EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-272
LHCb-PAPER-2024-041
November 7, 2024

Measurement of the $\psi(2S)$ to J/ψ cross-section ratio as a function of centrality in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02\,\text{TeV}$

LHCb collaboration[†]

Abstract

The dissociation of quarkonium states with different binding energies produced in heavy-ion collisions is a powerful probe for investigating the formation and properties of the quark-gluon plasma. The ratio of production cross-sections of $\psi(2S)$ and J/ψ mesons times the ratio of their branching fractions into the dimuon final state is measured as a function of centrality using data collected by the LHCb detector in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The measured ratio shows no dependence on the collision centrality, and is compared to the latest theory predictions and to the recent measurements in literature.

Submitted to JHEP

[†]Authors are listed at the end of this paper.

1 Introduction

The production of charmonia, in particular of the J/ψ and $\psi(2S)$ states, has long been considered a key probe for understanding the properties of the quark-gluon plasma (QGP). The idea that quarkonium suppression is an indicator of QGP formation was introduced by T. Matsui and H. Satz, who proposed that in deconfined nuclear matter, $c\bar{c}$ pairs become unbound under the effect of colour screening [1]. Following their theory, quarkonium states, and in particular those that are loosely bound (Fig. 1), dissociate in the hot and dense medium produced in heavy-ion collisions. Experimentally, the relative yields between different quarkonium states are thus expected to change with the centrality of the collision, the latter being closely related to the temperature of the medium.

Early results from the NA50 collaboration at the SPS showed J/ψ suppression in PbPb collisions [2,3]. These results were extensively debated but were not a conclusive signature of QGP formation as other competing mechanisms can also contribute to quarkonium suppression, including cold nuclear matter (CNM) effects such as shadowing and nuclear absorption, and final-state interactions with comoving particles. Further studies by the E866 [4], PHENIX [5], ALICE [6], CMS [7] and LHCb [8,9] experiments showed that the suppression is observed even in smaller collision systems like proton-nucleus (pA), known to be less prone to colour-screening effects. In particular, the suppression of $\psi(2S)$ production relative to that of J/ψ states in pA collisions suggests that comovers, rather than QGP effects alone, are important in understanding quarkonium behaviour in high-energy collisions. Theoretical models accounting for these effects have been developed to provide a more comprehensive interpretation of the data [10].

In addition, J/ψ production in heavy-ion collisions was extensively studied by RHIC and LHC experiments which played a crucial role in understanding quarkonium suppression in a hot and dense medium. Results from the PHENIX [11] and STAR [12] experiments demonstrated significant suppression of J/ψ yields in AuAu collisions, while also providing insight into the competing effects of QGP formation and CNM contributions. These findings were then complemented by the ALICE [13] and CMS [14] experiments which studied charmonium production in a variety of collision systems including PbPb, and also by the LHCb collaboration, which focused on the different production mechanisms [15]. Together, these studies have advanced the understanding of the interplay between cold and hot nuclear matter effects, motivating new investigations of the properties of the medium through the relative suppression of quarkonium states.

In this paper, the relative production of $\psi(2S)$ to J/ψ states, both decaying to two muons, is studied as a function of centrality using the 2018 PbPb collision data collected at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\rm NN}} = 5.02\,\text{TeV}$ by the LHCb experiment, corresponding to an integrated luminosity of around $230\,\mu\text{b}^{-1}$ [18]. The ratio of cross-sections (σ) of the two charmonium states multiplied by their branching fractions ($\mathcal{B}$) in the dimuon channel is measured as

$$\frac{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)} \cdot \frac{\sigma(\psi(2S))}{\sigma(J/\psi)} = \frac{N(\psi(2S))}{N(J/\psi)} \cdot \frac{\varepsilon_{\rm tot}(J/\psi)}{\varepsilon_{\rm tot}(\psi(2S))}, \tag{1}$$

where N and $\varepsilon_{\rm tot}$ are the signal yields and efficiencies, respectively.

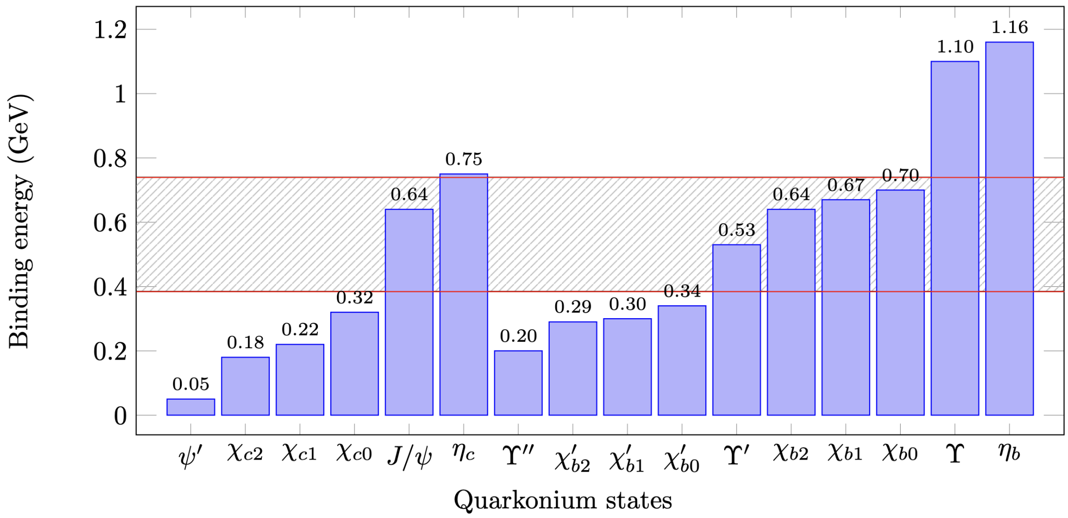

Figure 1: Binding energies of different quarkonium states taken from Ref. [16]. The hatched band indicates the QGP temperature estimated from thermal photon yields [17] in PbPb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The symbol ψ' stands for the $\psi(2S)$ state.

2 The LHCb detector and data selection

The LHCb detector [19,20] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the interaction region [21], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about $4\,\mathrm{T\,m}$, and three stations of silicon-strip detectors and straw drift tubes [22] placed downstream of the magnet. The tracking system provides a measurement of the momentum, p, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at $200\,\mathrm{GeV}/c$. The minimum distance of a track to a primary vertex (PV), the impact parameter, is measured with a resolution of $(15 + 29/p_{\mathrm{T}})\,\mu\mathrm{m}$, where p_{T} is the component of the momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors (RICH) [23]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter (ECAL and HCAL). Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [24].

The online event selection is performed by a trigger [25], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. At the hardware level, events are required to have a muon with high p_{T}. Events are selected at software level if the number of clusters in the VELO, N_{c}, satisfies $6000 < N_{\mathrm{c}} < 10000$ or if $N_{\mathrm{c}} < 6000$ and two muons with $p_{\mathrm{T}} > 400\,\mathrm{MeV}/c$ are identified. Moreover, to suppress contamination from Pb-gas interactions,[1] a minimum of 15 VELO tracks in the backward direction, $\eta < 0$, is required, along with the condition that the PV must be close to the beam collision point. The

[1]Neon gas was injected in the beam pipe near the interaction point, using the LHCb fixed-target SMOG system [18], concurrently with PbPb collisions.

J/ψ and $\psi(2S)$ candidates are reconstructed in the dimuon final state, satisfying selection requirements on transverse momentum, $0.3 < p_{\mathrm{T}} < 10\,\mathrm{GeV}/c$, and rapidity, $2.0 < y < 4.5$. The two muons are both required to have p_{T} greater then $900\,\mathrm{MeV}/c$ and to satisfy particle identification (PID) requirements based on information from the RICH, calorimeter and muon systems.

3 Yields in centrality intervals

The charmonium yields are determined in intervals of the collision centrality. Centrality intervals are defined as percentiles of the total inelastic hadronic PbPb cross-section and are associated with the impact parameter of the colliding particles and the mean number of participating nucleons, $\langle N_{\mathrm{part}}\rangle$ [26]. A higher centrality percentile corresponds to more peripheral collisions with a larger impact parameter, while a lower centrality percentile corresponds to more central collisions with a smaller impact parameter. To estimate these geometric quantities, the Glauber Monte Carlo (GMC) model adapted to LHCb conditions is used [26, 27]. The impact parameter cannot be measured directly and is instead estimated using the total energy deposited in the ECAL, with which it scales linearly. The method is based on a binned fit of the total ECAL energy in simulated minimum-bias PbPb interactions where the GMC model is used and the experimental conditions of the signal sample are reproduced. This fit establishes a per-event dependence of $\langle N_{\mathrm{part}}\rangle$ and the collision centrality in terms of the energy deposited in the ECAL. The centrality intervals used are defined in Table 1. The data used to determine the ratio are limited to centrality values down to about 65 % due to the inability of the detector to cope with the increasing occupancy.

The charmonium yields, $N(\psi(2S))$ and $N(J/\psi)$, are extracted by an unbinned maximum-likelihood fit to the dimuon invariant-mass distribution in each centrality interval where the J/ψ signal is modelled by a Crystal Ball function [28] with tail parameters fixed from simulation. A Gaussian function is used to describe the $\psi(2S)$ signal; the difference between the peak positions of the J/ψ and $\psi(2S)$ signals is fixed to the difference of the known masses of the two states [29]. The background is described by an exponential function. Figure 2 shows the dimuon invariant-mass distribution in each centrality interval compared to the fit results. The J/ψ and $\psi(2S)$ yields extracted by the fit are shown in Table 1.

Table 1: Range for the number of participating nucleons $\langle N_{\mathrm{part}}\rangle$ and signal yields in each centrality interval.

Centrality (%)	90–100	80–90	70–80	60–70
$\langle N_{\mathrm{part}}\rangle$	2.4–5.5	5.5–13.0	13.0–26.5	26.5–48.0
$N(J/\psi)$	596 ± 28	2099 ± 52	3320 ± 74	2221 ± 77
$N(\psi(2S))$	13 ± 5	53 ± 14	68 ± 26	85 ± 36

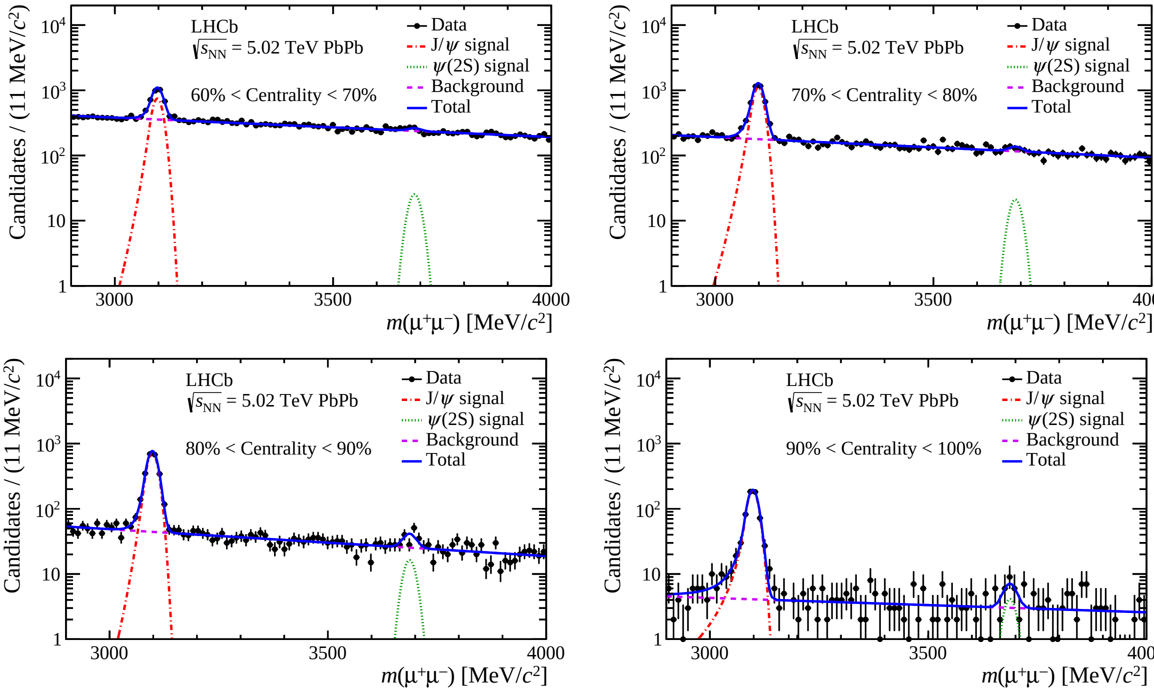

Figure 2: Dimuon invariant-mass distributions in each centrality interval after all selection requirements are applied, compared to the fit results.

4 Simulation and efficiencies

The total signal selection efficiencies $\varepsilon_{\rm tot}$ in Eq. 1 are determined using simulation. The simulated decays are reconstructed and analysed using the same software tools as those used to process the data. In the simulation, J/ψ and $\psi(2S)$ particles are generated using PYTHIA [30] and embedded into minimum-bias PbPb collisions from the EPOS event generator [31]. The decays of unstable particles are described by EVTGEN [32], in which final-state radiation is generated using PHOTOS [33]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [34, 35] adapted to LHCb [36]. After reconstruction, the simulated events are weighted to improve agreement with data. The correction weights are obtained as a function of $p_{\rm T}$ and $N_{\rm c}$ from the background-subtracted data and simulation sample of J/ψ candidates. The total efficiencies include the geometric acceptance of the detector, the candidate reconstruction and selection, the particle identification and the effect of the trigger, which are estimated in each centrality interval, using the weighted simulation.

The acceptance efficiency, defined as the fraction of $J/\psi \to \mu^+\mu^-$ decays with both muons entering the acceptance of the LHCb spectrometer, is determined using a simulation sample produced without any requirement on the kinematics of the decay products. This efficiency is found to be independent of centrality. The combined reconstruction and selection efficiency is calculated as the fraction of generated events in the acceptance that pass the selection requirements other than those related to PID and the trigger. The PID efficiency for the two muons is estimated from dedicated pp calibration data samples, and computed as a function of the muon kinematics. Specifically, the muon PID efficiency is determined in intervals of muon $p_{\rm T}$ and $N_{\rm c}$, showing a smooth dependence up to the

Table 2: Range of the relative systematic uncertainty contributions for the ratio measurement across the four centrality intervals.

Source	Uncertainty (%)
Signal fit model	0.5–2.2
Background fit model	0.5–6.3
Weighting procedure	0.1–0.2
PID efficiency extrapolation	0.1–2.8
Simulation sample size	0.5–1.0
Trigger efficiency estimation	< 0.1

edge of the multiplicity region at $N_c = 5000$. In each muon p_T bin, it is then extrapolated via a quadratic fit function to N_c values up to 10000, to cover the multiplicity region of the measurement reported here using PbPb collisions. Finally, the trigger efficiency is computed as the fraction of simulated signal particles that pass the trigger requirement.

5 Systematic uncertainties

Several sources of systematic uncertainty associated with the determination of the signal and background yields and with the evaluation of the efficiencies are considered.

The systematic uncertainty arising from the signal parametrisation consists of two contributions. The first is associated with the choice of the fixed parameters of the J/ψ signal fit function. It is estimated by varying the parameters within their uncertainties obtained in simulation. The second contribution is estimated by repeating the signal yield extraction with an alternative parametrisation of the J/ψ signal using the convolution of a Crystal Ball and a Gaussian function where both widths are free to vary. Compared to the large statistical uncertainty affecting the $\psi(2S)$ yield, the systematic uncertainty arising from the $\psi(2S)$ fit model is negligibly small and ignored. The uncertainty in background modelling is assessed by comparing the results from the baseline fit to those obtained using a second-order polynomial instead of the exponential function.

The systematic uncertainty arising from the evaluation of the efficiencies consists of different contributions. The first contribution is related to the weighting procedure applied to the simulation, and is taken into consideration by randomly varying each weight within its uncertainty and estimating the total efficiencies again. Using 50 different sets of generated weights, the uncertainty considered is the relative variation of the obtained efficiencies. Another contribution pertains to the estimation of the PID efficiency. An alternative approach is used, where the extrapolation to the high-multiplicity region that is not covered by the *pp* calibration sample is performed with a linear function instead of a second-order polynomial. The limited size of the simulation sample used to determine the efficiencies is also a source of systematic uncertainty, and is taken into account using the statistical uncertainties of the efficiencies determined from simulation. Finally, a systematic uncertainty due to the trigger efficiency is assigned by using a data-driven method where the efficiency is determined from events triggered independently of the signal muons [37]. The total systematic uncertainty is computed as the sum in quadrature of each contribution shown in Table 2.

6 Results

The results in different centrality intervals are listed in Table 3 and are presented as a function of the number of participating nucleons $\langle N_{\text{part}} \rangle$ in Figs. 3 and 4, where they are compared with some of the recently published measurements and with theory predictions, respectively. In particular, Fig. 3 compares these results to the ALICE measurement [38], performed in PbPb collisions at the same centre-of-mass energy and at similar rapidities and transverse momenta but covering different centrality region. The two measurements are in agreement within uncertainties in the overlapping region, showing no dependency on $\langle N_{\text{part}} \rangle$. The LHCb *pp* [39] and *p*Pb [40] measurements are reported in the same figure showing also agreement with the results reported here. The ratio measured in these studies is integrated over the kinematic range, and is associated with a number of participating nucleons of $\langle N_{\text{part}} \rangle = 2$ (8) for the *pp* (*p*Pb) measurement, as estimated using the GMC model [27].

Figure 4 shows a comparison of these results with two recent theoretical calculations. In the statistical hadronization model (SHMc) [41, 42], it is assumed that, near the phase boundary between the QGP at high temperatures and the confined hadronic matter at lower temperatures, a fireball is formed during collisions, which is near thermal equilibrium. The TAMU model [43, 44] is a transport model developed in a nonperturbative hydro-Langevin-RRM framework that includes collisional energy loss and heavy-quark diffusion in the medium. When compared to the data reported in this article, the SHMc model, although showing no dependency of the ratio on the centrality, generally underestimates its value. On the other hand, the TAMU model predictions are in better agreement with the experimental result, especially in the lower multiplicity intervals. A slight disagreement is observed in the highest multiplicity interval, where the data differ from the two theoretical predictions and the ALICE measurement by approximately 1.5 standard deviations.

Table 3: Cross-section times branching fraction ratio between $\psi(2S)$ and J/ψ states in intervals of centrality and corresponding number of participating nucleons $\langle N_{\text{part}} \rangle$. The first uncertainties are statistical and the second are systematic.

Centrality (%)	$\langle N_{\text{part}} \rangle$	$\frac{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)} \cdot \frac{\sigma(\psi(2S))}{\sigma(J/\psi)}$
90–100	2.40–5.50	$0.018 \pm 0.007 \pm 0.001$
80–90	5.50–13.0	$0.020 \pm 0.005 \pm 0.001$
70–80	13.0–26.5	$0.016 \pm 0.006 \pm 0.001$
60–70	26.5–48.0	$0.027 \pm 0.011 \pm 0.001$

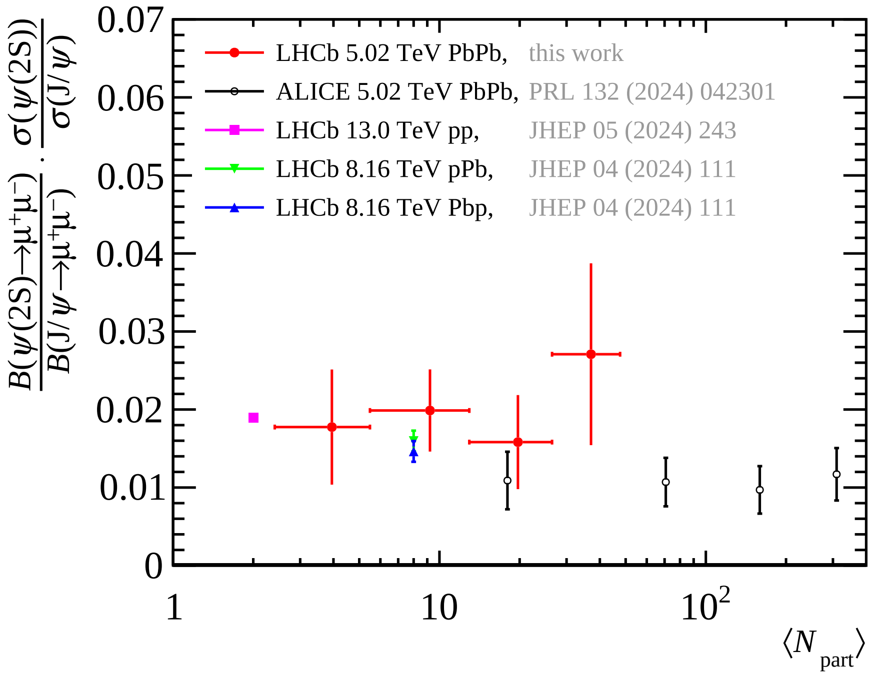

Figure 3: Cross-section times branching fraction ratio between $\psi(2S)$ and J/ψ states as a function of the number of participating nucleons $\langle N_{\text{part}}\rangle$ compared with ALICE PbPb [38] and LHCb pp [39] and pPb [40] results.

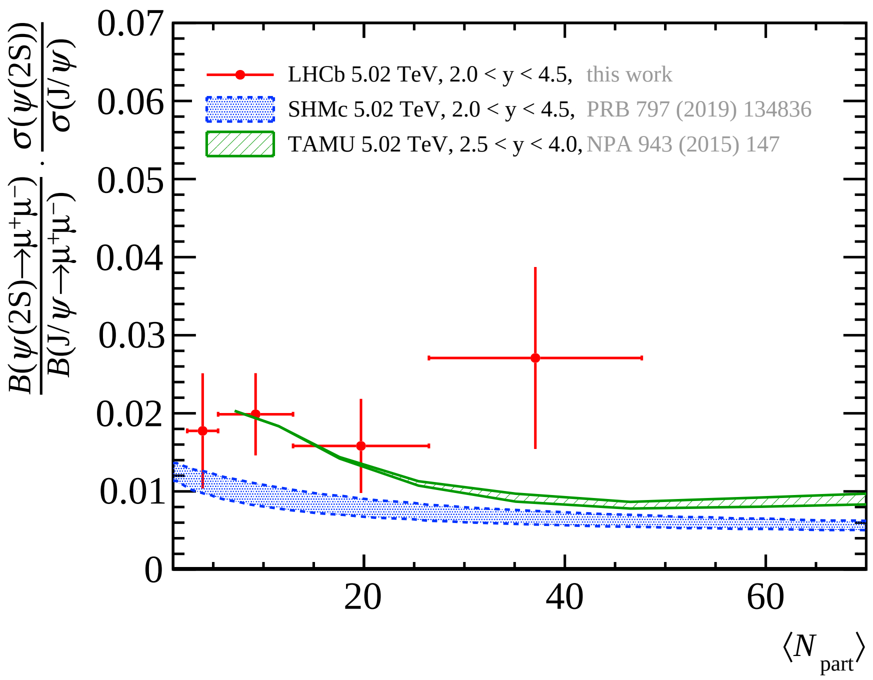

Figure 4: Cross-section times branching fraction ratio between $\psi(2S)$ and J/ψ states as a function of the number of participating nucleons $\langle N_{\text{part}}\rangle$ compared with the SHMc [41, 42] and TAMU models [43, 44] predictions shown by the coloured bands representing the uncertainties.

7 Conclusions

The $\psi(2S)$ to J/ψ production cross-section ratio in PbPb collisions at a centre-of-mass energy of 5.02 TeV corresponding to an integrated luminosity of around $230\,\mu b^{-1}$ is measured as a function of event centrality. No significant dependence on the centrality is found. The results are also compared to the latest theory predictions, with which they agree within 1.5 standard deviations or better, with a slight tension in the lowest centrality interval. The SHMc calculations tend to underestimate the data over the whole range; the TAMU model achieves a better description. However, the current experimental precision precludes any firm conclusion. This study is a first step towards a deeper understanding of quarkonium production in PbPb collisions at midcentrality that can be achieved by additional measurements with the upgraded LHCb detector in Run 3 [45].

Acknowledgements

We thank Anton Andronic, Ralf Rapp and Biao Gang for providing the theoretical predictions for our measurement. We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MCID/IFA (Romania); MICIU and AEI (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), and Polish WLCG (Poland). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); Minciencias (Colombia); EPLANET, Marie Skłodowska-Curie Actions, ERC and NextGenerationEU (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); AvH Foundation (Germany); ICSC (Italy); Severo Ochoa and María de Maeztu Units of Excellence, GVA, XuntaGal, GENCAT, InTalent-Inditex and Prog. Atracción Talento CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

References

[1] T. Matsui and H. Satz, *J/ψ suppression by quark-gluon plasma formation*, Phys. Lett. **B178** (1986) 416.

[2] NA50 collaboration, M. C. Abreu *et al.*, *J/ψ and Drell-Yan cross-sections in PbPb interactions at 158 GeV/c per nucleon*, Phys. Lett. **B410** (1997) 327.

[3] NA50 collaboration, B. Alessandro *et al.*, *A new measurement of J/ψ suppression in Pb-Pb collisions at 158 GeV per nucleon*, Eur. Phys. J. **C39** (2005) 335, arXiv:hep-ex/0412036.

[4] NuSea Collaboration, M. J. Leitch *et al.*, *Measurement of differences between J/ψ and ψ' suppression in $p - A$ collisions*, Phys. Rev. Lett. **84** (2000) 3256.

[5] PHENIX collaboration, U. A. Acharya *et al.*, *Measurement of $\psi(2S)$ nuclear modification at backward and forward rapidity in $p + p$, p + Al, and p + Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, Phys. Rev. **C105** (2022) 064912, arXiv:2202.03863.

[6] ALICE collaboration, B. B. Abelev *et al.*, *Suppression of ψ(2S) production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, JHEP **12** (2014) 073, arXiv:1405.3796.

[7] CMS collaboration, A. M. Sirunyan *et al.*, *Measurement of prompt ψ(2S) production cross sections in proton-lead and proton-proton collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV*, Phys. Lett. **B790** (2019) 509, arXiv:1805.02248.

[8] LHCb collaboration, R. Aaij *et al.*, *Study of $\psi(2S)$ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV*, JHEP **03** (2016) 133, arXiv:1601.07878.

[9] LHCb collaboration, R. Aaij *et al.*, *Prompt and nonprompt J/ψ production and nuclear modification in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV*, Phys. Lett. **B774** (2017) 159, arXiv:1706.07122.

[10] E. G. Ferreiro, *Excited charmonium suppression in proton–nucleus collisions as a consequence of comovers*, Phys. Lett. **B749** (2015) 98, arXiv:1411.0549.

[11] PHENIX collaboration, A. Adare *et al.*, *J/ψ production vs centrality, transverse momentum, and rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, Phys. Rev. Lett. **98** (2007) 232301, arXiv:nucl-ex/0611020.

[12] STAR collaboration, J. Adam *et al.*, *Measurement of inclusive J/ψ suppression in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV through the dimuon channel at STAR*, Phys. Lett. **B797** (2019) 134917, arXiv:1905.13669.

[13] ALICE collaboration, J. Adam *et al.*, *J/ψ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV*, Phys. Lett. **B766** (2017) 212, arXiv:1606.08197.

[14] CMS collaboration, S. Chatrchyan *et al.*, *Suppression of non-prompt J/ψ, prompt J/ψ, and $\Upsilon(1S)$ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, JHEP **05** (2012) 063, arXiv:1201.5069.

[15] LHCb collaboration, R. Aaij *et al.*, *Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions*, JHEP **06** (2023) 146, arXiv:2206.08221.

[16] H. Satz, *Colour deconfinement and quarkonium binding*, J. Phys. **G32** (2006) R25, arXiv:hep-ph/0512217.

[17] ALICE collaboration, J. Adam *et al.*, *Direct photon production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV*, Phys. Lett. **B754** (2016) 235, arXiv:1509.07324.

[18] LHCb collaboration, R. Aaij *et al.*, *Precision luminosity measurements at LHCb*, JINST **9** (2014) P12005, `arXiv:1410.0149`.

[19] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.

[20] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, `arXiv:1412.6352`.

[21] R. Aaij *et al.*, *Performance of the LHCb Vertex Locator*, JINST **9** (2014) P09007, `arXiv:1405.7808`.

[22] LHCb Outer Tracker Group, P. d'Argent *et al.*, *Improved performance of the LHCb Outer Tracker in LHC Run 2*, JINST **12** (2017) P11016, `arXiv:1708.00819`.

[23] LHCb RICH Group, M. Adinolfi *et al.*, *Performance of the LHCb RICH detector at the LHC*, Eur. Phys. J. **C73** (2013) 2431, `arXiv:1211.6759`.

[24] A. A. Alves, Jr. *et al.*, *Performance of the LHCb muon system*, JINST **8** (2013) P02022, `arXiv:1211.1346`.

[25] R. Aaij *et al.*, *Design and performance of the LHCb trigger and full real-time reconstruction in Run 2 of the LHC*, JINST **14** (2019) P04013, `arXiv:1812.10790`.

[26] LHCb collaboration, R. Aaij *et al.*, *Centrality determination in heavy-ion collisions with the LHCb detector*, JINST **17** (2022) P05009, `arXiv:2111.01607`.

[27] C. Loizides, J. Nagle, and P. Steinberg, *Improved version of the PHOBOS Glauber Monte Carlo*, SoftwareX **1-2** (2015) 13, `arXiv:1408.2549`.

[28] T. Skwarnicki, *A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances*, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.

[29] Particle Data Group, S. Navas *et al.*, *Review of particle physics*, Phys. Rev. **D110** (2024) 030001.

[30] T. Sjöstrand, S. Mrenna, and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, `arXiv:0710.3820`.

[31] T. Pierog *et al.*, *EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider*, Phys. Rev. **C92** (2015) 034906.

[32] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.

[33] P. Golonka and Z. Was, *PHOTOS Monte Carlo: a precision tool for QED correctionsin Z and W decays*, Eur. Phys. J. **C45** (2006) 97.

[34] Geant4 collaboration, S. Agostinelli *et al.*, *Geant4: A simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003) 250.

[35] Geant4 collaboration, J. Allison *et al.*, *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. **53** (2006) 270.

[36] M. Clemencic *et al.*, *The LHCb simulation application, Gauss: Design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.

[37] R. Aaij *et al.*, *The LHCb trigger and its performance in 2011*, JINST **8** (2013) P04022, arXiv:1211.3055.

[38] ALICE collaboration, S. Acharya *et al.*, *ψ(2S) suppression in Pb-Pb collisions at the LHC*, Phys. Rev. Lett. **132** (2024) 042301, arXiv:2210.08893.

[39] LHCb collaboration, R. Aaij *et al.*, *Multiplicity dependence of $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in pp collisions at $\sqrt{s} = 13$ TeV*, JHEP **05** (2024) 243, arXiv:2312.15201.

[40] LHCb collaboration, R. Aaij *et al.*, *Prompt and nonprompt $\psi(2S)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV*, JHEP **04** (2024) 111, arXiv:2401.11342.

[41] A. Andronic *et al.*, *Transverse momentum distributions of charmonium states with the statistical hadronization model*, Phys. Lett. **B797** (2019) 134836, arXiv:1901.09200.

[42] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, *Decoding the phase structure of QCD via particle production at high energy*, Nature **561** (2018) 321, arXiv:1710.09425.

[43] X. Du and R. Rapp, *Sequential regeneration of charmonia in heavy-ion collisions*, Nucl. Phys. **A943** (2015) 147, arXiv:1504.00670.

[44] B. Wu and R. Rapp, *Charmonium transport in heavy-ion collisions at the LHC*, Universe **10** (2024) 244, arXiv:2404.09881.

[45] LHCb collaboration, R. Aaij *et al.*, *The LHCb Upgrade I*, JINST **19** (2024) P05065, arXiv:2305.10515.

LHCb collaboration

R. Aaij[38], A.S.W. Abdelmotteleb[57], C. Abellan Beteta[51], F. Abudinén[57],
T. Ackernley[61], A. A. Adefisoye[69], B. Adeva[47], M. Adinolfi[55], P. Adlarson[82],
C. Agapopoulou[14], C.A. Aidala[83], Z. Ajaltouni[11], S. Akar[66], K. Akiba[38],
P. Albicocco[28], J. Albrecht[19], F. Alessio[49], M. Alexander[60], Z. Aliouche[63],
P. Alvarez Cartelle[56], R. Amalric[16], S. Amato[3], J.L. Amey[55], Y. Amhis[14],
L. An[6], L. Anderlini[27], M. Andersson[51], A. Andreianov[44], P. Andreola[51],
M. Andreotti[26], D. Andreou[69], A. Anelli[31,n], D. Ao[7], F. Archilli[37,t],
M. Argenton[26], S. Arguedas Cuendis[9,49], A. Artamonov[44], M. Artuso[69],
E. Aslanides[13], R. Ataíde Da Silva[50], M. Atzeni[65], B. Audurier[12], D. Bacher[64],
I. Bachiller Perea[10], S. Bachmann[22], M. Bachmayer[50], J.J. Back[57],
P. Baladron Rodriguez[47], V. Balagura[15], A. Balboni[26], W. Baldini[26], L. Balzani[19],
H. Bao[7], J. Baptista de Souza Leite[61], C. Barbero Pretel[47,12], M. Barbetti[27], I.
R. Barbosa[70], R.J. Barlow[63], M. Barnyakov[25], S. Barsuk[14], W. Barter[59],
M. Bartolini[56], J. Bartz[69], J.M. Basels[17], S. Bashir[40], G. Bassi[35,q], B. Batsukh[5],
P. B. Battista[14], A. Bay[50], A. Beck[57], M. Becker[19], F. Bedeschi[35], I.B. Bediaga[2],
N. A. Behling[19], S. Belin[47], K. Belous[44], I. Belov[29], I. Belyaev[36], G. Benane[13],
G. Bencivenni[28], E. Ben-Haim[16], A. Berezhnoy[44], R. Bernet[51], S. Bernet Andres[45],
A. Bertolin[33], C. Betancourt[51], F. Betti[59], J. Bex[56], Ia. Bezshyiko[51], J. Bhom[41],
M.S. Bieker[19], N.V. Biesuz[26], P. Billoir[16], A. Biolchini[38], M. Birch[62],
F.C.R. Bishop[10], A. Bitadze[63], A. Bizzeti, T. Blake[57], F. Blanc[50], J.E. Blank[19],
S. Blusk[69], V. Bocharnikov[44], J.A. Boelhauve[19], O. Boente Garcia[15],
T. Boettcher[66], A. Bohare[59], A. Boldyrev[44], C.S. Bolognani[79], R. Bolzonella[26,k],
R. B. Bonacci[1], N. Bondar[44], A. Bordelius[49], F. Borgato[33,o], S. Borghi[63],
M. Borsato[31,n], J.T. Borsuk[41], S.A. Bouchiba[50], M. Bovill[64], T.J.V. Bowcock[61],
A. Boyer[49], C. Bozzi[26], A. Brea Rodriguez[50], N. Breer[19], J. Brodzicka[41],
A. Brossa Gonzalo[47,†], J. Brown[61], D. Brundu[32], E. Buchanan[59], A. Buonaura[51],
L. Buonincontri[33,o], A.T. Burke[63], C. Burr[49], J.S. Butter[56], J. Buytaert[49],
W. Byczynski[49], S. Cadeddu[32], H. Cai[74], A. C. Caillet[16], R. Calabrese[26,k],
S. Calderon Ramirez[9], L. Calefice[46], S. Cali[28], M. Calvi[31,n], M. Calvo Gomez[45],
P. Camargo Magalhaes[2,x], J. I. Cambon Bouzas[47], P. Campana[28],
D.H. Campora Perez[79], A.F. Campoverde Quezada[7], S. Capelli[31], L. Capriotti[26],
R. Caravaca-Mora[9], A. Carbone[25,i], L. Carcedo Salgado[47], R. Cardinale[29,l],
A. Cardini[32], P. Carniti[31,n], L. Carus[22], A. Casais Vidal[65], R. Caspary[22],
G. Casse[61], M. Cattaneo[49], G. Cavallero[26,49], V. Cavallini[26,k], S. Celani[22],
D. Cervenkov[64], S. Cesare[30,m], A.J. Chadwick[61], I. Chahrour[83], M. Charles[16],
Ph. Charpentier[49], E. Chatzianagnostou[38], M. Chefdeville[10], C. Chen[13], S. Chen[5],
Z. Chen[7], A. Chernov[41], S. Chernyshenko[53], X. Chiotopoulos[79], V. Chobanova[81],
S. Cholak[50], M. Chrzaszcz[41], A. Chubykin[44], V. Chulikov[28], P. Ciambrone[28],
X. Cid Vidal[47], G. Ciezarek[49], P. Cifra[49], P.E.L. Clarke[59], M. Clemencic[49],
H.V. Cliff[56], J. Closier[49], C. Cocha Toapaxi[22], V. Coco[49], J. Cogan[13],
E. Cogneras[11], L. Cojocariu[43], S. Collaviti[50], P. Collins[49], T. Colombo[49], M. C.
Colonna[19], A. Comerma-Montells[46], L. Congedo[24], A. Contu[32], N. Cooke[60],
I. Corredoira [47], A. Correia[16], G. Corti[49], J.J. Cottee Meldrum[55], B. Couturier[49],
D.C. Craik[51], M. Cruz Torres[2,f], E. Curras Rivera[50], R. Currie[59], C.L. Da Silva[68],
S. Dadabaev[44], L. Dai[71], X. Dai[6], E. Dall'Occo[49], J. Dalseno[47],
C. D'Ambrosio[49], J. Daniel[11], A. Danilina[44], P. d'Argent[24], G. Darze[3], A.
Davidson[57], J.E. Davies[63], A. Davis[63], O. De Aguiar Francisco[63], C. De Angelis[32,j],
F. De Benedetti[49], J. de Boer[38], K. De Bruyn[78], S. De Capua[63], M. De Cian[22],

U. De Freitas Carneiro Da Graca[2,a], E. De Lucia[28], J.M. De Miranda[2], L. De Paula[3], M. De Serio[24,g], P. De Simone[28], F. De Vellis[19], J.A. de Vries[79], F. Debernardis[24], D. Decamp[10], V. Dedu[13], S. Dekkers[1], L. Del Buono[16], B. Delaney[65], H.-P. Dembinski[19], J. Deng[8], V. Denysenko[51], O. Deschamps[11], F. Dettori[32,j], B. Dey[77], P. Di Nezza[28], I. Diachkov[44], S. Didenko[44], S. Ding[69], L. Dittmann[22], V. Dobishuk[53], A. D. Docheva[60], C. Dong[4,b], A.M. Donohoe[23], F. Dordei[32], A.C. dos Reis[2], A. D. Dowling[69], W. Duan[72], P. Duda[80], M.W. Dudek[41], L. Dufour[49], V. Duk[34], P. Durante[49], M. M. Duras[80], J.M. Durham[68], O. D. Durmus[77], A. Dziurda[41], A. Dzyuba[44], S. Easo[58], E. Eckstein[18], U. Egede[1], A. Egorychev[44], V. Egorychev[44], S. Eisenhardt[59], E. Ejopu[63], L. Eklund[82], M. Elashri[66], J. Ellbracht[19], S. Ely[62], A. Ene[43], J. Eschle[69], S. Esen[22], T. Evans[63], F. Fabiano[32,j], L.N. Falcao[2], Y. Fan[7], B. Fang[7], L. Fantini[34,p,49], M. Faria[50], K. Farmer[59], D. Fazzini[31,n], L. Felkowski[80], M. Feng[5,7], M. Feo[19], A. Fernandez Casani[48], M. Fernandez Gomez[47], A.D. Fernez[67], F. Ferrari[25], F. Ferreira Rodrigues[3], M. Ferrillo[51], M. Ferro-Luzzi[49], S. Filippov[44], R.A. Fini[24], M. Fiorini[26,k], M. Firlej[40], K.L. Fischer[64], D.S. Fitzgerald[83], C. Fitzpatrick[63], T. Fiutowski[40], F. Fleuret[15], M. Fontana[25], L. F. Foreman[63], R. Forty[49], D. Foulds-Holt[56], V. Franco Lima[3], M. Franco Sevilla[67], M. Frank[49], E. Franzoso[26,k], G. Frau[63], C. Frei[49], D.A. Friday[63], J. Fu[7], Q. Fuehring[19,56], Y. Fujii[1], T. Fulghesu[16], E. Gabriel[38], G. Galati[24], M.D. Galati[38], A. Gallas Torreira[47], D. Galli[25,i], S. Gambetta[59], M. Gandelman[3], P. Gandini[30], B. Ganie[63], H. Gao[7], R. Gao[64], T.Q. Gao[56], Y. Gao[8], Y. Gao[6], Y. Gao[8], L.M. Garcia Martin[50], P. Garcia Moreno[46], J. García Pardiñas[49], P. Gardner[67], K. G. Garg[8], L. Garrido[46], C. Gaspar[49], R.E. Geertsema[38], L.L. Gerken[19], E. Gersabeck[63], M. Gersabeck[20], T. Gershon[57], S. G. Ghizzo[29], Z. Ghorbanimoghaddam[55], L. Giambastiani[33,o], F. I. Giasemis[16,e], V. Gibson[56], H.K. Giemza[42], A.L. Gilman[64], M. Giovannetti[28], A. Gioventù[46], L. Girardey[63], P. Gironella Gironell[46], C. Giugliano[26,k], M.A. Giza[41], E.L. Gkougkousis[62], F.C. Glaser[14,22], V.V. Gligorov[16,49], C. Göbel[70], E. Golobardes[45], D. Golubkov[44], A. Golutvin[62,44,49], S. Gomez Fernandez[46], W. Gomulka[40], F. Goncalves Abrantes[64], M. Goncerz[41], G. Gong[4,b], J. A. Gooding[19], I.V. Gorelov[44], C. Gotti[31], J.P. Grabowski[18], L.A. Granado Cardoso[49], E. Graugés[46], E. Graverini[50,r], L. Grazette[57], G. Graziani, A. T. Grecu[43], L.M. Greeven[38], N.A. Grieser[66], L. Grillo[60], S. Gromov[44], C. Gu[15], M. Guarise[26], L. Guerry[11], M. Guittiere[14], V. Guliaeva[44], P. A. Günther[22], A.-K. Guseinov[50], E. Gushchin[44], Y. Guz[6,44,49], T. Gys[49], K. Habermann[18], T. Hadavizadeh[1], C. Hadjivasiliou[67], G. Haefeli[50], C. Haen[49], M. Hajheidari[49], G. Hallett[57], M.M. Halvorsen[49], P.M. Hamilton[67], J. Hammerich[61], Q. Han[8], X. Han[22,49], S. Hansmann-Menzemer[22], L. Hao[7], N. Harnew[64], T. H. Harris[1], M. Hartmann[14], S. Hashmi[40], J. He[7,c], F. Hemmer[49], C. Henderson[66], R.D.L. Henderson[1,57], A.M. Hennequin[49], K. Hennessy[61], L. Henry[50], J. Herd[62], P. Herrero Gascon[22], J. Heuel[17], A. Hicheur[3], G. Hijano Mendizabal[51], J. Horswill[63], R. Hou[8], Y. Hou[11], N. Howarth[61], J. Hu[72], W. Hu[6], X. Hu[4,b], W. Huang[7], W. Hulsbergen[38], R.J. Hunter[57], M. Hushchyn[44], D. Hutchcroft[61], M. Idzik[40], D. Ilin[44], P. Ilten[66], A. Inglessi[44], A. Iniukhin[44], A. Ishteev[44], K. Ivshin[44], R. Jacobsson[49], H. Jage[17], S.J. Jaimes Elles[75,49,48], S. Jakobsen[49], E. Jans[38], B.K. Jashal[48], A. Jawahery[67,49], V. Jevtic[19], E. Jiang[67], X. Jiang[5,7], Y. Jiang[7], Y. J. Jiang[6], M. John[64], A. John Rubesh Rajan[23], D. Johnson[54], C.R. Jones[56], T.P. Jones[57], S. Joshi[42], B. Jost[49], J. Juan Castella[56], N. Jurik[49], I. Juszczak[41], D. Kaminaris[50], S. Kandybei[52], M. Kane[59], Y. Kang[4,b], C. Kar[11], M. Karacson[49],

D. Karpenkov[44], A. Kauniskangas[50], J.W. Kautz[66], M.K. Kazanecki[41], F. Keizer[49], M. Kenzie[56], T. Ketel[38], B. Khanji[69], A. Kharisova[44], S. Kholodenko[35,49], G. Khreich[14], T. Kirn[17], V.S. Kirsebom[31,n], O. Kitouni[65], S. Klaver[39], N. Kleijne[35,q], K. Klimaszewski[42], M.R. Kmiec[42], S. Koliiev[53], L. Kolk[19], A. Konoplyannikov[44], P. Kopciewicz[40,49], P. Koppenburg[38], M. Korolev[44], I. Kostiuk[38], O. Kot[53], S. Kotriakhova, A. Kozachuk[44], P. Kravchenko[44], L. Kravchuk[44], M. Kreps[57], P. Krokovny[44], W. Krupa[69], W. Krzemien[42], O.K. Kshyvanskyi[53], S. Kubis[80], M. Kucharczyk[41], V. Kudryavtsev[44], E. Kulikova[44], A. Kupsc[82], B. K. Kutsenko[13], D. Lacarrere[49], P. Laguarta Gonzalez[46], A. Lai[32], A. Lampis[32], D. Lancierini[56], C. Landesa Gomez[47], J.J. Lane[1], R. Lane[55], G. Lanfranchi[28], C. Langenbruch[22], J. Langer[19], O. Lantwin[44], T. Latham[57], F. Lazzari[35,r], C. Lazzeroni[54], R. Le Gac[13], H. Lee[61], R. Lefèvre[11], A. Leflat[44], S. Legotin[44], M. Lehuraux[57], E. Lemos Cid[49], O. Leroy[13], T. Lesiak[41], E. Lesser[49], B. Leverington[22], A. Li[4,b], C. Li[13], H. Li[72], K. Li[8], L. Li[63], M. Li[8], P. Li[7], P.-R. Li[73], Q. Li[5,7], S. Li[8], T. Li[5,d], T. Li[72], Y. Li[8], Y. Li[5], Z. Lian[4,b], X. Liang[69], S. Libralon[48], C. Lin[7], T. Lin[58], R. Lindner[49], H. Linton[62], V. Lisovskyi[50], R. Litvinov[32,49], F. L. Liu[1], G. Liu[72], K. Liu[73], S. Liu[5,7], W. Liu[8], Y. Liu[59], Y. Liu[73], Y. L. Liu[62], A. Lobo Salvia[46], A. Loi[32], T. Long[56], J.H. Lopes[3], A. Lopez Huertas[46], S. López Soliño[47], Q. Lu[15], C. Lucarelli[27], D. Lucchesi[33,o], M. Lucio Martinez[79], V. Lukashenko[38,53], Y. Luo[6], A. Lupato[33,h], E. Luppi[26,k], K. Lynch[23], X.-R. Lyu[7], G. M. Ma[4,b], S. Maccolini[19], F. Machefert[14], F. Maciuc[43], B. Mack[69], I. Mackay[64], L. M. Mackey[69], L.R. Madhan Mohan[56], M. J. Madurai[54], A. Maevskiy[44], D. Magdalinski[38], D. Maisuzenko[44], M.W. Majewski[40], J.J. Malczewski[41], S. Malde[64], L. Malentacca[49], A. Malinin[44], T. Maltsev[44], G. Manca[32,j], G. Mancinelli[13], C. Mancuso[30,14,m], R. Manera Escalero[46], F. M. Manganella[37], D. Manuzzi[25], D. Marangotto[30,m], J.F. Marchand[10], R. Marchevski[50], U. Marconi[25], E. Mariani[16], S. Mariani[49], C. Marin Benito[46,49], J. Marks[22], A.M. Marshall[55], L. Martel[64], G. Martelli[34,p], G. Martellotti[36], L. Martinazzoli[49], M. Martinelli[31,n], D. Martinez Gomez[78], D. Martinez Santos[81], F. Martinez Vidal[48], A. Martorell i Granollers[45], A. Massafferri[2], R. Matev[49], A. Mathad[49], V. Matiunin[44], C. Matteuzzi[69], K.R. Mattioli[15], A. Mauri[62], E. Maurice[15], J. Mauricio[46], P. Mayencourt[50], J. Mazorra de Cos[48], M. Mazurek[42], M. McCann[62], L. Mcconnell[23], T.H. McGrath[63], N.T. McHugh[60], A. McNab[63], R. McNulty[23], B. Meadows[66], G. Meier[19], D. Melnychuk[42], F. M. Meng[4,b], M. Merk[38,79], A. Merli[50], L. Meyer Garcia[67], D. Miao[5,7], H. Miao[7], M. Mikhasenko[76], D.A. Milanes[75], A. Minotti[31,n], E. Minucci[28], T. Miralles[11], B. Mitreska[19], D.S. Mitzel[19], A. Modak[58], R.A. Mohammed[64], R.D. Moise[17], S. Mokhnenko[44], E. F. Molina Cardenas[83], T. Mombächer[49], M. Monk[57,1], S. Monteil[11], A. Morcillo Gomez[47], G. Morello[28], M.J. Morello[35,q], M.P. Morgenthaler[22], J. Moron[40], W. Morren[38], A.B. Morris[49], A.G. Morris[13], R. Mountain[69], H. Mu[4,b], Z. M. Mu[6], E. Muhammad[57], F. Muheim[59], M. Mulder[78], K. Müller[51], F. Muñoz-Rojas[9], R. Murta[62], P. Naik[61], T. Nakada[50], R. Nandakumar[58], T. Nanut[49], I. Nasteva[3], M. Needham[59], N. Neri[30,m], S. Neubert[18], N. Neufeld[49], P. Neustroev[44], J. Nicolini[19,14], D. Nicotra[79], E.M. Niel[49], N. Nikitin[44], P. Nogarolli[3], P. Nogga[18], C. Normand[55], J. Novoa Fernandez[47], G. Nowak[66], C. Nunez[83], H. N. Nur[60], A. Oblakowska-Mucha[40], V. Obraztsov[44], T. Oeser[17], S. Okamura[26,k], A. Okhotnikov[44], O. Okhrimenko[53], R. Oldeman[32,j], F. Oliva[59], M. Olocco[19], C.J.G. Onderwater[79], R.H. O'Neil[59], D. Osthues[19], J.M. Otalora Goicochea[3], P. Owen[51], A. Oyanguren[48], O. Ozcelik[59], F. Paciolla[35,u],

A. Padee[42], K.O. Padeken[18], B. Pagare[57], P.R. Pais[22], T. Pajero[49], A. Palano[24], M. Palutan[28], X. Pan[4,b], G. Panshin[44], L. Paolucci[57], A. Papanestis[58,49], M. Pappagallo[24,g], L.L. Pappalardo[26,k], C. Pappenheimer[66], C. Parkes[63], D. Parmar[76], B. Passalacqua[26,k], G. Passaleva[27], D. Passaro[35,q], A. Pastore[24], M. Patel[62], J. Patoc[64], C. Patrignani[25,i], A. Paul[69], C.J. Pawley[79], A. Pellegrino[38], J. Peng[5,7], M. Pepe Altarelli[28], S. Perazzini[25], D. Pereima[44], H. Pereira Da Costa[68], A. Pereiro Castro[47], P. Perret[11], A. Perrevoort[78], A. Perro[49], M.J. Peters[66], K. Petridis[55], A. Petrolini[29,l], J. P. Pfaller[66], H. Pham[69], L. Pica[35,q], M. Piccini[34], L. Piccolo[32], B. Pietrzyk[10], G. Pietrzyk[14], D. Pinci[36], F. Pisani[49], M. Pizzichemi[31,n], V. Placinta[43], M. Plo Casasus[47], T. Poeschl[49], F. Polci[16,49], M. Poli Lener[28], A. Poluektov[13], N. Polukhina[44], I. Polyakov[44], E. Polycarpo[3], S. Ponce[49], D. Popov[7], S. Poslavskii[44], K. Prasanth[59], C. Prouve[81], D. Provenzano[32,j], V. Pugatch[53], G. Punzi[35,r], S. Qasim[51], Q. Q. Qian[6], W. Qian[7], N. Qin[4,b], S. Qu[4,b], R. Quagliani[49], R.I. Rabadan Trejo[57], J.H. Rademacker[55], M. Rama[35], M. Ramírez García[83], V. Ramos De Oliveira[70], M. Ramos Pernas[57], M.S. Rangel[3], F. Ratnikov[44], G. Raven[39], M. Rebollo De Miguel[48], F. Redi[30,h], J. Reich[55], F. Reiss[63], Z. Ren[7], P.K. Resmi[64], R. Ribatti[50], G. R. Ricart[15,12], D. Riccardi[35,q], S. Ricciardi[58], K. Richardson[65], M. Richardson-Slipper[59], K. Rinnert[61], P. Robbe[14,49], G. Robertson[60], E. Rodrigues[61], A. Rodriguez Alvarez[46], E. Rodriguez Fernandez[47], J.A. Rodriguez Lopez[75], E. Rodriguez Rodriguez[47], J. Roensch[19], A. Rogachev[44], A. Rogovskiy[58], D.L. Rolf[49], P. Roloff[49], V. Romanovskiy[66], A. Romero Vidal[47], G. Romolini[26], F. Ronchetti[50], T. Rong[6], M. Rotondo[28], S. R. Roy[22], M.S. Rudolph[69], M. Ruiz Diaz[22], R.A. Ruiz Fernandez[47], J. Ruiz Vidal[82,y], A. Ryzhikov[44], J. Ryzka[40], J. J. Saavedra-Arias[9], J.J. Saborido Silva[47], R. Sadek[15], N. Sagidova[44], D. Sahoo[77], N. Sahoo[54], B. Saitta[32,j], M. Salomoni[31,n,49], I. Sanderswood[48], R. Santacesaria[36], C. Santamarina Rios[47], M. Santimaria[28,49], L. Santoro [2], E. Santovetti[37], A. Saputi[26,49], D. Saranin[44], A. Sarnatskiy[78], G. Sarpis[59], M. Sarpis[63], C. Satriano[36,s], A. Satta[37], M. Saur[6], D. Savrina[44], H. Sazak[17], F. Sborzacchi[49,28], L.G. Scantlebury Smead[64], A. Scarabotto[19], S. Schael[17], S. Scherl[61], M. Schiller[60], H. Schindler[49], M. Schmelling[21], B. Schmidt[49], S. Schmitt[17], H. Schmitz[18], O. Schneider[50], A. Schopper[49], N. Schulte[19], S. Schulte[50], M.H. Schune[14], R. Schwemmer[49], G. Schwering[17], B. Sciascia[28], A. Sciuccati[49], I. Segal[76], S. Sellam[47], A. Semennikov[44], T. Senger[51], M. Senghi Soares[39], A. Sergi[29], N. Serra[51], L. Sestini[33], A. Seuthe[19], Y. Shang[6], D.M. Shangase[83], M. Shapkin[44], R. S. Sharma[69], I. Shchemerov[44], L. Shchutska[50], T. Shears[61], L. Shekhtman[44], Z. Shen[6], S. Sheng[5,7], V. Shevchenko[44], B. Shi[7], Q. Shi[7], Y. Shimizu[14], E. Shmanin[25], R. Shorkin[44], J.D. Shupperd[69], R. Silva Coutinho[69], G. Simi[33,o], S. Simone[24,g], N. Skidmore[57], T. Skwarnicki[69], M.W. Slater[54], J.C. Smallwood[64], E. Smith[65], K. Smith[68], M. Smith[62], A. Snoch[38], L. Soares Lavra[59], M.D. Sokoloff[66], F.J.P. Soler[60], A. Solomin[44,55], A. Solovev[44], I. Solovyev[44], N. S. Sommerfeld[18], R. Song[1], Y. Song[50], Y. Song[4,b], Y. S. Song[6], F.L. Souza De Almeida[69], B. Souza De Paula[3], E. Spadaro Norella[29], E. Spedicato[25], J.G. Speer[19], E. Spiridenkov[44], P. Spradlin[60], V. Sriskaran[49], F. Stagni[49], M. Stahl[49], S. Stahl[49], S. Stanislaus[64], E.N. Stein[49], O. Steinkamp[51], O. Stenyakin[44], H. Stevens[19], D. Strekalina[44], Y. Su[7], F. Suljik[64], J. Sun[32], L. Sun[74], D. Sundfeld[2], W. Sutcliffe[51], P.N. Swallow[54], K. Swientek[40], F. Swystun[56], A. Szabelski[42], T. Szumlak[40], Y. Tan[4,b], Y. Tang[74], M.D. Tat[64], A. Terentev[44], F. Terzuoli[35,u,49], F. Teubert[49], E. Thomas[49], D.J.D. Thompson[54], H. Tilquin[62], V. Tisserand[11], S. T'Jampens[10], M. Tobin[5,49], L. Tomassetti[26,k],

G. Tonani[30,m,49], X. Tong[6], D. Torres Machado[2], L. Toscano[19], D.Y. Tou[4,b], C. Trippl[45], G. Tuci[22], N. Tuning[38], L.H. Uecker[22], A. Ukleja[40], D.J. Unverzagt[22], B. Urbach[59], E. Ursov[44], A. Usachov[39], A. Ustyuzhanin[44], U. Uwer[22], V. Vagnoni[25], V. Valcarce Cadenas[47], G. Valenti[25], N. Valls Canudas[49], H. Van Hecke[68], E. van Herwijnen[62], C.B. Van Hulse[47,w], R. Van Laak[50], M. van Veghel[38], G. Vasquez[51], R. Vazquez Gomez[46], P. Vazquez Regueiro[47], C. Vázquez Sierra[47], S. Vecchi[26], J.J. Velthuis[55], M. Veltri[27,v], A. Venkateswaran[50], M. Verdoglia[32], M. Vesterinen[57], D. Vico Benet[64], P. V. Vidrier Villalba[46], M. Vieites Diaz[49], X. Vilasis-Cardona[45], E. Vilella Figueras[61], A. Villa[25], P. Vincent[16], F.C. Volle[54], D. vom Bruch[13], N. Voropaev[44], K. Vos[79], C. Vrahas[59], J. Wagner[19], J. Walsh[35], E.J. Walton[1,57], G. Wan[6], C. Wang[22], G. Wang[8], J. Wang[6], J. Wang[5], J. Wang[4,b], J. Wang[74], M. Wang[30], N. W. Wang[7], R. Wang[55], X. Wang[8], X. Wang[72], X. W. Wang[62], Y. Wang[6], Z. Wang[14], Z. Wang[4,b], Z. Wang[30], J.A. Ward[57,1], M. Waterlaat[49], N.K. Watson[54], D. Websdale[62], Y. Wei[6], J. Wendel[81], B.D.C. Westhenry[55], C. White[56], M. Whitehead[60], E. Whiter[54], A.R. Wiederhold[63], D. Wiedner[19], G. Wilkinson[64], M.K. Wilkinson[66], M. Williams[65], M. J. Williams[49], M.R.J. Williams[59], R. Williams[56], Z. Williams[55], F.F. Wilson[58], M. Winn[12], W. Wislicki[42], M. Witek[41], L. Witola[22], G. Wormser[14], S.A. Wotton[56], H. Wu[69], J. Wu[8], X. Wu[74], Y. Wu[6], Z. Wu[7], K. Wyllie[49], S. Xian[72], Z. Xiang[5], Y. Xie[8], A. Xu[35], J. Xu[7], L. Xu[4,b], L. Xu[4,b], M. Xu[57], Z. Xu[49], Z. Xu[7], Z. Xu[5], K. Yang[62], S. Yang[7], X. Yang[6], Y. Yang[29,l], Z. Yang[6], V. Yeroshenko[14], H. Yeung[63], H. Yin[8], C. Y. Yu[6], J. Yu[71], X. Yuan[5], Y Yuan[5,7], E. Zaffaroni[50], M. Zavertyaev[21], M. Zdybal[41], F. Zenesini[25,i], C. Zeng[5,7], M. Zeng[4,b], C. Zhang[6], D. Zhang[8], J. Zhang[7], L. Zhang[4,b], S. Zhang[71], S. Zhang[64], Y. Zhang[6], Y. Z. Zhang[4,b], Z. Zhang[4,b], Y. Zhao[22], A. Zharkova[44], A. Zhelezov[22], S. Z. Zheng[6], X. Z. Zheng[4,b], Y. Zheng[7], T. Zhou[6], X. Zhou[8], Y. Zhou[7], V. Zhovkovska[57], L. Z. Zhu[7], X. Zhu[4,b], X. Zhu[8], V. Zhukov[17], J. Zhuo[48], Q. Zou[5,7], D. Zuliani[33,o], G. Zunica[50].

[1] *School of Physics and Astronomy, Monash University, Melbourne, Australia*
[2] *Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*
[3] *Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[4] *Department of Engineering Physics, Tsinghua University, Beijing, China, Beijing, China*
[5] *Institute Of High Energy Physics (IHEP), Beijing, China*
[6] *School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[7] *University of Chinese Academy of Sciences, Beijing, China*
[8] *Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
[9] *Consejo Nacional de Rectores (CONARE), San Jose, Costa Rica*
[10] *Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
[11] *Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[12] *Département de Physique Nucléaire (DPhN), Gif-Sur-Yvette, France*
[13] *Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
[14] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*
[15] *Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[16] *LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
[17] *I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
[18] *Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany*
[19] *Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[20] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
[21] *Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*

[22] *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[23] *School of Physics, University College Dublin, Dublin, Ireland*
[24] *INFN Sezione di Bari, Bari, Italy*
[25] *INFN Sezione di Bologna, Bologna, Italy*
[26] *INFN Sezione di Ferrara, Ferrara, Italy*
[27] *INFN Sezione di Firenze, Firenze, Italy*
[28] *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[29] *INFN Sezione di Genova, Genova, Italy*
[30] *INFN Sezione di Milano, Milano, Italy*
[31] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[32] *INFN Sezione di Cagliari, Monserrato, Italy*
[33] *INFN Sezione di Padova, Padova, Italy*
[34] *INFN Sezione di Perugia, Perugia, Italy*
[35] *INFN Sezione di Pisa, Pisa, Italy*
[36] *INFN Sezione di Roma La Sapienza, Roma, Italy*
[37] *INFN Sezione di Roma Tor Vergata, Roma, Italy*
[38] *Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
[39] *Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
[40] *AGH - University of Krakow, Faculty of Physics and Applied Computer Science, Kraków, Poland*
[41] *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
[42] *National Center for Nuclear Research (NCBJ), Warsaw, Poland*
[43] *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[44] *Affiliated with an institute covered by a cooperation agreement with CERN*
[45] *DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
[46] *ICCUB, Universitat de Barcelona, Barcelona, Spain*
[47] *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
[48] *Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
[49] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[50] *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[51] *Physik-Institut, Universität Zürich, Zürich, Switzerland*
[52] *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
[53] *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
[54] *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[55] *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[56] *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[57] *Department of Physics, University of Warwick, Coventry, United Kingdom*
[58] *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
[59] *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[60] *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[61] *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[62] *Imperial College London, London, United Kingdom*
[63] *Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[64] *Department of Physics, University of Oxford, Oxford, United Kingdom*
[65] *Massachusetts Institute of Technology, Cambridge, MA, United States*
[66] *University of Cincinnati, Cincinnati, OH, United States*
[67] *University of Maryland, College Park, MD, United States*
[68] *Los Alamos National Laboratory (LANL), Los Alamos, NM, United States*
[69] *Syracuse University, Syracuse, NY, United States*
[70] *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to* [3]
[71] *School of Physics and Electronics, Hunan University, Changsha City, China, associated to* [8]
[72] *Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to* [4]
[73] *Lanzhou University, Lanzhou, China, associated to* [5]

[74] *School of Physics and Technology, Wuhan University, Wuhan, China, associated to* [4]
[75] *Departamento de Fisica , Universidad Nacional de Colombia, Bogota, Colombia, associated to* [16]
[76] *Ruhr Universitaet Bochum, Fakultaet f. Physik und Astronomie, Bochum, Germany, associated to* [19]
[77] *Eotvos Lorand University, Budapest, Hungary, associated to* [49]
[78] *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to* [38]
[79] *Universiteit Maastricht, Maastricht, Netherlands, associated to* [38]
[80] *Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland, associated to* [41]
[81] *Universidade da Coruña, A Coruna, Spain, associated to* [45]
[82] *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to* [60]
[83] *University of Michigan, Ann Arbor, MI, United States, associated to* [69]

[a] *Centro Federal de Educacão Tecnológica Celso Suckow da Fonseca, Rio De Janeiro, Brazil*
[b] *Center for High Energy Physics, Tsinghua University, Beijing, China*
[c] *Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China*
[d] *School of Physics and Electronics, Henan University , Kaifeng, China*
[e] *LIP6, Sorbonne Université, Paris, France*
[f] *Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras*
[g] *Università di Bari, Bari, Italy*
[h] *Università di Bergamo, Bergamo, Italy*
[i] *Università di Bologna, Bologna, Italy*
[j] *Università di Cagliari, Cagliari, Italy*
[k] *Università di Ferrara, Ferrara, Italy*
[l] *Università di Genova, Genova, Italy*
[m] *Università degli Studi di Milano, Milano, Italy*
[n] *Università degli Studi di Milano-Bicocca, Milano, Italy*
[o] *Università di Padova, Padova, Italy*
[p] *Università di Perugia, Perugia, Italy*
[q] *Scuola Normale Superiore, Pisa, Italy*
[r] *Università di Pisa, Pisa, Italy*
[s] *Università della Basilicata, Potenza, Italy*
[t] *Università di Roma Tor Vergata, Roma, Italy*
[u] *Università di Siena, Siena, Italy*
[v] *Università di Urbino, Urbino, Italy*
[w] *Universidad de Alcalá, Alcalá de Henares , Spain*
[x] *Facultad de Ciencias Fisicas, Madrid, Spain*
[y] *Department of Physics/Division of Particle Physics, Lund, Sweden*

[†] *Deceased*