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DOI
10.1103/PhysRevC.107.054912

Publication date
2023

Document Version
Final published version

Published in
Physical Review C

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Citation for published version (APA):
Aad, G., & ATLAS Collaboration (2023). Production of Y(*nS*) mesons in Pb+Pb and *pp* collisions at 5.02 TeV. *Physical Review C*, *107*(5), Article 054912. https://doi.org/10.1103/PhysRevC.107.054912

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Production of $\Upsilon(nS)$ mesons in Pb + Pb and pp collisions at 5.02 TeV

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(Received 9 May 2022; accepted 24 October 2022; published 22 May 2023)

A measurement of the production of vector bottomonium states, $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, in Pb + Pb and pp collisions at a center-of-mass energy per nucleon pair of 5.02 TeV is presented. The data correspond to integrated luminosities of 1.38 nb^{-1} of Pb + Pb data collected in 2018, 0.44 nb^{-1} of Pb + Pb data collected in 2015, and 0.26 fb^{-1} of pp data collected in 2017 by the ATLAS detector at the Large Hadron Collider. The measurements are performed in the dimuon decay channel for transverse momentum $p_{\mathrm{T}}^{\mu\mu} < 30$ GeV, absolute rapidity $|y^{\mu\mu}| < 1.5$, and Pb + Pb event centrality 0–80%. The production rates of the three bottomonium states in Pb + Pb collisions are compared with those in pp collisions to extract the nuclear modification factors as functions of event centrality, $p_{\mathrm{T}}^{\mu\mu}$, and $|y^{\mu\mu}|$. In addition, the suppression of the excited states relative to the ground state is studied. The results are compared with theoretical model calculations.

DOI: 10.1103/PhysRevC.107.054912

I. INTRODUCTION

Quantum chromodynamics (QCD) predicts that at high temperatures and energy densities, hadronic matter undergoes a phase transition and turns into a state of deconfined quarks and gluons known as quark-gluon plasma (QGP). This state of matter is typically thought to be created in the collisions of two heavy nuclei at ultrarelativistic energies. In such collisions, heavy-flavor quarks, especially charm and bottom, are produced at an early stage in hard scattering processes and hence can probe QGP over its full evolution.

Formation of the QGP and the consequent modification to the heavy-quark potential are expected to lead to different quarkonium states dissolving at different temperatures of the medium [1]. This effect is known as sequential suppression [2]. While the excited states are dissociated just above the transition temperature $T_{\mathrm{c}} \approx 155$ MeV needed to form the QGP, the ground states melt far above that value, creating a hierarchy in the measured suppression of quarkonium states. In particular, in Ref. [3], lattice calculations for the temperature-dependent behavior of the heavy-quark potential in full QCD theory were used to estimate the order of the suppression steps as functions of temperature and energy density. It was found that the $\Upsilon(1S)$ persists well above T_{c}, while $\Upsilon(2S)$ dissociates at about $1.1\,T_{\mathrm{c}}$ and $\Upsilon(3S)$ cannot exist at temperatures above T_{c}. Since then, quarkonium production and propagation through QGP have been extensively studied theoretically. Comprehensive reviews can be found in Refs. [4,5].

Quarkonia dissociation in QGP can happen along with recombination of uncorrelated heavy quarks [6–8], which increases quarkonia yields. In this regard, it is interesting to compare bottomonium [$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_{b}, etc.] to the charmonium family [J/ψ, $\psi(2S)$, χ_{c}, etc.], since recombination is expected to be much larger for the latter.

Experimentally, quarkonium suppression in nucleus-nucleus collisions has been studied extensively for both the bottomonia [9–16] and charmonia [17–23] families at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies. These measurements show strong suppression of quarkonia in nucleus-nucleus collisions compared to pp collisions, increasing for more central events, as well as stronger suppression of the excited Upsilon states [$\Upsilon(2S)$ and $\Upsilon(3S)$] relative to the ground state [$\Upsilon(1S)$].

In this paper, $\Upsilon(nS)$ production in pp and Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV per nucleon-nucleon pair is studied as a function of transverse momentum ($p_{\mathrm{T}}^{\mu\mu}$), rapidity, and Pb+Pb collision centrality.

II. THE ATLAS DETECTOR

The ATLAS detector [24] at the LHC covers nearly the entire solid angle around the collision point.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector (ID) system is immersed in a 2-T axial magnetic field and provides charged-particle tracking in

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[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$, and the rapidity is defined as $y = (1/2)[(E + p_z)/(E - p_z)]$.

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the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit normally being in the insertable B layer installed before run 2 [25,26]. It is followed by the silicon microstrip tracker, which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroids. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detectors. A set of precision chambers covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode strip chambers in the forward region, where the background is highest. Resistive plate chambers (RPCs) and thin gap chambers (TGCs) with a coarse position resolution but a fast response time are used primarily to trigger on muons in the ranges $|\eta| < 1.05$ and $1.05 < |\eta| < 2.4$, respectively.

The zero-degree calorimeters (ZDCs) are located symmetrically at $z = \pm 140$ m and cover $|\eta| > 8.3$. The ZDCs use tungsten plates as absorbers, and quartz rods sandwiched between the tungsten plates as the active medium. In Pb + Pb collisions, the ZDCs primarily measure "spectator" neutrons that do not interact hadronically when the incident nuclei collide.

Centrality in Pb+Pb collisions is determined by measuring the total transverse energy deposited in a liquid-argon forward calorimeter (FCal), which covers the pseudorapidity range $3.1 < |\eta| < 4.9$. The FCal is approximately ten interaction lengths deep, and consists of three modules: the first, with copper absorbers, is optimized for electromagnetic measurements, while the other two, with tungsten absorbers, are mainly sensitive to energy depositions associated with produced hadrons.

A two-level trigger system is used to select events of interest [27]. The first-level (L1) trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 100 kHz. This is followed by the software-based high-level trigger (HLT), which reduces the event rate to about 1–4 kHz. The L1 muon trigger requires coincidences between hits on different RPC or TGC planes, which are used as a seed for the HLT algorithms. The HLT uses dedicated algorithms to incorporate information from both the MS and the ID, achieving position and momentum resolution close to that provided by the offline muon reconstruction, as shown in Ref. [27].

An extensive software suite [28] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment. The offline event selection required that events pass in-time pileup cuts based on the ZDC energy.

III. DATA SELECTION AND SIMULATION SAMPLES

The results presented in this paper were obtained using pp data recorded in 2017 at a center-of-mass energy of 5.02 TeV as well as Pb+Pb data collected in 2015 and 2018 at 5.02 TeV per nucleon-nucleon pair.

The integrated luminosity of the analyzed pp collision samples is 0.26 fb^{-1}. The pp events were collected using a dimuon trigger which requires at least two spatially separated muon candidates at L1, while both satisfy the criterion of $p_{\text{T}}^{\mu} > 4$ GeV in the HLT. For the Pb+Pb analysis, the integrated luminosity is 0.44 nb^{-1} for the 2015 data sample and 1.38 nb^{-1} for the 2018 data sample. Pb+Pb events were collected using triggers which require at least one muon with $p_{\text{T}}^{\mu} > 4$ GeV at both L1 and the HLT, and at least one additional muon satisfying $p_{\text{T}}^{\mu} > 4$ GeV in the HLT, without requiring matching to L1.

Muon pairs were required to fulfill the following criteria: at least one reconstructed muon matching the HLT's dimuon trigger, and both muons matching the HLT without an L1 trigger requirement; both muons satisfy the *Medium* identification criteria (described in Ref. [29]) without any requirements on TRT hits; both muons are associated with the primary vertex reconstructed using all of the tracks in each event; the muon pair has a dimuon mass $7.7 < m_{\mu\mu} < 12.3$ GeV, dimuon transverse momentum $|p_{\text{T}}^{\mu\mu}| < 30$ GeV, and dimuon rapidity $|y^{\mu\mu}| < 1.5$; the selected muon pair is refitted to a common vertex, with the vertex fit quality satisfying $\chi^2 < 100$ and the significance of the transverse displacement of the refitted vertex relative to the primary vertex satisfying $|L_{xy}/\sigma(L_{xy})| < 3$, where $\sigma(L_{xy})$ is the primary-vertex resolution. The dimuon rapidity requirement was chosen to be $|y^{\mu\mu}| < 1.5$ because at more forward rapidities the Υ mass resolution starts to deteriorate quickly.

Monte Carlo (MC) simulation is used to study the $\Upsilon(nS)$ acceptance, the fit model used in Υ signal extraction, and the closure of muon reconstruction and identification corrections (due to residual biases associated with the yield correction procedure). The unpolarized prompt Υ(nS) in pp events was generated with the CTEQ6L1 [30] parton distribution function set in Pythia8 [31] with subsequent decay in muon pairs. Pythia8 implements prompt $\Upsilon(nS)$ production subprocesses using the nonrelativistic QCD Color Octet mechanism [32]. Prompt $\Upsilon(nS)$ production includes prompt production from the hard interactions, as well as the radiative feeddown from $\chi_b \to \Upsilon(nS)\gamma$ decays. The production of nonprompt J/ψ, used for determining per-muon corrections, was simulated in Pythia8 by forcing $b\bar{b}$ production and retaining only events consistent with J/ψ decays. The Pb+Pb MC sample was created by overlaying simulated Pythia8 pp events with recorded minimum-bias Pb+Pb events, so that the "data overlay" simulation samples contain the same level of underlying-event activity as is present in the Pb+Pb data. The response of the ATLAS detector was simulated [33] using GEANT4 [34]. The MC events are reconstructed with the same algorithms as used in data.

IV. ANALYSIS PROCEDURE

A. Centrality definition in Pb + Pb

The transverse energy measured in the forward calorimeter, $\Sigma E_{\text{T}}^{\text{FCal}}$, in minimum bias events, is used to estimate the

degree of overlap between the two colliding Pb nuclei. Each centrality class corresponds to a fixed percentile in the $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ distribution of minimum-bias events using the procedure described in Ref. [21], where a table containing exact centrality bin definitions can be found. A Monte Carlo Glauber-based model [35] is used to calculate the mean number of participant nucleons, $\langle N_{\mathrm{part}}\rangle$, and the mean nuclear overlap function, $\langle T_{\mathrm{AA}}\rangle$, for each centrality class.

B. Corrections to raw invariant mass distributions

Before the dimuon invariant mass distributions are fit to extract Upsilon yields, each candidate dimuon pair is corrected with a weight that accounts for the $\Upsilon(nS)$ dimuon acceptance, trigger efficiency, and reconstruction efficiency.

The kinematic acceptance $\mathcal{A}$ is defined as the probability that both muons from $\Upsilon \to \mu^+\mu^-$ decay pass the fiducial selection ($p_{\mathrm{T}}^{\mu} > 4\,\mathrm{GeV}$ and $|\eta^{\mu}| < 2.4$). The kinematic acceptance is calculated from a generator-level simulation separately for different Υ(nS) states as described in Ref. [36]. The acceptance correction also accounts for final-state radiation from one or both of the decay muons. In principle, the acceptance could depend on the spin alignment of the Υ(nS). In this analysis, Υ(nS) mesons are assumed to be produced unpolarized, following the previous measurements in pp collisions [37–39]. These measurements are consistent with no Υ polarization, but have large uncertainties. No extra systematic uncertainty due to Υ polarization is added in this paper.

The dimuon reconstruction efficiency, $\varepsilon_{\mathrm{reco}}(\mu_1\mu_2)$, is determined as the product of two single-muon reconstruction efficiencies. The single-muon reconstruction efficiency is factorized into ID track reconstruction efficiency and MS reconstruction efficiency. For pp collisions, the values of the reconstruction efficiency are obtained from the $J/\psi \to \mu^+\mu^-$ Pythia8 simulation, and additional data-to-MC efficiency scale factors are derived using a $J/\psi \to \mu^+\mu^-$ tag-and-probe method [29] using pp data to account for residual differences between data and simulation. The same $J/\psi \to \mu^+\mu^-$ tag-and-probe method is employed to measure the muon reconstruction efficiency in Pb+Pb collisions. The ID reconstruction efficiency is obtained directly from Pb+Pb data, with a requirement on the transverse displacement of the J/ψ vertex to suppress potential biases from displaced muons. The MS reconstruction efficiency is obtained from the $J/\psi \to \mu^+\mu^-$ Pythia8 simulation overlaid with minimum-bias Pb+Pb data, and additional data-to-MC scale factors are determined in Pb+Pb data to account for the small difference between data and simulation. The ID reconstruction efficiency is found to be larger than 99% in both pp and Pb+Pb collisions, with a weak centrality dependence at low p_{T}^{μ} in the latter case. The MS reconstruction efficiency at $p_{\mathrm{T}}^{\mu} = 4$ GeV is about 65% in the barrel region ($|\eta_{\mu}| < 1.05$) and 75% in the endcap region ($1.05 < |\eta_{\mu}| < 2.4$), and the MS efficiency increases with p_{T}^{μ} and saturates at 95% around $p_{\mathrm{T}}^{\mu} = 7$ GeV in both the barrel and endcap regions. Due to the absorption of most hadronic activity in the ATLAS calorimeters, the MS reconstruction efficiency has no centrality dependence. For a given muon pair, the dimuon trigger efficiency in pp collisions is factorized as the product of two single-muon efficiencies. The dimuon trigger efficiency in Pb + Pb collisions is the combined efficiency of either of the two muons matching the HLT trigger with the other one matching the HLT trigger without L1 trigger requirement.

The single-muon trigger efficiency is determined in data and simulation using a $J/\psi \to \mu^+\mu^-$ tag-and-probe method similar to that used for the muon reconstruction efficiency. Two different muon-trigger logic schemes are used in this analysis: (1) a full-chain muon trigger, which requires the formation of an L1 muon candidate that is subsequently confirmed in the HLT, and (2) a full-scan muon trigger, which is only performed in the HLT via a muon candidate search of the full MS system without any requirement at L1. The values of the full-chain muon trigger efficiency are determined from MC simulation, with data-to-MC scale factors determined from the pp data to take into account the difference between data and simulation. The same values are used for pp and Pb+Pb collisions, except that an additional centrality-dependent correction is applied to Pb+Pb data. The centrality-dependent correction is determined as the ratio of the trigger efficiency measured in Pb+Pb collisions as a function of centrality to the trigger efficiency in pp data. The full-chain muon trigger efficiency plateau value is found to be 70% in the barrel and 90% in the endcaps. The centrality-dependent correction factor is about 90% (100%) for the 0–10% (60–80%) centrality range. The full-scan muon trigger is only used in Pb+Pb collisions and its efficiency is determined directly from Pb+Pb data, using the tag-and-probe method. The full-scan trigger plateau is found to be 90% in both the barrel and endcap regions. The dimuon trigger efficiency in pp collisions is factorized as the product of two full-chain muon trigger efficiencies, and in Pb+Pb collisions the factorization form consisting of full-chain and full-scan muon trigger efficiencies, as detailed in Ref. [21], is used.

C. Upsilon signal extraction

Upsilon states are reconstructed in the $\mu^+\mu^-$ decay channel and their yields are determined via unbinned maximum-likelihood fits to the weighted dimuon invariant mass distributions, following the same procedure for both pp and Pb+Pb data. Each of the three Υ(nS) state signal shapes is described by a sum of Crystal Ball (CB) [40] and Gaussian functions.

The probability distribution function for the fit is defined as a normalized sum of three Υ signal components and a background component as

$$\begin{aligned}\mathrm{pdf}(m_{\mu\mu}) = {} & N_{\Upsilon(1\mathrm{S})} f_{\Upsilon(1\mathrm{S})}(m_{\mu\mu}) + N_{\Upsilon(2\mathrm{S})} f_{\Upsilon(2\mathrm{S})}(m_{\mu\mu}) \\ & + N_{\Upsilon(3\mathrm{S})} f_{\Upsilon(3\mathrm{S})}(m_{\mu\mu}) + N_{\mathrm{bkg}} f_{\mathrm{bkg}}(m_{\mu\mu}),\end{aligned}$$

where $f_{\Upsilon(\mathrm{nS})}(m_{\mu\mu}) = \omega F_{\mathrm{G}}(m_{\mu\mu}; M_{\mathrm{nS}}, \sigma_{\mathrm{nS}}) + (1-\omega) F_{\mathrm{CB}}(m_{\mu\mu}; M_{\mathrm{nS}}, 1.7\sigma_{\mathrm{nS}}, \alpha, n)$; $N_{\Upsilon(\mathrm{nS})}$ and N_{bkg} are the Upsilon and background yields, respectively; and F_{G} and F_{CB} are Gaussian and Crystal Ball functions, respectively, with ω representing relative weight of the Gaussian function. The quantities M_{nS} and σ_{nS} are the Gaussian function's mean and width for

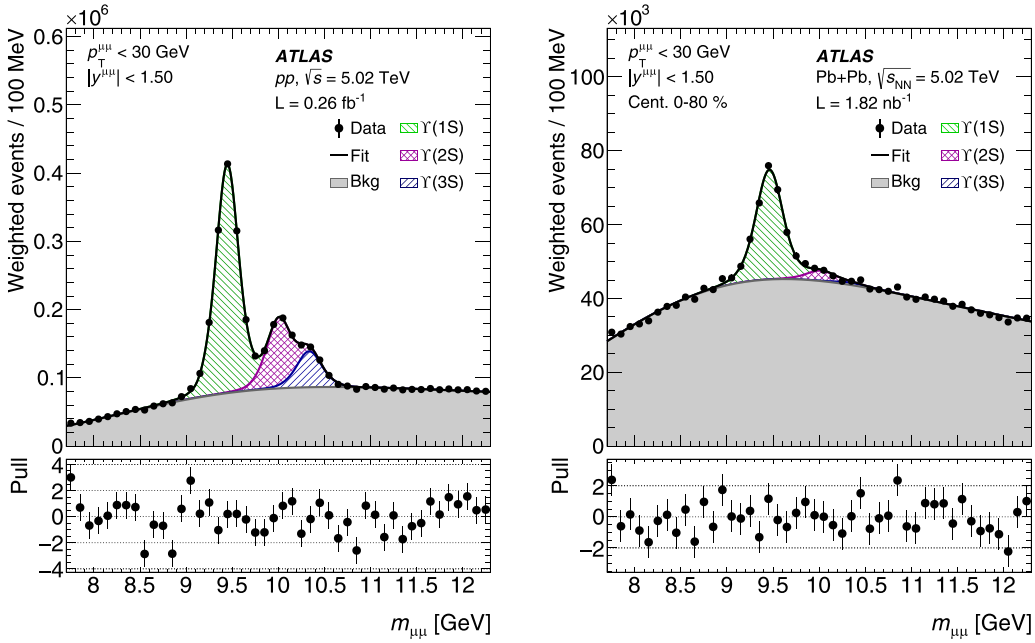

FIG. 1. Dimuon invariant mass distributions with the fit results for pp (left) and Pb+Pb (right) collisions at 5.02 TeV. The various curves are explained in the legend. Pull distributions are shown in the lower panels. For this selection, χ^2/NDF is 2.7 for pp and 1.3 for Pb + Pb.

each Upsilon state, and α and n are F_{CB} tail parameters. The line-shape parameters are assumed to be the same for all three Υ states since it is mostly determined by detector effects. The background shape, $f_{\mathrm{bkg}}(m_{\mu\mu})$, is represented by a second-order polynomial at high $p_{\mathrm{T}}^{\mu\mu}$ ($p_{\mathrm{T}}^{\mu\mu} > 6\,\mathrm{GeV}$) and as a product of an error function and an exponential function at low $p_{\mathrm{T}}^{\mu\mu}$.

The determination of the yield corrected for acceptance and efficiencies, $N_{\Upsilon(\mathrm{nS})}^{\mathrm{corr}}$, proceeds in several steps. First, a resonance-dependent weight, $w_{\mathrm{total}}[\Upsilon(\mathrm{nS})]$, is determined for each selected dimuon candidate as

$$w_{\mathrm{total}}[\Upsilon(\mathrm{nS})] = \frac{1}{\mathcal{A}[\Upsilon(\mathrm{nS})]\varepsilon_{\mathrm{reco}}(\mu_1\mu_2)\varepsilon_{\mathrm{trig}}(\mu_1\mu_2)\varepsilon_{\mathrm{pvAsso}}(\mu_1\mu_2)},$$

where $\mathcal{A}[\Upsilon(\mathrm{nS})]$ is the acceptance for $\Upsilon(\mathrm{nS}) \to \mu^+\mu^-$ decay, $\varepsilon_{\mathrm{reco}}$ is the muon reconstruction efficiency, $\varepsilon_{\mathrm{trig}}$ is the trigger efficiency, and $\varepsilon_{\mathrm{pvAsso}}$ is the efficiency related to the primary-vertex association. Next, an unbinned maximum-likelihood fit to the weighted dimuon invariant mass distribution ($m_{\mu\mu}$) is performed to extract the $\Upsilon(\mathrm{nS})$ yields. Three fits with an acceptance value corresponding to each state are performed to extract the yields for the three Υ states.

The mean and Gaussian width of the $\Upsilon(1\mathrm{S})$ signal, M_{1S} and σ_{1S}, are left unconstrained in each $p_{\mathrm{T}}^{\mu\mu}$, $|y^{\mu\mu}|$, and centrality range, while the means and widths of $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ in the same range are fixed to $\Upsilon(1\mathrm{S})$ parameters scaled by the respective Particle Data Group [41] mass ratios. The widths of the CB functions are set by scaling the corresponding Gaussian widths by a constant factor, 1.7, which was determined in a previous analysis [42] and validated with MC studies. The relative weight of the Gaussian and CB functions, ω, is not constrained, and has the same value for all three Upsilon states. For the pp collision analysis, the CB function parameter α, which defines the point at which the low-mass tail transitions from a Gaussian shape to a power-law shape, was fixed to the value obtained from $\Upsilon(1\mathrm{S})$ MC samples, while n, which describes the shape of the tail, was a free parameter. For Pb + Pb collisions, both α and n were fixed to the values from the fit for pp collisions, for each kinematic selection. The nominal signal fit model described above was validated by fitting the signal MC samples in various $p_{\mathrm{T}}^{\mu\mu}$, $|y^{\mu\mu}|$, and centrality intervals.

The background functional form varies with dimuon $p_{\mathrm{T}}^{\mu\mu}$. For $p_{\mathrm{T}}^{\mu\mu} > 6\,\mathrm{GeV}$ the background is parametrized as a second-order polynomial. However, for lower $p_{\mathrm{T}}^{\mu\mu}$ ($p_{\mathrm{T}}^{\mu\mu} < 6\,\mathrm{GeV}$), and for the integrated over $p_{\mathrm{T}}^{\mu\mu}$ fits, in order to describe the turn-on behavior of the dimuon acceptance caused by the single-muon transverse momentum requirement, an error function multiplied by an exponential function is used. The background model parameters are initialized using a background-enriched sample, which consists of events with same-sign muon pairs, as well as a control sample consisting primarily of muons from b-hadron decays. The control sample is produced by requiring at least one of the two muons to satisfy $|d_0|/\sigma_{d_0} > 2$ or $|z_0 \sin(\theta)| > 0.2$ mm, where d_0 and z_0 are the distances of closest approach of the muon to the primary vertex in the plane perpendicular to the beam and in the beam direction, respectively. After using the background distributions to determine the relevant parametrizations, the full model including signal and background contributions is used to fit the data, with the slope of the exponential function allowed to float.

Figure 1 shows an example of the fit to the dimuon mass plots for pp (left) and 0–80% centrality Pb+Pb (right) collisions for the inclusive $p_{\mathrm{T}}^{\mu\mu}$ and $|y^{\mu\mu}|$ selection. The lower panels show the pull distribution, which represents the

TABLE I. Summary of the sources of systematic uncertainty.

Collision type	Sources	Υ(1S) (%)	Υ(nS) (%)	Υ(nS)/Υ(1S) (%)
pp collisions	Luminosity	1.6	1.6	
	Acceptance	0.3–9.3	0.2–4.1	
	Efficiency	2.7–7.0	2.8–4.0	3.0–7.1
	Signal extraction	3.1–10.2	4.3–11.9	4.5–12.2
	Bin migration	<1	<1	
	Primary-vertex association	2.0	2.0	
Pb+Pb collisions	$\langle T_{\mathrm{AA}} \rangle$	0.8–8.2	0.8–8.2	
	Acceptance	0.3–9.3	0.2–4.1	
	Efficiency	4.0–15.0	3.9–25.3	4.4–28.8
	Signal extraction	3.8–16.3	14.6–28.7	16.6–31.5
	Bin migration	<2	<2	
	Primary-vertex association	3.4	3.4	

distance between data points and fit function normalized by the data points' statistical uncertainty: (Data − Fit)/σ(Data). The goodness of the fit is assessed by calculating the reduced chisquare, χ^2/NDF, summing the squared deviations of the data points from the fit (weighted by the inverse errors) and then dividing by the number of degrees of freedom (NDF) in the fit. Typically, χ^2/NDF for the fits varies from ≈2.5 to ≈1 for *pp* and from ≈2 to ≈1 for Pb + Pb, indicating that the data and model agree within statistical uncertainties. The extracted values of χ^2/NDF decrease with $p_{\mathrm{T}}^{\mu\mu}$, indicating that the fit quality improves with $p_{\mathrm{T}}^{\mu\mu}$. Some relatively large χ^2/NDF values are also found and can be explained by deviations of the functions used for background description from the actual background at the edges of the fit range.

D. Systematic uncertainties

The main sources of point-by-point uncorrelated systematic uncertainties pertain to the corrections for muon reconstruction and trigger efficiencies, and the yield extraction. For the lowest $p_{\mathrm{T}}^{\mu\mu}$ range, the final-state radiation correction is also a significant contribution. Other subdominant sources of systematic uncertainty considered in this paper are the primary-vertex association uncertainty and bin migration due to momentum resolution. Finally, the Upsilon states are assumed to be unpolarized and no extra systematic uncertainty is assigned to cover this assumption.

The systematic uncertainty in the MS reconstruction efficiency is dominated by the uncertainty in the data-to-MC scale-factor determination. The scale-factor uncertainty is evaluated following Ref. [29] by changing the tag-muon selection criteria and varying the line shapes in the efficiency extraction fit procedure in the data. The uncertainty related to the ID reconstruction efficiency, which is close to 1, is estimated by comparing the results while varying this efficiency in both up and down directions by one standard deviation.

The systematic uncertainty in the muon trigger efficiency is also dominated by the tag-and-probe efficiency determination procedure. For Pb+Pb collisions, an additional systematic uncertainty associated with the centrality-dependent correction is included. This uncertainty is evaluated by comparing the centrality-dependence-corrected Pb+Pb efficiency with the *pp* efficiency as a function of p_T^{μ}. Individual variations described above are added in quadrature to form the total systematic uncertainty of the efficiency corrections.

The sensitivity of the signal extraction to the choice of a particular fit model is evaluated by varying the line shape of each fit component. The maximum variation between the recalculated values and the central value is used to estimate their uncertainty. Eight variations are considered, and these can be categorized into three groups: signal resolution (width of the peak), shape of the final-state radiation tail, and background shape. The final uncertainty from the fit model is obtained by calculating the difference between the maximum and the minimum yield from the eight line-shape variations and dividing by $\sqrt{12}$, assuming a flat distribution.

The uncertainty in the Υ acceptance due to the final-state radiation correction was calculated by comparing the result of a fully simulated acceptance calculation with that obtained using an MC sample designed for a high-precision determination of the acceptance. The signal Monte Carlo samples were processed with a fast simulation [33] which relies on a parametrization of the calorimeter response [43]. This uncertainty is only important for the lowest $p_{\mathrm{T}}^{\mu\mu}$ range.

The global uncertainty of the integrated luminosity for the 2017 *pp* data is 1.6%, derived using methods described in Ref. [44]. Primary-vertex association uncertainty, which results mostly from small discrepancies between data and MC, was studied by varying the primary-vertex association requirements. Since the primary-vertex association affects all Upsilon state yields in the same way, it is treated as a global uncertainty together with those of the *pp* luminosity and T_{AA}. The combined systematic uncertainty for the luminosity and primary-vertex association in *pp* data is 2.6%. For Pb+Pb collisions, the global systematic uncertainty of $\langle T_{\mathrm{AA}} \rangle$ is estimated by varying the Glauber model parameters as detailed in Ref. [45]. The combined systematic uncertainty for $\langle T_{\mathrm{AA}} \rangle$ and primary-vertex association in Pb+Pb collisions is 3.7%.

Systematic uncertainties in *pp* and Pb + Pb collisions are summarized in Table I. While some systematic uncertainties for R_{AA} values and excited-state to ground-state double ratios are correlated (e.g., the acceptance) and cancel out in the

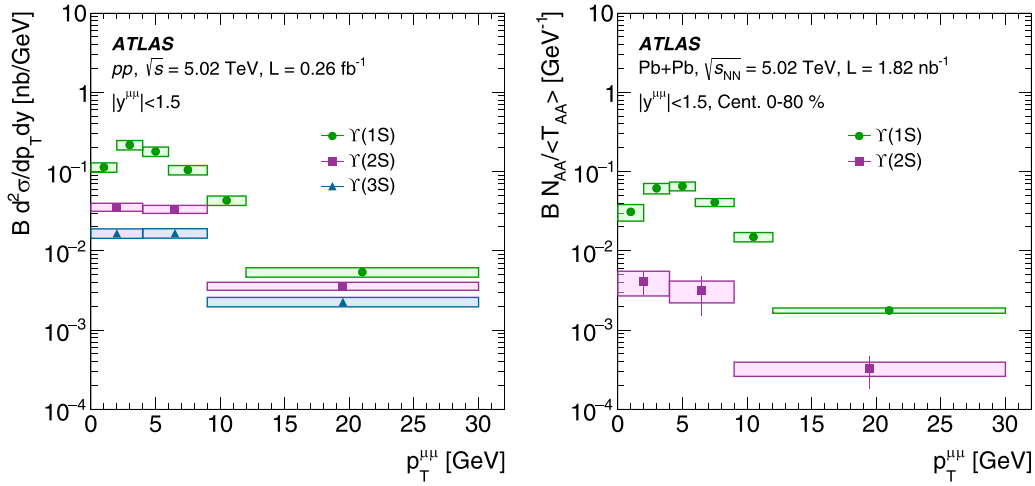

FIG. 2. Production cross sections of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as a function of $p_{\mathrm{T}}^{\mu\mu}$ in pp collisions (left) and per-event yields in Pb+Pb collisions (right) at 5.02 TeV. Error bars indicate the statistical uncertainties and boxes represent the systematic uncertainties. Not shown are the correlated systematic uncertainties of 2.6% for luminosity and primary-vertex association in pp and 3.7% for $\langle T_{\mathrm{AA}} \rangle$ and primary-vertex association in Pb+Pb collisions.

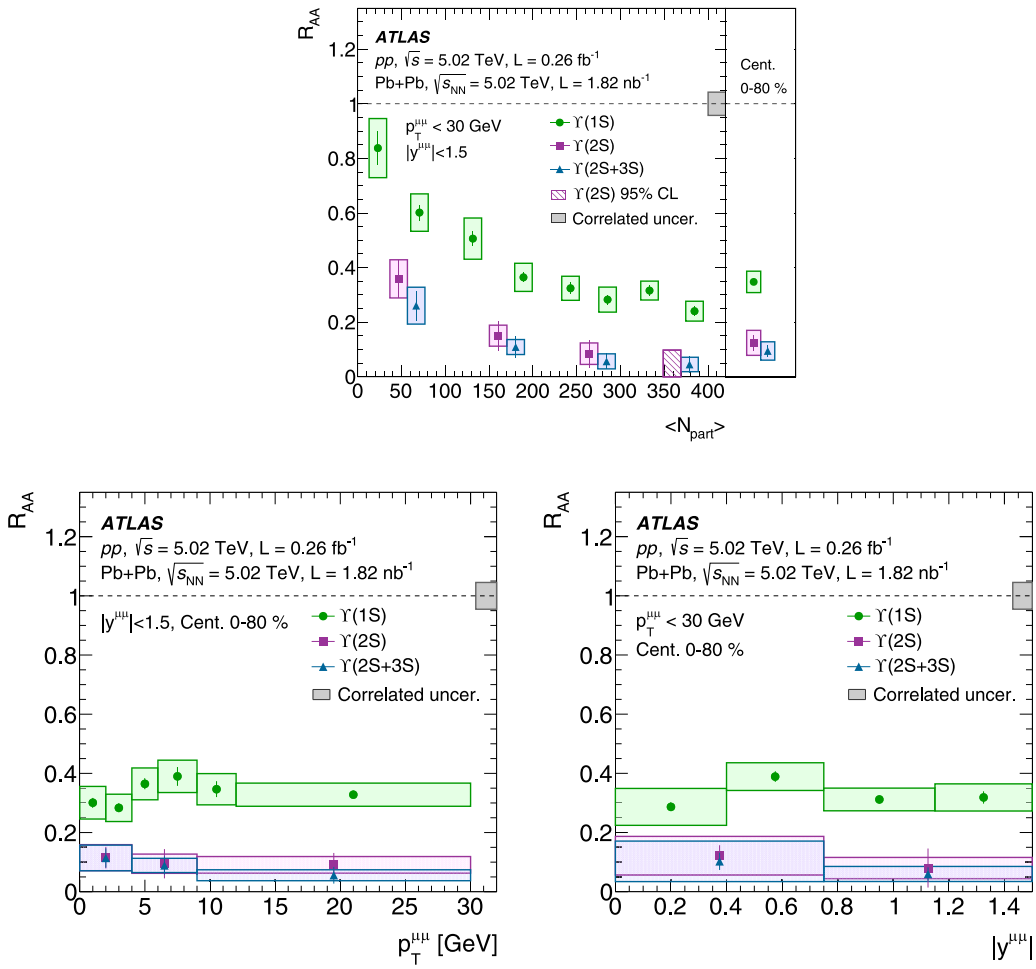

FIG. 3. The nuclear modification factor R_{AA} of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(2S+3S)$ as functions of centrality (top), $p_{\mathrm{T}}^{\mu\mu}$ (bottom left), and $|y^{\mu\mu}|$ (bottom right) at 5.02 TeV. Error bars indicate the statistical uncertainties and boxes represent the systematic uncertainties. The gray boxes around $R_{\mathrm{AA}} = 1$ correspond to the global systematic uncertainty. The right panel of the top plot shows the R_{AA} results integrated over centrality.

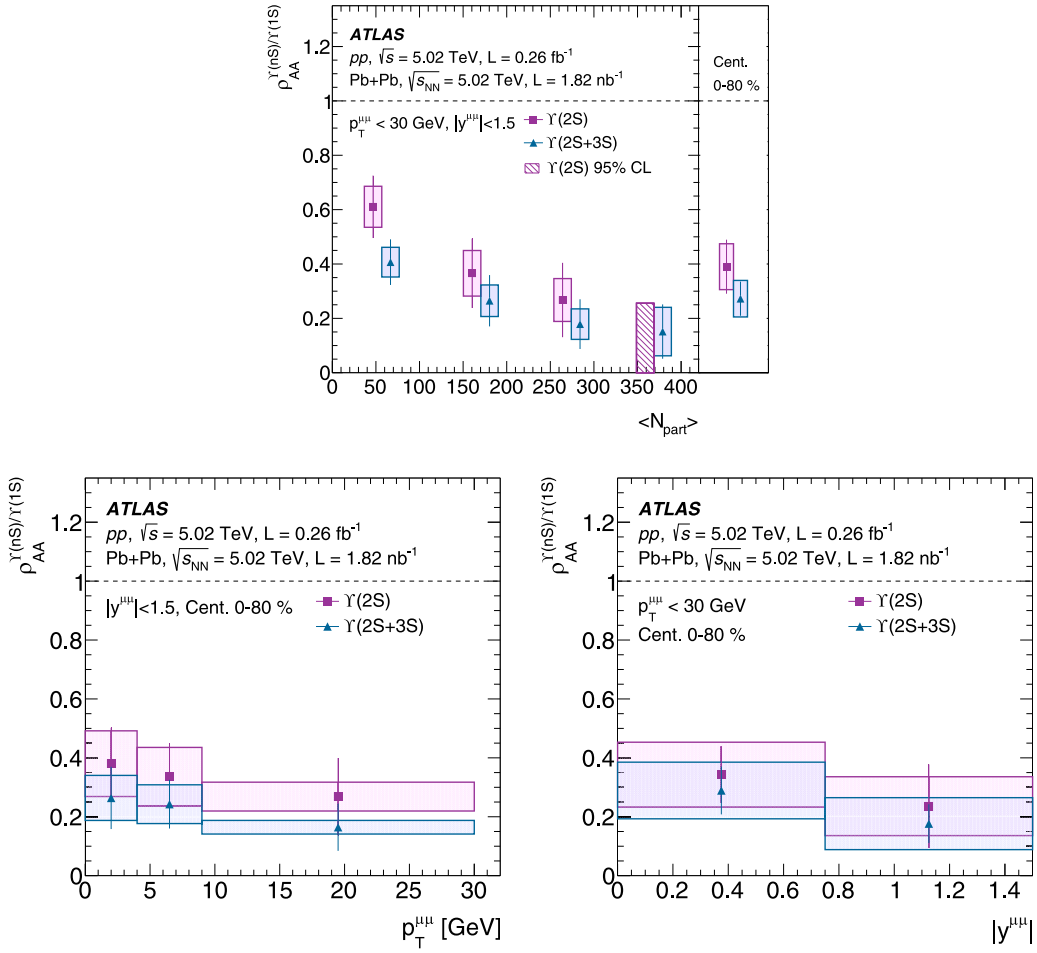

FIG. 4. The double ratio $\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})}$ for $\Upsilon(2\mathrm{S})$ and $\Upsilon(2\mathrm{S}+3\mathrm{S})$ as functions of centrality (top), $p_{\mathrm{T}}^{\mu\mu}$ (bottom left), and $|y^{\mu\mu}|$ (bottom right) at 5.02 TeV per nucleon-nucleon pair. Error bars indicate the statistical uncertainties and boxes represent the systematic uncertainties. The right panel of the top plot shows the results integrated over centrality.

ratios, most of the systematic uncertainties are not completely correlated and are estimated by directly studying their effects on the ratios.

V. RESULTS

A. Differential cross section

Differential $\Upsilon(\mathrm{nS})$ production cross sections in pp collisions are measured according to the relation

$$\frac{d^2\sigma_{\Upsilon(\mathrm{nS})}}{dp_{\mathrm{T}}^{\mu\mu}dy^{\mu\mu}}\mathcal{B}(\Upsilon(\mathrm{nS})\to\mu^+\mu^-)=\frac{N_{\Upsilon(\mathrm{nS})}^{\mathrm{corr}}}{\Delta p_{\mathrm{T}}^{\mu\mu}\Delta y^{\mu\mu}\int\mathcal{L}dt},$$

where $\mathcal{B}[\Upsilon(\mathrm{nS})\to\mu^+\mu^-]$ is the dimuon decay branching fraction, $N_{\Upsilon(\mathrm{nS})}^{\mathrm{corr}}$ is the $\Upsilon(\mathrm{nS})$ yield corrected for acceptance and efficiencies, $\Delta p_{\mathrm{T}}^{\mu\mu}$ and $\Delta y^{\mu\mu}$ are the bin widths in $p_{\mathrm{T}}^{\mu\mu}$ and $y^{\mu\mu}$, and $\int\mathcal{L}dt$ is the integrated luminosity.

The $\Upsilon(\mathrm{nS})$ differential cross sections in pp collisions at 5.02 TeV, multiplied by the respective dimuon branching fractions, are shown as a function of $p_{\mathrm{T}}^{\mu\mu}$ in the left panel of Fig. 2.

The per-event yields of $\Upsilon(\mathrm{nS})$ states in Pb+Pb collisions are defined by

$$N_{\mathrm{AA}}=\frac{N_{\Upsilon(\mathrm{nS})}^{\mathrm{corr}}}{\Delta p_{\mathrm{T}}^{\mu\mu}\Delta y^{\mu\mu}N_{\mathrm{evt}}},$$

where N_{evt} is the total number of minimum-bias Pb+Pb collisions in each centrality class. In particular, this number is 1.02×10^9 for the 0–10% centrality interval. Per-event Upsilon yields in Pb+Pb collisions divided by $\langle T_{\mathrm{AA}}\rangle$ are shown in the right panel of Fig. 2. The results for $\Upsilon(3\mathrm{S})$ mesons are not shown because their peaks are not statistically significant in Pb+Pb collisions.

B. Nuclear modification factor

The modifications of bottomonium production yields in Pb+Pb collisions relative to the pp system are quantified by the nuclear modification factor R_{AA}, which can be defined for each centrality interval as

$$R_{\mathrm{AA}}=\frac{N_{\mathrm{AA}}}{\langle T_{\mathrm{AA}}\rangle\sigma^{pp}},$$

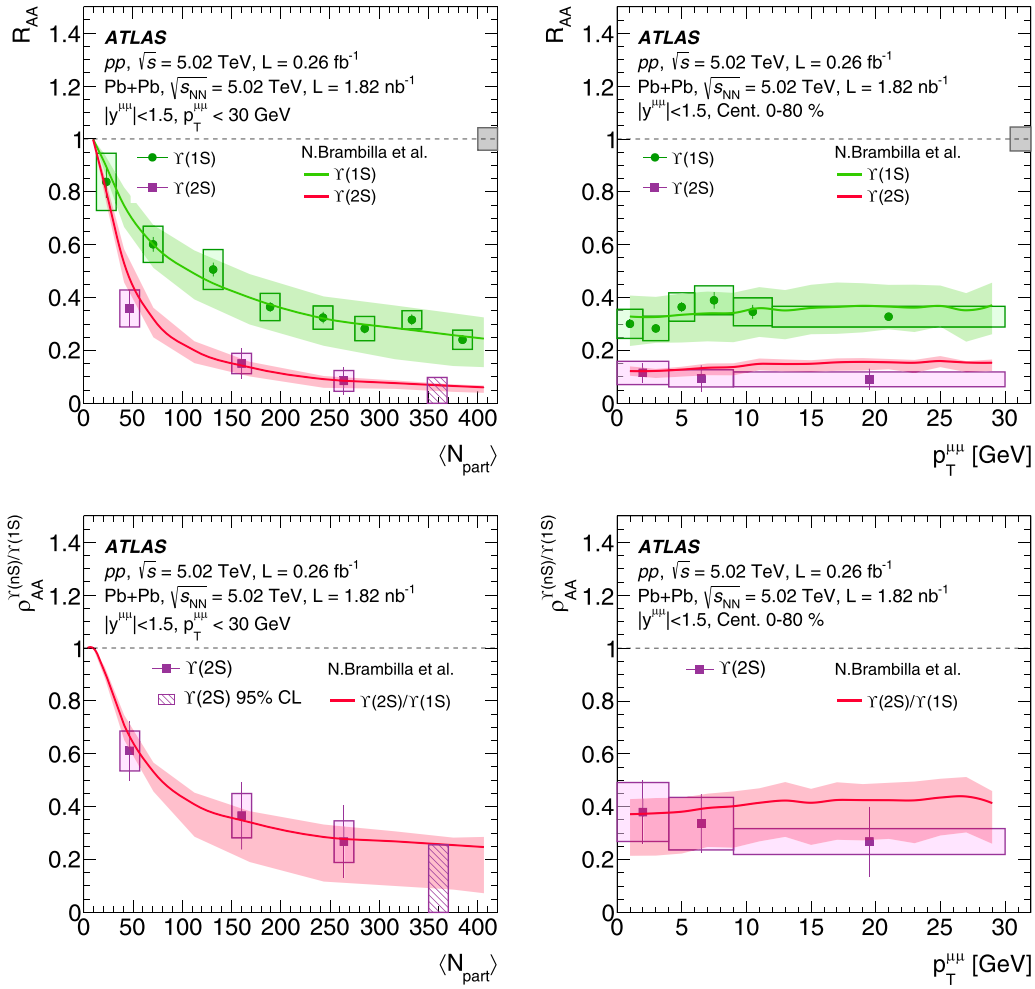

FIG. 5. The nuclear modification factor R_{AA} of Υ(1S) and Υ(2S) (top row) and the double ratio $\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})}$ for Υ(1S) and Υ(2S) (bottom row) as functions of centrality (left column) and $p_{\mathrm{T}}^{\mu\mu}$ (right column) at 5.02 TeV per nucleon-nucleon pair compared to a calculation by Brambilla *et al.* [46] (solid curves). Color bands represent model uncertainties due to variation of the model parameters.

where N_{AA} is the observed per-event yield of bottomonium states in Pb+Pb collisions, and σ^{pp} is the bottomonium production cross section in pp collisions at the same collision energy.

Figure 3 shows the R_{AA} values of Υ(nS) as functions of $\langle N_{\mathrm{part}}\rangle$ (top), dimuon $p_{\mathrm{T}}^{\mu\mu}$ (bottom left), and $|y^{\mu\mu}|$ (bottom right). The centrality-integrated results are also shown in the right panel of the top plot. In addition to the results for Υ(1S) and Υ(2S), only the combined result for the two excited states, $\Upsilon(2\mathrm{S}+3\mathrm{S})$, is presented because the Υ(3S) peak is not statistically significant in the Pb+Pb data. The Υ(nS) states are observed to be suppressed over the whole kinematic range investigated, and the R_{AA} values of Υ(2S) and $\Upsilon(2\mathrm{S}+3\mathrm{S})$ are always lower than those of Υ(1S). The R_{AA} value decreases with $\langle N_{\mathrm{part}}\rangle$ for all three states. No strong $p_{\mathrm{T}}^{\mu\mu}$ or $|y^{\mu\mu}|$ dependence is observed. When no statistically significant nonzero yield was extracted for a particular kinematic selection, the 95% confidence level upper limit was calculated.

C. Excited-state to ground-state double ratios

The suppression of different Upsilon states can be compared by constructing an excited-state to ground-state double ratio of nuclear modification factors. The advantage of measuring the double ratios is that the acceptance and efficiency corrections partially cancel out, and the overall systematic uncertainty is reduced. Although defined in terms of the individual nuclear suppression factors, the double ratio can be understood as being defined as the ratio of the yields of excited states Υ(2S) and Υ(3S) or of the combined yield of the two excited states $[\Upsilon(2S+3S)]$ to the yield of the ground state Υ(1S) in Pb+Pb collisions, divided by the same ratio in pp collisions:

$$\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})} = R_{\mathrm{AA}}[\Upsilon(\mathrm{nS})]/R_{\mathrm{AA}}[\Upsilon(1\mathrm{S})].$$

Figure 4 shows the $\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})}$ for Υ(2S) and $\Upsilon(2\mathrm{S}+3\mathrm{S})$ as functions of N_{part} (top), $p_{\mathrm{T}}^{\mu\mu}$ (bottom left), and $|y^{\mu\mu}|$ (bottom right). The centrality-integrated results are also shown in the right panel of the top plot. The $\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})}$ values for Υ(2S) and $\Upsilon(2\mathrm{S}+3\mathrm{S})$ are always less than 1, indicating the excited states are more suppressed than the ground state. The centrality-dependent $\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1\mathrm{S})}$ shows a slightly decreasing trend toward more central collisions, but no $p_{\mathrm{T}}^{\mu\mu}$ or $|y^{\mu\mu}|$ dependence is observed.

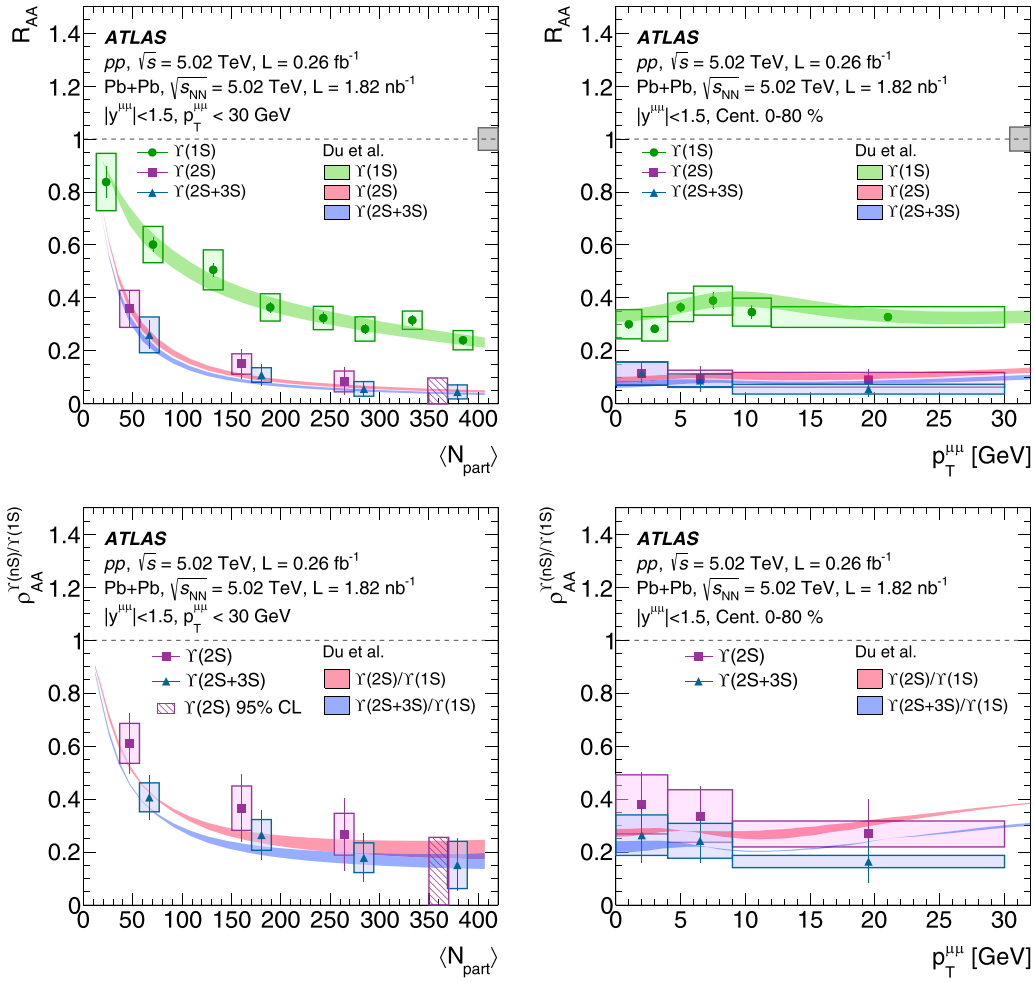

FIG. 6. The nuclear modification factor $R_{\rm AA}$ of Υ(1S) and Υ(2S) (top row) and the double ratio $\rho_{\rm AA}^{\Upsilon({\rm nS})/\Upsilon(1{\rm S})}$ for Υ(2S) (bottom row) as functions of centrality (left) and $p_{\rm T}^{\mu\mu}$ (right) at 5.02 TeV per nucleon-nucleon pair compared to a calculation by Du *et al.* [47]. The bands represent 95% confidence level (CL) limits.

These results are consistent with previous measurements of Upsilon suppression at LHC energies by the CMS [11] and ALICE [13] experiments.

D. Theory comparisons and discussion

Figure 5 shows the $R_{\rm AA}$ of Υ(1S) and Υ(2S) and the double ratio $\rho_{\rm AA}^{\Upsilon(2{\rm S})/\Upsilon(1{\rm S})}$ compared with a calculation by Brambilla *et al.* in Ref. [46]. This model uses potential Non-relativistic quantum chromodynamics and the formalism of open quantum systems to numerically solve the Lindblad equation using a stochastic unraveling called the quantum trajectories algorithm. Heavy-quark interactions with the strongly coupled medium are encoded in the two nonperturbative transport coefficients: the heavy-quark momentum diffusion coefficient and its dispersive counterpart. The authors of Ref. [46] have run variations of these parameters within reasonable ranges.

Figure 6 shows the $R_{\rm AA}$ of Υ(1S), Υ(2S), and $\Upsilon(2{\rm S}+3{\rm S})$, and the double ratio $\rho_{\rm AA}^{\Upsilon({\rm nS})/\Upsilon(1{\rm S})}$ for Υ(2S) and $\Upsilon(2{\rm S}+3{\rm S})$ compared to a calculation by Du *et al.* in Ref. [47]. This model uses a kinetic-rate equation approach including regeneration and has four dimensionless parameters which characterize the temperature dependence of the pertinent screening masses. These parameters are extracted through the fits to the data already available at RHIC and LHC. The band corresponding to the 95% confidence interval is shown in the figure.

Figure 7 shows the $R_{\rm AA}$ of Υ(1S), Υ(2S), and $\Upsilon(2{\rm S}+3{\rm S})$, as well as the double ratio $\rho_{\rm AA}^{\Upsilon({\rm nS})/\Upsilon(1{\rm S})}$ for Υ(1S) and Υ(2S), compared to a calculation by Yao *et al.* in Ref. [8]. This model uses a framework with coupled transport equations for open heavy-flavor and quarkonium states in order to describe their transport inside the quark-gluon plasma, including regeneration. Cold nuclear matter effects are included by using nuclear parton distribution functions for the initial primordial heavy-flavor production. A calibrated $(2+1)$-dimensional viscous hydrodynamic model is used to describe the bulk QCD medium. The model depends on the choice of nucleus parton distribution function and two coupling constant parameters, $\alpha_{\rm s}$ and $\alpha_{\rm s}^{\rm pot}$, which are varied by $\pm 10\%$ from their nominal values.

All three models are in agreement with the data within experimental and theoretical uncertainties. It is notable that all

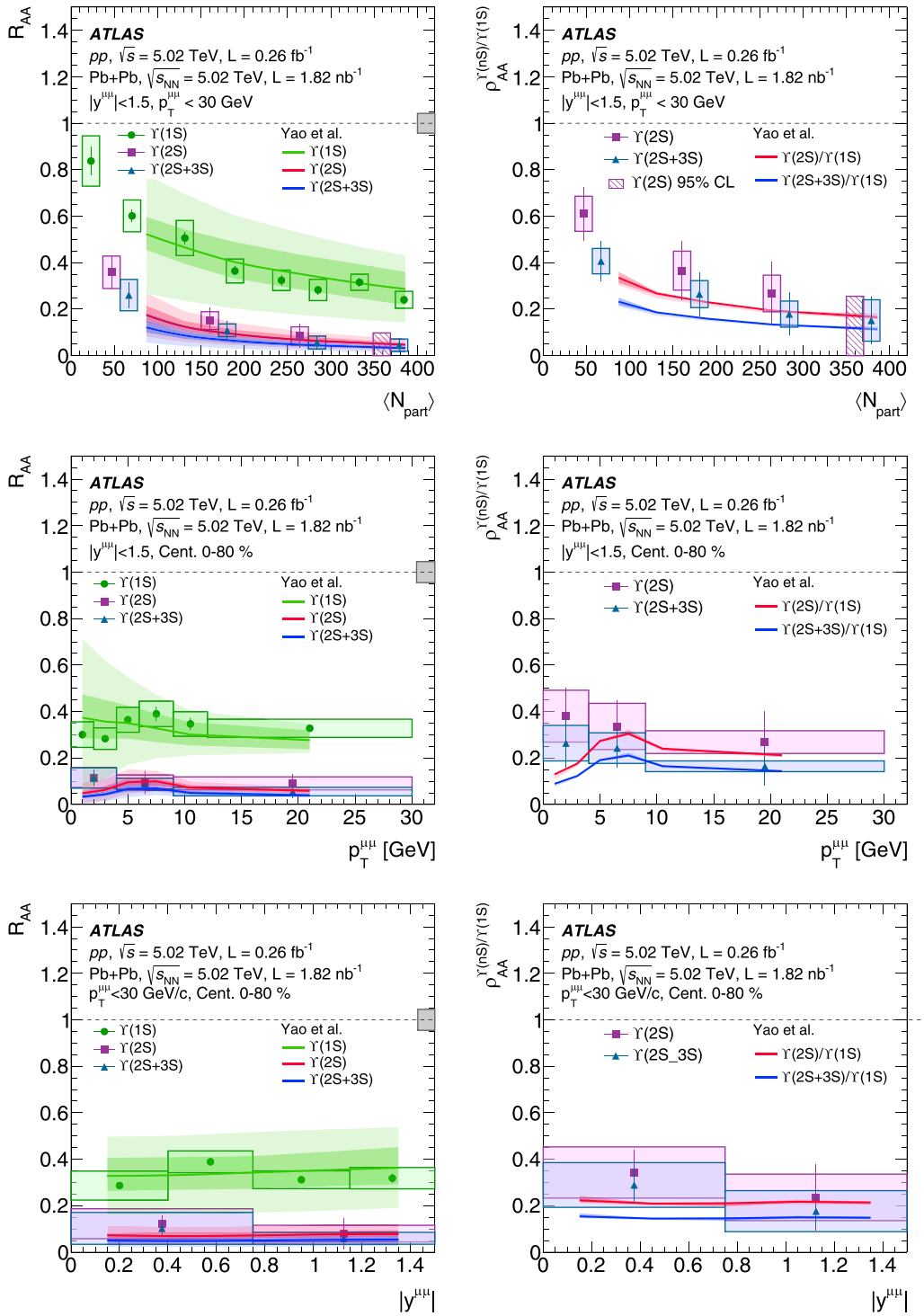

FIG. 7. The nuclear modification factor R_{AA} of Υ(1S), Υ(2S), and $\Upsilon(2S+3S)$ (left column) and the double ratio $\rho_{\mathrm{AA}}^{\Upsilon(\mathrm{nS})/\Upsilon(1S)}$ for Υ(2S) and $\Upsilon(2S+3S)$ (right column) as functions of centrality (top row), $p_{\mathrm{T}}^{\mu\mu}$ (center row), and rapidity (bottom row) at 5.02 TeV per nucleon-nucleon pair compared to a calculation by Yao *et al.* [8] (solid curves). Dark color bands show theory uncertainty due to the nucleus parton distribution function choice. Light color bands show model uncertainties due to varying the calculation parameters by ±10%.

three theoretical results were calculated after the publication of a CMS measurement of Υ suppression in Ref. [11] at the same beam energy.

Figure 8 shows the ATLAS results presented in this paper compared with CMS published values [12] for the Υ(1S) (left) and Υ(2S) (right) states. These measured nuclear modification factors, as well as the double ratios, are consistent between ATLAS and CMS within uncertainties. The kinematic selections are similar, though ATLAS uses a narrow rapidity window $|y| < 1.5$ compared with $|y| < 2.4$ in CMS.

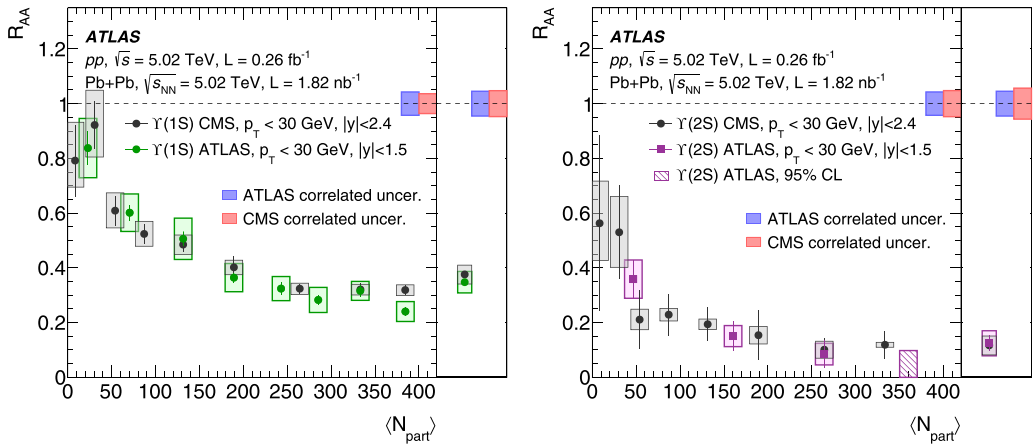

FIG. 8. The nuclear modification factor R_{AA} of $\Upsilon(1\mathrm{S})$ (left) and $\Upsilon(2\mathrm{S})$ (right) compared to the previous CMS measurement [12].

Published results by the ALICE Collaboration [13,14] are at more forward rapidities, and thus no direct comparison is made. The sequential melting of Upsilon states is thus confirmed by the present measurement. Suppression of the $\Upsilon(1\mathrm{S})$ observed at the level of approximately 0.25–0.30 in central Pb + Pb collisions indicates suppression of the directly produced $\Upsilon(1\mathrm{S})$ and not just suppression of higher states feeding down to the $\Upsilon(1\mathrm{S})$, thus providing important information on the highest temperatures achieved in the QGP.

More recently, CMS presented a measurement which includes the first observation of the $\Upsilon(3\mathrm{S})$ in Pb + Pb collisions at the LHC [48]. The $\Upsilon(3\mathrm{S})$ is even more suppressed than the $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$, further quantifying the sequential melting of quarkonium states in QGP. The combined nuclear modification factor for the two excited states $\Upsilon(2\mathrm{S}+3\mathrm{S})$ presented in this paper is consistent with the $\Upsilon(3\mathrm{S})$ CMS measurement.

Reference [49] quotes dissociation temperatures in the case of an isotropic QGP of $<$192, 228, and 593 MeV for the $\Upsilon(3\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(1\mathrm{S})$ states, respectively. It is notable that the $\Upsilon(1\mathrm{S})$ has a substantial decay feeddown fraction from $\Upsilon(2\mathrm{S})$, $\Upsilon(3\mathrm{S})$, $\chi_b(1S)$, and $\chi_b(2S)$ states, and that only about half of $\Upsilon(1\mathrm{S})$ are directly produced. Thus, the suppression at the level of approximately 0.25–0.30 for the $\Upsilon(1\mathrm{S})$ observed in central Pb + Pb collisions indicates at least some suppression of the directly produced $\Upsilon(1\mathrm{S})$, which has important implications regarding the temperatures achieved in the QGP.

VI. CONCLUSIONS

This paper presents a measurement of $\Upsilon(nS)$ yields in pp and Pb+Pb data at 5.02 TeV per nucleon-nucleon collision. The measurement uses data from pp collisions collected in 2017 with a total integrated luminosity of 0.26 fb^{-1} and Pb+Pb collisions collected in 2015 and 2018 with total integrated luminosities of 0.44 and 1.38 nb^{-1}, respectively, recorded by the ATLAS experiment at the LHC. The pp and Pb+Pb measurements are used to obtain the nuclear modification factor for $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(2\mathrm{S}+3\mathrm{S})$, as well as excited-state to ground-state double ratios of R_{AA} for $\Upsilon(2\mathrm{S})$ and $\Upsilon(2\mathrm{S}+3\mathrm{S})$ as functions of transverse momentum, rapidity, and centrality. Both the $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ yields are suppressed with increasing centrality in Pb+Pb compared to those in pp collisions, and the excited states are shown to be more strongly suppressed than the ground state, resulting in double ratios smaller than 1. The R_{AA} value for $\Upsilon(2\mathrm{S}+3\mathrm{S})$ appears to be systematically lower than that for $\Upsilon(2\mathrm{S})$, and so are the corresponding double ratios, which indicates that the $\Upsilon(3\mathrm{S})$ state is suppressed more than $\Upsilon(2\mathrm{S})$.

The measured nuclear modification factors and double ratios are found to be consistent with the previous CMS measurement [12] at similar kinematical conditions.

All theoretical calculations considered in this paper describe the data well and incorporate deconfinement as a key ingredient in the suppression of the Upsilon yields. Further discrimination between the different implementations of these deconfinement effects requires additional precision data from upcoming runs at RHIC and the LHC.

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; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE,

Compute Canada and CRC, Canada; PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN; 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 (USA); the Tier-2 facilities worldwide; and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [50].

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G. Aad,[101] B. Abbott,[119] D. C. Abbott,[102] K. Abeling,[55] S.H. Abidi,[29] A. Aboulhorma,[35e] H. Abramowicz,[150] H. Abreu,[149] Y. Abulaiti,[116] A. C. Abusleme Hoffman,[136a] B. S. Acharya,[68a,68b,a] B. Achkar,[55] L. Adam,[99] C. Adam Bourdarios,[4] L. Adamczyk,[84a] L. Adamek,[154] S. V. Addepalli,[26] J. Adelman,[114] A. Adiguzel,[21c] S. Adorni,[56] T. Adye,[133] A. A. Affolder,[135] Y. Afik,[36] M. N. Agaras,[13] J. Agarwala,[72a,72b] A. Aggarwal,[99] C. Agheorghiesei,[27c] J. A. Aguilar-Saavedra,[129f] A. Ahmad,[36] F. Ahmadov,[38,b] W. S. Ahmed,[103] X. Ai,[48] G. Aielli,[75a,75b] I. Aizenberg,[167] M. Akbiyik,[99] T. P. A. Åkesson,[97] A. V. Akimov,[37] K. Al Khoury,[41] G. L. Alberghi,[23b] J. Albert,[163] P. Albicocco,[53] M. J. Alconada Verzini,[89] S. Alderweireldt,[52] M. Aleksa,[36] I. N. Aleksandrov,[38] C. Alexa,[27b] T. Alexopoulos,[10] A. Alfonsi,[113] F. Alfonsi,[23b] M. Alhroob,[119] B. Ali,[131] S. Ali,[147] M. Aliev,[37] G. Alimonti,[70a] C. Allaire,[36] B. M.M. Allbrooke,[145] P. P. Allport,[20] A. Aloisio,[71a,71b] F. Alonso,[89] C. Alpigiani,[137] E. Alunno Camelia,[75a,75b] M. Alvarez Estevez,[98] M. G. Alviggi,[71a,71b] Y. Amaral Coutinho,[81b] A. Ambler,[103] C. Amelung,[36] C. G. Ames,[108] D. Amidei,[105] S. P. Amor Dos Santos,[129a] S. Amoroso,[48] K. R. Amos,[161] C. S. Amrouche,[56] V. Ananiev,[124] C. Anastopoulos,[138] N. Andari,[134] T. Andeen,[11] J. K. Anders,[19] S. Y. Andrean,[47a,47b] A. Andreazza,[70a,70b] S. Angelidakis,[9] A. Angerami,[41,c] A. V. Anisenkov,[37] A. Annovi,[73a] C. Antel,[56] M. T. Anthony,[138] E. Antipov,[120] M. Antonelli,[53] D. J.A. Antrim,[17a] F. Anulli,[74a] M. Aoki,[82] J. A. Aparisi Pozo,[161] M. A. Aparo,[145] L. Aperio Bella,[48] C. Appelt,[18] N. Aranzabal,[36] V. Araujo Ferraz,[81a] C. Arcangeletti,[53] A. T.H. Arce,[51] E. Arena,[91] J-F. Arguin,[107] S. Argyropoulos,[54] J.-H. Arling,[48] A. J. Armbruster,[36] O. Arnaez,[154] H. Arnold,[113] Z. P. Arrubarrena Tame,[108] G. Artoni,[74a,74b] H. Asada,[110] K. Asai,[117] S. Asai,[152] N. A. Asbah,[61] E. M. Asimakopoulou,[159] J. Assahsah,[35d] K. Assamagan,[29] R. Astalos,[28a] R. J. Atkin,[33a] M. Atkinson,[160] N. B. Atlay,[18] H. Atmani,[62b] P. A. Atmasiddha,[105] K. Augsten,[131] S. Auricchio,[71a,71b] A. D. Auriol,[20] V. A. Austrup,[169] G. Avner,[149] G. Avolio,[36] K. Axiotis,[56] M. K. Ayoub,[14c] G. Azuelos,[107,d] D. Babal,[28a] H. Bachacou,[134] K. Bachas,[151,e] A. Bachiu,[34] F. Backman,[47a,47b] A. Badea,[61] P. Bagnaia,[74a,74b] M. Bahmani,[18] A. J. Bailey,[161] V. R. Bailey,[160] J. T. Baines,[133] C. Bakalis,[10] O. K. Baker,[170] P. J. Bakker,[113] E. Bakos,[15] D. Bakshi Gupta,[8] S. Balaji,[146] R. Balasubramanian,[113] E. M. Baldin,[37] P. Balek,[132] E. Ballabene,[70a,70b] F. Balli,[134] L. M. Baltes,[63a] W. K. Balunas,[32] J. Balz,[99] E. Banas,[85] M. Bandieramonte,[128] A. Bandyopadhyay,[24] S. Bansal,[24] L. Barak,[150] E. L. Barberio,[104] D. Barberis,[57b,57a] M. Barbero,[101] G. Barbour,[95] K. N. Barends,[33a] T. Barillari,[109] M-S. Barisits,[36] J. Barkeloo,[122] T. Barklow,[142] R. M. Barnett,[17a] P. Baron,[121] D. A. Baron Moreno,[100] A. Baroncelli,[62a] G. Barone,[29] A. J. Barr,[125] L. Barranco Navarro,[47a,47b] F. Barreiro,[98] J. Barreiro Guimarães da Costa,[14a] U. Barron,[150] M. G. Barros Teixeira,[129a] S. Barsov,[37] F. Bartels,[63a] R. Bartoldus,[142] A. E. Barton,[90] P. Bartos,[28a] A. Basalaev,[48] A. Basan,[99] M. Baselga,[49] I. Bashta,[76a,76b]

A. Bassalat,[66,f] M. J. Basso,[154] C. R. Basson,[100] R. L. Bates,[59] S. Batlamous,[35e] J. R. Batley,[32] B. Batool,[140] M. Battaglia,[135] M. Bauce,[74a,74b] P. Bauer,[24] A. Bayirli,[21a] J. B. Beacham,[51] T. Beau,[126] P. H. Beauchemin,[157] F. Becherer,[54] P. Bechtle,[24] H. P. Beck,[19,g] K. Becker,[165] C. Becot,[48] A. J. Beddall,[21d] V. A. Bednyakov,[38] C. P. Bee,[144] L. J. Beemster,[15] T. A. Beermann,[36] M. Begalli,[81b] M. Begel,[29] A. Behera,[144] J. K. Behr,[48] C. Beirao Da Cruz E Silva,[36] J. F. Beirer,[55,36] F. Beisiegel,[24] M. Belfkir,[115b] G. Bella,[150] L. Bellagamba,[23b] A. Bellerive,[34] P. Bellos,[20] K. Beloborodov,[37] K. Belotskiy,[37] N. L. Belyaev,[37] D. Benchekroun,[35a] F. Bendebba,[35a] Y. Benhammou,[150] D. P. Benjamin,[29] M. Benoit,[29] J. R. Bensinger,[26] S. Bentvelsen,[113] L. Beresford,[36] M. Beretta,[53] D. Berge,[18] E. Bergeaas Kuutmann,[159] N. Berger,[4] B. Bergmann,[131] J. Beringer,[17a] S. Berlendis,[7] G. Bernardi,[5] C. Bernius,[142] F. U. Bernlochner,[24] T. Berry,[94] P. Berta,[132] A. Berthold,[50] I. A. Bertram,[90] O. Bessidskaia Bylund,[169] S. Bethke,[109] A. Betti,[44] A. J. Bevan,[93] M. Bhamjee,[33c] S. Bhatta,[144] D. S. Bhattacharya,[164] P. Bhattarai,[26] V. S. Bhopatkar,[6] R. Bi,[128] R. Bi,[29,h] R. M. Bianchi,[128] O. Biebel,[108] R. Bielski,[122] N. V. Biesuz,[73a,73b] M. Biglietti,[76a] T. R.V. Billoud,[131] M. Bindi,[55] A. Bingul,[21b] C. Bini,[74a,74b] S. Biondi,[23b,23a] A. Biondini,[91] C. J. Birch-sykes,[100] G. A. Bird,[20,133] M. Birman,[167] T. Bisanz,[36] D. Biswas,[168,i] A. Bitadze,[100] K. Bjørke,[124] I. Bloch,[48] C. Blocker,[26] A. Blue,[59] U. Blumenschein,[93] J. Blumenthal,[99] G. J. Bobbink,[113] V. S. Bobrovnikov,[37] M. Boehler,[54] D. Bogavac,[36] A. G. Bogdanchikov,[37] C. Bohm,[47a] V. Boisvert,[94] P. Bokan,[48] T. Bold,[84a] M. Bomben,[5] M. Bona,[93] M. Boonekamp,[134] C. D. Booth,[94] A. G. Borbély,[59] H. M. Borecka-Bielska,[107] L. S. Borgna,[95] G. Borissov,[90] D. Bortoletto,[125] D. Boscherini,[23b] M. Bosman,[13] J. D. Bossio Sola,[36] K. Bouaouda,[35a] J. Boudreau,[128] E. V. Bouhova-Thacker,[90] D. Boumediene,[40] R. Bouquet,[5] A. Boveia,[118] J. Boyd,[36] D. Boye,[29] I. R. Boyko,[38] J. Bracinik,[20] N. Brahimi,[62d,62c] G. Brandt,[169] O. Brandt,[32] F. Braren,[48] B. Brau,[102] J. E. Brau,[122] W. D. Breaden Madden,[59] K. Brendlinger,[48] R. Brener,[167] L. Brenner,[36] R. Brenner,[159] S. Bressler,[167] B. Brickwedde,[99] D. Britton,[59] D. Britzger,[109] I. Brock,[24] G. Brooijmans,[41] W. K. Brooks,[136f] E. Brost,[29] P. A. Bruckman de Renstrom,[85] B. Brüers,[48] D. Bruncko,[28b,j] A. Bruni,[23b] G. Bruni,[23b] M. Bruschi,[23b] N. Bruscino,[74a,74b] L. Bryngemark,[142] T. Buanes,[16] Q. Buat,[137] P. Buchholz,[140] A. G. Buckley,[59] I. A. Budagov,[38,j] M. K. Bugge,[124] O. Bulekov,[37] B. A. Bullard,[61] S. Burdin,[91] C. D. Burgard,[48] A. M. Burger,[40] B. Burghgrave,[8] J. T.P. Burr,[32] C. D. Burton,[11] J. C. Burzynski,[141] E. L. Busch,[41] V. Büscher,[99] P. J. Bussey,[59] J. M. Butler,[25] C. M. Buttar,[59] J. M. Butterworth,[95] W. Buttinger,[133] C. J. Buxo Vazquez,[106] A. R. Buzykaev,[37] G. Cabras,[23b] S. Cabrera Urbán,[161] D. Caforio,[58] H. Cai,[128] Y. Cai,[14a,14d] V. M.M. Cairo,[36] O. Cakir,[3a] N. Calace,[36] P. Calafiura,[17a] G. Calderini,[126] P. Calfayan,[67] G. Callea,[59] L. P. Caloba,[81b] D. Calvet,[40] S. Calvet,[40] T. P. Calvet,[101] M. Calvetti,[73a,73b] R. Camacho Toro,[126] S. Camarda,[36] D. Camarero Munoz,[98] P. Camarri,[75a,75b] M. T. Camerlingo,[76a,76b] D. Cameron,[124] C. Camincher,[163] M. Campanelli,[95] A. Camplani,[42] V. Canale,[71a,71b] A. Canesse,[103] M. Cano Bret,[79] J. Cantero,[161] Y. Cao,[160] F. Capocasa,[26] M. Capua,[43b,43a] A. Carbone,[70a,70b] R. Cardarelli,[75a] J. C.J. Cardenas,[8] F. Cardillo,[161] T. Carli,[36] G. Carlino,[71a] B. T. Carlson,[128,k] E. M. Carlson,[163,155a] L. Carminati,[70a,70b] M. Carnesale,[74a,74b] S. Caron,[112] E. Carquin,[136f] S. Carrá,[70a,70b] G. Carratta,[23b,23a] F. Carrio Argos,[33g] J. W.S. Carter,[154] T. M. Carter,[52] M. P. Casado,[13,l] A. F. Casha,[154] E. G. Castiglia,[170] F. L. Castillo,[63a] L. Castillo Garcia,[13] V. Castillo Gimenez,[161] N. F. Castro,[129a,129e] A. Catinaccio,[36] J. R. Catmore,[124] V. Cavaliere,[29] N. Cavalli,[23b,23a] V. Cavasinni,[73a,73b] E. Celebi,[21a] F. Celli,[125] M. S. Centonze,[69a,69b] K. Cerny,[121] A. S. Cerqueira,[81a] A. Cerri,[145] L. Cerrito,[75a,75b] F. Cerutti,[17a] A. Cervelli,[23b] S. A. Cetin,[21d] Z. Chadi,[35a] D. Chakraborty,[114] M. Chala,[129f] J. Chan,[168] W. S. Chan,[113] W. Y. Chan,[152] J. D. Chapman,[32,m] B. Chargeishvili,[148b] D. G. Charlton,[20] T. P. Charman,[93] M. Chatterjee,[19] S. Chekanov,[6] S. V. Chekulaev,[155a] G. A. Chelkov,[38,m] A. Chen,[105] B. Chen,[150] B. Chen,[163] C. Chen,[62a] H. Chen,[14c] H. Chen,[29] J. Chen,[62c] J. Chen,[26] S. Chen,[152] S. J. Chen,[14c] X. Chen,[62c] X. Chen,[14b,n] Y. Chen,[62a] C. L. Cheng,[168] H. C. Cheng,[64a] A. Cheplakov,[38] E. Cheremushkina,[48] E. Cherepanova,[113] R. Cherkaoui El Moursli,[35e] E. Cheu,[7] K. Cheung,[65] L. Chevalier,[134] V. Chiarella,[53] G. Chiarelli,[73a] G. Chiodini,[69a] A. S. Chisholm,[20] A. Chitan,[27b] Y. H. Chiu,[163] M. V. Chizhov,[38] K. Choi,[11] A. R. Chomont,[74a,74b] Y. Chou,[102] E. Y.S. Chow,[113] T. Chowdhury,[33g] L. D. Christopher,[33g] K. L. Chu,[64a] M. C. Chu,[64a] X. Chu,[14a,14d] J. Chudoba,[130] J. J. Chwastowski,[85] D. Cieri,[109] K. M. Ciesla,[84a] V. Cindro,[92] A. Ciocio,[17a] F. Cirotto,[71a,71b] Z. H. Citron,[167,o] M. Citterio,[70a] D. A. Ciubotaru,[27b] B. M. Ciungu,[154] A. Clark,[56] P. J. Clark,[52] J. M. Clavijo Columbie,[48] S. E. Clawson,[100] C. Clement,[47a,47b] J. Clercx,[48] L. Clissa,[23b,23a] Y. Coadou,[101] M. Cobal,[68a,68c] A. Coccaro,[57b] R. F. Coelho Barrue,[129a] R. Coelho Lopes De Sa,[102] S. Coelli,[70a] H. Cohen,[150] A. E.C. Coimbra,[70a,70b] B. Cole,[41] J. Collot,[60] P. Conde Muiño,[129a,129g] S. H. Connell,[33c] I. A. Connelly,[59] E. I. Conroy,[125] F. Conventi,[71a,p] H. G. Cooke,[20] A. M. Cooper-Sarkar,[125] F. Cormier,[162] L. D. Corpe,[36] M. Corradi,[74a,74b] E. E. Corrigan,[97] F. Corriveau,[103,q] A. Cortes-Gonzalez,[18] M. J. Costa,[161] F. Costanza,[4] D. Costanzo,[138] B. M. Cote,[118] G. Cowan,[94] J. W. Cowley,[32] K. Cranmer,[116] S. Crépé-Renaudin,[60] F. Crescioli,[126] M. Cristinziani,[140] M. Cristoforetti,[77a,77b,r] V. Croft,[157] G. Crosetti,[43b,43a] A. Cueto,[36] T. Cuhadar Donszelmann,[158] H. Cui,[14a,14d] Z. Cui,[7] A. R. Cukierman,[142] W. R. Cunningham,[59] F. Curcio,[43b,43a] P. Czodrowski,[36] M. M. Czurylo,[63b] M. J. Da Cunha Sargedas De Sousa,[62a] J. V. Da Fonseca Pinto,[81b] C. Da Via,[100] W. Dabrowski,[84a] T. Dado,[49] S. Dahbi,[33g] T. Dai,[105] C. Dallapiccola,[102] M. Dam,[42] G. D'amen,[29] V. D'Amico,[76a,76b] J. Damp,[99] J. R. Dandoy,[127] M. F. Daneri,[30] M. Danninger,[141] V. Dao,[36] G. Darbo,[57b]

S. Darmora,[6] S. J. Das,[29] A. Dattagupta,[122] S. D'Auria,[70a,70b] C. David,[155b] T. Davidek,[132] D. R. Davis,[51] B. Davis-Purcell,[34] I. Dawson,[93] K. De,[8] R. De Asmundis,[71a] M. De Beurs,[113] S. De Castro,[23b,23a] N. De Groot,[112] P. de Jong,[113] H. De la Torre,[106] A. De Maria,[14c] A. De Salvo,[74a] U. De Sanctis,[75a,75b] M. De Santis,[75a,75b] A. De Santo,[145] J. B. De Vivie De Regie,[60] D. V. Dedovich,[38] J. Degens,[113] A. M. Deiana,[44] F. Del Corso,[23b,23a] J. Del Peso,[98] F. Del Rio,[63a] F. Deliot,[134] C. M. Delitzsch,[49] M. Della Pietra,[71a,71b] D. Della Volpe,[56] A. Dell'Acqua,[36] L. Dell'Asta,[70a,70b] M. Delmastro,[4] P. A. Delsart,[60] S. Demers,[170] M. Demichev,[38] S. P. Denisov,[37] L. D'Eramo,[114] D. Derendarz,[85] F. Derue,[126] P. Dervan,[91] K. Desch,[24] K. Dette,[154] C. Deutsch,[24] P. O. Deviveiros,[36] F. A. Di Bello,[74a,74b] A. Di Ciaccio,[75a,75b] L. Di Ciaccio,[4] A. Di Domenico,[74a,74b] C. Di Donato,[71a,71b] A. Di Girolamo,[36] G. Di Gregorio,[73a,73b] A. Di Luca,[77a,77b] B. Di Micco,[76a,76b] R. Di Nardo,[76a,76b] C. Diaconu,[101] F. A. Dias,[113] T. Dias Do Vale,[141] M. A. Diaz,[136a,136b] F. G. Diaz Capriles,[24] M. Didenko,[161] E. B. Diehl,[105] L. Diehl,[54] S. Díez Cornell,[48] C. Diez Pardos,[140] C. Dimitriadi,[24,159] A. Dimitrievska,[17a] W. Ding,[14b] J. Dingfelder,[24] I-M. Dinu,[27b] S. J. Dittmeier,[63b] F. Dittus,[36] F. Djama,[101] T. Djobava,[148b] J. I. Djuvsland,[16] D. Dodsworth,[26] C. Doglioni,[100,97] J. Dolejsi,[132] Z. Dolezal,[132] M. Donadelli,[81c] B. Dong,[62c] J. Donini,[40] A. D'Onofrio,[14c] M. D'Onofrio,[91] J. Dopke,[133] A. Doria,[71a] M. T. Dova,[89] A. T. Doyle,[59] M. A. Draguet,[125] E. Drechsler,[141] E. Dreyer,[167] I. Drivas-koulouris,[10] A. S. Drobac,[157] D. Du,[62a] T. A. du Pree,[113] F. Dubinin,[37] M. Dubovsky,[28a] E. Duchovni,[167] G. Duckeck,[108] O. A. Ducu,[36] D. Duda,[109] A. Dudarev,[36] M. D'uffizi,[100] L. Duflot,[66] M. Dührssen,[36] C. Dülsen,[169] A. E. Dumitriu,[27b] M. Dunford,[63a] S. Dungs,[49] K. Dunne,[47a,47b] A. Duperrin,[101] H. Duran Yildiz,[3a] M. Düren,[58] A. Durglishvili,[148b] B. L. Dwyer,[114] G. I. Dyckes,[17a] M. Dyndal,[84a] S. Dysch,[100] B. S. Dziedzic,[85] Z. O. Earnshaw,[145] B. Eckerova,[28a] M. G. Eggleston,[51] E. Egidio Purcino De Souza,[81b] L. F. Ehrke,[56] G. Eigen,[16] K. Einsweiler,[17a] T. Ekelof,[159] P. A. Ekman,[97] Y. El Ghazali,[35b] H. El Jarrari,[35e,147] A. El Moussaouy,[35a] V. Ellajosyula,[159] M. Ellert,[159] F. Ellinghaus,[169] A. A. Elliot,[93] N. Ellis,[36] J. Elmsheuser,[29] M. Elsing,[36] D. Emeliyanov,[133] A. Emerman,[41] Y. Enari,[152] I. Ene,[17a] S. Epari,[13] J. Erdmann,[49] A. Ereditato,[19] P. A. Erland,[85] M. Errenst,[169] M. Escalier,[66] C. Escobar,[161] E. Etzion,[150] G. Evans,[129a] H. Evans,[67] M. O. Evans,[145] A. Ezhilov,[37] S. Ezzarqtouni,[35a] F. Fabbri,[59] L. Fabbri,[23b,23a] G. Facini,[95] V. Fadeyev,[135] R. M. Fakhrutdinov,[37] S. Falciano,[74a] P. J. Falke,[24] S. Falke,[36] J. Faltova,[132] Y. Fan,[14a] Y. Fang,[14a,14d] G. Fanourakis,[46] M. Fanti,[70a,70b] M. Faraj,[68a,68b] A. Farbin,[8] A. Farilla,[76a] T. Farooque,[106] S. M. Farrington,[52] F. Fassi,[35e] D. Fassouliotis,[9] M. Faucci Giannelli,[75a,75b] W. J. Fawcett,[32] L. Fayard,[66] O. L. Fedin,[37,m] G. Fedotov,[37] M. Feickert,[160] L. Feligioni,[101] A. Fell,[138] D. E. Fellers,[122] C. Feng,[62b] M. Feng,[14b] M. J. Fenton,[158] A. B. Fenyuk,[37] L. Ferencz,[48] S. W. Ferguson,[45] J. A. Fernandez Pretel,[54] J. Ferrando,[48] A. Ferrari,[159] P. Ferrari,[113] R. Ferrari,[72a] D. Ferrere,[56] C. Ferretti,[105] F. Fiedler,[99] A. Filipčič,[92] E. K. Filmer,[1] F. Filthaut,[112] M. C. N. Fiolhais,[129a,129c,s] L. Fiorini,[161] F. Fischer,[140] W. C. Fisher,[106] T. Fitschen,[20,66] I. Fleck,[140] P. Fleischmann,[105] T. Flick,[169] L. Flores,[127] M. Flores,[33d] L. R. Flores Castillo,[64a] F. M. Follega,[77a,77b] N. Fomin,[16] J. H. Foo,[154] B. C. Forland,[67] A. Formica,[134] A. C. Forti,[100] E. Fortin,[101] A. W. Fortman,[61] M. G. Foti,[17a] L. Fountas,[9] D. Fournier,[66] H. Fox,[90] P. Francavilla,[73a,73b] S. Francescato,[61] M. Franchini,[23b,23a] S. Franchino,[63a] D. Francis,[36] L. Franco,[112] L. Franconi,[19] M. Franklin,[61] G. Frattari,[26] A. C. Freegard,[93] P. M. Freeman,[20] W. S. Freund,[81b] N. Fritzsche,[50] A. Froch,[54] D. Froidevaux,[36] J. A. Frost,[125] Y. Fu,[62a] M. Fujimoto,[117] E. Fullana Torregrosa,[161,j] J. Fuster,[161] A. Gabrielli,[23b,23a] A. Gabrielli,[36] P. Gadow,[48] G. Gagliardi,[57b,57a] L. G. Gagnon,[17a] G. E. Gallardo,[125] E. J. Gallas,[125] B. J. Gallop,[133] R. Gamboa Goni,[93] K. K. Gan,[118] S. Ganguly,[152] J. Gao,[62a] Y. Gao,[52] F. M. Garay Walls,[136a,136b] B. Garcia,[29,h] C. García,[161] J. E. García Navarro,[161] J. A. García Pascual,[14a] M. Garcia-Sciveres,[17a] R. W. Gardner,[39] D. Garg,[79] R. B. Garg,[142] S. Gargiulo,[54] C. A. Garner,[154] V. Garonne,[29] S. J. Gasiorowski,[137] P. Gaspar,[81b] G. Gaudio,[72a] P. Gauzzi,[74a,74b] I. L. Gavrilenko,[37] A. Gavrilyuk,[37] C. Gay,[162] G. Gaycken,[48] E. N. Gazis,[10] A. A. Geanta,[27b] C. M. Gee,[135] J. Geisen,[97] M. Geisen,[99] C. Gemme,[57b] M. H. Genest,[60] S. Gentile,[74a,74b] S. George,[94] W. F. George,[20] T. Geralis,[46] L. O. Gerlach,[55] P. Gessinger-Befurt,[36] M. Ghasemi Bostanabad,[163] M. Ghneimat,[140] A. Ghosal,[140] A. Ghosh,[158] A. Ghosh,[7] B. Giacobbe,[23b] S. Giagu,[74a,74b] N. Giangiacomi,[154] P. Giannetti,[73a] A. Giannini,[62a] S. M. Gibson,[94] M. Gignac,[135] D. T. Gil,[84b] A. K. Gilbert,[84a] B. J. Gilbert,[41] D. Gillberg,[34] G. Gilles,[113] N. E.K. Gillwald,[48] L. Ginabat,[126] D. M. Gingrich,[2,d] M. P. Giordani,[68a,68c] P. F. Giraud,[134] G. Giugliarelli,[68a,68c] D. Giugni,[70a] F. Giuli,[36] I. Gkialas,[9,t] L. K. Gladilin,[37] C. Glasman,[98] G. R. Gledhill,[122] M. Glisic,[122] I. Gnesi,[43b,u] Y. Go,[29,h] M. Goblirsch-Kolb,[26] D. Godin,[107] S. Goldfarb,[104] T. Golling,[56] M. G.D. Gololo,[33g] D. Golubkov,[37] J. P. Gombas,[106] A. Gomes,[129a,129b] G. Gomes Da Silva,[140] A. J. Gomez Delegido,[161] R. Gonçalo,[129a,129c] R. Goncalves Gama,[55] G. Gonella,[122] L. Gonella,[20] A. Gongadze,[38] F. Gonnella,[20] J. L. Gonski,[41] R. Y. González Andana,[52] S. González de la Hoz,[161] S. Gonzalez Fernandez,[13] R. Gonzalez Lopez,[91] C. Gonzalez Renteria,[17a] S. Gonzalez-Sevilla,[56] R. Gonzalez Suarez,[159] G. R. Gonzalvo Rodriguez,[161] L. Goossens,[36] N. A. Gorasia,[20] P. A. Gorbounov,[37] B. Gorini,[36] E. Gorini,[69a,69b] A. Gorišek,[92] A. T. Goshaw,[51] M. I. Gostkin,[38] C. A. Gottardo,[112] M. Gouighri,[35b] V. Goumarre,[48] A. G. Goussiou,[137] N. Govender,[33c] C. Goy,[4] I. Grabowska-Bold,[84a] K. Graham,[34] E. Gramstad,[124] S. Grancagnolo,[18] M. Grandi,[145] V. Gratchev,[37,j] P. M. Gravila,[27f] F. G. Gravili,[69a,69b] H. M. Gray,[17a] M. Greco,[69a,69b] C. Grefe,[24] I. M. Gregor,[48] P. Grenier,[142]

C. Grieco,[13] A. A. Grillo,[135] K. Grimm,[31,v] S. Grinstein,[13,w] J.-F. Grivaz,[66] E. Gross,[167] J. Grosse-Knetter,[55] C. Grud,[105] A. Grummer,[111] J. C. Grundy,[125] L. Guan,[105] W. Guan,[168] C. Gubbels,[162] J. G.R. Guerrero Rojas,[161] G. Guerrieri,[68a,68c] F. Guescini,[109] R. Gugel,[99] J. A.M. Guhit,[105] A. Guida,[48] T. Guillemin,[4] E. Guilloton,[165,133] S. Guindon,[36] F. Guo,[14a,14d] J. Guo,[62c] L. Guo,[66] Y. Guo,[105] R. Gupta,[48] S. Gurbuz,[24] G. Gustavino,[36] M. Guth,[56] P. Gutierrez,[119] L. F. Gutierrez Zagazeta,[127] C. Gutschow,[95] C. Guyot,[134] C. Gwenlan,[125] C. B. Gwilliam,[91] E. S. Haaland,[124] A. Haas,[116] M. Habedank,[48] C. Haber,[17a] H. K. Hadavand,[8] A. Hadef,[99] S. Hadzic,[109] M. Haleem,[164] J. Haley,[120] J. J. Hall,[138] G. D. Hallewell,[101] L. Halser,[19] K. Hamano,[163] H. Hamdaoui,[35e] M. Hamer,[24] G. N. Hamity,[52] J. Han,[62b] K. Han,[62a] L. Han,[14c] L. Han,[62a] S. Han,[17a] Y. F. Han,[154] K. Hanagaki,[82] M. Hance,[135] D. A. Hangal,[41,c] M. D. Hank,[39] R. Hankache,[100] J. B. Hansen,[42] J. D. Hansen,[42] P. H. Hansen,[42] K. Hara,[156] D. Harada,[56] T. Harenberg,[169] S. Harkusha,[37] Y. T. Harris,[125] P. F. Harrison,[165] N. M. Hartman,[142] N. M. Hartmann,[108] Y. Hasegawa,[139] A. Hasib,[52] S. Haug,[19] R. Hauser,[106] M. Havranek,[131] C. M. Hawkes,[20] R. J. Hawkings,[36] S. Hayashida,[110] D. Hayden,[106] C. Hayes,[105] R. L. Hayes,[162] C. P. Hays,[125] J. M. Hays,[93] H. S. Hayward,[91] F. He,[62a] Y. He,[153] Y. He,[126] M. P. Heath,[52] V. Hedberg,[97] A. L. Heggelund,[124] N. D. Hehir,[93] C. Heidegger,[54] K. K. Heidegger,[54] W. D. Heidorn,[80] J. Heilman,[34] S. Heim,[48] T. Heim,[17a] J. G. Heinlein,[127] J. J. Heinrich,[122] L. Heinrich,[36] J. Hejbal,[130] L. Helary,[48] A. Held,[116] S. Hellesund,[124] C. M. Helling,[162] S. Hellman,[47a,47b] C. Helsens,[36] R. C.W. Henderson,[90] L. Henkelmann,[32] A. M. Henriques Correia,[36] H. Herde,[142] Y. Hernández Jiménez,[144] H. Herr,[99] M. G. Herrmann,[108] T. Herrmann,[50] G. Herten,[54] R. Hertenberger,[108] L. Hervas,[36] N. P. Hessey,[155a] H. Hibi,[83] E. Higón-Rodriguez,[161] S. J. Hillier,[20] I. Hinchliffe,[17a] F. Hinterkeuser,[24] M. Hirose,[123] S. Hirose,[156] D. Hirschbuehl,[169] T. G. Hitchings,[100] B. Hiti,[92] J. Hobbs,[144] R. Hobincu,[27e] N. Hod,[167] M. C. Hodgkinson,[138] B. H. Hodkinson,[32] A. Hoecker,[36] J. Hofer,[48] D. Hohn,[54] T. Holm,[24] M. Holzbock,[109] L. B.A. H. Hommels,[32] B. P. Honan,[100] J. Hong,[62c] T. M. Hong,[128] Y. Hong,[55] J. C. Honig,[54] A. Hönle,[109] B. H. Hooberman,[160] W. H. Hopkins,[6] Y. Horii,[110] S. Hou,[147] J. Howarth,[59] J. Hoya,[89] M. Hrabovsky,[121] A. Hrynevich,[37] T. Hryn'ova,[4] P. J. Hsu,[65] S.-C. Hsu,[137] Q. Hu,[41,c] Y. F. Hu,[14a,14d,x] D. P. Huang,[95] S. Huang,[64b] X. Huang,[14c] Y. Huang,[62a] Y. Huang,[14a] Z. Huang,[100] Z. Hubacek,[131] M. Huebner,[24] F. Huegging,[24] T. B. Huffman,[125] M. Huhtinen,[36] S. K. Huiberts,[16] R. Hulsken,[103] N. Huseynov,[12,m] J. Huston,[106,m] J. Huth,[61] R. Hyneman,[142] S. Hyrych,[28a] G. Iacobucci,[56] G. Iakovidis,[29] I. Ibragimov,[140] L. Iconomidou-Fayard,[66] P. Iengo,[71a,71b] R. Iguchi,[152] T. Iizawa,[56] Y. Ikegami,[82] A. Ilg,[19] N. Ilic,[154] H. Imam,[35a] T. Ingebretsen Carlson,[47a,47b] G. Introzzi,[72a,72b] M. Iodice,[76a] V. Ippolito,[74a,74b] M. Ishino,[152] W. Islam,[168] C. Issever,[18,48] S. Istin,[21a,y] H. Ito,[166] J. M. Iturbe Ponce,[64a] R. Iuppa,[77a,77b] A. Ivina,[167] J. M. Izen,[45] V. Izzo,[71a] P. Jacka,[130,131] P. Jackson,[1] R. M. Jacobs,[48] B. P. Jaeger,[141] C. S. Jagfeld,[108] G. Jäkel,[169] K. Jakobs,[54] T. Jakoubek,[167] J. Jamieson,[59] K. W. Janas,[84a] G. Jarlskog,[97] A. E. Jaspan,[91] T. Javůrek,[36] M. Javurkova,[102] F. Jeanneau,[134] L. Jeanty,[122] J. Jejelava,[148a,z] P. Jenni,[54,aa] C. E. Jessiman,[34] S. Jézéquel,[4] J. Jia,[144] X. Jia,[61] X. Jia,[14a,14d] Z. Jia,[14c] Y. Jiang,[62a] S. Jiggins,[52] J. Jimenez Pena,[109] S. Jin,[14c] A. Jinaru,[27b] O. Jinnouchi,[153] H. Jivan,[33g] P. Johansson,[138] K. A. Johns,[7] C. A. Johnson,[67] D. M. Jones,[32] E. Jones,[165] R. W.L. Jones,[90] T. J. Jones,[91] J. Jovicevic,[15] X. Ju,[17a] J. J. Junggeburth,[36] A. Juste Rozas,[13,w] S. Kabana,[136e] A. Kaczmarska,[85] M. Kado,[74a,74b] H. Kagan,[118] M. Kagan,[142] A. Kahn,[41] A. Kahn,[127] C. Kahra,[99] T. Kaji,[166] E. Kajomovitz,[149] N. Kakati,[167] C. W. Kalderon,[29] A. Kamenshchikov,[154] N. J. Kang,[135] Y. Kano,[110] D. Kar,[33g] K. Karava,[125] M. J. Kareem,[155b] E. Karentzos,[54] I. Karkanias,[151] S. N. Karpov,[38] Z. M. Karpova,[38] V. Kartvelishvili,[90] A. N. Karyukhin,[37] E. Kasimi,[151] C. Kato,[62d] J. Katzy,[48] S. Kaur,[34] K. Kawade,[139] K. Kawagoe,[88] T. Kawaguchi,[110] T. Kawamoto,[134] G. Kawamura,[55] E. F. Kay,[163] F. I. Kaya,[157] S. Kazakos,[13] V. F. Kazanin,[37] Y. Ke,[144] J. M. Keaveney,[33a] R. Keeler,[163] G. V. Kehris,[61] J. S. Keller,[34] A. S. Kelly,[95] D. Kelsey,[145] J. J. Kempster,[20] J. Kendrick,[20] K. E. Kennedy,[41] O. Kepka,[130] B. P. Kerridge,[165] S. Kersten,[169] B. P. Kerševan,[92] L. Keszeghova,[28a] S. Ketabchi Haghighat,[154] M. Khandoga,[126] A. Khanov,[120] A. G. Kharlamov,[37] T. Kharlamova,[37] E. E. Khoda,[137] T. J. Khoo,[18] G. Khoriauli,[164] J. Khubua,[148b] Y. A.R. Khwaira,[66] M. Kiehn,[36] A. Kilgallon,[122] D. W. Kim,[47a,47b] E. Kim,[153] Y. K. Kim,[39] N. Kimura,[95] A. Kirchhoff,[55] D. Kirchmeier,[50] C. Kirfel,[24] J. Kirk,[133] A. E. Kiryunin,[109] T. Kishimoto,[152] D. P. Kisliuk,[154] C. Kitsaki,[10] O. Kivernyk,[24] M. Klassen,[63a] C. Klein,[34] L. Klein,[164] M. H. Klein,[105] M. Klein,[91] U. Klein,[91] P. Klimek,[36] A. Klimentov,[29] F. Klimpel,[109] T. Klingl,[24] T. Klioutchnikova,[36] F. F. Klitzner,[108] P. Kluit,[113] S. Kluth,[109] E. Kneringer,[78] T. M. Knight,[154] A. Knue,[54] D. Kobayashi,[88] R. Kobayashi,[86] M. Kocian,[142] T. Kodama,[152] P. Kodyš,[132] D. M. Koeck,[145] P. T. Koenig,[24] T. Koffas,[34] N. M. Köhler,[36] M. Kolb,[134] I. Koletsou,[4] T. Komarek,[121] K. Köneke,[54] A. X.Y. Kong,[1] T. Kono,[117] N. Konstantinidis,[95] B. Konya,[97] R. Kopeliansky,[67] S. Koperny,[84a] K. Korcyl,[85] K. Kordas,[151] G. Koren,[150] A. Korn,[95] S. Korn,[55] I. Korolkov,[13] N. Korotkova,[37] B. Kortman,[113] O. Kortner,[109] S. Kortner,[109] W. H. Kostecka,[114] V. V. Kostyukhin,[140] A. Kotsokechagia,[66] A. Kotwal,[51] A. Koulouris,[36] A. Kourkoumeli-Charalampidi,[72a,72b] C. Kourkoumelis,[9] E. Kourlitis,[6] O. Kovanda,[145] R. Kowalewski,[163] W. Kozanecki,[134] A. S. Kozhin,[37] V. A. Kramarenko,[37] G. Kramberger,[92] P. Kramer,[99] M. W. Krasny,[126] A. Krasznahorkay,[36] J. A. Kremer,[99] J. Kretzschmar,[91] K. Kreul,[18] P. Krieger,[154] F. Krieter,[108] S. Krishnamurthy,[102] A. Krishnan,[63b] M. Krivos,[132] K. Krizka,[17a] K. Kroeninger,[49] H. Kroha,[109] J. Kroll,[130]

J. Kroll,[127] K. S. Krowpman,[106] U. Kruchonak,[38] H. Krüger,[24] N. Krumnack,[80] M. C. Kruse,[51] J. A. Krzysiak,[85] A. Kubota,[153] O. Kuchinskaia,[37] S. Kuday,[3a] D. Kuechler,[48] J. T. Kuechler,[48] S. Kuehn,[36] T. Kuhl,[48] V. Kukhtin,[38] Y. Kulchitsky,[37,m] S. Kuleshov,[136d,136b] M. Kumar,[33g] N. Kumari,[101] M. Kuna,[60] A. Kupco,[130] T. Kupfer,[49] A. Kupich,[37] O. Kuprash,[54] H. Kurashige,[83] L. L. Kurchaninov,[155a] Y. A. Kurochkin,[37] A. Kurova,[37] E. S. Kuwertz,[36] M. Kuze,[153] A. K. Kvam,[102] J. Kvita,[121] T. Kwan,[103] K. W. Kwok,[64a] C. Lacasta,[161] F. Lacava,[74a,74b] H. Lacker,[18] D. Lacour,[126] N. N. Lad,[95] E. Ladygin,[38] B. Laforge,[126] T. Lagouri,[136e] S. Lai,[55] I. K. Lakomiec,[84a] N. Lalloue,[60] J. E. Lambert,[119] S. Lammers,[67] W. Lampl,[7] C. Lampoudis,[151] A. N. Lancaster,[114] E. Lançon,[29] U. Landgraf,[54] M. P.J. Landon,[93] V. S. Lang,[54] R. J. Langenberg,[102] A. J. Lankford,[158] F. Lanni,[29] K. Lantzsch,[24] A. Lanza,[72a] A. Lapertosa,[57b,57a] J. F. Laporte,[134] T. Lari,[70a] F. Lasagni Manghi,[23b] M. Lassnig,[36] V. Latonova,[130] T. S. Lau,[64a] A. Laudrain,[99] A. Laurier,[34] S. D. Lawlor,[94] Z. Lawrence,[100] M. Lazzaroni,[70a,70b] B. Le,[100] B. Leban,[92] A. Lebedev,[80] M. LeBlanc,[36] T. LeCompte,[6] F. Ledroit-Guillon,[60] A. C.A. Lee,[95] G. R. Lee,[16] L. Lee,[61] S. C. Lee,[147] S. Lee,[47a,47b] L. L. Leeuw,[33c] H. P. Lefebvre,[94] M. Lefebvre,[163] C. Leggett,[17a] K. Lehmann,[141] G. Lehmann Miotto,[36] W. A. Leight,[102] A. Leisos,[151,ab] M. A.L. Leite,[81c] C. E. Leitgeb,[48] R. Leitner,[132] K. J.C. Leney,[44] T. Lenz,[24] S. Leone,[73a] C. Leonidopoulos,[52] A. Leopold,[143] C. Leroy,[107] R. Les,[106] C. G. Lester,[32] M. Levchenko,[37] J. Levêque,[4] D. Levin,[105] L. J. Levinson,[167] D. J. Lewis,[20] B. Li,[14b] B. Li,[62b] C. Li,[62a] C-Q. Li,[62c,62d] H. Li,[62a] H. Li,[62b] H. Li,[14c] H. Li,[62b] J. Li,[62c] K. Li,[137] L. Li,[62c] M. Li,[14a,14d] Q. Y. Li,[62a] S. Li,[62d,62c,ac] T. Li,[62b] X. Li,[103] Z. Li,[62b] Z. Li,[125] Z. Li,[103] Z. Li,[91] Z. Liang,[14a] M. Liberatore,[48] B. Liberti,[75a] K. Lie,[64c] J. Lieber Marin,[81b] K. Lin,[106] R. A. Linck,[67] R. E. Lindley,[7] J. H. Lindon,[2] A. Linss,[48] E. Lipeles,[127] A. Lipniacka,[16] T. M. Liss,[160,ad] A. Lister,[162] J. D. Little,[4] B. Liu,[14a] B. X. Liu,[141] D. Liu,[62d,62c] J. B. Liu,[62a] J. K.K. Liu,[32] K. Liu,[62d,62c] M. Liu,[62a] M. Y. Liu,[62a] P. Liu,[14a] Q. Liu,[62d,137,62c] X. Liu,[62a] Y. Liu,[48] Y. Liu,[14c,14d] Y. L. Liu,[105] Y. W. Liu,[62a] M. Livan,[72a,72b] J. Llorente Merino,[141] S. L. Lloyd,[93] E. M. Lobodzinska,[48] P. Loch,[7] S. Loffredo,[75a,75b] T. Lohse,[18] K. Lohwasser,[138] M. Lokajicek,[130] J. D. Long,[160] I. Longarini,[74a,74b] L. Longo,[69a,69b] R. Longo,[160] I. Lopez Paz,[36] A. Lopez Solis,[48] J. Lorenz,[108] N. Lorenzo Martinez,[4] A. M. Lory,[108] A. Lösle,[54] X. Lou,[47a,47b] X. Lou,[14a,14d] A. Lounis,[66] J. Love,[6] P. A. Love,[90] J. J. Lozano Bahilo,[161] G. Lu,[14a,14d] M. Lu,[79] S. Lu,[127] Y. J. Lu,[65] H. J. Lubatti,[137] C. Luci,[74a,74b] F. L. Lucio Alves,[14c] A. Lucotte,[60] F. Luehring,[67] I. Luise,[144] O. Lukianchuk,[66] O. Lundberg,[143] B. Lund-Jensen,[143] N. A. Luongo,[122] M. S. Lutz,[150] D. Lynn,[29] H. Lyons,[91] R. Lysak,[130] E. Lytken,[97] F. Lyu,[14a] V. Lyubushkin,[38] T. Lyubushkina,[38] H. Ma,[29] L. L. Ma,[62b] Y. Ma,[95] D. M. Mac Donell,[163] G. Maccarrone,[53] J. C. MacDonald,[138] R. Madar,[40] W. F. Mader,[50] J. Maeda,[83] T. Maeno,[29] M. Maerker,[50] V. Magerl,[54] J. Magro,[68a,68c] H. Maguire,[138] D. J. Mahon,[41] C. Maidantchik,[81b] A. Maio,[129a,129b,129d] K. Maj,[84a] O. Majersky,[28a] S. Majewski,[122] N. Makovec,[66] V. Maksimovic,[15] B. Malaescu,[126] Pa. Malecki,[85] V. P. Maleev,[37] F. Malek,[60] D. Malito,[43b,43a] U. Mallik,[79] C. Malone,[32] S. Maltezos,[10] S. Malyukov,[38] J. Mamuzic,[119] G. Mancini,[53] G. Manco,[72a,72b] J. P. Mandalia,[93] I. Mandić,[92] L. Manhaes de Andrade Filho,[81a] I. M. Maniatis,[151] M. Manisha,[134] J. Manjarres Ramos,[50] D. C. Mankad,[167] K. H. Mankinen,[97] A. Mann,[108] A. Manousos,[78] B. Mansoulie,[134] S. Manzoni,[36] A. Marantis,[151] G. Marchiori,[5] M. Marcisovsky,[130] L. Marcoccia,[75a,75b] C. Marcon,[97] M. Marinescu,[20] M. Marjanovic,[119] Z. Marshall,[17a] S. Marti-Garcia,[161] T. A. Martin,[165] V. J. Martin,[52] B. Martin dit Latour,[16] L. Martinelli,[74a,74b] M. Martinez,[13,w] P. Martinez Agullo,[161] V. I. Martinez Outschoorn,[102] P. Martinez Suarez,[13] S. Martin-Haugh,[133] V. S. Martoiu,[27b] A. C. Martyniuk,[95] A. Marzin,[36] S. R. Maschek,[109] L. Masetti,[99] T. Mashimo,[152] J. Masik,[100] A. L. Maslennikov,[37] L. Massa,[23b] P. Massarotti,[71a,71b] P. Mastrandrea,[73a,73b] A. Mastroberardino,[43b,43a] T. Masubuchi,[152] T. Mathisen,[159] A. Matic,[108] N. Matsuzawa,[152] J. Maurer,[27b] B. Maček,[92] D. A. Maximov,[37] R. Mazini,[147] I. Maznas,[151] M. Mazza,[106] S. M. Mazza,[135] C. Mc Ginn,[29,h] J. P. Mc Gowan,[103] S. P. Mc Kee,[105] T. G. McCarthy,[109] W. P. McCormack,[17a] E. F. McDonald,[104] A. E. McDougall,[113] J. A. Mcfayden,[145] G. Mchedlidze,[148b] R. P. Mckenzie,[33g] T. C. Mclachlan,[48] D. J. Mclaughlin,[95] K. D. McLean,[163] S. J. McMahon,[133] P. C. McNamara,[104] R. A. McPherson,[163,q] J. E. Mdhluli,[33g] S. Meehan,[36] T. Megy,[40] S. Mehlhase,[108] A. Mehta,[91] B. Meirose,[45] D. Melini,[149] B. R. Mellado Garcia,[33g] A. H. Melo,[55] F. Meloni,[48] E. D. Mendes Gouveia,[129a] A. M. Mendes Jacques Da Costa,[20] H. Y. Meng,[154] L. Meng,[90] S. Menke,[109] M. Mentink,[36] E. Meoni,[43b,43a] C. Merlassino,[125] L. Merola,[71a,71b] C. Meroni,[70a] G. Merz,[105] O. Meshkov,[37] J. K.R. Meshreki,[140] J. Metcalfe,[6] A. S. Mete,[6] C. Meyer,[67] J-P. Meyer,[134] M. Michetti,[18] R. P. Middleton,[133] L. Mijović,[52] G. Mikenberg,[167] M. Mikestikova,[130] M. Mikuž,[92] H. Mildner,[138] A. Milic,[154] C. D. Milke,[44] D. W. Miller,[39] L. S. Miller,[34] A. Milov,[167] D. A. Milstead,[47a,47b] T. Min,[14c] A. A. Minaenko,[37] I. A. Minashvili,[148b] L. Mince,[59] A. I. Mincer,[116] B. Mindur,[84a] M. Mineev,[38] Y. Minegishi,[152] Y. Mino,[86] L. M. Mir,[13] M. Miralles Lopez,[161] M. Mironova,[125] T. Mitani,[166] A. Mitra,[165] V. A. Mitsou,[161] O. Miu,[154] P. S. Miyagawa,[93] Y. Miyazaki,[88] A. Mizukami,[82] J. U. Mjörnmark,[97] T. Mkrtchyan,[63a] M. Mlynarikova,[114] T. Moa,[47a,47b] S. Mobius,[55] K. Mochizuki,[107] P. Moder,[48] P. Mogg,[108] A. F. Mohammed,[14a,14d] S. Mohapatra,[41] G. Mokgatitswane,[33g] B. Mondal,[140] S. Mondal,[131] K. Mönig,[48] E. Monnier,[101] L. Monsonis Romero,[161] J. Montejo Berlingen,[36] M. Montella,[118] F. Monticelli,[89] N. Morange,[66] A. L. Moreira De Carvalho,[129a] M. Moreno Llácer,[161] C. Moreno Martinez,[13] P. Morettini,[57b] S. Morgenstern,[165]

M. Morii,[61] M. Morinaga,[152] V. Morisbak,[124] A. K. Morley,[36] F. Morodei,[74a,74b] L. Morvaj,[36] P. Moschovakos,[36] B. Moser,[36] M. Mosidze,[148b] T. Moskalets,[54] P. Moskvitina,[112] J. Moss,[31,ae] E. J.W. Moyse,[102] S. Muanza,[101] J. Mueller,[128] D. Muenstermann,[90] R. Müller,[19] G. A. Mullier,[97] J. J. Mullin,[127] D. P. Mungo,[70a,70b] J. L. Munoz Martinez,[13] D. Munoz Perez,[161] F. J. Munoz Sanchez,[100] M. Murin,[100] W. J. Murray,[165,133] A. Murrone,[70a,70b] J. M. Muse,[119] M. Muškinja,[17a] C. Mwewa,[29] A. G. Myagkov,[37,m] A. J. Myers,[8] A. A. Myers,[128] G. Myers,[67] M. Myska,[131] B. P. Nachman,[17a] O. Nackenhorst,[49] A. Nag,[50] K. Nagai,[125] K. Nagano,[82] J. L. Nagle,[29,h] E. Nagy,[101] A. M. Nairz,[36] Y. Nakahama,[82] K. Nakamura,[82] H. Nanjo,[123] R. Narayan,[44] E. A. Narayanan,[111] I. Naryshkin,[37] M. Naseri,[34] C. Nass,[24] G. Navarro,[22a] J. Navarro-Gonzalez,[161] R. Nayak,[150] P. Y. Nechaeva,[37] F. Nechansky,[48] T. J. Neep,[20] A. Negri,[72a,72b] M. Negrini,[23b] C. Nellist,[112] C. Nelson,[103] K. Nelson,[105] S. Nemecek,[130] M. Nessi,[36,af] M. S. Neubauer,[160] F. Neuhaus,[99] J. Neundorf,[48] R. Newhouse,[162] P. R. Newman,[20] C. W. Ng,[128] Y. S. Ng,[18] Y. W.Y. Ng,[158] B. Ngair,[35e] H. D.N. Nguyen,[107] R. B. Nickerson,[125] R. Nicolaidou,[134] J. Nielsen,[135] M. Niemeyer,[55] N. Nikiforou,[36] V. Nikolaenko,[37,m] I. Nikolic-Audit,[126] K. Nikolopoulos,[20] P. Nilsson,[29] H. R. Nindhito,[56] A. Nisati,[74a] N. Nishu,[2] R. Nisius,[109] J-E. Nitschke,[50] E. K. Nkadimeng,[33g] S. J. Noacco Rosende,[89] T. Nobe,[152] D. L. Noel,[32] Y. Noguchi,[86] T. Nommensen,[146] M. A. Nomura,[29] M. B. Norfolk,[138] R. R.B. Norisam,[95] B. J. Norman,[34] J. Novak,[92] T. Novak,[48] O. Novgorodova,[50] L. Novotny,[131] R. Novotny,[111] L. Nozka,[121] K. Ntekas,[158] E. Nurse,[95] F. G. Oakham,[34,d] J. Ocariz,[126] A. Ochi,[83] I. Ochoa,[129a] S. Oda,[88] S. Oerdek,[159] A. Ogrodnik,[84a] A. Oh,[100] C. C. Ohm,[143] H. Oide,[153] R. Oishi,[152] M. L. Ojeda,[48] Y. Okazaki,[86] M. W. O'Keefe,[91] Y. Okumura,[152] A. Olariu,[27b] L. F. Oleiro Seabra,[129a] S. A. Olivares Pino,[136e] D. Oliveira Damazio,[29] D. Oliveira Goncalves,[81a] J. L. Oliver,[158] M. J.R. Olsson,[158] A. Olszewski,[85] J. Olszowska,[85,j] Ö. O. Öncel,[54] D. C. O'Neil,[141] A. P. O'Neill,[19] A. Onofre,[129a,129e] P. U.E. Onyisi,[11] M. J. Oreglia,[39] G. E. Orellana,[89] D. Orestano,[76a,76b] N. Orlando,[13] R. S. Orr,[154] V. O'Shea,[59] R. Ospanov,[62a] G. Otero y Garzon,[30] H. Otono,[88] P. S. Ott,[63a] G. J. Ottino,[17a] M. Ouchrif,[35d] J. Ouellette,[29,h] F. Ould-Saada,[124] M. Owen,[59] R. E. Owen,[133] K. Y. Oyulmaz,[21a] V. E. Ozcan,[21a] N. Ozturk,[8] S. Ozturk,[21d] J. Pacalt,[121] H. A. Pacey,[32] K. Pachal,[51] A. Pacheco Pages,[13] C. Padilla Aranda,[13] G. Padovano,[74a,74b] S. Pagan Griso,[17a] G. Palacino,[67] A. Palazzo,[69a,69b] S. Palazzo,[52] S. Palestini,[36] M. Palka,[84b] J. Pan,[170] D. K. Panchal,[11] C. E. Pandini,[113] J. G. Panduro Vazquez,[94] P. Pani,[48] G. Panizzo,[68a,68c] L. Paolozzi,[56] C. Papadatos,[107] S. Parajuli,[44] A. Paramonov,[6] C. Paraskevopoulos,[10] D. Paredes Hernandez,[64b] T. H. Park,[154] M. A. Parker,[32] F. Parodi,[57b,57a] E. W. Parrish,[114] V. A. Parrish,[52] J. A. Parsons,[41] U. Parzefall,[54] B. Pascual Dias,[107] L. Pascual Dominguez,[150] V. R. Pascuzzi,[17a] F. Pasquali,[113] E. Pasqualucci,[74a] S. Passaggio,[57b] F. Pastore,[94] P. Pasuwan,[47a,47b] J. R. Pater,[100] J. Patton,[91] T. Pauly,[36] J. Pearkes,[142] M. Pedersen,[124] R. Pedro,[129a] S. V. Peleganchuk,[37] O. Penc,[130] C. Peng,[64b] H. Peng,[62a] M. Penzin,[37] B. S. Peralva,[81a] A. P. Pereira Peixoto,[60] L. Pereira Sanchez,[47a,47b] D. V. Perepelitsa,[29,h] E. Perez Codina,[155a] M. Perganti,[10] L. Perini,[70a,70b,j] H. Pernegger,[36] S. Perrella,[36] A. Perrevoort,[112] O. Perrin,[40] K. Peters,[48] R. F.Y. Peters,[100] B. A. Petersen,[36] T. C. Petersen,[42] E. Petit,[101] V. Petousis,[131] C. Petridou,[151] A. Petrukhin,[140] M. Pettee,[17a] N. E. Pettersson,[36] A. Petukhov,[37] K. Petukhova,[132] A. Peyaud,[134] R. Pezoa,[136f] L. Pezzotti,[36] G. Pezzullo,[170] T. Pham,[104] P. W. Phillips,[133] M. W. Phipps,[160] G. Piacquadio,[144] E. Pianori,[17a] F. Piazza,[70a,70b] R. Piegaia,[30] D. Pietreanu,[27b] A. D. Pilkington,[100] M. Pinamonti,[68a,68c] J. L. Pinfold,[2] B. C. Pinheiro Pereira,[129a] C. Pitman Donaldson,[95] D. A. Pizzi,[34] L. Pizzimento,[75a,75b] A. Pizzini,[113] M.-A. Pleier,[29] V. Plesanovs,[54] V. Pleskot,[132] E. Plotnikova,[38] G. Poddar,[4] R. Poettgen,[97] R. Poggi,[56] L. Poggioli,[126] I. Pogrebnyak,[106] D. Pohl,[24] I. Pokharel,[55] S. Polacek,[132] G. Polesello,[72a] A. Poley,[141,155a] R. Polifka,[131] A. Polini,[23b] C. S. Pollard,[125] Z. B. Pollock,[118] V. Polychronakos,[29] D. Ponomarenko,[37] L. Pontecorvo,[36] S. Popa,[27a] G. A. Popeneciu,[27d] D. M. Portillo Quintero,[155a] S. Pospisil,[131] P. Postolache,[27c] K. Potamianos,[125] I. N. Potrap,[38] C. J. Potter,[32] H. Potti,[1] T. Poulsen,[48] J. Poveda,[161] G. Pownall,[48] M. E. Pozo Astigarraga,[36] A. Prades Ibanez,[161] M. M. Prapa,[46] D. Price,[100] M. Primavera,[69a] M. A. Principe Martin,[98] M. L. Proffitt,[137] N. Proklova,[37] K. Prokofiev,[64c] G. Proto,[75a,75b] S. Protopopescu,[29] J. Proudfoot,[6] M. Przybycien,[84a] J. E. Puddefoot,[138] D. Pudzha,[37] P. Puzo,[66] D. Pyatiizbyantseva,[37] J. Qian,[105] Y. Qin,[100] T. Qiu,[93] A. Quadt,[55] M. Queitsch-Maitland,[24] G. Rabanal Bolanos,[61] D. Rafanoharana,[54] F. Ragusa,[70a,70b] J. L. Rainbolt,[39] J. A. Raine,[56] S. Rajagopalan,[29] E. Ramakoti,[37] K. Ran,[14a,14d] V. Raskina,[126] D. F. Rassloff,[63a] S. Rave,[99] B. Ravina,[59] I. Ravinovich,[167] M. Raymond,[36] A. L. Read,[124] N. P. Readioff,[138] D. M. Rebuzzi,[72a,72b] G. Redlinger,[29] K. Reeves,[45] J. A. Reidelsturz,[169] D. Reikher,[150] A. Reiss,[99] A. Rej,[140] C. Rembser,[36] A. Renardi,[48] M. Renda,[27b] M. B. Rendel,[109] A. G. Rennie,[59] S. Resconi,[70a] M. Ressegotti,[57b,57a] E. D. Resseguie,[17a] S. Rettie,[95] B. Reynolds,[118] E. Reynolds,[17a] M. Rezaei Estabragh,[169] O. L. Rezanova,[37] P. Reznicek,[132] E. Ricci,[77a,77b] R. Richter,[109] S. Richter,[47a,47b] E. Richter-Was,[84b] M. Ridel,[126] P. Rieck,[116] P. Riedler,[36] M. Rijssenbeek,[144] A. Rimoldi,[72a,72b] M. Rimoldi,[48] L. Rinaldi,[23b,23a] T. T. Rinn,[29] M. P. Rinnagel,[108] G. Ripellino,[143] I. Riu,[13] P. Rivadeneira,[48] J. C. Rivera Vergara,[163] F. Rizatdinova,[120] E. Rizvi,[93] C. Rizzi,[56] B. A. Roberts,[165] B. R. Roberts,[17a] S. H. Robertson,[103,q] M. Robin,[48] D. Robinson,[32] C. M. Robles Gajardo,[136f] M. Robles Manzano,[99] A. Robson,[59] A. Rocchi,[75a,75b] C. Roda,[73a,73b] S. Rodriguez Bosca,[63a] Y. Rodriguez Garcia,[22a] A. Rodriguez Rodriguez,[54] A. M. Rodríguez Vera,[155b] S. Roe,[36]

J. T. Roemer,[158] A. R. Roepe-Gier,[119] J. Roggel,[169] O. Røhne,[124] R. A. Rojas,[163] B. Roland,[54] C. P.A. Roland,[67] J. Roloff,[29] A. Romaniouk,[37] E. Romano,[72a,72b] M. Romano,[23b] A. C. Romero Hernandez,[160] N. Rompotis,[91] L. Roos,[126] S. Rosati,[74a] B. J. Rosser,[39] E. Rossi,[4] E. Rossi,[71a,71b] L. P. Rossi,[57b] L. Rossini,[48] R. Rosten,[118] M. Rotaru,[27b] B. Rottler,[54] D. Rousseau,[66] D. Rousso,[32] G. Rovelli,[72a,72b] A. Roy,[160] A. Rozanov,[101] Y. Rozen,[149] X. Ruan,[33g] A. Rubio Jimenez,[161] A. J. Ruby,[91] T. A. Ruggeri,[1] F. Rühr,[54] A. Ruiz-Martinez,[161] A. Rummler,[36] Z. Rurikova,[54] N. A. Rusakovich,[38] H. L. Russell,[163] J. P. Rutherfoord,[7] E. M. Rüttinger,[138] K. Rybacki,[90] M. Rybar,[132] E. B. Rye,[124] A. Ryzhov,[37] J. A. Sabater Iglesias,[56] P. Sabatini,[161] L. Sabetta,[74a,74b] H.F-W. Sadrozinski,[135] F. Safai Tehrani,[74a] B. Safarzadeh Samani,[145] M. Safdari,[142] S. Saha,[103] M. Sahinsoy,[109] M. Saimpert,[134] M. Saito,[152] T. Saito,[152] D. Salamani,[36] G. Salamanna,[76a,76b] A. Salnikov,[142] J. Salt,[161] A. Salvador Salas,[13] D. Salvatore,[43b,43a] F. Salvatore,[145] A. Salzburger,[36] D. Sammel,[54] D. Sampsonidis,[151] D. Sampsonidou,[62d,62c] J. Sánchez,[161] A. Sanchez Pineda,[4] V. Sanchez Sebastian,[161] H. Sandaker,[124] C. O. Sander,[48] J. A. Sandesara,[102] M. Sandhoff,[169] C. Sandoval,[22b] D. P.C. Sankey,[133] A. Sansoni,[53] L. Santi,[74a,74b] C. Santoni,[40] H. Santos,[129a,129b] S. N. Santpur,[17a] A. Santra,[167] K. A. Saoucha,[138] J. G. Saraiva,[129a,129d] J. Sardain,[101] O. Sasaki,[82] K. Sato,[156] C. Sauer,[63b] F. Sauerburger,[54] E. Sauvan,[4] P. Savard,[154,d] R. Sawada,[152] C. Sawyer,[133] L. Sawyer,[96] I. Sayago Galvan,[161] C. Sbarra,[23b] A. Sbrizzi,[23b,23a] T. Scanlon,[95] J. Schaarschmidt,[137] P. Schacht,[109] D. Schaefer,[39] U. Schäfer,[99] A. C. Schaffer,[66] D. Schaile,[108] R. D. Schamberger,[144] E. Schanet,[108] C. Scharf,[18] V. A. Schegelsky,[37] D. Scheirich,[132] F. Schenck,[18] M. Schernau,[158] C. Scheulen,[55] C. Schiavi,[57b,57a] Z. M. Schillaci,[26] E. J. Schioppa,[69a,69b] M. Schioppa,[43b,43a] B. Schlag,[99] K. E. Schleicher,[54] S. Schlenker,[36] K. Schmieden,[99] C. Schmitt,[99] S. Schmitt,[48] L. Schoeffel,[134] A. Schoening,[63b] P. G. Scholer,[54] E. Schopf,[125] M. Schott,[99] J. Schovancova,[36] S. Schramm,[56] F. Schroeder,[169] H-C. Schultz-Coulon,[63a] M. Schumacher,[54] B. A. Schumm,[135] Ph. Schune,[134] A. Schwartzman,[142] T. A. Schwarz,[105] Ph. Schwemling,[134] R. Schwienhorst,[106] A. Sciandra,[135] G. Sciolla,[26] F. Scuri,[73a] F. Scutti,[104] C. D. Sebastiani,[91] K. Sedlaczek,[49] P. Seema,[18] S. C. Seidel,[111] A. Seiden,[135] B. D. Seidlitz,[41] T. Seiss,[39] C. Seitz,[48] J. M. Seixas,[81b] G. Sekhniaidze,[71a] S. J. Sekula,[44] L. Selem,[4] N. Semprini-Cesari,[23b,23a] S. Sen,[51] V. Senthilkumar,[161] L. Serin,[66] L. Serkin,[68a,68b] M. Sessa,[76a,76b] H. Severini,[119] S. Sevova,[142] F. Sforza,[57b,57a] A. Sfyrla,[56] E. Shabalina,[55] R. Shaheen,[143] J. D. Shahinian,[127] N. W. Shaikh,[47a,47b] D. Shaked Renous,[167] L. Y. Shan,[14a] M. Shapiro,[17a] A. Sharma,[36] A. S. Sharma,[162] P. Sharma,[79] S. Sharma,[48] P. B. Shatalov,[37] K. Shaw,[145] S. M. Shaw,[100] Q. Shen,[62c] P. Sherwood,[95] L. Shi,[95] C. O. Shimmin,[170] Y. Shimogama,[166] J. D. Shinner,[94] I. P.J. Shipsey,[125] S. Shirabe,[60] M. Shiyakova,[38] J. Shlomi,[167] M. J. Shochet,[39] J. Shojaii,[104] D. R. Shope,[143] S. Shrestha,[118] E. M. Shrif,[33g] M. J. Shroff,[163] P. Sicho,[130] A. M. Sickles,[160] E. Sideras Haddad,[33g] O. Sidiropoulou,[36] A. Sidoti,[23b] F. Siegert,[50] Dj. Sijacki,[15] R. Sikora,[84a] F. Sili,[89] J. M. Silva,[20] M. V. Silva Oliveira,[36] S. B. Silverstein,[47a] S. Simion,[66] R. Simoniello,[36] E. L. Simpson,[59] N. D. Simpson,[97] S. Simsek,[21d] S. Sindhu,[55] P. Sinervo,[154] V. Sinetckii,[37] S. Singh,[141] S. Singh,[154] S. Sinha,[48] S. Sinha,[33g] M. Sioli,[23b,23a] I. Siral,[122] S.Yu. Sivoklokov,[37,j] J. Sjölin,[47a,47b] A. Skaf,[55] E. Skorda,[97] P. Skubic,[119] M. Slawinska,[85] V. Smakhtin,[167] B. H. Smart,[133] J. Smiesko,[132] S.Yu. Smirnov,[37] Y. Smirnov,[37] L. N. Smirnova,[37,m] O. Smirnova,[97] E. A. Smith,[39] H. A. Smith,[125] J. L. Smith,[91] R. Smith,[142] M. Smizanska,[90] K. Smolek,[131] A. Smykiewicz,[85] A. A. Snesarev,[37] H. L. Snoek,[113] S. Snyder,[29] R. Sobie,[163,q] A. Soffer,[150] C. A. Solans Sanchez,[36] E.Yu. Soldatov,[37] U. Soldevila,[161] A. A. Solodkov,[37] S. Solomon,[54] A. Soloshenko,[38] K. Solovieva,[54] O. V. Solovyanov,[37] V. Solovyev,[37] P. Sommer,[36] A. Sonay,[13] W. Y. Song,[155b] A. Sopczak,[131] A. L. Sopio,[95] F. Sopkova,[28b] V. Sothilingam,[63a] S. Sottocornola,[72a,72b] R. Soualah,[115c] Z. Soumaimi,[35e] D. South,[48] S. Spagnolo,[69a,69b] M. Spalla,[109] F. Spanò,[94] D. Sperlich,[54] G. Spigo,[36] M. Spina,[145] S. Spinali,[90] D. P. Spiteri,[59] M. Spousta,[132] E. J. Staats,[34] A. Stabile,[70a,70b] R. Stamen,[63a] M. Stamenkovic,[113] A. Stampekis,[20] M. Standke,[24] E. Stanecka,[85] B. Stanislaus,[17a] M. M. Stanitzki,[48] M. Stankaityte,[125] B. Stapf,[48] E. A. Starchenko,[37] G. H. Stark,[135] J. Stark,[101] D. M. Starko,[155b] P. Staroba,[130] P. Starovoitov,[63a] S. Stärz,[103] R. Staszewski,[85] G. Stavropoulos,[46] J. Steentoft,[159] P. Steinberg,[29] A. L. Steinhebel,[122] B. Stelzer,[141,155a] H. J. Stelzer,[128] O. Stelzer-Chilton,[155a] H. Stenzel,[58] T. J. Stevenson,[145] G. A. Stewart,[36] M. C. Stockton,[36] G. Stoicea,[27b] M. Stolarski,[129a] S. Stonjek,[109] A. Straessner,[50] J. Strandberg,[143] S. Strandberg,[47a,47b] M. Strauss,[119] T. Strebler,[101] P. Strizenec,[28b] R. Ströhmer,[164] D. M. Strom,[122] L. R. Strom,[48] R. Stroynowski,[44] A. Strubig,[47a,47b] S. A. Stucci,[29] B. Stugu,[16] J. Stupak,[119] N. A. Styles,[48] D. Su,[142] S. Su,[62a] W. Su,[62d,137,62c] X. Su,[62a,66] K. Sugizaki,[152] V. V. Sulin,[37] M. J. Sullivan,[91] D. M.S. Sultan,[77a,77b] L. Sultanaliyeva,[37] S. Sultansoy,[3b] T. Sumida,[86] S. Sun,[105] S. Sun,[168] O. Sunneborn Gudnadottir,[159] M. R. Sutton,[145] M. Svatos,[130] M. Swiatlowski,[155a] T. Swirski,[164] I. Sykora,[28a] M. Sykora,[132] T. Sykora,[132] D. Ta,[99] K. Tackmann,[48,ag] A. Taffard,[158] R. Tafirout,[155a] J. S. Tafoya Vargas,[66] R. H.M. Taibah,[126] R. Takashima,[87] K. Takeda,[83] E. P. Takeva,[52] Y. Takubo,[82] M. Talby,[101] A. A. Talyshev,[37] K. C. Tam,[64b] N. M. Tamir,[150] A. Tanaka,[152] J. Tanaka,[152] R. Tanaka,[66] M. Tanasini,[57b,57a] J. Tang,[62c] Z. Tao,[162] S. Tapia Araya,[80] S. Tapprogge,[99] A. Tarek Abouelfadl Mohamed,[106] S. Tarem,[149] K. Tariq,[62b] G. Tarna,[27b] G. F. Tartarelli,[70a] P. Tas,[132] M. Tasevsky,[130] E. Tassi,[43b,43a] A. C. Tate,[160] G. Tateno,[152] Y. Tayalati,[35e] G. N. Taylor,[104] W. Taylor,[155b] H. Teagle,[91] A. S. Tee,[168] R. Teixeira De Lima,[142] P. Teixeira-Dias,[94] J. J. Teoh,[154] K. Terashi,[152] J. Terron,[98]

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