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M. Aaboud et al. (ATLAS Collaboration)

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Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

ATLAS Collaboration[†]

Light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics. This reaction is accessible at the Large Hadron Collider thanks to the large electromagnetic field strengths generated by ultra-relativistic colliding lead ions. Using $480 \mu\text{b}^{-1}$ of lead-lead collision data recorded at a centre-of-mass energy per nucleon pair of 5.02 TeV by the ATLAS detector, here we report evidence for light-by-light scattering. A total of 13 candidate events were observed with an expected background of 2.6 ± 0.7 events. After background subtraction and analysis corrections, the fiducial cross-section of the process $\text{Pb} + \text{Pb} (\gamma\gamma) \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)}\gamma\gamma$, for photon transverse energy $E_T > 3 \text{ GeV}$, photon absolute pseudorapidity $|\eta| < 2.4$, diphoton invariant mass greater than 6 GeV, diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01, is measured to be 70 ± 24 (stat.) ± 17 (syst.) nb, which is in agreement with the standard model predictions.

One of the key features of Maxwell's equations is their linearity in both the sources and the fields, from which follows the superposition principle. This forbids effects such as light-by-light (LbyL) scattering, $\gamma\gamma \rightarrow \gamma\gamma$, which is a purely quantum-mechanical process. It was realized in the early history of quantum electrodynamics (QED) that LbyL scattering is related to the polarization of the vacuum¹. In the standard model of particle physics, the virtual particles that mediate the LbyL coupling are electrically charged fermions or W^\pm bosons. In QED, the $\gamma\gamma \rightarrow \gamma\gamma$ reaction proceeds at lowest order in the fine-structure constant (α_{em}) via virtual one-loop box diagrams involving fermions (Fig. 1a), which is an $\mathcal{O}(\alpha_{\text{em}}^4 \approx 3 \times 10^9)$ process, making it challenging to test experimentally. Indeed, the elastic LbyL scattering has remained unobserved: even the ultra-intense laser experiments are not yet powerful enough to probe this phenomenon².

LbyL scattering via an electron loop has been precisely, albeit indirectly, tested in measurements of the anomalous magnetic moment of the electron and muon^{3,4} where it is predicted to contribute substantially, as one of the QED corrections⁵. The $\gamma\gamma \rightarrow \gamma\gamma$ reaction has been measured in photon scattering in the Coulomb field of a nucleus (Delbrück scattering) at fixed photon energies below 7 GeV (refs 6–9). The analogous process, where a photon splits into two photons by interaction with external fields (photon splitting), has been observed in the energy region of 0.1–0.5 GeV (ref. 10). A related process involving only real photons, in which several photons fuse to form an electron–positron pair (e^+e^-), has been measured in ref. 11. Similarly, the multiphoton Compton scattering, in which up to four laser photons interact with an electron, has been observed¹².

An alternative way by which LbyL interactions can be studied is by using relativistic heavy-ion collisions. In ‘ultra-peripheral collision’ (UPC) events, with impact parameters larger than twice the radius of the nuclei^{13,14}, the strong interaction does not play a role. The electromagnetic (EM) field strengths of relativistic ions scale with the proton number (Z). For example, for a lead (Pb) nucleus with $Z = 82$ the field can be up to 10^{25} V m^{-1} (ref. 15), much larger than the Schwinger limit¹⁶ above which QED corrections become important. In the 1930s it was found that highly

relativistic charged particles can be described by the equivalent photon approximation (EPA)^{17–19}, which is schematically shown in Fig. 1b. The EM fields produced by the colliding Pb nuclei can be treated as a beam of quasi-real photons with a small virtuality of $Q^2 < 1/R^2$, where R is the radius of the charge distribution and so $Q^2 < 10^{-3} \text{ GeV}^2$. Then, the cross-section for the reaction $\text{Pb} + \text{Pb} (\gamma\gamma) \rightarrow \text{Pb} + \text{Pb} \gamma\gamma$ can be calculated by convolving the respective photon flux with the elementary cross-section for the process $\gamma\gamma \rightarrow \gamma\gamma$. Since the photon flux associated with each nucleus scales as Z^2 , the cross-section is extremely enhanced as compared with proton–proton (pp) collisions.

In this article, a measurement of LbyL scattering in Pb + Pb collisions at the Large Hadron Collider (LHC) is reported, following the approach recently proposed in ref. 20. The final-state signature of interest is the exclusive production of two photons, $\text{Pb} + \text{Pb} (\gamma\gamma) \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)}\gamma\gamma$, where a possible EM excitation of the outgoing ions²¹ is denoted by (*). Hence, the expected signature is two photons and no further activity in the central detector, since the $\text{Pb}^{(*)}$ ions escape into the LHC beam pipe. Moreover, it is predicted that the background is relatively low in heavy-ion collisions and is dominated by exclusive dielectron ($\gamma\gamma \rightarrow e^+e^-$) production^{20,22}. The misidentification of electrons as photons can occur when the electron track is not reconstructed or the electron emits a hard-bremsstrahlung photon. The fiducial cross-section of the process $\gamma\gamma \rightarrow \gamma\gamma$ in Pb + Pb collisions is measured, using a data set recorded at a nucleon–nucleon centre-of-mass energy ($\sqrt{s_{\text{NN}}}$) of 5.02 TeV. This data set was recorded with the ATLAS detector at the LHC in 2015 and corresponds to an integrated luminosity of $480 \pm 30 \mu\text{b}^{-1}$. In addition to the measured fiducial cross-section, the significance of the observed number of signal candidate events is given, assuming the background-only hypothesis.

Experimental set-up

ATLAS is a cylindrical particle detector composed of several sub-detectors²³. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z axis along the beam pipe. The x axis points from the interaction point to the centre of the LHC ring, and the y

[†]A full list of authors and affiliations appears at the end of the paper.

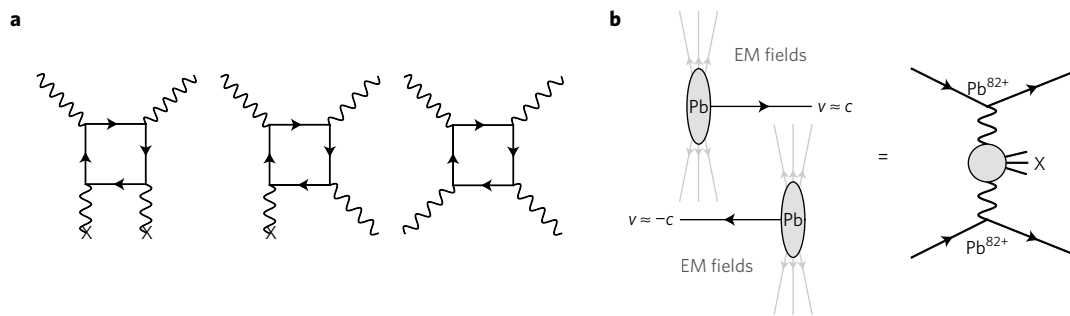


Figure 1 | Diagrams illustrating the QED LbyL interaction processes and the equivalent photon approximation. **a**, Diagrams for Delbrück scattering (left), photon splitting (middle) and elastic LbyL scattering (right). Each cross denotes external field legs, for example, an atomic Coulomb field or a strong background magnetic field. **b**, Illustration of an ultra-peripheral collision of two lead ions. Electromagnetic interaction between the ions can be described as an exchange of photons that can couple to form a given final state X. The flux of photons is determined from the Fourier transform of the electromagnetic field of the ion, taking into account the nuclear electromagnetic form factors.

axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, with ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The photon or electron transverse energy is $E_T = E \sin(\theta)$, where E is its energy. The inner tracking detector (ITD) consists of a silicon pixel system, a silicon microstrip detector and a straw-tube tracker immersed in a 2T magnetic field provided by a superconducting solenoid. The ITD track reconstruction efficiency is estimated in ref. 24 for minimum-bias pp events that, like UPC Pb + Pb events, have a low average track multiplicity. For charged hadrons in the transverse momentum range $100 < p_T < 200$ MeV the efficiency is about 50% and grows to 80% for $p_T > 200$ MeV. Around the tracker there is a system of EM and hadronic calorimeters, which use liquid argon and lead, copper or tungsten absorbers for the EM and forward ($|\eta| > 1.7$) hadronic components of the detector, and scintillator-tile active material and steel absorbers for the central ($|\eta| < 1.7$) hadronic component. The muon spectrometer consists of separate trigger and high-precision tracking chambers measuring the trajectory of muons in a magnetic field generated by superconducting air-core toroids. The ATLAS minimum-bias trigger scintillators (MBTSs) consist of scintillator slabs positioned between the ITD and the endcap calorimeters with each side having an outer ring of four slabs segmented in azimuthal angle, covering $2.07 < |\eta| < 2.76$ and an inner ring of eight slabs, covering $2.76 < |\eta| < 3.86$. The ATLAS zero-degree calorimeters (ZDCs), located along the beam axis at 140 m from the interaction point on both sides, detect neutral particles (including neutrons emitted from the nucleus). The ATLAS trigger system²⁵ consists of a Level-1 trigger implemented using a combination of dedicated electronics and programmable logic, and a software-based high-level trigger.

Monte Carlo simulation and theoretical predictions

Several Monte Carlo (MC) samples are produced to estimate background contributions and corrections to the fiducial measurement. The detector response is modelled using a simulation based on GEANT4 (refs 26,27). The data and MC simulated events are passed through the same reconstruction and analysis procedures.

LbyL signal events are generated taking into account box diagrams with charged leptons and quarks in the loops, as detailed in ref. 28. The contributions from W -boson loops are omitted in the calculations since they are mostly important for diphoton masses $m_{\gamma\gamma} > 2m_W$ (ref. 29). The calculations are then convolved with the Pb + Pb EPA spectrum from the STARlight 1.1 MC generator³⁰. Next, various diphoton kinematic distributions are cross-checked with predictions from ref. 20 and good agreement is found. The

theoretical uncertainty on the cross-section is mainly due to limited knowledge of the nuclear electromagnetic form factors and the related initial photon fluxes. This is studied in ref. 20 and the relevant uncertainty is conservatively estimated to be 20%. Higher-order corrections (not included in the calculations) are also part of the theoretical uncertainty and are of the order of a few per cent for diphoton invariant masses below 100 GeV (refs 31,32).

The sources of background considered in this analysis are: $\gamma\gamma \rightarrow e^+e^-$, central exclusive production (CEP) of photon pairs, exclusive production of quark-antiquark pairs ($\gamma\gamma \rightarrow q\bar{q}$) and other backgrounds that could mimic the diphoton event signatures. The $\gamma\gamma \rightarrow e^+e^-$ background is modelled with STARlight 1.1 (ref. 30), in which the cross-section is computed by combining the Pb + Pb EPA with the leading-order formula for $\gamma\gamma \rightarrow e^+e^-$. This process has been recently measured by the ALICE Collaboration, and a good agreement with STARlight is found³³. The exclusive diphoton final state can be also produced via the strong interaction through a quark loop in the exchange of two gluons in a colour-singlet state (see Supplementary Fig. 2). This CEP process, $gg \rightarrow \gamma\gamma$, is modelled using SUPERCHIC 2.03 (ref. 34), in which the pp cross-section has been scaled by $A^2 R_g^4$ as suggested in ref. 20, where $A = 208$ and $R_g \approx 0.7$ is a gluon shadowing correction³⁵. This process has a large theoretical uncertainty, of $\mathcal{O}(100\%)$, mostly related to incomplete knowledge of gluon densities³⁶. The $\gamma\gamma \rightarrow q\bar{q}$ contribution is estimated using Herwig++ 2.7.1 (ref. 37) where the EPA formalism in pp collisions is implemented. The $\gamma\gamma \rightarrow q\bar{q}$ sample is then normalized to the corresponding cross-section in Pb + Pb collisions³⁰.

Event selection

Candidate diphoton events were recorded in the Pb + Pb run in 2015 using a dedicated trigger for events with moderate activity in the calorimeter but little additional activity in the entire detector. At Level-1 the total E_T registered in the calorimeter after noise suppression was required to be between 5 and 200 GeV. Then at the high-level trigger, events were rejected if more than one hit was found in the inner ring of the MBTS (MBTS veto) or if more than ten hits were found in the pixel detector.

The efficiency of the Level-1 trigger is estimated with $\gamma\gamma \rightarrow e^+e^-$ events passing an independent supporting trigger. This trigger is designed to select events with mutual dissociation of Pb nuclei and small activity in the ITD. It is based on a coincidence of signals in both ZDC sides and a requirement on the total E_T in the calorimeter below 50 GeV. Event candidates are required to have only two reconstructed tracks and two EM energy clusters. Furthermore, to reduce possible backgrounds, each pair of clusters (cl1, cl2) is required to have a small acoplanarity ($1 - \Delta\phi_{cl1,cl2}/\pi < 0.2$). The extracted Level-1 trigger efficiency is provided as a function of the

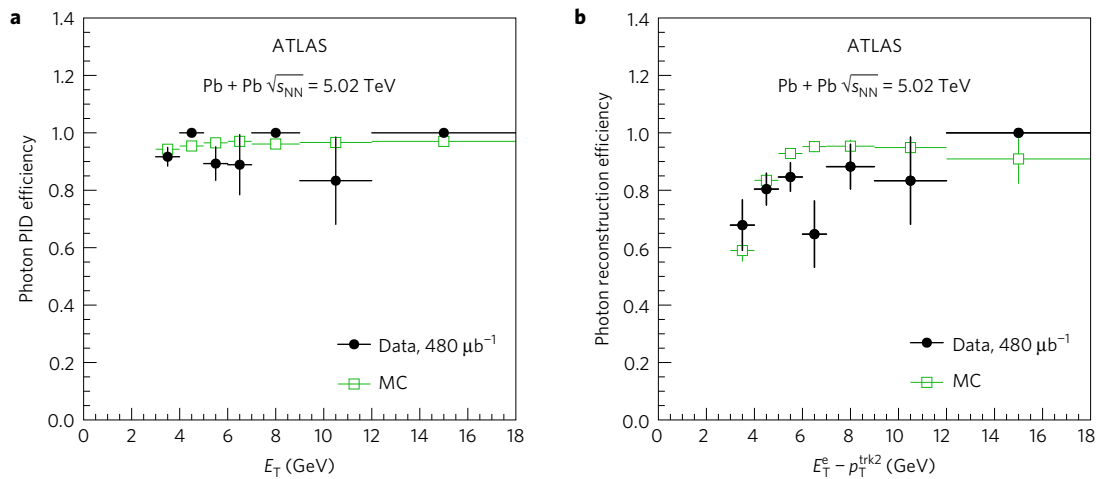


Figure 2 | Photon identification and reconstruction efficiencies. **a**, Photon PID efficiency as a function of photon E_T extracted from FSR event candidates. **b**, Photon reconstruction efficiency as a function of photon E_T (approximated with $E_T^e - p_T^{trk2}$) extracted from $\gamma\gamma \rightarrow e^+e^-$ events with a hard-bremsstrahlung photon. Data (filled markers) are compared with MC simulations (open markers). The statistical uncertainties arising from the finite size of the data and simulation samples are indicated by vertical bars.

sum of cluster transverse energies ($E_T^{cl1} + E_T^{cl2}$). The efficiency grows from about 70% at $(E_T^{cl1} + E_T^{cl2}) = 6$ GeV to 100% at $(E_T^{cl1} + E_T^{cl2}) > 9$ GeV. The efficiency is parameterized using an error function fit, which is then used to reweight the simulation. Due to the extremely low noise, very high hit reconstruction efficiency and low conversion probability of signal photons in the pixel detector (around 10%), the uncertainty due to the requirement for minimal activity in the ITD is negligible. The MBTS veto efficiency was studied using $\gamma\gamma \rightarrow \ell^+\ell^-$ events ($\ell = e, \mu$) passing a supporting trigger and it is estimated to be $(98 \pm 2)\%$.

Photons are reconstructed from EM clusters in the calorimeter and tracking information provided by the ITD, which allows the identification of photon conversions. Selection requirements are applied to remove EM clusters with a large amount of energy from poorly functioning calorimeter cells, and a timing requirement is made to reject out-of-time candidates. An energy calibration specifically optimized for photons³⁸ is applied to the candidates to account for upstream energy loss and both lateral and longitudinal shower leakage. A dedicated correction³⁹ is applied for photons in MC samples to correct for potential mismodelling of quantities that describe the properties ('shapes') of the associated EM showers.

The photon particle identification (PID) in this analysis is based on three shower-shape variables: the lateral width of the shower in the middle layer of the EM calorimeter, the ratio of the energy difference associated with the largest and second largest energy deposits to the sum of these energies in the first layer, and the fraction of energy reconstructed in the first layer relative to the total energy of the cluster. Only photons with $E_T > 3$ GeV and $|\eta| < 2.37$, excluding the calorimeter transition region $1.37 < |\eta| < 1.52$, are considered. The pseudorapidity requirement ensures that the photon candidates pass through regions of the EM calorimeter where the first layer is segmented into narrow strips, allowing for good separation between genuine prompt photons and photons coming from the decay of neutral hadrons. A constant photon PID efficiency of 95% as a function of η with respect to reconstructed photon candidates is maintained. This is optimized using multivariate analysis techniques⁴⁰, such that EM energy clusters induced by cosmic-ray muons are rejected with 95% efficiency.

Preselected events are required to have exactly two photons satisfying the above selection criteria, with a diphoton invariant mass greater than 6 GeV. To reduce the dielectron background, a veto on the presence of any charged-particle tracks (with $p_T > 100$ MeV, $|\eta| < 2.5$ and at least one hit in the pixel detector)

is imposed. This requirement further reduces the fake-photon background from the dielectron final state by a factor of 25, according to simulation. It has almost no impact on $\gamma\gamma \rightarrow \gamma\gamma$ signal events, since the probability of photon conversion in the pixel detector is relatively small and converted photons are suppressed at low E_T (3–6 GeV) by the photon selection requirements. According to MC studies, the photon selection requirements remove about 10% of low- E_T photons. To reduce other fake-photon backgrounds (for example, cosmic-ray muons), the transverse momentum of the diphoton system ($p_T^{\gamma\gamma}$) is required to be below 2 GeV. To reduce background from CEP $gg \rightarrow \gamma\gamma$ reactions, an additional requirement on diphoton acoplanarity, $A_{co} = 1 - \Delta\phi_{\gamma\gamma}/\pi < 0.01$, is imposed. This requirement is optimized to retain a high signal efficiency and reduce the CEP background significantly, since the transverse momentum transferred by the photon exchange is usually much smaller than that due to the colour-singlet-state gluons⁴¹.

Performance and validation of photon reconstruction

Since the analysis requires the presence of low-energy photons, which are not typically used in ATLAS analyses, detailed studies of photon reconstruction and calibration are performed.

High- p_T $\gamma\gamma \rightarrow \ell^+\ell^-$ production with a final-state radiation (FSR) photon is used for the measurement of the photon PID efficiency. Events with a photon and two tracks corresponding to oppositely charged particles with $p_T > 1$ GeV are required to pass the same trigger as in the diphoton selection or the supporting trigger. The ΔR between a photon candidate and a track is required to be greater than 0.2 to avoid leakage of the electron clusters from the $\gamma\gamma \rightarrow e^+e^-$ process to the photon cluster. The FSR event candidates are identified using a $p_T^{trk} < 1$ GeV requirement, where p_T^{trk} is the transverse momentum of the three-body system consisting of two charged-particle tracks and a photon. The FSR photons are then used to extract the photon PID efficiency, which is defined as the probability for a reconstructed photon to satisfy the identification criteria. Figure 2a shows the photon PID efficiencies in data and simulation as a function of reconstructed photon E_T . Within their statistical precision the two results agree.

The photon reconstruction efficiency is extracted from data using $\gamma\gamma \rightarrow e^+e^-$ events where one of the electrons emits a hard-bremsstrahlung photon due to interaction with the material of the detector. Events with exactly one identified electron, two reconstructed charged-particle tracks and exactly one photon are studied. The electron E_T is required to be above 5 GeV and the p_T

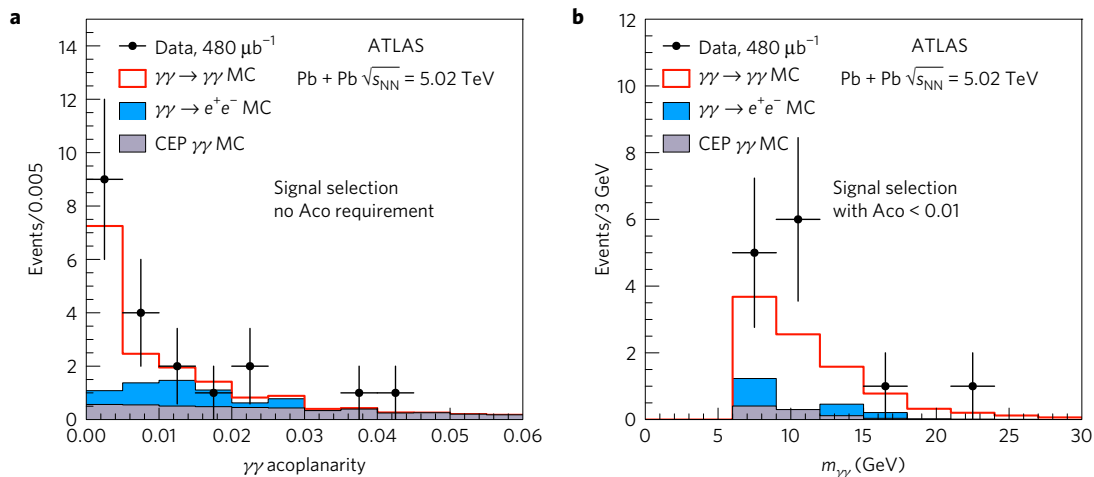


Figure 3 | Kinematic distributions for $\gamma\gamma \rightarrow \gamma\gamma$ event candidates. **a**, Diphoton acoplanarity before applying the $A_{\text{co}} < 0.01$ requirement. **b**, Diphoton invariant mass after applying the $A_{\text{co}} < 0.01$ requirement. Data (points) are compared to MC predictions (histograms). The statistical uncertainties on the data are shown as vertical bars.

of the track that is unmatched with the electron (trk2) is required to be below 2 GeV. The additional hard-bremsstrahlung photon is expected to have $E_T^{\gamma} \approx (E_T^e - p_T^{\text{trk2}})$. The $p_T^{\text{trk2}} < 2$ GeV requirement ensures a sufficient ΔR separation between the expected photon and the second electron, extrapolated to the first layer of the EM calorimeter. The data sample contains 247 $\gamma\gamma \rightarrow e^+e^-$ events that are used to extract the photon reconstruction efficiency, which is presented in Fig. 2b. Good agreement between data and $\gamma\gamma \rightarrow e^+e^-$ MC simulation is observed and the photon reconstruction efficiency is measured with a 5–10% relative uncertainty at low E_T (3–6 GeV).

In addition, a cross-check is performed on $Z \rightarrow \mu^+\mu^-\gamma$ events identified in pp collision data from 2015 corresponding to an integrated luminosity of 1.6 fb^{-1} . The results support (in a similar way to ref. 42) the choice to use the three shower-shape variables in this photon PID selection in an independent sample of low- E_T photons.

The photon cluster energy resolution is extracted from data using $\gamma\gamma \rightarrow e^+e^-$ events. The electrons from the $\gamma\gamma \rightarrow e^+e^-$ reaction (see Supplementary Information) are well balanced in their transverse momenta, with very small standard deviation, $\sigma_{p_T^+ - p_T^-} < 30$ MeV, much smaller than the expected EM calorimeter energy resolution. Therefore, by measuring $(E_T^{\text{cl1}} - E_T^{\text{cl2}})$ distributions in $\gamma\gamma \rightarrow e^+e^-$ events, one can extract the cluster energy resolution, $\sigma_{E_T^{\text{cl}}}$. For electrons with $E_T < 10$ GeV, the $\sigma_{E_T^{\text{cl}}}/E_T^{\text{cl}}$ is observed to be approximately 8% both in data and simulation. An uncertainty of $\delta\sigma_{E_T^{\text{cl}}}/\sigma_{E_T^{\text{cl}}} = 15\%$ is assigned to the simulated photon energy resolution and takes into account differences between $\sigma_{E_T^{\text{cl}}}$ in data and $\sigma_{E_T^{\text{cl}}}$ in simulation.

Similarly, the EM cluster energy scale can be studied using the $(E_T^{\text{cl1}} + E_T^{\text{cl2}})$ distribution. It is observed that the simulation provides a good description of this distribution, within the relative uncertainty of 5% that is assigned to the EM cluster energy-scale modelling.

Background estimation

Due to its relatively high rate, the exclusive production of electron pairs ($\gamma\gamma \rightarrow e^+e^-$) can be a source of fake diphoton events. The contribution from the dielectron background is estimated using $\gamma\gamma \rightarrow e^+e^-$ MC simulation (which gives 1.3 events) and is verified using the following data-driven technique. Two control regions are defined that are expected to be dominated by $\gamma\gamma \rightarrow e^+e^-$ backgrounds. The first control region is defined by requiring events with exactly one reconstructed charged-particle track and two identified photons that satisfy the same preselection criteria as for the signal definition. The second control region is defined similarly

to the first one, except exactly two tracks are required ($N_{\text{trk}} = 2$). Good agreement is observed between data and MC simulation in both control regions, but the precision is limited by the number of events in data. A conservative uncertainty of 25% is therefore assigned to the $\gamma\gamma \rightarrow e^+e^-$ background estimation, which reflects the statistical uncertainty of data in the $N_{\text{trk}} = 1$ control region. The contribution from a related QED process, $\gamma\gamma \rightarrow e^+e^-\gamma\gamma$, is evaluated using the MadGraph5_aMC@NLO MC generator⁴³ and is found to be negligible.

The $A_{\text{co}} < 0.01$ requirement significantly reduces the CEP $gg \rightarrow \gamma\gamma$ background. However, the MC prediction for this process has a large theoretical uncertainty; hence, an additional data-driven normalization is performed in the region $A_{\text{co}} > b$, where b is a value greater than 0.01 which can be varied. Three values of b (0.01, 0.02, 0.03) are used, where the central value $b = 0.02$ is chosen to derive the nominal background prediction and the values $b = 0.01$ and $b = 0.03$ to define the systematic uncertainty. The normalization is performed using the condition: $f_{gg \rightarrow \gamma\gamma}^{\text{norm},b} = (N_{\text{data}}(A_{\text{co}} > b) - N_{\text{sig}}(A_{\text{co}} > b) - N_{\gamma\gamma \rightarrow e^+e^-}(A_{\text{co}} > b)) / N_{gg \rightarrow \gamma\gamma}(A_{\text{co}} > b)$, for each value of b , where N_{data} is the number of observed events, N_{sig} is the expected number of signal events, $N_{\gamma\gamma \rightarrow e^+e^-}$ is the expected background from $\gamma\gamma \rightarrow e^+e^-$ events and $N_{gg \rightarrow \gamma\gamma}$ is the MC estimate of the expected background from CEP $gg \rightarrow \gamma\gamma$ events. The normalization factor is found to be $f_{gg \rightarrow \gamma\gamma}^{\text{norm}} = 0.5 \pm 0.3$ and the background due to CEP $gg \rightarrow \gamma\gamma$ is estimated to be $f_{gg \rightarrow \gamma\gamma}^{\text{norm}} \times N_{gg \rightarrow \gamma\gamma}(A_{\text{co}} < 0.01) = 0.9 \pm 0.5$ events. To verify the CEP $gg \rightarrow \gamma\gamma$ background estimation method, energy deposits in the ZDC are studied for events before the A_{co} selection. It is expected that the outgoing ions in CEP events predominantly dissociate, which results in the emission of neutrons detectable in the ZDC²⁰. Good agreement between the normalized CEP $gg \rightarrow \gamma\gamma$ MC expectation and the observed events with a ZDC signal corresponding to at least 1 neutron is observed in the full A_{co} range (see Supplementary Information for details).

Low- p_T dijet events can produce multiple π^0 mesons, which could potentially mimic diphoton events. The event selection requirements are efficient in rejecting such events, and based on studies performed with a supporting trigger, the background from hadronic processes is estimated to be 0.3 ± 0.3 events. MC studies show that the background from $\gamma\gamma \rightarrow q\bar{q}$ processes is negligible.

Exclusive neutral two-meson production can be a potential source of background for LbyL events, mainly due to their back-to-back topology being similar to that of the CEP $gg \rightarrow \gamma\gamma$ process. The cross-section for this process is calculated to be below 10% of the CEP $gg \rightarrow \gamma\gamma$ cross-section^{44,45} and it is therefore considered to

Table 1 | The number of events accepted by the sequential selection requirements for data, compared with the number of background and signal events expected from the simulation.

Selection	$\gamma\gamma \rightarrow e^+e^-$	CEP $gg \rightarrow \gamma\gamma$	Hadronic fakes	Other fakes	Total background	Signal	Data
Preselection	74	4.7	6	19	104	9.1	105
$N_{\text{trk}}=0$	4.0	4.5	6	19	33	8.7	39
$p_{\text{T}}^{\gamma\gamma} < 2 \text{ GeV}$	3.5	4.4	3	1.3	12.2	8.5	21
$A_{\text{co}} < 0.01$	1.3	0.9	0.3	0.1	2.6	7.3	13
Uncertainty	0.3	0.5	0.3	0.1	0.7	1.5	

The signal simulation is based on calculations from ref. 28. In addition, the uncertainties on the expected number of events passing all selection requirements are given.

give a negligible contribution to the signal region. The contribution from bottomonia production (for example, $\gamma\gamma \rightarrow \eta_b \rightarrow \gamma\gamma$ or $\gamma\text{Pb} \rightarrow \Upsilon \rightarrow \gamma\eta_b \rightarrow 3\gamma$) is calculated using parameters from refs 46, 47 and is found to be negligible.

The contribution from other fake diphoton events (for example those induced by cosmic-ray muons) is estimated using photons that fail to satisfy the longitudinal shower-shape requirement. The total background due to other fake photons is found to be 0.1 ± 0.1 events. As a further cross-check, additional activity in the muon spectrometer is studied. It is observed that out of 18 events satisfying the inverted $p_{\text{T}}^{\gamma\gamma}$ requirement, 13 have at least one additional reconstructed muon. In the region $p_{\text{T}}^{\gamma\gamma} < 2 \text{ GeV}$, no events with muon activity are found, which is compatible with the above-mentioned estimate of 0.1 ± 0.1 .

The contribution from UPC events where both nuclei emit a bremsstrahlung photon is estimated using calculations from ref. 13 and is found to be negligible for photons with $|\eta| < 2.4$ and $E_{\text{T}} > 3 \text{ GeV}$.

Results

Photon kinematic distributions for events satisfying the selection criteria are shown in Fig. 3. The shape of the diphoton acoplanarity distribution for $\gamma\gamma \rightarrow e^+e^-$ events in Fig. 3a reflects the trajectories of the electron and positron in the detector magnetic field, before they emit hard photons in their collisions with the ITD material. In total, 13 events are observed in data whereas 7.3 signal events and 2.6 background events are expected. In general, good agreement between data and MC simulation is observed. The effect of sequential selection requirements on the number of events selected is shown in Table 1, for each of the data, signal and background samples.

To quantify an excess of events over the background expectation, a test statistic based on the profile likelihood ratio⁴⁸ is used. The p value for the background-only hypothesis, defined as the probability for the background to fluctuate and give an excess of events as large or larger than that observed in the data, is found to be 5×10^{-6} . The p value can be expressed in terms of Gaussian tail probabilities, which, given in units of standard deviation (σ), corresponds to a significance of 4.4σ . The expected p value and significance (obtained before the fit of the signal-plus-background hypothesis to the data and using standard model predictions from ref. 28) are 8×10^{-5} and 3.8σ , respectively.

The cross-section for the $\text{Pb} + \text{Pb} (\gamma\gamma) \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)}\gamma\gamma$ process is measured in a fiducial phase space defined by the photon transverse energy $E_{\text{T}} > 3 \text{ GeV}$, photon absolute pseudorapidity $|\eta| < 2.4$, diphoton invariant mass greater than 6 GeV , diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01 . Experimentally, the fiducial cross-section is given by

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \times \int L dt} \quad (1)$$

where N_{data} is the number of selected events in data, N_{bkg} is the expected number of background events and $\int L dt$ is the integrated

Table 2 | Summary of systematic uncertainties.

Source of uncertainty	Relative uncertainty
Trigger	5%
Photon reco. efficiency	12%
Photon PID efficiency	16%
Photon energy scale	7%
Photon energy resolution	11%
Total	24%

The table shows the relative systematic uncertainty on detector correction factor C broken into its individual contributions. The total is obtained by adding them in quadrature.

luminosity. The factor C is used to correct for the net effect of the trigger efficiency, the diphoton reconstruction and PID efficiencies, as well as the impact of photon energy and angular resolution. It is defined as the ratio of the number of generated signal events satisfying the selection criteria after particle reconstruction and detector simulation to the number of generated events satisfying the fiducial criteria before reconstruction. The value of C and its total uncertainty is determined to be 0.31 ± 0.07 . The dominant systematic uncertainties come from the uncertainties on the photon reconstruction and identification efficiencies. Other minor sources of uncertainty are the photon energy scale and resolution uncertainties and trigger efficiency uncertainty. To check for a potential model dependence, calculations from ref. 28 are compared with predictions from ref. 20, and a negligible impact on the C -factor uncertainty is found. Table 2 lists the separate contributions to the systematic uncertainty. The uncertainty on the integrated luminosity is 6%. It is derived following a methodology similar to that detailed in refs 49,50, from a calibration of the luminosity scale using x - y beam-separation scans performed in December 2015.

The measured fiducial cross-section is $\sigma_{\text{fid}} = 70 \pm 24 \text{ (stat.)} \pm 17 \text{ (syst.) nb}$, which is in agreement with the predicted values of $45 \pm 9 \text{ nb}$ (ref. 20) and $49 \pm 10 \text{ nb}$ (ref. 28) within uncertainties.

Conclusion

In summary, this article presents evidence for the scattering of LbyL in quasi-real photon interactions from $480 \mu\text{b}^{-1}$ of ultra-peripheral $\text{Pb} + \text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ by the ATLAS experiment at the LHC. The statistical significance against the background-only hypothesis is found to be 4.4 standard deviations. After background subtraction and analysis corrections, the fiducial cross-section for the $\text{Pb} + \text{Pb} (\gamma\gamma) \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)}\gamma\gamma$ process was measured and is compatible with standard model predictions.

The analysis is mostly limited by the amount of data available and the lower limit on transverse energy for reconstructed photons ($E_{\text{T}} = 3 \text{ GeV}$), below which more signal is expected. Advancements on these two points would also allow for reconstruction of low-mass mesons decaying into two photons, which in turn could be used to improve detector calibration. The heavy-ion data yield is expected to double at the end of 2018 (and again increase tenfold after

LHC Run 4, scheduled to start in 2026), which would significantly reduce the statistical uncertainty. Future upgrades of ATLAS, such as extended tracking acceptance from $|\eta| < 2.5$ to $|\eta| < 4.0$, will further improve this.

Data availability. The experimental data that support the findings of this study are available in HEPData with the identifier <http://dx.doi.org/10.17182/hepdata.77761>.

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Author contributions

All authors have contributed to the publication, being variously involved in the design and the construction of the detectors, in writing software, calibrating subsystems, operating the detectors and acquiring data, and finally analysing the processed data. The ATLAS Collaboration members discussed and approved the scientific results. The manuscript was prepared by a subgroup of authors appointed by the collaboration and subject to an internal collaboration-wide review process. All authors reviewed and approved the final version of the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.



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ATLAS Collaboration

M. Aaboud¹⁸¹, G. Aad¹¹⁶, B. Abbott¹⁴⁵, J. Abdallah¹⁰, O. Abidinov^{14‡}, B. Abeloos¹⁴⁹, S. H. Abidi²¹⁰, O. S. AbouZeid¹⁸⁴, N. L. Abraham²⁰⁰, H. Abramowicz²⁰⁴, H. Abreu²⁰³, R. Abreu¹⁴⁸, Y. Abulaiti^{196,197}, B. S. Acharya^{218,219,236}, S. Adachi²⁰⁶, L. Adamczyk⁶¹, J. Adelman¹⁴⁰, M. Adersberger¹³¹, T. Adye¹⁷¹, A. A. Affolder¹⁸⁴, T. Agatonovic-Jovin¹⁶, C. Agheorghiesei³⁹, J. A. Aguilar-Saavedra^{160,165}, S. P. Ahlen³⁰, F. Ahmadov^{95,b}, G. Aielli^{174,175}, S. Akatsuka⁹⁸, H. Akerstedt^{196,197}, T. P. A. Åkesson¹¹², A. V. Akimov¹²⁷, G. L. Alberghi^{27,28}, J. Albert²²⁵, M. J. Alconada Verzin¹⁰¹, M. Aleksa⁴⁶, I. N. Aleksandrov⁹⁵, C. Alexa³⁸, G. Alexander²⁰⁴, T. Alexopoulos¹², M. Alhroob¹⁴⁵, B. Ali¹⁶⁸, M. Aliev^{103,104}, G. Alimonti¹²², J. Alison⁴⁷, S. P. Alkire⁵⁷, B. M. M. Allbrooke²⁰⁰, B. W. Allen¹⁴⁸, P. P. Allport²¹, A. Aloisio^{135,136}, A. Alonso⁵⁸, F. Alonso¹⁰¹, C. Alpigiani¹⁸⁵, A. A. Alshehri⁷⁹, M. Alstaty¹¹⁶, B. Alvarez Gonzalez⁴⁶, D. Álvarez Piqueras²²³, M. G. Alvigi^{135,136}, B. T. Amadio¹⁸, Y. Amaral Coutinho³², C. Amelung³¹, D. Amidei¹²⁰, S. P. Amor Dos Santos^{160,162}, A. Amorim^{160,161}, S. Amoroso⁴⁶, G. Amundsen³¹, C. Anastopoulos¹⁸⁶, L. S. Ancu⁷³, N. Andari²¹, T. Andeen¹³, C. F. Anders⁸⁴, J. K. Anders¹⁰⁵, K. J. Anderson⁴⁷, A. Andreazza^{122,123}, V. Andrei⁸³, S. Angelidakis¹¹, I. Angelozzi¹³⁹, A. Angerami⁵⁷, F. Anghinolfi⁴⁶, A. V. Anisenkov^{141,c}, N. Anjos¹⁵, A. Annovi^{157,158}, C. Antel⁸³, M. Antonelli⁷¹, A. Antonov^{129‡}, D. J. Antrim²¹⁷, F. Anulli¹⁷², M. Aoki⁹⁶, L. Aperio Bella⁴⁶, G. Arabidze¹²¹, Y. Arai⁹⁶, J. P. Araque¹⁶⁰, V. Araujo Ferraz³², A. T. H. Arce⁶⁹, R. E. Ardell¹⁰⁸, F. A. Arduh¹⁰¹, J.-F. Arguin¹²⁶, S. Argyropoulos⁹³, M. Arik²², A. J. Armbruster¹⁹⁰, L. J. Armitage¹⁰⁷, O. Arnaez⁴⁶, H. Arnold⁷², M. Arratia⁴⁴, O. Arslan²⁹, A. Artamonov¹²⁸, G. Artoni¹⁵², S. Artz¹¹⁴, S. Asai²⁰⁶, N. Asbah⁶⁶, A. Ashkenazi²⁰⁴, L. Asquith²⁰⁰, K. Assamagan³⁶, R. Astalos¹⁹¹, M. Atkinson²²², N. B. Atlay¹⁸⁸, K. Augsten¹⁶⁸, G. Avolio⁴⁶, B. Axen¹⁸, M. K. Ayoub¹⁴⁹, G. Azuelos^{126,d}, A. E. Baas⁸³, M. J. Baca²¹, H. Bachacou¹⁸³, K. Bachas^{103,104}, M. Backes¹⁵², M. Backhaus⁴⁶, P. Bagiacchi^{172,173}, P. Bagnaia^{172,173}, J. T. Baines¹⁷¹, M. Bajic⁵⁸, O. K. Baker²³², E. M. Baldwin^{141,c}, P. Balek²²⁸, T. Balestri¹⁹⁹, F. Balli¹⁸³, W. K. Balunas¹⁵⁵, E. Banas⁶³, Sw. Banerjee^{229,e}, A. A. E. Bannoura²³¹, L. Barak⁴⁶, E. L. Barberio¹¹⁹, D. Barberis^{74,75}, M. Barbero¹¹⁶, T. Barillari¹³², M.-S. Barisits⁴⁶, T. Barklow¹⁹⁰, N. Barlow⁴⁴, S. L. Barnes⁵⁵, B. M. Barnett¹⁷¹, R. M. Barnett¹⁸, Z. Barnovska-Blenessy⁵³, A. Baroncelli¹⁷⁶, G. Barone³¹, A. J. Barr¹⁵², L. Barranco Navarro²²³, F. Barreiro¹¹³, J. Barreiro Guimarães da Costa⁵⁰, R. Bartoldus¹⁹⁰, A. E. Barton¹⁰², P. Bartos¹⁹¹, A. Basalae¹⁵⁶, A. Bassalat^{149,f}, R. L. Bates⁷⁹, S. J. Batista²¹⁰, J. R. Batley⁴⁴, M. Battaglia¹⁸⁴, M. Bause^{172,173}, F. Bauer¹⁸³, H. S. Bawa^{190,g}, J. B. Beacham¹⁴³, M. D. Beattie¹⁰², T. Beau¹¹¹, P. H. Beauchemin²¹⁶, P. Bechtel²⁹, H. P. Beck^{20,h}, K. Becker¹⁵², M. Becker¹¹⁴, M. Beckingham²²⁶, C. Becot¹⁴², A. J. Beddall²⁵, A. Beddall²³, V. A. Bednyakov⁹⁵, M. Bedognetti¹³⁹, C. P. Bee¹⁹⁹, T. A. Beermann⁴⁶, M. Begalli³², M. Begel³⁶, J. K. Behr⁶⁶, A. S. Bell¹⁰⁹, G. Bella²⁰⁴, L. Bellagamba²⁷, A. Bellerive⁴⁵, M. Bellomo¹¹⁷, K. Belotskiy¹²⁹, O. Beltramello⁴⁶, N. L. Belyaev¹²⁹, O. Benary^{204‡}, D. Benchechroun¹⁷⁸, M. Bender¹³¹, K. Bendtz^{196,197}, N. Benekos¹², Y. Benhammou²⁰⁴, E. Benhar Noccioli²³², J. Benitez⁹³, D. P. Benjamin⁶⁹, M. Benoit⁷³, J. R. Bensinger³¹, S. Bentvelsen¹³⁹, L. Beresford¹⁵², M. Beretta⁷¹, D. Berge¹³⁹, E. Bergeas Kuutmann²²¹, N. Berger⁷, J. Beringer¹⁸, S. Berlendis⁸¹, N. R. Bernard¹¹⁷, G. Bernardi¹¹¹, C. Bernius¹⁴², F. U. Bernlochner²⁹, T. Berry¹⁰⁸, P. Berta¹⁶⁹, C. Bertella¹¹⁴, G. Bertoli^{196,197}, F. Bertolucci^{157,158}, I. A. Bertram¹⁰², C. Bertsche⁶⁶, D. Bertsche¹⁴⁵, G. J. Besjes⁵⁸, O. Bessidskaia Bylund^{196,197}, M. Bessner⁶⁶, N. Besson¹⁸³, C. Betancourt⁷², A. Bethani¹¹⁵, S. Bethke¹³², A. J. Bevan¹⁰⁷, R. M. Bianchi¹⁵⁹, M. Bianco⁴⁶, O. Biebel¹³¹, D. Biedermann¹⁹, R. Bielski¹¹⁵, N. V. Biesuz^{157,158}, M. Biglietti¹⁷⁶, J. Bilbao De Mendizabal⁷³, T. R. V. Billoud¹²⁶, H. Bilokon⁷¹, M. Bindi⁸⁰, A. Bingul²³, C. Bini^{172,173}, S. Biondi^{27,28}, T. Bisanz⁸⁰, C. Bittrich⁶⁸, D. M. Bjergaard⁶⁹, C. W. Black²⁰¹, J. E. Black¹⁹⁰, K. M. Black³⁰, D. Blackburn¹⁸⁵, R. E. Blair⁸, T. Blazek¹⁹¹, I. Bloch⁶⁶, C. Blocker³¹, A. Blue⁷⁹, W. Blum^{114‡}, U. Blumenschein¹⁰⁷, S. Blunier⁴⁸, G. J. Bobbink¹³⁹, V. S. Bobrovnikov^{141,c}, S. S. Bocchetta¹¹², A. Bocci⁶⁹, C. Bock¹³¹, M. Boehler⁷², D. Boerner²³¹, D. Bogavac¹³¹, A. G. Bogdanchikov¹⁴¹, C. Bohm¹⁹⁶, V. Boisvert¹⁰⁸, P. Bokan^{221,i}, T. Bold⁶¹, A. S. Boldyrev¹³⁰, M. Bomben¹¹¹, M. Bona¹⁰⁷, M. Boonekamp¹⁸³, A. Borisov¹⁷⁰, G. Borissov¹⁰², J. Bortfeldt⁴⁶, D. Bortoletto¹⁵², V. Bortolotto^{87,88,89}, K. Bos¹³⁹, D. Boscherini²⁷, M. Bosman¹⁵, J. D. Bossio Sola⁴³, J. Boudreau¹⁵⁹, J. Bouffard², E. V. Bouhova-Thacker¹⁰², D. Boumediene⁵⁶, C. Bourdarios¹⁴⁹, S. K. Boutle⁷⁹, A. Boveia¹⁴³, J. Boyd⁴⁶, I. R. Boyko⁹⁵, J. Bracinik²¹, A. Brandt¹⁰, G. Brandt⁸⁰, O. Brandt⁸³, U. Bratzler²⁰⁷, B. Brau¹¹⁷, J. E. Brau¹⁴⁸, W. D. Breaden Madden⁷⁹, K. Brendlinger⁶⁶, A. J. Brennan¹¹⁹, L. Brenner¹³⁹, R. Brenner²²¹, S. Bressler²²⁸, D. L. Brigrin²¹, T. M. Bristow⁷⁰, D. Britton⁷⁹, D. Britzger⁶⁶, F. M. Brochu⁴⁴, I. Brock²⁹, R. Brock¹²¹, G. Brooijmans⁵⁷, T. Brooks¹⁰⁸, W. K. Brooks⁴⁹, J. Brosamer¹⁸, E. Brost¹⁴⁰, J. H. Broughton²¹, P. A. Bruckman de Renstrom⁶³, D. Bruncko¹⁹², A. Bruni²⁷, G. Bruni²⁷, L. S. Bruni¹³⁹, B. H. Brunt⁴⁴, M. Bruschi²⁷, N. Bruscino²⁹, P. Bryant⁴⁷, L. Bryngemark¹¹², T. Buanes¹⁷, Q. Buat¹⁸⁹, P. Buchholz¹⁸⁸, A. G. Buckley⁷⁹, I. A. Budagov⁹⁵, F. Buehrer⁷², M. K. Bugge¹⁵¹, O. Bulekov¹²⁹, D. Bullock¹⁰, H. Burckhart⁴⁶, S. Burdin¹⁰⁵, C. D. Burgard⁷², A. M. Burger⁷, B. Burghgrave¹⁴⁰, K. Burka⁶³, S. Burke¹⁷¹, I. Burmeister⁶⁷, J. T. P. Burr¹⁵², E. Busato⁵⁶, D. Büscher⁷², V. Büscher¹¹⁴, P. Bussey⁷⁹, J. M. Butler³⁰, C. M. Buttar⁷⁹, J. M. Butterworth¹⁰⁹, P. Butti⁴⁶, W. Buttinger³⁶, A. Buzatu⁵², A. R. Buzykaev^{141,c}, S. Cabrera Urbán²²³, D. Caforio¹⁶⁸, V. M. Cairo^{59,60}, O. Cakir⁴, N. Calace⁷³, P. Calafiura¹⁸, A. Calandri¹¹⁶, G. Calderini¹¹¹, P. Calfayan⁹¹, G. Callea^{59,60}, L. P. Caloba³², S. Calvente Lopez¹¹³, D. Calvet⁵⁶, S. Calvet⁵⁶, T. P. Calvet¹¹⁶, R. Camacho Toro⁴⁷, S. Camarda⁴⁶, P. Camarri^{174,175}, D. Cameron¹⁵¹, R. Caminal Armadans²²², C. Camincher⁸¹, S. Campana⁴⁶, M. Campanelli¹⁰⁹, A. Camplani^{122,123}, A. Campoverde¹⁸⁸, V. Canale^{135,136}, M. Cano Bret⁵⁵, J. Cantero¹⁴⁶, T. Cao²⁰⁴, M. D. M. Capeans Garrido⁴⁶, I. Caprini³⁸, M. Caprini³⁸, M. Capua^{59,60}, R. M. Carbone⁵⁷, R. Cardarelli¹⁷⁴, F. Cardillo⁷², I. Carli¹⁶⁹, T. Carli⁴⁶, G. Carlino¹³⁵, B. T. Carlson¹⁵⁹, L. Carminati^{122,123}, R. M. D. Carney^{196,197}, S. Caron¹³⁸, E. Carquin⁴⁹, G. D. Carrillo-Montoya⁴⁶, J. Carvalho^{160,162}, D. Casadei²¹, M. P. Casado^{15,j}, M. Casolino¹⁵, D. W. Casper²¹⁷, R. Castelijns¹³⁹, A. Castelli¹³⁹, V. Castillo Gimenez²²³, N. F. Castro^{160,k}, A. Catinaccio⁴⁶, J. R. Catmore¹⁵¹, A. Cattai⁴⁶, J. Caudron²⁹, V. Cavaliere²²², E. Cavallaro¹⁵, D. Cavalli¹²², M. Cavalli-Sforza¹⁵, V. Cavasinni^{157,158}, E. Celebi²², F. Ceradini^{176,177}, L. Cerda Alberich²²³, A. S. Cerqueira³³, A. Cerri²⁰⁰, L. Cerrito^{174,175}, F. Cerutti¹⁸, A. Cervelli²⁰, S. A. Cetin²⁴, A. Chafaq¹⁷⁸,

D. Chakraborty¹⁴⁰, S. K. Chan⁸², W. S. Chan¹³⁹, Y. L. Chan⁸⁷, P. Chang²²², J. D. Chapman⁴⁴, D. G. Charlton²¹, A. Chatterjee⁷³, C. C. Chau²¹⁰, C. A. Chavez Barajas²⁰⁰, S. Che¹⁴³, S. Cheatham^{218,220}, A. Chegwidan¹²¹, S. Chekanov⁸, S. V. Chekulaev²¹³, G. A. Chelkov^{95,1}, M. A. Chelstowska⁴⁶, C. Chen⁹⁴, H. Chen³⁶, S. Chen⁵¹, S. Chen²⁰⁶, X. Chen^{52,m}, Y. Chen⁹⁷, H. C. Cheng¹²⁰, H. J. Cheng⁵⁰, Y. Cheng⁴⁷, A. Cheplakov⁹⁵, E. Cheremushkina¹⁷⁰, R. Cherkaoui El Moursli¹⁸², V. Chernyatin^{36,z}, E. Cheu⁹, L. Chevalier¹⁸³, V. Chiarella⁷¹, G. Chiarelli^{157,158}, G. Chiodini¹⁰³, A. S. Chisholm⁴⁶, A. Chitan³⁸, Y. H. Chiu²²⁵, M. V. Chizhov⁹⁵, K. Choi⁹¹, A. R. Chomont⁵⁶, S. Chouridou¹¹, B. K. B. Chow¹³¹, V. Christodoulou¹⁰⁹, D. Chromek-Burckhart⁴⁶, M. C. Chu⁸⁷, J. Chudoba¹⁶⁷, A. J. Chuinard¹¹⁸, J. J. Chwastowski⁶³, L. Chytka¹⁴⁷, A. K. Ciftci⁴, D. Cincă⁶⁷, V. Cindro¹⁰⁶, I. A. Cioara²⁹, C. Ciocca^{27,28}, A. Ciocio¹⁸, F. Ciotto^{135,136}, Z. H. Citron²²⁸, M. Citterio¹²², M. Ciubancan³⁸, A. Clark⁷³, B. L. Clark⁸², M. R. Clark⁵⁷, P. J. Clark⁷⁰, R. N. Clarke¹⁸, C. Clement^{196,197}, Y. Coadou¹¹⁶, M. Cobi^{218,220}, A. Coccaro⁷³, J. Cochran⁹⁴, L. Colasurdo¹³⁸, B. Cole⁵⁷, A. P. Colijn¹³⁹, J. Collot⁸¹, T. Colombo²¹⁷, P. Conde Muiño^{160,161}, E. Coniavitis⁷², S. H. Connell¹⁹⁴, I. A. Connelly¹¹⁵, V. Consorti⁷², S. Constantinescu³⁸, G. Conti⁴⁶, F. Conventi^{135,n}, M. Cooke¹⁸, B. D. Cooper¹⁰⁹, A. M. Cooper-Sarkar¹⁵², F. Cormier²²⁴, K. J. R. Cormier²¹⁰, T. Cornelissen²³¹, M. Corradi^{172,173}, F. Corriveau^{118,o}, A. Cortes-Gonzalez⁴⁶, G. Cortiana¹³², G. Costa¹²², M. J. Costa²²³, D. Costanzo¹⁸⁶, G. Cottin⁴⁴, G. Cowan¹⁰⁸, B. E. Cox¹¹⁵, K. Cranmer¹⁴², S. J. Crawley⁷⁹, R. A. Creager¹⁵⁵, G. Cree⁴⁵, S. Crépe-Renaudin⁸¹, F. Crescioli¹¹¹, W. A. Cribbs^{196,197}, M. Crispin Ortuzar¹⁵², M. Cristinziani²⁹, V. Croft¹³⁸, G. Crosetti^{59,60}, A. Cueto¹¹³, T. Cuhadar Donszelmann¹⁸⁶, J. Cummings²³², M. Curatolo⁷¹, J. Cúth¹¹⁴, H. Czirr¹⁸⁸, P. Czodrowski⁴⁶, G. D'amen^{27,28}, S. D'Auria⁷⁹, M. D'Onofrio¹⁰⁵, M. J. Da Cunha Sargedas De Sousa^{160,161}, C. Da Via¹¹⁵, W. Dabrowski⁶¹, T. Dado¹⁹¹, T. Dai¹²⁰, O. Dale¹⁷, F. Dallaire¹²⁶, C. Dallapiccola¹¹⁷, M. Dam⁵⁸, J. R. Dandoy¹⁵⁵, N. P. Dang⁷², A. C. Daniells²¹, N. S. Dann¹¹⁵, M. Danninger²²⁴, M. Dano Hoffmann¹⁸³, V. Dao¹⁹⁹, G. Darbo⁷⁴, S. Darmora¹⁰, J. Dassoulas³, A. Dattagupta¹⁴⁸, T. Daubney⁶⁶, W. Davey²⁹, C. David⁶⁶, T. Davidek¹⁶⁹, M. Davies²⁰⁴, P. Davison¹⁰⁹, E. Dawe¹¹⁹, I. Dawson¹⁸⁶, K. De¹⁰, R. de Asmundis¹³⁵, A. De Benedetti¹⁴⁵, S. De Castro^{27,28}, S. De Cecco¹¹¹, N. De Groot¹³⁸, P. de Jong¹³⁹, H. De la Torre¹²¹, F. De Lorenzi⁹⁴, A. De Maria⁸⁰, D. De Pedis¹⁷², A. De Salvo¹⁷², U. De Sanctis^{174,175}, A. De Santo²⁰⁰, K. De Vasconcelos Corga¹¹⁶, J. B. De Vivie De Regie¹⁴⁹, W. J. Dearnaley¹⁰², R. Debbe³⁶, C. Debenedetti¹⁸⁴, D. V. Dedovich⁹⁵, N. Dehghanian³, I. Deigaard¹³⁹, M. Del Gaudio^{59,60}, J. Del Peso¹¹³, T. Del Prete^{157,158}, D. Delgove¹⁴⁹, F. Deliot¹⁸³, C. M. Delitzsch⁷³, A. Dell'Acqua⁴⁶, L. Dell'Asta³⁰, M. Dell'Orso^{157,158}, M. Della Pietra^{135,136}, D. della Volpe⁷³, M. Delmastro⁷, C. Delporte¹⁴⁹, P. A. Delsart⁸¹, D. A. DeMarco²¹⁰, S. Demers²³², M. Demichev⁹⁵, A. Demilly¹¹¹, S. P. Denisov¹⁷⁰, D. Denysiuk¹⁸³, D. Derendarz⁶³, J. E. Derkaoui¹⁸¹, F. Derue¹¹¹, P. Dervan¹⁰⁵, K. Desch²⁹, C. Deterre⁶⁶, K. Dette⁶⁷, P. O. Deviveiros⁴⁶, A. Dewhurst¹⁷¹, S. Dhaliwal³¹, A. Di Ciaccio^{174,175}, L. Di Ciaccio⁷, W. K. Di Clemente¹⁵⁵, C. Di Donato^{135,136}, A. Di Girolamo⁴⁶, B. Di Girolamo⁴⁶, B. Di Micco^{176,177}, R. Di Nardo⁴⁶, K. F. Di Petrillo⁸², A. Di Simone⁷², R. Di Sipio²¹⁰, D. Di Valentino⁴⁵, C. Diaconu¹¹⁶, M. Diamond²¹⁰, F. A. Dias⁷⁰, M. A. Diaz⁴⁸, E. B. Diehl¹²⁰, J. Dietrich¹⁹, S. Díez Cornell⁶⁶, A. Dimitrievska¹⁶, J. Dingfelder²⁹, P. Dita³⁸, S. Dita³⁸, F. Dittus⁴⁶, F. Djama¹¹⁶, T. Djobava⁷⁷, J. I. Djusland⁸³, M. A. B. do Vale³⁴, D. Dobos⁴⁶, M. Dobre³⁸, C. Doglioni¹¹², J. Dolejsi¹⁶⁹, Z. Dolezal¹⁶⁹, M. Donadelli³⁵, S. Donati^{157,158}, P. Dondero^{153,154}, J. Donini⁵⁶, J. Dopke¹⁷¹, A. Doria¹³⁵, M. T. Dova¹⁰¹, A. T. Doyle⁷⁹, E. Drechsler⁸⁰, M. Dris¹², Y. Du⁵⁴, J. Duarte-Campderros²⁰⁴, E. Duchovni²²⁸, G. Duckeck¹³¹, A. Ducourthial¹¹¹, O. A. Ducu^{126,p}, D. Duda¹³⁹, A. Dudarev⁴⁶, A. Chr. Dudder¹¹⁴, E. M. Duffield¹⁸, L. Duflot¹⁴⁹, M. Dührssen⁴⁶, M. Dumancic²²⁸, A. E. Dumitriu³⁸, A. K. Duncan⁷⁹, M. Dunford⁸³, H. Duran Yildiz⁴, M. Düren⁷⁸, A. Durglishvili⁷⁷, D. Duschinger⁶⁸, B. Dutta⁶⁶, M. Dyndal⁶⁶, C. Eckardt⁶⁶, K. M. Ecker¹³², R. C. Edgar¹²⁰, T. Eifert⁴⁶, G. Eigen¹⁷, K. Einsweiler¹⁸, T. Ekelof²²¹, M. El Kacimi¹⁸⁰, R. El Kosseifi¹¹⁶, V. Ellajosyula¹¹⁶, M. Ellert²²¹, S. Elles⁷, F. Ellinghaus²³¹, A. A. Elliot²²⁵, N. Ellis⁴⁶, J. Elmsheuser³⁶, M. Elsing⁴⁶, D. Emelianov¹⁷¹, Y. Enari²⁰⁶, O. C. Endner¹¹⁴, J. S. Ennis²²⁶, J. Erdmann⁶⁷, A. Ereditato²⁰, G. Ernis²³¹, M. Ernst³⁶, S. Errede²²², E. Ertel¹¹⁴, M. Escalier¹⁴⁹, H. Esch⁶⁷, C. Escobar¹⁵⁹, B. Esposito⁷¹, A. I. Etienne¹⁸³, E. Etzion²⁰⁴, H. Evans⁹¹, A. Ezhilov¹⁵⁶, F. Fabbrì^{27,28}, L. Fabbrì^{27,28}, G. Facini⁴⁷, R. M. Fakhruddinov¹⁷⁰, S. Falciano¹⁷², R. J. Falla¹⁰⁹, J. Faltova⁴⁶, Y. Fang⁵⁰, M. Fantì^{122,123}, A. Farbin¹⁰, A. Farilla¹⁷⁶, C. Farina¹⁵⁹, E. M. Farina^{153,154}, T. Farooque¹²¹, S. Farrell¹⁸, S. M. Farrington²²⁶, P. Farthouat⁴⁶, F. Fassi¹⁸², P. Fassnacht⁴⁶, D. Fassouliotis¹¹, M. Fauci Giannelli¹⁰⁸, A. Favareto^{74,75}, W. J. Fawcett¹⁵², L. Fayard¹⁴⁹, O. L. Fedin^{156,q}, W. Fedorko²²⁴, S. Feigl¹⁵¹, L. Felgion¹¹⁶, C. Feng⁵⁴, E. J. Feng⁴⁶, H. Feng¹²⁰, A. B. Fenyuk¹⁷⁰, L. Feremenga¹⁰, P. Fernandez Martinez²²³, S. Fernandez Perez¹⁵, J. Ferrando⁶⁶, A. Ferrari²²¹, P. Ferrari¹³⁹, R. Ferrari¹⁵³, D. E. Ferreira de Lima⁸⁴, A. Ferrer²²³, D. Ferrere⁷³, C. Ferretti¹²⁰, F. Fiedler¹¹⁴, A. Filipčić¹⁰⁶, M. Filipuzzi⁶⁶, F. Filthaut¹³⁸, M. Fincke-Keeler²²⁵, K. D. Finelli²⁰¹, M. C. N. Fiolhais^{160,162,r}, L. Fiorini²²³, A. Fischer², C. Fischer¹⁵, J. Fischer²³¹, W. C. Fisher¹²¹, N. Flaschel⁶⁶, I. Fleck¹⁸⁸, P. Fleischmann¹²⁰, R. R. M. Fletcher¹⁵⁵, T. Flick²³¹, B. M. Flierl¹³¹, L. R. Flores Castillo⁸⁷, M. J. Flowerdew¹³², G. T. Forcolin¹¹⁵, A. Formica¹⁸³, A. Forti¹¹⁵, A. G. Foster²¹, D. Fournier¹⁴⁹, H. Fox¹⁰², S. Fracchia¹⁵, P. Francavilla¹¹¹, M. Franchini^{27,28}, S. Franchino⁸³, D. Francis⁴⁶, L. Franconi¹⁵¹, M. Franklin⁸², M. Frate²¹⁷, M. Fraternali^{153,154}, D. Freeborn¹⁰⁹, S. M. Fressard-Batraneanu⁴⁶, B. Freund¹²⁶, D. Froidevaux⁴⁶, J. A. Frost¹⁵², C. Fukunaga²⁰⁷, E. Fullana Torregrosa¹¹⁴, T. Fusayasu¹³³, J. Fuster²²³, C. Gabaldon⁸¹, O. Gabizon²⁰³, A. Gabrielli^{27,28}, A. Gabrielli¹⁸, G. P. Gach⁶¹, S. Gadatsch⁴⁶, S. Gadomski¹⁰⁸, G. Gagliardi^{74,75}, L. G. Gagnon¹²⁶, P. Gagnon⁹¹, C. Galea¹³⁸, B. Galhardo^{160,162}, E. J. Gallas¹⁵², B. J. Gallop¹⁷¹, P. Gallus¹⁶⁸, G. Galster⁵⁸, K. K. Gan¹⁴³, S. Ganguly⁵⁶, J. Gao⁵³, Y. Gao¹⁰⁵, Y. S. Gao^{190,g}, F. M. Garay Walls⁷⁰, C. García²²³, J. E. García Navarro²²³, M. Garcia-Sciveres¹⁸, R. W. Gardner⁴⁷, N. Garelli¹⁹⁰, V. Garonne¹⁵¹, A. Gascon Bravo⁶⁶, K. Gasnikova⁶⁶, C. Gatti⁷¹, A. Gaudiello^{74,75}, G. Gaudio¹⁵³, I. L. Gavrilenko¹²⁷, C. Gay²²⁴, G. Gaycken²⁹, E. N. Gazis¹², C. N. P. Gee¹⁷¹, M. Geisen¹¹⁴, M. P. Geisler⁸³, K. Gellerstedt^{196,197}, C. Gemme⁷⁴, M. H. Genest⁸¹, C. Geng^{53,s}, S. Gentile^{172,173}, C. Gentsos²⁰⁵, S. George¹⁰⁸, D. Gerbaudo¹⁵, A. Gershon²⁰⁴, S. Ghasemi¹⁸⁸, M. Ghneimat²⁹, B. Giacobbe²⁷, S. Giagu^{172,173}, P. Giannetti^{157,158}, S. M. Gibson¹⁰⁸, M. Gignac²²⁴, M. Gilchriese¹⁸, D. Gillberg⁴⁵, G. Gilles²³¹, D. M. Gingrich^{3,d}, N. Giokaris^{11z},

M. P. Giordani^{218,220}, F. M. Giorgi²⁷, P. F. Giraud¹⁸³, P. Giromini⁸², D. Giugni¹²², F. Giuli¹⁵², C. Giuliani¹³², M. Giulini⁸⁴, B. K. Gjelsten¹⁵¹, S. Gkaitatzis²⁰⁵, I. Gkialas¹¹, E. L. Gkougkousis¹⁸⁴, L. K. Gladilin¹³⁰, C. Glasman¹¹³, J. Glatzer¹⁵, P. C. F. Glaysheer⁶⁶, A. Glazov⁶⁶, M. Goblirsch-Kolb³¹, J. Godlewski⁶³, S. Goldfarb¹¹⁹, T. Golling⁷³, D. Golubkov¹⁷⁰, A. Gomes^{160,161,163}, R. Gonçalo¹⁶⁰, R. Goncalves Gama³², J. Goncalves Pinto Firmino Da Costa¹⁸³, G. Gonella⁷², L. Gonella²¹, A. Gongadze⁹⁵, S. González de la Hoz²²³, S. Gonzalez-Sevilla⁷³, L. Goossens⁴⁶, P. A. Gorbounov¹²⁸, H. A. Gordon³⁶, I. Gorelov¹³⁷, B. Gorini⁴⁶, E. Gorini^{103,104}, A. Gorišek¹⁰⁶, A. T. Goshaw⁶⁹, C. Gössling⁶⁷, M. I. Gostkin⁹⁵, C. R. Goudet¹⁴⁹, D. Goujdami¹⁸⁰, A. G. Goussiou¹⁸⁵, N. Govender^{194,t}, E. Gozani²⁰³, L. Graber⁸⁰, I. Grabowska-Bold⁶¹, P. O. J. Gradin²²¹, J. Gramling⁷³, E. Gramstad¹⁵¹, S. Grancagnolo¹⁹, V. Gratchev¹⁵⁶, P. M. Gravila⁴², H. M. Gray⁴⁶, Z. D. Greenwood^{110,u}, C. Greife²⁹, K. Gregersen¹⁰⁹, I. M. Gregor⁶⁶, P. Grenier¹⁹⁰, K. Grevtsov⁷, J. Griffiths¹⁰, A. A. Grillo¹⁸⁴, K. Grimm¹⁰², S. Grinstein^{15,v}, Ph. Gris⁵⁶, J.-F. Grivaz¹⁴⁹, S. Groh¹¹⁴, E. Gross²²⁸, J. Grosse-Knetter⁸⁰, G. C. Grossi¹¹⁰, Z. J. Grout¹⁰⁹, L. Guan¹²⁰, W. Guan²²⁹, J. Guenther⁹², F. Guescini²¹³, D. Guest²¹⁷, O. Gueta²⁰⁴, B. Gui¹⁴³, E. Guido^{74,75}, T. Guillemin⁷, S. Guindon², U. Gul⁷⁹, C. Gumpert⁴⁶, J. Guo⁵⁵, W. Guo¹²⁰, Y. Guo⁵³, R. Gupta⁶⁴, S. Gupta¹⁵², G. Gustavino^{172,173}, P. Gutierrez¹⁴⁵, N. G. Gutierrez Ortiz¹⁰⁹, C. Gutsche¹⁰⁹, C. Guyot¹⁸³, M. P. Guzik⁶¹, C. Gwenlan¹⁵², C. B. Gwilliam¹⁰⁵, A. Haas¹⁴², C. Haber¹⁸, H. K. Hadavand¹⁰, A. Hadeif¹¹⁶, S. Hageböck²⁹, M. Hagihara²¹⁵, H. Hakobyan^{233‡}, M. Haleem⁶⁶, J. Haley¹⁴⁶, G. Halladjian¹²¹, G. D. Hallowell¹¹⁶, K. Hamacher²³¹, P. Hamal¹⁴⁷, K. Hamano²²⁵, A. Hamilton¹⁹³, G. N. Hamity¹⁸⁶, P. G. Hamnett⁶⁶, L. Han⁵³, S. Han⁵⁰, K. Hanagaki^{96,w}, K. Hanawa²⁰⁶, M. Hance¹⁸⁴, B. Haney¹⁵⁵, P. Hanke⁸³, J. B. Hansen⁵⁸, J. D. Hansen⁵⁸, M. C. Hansen²⁹, P. H. Hansen⁵⁸, K. Hara²¹⁵, A. S. Hard²²⁹, T. Harenberg²³¹, F. Hariri¹⁴⁹, S. Harkusha¹²⁴, R. D. Harrington⁷⁰, P. F. Harrison²²⁶, F. Hartjes¹³⁹, N. M. Hartmann¹³¹, M. Hasegawa⁹⁷, Y. Hasegawa¹⁸⁷, A. Hasib⁷⁰, S. Hassani¹⁸³, S. Haug²⁰, R. Hauser¹²¹, L. Hauswald⁶⁸, L. B. Havener⁵⁷, M. Havranek¹⁶⁸, C. M. Hawkes²¹, R. J. Hawkings⁴⁶, D. Hayakawa²⁰⁸, D. Hayden¹²¹, C. P. Hays¹⁵², J. M. Hays¹⁰⁷, H. S. Hayward¹⁰⁵, S. J. Haywood¹⁷¹, S. J. Head²¹, T. Heck¹¹⁴, V. Hedberg¹¹², L. Heelan¹⁰, K. K. Heidegger⁷², S. Heim⁶⁶, T. Heim¹⁸, B. Heinemann^{66,x}, J. J. Heinrich¹³¹, L. Heinrich¹⁴², C. Heinz⁷⁸, J. Hejbal¹⁶⁷, L. Helary⁴⁶, A. Held²²⁴, S. Hellman^{196,197}, C. Helsen⁴⁶, J. Henderson¹⁵², R. C. W. Henderson¹⁰², Y. Heng²²⁹, S. Henkelmann²²⁴, A. M. Henriques Correia⁴⁶, S. Henrot-Versille¹⁴⁹, G. H. Herbert¹⁹, H. Herde³¹, V. Herget²³⁰, Y. Hernández Jiménez¹⁹⁵, G. Herten⁷², R. Hertenberger¹³¹, L. Hervas⁴⁶, T. C. Herwig¹⁵⁵, G. G. Hesketh¹⁰⁹, N. P. Hessey²¹³, J. W. Hetherly⁶⁴, S. Higashino⁹⁶, E. Higón-Rodríguez²²³, E. Hill²²⁵, J. C. Hill⁴⁴, K. H. Hiller⁶⁶, S. J. Hillier²¹, I. Hinchliffe¹⁸, M. Hirose⁷², D. Hirschbuehl²³¹, B. Hiti¹⁰⁶, O. Hladik¹⁶⁷, X. Hoad⁷⁰, J. Hobbs¹⁹⁹, N. Hod²¹³, M. C. Hodgkinson¹⁸⁶, P. Hodgson¹⁸⁶, A. Hoecker⁴⁶, M. R. Hoferkamp¹³⁷, F. Hoenic¹³¹, D. Hohn²⁹, T. R. Holmes¹⁸, M. Homann⁶⁷, S. Honda²¹⁵, T. Honda⁹⁶, T. M. Hong¹⁵⁹, B. H. Hoberman²²², W. H. Hopkins¹⁴⁸, Y. Horii¹³⁴, A. J. Horton¹⁸⁹, J.-Y. Hostachy⁸¹, S. Hou²⁰², A. Hoummada¹⁷⁸, J. Howarth⁶⁶, J. Hoya¹⁰¹, M. Hrabovsky¹⁴⁷, I. Hristova¹⁹, J. Hrivnac¹⁴⁹, T. Hryn'ova⁷, A. Hrynevich¹²⁵, P. J. Hsu⁹⁰, S.-C. Hsu¹⁸⁵, Q. Hu⁵³, S. Hu⁵⁵, Y. Huang⁵⁰, Z. Hubacek¹⁶⁸, F. Hubaut¹¹⁶, F. Huegging²⁹, T. B. Huffman¹⁵², E. W. Hughes⁵⁷, G. Hughes¹⁰², M. Huhtinen⁴⁶, P. Huo¹⁹⁹, N. Huseynov^{95,b}, J. Huston¹²¹, J. Huth⁸², G. Iacobucci⁷³, G. Iakovidis³⁶, I. Ibragimov¹⁸⁸, L. Iconomidou-Fayard¹⁴⁹, P. Iengo⁴⁶, O. Igonkina^{139,y}, T. Iizawa²²⁷, Y. Ikegami⁹⁶, M. Ikeno⁹⁶, Y. Ilchenko^{13,z}, D. Iliadis²⁰⁵, N. Ilic¹⁹⁰, G. Introzzi^{153,154}, P. Ioannou^{11‡}, M. Iodice¹⁷⁶, K. Iordanidou⁵⁷, V. Ippolito⁸², N. Ishijima¹⁵⁰, M. Ishino²⁰⁶, M. Ishitsuka²⁰⁸, C. Issever¹⁵², S. Istin²², F. Ito²¹⁵, J. M. Iturbe Ponce¹¹⁵, R. Iuppa^{211,212}, H. Iwasaki⁹⁶, J. M. Izen⁶⁵, V. Izzo¹³⁵, S. Jabbar³, P. Jackson¹, V. Jain², K. B. Jakobi¹¹⁴, K. Jakobs⁷², S. Jakobsen⁴⁶, T. Jakoubek¹⁶⁷, D. O. Jamin¹⁴⁶, D. K. Jana¹¹⁰, R. Jansky⁹², J. Janssen²⁹, M. Janus⁸⁰, P. A. Janus⁶¹, G. Jarlskog¹¹², N. Javadov^{95,b}, T. Javůrek⁷², M. Javurkova⁷², F. Jeanneau¹⁸³, L. Jeanty¹⁸, J. Jejelava^{76,aa}, A. Jelinskas²²⁶, P. Jenni^{72,ab}, C. Jeske²²⁶, S. Jézéquel⁷, H. Ji²²⁹, J. Jia¹⁹⁹, H. Jiang⁹⁴, Y. Jiang⁵³, Z. Jiang¹⁹⁰, S. Jiggins¹⁰⁹, J. Jimenez Pena²²³, S. Jin⁵⁰, A. Jinaru³⁸, O. Jinnouchi²⁰⁸, H. Jivan¹⁹⁵, P. Johansson¹⁸⁶, K. A. Johns⁹, C. A. Johnson⁹¹, W. J. Johnson¹⁸⁵, K. Jon-And^{196,197}, R. W. L. Jones¹⁰², S. Jones⁹, T. J. Jones¹⁰⁵, J. Jongmanns⁸³, P. M. Jorge^{160,161}, J. Jovicevic²¹³, X. Ju²²⁹, A. Juste Rozas^{15,v}, M. K. Köhler²²⁸, A. Kaczmarek⁶³, M. Kado¹⁴⁹, H. Kagan¹⁴³, M. Kagan¹⁹⁰, S. J. Kahn¹¹⁶, T. Kaji²²⁷, E. Kajomovitz⁶⁹, C. W. Kalderon¹¹², A. Kaluza¹¹⁴, S. Kama⁶⁴, A. Kamenshchikov¹⁷⁰, N. Kanaya²⁰⁶, S. Kaneti⁴⁴, L. Kanjir¹⁰⁶, V. A. Kantserov¹²⁹, J. Kanzaki⁹⁶, B. Kaplan¹⁴², L. S. Kaplan²²⁹, D. Kar¹⁹⁵, K. Karakostas¹², N. Karastathis¹², M. J. Kareem⁸⁰, E. Karentzos¹², S. N. Karpov⁹⁵, Z. M. Karpova⁹⁵, K. Karthik¹⁴², V. Kartvelishvili¹⁰², A. N. Karyukhin¹⁷⁰, K. Kasahara²¹⁵, L. Kashif²²⁹, R. D. Kass¹⁴³, A. Kastanas¹⁹⁸, Y. Kataoka²⁰⁶, C. Kato²⁰⁶, A. Katre⁷³, J. Katzy⁶⁶, K. Kawade¹³⁴, K. Kawageo¹⁰⁰, T. Kawamoto²⁰⁶, G. Kawamura⁸⁰, E. F. Kay¹⁰⁵, V. F. Kazanin^{141,c}, R. Keeler²²⁵, R. Kehoe⁶⁴, J. S. Keller⁶⁶, J. J. Kempster¹⁰⁸, Keoshkerian²¹⁰, O. Kepka¹⁶⁷, B. P. Kerševan¹⁰⁶, S. Kersten²³¹, R. A. Keyes¹¹⁸, M. Khader²²², F. Khalil-zada¹⁴, A. Khanov¹⁴⁶, A. G. Kharlamov^{141,c}, T. Kharlamova^{141,c}, A. Khodinov²⁰⁹, T. J. Khoo⁷³, V. Khovanskiy^{128‡}, E. Khramov⁹⁵, J. Khubua^{77,ac}, S. Kido⁹⁷, C. R. Kilby¹⁰⁸, H. Y. Kim¹⁰, S. H. Kim²¹⁵, Y. K. Kim⁴⁷, N. Kimura²⁰⁵, O. M. Kind¹⁹, B. T. King¹⁰⁵, D. Kirchmeier⁶⁸, J. Kirk¹⁷¹, A. E. Kiryunin¹³², T. Kishimoto²⁰⁶, D. Kisielewska⁶¹, K. Kiuchi²¹⁵, O. Kivernyk⁷, E. Kladiva¹⁹², T. Klapdor-Kleingrothaus⁷², M. H. Klein⁵⁷, M. Klein¹⁰⁵, U. Klein¹⁰⁵, K. Kleinknecht¹¹⁴, P. Klimek¹⁴⁰, A. Klimentov³⁶, R. Klingenberg⁶⁷, T. Klingl¹²⁹, T. Klioutchnikova⁴⁶, E.-E. Kluge⁸³, P. Kluit¹³⁹, S. Kluth¹³², J. Knapik⁶³, E. Kneringer⁹², E. B. F. G. Knoops¹¹⁶, A. Knue¹³², A. Kobayashi²⁰⁶, D. Kobayashi²⁰⁸, T. Kobayashi²⁰⁶, M. Kobel¹⁶⁸, M. Kocian¹⁹⁰, P. Kodys¹⁶⁹, T. Koffas⁴⁵, E. Koffeman¹³⁹, N. M. Köhler¹³², T. Koi¹⁹⁰, M. Kolb⁸⁴, I. Koletsou⁷, A. A. Komar^{127‡}, Y. Komori²⁰⁶, T. Kondo⁹⁶, N. Kondrashova⁵⁵, K. Köneke⁷², A. C. König¹³⁸, T. Kono^{96,ad}, R. Konoplich^{142,ae}, N. Konstantinidis¹⁰⁹, R. Kopeliansky⁹¹, S. Koperly⁶¹, A. K. Kopp⁷², K. Korcyl⁶³, K. Kordas²⁰⁵, A. Korn¹⁰⁹, A. A. Korol^{141,c}, I. Korolkov¹⁵, E. V. Korolkova¹⁸⁶, O. Kortner¹³², S. Kortner¹³², T. Kosek¹⁶⁹, V. V. Kostyukhin²⁹, A. Kotwal⁶⁹, A. Koulouris¹², A. Kourkouveli-Charalampidi^{153,154}, C. Kourkouvelis¹¹, E. Kourlitis¹⁸⁶, V. Kouskoura³⁶, A. B. Kowalewska⁶³, R. Kowalewski²²⁵, T. Z. Kowalski⁶¹, C. Kozakai²⁰⁶, W. Kozanecki¹⁸³, A. S. Kozhin¹⁷⁰, V. A. Kramarenko¹³⁰, G. Kramberger¹⁰⁶, D. Krasnopevtsev¹²⁹, A. Krasznahorkay⁴⁶,

D. Krauss¹³², A. Kravchenko³⁶, J. A. Kremer⁶¹, M. Kretz⁸⁵, J. Kretzschmar¹⁰⁵, K. Kreuzfeldt⁷⁸, P. Krieger²¹⁰, K. Krizka⁴⁷, K. Kroeninger⁶⁷, H. Kroha¹³², J. Kroll¹⁵⁵, J. Kroseberg²⁹, J. Krstic¹⁶, U. Kruchonak⁹⁵, H. Krüger²⁹, N. Krumnack⁹⁴, M. C. Kruse⁶⁹, M. Kruskal³⁰, T. Kubota¹¹⁹, H. Kucuk¹⁰⁹, S. Kудay⁵, J. T. Kuechler²³¹, S. Kuehn⁴⁶, A. Kugel⁸⁵, F. Kuger²³⁰, T. Kuhl⁶⁶, V. Kukhtin⁹⁵, R. Kukla¹¹⁶, Y. Kulchitsky¹²⁴, S. Kuleshov⁴⁹, Y. P. Kulinich²²², M. Kuna^{172,173}, T. Kunigo⁹⁸, A. Kupco¹⁶⁷, O. Kuprash²⁰⁴, H. Kurashige⁹⁷, L. L. Kurchaninov²¹³, Y. A. Kurochkin¹²⁴, M. G. Kurth⁵⁰, V. Kus¹⁶⁷, E. S. Kuwertz²²⁵, M. Kuze²⁰⁸, J. Kvita¹⁴⁷, T. Kwan²²⁵, D. Kyriazopoulos¹⁸⁶, A. La Rosa¹³², J. L. La Rosa Navarro³⁵, L. La Rotonda^{59,60}, C. Lacasta²²³, F. Lacava^{172,173}, J. Lacey⁶⁶, H. Lacker¹⁹, D. Lacour¹¹¹, E. Ladygin⁹⁵, R. Lafaye⁷, B. Laforge¹¹¹, T. Lagouri²³², S. Lai⁸⁰, S. Lammers⁹¹, W. Lamp⁹, E. Lançon³⁶, U. Landgraf⁷², M. P. J. Landon¹⁰⁷, M. C. Lanfermann⁷³, V. S. Lang⁸³, J. C. Lange¹⁵, A. J. Lankford²¹⁷, F. Lanni³⁶, K. Lantzsch²⁹, A. Lanza¹⁵³, A. Lapertosa^{74,75}, S. Laplace¹¹¹, J. F. Laporte¹⁸³, T. Lari¹²², F. Lasagni Manghi^{27,28}, M. Lassnig⁴⁶, P. Laurelli⁷¹, W. Lavrijsen¹⁸, A. T. Law¹⁸⁴, P. Laycock¹⁰⁵, T. Lazovich⁸², M. Lazzaroni^{122,123}, B. Le¹¹⁹, O. Le Dortz¹¹¹, E. Le Guirriec¹¹⁶, E. P. Le Quilleuc¹⁸³, M. LeBlanc²²⁵, T. LeCompte⁸, F. Ledroit-Guillon⁸¹, C. A. Lee³⁶, S. C. Lee²⁰², L. Lee¹, B. Lefebvre¹¹⁸, G. Lefebvre¹¹¹, M. Lefebvre²²⁵, F. Legger¹³¹, C. Leggett¹⁸, A. Lehan¹⁰⁵, G. Lehmann Miotto⁴⁶, X. Lei⁹, W. A. Leight⁶⁶, M. A. L. Leite³⁵, R. Leitner¹⁶⁹, D. Lellouch²²⁸, B. Lemmer⁸⁰, K. J. C. Leney¹⁰⁹, T. Lenz²⁹, B. Lenzi⁴⁶, R. Leone⁹, S. Leone^{157,158}, C. Leonidopoulos⁷⁰, G. Lerner²⁰⁰, C. Leroy¹²⁶, A. A. J. Lesage¹⁸³, C. G. Lester⁴⁴, M. Levchenko¹⁵⁶, J. Levêque⁷, D. Levin¹²⁰, L. J. Levinson²²⁸, M. Levy²¹, D. Lewis¹⁰⁷, M. Leyton⁶⁵, B. Li^{53,s}, C. Li⁵³, H. Li¹⁹⁹, L. Li⁶⁹, L. Li⁵⁵, Q. Li⁵⁰, S. Li⁶⁹, X. Li⁵⁵, Y. Li¹⁸⁸, Z. Liang⁵⁰, B. Liberti¹⁷⁴, A. Liblong²¹⁰, K. Lie²²², J. Liebal²⁹, W. Liebig¹⁷, A. Limosani²⁰¹, S. C. Lin^{202,af}, T. H. Lin¹¹⁴, B. E. Lindquist¹⁹⁹, A. E. Lioni⁷³, E. Lipeles¹⁵⁵, A. Lipniacka¹⁷, M. Lisovsky⁸⁴, T. M. Liss²²², A. Lister²²⁴, A. M. Litke¹⁸⁴, B. Liu^{202,ag}, H. Liu¹²⁰, H. Liu³⁶, J. Liu⁵⁴, J. B. Liu⁵³, K. Liu¹¹⁶, L. Liu²²², M. Liu⁵³, Y. L. Liu⁵³, Y. Liu⁵³, M. Livan^{153,154}, A. Lleres⁸¹, J. Llorente Merino⁵⁰, S. L. Lloyd¹⁰⁷, C. Y. Lo⁸⁸, F. Lo Sterzo²⁰², E. M. Lobodzinska⁶⁶, P. Loch⁹, F. K. Loebinger¹¹⁵, K. M. Loew³¹, A. Loginov^{232‡}, T. Lohse¹⁹, K. Lohwasser⁶⁶, M. Lokajicek¹⁶⁷, B. A. Long³⁰, J. D. Long²²², R. E. Long¹⁰², L. Longo^{103,104}, K. A. Looper¹⁴³, J. A. Lopez⁴⁹, D. Lopez Mateos⁸², I. Lopez Paz¹⁵, A. Lopez Solis¹¹¹, J. Lorenz¹³¹, N. Lorenzo Martinez⁷, M. Losada²⁶, P. J. Lösel¹³¹, X. Lou⁵⁰, A. Lounis¹⁴⁹, J. Love⁸, P. A. Love¹⁰², H. Lu⁸⁷, N. Lu¹²⁰, Y. J. Lu⁹⁰, H. J. Lubatti¹⁸⁵, C. Luci^{172,173}, A. Lucotte⁸¹, C. Luedtke⁷², F. Luehring⁹¹, W. Lukas⁹², L. Luminari¹⁷², O. Lundberg^{196,197}, B. Lund-Jensen¹⁹⁸, P. M. Luzzi¹¹¹, D. Lynn³⁶, R. Lysak¹⁶⁷, E. Lytken¹¹², V. Lyubushkin⁹⁵, H. Ma³⁶, L. L. Ma⁵⁴, Y. Ma⁵⁴, G. Maccarrone⁷¹, A. Macchiolo¹³², C. M. Macdonald¹⁸⁶, B. Maček¹⁰⁶, J. Machado Miguens^{155,161}, D. Madaffari¹¹⁶, R. Madar⁵⁶, H. J. Maddocks²²¹, W. F. Mader⁶⁸, A. Madsen⁶⁶, J. Maeda⁹⁷, S. Maeland¹⁷, T. Maeno³⁶, A. Maevskiy¹³⁰, E. Magradze⁸⁰, J. Mahlstedt¹³⁹, C. Maiani¹⁴⁹, C. Maidantchik³², A. A. Maier¹³², T. Maier¹³¹, A. Maio^{160,161}, S. Majewski¹⁴⁸, Y. Makida⁹⁶, N. Makovec¹⁴⁹, B. Malaescu¹¹¹, Pa. Malecki⁶³, V. P. Maleev¹⁵⁶, F. Malek⁸¹, U. Mallik⁹³, D. Malon⁸, C. Malone⁴⁴, S. Maltezos¹², S. Malyukov⁴⁶, J. Mamuzic²²³, G. Mancini⁷¹, L. Mandelli¹²², I. Mandic¹⁰⁶, J. Maneira^{160,161}, L. Manhaes de Andrade Filho³³, J. Manjarres Ramos²¹⁴, A. Mann¹³¹, A. Manousos⁴⁶, B. Mansoulié¹⁸³, J. D. Mansour⁵⁰, R. Mantifel¹¹⁸, M. Mantoani⁸⁰, S. Manzoni^{122,123}, L. Mapelli⁴⁶, G. Marceca⁴³, L. March⁷³, G. Marchiori¹¹¹, M. Marcisovsky¹⁶⁷, M. Marjanovic⁵⁶, D. E. Marley¹²⁰, F. Marroquim³², S. P. Marsden¹¹⁵, Z. Marshall¹⁸, M. U. F. Martensson²²¹, S. Marti-Garcia²²³, C. B. Martin¹⁴³, T. A. Martin²²⁶, V. J. Martin⁷⁰, B. Martin dit Latour¹⁷, M. Martinez^{15,v}, V. I. Martinez Outschoorn²²², S. Martin-Haugh¹⁷¹, V. S. Martoiu³⁸, A. C. Martyniuk¹⁰⁹, A. Marzin¹⁴⁵, L. Masetti¹¹⁴, T. Mashimo²⁰⁶, R. Mashinistov¹²⁷, J. Masik¹¹⁵, A. L. Maslennikov^{141,c}, L. Massa^{174,175}, P. Mastrandrea⁷, A. Mastroberardino^{59,60}, T. Masubuchi²⁰⁶, P. Mättig²³¹, J. Maurer³⁸, S. J. Maxfield¹⁰⁵, D. A. Maximov^{141,c}, R. Mazini²⁰², I. Maznas²⁰⁵, S. M. Mazza^{122,123}, N. C. Mc Fadden¹³⁷, G. McGoldrick²¹⁰, S. P. McKee¹²⁰, A. McCarn¹²⁰, R. L. McCarthy¹⁹⁹, T. G. McCarthy¹³², L. I. McClymont¹⁰⁹, E. F. McDonald¹¹⁹, J. A. McFayden¹⁰⁹, G. Mchedlidze⁸⁰, S. J. McMahon¹⁷¹, P. C. McNamara¹¹⁹, R. A. McPherson^{225,o}, S. Meehan¹⁸⁵, T. J. Megy⁷², S. Mehlhase¹³¹, A. Mehta¹⁰⁵, T. Meidecke⁸¹, K. Meier⁸³, C. Meineck¹³¹, B. Meirose⁶⁵, D. Melini^{223,ah}, B. R. Mellado Garcia¹⁹⁵, M. Melo¹⁹¹, F. Meloni²⁰, S. B. Menary¹¹⁵, L. Meng¹⁰⁵, X. T. Meng¹²⁰, A. Mengarelli^{27,28}, S. Menke¹³², E. Meoni²¹⁶, S. Mergelmeyer¹⁹, P. Mermod⁷³, L. Merola^{135,136}, C. Meroni¹²², F. S. Merritt⁴⁷, A. Messina^{172,173}, J. Metcalfe⁸, A. S. Mete²¹⁷, C. Meyer¹⁵⁵, J.-P. Meyer¹⁸³, J. Meyer¹³⁹, H. Meyer Zu Theenhausen⁸³, F. Miano²⁰⁰, R. P. Middleton¹⁷¹, S. Miglioranza^{74,75}, L. Mijovic⁷⁰, G. Mikenberg²²⁸, M. Mikesikova¹⁶⁷, M. Mikuš¹⁰⁶, M. Milesi¹¹⁹, A. Milic³⁶, D. W. Miller⁴⁷, C. Mills⁷⁰, A. Milov²²⁸, D. A. Milstead^{196,197}, A. A. Minaenko¹⁷⁰, Y. Minami²⁰⁶, I. A. Minashvili⁹⁵, A. I. Mincer¹⁴², B. Mindur⁶¹, M. Mineev⁹⁵, Y. Minegishi²⁰⁶, Y. Ming²²⁹, L. M. Mir¹⁵, K. P. Mistry¹⁵⁵, T. Mitani²²⁷, J. Mitrevski¹³¹, V. A. Mitsou²²³, A. Miucci²⁰, P. S. Miyagawa¹⁸⁶, A. Mizukami⁹⁶, J. U. Mjörnmark¹¹², M. Mlynarikova¹⁶⁹, T. Moa^{196,197}, K. Mochizuki¹²⁶, P. Mogg⁷², S. Mohapatra⁵⁷, S. Molander^{196,197}, R. Moles-Valls²⁹, R. Monden⁹⁸, M. C. Mondragon¹²¹, K. Mönig⁶⁶, J. Monk⁵⁸, E. Monnier¹¹⁶, A. Montalbano¹⁹⁹, J. Montejo Berlingen⁴⁶, F. Monticelli¹⁰¹, S. Monzani^{122,123}, R. W. Moore³, N. Morange¹⁴⁹, D. Moreno²⁶, M. Moreno Llácer⁸⁰, P. Morettini⁷⁴, S. Morgenstern⁴⁶, D. Mori¹⁸⁹, T. Mori²⁰⁶, M. Morii⁸², M. Morinaga²⁰⁶, V. Morisbak¹⁵¹, A. K. Morley²⁰¹, G. Mornacchi⁴⁶, J. D. Morris¹⁰⁷, L. Morvaj¹⁹⁹, P. Moschovakos¹², M. Mosidze⁷⁷, H. J. Moss¹⁸⁶, J. Moss^{190,ai}, K. Motohashi²⁰⁸, R. Mount¹⁹⁰, E. Mountricha³⁶, E. J. W. Moyses¹¹⁷, S. Muanza¹¹⁶, R. D. Mudd²¹, F. Mueller¹³², J. Mueller¹⁵⁹, R. S. P. Mueller¹³¹, D. Muenstermann¹⁰², P. Mullen⁷⁹, G. A. Mullier²⁰, F. J. Munoz Sanchez¹¹⁵, W. J. Murray^{226,171}, H. Musheghyan⁸⁰, M. Muškinja¹⁰⁶, A. G. Myagkov^{170,aj}, M. Myska¹⁶⁸, B. P. Nachman¹⁸, O. Nackenhörst⁷³, K. Nagai¹⁵², R. Nagai^{96,ad}, K. Nagano⁹⁶, Y. Nagasaka⁸⁶, K. Nagata²¹⁵, M. Nagel⁷², E. Nagy¹¹⁶, A. M. Nairz⁴⁶, Y. Nakahama¹³⁴, K. Nakamura⁹⁶, T. Nakamura²⁰⁶, I. Nakano¹⁴⁴, R. F. Naranjo Garcia⁶⁶, R. Narayan¹³, D. I. Narrias Villar⁸³, I. Naryshkin¹⁵⁶, T. Naumann⁶⁶, G. Navarro²⁶, R. Nayyar⁹, H. A. Neal¹²⁰, P. Yu. Nechaeva¹²⁷, T. J. Neep¹⁸³, A. Negri^{153,154}, M. Negrini²⁷, S. Nektarijevic¹³⁸, C. Nellist¹⁴⁹, A. Nelson²¹⁷, M. E. Nelson¹⁵², S. Nemecek¹⁶⁷, P. Nemethy¹⁴², A. A. Nepomuceno³², M. Nessi^{46,ak}, M. S. Neubauer²²²,

M. Neumann²³¹, R. M. Neves¹⁴², P. R. Newman²¹, T. Y. Ng⁸⁹, T. Nguyen Manh¹²⁶, R. B. Nickerson¹⁵², R. Nicolaidou¹⁸³, J. Nielsen¹⁸⁴, V. Nikolaenko^{170,aj}, I. Nikolic-Audit¹¹¹, K. Nikolopoulos²¹, J. K. Nilsen¹⁵¹, P. Nilsson³⁶, Y. Ninomiya²⁰⁶, A. Nisati¹⁷², N. Nishu⁵², R. Nisius¹³², T. Nobe²⁰⁶, Y. Noguchi⁹⁸, M. Nomachi¹⁵⁰, I. Nomidis⁴⁵, M. A. Nomura³⁶, T. Nooney¹⁰⁷, M. Nordberg⁴⁶, N. Norjoharuddeen¹⁵², O. Novgorodova⁶⁸, S. Nowak¹³², M. Nozaki⁹⁶, L. Nozka¹⁴⁷, K. Ntekas²¹⁷, E. Nurse¹⁰⁹, F. Nuti¹¹⁹, D. C. O’Neil¹⁸⁹, A. A. O’Rourke⁶⁶, V. O’Shea⁷⁹, F. G. Oakham^{45,d}, H. Oberlack¹³², T. Obermann²⁹, J. Ocariz¹¹¹, A. Ochi⁹⁷, I. Ochoa⁵⁷, J. P. Ochoa-Ricoux⁴⁸, S. Oda¹⁰⁰, S. Odaka⁹⁶, H. Ogren⁹¹, A. Oh¹¹⁵, S. H. Oh⁶⁹, C. C. Ohm¹⁸, H. Ohman²²¹, H. Oide^{74,75}, H. Okawa²¹⁵, Y. Okumura²⁰⁶, T. Okuyama⁹⁶, A. Olariu³⁸, L. F. Oleiro Seabra¹⁶⁰, S. A. Olivares Pino⁷⁰, D. Oliveira Damazio³⁶, A. Olszewski⁶³, J. Olszowska⁶³, A. Onofre^{160,164}, K. Onogi¹³⁴, P. U. E. Onyisi^{13,z}, M. J. Oreglia⁴⁷, Y. Oren²⁰⁴, D. Orestano^{176,177}, N. Orlando⁸⁸, R. S. Orr²¹⁰, B. Osculati^{74,75,†}, R. Ospanov¹¹⁵, G. Otero y Garzon⁴³, H. Otono¹⁰⁰, M. Ouchrif¹⁸¹, F. Ould-Saada¹⁵¹, A. Ouraou¹⁸³, K. P. Oussoren¹³⁹, Q. Ouyang⁵⁰, M. Owen⁷⁹, R. E. Owen²¹, V. E. Ozcan²², N. Ozturk¹⁰, K. Pachal¹⁸⁹, A. Pacheco Pages¹⁵, L. Pacheco Rodriguez¹⁸³, C. Padilla Aranda¹⁵, S. Pagan Griso¹⁸, M. Paganini²³², F. Paige³⁶, P. Pais¹¹⁷, G. Palacino⁹¹, S. Palazzo^{59,60}, S. Palestini⁴⁶, M. Palka⁶², D. Pallin⁵⁶, E. St. Panagiotopoulou¹², I. Panagoulas¹², C. E. Pandini¹¹¹, J. G. Panduro Vazquez¹⁰⁸, P. Pani⁴⁶, S. Panitkin³⁶, D. Pantea³⁸, L. Paolozzi⁷³, Th. D. Papadopoulos¹², K. Papageorgiou¹¹, A. Paramonov⁸, D. Paredes Hernandez²³², A. J. Parker¹⁰², M. A. Parker⁴⁴, K. A. Parker⁶⁶, F. Parodi^{74,75}, J. A. Parsons⁵⁷, U. Parzefall⁷², V. R. Pascuzzi²¹⁰, J. M. Pasner¹⁸⁴, E. Pasqualucci¹⁷², S. Passaggio⁷⁴, Fr. Pastore¹⁰⁸, S. Pataraja²³¹, J. R. Pater¹¹⁵, T. Pauly⁴⁶, J. Pearce²²⁵, B. Pearson¹³², L. E. Pedersen⁵⁸, S. Pedraza Lopez²²³, R. Pedro^{160,161}, S. V. Peleganchuk^{141,c}, O. Penc¹⁶⁷, C. Peng⁵⁰, H. Peng⁵³, J. Penwell⁹¹, B. S. Peralva³³, M. M. Perego¹⁸³, D. V. Perepelitsa³⁶, L. Perini^{122,123}, H. Pernegger⁴⁶, S. Perrella^{135,136}, R. Peschke⁶⁶, V. D. Peshekhonov⁹⁵, K. Peters⁶⁶, R. F. Y. Peters¹¹⁵, B. A. Petersen⁴⁶, T. C. Petersen⁵⁸, E. Petit⁸¹, A. Petridis¹, C. Petridou²⁰⁵, P. Petroff¹⁴⁹, E. Petrolo¹⁷², M. Petrov¹⁵², F. Petrucci^{176,177}, N. E. Pettersson¹¹⁷, A. Peyaud¹⁸³, R. Pezoa⁴⁹, P. W. Phillips¹⁷¹, G. Piacquadio¹⁹⁹, E. Pianori²²⁶, A. Picazio¹¹⁷, E. Piccaro¹⁰⁷, M. A. Pickering¹⁵², R. Piegaia⁴³, J. E. Pilcher⁴⁷, A. D. Pilkington¹¹⁵, A. W. J. Pin¹¹⁵, M. Pinamonti^{218,220,al}, J. L. Pinfold³, H. Pirumov⁶⁶, M. Pitt²²⁸, L. Plazak¹⁹¹, M.-A. Pleier³⁶, V. Pleskot¹¹⁴, E. Plotnikova⁹⁵, D. Pluth⁹⁴, P. Podberezko¹⁴¹, R. Poettgen^{196,197}, L. Poggioli¹⁴⁹, D. Pohl²⁹, G. Polesello¹⁵³, A. Poley⁶⁶, A. Policicchio^{59,60}, R. Polifka⁴⁶, A. Polini²⁷, C. S. Pollard⁷⁹, V. Polychronakos³⁶, K. Pommès⁴⁶, D. Ponomarenko¹²⁹, L. Pontecorvo¹⁷², B. G. Pope¹²¹, G. A. Popeneciu⁴⁰, A. Poppleton⁴⁶, S. Pospisil¹⁶⁸, K. Potamianos¹⁸, I. N. Potrap⁹⁵, C. J. Potter⁴⁴, C. T. Potter¹⁴⁸, G. Poulard⁴⁶, J. Poveda⁴⁶, M. E. Pozo Astigarraga⁴⁶, P. Pralavorio¹¹⁶, A. Pranko¹⁸, S. Prell⁹⁴, D. Price¹¹⁵, L. E. Price⁸, M. Primavera¹⁰³, S. Prince¹¹⁸, N. Proklova¹²⁹, K. Prokofiev⁸⁹, F. Prokoshin⁴⁹, S. Protopopescu³⁶, J. Proudfoot⁸, M. Przybycien⁶¹, D. Puudu^{176,177}, A. Puri²²², P. Puzo¹⁴⁹, J. Qian¹²⁰, G. Qin⁷⁹, Y. Qin¹¹⁵, A. Quadt⁸⁰, W. B. Quayle^{218,219}, M. Queitsch-Maitland⁶⁶, D. Quilty⁷⁹, S. Raddum¹⁵¹, V. Radeka³⁶, V. Radescu¹⁵², S. K. Radhakrishnan¹⁹⁹, P. Radloff¹⁴⁸, P. Rados¹¹⁹, F. Ragusa^{122,123}, G. Rahal²³⁵, J. A. Raine¹¹⁵, S. Rajagopalan³⁶, C. Rangel-Smith²²¹, M. G. Ratti^{122,123}, D. M. Rauch⁶⁶, F. Rauscher¹³¹, S. Rave¹¹⁴, T. Ravenscroft⁷⁹, I. Ravinovich²²⁸, J. H. Rawling¹¹⁵, M. Raymond⁴⁶, A. L. Read¹⁵¹, N. P. Readioff¹⁰⁵, M. Reale^{103,104}, D. M. Rebuffi^{153,154}, A. Redelbach²³⁰, G. Redlinger³⁶, R. Reece¹⁸⁴, R. G. Reed¹⁹⁵, K. Reeves⁶⁵, L. Rehnisch¹⁹, J. Reichert¹⁵⁵, A. Reiss¹¹⁴, C. Rembser⁴⁶, H. Ren⁵⁰, M. Rescigno¹⁷², S. Resconi¹²², E. D. Resseguie¹⁵⁵, S. Rettie²²⁴, E. Reynolds²¹, O. L. Rezanova^{141,c}, P. Reznicek¹⁶⁹, R. Rezvani¹²⁶, R. Richter¹³², S. Richter¹⁰⁹, E. Richter-Was⁶², O. Ricken²⁹, M. Ridel¹¹¹, P. Rieck¹³², C. J. Riegel²³¹, J. Rieger⁸⁰, O. Rifki¹⁴⁵, M. Rijssenbeek¹⁹⁹, A. Rimoldi^{153,154}, M. Rimoldi²⁰, L. Rinaldi²⁷, B. Ristic⁷³, E. Ritsch⁴⁶, I. Riu¹⁵, F. Rizatdinova¹⁴⁶, E. Rizvi¹⁰⁷, C. Rizzi¹⁵, R. T. Roberts¹¹⁵, S. H. Robertson^{118,o}, A. Robichaud-Veronneau¹¹⁸, D. Robinson⁴⁴, J. E. M. Robinson⁶⁶, A. Robson⁷⁹, C. Roda^{157,158}, Y. Rodina^{116,am}, A. Rodriguez Perez¹⁵, D. Rodriguez Rodriguez²²³, S. Roe⁴⁶, C. S. Rogan⁸², O. Røhne¹⁵¹, J. Roloff⁸², A. Romaniouk¹²⁹, M. Romano^{27,28}, S. M. Romano Saez⁵⁶, E. Romero Adam²²³, N. Rompotis¹⁰⁵, M. Ronzani⁷², L. Roos¹¹¹, S. Rosati¹⁷², K. Rosbach⁷², P. Rose¹⁸⁴, N.-A. Rosien⁸⁰, V. Rossetti^{196,197}, E. Rossi^{135,136}, L. P. Rossi⁷⁴, J. H. N. Rosten⁴⁴, R. Rosten¹⁸⁵, M. Rotaru³⁸, I. Roth²²⁸, J. Rothberg¹⁸⁵, D. Rousseau¹⁴⁹, A. Rozanov¹¹⁶, Y. Rozen²⁰³, X. Ruan¹⁹⁵, F. Rubbo¹⁹⁰, F. Rühr⁷², A. Ruiz-Martinez⁴⁵, Z. Rurikova⁷², N. A. Rusakovich⁹⁵, A. Ruschke¹³¹, H. L. Russell¹⁸⁵, J. P. Rutherford⁹, N. Ruthmann⁴⁶, Y. F. Ryabov¹⁵⁶, M. Rybar²²², G. Rybkin¹⁴⁹, S. Ryu⁸, A. Ryzhov¹⁷⁰, G. F. Rzehorz⁸⁰, A. F. Saavedra²⁰¹, G. Sabato¹³⁹, S. Sacerdoti⁴³, H. F.-W. Sadrozinski¹⁸⁴, R. Sadykov⁹⁵, F. Safai Tehrani¹⁷², P. Saha¹⁴⁰, M. Sahinsoy⁸³, M. Saimpert⁶, M. Saito²⁰⁶, T. Saito²⁰⁶, H. Sakamoto²⁰⁶, Y. Sakurai²²⁷, G. Salamanna^{176,177}, J. E. Salazar Loyola⁴⁹, D. Salek¹³⁹, P. H. Sales De Bruin²²¹, D. Saliagic¹³², A. Salnikov¹⁹⁰, J. Salt²²³, D. Salvatore^{59,60}, F. Salvatore²⁰⁰, A. Salvucci^{87,88,89}, A. Salzburger⁴⁶, D. Sammel⁷², D. Sampsonidis²⁰⁵, J. Sánchez²²³, V. Sanchez Martinez²²³, A. Sanchez Pineda^{218,220}, H. Sandaker¹⁵¹, R. L. Sandbach¹⁰⁷, C. O. Sander⁶⁶, M. Sandhoff²³¹, C. Sandoval²⁶, D. P. C. Sankey¹⁷¹, M. Sannino^{74,75}, A. Sansoni⁷¹, C. Santoni⁵⁶, R. Santonico^{174,175}, H. Santos¹⁶⁰, I. Santoyo Castillo²⁰⁰, K. Sapp¹⁵⁹, A. Saprnov⁹⁵, J. G. Saraiva^{160,163}, B. Sarrazin²⁹, O. Sasaki⁹⁶, K. Sato²¹⁵, E. Sauvan⁷, G. Savage¹⁰⁸, P. Savard^{210,d}, N. Savic¹³², C. Sawyer¹⁷¹, L. Sawyer^{110,u}, J. Saxon⁴⁷, C. Sbarra²⁷, A. Sbrizzi^{27,28}, T. Scanlon¹⁰⁹, D. A. Scannicchio²¹⁷, M. Scarcella²⁰¹, V. Scarfone^{59,60}, J. Schaarschmidt¹⁸⁵, P. Schacht¹³², B. M. Schachtner¹³¹, D. Schaefer⁴⁶, L. Schaefer¹⁵⁵, R. Schaefer⁶⁶, J. Schaeffer¹¹⁴, S. Schaepe²⁹, S. Schaezel⁸⁴, U. Schäfer¹¹⁴, A. C. Schaffer¹⁴⁹, D. Schaile¹³¹, R. D. Schamberger¹⁹⁹, V. Scharf⁸³, V. A. Schegelsky¹⁵⁶, D. Scheirich¹⁶⁹, M. Schernau²¹⁷, C. Schiavi^{74,75}, S. Schier¹⁸⁴, L. K. Schildgen²⁹, C. Schillo⁷², M. Schioppa^{59,60}, S. Schlenker⁴⁶, K. R. Schmidt-Sommerfeld¹³², K. Schmieden⁴⁶, C. Schmitt¹¹⁴, S. Schmitt⁶⁶, S. Schmitz¹¹⁴, U. Schnoor⁷², L. Schoeffel¹⁸³, A. Schoening⁸⁴, B. D. Schoenrock¹²¹, E. Schopf²⁹, M. Schott¹¹⁴, J. F. P. Schouwenberg¹³⁸, J. Schovancova²³⁴, S. Schramm⁷³, N. Schuh¹¹⁴, A. Schulte¹¹⁴, M. J. Schultens²⁹, H.-C. Schultz-Coulon⁸³, H. Schulz¹⁹, M. Schumacher⁷², B. A. Schumm¹⁸⁴, Ph. Schune¹⁸³, A. Schwartzman¹⁹⁰, T. A. Schwarz¹²⁰, H. Schweiger¹¹⁵, Ph. Schwemling¹⁸³, R. Schwienhorst¹²¹, J. Schwindling¹⁸³, T. Schwindt²⁹, A. Sciandra²⁹, G. Sciolla³¹, F. Scuri^{157,158}, F. Scutti¹¹⁹, J. Searcy¹²⁰, P. Seema²⁹, S. C. Seidel¹³⁷,

A. Seiden¹⁸⁴, J. M. Seixas³², G. Sekhniaidze¹³⁵, K. Sekhon¹²⁰, S. J. Sekula⁶⁴, N. Semprini-Cesari^{27,28}, C. Serfon¹⁵¹, L. Serin¹⁴⁹, L. Serkin^{218,219}, M. Sessa^{176,177}, R. Seuster²²⁵, H. Severini¹⁴⁵, T. Sfiligoj¹⁰⁶, F. Sforza⁴⁶, A. Sfyrly⁷³, E. Shabalina⁸⁰, N. W. Shaikh^{196,197}, L. Y. Shan⁵⁰, R. Shang²²², J. T. Shank³⁰, M. Shapiro¹⁸, P. B. Shatalov¹²⁸, K. Shaw^{218,219}, S. M. Shaw¹¹⁵, A. Shcherbakova^{196,197}, C. Y. Shehu²⁰⁰, Y. Shen¹⁴⁵, P. Sherwood¹⁰⁹, L. Shi^{202,an}, S. Shimizu⁹⁷, C. O. Shimmin²³², M. Shimojima¹³³, S. Shirabe¹⁰⁰, M. Shiyakova^{95,ao}, J. Shlomi²²⁸, A. Shmeleva¹²⁷, D. Shoaleh Saadi¹²⁶, M. J. Shochet⁴⁷, S. Shojaii¹²², D. R. Shope¹⁴⁵, S. Shrestha¹⁴³, E. Shulga¹²⁹, M. A. Shupe⁹, P. Sicho¹⁶⁷, A. M. Sickles²²², P. E. Sidebo¹⁹⁸, E. Sideras Haddad¹⁹⁵, O. Sidiropoulou²³⁰, D. Sidorov¹⁴⁶, A. Sidoti^{27,28}, F. Siegert⁶⁸, Dj. Sijacki¹⁶, J. Silva^{160,163}, S. B. Silverstein¹⁹⁶, V. Simak¹⁶⁸, Lj. Simic¹⁶, S. Simion¹⁴⁹, E. Simioni¹¹⁴, B. Simmons¹⁰⁹, M. Simon¹¹⁴, P. Sinervo²¹⁰, N. B. Sinev¹⁴⁸, M. Sioli^{27,28}, G. Siragusa²³⁰, I. Siral¹²⁰, S. Yu. Sivoklov¹³⁰, J. Sjölin^{196,197}, M. B. Skinner¹⁰², P. Skubic¹⁴⁵, M. Slater²¹, T. Slavicek¹⁶⁸, M. Slawinska¹³⁹, K. Sliwa²¹⁶, R. Slovak¹⁶⁹, V. Smakhtin²²⁸, B. H. Smart⁷, J. Smiesko¹⁹¹, N. Smirnov¹²⁹, S. Yu. Smirnov¹²⁹, Y. Smirnov¹²⁹, L. N. Smirnova^{130,ap}, O. Smirnova¹¹², J. W. Smith⁸⁰, M. N. K. Smith⁵⁷, R. W. Smith⁵⁷, M. Smizanska¹⁰², K. Smolek¹⁶⁸, A. A. Snesarev¹²⁷, I. M. Snyder¹⁴⁸, S. Snyder³⁶, R. Sobie^{225,o}, F. Socher⁶⁸, A. Soffer²⁰⁴, D. A. Soh²⁰², G. Sokhranyii¹⁰⁶, C. A. Solans Sanchez⁴⁶, M. Solar¹⁶⁸, E. Yu. Soldatov¹²⁹, U. Soldevila²²³, A. A. Solodkov¹⁷⁰, A. Soloshenko⁹⁵, O. V. Solovyanov¹⁷⁰, V. Solovyev¹⁵⁶, P. Sommer⁷², H. Son²¹⁶, H. Y. Song^{53,aq}, A. Sopczak¹⁶⁸, V. Sorin¹⁵, D. Sosa⁸⁴, C. L. Sotiropoulou^{157,158}, R. Soualah^{218,220}, A. M. Soukharev^{141,c}, D. South⁶⁶, B. C. Sowden¹⁰⁸, S. Spagnolo^{103,104}, M. Spalla^{157,158}, M. Spangenberg²²⁶, F. Spanò¹⁰⁸, D. Sperlich¹⁹, F. Spettel¹³², T. M. Spieker⁸³, R. Spighi²⁷, G. Spigo⁴⁶, L. A. Spiller¹¹⁹, M. Spusta¹⁶⁹, R. D. St. Denis^{79‡}, A. Stabile¹²², R. Stamen⁸³, S. Stamm¹⁹, E. Stanecka⁶³, R. W. Stanek⁸, C. Stanescu¹⁷⁶, M. M. Stanitzki⁶⁶, S. Stapnes¹⁵¹, E. A. Starchenko¹⁷⁰, G. H. Stark⁴⁷, J. Stark⁸¹, S. H. Stark⁵⁸, P. Staroba¹⁶⁷, P. Starovoitov⁸³, S. Stärz⁴⁶, R. Staszewski⁶³, P. Steinberg³⁶, B. Stelzer¹⁸⁹, H. J. Stelzer⁴⁶, O. Stelzer-Chilton²¹³, H. Stenzel⁷⁸, G. A. Stewart⁷⁹, J. A. Stillings²⁹, M. C. Stockton¹⁴⁸, M. Stoebe¹¹⁸, G. Stoicea³⁸, P. Stolte⁸⁰, S. Stonjek¹³², A. R. Stradling¹⁰, A. Straessner⁶⁸, M. E. Stramaglia²⁰, J. Strandberg¹⁹⁸, S. Strandberg^{196,197}, A. Strandlie¹⁵¹, M. Strauss¹⁴⁵, P. Strizenec¹⁹², R. Ströhmer²³⁰, D. M. Strom¹⁴⁸, R. Stroyanowski⁶⁴, A. Strubig¹³⁸, S. A. Stucci³⁶, B. Stugu¹⁷, N. A. Styles⁶⁶, D. Su¹⁹⁰, J. Su¹⁵⁹, S. Suchek⁸³, Y. Sugaya¹⁵⁰, M. Suk¹⁶⁸, V. V. Sulin¹²⁷, S. Sultansoy⁶, T. Sumida⁹⁸, S. Sun⁸², X. Sun³, K. Suruliz²⁰⁰, C. J. E. Suster²⁰¹, M. R. Sutton²⁰⁰, S. Suzuki⁹⁶, M. Svatos¹⁶⁷, M. Swiatlowski⁴⁷, S. P. Swift⁸⁰, A. Sydorenko¹¹⁴, I. Sykora¹⁹¹, T. Sykora¹⁶⁹, D. Ta⁷², K. Tackmann⁶⁶, J. Taenzer²⁰⁴, A. Taffard²¹⁷, R. Tafirout²¹³, N. Taiblum²⁰⁴, H. Takai³⁶, R. Takashima⁹⁹, T. Takeshita¹⁸⁷, Y. Takubo⁹⁶, M. Talby¹¹⁶, A. A. Talyshev^{141,c}, J. Tanaka²⁰⁶, M. Tanaka²⁰⁸, R. Tanaka¹⁴⁹, S. Tanaka⁹⁶, R. Tanioka⁹⁷, B. B. Tannenwald¹⁴³, S. Tapia Araya⁴⁹, S. Tapprogge¹¹⁴, S. Tarem²⁰³, G. F. Tartarelli¹²², P. Tas¹⁶⁹, M. Tasevsky¹⁶⁷, T. Tashiro⁹⁸, E. Tassi^{59,60}, A. Tavares Delgado^{160,161}, Y. Tayalati¹⁸², A. C. Taylor¹³⁷, G. N. Taylor¹¹⁹, P. T. E. Taylor¹¹⁹, W. Taylor²¹⁴, P. Teixeira-Dias¹⁰⁸, D. Temple¹⁸⁹, H. Ten Kate⁴⁶, P. K. Teng²⁰², J. J. Teoh¹⁵⁰, F. Tepel²³¹, S. Terada⁹⁶, K. Terashi²⁰⁶, J. Terron¹¹³, S. Terzo¹⁵, M. Testa⁷¹, R. J. Teuscher^{210,o}, T. Theveneaux-Pelzer¹¹⁶, J. P. Thomas²¹, J. Thomas-Wilsker¹⁰⁸, P. D. Thompson²¹, A. S. Thompson⁷⁹, L. A. Thomsen²³², E. Thomson¹⁵⁵, M. J. Tibbetts¹⁸, R. E. Ticse Torres¹¹⁶, V. O. Tikhomirov^{127,ar}, Yu. A. Tikhonov^{141,c}, S. Timoshenko¹²⁹, P. Tipton²³², S. Tisserant¹¹⁶, K. Todome²⁰⁸, S. Todorova-Nova⁷, J. Tojo¹⁰⁰, S. Tokár¹⁹¹, K. Tokushuku⁹⁶, E. Tolley⁸², L. Tomlinson¹¹⁵, M. Tomoto¹³⁴, L. Tompkins^{190,as}, K. Toms¹³⁷, B. Tong⁸², P. Tornambe⁷², E. Torrence¹⁴⁸, H. Torres¹⁸⁹, E. Torró Pastor¹⁸⁵, J. Toth^{116,at}, F. Touchard¹¹⁶, D. R. Tovey¹⁸⁶, C. J. Treado¹⁴², T. Trefzger²³⁰, A. Tricoli³⁶, I. M. Trigger²¹³, S. Trincaz-Duvoid¹¹¹, M. F. Tripania¹⁵, W. Trischuk²¹⁰, B. Trocmé⁸¹, A. Trofymov⁶⁶, C. Troncon¹²², M. Trottier-McDonald¹⁸, M. Trovatelli²²⁵, L. Truong^{218,219}, M. Trzebinski⁶³, A. Trzupek⁶³, K. W. Tsang⁸⁷, J. C.-L. Tseng¹⁵², P. V. Tsiarehka¹²⁴, G. Tsiapolitis¹², N. Tsirintanis¹¹, S. Tsiskaridze¹⁵, V. Tsiskaridze⁷², E. G. Tskhadadze⁷⁶, K. M. Tsui⁸⁷, I. I. Tsukerman¹²⁸, V. Tsulaia¹⁸, S. Tsuno⁹⁶, D. Tsybychev¹⁹⁹, Y. Tu⁸⁸, A. Tudorache³⁸, V. Tudorache³⁸, T. T. Tulbure³⁷, A. N. Tuna⁸², S. A. Tupputi^{27,28}, S. Turchikhin⁹⁵, D. Turgeman²²⁸, I. Turk Cakir^{5,au}, R. Turra^{122,123}, P. M. Tuts⁵⁷, G. Ucchielli^{27,28}, I. Ueda⁹⁶, M. Ughetto^{196,197}, F. Ukegawa²¹⁵, G. Unal⁴⁶, A. Undrus³⁶, G. Unel²¹⁷, F. C. Ungaro¹¹⁹, Y. Unno⁹⁶, C. Unverdorben¹³¹, J. Urban¹⁹², P. Urquijo¹¹⁹, P. Urrejola¹¹⁴, G. Usai¹⁰, J. Usui⁹⁶, L. Vacavant¹¹⁶, V. Vacek¹⁶⁸, B. Vachon¹¹⁸, C. Valderanis¹³¹, E. Valdes Santurio^{196,197}, N. Valencic¹³⁹, S. Valentini^{27,28}, A. Valero²²³, L. Valéry¹⁵, S. Valkar¹⁶⁹, A. Vallier⁷, J. A. Valls Ferrer²²³, W. Van Den Wollenberg¹³⁹, H. van der Graaf¹³⁹, N. van Eldik²⁰³, P. van Gemmeren⁸, J. Van Nieuwkoop¹⁸⁹, I. van Vulpen¹³⁹, M. C. van Woerden¹³⁹, M. Vanadia^{172,173}, W. Vandelli⁴⁶, R. Vanguri¹⁵⁵, A. Vaniachine²⁰⁹, P. Vankov¹³⁹, G. Vardanyan²³³, R. Vari¹⁷², E. W. Varnes⁹, C. Varni^{74,75}, T. Varol⁶⁴, D. Varouchas¹⁴⁹, A. Vartapetian¹⁰, K. E. Varvell²⁰¹, J. G. Vasquez²³², G. A. Vasquez⁴⁹, F. Vazeille⁵⁶, T. Vazquez Schroeder¹¹⁸, J. Veatch⁸⁰, V. Veeraraghavan⁹, L. M. Veloce²¹⁰, F. Veloso^{160,162}, S. Veneziano¹⁷², A. Ventura^{103,104}, M. Venturi²²⁵, N. Venturi²¹⁰, A. Venturini³¹, V. Vercesi¹⁵³, M. Verducci^{176,177}, W. Verkerke¹³⁹, J. C. Vermeulen¹³⁹, M. C. Vetterli^{189,d}, N. Viaux Maira⁴⁹, O. Viazlo¹¹², I. Vichou^{222‡}, T. Vickey¹⁸⁶, O. E. Vickey Boeriu¹⁸⁶, G. H. A. Viehhauser¹⁵², S. Viel¹⁸, L. Viganì¹⁵², M. Villa^{27,28}, M. Villaplana Perez^{122,123}, E. Vilucchi⁷¹, M. G. Vincker⁴⁵, V. B. Vinogradov⁹⁵, A. Vishwakarma⁶⁶, C. Vittori^{27,28}, I. Vivarelli²⁰⁰, S. Vlachos¹², M. Vlasak¹⁶⁸, M. Vogel²³¹, P. Vokac¹⁶⁸, G. Volpi^{157,158}, M. Volpi¹¹⁹, H. von der Schmitt¹³², E. von Toerne²⁹, V. Vorobel¹⁶⁹, K. Vorobev¹²⁹, M. Vos²²³, R. Voss⁴⁶, J. H. Vosseveld¹⁰⁵, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, V. Vrba¹⁶⁸, M. Vreeswijk¹³⁹, R. Vuillermet⁴⁶, I. Vukotic⁴⁷, P. Wagner²⁹, W. Wagner²³¹, H. Wahlberg¹⁰¹, S. Wahrenmund⁶⁸, J. Wakabayashi¹³⁴, J. Walder¹⁰², R. Walker¹³¹, W. Walkowiak¹⁸⁸, V. Wallangen^{196,197}, C. Wang⁵¹, C. Wang^{54,av}, F. Wang²²⁹, H. Wang¹⁸, H. Wang³, J. Wang⁶⁶, J. Wang²⁰¹, Q. Wang¹⁴⁵, R. Wang⁸, S. M. Wang²⁰², T. Wang⁵⁷, W. Wang^{202,aw}, W. Wang⁵³, Z. Wang⁵⁵, C. Wanotayaroj¹⁴⁸, A. Warburton¹¹⁸, C. P. Ward⁴⁴, D. R. Wardrop¹⁰⁹, A. Washbrook⁷⁰, P. M. Watkins²¹, A. T. Watson²¹, M. F. Watson²¹, G. Watts¹⁸⁵, S. Watts¹¹⁵, B. M. Waugh¹⁰⁹, A. F. Webb¹³, S. Webb¹¹⁴, M. S. Weber²⁰, S. W. Weber²³⁰, S. A. Weber⁴⁵, J. S. Webster⁸, A. R. Weidberg¹⁵², B. Weinert⁹¹, J. Weingarten⁸⁰, C. Weiser⁷², H. Weits¹³⁹, P. S. Wells⁴⁶, T. Wenaus³⁶, T. Wengler⁴⁶, S. Wenig⁴⁶, N. Wermes²⁹,

M. D. Werner⁹⁴, P. Werner⁴⁶, M. Wessels⁸³, K. Whalen¹⁴⁸, N. L. Whallon¹⁸⁵, A. M. Wharton¹⁰², A. White¹⁰, M. J. White¹, R. White⁴⁹, D. Whiteson²¹⁷, F. J. Wickens¹⁷¹, W. Wiedenmann²²⁹, M. Wieler¹⁷¹, C. Wigglesworth⁵⁸, L. A. M. Wiik-Fuchs²⁹, A. Wildauer¹³², F. Wilk¹¹⁵, H. G. Wilkens⁴⁶, H. H. Williams¹⁵⁵, S. Williams¹³⁹, C. Willis¹²¹, S. Willocq¹¹⁷, J. A. Wilson²¹, I. Wingerter-Seez⁷, F. Winklmeier¹⁴⁸, O. J. Winston²⁰⁰, B. T. Winter²⁹, M. Wittgen¹⁹⁰, M. Wobisch^{110,u}, T. M. H. Wolf¹³⁹, R. Wolff¹¹⁶, M. W. Wolter⁶³, H. Wolters^{160,162}, S. D. Worm²¹, B. K. Wosiek⁶³, J. Wotschack⁴⁶, M. J. Woudstra¹¹⁵, K. W. Wozniak⁶³, M. Wu⁴⁷, S. L. Wu²²⁹, X. Wu⁷³, Y. Wu¹²⁰, T. R. Wyatt¹¹⁵, B. M. Wynne⁷⁰, S. Xella⁵⁸, Z. Xi¹²⁰, L. Xia⁵², D. Xu⁵⁰, L. Xu³⁶, B. Yabsley²⁰¹, S. Yacoub¹⁹³, D. Yamaguchi²⁰⁸, Y. Yamaguchi¹⁵⁰, A. Yamamoto⁹⁶, S. Yamamoto²⁰⁶, T. Yamanaka²⁰⁶, K. Yamauchi¹³⁴, Y. Yamazaki⁹⁷, Z. Yan³⁰, H. Yang⁵⁵, H. Yang¹⁸, Y. Yang²⁰², Z. Yang¹⁷, W.-M. Yao¹⁸, Y. C. Yap¹¹¹, Y. Yasu⁹⁶, E. Yatsenko⁷, K. H. Yau Wong²⁹, J. Ye⁶⁴, S. Ye³⁶, I. Yeletsikh⁹⁵, E. Yigitbasi³⁰, E. Yildirim¹¹⁴, K. Yorita²²⁷, K. Yoshihara¹⁵⁵, C. Young¹⁹⁰, C. J. S. Young⁴⁶, S. Youssef³⁰, D. R. Yu¹⁸, J. Yu¹⁰, J. Yu⁹⁴, L. Yuan⁹⁷, S. P. Y. Yuen²⁹, I. Yusuff^{44,ax}, B. Zabinski⁶³, G. Zacharis¹², R. Zaidan¹⁵, A. M. Zaitsev^{170,aj}, N. Zakharchuk⁶⁶, J. Zalieckas¹⁷, A. Zaman¹⁹⁹, S. Zambito⁸², D. Zanzi¹¹⁹, C. Zeitnitz²³¹, M. Zeman¹⁶⁸, A. Zemla⁶¹, J. C. Zeng²²², Q. Zeng¹⁹⁰, O. Zenin¹⁷⁰, T. Ženiš¹⁹¹, D. Zerwas¹⁴⁹, D. Zhang¹²⁰, F. Zhang²²⁹, G. Zhang^{53,aq}, H. Zhang⁵¹, J. Zhang⁸, L. Zhang⁷², L. Zhang⁵³, M. Zhang²²², R. Zhang²⁹, R. Zhang^{53,av}, X. Zhang⁵⁴, Y. Zhang⁵⁰, Z. Zhang¹⁴⁹, X. Zhao⁶⁴, Y. Zhao^{54,ay}, Z. Zhao⁵³, A. Zhemchugov⁹⁵, J. Zhong¹⁵², B. Zhou¹²⁰, C. Zhou²²⁹, L. Zhou⁶⁴, M. Zhou⁵⁰, M. Zhou¹⁹⁹, N. Zhou⁵², C. G. Zhu⁵⁴, H. Zhu⁵⁰, J. Zhu¹²⁰, Y. Zhu⁵³, X. Zhuang⁵⁰, K. Zhukov¹²⁷, A. Zibell²³⁰, D. Zieminska⁹¹, N. I. Zimine⁹⁵, C. Zimmermann¹¹⁴, S. Zimmermann⁷², Z. Zinonos¹³², M. Zinser¹¹⁴, M. Ziolkowski¹⁸⁸, L. Živković¹⁶, G. Zobernig²²⁹, A. Zoccoli^{27,28}, R. Zou⁴⁷, M. zur Nedden¹⁹, L. Zwalinski⁴⁶

Primary affiliations

¹Department of Physics, University of Adelaide, Adelaide, Australia. ²Physics Department, SUNY Albany, Albany, New York, USA. ³Department of Physics, University of Alberta, Edmonton, Alberta, Canada. ⁴Department of Physics, Ankara University, Ankara, Turkey. ⁵Istanbul Aydin University, Istanbul, Turkey. ⁶Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey. ⁷LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France. ⁸High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA. ⁹Department of Physics, University of Arizona, Tucson, Arizona, USA. ¹⁰Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA. ¹¹Physics Department, National and Kapodistrian University of Athens, Athens, Greece. ¹²Physics Department, National Technical University of Athens, Zografou, Greece. ¹³Department of Physics, The University of Texas at Austin, Austin, Texas, USA. ¹⁴Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. ¹⁵Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain. 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, California, USA. ¹⁹Department of Physics, Humboldt University, 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, UK. ²²Department of Physics, Bogazici University, Istanbul, Turkey. ²³Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey. ²⁴Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey. ²⁵Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey. ²⁶Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia. ²⁷INFN Sezione di Bologna, Bologna, Italy. ²⁸Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy. ²⁹Physikalisches Institut, University of Bonn, Bonn, Germany. ³⁰Department of Physics, Boston University, Boston, Massachusetts, USA. ³¹Department of Physics, Brandeis University, Waltham, Massachusetts, USA. ³²Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil. ³³Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil. ³⁴Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil. ³⁵Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil. ³⁶Physics Department, Brookhaven National Laboratory, Upton, New York, USA. ³⁷Transilvania University of Brasov, Brasov, Romania. ³⁸Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania. ³⁹Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania. ⁴⁰National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania. ⁴¹University Politehnica Bucharest, Bucharest, Romania. ⁴²West University in Timisoara, Timisoara, Romania. ⁴³Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina. ⁴⁴Cavendish Laboratory, University of Cambridge, Cambridge, UK. ⁴⁵Department of Physics, Carleton University, Ottawa, Ontario, Canada. ⁴⁶CERN, Geneva, Switzerland. ⁴⁷Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA. ⁴⁸Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile. ⁴⁹Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile. ⁵⁰Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China. ⁵¹Department of Physics, Nanjing University, Jiangsu, China. ⁵²Physics Department, Tsinghua University, Beijing 100084, China. ⁵³Department of Modern Physics, University of Science and Technology of China, Anhui, China. ⁵⁴School of Physics, Shandong University, Shandong, China. ⁵⁵Department of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai (also at PKU-CHEP), China. ⁵⁶Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France. ⁵⁷Nevis Laboratory, Columbia University, Irvington, New York, USA. ⁵⁸Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark. ⁵⁹INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Rende, Italy. ⁶⁰Dipartimento di Fisica, Università della Calabria, Rende, Italy. ⁶¹AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland. ⁶²Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland. ⁶³Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland. ⁶⁴Physics Department, Southern Methodist University, Dallas, Texas, USA. ⁶⁵Physics Department, University of Texas at Dallas, Richardson, Texas, USA. ⁶⁶DESY, Hamburg and Zeuthen, Germany. ⁶⁷Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany. ⁶⁸Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany. ⁶⁹Department of Physics, Duke University, Durham, North Carolina, USA. ⁷⁰SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK. ⁷¹INFN Laboratori Nazionali di Frascati, Frascati, Italy. ⁷²Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany. ⁷³Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland. ⁷⁴INFN Sezione di Genova, Genova, Italy. ⁷⁵Dipartimento di Fisica, Università di Genova, Genova, Italy. ⁷⁶E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia. ⁷⁷High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia. ⁷⁸II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany. ⁷⁹SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, UK. ⁸⁰II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany. ⁸¹Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France. ⁸²Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA. ⁸³Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany. ⁸⁴Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany. ⁸⁵ZITI Institut für Technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany. ⁸⁶Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan. ⁸⁷Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China. ⁸⁸Department of Physics, The University of Hong Kong, Hong Kong, China.

⁸⁹Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China. ⁹⁰Department of Physics, National Tsing Hua University, Taiwan, Taiwan. ⁹¹Department of Physics, Indiana University, Bloomington, Indiana, USA. ⁹²Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria. ⁹³University of Iowa, Iowa City, Iowa, USA. ⁹⁴Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA. ⁹⁵Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia. ⁹⁶KEK, High Energy Accelerator Research Organization, Tsukuba, Japan. ⁹⁷Graduate School of Science, Kobe University, Kobe, Japan. ⁹⁸Faculty of Science, Kyoto University, Kyoto, Japan. ⁹⁹Kyoto University of Education, Kyoto, Japan. ¹⁰⁰Department of Physics, Kyushu University, Fukuoka, Japan. ¹⁰¹Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina. ¹⁰²Physics Department, Lancaster University, Lancaster, UK. ¹⁰³INFN Sezione di Lecce, Lecce, Italy. ¹⁰⁴Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy. ¹⁰⁵Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK. ¹⁰⁶Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia. ¹⁰⁷School of Physics and Astronomy, Queen Mary University of London, London, UK. ¹⁰⁸Department of Physics, Royal Holloway University of London, Egham, UK. ¹⁰⁹Department of Physics and Astronomy, University College London, London, UK. ¹¹⁰Louisiana Tech University, Ruston, Louisiana, USA. ¹¹¹Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France. ¹¹²Fysiska Institutionen, Lunds Universitet, Lund, Sweden. ¹¹³Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain. ¹¹⁴Institut für Physik, Universität Mainz, Mainz, Germany. ¹¹⁵School of Physics and Astronomy, University of Manchester, Manchester, UK. ¹¹⁶CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France. ¹¹⁷Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA. ¹¹⁸Department of Physics, McGill University, Montreal, Quebec, Canada. ¹¹⁹School of Physics, University of Melbourne, Victoria, Australia. ¹²⁰Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA. ¹²¹Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA. ¹²²INFN Sezione di Milano, Milano, Italy. ¹²³Dipartimento di Fisica, Università di Milano, Milano, Italy. ¹²⁴B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus. ¹²⁵Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus. ¹²⁶Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada. ¹²⁷P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia. ¹²⁸Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia. ¹²⁹National Research Nuclear University MEPhI, Moscow, Russia. ¹³⁰D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia. ¹³¹Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany. ¹³²Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany. ¹³³Nagasaki Institute of Applied Science, Nagasaki, Japan. ¹³⁴Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan. ¹³⁵INFN Sezione di Napoli, Napoli, Italy. ¹³⁶Dipartimento di Fisica, Università di Napoli, Napoli, Italy. ¹³⁷Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA. ¹³⁸Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, the Netherlands. ¹³⁹Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, the Netherlands. ¹⁴⁰Department of Physics, Northern Illinois University, DeKalb, Illinois, USA. ¹⁴¹Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia. ¹⁴²Department of Physics, New York University, New York, New York, USA. ¹⁴³Ohio State University, Columbus, Ohio, USA. ¹⁴⁴Faculty of Science, Okayama University, Okayama, Japan. ¹⁴⁵Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA. ¹⁴⁶Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA. ¹⁴⁷Palacký University, RCPTM, Olomouc, Czech Republic. ¹⁴⁸Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA. ¹⁴⁹LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France. ¹⁵⁰Graduate School of Science, Osaka University, Osaka, Japan. ¹⁵¹Department of Physics, University of Oslo, Oslo, Norway. ¹⁵²Department of Physics, Oxford University, Oxford, UK. ¹⁵³INFN Sezione di Pavia, Pavia, Italy. ¹⁵⁴Dipartimento di Fisica, Università di Pavia, Pavia, Italy. ¹⁵⁵Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA. ¹⁵⁶National Research Centre "Kurchatov Institute" B.P. Konstantinov Petersburg Nuclear Physics Institute, St Petersburg, Russia. ¹⁵⁷INFN Sezione di Pisa, Pisa, Italy. ¹⁵⁸Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy. ¹⁵⁹Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA. ¹⁶⁰Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal. ¹⁶¹Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal. ¹⁶²Department of Physics, University of Coimbra, Coimbra, Portugal. ¹⁶³Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal. ¹⁶⁴Departamento de Física, Universidade do Minho, Braga, Portugal. ¹⁶⁵Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain), Portugal. ¹⁶⁶Dep Física and CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal. ¹⁶⁷Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic. ¹⁶⁸Czech Technical University in Prague, Praha, Czech Republic. ¹⁶⁹Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic. ¹⁷⁰State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia. ¹⁷¹Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK. ¹⁷²INFN Sezione di Roma, Roma, Italy. ¹⁷³Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy. ¹⁷⁴INFN Sezione di Roma Tor Vergata, Roma, Italy. ¹⁷⁵Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy. ¹⁷⁶INFN Sezione di Roma Tre, Roma, Italy. ¹⁷⁷Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy. ¹⁷⁸Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco. ¹⁷⁹Centre National de l'Énergie des Sciences Techniques Nucleaires, Rabat, Morocco. ¹⁸⁰Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco. ¹⁸¹Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco. ¹⁸²Faculté des sciences, Université Mohammed V, Rabat, Morocco. ¹⁸³DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Énergie Atomique et aux Énergies Alternatives), Gif-sur-Yvette, France. ¹⁸⁴Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA. ¹⁸⁵Department of Physics, University of Washington, Seattle, Washington, USA. ¹⁸⁶Department of Physics and Astronomy, University of Sheffield, Sheffield, UK. ¹⁸⁷Department of Physics, Shinshu University, Nagano, Japan. ¹⁸⁸Department Physik, Universität Siegen, Siegen, Germany. ¹⁸⁹Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada. ¹⁹⁰SLAC National Accelerator Laboratory, Stanford, California, USA. ¹⁹¹Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic. ¹⁹²Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic. ¹⁹³Department of Physics, University of Cape Town, Cape Town, South Africa. ¹⁹⁴Department of Physics, University of Johannesburg, Johannesburg, South Africa. ¹⁹⁵School of Physics, University of the Witwatersrand, Johannesburg, South Africa. ¹⁹⁶Department of Physics, Stockholm University, Stockholm, Sweden. ¹⁹⁷The Oskar Klein Centre, Stockholm, Sweden. ¹⁹⁸Physics Department, Royal Institute of Technology, Stockholm, Sweden. ¹⁹⁹Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA. ²⁰⁰Department of Physics and Astronomy, University of Sussex, Brighton, UK. ²⁰¹School of Physics, University of Sydney, Sydney, Australia. ²⁰²Institute of Physics, Academia Sinica, Taipei, Taiwan. ²⁰³Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel. ²⁰⁴Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel. ²⁰⁵Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece. ²⁰⁶International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan. ²⁰⁷Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan. ²⁰⁸Department of Physics, Tokyo Institute of Technology, Tokyo, Japan. ²⁰⁹Tomsk State University, Tomsk, Russia. ²¹⁰Department of Physics, University of Toronto, Toronto, Ontario, Canada. ²¹¹INFN-TIFPA, Trento, Italy. ²¹²University of Trento, Trento, Italy. ²¹³TRIUMF, Vancouver, British Columbia, Canada. ²¹⁴Department of Physics and Astronomy, York University, Toronto, Ontario, Canada. ²¹⁵Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan. ²¹⁶Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA. ²¹⁷Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA. ²¹⁸INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy. ²¹⁹ICTP, Trieste, Italy. ²²⁰Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy. ²²¹Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden. ²²²Department of Physics, University of Illinois, Urbana, Illinois, USA. ²²³Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain. ²²⁴Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada. ²²⁵Department of

Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada. ²²⁶Department of Physics, University of Warwick, Coventry, UK. ²²⁷Waseda University, Tokyo, Japan. ²²⁸Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel. ²²⁹Department of Physics, University of Wisconsin, Madison, Wisconsin, USA. ²³⁰Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany. ²³¹Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany. ²³²Department of Physics, Yale University, New Haven, Connecticut, USA. ²³³Yerevan Physics Institute, Yerevan, Armenia. ²³⁴CH-1211, Geneva 23, Switzerland. ²³⁵Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France.

Secondary affiliations

^aDepartment of Physics, King's College London, London, UK. ^bInstitute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. ^cNovosibirsk State University, Novosibirsk, Russia. ^dTRIUMF, Vancouver, British Columbia, Canada. ^eDepartment of Physics & Astronomy, University of Louisville, Louisville, Kentucky, USA. ^fPhysics Department, An-Najah National University, Nablus, Palestine. ^gDepartment of Physics, California State University, Fresno, California, USA. ^hDepartment of Physics, University of Fribourg, Fribourg, Switzerland. ⁱIII Physikalisches Institut, Georg-August-Universität, Göttingen, Germany. ^jDepartament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain. ^kDepartamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal. ^lTomsk State University, Tomsk, Russia. ^mThe Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China. ⁿUniversità di Napoli Parthenope, Napoli, Italy. ^oInstitute of Particle Physics (IPP), Canada. ^pHoria Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania. ^qDepartment of Physics, St Petersburg State Polytechnical University, St Petersburg, Russia. ^rBorough of Manhattan Community College, City University of New York, New York City, USA. ^sDepartment of Physics, The University of Michigan, Ann Arbor, Michigan, USA. ^tCentre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa. ^uLouisiana Tech University, Ruston, Louisiana, USA. ^vInstitutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain. ^wGraduate School of Science, Osaka University, Osaka, Japan. ^xFakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany. ^yInstitute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, the Netherlands. ^zDepartment of Physics, The University of Texas at Austin, Austin, Texas, USA. ^{aa}Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia. ^{ab}CERN, Geneva, Switzerland. ^{ac}Georgian Technical University (GTU), Tbilisi, Georgia. ^{ad}Ochadai Academic Production, Ochanomizu University, Tokyo, Japan. ^{ae}Manhattan College, New York, New York, USA. ^{af}Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan. ^{ag}School of Physics, Shandong University, Shandong, China. ^{ah}Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain), Portugal. ^{ai}Department of Physics, California State University, Sacramento, California, USA. ^{aj}Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia. ^{ak}Departement de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland. ^{al}International School for Advanced Studies (SISSA), Trieste, Italy. ^{am}Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain. ^{an}School of Physics, Sun Yat-sen University, Guangzhou, China. ^{ao}Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria. ^{ap}Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia. ^{aq}Institute of Physics, Academia Sinica, Taipei, Taiwan. ^{ar}National Research Nuclear University MEPhI, Moscow, Russia. ^{as}Department of Physics, Stanford University, Stanford, California, USA. ^{at}Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary. ^{au}Giresun University, Faculty of Engineering, Turkey. ^{av}CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France. ^{aw}Department of Physics, Nanjing University, Jiangsu, China. ^{ax}University of Malaya, Department of Physics, Kuala Lumpur, Malaysia. ^{ay}LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France. ^zDeceased. *e-mail: atlas.publications@cern.ch