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DOI
10.1103/PhysRevD.93.112015

Publication date
2016

Document Version
Final published version

Published in
Physical Review D. Particles, Fields, Gravitation, and Cosmology

PHYSICAL REVIEW D **93,** 112015 (2016)

Search for metastable heavy charged particles with large ionization energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment

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(Received 18 April 2016; published 28 June 2016)

This paper presents a search for massive charged long-lived particles produced in pp collisions at $\sqrt{s} = 13$ TeV at the LHC using the ATLAS experiment. The data set used corresponds to an integrated luminosity of 3.2 fb^{-1}. Many extensions of the Standard Model predict the existence of massive charged long-lived particles, such as R-hadrons. These massive particles are expected to be produced with a velocity significantly below the speed of light, and therefore to have a specific ionization higher than any Standard Model particle of unit charge at high momenta. The Pixel subsystem of the ATLAS detector is used to measure the ionization energy loss of reconstructed charged particles and to search for such highly ionizing particles. The search presented here has much greater sensitivity than a similar search performed using the ATLAS detector in the $\sqrt{s} = 8$ TeV data set, thanks to the increase in expected signal cross section due to the higher center-of-mass energy of collisions, to an upgraded detector with a new silicon layer close to the interaction point, and to analysis improvements. No significant deviation from Standard Model background expectations is observed, and lifetime-dependent upper limits on R-hadron production cross sections and masses are set. Gluino R-hadrons with lifetimes above 0.4 ns and decaying to $q\bar{q}$ plus a 100 GeV neutralino are excluded at the 95% confidence level, with lower mass limit ranging between 740 and 1590 GeV. In the case of stable R-hadrons the lower mass limit at the 95% confidence level is 1570 GeV.

DOI: 10.1103/PhysRevD.93.112015

I. INTRODUCTION

Massive, long-lived particles (LLPs) are predicted by a wide range of physics models that extend the Standard Model (SM). LLPs arise in proposed solutions to the gauge hierarchy problem [1], including supersymmetric (SUSY) models that either violate [2–4] or conserve [5–12] R-parity. The lifetime of these particles depends on the mass difference between the particle and the lightest stable SUSY particle, and on the size of any R-parity-violating coupling [13].

Because of their large mass, LLPs are expected to be slow (β significantly below 1) and, if charged, to have a specific ionization higher than any SM particles of unit charge at high momenta. The Pixel subsystem [14] of the ATLAS detector [15] provides measurements of ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) for charged particles and can be used to distinguish such highly ionizing particles from SM particles. In this paper, this information is used to search for LLPs using data collected at $\sqrt{s} = 13$ TeV, extending in reach a study performed on data collected at $\sqrt{s} = 8$ TeV [16]. The increase in probability for high-energy parton-parton collisions significantly enhances the production cross section of LLPs via the strong interaction. Together with this enhancement, the search sensitivity has been considerably extended thanks to the upgrades to the Pixel detector (see Sec. II) and improvements to the analysis (see Sec. VI).

Many strategies have been explored to find LLPs at the LHC. A search using the complete $\sqrt{s} = 8$ TeV data set recorded by the ATLAS detector [17] combined Pixel $\mathrm{d}E/\mathrm{d}x$ information with time-of-flight measurements, made in both the calorimeters and the muon spectrometer, to search for LLPs that do not decay within the detector. Charginos that are nearly mass degenerate with the lightest stable particle have been searched for in ATLAS looking for disappearing tracks [18]. A displaced vertex search [19] performed by the ATLAS Collaboration provided limits on the mass of gluinos decaying due to couplings violating both R-parity and lepton number conservation. The CMS Collaboration published an analysis searching for non-decaying LLPs based on $\mathrm{d}E/\mathrm{d}x$, β, and muon identification [20]. Additional analyses at the CMS experiment searched for LLPs with short lifetimes by looking for secondary vertices [21,22] and for disappearing tracks [23].

The current study addresses many different models of new physics, in particular those that predict the production of metastable massive particles with $O(\mathrm{ns})$ lifetime at LHC energies, such as mini-split SUSY [11,24,25] or anomaly-mediated supersymmetry-breaking models [26,27]. A metastable gluino with a mass of approximately 1 TeV would be compatible with the measured Higgs boson mass according to mini-split SUSY models, which also predict squarks with masses of 10^3–10^5 TeV, therefore making the

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gluino the only observable sparticle produced through the strong interaction at LHC energies. Results are presented assuming the production of *R*-hadrons as composite colorless states of a gluino together with SM quarks or gluons and the subsequent decay, on nanosecond timescales, of the gluino to a stable neutralino and a $q\bar{q}$ pair [28]. This search could, in principle, also be sensitive to the production of LLPs through weak interactions, but these models are not considered here as the cross sections are much lower.

In the rest of this paper, *R*-hadrons with lifetimes consistent with decaying inside the ATLAS detector are referred to as metastable; the search strategy focuses on decays occurring within the active detector volume, which covers lifetimes from around 1 ns to several tens of ns. *R*-hadrons whose lifetime disfavors decay within the ATLAS detector are termed stable. The approach described in this paper allows direct observation of charged *R*-hadrons which are either stable or metastable and traverse the first seven layers of the ATLAS inner tracking system.

II. ATLAS DETECTOR AND PIXEL dE/dx MEASUREMENT

The ATLAS detector[1] consists of a tracker, for measuring the trajectories of charged particles, surrounded by a solenoid magnet, followed by calorimeters for measuring the energy of particles that interact electromagnetically or hadronically. A muon spectrometer immersed in a toroidal magnetic field surrounds the calorimeters, and provides tracking for muons. The detector is hermetic and can therefore measure the missing transverse momentum associated with each event. A complete description of the ATLAS detector can be found in Ref. [15]. The tracker is made of three detector systems. Moving from the solenoid magnet toward the beam collision region, there is first a transition radiation tracker with approximately 400,000 channels [29], followed by a silicon microstrip detector (SCT) with about 6 million channels [30], and at the innermost radius sits a roughly 92 million channel silicon Pixel detector, which is crucial for this measurement, and is described below in some detail.

The current Pixel detector provides at least four precision measurements for each track in the region $|\eta| < 2.5$ at radial distances of 3.4 to 13 cm from the LHC beam line. After Run 1, the ATLAS Pixel detector was upgraded with the insertion of an additional layer, the Insertable B-Layer (IBL), which was installed inside the Run 1 Pixel detector, mounted on a new beam pipe of smaller diameter. The IBL has smaller area pixels, reduced thickness, and different coding electronics, which provides charge measurements with lower resolution and dynamic range than the other Pixel layers. It therefore requires a separate treatment of the dE/dx information. At normal incidence, the average charge released by a minimum ionizing particle (MIP) in a pixel sensor is $\approx 20000e^-$ ($\approx 16000e^-$ for IBL) and the charge threshold is set to $3500 \pm 40e^-$ ($2500 \pm 40e^-$ for IBL). Signals are accepted if they are larger than this threshold. They are then matched to a specific beam crossing. The hit efficiency under these conditions exceeds 99%. When detector data are read out, the time over threshold (ToT), i.e. the time interval with the signal above the threshold, is digitized with 8 bits (4 bits for IBL). The ToT is approximately proportional to the ionization charge [31] and its dynamic range corresponds to 8.5 times (1.5 times for IBL) the average charge released by a MIP for a track normal to the silicon detectors which deposits all its ionization charge in a single pixel. If this value is exceeded, the hit charge information is either underestimated in the IBL, where the electronics signals the excess with an overflow bit, or lost in the other pixel layers.

The charge released by a track crossing the Pixel detector is rarely contained within just one pixel; neighboring pixels registering hits are joined together using a connected component analysis [32,33] to form clusters. The charge of a cluster is calculated by summing the charges of all

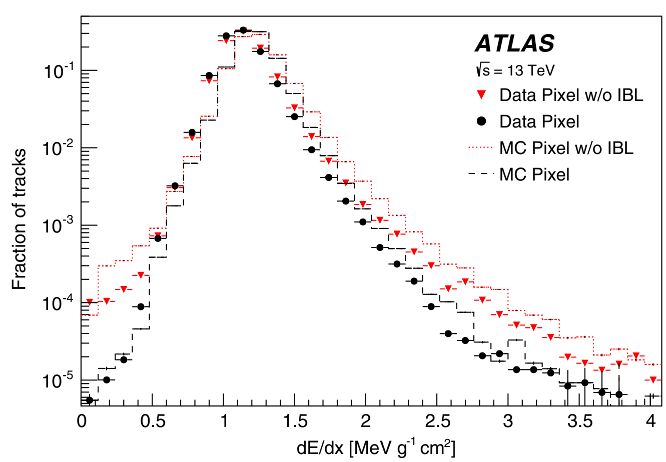

FIG. 1. Distribution of the dE/dx computed with the Pixel algorithm in data (black dots) and Pixel without IBL (red triangles) for minimum bias events. Tracks were selected as in Ref. [34], with the additional requirements of $p > 3$ GeV and at least two associated pixel clusters. The corresponding dE/dx distributions for simulation with and without the IBL are also plotted, respectively, as dashed and dotted lines. The simulation overestimates the dE/dx, which is taken into account in the systematic uncertainty evaluation. The addition of IBL clusters reduces the tails at both low and high dE/dx. The fraction of tracks with dE/d$x < 0.5 (> 1.8)$ MeV g^{-1} cm^2 decreases with the use of the IBL charge information from 0.065% to 0.018% (from 0.89% to 0.44%).

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z axis coinciding with the axis of the beam pipe. The x axis points from the interaction point 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 z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

pixels belonging to the cluster after calibration corrections; the IBL overflow information is accounted for separately. The $\mathrm{d}E/\mathrm{d}x$ is estimated using the average of the individual cluster ionization measurements (charge collected in the cluster per unit track length in the sensor), for the clusters associated with a track. To reduce the effect of the tails of the Landau distribution, the average is evaluated after removing the highest $\mathrm{d}E/\mathrm{d}x$ cluster, or the two highest $\mathrm{d}E/\mathrm{d}x$ clusters in the rare case of more than four clusters on the track. A track is considered to have a good ionization measurement only if there are at least two remaining clusters. Including the IBL charge information reduces the tails of the $\mathrm{d}E/\mathrm{d}x$ distribution, as illustrated in Fig. 1, and increases the fraction of tracks for which the ionization measurement is valid from 77% to 91%. The most probable value of the measured $\mathrm{d}E/\mathrm{d}x$ is 1.12 MeV g^{-1} cm^2 for a minimum ionizing particle. This value is obtained with a Gaussian fit to the data shown in Fig. 1, in a ± 1 standard deviation (0.13 MeV g^{-1} cm^2) range around the peak. The $\beta\gamma$ measurable with the current $\mathrm{d}E/\mathrm{d}x$ method cannot be smaller than approximately 0.3 for particles with unit charge because of the ToT dynamic range.

III. MASS CALCULATION

The average energy loss of massive, charged particles in matter is expected to follow the Bethe-Bloch distribution, which can be expressed as a function of the $\beta\gamma$ of the LLPs. Their mass can be derived from a fit of the measured specific energy loss and the reconstructed momentum to a parametric Bethe-Bloch distribution in the range $0.3 < \beta\gamma < 1.5$. This range overlaps the expected average $\beta\gamma$ of LLPs produced at the LHC, which decreases with the particle mass from $\langle\beta\gamma\rangle \approx 2.0$ at 100 GeV to $\langle\beta\gamma\rangle \approx 0.5$ at 1600 GeV. The parametric function describing the relationship between the most probable value of the energy loss $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{MPV}}$ and $\beta\gamma$ is

$$(\mathrm{d}E/\mathrm{d}x)_{\mathrm{MPV}}(\beta\gamma) = \frac{p_1}{\beta^{p_3}} \ln(1 + [p_2\beta\gamma]^{p_5}) - p_4. \qquad (1)$$

The p_i, with $i = 1\ldots5$, calibration constants were measured in this data set using the peak values of three Crystal Ball functions, fitted to the $\mathrm{d}E/\mathrm{d}x$ distribution observed in each of several low-momentum slices to model the energy loss distribution for pions, kaons and protons respectively, as described in Ref. [35].

The distribution of the $\mathrm{d}E/\mathrm{d}x$ versus momentum is shown in Fig. 2 together with the fits to the pion, kaon and proton masses. The mass calculation performed through the $\mathrm{d}E/\mathrm{d}x$ method is monitored by checking the stability of the proton mass measurement during the data taking.

A mass estimate M is obtained by numerically solving Eq. (1) for the unknown M. In simulated R-hadron events, the reconstructed mass is found to reproduce well the generated mass up to masses around 1800 GeV, and a residual 3% correction is applied to the reconstructed mass to improve the agreement. For particles with higher masses (beyond the current sensitivity of this analysis), the reconstructed mass is observed to slightly underestimate the generated mass. The half width at half maximum of the reconstructed mass distribution increases with the mass value. This is due to the momentum measurement uncertainty dominating the mass resolution for masses greater than ≈200 GeV.

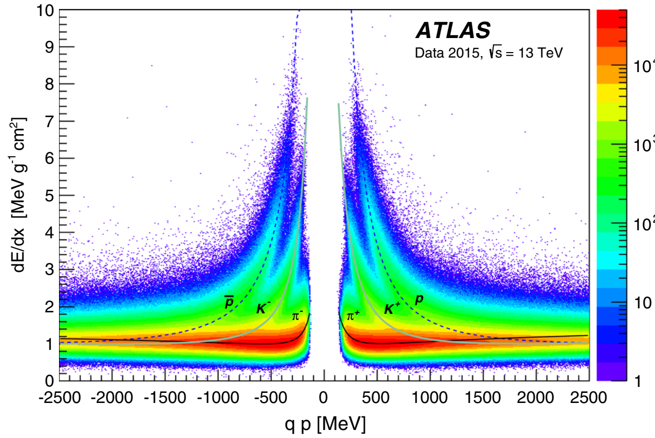

FIG. 2. Two-dimensional distribution of $\mathrm{d}E/\mathrm{d}x$ versus charge signed momentum (qp) for minimum-bias event tracks compatible with a primary vertex, which has the same data selection as in Ref. [34]. The distributions of the most probable value for the fitted probability density functions of pions, kaons and protons are superimposed.

IV. *R*-HADRON SIMULATION

A number of samples of simulated signal events are used in this analysis to determine the expected LLP signal efficiencies and to estimate uncertainties in the efficiency.

For stable R-hadrons, pair production of gluinos with masses between 800 GeV and 1800 GeV is simulated in PYTHIA 6.4.27 [36] with the AUET2B [37] set of tuned parameters for the underlying event and the CTEQ6L1 [38] parton distribution function (PDF) set, incorporating dedicated hadronization routines [39] to produce final states containing R-hadrons.

The cross sections are calculated at next-to-leading order (NLO) in the strong coupling constant including the resummation of soft-gluon emission at next-to-leading-logarithmic accuracy (NLO + NLL) [40–44] and assuming a squark mass of 10 TeV. The nominal cross-section predictions and the uncertainty are taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [45].

Selected events containing R-hadrons undergo a full detector simulation [46], where interactions of R-hadrons with matter are handled by dedicated GEANT4 [47] routines based on the physics model described in Refs. [39,48]. This model assumes, for each light valence quark, a cross section of 12 mb per nucleon and neglects the heavy parton, other than as a reservoir of kinetic energy. This hadronic scattering is described through a purely phase-space-driven approach. The probability for a gluino to form a gluon-gluino bound state is assumed to be 10% [5].

The simulation of samples of metastable gluino-based R-hadrons is performed similarly to the stable R-hadrons. The gluinos within R-hadrons are then required to decay via the process $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, using PYTHIA 6. Gluino masses (m) between 400 and 3000 GeV are simulated, with the neutralino mass fixed to 100 GeV. This benchmark decay mode is chosen as it has the highest sensitivity among those studied in Ref. [16]. Heavier neutralino masses would give lower signal efficiencies, mainly because of the smaller missing transverse momentum available to trigger. The gluino lifetime (τ) is varied from 0.4 to 50 ns.

All simulated samples include a modeling of pileup, adding the expected number of minimum-bias proton-proton interactions from the same (in-time pileup) and nearby (out-of-time pileup) bunch crossings. Simulated events are reconstructed using the software used for the collision data.

To get a more accurate description of radiative effects than PYTHIA 6 provides, additional samples of gluinos are generated for all mass points using MG5_aMC@NLO [49], interfaced to the PYTHIA 8.186 [50] parton shower model, with the A14 [51] set of tuning parameters together with the NNPDF2.3LO [52] PDF set. The distribution of the transverse momentum of the gluino-gluino system simulated with PYTHIA 6 is then reweighted in such a way as to match that obtained in samples simulated with MG5_aMC@NLO. This is especially important for stable R-hadrons as detailed in Sec. VI.

V. SEARCH STRATEGY

This search is based on the signature of R-hadron events containing at least one reconstructed track with large measured $\mathrm{d}E/\mathrm{d}x$ and high transverse momentum (p_{T}). This signature optimizes the search for metastable R-hadrons with lifetimes of $O(\mathrm{ns})$, as the selection requires that the R-hadron only live long enough to traverse the seven layers of the silicon detectors, corresponding to a distance from the beam axis of 37 cm. The search is also sensitive to R-hadrons with longer lifetimes, with a small dependence on the modeling of the interaction of R-hadrons in the calorimeter and muon systems.

The expected production and interaction of R-hadrons in the detector is described in detail in Ref. [53]. In the models studied in this search and described in Sec. IV, pair-produced gluinos hadronize into two colorless R-hadrons with the following charge states: approximately 33% events with two neutral R-hadrons, 47% events with one neutral and one charged R-hadron, and 20% events with two charged R-hadrons. The fragmentation is extremely hard and the R-hadrons are therefore isolated. As massive particles with $\beta < 1$, the charged R-hadrons are expected to deposit more ionization energy in the detector than typical particles of the same momentum. This ionization signature is used both to select signal events, as described in Sec. VI, and to calculate the mass of selected candidates, as described in Sec. III. The estimated candidate mass is used as the final search discriminant.

If the R-hadrons decay before or in the calorimeter, the decay products of R-hadrons in models studied here include quarks, which are identified as jets in the calorimeters (see Sec. VI), and a 100 GeV neutralino, which carries away significant momentum undetected. If R-hadrons traverse the calorimeter without decaying, they are expected to deposit significantly less energy in the calorimeters than SM hadrons of the same momentum, as the heavy parton carries almost all the momentum of the composite particle and limited kinetic energy is available for interactions between the light SM partons and the detector. In the models studied here, over 90% of stable R-hadrons, independent of mass, deposit less than 20 GeV of energy in the calorimeters. However, the electric charge of the R-hadron can change due to the hadronic interactions, even if little energy is lost, and the charge of the R-hadron leaving the calorimeter is expected to be decoupled from the charge at production [53]. As hadronic interactions are rare in the tracking detectors, the probability for an R-hadron to change its electric charge before the calorimeters is only around 3%.

Events are selected by a trigger requiring missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$), calculated from energy deposits in the calorimeter [54]. For events with R-hadrons that decay before or inside the calorimeter, undetected neutralinos contribute to the measured transverse momentum imbalance. As stable R-hadrons deposit little energy in the calorimeters, most stable R-hadron events are selected by the trigger only when QCD initial-state radiation (ISR) boosts the R-hadron pair system. Details of the event selection are given in Sec. VI.

VI. DATA SAMPLE AND EVENT SELECTION

The data sample used for this search was collected while tracking detectors, calorimeters, muon chambers, and magnets were operating normally and corresponds to an integrated luminosity of 3.2 fb^{-1} in 2015. The luminosity measurement was calibrated during dedicated beam-separation scans, using the same methodology as that described in Ref. [55]. The uncertainty in the luminosity measurement is 5%.

Candidate events are selected by an $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger, formed from energy deposits in the calorimeter [54], with a threshold of 70 GeV.

The event selection, described in detail below, was optimized relative to the $\sqrt{s} = 8$ TeV search [16] to improve the sensitivity to events with R-hadrons relative to background events from SM processes. Major improvements include the addition of selections designed to reject tracks from hadrons and electrons, as well as changes to the isolation requirements, which now reject background events from overlapping tracks by identifying clusters in the Pixel or SCT detectors which are consistent with energy deposition from multiple particles. Two signal regions are defined: one targets metastable R-hadrons with shorter lifetimes, and the other is optimized for metastable or stable R-hadrons that are expected to pass through the muon spectrometer before decaying.

A primary vertex reconstructed from at least two well-reconstructed charged-particle tracks, each with $p_{\mathrm{T}} > 400$ MeV, is required in order to remove noncollision background events. If there is more than one such vertex in an event, the primary vertex is defined as the vertex with the largest scalar sum of associated track momentum. To reduce backgrounds from SM processes, events must have $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV, where $E_{\mathrm{T}}^{\mathrm{miss}}$ is the off-line missing transverse momentum. Jets are reconstructed with the anti-k_t algorithm [56] with radius parameter $R = 0.4$ using clusters of energy depositions in the calorimeter as inputs. Events are rejected if they contain a jet with $E_{\mathrm{T}} > 20$ GeV that is consistent with noise contributions as determined based on timing and shower shape information. The off-line $E_{\mathrm{T}}^{\mathrm{miss}}$ is estimated from reconstructed electrons with $|\eta| < 2.47$, reconstructed muons with $|\eta| < 2.5$, calibrated jets with $p_{\mathrm{T}} > 20$ GeV within $|\eta| < 4.5$, and reconstructed tracks which are not associated with other objects and that pass kinematic requirements designed to reject poorly reconstructed tracks.

For signal events, the trigger efficiency varies significantly depending on the model considered. For metastable R-hadrons with a mass of 1000 GeV, decaying into a 100 GeV neutralino and quarks, the trigger efficiency increases from 65% for R-hadrons with a lifetime of 50 ns to 95% for R-hadrons with a lifetime of 0.4 ns. For an R-hadron with a lifetime of 10 ns, the trigger efficiency increases slightly with the R-hadron mass, from 91% for a mass of 1000 GeV to 96% for a mass of 1600 GeV. For stable R-hadrons, the trigger efficiency is approximately 40% for all masses studied. All efficiencies quoted in this section include both the acceptance and the selection efficiency effects.

The off-line $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation includes the momentum of identified muons, which is important to reject background events from SM processes with muons, such as $Z \to \mu\mu$, that pass the calorimetric $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger. For events with metastable R-hadrons, the off-line $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement is very efficient (around 95%) due to the neutralinos in the event. For stable R-hadrons that pass the trigger requirement, the off-line $E_{\mathrm{T}}^{\mathrm{miss}}$ cut is also efficient (around 90%), as the R-hadrons do not deposit significant energy in the calorimeter and in most events the R-hadron pair is boosted from initial-state radiation. Many R-hadrons fail to be identified as muons because they are in a neutral charge state going through either the inner detector or the muon spectrometer. Even if a charged R-hadron with $\beta < 1$ traverses the muon spectrometer, it can fail to be identified by the standard muon reconstruction algorithm as a prompt muon due to its late time of arrival. In a typical R-hadron model considered in this search, only 30% of stable R-hadrons with a reconstructed track in the inner detector are identified as prompt muons entering into the $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation.

Selected events must contain at least one candidate R-hadron track. However, if more than one track in an event passes all requirements, only the highest-p_{T} candidate is considered, in order not to bias the distribution of the variables and to allow for proper normalization of the background estimate.

For a track to be identified as a candidate, it must have $p_{\mathrm{T}} > 50$ GeV and meet the following selection criteria. The track must contain at least seven clusters from silicon detector layers in order to make a good measurement of the track's momentum, must have a cluster in the innermost Pixel layer if expected, and must be associated with the primary vertex. In order to ensure a good ionization measurement, the track must have at least two clusters in the Pixel detector used to measure $\mathrm{d}E/\mathrm{d}x$. These selection requirements on associated clusters are summarized as cluster requirements.

To reject background events with overlapping tracks that could produce clusters with significant measured ionization, the candidate track must not contain any cluster that is compatible with contributions from two or more tracks. This requirement is over 90% efficient for signal events with lifetimes of 3 ns or greater. For background tracks, it lessens the high ionization tail of the distribution from photon conversions and collimated particles, reducing the size of the background and leaving the remaining tracks with a $\mathrm{d}E/\mathrm{d}x$ distribution largely independent of background source. In order to reduce backgrounds from particles inside hadronic jets, the scalar sum of the p_{T} ($\sum p_{\mathrm{T}}$) of other tracks, with $p_{\mathrm{T}} > 1$ GeV and consistent with the primary vertex, in a cone of size $\Delta R < 0.25$, where $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, around the candidate track, must be less than 20 GeV.

The background from SM processes is further reduced by requiring that the candidate track momentum exceeds 150 GeV and that the relative uncertainty on the momentum measurement be less than 50%. The contribution from leptons from W boson decays is reduced by imposing a condition that the transverse mass, m_{T}, built with the candidate track and the $E_{\mathrm{T}}^{\mathrm{miss}}$, be greater than 130 GeV, where

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos(\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{track})))} \qquad (2)$$

and $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{track})$ is the azimuthal separation between the track and the $E_{\mathrm{T}}^{\mathrm{miss}}$. This selection has an efficiency between 78% and 89% for R-hadrons with lifetimes of 3 ns or greater, and reduces the background by roughly a factor of 3.

Background events due to tracks from electrons and hadrons are reduced by requiring that the energy of any jet associated with the candidate track must be less than the candidate track's measured momentum. Jets are associated with tracks if they are within $\Delta R < 0.05$ of the candidate track and have $p_T > 20$ GeV. Background events containing electrons are further reduced by rejecting candidate tracks associated with a jet with 95% or more of its energy deposited in the electromagnetic calorimeter. These selections are found to be 95% efficient for all signal models studied.

Tracks identified as well-reconstructed muons with $p_T >$ 25 GeV are rejected in the search for metastable R-hadrons with lifetimes of 30 ns or less. R-hadrons with a lifetime equal to or greater than 50 ns typically reach the muon spectrometer, and therefore no such veto is applied in the long-lived R-hadron search. To further reject hadronic background in the search for stable R-hadrons, the isolation requirement on the $\sum p_T$ of nearby tracks is tightened from 20 to 5 GeV for candidate R-hadron tracks, eliminating 30% of the remaining expected background.

The specific ionization of the candidate track, as measured by the Pixel detector, must be larger than $1.80 - 0.11|\eta| + 0.17\eta^2 - 0.05|\eta|^3$ MeV g^{-1} cm^{-2}. This requirement corrects the slight (5%) $|\eta|$ dependence of the $\mathrm{d}E/\mathrm{d}x$ measurement [57] while maximizing the expected sensitivity to signal events. This selection is approximately 70%–90% efficient for signal events with lifetimes of 3 ns or greater, depending on the R-hadron mass, and retains less than 1% of background events. Additionally, a time-dependent correction is applied to the ionization measurement in data to account for an observed variation in the charge measurement by the IBL electronics due to effects of radiation. The size of this correction is around 5%.

The observed numbers of events in data and the predicted numbers of simulated signal events, for a 1600 GeV R-hadron with a lifetime of 10 ns, are shown in Table I after each stage of the event selection. The total selection efficiency relative to generated events, which includes both the acceptance and efficiency effects, is also shown for the signal.

VII. SIGNAL SELECTION EFFICIENCY

The overall signal selection efficiency depends on the mass and lifetime of the signal, ranging from about 19% for a 1600 GeV R-hadron with a lifetime of 10 ns to less than 1% for R-hadrons with a lifetime of 0.4 ns. The trigger and off-line E_T^{miss} requirements are more efficient for R-hadrons that decay before or inside the calorimeters. However, as the R-hadron lifetime decreases, the probability of reconstructing the track from the original R-hadron in the silicon detectors decreases. For these two reasons, R-hadrons with lifetimes in the 10–30 ns range have the highest selection efficiency.

The inefficiency for selecting R-hadrons with short lifetimes can be better understood by calculating the selection efficiency relative to a simple fiducial region that separates out acceptance effects due to basic kinematic properties of the R-hadrons. An event is considered to be within the fiducial acceptance if it contains at least one R-hadron that passes the following requirements at Monte Carlo generator level: charged at production, $p_T > 50$ GeV, $p > 150$ GeV, $|\eta| < 2.5$, and transverse decay distance ≥ 37 cm from the origin. With this definition, the acceptance for R-hadron events with a lifetime of 1 ns ranges from 7% for a mass of 600 GeV to 4% for a mass of 1600 GeV. The selection efficiency for R-hadron events in the fiducial region has only a mild dependence on the mass; in the R-hadron mass range from 600 to 1600 GeV, the selection efficiencies are 20% to 25% ($\tau = 1$ ns), 35% to 39% ($\tau = 3$ ns), 39% to 45% ($\tau = 10$ ns), and 31% to 35% ($\tau = 30$ ns), respectively.

Table II summarizes the systematic uncertainties in the predicted signal yields. The systematic uncertainties are calculated and used independently for each mass bin and signal lifetime. In the table, only the maximum uncertainty is quoted.

TABLE I. Expected number of events at different steps of the selection for metastable 1600 GeV gluino R-hadrons decaying with a 10 ns lifetime, along with the number of events observed in data, for 3.2 fb^{-1}. The simulated yields are shown with statistical uncertainties only. The total efficiency × acceptance is also shown in parentheses for the signal.

Selection level	Expected signal events	Observed events in 3.2 fb^{-1}
Generated	26.0 ± 0.3	
E_T^{miss} trigger & preselection	24.8 ± 0.3 (95%)	
$E_T^{\mathrm{miss}} > 130$ GeV	23.9 ± 0.3 (92%)	
Track $p_T > 50$ and cluster requirements	10.7 ± 0.2 (41%)	368324
Isolation requirement	9.0 ± 0.2 (35%)	108079
Track $p > 150$ GeV	6.6 ± 0.2 (25%)	47463
$m_T > 130$ GeV	5.8 ± 0.2 (22%)	18746
Electron & hadron veto	5.5 ± 0.2 (21%)	3612
Muon veto	5.5 ± 0.2 (21%)	1668
Ionization requirement	5.0 ± 0.1 (19%)	11

TABLE II. Systematic uncertainties on the predicted signal yields. The uncertainty depends on the mass and on the lifetime; only the maximum negative and positive values across all signal models (see Sec. IV) are reported here.

Source of uncertainty	−[%]	+[%]
ISR modeling (R-hadron stable)	14	14
ISR modeling (R-hadron metastable)	1.5	1.5
Trigger turn-on	0.9	0.9
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	1.1	2.2
Pileup	1.1	1.1
Ionization parameterization	7.1	0
Momentum parameterization	0.3	0.3
μ identification (metastable only)	3.2	3.2
Total systematic uncertainty in acceptance × efficiency		
Stable R-hadron	16	14
Metastable R-hadron	9	5
Luminosity	5	5
Signal cross section	28	28

The trigger and off-line $E_{\mathrm{T}}^{\mathrm{miss}}$ selections are sensitive to the modeling of ISR in the event, in particular for signal events that do not decay inside the detector volume. Half of the difference between the selection efficiency of the PYTHIA 6 samples and those reweighted with MG5_aMC@NLO is taken as an uncertainty due to radiative effects.

The $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger modeling is studied in a sample of $Z \to \mu\mu$ events and an uncertainty is assigned based on differences between efficiencies measured in data and in simulation. The uncertainty in the $E_{\mathrm{T}}^{\mathrm{miss}}$ calibration comes primarily from uncertainties on the jet energy scale. A systematic uncertainty in the measurement of the Pixel ionization is evaluated by comparing the ionization of an inclusive sample of simulated and observed low-momentum tracks. An asymmetric uncertainty is assigned due to the selection efficiency difference observed after the most probable value of the signal distribution is reweighted based on the comparison of low-momentum tracks between data and simulation. The uncertainty in the signal acceptance is asymmetric since the ionization in simulation is systematically larger than that observed in data and larger at low mass (7.1% at 1000 GeV) than at high mass (2.0% at 1800 GeV). An uncertainty in the efficiency of the muon veto is estimated by studying the modeling of the muon spectrometer's timing measurement: it is 3.2% for the 30 ns samples and negligible for the shorter lifetime samples, as the R-hadrons rarely reach the spectrometer.

The signal selection efficiency is found to be largely independent of the number of pileup events in simulation. However, to cover any remaining difference, efficiency differences from variations in the pileup distributions are accounted for as an additional source of uncertainty. The uncertainty on the momentum scale and resolution of the tracks results in a small uncertainty in the selection efficiency. Variations of the requirements to reject tracks from electrons and hadrons are found to have a negligible effect on the signal efficiency. The theoretical uncertainty in the signal cross section is described in Sec. IV.

VIII. BACKGROUND ESTIMATION

The expected shape and normalization of the mass distribution of background events from SM processes is derived from data. The distributions of key variables are extracted in two control regions in data and these templates are used to generate the expected background distribution in the signal region. The choice of control samples takes into account the measured correlations between the key variables p, $\mathrm{d}E/\mathrm{d}x$ and η, and the control region selections minimize the possible signal contamination. The same regions are used in the searches for stable and metastable particles, except for the rejection of track candidates identified as muons in the latter case and for the tighter track isolation requirement in the former case.

The first control region (hereafter called CR1) is selected by applying all the selections described in Sec. VI, except for the requirement on high ionization, which is inverted. The tracks in this control region are kinematically similar to those in the signal region for SM processes, and the expected p and $\eta(p)$ distributions of tracks from background processes are extracted from this region. The second sample (CR2 hereafter) is selected by inverting the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement ($E_{\mathrm{T}}^{\mathrm{miss}} < 130$ GeV), while keeping all other selections unchanged. As more than 90% of R-hadron events that pass the trigger have $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV, while the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution from SM background processes falls steeply in the range 70–130 GeV, CR2 is background dominated. Tracks from this region are used to derive $\mathrm{d}E/\mathrm{d}x$ templates in bins of η, as $E_{\mathrm{T}}^{\mathrm{miss}}$ and $\mathrm{d}E/\mathrm{d}x$ are uncorrelated for tracks from SM processes. The signal contamination is less than 1% in both control regions for all R-hadron masses and lifetimes considered in this search.

The shape of the background in the signal region is estimated from the control region templates with the following procedure: 1 million $(p, \eta, \mathrm{d}E/\mathrm{d}x)$ triplets are generated, where the momentum is randomly sampled according to the template from CR1 tracks, the pseudorapidity is generated according to the $\eta(p)$-binned templates based on CR1 tracks, and the ionization is sampled according to $\mathrm{d}E/\mathrm{d}x(\eta)$-binned templates from CR2 tracks. This procedure maintains the measured correlations between p, η, and $\mathrm{d}E/\mathrm{d}x$ for tracks from SM sources. The particle mass M is calculated given the predicted $\mathrm{d}E/\mathrm{d}x$ and p values, using the technique explained in Sec. III.

The normalization of the generated background is obtained by scaling the background to the data in the shoulder region of the mass distribution (i.e. $M < 160$ GeV), where a possible signal has already been excluded [16]. The normalization is performed on the samples before the ionization requirement. The expected

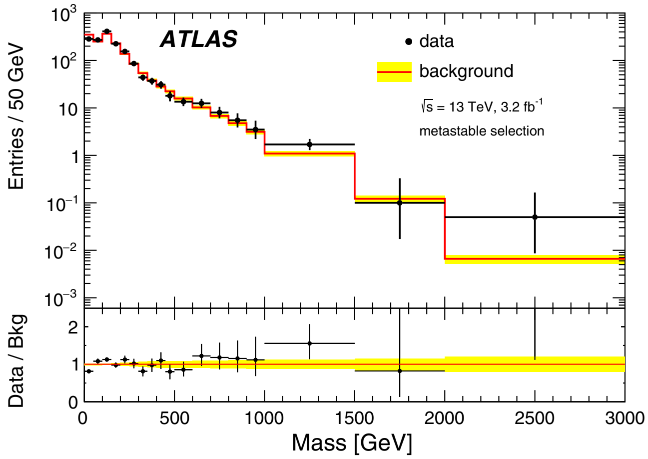

FIG. 3. Expected mass distribution from background events in the signal region for the metastable R-hadrons, before the ionization requirement is imposed. Data are superimposed. The yellow band around the background estimation includes both the statistical and systematic uncertainties. The ratio of data to expected background is shown in the lower panel with statistical uncertainties only.

mass distributions of the background and the observed data, before the ionization requirement, are shown in Fig. 3 for the metastable R-hadrons selection.

Systematic uncertainties in the background estimate are evaluated by varying the relative fraction of muons in the control regions, using an analytical description to vary the shape of the high ionization tail in the $\mathrm{d}E/\mathrm{d}x$ template, and by changing the IBL ionization correction by $\pm 1\sigma$. The statistical uncertainty in the template shape, which is estimated by Poisson fluctuations of the templates, dominates. There is also a small statistical uncertainty from the size of the normalization region. The breakdown of uncertainties in the background estimate is shown in Table III.

The complete procedure is tested on signal-depleted validation regions. The validation regions are selected with the same requirements as for the nominal signal and control regions, but requiring the track momentum to be in the range $50 < p < 150$ GeV. Applied to these validation samples, the procedure described above yields a calculated background of $20.0 \pm 3.0(\mathrm{stat}) \pm 1.2(\mathrm{syst})$ events in the validation region for metastable R-hadrons, while 14 events are observed in the data. For the control region for stable R-hadrons, $28.1 \pm 4.2(\mathrm{stat}) \pm 1.9(\mathrm{syst})$ events are estimated from this procedure and 20 are observed. While the observed numbers of events in the validation regions are lower than predicted, they are consistent with statistical fluctuations at the level of 1.7σ.

TABLE III. Summary table of the uncertainties in the background estimate. The uncertainties are evaluated integrating over the mass windows considered for the signal search (see Sec. IX). If the uncertainty depends on the mass, the largest value is quoted.

Source of uncertainty	[%]
Statistical uncertainty from control region templates	15
Statistical uncertainty from normalization region	3
Analytical description of $\mathrm{d}E/\mathrm{d}x$	4
Particle species composition of CR2	3
IBL ionization correction	4

IX. RESULTS

In data, 16 events are observed for the stable R-hadron selection and 11 are observed for the metastable selection. Table IV summarizes the background estimates with total statistical and systematic uncertainty as well as the observed events for the metastable and stable R-hadron selection. The observed mass distribution in data is shown in Fig. 4 for both selection regions, along with the background expectation.

No evidence of a signal above the background is observed. Expected and observed upper limits on R-hadron production cross sections are evaluated at 95% CL for a discrete set of R-hadron mass values by counting simulated signal, background and observed data events that survive the selection in a $\pm 1.4\sigma$ wide mass window around the position of each simulated signal mass peak for the corresponding mass hypothesis being probed. The peak position and width are estimated by a Gaussian fit to each individual signal mass distribution ($\sigma \approx 280[\approx 500]$ GeV at an R-hadron mass of 1200 [1600] GeV). When the lifetime of the R-hadron is long enough to reach the muon spectrometer, the stable selection becomes more efficient than the metastable one and improves the expected sensitivity. This transition happens around 50 ns. The choice of whether to apply the metastable or stable R-hadron selection to each lifetime is based on the best expected limit. Based on this procedure, the stable selection is applied to both the 50 ns and stable lifetimes.

The cross-section upper limits are extracted, separately for the stable and the metastable searches (in the latter case, for each lifetime value), with the CL_S method [58], using the profile likelihood ratio as a test statistic. In the procedure, the systematic uncertainties in the signal and background yields, as evaluated in Sec. VII and Sec. VIII, are treated as Gaussian-distributed nuisance parameters.

TABLE IV. Estimated number of background events and the number of observed events in data in the final selection regions. The background predictions show both the statistical and systematic uncertainties.

Selection region	Background expected	Data
Metastable R-hadron	$11.1 \pm 1.7 \pm 0.7$	11
Stable R-hadron	$17.2 \pm 2.6 \pm 1.2$	16

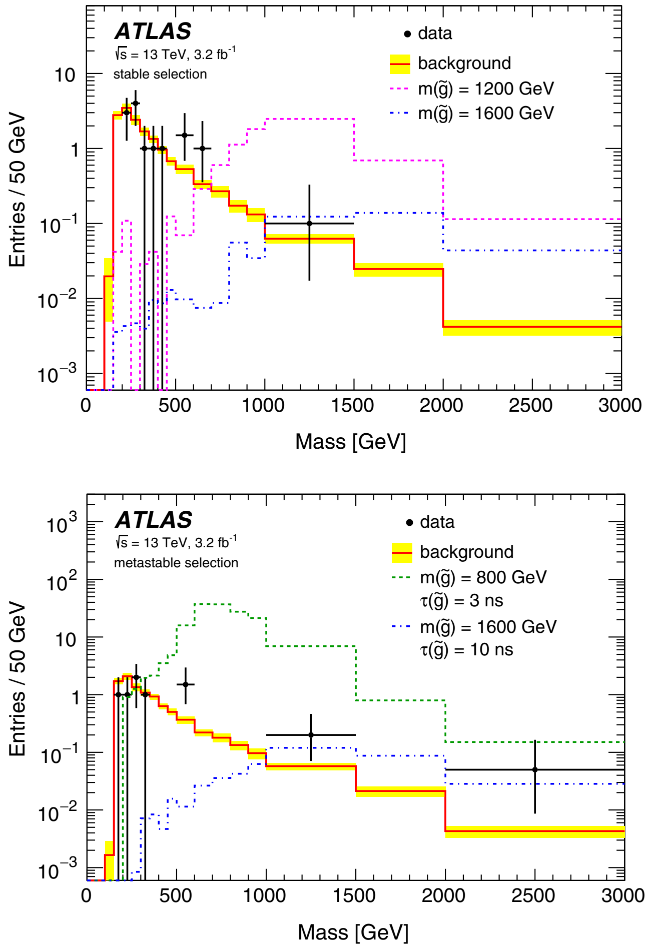

FIG. 4. Mass distribution for data and background for stable (top) and metastable (bottom) particle searches. The yellow band around the background estimation includes both the statistical and systematic uncertainties. Also shown are two examples for signals as expected for gluino R-hadrons in the explored mass range.

The statistical uncertainty in the background distribution also takes into account the uncertainty due to the normalization. Lower limits on the R-hadron mass are then derived, for each lifetime, by comparing the measured cross-section

TABLE V. Observed and expected 95% CL lower limit on mass is listed for gluino R-hadrons that are either stable or decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100$ GeV. The stable selection is more efficient for lifetimes of 50 ns or more.

Selection	τ [ns]	$M_{\rm obs} >$ [GeV]	$M_{\rm exp} >$ [GeV]
Metastable	0.4	740	730
Metastable	1.0	1110	1150
Metastable	3.0	1430	1470
Metastable	10	1570	1600
Metastable	30	1580	1620
Metastable	50	1540	1590
Stable	50	1590	1590
Stable	stable	1570	1580

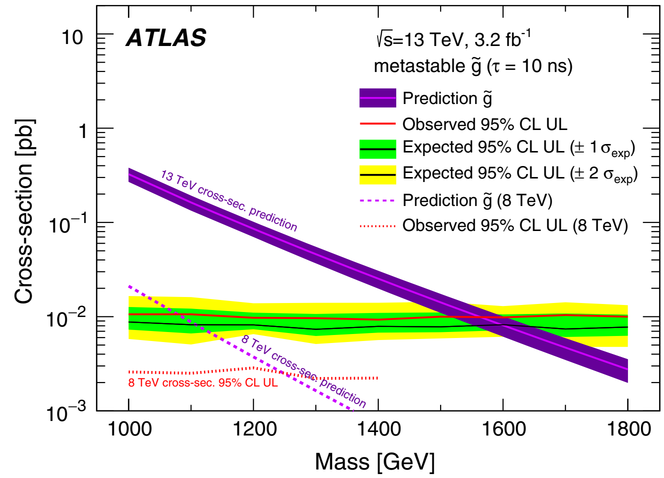

FIG. 5. Cross section as a function of mass for gluino R-hadrons with lifetime $\tau = 10$ ns, decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100$ GeV. Theoretical values for the cross section are shown with their error. The expected upper limits (UL) in the case of background only is shown by the solid black line, with its $\pm 1\sigma$ and $\pm 2\sigma$ bands, green and yellow respectively. The observed 95% UL is shown as a solid red line. The cross section for the same process and the corresponding 95% UL measured at $\sqrt{s} = 8$ TeV [16] are shown as dashed lines.

upper limits to the theoretically predicted production cross section. The resulting lower limits set on the mass of the stable and metastable particles are summarized in Table V.

The strongest mass limits are obtained for lifetimes of 10 ns or more. The cross-section upper limits for 10 ns

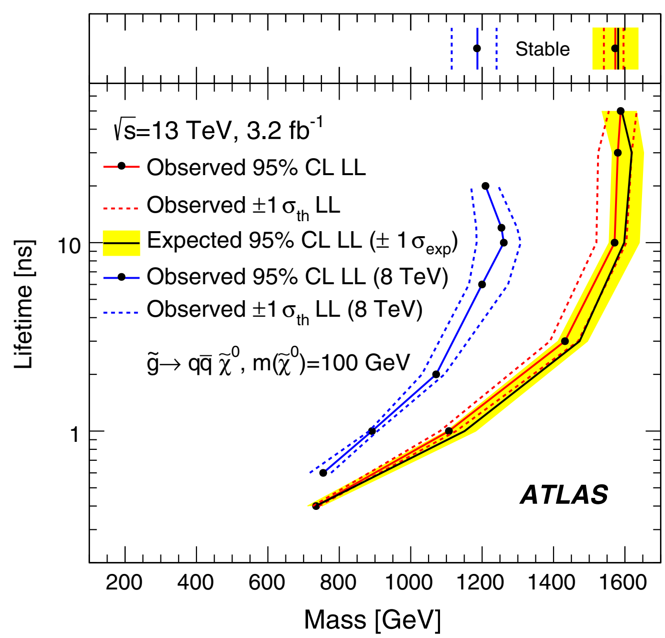

FIG. 6. Excluded range of lifetimes as a function of gluino R-hadron mass. The expected lower limit (LL), with its experimental $\pm 1\sigma$ band, is given with respect to the nominal theoretical cross section. The observed 95% LL obtained at $\sqrt{s} = 8$ TeV [16] is also shown for comparison.

lifetime R-hadrons decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100$ GeV are shown in Fig. 5. For this signal, the expected and observed lower mass limits are 1600 GeV and 1570 GeV, respectively. The 8 TeV result excluded R-hadrons with a 10 ns lifetime and masses up to 1185 GeV, using the lower edge of the $\pm 1\sigma$ band around the theoretical cross section.

The excluded regions on the lifetime-mass plane for R-hadrons decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100$ GeV are shown in Fig. 6.

X. CONCLUSION

This paper presents the results of a search for massive, long-lived particles with lifetimes of $O(\text{ns})$ or longer, produced in 3.2 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV at the LHC, and identified by anomalous specific ionization energy loss in the ATLAS Pixel detector. This analysis takes advantage of the addition of a fourth silicon layer to the Pixel detector, the increased parton luminosity, and analysis improvements to significantly extend a search performed at $\sqrt{s} = 8$ TeV [16]. No excess of events is observed over the background estimate. Gluino R-hadrons with lifetimes above 0.4 ns and decaying to $q\bar{q}$ plus a 100 GeV neutralino are excluded at the 95% confidence level with lower mass limit range between 740 and 1590 GeV. In the case of stable R-hadrons the lower mass limit at the 95% confidence level is 1570 GeV. The observed lower limit on R-hadron masses increases by up to approximately 400 GeV relative to the equivalent analysis at $\sqrt{s} = 8$ TeV.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, U.K.; DOE and NSF, U.S. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, U.K. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (U.S.) and in the Tier-2 facilities worldwide.

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M. Aaboud,[136d] G. Aad,[87] B. Abbott,[114] J. Abdallah,[65] O. Abdinov,[12] B. Abeloos,[118] R. Aben,[108] O. S. AbouZeid,[138] N. L. Abraham,[150] H. Abramowicz,[154] H. Abreu,[153] R. Abreu,[117] Y. Abulaiti,[147a,147b] B. S. Acharya,[164a,164b,b] L. Adamczyk,[40a] D. L. Adams,[27] J. Adelman,[109] S. Adomeit,[101] T. Adye,[132] A. A. Affolder,[76] T. Agatonovic-Jovin,[14] J. Agricola,[56] J. A. Aguilar-Saavedra,[127a,127f] S. P. Ahlen,[24] F. Ahmadov,[67,c] G. Aielli,[134a,134b] H. Akerstedt,[147a,147b] T. P. A. Åkesson,[83] A. V. Akimov,[97] G. L. Alberghi,[22a,22b] J. Albert,[169] S. Albrand,[57] M. J. Alconada Verzini,[73] M. Aleksa,[32] I. N. Aleksandrov,[67] C. Alexa,[28b] G. Alexander,[154] T. Alexopoulos,[10] M. Alhroob,[114] M. Aliev,[75a,75b] G. Alimonti,[93a] J. Alison,[33] S. P. Alkire,[37] B. M. M. Allbrooke,[150] B. W. Allen,[117] P. P. Allport,[19] A. Aloisio,[105a,105b] A. Alonso,[38] F. Alonso,[73] C. Alpigiani,[139] M. Alstaty,[87] B. Alvarez Gonzalez,[32] D. Álvarez Piqueras,[167] M. G. Alviggi,[105a,105b] B. T. Amadio,[16] K. Amako,[68] Y. Amaral Coutinho,[26a] C. Amelung,[25] D. Amidei,[91] S. P. Amor Dos Santos,[127a,127c] A. Amorim,[127a,127b] S. Amoroso,[32] G. Amundsen,[25] C. Anastopoulos,[140] L. S. Ancu,[51] N. Andari,[109] T. Andeen,[11] C. F. Anders,[60b] G. Anders,[32] J. K. Anders,[76] K. J. Anderson,[33] A. Andreazza,[93a,93b] V. Andrei,[60a] S. Angelidakis,[9] I. Angelozzi,[108] P. Anger,[46] A. Angerami,[37] F. Anghinolfi,[32] A. V. Anisenkov,[110,d] N. Anjos,[13] A. Annovi,[125a,125b] M. Antonelli,[49] A. Antonov,[99] F. Anulli,[133a] M. Aoki,[68] L. Aperio Bella,[19] G. Arabidze,[92] Y. Arai,[68] J. P. Araque,[127a] A. T. H. Arce,[47] F. A. Arduh,[73] J-F. Arguin,[96] S. Argyropoulos,[65] M. Arik,[20a] A. J. Armbruster,[144] L. J. Armitage,[78] O. Arnaez,[32] H. Arnold,[50] M. Arratia,[30] O. Arslan,[23] A. Artamonov,[98] G. Artoni,[121] S. Artz,[85] S. Asai,[156] N. Asbah,[44] A. Ashkenazi,[154] B. Åsman,[147a,147b] L. Asquith,[150] K. Assamagan,[27] R. Astalos,[145a] M. Atkinson,[166] N. B. Atlay,[142] K. Augsten,[129] G. Avolio,[32] B. Axen,[16] M. K. Ayoub,[118] G. Azuelos,[96,e] M. A. Baak,[32] A. E. Baas,[60a] M. J. Baca,[19] H. Bachacou,[137] K. Bachas,[75a,75b] M. Backes,[32] M. Backhaus,[32] P. Bagiacchi,[133a,133b] P. Bagnaia,[133a,133b] Y. Bai,[35a] J. T. Baines,[132] O. K. Baker,[176] E. M. Baldin,[110,d] P. Balek,[130] T. Balestri,[149] F. Balli,[137] W. K. Balunas,[123] E. Banas,[41] Sw. Banerjee,[173,f] A. A. E. Bannoura,[175] L. Barak,[32] E. L. Barberio,[90] D. Barberis,[52a,52b] M. Barbero,[87] T. Barillari,[102] T. Barklow,[144] N. Barlow,[30] S. L. Barnes,[86] B. M. Barnett,[132] R. M. Barnett,[16] Z. Barnovska,[5] A. Baroncelli,[135a] G. Barone,[25] A. J. Barr,[121] L. Barranco Navarro,[167] F. Barreiro,[84] J. Barreiro Guimarães da Costa,[35a] R. Bartoldus,[144] A. E. Barton,[74] P. Bartos,[145a] A. Basalaev,[124] A. Bassalat,[118] R. L. Bates,[55] S. J. Batista,[159] J. R. Batley,[30] M. Battaglia,[138] M. Bauce,[133a,133b] F. Bauer,[137] H. S. Bawa,[144,g] J. B. Beacham,[112] M. D. Beattie,[74] T. Beau,[82] P. H. Beauchemin,[162] P. Bechtle,[23] H. P. Beck,[18,h] K. Becker,[121] M. Becker,[85] M. Beckingham,[170] C. Becot,[111] A. J. Beddall,[20e] A. Beddall,[20b] V. A. Bednyakov,[67] M. Bedognetti,[108] C. P. Bee,[149] L. J. Beemster,[108] T. A. Beermann,[32] M. Begel,[27] J. K. Behr,[44] C. Belanger-Champagne,[89] A. S. Bell,[80] G. Bella,[154] L. Bellagamba,[22a] A. Bellerive,[31] M. Bellomo,[88] K. Belotskiy,[99] O. Beltramello,[32] N. L. Belyaev,[99] O. Benary,[154] D. Benchekroun,[136a] M. Bender,[101] K. Bendtz,[147a,147b] N. Benekos,[10] Y. Benhammou,[154] E. Benhar Noccioli,[176] J. Benitez,[65] D. P. Benjamin,[47] J. R. Bensinger,[25] S. Bentvelsen,[108] L. Beresford,[121] M. Beretta,[49] D. Berge,[108] E. Bergeaas Kuutmann,[165] N. Berger,[5] J. Beringer,[16] S. Berlendis,[57] N. R. Bernard,[88] C. Bernius,[111] F. U. Bernlochner,[23] T. Berry,[79] P. Berta,[130] C. Bertella,[85] G. Bertoli,[147a,147b] F. Bertolucci,[125a,125b] I. A. Bertram,[74] C. Bertsche,[44] D. Bertsche,[114] G. J. Besjes,[38] O. Bessidskaia Bylund,[147a,147b] M. Bessner,[44] N. Besson,[137] C. Betancourt,[50] S. Bethke,[102] A. J. Bevan,[78] W. Bhimji,[16] R. M. Bianchi,[126] L. Bianchini,[25] M. Bianco,[32] O. Biebel,[101] D. Biedermann,[17] R. Bielski,[86] N. V. Biesuz,[125a,125b] M. Biglietti,[135a] J. Bilbao De Mendizabal,[51] H. Bilokon,[49] M. Bindi,[56] S. Binet,[118] A. Bingul,[20b] C. Bini,[133a,133b] S. Biondi,[22a,22b] D. M. Bjergaard,[47] C. W. Black,[151] J. E. Black,[144] K. M. Black,[24] D. Blackburn,[139] R. E. Blair,[6] J.-B. Blanchard,[137] J. E. Blanco,[79] T. Blazek,[145a] I. Bloch,[44] C. Blocker,[25] W. Blum,[85,a] U. Blumenschein,[56] S. Blunier,[34a] G. J. Bobbink,[108] V. S. Bobrovnikov,[110,d] S. S. Bocchetta,[83] A. Bocci,[47] C. Bock,[101] M. Boehler,[50] D. Boerner,[175] J. A. Bogaerts,[32] D. Bogavac,[14] A. G. Bogdanchikov,[110] C. Bohm,[147a] V. Boisvert,[79]

P. Bokan,[14] T. Bold,[40a] A. S. Boldyrev,[164a,164c] M. Bomben,[82] M. Bona,[78] M. Boonekamp,[137] A. Borisov,[131] G. Borissov,[74] J. Bortfeldt,[101] D. Bortoletto,[121] V. Bortolotto,[62a,62b,62c] K. Bos,[108] D. Boscherini,[22a] M. Bosman,[13] J. D. Bossio Sola,[29] J. Boudreau,[126] J. Bouffard,[2] E. V. Bouhova-Thacker,[74] D. Boumediene,[36] C. Bourdarios,[118] S. K. Boutle,[55] A. Boveia,[32] J. Boyd,[32] I. R. Boyko,[67] J. Bracinik,[19] A. Brandt,[8] G. Brandt,[56] O. Brandt,[60a] U. Bratzler,[157] B. Brau,[88] J. E. Brau,[117] H. M. Braun,[175,a] W. D. Breaden Madden,[55] K. Brendlinger,[123] A. J. Brennan,[90] L. Brenner,[108] R. Brenner,[165] S. Bressler,[172] T. M. Bristow,[48] D. Britton,[55] D. Britzger,[44] F. M. Brochu,[30] I. Brock,[23] R. Brock,[92] G. Brooijmans,[37] T. Brooks,[79] W. K. Brooks,[34b] J. Brosamer,[16] E. Brost,[117] J.H Broughton,[19] P. A. Bruckman de Renstrom,[41] D. Bruncko,[145b] R. Bruneliere,[50] A. Bruni,[22a] G. Bruni,[22a] BH Brunt,[30] M. Bruschi,[22a] N. Bruscino,[23] P. Bryant,[33] L. Bryngemark,[83] T. Buanes,[15] Q. Buat,[143] P. Buchholz,[142] A. G. Buckley,[55] I. A. Budagov,[67] F. Buehrer,[50] M. K. Bugge,[120] O. Bulekov,[99] D. Bullock,[8] H. Burckhart,[32] S. Burdin,[76] C. D. Burgard,[50] B. Burghgrave,[109] K. Burka,[41] S. Burke,[132] I. Burmeister,[45] E. Busato,[36] D. Büscher,[50] V. Büscher,[85] P. Bussey,[55] J. M. Butler,[24] C. M. Buttar,[55] J. M. Butterworth,[80] P. Butti,[108] W. Buttinger,[27] A. Buzatu,[55] A. R. Buzykaev,[110,d] S. Cabrera Urbán,[167] D. Caforio,[129] V. M. Cairo,[39a,39b] O. Cakir,[4a] N. Calace,[51] P. Calafiura,[16] A. Calandri,[87] G. Calderini,[82] P. Calfayan,[101] L. P. Caloba,[26a] D. Calvet,[36] S. Calvet,[36] T. P. Calvet,[87] R. Camacho Toro,[33] S. Camarda,[32] P. Camarri,[134a,134b] D. Cameron,[120] R. Caminal Armadans,[166] C. Camincher,[57] S. Campana,[32] M. Campanelli,[80] A. Camplani,[93a,93b] A. Campoverde,[149] V. Canale,[105a,105b] A. Canepa,[160a] M. Cano Bret,[35e] J. Cantero,[115] R. Cantrill,[127a] T. Cao,[42] M. D. M. Capeans Garrido,[32] I. Caprini,[28b] M. Caprini,[28b] M. Capua,[39a,39b] R. Caputo,[85] R. M. Carbone,[37] R. Cardarelli,[134a] F. Cardillo,[50] I. Carli,[130] T. Carli,[32] G. Carlino,[105a] L. Carminati,[93a,93b] S. Caron,[107] E. Carquin,[34b] G. D. Carrillo-Montoya,[32] J. R. Carter,[30] J. Carvalho,[127a,127c] D. Casadei,[19] M. P. Casado,[13,i] M. Casolino,[13] D. W. Casper,[163] E. Castaneda-Miranda,[146a] R. Castelijn,[108] A. Castelli,[108] V. Castillo Gimenez,[167] N. F. Castro,[127a,j] A. Catinaccio,[32] J. R. Catmore,[120] A. Cattai,[32] J. Caudron,[85] V. Cavaliere,[166] E. Cavallaro,[13] D. Cavalli,[93a] M. Cavalli-Sforza,[13] V. Cavasinni,[125a,125b] F. Ceradini,[135a,135b] L. Cerda Alberich,[167] B. C. Cerio,[47] A. S. Cerqueira,[26b] A. Cerri,[150] L. Cerrito,[78] F. Cerutti,[16] M. Cerv,[32] A. Cervelli,[18] S. A. Cetin,[20d] A. Chafaq,[136a] D. Chakraborty,[109] S. K. Chan,[59] Y. L. Chan,[62a] P. Chang,[166] J. D. Chapman,[30] D. G. Charlton,[19] A. Chatterjee,[51] C. C. Chau,[159] C. A. Chavez Barajas,[150] S. Che,[112] S. Cheatham,[74] A. Chegwidden,[92] S. Chekanov,[6] S. V. Chekulaev,[160a] G. A. Chelkov,[67,k] M. A. Chelstowska,[91] C. Chen,[66] H. Chen,[27] K. Chen,[149] S. Chen,[35c] S. Chen,[156] X. Chen,[35f] Y. Chen,[69] H. C. Cheng,[91] H.J Cheng,[35a] Y. Cheng,[33] A. Cheplakov,[67] E. Cheremushkina,[131] R. Cherkaoui El Moursli,[136e] V. Chernyatin,[27,a] E. Cheu,[7] L. Chevalier,[137] V. Chiarella,[49] G. Chiarelli,[125a,125b] G. Chiodini,[75a] A. S. Chisholm,[19] A. Chitan,[28b] M. V. Chizhov,[67] K. Choi,[63] A. R. Chomont,[36] S. Chouridou,[9] B. K. B. Chow,[101] V. Christodoulou,[80] D. Chromek-Burckhart,[32] J. Chudoba,[128] A. J. Chuinard,[89] J. J. Chwastowski,[41] L. Chytka,[116] G. Ciapetti,[133a,133b] A. K. Ciftci,[4a] D. Cinca,[55] V. Cindro,[77] I. A. Cioara,[23] A. Ciocio,[16] F. Cirotto,[105a,105b] Z. H. Citron,[172] M. Citterio,[93a] M. Ciubancan,[28b] A. Clark,[51] B. L. Clark,[59] M. R. Clark,[37] P. J. Clark,[48] R. N. Clarke,[16] C. Clement,[147a,147b] Y. Coadou,[87] M. Cobal,[164a,164c] A. Coccaro,[51] J. Cochran,[66] L. Coffey,[25] L. Colasurdo,[107] B. Cole,[37] A. P. Colijn,[108] J. Collot,[57] T. Colombo,[32] G. Compostella,[102] P. Conde Muiño,[127a,127b] E. Coniavitis,[50] S. H. Connell,[146b] I. A. Connelly,[79] V. Consorti,[50] S. Constantinescu,[28b] G. Conti,[32] F. Conventi,[105a,l] M. Cooke,[16] B. D. Cooper,[80] A. M. Cooper-Sarkar,[121] K. J. R. Cormier,[159] T. Cornelissen,[175] M. Corradi,[133a,133b] F. Corriveau,[89,m] A. Corso-Radu,[163] A. Cortes-Gonzalez,[13] G. Cortiana,[102] G. Costa,[93a] M. J. Costa,[167] D. Costanzo,[140] G. Cottin,[30] G. Cowan,[79] B. E. Cox,[86] K. Cranmer,[111] S. J. Crawley,[55] G. Cree,[31] S. Crépé-Renaudin,[57] F. Crescioli,[82] W. A. Cribbs,[147a,147b] M. Crispin Ortuzar,[121] M. Cristinziani,[23] V. Croft,[107] G. Crosetti,[39a,39b] T. Cuhadar Donszelmann,[140] J. Cummings,[176] M. Curatolo,[49] J. Cúth,[85] C. Cuthbert,[151] H. Czirr,[142] P. Czodrowski,[3] G. D'amen,[22a,22b] S. D'Auria,[55] M. D'Onofrio,[76] M. J. Da Cunha Sargedas De Sousa,[127a,127b] C. Da Via,[86] W. Dabrowski,[40a] T. Dado,[145a] T. Dai,[91] O. Dale,[15] F. Dallaire,[96] C. Dallapiccola,[88] M. Dam,[38] J. R. Dandoy,[33] N. P. Dang,[50] A. C. Daniells,[19] N. S. Dann,[86] M. Danninger,[168] M. Dano Hoffmann,[137] V. Dao,[50] G. Darbo,[52a] S. Darmora,[8] J. Dassoulas,[3] A. Dattagupta,[63] W. Davey,[23] C. David,[169] T. Davidek,[130] M. Davies,[154] P. Davison,[80] E. Dawe,[90] I. Dawson,[140] R. K. Daya-Ishmukhametova,[88] K. De,[8] R. de Asmundis,[105a] A. De Benedetti,[114] S. De Castro,[22a,22b] S. De Cecco,[82] N. De Groot,[107] P. de Jong,[108] H. De la Torre,[84] F. De Lorenzi,[66] A. De Maria,[56] D. De Pedis,[133a] A. De Salvo,[133a] U. De Sanctis,[150] A. De Santo,[150] J. B. De Vivie De Regie,[118] W. J. Dearnaley,[74] R. Debbe,[27] C. Debenedetti,[138] D. V. Dedovich,[67] N. Dehghanian,[3] I. Deigaard,[108] M. Del Gaudio,[39a,39b] J. Del Peso,[84] T. Del Prete,[125a,125b] D. Delgove,[118] F. Deliot,[137] C. M. Delitzsch,[51] M. Deliyergiyev,[77] A. Dell'Acqua,[32] L. Dell'Asta,[24] M. Dell'Orso,[125a,125b] M. Della Pietra,[105a,l] D. della Volpe,[51] M. Delmastro,[5] P. A. Delsart,[57] C. Deluca,[108] D. A. DeMarco,[159] S. Demers,[176] M. Demichev,[67] A. Demilly,[82]

S. P. Denisov,[131] D. Denysiuk,[137] D. Derendarz,[41] J. E. Derkaoui,[136d] F. Derue,[82] P. Dervan,[76] K. Desch,[23] C. Deterre,[44] K. Dette,[45] P. O. Deviveiros,[32] A. Dewhurst,[132] S. Dhaliwal,[25] A. Di Ciaccio,[134a,134b] L. Di Ciaccio,[5] W. K. Di Clemente,[123] C. Di Donato,[133a,133b] A. Di Girolamo,[32] B. Di Girolamo,[32] B. Di Micco,[135a,135b] R. Di Nardo,[32] A. Di Simone,[50] R. Di Sipio,[159] D. Di Valentino,[31] C. Diaconu,[87] M. Diamond,[159] F. A. Dias,[48] M. A. Diaz,[34a] E. B. Diehl,[91] J. Dietrich,[17] S. Diglio,[87] A. Dimitrievska,[14] J. Dingfelder,[23] P. Dita,[28b] S. Dita,[28b] F. Dittus,[32] F. Djama,[87] T. Djobava,[53b] J. I. Djuvsland,[60a] M. A. B. do Vale,[26c] D. Dobos,[32] M. Dobre,[28b] C. Doglioni,[83] T. Dohmae,[156] J. Dolejsi,[130] Z. Dolezal,[130] B. A. Dolgoshein,[99,a] M. Donadelli,[26d] S. Donati,[125a,125b] P. Dondero,[122a,122b] J. Donini,[36] J. Dopke,[132] A. Doria,[105a] M. T. Dova,[73] A. T. Doyle,[55] E. Drechsler,[56] M. Dris,[10] Y. Du,[35d] J. Duarte-Campderros,[154] E. Duchovni,[172] G. Duckeck,[101] O. A. Ducu,[96,n] D. Duda,[108] A. Dudarev,[32] E. M. Duffield,[16] L. Duflot,[118] L. Duguid,[79] M. Dührssen,[32] M. Dumancic,[172] M. Dunford,[60a] H. Duran Yildiz,[4a] M. Düren,[54] A. Durglishvili,[53b] D. Duschinger,[46] B. Dutta,[44] M. Dyndal,[44] C. Eckardt,[44] K. M. Ecker,[102] R. C. Edgar,[91] N. C. Edwards,[48] T. Eifert,[32] G. Eigen,[15] K. Einsweiler,[16] T. Ekelof,[165] M. El Kacimi,[136c] V. Ellajosyula,[87] M. Ellert,[165] S. Elles,[5] F. Ellinghaus,[175] A. A. Elliot,[169] N. Ellis,[32] J. Elmsheuser,[27] M. Elsing,[32] D. Emeliyanov,[132] Y. Enari,[156] O. C. Endner,[85] M. Endo,[119] J. S. Ennis,[170] J. Erdmann,[45] A. Ereditato,[18] G. Ernis,[175] J. Ernst,[2] M. Ernst,[27] S. Errede,[166] E. Ertel,[85] M. Escalier,[118] H. Esch,[45] C. Escobar,[126] B. Esposito,[49] A. I. Etienvre,[137] E. Etzion,[154] H. Evans,[63] A. Ezhilov,[124] F. Fabbri,[22a,22b] L. Fabbri,[22a,22b] G. Facini,[33] R. M. Fakhrutdinov,[131] S. Falciano,[133a] R. J. Falla,[80] J. Faltova,[130] Y. Fang,[35a] M. Fanti,[93a,93b] A. Farbin,[8] A. Farilla,[135a] C. Farina,[126] T. Farooque,[13] S. Farrell,[16] S. M. Farrington,[170] P. Farthouat,[32] F. Fassi,[136e] P. Fassnacht,[32] D. Fassouliotis,[9] M. Faucci Giannelli,[79] A. Favareto,[52a,52b] W. J. Fawcett,[121] L. Fayard,[118] O. L. Fedin,[124,o] W. Fedorko,[168] S. Feigl,[120] L. Feligioni,[87] C. Feng,[35d] E. J. Feng,[32] H. Feng,[91] A. B. Fenyuk,[131] L. Feremenga,[8] P. Fernandez Martinez,[167] S. Fernandez Perez,[13] J. Ferrando,[55] A. Ferrari,[165] P. Ferrari,[108] R. Ferrari,[122a] D. E. Ferreira de Lima,[60b] A. Ferrer,[167] D. Ferrere,[51] C. Ferretti,[91] A. Ferretto Parodi,[52a,52b] F. Fiedler,[85] A. Filipčič,[77] M. Filipuzzi,[44] F. Filthaut,[107] M. Fincke-Keeler,[169] K. D. Finelli,[151] M. C. N. Fiolhais,[127a,127c] L. Fiorini,[167] A. Firan,[42] A. Fischer,[2] C. Fischer,[13] J. Fischer,[175] W. C. Fisher,[92] N. Flaschel,[44] I. Fleck,[142] P. Fleischmann,[91] G. T. Fletcher,[140] R. R. M. Fletcher,[123] T. Flick,[175] A. Floderus,[83] L. R. Flores Castillo,[62a] M. J. Flowerdew,[102] G. T. Forcolin,[86] A. Formica,[137] A. Forti,[86] A. G. Foster,[19] D. Fournier,[118] H. Fox,[74] S. Fracchia,[13] P. Francavilla,[82] M. Franchini,[22a,22b] D. Francis,[32] L. Franconi,[120] M. Franklin,[59] M. Frate,[163] M. Fraternali,[122a,122b] D. Freeborn,[80] S. M. Fressard-Batraneanu,[32] F. Friedrich,[46] D. Froidevaux,[32] J. A. Frost,[121] C. Fukunaga,[157] E. Fullana Torregrosa,[85] T. Fusayasu,[103] J. Fuster,[167] C. Gabaldon,[57] O. Gabizon,[175] A. Gabrielli,[22a,22b] A. Gabrielli,[16] G. P. Gach,[40a] S. Gadatsch,[32] S. Gadomski,[51] G. Gagliardi,[52a,52b] L. G. Gagnon,[96] P. Gagnon,[63] C. Galea,[107] B. Galhardo,[127a,127c] E. J. Gallas,[121] B. J. Gallop,[132] P. Gallus,[129] G. Galster,[38] K. K. Gan,[112] J. Gao,[35b,87] Y. Gao,[48] Y. S. Gao,[144,g] F. M. Garay Walls,[48] C. García,[167] J. E. García Navarro,[167] M. Garcia-Sciveres,[16] R. W. Gardner,[33] N. Garelli,[144] V. Garonne,[120] A. Gascon Bravo,[44] C. Gatti,[49] A. Gaudiello,[52a,52b] G. Gaudio,[122a] B. Gaur,[142] L. Gauthier,[96] I. L. Gavrilenko,[97] C. Gay,[168] G. Gaycken,[23] E. N. Gazis,[10] Z. Gecse,[168] C. N. P. Gee,[132] Ch. Geich-Gimbel,[23] M. Geisen,[85] M. P. Geisler,[60a] C. Gemme,[52a] M. H. Genest,[57] C. Geng,[35b,p] S. Gentile,[133a,133b] S. George,[79] D. Gerbaudo,[13] A. Gershon,[154] S. Ghasemi,[142] H. Ghazlane,[136b] M. Ghneimat,[23] B. Giacobbe,[22a] S. Giagu,[133a,133b] P. Giannetti,[125a,125b] B. Gibbard,[27] S. M. Gibson,[79] M. Gignac,[168] M. Gilchriese,[16] T. P. S. Gillam,[30] D. Gillberg,[31] G. Gilles,[175] D. M. Gingrich,[3,e] N. Giokaris,[9] M. P. Giordani,[164a,164c] F. M. Giorgi,[22a] F. M. Giorgi,[17] P. F. Giraud,[137] P. Giromini,[59] D. Giugni,[93a] F. Giuli,[121] C. Giuliani,[102] M. Giulini,[60b] B. K. Gjelsten,[120] S. Gkaitatzis,[155] I. Gkialas,[155] E. L. Gkougkousis,[118] L. K. Gladilin,[100] C. Glasman,[84] J. Glatzer,[32] P. C. F. Glaysher,[48] A. Glazov,[44] M. Goblirsch-Kolb,[102] J. Godlewski,[41] S. Goldfarb,[91] T. Golling,[51] D. Golubkov,[131] A. Gomes,[127a,127b,127d] R. Gonçalo,[127a] J. Goncalves Pinto Firmino Da Costa,[137] G. Gonella,[50] L. Gonella,[19] A. Gongadze,[67] S. González de la Hoz,[167] G. Gonzalez Parra,[13] S. Gonzalez-Sevilla,[51] L. Goossens,[32] P. A. Gorbounov,[98] H. A. Gordon,[27] I. Gorelov,[106] B. Gorini,[32] E. Gorini,[75a,75b] A. Gorišek,[77] E. Gornicki,[41] A. T. Goshaw,[47] C. Gössling,[45] M. I. Gostkin,[67] C. R. Goudet,[118] D. Goujdami,[136c] A. G. Goussiou,[139] N. Govender,[146b,q] E. Gozani,[153] L. Graber,[56] I. Grabowska-Bold,[40a] P. O. J. Gradin,[57] P. Grafström,[22a,22b] J. Gramling,[51] E. Gramstad,[120] S. Grancagnolo,[17] V. Gratchev,[124] P. M. Gravila,[28e] H. M. Gray,[32] E. Graziani,[135a] Z. D. Greenwood,[81,r] C. Grefe,[23] K. Gregersen,[80] I. M. Gregor,[44] P. Grenier,[144] K. Grevtsov,[5] J. Griffiths,[8] A. A. Grillo,[138] K. Grimm,[74] S. Grinstein,[13,s] Ph. Gris,[36] J.-F. Grivaz,[118] S. Groh,[85] J. P. Grohs,[46] E. Gross,[172] J. Grosse-Knetter,[56] G. C. Grossi,[81] Z. J. Grout,[150] L. Guan,[91] W. Guan,[173] J. Guenther,[129] F. Guescini,[51] D. Guest,[163] O. Gueta,[154] E. Guido,[52a,52b] T. Guillemin,[5] S. Guindon,[2] U. Gul,[55] C. Gumpert,[32] J. Guo,[35e] Y. Guo,[35b,p] S. Gupta,[121] G. Gustavino,[133a,133b] P. Gutierrez,[114] N. G. Gutierrez Ortiz,[80] C. Gutschow,[46] C. Guyot,[137] C. Gwenlan,[121] C. B. Gwilliam,[76] A. Haas,[111] C. Haber,[16] H. K. Hadavand,[8] N. Haddad,[136e]

A. Hadef,[87] P. Haefner,[23] S. Hageböck,[23] Z. Hajduk,[41] H. Hakobyan,[177,a] M. Haleem,[44] J. Haley,[115] G. Halladjian,[92] G. D. Hallewell,[87] K. Hamacher,[175] P. Hamal,[116] K. Hamano,[169] A. Hamilton,[146a] G. N. Hamity,[140] P. G. Hamnett,[44] L. Han,[35b] K. Hanagaki,[68,t] K. Hanawa,[156] M. Hance,[138] B. Haney,[123] P. Hanke,[60a] R. Hanna,[137] J. B. Hansen,[38] J. D. Hansen,[38] M. C. Hansen,[23] P. H. Hansen,[38] K. Hara,[161] A. S. Hard,[173] T. Harenberg,[175] F. Hariri,[118] S. Harkusha,[94] R. D. Harrington,[48] P. F. Harrison,[170] F. Hartjes,[108] N. M. Hartmann,[101] M. Hasegawa,[69] Y. Hasegawa,[141] A. Hasib,[114] S. Hassani,[137] S. Haug,[18] R. Hauser,[92] L. Hauswald,[46] M. Havranek,[128] C. M. Hawkes,[19] R. J. Hawkings,[32] D. Hayden,[92] C. P. Hays,[121] J. M. Hays,[78] H. S. Hayward,[76] S. J. Haywood,[132] S. J. Head,[19] T. Heck,[85] V. Hedberg,[83] L. Heelan,[8] S. Heim,[123] T. Heim,[16] B. Heinemann,[16] J. J. Heinrich,[101] L. Heinrich,[111] C. Heinz,[54] J. Hejbal,[128] L. Helary,[24] S. Hellman,[147a,147b] C. Helsens,[32] J. Henderson,[121] R. C. W. Henderson,[74] Y. Heng,[173] S. Henkelmann,[168] A. M. Henriques Correia,[32] S. Henrot-Versille,[118] G. H. Herbert,[17] Y. Hernández Jiménez,[167] G. Herten,[50] R. Hertenberger,[101] L. Hervas,[32] G. G. Hesketh,[80] N. P. Hessey,[108] J. W. Hetherly,[42] R. Hickling,[78] E. Higón-Rodriguez,[167] E. Hill,[169] J. C. Hill,[30] K. H. Hiller,[44] S. J. Hillier,[19] I. Hinchliffe,[16] E. Hines,[123] R. R. Hinman,[16] M. Hirose,[158] D. Hirschbuehl,[175] J. Hobbs,[149] N. Hod,[160a] M. C. Hodgkinson,[140] P. Hodgson,[140] A. Hoecker,[32] M. R. Hoeferkamp,[106] F. Hoenig,[101] D. Hohn,[23] T. R. Holmes,[16] M. Homann,[45] T. M. Hong,[126] B. H. Hooberman,[166] W. H. Hopkins,[117] Y. Horii,[104] A. J. Horton,[143] J-Y. Hostachy,[57] S. Hou,[152] A. Hoummada,[136a] J. Howarth,[44] M. Hrabovsky,[116] I. Hristova,[17] J. Hrivnac,[118] T. Hryn'ova,[5] A. Hrynevich,[95] C. Hsu,[146c] P. J. Hsu,[152,u] S.-C. Hsu,[139] D. Hu,[37] Q. Hu,[35b] Y. Huang,[44] Z. Hubacek,[129] F. Hubaut,[87] F. Huegging,[23] T. B. Huffman,[121] E. W. Hughes,[37] G. Hughes,[74] M. Huhtinen,[32] T. A. Hülsing,[85] P. Huo,[149] N. Huseynov,[67,c] J. Huston,[92] J. Huth,[59] G. Iacobucci,[51] G. Iakovidis,[27] I. Ibragimov,[142] L. Iconomidou-Fayard,[118] E. Ideal,[176] Z. Idrissi,[136e] P. Iengo,[32] O. Igonkina,[108,v] T. Iizawa,[171] Y. Ikegami,[68] M. Ikeno,[68] Y. Ilchenko,[11,w] D. Iliadis,[155] N. Ilic,[144] T. Ince,[102] G. Introzzi,[122a,122b] P. Ioannou,[9,a] M. Iodice,[135a] K. Iordanidou,[37] V. Ippolito,[59] M. Ishino,[70] M. Ishitsuka,[158] R. Ishmukhametov,[112] C. Issever,[121] S. Istin,[20a] F. Ito,[161] J. M. Iturbe Ponce,[86] R. Iuppa,[134a,134b] W. Iwanski,[41] H. Iwasaki,[68] J. M. Izen,[43] V. Izzo,[105a] S. Jabbar,[3] B. Jackson,[123] M. Jackson,[76] P. Jackson,[1] V. Jain,[2] K. B. Jakobi,[85] K. Jakobs,[50] S. Jakobsen,[32] T. Jakoubek,[128] D. O. Jamin,[115] D. K. Jana,[81] E. Jansen,[80] R. Jansky,[64] J. Janssen,[23] M. Janus,[56] G. Jarlskog,[83] N. Javadov,[67,c] T. Javůrek,[50] F. Jeanneau,[137] L. Jeanty,[16] J. Jejelava,[53a,x] G.-Y. Jeng,[151] D. Jennens,[90] P. Jenni,[50,y] J. Jentzsch,[45] C. Jeske,[170] S. Jézéquel,[5] H. Ji,[173] J. Jia,[149] H. Jiang,[66] Y. Jiang,[35b] S. Jiggins,[80] J. Jimenez Pena,[167] S. Jin,[35a] A. Jinaru,[28b] O. Jinnouchi,[158] P. Johansson,[140] K. A. Johns,[7] W. J. Johnson,[139] K. Jon-And,[147a,147b] G. Jones,[170] R. W. L. Jones,[74] S. Jones,[7] T. J. Jones,[76] J. Jongmanns,[60a] P. M. Jorge,[127a,127b] J. Jovicevic,[160a] X. Ju,[173] A. Juste Rozas,[13,s] M. K. Köhler,[172] A. Kaczmarska,[41] M. Kado,[118] H. Kagan,[112] M. Kagan,[144] S. J. Kahn,[87] E. Kajomovitz,[47] C. W. Kalderon,[121] A. Kaluza,[85] S. Kama,[42] A. Kamenshchikov,[131] N. Kanaya,[156] S. Kaneti,[30] L. Kanjir,[77] V. A. Kantserov,[99] J. Kanzaki,[68] B. Kaplan,[111] L. S. Kaplan,[173] A. Kapliy,[33] D. Kar,[146c] K. Karakostas,[10] A. Karamaoun,[3] N. Karastathis,[10] M. J. Kareem,[56] E. Karentzos,[10] M. Karnevskiy,[85] S. N. Karpov,[67] Z. M. Karpova,[67] K. Karthik,[111] V. Kartvelishvili,[74] A. N. Karyukhin,[131] K. Kasahara,[161] L. Kashif,[173] R. D. Kass,[112] A. Kastanas,[15] Y. Kataoka,[156] C. Kato,[156] A. Katre,[51] J. Katzy,[44] K. Kawagoe,[72] T. Kawamoto,[156] G. Kawamura,[56] S. Kazama,[156] V. F. Kazanin,[110,d] R. Keeler,[169] R. Kehoe,[42] J. S. Keller,[44] J. J. Kempster,[79] K Kentaro,[104] H. Keoshkerian,[159] O. Kepka,[128] B. P. Kerševan,[77] S. Kersten,[175] R. A. Keyes,[89] F. Khalil-zada,[12] A. Khanov,[115] A. G. Kharlamov,[110,d] T. J. Khoo,[51] V. Khovanskiy,[98] E. Khramov,[67] J. Khubua,[53b,z] S. Kido,[69] H. Y. Kim,[8] S. H. Kim,[161] Y. K. Kim,[33] N. Kimura,[155] O. M. Kind,[17] B. T. King,[76] M. King,[167] S. B. King,[168] J. Kirk,[132] A. E. Kiryunin,[102] T. Kishimoto,[69] D. Kisielewska,[40a] F. Kiss,[50] K. Kiuchi,[161] O. Kivernyk,[137] E. Kladiva,[145b] M. H. Klein,[37] M. Klein,[76] U. Klein,[76] K. Kleinknecht,[85] P. Klimek,[147a,147b] A. Klimentov,[27] R. Klingenberg,[45] J. A. Klinger,[140] T. Klioutchnikova,[32] E.-E. Kluge,[60a] P. Kluit,[108] S. Kluth,[102] J. Knapik,[41] E. Kneringer,[64] E. B. F. G. Knoops,[87] A. Knue,[55] A. Kobayashi,[156] D. Kobayashi,[158] T. Kobayashi,[156] M. Kobel,[46] M. Kocian,[144] P. Kodys,[130] T. Koffas,[31] E. Koffeman,[108] T. Koi,[144] H. Kolanoski,[17] M. Kolb,[60b] I. Koletsou,[5] A. A. Komar,[97,a] Y. Komori,[156] T. Kondo,[68] N. Kondrashova,[44] K. Köneke,[50] A. C. König,[107] T. Kono,[68,aa] R. Konoplich,[111,bb] N. Konstantinidis,[80] R. Kopeliansky,[63] S. Koperny,[40a] L. Köpke,[85] A. K. Kopp,[50] K. Korcyl,[41] K. Kordas,[155] A. Korn,[80] A. A. Korol,[110,d] I. Korolkov,[13] E. V. Korolkova,[140] O. Kortner,[102] S. Kortner,[102] T. Kosek,[130] V. V. Kostyukhin,[23] A. Kotwal,[47] A. Kourkoumeli-Charalampidi,[155] C. Kourkoumelis,[9] V. Kouskoura,[27] A. B. Kowalewska,[41] R. Kowalewski,[169] T. Z. Kowalski,[40a] C. Kozakai,[156] W. Kozanecki,[137] A. S. Kozhin,[131] V. A. Kramarenko,[100] G. Kramberger,[77] D. Krasnopevtsev,[99] M. W. Krasny,[82] A. Krasznahorkay,[32] J. K. Kraus,[23] A. Kravchenko,[27] M. Kretz,[60c] J. Kretzschmar,[76] K. Kreutzfeldt,[54] P. Krieger,[159] K. Krizka,[33] K. Kroeninger,[45] H. Kroha,[102] J. Kroll,[123] J. Kroseberg,[23] J. Krstic,[14] U. Kruchonak,[67] H. Krüger,[23] N. Krumnack,[66] A. Kruse,[173] M. C. Kruse,[47]

M. Kruskal,[24] T. Kubota,[90] H. Kucuk,[80] S. Kuday,[4b] J. T. Kuechler,[175] S. Kuehn,[50] A. Kugel,[60c] F. Kuger,[174] A. Kuhl,[138] T. Kuhl,[44] V. Kukhtin,[67] R. Kukla,[137] Y. Kulchitsky,[94] S. Kuleshov,[34b] M. Kuna,[133a,133b] T. Kunigo,[70] A. Kupco,[128] H. Kurashige,[69] Y. A. Kurochkin,[94] V. Kus,[128] E. S. Kuwertz,[169] M. Kuze,[158] J. Kvita,[116] T. Kwan,[169] D. Kyriazopoulos,[140] A. La Rosa,[102] J. L. La Rosa Navarro,[26d] L. La Rotonda,[39a,39b] C. Lacasta,[167] F. Lacava,[133a,133b] J. Lacey,[31] H. Lacker,[17] D. Lacour,[82] V. R. Lacuesta,[167] E. Ladygin,[67] R. Lafaye,[5] B. Laforge,[82] T. Lagouri,[176] S. Lai,[56] S. Lammers,[63] W. Lampl,[7] E. Lançon,[137] U. Landgraf,[50] M. P. J. Landon,[78] V. S. Lang,[60a] J. C. Lange,[13] A. J. Lankford,[163] F. Lanni,[27] K. Lantzsch,[23] A. Lanza,[122a] S. Laplace,[82] C. Lapoire,[32] J. F. Laporte,[137] T. Lari,[93a] F. Lasagni Manghi,[22a,22b] M. Lassnig,[32] P. Laurelli,[49] W. Lavrijsen,[16] A. T. Law,[138] P. Laycock,[76] T. Lazovich,[59] M. Lazzaroni,[93a,93b] B. Le,[90] O. Le Dortz,[82] E. Le Guirriec,[87] E. P. Le Quilleuc,[137] M. LeBlanc,[169] T. LeCompte,[6] F. Ledroit-Guillon,[57] C. A. Lee,[27] S. C. Lee,[152] L. Lee,[1] G. Lefebvre,[82] M. Lefebvre,[169] F. Legger,[101] C. Leggett,[16] A. Lehan,[76] G. Lehmann Miotto,[32] X. Lei,[7] W. A. Leight,[31] A. Leisos,[155,cc] A. G. Leister,[176] M. A. L. Leite,[26d] R. Leitner,[130] D. Lellouch,[172] B. Lemmer,[56] K. J. C. Leney,[80] T. Lenz,[23] B. Lenzi,[32] R. Leone,[7] S. Leone,[125a,125b] C. Leonidopoulos,[48] S. Leontsinis,[10] G. Lerner,[150] C. Leroy,[96] A. A. J. Lesage,[137] C. G. Lester,[30] M. Levchenko,[124] J. Levêque,[5] D. Levin,[91] L. J. Levinson,[172] M. Levy,[19] D. Lewis,[78] A. M. Leyko,[23] M. Leyton,[43] B. Li,[35b,p] H. Li,[149] H. L. Li,[33] L. Li,[47] L. Li,[35e] Q. Li,[35a] S. Li,[47] X. Li,[86] Y. Li,[142] Z. Liang,[35a] B. Liberti,[134a] A. Liblong,[159] P. Lichard,[32] K. Lie,[166] J. Liebal,[23] W. Liebig,[15] A. Limosani,[151] S. C. Lin,[152,dd] T. H. Lin,[85] B. E. Lindquist,[149] A. E. Lionti,[51] E. Lipeles,[123] A. Lipniacka,[15] M. Lisovyi,[60b] T. M. Liss,[166] A. Lister,[168] A. M. Litke,[138] B. Liu,[152,ee] D. Liu,[152] H. Liu,[91] H. Liu,[27] J. Liu,[87] J. B. Liu,[35b] K. Liu,[87] L. Liu,[166] M. Liu,[47] M. Liu,[35b] Y. L. Liu,[35b] Y. Liu,[35b] M. Livan,[122a,122b] A. Lleres,[57] J. Llorente Merino,[35a] S. L. Lloyd,[78] F. Lo Sterzo,[152] E. Lobodzinska,[44] P. Loch,[7] W. S. Lockman,[138] F. K. Loebinger,[86] A. E. Loevschall-Jensen,[38] K. M. Loew,[25] A. Loginov,[176] T. Lohse,[17] K. Lohwasser,[44] M. Lokajicek,[128] B. A. Long,[24] J. D. Long,[166] R. E. Long,[74] L. Longo,[75a,75b] K. A. Looper,[112] L. Lopes,[127a] D. Lopez Mateos,[59] B. Lopez Paredes,[140] I. Lopez Paz,[13] A. Lopez Solis,[82] J. Lorenz,[101] N. Lorenzo Martinez,[63] M. Losada,[21] P. J. Lösel,[101] X. Lou,[35a] A. Lounis,[118] J. Love,[6] P. A. Love,[74] H. Lu,[62a] N. Lu,[91] H. J. Lubatti,[139] C. Luci,[133a,133b] A. Lucotte,[57] C. Luedtke,[50] F. Luehring,[63] W. Lukas,[64] L. Luminari,[133a] O. Lundberg,[147a,147b] B. Lund-Jensen,[148] P. M. Luzi,[82] D. Lynn,[27] R. Lysak,[128] E. Lytken,[83] V. Lyubushkin,[67] H. Ma,[27] L. L. Ma,[35d] Y. Ma,[35d] G. Maccarrone,[49] A. Macchiolo,[102] C. M. Macdonald,[140] B. Maček,[77] J. Machado Miguens,[123,127b] D. Madaffari,[87] R. Madar,[36] H. J. Maddocks,[165] W. F. Mader,[46] A. Madsen,[44] J. Maeda,[69] S. Maeland,[15] T. Maeno,[27] A. Maevskiy,[100] E. Magradze,[56] J. Mahlstedt,[108] C. Maiani,[118] C. Maidantchik,[26a] A. A. Maier,[102] T. Maier,[101] A. Maio,[127a,127b,127d] S. Majewski,[117] Y. Makida,[68] N. Makovec,[118] B. Malaescu,[82] Pa. Malecki,[41] V. P. Maleev,[124] F. Malek,[57] U. Mallik,[65] D. Malon,[6] C. Malone,[144] S. Maltezos,[10] S. Malyukov,[32] J. Mamuzic,[167] G. Mancini,[49] B. Mandelli,[32] L. Mandelli,[93a] I. Mandić,[77] J. Maneira,[127a,127b] L. Manhaes de Andrade Filho,[26b] J. Manjarres Ramos,[160b] A. Mann,[101] A. Manousos,[32] B. Mansoulie,[137] J. D. Mansour,[35a] R. Mantifel,[89] M. Mantoani,[56] S. Manzoni,[93a,93b] L. Mapelli,[32] G. Marceca,[29] L. March,[51] G. Marchiori,[82] M. Marcisovsky,[128] M. Marjanovic,[14] D. E. Marley,[91] F. Marroquim,[26a] S. P. Marsden,[86] Z. Marshall,[16] S. Marti-Garcia,[167] B. Martin,[92] T. A. Martin,[170] V. J. Martin,[48] B. Martin dit Latour,[15] M. Martinez,[13,s] S. Martin-Haugh,[132] V. S. Martoiu,[28b] A. C. Martyniuk,[80] M. Marx,[139] A. Marzin,[32] L. Masetti,[85] T. Mashimo,[156] R. Mashinistov,[97] J. Masik,[86] A. L. Maslennikov,[110,d] I. Massa,[22a,22b] L. Massa,[22a,22b] P. Mastrandrea,[5] A. Mastroberardino,[39a,39b] T. Masubuchi,[156] P. Mättig,[175] J. Mattmann,[85] J. Maurer,[28b] S. J. Maxfield,[76] D. A. Maximov,[110,d] R. Mazini,[152] S. M. Mazza,[93a,93b] N. C. Mc Fadden,[106] G. Mc Goldrick,[159] S. P. Mc Kee,[91] A. McCarn,[91] R. L. McCarthy,[149] T. G. McCarthy,[102] L. I. McClymont,[80] E. F. McDonald,[90] K. W. McFarlane,[58,a] J. A. Mcfayden,[80] G. Mchedlidze,[56] S. J. McMahon,[132] R. A. McPherson,[169,m] M. Medinnis,[44] S. Meehan,[139] S. Mehlhase,[101] A. Mehta,[76] K. Meier,[60a] C. Meineck,[101] B. Meirose,[43] D. Melini,[167] B. R. Mellado Garcia,[146c] M. Melo,[145a] F. Meloni,[18] A. Mengarelli,[22a,22b] S. Menke,[102] E. Meoni,[162] S. Mergelmeyer,[17] P. Mermod,[51] L. Merola,[105a,105b] C. Meroni,[93a] F. S. Merritt,[33] A. Messina,[133a,133b] J. Metcalfe,[6] A. S. Mete,[163] C. Meyer,[85] C. Meyer,[123] J-P. Meyer,[137] J. Meyer,[108] H. Meyer Zu Theenhausen,[60a] F. Miano,[150] R. P. Middleton,[132] S. Miglioranzi,[52a,52b] L. Mijović,[23] G. Mikenberg,[172] M. Mikestikova,[128] M. Mikuž,[77] M. Milesi,[90] A. Milic,[64] D. W. Miller,[33] C. Mills,[48] A. Milov,[172] D. A. Milstead,[147a,147b] A. A. Minaenko,[131] Y. Minami,[156] I. A. Minashvili,[67] A. I. Mincer,[111] B. Mindur,[40a] M. Mineev,[67] Y. Ming,[173] L. M. Mir,[13] K. P. Mistry,[123] T. Mitani,[171] J. Mitrevski,[101] V. A. Mitsou,[167] A. Miucci,[51] P. S. Miyagawa,[140] J. U. Mjörnmark,[83] T. Moa,[147a,147b] K. Mochizuki,[96] S. Mohapatra,[37] S. Molander,[147a,147b] R. Moles-Valls,[23] R. Monden,[70] M. C. Mondragon,[92] K. Mönig,[44] J. Monk,[38] E. Monnier,[87] A. Montalbano,[149] J. Montejo Berlingen,[32] F. Monticelli,[73] S. Monzani,[93a,93b] R. W. Moore,[3] N. Morange,[118] D. Moreno,[21] M. Moreno Llácer,[56] P. Morettini,[52a] D. Mori,[143] T. Mori,[156] M. Morii,[59] M. Morinaga,[156] V. Morisbak,[120] S. Moritz,[85] A. K. Morley,[151] G. Mornacchi,[32] J. D. Morris,[78]

S. S. Mortensen,[38] L. Morvaj,[149] M. Mosidze,[53b] J. Moss,[144] K. Motohashi,[158] R. Mount,[144] E. Mountricha,[27] S. V. Mouraviev,[97,a] E. J. W. Moyse,[88] S. Muanza,[87] R. D. Mudd,[19] F. Mueller,[102] J. Mueller,[126] R. S. P. Mueller,[101] T. Mueller,[30] D. Muenstermann,[74] P. Mullen,[55] G. A. Mullier,[18] F. J. Munoz Sanchez,[86] J. A. Murillo Quijada,[19] W. J. Murray,[170,132] H. Musheghyan,[56] M. Muškinja,[77] A. G. Myagkov,[131,ff] M. Myska,[129] B. P. Nachman,[144] O. Nackenhorst,[51] K. Nagai,[121] R. Nagai,[68,aa] K. Nagano,[68] Y. Nagasaka,[61] K. Nagata,[161] M. Nagel,[50] E. Nagy,[87] A. M. Nairz,[32] Y. Nakahama,[32] K. Nakamura,[68] T. Nakamura,[156] I. Nakano,[113] H. Namasivayam,[43] R. F. Naranjo Garcia,[44] R. Narayan,[11] D. I. Narrias Villar,[60a] I. Naryshkin,[124] T. Naumann,[44] G. Navarro,[21] R. Nayyar,[7] H. A. Neal,[91] P. Yu. Nechaeva,[97] T. J. Neep,[86] P. D. Nef,[144] A. Negri,[122a,122b] M. Negrini,[22a] S. Nektarijevic,[107] C. Nellist,[118] A. Nelson,[163] S. Nemecek,[128] P. Nemethy,[111] A. A. Nepomuceno,[26a] M. Nessi,[32,gg] M. S. Neubauer,[166] M. Neumann,[175] R. M. Neves,[111] P. Nevski,[27] P. R. Newman,[19] D. H. Nguyen,[6] T. Nguyen Manh,[96] R. B. Nickerson,[121] R. Nicolaidou,[137] J. Nielsen,[138] A. Nikiforov,[17] V. Nikolaenko,[131,ff] I. Nikolic-Audit,[82] K. Nikolopoulos,[19] J. K. Nilsen,[120] P. Nilsson,[27] Y. Ninomiya,[156] A. Nisati,[133a] R. Nisius,[102] T. Nobe,[156] L. Nodulman,[6] M. Nomachi,[119] I. Nomidis,[31] T. Nooney,[78] S. Norberg,[114] M. Nordberg,[32] N. Norjoharuddeen,[121] O. Novgorodova,[46] S. Nowak,[102] M. Nozaki,[68] L. Nozka,[116] K. Ntekas,[10] E. Nurse,[80] F. Nuti,[90] F. O'grady,[7] D. C. O'Neil,[143] A. A. O'Rourke,[44] V. O'Shea,[55] F. G. Oakham,[31,e] H. Oberlack,[102] T. Obermann,[23] J. Ocariz,[82] A. Ochi,[69] I. Ochoa,[37] J. P. Ochoa-Ricoux,[34a] S. Oda,[72] S. Odaka,[68] H. Ogren,[63] A. Oh,[86] S. H. Oh,[47] C. C. Ohm,[16] H. Ohman,[165] H. Oide,[32] H. Okawa,[161] Y. Okumura,[33] T. Okuyama,[68] A. Olariu,[28b] L. F. Oleiro Seabra,[127a] S. A. Olivares Pino,[48] D. Oliveira Damazio,[27] A. Olszewski,[41] J. Olszowska,[41] A. Onofre,[127a,127e] K. Onogi,[104] P. U. E. Onyisi,[11,w] M. J. Oreglia,[33] Y. Oren,[154] D. Orestano,[135a,135b] N. Orlando,[62b] R. S. Orr,[159] B. Osculati,[52a,52b] R. Ospanov,[86] G. Otero y Garzon,[29] H. Otono,[72] M. Ouchrif,[136d] F. Ould-Saada,[120] A. Ouraou,[137] K. P. Oussoren,[108] Q. Ouyang,[35a] M. Owen,[55] R. E. Owen,[19] V. E. Ozcan,[20a] N. Ozturk,[8] K. Pachal,[143] A. Pacheco Pages,[13] C. Padilla Aranda,[13] M. Pagáčová,[50] S. Pagan Griso,[16] F. Paige,[27] P. Pais,[88] K. Pajchel,[120] G. Palacino,[160b] S. Palestini,[32] M. Palka,[40b] D. Pallin,[36] A. Palma,[127a,127b] E. St. Panagiotopoulou,[10] C. E. Pandini,[82] J. G. Panduro Vazquez,[79] P. Pani,[147a,147b] S. Panitkin,[27] D. Pantea,[28b] L. Paolozzi,[51] Th. D. Papadopoulou,[10] K. Papageorgiou,[155] A. Paramonov,[6] D. Paredes Hernandez,[176] A. J. Parker,[74] M. A. Parker,[30] K. A. Parker,[140] F. Parodi,[52a,52b] J. A. Parsons,[37] U. Parzefall,[50] V. R. Pascuzzi,[159] E. Pasqualucci,[133a] S. Passaggio,[52a] Fr. Pastore,[79] G. Pásztor,[31,hh] S. Pataraia,[175] J. R. Pater,[86] T. Pauly,[32] J. Pearce,[169] B. Pearson,[114] L. E. Pedersen,[38] M. Pedersen,[120] S. Pedraza Lopez,[167] R. Pedro,[127a,127b] S. V. Peleganchuk,[110,d] D. Pelikan,[165] O. Penc,[128] C. Peng,[35a] H. Peng,[35b] J. Penwell,[63] B. S. Peralva,[26b] M. M. Perego,[137] D. V. Perepelitsa,[27] E. Perez Codina,[160a] L. Perini,[93a,93b] H. Pernegger,[32] S. Perrella,[105a,105b] R. Peschke,[44] V. D. Peshekhonov,[67] K. Peters,[44] R. F. Y. Peters,[86] B. A. Petersen,[32] T. C. Petersen,[38] E. Petit,[57] A. Petridis,[1] C. Petridou,[155] P. Petroff,[118] E. Petrolo,[133a] M. Petrov,[121] F. Petrucci,[135a,135b] N. E. Pettersson,[88] A. Peyaud,[137] R. Pezoa,[34b] P. W. Phillips,[132] G. Piacquadio,[144] E. Pianori,[170] A. Picazio,[88] E. Piccaro,[78] M. Piccinini,[22a,22b] M. A. Pickering,[121] R. Piegaia,[29] J. E. Pilcher,[33] A. D. Pilkington,[86] A. W. J. Pin,[86] M. Pinamonti,[164a,164c,ii] J. L. Pinfold,[3] A. Pingel,[38] S. Pires,[82] H. Pirumov,[44] M. Pitt,[172] L. Plazak,[145a] M.-A. Pleier,[27] V. Pleskot,[85] E. Plotnikova,[67] P. Plucinski,[92] D. Pluth,[66] R. Poettgen,[147a,147b] L. Poggioli,[118] D. Pohl,[23] G. Polesello,[122a] A. Poley,[44] A. Policicchio,[39a,39b] R. Polifka,[159] A. Polini,[22a] C. S. Pollard,[55] V. Polychronakos,[27] K. Pommès,[32] L. Pontecorvo,[133a] B. G. Pope,[92] G. A. Popeneciu,[28c] D. S. Popovic,[14] A. Poppleton,[32] S. Pospisil,[129] K. Potamianos,[16] I. N. Potrap,[67] C. J. Potter,[30] C. T. Potter,[117] G. Poulard,[32] J. Poveda,[32] V. Pozdnyakov,[67] M. E. Pozo Astigarraga,[32] P. Pralavorio,[87] A. Pranko,[16] S. Prell,[66] D. Price,[86] L. E. Price,[6] M. Primavera,[75a] S. Prince,[89] M. Proissl,[48] K. Prokofiev,[62c] F. Prokoshin,[34b] S. Protopopescu,[27] J. Proudfoot,[6] M. Przybycien,[40a] D. Puddu,[135a,135b] M. Purohit,[27,jj] P. Puzo,[118] J. Qian,[91] G. Qin,[55] Y. Qin,[86] A. Quadt,[56] W. B. Quayle,[164a,164b] M. Queitsch-Maitland,[86] D. Quilty,[55] S. Raddum,[120] V. Radeka,[27] V. Radescu,[60b] S. K. Radhakrishnan,[149] P. Radloff,[117] P. Rados,[90] F. Ragusa,[93a,93b] G. Rahal,[178] J. A. Raine,[86] S. Rajagopalan,[27] M. Rammensee,[32] C. Rangel-Smith,[165] M. G. Ratti,[93a,93b] F. Rauscher,[101] S. Rave,[85] T. Ravenscroft,[55] I. Ravinovich,[172] M. Raymond,[32] A. L. Read,[120] N. P. Readioff,[76] M. Reale,[75a,75b] D. M. Rebuzzi,[122a,122b] A. Redelbach,[174] G. Redlinger,[27] R. Reece,[138] K. Reeves,[43] L. Rehnisch,[17] J. Reichert,[123] H. Reisin,[29] C. Rembser,[32] H. Ren,[35a] M. Rescigno,[133a] S. Resconi,[93a] O. L. Rezanova,[110,d] P. Reznicek,[130] R. Rezvani,[96] R. Richter,[102] S. Richter,[80] E. Richter-Was,[40b] O. Ricken,[23] M. Ridel,[82] P. Rieck,[17] C. J. Riegel,[175] J. Rieger,[56] O. Rifki,[114] M. Rijssenbeek,[149] A. Rimoldi,[122a,122b] M. Rimoldi,[18] L. Rinaldi,[22a] B. Ristić,[51] E. Ritsch,[32] I. Riu,[13] F. Rizatdinova,[115] E. Rizvi,[78] C. Rizzi,[13] S. H. Robertson,[89,m] A. Robichaud-Veronneau,[89] D. Robinson,[30] J. E. M. Robinson,[44] A. Robson,[55] C. Roda,[125a,125b] Y. Rodina,[87] A. Rodriguez Perez,[13] D. Rodriguez Rodriguez,[167] S. Roe,[32] C. S. Rogan,[59] O. Røhne,[120] A. Romaniouk,[99] M. Romano,[22a,22b] S. M. Romano Saez,[36] E. Romero Adam,[167] N. Rompotis,[139] M. Ronzani,[50] L. Roos,[82]

E. Ros,[167] S. Rosati,[133a] K. Rosbach,[50] P. Rose,[138] O. Rosenthal,[142] N.-A. Rosien,[56] V. Rossetti,[147a,147b] E. Rossi,[105a,105b] L. P. Rossi,[52a] J. H. N. Rosten,[30] R. Rosten,[139] M. Rotaru,[28b] I. Roth,[172] J. Rothberg,[139] D. Rousseau,[118] C. R. Royon,[137] A. Rozanov,[87] Y. Rozen,[153] X. Ruan,[146c] F. Rubbo,[144] M. S. Rudolph,[159] F. Rühr,[50] A. Ruiz-Martinez,[31] Z. Rurikova,[50] N. A. Rusakovich,[67] A. Ruschke,[101] H. L. Russell,[139] J. P. Rutherfoord,[7] N. Ruthmann,[32] Y. F. Ryabov,[124] M. Rybar,[166] G. Rybkin,[118] S. Ryu,[6] A. Ryzhov,[131] G. F. Rzehorz,[56] A. F. Saavedra,[151] G. Sabato,[108] S. Sacerdoti,[29] H. F-W. Sadrozinski,[138] R. Sadykov,[67] F. Safai Tehrani,[133a] P. Saha,[109] M. Sahinsoy,[60a] M. Saimpert,[137] T. Saito,[156] H. Sakamoto,[156] Y. Sakurai,[171] G. Salamanna,[135a,135b] A. Salamon,[134a,134b] J. E. Salazar Loyola,[34b] D. Salek,[108] P. H. Sales De Bruin,[139] D. Salihagic,[102] A. Salnikov,[144] J. Salt,[167] D. Salvatore,[39a,39b] F. Salvatore,[150] A. Salvucci,[62a] A. Salzburger,[32] D. Sammel,[50] D. Sampsonidis,[155] A. Sanchez,[105a,105b] J. Sánchez,[167] V. Sanchez Martinez,[167] H. Sandaker,[120] R. L. Sandbach,[78] H. G. Sander,[85] M. Sandhoff,[175] C. Sandoval,[21] R. Sandstroem,[102] D. P. C. Sankey,[132] M. Sannino,[52a,52b] A. Sansoni,[49] C. Santoni,[36] R. Santonico,[134a,134b] H. Santos,[127a] I. Santoyo Castillo,[150] K. Sapp,[126] A. Sapronov,[67] J. G. Saraiva,[127a,127d] B. Sarrazin,[23] O. Sasaki,[68] Y. Sasaki,[156] K. Sato,[161] G. Sauvage,[5,a] E. Sauvan,[5] G. Savage,[79] P. Savard,[159,e] C. Sawyer,[132] L. Sawyer,[81,r] J. Saxon,[33] C. Sbarra,[22a] A. Sbrizzi,[22a,22b] T. Scanlon,[80] D. A. Scannicchio,[163] M. Scarcella,[151] V. Scarfone,[39a,39b] J. Schaarschmidt,[172] P. Schacht,[102] B. M. Schachtner,[101] D. Schaefer,[32] R. Schaefer,[44] J. Schaeffer,[85] S. Schaepe,[23] S. Schaetzel,[60b] U. Schäfer,[85] A. C. Schaffer,[118] D. Schaile,[101] R. D. Schamberger,[149] V. Scharf,[60a] V. A. Schegelsky,[124] D. Scheirich,[130] M. Schernau,[163] C. Schiavi,[52a,52b] S. Schier,[138] C. Schillo,[50] M. Schioppa,[39a,39b] S. Schlenker,[32] K. R. Schmidt-Sommerfeld,[102] K. Schmieden,[32] C. Schmitt,[85] S. Schmitt,[44] S. Schmitz,[85] B. Schneider,[160a] U. Schnoor,[50] L. Schoeffel,[137] A. Schoening,[60b] B. D. Schoenrock,[92] E. Schopf,[23] M. Schott,[85] J. Schovancova,[8] S. Schramm,[51] M. Schreyer,[174] N. Schuh,[85] M. J. Schultens,[23] H.-C. Schultz-Coulon,[60a] H. Schulz,[17] M. Schumacher,[50] B. A. Schumm,[138] Ph. Schune,[137] A. Schwartzman,[144] T. A. Schwarz,[91] Ph. Schwegler,[102] H. Schweiger,[86] Ph. Schwemling,[137] R. Schwienhorst,[92] J. Schwindling,[137] T. Schwindt,[23] G. Sciolla,[25] F. Scuri,[125a,125b] F. Scutti,[90] J. Searcy,[91] P. Seema,[23] S. C. Seidel,[106] A. Seiden,[138] F. Seifert,[129] J. M. Seixas,[26a] G. Sekhniaidze,[105a] K. Sekhon,[91] S. J. Sekula,[42] D. M. Seliverstov,[124,a] N. Semprini-Cesari,[22a,22b] C. Serfon,[120] L. Serin,[118] L. Serkin,[164a,164b] M. Sessa,[135a,135b] R. Seuster,[169] H. Severini,[114] T. Sfiligoj,[77] F. Sforza,[32] A. Sfyrla,[51] E. Shabalina,[56] N. W. Shaikh,[147a,147b] L. Y. Shan,[35a] R. Shang,[166] J. T. Shank,[24] M. Shapiro,[16] P. B. Shatalov,[98] K. Shaw,[164a,164b] S. M. Shaw,[86] A. Shcherbakova,[147a,147b] C. Y. Shehu,[150] P. Sherwood,[80] L. Shi,[152,kk] S. Shimizu,[69] C. O. Shimmin,[163] M. Shimojima,[103] M. Shiyakova,[67,ll] A. Shmeleva,[97] D. Shoaleh Saadi,[96] M. J. Shochet,[33] S. Shojaii,[93a,93b] S. Shrestha,[112] E. Shulga,[99] M. A. Shupe,[7] P. Sicho,[128] A. M. Sickles,[166] P. E. Sidebo,[148] O. Sidiropoulou,[174] D. Sidorov,[115] A. Sidoti,[22a,22b] F. Siegert,[46] Dj. Sijacki,[14] J. Silva,[127a,127d] S. B. Silverstein,[147a] V. Simak,[129] O. Simard,[5] Lj. Simic,[14] S. Simion,[118] E. Simioni,[85] B. Simmons,[80] D. Simon,[36] M. Simon,[85] P. Sinervo,[159] N. B. Sinev,[117] M. Sioli,[22a,22b] G. Siragusa,[174] S. Yu. Sivoklokov,[100] J. Sjölin,[147a,147b] T. B. Sjursen,[15] M. B. Skinner,[74] H. P. Skottowe,[59] P. Skubic,[114] M. Slater,[19] T. Slavicek,[129] M. Slawinska,[108] K. Sliwa,[162] R. Slovak,[130] V. Smakhtin,[172] B. H. Smart,[5] L. Smestad,[15] J. Smiesko,[145a] S. Yu. Smirnov,[99] Y. Smirnov,[99] L. N. Smirnova,[100,mm] O. Smirnova,[83] M. N. K. Smith,[37] R. W. Smith,[37] M. Smizanska,[74] K. Smolek,[129] A. A. Snesarev,[97] S. Snyder,[27] R. Sobie,[169,m] F. Socher,[46] A. Soffer,[154] D. A. Soh,[152] G. Sokhrannyi,[77] C. A. Solans Sanchez,[32] M. Solar,[129] E. Yu. Soldatov,[99] U. Soldevila,[167] A. A. Solodkov,[131] A. Soloshenko,[67] O. V. Solovyanov,[131] V. Solovyev,[124] P. Sommer,[50] H. Son,[162] H. Y. Song,[35b,nn] A. Sood,[16] A. Sopczak,[129] V. Sopko,[129] V. Sorin,[13] D. Sosa,[60b] C. L. Sotiropoulou,[125a,125b] R. Soualah,[164a,164c] A. M. Soukharev,[110,d] D. South,[44] B. C. Sowden,[79] S. Spagnolo,[75a,75b] M. Spalla,[125a,125b] M. Spangenberg,[170] F. Spanò,[79] D. Sperlich,[17] F. Spettel,[102] R. Spighi,[22a] G. Spigo,[32] L. A. Spiller,[90] M. Spousta,[130] R. D. St. Denis,[55,a] A. Stabile,[93a] R. Stamen,[60a] S. Stamm,[17] E. Stanecka,[41] R. W. Stanek,[6] C. Stanescu,[135a] M. Stanescu-Bellu,[44] M. M. Stanitzki,[44] S. Stapnes,[120] E. A. Starchenko,[131] G. H. Stark,[33] J. Stark,[57] P. Staroba,[128] P. Starovoitov,[60a] S. Stärz,[32] R. Staszewski,[41] P. Steinberg,[27] B. Stelzer,[143] H. J. Stelzer,[32] O. Stelzer-Chilton,[160a] H. Stenzel,[54] G. A. Stewart,[55] J. A. Stillings,[23] M. C. Stockton,[89] M. Stoebe,[89] G. Stoicea,[28b] P. Stolte,[56] S. Stonjek,[102] A. R. Stradling,[8] A. Straessner,[46] M. E. Stramaglia,[18] J. Strandberg,[148] S. Strandberg,[147a,147b] A. Strandlie,[120] M. Strauss,[114] P. Strizenec,[145b] R. Ströhmer,[174] D. M. Strom,[117] R. Stroynowski,[42] A. Strubig,[107] S. A. Stucci,[18] B. Stugu,[15] N. A. Styles,[44] D. Su,[144] J. Su,[126] R. Subramaniam,[81] S. Suchek,[60a] Y. Sugaya,[119] M. Suk,[129] V. V. Sulin,[97] S. Sultansoy,[4c] T. Sumida,[70] S. Sun,[59] X. Sun,[35a] J. E. Sundermann,[50] K. Suruliz,[150] G. Susinno,[39a,39b] M. R. Sutton,[150] S. Suzuki,[68] M. Svatos,[128] M. Swiatlowski,[33] I. Sykora,[145a] T. Sykora,[130] D. Ta,[50] C. Taccini,[135a,135b] K. Tackmann,[44] J. Taenzer,[159] A. Taffard,[163] R. Tafirout,[160a] N. Taiblum,[154] H. Takai,[27] R. Takashima,[71] T. Takeshita,[141] Y. Takubo,[68] M. Talby,[87] A. A. Talyshev,[110,d] K. G. Tan,[90] J. Tanaka,[156] R. Tanaka,[118] S. Tanaka,[68] B. B. Tannenwald,[112]

S. Tapia Araya,[34b] S. Tapprogge,[85] S. Tarem,[153] G. F. Tartarelli,[93a] P. Tas,[130] M. Tasevsky,[128] T. Tashiro,[70] E. Tassi,[39a,39b] A. Tavares Delgado,[127a,127b] Y. Tayalati,[136d] A. C. Taylor,[106] G. N. Taylor,[90] P. T. E. Taylor,[90] W. Taylor,[160b] F. A. Teischinger,[32] P. Teixeira-Dias,[79] K. K. Temming,[50] D. Temple,[143] H. Ten Kate,[32] P. K. Teng,[152] J. J. Teoh,[119] F. Tepel,[175] S. Terada,[68] K. Terashi,[156] J. Terron,[84] S. Terzo,[102] M. Testa,[49] R. J. Teuscher,[159,m] T. Theveneaux-Pelzer,[87] J. P. Thomas,[19] J. Thomas-Wilsker,[79] E. N. Thompson,[37] P. D. Thompson,[19] A. S. Thompson,[55] L. A. Thomsen,[176] E. Thomson,[123] M. Thomson,[30] M. J. Tibbetts,[16] R. E. Ticse Torres,[87] V. O. Tikhomirov,[97,oo] Yu. A. Tikhonov,[110,d] S. Timoshenko,[99] P. Tipton,[176] S. Tisserant,[87] K. Todome,[158] T. Todorov,[5,a] S. Todorova-Nova,[130] J. Tojo,[72] S. Tokár,[145a] K. Tokushuku,[68] E. Tolley,[59] L. Tomlinson,[86] M. Tomoto,[104] L. Tompkins,[144,pp] K. Toms,[106] B. Tong,[59] E. Torrence,[117] H. Torres,[143] E. Torró Pastor,[139] J. Toth,[87,qq] F. Touchard,[87] D. R. Tovey,[140] T. Trefzger,[174] A. Tricoli,[27] I. M. Trigger,[160a] S. Trincaz-Duvoid,[82] M. F. Tripiana,[13] W. Trischuk,[159] B. Trocmé,[57] A. Trofymov,[44] C. Troncon,[93a] M. Trottier-McDonald,[16] M. Trovatelli,[169] L. Truong,[164a,164c] M. Trzebinski,[41] A. Trzupek,[41] J. C-L. Tseng,[121] P. V. Tsiareshka,[94] G. Tsipolitis,[10] N. Tsirintanis,[9] S. Tsiskaridze,[13] V. Tsiskaridze,[50] E. G. Tskhadadze,[53a] K. M. Tsui,[62a] I. I. Tsukerman,[98] V. Tsulaia,[16] S. Tsuno,[68] D. Tsybychev,[149] A. Tudorache,[28b] V. Tudorache,[28b] A. N. Tuna,[59] S. A. Tupputi,[22a,22b] S. Turchikhin,[100,mm] D. Turecek,[129] D. Turgeman,[172] R. Turra,[93a,93b] A. J. Turvey,[42] P. M. Tuts,[37] M. Tyndel,[132] G. Ucchielli,[22a,22b] I. Ueda,[156] R. Ueno,[31] M. Ughetto,[147a,147b] F. Ukegawa,[161] G. Unal,[32] A. Undrus,[27] G. Unel,[163] F. C. 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