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# Search for decays of the Higgs boson into pair-produced pseudoscalar particles decaying into $\tau^+\tau^-\tau^+\tau^-$ using $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

**Keywords:** Higgs boson, pseudoscalar, ATLAS

## Abstract

A search for a pair of low-mass pseudoscalars $a$ that promptly decay into $\tau$-leptons is presented using 140 fb$^{-1}$ of proton–proton collision data at 13 TeV centre-of-mass energy recorded with the ATLAS detector at the Large Hadron Collider. The result is used to place constraints on exotic decays of the Higgs boson into four $\tau$-leptons, $H \to aa \to \tau^+\tau^-\tau^+\tau^-$. This search focuses on events with either one or two $\tau$-leptons decaying into hadrons and neutrinos, and the remaining three or two $\tau$-leptons decaying into either electron or muon and neutrinos. No significant excess is observed above the expected Standard Model background and upper limits at the 95% confidence level on $\mathcal{B}(H \to aa \to \tau^+\tau^-\tau^+\tau^-)$ are set ranging from 0.06 to 0.23, depending on the mass $m_a$ ranging from 15 to 60 GeV.

Beyond-the-Standard-Model (BSM) pseudoscalar particles $a$ with masses below the electroweak scale were proposed to explain several open problems in particle physics, for example as dark matter interaction mediators [1–6], or in the context of models of neutral naturalness [7–9]. One interesting scenario posits new light pseudoscalars coupled to the Higgs field, which can drive electroweak phase transition at leading-order (LO) in perturbation theory [10, 11]. If lighter than half the Higgs boson mass ($m_a < m_{\mathrm{H}}/2$), these pseudoscalars can be produced in pairs in exotic decays of the Higgs boson [12]. The narrow natural width of the Higgs boson predicted by the Standard Model ($\Gamma_{\mathrm{H}}^{\mathrm{SM}} = 3.7$ MeV) [13] implies that even a small BSM partial width for an exotic decay can result in a sizeable branching ratio. Together with the large number of Higgs bosons produced in the proton–proton ($pp$) collisions at $\sqrt{s} = 13$ TeV at the Large Hadron Collider (LHC) [14], such light pseudoscalars $a$ could become detectable through $H \to aa$ decays, even for very feeble coupling constants [15–18].

A search for the production of a pair of new pseudoscalar particles promptly decaying into four $\tau$-leptons is presented. The result presented uses the full Run-2 collision data at a centre-of-mass energy $\sqrt{s} = 13$ TeV recorded with the ATLAS detector. The data collected from 2015 to 2018 corresponds to an integrated luminosity of 140 fb$^{-1}$. The search targets the process $H \to aa \to \tau^+\tau^-\tau^+\tau^-$ and probes the mass range 15 GeV $< m_a <$ 60 GeV. The sensitivity is limited below the lower mass value by the angular separation required for the final-state objects, while it is limited beyond the upper mass value by the kinematic threshold for on-shell Higgs boson decays, $m_{\mathrm{H}}/2 = 62.5$ GeV. This search complements a previous search by the ATLAS Collaboration that focused on the lower mass range 4 GeV $< m_a <$ 15 GeV where the $\tau$-leptons are Lorentz-boosted and overlap, requiring a different analysis strategy [19]. Limits have also been set on this model by the CMS Collaboration [20, 21]. The ATLAS Collaboration has also performed searches for new pseudoscalar particles produced in exotic Higgs boson decays in the $b\bar{b}b\bar{b}$ [22–25], $b\bar{b}\tau^+\tau^-$ [26], $b\bar{b}\mu^+\mu^-$ [27], and $\ell^+\ell^-\ell'^+\ell'^-$($\ell = e$ or $\mu$) [28, 29] final states. The $H \to aa$ searches can also be interpreted within the Two-Higgs-Doublet Model [30] extended by a new light pseudoscalar singlet (2HDM+S) framework [12, 31]. The 2HDM+S model effectively captures the phenomenology of the Higgs sector in the Next-to-Minimal Supersymmetric Standard Model, which extends the Minimal Supersymmetric Standard Model by adding a singlet field [31]. In this context, the $\tau^+\tau^-\tau^+\tau^-$ final state is expected to complement the existing searches, particularly for Type III models with large $\tan\beta$ [12], where the new pseudoscalar decays almost exclusively to $\tau$-leptons. This makes the four-$\tau$ final state particularly sensitive in the mass range probed in this analysis, which fills the gap between the existing low-mass ATLAS result [19] and the kinematic threshold of the $H \to aa$ decay. The resulting limits on $\mathcal{B}(H \to aa \to 4\tau)$ therefore constrain the mixing between the Higgs boson and the new pseudoscalar state and, more broadly, the viable parameter space of scenarios in which such a light pseudoscalar acts as a portal to a dark sector or drives a strong first-order electroweak phase transition.

The ATLAS experiment [32] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle[1]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) 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 detectors. Lead/liquid-argon (LAr) sampling calorimeters provide 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 surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [33] detector that is located close to the beampipe. A two-level trigger system was used to select events [34]. The first-level trigger is implemented in hardware and used 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 reduced the accepted rate of complete events to 1.25 kHz on average depending on the data-taking conditions. A software suite [35] 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.

Objects are reconstructed by combining the information from different sub-detectors and using dedicated identification algorithms. Electrons are reconstructed by matching narrow clusters in the electromagnetic calorimeter with tracks in the inner detector. Electron candidates are required to satisfy $p_\mathrm{T} > 7\,\mathrm{GeV}$ and $|\eta| < 2.47$, where $p_\mathrm{T}$ is the transverse momentum. Candidates in the transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$) are excluded. All electrons are required to satisfy the *Tight* charge-identification algorithm [36] to reduce charge misidentification. The baseline electron selection is defined by the *Loose* working point of the ATLAS likelihood-based electron identification algorithm [36] where no isolation requirement is applied. A more exclusive electron selection requires the electron candidates to satisfy the *Medium* identification working point and the *Tight* track-based isolation [36].

Muons are reconstructed by matching tracks in the muon spectrometer with tracks in the inner detector. Muon candidates are required to satisfy $p_\mathrm{T} > 5\,\mathrm{GeV}$ and $|\eta| < 2.5$. Additional conditions, corresponding to the *Medium* working point of the ATLAS muon identification algorithm [37], are imposed on the quality of the tracks to define the baseline muon selection criteria. The exclusive muon identification further requires the *Tight* track-based isolation [37].

Both electrons and muons are required to satisfy $|z_0 \sin\theta| < 0.5\,\mathrm{mm}$, where $z_0$ is the longitudinal impact parameter relative to the primary vertex (PV), which is the reconstructed vertex with the highest sum of squared transverse momenta of associated tracks. Electrons (muons) are require to further satisfy $|d_0|/\sigma_{d_0} < 5(7)$ where $d_0$ is the transverse impact parameter relative to the beam line and $\sigma_{d_0}$ is its uncertainty. The $\tau$-lepton is long-lived, but it has a shorter lifetime compared to $b$-hadrons, so the value of the impact parameter $|d_0|$ is optimised to maintain good acceptance to $\tau$-lepton decays while still reducing contributions from heavy-flavour hadron decays.

Jets are reconstructed using the anti-$k_t$ algorithm [38] as implemented in FastJet [39] with a jet radius parameter $R = 0.4$. The inputs to this algorithm are particle flow objects [40], which combine measurements from the ATLAS inner detector and calorimeters [41] to improve the jet energy resolution and increase the jet reconstruction efficiency, especially at low jet $p_\mathrm{T}$ . The jet energy scale is calibrated to particle-level using simulation and corrections obtained from *in situ* techniques [42]. A multivariate jet vertex tagger is used to identify jets with $p_\mathrm{T} < 60$ *GeV* and $|\eta| < 2.4$ as originating from the PV, suppressing jets from secondary collisions in the same bunch crossing of the event of interest (pileup) [43].

[1] ATLAS 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 $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ 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 $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

All jets are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$. Jets containing $b$-hadrons, referred to as $b$-jets, are identified using the DL1r algorithm [44]. The chosen working point has an efficiency of 85% for selecting $b$-jets [45] as estimated from $t\bar{t}$ simulation.

The reconstruction of $\tau_{\mathrm{had}}$ candidates is seeded by jets formed using the anti-$k_t$ algorithm with a radius parameter $R = 0.4$, using topological clusters of calorimeter cells [41] as inputs. The $\tau_{\mathrm{had}}$ candidates are required to satisfy $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$, excluding the transition region $1.37 < |\eta| < 1.52$. The $\tau_{\mathrm{had}}$ identification uses a recurrent neural network (RNN) algorithm [46]. All $\tau_{\mathrm{had}}$ candidates are required to have exactly one or three charged-particle tracks associated with its seed jet. A baseline $\tau_{\mathrm{had}}$ selection requires the candidate to satisfy the *VeryLoose* RNN working point, while a more exclusive $\tau_{\mathrm{had}}$ selection requires the candidates to further satisfy the *Loose* RNN working point [46]. In addition, a dedicated multivariate electron veto is applied to $\tau_{\mathrm{had}}$ candidates [47].

The missing transverse momentum, with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$, is calculated as the negative vector sum of the transverse momenta of all reconstructed physics objects in events and a track-based soft term [48]. The soft term is constructed from charged-particle tracks that are consistent with originating from the PV but are not associated with any of the primary reconstructed objects.

This search uses events selected with a combination of triggers that require the presence of either a single lepton ($e$ or $\mu$) or a lepton pair with same/different flavours ($ee$, $\mu\mu$ or $e\mu$) [49, 50]. These triggers varied throughout the data-taking period to manage the increasing luminosity and pileup conditions. The single-lepton triggers had thresholds ranging from 20 GeV to 26 GeV and the dilepton triggers had various combinations of $p_{\mathrm{T}}$ thresholds ranging from 10 GeV to 24 GeV for the two leptons, depending on the data-taking period and lepton flavour. To ensure that the reconstructed leptons are associated with the trigger decision, offline leptons are geometrically matched to corresponding trigger-level objects from the specific trigger chain that accepted the event.

Two non-overlapping signal regions (SRs) are used to capture different decay modes of the $\tau$-leptons. The first SR, called $2\ell 2\tau_{\mathrm{had}}$, targets decays of the kind $H \to aa \to (\tau_\ell \tau_{\mathrm{had}})(\tau_{\ell'} \tau_{\mathrm{had}})$, where $\ell$ or $\ell'$ denotes an electron or a muon. Events in the $2\ell 2\tau_{\mathrm{had}}$ region are selected by requiring two same-charge electrons or muons, and two same-charge $\tau_{\mathrm{had}}$. In addition, the total charge of the four selected leptons is required to be zero. The same-charge selection reduces the number of background events from Drell–Yan processes while being consistent with exotic Higgs boson decays into four $\tau$-leptons. The second SR, called $3\ell 1\tau_{\mathrm{had}}$, targets decays of the kind $H \to aa \to (\tau_\ell \tau_{\ell'})(\tau_{\ell''} \tau_{\mathrm{had}})$. Events in the $3\ell 1\tau_{\mathrm{had}}$ region are selected by requiring three electrons or muons and one $\tau_{\mathrm{had}}$. A charge-based selection is also used. The three electrons or muons are required to have a total charge $+1$ or $-1$. The four bodies are required to have a total charge of zero. To significantly reduce the large background from Drell–Yan production, a $Z$ boson veto is applied. Any opposite-charge electron or muon pair is required to have an invariant mass $m_{\ell\ell}$ outside the $Z$ boson mass window, satisfying $m_{\ell\ell} < 71\,\mathrm{GeV}$ or $m_{\ell\ell} > 111\,\mathrm{GeV}$.

In both SRs, events are required to have zero $b$-jets to reduce the number of background events with top quarks. The leading and subleading leptons are required to have $p_{\mathrm{T}} >$ 20 and 15 GeV. These thresholds are chosen to be least 1 GeV above the threshold of the loosest HLT selection in order to ensure a constant trigger efficiency above 98% for all $a$-boson mass points. Finally, the visible mass ($m_{\mathrm{vis}}$) of the four-body system in both SRs is required to satisfy $m_{\mathrm{vis}} < 110\,\mathrm{GeV}$. The value of $110\,\mathrm{GeV}$, below the Higgs boson mass of $125\,\mathrm{GeV}$, accounts for the energy carried away by the neutrinos in $\tau$-lepton decays. After the event selection, there are only two relevant sources of background events. The dominant background source are events with fake/non-prompt (FNP) leptons, estimated by a dedicated data-driven method [51] that is further explained below. The second source are diboson ($WZ$ and $ZZ$) events with prompt leptons that escape the $Z$ boson mass veto selection and is estimated with Monte Carlo (MC) simulations. The contribution from other processes, including $WW$, is found to be negligible.

The MC simulation of $ZZ$ and $WZ$ events is performed with the SHERPA 2.2.2 [52] generator, including off-shell effects and Higgs boson contributions where appropriate. Fully leptonic final states are simulated using matrix elements at next-to-LO (NLO) accuracy in quantum chromodynamics (QCD) for up to one additional parton and at LO accuracy for up to three additional parton emissions. Samples for the loop-induced processes $gg \to VV$ (where $V = W, Z$) are simulated using LO-accurate matrix elements for up to one additional parton emission. The matrix element calculations are matched and merged with the SHERPA parton shower based on Catani–Seymour dipole factorisation [53, 54] using the MEPS@NLO prescription [55–58]. The virtual QCD corrections are provided by the OPENLOOPS library [59–61]. The NNPDF 3.0nnlo set of parton distribution functions (PDFs) is used [62], along with the dedicated set of tuned parton-shower parameters developed by the SHERPA authors.

The signal $pp \to H \to aa \to \tau^+\tau^-\tau^+\tau^-$ is simulated using the gluon–gluon fusion production mode at NLO accuracy in QCD using POWHEGBOX v2 [63–65], with the CT10 PDF set [66]. The cross section is normalised to the Higgs boson inclusive production cross section 55.6 pb [67] since the difference in the acceptance compared to other Higgs boson production modes is negligible. The decay of the Higgs boson and the further hadronisation is performed with PYTHIA[8.245] [68] which is configured to use the EvtGen [69] programme for the decay of $b$-hadrons, using the AZNLO set of tuned parameters (AZNLO tune) [70].

All generated events are simulated with the ATLAS detector simulation [71] based on GEANT [72], and reconstructed with the same software as the data. The signal samples are processed through a faster simulation where the full GEANT simulation of the calorimeter response is replaced by a parameterisation of the shower shapes [71]. The effect of pileup was modelled by overlaying the simulated hard-scattering event with inelastic $pp$ events generated with PYTHIA 8.186 [73] using the NNPDF 2.3lo set of PDF [74] and the A3 set of tuned parameters [75].

The main source of background is composed of FNP leptons (from decays of heavy-flavour hadrons or jets faking leptons) from processes such as $WZ$, $Z/\gamma^* +$jets and $t\bar{t}$. These processes can contribute both to prompt leptons from $W$ or $Z$ boson decays and FNP leptons from $b$-quark decays and jets, which compose the mis-identified background of the analysis. Despite the lifetime of the $\tau$-lepton, electrons and muons produced in $\tau \to \ell\nu_\ell\nu_\tau$ decays are considered prompt. The relaxed impact parameter selection used in the exclusive electron and muon selection criteria ensure good acceptance for most of these decays. Sources of FNP electrons include mis-reconstructed jets and photon conversions. Non-prompt muons arise almost exclusively from the semileptonic decay of hadrons. Finally, FNP $\tau_{\text{had}}$ are mis-identified quark- or gluon-initiated jets. Electrons mis-reconstructed as $\tau_{\text{had}}$ decays with one charged-particle track are estimated from MC. Leptons reconstructed with the wrong charge assignment are always considered FNP. This FNP background is derived using a data-driven fake-factor method [51], using events in which at least one lepton fails to meet the exclusive selection criteria. A weight fake factor $f/(1-f)$, where $f$ is the fake rate—the fraction of events for which the baseline lepton also satisfies the exclusive selection criterion—is applied to each lepton failing to satisfy the exclusive selection criterion. For events containing multiple objects failing to meet the exclusive selection criteria, a combinatoric weight is calculated to account for all possible combinations of fake objects while avoiding over-correction [51]. The contribution of background processes with prompt leptons that fail to satisfy the exclusive selection criteria is removed using MC simulation but has a negligible impact on the final expected yield.

The fake factors are determined in two steps: they are first measured in a data control region enriched in $Z$+jets events, and this measure is then refined in FNP-enriched validation regions (VRs) containing same-sign leptons. In the first step, a $Z$+jets sample is selected by requiring $e^+e^-$ or $\mu^+\mu^-$ pairs, where both leptons satisfy the exclusive selection criterion and $71 < m_{\ell\ell} < 111\,\text{GeV}$, and an additional baseline lepton. Events are required to satisfy $E_{\text{T}}^{\text{miss}} < 30\,\text{GeV}$ to reduce the contamination from $WZ$ events in this control region to a negligible level. The measured fake factor for electrons and muons is extracted in bins of lepton $p_{\text{T}}$ and $\eta$. For taus, the fake factor is measured in bins of visible $p_{\text{T}}$ and as a function of the number of charged-particle tracks associated with the seed jet. The measured fake factors range from approximately 0.3–0.6 for muons, 0.01–0.09 for electrons and 0.25–0.5 for $\tau_{\text{had}}$ candidates with one or three tracks.

The background processes that contribute to FNP leptons vary in proportions in the $Z$+jets regions and in the two SRs. To assess the possible impact of such variation in composition, three VR are defined. The VRs are similar to the SRs but require exactly three objects in the final state. Two VRs, called $\ell e\tau_{\text{had}}$ and $\ell\mu\tau_{\text{had}}$, require the presence of two same-charge leptons (electrons or muons) and one $\tau_{\text{had}}$. The $\ell e\tau_{\text{had}}$ and $\ell\mu\tau_{\text{had}}$ VRs are distinguished by the flavour of the subleading electron or muon. A third VR, called $1\ell 2\tau_{\text{had}}$, is formed by selecting events with two same-charge $\tau_{\text{had}}$ and one electron or muon. In the VRs, similar to the SRs, the three-body visible mass is required to satisfy $m_{\text{vis}}^{\text{3-body}} < 110\,\text{GeV}$ to be kinematically compatible with the SR topology, and the number of $b$-jets is required to be zero.

The $\ell e\tau_{\text{had}}$ ($\ell\mu\tau_{\text{had}}$) VR is designed such that the subleading electron (muon) is dominantly from FNP sources, and similarly, the subleading $\tau_{\text{had}}$ in the $2\tau_{\text{had}}1\ell$ VR is dominated by FNP as well. The VRs serve two purposes: constraining systematic uncertainties and providing a refined fake factor estimate. A profile-likelihood fit to the observed yields in the VRs is performed to propagate the impact of experimental and modelling uncertainties into an uncertainty model for the fake factors. This fit includes dedicated modelling uncertainties evaluated by varying key selection criteria for the three types of objects in the final states, the $\tau_{\text{had}}$ seed jet width, the electron ambiguity (which discriminates against electrons from photon conversions), and the muon $|d_0|/\sigma_{d_0}$ selection.

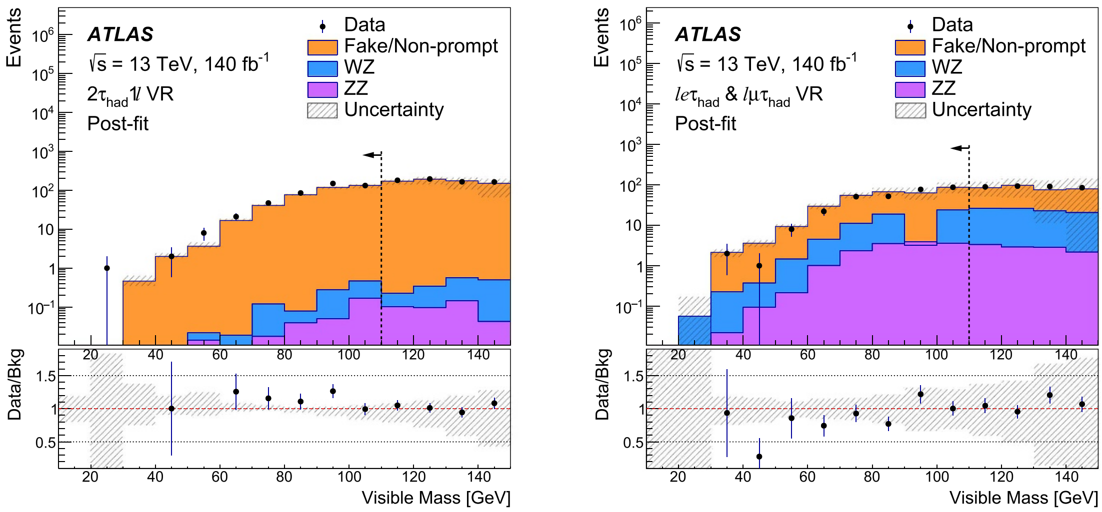


**Figure 1.** Post-fit visible mass, $m_{\mathrm{vis}}^{\text{3-body}}$, distribution in the $1\ell 2\tau_{\mathrm{had}}$ (left) and $\ell e\tau_{\mathrm{had}}/\ell\mu\tau_{\mathrm{had}}$ (right) validation regions. The data (points) are compared with the background prediction, with the post-fit total uncertainty shown as a hashed band. The vertical dashed line at $m_{\mathrm{vis}}^{\text{3-body}} = 110\,\mathrm{GeV}$ indicates the upper bound of the regions. The agreement between data and prediction in the high-mass sideband ($m_{\mathrm{vis}}^{\text{3-body}} > 110\,\mathrm{GeV}$) validates the modelling of the fake/non-prompt background.

**Table 1.** Total number of observed and expected events in the two signal regions after the background-only fit, where the signal strength is fixed at zero in the fit. The expected number of signal events is listed only for the $m_a = 45\,\mathrm{GeV}$ hypothesis assuming $\mathcal{B}(H \to aa \to 4\tau) = 10\%$ and the inclusive Higgs boson cross-section. The uncertainties include both statistical and systematic uncertainties.

| Process | $2\ell 2\tau_{\mathrm{had}}$ SR | $3\ell 1\tau_{\mathrm{had}}$ SR |
|---|---|---|
| Data | 0 | 31 |
| Total background | $0.12^{+0.17}_{-0.12}$ | $28.0 \pm 4.6$ |
| Fake/non-prompt | $0.12^{+0.17}_{-0.12}$ | $21.1 \pm 4.7$ |
| $WZ$ | $< 0.01$ | $0.11 \pm 0.02$ |
| $ZZ$ | $0.01 \pm 0.01$ | $6.7 \pm 0.7$ |
| $H \to aa \to 4\tau$ ($\mathcal{B} = 10\%$ $m_a = 45\,\mathrm{GeV}$) | $2.6 \pm 0.3$ | $20.5 \pm 2.4$ |

In the profile-likelihood fit, the $\ell e\tau_{\mathrm{had}}$ / $\ell\mu\tau_{\mathrm{had}}$ VRs are binned in the $p_{\mathrm{T}}$ and $|\eta|$ of the subleading electron (muon). The $1\ell 2\tau_{\mathrm{had}}$ VR is binned in the visible $p_{\mathrm{T}}$ and number of tracks of the subleading $\tau_{\mathrm{had}}$. The binning is exactly the same as the one used for the fake-factor parameterisation. The pre-fit difference between data and expectation, which is found to be approximately 10% across the VRs, is incorporated as an additional non-closure uncertainty. The post-fit values are used as a refined estimate of the fake factor values to be used when estimating the FNP background in the SRs. Figure 1 shows the post-fit comparison between data and expectation in VRs.

A statistical combination of the two SRs is performed. Signal hypotheses for $m_a$ ranging from 15 GeV to 60 GeV are tested against the background-only hypothesis by comparing the observed data to the expected background using a profile likelihood ratio test statistic [76] built from the product of Poisson densities in the two regions. Nuisance parameters and Gaussian constraint terms [76] are added to model systematic uncertainties. Systematic uncertainties related to the electron, muon, $\tau$-lepton, and jet energy scale and resolution, and the electron, muon and $\tau$-lepton efficiencies are included [37, 42, 47, 77]. Systematic uncertainties in the modelling of the prompt $ZZ$ and $WZ$ background are estimated by varying PDFs and renormalisation and factorisation scales [66]. The dominant systematic uncertainties in this search are associated with the modelling of the FNP background, in particular uncertainties from variations in the fake composition, with a magnitude of these uncertainties less than 10%.

Table 1 and figure 2 show the expected yields and uncertainties for the two SRs. In the $2\ell 2\tau_{\mathrm{had}}$ SR, zero data events are observed, while 31 data events are observed in the $3\ell 1\tau_{\mathrm{had}}$ SR. The total number of expected background events after the fit are $0.12^{+0.17}_{-0.12}$ and $28.0 \pm 4.6$. The numbers of expected signal events for a 10% of branching ratio range from 0.6 (10.8) to 4.3 (27.3) in the $2\ell 2\tau_{\mathrm{had}}(3\ell 1\tau_{\mathrm{had}})$ SR for $m_a$ from 15 to 60 GeV. The number of observed events in both SRs is consistent with the expected

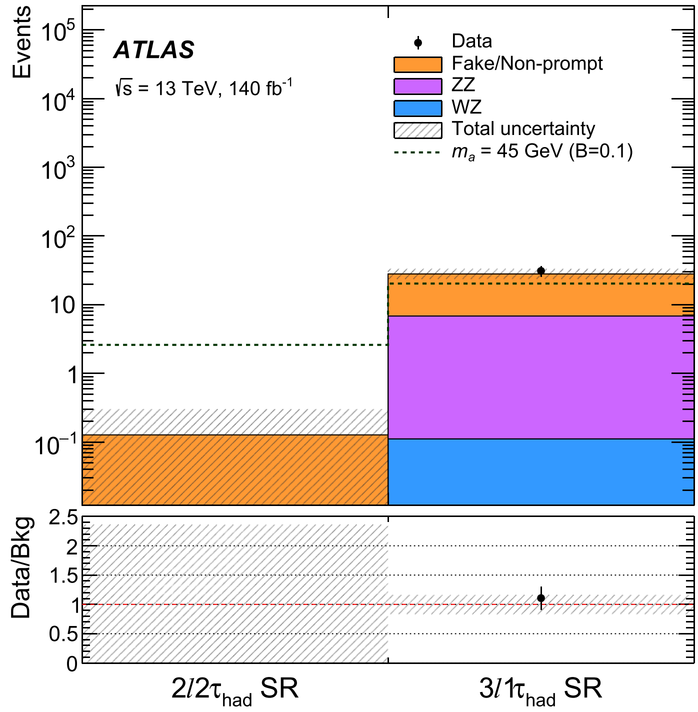


**Figure 2.** Post-fit yield in the $2\ell 2\tau_{\rm had}$ and $3\ell 1\tau_{\rm had}$ signal regions from the background-only fit. The data (points) are compared with the background prediction, with the background total uncertainty shown as a hashed band. No data events were observed in the $2\ell 2\tau_{\rm had}$ SR. The expected number of signal events is shown for the $m_a = 45\,\text{GeV}$ hypothesis assuming $\mathcal{B}(H \to aa \to 4\tau) = 10\%$ and the inclusive Higgs boson cross-section.

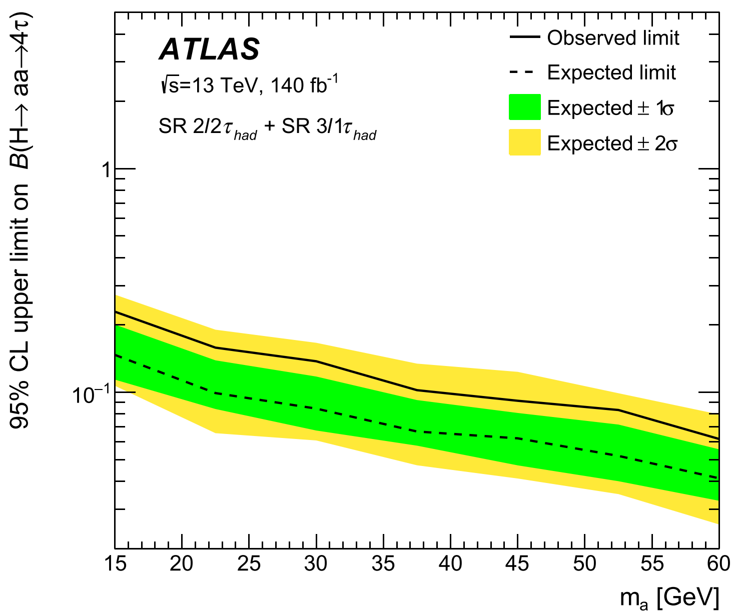


**Figure 3.** The expected and observed 95% CL upper limits on the branching ratio of $H \to aa \to \tau^+\tau^-\tau^+\tau^-$ in the mass range $15 < m_a < 60\,\text{GeV}$.

Standard Model background estimate. Since no significant excess above the Standard Model prediction is observed, upper limits are set on the branching fraction of the Higgs boson to $aa \to \tau^+\tau^-\tau^+\tau^-$. The limits are derived using the CLs method [78] with a modified test statistic $\tilde{q}_\mu$ [76] that is set to zero if the expected number of events is below the best fit value. The upper limits are determined by generating and evaluating multiple pseudo-experiments for each signal hypothesis. The observed (expected) 95% CL upper limit on the branching ratio $\mathcal{B}(H \to aa \to \tau^+\tau^-\tau^+\tau^-)$ varies from 0.23 (0.15) to 0.06 (0.04) in the mass range from $m_a = 15\,\text{GeV}$ to $m_a = 60\,\text{GeV}$, as depicted in figure 3. The range of the observed (expected) 95% CL upper limit on $\mathcal{B}(H \to aa \to \tau^+\tau^-\tau^+\tau^-)$ in the $2\ell 2\tau_{\text{had}}$ SR is 0.53–0.07 (0.54–0.07). In the $3\ell 1\tau_{\text{had}}$ SR, the corresponding observed (expected) limit is 0.26–0.10 (0.17–0.06).

This result constitutes the first search by the ATLAS Collaboration for the exotic Higgs boson decays $H \to aa \to \tau^+\tau^-\tau^+\tau^-$ in the mass range $15 < m_a < 60\,\text{GeV}$, complementing the low mass search in the mass range of $4 < m_a < 15\,\text{GeV}$ with the upper limit on $\mathcal{B}(H \to aa \to 4\tau)$ from 0.03 to 0.10 [19]. The sensitivity is largely limited by the statistical uncertainty of the data. The limits on $\mathcal{B}(H \to aa \to \tau^+\tau^-\tau^+\tau^-)$ are complementary to previous searches in different final states within type-III 2HDM+s models with large values of $\tan\beta$ in the mass range $15 < m_a < 60\,\text{GeV}$.

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## Data availability statement

The public release of data supporting the findings of this article will follow the CERN Open Data Policy [80]. Inquiries about plots and tables associated with this article can be addressed to atlas.publications@cern.ch. For code availability: The ATLAS Collaboration's Athena software, including the configuration of the event generators, is open source (http://gitlab.cern.ch/atlas/athena). The citation to CERN-OPEN-2020-013 (https://cds.cern.ch/record/2745133/export/hx?ln=en) [80]. The data that support the findings of this study are available upon reasonable request from the authors.

## The ATLAS Collaboration

G Aad[102], E Aakvaag[17], B Abbott[121], S Abdelhameed[83b], K Abeling[54], N J Abicht[48], S H Abidi[30], M Aboelela[44], A Aboulhorma[36e], H Abramowicz[154], B S Acharya[68a,68b,m], A Ackermann[62a], C Adam Bourdarios[4], L Adamczyk[85a], S V Addepalli[146], M J Addison[101], J Adelman[117], A Adiguzel[22c], T Adye[135], A A Affolder[137], Y Afik[39], M N Agaras[13], A Aggarwal[100], C Agheorghiesei[28c], A Ahmad[83a], F Ahmadov[38,ad], S Ahuja[95], S Ahuja[166], X Ai[113c], G Aielli[75a,75b], A Aikot[166], M Ait Tamlihat[36e], B Aitbenchikh[36a], T P A Åkesson[98], D Akiyama[171], N N Akolkar[25], S Aktas[169], G L Alberghi[24b], J Albert[168], U Alberti[20], P Albicocco[52], G L Albouy[59], S Alderweireldt[51], Z L Alegria[122], M Aleksa[37], I N Aleksandrov[38], C Alexa[28b], T Alexopoulos[10], F Alfonsi[24b], M Algren[55], M Alhroob[170], B Ali[133], H M J Ali[91,v], S Ali[32], S W Alibocus[92], M Aliev[34c], G Alimonti[70a], C Allaire[65], B M M Allbrooke[149], D R Allen[122], J S Allen[101], J F Allen[51], C S Alley[1], E R Almazan[137], A Aloisio[71a,71b], F Alonso[90], C Alpigiani[140], Z M K Alsolami[91], A Alvarez Fernandez[100], M Alves Cardoso[55], M G Alviggi[71a,71b], M Aly[101], Y Amaral Coutinho[81b], A Ambler[104], C Amelung[37], M Amerl[101], T Amezza[128], B Amini[53], K Amirie[158], A Amirkhanov[38], S P Amor Dos Santos[131a], D Amperiadou[155], S An[82], C Anastopoulos[142], T Andeen[11], J K Anders[92], A C Anderson[58], A Andreazza[70a,70b], S Angelidakis[9], A Angerami[41], A V Anisenkov[38], A Annovi[73a], C Antel[37], E Antipov[148], M Antonelli[52], F Anulli[74a], M Aoki[82], T Aoki[156], M A Aparo[13], L Aperio Bella[47], M Apicella[31], C Appelt[154], A Apyan[27], M Arampatzi[10], S J Arbiol Val[86], C Arcangeletti[52], A T H Arce[50], J-F Arguin[108], S Argyropoulos[155], J-H Arling[47], O Arnaez[4], H Arnold[148], G Artoni[74a,74b], H Asada[111], S Asatryan[176], N A Asbah[37], R A Ashby Pickering[170], A M Aslam[95], K 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Cueto[99], H Cui[96], Z Cui[7], B M Cunnett[149], W R Cunningham[58], E Cuppini[110], F Curcio[166], J R Curran[51], M J Da Cunha Sargedas De Sousa[56b,56a], J V Da Fonseca Pinto[81b], C Da Via[101], W Dabrowski[85a], T Dado[37], S Dahbi[151], T Dai[106], D Dal Santo[20], C Dallapiccola[103], M Dam[42], G D'amen[30], V D'Amico[109], J R Dandoy[35], M D'Andrea[56b,56a], D Dannheim[37], G D'anniballe[73a,73b], M Danninger[145], V Dao[148], G Darbo[56b], S J Das[30], F Dattola[47], S D'Auria[70a,70b], A D'Avanzo[71a,71b], T Davidek[134], J Davidson[170], I Dawson[94], K De[8], C De Almeida Rossi[158], R De Asmundis[71a], N De Biase[47], S De Castro[24b,24a], N De Groot[115], P de Jong[116], H De la Torre[117], A De Maria[112a], S De Miranda Rimes[81d], A De Salvo[74a], U De Sanctis[75a,75b], F De Santis[69a,69b], A De Santo[149], J B De Vivie De Regie[59], J Debevc[93], D V Dedovich[38], J Degens[92], A M Deiana[44], J Del Peso[99], L Delagrange[27], F Deliot[136], C M Delitzsch[48], M Della Pietra[71a,71b], D Della Volpe[55], A Dell'Acqua[37], L Dell'Asta[70a,70b], M Delmastro[4], C C Delogu[56b,56a], P A Delsart[59], S Demers[175], M Demichev[38], H Denizli[22a,l], M G Depala[92], L D'Eramo[40], D Derendarz[86], L Derin[56b,56a], F Derue[128], P Dervan[92,*], A M Desai[1], K Desch[25], F A Di Bello[73a,73b], A Di Ciaccio[75a,75b], L Di Ciaccio[4], D Di Croce[37], C Di Donato[71a,71b], A Di Girolamo[37], G Di Gregorio[65], A Di Luca[77a,77b], B Di Micco[76a,76b], R Di Nardo[76a,76b], K F Di Petrillo[39], M Diamantopoulou[35], F A Dias[116], M A Diaz[138a,138b], A R Didenko[38], M Didenko[166], S D Diefenbacher[18a], E B Diehl[106], S Díez Cornell[47], C Diez Pardos[144], C Dimitriadi[147], A Dimitrievska[21], A Dimri[148], Y Ding[61], J Dingfelder[25], T Dingley[127], I-M Dinu[28b], S J Dittmeier[62b], F Dittus[37], M Divisek[134], B Dixit[92], F Djama[102], T Djobava[152b], C Doglioni[101,98], A Dohnalova[29a], Z Dolezal[134], K Domijan[85a], K M Dona[39], M 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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 Verbytskyi[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,aj], A Vgenopoulos[100], N Viaux Maira[138g,af], T Vickey[142], O E Vickey Boeriu[142], G H A Viehhauser[127], L Vigani[62b], M Vigl[110], M Villa[24b,24a], M Villaplana Perez[166], E M Villhauer[39], E Vilucchi[52], M Vincent[166], 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[166], K Voss[144], M Vozak[37], L 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A R Weidberg[127], E J Weik[118], J Weingarten[48], C Weiser[53], C J Wells[47], T Wenaus[30], T Wengler[37], N S Wenke[110], N Wermes[25], M Wessels[62a], A M Wharton[91], A S White[37], A White[8], M J White[1], D Whiteson[162], L Wickremasinghe[125], W Wiedenmann[173], M Wielers[135], R Wierda[147], C Wiglesworth[42], H G Wilkens[37], J J H Wilkinson[33], S Williams[33], S Willocq[103], D J Wilson[101], P J Windischhofer[39], F I Winkel[31], F Winklmeier[124], B T Winter[53], M Wittgen[146], M Wobisch[97], T Wojtkowski[59], Z Wolffs[116], J Wollrath[37], M W Wolter[86], H Wolters[131a,131c], M C Wong[137], E L Woodward[41], S D Worm[47], B K Wosiek[86], K A Wozniak[55], K W Woźniak[86], S Wozniewski[54], K Wraight[58], C Wu[158], C Wu[21], J Wu[156], M Wu[112b], M Wu[115], S L Wu[173], S Wu[14,an], X Wu[61], Y Q Wu[158], Y Wu[61], Z Wu[102], Z Wu[112a], J Wuerzinger[110], T R Wyatt[101], B M Wynne[51], S Xella[42], L Xia[112a], M Xie[61], A Xiong[124], I Xiotidis[37], D Xu[14], H Xu[61], L Xu[61], R Xu[129], T Xu[106], W Xu[112a], Y Xu[140], Z Xu[51], R Xue[130], B Yabsley[150], S Yacoob[11], Y Yamaguchi[82], E Yamashita[156], H Yamauchi[160], T Yamazaki[18a], Y Yamazaki[84], S Yan[58], Z Yan[103], H J Yang[141a], H T Yang[61], S Yang[61], X Yang[37], X Yang[14], Y Yang[156], Y Yang[61], W-M Yao[18a], C L Yardley[149], J Ye[14], S Ye[30], X Ye[61], Y Yeh[96], I Yeletskikh[38], B Yeo[18b], M R Yexley[96], T P Yildirim[127], K Yorita[171], C J S Young[37], C Young[146], I N L Young[58], N D Young[124], Y Yu[61], J Yuan[14,112c,an], M Yuan[106], R Yuan[141b], L Yue[96], M Zaazoua[61], B Zabinski[86], I Zahir[36a], A Zaio[56b,56a], Z K Zak[86], T Zakareishvili[166], S Zambito[55], J Zang[156], R Zanzottera[70a,70b], O Zaplatilek[133], E Zaya[147], C Zeitnitz[174], H Zeng[14], D T Zenger Jr[27], T Ženiš[29a], S Zenz[94], D Zerwas[65], B Zhang[170], D F Zhang[142], G Zhang[14,an], J Zhang[113b], J Zhang[6], L Zhang[61], L Zhang[112a], P Zhang[14,112c], R Zhang[112a], S Zhang[89], Y Zhang[140], Y Zhang[96], Y Zhang[61], Y Zhang[112a], Z Zhang[18a], Z Zhang[113b], Z Zhang[65], H Zhao[140], T Zhao[113b], Y Zhao[35], Z Zhao[61], Z Zhao[61], A Zhemchugov[38], J Zheng[112a], K Zheng[165], L Zheng[113b], X Zheng[61], Z Zheng[146], D Zhong[165], B Zhou[106], B Zhou[141b,141a], H Zhou[7], N Zhou[141a], Y Zhou[15], Y Zhou[112a], Y Zhou[7], J Zhu[106], X Zhu[141b], Y Zhu[141a], X Zhuang[14], K Zhukov[67], N I Zimine[38], J Zinsser[62b], M Ziolkowski[144], L Živković[16], A Zoccoli[24b,24a], K Zoch[60], A Zografos[37], T G Zorbas[142], L Zwalinski[37]

[1]Department of Physics, University of Adelaide, Adelaide, Australia
[2]Department of Physics, University of Alberta, Edmonton AB, Canada
[3(a)]Department of Physics, Ankara University, Ankara, Türkiye;[(b)]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, United States of America
[7]Department of Physics, University of Arizona, Tucson AZ, United States of America
[8]Department of Physics, University of Texas at Arlington, Arlington TX, United States of America
[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, United States of America
[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
[18(a)]Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA, United States of America;[(b)]University of California, Berkeley CA, United States of America
[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, United Kingdom
[22(a)]Department of Physics, Bogazici University, Istanbul, Türkiye;[(b)]Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye;[(c)]Department of Physics, Istanbul University, Istanbul; Türkiye
[23(a)]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia;[(b)]Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
[24(a)]Dipartimento di Fisica e Astronomia A. Righi, Universitá di Bologna, Bologna;[(b)]INFN Sezione di Bologna, Italy
[25]Physikalisches Institut, Universität Bonn, Bonn, Germany
[26]Department of Physics, Boston University, Boston MA, United States of America
[27]Department of Physics, Brandeis University, Waltham MA, United States of America
[28(a)]Transilvania University of Brasov, Brasov, Romania;[(b)]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania;[(c)]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania;[(d)]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania;[(e)]National University of Science and Technology Politechnica, Bucharest, Romania;[(f)]West University in Timisoara, Timisoara, Romania;[(g)]Faculty of Physics, University of Bucharest, Bucharest, Romania
[29(a)]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic;[(b)]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, United States of America
[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, United States of America
[33]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[34(a)]Department of Physics, University of Cape Town, Cape Town, South Africa;[(b)]iThemba Labs, Western Cape, South Africa;[(c)]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa;[(d)]National Institute of Physics, University of the Philippines Diliman (Philippines), South Africa;[(e)]Department of Physics, Stellenbosch University, Matieland, South Africa;[(f)]University of KwaZulu-Natal, School of Agriculture and Science, Mathematics, Westville, South

Africa;[(g)]University of South Africa, Department of Physics, Pretoria, South Africa;[(h)]University of Pretoria, Department of Mechanical and Aeronautical Engineering, Pretoria, South Africa;[(i)]University of Zululand, KwaDlangezwa, South Africa;[(j)]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[35]Department of Physics, Carleton University, Ottawa ON, Canada
[36(a)]Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Morocco;[(b)]Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco;[(c)]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco;[(d)]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco;[(e)]Faculté des sciences, Université Mohammed V, Rabat, Morocco;[(f)]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, United States of America
[40]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
[41]Nevis Laboratory, Columbia University, Irvington NY, United States of America
[42]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[43(a)]Dipartimento di Fisica, Università della Calabria, Rende, Italy;[(b)]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
[44]Physics Department, Southern Methodist University, Dallas TX, United States of America
[45]National Centre for Scientific Research 'Demokritos', Agia Paraskevi, Greece
[46(a)]Department of Physics, Stockholm University, Sweden;[(b)]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, United States of America
[51]SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[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
[56(a)]Dipartimento di Fisica, Università di Genova, Genova, Italy;[(b)]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, United Kingdom
[59]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
[60]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
[61]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[62(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany;[(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[63(a)]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China;[(b)]Department of Physics, University of Hong Kong, Hong Kong, China;[(c)]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, United States of America
[68(a)]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy[(b)]ICTP, Trieste, Italy;[(c)]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
[69(a)]INFN Sezione di Lecce, Italy;[(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[70(a)]INFN Sezione di Milano, Italy;[(b)]Dipartimento di Fisica, Università di Milano, Milano, Italy
[71(a)]INFN Sezione di Napoli, Italy;[(b)]Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[72(a)]INFN Sezione di Pavia, Italy;[(b)]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[73(a)]INFN Sezione di Pisa, Italy;[(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[74(a)]INFN Sezione di Roma, Italy;[(b)]Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
[75(a)]INFN Sezione di Roma Tor Vergata, Italy;[(b)]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy

[76(a)]INFN Sezione di Roma Tre, Roma, Italy;[(b)]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
[77(a)]INFN-TIFPA, Italy;[(b)]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, United States of America
[80]Istinye University, Sariyer, Istanbul, Türkiye
[81(a)]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil;[(b)]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil;[(c)]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil;[(d)]Rio de Janeiro State University, Rio de Janeiro, Brazil;[(e)]Federal University of Bahia, Bahia, Brazil
[82]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[83(a)]Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates;[(b)]New York University Abu Dhabi, Abu Dhabi, United Arab Emirates;[(c)]United Arab Emirates University, Al Ain, United Arab Emirates;[(d)]University of Sharjah, Sharjah, United Arab Emirates
[84]Graduate School of Science, Kobe University, Kobe, Japan
[85(a)]AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland;[(b)]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, United Kingdom
[92]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[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, United Kingdom
[95]Department of Physics, Royal Holloway University of London, Egham, United Kingdom
[96]Department of Physics and Astronomy, University College London, London, United Kingdom
[97]Louisiana Tech University, Ruston LA, United States of America
[98]Fysiska institutionen, Lunds universitet, Lund, Sweden
[99]Departamento de Física Teorica 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, United Kingdom
[102]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[103]Department of Physics, University of Massachusetts, Amherst MA, United States of America
[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, United States of America
[107]Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[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
[112(a)]Department of Physics, Nanjing University, Nanjing, China;[(b)]School of Science, Shenzhen Campus of Sun Yat-sen University, China;[(c)]University of Chinese Academy of Science (UCAS), Beijing, China
[113(a)]School of Physics, Nankai University, Tianjin, China;[(b)]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China;[(c)]School of Physics, Zhengzhou University, China
[114]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
[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, United States of America
[118]Department of Physics, New York University, New York NY, United States of America

[119]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
[120]Ohio State University, Columbus OH, United States of America
[121]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
[122]Department of Physics, Oklahoma State University, Stillwater OK, United States of America
[123]Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
[124]Institute for Fundamental Science, University of Oregon, Eugene, OR, United States of America
[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, United Kingdom
[128]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
[129]Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
[130]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
[131][(a)]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal;[(b)]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal;[(c)]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal;[(d)]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal;[(e)]Departamento de Física, Escola de Ciências, Universidade do Minho, Braga, Portugal;[(f)]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Portugal;[(g)]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, United Kingdom
[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, United States of America
[138][(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile;[(b)]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile;[(c)]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile;[(d)]Universidad Andres Bello, Department of Physics, Santiago, Chile;[(e)]Universidad San Sebastian, Recoleta, Chile;[(f)]Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile;[(g)]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, United States of America
[141][(a)]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;[(b)]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, United Kingdom
[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, United States of America
[147]Department of Physics, Royal Institute of Technology, Stockholm, Sweden
[148]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
[149]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150]School of Physics, University of Sydney, Sydney, Australia
[151]Institute of Physics, Academia Sinica, Taipei, Taiwan
[152][(a)]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia;[(b)]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia;[(c)]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
[159(a)]TRIUMF, Vancouver BC;[(b)]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, United States of America
[162]Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
[163]University of West Attica, Athens, Greece
[164]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[165]Department of Physics, University of Illinois, Urbana IL, United States of America
[166]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
[167]Department of Physics, University of British Columbia, Vancouver BC, Canada
[168]Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[169]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
[170]Department of Physics, University of Warwick, Coventry, United Kingdom
[171]Waseda University, Tokyo, Japan
[172]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
[173]Department of Physics, University of Wisconsin, Madison WI, United States of America
[174]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[175]Department of Physics, Yale University, New Haven CT, United States of America
[176]Yerevan Physics Institute, Yerevan, Armenia
[a] Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN
[b] Also at An-Najah National University, Nablus, Palestine
[c] Also at Borough of Manhattan Community College, City University of New York, New York NY, United States of America
[d] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece
[e] Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP), Portugal
[f] Also at CERN, Geneva, Switzerland
[g] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[h] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain
[i] Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
[j] Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[k] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel
[l] Also at Department of Physics, Bolu Abant Izzet Baysal University, Bolu, Türkiye
[m] Also at Department of Physics, King's College London, London, United Kingdom
[n] Also at Department of Physics, Stellenbosch University, South Africa
[o] Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
[p] Also at Department of Physics, University of Thessaly, Greece
[q] Also at Department of Physics, Westmont College, Santa Barbara, United States of America
[r] Also at Faculty of Physics, Sofia University,'St. Kliment Ohridski', Sofia, Bulgaria
[s] Also at Faculty of Physics, University of Bucharest, Romania
[t] Also at Hellenic Open University, Patras, Greece
[u] Also at Henan University, China
[v] Also at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia
[w] Also at Indian Institute of Technology (IIT), Jodhpur, India
[x] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
[y] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
[z] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
[aa] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco
[ab] Also at Institute of Particle Physics (IPP), Canada
[ac] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia
[ad] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[ae] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia

[af] Also at Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile
[ag] Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines
[ah] Also at School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[ai] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
[aj] Also at TRIUMF, Vancouver BC, Canada
[ak] Also at Università di Napoli Parthenope, Napoli, Italy
[al] Also at Universita degli Studi Link, Italy
[am] Also at University and INFN Torino, Torino, Italy
[an] Also at University of Chinese Academy of Sciences (UCAS), Beijing, China
[ao] Also at University of Colorado Boulder, Department of Physics, Colorado, United States of America
[ap] Also at University of Siena, Italy
[aq] Also at Washington College, Chestertown, MD, United States of America
[ar] Also at Yeditepe University, Physics Department, Istanbul, Türkiye
* Deceased

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