Article:

Aad, G. orcid.org/0000-0002-6665-4934, Aakvaag, E. orcid.org/0000-0001-7616-1554, Abbott, B. orcid.org/0000-0002-5888-2734 et al. (2918 more authors) (2025) Search for magnetic monopole pair production in ultraperipheral Pb+Pb collisions at sNN =5.36 TeV with the ATLAS detector at the LHC. Physical Review Letters, 134. 061803. ISSN 0031-9007

https://doi.org/10.1103/physrevlett.134.061803

PHYSICAL REVIEW LETTERS **134,** 061803 (2025)

Search for Magnetic Monopole Pair Production in Ultraperipheral Pb + Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV with the ATLAS Detector at the LHC

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

(Received 22 August 2024; revised 9 November 2024; accepted 15 January 2025; published 14 February 2025)

This Letter presents a search for highly ionizing magnetic monopoles in 262 $\mu\mathrm{b}^{-1}$ of ultraperipheral Pb + Pb collision data at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV collected by the ATLAS detector at the LHC. A new methodology that exploits the properties of clusters of hits reconstructed in the innermost silicon detector layers is introduced to study highly ionizing particles in heavy-ion data. No significant excess above the background, which is estimated using a data-driven technique, is observed. Using a nonperturbative semiclassical model, upper limits at 95% confidence level are set on the cross section for pair production of monopoles with a single Dirac magnetic charge in the mass range of 20–150 GeV. Depending on the model, monopoles with a single Dirac magnetic charge and mass below 80–120 GeV are excluded.

DOI: 10.1103/PhysRevLett.134.061803

Magnetic monopoles are hypothetical particles that carry isolated magnetic charge. The existence of a magnetically charged particle would restore symmetry to Maxwell's equations and explain why electric charge is quantized in nature, as shown by Dirac [1]. Dirac's argument predicts the magnetic charge of a monopole to be $q_{\mathrm{m}} = N g_{\mathrm{D}}$, where N is a nonzero integer number, $g_{\mathrm{D}} = e/(2\alpha) \approx 68.5e$ is the Dirac elementary charge in cgs Gaussian units, α is the fine-structure constant, and e is the elementary electric charge. Since the energy loss is proportional to the square of the charge, a monopole with $|q_{\mathrm{m}}| = 1 g_{\mathrm{D}}$ would deposit 4700 times more energy by ionization than a proton. The high stopping power also results in the production of a large number of δ electrons. Hence, magnetic monopoles would manifest as highly ionizing particles, with unique trajectories in a magnetic field [2].

While monopoles appearing in grand unification theories typically have masses of the order of the unification scale ($m \approx 10^{16}$ GeV) [3], some extensions of the standard model (SM) predict composite monopoles with masses near the TeV scale [4]. This improves the prospects for monopole production at existing colliders.

In ultrarelativistic heavy-ion collisions, the ion beams are accompanied by large electromagnetic (EM) fields. At impact parameters b larger than twice the nuclear radius, $b > 2R_{\mathrm{A}}$, EM-induced reactions become the dominant interaction mechanism. These events, referred to as ultraperipheral collisions (UPC), have been used to study photon-nucleus (photonuclear) and photon-photon ($\gamma\gamma$) collisions [5]. These events typically have features such as rapidity gaps and lower particle multiplicity, or exclusive final states with no extra particle production, that make them qualitatively different from nuclear collisions where hadronic interactions occur [6]. The interaction of strong magnetic fields in UPC can also give rise to the production of magnetic monopole-antimonopole pairs ($M\bar{M}$). Using a simplified (leading order, LO) approach, the process corresponds to a $\gamma\gamma$ fusion reaction, $\gamma\gamma \to M\bar{M}$ [7].

Most searches for the direct production of magnetic monopoles at particle colliders have focused on collisions of elementary particles such as electrons or quarks, assuming pair production of spin-0 or spin-$\frac{1}{2}$ point-like monopoles via the Drell-Yan mechanism or $\gamma\gamma$ fusion process [8–39]. However, because of the large coupling constant, $1/(4\alpha) \approx 34$ [40], perturbative treatments in terms of Feynman diagrams are generally not well defined. Indeed, it has been argued that the production of composite monopoles from elementary-particle collisions is suppressed by a factor of $\mathrm{e}^{-4/\alpha} \approx 10^{-238}$ [41].

Magnetic monopoles could be produced in strong magnetic fields by a magnetic analog of the Schwinger mechanism [42]. The Schwinger effect describes how strong EM fields, particularly intense magnetic fields from ion collisions, can decay via quantum tunneling to generate particle pairs such as $M\bar{M}$ pairs. In this case, the $M\bar{M}$ production cross section can be computed nonperturbatively using semiclassical techniques such as the free-particle approximation (FPA) [43]. In the FPA model the formula for the total cross section for magnetic monopole production in Pb + Pb UPC [43–45] is

---

[*] Full author list given at the end of the Letter.

$$\sigma_{\mathrm{FPA}} \approx \frac{2(q_{\mathrm{m}}B)^4 R_{\mathrm{Pb}}^4}{9\pi^2 m^5 \omega} \exp(-4m/\omega), \qquad (1)$$

where m is the monopole mass, q_{m} is the magnetic charge, $R_{\mathrm{Pb}} = 6.62 \pm 0.06$ fm is the radius of a lead nucleus, $B = (4.5 \pm 0.2) \times 10^{16}$ T is the peak magnetic field strength of the two nuclei at a nucleon-nucleon (NN) center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV, which occurs at $b \approx 2R_{\mathrm{Pb}}$, and $\omega = (1.19 \pm 0.05) \times 10^{26}\ \mathrm{s}^{-1}$ is the field inverse decay time. The uncertainties quoted on these parameters follow those estimated in Ref. [45]. It should be noted that Eq. (1) was derived for scalar (spin-0) monopoles, and the effect of monopole spin should enhance the production cross section [43]. Because of the coherence of the magnetic field, the potential $\mathrm{e}^{-4/\alpha}$ suppression is absent for composite monopole production via the Schwinger formalism in UPC. This fact was used in the recent searches performed by the MoEDAL Collaboration in Pb + Pb collisions [45,46] using the trapping technique [47], a method designed to physically capture magnetic monopoles and detect their presence by measuring the induced persistent currents generated after their passage through a superconducting magnetometer.

The FPA model includes the effect of the magnetic field to all orders but neglects possible $M\bar{M}$ self-interactions. Consequently, an alternative model, the locally constant field approximation (LCFA) [43–46], is also considered. The LCFA includes self-interactions to all orders but neglects the effect of the nonperturbative interaction with the magnetic field. Both approaches offer conservative lower limits on the production cross section, as including the self-interactions and the effect of the magnetic field has been shown to increase the $M\bar{M}$ production [43,44]. It is also worth mentioning that while the quoted semiclassical calculations apply to elementary monopoles, the effects of finite monopole size are expected to enhance monopole production in these models [43].

The mass of magnetic monopoles that could be produced in Pb + Pb collisions via the Schwinger mechanism is limited by the total energy in the EM field available for $M\bar{M}$ production [46]. This total energy reaches its peak value at $b \approx 2R_{\mathrm{Pb}}$. For Pb + Pb collisions at the Large Hadron Collider (LHC) at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV, this implies a maximum monopole mass of approximately 160 GeV.

This Letter presents a search for magnetic monopoles with $|q_{\mathrm{m}}| = 1g_{\mathrm{D}}$ using 262 $\mu\mathrm{b}^{-1}$ of UPC Pb + Pb collision data collected by the ATLAS detector at the LHC in 2023 at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV. The ATLAS experiment [48,49] is a multipurpose particle detector with cylindrical geometry [50], comprising an inner detector (ID) tracker surrounded by a thin superconducting solenoid, EM and hadronic calorimeters, and a muon spectrometer. A software suite [51] is used in Monte Carlo (MC) simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

This analysis primarily makes use of the ID pixel detector and the zero-degree calorimeters (ZDC). The high-granularity silicon pixel detector surrounds the collision region. The innermost pixel-detector layer, the IBL, consists of 280 pixel-sensor modules that cover the region $|\eta| < 3.03$, and was installed at a mean distance of 3.3 cm from the beam axis before the start of Run 2 [52,53]. In addition to the IBL, the pixel detector contains three other barrel layers and two endcaps with three disks each. It is followed by silicon microstrip (SCT) and transition radiation tracking detectors. ZDCs are located at $z = \pm 140$ m from the interaction point, and detect neutral particles such as neutrons emitted from interacting nuclei.

Events of interest are selected by the first-level (L1) trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger (HLT) [54]. In UPC, soft photons emitted by one lead nucleus can excite the other, typically through the giant dipole resonance [55], and induce the emission of one or more neutrons, each of which carries, on average, the full per-nucleon beam energy. This can give rise to three distinct EM breakup topologies: $0n0n$ (no neutrons are emitted), $0n\mathrm{X}n$ (at least one neutron is emitted by exactly one nucleus), and $\mathrm{X}n\mathrm{X}n$ (at least one neutron is emitted by each nucleus). They are shown schematically in Fig. 1. This analysis exploits the $\mathrm{X}n\mathrm{X}n$ topology, mainly because of limitations in triggering on monopole production. The ATLAS L1 trigger system can recognize energy deposited in the calorimeters; however, low-energy monopoles typically do not reach them. Moreover, no information from the ID tracker is available at L1. Therefore, the only viable option is to trigger at L1 on the presence of forward neutrons in the ZDC. The primary trigger for this analysis requires a L1 signal consistent with the presence of one or more neutrons in both arms of the ZDC. In addition, the total transverse energy recorded in the calorimeter is required to be below 10 GeV.

As the monopoles considered in this analysis have relatively low masses (below 150 GeV) and typically have low energy, they deposit their energy in the innermost parts of the ATLAS detector, primarily in the pixel detector, thereby producing a sizable number of δ electrons. Hence this approach complements the trapping technique used by MoEDAL. The presence of more than 100 clusters of pixel hits is required in the HLT, with no specific selection on the presence of any charged-particle tracks. Because of the large cross section for double EM dissociation [56] and limitations in the allowed data-recording rate at L1, the trigger was prescaled so that approximately one event in every six was saved, resulting in an effective integrated luminosity of 262 $\mu\mathrm{b}^{-1}$, compared to the 1.67 nb^{-1} recorded by unprescaled triggers.

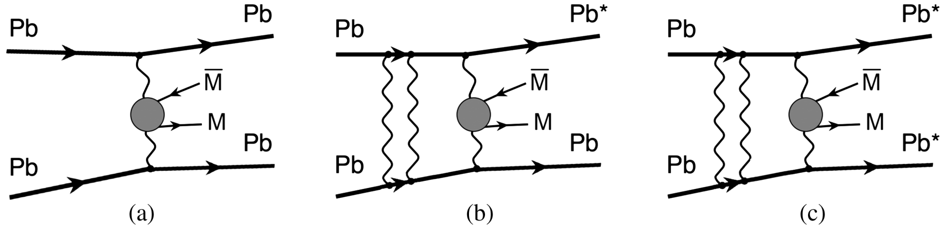


FIG. 1. Schematic diagrams for magnetic monopole pair production in ultraperipheral Pb + Pb collisions for (a) no, (b) single, and (c) mutual ion excitation due to extra soft-photon exchanges. These three topologies are labeled in the text as $0n0n$, $0n\mathrm{X}n$, and $\mathrm{X}n\mathrm{X}n$, respectively. EM breakup of the ion, denoted by Pb^*, results in the production of forward neutrons, detectable in the ATLAS ZDC. The signal process in this Letter targets events with the $\mathrm{X}n\mathrm{X}n$ topology (c).

Monte Carlo simulated signal samples were produced using a semiclassical (nonperturbative) approach based on the FPA model. The semiclassical approximation breaks down [45] for sufficiently light monopoles, $m < 20$ GeV for 5.36 TeV Pb + Pb collisions, so monopole mass hypotheses below 20 GeV are not considered. For the distributions of monopole kinematic quantities, simplified predictions based on the FPA model are used to model back-to-back monopole pair production, in particular with isotropic polar angle distributions of the pairs and with a distribution of monopole momentum k that follows the relative probability [44]

$$d\sigma_{\mathrm{FPA}}(|k|)/d\sigma_{\mathrm{FPA}}(0) = \exp\left[-\frac{4}{\omega}\left(\sqrt{m^2 + |k|^2} - m\right)\right].$$

The same model was used in the MoEDAL analysis [45]. A monopole charge of $|q_{\mathrm{m}}| = 1 g_{\mathrm{D}}$ is set in all signal samples and the monopole masses considered are 20, 30, 40, 50, 60, 70, 90, 100, 120, and 150 GeV. The signal simulation setup includes all possible configurations for the EM breakup of the nuclei, as described below. A sample with no interacting particles was simulated to mimic detector noise and check for potential noise mismodeling, ensuring the reliability of the detector noise simulation in the signal modeling.

Signal efficiency estimates rely on an extension of the ATLAS detector simulation [57] based on GEANT4 [58]. This extension, originally developed for monopole searches in pp collisions [32–35], includes descriptions of monopole acceleration in the detector's magnetic field, ionization energy losses in matter, and δ-electron production along the monopole's trajectory. After losing their kinetic energy, monopoles could potentially get trapped in the detector material [47]. For all the simulated samples, the monopoles are assumed to be stable, and the simulation does not account for the trapping effect.

In order to correct the signal MC simulation for the $\mathrm{X}n\mathrm{X}n$ topology requirement, exclusive dilepton (ee and $\mu\mu$) events from the process $\gamma\gamma \to \ell\ell$ are studied. Because of the relatively large instantaneous luminosity of Pb + Pb collisions at the LHC, additional neutrons might be generated in each bunch crossing and detected in one or both arms of the ZDC (EM pileup). This leads to an outflow of events, primarily from the $0n\mathrm{X}n$ category, to the $\mathrm{X}n\mathrm{X}n$ category. To account for this effect in MC simulation, the yield of simulated signal events is scaled by the effective probability for the $\mathrm{X}n\mathrm{X}n$ topology, parameterized as a function of total system mass m_X and system rapidity y_X:

$$P^{\mathrm{eff}}_{\mathrm{X}n\mathrm{X}n}(m_X, y_X) = 0.8 \times (2 f_{0n\mathrm{X}n} P_{\mathrm{EM}} + f_{\mathrm{X}n\mathrm{X}n})(1 + f_{\mathrm{diss}}), \tag{2}$$

where $f_{0n\mathrm{X}n}$ and $f_{\mathrm{X}n\mathrm{X}n}$ are the predicted fractions of events with single and double EM breakup, respectively, P_{EM} is the probability of having at least one neutron from EM pileup on a given detector side, and f_{diss} is the small fraction of dissociative (incoherent) events [59] from the $\gamma^*\gamma \to \ell\ell$ and $\gamma^*\gamma^* \to \ell\ell$ reactions, where γ^* denotes a virtual photon. The $f_{0n\mathrm{X}n}$ and $f_{\mathrm{X}n\mathrm{X}n}$ values are based on the SUPERCHIC4.2 MC predictions [60], and are provided differentially in dilepton invariant mass ($m_{\ell\ell}$) and dilepton absolute rapidity ($|y_{\ell\ell}|$). The value of P_{EM}, estimated as outlined in Ref. [61], is $P_{\mathrm{EM}} = 0.038$ for the signal trigger and 2023 Pb + Pb data-taking conditions. The value of f_{diss} for the $\mathrm{X}n\mathrm{X}n$ selection is estimated to be $f_{\mathrm{diss}} = 0.13$, based on the study of exclusive dimuon and dielectron events [61,62]. A possible enhancement of the dissociative contribution at the largest considered monopole masses (due to very small Pb + Pb impact parameters), leading to larger values of $P^{\mathrm{eff}}_{\mathrm{X}n\mathrm{X}n}$, is conservatively neglected. The factor of 0.8 in Eq. (2) accounts for mismodeling of $f_{0n\mathrm{X}n}$ and $f_{\mathrm{X}n\mathrm{X}n}$ in SUPERCHIC, based on the calculation in Ref. [60]. The model based on Eq. (2) is validated using UPC $\gamma\gamma \to \ell\ell$ data and good agreement (within 10%) is found. The value of $P^{\mathrm{eff}}_{\mathrm{X}n\mathrm{X}n}$ is about 15% for $m_X = 40$ GeV and grows to about 30% for $m_X = 200$ GeV.

The backgrounds considered in this analysis include those from particles produced in Pb + Pb interactions (collision events) and from beam-induced sources. Beam-induced background (BIB) is caused by beam particle losses in the LHC ring upstream of the ATLAS experiment, due to interactions with residual gas within the beam pipe or with machine elements [63–66]. It is characterized by particles moving almost parallel to the beam line.

A requirement of at most one reconstructed charged-particle track is used to suppress collision backgrounds and has only a minor impact on the signal efficiency because a monopole's trajectory in the axial magnetic field provided by a solenoid is straight in the $r-\phi$ plane and bends in the r–z plane [67] (whereas the opposite applies to electrically charged particles). Charged-particle tracks are required to pass the track selection, which is optimized to suppress combinatorial (fake) tracks in the dense track environment around $\mathrm{Pb}+\mathrm{Pb}$ collisions [68], and to have transverse momentum $p_{\mathrm{T}} > 0.1$ GeV, $|\eta| < 2.5$, and a transverse impact parameter of $|d_0| < 1$ mm calculated relative to the measured beam-line position.

Signal events are required to have at most one topological cluster of calorimeter-cell energy deposits [69], which effectively removes collision backgrounds with neutral particles. These topoclusters, calibrated to take into account the noise suppression, must have transverse energy $E_{\mathrm{T}} > 0.1$ GeV and $|\eta| < 4.9$. They are also required to meet the cell significance criteria for the measured energy as outlined in Ref. [70] to suppress the contribution from electronic noise fluctuations.

Events are also required to have more than 150 pixel clusters [71], $n_{\mathrm{PixCl}} > 150$, including more than 50 IBL clusters, $n_{\mathrm{IBLCl}} > 50$. Clusters from the four pixel-sensor modules observed to have abnormal noise distributions in data are not considered in the cluster counting. Furthermore, events are rejected if the number of clusters in a particular module exceeds 90% of all pixel clusters in the event.

The selection requirements imposed on tracks, topoclusters, and pixel clusters fully suppress the collision background. In particular, the track and topocluster requirements are designed to remove hadronic $\mathrm{Pb}+\mathrm{Pb}$ interactions, which typically involve a high multiplicity of tracks and larger energy deposits in the calorimeters. Furthermore, the additional requirement of a large number of pixel clusters specifically eliminates background from SM photon-induced processes in UPC, which tend to produce low hadronic activity and fewer pixel hits.

To further reduce the BIB, the azimuthal distribution of reconstructed pixel clusters is examined. A variable T, inspired by the *transverse thrust* [72], is defined as

$$T = (1/n_{\mathrm{PixCl}}) \sum_{i=1}^{n_{\mathrm{PixCl}}} |\hat{r}_i \cdot \hat{n}|,$$

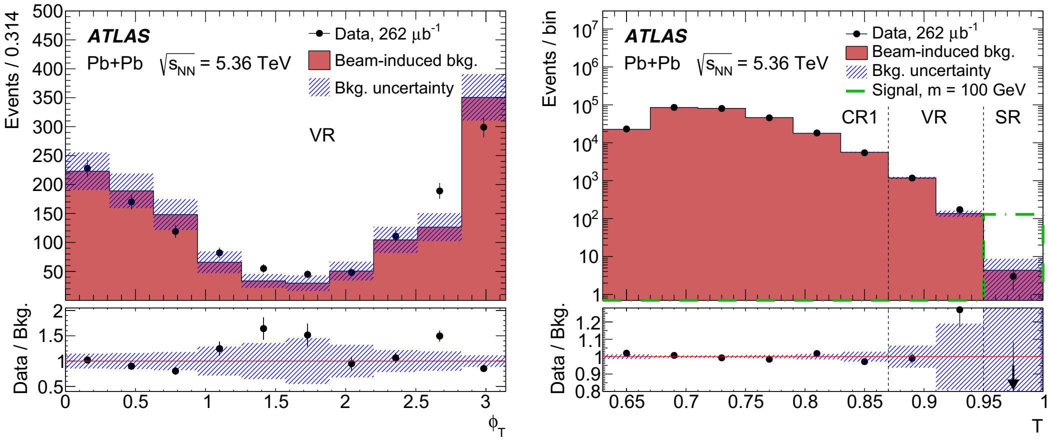
where $\hat{r}_i$ is the direction (unit vector) of a given pixel cluster in the transverse plane with respect to the origin of the ATLAS coordinate system, and the transverse direction $\hat{n}$ maximizes the expression and corresponds to an azimuthal angle ϕ_T. The solution for $\hat{n}$ (or ϕ_T) is found iteratively. The direction of $\hat{n}$ roughly aligns in $r-\phi$ with the monopole's trajectory. The T variable has a maximum value of 1, for a set of fully aligned pixel clusters, and a minimum value of around $2/\pi$, for a uniform distribution of clusters in the transverse plane. Simulated signal events tend to have T values near unity, whereas the backgrounds concentrate at much lower T values, typically just above $2/\pi$. A requirement of $T > 0.95$ is therefore used in the signal region (SR) selection, based on the simulated signal properties. The signal acceptance times efficiency of the SR selection varies between 4% and 0.2% for simulated events with low and high monopole masses, respectively, and is driven by the $n_{\mathrm{PixCl}} > 150$ requirement.

The background yield in this analysis is estimated using a fully data-driven method. A control region (CR1) is defined by requiring $T \leq 0.87$. It is observed that the event characteristics in CR1 are consistent with those of BIB. Since the BIB typically results in asymmetric event activity, an additional control region (CR2) enriched in BIB is defined from events passing a supporting trigger that selects events with ZDC activity on one side and no activity on the opposite side. The same event selection criteria as for the SR, except no requirement on T and a different topocluster requirement, are applied to CR2. To help enrich the CR2 sample in BIB events and consequently reduce the signal contamination, only events with one to three topoclusters are used, with at least one out-of-time energy deposit in the calorimeter, i.e., a topocluster with reconstructed time more than 10 ns before the bunch-crossing time. The presence of topoclusters with negative reconstructed time is one of the characteristic features of BIB [63]. The signal contamination in both CR1 and CR2 is studied in the MC simulated samples and is found to be negligible.

Events in CR2 are used to extrapolate the background contribution from CR1 to SR, by using the relation $N_{\mathrm{bkg}}^{\mathrm{SR}} = (N^{\mathrm{CR1}}/N_{T<0.87}^{\mathrm{CR2}})N_{T>0.95}^{\mathrm{CR2}}$, where N^{CR1} is the event yield in CR1, and $N_{T<0.87}^{\mathrm{CR2}}$ ($N_{T>0.95}^{\mathrm{CR2}}$) is the number of CR2 events having $T < 0.87$ ($T > 0.95$). To cross-check this procedure, a validation region (VR) is defined by requiring $0.87 < T \leq 0.95$. Figure 2(a) shows the ϕ_T distributions in the VR. The CR2-based background estimate describes the data adequately. The enhanced event activity at $\phi_T \approx 0$ and $\phi_T \approx \pi$ is characteristic of BIB [63,64].

The number of pixel clusters is correlated with the number of SCT space points [73], n_{SCTsp}. To address a small discrepancy between the CR1 and CR2 n_{SCTsp} distributions at low n_{SCTsp}, extra reweighting of the n_{SCTsp} distribution is performed for events in CR2 to better match the distribution observed in CR1. The correction applied to the n_{SCTsp} distribution improves the modeling of the n_{PixCl} distribution. This correction changes the shape of the T distribution by a few percent at low T and by about 10% at high T.

Figure 2(b) shows the T distribution in CR1, the VR, and the SR. The background in the SR is estimated to be 4 ± 4 (stat.) events.



(a)

(b)

FIG. 2. (a) ϕ_T distribution for data in the VR and (b) T distribution for data in CR1, the VR, and the SR. Data (markers) are shown together with the estimated beam-induced background (filled histograms). The distributions for background use events from CR2 scaled as described in the text. The lower panels show the ratio of data to the estimated background. The shaded bands represent the statistical uncertainty of the background. In (b) the green dotted-dashed line shows the representative signal contribution for a monopole mass of 100 GeV, and the arrow in the ratio plot is for the point that is outside the range.

The systematic uncertainties that were considered are related to the modeling of the detector response to the monopole, the overall noise level in the pixel detector, potential mismodeling of the XnXn selection, the background uncertainty, and the luminosity uncertainty. Uncertainties evaluated in one direction are assumed to be symmetric.

The uncertainty due to the ID material modeling in the GEANT4 simulation is accounted for by comparing the signal efficiency with its value in alternative signal samples. These samples differ by having modified descriptions of the ATLAS ID geometry: the passive material of the ID is scaled up by 5%, the passive material of the IBL is scaled up by 10%, or the passive material in the services region is scaled up by 25%. These variations capture the full range of data-MC differences observed in studies of the ID material [74]. The changes in signal yield depend on the monopole mass hypothesis and range from 3% to 20% for the lowest and highest mass points, respectively.

The kinetic energy threshold below which δ electrons are not propagated explicitly in the ATLAS simulation depends on the GEANT4 "range cut" parameter [75]. Reducing the value of this parameter by a factor of five produces less than a 3% signal yield change, which is taken as a systematic uncertainty.

The modified Bethe-Bloch formula for ionization by monopoles has a theoretical uncertainty of about ±3% [76]. Alternative signal samples where δ-electron production is reduced by 3% were therefore simulated. This results in a 1%–4% decrease in signal yield for the mass range considered, which is included as a systematic uncertainty.

Noise activity in the pixel detector is not fully accounted for in the simulation. Less activity is observed in MC simulated events with no interacting particles than in "empty" data events with no tracks or topoclusters, and with at least one neutron emitted by the EM breakup of an ion. These data events, selected by an unbiased trigger that requires ZDC activity on one side, are fully equivalent to empty bunch-crossing events. To obtain better data-MC agreement, the MC simulated "empty" events are overlayed, on an event-by-event basis, with additional pixel clusters randomly assigned to pixel-cluster positions seen in "empty" data events. The same degree of pixel-cluster overlay is then applied in MC signal events, resulting in a 1%–2% decrease in signal yield, which is taken as a systematic uncertainty. A similar procedure is used to estimate calorimeter noise, resulting in a 1% decrease in signal yield.

To cover the XnXn selection modeling, a 20% uncertainty is assigned to $p^{\mathrm{eff}}_{\mathrm{X}n\mathrm{X}n}$. A value of 20% is chosen to primarily cover the 10%–20% differences observed between the $f_{0n\mathrm{X}n}$ and $f_{\mathrm{X}n\mathrm{X}n}$ values in ATLAS data and those predicted by SUPERCHIC4.2 [60]. It also covers differences between SUPERCHIC and alternative STARLIGHT [77] or GAMMA-UPC [78] predictions for $f_{0n\mathrm{X}n}$ and $f_{\mathrm{X}n\mathrm{X}n}$.

The difference between the background estimates from the reweighted and nonreweighted n_{SCTsp} distributions in CR2 affects the background yield in SR by 10% and is taken as a systematic uncertainty. The reweighting of other distributions that show slight differences between CR1 and CR2 has a negligible impact on the background estimate.

The uncertainty in the integrated luminosity of the data sample is 3.5%. It is derived from the calibration of the luminosity following a methodology similar to that detailed in Ref. [79], and using the LUCID-2 detector [80] for the baseline luminosity measurements. The total systematic uncertainty affecting the selection efficiency, computed by

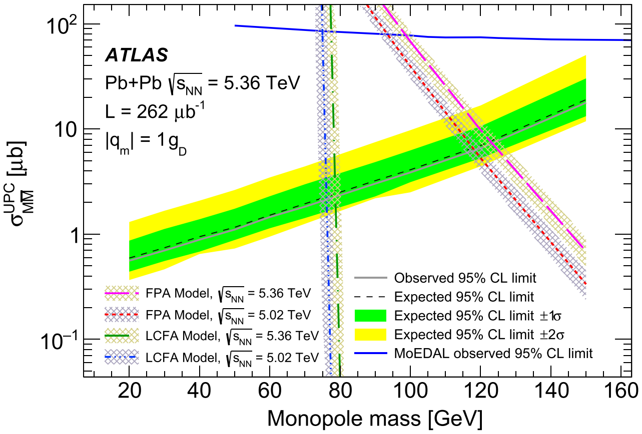


FIG. 3. Expected and observed upper limits on the monopole pair-production cross section in Pb + Pb UPC at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV for $|q_{\mathrm{m}}| = 1g_{\mathrm{D}}$. The gray solid line (black dashed line) represents observed (expected) limits, whereas the darker and lighter shaded bands around the expected limits represent the $\pm 1\sigma$ and $\pm 2\sigma$ intervals, respectively. The limits are compared with the observed limits by MoEDAL for $|q_{\mathrm{m}}| = 1g_{\mathrm{D}}$ at a lower center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [45] (blue line), and with two model predictions: FPA and LCFA [43]. The two sets of model curves (5.36 TeV and 5.02 TeV) are shown to allow a comparison of the theoretical predictions at different center-of-mass energies, relevant for ATLAS and MoEDAL experiments, respectively. The hatched bands represent the uncertainty of the models, estimated by propagating the uncertainties of the model parameters.

adding in quadrature all of the individual systematic uncertainties, varies between 21% (lowest masses) and 38% (highest masses).

Three data events were found in the SR. This is consistent with the estimate of $4 \pm 4(\mathrm{stat}) \pm 1(\mathrm{syst})$ background events. Consequently, exclusion limits are set at 95% confidence level (CL) using the $\mathrm{CL_s}$ method [81] implemented in RooStats [82]. The cross-section limits are obtained by exploiting the selection efficiency and its uncertainty for each signal sample, the systematic uncertainty of the background estimate, and the integrated luminosity's uncertainty. Limits are calculated using the pseudo-experiment approach, with 20 000 "toys" per mass point. Figure 3 shows the obtained 95% CL limits. These results are compared with the observed limits by MoEDAL [45]. In addition, a comparison is made with the FPA model predictions [43] [Eq. (1)] and with the alternative LCFA model [43,45,46]. The present search significantly improves on the previous cross-section limits reported by MoEDAL for $|q_{\mathrm{m}}| = 1g_{\mathrm{D}}$ and excludes monopoles with masses below 120 GeV, assuming the FPA model. Assuming the total cross section follows the LCFA model, magnetic monopoles with charge $|q_{\mathrm{m}}| = 1g_{\mathrm{D}}$ and masses below 80 GeV are excluded. Limits obtained from alternative production channels, like from indirect searches of monopoles produced close to the surface of neutron stars via the thermal Schwinger process [83], are much less stringent and are not shown here.

In conclusion, this Letter presents a search for magnetic monopoles with mass in the range 20–150 GeV in ultra-peripheral heavy-ion collisions using 262 $\mu\mathrm{b}^{-1}$ of Pb + Pb collision data at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV collected by the ATLAS detector at the LHC. This analysis uses an alternative way of detecting low-mass monopoles in heavy-ion collisions, complementary to the trapping technique used by the MoEDAL experiment. The targeted monopole signature is based on high ionization in the ATLAS pixel detector. The background is mainly beam-induced, and its yield is estimated using a data-driven procedure. No excess of events over the expected background is observed. For monopoles with a single Dirac magnetic charge, the derived upper limits on monopole pair-production cross sections, based on a nonperturbative semiclassical model and derived at 95% confidence level, are more stringent than the recently reported limits from MoEDAL, also using Pb + Pb collisions. Depending on the model, monopoles with a single Dirac magnetic charge and mass below 80–120 GeV are excluded. The exploration of higher magnetic charges will be a subject of future investigations.

Acknowledgments—We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [84]. We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, United States of America. Individual groups and members have received support from BCKDF, CANARIE, CRC, and DRAC, Canada; CERN-CZ, FORTE, and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU, and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex, and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF, Greece;T BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya, and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. In addition, individual members wish to acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN PJAS); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1230987, FONDECYT 1240864); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), National Natural Science Foundation of China (NSFC—12175119, NSFC 12275265, NSFC-12075060); Czech Republic: Czech Science Foundation (GACR—24-11373S), Ministry of Education Youth and Sports (FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21SCI/017); EU: H2020 European Research Council (ERC—101002463); European Union: European Research Council (ERC—948254, ERC 101089007), Horizon 2020 Framework Programme (MUCCA—CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-20-CE31-0013, ANR-21-CE31-0013, ANR-21-CE31-0022, ANR-22-EDIR-0002), Investissements d'Avenir Labex (ANR-11-LABX-0012); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG—469666862, DFG—CR 312/5-2); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (PRIN—20223N7F8K—PNRR M4.C2.1.1); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP23KK0245); Netherlands: Netherlands Organisation for Scientific Research (NWO Veni 2020—VI.Veni.202.179); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Agency for Academic Exchange (PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, NCN & H2020 MSCA 945339, UMO-2020/37/B/ST2/01043, UMO-2021/40/C/ST2/00187, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920); Slovenia: Slovenian Research Agency (ARIS Grant No. J1-3010); Spain: Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2018-00482, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR grant 2021-03651), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2019.0447, KAW 2022.0358); Switzerland: Swiss National Science Foundation (SNSF—PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); USA: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

[1] P. A. M. Dirac, Quantised singularities in the electromagnetic field, Proc. R. Soc. A **133**, 60 (1931).

[2] J. C. Maxwell, On physical lines of force, Philos. Mag. **90**, 11 (1861).

[3] G. 't Hooft, Magnetic monopoles in unified gauge theories, Nucl. Phys. B **79**, 276 (1974).

[4] N. E. Mavromatos and V. A. Mitsou, Magnetic monopoles revisited: Models and searches at colliders and in the cosmos, Int. J. Mod. Phys. A **35**, 2030012 (2020).

[5] S. Klein and P. Steinberg, Photonuclear and two-photon interactions at high-energy nuclear colliders, Annu. Rev. Nucl. Part. Sci. **70**, 323 (2020).

[6] ATLAS Collaboration, Two-particle azimuthal correlations in photonuclear ultraperipheral $\mathrm{Pb}+\mathrm{Pb}$ collisions at 5.02 TeV with ATLAS, Phys. Rev. C **104**, 014903 (2021).

[7] L. N. Epele, H. Fanchiotti, C. A. García Canal, V. A. Mitsou, and V. Vento, Looking for magnetic monopoles at LHC with diphoton events, Eur. Phys. J. Plus **127**, 60 (2012).

[8] P. Musset, M. Price, and E. Lohrmann, Search for magnetic monopoles in electron-positron collisions at 34 GeV CM energy, Phys. Lett. **128B**, 333 (1983).

[9] K. Kinoshita, P. B. Price, and D. Fryberger, Search for highly ionizing particles in e^+e^- collisions at $\sqrt{s}=29$ GeV, Phys. Rev. Lett. **48**, 77 (1982).

[10] D. Fryberger, T. E. Coan, K. Kinoshita, and P. B. Price, Search for highly ionizing particles in e^+e^- collisions at $\sqrt{s}=29$ GeV, Phys. Rev. D **29**, 1524 (1984).

[11] T. Gentile *et al.*, Search for magnetically charged particles produced in e^+e^- annihilations at $\sqrt{s} = 10.6$ GeV, Phys. Rev. D **35**, 1081 (1987).

[12] Tasso Collaboration, A search for particles with magnetic charge produced in e^+e^- annihilations at $\sqrt{s} = 35$ GeV, Z. Phys. C **38**, 543 (1988).

[13] K. Kinoshita, M. Fujii, K. Nakajima, P. B. Price, and S. Tasaka, Search for highly ionizing particles in e^+e^- annihilations at $\sqrt{s} = 50$–52 GeV, Phys. Rev. Lett. **60**, 1610 (1988).

[14] K. Kinoshita, M. Fujii, K. Nakajima, P. B. Price, and S. Tasaka, Search for highly ionizing particles in e^+e^- annihilations at $\sqrt{s} = 50$–60.8 GeV, Phys. Lett. B **228**, 543 (1989).

[15] OPAL Collaboration, Search for Dirac magnetic monopoles in e^+e^- collisions with the OPAL detector at LEP2, Phys. Lett. B **663**, 37 (2008).

[16] K. Kinoshita *et al.*, Search for highly ionizing particles in e^+e^- annihilations at $\sqrt{s} = 91.1$ GeV, Phys. Rev. D **46**, R881 (1992).

[17] J. L. Pinfold *et al.*, A search for highly ionizing particles produced at the OPAL intersection point at LEP, Phys. Lett. B **316**, 407 (1993).

[18] H1 Collaboration, A direct search for stable magnetic monopoles produced in positron-proton collisions at HERA, Eur. Phys. J. C **41**, 133 (2005).

[19] CDF Collaboration, Direct search for Dirac magnetic monopoles in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. **96**, 201801 (2006).

[20] G. R. Kalbfleisch, W. Luo, K. A. Milton, E. H. Smith, and M. G. Strauss, Limits on production of magnetic monopoles utilizing samples from the D0 and CDF detectors at the Fermilab Tevatron, Phys. Rev. D **69**, 052002 (2004).

[21] G. R. Kalbfleisch *et al.*, Improved experimental limits on the production of magnetic monopoles, Phys. Rev. Lett. **85**, 5292 (2000).

[22] D0 Collaboration, Search for heavy pointlike Dirac monopoles, Phys. Rev. Lett. **81**, 524 (1998).

[23] P. B. Price, R. Guoxiao, and K. Kinoshita, Search for highly ionizing particles at the Fermilab proton-antiproton collider, Phys. Rev. Lett. **59**, 2523 (1987).

[24] P. B. Price, J. Guiru, and K. Kinoshita, High-luminosity search for highly ionizing particles at the Fermilab collider, Phys. Rev. Lett. **65**, 149 (1990).

[25] M. Bertani *et al.*, Search for magnetic monopoles at the Tevatron collider, Europhys. Lett. **12**, 613 (1990).

[26] H. Hoffmann *et al.*, A new search for magnetic monopoles at the CERN-ISR with plastic detectors, Lett. Nuovo Cimento **23**, 357 (1978).

[27] R. A. Carrigan, Jr., B. P. Strauss, and G. Giacomelli, Search for magnetic monopoles at the CERN intersecting storage rings, Phys. Rev. D **17**, 1754 (1978).

[28] B. Aubert, P. Musset, M. Price, and J. P. Vialle, Search for magnetic monopoles in proton-antiproton interactions at 540 GeV cm energy, Phys. Lett. **120B**, 465 (1983).

[29] R. A. Carrigan, F. A. Nezrick, and B. P. Strauss, Search for magnetic-monopole production by 300-GeV protons, Phys. Rev. D **8**, 3717 (1973).

[30] R. A. Carrigan, F. A. Nezrick, and B. P. Strauss, Extension of Fermi National Accelerator Laboratory magnetic-monopole search to 400 GeV, Phys. Rev. D **10**, 3867 (1974).

[31] Y. D. He, Search for a Dirac magnetic monopole in high energy nucleus-nucleus collisions, Phys. Rev. Lett. **79**, 3134 (1997).

[32] ATLAS Collaboration, Search for magnetic monopoles in $\sqrt{s} = 7$ TeV pp collisions with the Atlas detector, Phys. Rev. Lett. **109**, 261803 (2012).

[33] ATLAS Collaboration, Search for magnetic monopoles and stable particles with high electric charges in 8 TeV pp collisions with the ATLAS detector, Phys. Rev. D **93**, 052009 (2016).

[34] ATLAS Collaboration, Search for magnetic monopoles and stable high-electric-charge objects in 13 TeV proton-proton collisions with the ATLAS detector, Phys. Rev. Lett. **124**, 031802 (2020).

[35] ATLAS Collaboration, Search for magnetic monopoles and stable high-electric-charge objects in 13 TeV proton-proton collisions with the ATLAS detector, J. High Energy Phys. 11 (2023) 112.

[36] MoEDAL Collaboration, Search for magnetic monopoles with the MoEDAL prototype trapping detector in 8 TeV proton-proton collisions at the LHC, J. High Energy Phys. 08 (2016) 067.

[37] MoEDAL Collaboration, Search for magnetic monopoles with the MoEDAL forward trapping detector in 13 TeV proton-proton collisions at the LHC, Phys. Rev. Lett. **118**, 061801 (2017).

[38] MoEDAL Collaboration, Search for magnetic monopoles with the MoEDAL forward trapping detector in 2.11 fb^{-1} of 13 TeV proton-proton collisions at the LHC, Phys. Lett. B **782**, 510 (2018).

[39] MoEDAL Collaboration, Magnetic monopole search with the full MoEDAL trapping detector in 13 TeV pp collisions interpreted in photon-fusion and Drell-Yan production, Phys. Rev. Lett. **123**, 021802 (2019).

[40] W.-Y. Song and W. Taylor, Pair production of magnetic monopoles and stable high-electric-charge objects in proton-proton and heavy-ion collisions, J. Phys. G **49**, 045002 (2022).

[41] A. K. Drukier and S. Nussinov, Monopole pair creation in energetic collisions: Is it possible?, Phys. Rev. Lett. **49**, 102 (1982).

[42] J. Schwinger, On gauge invariance and vacuum polarization, Phys. Rev. **82**, 664 (1951).

[43] O. Gould, D. L.-J. Ho, and A. Rajantie, Towards Schwinger production of magnetic monopoles in heavy-ion collisions, Phys. Rev. D **100**, 015041 (2019).

[44] O. Gould, D. L.-J. Ho, and A. Rajantie, Schwinger pair production of magnetic monopoles: Momentum distribution for heavy-ion collisions, Phys. Rev. D **104**, 015033 (2021).

[45] MoEDAL Collaboration, Search for magnetic monopoles produced via the Schwinger mechanism, Nature (London) **602**, 63 (2022).

[46] MoEDAL Collaboration, MoEDAL search in the CMS beam pipe for magnetic monopoles produced via the Schwinger effect, Phys. Rev. Lett. **133**, 071803 (2024).

[47] K. A. Milton, Theoretical and experimental status of magnetic monopoles, Rep. Prog. Phys. **69**, 1637 (2006).

[48] ATLAS Collaboration, The ATLAS experiment at the CERN Large Hadron Collider, J. Instrum. **3**, S08003 (2008).

[49] ATLAS Collaboration, The ATLAS experiment at the CERN Large Hadron Collider: a description of the detector configuration for Run 3, J. Instrum. **19**, P05063 (2024).

[50] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis coinciding with the axis of the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

[51] ATLAS Collaboration, Software and computing for Run 3 of the ATLAS experiment at the LHC, arXiv:2404.06335.

[52] ATLAS Collaboration, ATLAS insertable B-layer technical design report, CERN ATLAS-TDR-19; CERN-LHCC-2010-013, 2010, https://cds.cern.ch/record/1291633; Addendum: ATLAS-TDR-19-ADD-1; CERN-LHCC-2012-009, 2012, https://cds.cern.ch/record/1451888.

[53] B. Abbott *et al.*, Production and integration of the ATLAS insertable B-layer, J. Instrum. **13**, T05008 (2018).

[54] ATLAS Collaboration, The ATLAS trigger system for LHC Run 3 and trigger performance in 2022, J. Instrum. **19**, P06029 (2024).

[55] A. Veyssiere, H. Beil, R. Bergere, P. Carlos, and A. Lepretre, Photoneutron cross sections of 208 Pb and 197 Au, Nucl. Phys. A **159**, 561 (1970).

[56] ALICE Collaboration, Measurement of the cross section for electromagnetic dissociation with neutron emission in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. Lett. **109**, 252302 (2012).

[57] ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C **70**, 823 (2010).

[58] S. Agostinelli *et al.*, GEANT4—A simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).

[59] The omission of the dissociative contribution to the signal, motivated by the possible suppression of monopole-pair production in the elementary $\gamma\gamma$ fusion process in semi-classical models, weakens the cross-section limits by about 10%.

[60] L. A. Harland-Lang, Exciting ions: A systematic treatment of ultraperipheral heavy ion collisions with nuclear breakup, Phys. Rev. D **107**, 093004 (2023).

[61] ATLAS Collaboration, Exclusive dimuon production in ultraperipheral $\mathrm{Pb}+\mathrm{Pb}$ collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with ATLAS, Phys. Rev. C **104**, 024906 (2021).

[62] ATLAS Collaboration, Exclusive dielectron production in ultraperipheral $\mathrm{Pb}+\mathrm{Pb}$ collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with ATLAS, J. High Energy Phys. 06 (2023) 182.

[63] ATLAS Collaboration, Characterisation and mitigation of beam-induced backgrounds observed in the ATLAS detector during the 2011 proton-proton run, J. Instrum. **8**, P07004 (2013).

[64] ATLAS Collaboration, Beam-induced and cosmic-ray backgrounds observed in the ATLAS detector during the LHC 2012 proton-proton running period, J. Instrum. **11**, P05013 (2016).

[65] ATLAS Collaboration, Comparison between simulated and observed LHC beam backgrounds in the ATLAS experiment at $E_{\mathrm{beam}} = 4$ TeV, J. Instrum. **13**, P12006 (2018).

[66] ATLAS Collaboration, Beam-induced backgrounds measured in the ATLAS detector during local gas injection into the LHC beam vacuum, J. Instrum. **19**, P06014 (2024).

[67] A. De Roeck, A. Katre, P. Mermod, D. Milstead, and T. Sloan, Sensitivity of LHC experiments to exotic highly ionising particles, Eur. Phys. J. C **72**, 1985 (2012).

[68] ATLAS Collaboration, Measurement of the azimuthal anisotropy of charged particles produced in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV $\mathrm{Pb}+\mathrm{Pb}$ collisions with the ATLAS detector, Eur. Phys. J. C **78**, 997 (2018).

[69] ATLAS Collaboration, Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1, Eur. Phys. J. C **77**, 490 (2017).

[70] ATLAS Collaboration, Rapidity gap cross sections measured with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C **72**, 1926 (2012).

[71] ATLAS Collaboration, A neural network clustering algorithm for the ATLAS silicon pixel detector, J. Instrum. **9**, P09009 (2014).

[72] ATLAS Collaboration, Measurement of distributions sensitive to the underlying event in inclusive Z boson production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Eur. Phys. J. C **79**, 666 (2019).

[73] An SCT space point is a pair of matched clusters on two sides of an SCT detector module.

[74] ATLAS Collaboration, Study of the material of the ATLAS inner detector for Run 2 of the LHC, J. Instrum. **12**, P12009 (2017).

[75] ATLAS Collaboration, First report of the simulation optimization group, CERN ATL-SOFT-PUB-2008-002, 2008, https://cds.cern.ch/record/1097789.

[76] S. P. Ahlen, Theoretical and experimental aspects of the energy loss of relativistic heavily ionizing particles, Rev. Mod. Phys. **52**, 121 (1980); **52**, 653(E) (1980).

[77] S. R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, and J. Butterworth, STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions, Comput. Phys. Commun. **212**, 258 (2017).

[78] H.-S. Shao and D. d'Enterria, Gamma-UPC: automated generation of exclusive photon-photon processes in ultraperipheral proton and nuclear collisions with varying form factors, J. High Energy Phys. 09 (2022) 248.

[79] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC, Eur. Phys. J. C **83**, 982 (2023).

[80] G. Avoni *et al.*, The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS, J. Instrum. **13**, P07017 (2018).

[81] A. L. Read, Presentation of search results: The CL_S technique, J. Phys. G **28**, 2693 (2002).

[82] K. Cranmer, G. Lewis, L. Moneta, A. Shibata, and W. Verkerke, HistFactory: A tool for creating statistical models for use with RooFit and RooStats, New York U., CERN, NIKHEF CERN-OPEN-2012-016, 2012, https://cds.cern.ch/record/1456844.

[83] O. Gould and A. Rajantie, Magnetic monopole mass bounds from heavy ion collisions and neutron stars, Phys. Rev. Lett. **119**, 241601 (2017).

[84] ATLAS Collaboration, ATLAS computing acknowledgements, CERN ATL-SOFT-PUB-2023-001, 2023, https://cds.cern.ch/record/2869272.

G. Aad,[105] E. Aakvaag,[17] B. Abbott,[124] S. Abdelhameed,[120a] K. Abeling,[57] N. J. Abicht,[51] S. H. Abidi,[30]
M. Aboelela,[46] A. Aboulhorma,[36e] H. Abramowicz,[156] H. Abreu,[155] Y. Abulaiti,[121] B. S. Acharya,[71a,71b,b]
A. Ackermann,[65a] C. Adam Bourdarios,[4] L. Adamczyk,[88a] S. V. Addepalli,[27] M. J. Addison,[104] J. Adelman,[119]
A. Adiguzel,[22c] T. Adye,[138] A. A. Affolder,[140] Y. Afik,[41] M. N. Agaras,[13] A. Aggarwal,[103] C. Agheorghiesei,[28c]
F. Ahmadov,[40,c] S. Ahuja,[98] X. Ai,[64e] G. Aielli,[78a,78b] A. Aikot,[168] M. Ait Tamlihat,[36e] B. Aitbenchikh,[36a]
M. Akbiyik,[103] T. P. A. Åkesson,[101] A. V. Akimov,[150] D. Akiyama,[173] N. N. Akolkar,[25] S. Aktas,[22a]
K. Al Khoury,[43] G. L. Alberghi,[24b] J. Albert,[170] P. Albicocco,[55] G. L. Albouy,[62] S. Alderweireldt,[54]
Z. L. Alegria,[125] M. Aleksa,[37] I. N. Aleksandrov,[40] C. Alexa,[28b] T. Alexopoulos,[10] F. Alfonsi,[24b] M. Algren,[58]
M. Alhroob,[172] B. Ali,[136] H. M. J. Ali,[94,d] S. Ali,[32] S. W. Alibocus,[95] M. Aliev,[34c] G. Alimonti,[73a]
W. Alkakhi,[57] C. Allaire,[68] B. M. M. Allbrooke,[151] J. S. Allen,[104] J. F. Allen,[54] C. A. Allendes Flores,[141f]
P. P. Allport,[21] A. Aloisio,[74a,74b] F. Alonso,[93] C. Alpigiani,[143] Z. M. K. Alsolami,[94] M. Alvarez Estevez,[102]
A. Alvarez Fernandez,[103] M. Alves Cardoso,[58] M. G. Alviggi,[74a,74b] M. Aly,[104] Y. Amaral Coutinho,[85b]
A. Ambler,[107] C. Amelung,[37] M. Amerl,[104] C. G. Ames,[112] D. Amidei,[109] B. Amini,[56] K. J. Amirie,[159]
S. P. Amor Dos Santos,[134a] K. R. Amos,[168] D. Amperiadou,[157] S. An,[86] V. Ananiev,[129] C. Anastopoulos,[144]
T. Andeen,[11] J. K. Anders,[37] A. C. Anderson,[61] S. Y. Andrean,[49a,49b] A. Andreazza,[73a,73b] S. Angelidakis,[9]
A. Angerami,[43] A. V. Anisenkov,[39] A. Annovi,[76a] C. Antel,[58] E. Antipov,[150] M. Antonelli,[55] F. Anulli,[77a]
M. Aoki,[86] T. Aoki,[158] M. A. Aparo,[151] L. Aperio Bella,[50] C. Appelt,[156] A. Apyan,[27] S. J. Arbiol Val,[89]
C. Arcangeletti,[55] A. T. H. Arce,[53] J-F. Arguin,[111] S. Argyropoulos,[157] J.-H. Arling,[50] O. Arnaez,[4] H. Arnold,[150]
G. Artoni,[77a,77b] H. Asada,[114] K. Asai,[122] S. Asai,[158] N. A. Asbah,[37] R. A. Ashby Pickering,[172] K. Assamagan,[30]
R. Astalos,[29a] K. S. V. Astrand,[101] S. Atashi,[163] R. J. Atkin,[34a] M. Atkinson,[167] H. Atmani,[36f] P. A. Atmasiddha,[132]
K. Augsten,[136] A. D. Auriol,[21] V. A. Austrup,[104] G. Avolio,[37] K. Axiotis,[58] G. Azuelos,[111,e] D. Babal,[29b]
H. Bachacou,[139] K. Bachas,[157,f] A. Bachiu,[35] E. Bachmann,[52] A. Badea,[41] T. M. Baer,[109] P. Bagnaia,[77a,77b]
M. Bahmani,[19] D. Bahner,[56] K. Bai,[127] J. T. Baines,[138] L. Baines,[97] O. K. Baker,[177] E. Bakos,[16]
D. Bakshi Gupta,[8] L. E. Balabram Filho,[85b] V. Balakrishnan,[124] R. Balasubramanian,[4] E. M. Baldin,[39] P. Balek,[88a]
E. Ballabene,[24b,24a] F. Balli,[139] L. M. Baltes,[65a] W. K. Balunas,[33] J. Balz,[103] I. Bamwidhi,[120b] E. Banas,[89]
M. Bandieramonte,[133] A. Bandyopadhyay,[25] S. Bansal,[25] L. Barak,[156] M. Barakat,[50] E. L. Barberio,[108]
D. Barberis,[59b,59a] M. Barbero,[105] M. Z. Barel,[118] T. Barillari,[113] M-S. Barisits,[37] T. Barklow,[148] P. Baron,[126]
D. A. Baron Moreno,[104] A. Baroncelli,[64a] A. J. Barr,[130] J. D. Barr,[99] F. Barreiro,[102]
J. Barreiro Guimarães da Costa,[14] M. G. Barros Teixeira,[134a] S. Barsov,[39] F. Bartels,[65a] R. Bartoldus,[148]
A. E. Barton,[94] P. Bartos,[29a] A. Basan,[103] M. Baselga,[51] A. Bassalat,[68,g] M. J. Basso,[160a] S. Bataju,[46]
R. Bate,[169] R. L. Bates,[61] S. Batlamous,[102] B. Batool,[146] M. Battaglia,[140] D. Battulga,[19] M. Bauce,[77a,77b]
M. Bauer,[81] P. Bauer,[25] L. T. Bazzano Hurrell,[31] J. B. Beacham,[53] T. Beau,[131] J. Y. Beaucamp,[93]
P. H. Beauchemin,[162] P. Bechtle,[25] H. P. Beck,[20,h] K. Becker,[172] A. J. Beddall,[84] V. A. Bednyakov,[40]
C. P. Bee,[150] L. J. Beemster,[16] T. A. Beermann,[37] M. Begalli,[85d] M. Begel,[30] A. Behera,[150] J. K. Behr,[50]
J. F. Beirer,[37] F. Beisiegel,[25] M. Belfkir,[120b] G. Bella,[156] L. Bellagamba,[24b] A. Bellerive,[35] P. Bellos,[21]
K. Beloborodov,[39] D. Benchekroun,[36a] F. Bendebba,[36a] Y. Benhammou,[156] K. C. Benkendorfer,[63] L. Beresford,[50]
M. Beretta,[55] E. Bergeaas Kuutmann,[166] N. Berger,[4] B. Bergmann,[136] J. Beringer,[18a] G. Bernardi,[5]
C. Bernius,[148] F. U. Bernlochner,[25] F. Bernon,[37] A. Berrocal Guardia,[13] T. Berry,[98] P. Berta,[137] A. Berthold,[52]
S. Bethke,[113] A. Betti,[77a,77b] A. J. Bevan,[97] N. K. Bhalla,[56] S. Bhatta,[150] D. S. Bhattacharya,[171] P. Bhattarai,[148]
Z. M. Bhatti,[121] K. D. Bhide,[56] V. S. Bhopatkar,[125] R. M. Bianchi,[133] G. Bianco,[24b,24a] O. Biebel,[112]
R. Bielski,[127] M. Biglietti,[79a] C. S. Billingsley,[46] Y. Bimgdi,[36f] M. Bindi,[57] A. Bingham,[176] A. Bingul,[22b]
C. Bini,[77a,77b] G. A. Bird,[33] M. Birman,[174] M. Biros,[137] S. Biryukov,[151] T. Bisanz,[51] E. Bisceglie,[45b,45a]
J. P. Biswal,[138] D. Biswas,[146] I. Bloch,[50] A. Blue,[61] U. Blumenschein,[97] J. Blumenthal,[103] V. S. Bobrovnikov,[39]

M. Boehler,[56] B. Boehm,[171] D. Bogavac,[37] A. G. Bogdanchikov,[39] L. S. Boggia,[131] C. Bohm,[49a] V. Boisvert,[98]
P. Bokan,[37] T. Bold,[88a] M. Bomben,[5] M. Bona,[97] M. Boonekamp,[139] A. G. Borbély,[61] I. S. Bordulev,[39]
G. Borissov,[94] D. Bortoletto,[130] D. Boscherini,[24b] M. Bosman,[13] K. Bouaouda,[36a] N. Bouchhar,[168] L. Boudet,[4]
J. Boudreau,[133] E. V. Bouhova-Thacker,[94] D. Boumediene,[42] R. Bouquet,[59b,59a] A. Boveia,[123] J. Boyd,[37]
D. Boye,[30] I. R. Boyko,[40] L. Bozianu,[58] J. Bracinik,[21] N. Brahimi,[4] G. Brandt,[176] O. Brandt,[33] F. Braren,[50]
B. Brau,[106] J. E. Brau,[127] R. Brener,[174] L. Brenner,[118] R. Brenner,[166] S. Bressler,[174] G. Brianti,[80a,80b]
D. Britton,[61] D. Britzger,[113] I. Brock,[25] R. Brock,[110] G. Brooijmans,[43] A. J. Brooks,[70] E. M. Brooks,[160b]
E. Brost,[30] L. M. Brown,[170] L. E. Bruce,[63] T. L. Bruckler,[130] P. A. Bruckman de Renstrom,[89] B. Brüers,[50]
A. Bruni,[24b] G. Bruni,[24b] D. Brunner,[49a,49b] M. Bruschi,[24b] N. Bruscino,[77a,77b] T. Buanes,[17] Q. Buat,[143]
D. Buchin,[113] A. G. Buckley,[61] O. Bulekov,[39] B. A. Bullard,[148] S. Burdin,[95] C. D. Burgard,[51] A. M. Burger,[37]
B. Burghgrave,[8] O. Burlayenko,[56] J. Burleson,[167] J. T. P. Burr,[33] J. C. Burzynski,[147] E. L. Busch,[43] V. Büscher,[103]
P. J. Bussey,[61] J. M. Butler,[26] C. M. Buttar,[61] J. M. Butterworth,[99] W. Buttinger,[138] C. J. Buxo Vazquez,[110]
A. R. Buzykaev,[39] S. Cabrera Urbán,[168] L. Cadamuro,[68] D. Caforio,[60] H. Cai,[133] Y. Cai,[14,115c] Y. Cai,[115a]
V. M. M. Cairo,[37] O. Cakir,[3a] N. Calace,[37] P. Calafiura,[18a] G. Calderini,[131] P. Calfayan,[35] G. Callea,[61]
L. P. Caloba,[85b] D. Calvet,[42] S. Calvet,[42] M. Calvetti,[76a,76b] R. Camacho Toro,[131] S. Camarda,[37]
D. Camarero Munoz,[27] P. Camarri,[78a,78b] M. T. Camerlingo,[74a,74b] D. Cameron,[37] C. Camincher,[170]
M. Campanelli,[99] A. Camplani,[44] V. Canale,[74a,74b] A. C. Canbay,[3a] E. Canonero,[98] J. Cantero,[168] Y. Cao,[167]
F. Capocasa,[27] M. Capua,[45b,45a] A. Carbone,[73a,73b] R. Cardarelli,[78a] J. C. J. Cardenas,[8] G. Carducci,[45b,45a]
T. Carli,[37] G. Carlino,[74a] J. I. Carlotto,[13] B. T. Carlson,[133,i] E. M. Carlson,[170,160a] J. Carmignani,[95]
L. Carminati,[73a,73b] A. Carnelli,[139] M. Carnesale,[37] S. Caron,[117] E. Carquin,[141f] I. B. Carr,[108] S. Carrá,[73a]
G. Carratta,[24b,24a] A. M. Carroll,[127] M. P. Casado,[13,j] M. Caspar,[50] F. L. Castillo,[4] L. Castillo Garcia,[13]
V. Castillo Gimenez,[168] N. F. Castro,[134a,134e] A. Catinaccio,[37] J. R. Catmore,[129] T. Cavaliere,[4] V. Cavaliere,[30]
L. J. Caviedes Betancourt,[23b] Y. C. Cekmecelioglu,[50] E. Celebi,[84] S. Cella,[37] V. Cepaitis,[58] K. Cerny,[126]
A. S. Cerqueira,[85a] A. Cerri,[151] L. Cerrito,[78a,78b] F. Cerutti,[18a] B. Cervato,[146] A. Cervelli,[24b] G. Cesarini,[55]
S. A. Cetin,[84] D. Chakraborty,[119] J. Chan,[18a] W. Y. Chan,[158] J. D. Chapman,[33] E. Chapon,[139]
B. Chargeishvili,[154b] D. G. Charlton,[21] M. Chatterjee,[20] C. Chauhan,[137] Y. Che,[115a] S. Chekanov,[6]
S. V. Chekulaev,[160a] G. A. Chelkov,[40,k] A. Chen,[109] B. Chen,[156] B. Chen,[170] H. Chen,[115a] H. Chen,[30]
J. Chen,[64c] J. Chen,[147] M. Chen,[130] S. Chen,[90] S. J. Chen,[115a] X. Chen,[64c] X. Chen,[15,l] Y. Chen,[64a]
C. L. Cheng,[175] H. C. Cheng,[66a] S. Cheong,[148] A. Cheplakov,[40] E. Cheremushkina,[50] E. Cherepanova,[118]
R. Cherkaoui El Moursli,[36e] E. Cheu,[7] K. Cheung,[67] L. Chevalier,[139] V. Chiarella,[55] G. Chiarelli,[76a]
N. Chiedde,[105] G. Chiodini,[72a] A. S. Chisholm,[21] A. Chitan,[28b] M. Chitishvili,[168] M. V. Chizhov,[40,m] K. Choi,[11]
Y. Chou,[143] E. Y. S. Chow,[117] K. L. Chu,[174] M. C. Chu,[66a] X. Chu,[14,115c] Z. Chubinidze,[55] J. Chudoba,[135]
J. J. Chwastowski,[89] D. Cieri,[113] K. M. Ciesla,[88a] V. Cindro,[96] A. Ciocio,[18a] F. Cirotto,[74a,74b] Z. H. Citron,[174]
M. Citterio,[73a] D. A. Ciubotaru,[28b] A. Clark,[58] P. J. Clark,[54] N. Clarke Hall,[99] C. Clarry,[159]
J. M. Clavijo Columbie,[50] S. E. Clawson,[50] C. Clement,[49a,49b] Y. Coadou,[105] M. Cobal,[71a,71c] A. Coccaro,[59b]
R. F. Coelho Barrue,[134a] R. Coelho Lopes De Sa,[106] S. Coelli,[73a] L. S. Colangeli,[159] B. Cole,[43] J. Collot,[62]
P. Conde Muiño,[134a,134g] M. P. Connell,[34c] S. H. Connell,[34c] E. I. Conroy,[130] F. Conventi,[74a,n] H. G. Cooke,[21]
A. M. Cooper-Sarkar,[130] F. A. Corchia,[24b,24a] A. Cordeiro Oudot Choi,[131] L. D. Corpe,[42] M. Corradi,[77a,77b]
F. Corriveau,[107,o] A. Cortes-Gonzalez,[19] M. J. Costa,[168] F. Costanza,[4] D. Costanzo,[144] B. M. Cote,[123]
J. Couthures,[4] G. Cowan,[98] K. Cranmer,[175] L. Cremer,[51] D. Cremonini,[24b,24a] S. Crépé-Renaudin,[62]
F. Crescioli,[131] M. Cristinziani,[146] M. Cristoforetti,[80a,80b] V. Croft,[118] J. E. Crosby,[125] G. Crosetti,[45b,45a]
A. Cueto,[102] H. Cui,[99] Z. Cui,[7] W. R. Cunningham,[61] F. Curcio,[168] J. R. Curran,[54] P. Czodrowski,[37]
M. J. Da Cunha Sargedas De Sousa,[59b,59a] J. V. Da Fonseca Pinto,[85b] C. Da Via,[104] W. Dabrowski,[88a] T. Dado,[37]
S. Dahbi,[153] T. Dai,[109] D. Dal Santo,[20] C. Dallapiccola,[106] M. Dam,[44] G. D'amen,[30] V. D'Amico,[112]
J. Damp,[103] J. R. Dandoy,[35] D. Dannheim,[37] M. Danninger,[147] V. Dao,[150] G. Darbo,[59b] S. J. Das,[30]
F. Dattola,[50] S. D'Auria,[73a,73b] A. D'Avanzo,[74a,74b] C. David,[34a] T. Davidek,[137] I. Dawson,[97] H. A. Day-hall,[136]
K. De,[8] R. De Asmundis,[74a] N. De Biase,[50] S. De Castro,[24b,24a] N. De Groot,[117] P. de Jong,[118] H. De la Torre,[119]
A. De Maria,[115a] A. De Salvo,[77a] U. De Sanctis,[78a,78b] F. De Santis,[72a,72b] A. De Santo,[151]
J. B. De Vivie De Regie,[62] J. Debevc,[96] D. V. Dedovich,[40] J. Degens,[95] A. M. Deiana,[46] F. Del Corso,[24b,24a]

J. Del Peso,[102] L. Delagrange,[131] F. Deliot,[139] C. M. Delitzsch,[51] M. Della Pietra,[74a,74b] D. Della Volpe,[58]
A. Dell'Acqua,[37] L. Dell'Asta,[73a,73b] M. Delmastro,[4] C. C. Delogu,[103] P. A. Delsart,[62] S. Demers,[177]
M. Demichev,[40] S. P. Denisov,[39] L. D'Eramo,[42] D. Derendarz,[89] F. Derue,[131] P. Dervan,[95] K. Desch,[25]
C. Deutsch,[25] F. A. Di Bello,[59b,59a] A. Di Ciaccio,[78a,78b] L. Di Ciaccio,[4] A. Di Domenico,[77a,77b]
C. Di Donato,[74a,74b] A. Di Girolamo,[37] G. Di Gregorio,[37] A. Di Luca,[80a,80b] B. Di Micco,[79a,79b] R. Di Nardo,[79a,79b]
K. F. Di Petrillo,[41] M. Diamantopoulou,[35] F. A. Dias,[118] T. Dias Do Vale,[147] M. A. Diaz,[141a,141b] A. R. Didenko,[40]
M. Didenko,[168] E. B. Diehl,[109] S. Díez Cornell,[50] C. Diez Pardos,[146] C. Dimitriadi,[166] A. Dimitrievska,[21]
J. Dingfelder,[25] T. Dingley,[130] I-M. Dinu,[28b] S. J. Dittmeier,[65b] F. Dittus,[37] M. Divisek,[137] B. Dixit,[95]
F. Djama,[105] T. Djobava,[154b] C. Doglioni,[104,101] A. Dohnalova,[29a] J. Dolejsi,[137] Z. Dolezal,[137] K. Domijan,[88a]
K. M. Dona,[41] M. Donadelli,[85d] B. Dong,[110] J. Donini,[42] A. D'Onofrio,[74a,74b] M. D'Onofrio,[95] J. Dopke,[138]
A. Doria,[74a] N. Dos Santos Fernandes,[134a] P. Dougan,[104] M. T. Dova,[93] A. T. Doyle,[61] M. A. Draguet,[130]
M. P. Drescher,[57] E. Dreyer,[174] I. Drivas-koulouris,[10] M. Drnevich,[121] M. Drozdova,[58] D. Du,[64a]
T. A. du Pree,[118] F. Dubinin,[39] M. Dubovsky,[29a] E. Duchovni,[174] G. Duckeck,[112] O. A. Ducu,[28b] D. Duda,[54]
A. Dudarev,[37] E. R. Duden,[27] M. D'uffizi,[104] L. Duflot,[68] M. Dührssen,[37] I. Duminica,[28g] A. E. Dumitriu,[28b]
M. Dunford,[65a] S. Dungs,[51] K. Dunne,[49a,49b] A. Duperrin,[105] H. Duran Yildiz,[3a] M. Düren,[60] A. Durglishvili,[154b]
D. Duvnjak,[35] B. L. Dwyer,[119] G. I. Dyckes,[18a] M. Dyndal,[88a] B. S. Dziedzic,[37] Z. O. Earnshaw,[151]
G. H. Eberwein,[130] B. Eckerova,[29a] S. Eggebrecht,[57] E. Egidio Purcino De Souza,[85e] L. F. Ehrke,[58] G. Eigen,[17]
K. Einsweiler,[18a] T. Ekelof,[166] P. A. Ekman,[101] S. El Farkh,[36b] Y. El Ghazali,[64a] H. El Jarrari,[37]
A. El Moussaouy,[36a] V. Ellajosyula,[166] M. Ellert,[166] F. Ellinghaus,[176] N. Ellis,[37] J. Elmsheuser,[30] M. Elsawy,[120a]
M. Elsing,[37] D. Emeliyanov,[138] Y. Enari,[86] I. Ene,[18a] S. Epari,[13] P. A. Erland,[89] D. Ernani Martins Neto,[89]
M. Errenst,[176] M. Escalier,[68] C. Escobar,[168] E. Etzion,[156] G. Evans,[134a,134b] H. Evans,[70] L. S. Evans,[98]
A. Ezhilov,[39] S. Ezzarqtouni,[36a] F. Fabbri,[24b,24a] L. Fabbri,[24b,24a] G. Facini,[99] V. Fadeyev,[140]
R. M. Fakhrutdinov,[39] D. Fakoudis,[103] S. Falciano,[77a] L. F. Falda Ulhoa Coelho,[37] F. Fallavollita,[113]
G. Falsetti,[45b,45a] J. Faltova,[137] C. Fan,[167] K. Y. Fan,[66b] Y. Fan,[14] Y. Fang,[14,115c] M. Fanti,[73a,73b] M. Faraj,[71a,71b]
Z. Farazpay,[100] A. Farbin,[8] A. Farilla,[79a] T. Farooque,[110] S. M. Farrington,[138,54] F. Fassi,[36e] D. Fassouliotis,[9]
M. Faucci Giannelli,[78a,78b] W. J. Fawcett,[33] L. Fayard,[68] P. Federic,[137] P. Federicova,[135] O. L. Fedin,[39,k]
M. Feickert,[175] L. Feligioni,[105] D. E. Fellers,[127] C. Feng,[64b] Z. Feng,[118] M. J. Fenton,[163] L. Ferencz,[50]
R. A. M. Ferguson,[94] S. I. Fernandez Luengo,[141f] P. Fernandez Martinez,[69] M. J. V. Fernoux,[105] J. Ferrando,[94]
A. Ferrari,[166] P. Ferrari,[118,117] R. Ferrari,[75a] D. Ferrere,[58] C. Ferretti,[109] D. Fiacco,[77a,77b] F. Fiedler,[103]
P. Fiedler,[136] S. Filimonov,[39] A. Filipčič,[96] E. K. Filmer,[160a] F. Filthaut,[117] M. C. N. Fiolhais,[134a,134c,p]
L. Fiorini,[168] W. C. Fisher,[110] T. Fitschen,[104] P. M. Fitzhugh,[139] I. Fleck,[146] P. Fleischmann,[109] T. Flick,[176]
M. Flores,[34d,q] L. R. Flores Castillo,[66a] L. Flores Sanz De Acedo,[37] F. M. Follega,[80a,80b] N. Fomin,[33] J. H. Foo,[159]
A. Formica,[139] A. C. Forti,[104] E. Fortin,[37] A. W. Fortman,[18a] M. G. Foti,[18a] L. Fountas,[9,r] D. Fournier,[68]
H. Fox,[94] P. Francavilla,[76a,76b] S. Francescato,[63] S. Franchellucci,[58] M. Franchini,[24b,24a] S. Franchino,[65a]
D. Francis,[37] L. Franco,[117] V. Franco Lima,[37] L. Franconi,[50] M. Franklin,[63] G. Frattari,[27] Y. Y. Frid,[156]
J. Friend,[61] N. Fritzsche,[37] A. Froch,[56] D. Froidevaux,[37] J. A. Frost,[130] Y. Fu,[64a] S. Fuenzalida Garrido,[141f]
M. Fujimoto,[105] K. Y. Fung,[66a] E. Furtado De Simas Filho,[85e] M. Furukawa,[158] J. Fuster,[168] A. Gaa,[57]
A. Gabrielli,[24b,24a] A. Gabrielli,[159] P. Gadow,[37] G. Gagliardi,[59b,59a] L. G. Gagnon,[18a] S. Gaid,[165] S. Galantzan,[156]
J. Gallagher,[1] E. J. Gallas,[130] B. J. Gallop,[138] K. K. Gan,[123] S. Ganguly,[158] Y. Gao,[54] F. M. Garay Walls,[141a,141b]
B. Garcia,[30] C. García,[168] A. Garcia Alonso,[118] A. G. Garcia Caffaro,[177] J. E. García Navarro,[168] M. Garcia-Sciveres,[18a]
G. L. Gardner,[132] R. W. Gardner,[41] N. Garelli,[162] D. Garg,[82] R. B. Garg,[148] J. M. Gargan,[54] C. A. Garner,[159]
C. M. Garvey,[34a] V. K. Gassmann,[162] G. Gaudio,[75a] V. Gautam,[13] P. Gauzzi,[77a,77b] J. Gavranovic,[96]
I. L. Gavrilenko,[39] A. Gavrilyuk,[39] C. Gay,[169] G. Gaycken,[127] E. N. Gazis,[10] A. A. Geanta,[28b] C. M. Gee,[140]
A. Gekow,[123] C. Gemme,[59b] M. H. Genest,[62] A. D. Gentry,[116] S. George,[98] W. F. George,[21] T. Geralis,[48]
P. Gessinger-Befurt,[37] M. E. Geyik,[176] M. Ghani,[172] K. Ghorbanian,[97] A. Ghosal,[146] A. Ghosh,[163] A. Ghosh,[7]
B. Giacobbe,[24b] S. Giagu,[77a,77b] T. Giani,[118] A. Giannini,[64a] S. M. Gibson,[98] M. Gignac,[140] D. T. Gil,[88b]
A. K. Gilbert,[88a] B. J. Gilbert,[43] D. Gillberg,[35] G. Gilles,[118] L. Ginabat,[131] D. M. Gingrich,[2,e]
M. P. Giordani,[71a,71c] P. F. Giraud,[139] G. Giugliarelli,[71a,71c] D. Giugni,[73a] F. Giuli,[78a,78b] I. Gkialas,[9,r]
L. K. Gladilin,[39] C. Glasman,[102] G. R. Gledhill,[127] G. Glemža,[50] M. Glisic,[127] I. Gnesi,[45b] Y. Go,[30]

M. Goblirsch-Kolb,[37] B. Gocke,[51] D. Godin,[111] B. Gokturk,[22a] S. Goldfarb,[108] T. Golling,[58] M. G. D. Gololo,[34g]
D. Golubkov,[39] J. P. Gombas,[110] A. Gomes,[134a,134b] G. Gomes Da Silva,[146] A. J. Gomez Delegido,[168]
R. Gonçalo,[134a] L. Gonella,[21] A. Gongadze,[154c] F. Gonnella,[21] J. L. Gonski,[148] R. Y. González Andana,[54]
S. González de la Hoz,[168] R. Gonzalez Lopez,[95] C. Gonzalez Renteria,[18a] M. V. Gonzalez Rodrigues,[50]
R. Gonzalez Suarez,[166] S. Gonzalez-Sevilla,[58] L. Goossens,[37] B. Gorini,[37] E. Gorini,[72a,72b] A. Gorišek,[96]
T. C. Gosart,[132] A. T. Goshaw,[53] M. I. Gostkin,[40] S. Goswami,[125] C. A. Gottardo,[37] S. A. Gotz,[112]
M. Gouighri,[36b] V. Goumarre,[50] A. G. Goussiou,[143] N. Govender,[34c] R. P. Grabarczyk,[130] I. Grabowska-Bold,[88a]
K. Graham,[35] E. Gramstad,[129] S. Grancagnolo,[72a,72b] C. M. Grant,[1,139] P. M. Gravila,[28f] F. G. Gravili,[72a,72b]
H. M. Gray,[18a] M. Greco,[72a,72b] M. J. Green,[1] C. Grefe,[25] A. S. Grefsrud,[17] I. M. Gregor,[50] K. T. Greif,[163]
P. Grenier,[148] S. G. Grewe,[113] A. A. Grillo,[140] K. Grimm,[32] S. Grinstein,[13,s] J.-F. Grivaz,[68] E. Gross,[174]
J. Grosse-Knetter,[57] L. Guan,[109] J. G. R. Guerrero Rojas,[168] G. Guerrieri,[37] R. Gugel,[103] J. A. M. Guhit,[109]
A. Guida,[19] E. Guilloton,[172] S. Guindon,[37] F. Guo,[14,115c] J. Guo,[64c] L. Guo,[50] L. Guo,[14] Y. Guo,[109]
A. Gupta,[51] R. Gupta,[133] S. Gurbuz,[25] S. S. Gurdasani,[56] G. Gustavino,[77a,77b] P. Gutierrez,[124]
L. F. Gutierrez Zagazeta,[132] M. Gutsche,[52] C. Gutschow,[99] C. Gwenlan,[130] C. B. Gwilliam,[95] E. S. Haaland,[129]
A. Haas,[121] M. Habedank,[61] C. Haber,[18a] H. K. Hadavand,[8] A. Hadef,[52] A. I. Hagan,[94] J. J. Hahn,[146]
E. H. Haines,[99] M. Haleem,[171] J. Haley,[125] G. D. Hallewell,[105] L. Halser,[20] K. Hamano,[170] M. Hamer,[25]
E. J. Hampshire,[98] J. Han,[64b] L. Han,[115a] L. Han,[64a] S. Han,[18a] Y. F. Han,[159] K. Hanagaki,[86] M. Hance,[140]
D. A. Hangal,[43] H. Hanif,[147] M. D. Hank,[132] J. B. Hansen,[44] P. H. Hansen,[44] D. Harada,[58] T. Harenberg,[176]
S. Harkusha,[178] M. L. Harris,[106] Y. T. Harris,[25] J. Harrison,[13] N. M. Harrison,[123] P. F. Harrison,[172]
N. M. Hartman,[113] N. M. Hartmann,[112] R. Z. Hasan,[98,138] Y. Hasegawa,[145] F. Haslbeck,[130] S. Hassan,[17]
R. Hauser,[110] C. M. Hawkes,[21] R. J. Hawkings,[37] Y. Hayashi,[158] D. Hayden,[110] C. Hayes,[109] R. L. Hayes,[118]
C. P. Hays,[130] J. M. Hays,[97] H. S. Hayward,[95] F. He,[64a] M. He,[14,115c] Y. He,[50] Y. He,[99] N. B. Heatley,[97]
V. Hedberg,[101] A. L. Heggelund,[129] N. D. Hehir,[97,a] C. Heidegger,[56] K. K. Heidegger,[56] J. Heilman,[35]
S. Heim,[50] T. Heim,[18a] J. G. Heinlein,[132] J. J. Heinrich,[127] L. Heinrich,[113,t] J. Hejbal,[135] A. Held,[175]
S. Hellesund,[17] C. M. Helling,[169] S. Hellman,[49a,49b] R. C. W. Henderson,[94] L. Henkelmann,[33]
A. M. Henriques Correia,[37] H. Herde,[101] Y. Hernández Jiménez,[150] L. M. Herrmann,[25] T. Herrmann,[52] G. Herten,[56]
R. Hertenberger,[112] L. Hervas,[37] M. E. Hesping,[103] N. P. Hessey,[160a] J. Hessler,[113] M. Hidaoui,[36b] N. Hidic,[137]
E. Hill,[159] S. J. Hillier,[21] J. R. Hinds,[110] F. Hinterkeuser,[25] M. Hirose,[128] S. Hirose,[161] D. Hirschbuehl,[176]
T. G. Hitchings,[104] B. Hiti,[96] J. Hobbs,[150] R. Hobincu,[28e] N. Hod,[174] M. C. Hodgkinson,[144] B. H. Hodkinson,[130]
A. Hoecker,[37] D. D. Hofer,[109] J. Hofer,[168] T. Holm,[25] M. Holzbock,[37] L. B. A. H. Hommels,[33] B. P. Honan,[104]
J. J. Hong,[70] J. Hong,[64c] T. M. Hong,[133] B. H. Hooberman,[167] W. H. Hopkins,[6] M. C. Hoppesch,[167] Y. Horii,[114]
M. E. Horstmann,[113] S. Hou,[153] M. R. Housenga,[167] A. S. Howard,[96] J. Howarth,[61] J. Hoya,[6] M. Hrabovsky,[126]
A. Hrynevich,[50] T. Hryn'ova,[4] P. J. Hsu,[67] S.-C. Hsu,[143] T. Hsu,[68] M. Hu,[18a] Q. Hu,[64a] S. Huang,[33]
X. Huang,[14,115c] Y. Huang,[144] Y. Huang,[103] Y. Huang,[14] Z. Huang,[104] Z. Hubacek,[136] M. Huebner,[25]
F. Huegging,[25] T. B. Huffman,[130] M. Hufnagel Maranha De Faria,[85a] C. A. Hugli,[50] M. Huhtinen,[37]
S. K. Huiberts,[17] R. Hulsken,[107] N. Huseynov,[12,u] J. Huston,[110] J. Huth,[63] R. Hyneman,[148] G. Iacobucci,[58]
G. Iakovidis,[30] L. Iconomidou-Fayard,[68] J. P. Iddon,[37] P. Iengo,[74a,74b] R. Iguchi,[158] Y. Iiyama,[158] T. Iizawa,[130]
Y. Ikegami,[86] N. Ilic,[159] H. Imam,[85c] G. Inacio Goncalves,[85d] T. Ingebretsen Carlson,[49a,49b] J. M. Inglis,[97]
G. Introzzi,[75a,75b] M. Iodice,[79a] V. Ippolito,[77a,77b] R. K. Irwin,[95] M. Ishino,[158] W. Islam,[175] C. Issever,[19]
S. Istin,[22a,v] H. Ito,[173] R. Iuppa,[80a,80b] A. Ivina,[174] J. M. Izen,[47] V. Izzo,[74a] P. Jacka,[135] P. Jackson,[1]
C. S. Jagfeld,[112] G. Jain,[160a] P. Jain,[50] K. Jakobs,[56] T. Jakoubek,[174] J. Jamieson,[61] W. Jang,[158] M. Javurkova,[106]
P. Jawahar,[104] L. Jeanty,[127] J. Jejelava,[154a] P. Jenni,[56,w] C. E. Jessiman,[35] C. Jia,[64b] H. Jia,[169] J. Jia,[150]
X. Jia,[14,115c] Z. Jia,[115a] C. Jiang,[54] S. Jiggins,[50] J. Jimenez Pena,[13] S. Jin,[115a] A. Jinaru,[28b] O. Jinnouchi,[142]
P. Johansson,[144] K. A. Johns,[7] J. W. Johnson,[140] F. A. Jolly,[50] D. M. Jones,[151] E. Jones,[50] K. S. Jones,[8]
P. Jones,[33] R. W. L. Jones,[94] T. J. Jones,[95] H. L. Joos,[57,37] R. Joshi,[123] J. Jovicevic,[16] X. Ju,[18a]
J. J. Junggeburth,[37] T. Junkermann,[65a] A. Juste Rozas,[13,s] M. K. Juzek,[89] S. Kabana,[141e] A. Kaczmarska,[89]
M. Kado,[113] H. Kagan,[123] M. Kagan,[148] A. Kahn,[132] C. Kahra,[103] T. Kaji,[158] E. Kajomovitz,[155] N. Kakati,[174]
I. Kalaitzidou,[56] C. W. Kalderon,[30] N. J. Kang,[140] D. Kar,[34g] K. Karava,[130] M. J. Kareem,[160b] E. Karentzos,[25]
O. Karkout,[118] S. N. Karpov,[40] Z. M. Karpova,[40] V. Kartvelishvili,[94] A. N. Karyukhin,[39] E. Kasimi,[157]

J. Katzy,[50] S. Kaur,[35] K. Kawade,[145] M. P. Kawale,[124] C. Kawamoto,[90] T. Kawamoto,[64a] E. F. Kay,[37]
F. I. Kaya,[162] S. Kazakos,[110] V. F. Kazanin,[39] Y. Ke,[150] J. M. Keaveney,[34a] R. Keeler,[170] G. V. Kehris,[63]
J. S. Keller,[35] J. J. Kempster,[151] O. Kepka,[135] B. P. Kerridge,[138] S. Kersten,[176] B. P. Kerševan,[96]
L. Keszeghova,[29a] S. Ketabchi Haghighat,[159] R. A. Khan,[133] A. Khanov,[125] A. G. Kharlamov,[39] T. Kharlamova,[39]
E. E. Khoda,[143] M. Kholodenko,[134a] T. J. Khoo,[19] G. Khoriauli,[171] J. Khubua,[154b,a] Y. A. R. Khwaira,[131]
B. Kibirige,[34g] D. Kim,[6] D. W. Kim,[49a,49b] Y. K. Kim,[41] N. Kimura,[99] M. K. Kingston,[57] A. Kirchhoff,[57]
C. Kirfel,[25] F. Kirfel,[25] J. Kirk,[138] A. E. Kiryunin,[113] S. Kita,[161] C. Kitsaki,[10] O. Kivernyk,[25] M. Klassen,[162]
C. Klein,[35] L. Klein,[171] M. H. Klein,[46] S. B. Klein,[58] U. Klein,[95] A. Klimentov,[30] T. Klioutchnikova,[37]
P. Kluit,[118] S. Kluth,[113] E. Kneringer,[81] T. M. Knight,[159] A. Knue,[51] D. Kobylianskii,[174] S. F. Koch,[130]
M. Kocian,[148] P. Kodyš,[137] D. M. Koeck,[127] P. T. Koenig,[25] T. Koffas,[35] O. Kolay,[52] I. Koletsou,[4]
T. Komarek,[89] K. Köneke,[56] A. X. Y. Kong,[1] T. Kono,[122] N. Konstantinidis,[99] P. Kontaxakis,[58] B. Konya,[101]
R. Kopeliansky,[43] S. Koperny,[88a] K. Korcyl,[89] K. Kordas,[157,x] A. Korn,[99] S. Korn,[57] I. Korolkov,[13]
N. Korotkova,[39] B. Kortman,[118] O. Kortner,[113] S. Kortner,[113] W. H. Kostecka,[119] V. V. Kostyukhin,[146]
A. Kotsokechagia,[37] A. Kotwal,[53] A. Koulouris,[37] A. Kourkoumeli-Charalampidi,[75a,75b] C. Kourkoumelis,[9]
E. Kourlitis,[113] O. Kovanda,[127] R. Kowalewski,[170] W. Kozanecki,[127] A. S. Kozhin,[39] V. A. Kramarenko,[39]
G. Kramberger,[96] P. Kramer,[25] M. W. Krasny,[131] A. Krasznahorkay,[37] A. C. Kraus,[119] J. W. Kraus,[176]
J. A. Kremer,[50] T. Kresse,[52] L. Kretschmann,[176] J. Kretzschmar,[95] K. Kreul,[19] P. Krieger,[159] K. Krizka,[21]
K. Kroeninger,[51] H. Kroha,[113] J. Kroll,[135] J. Kroll,[132] K. S. Krowpman,[110] U. Kruchonak,[40] H. Krüger,[25]
N. Krumnack,[83] M. C. Kruse,[53] O. Kuchinskaia,[39] S. Kuday,[3a] S. Kuehn,[37] R. Kuesters,[56] T. Kuhl,[50]
V. Kukhtin,[40] Y. Kulchitsky,[40] S. Kuleshov,[141d,141b] M. Kumar,[34g] N. Kumari,[50] P. Kumari,[160b] A. Kupco,[135]
T. Kupfer,[51] A. Kupich,[39] O. Kuprash,[56] H. Kurashige,[87] L. L. Kurchaninov,[160a] O. Kurdysh,[68]
Y. A. Kurochkin,[38] A. Kurova,[39] M. Kuze,[142] A. K. Kvam,[106] J. Kvita,[126] T. Kwan,[107] N. G. Kyriacou,[109]
L. A. O. Laatu,[105] C. Lacasta,[168] F. Lacava,[77a,77b] H. Lacker,[19] D. Lacour,[131] N. N. Lad,[99] E. Ladygin,[40]
A. Lafarge,[42] B. Laforge,[131] T. Lagouri,[177] F. Z. Lahbabi,[36a] S. Lai,[57] J. E. Lambert,[170] S. Lammers,[70]
W. Lampl,[7] C. Lampoudis,[157,x] G. Lamprinoudis,[103] A. N. Lancaster,[119] E. Lançon,[30] U. Landgraf,[56]
M. P. J. Landon,[97] V. S. Lang,[56] O. K. B. Langrekken,[129] A. J. Lankford,[163] F. Lanni,[37] K. Lantzsch,[25]
A. Lanza,[75a] M. Lanzac Berrocal,[168] J. F. Laporte,[139] T. Lari,[73a] F. Lasagni Manghi,[24b] M. Lassnig,[37]
V. Latonova,[135] A. Laurier,[155] S. D. Lawlor,[144] Z. Lawrence,[104] R. Lazaridou,[172] M. Lazzaroni,[73a,73b] B. Le,[104]
H. D. M. Le,[110] E. M. Le Boulicaut,[177] L. T. Le Pottier,[18a] B. Leban,[24b,24a] A. Lebedev,[83] M. LeBlanc,[104]
F. Ledroit-Guillon,[62] S. C. Lee,[153] S. Lee,[49a,49b] T. F. Lee,[95] L. L. Leeuw,[34c] M. Lefebvre,[170] C. Leggett,[18a]
G. Lehmann Miotto,[37] M. Leigh,[58] W. A. Leight,[106] W. Leinonen,[117] A. Leisos,[157,y] M. A. L. Leite,[85c]
C. E. Leitgeb,[19] R. Leitner,[137] K. J. C. Leney,[46] T. Lenz,[25] S. Leone,[76a] C. Leonidopoulos,[54] A. Leopold,[149]
R. Les,[110] C. G. Lester,[33] M. Levchenko,[39] J. Levêque,[4] L. J. Levinson,[174] G. Levrini,[24b,24a] M. P. Lewicki,[89]
C. Lewis,[143] D. J. Lewis,[4] L. Lewitt,[144] A. Li,[30] B. Li,[64b] C. Li,[64a] C-Q. Li,[113] H. Li,[64a] H. Li,[64b] H. Li,[115a]
H. Li,[15] H. Li,[64b] J. Li,[64c] K. Li,[14] L. Li,[64c] M. Li,[14,115c] S. Li,[14,115c] S. Li,[64d,64c,z] T. Li,[5] X. Li,[107] Z. Li,[158]
Z. Li,[14,115c] Z. Li,[64a] S. Liang,[14,115c] Z. Liang,[14] M. Liberatore,[139] B. Liberti,[78a] K. Lie,[66c] J. Lieber Marin,[85e]
H. Lien,[70] H. Lin,[109] K. Lin,[110] L. Linden,[112] R. E. Lindley,[7] J. H. Lindon,[2] J. Ling,[63] E. Lipeles,[132]
A. Lipniacka,[17] A. Lister,[169] J. D. Little,[70] B. Liu,[14] B. X. Liu,[115b] D. Liu,[64d,64c] E. H. L. Liu,[21] J. B. Liu,[64a]
J. K. K. Liu,[33] K. Liu,[64d] K. Liu,[64d,64c] M. Liu,[64a] M. Y. Liu,[64a] P. Liu,[14] Q. Liu,[64d,143,64c] X. Liu,[64a] X. Liu,[64b]
Y. Liu,[115b,115c] Y. L. Liu,[64b] Y. W. Liu,[64a] S. L. Lloyd,[97] E. M. Lobodzinska,[50] P. Loch,[7] E. Lodhi,[159]
T. Lohse,[19] K. Lohwasser,[144] E. Loiacono,[50] J. D. Lomas,[21] J. D. Long,[43] I. Longarini,[163] R. Longo,[167]
I. Lopez Paz,[69] A. Lopez Solis,[50] N. A. Lopez-canelas,[7] N. Lorenzo Martinez,[4] A. M. Lory,[112] M. Losada,[120a]
G. Löschcke Centeno,[151] O. Loseva,[39] X. Lou,[49a,49b] X. Lou,[14,115c] A. Lounis,[68] P. A. Love,[94] G. Lu,[14,115c]
M. Lu,[68] S. Lu,[132] Y. J. Lu,[67] H. J. Lubatti,[143] C. Luci,[77a,77b] F. L. Lucio Alves,[115a] F. Luehring,[70]
O. Lukianchuk,[68] B. S. Lunday,[132] O. Lundberg,[149] B. Lund-Jensen,[149,a] N. A. Luongo,[6] M. S. Lutz,[37]
A. B. Lux,[26] D. Lynn,[30] R. Lysak,[135] E. Lytken,[101] V. Lyubushkin,[40] T. Lyubushkina,[40] M. M. Lyukova,[150]
M. Firdaus M. Soberi,[54] H. Ma,[30] K. Ma,[64a] L. L. Ma,[64b] W. Ma,[64a] Y. Ma,[125] J. C. MacDonald,[103]
P. C. Machado De Abreu Farias,[85e] R. Madar,[42] T. Madula,[99] J. Maeda,[87] T. Maeno,[30] H. Maguire,[144]
V. Maiboroda,[139] A. Maio,[134a,134b,134d] K. Maj,[88a] O. Majersky,[50] S. Majewski,[127] N. Makovec,[68]

V. Maksimovic,[16] B. Malaescu,[131] Pa. Malecki,[89] V. P. Maleev,[39] F. Malek,[62,aa] M. Mali,[96] D. Malito,[98]
U. Mallik,[82,a] S. Maltezos,[10] S. Malyukov,[40] J. Mamuzic,[13] G. Mancini,[55] M. N. Mancini,[27] G. Manco,[75a,75b]
J. P. Mandalia,[97] S. S. Mandarry,[151] I. Mandić,[96] L. Manhaes de Andrade Filho,[85a] I. M. Maniatis,[174]
J. Manjarres Ramos,[92] D. C. Mankad,[174] A. Mann,[112] S. Manzoni,[37] L. Mao,[64c] X. Mapekula,[34c]
A. Marantis,[157,y] G. Marchiori,[5] M. Marcisovsky,[135] C. Marcon,[73a] M. Marinescu,[21] S. Marium,[50]
M. Marjanovic,[124] A. Markhoos,[56] M. Markovitch,[68] M. K. Maroun,[106] E. J. Marshall,[94] Z. Marshall,[18a]
S. Marti-Garcia,[168] J. Martin,[99] T. A. Martin,[138] V. J. Martin,[54] B. Martin dit Latour,[17] L. Martinelli,[77a,77b]
M. Martinez,[13,s] P. Martinez Agullo,[168] V. I. Martinez Outschoorn,[106] P. Martinez Suarez,[13] S. Martin-Haugh,[138]
G. Martinovicova,[137] V. S. Martoiu,[28b] A. C. Martyniuk,[99] A. Marzin,[37] D. Mascione,[80a,80b] L. Masetti,[103]
J. Masik,[104] A. L. Maslennikov,[39] S. L. Mason,[43] P. Massarotti,[74a,74b] P. Mastrandrea,[76a,76b]
A. Mastroberardino,[45b,45a] T. Masubuchi,[128] T. T. Mathew,[127] T. Mathisen,[166] J. Matousek,[137] D. M. Mattern,[51]
J. Maurer,[28b] T. Maurin,[61] A. J. Maury,[68] B. Maček,[96] D. A. Maximov,[39] A. E. May,[104] R. Mazini,[34g]
I. Maznas,[119] M. Mazza,[110] S. M. Mazza,[140] E. Mazzeo,[73a,73b] J. P. Mc Gowan,[170] S. P. Mc Kee,[109]
C. A. Mc Lean,[6] C. C. McCracken,[169] E. F. McDonald,[108] A. E. McDougall,[118] J. A. Mcfayden,[151]
R. P. McGovern,[132] R. P. Mckenzie,[34g] T. C. Mclachlan,[50] D. J. Mclaughlin,[99] S. J. McMahon,[138]
C. M. Mcpartland,[95] R. A. McPherson,[170,o] S. Mehlhase,[112] A. Mehta,[95] D. Melini,[168] B. R. Mellado Garcia,[34g]
A. H. Melo,[57] F. Meloni,[50] A. M. Mendes Jacques Da Costa,[104] H. Y. Meng,[159] L. Meng,[94] S. Menke,[113]
M. Mentink,[37] E. Meoni,[45b,45a] G. Mercado,[119] S. Merianos,[157] C. Merlassino,[71a,71c] L. Merola,[74a,74b]
C. Meroni,[73a,73b] J. Metcalfe,[6] A. S. Mete,[6] E. Meuser,[103] C. Meyer,[70] J-P. Meyer,[139] R. P. Middleton,[138]
L. Mijović,[54] G. Mikenberg,[174] M. Mikestikova,[135] M. Mikuž,[96] H. Mildner,[103] A. Milic,[37] D. W. Miller,[41]
E. H. Miller,[148] L. S. Miller,[35] A. Milov,[174] D. A. Milstead,[49a,49b] T. Min,[115a] A. A. Minaenko,[39]
I. A. Minashvili,[154b] A. I. Mincer,[121] B. Mindur,[88a] M. Mineev,[40] Y. Mino,[90] L. M. Mir,[13] M. Miralles Lopez,[61]
M. Mironova,[18a] M. C. Missio,[117] A. Mitra,[172] V. A. Mitsou,[168] Y. Mitsumori,[114] O. Miu,[159] P. S. Miyagawa,[97]
T. Mkrtchyan,[65a] M. Mlinarevic,[99] T. Mlinarevic,[99] M. Mlynarikova,[37] S. Mobius,[20] P. Mogg,[112]
M. H. Mohamed Farook,[116] A. F. Mohammed,[14,115c] S. Mohapatra,[43] G. Mokgatitswane,[34g] L. Moleri,[174]
B. Mondal,[146] S. Mondal,[136] K. Mönig,[50] E. Monnier,[105] L. Monsonis Romero,[168] J. Montejo Berlingen,[13]
A. Montella,[49a,49b] M. Montella,[123] F. Montereali,[79a,79b] F. Monticelli,[93] S. Monzani,[71a,71c] A. Morancho Tarda,[44]
N. Morange,[68] A. L. Moreira De Carvalho,[50] M. Moreno Llácer,[168] C. Moreno Martinez,[58] J. M. Moreno Perez,[23b]
P. Morettini,[59b] S. Morgenstern,[37] M. Morii,[63] M. Morinaga,[158] M. Moritsu,[91] F. Morodei,[77a,77b]
P. Moschovakos,[37] B. Moser,[130] M. Mosidze,[154b] T. Moskalets,[46] P. Moskvitina,[117] J. Moss,[32,bb]
P. Moszkowicz,[88a] A. Moussa,[36d] Y. Moyal,[174] E. J. W. Moyse,[106] O. Mtintsilana,[34g] S. Muanza,[105]
J. Mueller,[133] D. Muenstermann,[94] R. Müller,[37] G. A. Mullier,[166] A. J. Mullin,[33] J. J. Mullin,[132] A. E. Mulski,[63]
D. P. Mungo,[159] D. Munoz Perez,[168] F. J. Munoz Sanchez,[104] M. Murin,[104] W. J. Murray,[172,138] M. Muškinja,[96]
C. Mwewa,[30] A. G. Myagkov,[39,k] A. J. Myers,[8] G. Myers,[109] M. Myska,[136] B. P. Nachman,[18a] K. Nagai,[130]
K. Nagano,[86] R. Nagasaka,[158] J. L. Nagle,[30,cc] E. Nagy,[105] A. M. Nairz,[37] Y. Nakahama,[86] K. Nakamura,[86]
K. Nakkalil,[5] H. Nanjo,[128] E. A. Narayanan,[46] I. Naryshkin,[39] L. Nasella,[73a,73b] S. Nasri,[120b] C. Nass,[25]
G. Navarro,[23a] J. Navarro-Gonzalez,[168] R. Nayak,[156] A. Nayaz,[19] P. Y. Nechaeva,[39] S. Nechaeva,[24b,24a]
F. Nechansky,[135] L. Nedic,[130] T. J. Neep,[21] A. Negri,[75a,75b] M. Negrini,[24b] C. Nellist,[118] C. Nelson,[107]
K. Nelson,[109] S. Nemecek,[135] M. Nessi,[37,dd] M. S. Neubauer,[167] F. Neuhaus,[103] J. Neundorf,[50] J. Newell,[95]
P. R. Newman,[21] C. W. Ng,[133] Y. W. Y. Ng,[50] B. Ngair,[120a] H. D. N. Nguyen,[111] R. B. Nickerson,[130]
R. Nicolaidou,[139] J. Nielsen,[140] M. Niemeyer,[57] J. Niermann,[57] N. Nikiforou,[37] V. Nikolaenko,[39,k]
I. Nikolic-Audit,[131] K. Nikolopoulos,[21] P. Nilsson,[30] I. Ninca,[50] G. Ninio,[156] A. Nisati,[77a] N. Nishu,[2]
R. Nisius,[113] N. Nitika,[71a,71c] J-E. Nitschke,[52] E. K. Nkadimeng,[34g] T. Nobe,[158] T. Nommensen,[152]
M. B. Norfolk,[144] B. J. Norman,[35] M. Noury,[36a] J. Novak,[96] T. Novak,[96] L. Novotny,[136] R. Novotny,[116]
L. Nozka,[126] K. Ntekas,[163] N. M. J. Nunes De Moura Junior,[85b] J. Ocariz,[131] A. Ochi,[87] I. Ochoa,[134a]
S. Oerdek,[50,ee] J. T. Offermann,[41] A. Ogrodnik,[137] A. Oh,[104] C. C. Ohm,[149] H. Oide,[86] R. Oishi,[158]
M. L. Ojeda,[37] Y. Okumura,[158] L. F. Oleiro Seabra,[134a] I. Oleksiyuk,[58] S. A. Olivares Pino,[141d] G. Oliveira Correa,[13]
D. Oliveira Damazio,[30] J. L. Oliver,[163] Ö. O. Öncel,[56] A. P. O'Neill,[20] A. Onofre,[134a,134e] P. U. E. Onyisi,[11]
M. J. Oreglia,[41] D. Orestano,[79a,79b] N. Orlando,[13] R. S. Orr,[159] L. M. Osojnak,[132] R. Ospanov,[64a] Y. Osumi,[114]

G. Otero y Garzon,[31] H. Otono,[91] P. S. Ott,[65a] G. J. Ottino,[18a] M. Ouchrif,[36d] F. Ould-Saada,[129]
T. Ovsiannikova,[143] M. Owen,[61] R. E. Owen,[138] V. E. Ozcan,[22a] F. Ozturk,[89] N. Ozturk,[8] S. Ozturk,[84]
H. A. Pacey,[130] A. Pacheco Pages,[13] C. Padilla Aranda,[13] G. Padovano,[77a,77b] S. Pagan Griso,[18a] G. Palacino,[70]
A. Palazzo,[72a,72b] J. Pampel,[25] J. Pan,[177] T. Pan,[66a] D. K. Panchal,[11] C. E. Pandini,[118] J. G. Panduro Vazquez,[138]
H. D. Pandya,[1] H. Pang,[15] P. Pani,[50] G. Panizzo,[71a,71c] L. Panwar,[131] L. Paolozzi,[58] S. Parajuli,[167]
A. Paramonov,[6] C. Paraskevopoulos,[55] D. Paredes Hernandez,[66b] A. Pareti,[75a,75b] K. R. Park,[43] T. H. Park,[159]
M. A. Parker,[33] F. Parodi,[59b,59a] V. A. Parrish,[54] J. A. Parsons,[43] U. Parzefall,[56] B. Pascual Dias,[111]
L. Pascual Dominguez,[102] E. Pasqualucci,[77a] S. Passaggio,[59b] F. Pastore,[98] P. Patel,[89] U. M. Patel,[53]
J. R. Pater,[104] T. Pauly,[37] F. Pauwels,[137] C. I. Pazos,[162] M. Pedersen,[129] R. Pedro,[134a] S. V. Peleganchuk,[39]
O. Penc,[37] E. A. Pender,[54] S. Peng,[15] G. D. Penn,[177] K. E. Penski,[112] M. Penzin,[39] B. S. Peralva,[85d]
A. P. Pereira Peixoto,[143] L. Pereira Sanchez,[148] D. V. Perepelitsa,[30,cc] G. Perera,[106] E. Perez Codina,[160a]
M. Perganti,[10] H. Pernegger,[37] S. Perrella,[77a,77b] O. Perrin,[42] K. Peters,[50] R. F. Y. Peters,[104] B. A. Petersen,[37]
T. C. Petersen,[44] E. Petit,[105] V. Petousis,[136] C. Petridou,[157,x] T. Petru,[137] A. Petrukhin,[146] M. Pettee,[18a]
A. Petukhov,[39] K. Petukhova,[37] R. Pezoa,[141f] L. Pezzotti,[37] G. Pezzullo,[177] A. J. Pfleger,[37] T. M. Pham,[175]
T. Pham,[108] P. W. Phillips,[138] G. Piacquadio,[150] E. Pianori,[18a] F. Piazza,[127] R. Piegaia,[31] D. Pietreanu,[28b]
A. D. Pilkington,[104] M. Pinamonti,[71a,71c] J. L. Pinfold,[2] B. C. Pinheiro Pereira,[134a] J. Pinol Bel,[13]
A. E. Pinto Pinoargote,[139] L. Pintucci,[71a,71c] K. M. Piper,[151] A. Pirttikoski,[58] D. A. Pizzi,[35] L. Pizzimento,[66b]
A. Pizzini,[118] M.-A. Pleier,[30] V. Pleskot,[137] E. Plotnikova,[40] G. Poddar,[97] R. Poettgen,[101] L. Poggioli,[131]
S. Polacek,[137] G. Polesello,[75a] A. Poley,[147,160a] A. Polini,[24b] C. S. Pollard,[172] Z. B. Pollock,[123]
E. Pompa Pacchi,[77a,77b] N. I. Pond,[99] D. Ponomarenko,[70] L. Pontecorvo,[37] S. Popa,[28a] G. A. Popeneciu,[28d]
A. Poreba,[37] D. M. Portillo Quintero,[160a] S. Pospisil,[136] M. A. Postill,[144] P. Postolache,[28c] K. Potamianos,[172]
P. A. Potepa,[88a] I. N. Potrap,[40] C. J. Potter,[33] H. Potti,[152] J. Poveda,[168] M. E. Pozo Astigarraga,[37]
A. Prades Ibanez,[78a,78b] J. Pretel,[170] D. Price,[104] M. Primavera,[72a] L. Primomo,[71a,71c] M. A. Principe Martin,[102]
R. Privara,[126] T. Procter,[61] M. L. Proffitt,[143] N. Proklova,[132] K. Prokofiev,[66c] G. Proto,[113] J. Proudfoot,[6]
M. Przybycien,[88a] W. W. Przygoda,[88b] A. Psallidas,[48] J. E. Puddefoot,[144] D. Pudzha,[56] D. Pyatiizbyantseva,[39]
J. Qian,[109] R. Qian,[110] D. Qichen,[104] Y. Qin,[13] T. Qiu,[54] A. Quadt,[57] M. Queitsch-Maitland,[104] G. Quetant,[58]
R. P. Quinn,[169] G. Rabanal Bolanos,[63] D. Rafanoharana,[56] F. Raffaeli,[78a,78b] F. Ragusa,[73a,73b] J. L. Rainbolt,[41]
J. A. Raine,[58] S. Rajagopalan,[30] E. Ramakoti,[39] L. Rambelli,[59b,59a] I. A. Ramirez-Berend,[35] K. Ran,[50,115c]
D. S. Rankin,[132] N. P. Rapheeha,[34g] H. Rasheed,[28b] V. Raskina,[131] D. F. Rassloff,[65a] A. Rastogi,[18a] S. Rave,[103]
S. Ravera,[59b,59a] B. Ravina,[57] I. Ravinovich,[174] M. Raymond,[37] A. L. Read,[129] N. P. Readioff,[144]
D. M. Rebuzzi,[75a,75b] G. Redlinger,[30] A. S. Reed,[113] K. Reeves,[27] J. A. Reidelsturz,[176] D. Reikher,[127] A. Rej,[51]
C. Rembser,[37] M. Renda,[28b] F. Renner,[50] A. G. Rennie,[163] A. L. Rescia,[50] S. Resconi,[73a] M. Ressegotti,[59b,59a]
S. Rettie,[37] J. G. Reyes Rivera,[110] E. Reynolds,[18a] O. L. Rezanova,[39] P. Reznicek,[137] H. Riani,[36d] N. Ribaric,[53]
E. Ricci,[80a,80b] R. Richter,[113] S. Richter,[49a,49b] E. Richter-Was,[88b] M. Ridel,[131] S. Ridouani,[36d] P. Rieck,[121]
P. Riedler,[37] E. M. Riefel,[49a,49b] J. O. Rieger,[118] M. Rijssenbeek,[150] M. Rimoldi,[37] L. Rinaldi,[24b,24a]
P. Rincke,[57,166] T. T. Rinn,[30] M. P. Rinnagel,[112] G. Ripellino,[166] I. Riu,[13] J. C. Rivera Vergara,[170]
F. Rizatdinova,[125] E. Rizvi,[97] B. R. Roberts,[18a] S. S. Roberts,[140] S. H. Robertson,[107,o] D. Robinson,[33]
M. Robles Manzano,[103] A. Robson,[61] A. Rocchi,[78a,78b] C. Roda,[76a,76b] S. Rodriguez Bosca,[37]
Y. Rodriguez Garcia,[23a] A. M. Rodríguez Vera,[119] S. Roe,[37] J. T. Roemer,[37] A. R. Roepe-Gier,[140] O. Røhne,[129]
R. A. Rojas,[37] C. P. A. Roland,[131] J. Roloff,[30] A. Romaniouk,[81] E. Romano,[75a,75b] M. Romano,[24b]
A. C. Romero Hernandez,[167] N. Rompotis,[95] L. Roos,[131] S. Rosati,[77a] B. J. Rosser,[41] E. Rossi,[130] E. Rossi,[74a,74b]
L. P. Rossi,[63] L. Rossini,[56] R. Rosten,[123] M. Rotaru,[28b] B. Rottler,[56] C. Rougier,[92] D. Rousseau,[68]
D. Rousso,[50] A. Roy,[167] S. Roy-Garand,[159] A. Rozanov,[105] Z. M. A. Rozario,[61] Y. Rozen,[155]
A. Rubio Jimenez,[168] V. H. Ruelas Rivera,[19] T. A. Ruggeri,[1] A. Ruggiero,[130] A. Ruiz-Martinez,[168] A. Rummler,[37]
Z. Rurikova,[56] N. A. Rusakovich,[40] H. L. Russell,[170] G. Russo,[77a,77b] J. P. Rutherfoord,[7]
S. Rutherford Colmenares,[33] M. Rybar,[137] E. B. Rye,[129] A. Ryzhov,[46] J. A. Sabater Iglesias,[58]
H. F-W. Sadrozinski,[140] F. Safai Tehrani,[77a] B. Safarzadeh Samani,[138] S. Saha,[1] M. Sahinsoy,[84] A. Saibel,[168]
M. Saimpert,[139] M. Saito,[158] T. Saito,[158] A. Sala,[73a,73b] D. Salamani,[37] A. Salnikov,[148] J. Salt,[168]
A. Salvador Salas,[156] D. Salvatore,[45b,45a] F. Salvatore,[151] A. Salzburger,[37] D. Sammel,[56] E. Sampson,[94]

D. Sampsonidis,[157,x] D. Sampsonidou,[127] J. Sánchez,[168] V. Sanchez Sebastian,[168] H. Sandaker,[129] C. O. Sander,[50]
J. A. Sandesara,[106] M. Sandhoff,[176] C. Sandoval,[23b] L. Sanfilippo,[65a] D. P. C. Sankey,[138] T. Sano,[90]
A. Sansoni,[55] L. Santi,[37,77b] C. Santoni,[42] H. Santos,[134a,134b] A. Santra,[174] E. Sanzani,[24b,24a] K. A. Saoucha,[165]
J. G. Saraiva,[134a,134d] J. Sardain,[7] O. Sasaki,[86] K. Sato,[161] C. Sauer,[37] E. Sauvan,[4] P. Savard,[159,e] R. Sawada,[158]
C. Sawyer,[138] L. Sawyer,[100] C. Sbarra,[24b] A. Sbrizzi,[24b,24a] T. Scanlon,[99] J. Schaarschmidt,[143] U. Schäfer,[103]
A. C. Schaffer,[68,46] D. Schaile,[112] R. D. Schamberger,[150] C. Scharf,[19] M. M. Schefer,[20] V. A. Schegelsky,[39]
D. Scheirich,[137] M. Schernau,[141e] C. Scheulen,[57] C. Schiavi,[59b,59a] M. Schioppa,[45b,45a] B. Schlag,[148]
S. Schlenker,[37] J. Schmeing,[176] M. A. Schmidt,[176] K. Schmieden,[103] C. Schmitt,[103] N. Schmitt,[103] S. Schmitt,[50]
L. Schoeffel,[139] A. Schoening,[65b] P. G. Scholer,[35] E. Schopf,[130] M. Schott,[25] J. Schovancova,[37] S. Schramm,[58]
T. Schroer,[58] H-C. Schultz-Coulon,[65a] M. Schumacher,[56] B. A. Schumm,[140] Ph. Schune,[139] A. J. Schuy,[143]
H. R. Schwartz,[140] A. Schwartzman,[148] T. A. Schwarz,[109] Ph. Schwemling,[139] R. Schwienhorst,[110]
F. G. Sciacca,[20] A. Sciandra,[30] G. Sciolla,[27] F. Scuri,[76a] C. D. Sebastiani,[95] K. Sedlaczek,[119] S. C. Seidel,[116]
A. Seiden,[140] B. D. Seidlitz,[43] C. Seitz,[50] J. M. Seixas,[85b] G. Sekhniaidze,[74a] L. Selem,[62]
N. Semprini-Cesari,[24b,24a] A. Semushin,[178,39] D. Sengupta,[58] V. Senthilkumar,[168] L. Serin,[68] M. Sessa,[78a,78b]
H. Severini,[124] F. Sforza,[59b,59a] A. Sfyrla,[58] Q. Sha,[14] E. Shabalina,[57] A. H. Shah,[33] R. Shaheen,[149]
J. D. Shahinian,[132] D. Shaked Renous,[174] L. Y. Shan,[14] M. Shapiro,[18a] A. Sharma,[37] A. S. Sharma,[169]
P. Sharma,[82] P. B. Shatalov,[39] K. Shaw,[151] S. M. Shaw,[104] Q. Shen,[64c] D. J. Sheppard,[147] P. Sherwood,[99]
L. Shi,[99] X. Shi,[14] S. Shimizu,[86] C. O. Shimmin,[177] I. P. J. Shipsey,[130,a] S. Shirabe,[91] M. Shiyakova,[40,ff]
M. J. Shochet,[41] D. R. Shope,[129] B. Shrestha,[124] S. Shrestha,[123,gg] I. Shreyber,[39] M. J. Shroff,[170] P. Sicho,[135]
A. M. Sickles,[167] E. Sideras Haddad,[34g,164] A. C. Sidley,[118] A. Sidoti,[24b] F. Siegert,[52] Dj. Sijacki,[16] F. Sili,[93]
J. M. Silva,[54] I. Silva Ferreira,[85b] M. V. Silva Oliveira,[30] S. B. Silverstein,[49a] S. Simion,[68] R. Simoniello,[37]
E. L. Simpson,[104] H. Simpson,[151] L. R. Simpson,[109] S. Simsek,[84] S. Sindhu,[57] P. Sinervo,[159] S. Singh,[30]
S. Sinha,[50] S. Sinha,[104] M. Sioli,[24b,24a] I. Siral,[37] E. Sitnikova,[50] J. Sjölin,[49a,49b] A. Skaf,[57] E. Skorda,[21]
P. Skubic,[124] M. Slawinska,[89] V. Smakhtin,[174] B. H. Smart,[138] S. Yu. Smirnov,[39] Y. Smirnov,[39]
L. N. Smirnova,[39,k] O. Smirnova,[101] A. C. Smith,[43] D. R. Smith,[163] E. A. Smith,[41] J. L. Smith,[104] R. Smith,[148]
H. Smitmanns,[103] M. Smizanska,[94] K. Smolek,[136] A. A. Snesarev,[39] H. L. Snoek,[118] S. Snyder,[30] R. Sobie,[170,o]
A. Soffer,[156] C. A. Solans Sanchez,[37] E. Yu. Soldatov,[39] U. Soldevila,[168] A. A. Solodkov,[39] S. Solomon,[27]
A. Soloshenko,[40] K. Solovieva,[56] O. V. Solovyanov,[42] P. Sommer,[52] A. Sonay,[13] W. Y. Song,[160b] A. Sopczak,[136]
A. L. Sopio,[54] F. Sopkova,[29b] J. D. Sorenson,[116] I. R. Sotarriva Alvarez,[142] V. Sothilingam,[65a]
O. J. Soto Sandoval,[141c,141b] S. Sottocornola,[70] R. Soualah,[165] Z. Soumaimi,[36e] D. South,[50] N. Soybelman,[174]
S. Spagnolo,[72a,72b] M. Spalla,[113] D. Sperlich,[56] G. Spigo,[37] B. Spisso,[74a,74b] D. P. Spiteri,[61] M. Spousta,[137]
E. J. Staats,[35] R. Stamen,[65a] A. Stampekis,[21] E. Stanecka,[89] W. Stanek-Maslouska,[50] M. V. Stange,[52]
B. Stanislaus,[18a] M. M. Stanitzki,[50] B. Stapf,[50] E. A. Starchenko,[39] G. H. Stark,[140] J. Stark,[92] P. Staroba,[135]
P. Starovoitov,[65a] S. Stärz,[107] R. Staszewski,[89] G. Stavropoulos,[48] A. Stefl,[37] P. Steinberg,[30] B. Stelzer,[147,160a]
H. J. Stelzer,[133] O. Stelzer-Chilton,[160a] H. Stenzel,[60] T. J. Stevenson,[151] G. A. Stewart,[37] J. R. Stewart,[125]
M. C. Stockton,[37] G. Stoicea,[28b] M. Stolarski,[134a] S. Stonjek,[113] A. Straessner,[52] J. Strandberg,[149]
S. Strandberg,[49a,49b] M. Stratmann,[176] M. Strauss,[124] T. Strebler,[105] P. Strizenec,[29b] R. Ströhmer,[171]
D. M. Strom,[127] R. Stroynowski,[46] A. Strubig,[49a,49b] S. A. Stucci,[30] B. Stugu,[17] J. Stupak,[124] N. A. Styles,[50]
D. Su,[148] S. Su,[64a] W. Su,[64d] X. Su,[64a] D. Suchy,[29a] K. Sugizaki,[158] V. V. Sulin,[39] M. J. Sullivan,[95]
D. M. S. Sultan,[130] L. Sultanaliyeva,[39] S. Sultansoy,[3b] T. Sumida,[90] S. Sun,[175] O. Sunneborn Gudnadottir,[166]
N. Sur,[105] M. R. Sutton,[151] H. Suzuki,[161] M. Svatos,[135] M. Swiatlowski,[160a] T. Swirski,[171] I. Sykora,[29a]
M. Sykora,[137] T. Sykora,[137] D. Ta,[103] K. Tackmann,[50,ee] A. Taffard,[163] R. Tafirout,[160a] J. S. Tafoya Vargas,[68]
Y. Takubo,[86] M. Talby,[105] A. A. Talyshev,[39] K. C. Tam,[66b] N. M. Tamir,[156] A. Tanaka,[158] J. Tanaka,[158]
R. Tanaka,[68] M. Tanasini,[150] Z. Tao,[169] S. Tapia Araya,[141f] S. Tapprogge,[103] A. Tarek Abouelfadl Mohamed,[110]
S. Tarem,[155] K. Tariq,[14] G. Tarna,[28b] G. F. Tartarelli,[73a] M. J. Tartarin,[92] P. Tas,[137] M. Tasevsky,[135]
E. Tassi,[45b,45a] A. C. Tate,[167] G. Tateno,[158] Y. Tayalati,[36e,hh] G. N. Taylor,[108] W. Taylor,[160b]
R. Teixeira De Lima,[148] P. Teixeira-Dias,[98] J. J. Teoh,[159] K. Terashi,[158] J. Terron,[102] S. Terzo,[13] M. Testa,[55]
R. J. Teuscher,[159,o] A. Thaler,[81] O. Theiner,[58] T. Theveneaux-Pelzer,[105] O. Thielmann,[176] D. W. Thomas,[98]
J. P. Thomas,[21] E. A. Thompson,[18a] P. D. Thompson,[21] E. Thomson,[132] R. E. Thornberry,[46] C. Tian,[64a]

Y. Tian,[58] V. Tikhomirov,[39,k] Yu. A. Tikhonov,[39] S. Timoshenko,[39] D. Timoshyn,[137] E. X. L. Ting,[1] P. Tipton,[177]
A. Tishelman-Charny,[30] S. H. Tlou,[34g] K. Todome,[142] S. Todorova-Nova,[137] S. Todt,[52] L. Toffolin,[71a,71c]
M. Togawa,[86] J. Tojo,[91] S. Tokár,[29a] K. Tokushuku,[86] O. Toldaiev,[70] M. Tomoto,[86,114] L. Tompkins,[148,ii]
K. W. Topolnicki,[88b] E. Torrence,[127] H. Torres,[92] E. Torró Pastor,[168] M. Toscani,[31] C. Tosciri,[41] M. Tost,[11]
D. R. Tovey,[144] I. S. Trandafir,[28b] T. Trefzger,[171] A. Tricoli,[30] I. M. Trigger,[160a] S. Trincaz-Duvoid,[131]
D. A. Trischuk,[27] B. Trocmé,[62] A. Tropina,[40] L. Truong,[34c] M. Trzebinski,[89] A. Trzupek,[89] F. Tsai,[150]
M. Tsai,[109] A. Tsiamis,[157] P. V. Tsiareshka,[40] S. Tsigaridas,[160a] A. Tsirigotis,[157,y] V. Tsiskaridze,[159]
E. G. Tskhadadze,[154a] M. Tsopoulou,[157] Y. Tsujikawa,[90] I. I. Tsukerman,[39] V. Tsulaia,[18a] S. Tsuno,[86]
K. Tsuri,[122] D. Tsybychev,[150] Y. Tu,[66b] A. Tudorache,[28b] V. Tudorache,[28b] A. N. Tuna,[63] S. Turchikhin,[59b,59a]
I. Turk Cakir,[3a] R. Turra,[73a] T. Turtuvshin,[40,jj] P. M. Tuts,[43] S. Tzamarias,[157,x] E. Tzovara,[103] F. Ukegawa,[161]
P. A. Ulloa Poblete,[141c,141b] E. N. Umaka,[30] G. Unal,[37] A. Undrus,[30] G. Unel,[163] J. Urban,[29b] P. Urrejola,[141a]
G. Usai,[8] R. Ushioda,[142] M. Usman,[111] F. Ustuner,[54] Z. Uysal,[84] V. Vacek,[136] B. Vachon,[107] T. Vafeiadis,[37]
A. Vaitkus,[99] C. Valderanis,[112] E. Valdes Santurio,[49a,49b] M. Valente,[160a] S. Valentinetti,[24b,24a] A. Valero,[168]
E. Valiente Moreno,[168] A. Vallier,[92] J. A. Valls Ferrer,[168] D. R. Van Arneman,[118] T. R. Van Daalen,[143]
A. Van Der Graaf,[51] P. Van Gemmeren,[6] M. Van Rijnbach,[37] S. Van Stroud,[99] I. Van Vulpen,[118] P. Vana,[137]
M. Vanadia,[78a,78b] U. M. Vande Voorde,[149] W. Vandelli,[37] E. R. Vandewall,[125] D. Vannicola,[156] L. Vannoli,[55]
R. Vari,[77a] E. W. Varnes,[7] C. Varni,[18b] T. Varol,[153] D. Varouchas,[68] L. Varriale,[168] K. E. Varvell,[152]
M. E. Vasile,[28b] L. Vaslin,[86] A. Vasyukov,[40] L. M. Vaughan,[125] R. Vavricka,[103] T. Vazquez Schroeder,[37] J. Veatch,[32]
V. Vecchio,[104] M. J. Veen,[106] I. Veliscek,[30] L. M. Veloce,[159] F. Veloso,[134a,134c] S. Veneziano,[77a] A. Ventura,[72a,72b]
S. Ventura Gonzalez,[139] A. Verbytskyi,[113] M. Verducci,[76a,76b] C. Vergis,[97] M. Verissimo De Araujo,[85b]
W. Verkerke,[118] J. C. Vermeulen,[118] C. Vernieri,[148] M. Vessella,[106] M. C. Vetterli,[147,e] A. Vgenopoulos,[103]
N. Viaux Maira,[141f] T. Vickey,[144] O. E. Vickey Boeriu,[144] G. H. A. Viehhauser,[130] L. Vigani,[65b] M. Vigl,[113]
M. Villa,[24b,24a] M. Villaplana Perez,[168] E. M. Villhauer,[54] E. Vilucchi,[55] M. G. Vincter,[35] A. Visibile,[118] C. Vittori,[37]
I. Vivarelli,[24b,24a] E. Voevodina,[113] F. Vogel,[112] J. C. Voigt,[52] P. Vokac,[136] Yu. Volkotrub,[88b] E. Von Toerne,[25]
B. Vormwald,[37] V. Vorobel,[137] K. Vorobev,[39] M. Vos,[168] K. Voss,[146] M. Vozak,[118] L. Vozdecky,[124]
N. Vranjes,[16] M. Vranjes Milosavljevic,[16] M. Vreeswijk,[118] N. K. Vu,[64d,64c] R. Vuillermet,[37] O. Vujinovic,[103]
I. Vukotic,[41] I. K. Vyas,[35] S. Wada,[161] C. Wagner,[148] J. M. Wagner,[18a] W. Wagner,[176] S. Wahdan,[176]
H. Wahlberg,[93] C. H. Waits,[124] J. Walder,[138] R. Walker,[112] W. Walkowiak,[146] A. Wall,[132] E. J. Wallin,[101]
T. Wamorkar,[6] A. Z. Wang,[140] C. Wang,[103] C. Wang,[11] H. Wang,[18a] J. Wang,[66c] P. Wang,[99] R. Wang,[63]
R. Wang,[6] S. M. Wang,[153] S. Wang,[14] T. Wang,[64a] W. T. Wang,[82] W. Wang,[14] X. Wang,[115a] X. Wang,[167]
X. Wang,[64c] Y. Wang,[64d] Y. Wang,[115a] Y. Wang,[64a] Z. Wang,[109] Z. Wang,[64d,53,64c] Z. Wang,[109] A. Warburton,[107]
R. J. Ward,[21] N. Warrack,[61] S. Waterhouse,[98] A. T. Watson,[21] H. Watson,[54] M. F. Watson,[21] E. Watton,[61,138]
G. Watts,[143] B. M. Waugh,[99] J. M. Webb,[56] C. Weber,[30] H. A. Weber,[19] M. S. Weber,[20] S. M. Weber,[65a]
C. Wei,[64a] Y. Wei,[56] A. R. Weidberg,[130] E. J. Weik,[121] J. Weingarten,[51] C. Weiser,[56] C. J. Wells,[50] T. Wenaus,[30]
B. Wendland,[51] T. Wengler,[37] N. S. Wenke,[113] N. Wermes,[25] M. Wessels,[65a] A. M. Wharton,[94] A. S. White,[63]
A. White,[8] M. J. White,[1] D. Whiteson,[163] L. Wickremasinghe,[128] W. Wiedenmann,[175] M. Wielers,[138]
C. Wiglesworth,[44] D. J. Wilbern,[124] H. G. Wilkens,[37] J. J. H. Wilkinson,[33] D. M. Williams,[43] H. H. Williams,[132]
S. Williams,[33] S. Willocq,[106] B. J. Wilson,[104] P. J. Windischhofer,[41] F. I. Winkel,[31] F. Winklmeier,[127]
B. T. Winter,[56] J. K. Winter,[104] M. Wittgen,[148] M. Wobisch,[100] T. Wojtkowski,[62] Z. Wolffs,[118] J. Wollrath,[37]
M. W. Wolter,[89] H. Wolters,[134a,134c] M. C. Wong,[140] E. L. Woodward,[43] S. D. Worm,[50] B. K. Wosiek,[89]
K. W. Woźniak,[89] S. Wozniewski,[57] K. Wraight,[61] C. Wu,[21] M. Wu,[115b] M. Wu,[117] S. L. Wu,[175] X. Wu,[58]
Y. Wu,[64a] Z. Wu,[4] J. Wuerzinger,[113,t] T. R. Wyatt,[104] B. M. Wynne,[54] S. Xella,[44] L. Xia,[115a] M. Xia,[15]
M. Xie,[64a] S. Xin,[14,115c] A. Xiong,[127] J. Xiong,[18a] D. Xu,[14] H. Xu,[64a] L. Xu,[64a] R. Xu,[132] T. Xu,[109] Y. Xu,[143]
Z. Xu,[54] Z. Xu,[115a] B. Yabsley,[152] S. Yacoob,[34a] Y. Yamaguchi,[86] E. Yamashita,[158] H. Yamauchi,[161]
T. Yamazaki,[18a] Y. Yamazaki,[87] S. Yan,[61] Z. Yan,[106] H. J. Yang,[64c,64d] H. T. Yang,[64a] S. Yang,[64a] T. Yang,[66c]
X. Yang,[37] X. Yang,[14] Y. Yang,[46] Y. Yang,[64a] W-M. Yao,[18a] H. Ye,[115a] H. Ye,[57] J. Ye,[14] S. Ye,[30] X. Ye,[64a]
Y. Yeh,[99] I. Yeletskikh,[40] B. Yeo,[18b] M. R. Yexley,[99] T. P. Yildirim,[130] P. Yin,[43] K. Yorita,[173] S. Younas,[28b]
C. J. S. Young,[37] C. Young,[148] C. Yu,[14,115c] Y. Yu,[64a] J. Yuan,[14,115c] M. Yuan,[109] R. Yuan,[64d,64c] L. Yue,[99]
M. Zaazoua,[64a] B. Zabinski,[89] E. Zaid,[54] Z. K. Zak,[89] T. Zakareishvili,[168] S. Zambito,[58] J. A. Zamora Saa,[141d,141b]

J. Zang,[158] D. Zanzi,[56] O. Zaplatilek,[136] C. Zeitnitz,[176] H. Zeng,[14] J. C. Zeng,[167] D. T. Zenger Jr.,[27] O. Zenin,[39] T. Ženiš,[29a] S. Zenz,[97] S. Zerradi,[36a] D. Zerwas,[68] M. Zhai,[14,115c] D. F. Zhang,[144] J. Zhang,[64b] J. Zhang,[6] K. Zhang,[14,115c] L. Zhang,[64a] L. Zhang,[115a] P. Zhang,[14,115c] R. Zhang,[175] S. Zhang,[109] S. Zhang,[92] T. Zhang,[158] X. Zhang,[64c] Y. Zhang,[143] Y. Zhang,[99] Y. Zhang,[115a] Z. Zhang,[18a] Z. Zhang,[64b] Z. Zhang,[68] H. Zhao,[143] T. Zhao,[64b] Y. Zhao,[140] Z. Zhao,[64a] Z. Zhao,[64a] A. Zhemchugov,[40] J. Zheng,[115a] K. Zheng,[167] X. Zheng,[64a] Z. Zheng,[148] D. Zhong,[167] B. Zhou,[109] H. Zhou,[7] N. Zhou,[64c] Y. Zhou,[15] Y. Zhou,[115a] Y. Zhou,[7] C. G. Zhu,[64b] J. Zhu,[109] X. Zhu,[64d] Y. Zhu,[64c] Y. Zhu,[64a] X. Zhuang,[14] K. Zhukov,[70] N. I. Zimine,[40] J. Zinsser,[65b] M. Ziolkowski,[146] L. Živković,[16] A. Zoccoli,[24b,24a] K. Zoch,[63] T. G. Zorbas,[144] O. Zormpa,[48] W. Zou,[43] and L. Zwalinski[37]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Department of Physics, University of Alberta, Edmonton AB, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Türkiye*
[3b]*Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye*
[4]*LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*
[5]*APC, Université Paris Cité, CNRS/IN2P3, Paris, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*
[9]*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
[12]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[13]*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
[14]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[15]*Physics Department, Tsinghua University, Beijing, China*
[16]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[17]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[18a]*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[18b]*University of California, Berkeley, California, USA*
[19]*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
[20]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[21]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[22a]*Department of Physics, Bogazici University, Istanbul, Türkiye*
[22b]*Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye*
[22c]*Department of Physics, Istanbul University, Istanbul, Türkiye*
[23a]*Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia*
[23b]*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*
[24a]*Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy*
[24b]*INFN Sezione di Bologna, Italy*
[25]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[26]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[27]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[28a]*Transilvania University of Brasov, Brasov, Romania*
[28b]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[28c]*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
[28d]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
[28e]*National University of Science and Technology Politechnica, Bucharest, Romania*
[28f]*West University in Timisoara, Timisoara, Romania*
[28g]*Faculty of Physics, University of Bucharest, Bucharest, Romania*
[29a]*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
[29b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[30]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*

[31]*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*
[32]*California State University, California, USA*
[33]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[34a]*Department of Physics, University of Cape Town, Cape Town, South Africa*
[34b]*iThemba Labs, Western Cape, South Africa*
[34c]*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
[34d]*National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines*
[34e]*University of South Africa, Department of Physics, Pretoria, South Africa*
[34f]*University of Zululand, KwaDlangezwa, South Africa*
[34g]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[35]*Department of Physics, Carleton University, Ottawa ON, Canada*
[36a]*Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Morocco*
[36b]*Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco*
[36c]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
[36d]*LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco*
[36e]*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
[36f]*Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco*
[37]*CERN, Geneva, Switzerland*
[38]*Affiliated with an institute formerly covered by a cooperation agreement with CERN*
[39]*Affiliated with an institute covered by a cooperation agreement with CERN*
[40]*Affiliated with an international laboratory covered by a cooperation agreement with CERN*
[41]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[42]*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
[43]*Nevis Laboratory, Columbia University, Irvington, New York, USA*
[44]*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[45a]*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[45b]*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
[46]*Physics Department, Southern Methodist University, Dallas, Texas, USA*
[47]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[48]*National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece*
[49a]*Department of Physics, Stockholm University, Sweden*
[49b]*Oskar Klein Centre, Stockholm, Sweden*
[50]*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
[51]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[52]*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
[53]*Department of Physics, Duke University, Durham, North Carolina, USA*
[54]*SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[55]*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
[56]*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
[57]*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
[58]*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
[59a]*Dipartimento di Fisica, Università di Genova, Genova, Italy*
[59b]*INFN Sezione di Genova, Italy*
[60]*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[61]*SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[62]*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
[63]*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
[64a]*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
[64b]*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
[64c]*School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China*
[64d]*Tsung-Dao Lee Institute, Shanghai, China*
[64e]*School of Physics, Zhengzhou University, China*
[65a]*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[65b]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[66a]*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
[66b]*Department of Physics, University of Hong Kong, Hong Kong, China*

[66c]*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[67]*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
[68]*IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
[69]*Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain*
[70]*Department of Physics, Indiana University, Bloomington, IIndiana, USA*
[71a]*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
[71b]*ICTP, Trieste, Italy*
[71c]*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
[72a]*INFN Sezione di Lecce, Italy*
[72b]*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
[73a]*INFN Sezione di Milano, Italy*
[73b]*Dipartimento di Fisica, Università di Milano, Milano, Italy*
[74a]*INFN Sezione di Napoli, Italy*
[74b]*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
[75a]*INFN Sezione di Pavia, Italy*
[75b]*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[76a]*INFN Sezione di Pisa, Italy*
[76b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[77a]*INFN Sezione di Roma, Italy*
[77b]*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
[78a]*INFN Sezione di Roma Tor Vergata, Italy*
[78b]*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[79a]*INFN Sezione di Roma Tre, Italy*
[79b]*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
[80a]*INFN-TIFPA, Italy*
[80b]*Università degli Studi di Trento, Trento, Italy*
[81]*Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
[82]*University of Iowa, Iowa City, Iowa, USA*
[83]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
[84]*Istinye University, Sariyer, Istanbul, Türkiye*
[85a]*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[85b]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[85c]*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
[85d]*Rio de Janeiro State University, Rio de Janeiro, Brazil*
[85e]*Federal University of Bahia, Bahia, Brazil*
[86]*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[87]*Graduate School of Science, Kobe University, Kobe, Japan*
[88a]*AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[88b]*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[89]*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
[90]*Faculty of Science, Kyoto University, Kyoto, Japan*
[91]*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
[92]*L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France*
[93]*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[94]*Physics Department, Lancaster University, Lancaster, United Kingdom*
[95]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[96]*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
[97]*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
[98]*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
[99]*Department of Physics and Astronomy, University College London, London, United Kingdom*
[100]*Louisiana Tech University, Ruston, Louisiana, USA*
[101]*Fysiska institutionen, Lunds universitet, Lund, Sweden*
[102]*Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
[103]*Institut für Physik, Universität Mainz, Mainz, Germany*
[104]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[105]*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[106]*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
[107]*Department of Physics, McGill University, Montreal QC, Canada*

[108]School of Physics, University of Melbourne, Victoria, Australia
[109]Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
[110]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[111]Group of Particle Physics, University of Montreal, Montreal QC, Canada
[112]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[113]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[114]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[115a]Department of Physics, Nanjing University, Nanjing, China
[115b]School of Science, Shenzhen Campus of Sun Yat-sen University, China
[115c]University of Chinese Academy of Science (UCAS), Beijing, China
[116]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[117]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
[118]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[119]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[120a]New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
[120b]United Arab Emirates University, Al Ain, United Arab Emirates
[121]Department of Physics, New York University, New York, New York, USA
[122]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
[123]The Ohio State University, Columbus, Ohio, USA
[124]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[125]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
[126]Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
[127]Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
[128]Graduate School of Science, Osaka University, Osaka, Japan
[129]Department of Physics, University of Oslo, Oslo, Norway
[130]Department of Physics, Oxford University, Oxford, United Kingdom
[131]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
[132]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
[133]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[134a]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
[134b]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[134c]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
[134d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[134e]Departamento de Física, Universidade do Minho, Braga, Portugal
[134f]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
[134g]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[135]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[136]Czech Technical University in Prague, Prague, Czech Republic
[137]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[138]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[139]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[140]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[141a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[141b]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile
[141c]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile
[141d]Universidad Andres Bello, Department of Physics, Santiago, Chile
[141e]Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
[141f]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[142]Department of Physics, Institute of Science, Tokyo, Japan
[143]Department of Physics, University of Washington, Seattle, Washington, USA
[144]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[145]Department of Physics, Shinshu University, Nagano, Japan
[146]Department Physik, Universität Siegen, Siegen, Germany
[147]Department of Physics, Simon Fraser University, Burnaby BC, Canada
[148]SLAC National Accelerator Laboratory, Stanford, California, USA
[149]Department of Physics, Royal Institute of Technology, Stockholm, Sweden
[150]Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
[151]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[152]School of Physics, University of Sydney, Sydney, Australia
[153]Institute of Physics, Academia Sinica, Taipei, Taiwan

[154a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[154b]*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[154c]*University of Georgia, Tbilisi, Georgia*
[155]*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
[156]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[157]*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[158]*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
[159]*Department of Physics, University of Toronto, Toronto ON, Canada*
[160a]*TRIUMF, Vancouver BC, Canada*
[160b]*Department of Physics and Astronomy, York University, Toronto ON, Canada*
[161]*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
[162]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[163]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[164]*University of West Attica, Athens, Greece*
[165]*University of Sharjah, Sharjah, United Arab Emirates*
[166]*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[167]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[168]*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
[169]*Department of Physics, University of British Columbia, Vancouver BC, Canada*
[170]*Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*
[171]*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
[172]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[173]*Waseda University, Tokyo, Japan*
[174]*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
[175]*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
[176]*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[177]*Department of Physics, Yale University, New Haven, Connecticut, USA*
[178]*Yerevan Physics Institute, Yerevan, Armenia*

[a] Deceased.
[b] Also at Department of Physics, King's College London, London, United Kingdom.
[c] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[d] Also at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia.
[e] Also at TRIUMF, Vancouver BC, Canada.
[f] Also at Department of Physics, University of Thessaly, Greece.
[g] Also at An-Najah National University, Nablus, Palestine.
[h] Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[i] Also at Department of Physics, Westmont College, Santa Barbara, USA.
[j] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[k] Also at Affiliated with an institute covered by a cooperation agreement with CERN.
[l] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[m] Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia, Bulgaria.
[n] Also at Università di Napoli Parthenope, Napoli, Italy.
[o] Also at Institute of Particle Physics (IPP), Canada.
[p] Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
[q] Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines.
[r] Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[s] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[t] Also at Technical University of Munich, Munich, Germany.
[u] Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC), Azerbaijan.
[v] Also at Yeditepe University, Physics Department, Istanbul, Türkiye.
[w] Also at CERN, Geneva, Switzerland.
[x] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.
[y] Also at Hellenic Open University, Patras, Greece.
[z] Also at Center for High Energy Physics, Peking University, China.
[aa] Also at Department of Physics, Stellenbosch University, South Africa.
[bb] Also at Department of Physics, California State University, Sacramento, USA.
[cc] Also at University of Colorado Boulder, Department of Physics, Colorado, USA.
[dd] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

[ee] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[ff] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
[gg] Also at Washington College, Chestertown, Maryland, USA.
[hh] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.
[ii] Also at Department of Physics, Stanford University, Stanford, California, USA.
[jj] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.