

Measurement of the Lund Jet Plane Using Charged Particles in 13 TeV Proton-Proton Collisions with the ATLAS Detector

G. Aad *et al.**
(ATLAS Collaboration)

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The prevalence of hadronic jets at the LHC requires that a deep understanding of jet formation and structure is achieved in order to reach the highest levels of experimental and theoretical precision. There have been many measurements of jet substructure at the LHC and previous colliders, but the targeted observables mix physical effects from various origins. Based on a recent proposal to factorize physical effects, this Letter presents a double-differential cross-section measurement of the Lund jet plane using 139 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton-proton collision data collected with the ATLAS detector using jets with transverse momentum above 675 GeV. The measurement uses charged particles to achieve a fine angular resolution and is corrected for acceptance and detector effects. Several parton shower Monte Carlo models are compared with the data. No single model is found to be in agreement with the measured data across the entire plane.

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Jets are collimated sprays of particles resulting from high-energy quark and gluon production. The details of the process that underlies the fragmentation of quarks and gluons with quantum chromodynamic (QCD) charge into neutral hadrons is not fully understood. In the soft gluon (“eikonal”) picture of jet formation, a quark or gluon radiates a haze of relatively low energy and statistically independent gluons [1,2]. As QCD is nearly scale invariant, this emission pattern is approximately uniform in the two-dimensional space spanned by $\ln(1/z)$ and $\ln(1/\theta)$, where z is the momentum fraction of the emitted gluon relative to the primary quark or gluon core and θ is the emission opening angle. This space is called the Lund plane [3]. The Lund plane probability density can be extended to higher orders in QCD and is the basis for many calculations of jet substructure observables [4–7].

The Lund plane is a powerful representation for providing insight into jet substructure; however, the plane is not observable because it is built from quarks and gluons. A recent proposal [8] describes a method to construct an observable analog of the Lund plane using jets, which captures the salient features of this representation. Jets are formed using clustering algorithms that sequentially combine pairs of protojets starting from the initial set of constituents [9]. Following the proposal, a jet’s constituents

are reclustered using the Cambridge/Aachen (C/A) algorithm [10,11], which imposes an angle-ordered hierarchy on the clustering history. Then, the C/A history is followed in reverse (“declustered”), starting from the hardest protojet. The Lund plane can be approximated by using the softer (harder) protojet to represent the emission (core) in the original theoretical depiction. For each proto-jet pair, at each step in the C/A declustering sequence, an entry is made in the approximate Lund plane (henceforth, the “primary Lund jet plane” or LJP) using the observables $\ln(1/z)$ and $\ln(R/\Delta R)$, with

$$z = \frac{p_T^{\text{emission}}}{p_T^{\text{emission}} + p_T^{\text{core}}} \quad \text{and} \\ \Delta R^2 = (y_{\text{emission}} - y_{\text{core}})^2 + (\phi_{\text{emission}} - \phi_{\text{core}})^2,$$

where p_T is transverse momentum [12], y is rapidity, R is the jet radius parameter, and ΔR measures the angular separation. Using this approach, individual jets are represented as a set of points within the LJP. Ensembles of jets may be studied by measuring the double-differential cross section in this space. The substructure of emissions, which may themselves be composite objects, is not considered in this analysis. To leading-logarithm (LL) accuracy, the average density of emissions within the LJP is uniform [8]:

$$\frac{1}{N_{\text{jets}}} \frac{d^2 N_{\text{emissions}}}{d \ln(1/z) d \ln(R/\Delta R)} \propto \text{constant}, \quad (1)$$

where N_{jets} is the number of jets. This construction of the plane is selected to separate momentum and angular

*Full author list given at the end of the article.

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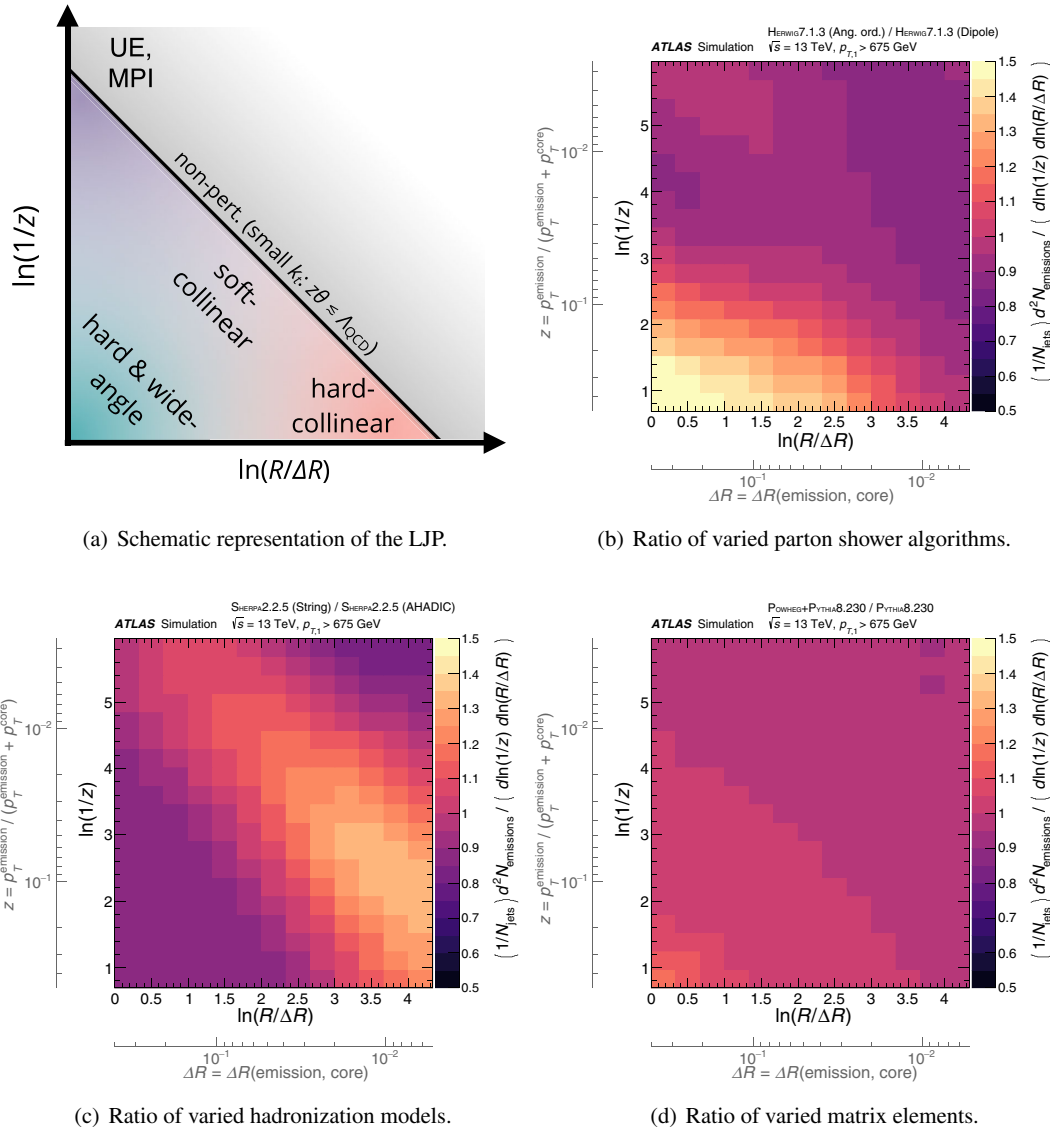


FIG. 1. (a) Schematic representation of the LJP. The line $z\theta \lesssim \Lambda_{\text{QCD}}$ roughly indicates the transition between regions where either perturbative ($z\theta > \Lambda_{\text{QCD}}$) or nonperturbative ($z\theta < \Lambda_{\text{QCD}}$) effects are expected to dominate. “UE/MPI” denotes the region where sources of nearly uniform radiation are relevant. (b) The ratio of the Lund jet plane as simulated by the HERWIG7.1.3 MC generator with either an angle-ordered parton shower or a dipole parton shower. (c) The ratio of the Lund jet plane as simulated by the SHERPA2.2.5 MC generator with either the AHADIC cluster-based or Lund string-based hadronization algorithm. (d) The ratio of the LJP as simulated by either the POWHEG+PYTHIA8.230 or PYTHIA8.230 MC generators. The inner set of axes indicate the coordinates of the LJP itself, while the outer set indicate corresponding values of z and ΔR .

measurements, although other choices such as $[\ln(R/\Delta R), k_t = z\Delta R]$ are valid.

The Lund plane has played a central role in state-of-the-art QCD calculations of jet substructure [13–18] which have so far only been studied with the jet mass m_{jet} [19,20] (which is itself a diagonal line in the LJP: $\ln 1/z \sim \ln m_{\text{jet}}^2/p_T^2 - 2 \ln R/\Delta R$) and groomed jet radius [21,22]. The number of emissions within regions of the LJP is also calculable and provides optimal discrimination between quark and gluon jets [5].

This Letter presents a double-differential cross-section measurement of the LJP, corrected for detector effects, using an integrated luminosity of 139 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton-proton (pp) collision data collected by the ATLAS detector. A unique feature of this measurement is that contributions from various QCD effects such as initial-state radiation, the underlying event and multiparton interactions, hadronization, and perturbative emissions are well localized in the LJP. This factorization is shown in Fig. 1(a), which qualitatively indicates the regions

populated by soft vs hard, wide-angle vs collinear, and perturbative vs nonperturbative radiation. Since different regions are dominated by factorized processes, the LJP measurement can be useful for tuning non-perturbative models and for constraining the model parameters of advanced parton shower (PS) Monte Carlo (MC) programs [23–26].

The ATLAS detector [27–29] is a general-purpose particle detector which provides nearly 4π coverage in solid angle. The inner tracking detector (ID) is inside a 2 T magnetic field and measures charged-particle trajectories up to $|\eta| = 2.5$. The innermost component of the ID is a pixelated silicon detector with fine granularity that is able to resolve ambiguities inside the dense hit environment of jet cores [30], surrounded by silicon strip and transition radiation detectors. Beyond the ID are electromagnetic and hadronic calorimeters, from which topologically connected clusters of cells [31] are formed into jets using the anti- k_t algorithm with radius parameter $R = 0.4$ [32,33]. The jet energy scale is calibrated so that, on average, the detector-level jet energy is the same as that of the corresponding particle-level jets [34].

Events are selected using single-jet triggers [35,36]. The leading and subleading jets are used for the measurement and are required to satisfy $p_T^{\text{leading}} > 675$ GeV and $p_T^{\text{leading}} < 1.5 \times p_T^{\text{subleading}}$. This jet- p_T balance simplifies the interpretation of the final state in terms of a $2 \rightarrow 2$ scattering process. Both jets must be within the ID acceptance ($|\eta| < 2.1$). About 29.5 million jets satisfy these selection criteria.

Particle-level charged hadrons and their reconstructed tracks are used for this measurement because individual particle trajectories can be precisely identified with the ID. As the LJP observables are dimensionless and isospin is an approximate symmetry of the strong force, the difference between the LJP observables constructed using all interacting particles and charged particles is small [21]. Tracks are required to have $p_T > 500$ MeV and be associated with the primary vertex with the largest sum of track p_T^2 in the event [37]. Tracks within $\Delta R = 0.4$ of the cores of selected jets are used to construct the LJP observables by clustering them using the C/A algorithm and populating the plane by iterative declustering. The fiducial region of the measurement spans 19 bins in $\ln(1/z)$ between $\ln(1/0.5)$ and $8.4 \times \ln(1/0.5)$, and 13 bins in $\ln(R/\Delta R)$ between 0.0 and 4.33. The maximum ΔR is the jet radius and the minimum ΔR is comparable to the pixel pitch. The maximum z is 0.5 and the minimum is $500 \text{ MeV}/p_T^{\text{jet}}$.

Samples of dijet events were simulated in order to perform the unfolding and compare with the corrected data. The nominal sample was simulated using PYTHIA8.186 [38,39] with the NNPDF2.3 LO [40] set of parton distribution functions (PDF), a p_T -ordered PS, Lund string hadronization [41,42], and the A14 set of tuned parameters

(tune) [43]. Additional samples were simulated by PYTHIA8.230 [44] with the NNPDF2.3 LO PDF set and the A14 tune, using either the PYTHIA LO matrix elements (MEs) or NLO MEs from POWHEG [45–48]; SHERPA2.1.1 [49] with the CT10LO PDF set, a p_T -ordered PS [50], an ME with up to three partons (merged with the CKKW prescription [51]) and the AHADIC (A HADronization model In C++) cluster-based hadronization model [52,53]; SHERPA2.2.5 with the CT14NNLO PDF set [54] including $2 \rightarrow 2$ MEs and either the AHADIC hadronization model or the Lund string model; and HERWIG7.1.3 [26,55,56] with the MMHT2014NLO PDF set [57] and either the default angle-ordered (Ang. ord.) PS or a dipole PS and cluster hadronization [52]. Further details of these samples may be found in Ref. [58]. The PYTHIA8.186 and SHERPA2.1.1 events were passed through the ATLAS detector simulation [59] based on GEANT4 [60]. The effect of multiple pp interactions in the same and neighboring bunch crossings (pileup) was modeled by overlaying the hard-scatter event with minimum-bias pp collisions generated by PYTHIA8 with the A3 tune [61] and the NNPDF2.3 LO PDF set. The distribution of pileup vertices was reweighted to match data, which have an average of 33.7 simultaneous interactions per bunch crossing.

Figures 1(b)–1(d) illustrate the kinematic domains of various physical effects in the LJP using ratios at charged-particle level between pairs of MC simulations where one component of the simulation is varied. Varying the PS model in HERWIG7.1.3 [Fig. 1(b)] results in differences of up to 50% in the perturbative hard and wide-angle emissions entering the lower-left region of the LJP. Changing the hadronization model in SHERPA2.1.1 [Fig. 1(c)] causes variations up to 50% in a different region of the plane, populated by softer and more collinear emissions at the boundary between perturbative and nonperturbative regions. Varying the ME from LO (PYTHIA8.230) to NLO (POWHEG+PYTHIA8.230) [Fig. 1(d)] causes small changes of up to 10% in the region populated by the hardest and widest-angle emissions.

Selected data are unfolded to correct for detector bias, resolution, and acceptance effects by applying iterative Bayesian unfolding [62] with four iterations implemented in RooUnfold [63]. The MC generator used to unfold the data is PYTHIA8.186. The number of iterations was chosen to minimize the total uncertainty. The unfolding procedure corrects the LJP constructed from detector-level objects to charged-particle level, where jets and charged particles are defined similarly to those at detector level: jets are reconstructed using the same anti- k_t algorithm with detector-level stable ($c\tau > 10$ mm) nonpileup particles, excluding muons and neutrinos, as inputs. The same kinematic requirements as for detector-level jets are imposed on these jets; charged particles with $p_T > 500$ MeV within $\Delta R = 0.4$ of the cores of particle-level jets are used to populate the charged-particle-level LJP.

Emissions at detector level and charged-particle level are uniquely matched in η - ϕ to construct the response matrix. The matching procedure follows the order of the C/A declustering, starting from the widest-angle detector-level emission and iterating towards the jet core. The closest charged-particle-level match with angular separation $\Delta R < 0.1$ takes precedence. Unmatched emissions from tracks not due to a single charged particle (detector level) and from nonreconstructed charged particles (charged-particle level) are accounted for with purity and efficiency corrections. Corrections are applied before (purity) and after (efficiency) the regularized inversion of the response matrix. Both the purity and efficiency corrections are about 20% for wide-angle, hard emissions (lower-left quadrant of the LJP), increasing to 80% for the most collinear splittings and 50% in the lowest- z bins. For matched emissions, the $\ln(1/z)$ and $\ln(R/\Delta R)$ bin migrations between particle and detector levels are largely independent. Furthermore, since the differential cross section varies slowly across the LJP, the purities and efficiencies are approximately the same across the entire LJP. The $\ln(R/\Delta R)$ migrations in a given $\ln(1/z)$ bin are less than 60% for the smallest opening angles and decrease to less than 40% for the widest angles. The $\ln(1/z)$ migrations decrease from about 50% for the softest to about 20% for the hardest emissions, with some degradation for the softest emissions at small opening angles. Migrations for both observables are nearly symmetric except for $\ln(R/\Delta R) > 3$, where harder-to-resolve small opening angles are measured with asymmetric resolution. In less than 10% of these cases, particle-level and detector-level emissions are mismatched and therefore measured with the wrong $\ln(1/z)$. While the $\ln(R/\Delta R)$ migrations are nearly the same when $\ln(1/z)$ migrates by one bin, the $\ln(1/z)$ migrations increase by about 30% when $\ln(R/\Delta R)$ migrates by one bin.

The unfolded distribution is normalized to the number of jets that pass the event selection, rendering the measurement insensitive to the total jet cross section. After normalization, the integral of the LJP is the average number of emissions within the fiducial region.

Experimental systematic uncertainties are evaluated by applying variations to each source, propagating them through the unfolding procedure, and taking the difference between the modified and nominal results. Theoretical uncertainties arise from jet fragmentation modeling. Different systematic uncertainties are treated as being independent. The size of various sources of uncertainty within selected regions of the LJP is displayed in Fig. 3.

Uncertainties in the jet energy are determined using a mixture of simulation-based and *in situ* techniques [34]. These uncertainties cause the migration of jets into or out of the fiducial acceptance, and are typically above 3% in total, reaching at most 7%. Uncertainties related to the reconstruction of isolated tracks and tracks within dense environments are considered by modifying the measured p_T

of individual tracks or removing them completely [30,64]. These uncertainties are small, contributing less than 0.5%. Other experimental uncertainties related to the modeling of pileup and the stability of the measurement across data-taking periods are less than 1% except for the most collinear splittings, where they reach 5%. A data-driven nonclosure uncertainty is determined by unfolding the detector-level distribution following a reweighting based on a comparison of the corresponding simulated detector-level distribution with the data [65]. This uncertainty is less than 1% except for the most collinear splittings, where it approaches 5%. An uncertainty for the matching procedure between emissions at detector and charged-particle levels is determined by repeating the unfolding and iterating through the C/A declustering sequence in reverse (from collinear to wide-angle emissions), taking the change in the result as an uncertainty. This uncertainty is less than 1% everywhere.

Theoretical uncertainties arise mainly from the accuracy of jet fragmentation modeling. Variations in jet fragmentation can impact the result through a combination of sources: efficiency or purity corrections, response matrix, and unfolding prior. These contributions are estimated by repeating the unfolding with SHERPA2.2.1. As the correlation between the uncertainty sources is unknown, an envelope of the 100% and 0% correlation hypotheses is taken as the total modeling uncertainty. This uncertainty ranges between 5% and 20% depending on the region (larger for soft-collinear splittings) and is the largest single source of uncertainty. Experimental uncertainties are found to be comparable to those arising from modeling in some regions of the LJP.

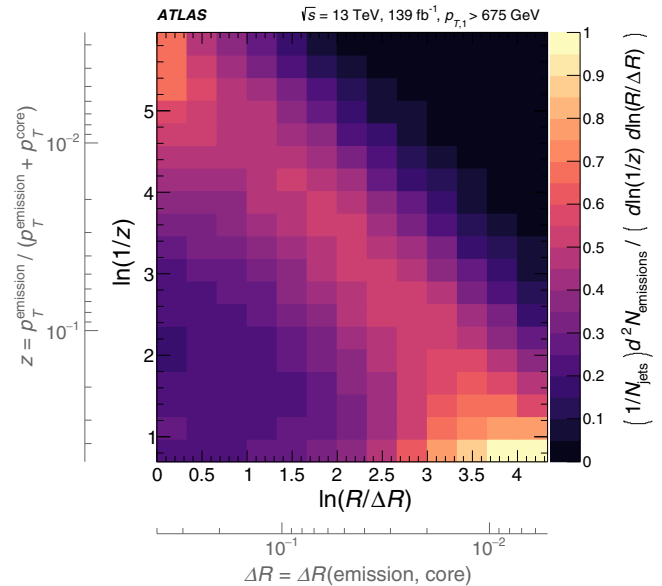


FIG. 2. The LJP measured using jets in 13 TeV pp collision data, corrected to particle level. The inner set of axes indicates the coordinates of the LJP itself, while the outer set indicates corresponding values of z and ΔR .

The total systematic uncertainty varies across the LJP; an uncertainty between 5% and 20% is achieved. The uncertainty is found to increase as $k_t = z\Delta R$ decreases: the bin with the smallest k_t is also measured least precisely, and has a total uncertainty of about 20%.

The unfolded LJP is shown in Fig. 2. A triangular region with $k_t \gtrsim \Lambda_{\text{QCD}}$ is populated nearly uniformly by perturbative emissions, agreeing with the LL expectation [Eq. (1)].

A large number of emissions are found at the transition to the nonperturbative regime, as α_s is enhanced for small values of k_t . Emissions beyond the transition fall within the nonperturbative region of the LJP ($k_t \lesssim \Lambda_{\text{QCD}}$), and are suppressed. The average number of emissions in the fiducial region is measured to be $7.34 \pm 0.03(\text{syst}) \pm 0.11(\text{stat})$. The uncertainty is estimated by propagating uncertainties from the measurement in an uncorrelated and symmetrized

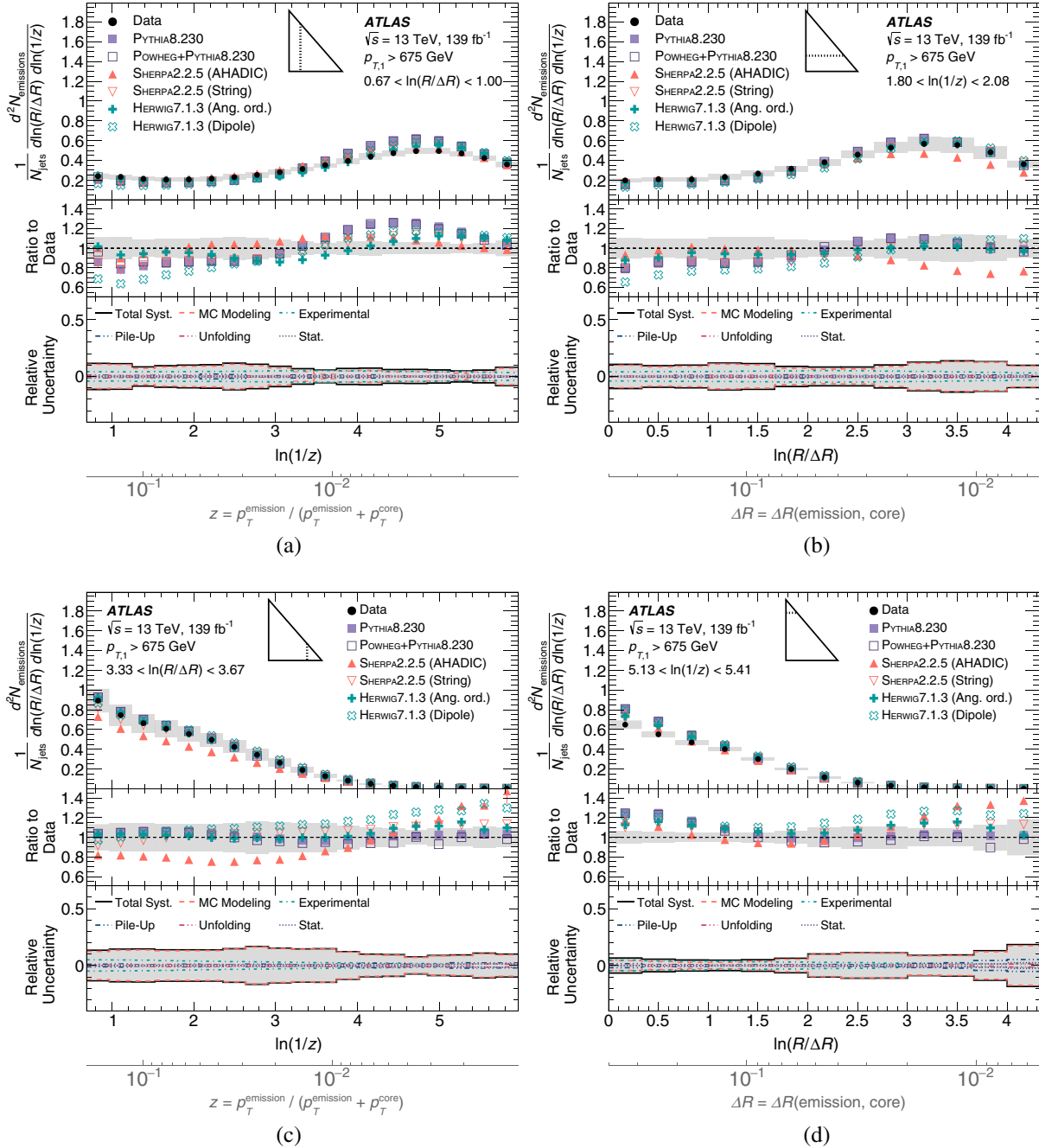


FIG. 3. Representative horizontal and vertical slices through the LJP. Unfolded data are compared with particle-level simulation from several MC generators. The uncertainty band includes all sources of systematic and statistical uncertainty. The inset triangle illustrates which slice of the plane is depicted: (a) $0.67 < \ln(R/\Delta R) < 1.00$, (b) $1.80 < \ln(1/z) < 2.08$, (c) $3.33 < \ln(R/\Delta R) < 3.67$, and (d) $5.13 < \ln(1/z) < 5.41$.

manner. The corresponding average emissions for PYTHIA8.230 is 7.64 and 7.67 for POWHEG+PYTHIA8.230. The average value for SHERPA2.2.5 is 6.90 for AHADIC hadronization and 7.30 for Lund string hadronization. The average value for HERWIG7 is 7.41 for the dipole PS and 7.37 for the angle-ordered PS. While a similar bracketing of the data by PYTHIA and SHERPA with AHADIC hadronization was noted in Ref. [66], the particle multiplicity inside jets has not previously been decomposed into perturbative and non-perturbative components.

Figure 3 shows data from four selected horizontal and vertical slices through the LJP, along with a breakdown of the systematic uncertainties [67]. The data are compared with predictions from several MC generators. While no prediction describes the data accurately in all regions, the HERWIG7.1.3 angle-ordered prediction provides the best description across most of the plane. The differences between the PS algorithms implemented in HERWIG7.1.3 are notable at large values of $k_t = z\Delta R$, where the two models disagree most significantly for hard emissions reconstructed at the widest angles [Fig. 3(a) and 3(b)]. The POWHEG+PYTHIA and PYTHIA predictions only differ significantly for hard and wide-angle perturbative emissions, where ME corrections are relevant. The hadronization algorithms implemented in SHERPA2.2.5 are most different at small values of k_t , particularly for soft-collinear splittings at the transition between perturbative and non-perturbative regions of the plane. The ability of the LJP to isolate physical effects is highlighted in Fig. 3(b), where as emissions change from wide angled to more collinear, the distribution passes through a region sensitive to the choice of PS model, and then enters a region which is instead sensitive to the hadronization model. Figures 3(c) and 3(d) show regions dominated by nonperturbative effects. The PYTHIA samples describe the data in the collinear region of the jet core well, but all simulations fail to describe the softest, widest-angle emissions, which are characteristic of contributions from the underlying event. The PYTHIA8.186 and SHERPA2.2.1 predictions are not shown, but are consistent with the PYTHIA8.230 and SHERPA2.2.5 (Lund string hadronization) predictions, respectively. These observations indicate that the LJP may provide useful input to both perturbative and nonperturbative model development and tuning.

In summary, a measurement of the jet substructure based on the Lund jet plane is reported. The analysis dataset corresponds to an integrated luminosity of 139 fb^{-1} of 13 TeV LHC proton-proton collisions recorded by the ATLAS detector. The measurement is performed on an inclusive selection of dijet events, with a leading jet $p_T > 675 \text{ GeV}$. Selected jets are reconstructed from topological clusters using the anti- k_t algorithm with $R = 0.4$, and their associated charged-particle tracks are used to construct the observables of interest. The data are presented as an unfolded double-differential cross section, and

compared with several Monte Carlo generators with various degrees of modeling accuracy. This measurement illustrates the ability of the Lund jet plane to isolate various physical effects, and will provide useful input to both perturbative and nonperturbative model development and tuning.

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[1] J. Gatheral, Exponentiation of eikonal cross sections in nonabelian gauge theories, *Phys. Lett.* **133B**, 90 (1983).

- [2] J. Frenkel and J. C. Taylor, Non-Abelian eikonal exponentiation, *Nucl. Phys.* **B246**, 231 (1984).
- [3] B. Andersson, G. Gustafson, L. Lönnblad, and U. Petterson, Coherence effects in deep inelastic scattering, *Z. Phys. C* **43**, 625 (1989).
- [4] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, Towards an understanding of jet substructure, *J. High Energy Phys.* **09** (2013) 029.
- [5] C. Frye, A. J. Larkoski, J. Thaler, and K. Zhou, Casimir meets Poisson: Improved quark/gluon discrimination with counting observables, *J. High Energy Phys.* **09** (2017) 083.
- [6] M. Dasgupta, F. A. Dreyer, K. Hamilton, P. F. Monni, and G. P. Salam, Logarithmic accuracy of parton showers: A fixed-order study, *J. High Energy Phys.* **09** (2018) 033.
- [7] G. P. Salam, L. Schunk, and G. Soyez, Dichroic subjettness ratios to distinguish colour flows in boosted boson tagging, *J. High Energy Phys.* **03** (2017) 022.
- [8] F. A. Dreyer, G. P. Salam, and G. Soyez, The Lund jet plane, *J. High Energy Phys.* **12** (2018) 064.
- [9] G. P. Salam, Towards jetography, *Eur. Phys. J. C* **67**, 637 (2010).
- [10] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, Better jet clustering algorithms, *J. High Energy Phys.* **08** (1997) 001.
- [11] M. Wobisch and T. Wengler, Hadronization corrections to Jet Cross-Sections in Deep-Inelastic scattering, in *Monte Carlo generators for HERA physics. Proceedings, Workshop, Hamburg, Germany, 1998* (DESY, Hamburg, 1998), p. 270, <https://www.desy.de/~heramc/proceedings/>.
- [12] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the center of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle ϑ as $\eta = -\ln \tan(\vartheta/2)$.
- [13] C. Frye, A. J. Larkoski, M. D. Schwartz, and K. Yan, Factorization for groomed jet substructure beyond the next-to-leading logarithm, *J. High Energy Phys.* **07** (2016) 064.
- [14] C. Frye, A. J. Larkoski, M. D. Schwartz, and K. Yan, Precision physics with pile-up insensitive observables, [arXiv:1603.06375](https://arxiv.org/abs/1603.06375).
- [15] S. Marzani, L. Schunk, and G. Soyez, A study of jet mass distributions with grooming, *J. High Energy Phys.* **07** (2017) 132.
- [16] S. Marzani, L. Schunk, and G. Soyez, The jet mass distribution after Soft Drop, *Eur. Phys. J. C* **78**, 96 (2018).
- [17] Z.-B. Kang, K. Lee, X. Liu, and F. Ringer, Soft drop groomed jet angularities at the LHC, *Phys. Lett. B* **793**, 41 (2019).
- [18] Z.-B. Kang, K. Lee, X. Liu, and F. Ringer, The groomed and ungroomed jet mass distribution for inclusive jet production at the LHC, *J. High Energy Phys.* **10** (2018) 137.
- [19] ATLAS Collaboration, Measurement of the Soft-Drop Jet Mass in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector, *Phys. Rev. Lett.* **121**, 092001 (2018).
- [20] CMS Collaboration, Measurements of the differential jet cross section as a function of the jet mass in dijet events from proton–proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **11** (2018) 113.
- [21] ATLAS Collaboration, A measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* **101**, 052007 (2020).
- [22] STAR Collaboration, Measurement of groomed jet substructure observables in pp Collisions at $\sqrt{s} = 200$ GeV with STAR, [arXiv:2003.02114](https://arxiv.org/abs/2003.02114).
- [23] N. Fischer, S. Prestel, M. Ritzmann, and P. Skands, VINCIA for hadron colliders, *Eur. Phys. J. C* **76**, 589 (2016).
- [24] S. Höche and S. Prestel, The midpoint between dipole and parton showers, *Eur. Phys. J. C* **75**, 461 (2015).
- [25] Z. Nagy and D. E. Soper, Effects of subleading color in a parton shower, *J. High Energy Phys.* **07** (2015) 119.
- [26] J. Bellm *et al.*, Herwig 7.0/Herwig++ 3.0 release note, *Eur. Phys. J. C* **76**, 196 (2016).
- [27] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, *J. Instrum.* **3**, S08003 (2008).
- [28] ATLAS Collaboration, ATLAS Insertable B-Layer Technical Design Report No. ATLAS-TDR-19, 2010, <https://cds.cern.ch/record/1291633>; Addendum, CERN, Report No. ATLAS-TDR-19-ADD-1, 2012.
- [29] B. Abbott *et al.*, Production and integration of the ATLAS insertable B-layer, *J. Instrum.* **13**, T05008 (2018).
- [30] ATLAS Collaboration, Performance of the ATLAS track reconstruction algorithms in dense environments in LHC Run 2, *Eur. Phys. J. C* **77**, 673 (2017).
- [31] ATLAS Collaboration, Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1, *Eur. Phys. J. C* **77**, 490 (2017).
- [32] M. Cacciari, G. P. Salam, and G. Soyez, The anti- k_t jet clustering algorithm, *J. High Energy Phys.* **04** (2008) 063.
- [33] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, *Eur. Phys. J. C* **72**, 1896 (2012).
- [34] ATLAS Collaboration, Jet energy scale measurements and their systematic uncertainties in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Rev. D* **96**, 072002 (2017).
- [35] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, *Eur. Phys. J. C* **77**, 317 (2017).
- [36] ATLAS Collaboration, The performance of the jet trigger for the ATLAS detector during 2011 data taking, *Eur. Phys. J. C* **76**, 526 (2016).
- [37] ATLAS Collaboration, Early Inner Detector Tracking Performance in the 2015 Data at $\sqrt{s} = 13$ TeV, CERN, Report No. ATL-PHYS-PUB-2015-051, 2015 <https://cds.cern.ch/record/2110140>.
- [38] T. Sjöstrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026.
- [39] T. Sjöstrand, S. Mrenna, and P. Z. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008).
- [40] R. D. Ball *et al.*, Parton distributions with LHC data, *Nucl. Phys.* **B867**, 244 (2013).
- [41] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Parton fragmentation and string dynamics, *Phys. Rep.* **97**, 31 (1983).
- [42] T. Sjöstrand, Jet fragmentation of multiparton configurations in a string framework, *Nucl. Phys.* **B248**, 469 (1984).

- [43] ATLAS Collaboration, ATLAS Pythia 8 tunes to 7 TeV data, CERN, Report No. ATL-PHYS-PUB-2014-021, 2014, <https://cds.cern.ch/record/1966419>.
- [44] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* **191**, 159 (2015).
- [45] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* **11** (2004) 040.
- [46] S. Frixione, P. Nason, and C. Oleari, Matching NLO QCD computations with parton shower simulations: The POWHEG method, *J. High Energy Phys.* **11** (2007) 070.
- [47] S. Alioli, K. Hamilton, P. Nason, C. Oleari, and E. Re, Jet pair production in POWHEG, *J. High Energy Phys.* **04** (2011) 081.
- [48] S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: The POWHEG BOX, *J. High Energy Phys.* **06** (2010) 043.
- [49] T. Gleisberg *et al.*, Event generation with SHERPA 1.1, *J. High Energy Phys.* **02** (2009) 007.
- [50] S. Schumann and F. Krauss, A parton shower algorithm based on Catani-Seymour dipole factorisation, *J. High Energy Phys.* **03** (2008) 038.
- [51] S. Höche, F. Krauss, M. Schönherr, and F. Siegert, QCD matrix elements + parton showers: The NLO case, *J. High Energy Phys.* **04** (2013) 027.
- [52] B. R. Webber, A QCD model for jet fragmentation including soft gluon interference, *Nucl. Phys.* **B238**, 492 (1984).
- [53] J.-C. Winter, F. Krauss, and G. Soff, A modified cluster hadronization model, *Eur. Phys. J. C* **36**, 381 (2004).
- [54] S. Dulat *et al.*, New parton distribution functions from a global analysis of quantum chromodynamics, *Phys. Rev. D* **93**, 033006 (2016).
- [55] M. Bahr *et al.*, Herwig++ physics and manual, *Eur. Phys. J. C* **58**, 639 (2008).
- [56] J. Bellm *et al.*, Herwig 7.1 Release Note, [arXiv:1705.06919](https://arxiv.org/abs/1705.06919).
- [57] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, Parton distributions in the LHC era: MMHT 2014 PDFs, *Eur. Phys. J. C* **75**, 204 (2015).
- [58] ATLAS Collaboration, Multijet simulation for 13 TeV ATLAS analyses, Report No. ATL-PHYS-PUB-2019-017, 2019, <https://cds.cern.ch/record/2672252>.
- [59] ATLAS Collaboration, The ATLAS simulation infrastructure, *Eur. Phys. J. C* **70**, 823 (2010).
- [60] S. Agostinelli *et al.*, Geant4—A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [61] ATLAS Collaboration, The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model, Report No. ATL-PHYS-PUB-2016-017, 2016, <https://cds.cern.ch/record/2206965>.
- [62] G. D’Agostini, A multidimensional unfolding method based on Bayes’ theorem, *Nucl. Instrum. Methods Phys. Res., Sect. A* **362**, 487 (1995).
- [63] T. Adye, Unfolding algorithms and tests using RooUnfold, [arXiv:1105.1160](https://arxiv.org/abs/1105.1160).
- [64] ATLAS Collaboration, Study of the material of the ATLAS inner detector for Run 2 of the LHC, *J. Instrum.* **12**, P12009 (2017).
- [65] B. Malaescu, An iterative, dynamically stabilized method of data unfolding, [arXiv:0907.3791](https://arxiv.org/abs/0907.3791).
- [66] ATLAS Collaboration, Measurement of the charged-particle multiplicity inside jets from $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector, *Eur. Phys. J. C* **76**, 322 (2016).
- [67] See the Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.124.222002> for the complete set of comparisons between data and simulation and other details.
- [68] ATLAS Collaboration, ATLAS Computing Acknowledgements, Report No. ATL-GEN-PUB-2016-002, <https://cds.cern.ch/record/2202407>.

G. Aad,¹⁰² B. Abbott,¹²⁹ D. C. Abbott,¹⁰³ A. Abed Abud,^{71a,71b} K. Abeling,⁵³ D. K. Abhayasinghe,⁹⁴ S. H. Abidi,¹⁶⁷ O. S. AbouZeid,⁴⁰ N. L. Abraham,¹⁵⁶ H. Abramowicz,¹⁶¹ H. Abreu,¹⁶⁰ Y. Abulaiti,⁶ B. S. Acharya,^{67a,67b,b} B. Achkar,⁵³ S. Adachi,¹⁶³ L. Adam,¹⁰⁰ C. Adam Bourdarios,⁵ L. Adamczyk,^{84a} L. Adamek,¹⁶⁷ J. Adelman,¹²¹ M. Adersberger,¹¹⁴ A. Adiguzel,^{12c} S. Adorni,⁵⁴ T. Adye,¹⁴⁴ A. A. Affolder,¹⁴⁶ Y. Afik,¹⁶⁰ C. Agapopoulou,⁶⁵ M. N. Agaras,³⁸ A. Aggarwal,¹¹⁹ C. Agheorghiesei,^{27c} J. A. Aguilar-Saavedra,^{140f,140a,c} F. Ahmadov,⁸⁰ W. S. Ahmed,¹⁰⁴ X. Ai,¹⁸ G. Aielli,^{74a,74b} S. Akatsuka,⁸⁶ T. P. A. Åkesson,⁹⁷ E. Akilli,⁵⁴ A. V. Akimov,¹¹¹ K. Al Khoury,⁶⁵ G. L. Alberghi,^{23b,23a} J. Albert,¹⁷⁶ M. J. Alconada Verzini,¹⁶¹ S. Alderweireldt,³⁶ M. Aleksa,³⁶ I. N. Aleksandrov,⁸⁰ C. Alexa,^{27b} T. Alexopoulos,¹⁰ A. Alfonsi,¹²⁰ F. Alfonsi,^{23b,23a} M. Alhroob,¹²⁹ B. Ali,¹⁴² M. Aliev,¹⁶⁶ G. Alimonti,^{69a} S. P. Alkire,¹⁴⁸ C. Allaire,⁶⁵ B. M. M. Allbrooke,¹⁵⁶ B. W. Allen,¹³² P. P. Allport,²¹ A. Aloisio,^{70a,70b} A. Alonso,⁴⁰ F. Alonso,⁸⁹ C. Alpigiani,¹⁴⁸ A. A. Alshehri,⁵⁷ M. Alvarez Estevez,⁹⁹ D. Álvarez Piqueras,¹⁷⁴ M. G. Alvigi,^{70a,70b} Y. Amaral Coutinho,^{81b} A. Ambler,¹⁰⁴ L. Ambroz,¹³⁵ C. Amelung,²⁶ D. Amidei,¹⁰⁶ S. P. Amor Dos Santos,^{140a} S. Amoroso,⁴⁶ C. S. Amrouche,⁵⁴ F. An,⁷⁹ C. Anastopoulos,¹⁴⁹ N. Andari,¹⁴⁵ T. Andeen,¹¹ C. F. Anders,^{61b} J. K. Anders,²⁰ A. Andreazza,^{69a,69b} V. Andrei,^{61a} C. R. Anelli,¹⁷⁶ S. Angelidakis,³⁸ A. Angerami,³⁹ A. V. Anisenkov,^{122b,122a} A. Annovi,^{72a} C. Antel,⁵⁴ M. T. Anthony,¹⁴⁹ E. Antipov,¹³⁰ M. Antonelli,⁵¹ D. J. A. Antrim,¹⁷¹ F. Anulli,^{73a} M. Aoki,⁸² J. A. Aparisi Pozo,¹⁷⁴ L. Aperio Bella,^{15a} J. P. Araque,^{140a} V. Araujo Ferraz,^{81b} R. Araujo Pereira,^{81b} C. Arcangeletti,⁵¹ A. T. H. Arce,⁴⁹ F. A. Arduh,⁸⁹ J.-F. Arguin,¹¹⁰ S. Argyropoulos,⁷⁸ J.-H. Arling,⁴⁶ A. J. Armbruster,³⁶ A. Armstrong,¹⁷¹ O. Arnaez,¹⁶⁷ H. Arnold,¹²⁰

Z. P. Arrubarrena Tame,¹¹⁴ G. Artoni,¹³⁵ S. Artz,¹⁰⁰ S. Asai,¹⁶³ N. Asbah,⁵⁹ E. M. Asimakopoulou,¹⁷² L. Asquith,¹⁵⁶ J. Assahsah,^{35d} K. Assamagan,²⁹ R. Astalos,^{28a} R. J. Atkin,^{33a} M. Atkinson,¹⁷³ N. B. Atlay,¹⁹ H. Atmani,⁶⁵ K. Augsten,¹⁴² G. Avolio,³⁶ R. Avramidou,^{60a} M. K. Ayoub,^{15a} A. M. Azoulay,^{168b} G. Azuelos,^{110,d} H. Bachacou,¹⁴⁵ K. Bachas,^{68a,68b} M. Backes,¹³⁵ F. Backman,^{45a,45b} P. Bagnaia,^{73a,73b} M. Bahmani,⁸⁵ H. Bahrsemani,¹⁵² A. J. Bailey,¹⁷⁴ V. R. Bailey,¹⁷³ J. T. Baines,¹⁴⁴ M. Bajic,⁴⁰ C. Bakalis,¹⁰ O. K. Baker,¹⁸³ P. J. Bakker,¹²⁰ D. Bakshi Gupta,⁸ S. Balaji,¹⁵⁷ E. M. Baldin,^{122b,122a} P. Balek,¹⁸⁰ F. Balli,¹⁴⁵ W. K. Balunas,¹³⁵ J. Balz,¹⁰⁰ E. Banas,⁸⁵ A. Bandyopadhyay,²⁴ Sw. Banerjee,^{181.e} A. A. E. Bannoura,¹⁸² L. Barak,¹⁶¹ W. M. Barbe,³⁸ E. L. Barberio,¹⁰⁵ D. Barberis,^{55b,55a} M. Barbero,¹⁰² G. Barbour,⁹⁵ T. Barillari,¹¹⁵ M-S. Barisits,³⁶ J. Barkeloo,¹³² T. Barklow,¹⁵³ R. Barnea,¹⁶⁰ S. L. Barnes,^{60c} B. M. Barnett,¹⁴⁴ R. M. Barnett,¹⁸ Z. Barnovska-Blenessy,^{60a} A. Baroncelli,^{60a} G. Barone,²⁹ A. J. Barr,¹³⁵ L. Barranco Navarro,^{45a,45b} F. Barreiro,⁹⁹ J. Barreiro Guimarães da Costa,^{15a} S. Barsov,¹³⁸ R. Bartoldus,¹⁵³ G. Bartolini,¹⁰² A. E. Barton,⁹⁰ P. Bartos,^{28a} A. Basalaev,⁴⁶ A. Basan,¹⁰⁰ A. Bassalat,^{65,f} M. J. Basso,¹⁶⁷ R. L. Bates,⁵⁷ S. Batlamous,^{35e} J. R. Batley,³² B. Batool,¹⁵¹ M. Battaglia,¹⁴⁶ M. Baucé,^{73a,73b} F. Bauer,¹⁴⁵ K. T. Bauer,¹⁷¹ H. S. Bawa,^{31,g} J. B. Beacham,⁴⁹ T. Beau,¹³⁶ P. H. Beauchemin,¹⁷⁰ F. Becherer,⁵² P. Bechtel,²⁴ H. C. Beck,⁵³ H. P. Beck,^{20,h} K. Becker,⁵² M. Becker,¹⁰⁰ C. Becot,⁴⁶ A. Beddall,^{12d} A. J. Beddall,^{12a} V. A. Bednyakov,⁸⁰ M. Bedognetti,¹²⁰ C. P. Bee,¹⁵⁵ T. A. Beermann,¹⁸² M. Begalli,^{81b} M. Begel,²⁹ A. Behera,¹⁵⁵ J. K. Behr,⁴⁶ F. Beisiegel,²⁴ A. S. Bell,⁹⁵ G. Bella,¹⁶¹ L. Bellagamba,^{23b} A. Bellerive,³⁴ P. Bellos,⁹ K. Beloborodov,^{122b,122a} K. Belotskiy,¹¹² N. L. Belyaev,¹¹² D. Benckekroun,^{35a} N. Benekos,¹⁰ Y. Benhammou,¹⁶¹ D. P. Benjamin,⁶ M. Benoit,⁵⁴ J. R. Bensinger,²⁶ S. Bentvelsen,¹²⁰ L. Beresford,¹³⁵ M. Beretta,⁵¹ D. Berge,⁴⁶ E. Bergeaas Kuutmann,¹⁷² N. Berger,⁵ B. Bergmann,¹⁴² L. J. Bergsten,²⁶ J. Beringer,¹⁸ S. Berlendis,⁷ G. Bernardi,¹³⁶ C. Bernius,¹⁵³ F. U. Bernlochner,²⁴ T. Berry,⁹⁴ P. Berta,¹⁰⁰ C. Bertella,^{15a} I. A. Bertram,⁹⁰ O. Bessidskaia Bylund,¹⁸² N. Besson,¹⁴⁵ A. Bethani,¹⁰¹ S. Bethke,¹¹⁵ A. Betti,⁴² A. J. Bevan,⁹³ J. Beyer,¹¹⁵ D. S. Bhattacharya,¹⁷⁷ P. Bhattarai,²⁶ R. Bi,¹³⁹ R. M. Bianchi,¹³⁹ O. Biebel,¹¹⁴ D. Biedermann,¹⁹ R. Bielski,³⁶ K. Bierwagen,¹⁰⁰ N. V. Biesuz,^{72a,72b} M. Biglietti,^{75a} T. R. V. Billoud,¹¹⁰ M. Bindi,⁵³ A. Bingul,^{12d} C. Bini,^{73a,73b} S. Biondi,^{23b,23a} M. Birman,¹⁸⁰ T. Bisanz,⁵³ J. P. Biswal,¹⁶¹ D. Biswas,^{181.e} A. Bitadze,¹⁰¹ C. Bittrich,⁴⁸ K. Bjørke,¹³⁴ K. M. Black,²⁵ T. Blazek,^{28a} I. Bloch,⁴⁶ C. Blocker,²⁶ A. Blue,⁵⁷ U. Blumenschein,⁹³ G. J. Bobbink,¹²⁰ V. S. Bobrovnikov,^{122b,122a} S. S. Bocchetta,⁹⁷ A. Bocci,⁴⁹ D. Boerner,⁴⁶ D. Bogavac,¹⁴ A. G. Bogdanchikov,^{122b,122a} C. Bohm,^{45a} V. Boisvert,⁹⁴ P. Bokan,^{53,172} T. Bold,^{84a} A. S. Boldyrev,¹¹³ A. E. Bolz,^{61b} M. Bomben,¹³⁶ M. Bona,⁹³ J. S. Bonilla,¹³² M. Boonekamp,¹⁴⁵ C. D. Booth,⁹⁴ H. M. Borecka-Bielska,⁹¹ A. Borisov,¹²³ G. Borissov,⁹⁰ J. Bortfeldt,³⁶ D. Bortoletto,¹³⁵ D. Boscherini,^{23b} M. Bosman,¹⁴ J. D. Bossio Sola,¹⁰⁴ K. Bouaouda,^{35a} J. Boudreau,¹³⁹ E. V. Bouhova-Thacker,⁹⁰ D. Boumediene,³⁸ S. K. Boutle,⁵⁷ A. Boveia,¹²⁷ J. Boyd,³⁶ D. Boye,^{33c,i} I. R. Boyko,⁸⁰ A. J. Bozson,⁹⁴ J. Bracinič,²¹ N. Brahimi,¹⁰² G. Brandt,¹⁸² O. Brandt,³² F. Braren,⁴⁶ B. Brau,¹⁰³ J. E. Brau,¹³² W. D. Breaden Madden,⁵⁷ K. Brendlinger,⁴⁶ L. Brenner,⁴⁶ R. Brenner,¹⁷² S. Bressler,¹⁸⁰ B. Brickwedde,¹⁰⁰ D. L. Briglin,²¹ D. Britton,⁵⁷ D. Britzger,¹¹⁵ I. Brock,²⁴ R. Brock,¹⁰⁷ G. Brooijmans,³⁹ W. K. Brooks,^{147d} E. Brost,¹²¹ J. H. Broughton,²¹ P. A. Bruckman de Renstrom,⁸⁵ D. Bruncko,^{28b} A. Bruni,^{23b} G. Bruni,^{23b} L. S. Bruni,¹²⁰ S. Bruno,^{74a,74b} M. Bruschi,^{23b} N. Bruscino,^{73a,73b} P. Bryant,³⁷ L. Bryngemark,⁹⁷ T. Buanes,¹⁷ Q. Buat,³⁶ P. Buchholz,¹⁵¹ A. G. Buckley,⁵⁷ I. A. Budagov,⁸⁰ M. K. Bugge,¹³⁴ F. Bühner,⁵² O. Bulekov,¹¹² T. J. Burch,¹²¹ S. Burdin,⁹¹ C. D. Burgard,¹²⁰ A. M. Burger,¹³⁰ B. Burghgrave,⁸ J. T. P. Burr,⁴⁶ C. D. Burton,¹¹ J. C. Burzynski,¹⁰³ V. Büscher,¹⁰⁰ E. Buschmann,⁵³ P. J. Bussey,⁵⁷ J. M. Butler,²⁵ C. M. Buttar,⁵⁷ J. M. Butterworth,⁹⁵ P. Butti,³⁶ W. Buttinger,³⁶ C. J. Buxo Vazquez,¹⁰⁷ A. Buzatu,¹⁵⁸ A. R. Buzykaev,^{122b,122a} G. Cabras,^{23b,23a} S. Cabrera Urbán,¹⁷⁴ D. Caforio,⁵⁶ H. Cai,¹⁷³ V. M. M. Cairo,¹⁵³ O. Cakir,^{4a} N. Calace,³⁶ P. Calafiura,¹⁸ A. Calandri,¹⁰² G. Calderini,¹³⁶ P. Calfayan,⁶⁶ G. Callea,⁵⁷ L. P. Caloba,^{81b} A. Caltabiano,^{74a,74b} S. Calvente Lopez,⁹⁹ D. Calvet,³⁸ S. Calvet,³⁸ T. P. Calvet,¹⁵⁵ M. Calvetti,^{72a,72b} R. Camacho Toro,¹³⁶ S. Camarda,³⁶ D. Camarero Munoz,⁹⁹ P. Camarri,^{74a,74b} D. Cameron,¹³⁴ R. Caminal Armadans,¹⁰³ C. Camincher,³⁶ S. Campana,³⁶ M. Campanelli,⁹⁵ A. Camplani,⁴⁰ A. Campoverde,¹⁵¹ V. Canale,^{70a,70b} A. Canesse,¹⁰⁴ M. Cano Bret,^{60c} J. Cantero,¹³⁰ T. Cao,¹⁶¹ Y. Cao,¹⁷³ M. D. M. Capeans Garrido,³⁶ M. Capua,^{41b,41a} R. Cardarelli,^{74a} F. Cardillo,¹⁴⁹ G. Carducci,^{41b,41a} I. Carli,¹⁴³ T. Carli,³⁶ G. Carlino,^{70a} B. T. Carlson,¹³⁹ L. Carminati,^{69a,69b} R. M. D. Carney,^{45a,45b} S. Caron,¹¹⁹ E. Carquin,^{147d} S. Carrá,⁴⁶ J. W. S. Carter,¹⁶⁷ M. P. Casado,^{14j} A. F. Casha,¹⁶⁷ D. W. Casper,¹⁷¹ R. Castelijm,¹²⁰ F. L. Castillo,¹⁷⁴ V. Castillo Gimenez,¹⁷⁴ N. F. Castro,^{140a,140e} A. Catinaccio,³⁶ J. R. Catmore,¹³⁴ A. Cattai,³⁶ V. Cavaliere,²⁹ E. Cavallaro,¹⁴ M. Cavalli-Sforza,¹⁴ V. Cavasinni,^{72a,72b} E. Celebi,^{12b} F. Ceradini,^{75a,75b} L. Cerda Alberich,¹⁷⁴ K. Cerny,¹³¹ A. S. Cerqueira,^{81a} A. Cerri,¹⁵⁶ L. Cerrito,^{74a,74b} F. Cerutti,¹⁸ A. Cervelli,^{23b,23a} S. A. Cetin,^{12b} Z. Chadi,^{35a} D. Chakraborty,¹²¹ W. S. Chan,¹²⁰ W. Y. Chan,⁹¹ J. D. Chapman,³² B. Chargeishvili,^{159b} D. G. Charlton,²¹ T. P. Charman,⁹³ C. C. Chau,³⁴ S. Che,¹²⁷ S. Chekanov,⁶ S. V. Chekulaev,^{168a} G. A. Chelkov,⁸⁰ M. A. Chelstowska,³⁶ B. Chen,⁷⁹ C. Chen,^{60a} C. H. Chen,⁷⁹ H. Chen,²⁹ J. Chen,^{60a}

J. Chen,³⁹ S. Chen,¹³⁷ S. J. Chen,^{15c} X. Chen,^{15b} Y-H. Chen,⁴⁶ H. C. Cheng,^{63a} H. J. Cheng,^{15a} A. Cheplakov,⁸⁰
 E. Cheremushkina,¹²³ R. Cherkaoui El Moursli,^{35e} E. Cheu,⁷ K. Cheung,⁶⁴ T. J. A. Chevalérias,¹⁴⁵ L. Chevalier,¹⁴⁵
 V. Chiarella,⁵¹ G. Chiarelli,^{72a} G. Chiodini,^{68a} A. S. Chisholm,²¹ A. Chitan,^{27b} I. Chiu,¹⁶³ Y. H. Chiu,¹⁷⁶ M. V. Chizhov,⁸⁰
 K. Choi,⁶⁶ A. R. Chomont,^{73a,73b} S. Chouridou,¹⁶² Y. S. Chow,¹²⁰ M. C. Chu,^{63a} X. Chu,^{15a,15d} J. Chudoba,¹⁴¹
 A. J. Chuinard,¹⁰⁴ J. J. Chwastowski,⁸⁵ L. Chytka,¹³¹ D. Cieri,¹¹⁵ K. M. Ciesla,⁸⁵ D. Cinca,⁴⁷ V. Cindro,⁹² I. A. Cioară,^{27b}
 A. Ciocio,¹⁸ F. Cirotto,^{70a,70b} Z. H. Citron,^{180,k} M. Citterio,^{69a} D. A. Ciubotaru,^{27b} B. M. Ciungu,¹⁶⁷ A. Clark,⁵⁴
 M. R. Clark,³⁹ P. J. Clark,⁵⁰ C. Clement,^{45a,45b} Y. Coadou,¹⁰² M. Cobal,^{67a,67c} A. Coccaro,^{55b} J. Cochran,⁷⁹ H. Cohen,¹⁶¹
 A. E. C. Coimbra,³⁶ L. Colasurdo,¹¹⁹ B. Cole,³⁹ A. P. Colijn,¹²⁰ J. Collot,⁵⁸ P. Conde Muiño,^{140a,140h} S. H. Connell,^{33c}
 I. A. Connelly,⁵⁷ S. Constantinescu,^{27b} F. Conventi,^{70a,l} A. M. Cooper-Sarkar,¹³⁵ F. Cormier,¹⁷⁵ K. J. R. Cormier,¹⁶⁷
 L. D. Corpe,⁹⁵ M. Corradi,^{73a,73b} E. E. Corrigan,⁹⁷ F. Corriveau,^{104,m} A. Cortes-Gonzalez,³⁶ M. J. Costa,¹⁷⁴ F. Costanza,⁵
 D. Costanzo,¹⁴⁹ G. Cowan,⁹⁴ J. W. Cowley,³² J. Crane,¹⁰¹ K. Cranmer,¹²⁵ S. J. Crawley,⁵⁷ R. A. Creager,¹³⁷
 S. Crépé-Renaudin,⁵⁸ F. Crescioli,¹³⁶ M. Cristinziani,²⁴ V. Croft,¹²⁰ G. Crosetti,^{41b,41a} A. Cueto,⁵
 T. Cuhadar Donszelmann,¹⁴⁹ A. R. Cukierman,¹⁵³ W. R. Cunningham,⁵⁷ S. Czekierda,⁸⁵ P. Czodrowski,³⁶
 M. J. Da Cunha Sargedas De Sousa,^{60b} J. V. Da Fonseca Pinto,^{81b} C. Da Via,¹⁰¹ W. Dabrowski,^{84a} F. Dachs,³⁶ T. Dado,^{28a}
 S. Dahbi,^{35e} T. Dai,¹⁰⁶ C. Dallapiccola,¹⁰³ M. Dam,⁴⁰ G. D'amen,²⁹ V. D'Amico,^{75a,75b} J. Damp,¹⁰⁰ J. R. Dandoy,¹³⁷
 M. F. Daneri,³⁰ N. P. Dang,^{181,e} N. S. Dann,¹⁰¹ M. Danninger,¹⁷⁵ V. Dao,³⁶ G. Darbo,^{55b} O. Dartsis,⁵ A. Dattagupta,¹³²
 T. Daubney,⁴⁶ S. D'Auria,^{69a,69b} C. David,⁴⁶ T. Davidek,¹⁴³ D. R. Davis,⁴⁹ I. Dawson,¹⁴⁹ K. De,⁸ R. De Asmundis,^{70a}
 M. De Beurs,¹²⁰ S. De Castro,^{23b,23a} S. De Cecco,^{73a,73b} N. De Groot,¹¹⁹ P. de Jong,¹²⁰ H. De la Torre,¹⁰⁷ A. De Maria,^{15c}
 D. De Pedis,^{73a} A. De Salvo,^{73a} U. De Sanctis,^{74a,74b} M. De Santis,^{74a,74b} A. De Santo,¹⁵⁶ K. De Vasconcelos Corga,¹⁰²
 J. B. De Vivie De Regie,⁶⁵ C. Debenedetti,¹⁴⁶ D. V. Dedovich,⁸⁰ A. M. Deiana,⁴² J. Del Peso,⁹⁹ Y. Delabat Diaz,⁴⁶
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 K. Dette,¹⁶⁷ C. Deutsch,²⁴ M. R. Devesa,³⁰ P. O. Deviveiros,³⁶ A. Dewhurst,¹⁴⁴ F. A. Di Bello,⁵⁴ A. Di Ciaccio,^{74a,74b}
 L. Di Ciaccio,⁵ W. K. Di Clemente,¹³⁷ C. Di Donato,^{70a,70b} A. Di Girolamo,³⁶ G. Di Gregorio,^{72a,72b} B. Di Micco,^{75a,75b}
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 M. D'Onofrio,⁹¹ J. Dopke,¹⁴⁴ A. Doria,^{70a} M. T. Dova,⁸⁹ A. T. Doyle,⁵⁷ E. Drechsler,¹⁵² E. Dreyer,¹⁵² T. Dreyer,⁵³
 A. S. Drobac,¹⁷⁰ D. Du,^{60b} Y. Duan,^{60b} F. Dubinin,¹¹¹ M. Dubovsky,^{28a} A. Dubreuil,⁵⁴ E. Duchovni,¹⁸⁰ G. Duckeck,¹¹⁴
 A. Ducourthial,¹³⁶ O. A. Ducu,¹¹⁰ D. Duda,¹¹⁵ A. Dudarev,³⁶ A. C. Dudder,¹⁰⁰ E. M. Duffield,¹⁸ L. Dufлот,⁶⁵ M. Dührssen,³⁶
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 M. Düren,⁵⁶ A. Durglishvili,^{159b} D. Duschinger,⁴⁸ B. Dutta,⁴⁶ D. Duvnjak,¹ G. I. Dyckes,¹³⁷ M. Dyndal,³⁶ S. Dysch,¹⁰¹
 B. S. Dziedzic,⁸⁵ K. M. Ecker,¹¹⁵ R. C. Edgar,¹⁰⁶ M. G. Eggleston,⁴⁹ T. Eifert,³⁶ G. Eigen,¹⁷ K. Einsweiler,¹⁸ T. Ekelof,¹⁷²
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 L. Fabbri,^{23b,23a} V. Fabiani,¹¹⁹ G. Facini,⁹⁵ R. M. Faisca Rodrigues Pereira,^{140a} R. M. Fakhruddinov,¹²³ S. Falciano,^{73a}
 P. J. Falke,⁵ S. Falke,⁵ J. Faltova,¹⁴³ Y. Fang,^{15a} Y. Fang,^{15a} G. Fanourakis,⁴⁴ M. Fanti,^{69a,69b} M. Faraj,^{67a,67c,o} A. Farbin,⁸
 A. Farilla,^{75a} E. M. Farina,^{71a,71b} T. Farooque,¹⁰⁷ S. Farrell,¹⁸ S. M. Farrington,⁵⁰ P. Farthouat,³⁶ F. Fassi,^{35e} P. Fassnacht,³⁶
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 J. Ferrando,⁴⁶ A. Ferrante,¹⁷³ A. Ferrari,¹⁷² P. Ferrari,¹²⁰ R. Ferrari,^{71a} D. E. Ferreira de Lima,^{61b} A. Ferrer,¹⁷⁴ D. Ferrere,⁵⁴
 C. Ferretti,¹⁰⁶ F. Fiedler,¹⁰⁰ A. Filipčić,⁹² F. Filthaut,¹¹⁹ K. D. Finelli,²⁵ M. C. N. Fiolhais,^{140a,140c,q} L. Fiorini,¹⁷⁴ F. Fischer,¹¹⁴
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 L. R. Flores Castillo,^{63a} F. M. Follega,^{76a,76b} N. Fomin,¹⁷ J. H. Foo,¹⁶⁷ G. T. Forcolin,^{76a,76b} A. Formica,¹⁴⁵ F. A. Förster,¹⁴
 A. C. Forti,¹⁰¹ A. G. Foster,²¹ M. G. Foti,¹³⁵ D. Fournier,⁶⁵ H. Fox,⁹⁰ P. Francavilla,^{72a,72b} S. Francescato,^{73a,73b}
 M. Franchini,^{23b,23a} S. Franchino,^{61a} D. Francis,³⁶ L. Franconi,²⁰ M. Franklin,⁵⁹ A. N. Fray,⁹³ P. M. Freeman,²¹ B. Freund,¹¹⁰

W. S. Freund,^{81b} E. M. Freundlich,⁴⁷ D. C. Frizzell,¹²⁹ D. Froidevaux,³⁶ J. A. Frost,¹³⁵ C. Fukunaga,¹⁶⁴
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 E. Gorini,^{68a,68b} A. Gorišek,⁹² A. T. Goshaw,⁴⁹ M. I. Gostkin,⁸⁰ C. A. Gottardo,¹¹⁹ M. Gouighri,^{35b} D. Goujdami,^{35c}
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 S. Hageböck,³⁶ M. Haleem,¹⁷⁷ J. Haley,¹³⁰ G. Halladjian,¹⁰⁷ G. D. Hallowell,¹⁰² K. Hamacher,¹⁸² P. Hamal,¹³¹ K. Hamano,¹⁷⁶
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 P. H. Hansen,⁴⁰ E. C. Hanson,¹⁰¹ K. Hara,¹⁶⁹ T. Harenberg,¹⁸² S. Harkusha,¹⁰⁸ P. F. Harrison,¹⁷⁸ N. M. Hartmann,¹¹⁴
 Y. Hasegawa,¹⁵⁰ A. Hasib,⁵⁰ S. Hassani,¹⁴⁵ S. Haug,²⁰ R. Hauser,¹⁰⁷ L. B. Havener,³⁹ M. Havranek,¹⁴² C. M. Hawkes,²¹
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 S. J. Haywood,¹⁴⁴ F. He,^{60a} M. P. Heath,⁵⁰ V. Hedberg,⁹⁷ L. Heelan,⁸ S. Heer,²⁴ K. K. Heidegger,⁵² W. D. Heidorn,⁷⁹
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 S. Hellesund,¹³⁴ C. M. Helling,¹⁴⁶ S. Hellman,^{45a,45b} C. Helsens,³⁶ R. C. W. Henderson,⁹⁰ Y. Heng,¹⁸¹ L. Henkelmann,^{61a}
 S. Henkelmann,¹⁷⁵ A. M. Henriques Correia,³⁶ G. H. Herbert,¹⁹ H. Herde,²⁶ V. Herget,¹⁷⁷ Y. Hernández Jiménez,^{33e}
 H. Herr,¹⁰⁰ M. G. Herrmann,¹¹⁴ T. Herrmann,⁴⁸ G. Herten,⁵² R. Hertenberger,¹¹⁴ L. Hervas,³⁶ T. C. Herwig,¹³⁷
 G. G. Hesketh,⁹⁵ N. P. Hessey,^{168a} A. Higashida,¹⁶³ S. Higashino,⁸² E. Higón-Rodríguez,¹⁷⁴ K. Hildebrand,³⁷ E. Hill,¹⁷⁶
 J. C. Hill,³² K. K. Hill,²⁹ K. H. Hiller,⁴⁶ S. J. Hillier,²¹ M. Hils,⁴⁸ I. Hinchliffe,¹⁸ F. Hinterkeuser,²⁴ M. Hirose,¹³³ S. Hirose,⁵²
 D. Hirschbuehl,¹⁸² B. Hiti,⁹² O. Hladik,¹⁴¹ D. R. Hlaluku,^{33e} X. Hoad,⁵⁰ J. Hobbs,¹⁵⁵ N. Hod,¹⁸⁰ M. C. Hodgkinson,¹⁴⁹
 A. Hoecker,³⁶ D. Hohn,⁵² D. Hohov,⁶⁵ T. Holm,²⁴ T. R. Holmes,³⁷ M. Holzbock,¹¹⁴ L. B. A. H. Hommels,³² S. Honda,¹⁶⁹
 T. M. Hong,¹³⁹ J. C. Honig,⁵² A. Hönle,¹¹⁵ B. H. Hooberman,¹⁷³ W. H. Hopkins,⁶ Y. Horii,¹¹⁷ P. Horn,⁴⁸ L. A. Horyn,³⁷
 S. Hou,¹⁵⁸ A. Hoummada,^{35a} J. Howarth,¹⁰¹ J. Hoya,⁸⁹ M. Hrabovsky,¹³¹ J. Hrdinka,⁷⁷ I. Hristova,¹⁹ J. Hrivnac,⁶⁵
 A. Hrynevich,¹⁰⁹ T. Hryn'ova,⁵ P. J. Hsu,⁶⁴ S.-C. Hsu,¹⁴⁸ Q. Hu,²⁹ S. Hu,^{60c} Y. F. Hu,^{15a,15d} D. P. Huang,⁹⁵ Y. Huang,^{60a}
 Y. Huang,^{15a} Z. Hubacek,¹⁴² F. Hubaut,¹⁰² M. Huebner,²⁴ F. Huegging,²⁴ T. B. Huffman,¹³⁵ M. Huhtinen,³⁶ R. F. H. Hunter,³⁴
 P. Huo,¹⁵⁵ A. M. Hupe,³⁴ N. Huseynov,^{80,y} J. Huston,¹⁰⁷ J. Huth,⁵⁹ R. Hyneman,¹⁰⁶ S. Hyrych,^{28a} G. Iacobucci,⁵⁴
 G. Iakovidis,²⁹ I. Ibragimov,¹⁵¹ L. Iconomidou-Fayard,⁶⁵ Z. Idrissi,^{35e} P. Iengo,³⁶ R. Ignazzi,⁴⁰ O. Igonkina,^{120,a,z}
 R. Iguchi,¹⁶³ T. Iizawa,⁵⁴ Y. Ikegami,⁸² M. Ikeno,⁸² D. Iliadis,¹⁶² N. Ilic,^{119,167,m} F. Iltzsche,⁴⁸ G. Introzzi,^{71a,71b} M. Iodice,^{75a}
 K. Iordanidou,^{168a} V. Ippolito,^{73a,73b} M. F. Isacson,¹⁷² M. Ishino,¹⁶³ W. Islam,¹³⁰ C. Issever,^{19,46} S. Istin,¹⁶⁰ F. Ito,¹⁶⁹
 J. M. Iturbe Ponce,^{63a} R. Iuppa,^{76a,76b} A. Ivina,¹⁸⁰ H. Iwasaki,⁸² J. M. Izen,⁴³ V. Izzo,^{70a} P. Jacka,¹⁴¹ P. Jackson,¹

R. M. Jacobs,²⁴ B. P. Jaeger,¹⁵² V. Jain,² G. Jäkel,¹⁸² K. B. Jakobi,¹⁰⁰ K. Jakobs,⁵² T. Jakoubek,¹⁴¹ J. Jamieson,⁵⁷ K. W. Janas,^{84a} R. Jansky,⁵⁴ J. Janssen,²⁴ M. Janus,⁵³ P. A. Janus,^{84a} G. Jarlskog,⁹⁷ N. Javadov,^{80,y} T. Javůrek,³⁶ M. Javurkova,¹⁰³ F. Jeanneau,¹⁴⁵ L. Jeanty,¹³² J. Jejelava,^{159a} A. Jelinskas,¹⁷⁸ P. Jenni,^{52,aa} J. Jeong,⁴⁶ N. Jeong,⁴⁶ S. Jézéquel,⁵ H. Ji,¹⁸¹ J. Jia,¹⁵⁵ H. Jiang,⁷⁹ Y. Jiang,^{60a} Z. Jiang,^{153,bb} S. Jiggins,⁵² F. A. Jimenez Morales,³⁸ J. Jimenez Pena,¹¹⁵ S. Jin,^{15c} A. Jinaru,^{27b} O. Jinnouchi,¹⁶⁵ H. Jivan,^{33e} P. Johansson,¹⁴⁹ K. A. Johns,⁷ C. A. Johnson,⁶⁶ K. Jon-And,^{45a,45b} R. W. L. Jones,⁹⁰ S. D. Jones,¹⁵⁶ S. Jones,⁷ T. J. Jones,⁹¹ J. Jongmanns,^{61a} P. M. Jorge,^{140a} J. Jovicevic,³⁶ X. Ju,¹⁸ J. J. Junggeburth,¹¹⁵ A. Juste Rozas,^{14,t} A. Kaczmarek,⁸⁵ M. Kado,^{73a,73b} H. Kagan,¹²⁷ M. Kagan,¹⁵³ A. Kahn,³⁹ C. Kahra,¹⁰⁰ T. Kaji,¹⁷⁹ E. Kajomovitz,¹⁶⁰ C. W. Kalderon,⁹⁷ A. Kaluza,¹⁰⁰ A. Kamenshchikov,¹²³ M. Kaneda,¹⁶³ N. J. Kang,¹⁴⁶ L. Kanjir,⁹² Y. Kano,¹¹⁷ V. A. Kantserov,¹¹² J. Kanzaki,⁸² L. S. Kaplan,¹⁸¹ D. Kar,^{33e} K. Karava,¹³⁵ M. J. Kareem,^{168b} S. N. Karpov,⁸⁰ Z. M. Karpova,⁸⁰ V. Kartvelishvili,⁹⁰ A. N. Karyukhin,¹²³ L. Kashif,¹⁸¹ R. D. Kass,¹²⁷ A. Kastanas,^{45a,45b} C. Kato,^{60d,60c} J. Katzy,⁴⁶ K. Kawade,¹⁵⁰ K. Kawagoe,⁸⁸ T. Kawaguchi,¹¹⁷ T. Kawamoto,¹⁶³ G. Kawamura,⁵³ E. F. Kay,¹⁷⁶ V. F. Kazanin,^{122b,122a} R. Keeler,¹⁷⁶ R. Kehoe,⁴² J. S. Keller,³⁴ E. Kellermann,⁹⁷ D. Kelsey,¹⁵⁶ J. J. Kempster,²¹ J. Kendrick,²¹ K. E. Kennedy,³⁹ O. Kepka,¹⁴¹ S. Kersten,¹⁸² B. P. Kerševan,⁹² S. Ketabchi Haghighat,¹⁶⁷ M. Khader,¹⁷³ F. Khalil-Zada,¹³ M. Khandoga,¹⁴⁵ A. Khanov,¹³⁰ A. G. Kharlamov,^{122b,122a} T. Kharlamova,^{122b,122a} E. E. Khoda,¹⁷⁵ A. Khodinov,¹⁶⁶ T. J. Khoo,⁵⁴ E. Khramov,⁸⁰ J. Khubua,^{159b} S. Kido,⁸³ M. Kiehn,⁵⁴ C. R. Kilby,⁹⁴ Y. K. Kim,³⁷ N. Kimura,⁹⁵ O. M. Kind,¹⁹ B. T. King,^{91,a} D. Kirchmeier,⁴⁸ J. Kirk,¹⁴⁴ A. E. Kiryunin,¹¹⁵ T. Kishimoto,¹⁶³ D. P. Kisliuk,¹⁶⁷ V. Kitali,⁴⁶ O. Kivernyk,⁵ T. Klapdor-Kleingrothaus,⁵² M. Klassen,^{61a} M. H. Klein,¹⁰⁶ M. Klein,⁹¹ U. Klein,⁹¹ K. Kleinknecht,¹⁰⁰ P. Klimek,¹²¹ A. Klimentov,²⁹ T. Klingl,²⁴ T. Klioutchnikova,³⁶ F. F. Klitzner,¹¹⁴ P. Kluit,¹²⁰ S. Kluth,¹¹⁵ E. Kneringer,⁷⁷ E. B. F. G. Knoops,¹⁰² A. Knue,⁵² D. Kobayashi,⁸⁸ T. Kobayashi,¹⁶³ M. Kobel,⁴⁸ M. Kocian,¹⁵³ P. Kodys,¹⁴³ P. T. Koenig,²⁴ T. Koffas,³⁴ N. M. Köhler,³⁶ T. Koi,¹⁵³ M. Kolb,¹⁴⁵ I. Koletsou,⁵ T. Komarek,¹³¹ T. Kondo,⁸² K. Köneke,⁵² A. X. Y. Kong,¹ A. C. König,¹¹⁹ T. Kono,¹²⁶ R. Konoplich,^{125,cc} V. Konstantinides,⁹⁵ N. Konstantinidis,⁹⁵ B. Konya,⁹⁷ R. Kopeliainsky,⁶⁶ S. Koperny,^{84a} K. Korcyl,⁸⁵ K. Kordas,¹⁶² G. Koren,¹⁶¹ A. Korn,⁹⁵ I. Korolkov,¹⁴ E. V. Korolkova,¹⁴⁹ N. Korotkova,¹¹³ O. Kortner,¹¹⁵ S. Kortner,¹¹⁵ T. Kosek,¹⁴³ V. V. Kostyukhin,¹⁶⁶ A. Kotsokechagia,⁶⁵ A. Kotwal,⁴⁹ A. Koulouris,¹⁰ A. Kourkouveli-Charalampidi,^{71a,71b} C. Kourkouvelis,⁹ E. Kourlitis,¹⁴⁹ V. Kouskoura,²⁹ A. B. Kowalewska,⁸⁵ R. Kowalewski,¹⁷⁶ C. Kozakai,¹⁶³ W. Kozanecki,¹⁴⁵ A. S. Kozhin,¹²³ V. A. Kramarenko,¹¹³ G. Kramberger,⁹² D. Krasnopevtsev,^{60a} M. W. Krasny,¹³⁶ A. Krasznahorkay,³⁶ D. Krauss,¹¹⁵ J. A. Kremer,^{84a} J. Kretschmar,⁹¹ P. Krieger,¹⁶⁷ F. Krieter,¹¹⁴ A. Krishnan,^{61b} K. Krizka,¹⁸ K. Kroeninger,⁴⁷ H. Kroha,¹¹⁵ J. Kroll,¹⁴¹ J. Kroll,¹³⁷ K. S. Krowpman,¹⁰⁷ J. Krstic,¹⁶ U. Kruchonak,⁸⁰ H. Krüger,²⁴ N. Krumnack,⁷⁹ M. C. Kruse,⁴⁹ J. A. Krzysiak,⁸⁵ T. Kubota,¹⁰⁵ O. Kuchinskaia,¹⁶⁶ S. Kuday,^{4b} J. T. Kuechler,⁴⁶ S. Kuehn,³⁶ A. Kugel,^{61a} T. Kuhl,⁴⁶ V. Kukhtin,⁸⁰ R. Kukla,¹⁰² Y. Kulchitsky,^{108,dd} S. Kuleshov,^{147d} Y. P. Kulinich,¹⁷³ M. Kuna,⁵⁸ T. Kunigo,⁸⁶ A. Kupco,¹⁴¹ T. Kupfer,⁴⁷ O. Kuprash,⁵² H. Kurashige,⁸³ L. L. Kurchaninov,^{168a} Y. A. Kurochkin,¹⁰⁸ A. Kurova,¹¹² M. G. Kurth,^{15a,15d} E. S. Kuwertz,³⁶ M. Kuze,¹⁶⁵ A. K. Kvam,¹⁴⁸ J. Kvita,¹³¹ T. Kwan,¹⁰⁴ A. La Rosa,¹¹⁵ L. La Rotonda,^{41b,41a} F. La Ruffa,^{41b,41a} C. Lacasta,¹⁷⁴ F. Lacava,^{73a,73b} D. P. J. Lack,¹⁰¹ H. Lacker,¹⁹ D. Lacour,¹³⁶ E. Ladygin,⁸⁰ R. Lafaye,⁵ B. Laforge,¹³⁶ T. Lagouri,^{33e} S. Lai,⁵³ I. K. Lakomic,^{84a} S. Lammers,⁶⁶ W. Lampl,⁷ C. Lampoudis,¹⁶² E. Lançon,²⁹ U. Landgraf,⁵² M. P. J. Landon,⁹³ M. C. Lanfermann,⁵⁴ V. S. Lang,⁴⁶ J. C. Lange,⁵³ R. J. Langenberg,¹⁰³ A. J. Lankford,¹⁷¹ F. Lanni,²⁹ K. Lantsch,²⁴ A. Lanza,^{71a} A. Lapertosa,^{55b,55a} S. Laplace,¹³⁶ J. F. Laporte,¹⁴⁵ T. Lari,^{69a} F. Lasagni Manghi,^{23b,23a} M. Lassnig,³⁶ T. S. Lau,^{63a} A. Laudrain,⁶⁵ A. Laurier,³⁴ M. Lavorgna,^{70a,70b} S. D. Lawlor,⁹⁴ M. Lazzaroni,^{69a,69b} B. Le,¹⁰⁵ E. Le Guirriec,¹⁰² M. LeBlanc,⁷ T. LeCompte,⁶ F. Ledroit-Guillon,⁵⁸ A. C. A. Lee,⁹⁵ C. A. Lee,²⁹ G. R. Lee,¹⁷ L. Lee,⁵⁹ S. C. Lee,¹⁵⁸ S. J. Lee,³⁴ S. Lee,⁷⁹ B. Lefebvre,^{168a} H. P. Lefebvre,⁹⁴ M. Lefebvre,¹⁷⁶ F. Legger,¹¹⁴ C. Leggett,¹⁸ K. Lehmann,¹⁵² N. Lehmann,¹⁸² G. Lehmann Miotto,³⁶ W. A. Leight,⁴⁶ A. Leisos,^{162,ee} M. A. L. Leite,^{81d} C. E. Leitgeb,¹¹⁴ R. Leitner,¹⁴³ D. Lellouch,^{180,a} K. J. C. Leney,⁴² T. Lenz,²⁴ R. Leone,⁷ S. Leone,^{72a} C. Leonidopoulos,⁵⁰ A. Leopold,¹³⁶ C. Leroy,¹¹⁰ R. Les,¹⁶⁷ C. G. Lester,³² M. Levchenko,¹³⁸ J. Levêque,⁵ D. Levin,¹⁰⁶ L. J. Levinson,¹⁸⁰ D. J. Lewis,²¹ B. Li,^{15b} B. Li,¹⁰⁶ C-Q. Li,^{60a} F. Li,^{60c} H. Li,^{60a} H. Li,^{60b} J. Li,^{60c} K. Li,¹⁵³ L. Li,^{60c} M. Li,^{15a,15d} Q. Li,^{15a,15d} Q. Y. Li,^{60a} S. Li,^{60d,60c} X. Li,⁴⁶ Y. Li,⁴⁶ Z. Li,^{60b} Z. Liang,^{15a} B. Liberti,^{74a} A. Liblong,¹⁶⁷ K. Lie,^{63c} S. Lim,²⁹ C. Y. Lin,³² K. Lin,¹⁰⁷ T. H. Lin,¹⁰⁰ R. A. Linck,⁶⁶ J. H. Lindon,²¹ A. L. Lioni,⁵⁴ E. Lipeles,¹³⁷ A. Lipniacka,¹⁷ T. M. Liss,^{173,ff} A. Lister,¹⁷⁵ A. M. Litke,¹⁴⁶ J. D. Little,⁸ B. Liu,⁷⁹ B. L. Liu,⁶ H. B. Liu,²⁹ H. Liu,¹⁰⁶ J. B. Liu,^{60a} J. K. K. Liu,¹³⁵ K. Liu,¹³⁶ M. Liu,^{60a} P. Liu,¹⁸ Y. Liu,^{15a,15d} Y. L. Liu,¹⁰⁶ Y. W. Liu,^{60a} M. Livan,^{71a,71b} A. Lleres,⁵⁸ J. Llorente Merino,¹⁵² S. L. Lloyd,⁹³ C. Y. Lo,^{63b} F. Lo Sterzo,⁴² E. M. Lobodzinska,⁴⁶ P. Loch,⁷ S. Loffredo,^{74a,74b} T. Lohse,¹⁹ K. Lohwasser,¹⁴⁹ M. Lokajicek,¹⁴¹ J. D. Long,¹⁷³ R. E. Long,⁹⁰ L. Longo,³⁶ K. A. Looper,¹²⁷ J. A. Lopez,^{147d} I. Lopez Paz,¹⁰¹ A. Lopez Solis,¹⁴⁹ J. Lorenz,¹¹⁴

N. Lorenzo Martinez,⁵ A. M. Lory,¹¹⁴ M. Losada,^{22a} P. J. Lösel,¹¹⁴ A. Lösle,⁵² X. Lou,⁴⁶ X. Lou,^{15a} A. Lounis,⁶⁵ J. Love,⁶ P. A. Love,⁹⁰ J. J. Lozano Bahilo,¹⁷⁴ M. Lu,^{60a} Y. J. Lu,⁶⁴ H. J. Lubatti,¹⁴⁸ C. Luci,^{73a,73b} A. Lucotte,⁵⁸ C. Luedtke,⁵² F. Luehring,⁶⁶ I. Luise,¹³⁶ L. Luminari,^{73a} B. Lund-Jensen,¹⁵⁴ M. S. Lutz,¹⁰³ D. Lynn,²⁹ H. Lyons,⁹¹ R. Lysak,¹⁴¹ E. Lytken,⁹⁷ F. Lyu,^{15a} V. Lyubushkin,⁸⁰ T. Lyubushkina,⁸⁰ H. Ma,²⁹ L. L. Ma,^{60b} Y. Ma,^{60b} G. Maccarrone,⁵¹ A. Macchiolo,¹¹⁵ C. M. Macdonald,¹⁴⁹ J. Machado Miguens,¹³⁷ D. Madaffari,¹⁷⁴ R. Madar,³⁸ W. F. Mader,⁴⁸ N. Madysa,⁴⁸ J. Maeda,⁸³ T. Maeno,²⁹ M. Maerker,⁴⁸ A. S. Maevskiy,¹¹³ V. Magerl,⁵² N. Magini,⁷⁹ D. J. Mahon,³⁹ C. Maidantchik,^{81b} T. Maier,¹¹⁴ A. Maio,^{140a,140b,140d} K. Maj,^{84a} O. Majersky,^{28a} S. Majewski,¹³² Y. Makida,⁸² N. Makovec,⁶⁵ B. Malaescu,¹³⁶ Pa. Malecki,⁸⁵ V. P. Maleev,¹³⁸ F. Malek,⁵⁸ U. Mallik,⁷⁸ D. Malon,⁶ C. Malone,³² S. Maltezos,¹⁰ S. Malyukov,⁸⁰ J. Mamuzic,¹⁷⁴ G. Mancini,⁵¹ I. Mandić,⁹² L. Manhaes de Andrade Filho,^{81a} I. M. Maniatis,¹⁶² J. Manjarres Ramos,⁴⁸ K. H. Mankinen,⁹⁷ A. Mann,¹¹⁴ A. Manousos,⁷⁷ B. Mansoulie,¹⁴⁵ I. Manthos,¹⁶² S. Manzoni,¹²⁰ A. Marantis,¹⁶² G. Marceca,³⁰ L. Marchese,¹³⁵ G. Marchiori,¹³⁶ M. Marcisovsky,¹⁴¹ L. Marcoccia,^{74a,74b} C. Marcon,⁹⁷ C. A. Marin Tobon,³⁶ M. Marjanovic,¹²⁹ Z. Marshall,¹⁸ M. U. F. Martensson,¹⁷² S. Marti-Garcia,¹⁷⁴ C. B. Martin,¹²⁷ T. A. Martin,¹⁷⁸ V. J. Martin,⁵⁰ B. Martin dit Latour,¹⁷ L. Martinelli,^{75a,75b} M. Martinez,^{14t} V. I. Martinez Outschoorn,¹⁰³ S. Martin-Haugh,¹⁴⁴ V. S. Martoiu,^{27b} A. C. Martyniuk,⁹⁵ A. Marzin,³⁶ S. R. Maschek,¹¹⁵ L. Masetti,¹⁰⁰ T. Mashimo,¹⁶³ R. Mashinistov,¹¹¹ J. Masik,¹⁰¹ A. L. Maslennikov,^{122b,122a} L. Massa,^{74a,74b} P. Massarotti,^{70a,70b} P. Mastrandrea,^{72a,72b} A. Mastroberardino,^{41b,41a} T. Masubuchi,¹⁶³ D. Matakias,¹⁰ A. Matic,¹¹⁴ N. Matsuzawa,¹⁶³ P. Mättig,²⁴ J. Maurer,^{27b} B. Maček,⁹² D. A. Maximov,^{122b,122a} R. Mazini,¹⁵⁸ I. Maznas,¹⁶² S. M. Mazza,¹⁴⁶ S. P. Mc Kee,¹⁰⁶ T. G. McCarthy,¹¹⁵ W. P. McCormack,¹⁸ E. F. McDonald,¹⁰⁵ J. A. Mcfayden,³⁶ G. Mchedlidze,^{159b} M. A. McKay,⁴² K. D. McLean,¹⁷⁶ S. J. McMahan,¹⁴⁴ P. C. McNamara,¹⁰⁵ C. J. McNicol,¹⁷⁸ R. A. McPherson,^{176,m} J. E. Mdhului,^{33e} Z. A. Meadows,¹⁰³ S. Meehan,³⁶ T. Megy,⁵² S. Mehlhase,¹¹⁴ A. Mehta,⁹¹ T. Meideck,⁵⁸ B. Meirose,⁴³ D. Melini,¹⁶⁰ B. R. Mellado Garcia,^{33e} J. D. Mellenthin,⁵³ M. Melo,^{28a} F. Meloni,⁴⁶ A. Melzer,²⁴ S. B. Menary,¹⁰¹ E. D. Mendes Gouveia,^{140a,140e} L. Meng,³⁶ X. T. Meng,¹⁰⁶ S. Menke,¹¹⁵ E. Meoni,^{41b,41a} S. Mergelmeyer,¹⁹ S. A. M. Merkt,¹³⁹ C. Merlassino,²⁰ P. Mermod,⁵⁴ L. Merola,^{70a,70b} C. Meroni,^{69a} G. Merz,¹⁰⁶ O. Meshkov,^{113,111} J. K. R. Meshreki,¹⁵¹ A. Messina,^{73a,73b} J. Metcalfe,⁶ A. S. Mete,¹⁷¹ C. Meyer,⁶⁶ J-P. Meyer,¹⁴⁵ H. Meyer Zu Theenhausen,^{61a} F. Miano,¹⁵⁶ M. Michetti,¹⁹ R. P. Middleton,¹⁴⁴ L. Mijović,⁵⁰ G. Mikenberg,¹⁸⁰ M. Mikestikova,¹⁴¹ M. Mikuž,⁹² H. Mildner,¹⁴⁹ M. Milesi,¹⁰⁵ A. Milic,¹⁶⁷ D. A. Millar,⁹³ D. W. Miller,³⁷ A. Milov,¹⁸⁰ D. A. Milstead,^{45a,45b} R. A. Mina,¹⁵³ A. A. Minaenko,¹²³ M. Miñano Moya,¹⁷⁴ I. A. Minashvili,^{159b} A. I. Mincer,¹²⁵ B. Mindur,^{84a} M. Mineev,⁸⁰ Y. Minegishi,¹⁶³ L. M. Mir,¹⁴ A. Mirto,^{68a,68b} K. P. Mistry,¹³⁷ T. Mitani,¹⁷⁹ J. Mitrevski,¹¹⁴ V. A. Mitsou,¹⁷⁴ M. Mittal,^{60c} O. Miu,¹⁶⁷ A. Miucci,²⁰ P. S. Miyagawa,¹⁴⁹ A. Mizukami,⁸² J. U. Mjörnmark,⁹⁷ T. Mkrtchyan,^{61a} M. Mlynarikova,¹⁴³ T. Moa,^{45a,45b} K. Mochizuki,¹¹⁰ P. Mogg,⁵² S. Mohapatra,³⁹ R. Moles-Valls,²⁴ M. C. Mondragon,¹⁰⁷ K. Mönig,⁴⁶ J. Monk,⁴⁰ E. Monnier,¹⁰² A. Montalbano,¹⁵² J. Montejo Berlingen,³⁶ M. Montella,⁹⁵ F. Monticelli,⁸⁹ S. Monzani,^{69a} N. Morange,⁶⁵ D. Moreno,^{22a} M. Moreno Llácer,¹⁷⁴ C. Moreno Martinez,¹⁴ P. Morettini,^{55b} M. Morgenstern,¹²⁰ S. Morgenstern,⁴⁸ D. Mori,¹⁵² M. Morii,⁵⁹ M. Morinaga,¹⁷⁹ V. Morisbak,¹³⁴ A. K. Morley,³⁶ G. Mornacchi,³⁶ A. P. Morris,⁹⁵ L. Morvaj,¹⁵⁵ P. Moschovakos,³⁶ B. Moser,¹²⁰ M. Mosidze,^{159b} T. Moskalets,¹⁴⁵ H. J. Moss,¹⁴⁹ J. Moss,^{31,gg} E. J. W. Moyse,¹⁰³ S. Muanza,¹⁰² J. Mueller,¹³⁹ R. S. P. Mueller,¹¹⁴ D. Muenstermann,⁹⁰ G. A. Mullier,⁹⁷ D. P. Mungo,^{69a,69b} J. L. Munoz Martinez,¹⁴ F. J. Munoz Sanchez,¹⁰¹ P. Murin,^{28b} W. J. Murray,^{178,144} A. Murrone,^{69a,69b} M. Muškinja,¹⁸ C. Mwewa,^{33a} A. G. Myagkov,^{123,hh} A. A. Myers,¹³⁹ J. Myers,¹³² M. Myska,¹⁴² B. P. Nachman,¹⁸ O. Nackenhorst,⁴⁷ A. Nag Nag,⁴⁸ K. Nagai,¹³⁵ K. Nagano,⁸² Y. Nagasaka,⁶² J. L. Nagle,²⁹ E. Nagy,¹⁰² A. M. Nairz,³⁶ Y. Nakahama,¹¹⁷ K. Nakamura,⁸² T. Nakamura,¹⁶³ I. Nakano,¹²⁸ H. Nanjo,¹³³ F. Napolitano,^{61a} R. F. Naranjo Garcia,⁴⁶ R. Narayan,⁴² I. Naryshkin,¹³⁸ T. Naumann,⁴⁶ G. Navarro,^{22a} P. Y. Nechaeva,¹¹¹ F. Nechansky,⁴⁶ T. J. Neep,²¹ A. Negri,^{71a,71b} M. Negrini,^{23b} C. Nellist,⁵³ M. E. Nelson,^{45a,45b} S. Nemecek,¹⁴¹ P. Nemethy,¹²⁵ M. Nessi,^{36,ii} M. S. Neubauer,¹⁷³ M. Neumann,¹⁸² R. Newhouse,¹⁷⁵ P. R. Newman,²¹ Y. S. Ng,¹⁹ Y. W. Y. Ng,¹⁷¹ B. Ngair,^{35e} H. D. N. Nguyen,¹⁰² T. Nguyen Manh,¹¹⁰ E. Nibigira,³⁸ R. B. Nickerson,¹³⁵ R. Nicolaidou,¹⁴⁵ D. S. Nielsen,⁴⁰ J. Nielsen,¹⁴⁶ N. Nikiforou,¹¹ V. Nikolaenko,^{123,hh} I. Nikolic-Audit,¹³⁶ K. Nikolopoulos,²¹ P. Nilsson,²⁹ H. R. Nindhito,⁵⁴ Y. Ninomiya,⁸² A. Nisati,^{73a} N. Nishu,^{60c} R. Nisius,¹¹⁵ I. Nitsche,⁴⁷ T. Nitta,¹⁷⁹ T. Nobe,¹⁶³ Y. Noguchi,⁸⁶ I. Nomidis,¹³⁶ M. A. Nomura,²⁹ M. Nordberg,³⁶ N. Norjoharuddeen,¹³⁵ T. Novak,⁹² O. Novgorodova,⁴⁸ R. Novotny,¹⁴² L. Nozka,¹³¹ K. Ntekas,¹⁷¹ E. Nurse,⁹⁵ F. G. Oakham,^{34,d} H. Oberlack,¹¹⁵ J. Ocariz,¹³⁶ A. Ochi,⁸³ I. Ochoa,³⁹ J. P. Ochoa-Ricoux,^{147a} K. O'Connor,²⁶ S. Oda,⁸⁸ S. Odaka,⁸² S. Oerdek,⁵³ A. Ogrodnik,^{84a} A. Oh,¹⁰¹ S. H. Oh,⁴⁹ C. C. Ohm,¹⁵⁴ H. Oide,¹⁶⁵ M. L. Ojeda,¹⁶⁷ H. Okawa,¹⁶⁹ Y. Okazaki,⁸⁶ M. W. O'Keefe,⁹¹ Y. Okumura,¹⁶³ T. Okuyama,⁸² A. Olariu,^{27b} L. F. Oleiro Seabra,^{140a} S. A. Olivares Pino,^{147a} D. Oliveira Damazio,²⁹ J. L. Oliver,¹

M. J. R. Olsson,¹⁷¹ A. Olszewski,⁸⁵ J. Olszowska,⁸⁵ D. C. O'Neil,¹⁵² A. P. O'Neill,¹³⁵ A. Onofre,^{140a,140e} P. U. E. Onyisi,¹¹ H. Oppen,¹³⁴ M. J. Oreglia,³⁷ G. E. Orellana,⁸⁹ D. Orestano,^{75a,75b} N. Orlando,¹⁴ R. S. Orr,¹⁶⁷ V. O'Shea,⁵⁷ R. Ospanov,^{60a} G. Otero y Garzon,³⁰ H. Otono,⁸⁸ P. S. Ott,^{61a} M. Ouchrif,^{35d} J. Ouellette,²⁹ F. Ould-Saada,¹³⁴ A. Ouraou,¹⁴⁵ Q. Ouyang,^{15a} M. Owen,⁵⁷ R. E. Owen,²¹ V. E. Ozcan,^{12c} N. Ozturk,⁸ J. Pacalt,¹³¹ H. A. Pacey,³² K. Pachal,⁴⁹ A. Pacheco Pages,¹⁴ C. Padilla Aranda,¹⁴ S. Pagan Griso,¹⁸ M. Paganini,¹⁸³ G. Palacino,⁶⁶ S. Palazzo,⁵⁰ S. Palestini,³⁶ M. Palka,^{84b} D. Pallin,³⁸ I. Panagoulas,¹⁰ C. E. Pandini,³⁶ J. G. Panduro Vazquez,⁹⁴ P. Pani,⁴⁶ G. Panizzo,^{67a,67c} L. Paolozzi,⁵⁴ C. Papadatos,¹¹⁰ K. Papageorgiou,^{9,r} S. Parajuli,⁴³ A. Paramonov,⁶ D. Paredes Hernandez,^{63b} S. R. Paredes Saenz,¹³⁵ B. Parida,¹⁶⁶ T. H. Park,¹⁶⁷ A. J. Parker,³¹ M. A. Parker,³² F. Parodi,^{55b,55a} E. W. Parrish,¹²¹ J. A. Parsons,³⁹ U. Parzefall,⁵² L. Pascual Dominguez,¹³⁶ V. R. Pascuzzi,¹⁶⁷ J. M. P. Pasner,¹⁴⁶ F. Pasquali,¹²⁰ E. Pasqualucci,^{73a} S. Passaggio,^{55b} F. Pastore,⁹⁴ P. Pasuwan,^{45a,45b} S. Pataria,¹⁰⁰ J. R. Pater,¹⁰¹ A. Pathak,^{181,e} T. Pauly,³⁶ J. Pearkes,¹⁵³ B. Pearson,¹¹⁵ M. Pedersen,¹³⁴ L. Pedraza Diaz,¹¹⁹ R. Pedro,^{140a} T. Peiffer,⁵³ S. V. Peleganchuk,^{122b,122a} O. Penc,¹⁴¹ H. Peng,^{60a} B. S. Peralva,^{81a} M. M. Perego,⁶⁵ A. P. Pereira Peixoto,^{140a} D. V. Perepelitsa,²⁹ F. Peri,¹⁹ L. Perini,^{69a,69b} H. Pernegger,³⁶ S. Perrella,^{70a,70b} A. Perrevoort,¹²⁰ K. Peters,⁴⁶ R. F. Y. Peters,¹⁰¹ B. A. Petersen,³⁶ T. C. Petersen,⁴⁰ E. Petit,¹⁰² A. Petridis,¹ C. Petridou,¹⁶² P. Petroff,⁶⁵ M. Petrov,¹³⁵ F. Petrucci,^{75a,75b} M. Pettee,¹⁸³ N. E. Pettersson,¹⁰³ K. Petukhova,¹⁴³ A. Peyaud,¹⁴⁵ R. Pezoa,^{147d} L. Pezzotti,^{71a,71b} T. Pham,¹⁰⁵ F. H. Phillips,¹⁰⁷ P. W. Phillips,¹⁴⁴ M. W. Phipps,¹⁷³ G. Piacquadio,¹⁵⁵ E. Pianori,¹⁸ A. Picazio,¹⁰³ R. H. Pickles,¹⁰¹ R. Piegai,³⁰ D. Pietreanu,^{27b} J. E. Pilcher,³⁷ A. D. Pilkington,¹⁰¹ M. Pinamonti,^{67a,67c} J. L. Pinfold,³ M. Pitt,¹⁶¹ L. Pizzimento,^{74a,74b} M.-A. Pleier,²⁹ V. Pleskot,¹⁴³ E. Plotnikova,⁸⁰ P. Podberezko,^{122b,122a} R. Poettgen,⁹⁷ R. Poggi,⁵⁴ L. Poggioli,⁶⁵ I. Pogrebnyak,¹⁰⁷ D. Pohl,²⁴ I. Pokharel,⁵³ G. Polesello,^{71a} A. Poley,¹⁸ A. Policicchio,^{73a,73b} R. Polifka,¹⁴³ A. Polini,^{23b} C. S. Pollard,⁴⁶ V. Polychronakos,²⁹ D. Ponomarenko,¹¹² L. Pontecorvo,³⁶ S. Popa,^{27a} G. A. Popeneciu,^{27d} L. Portales,⁵ D. M. Portillo Quintero,⁵⁸ S. Pospisil,¹⁴² K. Potamianos,⁴⁶ I. N. Potrap,⁸⁰ C. J. Potter,³² H. Potti,¹¹ T. Poulsen,⁹⁷ J. Poveda,³⁶ T. D. Powell,¹⁴⁹ G. Pownall,⁴⁶ M. E. Pozo Astigarraga,³⁶ P. Pralavorio,¹⁰² S. Prell,⁷⁹ D. Price,¹⁰¹ M. Primavera,^{68a} S. Prince,¹⁰⁴ M. L. Proffitt,¹⁴⁸ N. Proklova,¹¹² K. Prokofiev,^{63c} F. Prokoshin,⁸⁰ S. Protopopescu,²⁹ J. Proudfoot,⁶ M. Przybycien,^{84a} D. Pudzha,¹³⁸ A. Puri,¹⁷³ P. Puzo,⁶⁵ J. Qian,¹⁰⁶ Y. Qin,¹⁰¹ A. Quadt,⁵³ M. Queitsch-Maitland,³⁶ A. Qureshi,¹ M. Racko,^{28a} F. Ragusa,^{69a,69b} G. Rahal,⁹⁸ J. A. Raine,⁵⁴ S. Rajagopalan,²⁹ A. Ramirez Morales,⁹³ K. Ran,^{15a,15d} T. Rashid,⁶⁵ S. Raspopov,⁵ D. M. Rauch,⁴⁶ F. Rauscher,¹¹⁴ S. Rave,¹⁰⁰ B. Ravina,¹⁴⁹ I. Ravinovich,¹⁸⁰ J. H. Rawling,¹⁰¹ M. Raymond,³⁶ A. L. Read,¹³⁴ N. P. Readioff,⁵⁸ M. Reale,^{68a,68b} D. M. Rebuffi,^{71a,71b} A. Redelbach,¹⁷⁷ G. Redlinger,²⁹ K. Reeves,⁴³ L. Rehnisch,¹⁹ J. Reichert,¹³⁷ D. Reikher,¹⁶¹ A. Reiss,¹⁰⁰ A. Rej,¹⁵¹ C. Rembser,³⁶ M. Renda,^{27b} M. Rescigno,^{73a} S. Resconi,^{69a} E. D. Resseguie,¹³⁷ S. Rettie,¹⁷⁵ B. Reynolds,¹²⁷ E. Reynolds,²¹ O. L. Rezanova,^{122b,122a} P. Reznicek,¹⁴³ E. Ricci,^{76a,76b} R. Richter,¹¹⁵ S. Richter,⁴⁶ E. Richter-Was,^{84b} O. Ricken,²⁴ M. Ridel,¹³⁶ P. Rieck,¹¹⁵ O. Rifki,⁴⁶ M. Rijssenbeek,¹⁵⁵ A. Rimoldi,^{71a,71b} M. Rimoldi,⁴⁶ L. Rinaldi,^{23b} G. Ripellino,¹⁵⁴ I. Riu,¹⁴ J. C. Rivera Vergara,¹⁷⁶ F. Rizatdinova,¹³⁰ E. Rizvi,⁹³ C. Rizzi,³⁶ R. T. Roberts,¹⁰¹ S. H. Robertson,^{104,m} M. Robin,⁴⁶ D. Robinson,³² J. E. M. Robinson,⁴⁶ C. M. Robles Gajardo,^{147d} A. Robson,⁵⁷ A. Rocchi,^{74a,74b} E. Rocco,¹⁰⁰ C. Roda,^{72a,72b} S. Rodriguez Bosca,¹⁷⁴ A. Rodriguez Perez,¹⁴ D. Rodriguez Rodriguez,¹⁷⁴ A. M. Rodriguez Vera,^{168b} S. Roe,³⁶ O. Röhne,¹³⁴ R. Röhrig,¹¹⁵ R. A. Rojas,^{147d} C. P. A. Roland,⁶⁶ J. Roloff,²⁹ A. Romaniouk,¹¹² M. Romano,^{23b,23a} N. Rompotis,⁹¹ M. Ronzani,¹²⁵ L. Roos,¹³⁶ S. Rosati,^{73a} G. Rosin,¹⁰³ B. J. Rosser,¹³⁷ E. Rossi,⁴⁶ E. Rossi,^{75a,75b} E. Rossi,^{70a,70b} L. P. Rossi,^{55b} L. Rossini,^{69a,69b} R. Rosten,¹⁴ M. Rotaru,^{27b} J. Rothberg,¹⁴⁸ D. Rousseau,⁶⁵ G. Rovelli,^{71a,71b} A. Roy,¹¹ D. Roy,^{33e} A. Rozanov,¹⁰² Y. Rozen,¹⁶⁰ X. Ruan,^{33e} F. Rühr,⁵² A. Ruiz-Martinez,¹⁷⁴ A. Rummler,³⁶ Z. Rurikova,⁵² N. A. Rusakovich,⁸⁰ H. L. Russell,¹⁰⁴ L. Rustige,^{38,47} J. P. Rutherford,⁷ E. M. Rüttinger,¹⁴⁹ M. Rybar,³⁹ G. Rybkin,⁶⁵ E. B. Rye,¹³⁴ A. Ryzhov,¹²³ J. A. Sabater Iglesias,⁴⁶ P. Sabatini,⁵³ G. Sabato,¹²⁰ S. Sacerdoti,⁶⁵ H. F.-W. Sadrozinski,¹⁴⁶ R. Sadykov,⁸⁰ F. Safai Tehrani,^{73a} B. Safarzadeh Samani,¹⁵⁶ P. Saha,¹²¹ S. Saha,¹⁰⁴ M. Sahinsoy,^{61a} A. Sahu,¹⁸² M. Saimpert,⁴⁶ M. Saito,¹⁶³ T. Saito,¹⁶³ H. Sakamoto,¹⁶³ A. Sakharov,^{125,cc} D. Salamani,⁵⁴ G. Salamanna,^{75a,75b} J. E. Salazar Loyola,^{147d} A. Salnikov,¹⁵³ J. Salt,¹⁷⁴ D. Salvatore,^{41b,41a} F. Salvatore,¹⁵⁶ A. Salvucci,^{63a,63b,63c} A. Salzburger,³⁶ J. Samarati,³⁶ D. Sammel,⁵² D. Sampsonidis,¹⁶² D. Sampsonidou,¹⁶² J. Sánchez,¹⁷⁴ A. Sanchez Pineda,^{67a,36,67c} H. Sandaker,¹³⁴ C. O. Sander,⁴⁶ I. G. Sanderswood,⁹⁰ M. Sandhoff,¹⁸² C. Sandoval,^{22a} D. P. C. Sankey,¹⁴⁴ M. Sannino,^{55b,55a} Y. Sano,¹¹⁷ A. Sansoni,⁵¹ C. Santoni,³⁸ H. Santos,^{140a,140b} S. N. Santpur,¹⁸ A. Santra,¹⁷⁴ A. Saponov,⁸⁰ J. G. Saraiva,^{140a,140d} O. Sasaki,⁸² K. Sato,¹⁶⁹ F. Sauerburger,⁵² E. Sauvan,⁵ P. Savard,^{167,d} N. Savic,¹¹⁵ R. Sawada,¹⁶³ C. Sawyer,¹⁴⁴ L. Sawyer,^{96,ij} C. Sbarra,^{23b} A. Sbrizzi,^{23a} T. Scanlon,⁹⁵ J. Schaarschmidt,¹⁴⁸ P. Schacht,¹¹⁵ B. M. Schachtner,¹¹⁴ D. Schaefer,³⁷ L. Schaefer,¹³⁷ J. Schaeffer,¹⁰⁰ S. Schaepe,³⁶ U. Schäfer,¹⁰⁰ A. C. Schaffer,⁶⁵ D. Schaile,¹¹⁴ R. D. Schamberger,¹⁵⁵ N. Scharmberg,¹⁰¹ V. A. Schegelsky,¹³⁸ D. Scheirich,¹⁴³ F. Schenck,¹⁹ M. Schernau,¹⁷¹ C. Schiavi,^{55b,55a} S. Schier,¹⁴⁶ L. K. Schildgen,²⁴

Z. M. Schillaci,²⁶ E. J. Schioppa,³⁶ M. Schioppa,^{41b,41a} K. E. Schleicher,⁵² S. Schlenker,³⁶ K. R. Schmidt-Sommerfeld,¹¹⁵
 K. Schmieden,³⁶ C. Schmitt,¹⁰⁰ S. Schmitt,⁴⁶ S. Schmitz,¹⁰⁰ J. C. Schmoedel,⁴⁶ U. Schnoor,⁵² L. Schoeffel,¹⁴⁵
 A. Schoening,^{61b} P. G. Scholer,⁵² E. Schopf,¹³⁵ M. Schott,¹⁰⁰ J. F. P. Schouwenberg,¹¹⁹ J. Schovancova,³⁶ S. Schramm,⁵⁴
 F. Schroeder,¹⁸² A. Schulte,¹⁰⁰ H-C. Schultz-Coulon,^{61a} M. Schumacher,⁵² B. A. Schumm,¹⁴⁶ Ph. Schune,¹⁴⁵
 A. Schwartzman,¹⁵³ T. A. Schwarz,¹⁰⁶ Ph. Schwemling,¹⁴⁵ R. Schwienhorst,¹⁰⁷ A. Sciandra,¹⁴⁶ G. Sciolla,²⁶
 M. Scodreggio,⁴⁶ M. Scornajenghi,^{41b,41a} F. Scuri,^{72a} F. Scutti,¹⁰⁵ L. M. Scyboz,¹¹⁵ C. D. Sebastiani,^{73a,73b} P. Seema,¹⁹
 S. C. Seidel,¹¹⁸ A. Seiden,¹⁴⁶ B. D. Seidlitz,²⁹ T. Seiss,³⁷ J. M. Seixas,^{81b} G. Sekhniaidze,^{70a} K. Sekhon,¹⁰⁶ S. J. Sekula,⁴²
 N. Semprini-Cesari,^{23b,23a} S. Sen,⁴⁹ C. Serfon,⁷⁷ L. Serin,⁶⁵ L. Serkin,^{67a,67b} M. Sessa,^{60a} H. Severini,¹²⁹ T. Šfiligoj,⁹²
 F. Sforza,^{55b,55a} A. Sfyrla,⁵⁴ E. Shabalina,⁵³ J. D. Shahinian,¹⁴⁶ N. W. Shaikh,^{45a,45b} D. Shaked Renous,¹⁸⁰ L. Y. Shan,^{15a}
 J. T. Shank,²⁵ M. Shapiro,¹⁸ A. Sharma,¹³⁵ A. S. Sharma,¹ P. B. Shatalov,¹²⁴ K. Shaw,¹⁵⁶ S. M. Shaw,¹⁰¹ M. Shehade,¹⁸⁰
 Y. Shen,¹²⁹ A. D. Sherman,²⁵ P. Sherwood,⁹⁵ L. Shi,^{158,kk} S. Shimizu,⁸² C. O. Shimmin,¹⁸³ Y. Shimogama,¹⁷⁹
 M. Shimojima,¹¹⁶ I. P. J. Shipsey,¹³⁵ S. Shirabe,¹⁶⁵ M. Shiyakova,^{80,ll} J. Shlomi,¹⁸⁰ A. Shmeleva,¹¹¹ M. J. Shochet,³⁷
 J. Shojaii,¹⁰⁵ D. R. Shope,¹²⁹ S. Shrestha,¹²⁷ E. M. Shrif,^{33e} E. Shulga,¹⁸⁰ P. Sicho,¹⁴¹ A. M. Sickles,¹⁷³ P. E. Sidebo,¹⁵⁴
 E. Sideras Haddad,^{33e} O. Sidiropoulou,³⁶ A. Sidoti,^{23b,23a} F. Siegert,⁴⁸ Dj. Sijacki,¹⁶ M. Silva Jr.,¹⁸¹ M. V. Silva Oliveira,^{81a}
 S. B. Silverstein,^{45a} S. Simion,⁶⁵ R. Simoniello,¹⁰⁰ S. Simsek,^{12b} P. Sinervo,¹⁶⁷ V. Sinetckii,¹¹³ N. B. Sinev,¹³² S. Singh,¹⁵²
 M. Sioli,^{23b,23a} I. Siral,¹³² S. Yu. Sivoklov,¹¹³ J. Sjölin,^{45a,45b} E. Skorda,⁹⁷ P. Skubic,¹²⁹ M. Slawinska,⁸⁵ K. Sliwa,¹⁷⁰
 R. Slovak,¹⁴³ V. Smakhtin,¹⁸⁰ B. H. Smart,¹⁴⁴ J. Smiesko,^{28a} N. Smirnov,¹¹² S. Yu. Smirnov,¹¹² Y. Smirnov,¹¹²
 L. N. Smirnova,^{113,mm} O. Smirnova,⁹⁷ J. W. Smith,⁵³ M. Smizanska,⁹⁰ K. Smolek,¹⁴² A. Smykiewicz,⁸⁵ A. A. Snesev,¹¹¹
 H. L. Snoek,¹²⁰ I. M. Snyder,¹³² S. Snyder,²⁹ R. Sobie,^{176,m} A. Soffer,¹⁶¹ A. Søggaard,⁵⁰ F. Sohns,⁵³ C. A. Solans Sanchez,³⁶
 E. Yu. Soldatov,¹¹² U. Soldevila,¹⁷⁴ A. A. Solodkov,¹²³ A. Soloshenko,⁸⁰ O. V. Solovyanov,¹²³ V. Solovyeu,¹³⁸ P. Sommer,¹⁴⁹
 H. Son,¹⁷⁰ W. Song,¹⁴⁴ W. Y. Song,^{168b} A. Sopczak,¹⁴² A. L. Soppio,⁹⁵ F. Sopkova,^{28b} C. L. Sotiropoulou,^{72a,72b}
 S. Sottocornola,^{71a,71b} R. Soualah,^{67a,67c,nn} A. M. Soukharev,^{122b,122a} D. South,⁴⁶ S. Spagnolo,^{68a,68b} M. Spalla,¹¹⁵
 M. Spangenberg,¹⁷⁸ F. Spanò,⁹⁴ D. Sperlich,⁵² T. M. Spieker,^{61a} R. Spighi,^{23b} G. Spigo,³⁶ M. Spina,¹⁵⁶ D. P. Spiteri,⁵⁷
 M. Spousta,¹⁴³ A. Stabile,^{69a,69b} B. L. Stamas,¹²¹ R. Stamen,^{61a} M. Stamenkovic,¹²⁰ E. Stanecka,⁸⁵ B. Stanislaus,¹³⁵
 M. M. Stanitzki,⁴⁶ M. Stankaityte,¹³⁵ B. Stapf,¹²⁰ E. A. Starchenko,¹²³ G. H. Stark,¹⁴⁶ J. Stark,⁵⁸ S. H. Stark,⁴⁰ P. Staroba,¹⁴¹
 P. Starovoitov,^{61a} S. Stärz,¹⁰⁴ R. Staszewski,⁸⁵ G. Stavropoulos,⁴⁴ M. Stegler,⁴⁶ P. Steinberg,²⁹ A. L. Steinhebel,¹³²
 B. Stelzer,¹⁵² H. J. Stelzer,¹³⁹ O. Stelzer-Chilton,^{168a} H. Stenzel,⁵⁶ T. J. Stevenson,¹⁵⁶ G. A. Stewart,³⁶ M. C. Stockton,³⁶
 G. Stoicica,^{27b} M. Stolarski,^{140a} S. Stonjek,¹¹⁵ A. Straessner,⁴⁸ J. Strandberg,¹⁵⁴ S. Strandberg,^{45a,45b} M. Strauss,¹²⁹
 P. Strizenec,^{28b} R. Ströhmer,¹⁷⁷ D. M. Strom,¹³² R. Stroynowski,⁴² A. Strubig,⁵⁰ S. A. Stucci,²⁹ B. Stugu,¹⁷ J. Stupak,¹²⁹
 N. A. Styles,⁴⁶ D. Su,¹⁵³ S. Suchek,^{61a} V. V. Sulin,¹¹¹ M. J. Sullivan,⁹¹ D. M. S. Sultan,⁵⁴ S. Sultansoy,^{4c} T. Sumida,⁸⁶
 S. Sun,¹⁰⁶ X. Sun,³ K. Suruliz,¹⁵⁶ C. J. E. Suster,¹⁵⁷ M. R. Sutton,¹⁵⁶ S. Suzuki,⁸² M. Svatos,¹⁴¹ M. Swiatlowski,³⁷
 S. P. Swift,² T. Swirski,¹⁷⁷ A. Sydorenko,¹⁰⁰ I. Sykora,^{28a} M. Sykora,¹⁴³ T. Sykora,¹⁴³ D. Ta,¹⁰⁰ K. Tackmann,^{46,oo}
 J. Taenzer,¹⁶¹ A. Taffard,¹⁷¹ R. Tafirout,^{168a} H. Takai,²⁹ R. Takashima,⁸⁷ K. Takeda,⁸³ T. Takeshita,¹⁵⁰ E. P. Takeva,⁵⁰
 Y. Takubo,⁸² M. Talby,¹⁰² A. A. Talyshv,^{122b,122a} N. M. Tamir,¹⁶¹ J. Tanaka,¹⁶³ M. Tanaka,¹⁶⁵ R. Tanaka,⁶⁵ S. Tapia Araya,¹⁷³
 S. Tapprogge,¹⁰⁰ A. Tarek Abouelfadl Mohamed,¹³⁶ S. Tarem,¹⁶⁰ K. Tariq,^{60b} G. Tarna,^{27b,pp} G. F. Tartarelli,^{69a} P. Tas,¹⁴³
 M. Tasevsky,¹⁴¹ T. Tashiro,⁸⁶ E. Tassi,^{41b,41a} A. Tavares Delgado,^{140a} Y. Tayalati,^{35e} A. J. Taylor,⁵⁰ G. N. Taylor,¹⁰⁵
 W. Taylor,^{168b} A. S. Tee,⁹⁰ R. Teixeira De Lima,¹⁵³ P. Teixeira-Dias,⁹⁴ H. Ten Kate,³⁶ J. J. Teoh,¹²⁰ S. Terada,⁸² K. Terashi,¹⁶³
 J. Terron,⁹⁹ S. Terzo,¹⁴ M. Testa,⁵¹ R. J. Teuscher,^{167,m} S. J. Thais,¹⁸³ T. Thevenaux-Pelzer,⁴⁶ F. Thiele,⁴⁰ D. W. Thomas,⁹⁴
 J. O. Thomas,⁴² J. P. Thomas,²¹ A. S. Thompson,⁵⁷ P. D. Thompson,²¹ L. A. Thomsen,¹⁸³ E. Thomson,¹³⁷ E. J. Thorpe,⁹³
 R. E. Tisce Torres,⁵³ V. O. Tikhomirov,^{111,qq} Yu. A. Tikhonov,^{122b,122a} S. Timoshenko,¹¹² P. Tipton,¹⁸³ S. Tisserant,¹⁰²
 K. Todome,^{23b,23a} S. Todorova-Nova,⁵ S. Todt,⁴⁸ J. Tojo,⁸⁸ S. Tokár,^{28a} K. Tokushuku,⁸² E. Tolley,¹²⁷ K. G. Tomiwa,^{33e}
 M. Tomoto,¹¹⁷ L. Tompkins,^{153,bb} B. Tong,⁵⁹ P. Tornambe,¹⁰³ E. Torrence,¹³² H. Torres,⁴⁸ E. Torró Pastor,¹⁴⁸ C. Tosciri,¹³⁵
 J. Toth,^{102,rr} D. R. Tovey,¹⁴⁹ A. Traet,¹⁷ C. J. Treado,¹²⁵ T. Trefzger,¹⁷⁷ F. Tresoldi,¹⁵⁶ A. Tricoli,²⁹ I. M. Trigger,^{168a}
 S. Trincaz-Duvoid,¹³⁶ D. A. Trischuk,¹⁷⁵ W. Trischuk,¹⁶⁷ B. Trocmé,⁵⁸ A. Trofymov,¹⁴⁵ C. Troncon,^{69a} M. Trovatelli,¹⁷⁶
 F. Trovato,¹⁵⁶ L. Truong,^{33c} M. Trzebinski,⁸⁵ A. Trzupek,⁸⁵ F. Tsai,⁴⁶ J.C-L. Tseng,¹³⁵ P. V. Tsiarehka,^{108,dd}
 A. Tsigotis,^{162,ee} V. Tsiskaridze,¹⁵⁵ E. G. Tskhadadze,^{159a} M. Tsopoulou,¹⁶² I. I. Tsukerman,¹²⁴ V. Tsulaia,¹⁸ S. Tsuno,⁸²
 D. Tsybychev,¹⁵⁵ Y. Tu,^{63b} A. Tudorache,^{27b} V. Tudorache,^{27b} T. T. Tulbure,^{27a} A. N. Tuna,⁵⁹ S. Turchikhin,⁸⁰
 D. Turgeman,¹⁸⁰ I. Turk Cakir,^{4b,ss} R. J. Turner,²¹ R. T. Turra,^{69a} P. M. Tuts,³⁹ S. Tzamarias,¹⁶² E. Tzovara,¹⁰⁰ G. Ucchielli,⁴⁷
 K. Uchida,¹⁶³ I. Ueda,⁸² F. Ukegawa,¹⁶⁹ G. Unal,³⁶ A. Undrus,²⁹ G. Unel,¹⁷¹ F. C. Ungaro,¹⁰⁵ Y. Unno,⁸² K. Uno,¹⁶³

J. Urban,^{28b} P. Urquijo,¹⁰⁵ G. Usai,⁸ Z. Uysal,^{12d} V. Vacek,¹⁴² B. Vachon,¹⁰⁴ K. O. H. Vadla,¹³⁴ A. Vaidya,⁹⁵ C. Valderanis,¹¹⁴
 E. Valdes Santurio,^{45a,45b} M. Valente,⁵⁴ S. Valentinetti,^{23b,23a} A. Valero,¹⁷⁴ L. Valéry,⁴⁶ R. A. Vallance,²¹ A. Vallier,³⁶
 J. A. Valls Ferrer,¹⁷⁴ T. R. Van Daalen,¹⁴ P. Van Gemmeren,⁶ I. Van Vulpen,¹²⁰ M. Vanadia,^{74a,74b} W. Vandelli,³⁶
 M. Vandenbroucke,¹⁴⁵ E. R. Vandewall,¹³⁰ A. Vaniachine,¹⁶⁶ D. Vannicola,^{73a,73b} R. Vari,^{73a} E. W. Varnes,⁷ C. Varni,^{55b,55a}
 T. Varol,¹⁵⁸ D. Varouchas,⁶⁵ K. E. Varvell,¹⁵⁷ M. E. Vasile,^{27b} G. A. Vasquez,¹⁷⁶ F. Vazeille,³⁸ D. Vazquez Furelos,¹⁴
 T. Vazquez Schroeder,³⁶ J. Veatch,⁵³ V. Vecchio,^{75a,75b} M. J. Veen,¹²⁰ L. M. Veloce,¹⁶⁷ F. Veloso,^{140a,140c} S. Veneziano,^{73a}
 A. Ventura,^{68a,68b} N. Venturi,³⁶ A. Verbytskyi,¹¹⁵ V. Vercesi,^{71a} M. Verducci,^{72a,72b} C. M. Vergel Infante,⁷⁹ C. Vergis,²⁴
 W. Verkerke,¹²⁰ A. T. Vermeulen,¹²⁰ J. C. Vermeulen,¹²⁰ M. C. Vetterli,^{152,d} N. Viaux Maira,^{147d} M. Vicente Barreto Pinto,⁵⁴
 T. Vickey,¹⁴⁹ O. E. Vickey Boeriu,¹⁴⁹ G. H. A. Viehhauser,¹³⁵ L. Vigani,^{61b} M. Villa,^{23b,23a} M. Villaplana Perez,^{69a,69b}
 E. Vilucchi,⁵¹ M. G. Vinciter,³⁴ G. S. Virdee,²¹ A. Vishwakarma,⁴⁶ C. Vittori,^{23b,23a} I. Vivarelli,¹⁵⁶ M. Vogel,¹⁸² P. Vokac,¹⁴²
 S. E. von Buddenbrock,^{33e} E. Von Toerne,²⁴ V. Vorobel,¹⁴³ K. Vorobev,¹¹² M. Vos,¹⁷⁴ J. H. Vosseveld,⁹¹ M. Vozak,¹⁰¹
 N. Vranjes,¹⁶ M. Vranjes Milosavljevic,¹⁶ V. Vrba,¹⁴² M. Vreeswijk,¹²⁰ R. Vuillermet,³⁶ I. Vukotic,³⁷ P. Wagner,²⁴
 W. Wagner,¹⁸² J. Wagner-Kuhr,¹¹⁴ S. Wahdan,¹⁸² H. Wahlberg,⁸⁹ V. M. Walbrecht,¹¹⁵ J. Walder,⁹⁰ R. Walker,¹¹⁴
 S. D. Walker,⁹⁴ W. Walkowiak,¹⁵¹ V. Wallangen,^{45a,45b} A. M. Wang,⁵⁹ C. Wang,^{60c} C. Wang,^{60b} F. Wang,¹⁸¹ H. Wang,¹⁸
 H. Wang,³ J. Wang,^{63a} J. Wang,¹⁵⁷ J. Wang,^{61b} P. Wang,⁴² Q. Wang,¹²⁹ R.-J. Wang,¹⁰⁰ R. Wang,^{60a} R. Wang,⁶ S. M. Wang,¹⁵⁸
 W. T. Wang,^{60a} W. Wang,^{15c} W. X. Wang,^{60a} Y. Wang,^{60a} Z. Wang,^{60c} C. Wanotayaroj,⁴⁶ A. Warburton,¹⁰⁴ C. P. Ward,³²
 D. R. Wardrope,⁹⁵ N. Warrack,⁵⁷ A. Washbrook,⁵⁰ A. T. Watson,²¹ M. F. Watson,²¹ G. Watts,¹⁴⁸ B. M. Waugh,⁹⁵
 A. F. Webb,¹¹ S. Webb,¹⁰⁰ C. Weber,¹⁸³ M. S. Weber,²⁰ S. A. Weber,³⁴ S. M. Weber,^{61a} A. R. Weidberg,¹³⁵ J. Weingarten,⁴⁷
 M. Weirich,¹⁰⁰ C. Weiser,⁵² P. S. Wells,³⁶ T. Wenaus,²⁹ T. Wengler,³⁶ S. Wenig,³⁶ N. Vermes,²⁴ M. D. Werner,⁷⁹
 M. Wessels,^{61a} T. D. Weston,²⁰ K. Whalen,¹³² N. L. Whallon,¹⁴⁸ A. M. Wharton,⁹⁰ A. S. White,¹⁰⁶ A. White,⁸ M. J. White,¹
 D. Whiteson,¹⁷¹ B. W. Whitmore,⁹⁰ W. Wiedenmann,¹⁸¹ M. Wielers,¹⁴⁴ N. Wieseotte,¹⁰⁰ C. Wiglesworth,⁴⁰
 L. A. M. Wiik-Fuchs,⁵² F. Wilk,¹⁰¹ H. G. Wilkens,³⁶ L. J. Wilkins,⁹⁴ H. H. Williams,¹³⁷ S. Williams,³² C. Willis,¹⁰⁷
 S. Willocq,¹⁰³ J. A. Wilson,²¹ I. Wingerter-Seez,⁵ E. Winkels,¹⁵⁶ F. Winklmeier,¹³² O. J. Winston,¹⁵⁶ B. T. Winter,⁵²
 M. Wittgen,¹⁵³ M. Wobisch,⁹⁶ A. Wolf,¹⁰⁰ T. M. H. Wolf,¹²⁰ R. Wolff,¹⁰² R. Wölker,¹³⁵ J. Wollrath,⁵² M. W. Wolter,⁸⁵
 H. Wolters,^{140a,140c} V. W. S. Wong,¹⁷⁵ N. L. Woods,¹⁴⁶ S. D. Worm,²¹ B. K. Wosiek,⁸⁵ K. W. Woźniak,⁸⁵ K. Wraight,⁵⁷
 S. L. Wu,¹⁸¹ X. Wu,⁵⁴ Y. Wu,^{60a} T. R. Wyatt,¹⁰¹ B. M. Wynne,⁵⁰ S. Xella,⁴⁰ Z. Xi,¹⁰⁶ L. Xia,¹⁷⁸ X. Xiao,¹⁰⁶ I. Xiotidis,¹⁵⁶
 D. Xu,^{15a} H. Xu,^{60a,pp} L. Xu,²⁹ T. Xu,¹⁴⁵ W. Xu,¹⁰⁶ Z. Xu,^{60b} Z. Xu,¹⁵³ B. Yabsley,¹⁵⁷ S. Yacoob,^{33a} K. Yajima,¹³³
 D. P. Yallup,⁹⁵ N. Yamaguchi,⁸⁸ Y. Yamaguchi,¹⁶⁵ A. Yamamoto,⁸² M. Yamatani,¹⁶³ T. Yamazaki,¹⁶³ Y. Yamazaki,⁸³
 Z. Yan,²⁵ H. J. Yang,^{60c,60d} H. T. Yang,¹⁸ S. Yang,⁷⁸ X. Yang,^{60b,58} Y. Yang,¹⁶³ W.-M. Yao,¹⁸ Y. C. Yap,⁴⁶ Y. Yasu,⁸²
 E. Yatsenko,^{60c,60d} J. Ye,⁴² S. Ye,²⁹ I. Yeletsikh,⁸⁰ M. R. Yexley,⁹⁰ E. Yigitbasi,²⁵ K. Yorita,¹⁷⁹ K. Yoshihara,¹³⁷
 C. J. S. Young,³⁶ C. Young,¹⁵³ J. Yu,⁷⁹ R. Yuan,^{60b,tt} X. Yue,^{61a} S. P. Y. Yuen,²⁴ M. Zaazoua,^{35e} B. Zabinski,⁸⁵ G. Zacharis,¹⁰
 E. Zaffaroni,⁵⁴ J. Zahreddine,¹³⁶ A. M. Zaitsev,^{123,hh} T. Zakareishvili,^{159b} N. Zakharchuk,³⁴ S. Zambito,⁵⁹ D. Zanzi,³⁶
 D. R. Zariповas,⁵⁷ S. V. Zeißner,⁴⁷ C. Zeitnitz,¹⁸² G. Zemaityte,¹³⁵ J. C. Zeng,¹⁷³ O. Zenin,¹²³ T. Ženiš,^{28a} D. Zerwas,⁶⁵
 M. Zgubič,¹³⁵ B. Zhang,^{15c} D. F. Zhang,^{15b} G. Zhang,^{15b} H. Zhang,^{15c} J. Zhang,⁶ L. Zhang,^{15c} L. Zhang,^{60a} M. Zhang,¹⁷³
 R. Zhang,¹⁸¹ S. Zhang,¹⁰⁶ X. Zhang,^{60b} Y. Zhang,^{15a,15d} Z. Zhang,^{63a} Z. Zhang,⁶⁵ P. Zhao,⁴⁹ Y. Zhao,^{60b} Z. Zhao,^{60a}
 A. Zhemchugov,⁸⁰ Z. Zheng,¹⁰⁶ D. Zhong,¹⁷³ B. Zhou,¹⁰⁶ C. Zhou,¹⁸¹ M. S. Zhou,^{15a,15d} M. Zhou,¹⁵⁵ N. Zhou,^{60c} Y. Zhou,⁷
 C. G. Zhu,^{60b} C. Zhu,^{15a,15d} H. L. Zhu,^{60a} H. Zhu,^{15a} J. Zhu,¹⁰⁶ Y. Zhu,^{60a} X. Zhuang,^{15a} K. Zhukov,¹¹¹ V. Zhulanov,^{122b,122a}
 D. Zieminska,⁶⁶ N. I. Zimine,⁸⁰ S. Zimmermann,⁵² Z. Zinonos,¹¹⁵ M. Ziolkowski,¹⁵¹ L. Živković,¹⁶ G. Zobernig,¹⁸¹
 A. Zoccoli,^{23b,23a} K. Zoch,⁵³ T. G. Zorbas,¹⁴⁹ R. Zou,³⁷ and L. Zwalinski³⁶

(ATLAS Collaboration)

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

²Physics Department, SUNY Albany, Albany NY, United States of America

³Department of Physics, University of Alberta, Edmonton AB, Canada

^{4a}Department of Physics, Ankara University, Ankara, Turkey

^{4b}Istanbul Aydin University, Istanbul, Turkey

^{4c}Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

⁵LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

⁶High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

- ⁷Department of Physics, University of Arizona, Tucson AZ, United States of America
- ⁸Department of Physics, University of Texas at Arlington, Arlington TX, United States of America
- ⁹Physics Department, National and Kapodistrian University of Athens, Athens, Greece
- ¹⁰Physics Department, National Technical University of Athens, Zografou, Greece
- ¹¹Department of Physics, University of Texas at Austin, Austin TX, United States of America
- ^{12a}Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- ^{12b}Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- ^{12c}Department of Physics, Bogazici University, Istanbul, Turkey
- ^{12d}Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- ¹³Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹⁴Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
- ^{15a}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
- ^{15b}Physics Department, Tsinghua University, Beijing, China
- ^{15c}Department of Physics, Nanjing University, Nanjing, China
- ^{15d}University of Chinese Academy of Science (UCAS), Beijing, China
- ¹⁶Institute of Physics, University of Belgrade, Belgrade, Serbia
- ¹⁷Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁸Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
- ¹⁹Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
- ²⁰Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ²¹School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ^{22a}Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia
- ^{22b}Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia, Colombia
- ^{23a}INFN Bologna and Università di Bologna, Dipartimento di Fisica, Italy
- ^{23b}INFN Sezione di Bologna, Italy
- ²⁴Physikalisches Institut, Universität Bonn, Bonn, Germany
- ²⁵Department of Physics, Boston University, Boston MA, United States of America
- ²⁶Department of Physics, Brandeis University, Waltham MA, United States of America
- ^{27a}Transilvania University of Brasov, Brasov, Romania
- ^{27b}Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- ^{27c}Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
- ^{27d}National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
- ^{27e}University Politehnica Bucharest, Bucharest, Romania
- ^{27f}West University in Timisoara, Timisoara, Romania
- ^{28a}Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
- ^{28b}Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ²⁹Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- ³⁰Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ³¹California State University, CA, United States of America
- ³²Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ^{33a}Department of Physics, University of Cape Town, Cape Town, South Africa
- ^{33b}Themba Labs, Western Cape, South Africa
- ^{33c}Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
- ^{33d}University of South Africa, Department of Physics, Pretoria, South Africa
- ^{33e}School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ³⁴Department of Physics, Carleton University, Ottawa ON, Canada
- ^{35a}Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
- ^{35b}Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
- ^{35c}Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
- ^{35d}Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda, Morocco
- ^{35e}Faculté des sciences, Université Mohammed V, Rabat, Morocco
- ³⁶CERN, Geneva, Switzerland
- ³⁷Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- ³⁸LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
- ³⁹Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ⁴⁰Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ^{41a}Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ^{41b}INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy

- ⁴²*Physics Department, Southern Methodist University, Dallas TX, United States of America*
- ⁴³*Physics Department, University of Texas at Dallas, Richardson TX, United States of America*
- ⁴⁴*National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece*
- ^{45a}*Department of Physics, Stockholm University, Sweden*
- ^{45b}*Oskar Klein Centre, Stockholm, Sweden*
- ⁴⁶*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- ⁴⁷*Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- ⁴⁸*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- ⁴⁹*Department of Physics, Duke University, Durham NC, United States of America*
- ⁵⁰*SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵¹*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵²*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ⁵³*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁵⁴*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
- ^{55a}*Dipartimento di Fisica, Università di Genova, Genova, Italy*
- ^{55b}*INFN Sezione di Genova, Italy*
- ⁵⁶*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁷*SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁸*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- ⁵⁹*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America*
- ^{60a}*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- ^{60b}*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- ^{60c}*School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China*
- ^{60d}*Tsung-Dao Lee Institute, Shanghai, China*
- ^{61a}*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ^{61b}*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ⁶²*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- ^{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*Department of Physics, Indiana University, Bloomington IN, United States of America*
- ^{67a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
- ^{67b}*ICTP, Trieste, Italy*
- ^{67c}*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
- ^{68a}*INFN Sezione di Lecce, Italy*
- ^{68b}*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- ^{69a}*INFN Sezione di Milano, Italy*
- ^{69b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
- ^{70a}*INFN Sezione di Napoli, Italy*
- ^{70b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- ^{71a}*INFN Sezione di Pavia, Italy*
- ^{71b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ^{72a}*INFN Sezione di Pisa, Italy*
- ^{72b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ^{73a}*INFN Sezione di Roma, Italy*
- ^{73b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- ^{74a}*INFN Sezione di Roma Tor Vergata, Italy*
- ^{74b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ^{75a}*INFN Sezione di Roma Tre, Italy*
- ^{75b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- ^{76a}*INFN-TIFPA, Italy*
- ^{76b}*Università degli Studi di Trento, Trento, Italy*
- ⁷⁷*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
- ⁷⁸*University of Iowa, Iowa City IA, United States of America*
- ⁷⁹*Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America*

- ⁸⁰*Joint Institute for Nuclear Research, Dubna, Russia*
- ^{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}*Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil*
- ^{81d}*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- ⁸²*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- ⁸³*Graduate School of Science, Kobe University, Kobe, Japan*
- ^{84a}*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
- ^{84b}*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- ⁸⁵*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
- ⁸⁶*Faculty of Science, Kyoto University, Kyoto, Japan*
- ⁸⁷*Kyoto University of Education, Kyoto, Japan*
- ⁸⁸*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- ⁸⁹*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- ⁹⁰*Physics Department, Lancaster University, Lancaster, United Kingdom*
- ⁹¹*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁹²*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
- ⁹³*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- ⁹⁴*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
- ⁹⁵*Department of Physics and Astronomy, University College London, London, United Kingdom*
- ⁹⁶*Louisiana Tech University, Ruston LA, United States of America*
- ⁹⁷*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁹⁸*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- 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, 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*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
- ¹⁰⁹*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus*
- ¹¹⁰*Group of Particle Physics, University of Montreal, Montreal QC, Canada*
- ¹¹¹*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
- ¹¹²*National Research Nuclear University MEPhI, Moscow, Russia*
- ¹¹³*D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- ¹¹⁴*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ¹¹⁵*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ¹¹⁶*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ¹¹⁷*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ¹¹⁸*Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America*
- ¹¹⁹*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹²⁰*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹²¹*Department of Physics, Northern Illinois University, DeKalb IL, United States of America*
- ^{122a}*Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia*
- ^{122b}*Novosibirsk State University Novosibirsk, Russia*
- ¹²³*Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia*
- ¹²⁴*Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow, Russia*
- ¹²⁵*Department of Physics, New York University, New York NY, United States of America*
- ¹²⁶*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
- ¹²⁷*Ohio State University, Columbus OH, United States of America*
- ¹²⁸*Faculty of Science, Okayama University, Okayama, Japan*
- ¹²⁹*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America*
- ¹³⁰*Department of Physics, Oklahoma State University, Stillwater OK, United States of America*
- ¹³¹*Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic*
- ¹³²*Institute for Fundamental Science, University of Oregon, Eugene, OR, United States of America*

- ¹³³Graduate School of Science, Osaka University, Osaka, Japan
¹³⁴Department of Physics, University of Oslo, Oslo, Norway
¹³⁵Department of Physics, Oxford University, Oxford, United Kingdom
¹³⁶LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France
¹³⁷Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
¹³⁸Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
¹³⁹Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
^{140a}Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
^{140b}Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
^{140c}Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
^{140d}Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
^{140e}Departamento de Física, Universidade do Minho, Braga, Portugal
^{140f}Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
^{140g}Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
^{140h}Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
¹⁴¹Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
¹⁴²Czech Technical University in Prague, Prague, Czech Republic
¹⁴³Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
¹⁴⁴Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
¹⁴⁵IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
¹⁴⁶Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
^{147a}Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
^{147b}Universidad Andres Bello, Department of Physics, Santiago, Chile
^{147c}Instituto de Alta Investigación, Universidad de Tarapacá, Chile
^{147d}Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
¹⁴⁸Department of Physics, University of Washington, Seattle WA, United States of America
¹⁴⁹Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
¹⁵⁰Department of Physics, Shinshu University, Nagano, Japan
¹⁵¹Department Physik, Universität Siegen, Siegen, Germany
¹⁵²Department of Physics, Simon Fraser University, Burnaby BC, Canada
¹⁵³SLAC National Accelerator Laboratory, Stanford CA, United States of America
¹⁵⁴Physics Department, Royal Institute of Technology, Stockholm, Sweden
¹⁵⁵Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
¹⁵⁶Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
¹⁵⁷School of Physics, University of Sydney, Sydney, Australia
¹⁵⁸Institute of Physics, Academia Sinica, Taipei, Taiwan
^{159a}E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi, Georgia
^{159b}High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
¹⁶⁰Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
¹⁶¹Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
¹⁶²Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
¹⁶³International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
¹⁶⁴Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
¹⁶⁵Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
¹⁶⁶Tomsk State University, Tomsk, Russia
¹⁶⁷Department of Physics, University of Toronto, Toronto ON, Canada
^{168a}TRIUMF, Vancouver BC, Canada
^{168b}Department of Physics and Astronomy, York University, Toronto ON, Canada
¹⁶⁹Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
¹⁷⁰Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
¹⁷¹Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
¹⁷²Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
¹⁷³Department of Physics, University of Illinois, Urbana IL, United States of America
¹⁷⁴Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
¹⁷⁵Department of Physics, University of British Columbia, Vancouver BC, Canada
¹⁷⁶Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
¹⁷⁷Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
¹⁷⁸Department of Physics, University of Warwick, Coventry, United Kingdom

¹⁷⁹*Waseda University, Tokyo, Japan*

¹⁸⁰*Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*

¹⁸¹*Department of Physics, University of Wisconsin, Madison WI, United States of America*

¹⁸²*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*

¹⁸³*Department of Physics, Yale University, New Haven CT, United States of America*

^aDeceased.

^bAlso at Department of Physics, King's College London, London, United Kingdom

^cAlso at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain

^dAlso at TRIUMF, Vancouver BC, Canada

^eAlso at Department of Physics and Astronomy, University of Louisville, Louisville, KY, United States of America

^fAlso at Physics Department, An-Najah National University, Nablus, Palestine

^gAlso at Department of Physics, California State University, Fresno, United States of America

^hAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland

ⁱAlso at Physics Dept, University of South Africa, Pretoria, South Africa

^jAlso at Departament de Fisica de la Universitat Autònoma de Barcelona, Barcelona, Spain

^kAlso at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel

^lAlso at Università di Napoli Parthenope, Napoli, Italy

^mAlso at Institute of Particle Physics (IPP), Vancouver, Canada

ⁿAlso at Department of Physics, University of Adelaide, Adelaide, Australia

^oAlso at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy

^pAlso at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia

^qAlso at Borough of Manhattan Community College, City University of New York, New York NY, United States of America

^rAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece

^sAlso at Department of Physics, California State University, East Bay, United States of America

^tAlso at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain

^uAlso at Department of Physics, University of Michigan, Ann Arbor MI, United States of America

^vAlso at IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France

^wAlso at Graduate School of Science, Osaka University, Osaka, Japan

^xAlso at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

^yAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

^zAlso at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

^{aa}Also at CERN, Geneva, Switzerland

^{bb}Also at Department of Physics, Stanford University, Stanford CA, United States of America

^{cc}Also at Manhattan College, New York NY, United States of America

^{dd}Also at Joint Institute for Nuclear Research, Dubna, Russia

^{ee}Also at Hellenic Open University, Patras, Greece

^{ff}Also at The City College of New York, New York NY, United States of America

^{gg}Also at Department of Physics, California State University, Sacramento, United States of America

^{hh}Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

ⁱⁱAlso at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland

^{jj}Also at Louisiana Tech University, Ruston LA, United States of America

^{kk}Also at School of Physics, Sun Yat-sen University, Guangzhou, China

^{ll}Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria

^{mm}Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

ⁿⁿAlso at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates

^{oo}Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

^{pp}Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

^{qq}Also at National Research Nuclear University MEPhI, Moscow, Russia

^{rr}Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

^{ss}Also at Giresun University, Faculty of Engineering, Giresun, Turkey

^{tt}Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America