-M. Dinu [ID](#)^{28b}, S.J. Dittmeier [ID](#)^{62b}, F. Dittus [ID](#)³⁷, M. Divisek [ID](#)¹³⁴, B. Dixit [ID](#)⁹², F. Djama [ID](#)¹⁰², T. Djobava [ID](#)^{152b}, C. Doglioni [ID](#)^{101,98}, A. Dohmalova [ID](#)^{29a}, Z. Dolezal [ID](#)¹³⁴, K. Domijan [ID](#)^{85a}, K.M. Dona [ID](#)³⁹, M. Donadelli [ID](#)^{81d},

B. Dong^{[107](#)}, J. Donini^{[40](#)}, J. Dopke^{[135](#)}, A. Doria^{[71a](#)}, N. Dos Santos Fernandes^{[131a](#)},
 I.A. Dos Santos Luz^{[81e](#)}, P. Dougan^{[44](#)}, M.T. Dova^{[90](#)}, A.T. Doyle^{[58](#)}, M.P. Drescher^{[54](#)},
 E. Dreyer^{[171](#)}, I. Drivas-koulouris^{[10](#)}, M. Drnevich^{[118](#)}, D. Du^{[61](#)}, T. Du^{[39](#)}, T.A. du Pree^{[116](#)},
 Z. Duan^{[112a](#)}, M. Dubau^{[4](#)}, F. Dubinin^{[38](#)}, M. Dubovsky^{[29a](#)}, E. Duchovni^{[171](#)}, G. Duckeck^{[109](#)},
 P. K. Duckett^{[96](#)}, O.A. Ducu^{[28b](#)}, D. Duda^{[51](#)}, A. Dudarev^{[37](#)}, M.M. Dudek^{[86](#)}, E. R. Duden^{[27](#)},
 L. Duffot^{[65](#)}, M. Dührssen^{[37](#)}, I. Duminica^{[28g](#)}, A.E. Dumitriu^{[28b](#)}, M. Dunford^{[62a](#)}, T. Duong^{[4](#)},
 A. Duperrin^{[102](#)}, A.F. Duque Bran^{[40](#)}, H. Duran Yildiz^{[3a](#)}, A. Durglishvili^{[152b](#)},
 G.I. Dyckes^{[18a](#)}, M. Dyndal^{[85a](#)}, B.S. Dziedzic^{[37](#)}, G.H. Eberwein^{[127](#)}, B. Eckerova^{[29a](#)},
 J.C. Egan^{[96](#)}, S. Eggebrecht^{[54](#)}, E. Egidio Purcino De Souza^{[81e](#)}, G. Eigen^{[17](#)},
 K. Einsweiler^{[18a](#)}, T. Ekelof^{[163](#)}, P.A. Ekman^{[98](#)}, S. El Farkh^{[36b](#)}, Y. El Ghazali^{[61](#)},
 H. El Jarrari^{[104](#)}, A. El Moussaouy^{[36a](#)}, I. Elbaz^{[154](#)}, D. Elitez^{[37](#)}, M. Ellert^{[163](#)},
 F. Ellinghaus^{[173](#)}, T.A. Elliot^{[95](#)}, J. Elmsheuser^{[30](#)}, M. Elsayy^{[83b](#)}, M. Elsing^{[37](#)},
 D. Emeliyanov^{[135](#)}, Y. Enari^{[82](#)}, S. Epari^{[108](#)}, D. Ernani Martins Neto^{[86](#)}, F. Ernst^{[37](#)},
 M. Escalier^{[65](#)}, C. Escobar^{[165](#)}, R. Estevam De Paula^{[81c](#)}, E. Etzion^{[154](#)}, G. Evans^{[131a,131b](#)},
 H. Evans^{[67](#)}, L.S. Evans^{[47](#)}, S. Ezzarqtouni^{[36a](#)}, F. Fabbri^{[24b,24a](#)}, L. Fabbri^{[24b,24a](#)},
 G. Facini^{[96](#)}, V. Fadeyev^{[137](#)}, D. Fakoudis^{[100](#)}, S. Falciano^{[74a](#)}, L.F. Falda Ulhoa Coelho^{[27](#)},
 F. Fallavollita^{[110](#)}, G. Falsetti^{[43b,43a](#)}, J. Faltova^{[134](#)}, C. Fan^{[164](#)}, K. Y. Fan^{[63b](#)}, Y. Fan^{[14](#)},
 Y. Fang^{[14,112c](#)}, M. Fanti^{[70a,70b](#)}, M. Faraj^{[68a,68c](#)}, Z. Farazpay^{[97](#)}, A. Farbin^{[8](#)}, A. Farilla^{[76a](#)},
 K. Farman^{[151](#)}, J. N. Farr^{[174](#)}, M. S. Farrington^{[60](#)}, S.M. Farrington^{[135,51](#)}, F. Fassi^{[36e](#)},
 D. Fassouliotis^{[9](#)}, L. Fayard^{[65](#)}, G. Fazzino^{[62b](#)}, P. Federic^{[134](#)}, P. Federicova^{[132](#)},
 M. Feickert^{[172](#)}, L. Feligioni^{[102](#)}, D.E. Fellers^{[18a](#)}, C. Feng^{[113b](#)}, Y. Feng^{[14](#)}, Z. Feng^{[65](#)},
 B. Fernandez Barbadillo^{[91](#)}, P. Fernandez Martinez^{[66](#)}, C. Fernandez Ruiz^{[33](#)}, J. Ferrando^{[91](#)},
 A. Ferrari^{[163](#)}, P. Ferrari^{[116,115](#)}, R. Ferrari^{[72a](#)}, D. Ferrere^{[55](#)}, C. Ferretti^{[106](#)}, M. P. Fewell^{[1](#)},
 D. Fiacco^{[74a,74b](#)}, F. Fiedler^{[100](#)}, P. Fiedler^{[133](#)}, S. Filimonov^{[38](#)}, M.S. Filip^{[28b,p](#)},
 A. Filipčič^{[93](#)}, E.K. Filmer^{[159a](#)}, F. Filthaut^{[115](#)}, M.C.N. Fiolhais^{[131a,131c,q](#)}, L. Fiorini^{[165](#)},
 W.C. Fisher^{[107](#)}, T. Fitschen^{[101](#)}, I. Fleck^{[144](#)}, P. Fleischmann^{[106](#)}, T. Flick^{[173](#)},
 M. Flores^{[34d,r](#)}, L.R. Flores Castillo^{[63a](#)}, M. Foll^{[126](#)}, F.M. Follega^{[77a,77b](#)}, N. Fomin^{[33](#)},
 J.H. Foo^{[158](#)}, A. Formica^{[136](#)}, M. Fornasiero^{[149](#)}, A.C. Forti^{[101](#)}, N. Forti^{[24b,24a](#)}, E. Fortin^{[102](#)},
 A.W. Fortman^{[18a](#)}, L. Foster^{[18a](#)}, L. Fountas^{[9](#)}, H. Fox^{[91](#)}, P. Francavilla^{[73a,73b](#)},
 S. Francescato^{[60](#)}, S. Franchellucci^{[20](#)}, M. Franchini^{[24b,24a](#)}, S. Franchino^{[62a](#)}, D. Francis^{[37](#)},
 L. Franco^{[47](#)}, L. Franconi^{[47](#)}, M. Franklin^{[60](#)}, G. Frattari^{[37](#)}, Y.Y. Frid^{[154](#)}, N. Fritzsche^{[37](#)},
 A. Froch^{[55](#)}, D. Froidevaux^{[37](#)}, J.A. Frost^{[135](#)}, Y. Fu^{[107](#)}, S. Fuenzalida Garrido^{[138g](#)},
 Y.C. Fujikake^{[137](#)}, M. Fujimoto^{[148](#)}, K. Y. Fung^{[63a](#)}, E. Furtado De Simas Filho^{[81e](#)},
 M. Furukawa^{[156](#)}, M. Fuste Costa^{[47](#)}, P. Fuste Martin^{[13](#)}, J. Fuster^{[165](#)}, A. Gaa^{[54](#)},
 A. Gabrielli^{[24b,24a](#)}, A. Gabrielli^{[158](#)}, G. Gagliardi^{[56b,56a](#)}, L.G. Gagnon^{[18a](#)}, S. Galantzan^{[154](#)},
 J. Gallagher^{[1](#)}, E.J. Gallas^{[127](#)}, A.L. Gallen^{[163](#)}, B.J. Gallop^{[135](#)}, K.K. Gan^{[120](#)}, Y. Gao^{[51](#)},
 Z. Gao^{[112a](#)}, A. Garabaglu^{[140](#)}, F.M. Garay Walls^{[138a,138b](#)}, C. García^{[165](#)},
 A. Garcia Alonso^{[116](#)}, A.G. Garcia Caffaro^{[174](#)}, J.E. García Navarro^{[165](#)}, M. A. Garcia Ruiz^{[23b](#)},
 M. Garcia-Sciveres^{[18a](#)}, G.L. Gardner^{[129](#)}, R.W. Gardner^{[39](#)}, N. Garelli^{[161](#)}, R.B. Garg^{[146](#)},
 J.M. Gargan^{[33](#)}, C.A. Garner^{[158](#)}, C.M. Garvey^{[34a](#)}, V. K. Gassmann^{[161](#)}, G. Gaudio^{[72a](#)},
 A.J. Gavin^{[94](#)}, J. Gavranovic^{[93](#)}, I.L. Gavrilenko^{[131a](#)}, C. Gay^{[166](#)}, G. Gaycken^{[124](#)},
 A. Gekow^{[120](#)}, C. Gemme^{[56b](#)}, M.H. Genest^{[59](#)}, A. D. Gentry^{[114](#)}, S. George^{[95](#)}, T. Geralis^{[45](#)},
 A. A. Gerwin^{[121](#)}, P. Gessinger-Befurt^{[37](#)}, M. Ghani^{[169](#)}, K. Ghorbanian^{[94](#)}, A. Ghosal^{[144](#)},

A. Ghosh ¹⁶², A. Ghosh ⁷, B. Giacobbe ^{24b}, S. Giagu ^{74a,74b}, A. Giannini ⁶¹, S.M. Gibson ⁹⁵, D.T. Gil ^{85b}, B.J. Gilbert ⁴¹, D. Gillberg ³⁵, G. Gilles ¹¹⁶, D.M. Gingrich ^{2,s}, M.P. Giordani ^{68a,68c}, P.F. Giraud ¹³⁶, G. Giulianielli ^{68a,68c}, D. Giugni ^{70a}, F. Giuli ^{75a,75b,t}, I. Gkialas ^{9,u}, B.C. Gladwyn ¹²⁷, C. Glasman ⁹⁹, M. Glazewska ²⁰, R. M. Gleason ¹⁶², G. Glemža ⁴⁷, I. Gnesi ^{24b,24a,v}, Y. Go ³⁰, M. Goblirsch-Kolb ³⁷, B. Gocke ⁴⁸, D. Godin ¹⁰⁸, B. Gokturk ^{22a}, S. Goldfarb ¹⁰⁵, T. Golling ⁵⁵, M.G.D. Gololo ^{34c}, A. Golub ¹⁴⁰, J.P. Gombas ¹⁰⁷, A. Gomes ^{131a,131b}, G. Gomes Da Silva ¹⁴⁴, A.J. Gomez Delegido ³⁷, R. Gonçalves ^{131a}, A. Gongadze ^{152c}, F. Gonnella ²¹, J.L. Gonski ¹⁴⁶, R.Y. González Andana ⁵¹, S. González de la Hoz ¹⁶⁵, M. V. Gonzalez Rodrigues ⁴⁷, R. Gonzalez Suarez ¹⁶³, S. Gonzalez-Sevilla ⁵⁵, L. Goossens ³⁷, B. Gorini ³⁷, E. Gorini ^{69a,69b}, A. Gorišek ⁹³, T.C. Gosart ¹²⁹, A.T. Goshaw ⁵⁰, M.I. Gostkin ³⁸, S. Goswami ¹²², C.A. Gottardo ³⁷, S. A. Gotz ¹⁰⁹, M. Gouighri ^{36b}, A.G. Goussiou ¹⁴⁰, N. Govender ^{34c}, R. P. Grabarczyk ¹²⁷, I. Grabowska-Bold ^{85a}, K. Graham ³⁵, E. Gramstad ¹²⁶, S. Grancagnolo ^{69a,69b}, C.M. Grant ¹, P.M. Gravila ^{28f}, F.G. Gravili ^{69a,69b}, H.M. Gray ^{18a}, M. Greco ¹¹⁰, M. J. Green ¹, C. Grefe ²⁵, A. S. Grefsrud ¹⁷, I.M. Gregor ⁴⁷, K.T. Greif ¹⁶², P. Grenier ¹⁴⁶, S.G. Grewe ¹¹⁰, K. Grimm ³², S. Grinstein ^{13,w}, E. Gross ¹⁷¹, J. Grosse-Knetter ⁵⁴, L.H. Grossman ^{18b}, L. Guan ¹⁰⁶, W. Guérin ⁸⁹, G. Guerrieri ³⁷, R. Guevara ¹²⁶, R. Gugel ¹⁰⁰, J.A.M. Guhit ¹⁰⁶, A. Guida ¹⁹, E. Guilloton ¹⁶⁹, S. Guindon ³⁷, F. Guo ^{14,112c}, J. Guo ^{141a}, L. Guo ⁴⁷, L. Guo ^{112b,x}, Y. Guo ¹⁰⁶, Y. Guo ⁴¹, A. Gupta ⁴⁸, R. Gupta ¹³⁰, S. Gupta ²⁷, S. Gurbuz ²⁵, S.S. Gurdasani ⁴⁷, G. Gustavino ^{74a,74b}, P. Gutierrez ¹²¹, L.F. Gutierrez Zagazeta ¹²⁹, M. Gutsche ⁴⁹, C. Gutschow ⁹⁶, C. Gwenlan ¹²⁷, C.B. Gwilliam ⁹², E.S. Haaland ¹²⁶, A. Haas ¹¹⁸, M. Habedank ⁵⁸, C. Haber ^{18a}, R.J. Haberle ¹⁷¹, H.K. Hadavand ⁸, A. Haddad ⁴⁰, A. Hadeef ⁴⁹, A.I. Hagan ⁹¹, J. J. Hahn ¹⁴⁴, M. Haleem ¹⁶⁸, J. Haley ¹²², G.D. Hallowell ¹⁰², J.A. Hallford ⁴⁷, K. Hamano ¹⁶⁷, H. Hamdaoui ¹⁶³, M. Hamer ²⁵, S. E. D. Hammoud ⁶⁵, E.J. Hampshire ⁹⁵, L. Han ^{112a}, L. Han ⁶¹, S. Han ¹⁴, K. Hanagaki ⁸², M. Hance ¹³⁷, D.A. Hangal ⁴¹, H. Hanif ¹⁴⁵, M.D. Hank ¹²⁹, J.B. Hansen ⁴², P.H. Hansen ⁴², T. Harenberg ¹⁷³, S. Harkusha ¹⁷⁵, M.L. Harris ¹⁰³, Y.T. Harris ²⁵, J. Harrison ¹³, P.F. Harrison ¹⁶⁹, M. L. E. Hart ⁹⁶, N.M. Hartman ¹¹⁰, N.M. Hartmann ¹⁰⁹, R. Z. Hasan ^{95,135}, Y. Hasegawa ¹⁴³, D. Hashimoto ¹¹¹, F. Haslbeck ³⁷, S. Hassan ¹²⁶, R. Hauser ¹⁰⁷, M. Haviernik ¹³⁴, C.M. Hawkes ²¹, R.J. Hawkins ³⁷, Y. Hayashi ¹⁵⁶, D. Hayden ¹⁰⁷, R.L. Hayes ¹¹⁶, C.P. Hays ¹²⁷, J.M. Hays ⁹⁴, H.S. Hayward ⁹², M. He ^{14,112c}, Y. He ⁴⁷, Y. He ⁹⁶, N.B. Heatley ⁹⁴, V. Hedberg ⁹⁸, J. Heilman ³⁵, S. Heim ⁴⁷, T. Heim ^{18a}, J.J. Heinrich ¹²⁴, L. Heinrich ¹¹⁰, J. Hejbal ¹³², M. Helbig ⁴⁹, A. Held ¹⁷², S. Hellesund ¹⁷, C.M. Helling ¹⁶⁶, F.N.E. Henry ⁵⁸, H. Herde ⁹⁸, Y. Hernández Jiménez ¹⁴⁸, G. Herten ⁵³, R. Hertenberger ¹⁰⁹, L. Hervas ³⁷, M.E. Hespings ¹⁰⁰, N.P. Hessey ^{159a}, J. Hessler ¹¹⁰, R. Hicks ¹²⁹, M. Hidaoui ^{36b}, N. Hidic ¹³⁴, E. Hill ¹⁵⁸, T. S. Hillersoy ¹⁷, S.J. Hillier ²¹, J.R. Hinds ¹⁰⁷, F. Hinterkeuser ²⁵, M. Hirose ¹²⁵, S. Hirose ¹⁶⁰, D. Hirschbuehl ¹⁷³, B. Hiti ⁹³, J. Hobbs ¹⁴⁸, R. Hobincu ^{28e}, N. Hod ¹⁷¹, A.M. Hodges ¹⁶⁴, M.C. Hodgkinson ¹⁴², B.H. Hodgkinson ¹²⁷, A. Hoecker ³⁷, D. D. Hofer ¹⁰⁶, J. Hofer ¹⁶⁵, J. Hofner ¹⁰⁰, M. Holzbock ³⁷, L.B.A.H. Hommels ³³, V. Homsak ¹²⁷, J. J. Hong ⁶⁷, T.M. Hong ¹³⁰, B.H. Hooberman ¹⁶⁴, W.H. Hopkins ⁶, M. C. Hoppesch ¹⁶⁴, Y. Horii ¹¹¹, M. E. Horstmann ¹¹⁰, M.M. Horzela ⁵⁴, S. Hou ¹⁵¹, M. R. Housenga ¹⁶⁴, J. Howarth ⁵⁸, J. Hoya ⁶, M. Hrabovsky ¹²³, T. Hryn'ova ⁴, P.J. Hsu ⁶⁴,

S.-C. Hsu ¹⁴⁰, T. Hsu ⁶⁵, M. Hu ^{18a}, P. Hu ^{63b}, Q. Hu ⁶¹, S. Huang ³³, X. Huang ^{14,112c}, Y. Huang ¹³⁴, Y. Huang ^{112b}, Y. Huang ¹⁴, Z. Huang ⁶⁵, Z. Hubacek ¹³³, F. Huegging ²⁵, T.B. Huffman ¹²⁷, M. Hufnagel Maranha De Faria ^{81a}, C. A. Hugli ⁴⁷, M. Huhtinen ³⁷, S.K. Huiberts ¹⁷, R. Hulsken ¹⁰⁴, C. E. Hultquist ^{18a}, D.L. Humphreys ¹⁰³, N. Huseynov ¹², J. Huston ¹⁰⁷, B. Huth ³⁷, J. Huth ⁶⁰, L. Huth ⁴⁷, R. Hyneman ⁷, G. Iacobucci ⁵⁵, G. Iakovidis ³⁰, L. Iconomidou-Fayard ⁶⁵, J. P. Iddon ³⁷, P. Iengo ^{71a,71b}, Y. Iiyama ¹⁵⁶, T. Iizawa ¹⁵⁶, Y. Ikegami ⁸², D. Iliadis ¹⁵⁵, N. Ilic ¹⁵⁸, H. Imam ^{36a}, G. Inacio Goncalves ^{81d}, S. A. Infante Cabanas ^{138c}, T. Ingebretsen Carlson ^{46a,46b}, J. M. Inglis ⁹⁴, G. Introzzi ^{72a,72b}, M. Iodice ^{76a}, V. Ippolito ^{74a,74b}, R. K. Irwin ⁹², M. Ishino ¹⁵⁶, W. Islam ¹⁷², C. Issever ¹⁹, S. Istin ^{22a,y}, K. Itabashi ¹²⁵, H. Ito ¹⁷⁰, R. Iuppa ^{77a,77b}, A. Ivina ¹⁷¹, F. Ivone ³⁷, S. Izumiyama ¹¹¹, V. Izzo ^{71a}, P. Jacka ¹³³, P. Jackson ¹, P. R. Jacobson ⁵⁰, P. Jain ⁴⁷, K. Jakobs ⁵³, J. Jamieson ⁵⁸, W. Jang ¹⁵⁶, S. Jankovych ¹¹⁶, B. K. Jashal ¹³⁵, M. Javurkova ¹⁰³, P. Jawahar ¹⁰¹, L. Jeanty ¹²⁴, J. Jejelava ^{152a,z}, P. Jenni ^{53,aa}, L. Jerala ⁹³, C.E. Jessiman ³⁵, H. Jia ¹⁶⁶, J. Jia ¹⁴⁸, X. Jia ^{110,112c}, C. Jiang ⁵¹, Q. Jiang ^{63b}, S. Jiggins ⁴⁷, M. Jimenez Ortega ¹⁶⁵, J. Jimenez Pena ¹³, S. Jin ^{112a}, A. Jinaru ^{28b}, O. Jinnouchi ¹³⁹, P. Johansson ¹⁴², K.A. Johns ⁷, J.W. Johnson ¹³⁷, F. A. Jolly ⁴⁷, D.M. Jones ¹⁴⁹, E. Jones ⁴⁷, K.S. Jones ⁸, P. Jones ³³, R.W.L. Jones ⁹¹, T.J. Jones ⁹², H.L. Joos ³⁷, R. Joshi ¹²⁰, J. Jovicevic ¹⁶, X. Ju ^{18a}, J.J. Junggeburth ³⁷, T. Junkermann ^{62a}, A. Juste Rozas ^{13,w}, M.K. Juzek ⁸⁶, S. Kabana ^{138f}, A. Kaczmarska ⁸⁶, S. A. Kadir ¹⁴⁶, M. Kado ¹¹⁰, H. Kagan ¹²⁰, M. Kagan ¹⁴⁶, A. Kahn ¹²⁹, C. Kahra ¹⁰⁰, T. Kaji ¹⁵⁶, E. Kajomovitz ¹⁵³, N. Kakati ¹⁷¹, N. Kakoty ¹³, S. Kandel ⁸, E. Kanellaki ⁴⁵, N. Kanellos ¹⁰, D. Kar ^{34j,†}, E. Karentzos ²⁵, K. Karki ⁸, O. Karkout ¹¹⁶, S.N. Karpov ³⁸, Z.M. Karpova ³⁸, V. Kartvelishvili ^{91,152b}, E. Kasimi ¹⁵⁵, J. Katzy ⁴⁷, S. Kaur ³⁵, R. Kavak ¹⁶⁴, K. Kawade ¹⁴³, M.P. Kawale ¹²¹, C. Kawamoto ⁸⁷, E.F. Kay ³⁷, S. Kazakos ¹⁰⁷, K. Kazakova ¹⁰², J.M. Keaveney ^{34a}, R. Keeler ¹⁶⁷, G.V. Kehris ⁶⁰, J.S. Keller ³⁵, J. M. Kelly ¹⁶⁷, J.J. Kempster ¹⁴⁹, O. Kepka ¹³², J. Kerr ^{159b}, B.P. Kerridge ¹³⁵, B.P. Kerševan ⁹³, L. Keszeghova ^{29a}, R. A. Khan ¹³⁰, A. Khanov ¹²², M. Kholodenko ^{131a}, T.J. Khoo ¹⁹, G. Khorauli ¹⁶⁸, Y. Khoulaki ^{36a}, Y.A.R. Khwaira ¹²⁸, D. Kim ⁶, D.W. Kim ^{18b}, Y.K. Kim ³⁹, N. Kimura ⁹⁶, M.K. Kingston ⁵⁴, F. Kirfel ²⁵, J. Kirk ¹³⁵, A.E. Kiryunin ¹¹⁰, S. Kita ¹⁶⁰, O. Kivernyk ²⁵, M. Klassen ¹⁶¹, C. Klein ³⁵, L. Klein ¹⁶⁸, M.H. Klein ⁴⁴, S.B. Klein ⁵⁵, U. Klein ⁹², A. Klimentov ³⁰, P. Kluit ¹¹⁶, S. Kluth ¹¹⁰, E. Kneringer ⁷⁸, T.M. Knight ¹⁵⁸, A. Knue ⁴⁸, M. Kobel ⁴⁹, D. Kobylanskii ¹⁷¹, S.F. Koch ³⁷, M. Kocian ¹⁴⁶, P. Kodyš ¹³⁴, D.M. Koeck ¹²⁴, T. Koffas ³⁵, K. Kojima ⁸², O. Kolay ⁴⁹, I. Koletsou ⁴, T. Komarek ⁸⁶, S. Kondo ¹⁵⁶, K. Köneke ⁵⁴, A.X.Y. Kong ¹, T. Kono ¹¹⁹, N. Konstantinidis ⁹⁶, P. Kontaxakis ⁵⁵, B. Konya ⁹⁸, R. Kopeliansky ⁴¹, S. Koperny ^{85a}, R. Koppenhofer ⁵³, I. Kopsalis ¹⁰, K. Korcyl ⁸⁶, K. Kordas ^{155,ab}, A. Korn ⁹⁶, S. Korn ⁵⁴, I. Korolkov ¹³, B. Kortman ¹¹⁶, O. Kortner ¹¹⁰, S. Kortner ¹¹⁰, W.H. Kostecka ¹¹⁷, M. Kostov ^{29a}, V.V. Kostyukhin ¹⁴⁴, A. Kotskechagia ³⁷, A. Kotwal ⁵⁰, A. Koulouris ³⁷, A. Kourkoumeli-Charalampidi ^{72a,72b}, O. Kovanda ¹²⁴, R. Kowalewski ¹⁶⁷, W. Kozanecki ¹²⁴, G. Kramberger ⁹³, P. Kramer ²⁵, A. Krasznahorkay ¹⁰³, A. C. Kraus ¹¹⁷, J.W. Kraus ¹⁷³, J.A. Kremer ⁴⁷, N. B. Krenzel ¹⁴⁴, T. Kresse ¹⁵⁸, L. Kretschmann ¹⁷³, J. Kretzschmar ⁹², P. Krieger ¹⁵⁸, K. Krizka ²¹, K. Kroeninger ⁴⁸, H. Kroha ¹¹⁰, J. Kroll ¹³², J. Kroll ¹²⁹, K.S. Krowpman ¹⁰⁷, U. Kruchonak ³⁸, H. Krüger ²⁵, N. Krumnack ⁷⁹,

J. Krupa [146](#), M.C. Kruse [50](#), O. Kuchinskaia [38](#), S. Kuday [3a](#), S. Kuehn [37](#), R. Kuesters [53](#), T. Kuhl [47](#), V. Kukhtin [38](#), Y. Kulchitsky [38](#), S. Kuleshov [138d,138b](#), J. Kull [1](#), E. V. Kumar [109](#), M. Kumar [34j](#), N. Kumari [47](#), P. Kumari [159b](#), A. Kupco [132](#), O. Kuprash [53](#), H. Kurashige [84](#), L.L. Kurchaninov [159a](#), O. Kurdysh [4](#), M. Kuze [139](#), A.K. Kvam [103](#), J. Kvita [123](#), N.G. Kyriacou [140](#), M. Laassiri [30](#), C. Lacasta [165](#), H. Lacker [19](#), D. Lacour [128](#), E. Ladygin [38](#), A. Lafarge [40](#), B. Laforge [128](#), T. Lagouri [174](#), F.Z. Lahbabi [36a](#), S. Lai [54](#), W. S. Lai [96](#), I.K. Lakomic [54](#), J.E. Lambert [167](#), S. Lammers [67](#), W. Lampl [7](#), C. Lampoudis [155](#), G. Lamprinoudis [168](#), A.N. Lancaster [117](#), U. Landgraf [53](#), M.P.J. Landon [94](#), V.S. Lang [53](#), A.J. Lankford [162](#), F. Lanni [37](#), C. S. Lantz [164](#), K. Lantzsich [25](#), A. Lanza [72a](#), M. Lanzac Berrocal [165](#), T. Lari [70a](#), D. Larsen [17](#), L. Larson [11](#), F. Lasagni Manghi [24b](#), M. Lassnig [37](#), H.C. Lau [167](#), S.D. Lawlor [142](#), R. Lazaridou [162](#), M. Lazzaroni [70a,70b](#), E. T. T. Le [162](#), H. D. M. Le [107](#), E.M. Le Boulicaut [174](#), D.O. Le Guennec [136](#), L.T. Le Pottier [18a](#), B. Leban [24b,24a](#), F. Ledroit-Guillon [59](#), T.F. Lee [159b](#), L.L. Leeuw [34h](#), M. Lefebvre [167](#), C. Leggett [18a](#), L.M. Lehmann [116](#), G. Lehmann Miotto [37](#), M. Leigh [55](#), W.A. Leight [103](#), W. Leinonen [115](#), A. Leisos [155,ac](#), M.A.L. Leite [81c](#), C.E. Leitgeb [19](#), R. Leitner [134](#), K.J.C. Leney [44](#), T. Lenz [25](#), S. Leone [73a](#), C. Leonidopoulos [51](#), A. Leopold [147](#), J. LePage-Bourbonnais [35](#), R. Les [107](#), C.G. Lester [33](#), J. Levêque [4](#), L.J. Levinson [171](#), G. Levrini [24b,24a](#), M.P. Lewicki [86](#), C. Lewis [140](#), D.J. Lewis [4](#), L. Lewitt [142](#), A. Li [30](#), B. Li [113b](#), C-Q. Li [110](#), C. Li [106](#), H. Li [113b](#), H. Li [101](#), H. Li [15](#), H. Li [61](#), H. Li [113b](#), J. Li [141a](#), L. Li [141a](#), R. Li [174](#), S. Li [141b,141a](#), T. Li [5](#), Y. Li [14](#), Z. Li [14,112c](#), Z. Li [61](#), S. Liang [14,112c](#), Z. Liang [14](#), M. Liberatore [136](#), B. Liberti [75a](#), G. B. Libotte [81d](#), K. Lie [63c](#), J. Lieber Marin [81e](#), H. Lien [67](#), H. Lin [106](#), S. F. Lin [148](#), L. Linden [109](#), R.E. Lindley [7](#), J.H. Lindon [37](#), J. Ling [60](#), E. Lipeles [129](#), A. Lipniacka [17](#), A. Lister [166](#), J.D. Little [67](#), B. Liu [113a](#), B.X. Liu [112b](#), D. Liu [153](#), D. Liu [137](#), E. H. L. Liu [21](#), H. Liu [112b](#), J.K.K. Liu [118](#), K. Liu [141b](#), K. Liu [141b](#), M. Liu [61](#), M.Y. Liu [61](#), P. Liu [113b](#), Q. Liu [146](#), S. Liu [148](#), X. Liu [113b](#), Y. Liu [112b,112c](#), Y. Liu [164](#), Y.L. Liu [113b](#), Y.W. Liu [61](#), Z. Liu [65,ad](#), S.L. Lloyd [94](#), E.M. Lobodzinska [47](#), P. Loch [7](#), E. Lodhi [158](#), K. Lohwasser [142](#), E. Loiacono [122](#), J. D. Lomas [21](#), I. Longarini [162](#), R. Longo [24b,24a,v](#), A. Lopez Solis [13](#), N.A. Lopez-canelas [7](#), N. Lorenzo Martinez [4](#), A.M. Lory [109](#), M. Losada [83b](#), G. Lösckce Centeno [4](#), X. Lou [14,112c](#), P.A. Love [91](#), M. Lu [65](#), S. Lu [129](#), Y.J. Lu [151](#), H.J. Lubatti [140](#), C. Luci [74a,74b](#), F.L. Lucio Alves [112a](#), J.A. Lue [124](#), F. Luehring [67](#), B. S. Lunday [129](#), O. Lundberg [147](#), J. Lunde [37](#), N.A. Luongo [6](#), M.S. Lutz [158](#), A.B. Lux [26](#), D. Lynn [30](#), R. Lysak [132](#), V. Lysenko [133](#), E. Lytken [98](#), V. Lyubushkin [38](#), T. Lyubushkina [38](#), M.M. Lyukova [148](#), H. Ma [30](#), K. Ma [61](#), L.L. Ma [113b](#), W. Ma [61](#), Y. Ma [113b](#), J.C. MacDonald [100](#), B. Maček [93](#), P.C. Machado De Abreu Farias [81e](#), D. Macina [37](#), R. Madar [40](#), T. Madula [96](#), J. Maeda [84](#), T. Maeno [30](#), P.T. Mafa [34f](#), H. Maguire [142](#), M. Maheshwari [33](#), V. Maiboroda [65](#), G. Maineri [70a,70b](#), A. Maio [131a,131b,131d](#), K. Maj [85a](#), O. Majersky [47](#), S. Majewski [124](#), A. Makita [156](#), N. Makovec [65](#), V. Maksimovic [16](#), B. Malaescu [128](#), J. Malamant [126](#), Pa. Malecki [86](#), F. Malek [59,ae](#), M. Mali [93](#), D. Malito [95](#), A. Maloizel [5](#), A. Malvezzi Lopes [81d](#), S. Malyukov [38](#), J. Mamuzic [93](#), G. Mancini [52](#), M. N. Mancini [27](#), G. Manco [72a,72b](#), S.S. Mandarri [149](#), I. Mandić [93](#), L. Manhaes de Andrade Filho [81a](#), I.M. Maniatis [171](#), J. Manjarres Ramos [89](#), D.C. Mankad [171](#), A. Mann [109](#), T. Manoussos [37](#), M.N. Mantinan [39](#), S. Manzoni [37](#), L. Mao [141a](#),

X. Mapekula ^{34c}, A. Marantis ¹⁵⁵, R.R. Marcelo Gregorio ¹, G. Marchiori ⁵, C. Marcon ^{70a}, E. Maricic ¹⁶, M. Marinescu ⁴⁷, S. Marium ⁴⁷, M. Marjanovic ¹²¹, A. Markhoos ⁵³, M. Markovitch ⁶⁵, M. K. Maroun ¹⁰³, M. C. Marr ¹⁴⁵, T. L. Marsault ¹³⁶, G. T. Marsden ¹⁰¹, Z. Marshall ^{18a}, S. Marti-Garcia ¹⁶⁵, J. Martin ⁹⁶, T.A. Martin ¹³⁵, V.J. Martin ⁵¹, B. Martin dit Latour ¹⁷, S. Martin-Haugh ¹³⁵, L. Martinelli ^{74a,74b}, V.I. Martinez Outschoorn ¹⁰³, P. Martinez Suarez ³⁷, G. Martinovicova ¹³⁴, V.S. Martoiu ^{28b}, A. Martone ⁸⁹, A.C. Martyniuk ⁹⁶, A. Marzin ³⁷, D. Mascione ^{77a,77b}, L. Masetti ¹⁰⁰, J. Masik ¹⁰¹, A.L. Maslennikov ³⁸, S.L. Mason ⁴¹, P. Massarotti ^{71a,71b}, P. Mastrandrea ^{73a,73b}, A. Mastroberardino ^{43b,43a}, R. Mastrofrancesco ^{72a,72b}, T. Masubuchi ¹²⁵, T.T. Mathew ¹²⁴, J. Matousek ¹³⁴, D.M. Mattern ⁴⁸, K. Mauer ⁴⁷, J. Maurer ^{28b}, T. Maurin ⁵⁸, A.J. Maury ⁶⁵, C. Mavungu Tsava ¹⁰², A. E. May ¹⁰¹, E. Mayer ⁴⁰, R. Mazini ^{34j}, S.M. Mazza ¹³⁷, E. Mazzeo ³⁷, J.P. Mc Gowan ¹⁶⁷, S.P. Mc Kee ¹⁰⁶, C.C. McCracken ¹⁶⁶, E.F. McDonald ¹⁰⁵, L. F. Mcelhinney ⁹¹, J.A. Mcfayden ¹⁴⁹, R.P. McGovern ¹²⁹, R.P. Mckenzie ^{34j}, D.J. McLaughlin ⁹⁶, S.J. McMahon ¹³⁵, C.M. Mcpartland ⁹², R.A. McPherson ^{167,n}, S. Mehlhase ¹⁰⁹, A. Mehta ⁹², D. Melini ¹⁶⁵, B.R. Mellado Garcia ^{14,af}, A.H. Melo ⁵⁴, F. Meloni ⁴⁷, A.M. Mendes Jacques Da Costa ¹⁰¹, L. Meng ⁹¹, S. Menke ¹¹⁰, M. Mentink ³⁷, E. Meoni ^{43b,43a}, G. Mercado ¹¹⁷, S. Merianos ¹⁵⁵, C. Merlassino ^{68a,68c}, C. Meroni ^{70a,70b}, J. Metcalfe ⁶, A.S. Mete ⁶, E. Meuser ¹⁰⁰, C. Meyer ⁶⁷, J-P. Meyer ¹³⁶, Y. Miao ^{112a}, R.P. Middleton ¹³⁵, M. Mihovilovic ⁶⁵, L. Mijović ⁵¹, G. Mikenberg ¹⁷¹, M. Mikestikova ¹³², M. Mikuž ⁹³, H. Mildner ¹⁰⁰, A. Milic ³⁷, D.W. Miller ³⁹, E. H. Miller ¹⁴⁶, A. Milov ¹⁷¹, D.A. Milstead ^{46a,46b}, T. Min ^{112a}, I.A. Minashvili ^{152b}, A.I. Mincer ¹¹⁸, B. Mindur ^{85a}, M. Mineev ³⁸, Y. Mino ⁸⁷, L.M. Mir ¹³, M. Miralles Lopez ⁵⁸, M. Mironova ^{18a}, M. Missio ⁴⁰, A. Mitra ¹⁶⁹, V.A. Mitsou ¹⁶⁵, Y. Mitsumori ¹¹¹, P.S. Miyagawa ⁹⁴, R. Mizuhiki ⁸⁴, T. Mkrtchyan ³⁷, M. Mlinarevic ⁹⁶, T. Mlinarevic ⁹⁶, M. Mlynarikova ¹³⁴, L. Mlynarska ^{85a}, C. Mo ^{141a}, H. Mobius ⁴⁷, S. Mobius ²⁰, M. H. Mohamed Farook ¹¹⁴, S. Mohapatra ⁴¹, M.F. Mohd Soberi ⁵¹, S. Mohiuddin ¹²², G. Mokgatitswane ^{34j}, R. Mole ²¹, L. Moleri ¹⁷¹, U. Molinatti ¹²⁷, L.G. Mollier ²⁰, L. Monaco ^{37,58}, B. Mondal ¹³², S. Mondal ¹³⁴, K. Mönig ⁴⁷, E. Monnier ¹⁰², L. Monsonis Romero ¹⁶⁵, A. Montella ^{46a,46b}, M. Montella ¹²⁰, F. Montereali ^{76a,76b}, F. Monticelli ⁹⁰, S. Monzani ^{68a,68c}, M.E.E. Moors ²⁵, A. Moranco Tarda ⁴², N. Morange ⁶⁵, M. Moreno Llácer ¹⁶⁵, C. Moreno Martinez ⁵⁵, J.M. Moreno Perez ^{23b}, P. Morettini ^{56b}, S. Morgenstern ^{62a}, M. Morii ⁶⁰, M. Morinaga ¹⁵⁶, F. Morodei ^{74a,74b}, P. Moschovakos ³⁷, B. Moser ⁵³, M. Mosidze ^{152b}, T. Moskalets ⁴⁴, P. Moskvitina ¹¹⁵, C.J. Mosomane ^{34b}, J. Moss ³², T. Motta Quirino ^{81d}, A. Moussa ^{36d}, Y. Moyal ^{171,ag}, H. Moyano Gomez ¹³, E.J.W. Moyse ¹⁰³, T.G. Mroz ⁸⁶, S. Muanza ¹⁰², M. Mucha ²⁵, J. Mueller ¹³⁰, D. Muller ¹⁴⁴, G.A. Mullier ¹⁶³, A.J. Mullin ³³, J.J. Mullin ⁵⁰, A.C. Mullins ⁴⁴, A.E. Mulski ⁶⁰, D.P. Mungo ¹⁵⁸, D. Munoz Perez ¹²², F.J. Munoz Sanchez ¹⁰¹, W.J. Murray ^{169,135}, E. Musajan ⁶¹, M. Muškinja ⁹³, C. Mwewa ⁴⁷, A.J. Myers ⁸, G. Myers ¹⁰⁶, M. Myska ¹³³, B.P. Nachman ¹⁴⁶, K. Nagai ¹²⁷, K. Nagano ⁸², R. Nagasaka ¹⁵⁶, J.L. Nagle ^{30,ah}, E. Nagy ¹⁰², A.M. Nairz ³⁷, T. Nakagawa ⁸⁷, Y. Nakahama ⁸², K. Nakamura ⁸², K. Nakkalil ⁵, A. Nandi ^{62b}, H. Nanjo ¹²⁵, E.A. Narayanan ⁴⁴, Y. Narukawa ¹⁵⁶, L. Nasella ^{70a,70b}, S. Nasri ^{83c}, C. Nass ²⁵, G. Navarro ^{23a}, A. Nayaz ¹⁹, S. Nechaeva ^{24b,24a}, F. Nechansky ¹³², L. Nedic ¹²⁷, A. Negri ^{72a,72b}, M. Negrini ^{24b}, C. Nellist ¹¹⁶, C. Nelson ¹⁰⁴, K. Nelson ¹⁰⁶, S. Nemecek ¹³², M. Nessi ^{37,ai},

M.S. Neubauer ¹⁶⁴, J. Newell ⁹², P.R. Newman ²¹, Y.W.Y. Ng ¹⁶⁴, B. Ngair ^{83b},
H.D.N. Nguyen ¹⁰⁸, J.D. Nichols ¹²¹, R. Nicolaidou ¹³⁶, J. Nielsen ¹³⁷, M. Niemeyer ⁵⁴,
J. Niermann ³⁷, N. Nikiforou ³⁷, I. Nikolic-Audit ¹²⁸, P. Nilsson ³⁰, G. Ninio ¹⁵⁴,
A. Nisati ^{74a}, D. Nishimura ¹⁵⁶, R. Nisius ¹¹⁰, N. Nitika ¹⁷¹, E.K. Nkadimeng ^{34b},
T. Nobe ¹⁵⁶, D. Noll ¹⁴⁶, T. Nommensen ¹⁵⁰, M.B. Norfolk ¹⁴², B.J. Norman ³⁵,
L.C. Nosler ^{18a}, M. Noury ^{36a}, J. Novak ⁹³, T. Novak ⁹³, P. Novotny ¹⁷¹, R. Novotny ¹³³,
L. Nozka ¹²³, K. Ntekas ³⁷, D. Ntounis ¹⁴⁶, N.M.J. Nunes De Moura Junior ^{81b},
A.P. O'Neill ²⁰, J. Ocariz ¹²⁸, I. Ochoa ^{131a}, A. Odella Rodriguez ¹³, S. Oerdek ⁴⁷,
J.T. Offermann ³⁹, A. Ogrodnik ⁸⁶, A. Oh ¹⁰¹, C.C. Ohm ¹⁴⁷, H. Oide ⁸², M.L. Ojeda ³⁷,
Y. Okumura ¹⁵⁶, L.F. Oleiro Seabra ^{131a}, I. Oleksiyuk ⁵⁵, G. Oliveira Correa ¹³,
D. Oliveira Damazio ³⁰, J.L. Oliver ¹, R. Omar ⁶⁷, Y. Onoda ¹³⁹, A. Onofre ^{131a,131e,aj},
P.U.E. Onyisi ¹¹, M.J. Oreglia ³⁹, D. Orestano ^{76a,76b}, R. Orlandini ^{76a,76b}, R.S. Orr ¹⁵⁸,
L.M. Osojnak ⁴¹, Y. Osumi ¹¹¹, G. Otero y Garzón ³¹, H. Otono ⁸⁸, M. Ouchrif ^{36d},
F. Ould-Saada ¹²⁶, T. Ovsiannikova ¹⁴⁰, M. Owen ⁵⁸, R.E. Owen ¹³⁵, S.A. Oyeniran ¹¹⁴,
V.E. Ozcan ^{22a}, F. Ozturk ⁸⁶, N. Ozturk ⁸, S. Ozturk ⁸⁰, H.A. Pacey ¹²⁷, K. Pachal ^{159a},
A. Pacheco Pages ¹³, C. Padilla Aranda ¹³, G. Padovano ^{74a,74b}, S. Pagan Griso ^{18a},
L. Pagani ^{75a,75b}, J. Pampel ²⁵, D.K. Panchal ¹¹, C.E. Pandini ⁵⁹, J.G. Panduro Vazquez ¹³⁵,
H.D. Pandya ¹, H. Pang ¹³⁶, P. Pani ⁴⁷, G. Panizzo ^{68a,68c}, L. Panwar ^{128,ak}, L. Paolozzi ²¹,
S. Parajuli ¹⁶⁴, A. Paramonov ⁶, C. Paraskevopoulos ⁵², D. Paredes Hernandez ^{63b},
S.R. Paredes Saenz ⁵¹, A. Pareti ^{72a,72b}, K.R. Park ⁴¹, T.H. Park ¹¹⁰, F. Parodi ^{56b,56a},
J.A. Parsons ⁴¹, U. Parzefall ⁵³, B.A. Paschen ^{18a}, B. Pascual Dias ⁴⁰,
L. Pascual Dominguez ⁹⁹, E. Pasqualucci ^{74a}, S. Passaggio ^{56b}, F. Pastore ⁹⁵, P. Patel ⁸⁶,
U.M. Patel ⁵⁰, J.R. Pater ¹⁰¹, T. Pauly ³⁷, A. Paunovic ¹⁶, F. Pauwels ¹³⁴, C.I. Pazos ¹⁶¹,
M. Pedersen ¹²⁶, R. Pedro ^{131a}, O. Penc ¹³², C.C. Penelaud ¹²⁸, S. Peng ¹⁵, G. D. Penn ¹⁷⁴,
B.S. Peralva ^{81d}, A.P. Pereira Peixoto ¹⁴⁰, L. Pereira Sanchez ¹⁴⁶, D.V. Perepelitsa ^{30,ah},
G. Perera ¹⁰³, E. Perez Codina ³⁷, M. Perganti ¹⁰, H. Pernegger ³⁷, S. Perrella ^{74a,74b},
K. Peters ⁴⁷, R.F.Y. Peters ¹⁰¹, B.A. Petersen ³⁷, T.C. Petersen ⁴², E. Petit ¹⁰²,
V. Petousis ¹³³, A. R. Petri ^{70a,70b}, T. Petru ¹³⁴, M. Pettee ^{18a}, A. Petukhov ⁸⁰,
K. Petukhova ³⁷, R. Pezoa ^{138g}, L. Pezzotti ^{24b,24a}, G. Pezzullo ¹⁷⁴, L. Pfaffenbichler ³⁷,
A. J. Pflieger ⁷⁸, T. Pham ¹⁰⁵, T.M. Pham ¹⁷², P.W. Phillips ¹³⁵, G. Piacquadio ¹⁴⁸,
E. Pianori ^{18a}, F. Piazza ¹²⁴, R. Piegai ³¹, D. Pietreanu ^{28b}, A.D. Pilkington ¹⁰¹,
T. Pilusa ^{34j}, M. Pinamonti ^{68a,68c}, J.L. Pinfeld ², G. Pinheiro Matos ⁴¹,
B.C. Pinheiro Pereira ^{131a}, J. Pinol Bel ¹³, A. E. Pinto Pinoargote ¹²⁸, L. Pintucci ^{68a,68c},
K. M. Piper ¹⁴⁹, A. Pirttikoski ⁵⁵, D.A. Pizzi ³⁵, L. Pizzimento ^{63b}, A. Plebani ³³,
M.-A. Pleier ³⁰, V. Pleskot ¹³⁴, E. Plotnikova ³⁸, G. Poddar ⁹⁴, R. Poettgen ⁹⁸, L. Poggioli ¹²⁸,
S. Polacek ¹³⁴, G. Polesello ^{72a}, A. Poley ¹⁴⁵, A. Polini ^{24b}, C.S. Pollard ¹⁶⁹, Z.B. Pollock ¹²⁰,
E. Pompa Pacchi ¹²¹, N. I. Pond ⁹⁶, D. Ponomarenko ⁶⁷, L. Pontecorvo ³⁷, S. Popa ^{28a},
G.A. Popeneciu ^{28d}, A. Poreba ³⁷, D.M. Portillo Quintero ^{159a}, S. Pospisil ¹³³,
M. A. Postill ¹⁴², P. Postolache ^{28c}, K. Potamianos ¹⁶⁹, P.A. Potepa ^{85a}, I.N. Potrap ³⁸,
C.J. Potter ³³, H. Potti ¹⁵⁰, J. Poveda ¹⁶⁵, M.E. Pozo Astigarraga ³⁷, R. Pozzi ³⁷,
A. Prades Ibanez ^{75a,75b}, S.R. Pradhan ¹⁴², J. Pretel ¹⁶⁷, D. Price ¹⁰¹, M. Primavera ^{69a},
L. Primomo ^{68a,68c}, M.A. Principe Martin ⁹⁹, R. Privara ¹²³, T. Procter ^{85b}, M.L. Proffitt ¹⁴⁰,
N. Proklova ¹²⁹, K. Prokofiev ^{63c}, G. Proto ¹¹⁰, J. Proudfoot ⁶, M. Przybycien ^{85a},

W.W. Przygoda [ID](#)^{85b}, A. Psallidas [ID](#)⁴⁵, D. Pudzha [ID](#)⁵², P. Puhl [ID](#)⁵⁷, H. I. Purnell [ID](#)¹,
D. Pyatiizbyantseva [ID](#)¹¹⁵, J. Qian [ID](#)¹⁰⁶, R. Qian [ID](#)¹⁰⁷, D. Qichen [ID](#)¹²⁷, Y. Qin [ID](#)¹³, T. Qiu [ID](#)⁵¹,
A. Quadt [ID](#)⁵⁴, M. Queitsch-Maitland [ID](#)¹⁰¹, G. Quetant [ID](#)⁵⁵, R.P. Quinn [ID](#)¹⁶⁶, D. Rafanoharana [ID](#)¹¹⁰,
J.L. Rainbolt [ID](#)³⁹, S. Rajagopalan [ID](#)³⁰, E. Ramakoti [ID](#)³⁸, L. Rambelli [ID](#)^{56b,56a},
I.A. Ramirez-Berend [ID](#)³⁵, K. Ran [ID](#)^{106,112c}, S. D. Randles [ID](#)⁹², D. S. Rankin [ID](#)¹²⁹,
N.P. Rapheeha [ID](#)^{34j}, H. Rasheed [ID](#)^{28b}, A. Rastogi [ID](#)^{18a}, S. Rave [ID](#)¹⁰⁰, S. Ravera [ID](#)^{56b,56a},
B. Ravina [ID](#)³⁷, I. Ravinovich [ID](#)¹⁷¹, M. Raymond [ID](#)³⁷, A.L. Read [ID](#)¹²⁶, N.P. Readioff [ID](#)¹⁴²,
D.M. Rebuzzi [ID](#)^{72a,72b}, A. S. Reed [ID](#)⁵⁸, K. Reeves [ID](#)²⁷, D. Reikher [ID](#)³⁷, A. Rej [ID](#)⁴⁸, C. Rembser [ID](#)³⁷,
H. Ren [ID](#)⁶¹, M. Renda [ID](#)^{28b}, F. Renner [ID](#)⁴⁷, A.G. Rennie [ID](#)⁵⁸, M. Repik [ID](#)⁵⁵, A.L. Rescia [ID](#)^{56b,56a},
S. Resconi [ID](#)^{70a}, M. Ressegotti [ID](#)^{56b}, S. Rettie [ID](#)¹¹⁶, W.F. Rettie [ID](#)³⁵, M. M. Revering [ID](#)³³,
O.L. Rezanova [ID](#)³⁸, P. Reznicek [ID](#)¹³⁴, H. Riani [ID](#)^{36d}, N. Ribaric [ID](#)⁵⁰, B. Ricci [ID](#)^{68a,68c},
E. Ricci [ID](#)^{77a,77b}, R. Richter [ID](#)¹¹⁰, E. Richter-Was [ID](#)^{85b}, M. Ridel [ID](#)¹²⁸, S. Ridouani [ID](#)^{36d},
P. Riedler [ID](#)³⁷, E.M. Riefel [ID](#)^{46a,46b}, J. O. Rieger [ID](#)¹¹⁶, M. Rimoldi [ID](#)^{34c}, L. Rinaldi [ID](#)^{24b,24a},
P. Rincke [ID](#)^{163,54}, G. Ripellino [ID](#)¹⁶³, I. Riu [ID](#)¹³, J.C. Rivera Vergara [ID](#)¹⁶⁷, F. Rizatdinova [ID](#)¹²²,
E. Rizvi [ID](#)⁹⁴, B.R. Roberts [ID](#)³⁹, S.S. Roberts [ID](#)¹³⁷, D. Robinson [ID](#)³³, A. Robson [ID](#)⁵⁸,
A. Rocchi [ID](#)^{75a,75b}, C. Roda [ID](#)^{73a,73b}, F.A. Rodriguez [ID](#)¹¹⁷, S. Rodriguez Bosca [ID](#)³⁷,
Y. Rodriguez Garcia [ID](#)^{23a}, A.M. Rodríguez Vera [ID](#)¹¹⁷, S. Roe [ID](#)³⁷, J.T. Roemer [ID](#)³⁷, O. Røhne [ID](#)¹²⁶,
R.A. Rojas [ID](#)³⁷, Z. Rokavec [ID](#)⁹³, C.P.A. Roland [ID](#)¹²⁸, A. Romaniouk [ID](#)⁷⁸, E. Romano [ID](#)^{72a,72b},
M. Romano [ID](#)^{24b}, N. Rompotis [ID](#)⁹², L. Roos [ID](#)¹²⁸, S. Rosati [ID](#)^{74a}, L. Roscher [ID](#)⁴⁷, B.J. Rosser [ID](#)³⁹,
E. Rossi [ID](#)¹²⁷, E. Rossi [ID](#)^{71a,71b}, L.P. Rossi [ID](#)⁶⁰, L. Rossini [ID](#)⁵³, R. Rosten [ID](#)¹²⁰, M. Rotaru [ID](#)^{28b},
R. Roth [ID](#)³⁷, D. Rousseau [ID](#)⁶⁵, D. Rouso [ID](#)⁴⁷, S. Roy-Garand [ID](#)⁵⁵, A. Rozanov [ID](#)¹⁰²,
Z. M. A. Rozario [ID](#)⁵⁸, Y. Rozen [ID](#)¹⁵³, A. Rubio Jimenez [ID](#)¹⁶⁵, V.H. Ruelas Rivera [ID](#)¹⁹,
T.A. Ruggeri [ID](#)¹, A. Ruggiero [ID](#)¹²⁷, A. Ruiz-Martinez [ID](#)¹⁶⁵, A. Rummler [ID](#)³⁷, G.B. Rupnik Boero [ID](#)³⁷,
N.A. Rusakovich [ID](#)³⁸, S. Ruscelli [ID](#)⁴⁸, H.L. Russell [ID](#)¹⁶⁷, G. Russo [ID](#)¹³⁷, J.P. Rutherford [ID](#)⁷,
S. Rutherford Colmenares [ID](#)¹¹⁸, M. Rybar [ID](#)¹³⁴, P. Rybczynski [ID](#)^{85a}, A. Ryzhov [ID](#)⁴⁴,
F. Safai Tehrani [ID](#)^{74a}, S. Saha [ID](#)¹, B. Sahoo [ID](#)¹⁷¹, B. T. Saifuddin [ID](#)¹²¹, M. Saimpert [ID](#)¹³⁶,
I. Sainz Saenz Diez [ID](#)^{62a}, G.T. Saito [ID](#)^{81c}, M. Saito [ID](#)¹⁵⁶, T. Saito [ID](#)¹⁵⁶, A. Sala [ID](#)^{70a,70b},
O. T. Salin [ID](#)⁶⁵, A. Salnikov [ID](#)¹⁴⁶, J. Salt [ID](#)¹⁶⁵, A. Salvador Salas [ID](#)¹⁵⁴, F. Salvatore [ID](#)¹⁴⁹,
A. Salzburger [ID](#)³⁷, D. Sammel [ID](#)⁵³, E. Sampson [ID](#)⁹¹, D. Sampsonidis [ID](#)^{155,ab}, D. Sampsonidou [ID](#)¹²⁴,
M.A.A. Samy [ID](#)⁵⁸, J. Sánchez [ID](#)¹⁶⁵, V. Sanchez Sebastian [ID](#)¹⁶⁵, H. Sandaker [ID](#)¹²⁶, C.O. Sander [ID](#)⁴⁷,
J.A. Sandesara [ID](#)¹⁷², M. Sandhoff [ID](#)¹⁷³, C. Sandoval [ID](#)^{23b}, L. Sanfilippo [ID](#)^{62a}, D.P.C. Sankey [ID](#)¹³⁵,
T. Sano [ID](#)⁸⁷, A. Sansar [ID](#)^{22c}, A. Sansoni [ID](#)⁵², M. Santana Queiroz [ID](#)^{18b}, L. Santi [ID](#)³⁷, C. Santoni [ID](#)⁴⁰,
H. Santos [ID](#)^{131a,131b}, L. Santos Pereira Trigo [ID](#)⁴⁷, E. Sanzani [ID](#)^{24b,24a}, K.A. Saoucha [ID](#)^{83d},
J.G. Saraiva [ID](#)^{131a,131d}, J. Sardain [ID](#)⁷, S. Sarkar [ID](#)⁵⁰, O. Sasaki [ID](#)⁸², K. Sato [ID](#)¹⁶⁰, C. Sauer [ID](#)³⁷,
E. Sauvan [ID](#)⁴, P. Savard [ID](#)^{158,s}, R. Sawada [ID](#)¹⁵⁶, C. Sawyer [ID](#)¹³⁵, L. Sawyer [ID](#)⁹⁷, A. M. Sayed [ID](#)²⁷,
C. Sbarra [ID](#)^{24b}, A. Sbrizzi [ID](#)^{24b,24a}, R. Scaglioni [ID](#)^{72a,72b}, T. Scanlon [ID](#)⁹⁶, J. Schaarschmidt [ID](#)¹⁴⁰,
U. Schäfer [ID](#)¹⁰⁰, A.C. Schaffer [ID](#)^{65,44}, D. Schaile [ID](#)¹⁰⁹, R.D. Schamberger [ID](#)¹⁴⁸, C. Scharf [ID](#)¹⁹,
M.M. Schefer [ID](#)²⁰, D. Scheirich [ID](#)¹³⁴, M. Schernau [ID](#)^{138f}, C. Scheulen [ID](#)⁵⁵, C. Schiavi [ID](#)^{56b,56a},
M. Schioppa [ID](#)^{43b,43a}, S. Schlenker [ID](#)³⁷, T. Schlomer [ID](#)⁵⁴, J. Schmeing [ID](#)¹⁷³, C. R. Schmidt [ID](#)⁴⁹,
E. Schmidt [ID](#)¹¹⁰, M. A. Schmidt [ID](#)¹⁷³, K. Schmieden [ID](#)²⁵, C. Schmitt [ID](#)¹⁰⁰, N. Schmitt [ID](#)¹⁰⁰,
S. Schmitt [ID](#)⁴⁷, N.A. Schneider [ID](#)¹⁰⁹, L. Schoeffel [ID](#)¹³⁶, A. Schoening [ID](#)^{62b}, P.G. Scholer [ID](#)³⁵,
E. Schopf [ID](#)¹⁴⁴, M. Schott [ID](#)²⁵, S. Schramm [ID](#)⁵⁵, T. Schroer [ID](#)⁵⁵, H-C. Schultz-Coulon [ID](#)^{62a},
M. Schumacher [ID](#)⁵³, B.A. Schumm [ID](#)¹³⁷, Ph. Schune [ID](#)¹³⁶, H.R. Schwartz [ID](#)⁷, A. Schwartzman [ID](#)¹⁴⁶,

T.A. Schwarz ¹⁰⁶, Ph. Schwemling ¹³⁶, R. Schwienhorst ¹⁰⁷, F.G. Sciacca ²⁰, A. Sciandra ³⁰, G. Sciolla ²⁷, S. A. Scoville ¹³⁰, F. Scuri ^{73a}, C.D. Sebastiani ³⁷, K. Sedlaczek ¹¹⁷, A. Sehrawat ^{138b}, S.C. Seidel ¹¹⁴, B.D. Seidlitz ⁴¹, C. Seitz ⁴⁷, J.M. Seixas ^{81b}, G. Sekhniaidze ^{71a}, L. Selem ¹²⁸, N. Semprini-Cesari ^{24b,24a}, A. Semushin ¹⁷⁵, V. Senthilkumar ¹¹⁶, L. Serin ⁶⁵, M. Sessa ^{71a,71b}, H. Severini ¹²¹, F. Sforza ^{56b,56a}, A. Sfyrila ⁵⁵, Q. Sha ¹⁴, H. Shaddix ¹¹⁷, A.H. Shah ³³, R. Shaheen ¹⁴⁷, J.D. Shahinian ¹²⁹, M. Shamim ³⁷, L.Y. Shan ¹⁴, M. Shapiro ^{18a}, A. Sharma ³⁷, A.S. Sharma ¹⁶⁶, P. Sharma ³⁰, K. Shaw ¹⁴⁹, S.M. Shaw ¹⁰¹, D. Shemyakin ¹⁷¹, Q. Shen ¹⁴, D.J. Sheppard ¹⁴⁵, P. Sherwood ⁹⁶, L. Shi ^{112b}, X. Shi ¹⁴, S. Shimizu ⁸², S. Shirabe ⁸⁸, M. Shiyakova ^{38,al}, M.J. Shochet ³⁹, D.R. Shope ¹²⁶, B. Shrestha ¹²¹, S. Shrestha ^{120,am}, I. Shreyber ³⁸, M.J. Shroff ¹⁰⁴, P. Sicho ¹³², A.M. Sickles ¹⁶⁴, E. Sideras Haddad ^{34j}, A. C. Sidley ¹¹⁶, A. Sidoti ^{24b}, F. Siegert ⁴⁹, Dj. Sijacki ¹⁶, F. Sili ⁶¹, J.M. Silva ⁵¹, I. Silva Ferreira ^{81b}, M.V. Silva Oliveira ³⁰, S.B. Silverstein ^{46a}, S. Simion ⁶⁵, R. Simoniello ³⁷, E.L. Simpson ¹⁰¹, H. Simpson ¹⁴⁹, L.R. Simpson ⁶, S. Simsek ⁸⁰, S. Sindhu ⁵⁴, S. Singh ³⁰, S. N. Singh ²⁷, S. Sinha ⁴⁷, S. Sinha ¹⁰¹, M. Sioli ^{24b,24a}, K. Sioulas ⁹, I. Siral ³⁷, E. Sitnikova ⁴⁷, J. Sjölin ^{46a,46b}, A. Skaf ⁵⁴, E. Skorda ²¹, P. Skubic ¹²¹, M. Slawinska ⁸⁶, I. Slazyk ¹⁷, I. Sliusar ¹²⁶, V. Smakhtin ¹⁷¹, B.H. Smart ¹³⁵, S.Yu. Smirnov ^{138b}, Y. Smirnov ^{34c}, O. Smirnova ⁹⁸, J.L. Smith ¹⁰¹, M. B. Smith ³⁵, R. Smith ¹⁴⁶, H. Smitmanns ¹⁰⁰, M. Smizanska ⁹¹, K. Smolek ¹³³, P. Smolyanskiy ¹³³, A.A. Snesarev ³⁸, H.L. Snoek ¹¹⁶, R. M. Snyder ⁵⁰, S. Snyder ³⁰, R. Sobie ^{167,n}, A. Soffer ¹⁵⁴, C.A. Solans Sanchez ³⁷, E.Yu. Soldatov ³⁸, U. Soldevila ¹⁶⁵, A.A. Solodkov ^{34j}, S. Solomon ²⁷, A. Soloshenko ³⁸, O.V. Solovyanov ⁴⁰, P. Sommer ⁴⁹, A. Sopczak ¹³³, A.L. Sopio ⁵¹, F. Sopkova ^{29b}, J. D. Sorenson ¹¹⁴, I.R. Sotarriva Alvarez ¹³⁹, V. Sothilingam ^{62a}, O. J. Soto Sandoval ^{138c,138b}, S. Sottocornola ⁶⁷, R. Soualah ^{83a}, D. South ⁴⁷, N. Soybelman ¹⁷¹, S. Spagnolo ^{69a,69b}, A.S. Spellman ¹²⁴, D. Sperlich ⁵³, B. Spisso ^{71a,71b}, L. M. Spitzauer ¹¹⁰, L. Splendori ¹⁰², M. Spousta ¹³⁴, E.J. Staats ³⁵, R. Stamen ^{62a}, E. Stanecka ⁸⁶, W. Stanek-Maslouska ⁴⁷, M.V. Stange ⁴⁹, B. Stanislaus ^{18a}, M.M. Stanitzki ⁴⁷, G.H. Stark ¹³⁷, J. Stark ⁸⁹, P. Staroba ¹³², P. Starovoitov ^{83d}, R. Staszewski ⁸⁶, C. Stauch ¹⁰⁹, G. Stavropoulos ⁴⁵, A. Steff ³⁷, A. Stein ¹⁰⁰, P. Steinberg ³⁰, B. Stelzer ^{145,159a}, H.J. Stelzer ¹³⁰, O. Stelzer ^{159a}, H. Stenzel ⁵⁷, T.J. Stevenson ¹⁴⁹, G.A. Stewart ⁴⁷, G. Stoicea ^{28b}, M. Stolarski ^{131a}, S. Stonjek ¹¹⁰, A. Straessner ⁴⁹, J. Strandberg ¹⁴⁷, S. Strandberg ^{46a,46b}, M. Stratmann ¹⁷³, M. Strauss ¹²¹, T. Strebler ¹⁰², P. Strizenec ^{29b}, R. Ströhmer ¹⁶⁸, D.M. Strom ¹²⁴, R. Stroynowski ⁴⁴, A. Strubig ^{46a,46b}, S.A. Stucci ³⁰, B. Stugu ¹⁷, J. Stupak ¹²¹, N.A. Styles ⁴⁷, D. Su ¹⁴⁶, S. Su ⁶¹, X. Su ⁶¹, D. Suchy ^{29a}, A. D. Sudhakar Ponnu ⁵⁴, L. Sudit ¹⁷¹, Y. Sue ⁸², K. Sugizaki ¹²⁹, D.M.S. Sultan ¹²⁷, L. Sultanaliyeva ²⁵, S. Sultansoy ^{3b}, S. Sun ¹⁷², W. Sun ¹⁴, S. Sundar Raman ¹⁶⁶, N. Sur ⁹⁸, J.P. Surdutovich ¹²⁰, N. Suri Jr ¹⁷⁴, M.R. Sutton ¹⁴⁹, M. Svatos ¹³², P. N. Swallow ³³, S.N. Swatman ³⁷, M. Swiatlowski ^{159a}, A. Swoboda ³⁷, I. Sykora ^{29a}, M. Sykora ¹³⁴, T. Sykora ¹³⁴, D. Ta ¹⁰⁰, K. Tackmann ^{47,an}, A. Taffard ¹⁶², R. Tafirout ^{159a}, Y. Takubo ⁸², M. Talby ¹⁰², N.M. Tamir ¹⁵⁴, A. Tanaka ¹⁵⁶, J. Tanaka ¹⁵⁶, R. Tanaka ⁶⁵, M. Tanasini ¹⁴⁸, Z. Tao ¹⁶⁶, S. Tapia Araya ^{138g}, S. Tapprogge ¹⁰⁰, A. Tarek Abouelfadl Mohamed ³⁷, S. Tarem ¹⁵³, K. Tariq ¹⁴, G. Tarna ³⁷, G.F. Tartarelli ^{70a}, M. J. Tartarin ^{141b}, P. Tas ¹³⁴, M. Tasevsky ¹³², E. Tassi ^{43b,43a}, A.C. Tate ¹⁶⁴, Y. Tayalati ^{36e,ao}, G.N. Taylor ¹⁰⁵, W. Taylor ^{159b},

R.J. Taylor Vara ¹⁶⁵, A.S. Tegetmeier ⁸⁹, P. Teixeira-Dias ⁹⁵, J.J. Teoh ¹⁵⁸, K. Terashi ¹⁵⁶, J. Terron ⁹⁹, S. Terzo ¹³, M. Testa ⁵², R.J. Teuscher ^{158,n}, A. Thaler ⁷⁸, T. Theveneaux-Pelzer ¹⁰², J.P. Thomas ²¹, E.A. Thompson ^{18a}, P.D. Thompson ²¹, E. Thomson ¹²⁹, R. E. Thornberry ³⁰, T.M. Thory-Rao ²¹, C.N. Thotamuna Wijewardhana ¹⁴⁸, C. Tian ⁶¹, Y. Tian ⁵⁵, V. Tikhomirov ⁸⁰, Yu.A. Tikhonov ³⁸, D. Timoshyn ¹³⁴, E.X.L. Ting ¹, P. Tipton ¹⁷⁴, A. Tishelman-Charny ³⁰, K. Todome ¹³⁹, S. Todorova-Nova ¹³⁴, L. Toffolin ^{68a,68c}, M. Togawa ⁸², J. Tojo ⁸⁸, S. Tokár ^{29a}, O. Toldaiev ⁶⁷, G. Tolkachev ¹⁰², M. Tomoto ⁸², L. Tompkins ¹⁴⁶, E. Torrence ¹²⁴, H. Torres ⁸⁹, D. I. Torres Arza ^{138g}, E. Torres Reoyo ¹⁶⁵, E. Torró Pastor ¹⁶⁵, M. Toscani ³¹, C. Tosciri ³⁹, M. Tost ¹¹, D.R. Tovey ¹⁴², T. Trefzger ¹⁶⁸, P.M. Tricarico ¹³, A. Tricoli ³⁰, I.M. Trigger ^{159a}, S. Trincas-Duvold ¹²⁸, D.A. Trischuk ¹⁶⁷, A. Tropina ³⁸, D. Truncali ^{75a,75b}, L. Truong ^{34c}, M. Trzebinski ⁸⁶, A. Trzupke ⁸⁶, F. Tsai ¹⁴⁸, A. Tsiamis ¹⁵⁵, P.V. Tsireshka ³⁸, S. Tsigaridas ^{159a}, A. Tsirigotis ^{155,ac}, V. Tsiskaridze ^{152a}, E.G. Tskhadadze ^{152a}, H. F. Tsoi ¹²⁹, Y. Tsujikawa ⁸⁷, V. Tsulaia ^{18a}, K. Tsurii ¹¹⁹, D. Tsybychev ¹⁴⁸, Y. Tu ^{63b}, A. Tudorache ^{28b}, V. Tudorache ^{28b}, S. B. Tuncay ¹²⁷, S. Turchikhin ^{56b,56a}, I. Turk Cakir ^{3a}, R. Turra ^{70a}, T. Turtuvshin ^{38,ap}, P.M. Tuts ⁴¹, Y. Uematsu ⁸², F. Ukegawa ¹⁶⁰, P.A. Ulloa Poblete ^{138c,138b}, G. Unal ³⁷, A. Undrus ³⁰, J. Urban ^{29b}, P. Urrejola ^{138e}, G. Usai ⁸, R. Ushioda ¹⁵⁷, M. Usman ¹⁰⁸, F. Ustuner ⁵¹, Z. Uysal ⁸⁰, V. Vacek ¹³³, B. Vachon ¹⁰⁴, T. Vafeiadis ³⁷, A. Vaitkus ⁹⁶, C. Valderanis ¹⁰⁹, E. Valdes Santurio ^{46a,46b}, M. Valente ³⁷, S. Valentinetti ^{24b,24a}, A. Valero ¹⁶⁵, E. Valiente Moreno ¹⁶⁵, A. Vallier ⁸⁹, J.A. Valls Ferrer ¹⁶⁵, D. R. Van Arneman ¹¹⁶, R. Van Den Broucke ¹²⁸, A. Van Der Graaf ⁴⁸, H. Z. Van Der Schyf ^{34j}, P. Van Gemmeren ⁶, M. Van Rijnbach ³⁷, S. Van Stroud ⁹⁶, I. Van Vulpen ¹¹⁶, P. Vana ¹³⁴, M. Vanadia ^{75a,75b}, U. M. Vande Voorde ¹⁴⁷, W. Vandelli ³⁷, E.R. Vandewall ¹⁴⁶, D. Vannicola ¹⁵⁴, R. Vari ^{74a}, M. Varma ¹⁷⁴, E.W. Varnes ⁷, C. Varni ^{85a}, D. Varouchas ⁶⁵, L. Varriale ¹⁶⁵, K.E. Varvell ¹⁵⁰, M.E. Vasile ^{28b}, A. Vasileiadou ⁹, L. Vaslin ⁸², M. D. Vassilev ¹⁴⁶, A. Vasyukov ³⁸, L. M. Vaughan ¹²², R. Vavricka ¹³⁴, T. Vazquez Schroeder ¹³, J. Veatch ³², V. Vecchio ¹⁰¹, M.J. Veen ¹⁰³, I. Veliscek ³⁰, I. Velkovska ⁹³, L.M. Veloce ¹⁵⁸, F. Veloso ^{131a,131c}, A.G. Veltman ⁵¹, S.H. Venetianer ¹⁶¹, S. Veneziano ^{74a}, A. Ventura ^{69a,69b}, A. Verbitskiy ¹¹⁰, M. Verducci ^{73a,73b}, C. Vergis ⁹⁴, M. Verissimo De Araujo ^{81b}, W. Verkerke ¹¹⁶, J.C. Vermeulen ¹¹⁶, C. Vernieri ¹⁴⁶, M. Vessella ¹⁶², M.C. Vetterli ^{145,s}, A. Vgenopoulos ¹⁰⁰, N. Viaux Maira ^{138g,aq}, L. Vicenik ¹³³, T. Vickey ¹⁴², O.E. Vickey Boeriu ¹⁴², G.H.A. Viehhauser ¹²⁷, L. Vigani ^{62b}, M. Vigil ¹¹⁰, M. Villa ^{24b,24a}, M. Villaplana Perez ¹⁶⁵, E.M. Villhauer ³⁹, E. Vilucchi ⁵², M. Vincent ¹⁶⁵, M.G. Vincter ³⁵, A. Visibile ¹¹⁶, A. Visive ¹¹⁶, C. Vittori ¹⁶¹, I. Vivarelli ^{24b,24a}, M.I. Vivas Albornoz ⁴⁷, E. Voevodina ¹¹⁰, F. Vogel ¹⁰⁹, J.C. Voigt ⁴⁹, P. Vokac ¹³³, Yu. Volkotrub ^{85b}, L. Vomberg ²⁵, E. Von Toerne ²⁵, B. Vormwald ³⁷, K. Vorobev ⁵⁰, M. Vos ¹⁶⁵, K. Voss ¹⁴⁴, M. Vozak ³⁷, L. Vozdecky ¹²¹, N. Vranjes ¹⁶, M. Vranjes Milosavljevic ¹⁶, M. Vreeswijk ¹¹⁶, N.K. Vu ^{112a}, R. Vuillermet ³⁷, O. Vujinovic ¹⁰⁰, I. Vukotic ³⁹, I. K. Vyas ³⁵, J.F. Wack ³³, A. Wada ¹¹¹, S. Wada ¹⁶⁰, C. Wagner ¹⁴⁶, J.M. Wagner ^{18a}, W. Wagner ¹⁷³, S. Wahdan ¹⁷³, H. Wahlberg ⁹⁰, C. H. Waits ¹²¹, J. Walder ¹³⁵, R. Walker ¹⁰⁹, K. Walkingshaw Pass ⁵⁸, W. Walkowiak ¹⁴⁴, A. Wall ¹²⁹, E.J. Wallin ⁹⁸, T. Wamorkar ¹⁴⁶, K. Wandall-Christensen ¹⁶⁵, A. Wang ⁶¹, A.Z. Wang ¹³⁷, C. Wang ⁴⁷, C. Wang ¹¹, H. Wang ^{18a}, J. Wang ^{63c}, P. Wang ¹⁰¹,

P. Wang^{[1](#)}^{[96](#)}, R. Wang^{[1](#)}^{[60](#)}, R. Wang^{[1](#)}^{[106](#)}, R. Wang^{[1](#)}^{[6](#)}, S. Wang^{[1](#)}^{[14,ar](#)}, S.M. Wang^{[1](#)}^{[151](#)},
T. Wang^{[1](#)}^{[115](#)}, T. Wang^{[1](#)}^{[61](#)}, W. Wang^{[1](#)}^{[113c](#)}, W.T. Wang^{[1](#)}^{[127](#)}, X. Wang^{[1](#)}^{[164](#)}, X. Wang^{[1](#)}^{[141a](#)},
X. Wang^{[1](#)}^{[47](#)}, Y. Wang^{[1](#)}^{[148](#)}, Y. Wang^{[1](#)}^{[114](#)}, Z. Wang^{[1](#)}^{[106](#)}, Z. Wang^{[1](#)}^{[14](#)}, Z. Wang^{[1](#)}^{[63b](#)},
C. Wanotayaroj^{[1](#)}^{[82](#)}, A. Warburton^{[1](#)}^{[104](#)}, A.L. Warnerbring^{[1](#)}^{[144](#)}, S. Waterhouse^{[1](#)}^{[96](#)},
A.T. Watson^{[1](#)}^{[21](#)}, H. Watson^{[1](#)}^{[51](#)}, M.F. Watson^{[1](#)}^{[21](#)}, E. Watton^{[1](#)}^{[37](#)}, G. Watts^{[1](#)}^{[140](#)}, B.M. Waugh^{[1](#)}^{[96](#)},
J. M. Webb^{[1](#)}^{[53](#)}, C. Weber^{[1](#)}^{[30](#)}, M.S. Weber^{[1](#)}^{[20](#)}, C. Wei^{[1](#)}^{[61](#)}, Y. Wei^{[1](#)}^{[53](#)}, A.R. Weidberg^{[1](#)}^{[127](#)},
E.J. Weik^{[1](#)}^{[118](#)}, J. Weingarten^{[1](#)}^{[48](#)}, C. Weiser^{[1](#)}^{[53](#)}, C.J. Wells^{[1](#)}^{[47](#)}, P.S. Wells^{[1](#)}^{[37](#)}, T. Wenaus^{[1](#)}^{[30](#)},
T. Wengler^{[1](#)}^{[37](#)}, N.S. Wenke^{[1](#)}^{[110](#)}, N. Wermes^{[1](#)}^{[25](#)}, D. Werner^{[1](#)}^{[47](#)}, M. Wessels^{[1](#)}^{[62a](#)}, A.M. Wharton^{[1](#)}^{[91](#)},
A. White^{[1](#)}^{[8](#)}, A.S. White^{[1](#)}^{[37](#)}, M.J. White^{[1](#)}^{[1](#)}, D. Whiteson^{[1](#)}^{[162](#)}, L. Wickremasinghe^{[1](#)}^{[125](#)},
W. Wiedenmann^{[1](#)}^{[172](#)}, M. WIELERS^{[1](#)}^{[135](#)}, R. Wierda^{[1](#)}^{[147](#)}, C. Wigglesworth^{[1](#)}^{[42](#)}, H.G. Wilkens^{[1](#)}^{[37](#)},
J. J. H. Wilkinson^{[1](#)}^{[33](#)}, S. Williams^{[1](#)}^{[33](#)}, S. Willocq^{[1](#)}^{[103](#)}, D.J. Wilson^{[1](#)}^{[101](#)}, P.J. Windischhofer^{[1](#)}^{[39](#)},
F.I. Winkel^{[1](#)}^{[31](#)}, F. Winklmeier^{[1](#)}^{[124](#)}, B.T. Winter^{[1](#)}^{[53](#)}, M. Wittgen^{[1](#)}^{[146](#)}, M. Wobisch^{[1](#)}^{[97](#)},
T. Wojtkowski^{[1](#)}^{[59](#)}, Z. Wolffs^{[1](#)}^{[116](#)}, J. Wollrath^{[1](#)}^{[37](#)}, M.W. Wolter^{[1](#)}^{[86](#)}, H. Wolters^{[1](#)}^{[131a,131c](#)},
M.C. Wong^{[1](#)}^{[137](#)}, E.L. Woodward^{[1](#)}^{[41](#)}, S.D. Worm^{[1](#)}^{[47](#)}, B.K. Wosiek^{[1](#)}^{[86](#)}, K. A. Wozniak^{[1](#)}^{[55](#)},
K.W. Woźniak^{[1](#)}^{[86](#)}, S. Wozniowski^{[1](#)}^{[54](#)}, K. Wraight^{[1](#)}^{[58](#)}, C. Wu^{[1](#)}^{[158](#)}, C. Wu^{[1](#)}^{[21](#)}, J. Wu^{[1](#)}^{[156](#)},
M. Wu^{[1](#)}^{[112b](#)}, M. Wu^{[1](#)}^{[115](#)}, S. Wu^{[1](#)}^{[14,ar](#)}, S.L. Wu^{[1](#)}^{[172](#)}, X. Wu^{[1](#)}^{[61](#)}, Y. Wu^{[1](#)}^{[61](#)}, Y.Q. Wu^{[1](#)}^{[158](#)},
Z. Wu^{[1](#)}^{[102](#)}, Z. Wu^{[1](#)}^{[112a](#)}, J. Wuerzinger^{[1](#)}^{[110](#)}, T.R. Wyatt^{[1](#)}^{[101](#)}, B.M. Wynne^{[1](#)}^{[51](#)}, S. Xella^{[1](#)}^{[42](#)},
L. Xia^{[1](#)}^{[112a](#)}, M. Xie^{[1](#)}^{[61](#)}, A. Xiong^{[1](#)}^{[124](#)}, I. Xiotidis^{[1](#)}^{[37](#)}, D. Xu^{[1](#)}^{[14](#)}, H. Xu^{[1](#)}^{[61](#)}, L. Xu^{[1](#)}^{[61](#)},
R. Xu^{[1](#)}^{[129](#)}, T. Xu^{[1](#)}^{[106](#)}, W. Xu^{[1](#)}^{[112a](#)}, Y. Xu^{[1](#)}^{[140](#)}, Z. Xu^{[1](#)}^{[51](#)}, R. Xue^{[1](#)}^{[130](#)}, B. Yabsley^{[1](#)}^{[150](#)},
S. Yacoob^{[1](#)}^{[11](#)}, Y. Yamaguchi^{[1](#)}^{[82](#)}, E. Yamashita^{[1](#)}^{[156](#)}, H. Yamauchi^{[1](#)}^{[160](#)}, T. Yamazaki^{[1](#)}^{[18a](#)},
Y. Yamazaki^{[1](#)}^{[84](#)}, S. Yan^{[1](#)}^{[58](#)}, Z. Yan^{[1](#)}^{[103](#)}, C. Yang^{[1](#)}^{[18a](#)}, H.J. Yang^{[1](#)}^{[141a](#)}, H.T. Yang^{[1](#)}^{[61](#)},
S. Yang^{[1](#)}^{[61](#)}, X. Yang^{[1](#)}^{[37](#)}, X. Yang^{[1](#)}^{[14](#)}, Y. Yang^{[1](#)}^{[156](#)}, Y. Yang^{[1](#)}^{[61](#)}, W-M. Yao^{[1](#)}^{[18a](#)},
C. L. Yardley^{[1](#)}^{[149](#)}, J. Ye^{[1](#)}^{[14](#)}, S. Ye^{[1](#)}^{[30](#)}, X. Ye^{[1](#)}^{[61](#)}, I. Yeletsikh^{[1](#)}^{[38](#)}, B. Yeo^{[1](#)}^{[18b](#)}, M.R. Yexley^{[1](#)}^{[96](#)},
T. P. Yildirim^{[1](#)}^{[127](#)}, K. Yorita^{[1](#)}^{[170](#)}, C. Young^{[1](#)}^{[146](#)}, C.J.S. Young^{[1](#)}^{[37](#)}, I.N.L. Young^{[1](#)}^{[58](#)},
N.D. Young^{[1](#)}^{[124](#)}, Y. Yu^{[1](#)}^{[61](#)}, J. Yuan^{[1](#)}^{[14,112c,ar](#)}, M. Yuan^{[1](#)}^{[106](#)}, R. Yuan^{[1](#)}^{[141b](#)}, L. Yue^{[1](#)}^{[96](#)},
M. Zaaoua^{[1](#)}^{[61](#)}, B. Zabinski^{[1](#)}^{[86](#)}, I. Zahir^{[1](#)}^{[36a](#)}, Q.U.A. Zahoor^{[1](#)}^{[51](#)}, A. Zaio^{[1](#)}^{[56b,56a](#)}, Z.K. Zak^{[1](#)}^{[86](#)},
T. Zakareishvili^{[1](#)}^{[165](#)}, S. Zambito^{[1](#)}^{[55](#)}, J. Zang^{[1](#)}^{[156](#)}, R. Zanzottera^{[1](#)}^{[70a,70b](#)}, O. Zaplatilek^{[1](#)}^{[133](#)},
E. Zaya^{[1](#)}^{[147](#)}, C. Zeitnitz^{[1](#)}^{[173](#)}, H. Zeng^{[1](#)}^{[14](#)}, D.T. Zenger Jr^{[1](#)}^{[27](#)}, T. Ženiš^{[1](#)}^{[29a](#)}, S. Zenz^{[1](#)}^{[94](#)},
D. Zerwas^{[1](#)}^{[65](#)}, W. Zhan^{[1](#)}^{[61](#)}, B. Zhang^{[1](#)}^{[169](#)}, D.F. Zhang^{[1](#)}^{[142](#)}, G. Zhang^{[1](#)}^{[14,ar](#)}, J. Zhang^{[1](#)}^{[113b](#)},
J. Zhang^{[1](#)}^{[6](#)}, L. Zhang^{[1](#)}^{[61](#)}, L. Zhang^{[1](#)}^{[112a](#)}, P. Zhang^{[1](#)}^{[14,112c](#)}, R. Zhang^{[1](#)}^{[112a](#)}, S. Zhang^{[1](#)}^{[36e](#)},
Y. Zhang^{[1](#)}^{[140](#)}, Y. Zhang^{[1](#)}^{[96](#)}, Y. Zhang^{[1](#)}^{[61](#)}, Y. Zhang^{[1](#)}^{[112a](#)}, Z. Zhang^{[1](#)}^{[101](#)}, Z. Zhang^{[1](#)}^{[18a](#)},
Z. Zhang^{[1](#)}^{[113b](#)}, Z. Zhang^{[1](#)}^{[65](#)}, H. Zhao^{[1](#)}^{[140](#)}, T. Zhao^{[1](#)}^{[113b](#)}, Y. Zhao^{[1](#)}^{[35](#)}, Z. Zhao^{[1](#)}^{[61](#)}, Z. Zhao^{[1](#)}^{[61](#)},
A. Zhemchugov^{[1](#)}^{[38](#)}, J. Zheng^{[1](#)}^{[112a](#)}, K. Zheng^{[1](#)}^{[164](#)}, L. Zheng^{[1](#)}^{[113b](#)}, X. Zheng^{[1](#)}^{[61](#)}, Z. Zheng^{[1](#)}^{[146](#)},
D. Zhong^{[1](#)}^{[164](#)}, B. Zhou^{[1](#)}^{[106](#)}, B. Zhou^{[1](#)}^{[141b,141a](#)}, N. Zhou^{[1](#)}^{[141a](#)}, Y. Zhou^{[1](#)}^{[15](#)}, Y. Zhou^{[1](#)}^{[112a](#)},
Y. Zhou^{[1](#)}^{[7](#)}, Z. Zhou^{[1](#)}^{[61](#)}, J. Zhu^{[1](#)}^{[106](#)}, X. Zhu^{[1](#)}^{[141b](#)}, Y. Zhu^{[1](#)}^{[141a](#)}, X. Zhuang^{[1](#)}^{[14](#)}, K. Zhukov^{[1](#)}^{[67](#)},
P. Ziakas^{[1](#)}^{[4](#)}, N.I. Zimine^{[1](#)}^{[38](#)}, J. Zinsser^{[1](#)}^{[62b](#)}, M. Ziolkowski^{[1](#)}^{[144](#)}, L. Živković^{[1](#)}^{[16](#)},
A. Zoccoli^{[1](#)}^{[24b,24a](#)}, K. Zoch^{[1](#)}^{[37](#)}, A. Zografos^{[1](#)}^{[37](#)}, T.G. Zorbas^{[1](#)}^{[142](#)}, L. Zwalinski^{[1](#)}^{[37](#)}

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Department of Physics, University of Alberta, Edmonton AB, Canada

^{3a} Department of Physics, Ankara University, Ankara, Türkiye

^{3b} Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye

⁴ LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

⁵ APC, Université Paris Cité, CNRS/IN2P3, Paris, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL, U.S.A.

- ⁷ Department of Physics, University of Arizona, Tucson AZ, U.S.A.
- ⁸ Department of Physics, University of Texas at Arlington, Arlington TX, U.S.A.
- ⁹ Physics Department, National and Kapodistrian University of Athens, Athens, Greece
- ¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece
- ¹¹ Department of Physics, University of Texas at Austin, Austin TX, U.S.A.
- ¹² Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹³ Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
- ¹⁴ Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
- ¹⁵ Physics Department, Tsinghua University, Beijing, China
- ¹⁶ Institute of Physics, University of Belgrade, Belgrade, Serbia
- ¹⁷ Department for Physics and Technology, University of Bergen, Bergen, Norway
- ^{18a} Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA, U.S.A.
- ^{18b} University of California, Berkeley CA, U.S.A.
- ¹⁹ Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
- ²⁰ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ²¹ School of Physics and Astronomy, University of Birmingham, Birmingham, U.K.
- ^{22a} Department of Physics, Bogazici University, Istanbul, Türkiye
- ^{22b} Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye
- ^{22c} Department of Physics, Istanbul University, Istanbul, Türkiye
- ^{23a} Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia
- ^{23b} Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
- ^{24a} Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy
- ^{24b} INFN Sezione di Bologna, Italy
- ²⁵ Physikalisches Institut, Universität Bonn, Bonn, Germany
- ²⁶ Department of Physics, Boston University, Boston MA, U.S.A.
- ²⁷ Department of Physics, Brandeis University, Waltham MA, U.S.A.
- ^{28a} Transilvania University of Brasov, Brasov, Romania
- ^{28b} Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- ^{28c} Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
- ^{28d} National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
- ^{28e} National University of Science and Technology Politehnica, Bucharest, Romania
- ^{28f} West University in Timisoara, Timisoara, Romania
- ^{28g} Faculty of Physics, University of Bucharest, Bucharest, Romania
- ^{29a} Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
- ^{29b} Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ³⁰ Physics Department, Brookhaven National Laboratory, Upton NY, U.S.A.
- ³¹ Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina
- ³² California State University, CA, U.S.A.
- ³³ Cavendish Laboratory, University of Cambridge, Cambridge, U.K.
- ^{34a} Department of Physics, University of Cape Town, Cape Town, South Africa
- ^{34b} iThemba Labs, Western Cape, South Africa
- ^{34c} Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
- ^{34d} National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines
- ^{34e} Department of Physics, Stellenbosch University, Matieland, South Africa
- ^{34f} University of KwaZulu-Natal, School of Agriculture and Science, Mathematics, Westville, South Africa
- ^{34g} University of South Africa, Department of Physics, Pretoria, South Africa
- ^{34h} University of Pretoria, Department of Mechanical and Aeronautical Engineering, Pretoria, South Africa
- ³⁴ⁱ University of Zululand, KwaDlangezwa, South Africa

- ^{34j} *School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ³⁵ *Department of Physics, Carleton University, Ottawa ON, Canada*
- ^{36a} *Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Morocco*
- ^{36b} *Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
- ^{36c} *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
- ^{36d} *LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
- ^{36e} *Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ^{36f} *Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*
- ³⁷ *CERN, Geneva, Switzerland*
- ³⁸ *Affiliated with an international laboratory covered by a cooperation agreement with CERN*
- ³⁹ *Enrico Fermi Institute, University of Chicago, Chicago IL, U.S.A.*
- ⁴⁰ *LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
- ⁴¹ *Nevis Laboratory, Columbia University, Irvington NY, U.S.A.*
- ⁴² *Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- ^{43a} *Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- ^{43b} *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- ⁴⁴ *Physics Department, Southern Methodist University, Dallas TX, U.S.A.*
- ⁴⁵ *National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece*
- ^{46a} *Department of Physics, Stockholm University, Sweden*
- ^{46b} *Oskar Klein Centre, Stockholm, Sweden*
- ⁴⁷ *Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- ⁴⁸ *Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
- ⁴⁹ *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- ⁵⁰ *Department of Physics, Duke University, Durham NC, U.S.A.*
- ⁵¹ *SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, U.K.*
- ⁵² *INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵³ *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ⁵⁴ *II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁵⁵ *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- ^{56a} *Dipartimento di Fisica, Università di Genova, Genova, Italy*
- ^{56b} *INFN Sezione di Genova, Italy*
- ⁵⁷ *II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁸ *SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, U.K.*
- ⁵⁹ *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- ⁶⁰ *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, U.S.A.*
- ⁶¹ *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- ^{62a} *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{62b} *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{63a} *Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
- ^{63b} *Department of Physics, University of Hong Kong, Hong Kong, China*
- ^{63c} *Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- ⁶⁴ *Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- ⁶⁵ *IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
- ⁶⁶ *Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain*
- ⁶⁷ *Department of Physics, Indiana University, Bloomington IN, U.S.A.*
- ^{68a} *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
- ^{68b} *ICTP, Trieste, Italy*
- ^{68c} *Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
- ^{69a} *INFN Sezione di Lecce, Italy*
- ^{69b} *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- ^{70a} *INFN Sezione di Milano, Italy*

- ^{70b} *Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ^{71a} *INFN Sezione di Napoli, Italy*
- ^{71b} *Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- ^{72a} *INFN Sezione di Pavia, Italy*
- ^{72b} *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ^{73a} *INFN Sezione di Pisa, Italy*
- ^{73b} *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ^{74a} *INFN Sezione di Roma, Italy*
- ^{74b} *Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- ^{75a} *INFN Sezione di Roma Tor Vergata, Italy*
- ^{75b} *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ^{76a} *INFN Sezione di Roma Tre, Italy*
- ^{76b} *Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- ^{77a} *INFN-TIFPA, Italy*
- ^{77b} *Università degli Studi di Trento, Trento, Italy*
- ⁷⁸ *Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
- ⁷⁹ *Department of Physics and Astronomy, Iowa State University, Ames IA, U.S.A.*
- ⁸⁰ *Istinye University, Sariyer, Istanbul, Türkiye*
- ^{81a} *Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
- ^{81b} *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
- ^{81c} *Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- ^{81d} *Rio de Janeiro State University, Rio de Janeiro, Brazil*
- ^{81e} *Federal University of Bahia, Bahia, Brazil*
- ⁸² *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- ^{83a} *Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates*
- ^{83b} *New York University Abu Dhabi, Abu Dhabi, United Arab Emirates*
- ^{83c} *United Arab Emirates University, Al Ain, United Arab Emirates*
- ^{83d} *University of Sharjah, Sharjah, United Arab Emirates*
- ⁸⁴ *Graduate School of Science, Kobe University, Kobe, Japan*
- ^{85a} *AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland*
- ^{85b} *Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- ⁸⁶ *Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
- ⁸⁷ *Faculty of Science, Kyoto University, Kyoto, Japan*
- ⁸⁸ *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- ⁸⁹ *L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France*
- ⁹⁰ *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- ⁹¹ *Physics Department, Lancaster University, Lancaster, U.K.*
- ⁹² *Oliver Lodge Laboratory, University of Liverpool, Liverpool, U.K.*
- ⁹³ *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- ⁹⁴ *Department of Physics and Astronomy, Queen Mary University of London, London, U.K.*
- ⁹⁵ *Department of Physics, Royal Holloway University of London, Egham, U.K.*
- ⁹⁶ *Department of Physics and Astronomy, University College London, London, U.K.*
- ⁹⁷ *Louisiana Tech University, Ruston LA, U.S.A.*
- ⁹⁸ *Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁹⁹ *Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
- ¹⁰⁰ *Institut für Physik, Universität Mainz, Mainz, Germany*
- ¹⁰¹ *School of Physics and Astronomy, University of Manchester, Manchester, U.K.*
- ¹⁰² *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- ¹⁰³ *Department of Physics, University of Massachusetts, Amherst MA, U.S.A.*
- ¹⁰⁴ *Department of Physics, McGill University, Montreal QC, Canada*
- ¹⁰⁵ *School of Physics, University of Melbourne, Victoria, Australia*

- ¹⁰⁶ *Department of Physics, University of Michigan, Ann Arbor MI, U.S.A.*
- ¹⁰⁷ *Department of Physics and Astronomy, Michigan State University, East Lansing MI, U.S.A.*
- ¹⁰⁸ *Group of Particle Physics, University of Montreal, Montreal QC, Canada*
- ¹⁰⁹ *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ¹¹⁰ *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ¹¹¹ *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ^{112a} *Department of Physics, Nanjing University, Nanjing, China*
- ^{112b} *School of Science, Shenzhen Campus of Sun Yat-sen University, China*
- ^{112c} *University of Chinese Academy of Science (UCAS), Beijing, China*
- ^{113a} *School of Physics, Nankai University, Tianjin, China*
- ^{113b} *Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- ^{113c} *School of Physics, Zhengzhou University, China*
- ¹¹⁴ *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, U.S.A.*
- ¹¹⁵ *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands*
- ¹¹⁶ *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹¹⁷ *Department of Physics, Northern Illinois University, DeKalb IL, U.S.A.*
- ¹¹⁸ *Department of Physics, New York University, New York NY, U.S.A.*
- ¹¹⁹ *Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
- ¹²⁰ *Ohio State University, Columbus OH, U.S.A.*
- ¹²¹ *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, U.S.A.*
- ¹²² *Department of Physics, Oklahoma State University, Stillwater OK, U.S.A.*
- ¹²³ *Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic*
- ¹²⁴ *Institute for Fundamental Science, University of Oregon, Eugene, OR, U.S.A.*
- ¹²⁵ *Graduate School of Science, University of Osaka, Osaka, Japan*
- ¹²⁶ *Department of Physics, University of Oslo, Oslo, Norway*
- ¹²⁷ *Department of Physics, Oxford University, Oxford, U.K.*
- ¹²⁸ *LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France*
- ¹²⁹ *Department of Physics, University of Pennsylvania, Philadelphia PA, U.S.A.*
- ¹³⁰ *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, U.S.A.*
- ^{131a} *Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal*
- ^{131b} *Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- ^{131c} *Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- ^{131d} *Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- ^{131e} *Departamento de Física, Escola de Ciências, Universidade do Minho, Braga, Portugal*
- ^{131f} *Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
- ^{131g} *Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
- ¹³² *Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
- ¹³³ *Czech Technical University in Prague, Prague, Czech Republic*
- ¹³⁴ *Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- ¹³⁵ *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, U.K.*
- ¹³⁶ *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ¹³⁷ *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, U.S.A.*
- ^{138a} *Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- ^{138b} *Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile*
- ^{138c} *Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile*
- ^{138d} *Universidad Andres Bello, Department of Physics, Santiago, Chile*
- ^{138e} *Universidad San Sebastian, Recoleta, Chile*
- ^{138f} *Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile*
- ^{138g} *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ¹³⁹ *Department of Physics, Institute of Science, Tokyo, Japan*

- ¹⁴⁰ *Department of Physics, University of Washington, Seattle WA, U.S.A.*
- ^{141a} *State Key Laboratory of Dark Matter Physics, School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China*
- ^{141b} *State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China*
- ¹⁴² *Department of Physics and Astronomy, University of Sheffield, Sheffield, U.K.*
- ¹⁴³ *Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴⁴ *Department Physik, Universität Siegen, Siegen, Germany*
- ¹⁴⁵ *Department of Physics, Simon Fraser University, Burnaby BC, Canada*
- ¹⁴⁶ *SLAC National Accelerator Laboratory, Stanford CA, U.S.A.*
- ¹⁴⁷ *Department of Physics, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁴⁸ *Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, U.S.A.*
- ¹⁴⁹ *Department of Physics and Astronomy, University of Sussex, Brighton, U.K.*
- ¹⁵⁰ *School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵¹ *Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ^{152a} *E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
- ^{152b} *High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- ^{152c} *University of Georgia, Tbilisi, Georgia*
- ¹⁵³ *Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
- ¹⁵⁴ *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵⁵ *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁵⁶ *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
- ¹⁵⁷ *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
- ¹⁵⁸ *Department of Physics, University of Toronto, Toronto ON, Canada*
- ^{159a} *TRIUMF, Vancouver BC, Canada*
- ^{159b} *Department of Physics and Astronomy, York University, Toronto ON, Canada*
- ¹⁶⁰ *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
- ¹⁶¹ *Department of Physics and Astronomy, Tufts University, Medford MA, U.S.A.*
- ¹⁶² *Department of Physics and Astronomy, University of California Irvine, Irvine CA, U.S.A.*
- ¹⁶³ *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶⁴ *Department of Physics, University of Illinois, Urbana IL, U.S.A.*
- ¹⁶⁵ *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain*
- ¹⁶⁶ *Department of Physics, University of British Columbia, Vancouver BC, Canada*
- ¹⁶⁷ *Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*
- ¹⁶⁸ *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
- ¹⁶⁹ *Department of Physics, University of Warwick, Coventry, U.K.*
- ¹⁷⁰ *Waseda University, Tokyo, Japan*
- ¹⁷¹ *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
- ¹⁷² *Department of Physics, University of Wisconsin, Madison WI, U.S.A.*
- ¹⁷³ *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- ¹⁷⁴ *Department of Physics, Yale University, New Haven CT, U.S.A.*
- ¹⁷⁵ *Yerevan Physics Institute, Yerevan, Armenia*

^a *Also at Department of Physics, King's College London, London, U.K.*

^b *Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*

^c *Also at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia*

^d *Also at Department of Physics, University of Thessaly, Greece*

^e *Also at An-Najah National University, Nablus, Palestine*

^f *Also at Department of Physics, University of Fribourg, Fribourg, Switzerland*

^g *Also at Department of Physics, Westmont College, Santa Barbara, U.S.A.*

- ^h Also at *Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain*
- ⁱ Also at *University of Siena, Italy*
- ^j Also at *Affiliated with an institute formerly covered by a cooperation agreement with CERN*
- ^k Also at *The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China*
- ^l Also at *Faculty of Physics, Sofia University, ‘St. Kliment Ohridski’, Sofia, Bulgaria*
- ^m Also at *Università di Napoli Parthenope, Napoli, Italy*
- ⁿ Also at *Institute of Particle Physics (IPP), Canada*
- ^o Also at *Department of Physics, Bolu Abant İzzet Baysal University, Bolu, Türkiye*
- ^p Also at *Faculty of Physics, University of Bucharest, Romania*
- ^q Also at *Borough of Manhattan Community College, City University of New York, New York NY, U.S.A.*
- ^r Also at *National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines*
- ^s Also at *TRIUMF, Vancouver BC, Canada*
- ^t Also at *Università degli Studi Link, Italy*
- ^u Also at *Department of Financial and Management Engineering, University of the Aegean, Chios, Greece*
- ^v Also at *University and INFN Torino, Torino, Italy*
- ^w Also at *Institució Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain*
- ^x Also at *Henan University, China*
- ^y Also at *Yeditepe University, Physics Department, Istanbul, Türkiye*
- ^z Also at *Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia*
- ^{aa} Also at *CERN, Geneva, Switzerland*
- ^{ab} Also at *Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece*
- ^{ac} Also at *Hellenic Open University, Patras, Greece*
- ^{ad} Also at *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- ^{ae} Also at *Department of Physics, Stellenbosch University, South Africa*
- ^{af} Also at *School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ^{ag} Also at *Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel*
- ^{ah} Also at *University of Colorado Boulder, Department of Physics, Colorado, U.S.A.*
- ^{ai} Also at *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- ^{aj} Also at *Centre of Physics of the Universities of Minho and Porto (CF-UM-UP), Portugal*
- ^{ak} Also at *Indian Institute of Technology (IIT), Jodhpur, India*
- ^{al} Also at *Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria*
- ^{am} Also at *Washington College, Chestertown, MD, U.S.A.*
- ^{an} Also at *Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany*
- ^{ao} Also at *Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*
- ^{ap} Also at *Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia*
- ^{aq} Also at *Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile*
- ^{ar} Also at *University of Chinese Academy of Sciences (UCAS), Beijing, China*
- [†] Deceased