

# Study of $\psi(2S)$ production and cold nuclear matter effects in $p\text{Pb}$ collisions at $\sqrt{s_{NN}} = 5 \text{ TeV}$



## The LHCb collaboration

*E-mail:* [yangzhw@tsinghua.edu.cn](mailto:yangzhw@tsinghua.edu.cn)

**ABSTRACT:** The production of  $\psi(2S)$  mesons is studied in dimuon final states using proton-lead ( $p\text{Pb}$ ) collision data collected by the LHCb detector. The data sample corresponds to an integrated luminosity of  $1.6 \text{ nb}^{-1}$ . The nucleon-nucleon centre-of-mass energy of the  $p\text{Pb}$  collisions is  $\sqrt{s_{NN}} = 5 \text{ TeV}$ . The measurement is performed using  $\psi(2S)$  mesons with transverse momentum less than  $14 \text{ GeV}/c$  and rapidity  $y$  in the ranges  $1.5 < y < 4.0$  and  $-5.0 < y < -2.5$  in the nucleon-nucleon centre-of-mass system. The forward-backward production ratio and the nuclear modification factor are determined for  $\psi(2S)$  mesons. Using the production cross-section results of  $\psi(2S)$  and  $J/\psi$  mesons from  $b$ -hadron decays, the  $b\bar{b}$  cross-section in  $p\text{Pb}$  collisions at  $\sqrt{s_{NN}} = 5 \text{ TeV}$  is obtained.

**KEYWORDS:** Particle and resonance production, Quarkonium, Relativistic heavy ion physics, Heavy Ion Experiments, Heavy-ion collision

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## 1 Introduction

The quark-gluon plasma (QGP) is a state of matter with asymptotically free partons, which is expected to exist at extremely high temperature and density. It is predicted that heavy quarkonium production will be significantly suppressed in ultrarelativistic heavy-ion collisions if a QGP is created [1]. This suppression is regarded as one of the most important signatures for the formation of the QGP. Heavy quarkonium production can also be suppressed in proton-nucleus ( $pA$ ) collisions, where hot nuclear matter, *i.e.* QGP, is not expected to be created and only cold nuclear matter (CNM) effects exist. Such CNM effects include: initial-state nuclear effects on the parton densities (shadowing); coherent energy loss consisting of initial-state parton energy loss and final-state energy loss; and final-state absorption by nucleons, which is expected to be negligible at LHC energies [2–9]. The study of  $pA$  collisions is important to disentangle the effects of QGP from those of CNM, and to provide essential input to the understanding of nucleus-nucleus collisions.

Nuclear effects are usually characterized by the nuclear modification factor, defined as the production cross-section of a given particle per nucleon in  $pA$  collisions divided by that in proton-proton ( $pp$ ) collisions,

$$R_{pA}(y, p_T, \sqrt{s_{NN}}) \equiv \frac{1}{A} \frac{d^2\sigma_{pA}(y, p_T, \sqrt{s_{NN}})/dydp_T}{d^2\sigma_{pp}(y, p_T, \sqrt{s_{NN}})/dydp_T}, \quad (1.1)$$

where  $A$  is the atomic mass number of the nucleus,  $y$  ( $p_T$ ) is the rapidity (transverse momentum) of the produced particle, and  $\sqrt{s_{NN}}$  is the centre-of-mass energy of the proton-nucleon system. Throughout this paper,  $y$  always indicates the rapidity in the nucleon-nucleon centre-of-mass system.

The suppression of quarkonium and light hadrons at large rapidity has been observed in  $pA$  collisions [10–13] and in deuteron-gold collisions [14–18]. The proton-lead ( $pPb$ ) collisions recorded at the LHC in 2013 enable the study of CNM effects at the TeV scale. With these  $pPb$  data, the production cross-sections of prompt  $J/\psi$  mesons,  $J/\psi$  mesons from  $b$ -hadron decays, and  $\Upsilon$  mesons were measured, and the CNM effects were studied by determining the nuclear modification factor  $R_{pPb}$  and the forward-backward production ratio  $R_{FB}$  [19, 20]. Working in the nucleon-nucleon rest frame, the “forward” and “backward” directions are defined with respect to the direction of the proton beam. The ratio  $R_{FB}$  is defined as

$$R_{FB}(y, p_T, \sqrt{s_{NN}}) \equiv \frac{\sigma_{pPb}(+|y|, p_T, \sqrt{s_{NN}})}{\sigma_{pPb}(-|y|, p_T, \sqrt{s_{NN}})}. \quad (1.2)$$

The advantage of measuring this ratio is that it does not rely on knowledge of the production cross-section in  $pp$  collisions. Furthermore, part of the experimental systematic uncertainties and theoretical scale uncertainties cancel in the ratio.

The measurements in the fixed-target  $pA$  collisions [10–12] showed stronger suppression at central rapidity for  $\psi(2S)$  mesons than for  $J/\psi$  mesons, while at forward rapidity the suppressions were compatible within large uncertainties. The PHENIX experiment made similar observations at central rapidity in  $dAu$  collisions at RHIC [18]. The ALICE experiment measured the  $\psi(2S)$  suppression in the forward and backward rapidity regions in  $pPb$  collisions at the LHC [21]. Nuclear shadowing and energy loss predict equal suppression of  $J/\psi$  and  $\psi(2S)$  mesons, and so cannot explain the observations. One explanation for the fixed-target results is that the charmonium states produced at central rapidity spend more time in the medium than those at forward rapidities; therefore the loosely bound  $\psi(2S)$  mesons are more easily suppressed than  $J/\psi$  mesons at central rapidity [22–24]. In this picture it is expected that the charmonium states will spend a much shorter time in the CNM at LHC energies than at lower energies, leading to similar suppression for  $\psi(2S)$  and  $J/\psi$  mesons even at central rapidity.

The excellent reconstruction resolution of the LHCb detector for primary and secondary vertices [25] provides the ability to separate prompt  $\psi(2S)$  mesons, which are produced directly from  $pp$  collisions, from those originating from  $b$ -hadron decays (called “ $\psi(2S)$  from  $b$ ” in the following). In this analysis, the production cross-sections of prompt  $\psi(2S)$  mesons and  $\psi(2S)$  from  $b$  are measured in  $pPb$  collisions at  $\sqrt{s_{NN}} = 5.02\text{TeV}$ , approximated in the following to 5 TeV. The nuclear modification factor  $R_{pPb}$  and the forward-backward production ratio  $R_{FB}$  are determined in the range  $2.5 < |y| < 4.0$ . Using the production cross-sections of  $\psi(2S)$  from  $b$  and  $J/\psi$  from  $b$ , the  $b\bar{b}$  production cross-section in  $pPb$  collisions is obtained.

## 2 Detector and datasets

The LHCb detector [25, 26] 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 surrounding the  $p\text{Pb}$  interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of momentum,  $p$ , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ $c$ . The minimum distance of a track to a primary vertex, the impact parameter, is measured with a resolution of  $(15 + 29/p_T) \mu\text{m}$ , 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. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The online event selection is performed by a trigger, 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.

With the proton beam travelling in the direction from the vertex detector to the muon system and the lead beam circulating in the opposite direction, the LHCb spectrometer covers forward rapidities. With reversed beam directions backward rapidities are accessible. The data sample used in this analysis is collected from the  $p\text{Pb}$  collisions in early 2013, corresponding to an integrated luminosity of  $1.1 \text{ nb}^{-1}$  ( $0.5 \text{ nb}^{-1}$ ) for forward (backward) collisions. The instantaneous luminosity was around  $5 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ , five orders of magnitude below the nominal LHCb luminosity for  $pp$  collisions. Therefore, the data were taken using a hardware trigger which simply rejected empty events. The software trigger for this analysis required one well-reconstructed track with hits in the muon system and  $p_T$  greater than 600 MeV/ $c$ .

Simulated samples based on  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  are used to determine the acceptance and reconstruction efficiencies. The simulation samples are reweighted so that the track multiplicity distribution reproduces the experimental data of  $p\text{Pb}$  collisions at  $\sqrt{s} = 5 \text{ TeV}$ . In the simulation,  $pp$  collisions are generated using PYTHIA [27] with a specific LHCb configuration [28]. Decays of hadronic particles are described by EVTGEN [29], in which final-state radiation is generated using PHOTOS [30]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [31, 32] as described in ref. [33].

## 3 Event selection and cross-section determination

The measurement of  $\psi(2S)$  production is based on the method described in refs. [19, 34, 35]. The  $\psi(2S)$  candidates are reconstructed using dimuon final states from events with at least

one primary vertex. The tracks should be of good quality, have opposite sign charges and be identified as muons with high  $p_T$ . The two muon tracks are required to originate from a common vertex with good vertex fit quality, and the reconstructed  $\psi(2S)$  mass should be in the range  $\pm 145 \text{ MeV}/c^2$  around the known  $\psi(2S)$  mass [36].

Due to the small size of the data sample, only one-dimensional differential cross-sections are measured. The differential production cross-section of  $\psi(2S)$  mesons in a given kinematic bin is defined as

$$\frac{d\sigma}{dX} = \frac{N}{\mathcal{L} \times \mathcal{B} \times \Delta X}, \quad (3.1)$$

where  $X$  denotes  $p_T$  or  $y$ ,  $N$  is the efficiency-corrected number of  $\psi(2S)$  signal candidates reconstructed with the dimuon final state in the given bin of  $X$ ,  $\Delta X$  is the bin width,  $\mathcal{L}$  is the integrated luminosity, and  $\mathcal{B}$  is the branching fraction of the  $\psi(2S) \rightarrow \mu^+\mu^-$  decay,  $\mathcal{B}(\psi(2S) \rightarrow \mu^+\mu^-) = (7.9 \pm 0.9) \times 10^{-3}$  [36]. Assuming lepton universality in electromagnetic decays, this branching fraction is replaced by that of the  $\psi(2S) \rightarrow e^+e^-$ , which has a much smaller uncertainty,  $\mathcal{B}(\psi(2S) \rightarrow e^+e^-) = (7.89 \pm 0.17) \times 10^{-3}$  [36].

The integrated luminosity of the data sample used in this analysis was determined using a van der Meer scan, and calibrated separately for the  $p\text{Pb}$  forward and backward samples [37]. The kinematic region of the measurement is  $p_T < 14 \text{ GeV}/c$  and  $1.5 < y < 4.0$  ( $-5.0 < y < -2.5$ ) for the forward (backward) sample. For the single differential cross-section measurements, the transverse momentum range  $p_T < 14 \text{ GeV}/c$  is divided into five bins with edges at (0, 2, 3, 5, 7, 14)  $\text{GeV}/c$ . The rapidity range is divided into five bins of width  $\Delta y = 0.5$ .

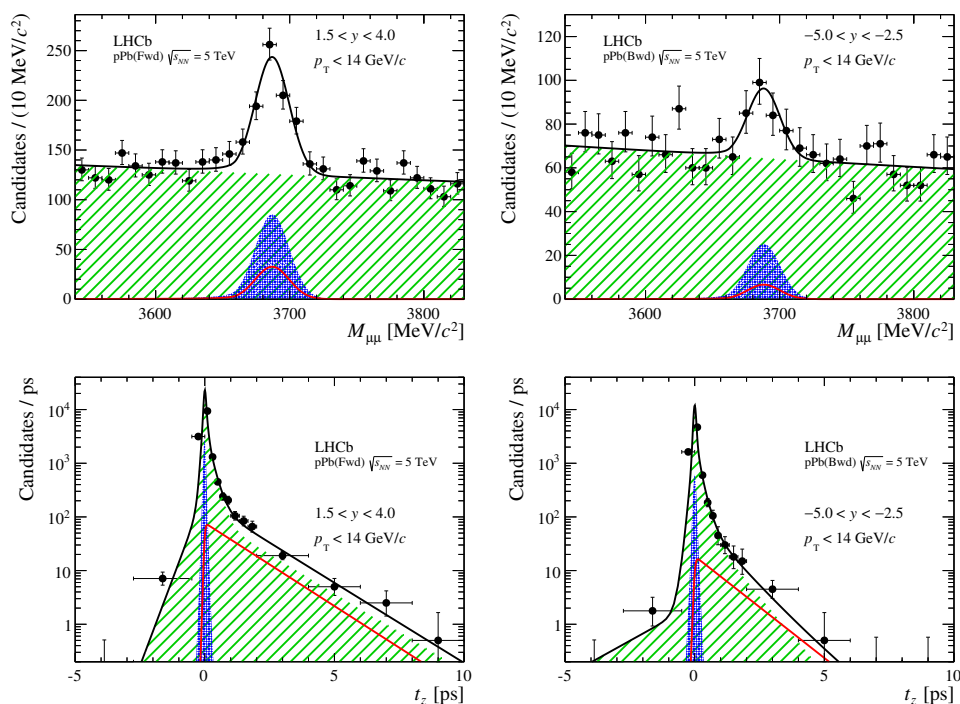
#### 4 Signal extraction and efficiencies

The numbers of prompt  $\psi(2S)$  and  $\psi(2S)$  from  $b$  in each kinematic bin are determined from an extended unbinned maximum likelihood fit performed simultaneously to the distributions of the dimuon invariant mass  $M_{\mu\mu}$  and the pseudo proper decay time  $t_z$  [34], defined as

$$t_z = \frac{(z_\psi - z_{\text{PV}}) \times M_\psi}{p_z}, \quad (4.1)$$

where  $z_\psi$  is the position of the  $\psi(2S)$  decay vertex along the beam axis,  $z_{\text{PV}}$  that of the primary vertex refitted after removing the two muon tracks from the  $\psi(2S)$  candidate,  $p_z$  the  $z$  component of the measured  $\psi(2S)$  momentum, and  $M_\psi$  the known  $\psi(2S)$  mass [36].

The invariant mass distribution of the signal in each bin is modelled by a Crystal Ball (CB) function [38], where the tail parameters are fixed to the values found in simulation and the other parameters are allowed to vary. For differential cross-section measurements, the sample size in each bin is very small. Therefore, in order to stabilise the fit, the mass resolution of the CB function is fixed to the value obtained from the  $J/\psi$  sample, scaled by the ratio of the known  $\psi(2S)$  and  $J/\psi$  masses [36]. The invariant mass distribution of the combinatorial background is described by an exponential function with variable slope parameter. The signal distribution of  $t_z$  can be described [39] by a  $\delta$ -function at  $t_z = 0$  for prompt  $\psi(2S)$  and an exponential function for the component of  $\psi(2S)$  from  $b$ , both



**Figure 1.** Projections of the fit results to (top) the dimuon invariant mass  $M_{\mu\mu}$  and (bottom) the pseudo proper decay time  $t_z$  in (left)  $p$ Pb forward and (right) backward data. In all plots the total fitted function is shown by the (black) solid line, the combinatorial background component is shown as the (green) hatched area, the prompt signal component by the (blue) shaded area, and the  $b$ -component by the (red) light solid line.

convolved with a Gaussian resolution function. The width of the resolution function and the slope of the exponential function are free in the fit. The background distribution of  $t_z$  in each kinematic bin is modelled with an empirical function determined from sidebands of the invariant mass distribution.

Figure 1 shows projections of the fit to  $M_{\mu\mu}$  and  $t_z$  for the full  $p$ Pb forward and backward samples. The combinatorial background in the backward region is higher than that in the forward region, because the track multiplicity in the backward region is larger. The mass resolution is  $13 \text{ MeV}/c^2$  for both the forward and backward samples. The total estimated signal yield for prompt  $\psi(2S)$  mesons in the forward (backward) sample is  $285 \pm 34$  ( $81 \pm 23$ ), and that for  $\psi(2S)$  from  $b$  in the forward (backward) sample is  $108 \pm 16$  ( $21 \pm 8$ ), where the uncertainties are statistical only.

The efficiency-corrected signal yield  $N$  is obtained from the sum of  $w_i/\varepsilon_i$  over all candidates in the given bin. The weight  $w_i$  is obtained with the *sPlot* technique using  $M_{\mu\mu}$  and  $t_z$  as discriminating variables [40]. The total efficiency  $\varepsilon_i$ , which depends on  $p_T$  and  $y$ , includes the geometrical acceptance, the reconstruction efficiency, the muon identification efficiency, and the trigger efficiency. The acceptance and reconstruction efficiencies are determined from simulation, assuming that the produced  $\psi(2S)$  mesons are unpolarised. The efficiency of the muon identification and the trigger efficiency are obtained from data using a tag-and-probe method as described below.

Source	Forward			Backward		
	prompt	from $b$	inclusive	prompt	from $b$	inclusive
<i>Correlated between bins</i>						
Track reconstruction	1.5	1.5	1.5	1.5	1.5	1.5
Muon identification	1.3	1.3	1.3	1.3	1.3	1.3
Trigger	1.9	1.9	1.9	1.9	1.9	1.9
Luminosity	1.9	1.9	1.9	2.1	2.1	2.1
Branching fraction	2.2	2.2	2.2	2.2	2.2	2.2
Track quality and radiative tail	1.5	1.5	1.5	1.5	1.5	1.5
Mass fit	3.8–6.9	0.3–3.9	3.2–8.2	9.2–10	16–20	3.0–5.4
<i>Uncorrelated between bins</i>						
Multiplicity reweighting	0.7	0.7	0.7	1.7	1.7	1.7
Simulation kinematics	0.6–10	0.4–10	0.2–9.8	1.4	2.4	0.7–23
$t_z$ fit	1.6–12	0.3–92	0.1–18	1.4–7.8	8.5–29	0.1–17

**Table 1.** Summary of the relative systematic uncertainties on cross-section measurements (%).

## 5 Systematic uncertainties

Several sources of systematic uncertainties affecting the production cross-section measurements are discussed in the following and summarised in table 1.

The uncertainty on the muon track reconstruction efficiency is studied with a data-driven tag-and-probe method, using a  $J/\psi$  sample in which one muon track is fully reconstructed while the other one is reconstructed using only specific sub-detectors [41]. Taking into account the difference of the track multiplicity distribution between data and simulation, the total uncertainty is found to be 1.5%.

The uncertainty due to the muon identification efficiency is assigned to be 1.3% for both the forward and backward samples as obtained in the  $J/\psi$  analysis in  $p$ Pb collisions [19]. It is estimated using  $J/\psi$  candidates reconstructed with one muon identified by the muon system and the other identified by selecting a track depositing the energy of a minimum-ionising particle in the calorimeters.

The trigger efficiency is determined from data using a sample unbiased with respect to the trigger decision. The corresponding uncertainty of 1.9% is taken as the systematic uncertainty due to the trigger efficiency.

To estimate the uncertainty due to reweighting the track multiplicity in simulation, the efficiency is calculated without reweighting. The difference between cross-sections calculated with these two efficiencies is considered as the systematic uncertainty, which is less than 0.7% in the forward sample, and about 1.7% in the backward sample.

The possible difference of the  $p_T$  and  $y$  spectra inside each kinematic bin between data and simulation can introduce a systematic uncertainty. To estimate the size of this effect the acceptance and reconstruction efficiencies have been checked by doubling the number of bins in  $p_T$  or in  $y$ . The difference from the nominal binning scheme is taken as systematic uncertainty, which is 0.2% – 10% (0.7% – 23%) in the forward (backward) sample. For the backward sample the separation into prompt  $\psi(2S)$  and  $\psi(2S)$  from  $b$  was not done in bins of  $p_T$  and  $y$  due to the limited sample size.

		prompt [ $\mu\text{b}$ ]	from $b$ [ $\mu\text{b}$ ]	inclusive [ $\mu\text{b}$ ]
Forward	$(+1.5 < y < +4.0)$	$138 \pm 17 \pm 8$	$53.7 \pm 7.9 \pm 3.6$	$192 \pm 19 \pm 10$
Backward	$(-5.0 < y < -2.5)$	$93 \pm 25 \pm 10$	$20.2 \pm 8.0 \pm 4.3$	$113 \pm 26 \pm 11$
Forward	$(+2.5 < y < +4.0)$	$65 \pm 10 \pm 6$	$21.4 \pm 4.5 \pm 1.1$	$86 \pm 11 \pm 7$
Backward	$(-4.0 < y < -2.5)$	$76 \pm 23 \pm 10$	$13.8 \pm 6.9 \pm 5.7$	$90 \pm 24 \pm 12$

**Table 2.** Integrated production cross-sections for prompt  $\psi(2S)$ ,  $\psi(2S)$  from  $b$ , and inclusive  $\psi(2S)$  in the forward region and the backward region. The  $p_T$  range is  $p_T < 14 \text{ GeV}/c$ . The first uncertainty is statistical and the second is systematic.

The luminosity is determined with an uncertainty of 1.9% (2.1%) for the  $p\text{Pb}$  forward (backward) sample [37]. The uncertainty on the  $\psi(2S) \rightarrow \mu^+\mu^-$  branching fraction is 2.2%. The combined uncertainty related to the track quality, the vertex finding and the radiative tail is estimated to be 1.5%.

The uncertainty due to modelling the invariant mass distribution is estimated by using the signal shape from simulation convolved with a Gaussian function, or by replacing the exponential function by a second-order polynomial. The maximum differences from the nominal results are taken as the systematic uncertainties due to the mass fit. To estimate the corresponding systematic uncertainty on the differential production cross-section due to the fixed mass resolution, the mass resolution is shifted by one standard deviation. It is found that this uncertainty is negligible. The uncertainty due to modelling the  $t_z$  distribution is estimated by fitting the signal sample extracted from the *sPlot* technique using the invariant mass alone as the discriminating variable.

## 6 Results

### 6.1 Cross-sections

The differential cross-sections of prompt  $\psi(2S)$ ,  $\psi(2S)$  from  $b$  and inclusive  $\psi(2S)$  in the  $p\text{Pb}$  forward region as functions of  $p_T$  and  $y$  are shown in figure 2. The differential cross-sections of inclusive  $\psi(2S)$  in the  $p\text{Pb}$  backward region as functions of  $p_T$  and  $y$  are shown in figure 3. As stated in section 5, for the differential production cross-section in the backward data sample, no attempt is made to separate prompt  $\psi(2S)$  and  $\psi(2S)$  from  $b$  due to the small statistics. However, these two components are separated for the integrated production cross-sections. All these cross-sections decrease with increasing  $|y|$ .

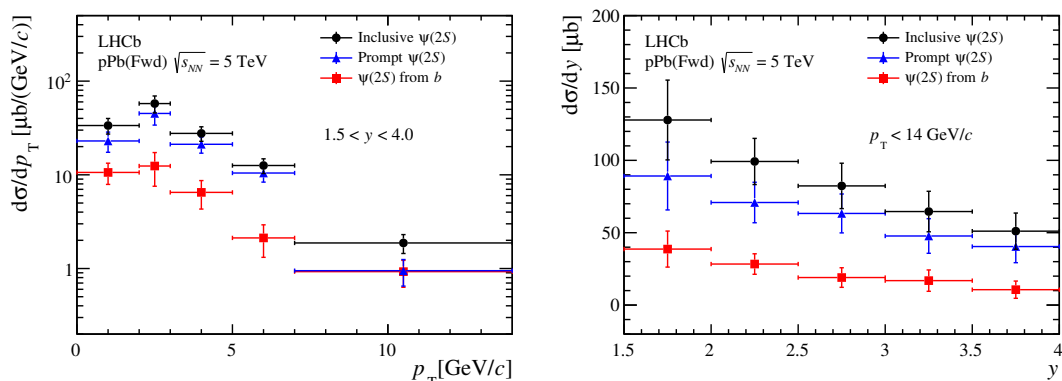
The integrated production cross-sections for prompt  $\psi(2S)$ ,  $\psi(2S)$  from  $b$ , and their sum representing inclusive  $\psi(2S)$ , are given in table 2. To determine the forward-backward production ratio  $R_{\text{FB}}$ , the integrated production cross-sections in the common rapidity region,  $2.5 < |y| < 4.0$ , are also given in the table.

The production cross-sections,  $\sigma(b\bar{b})$ , of the  $b\bar{b}$  pair can be obtained from

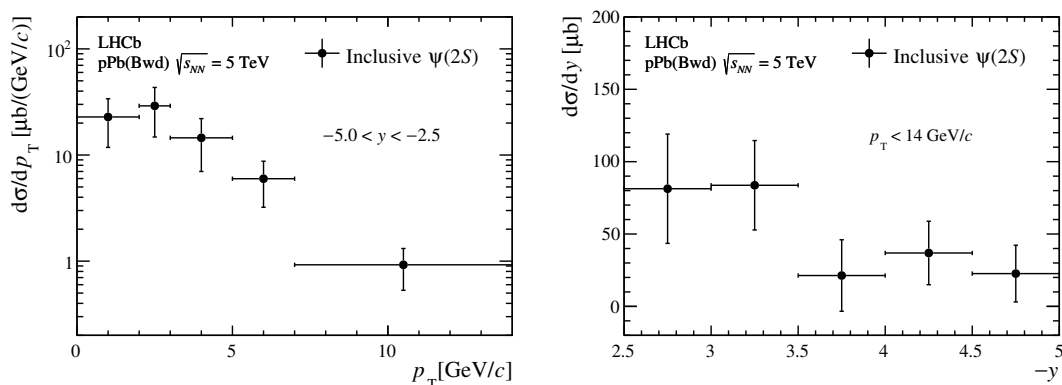
$$\sigma(b\bar{b}) = \sigma(\psi(2S) \text{ from } b)/2f_{b \rightarrow \psi(2S)} = \sigma(J/\psi \text{ from } b)/2f_{b \rightarrow J/\psi}, \quad (6.1)$$

where  $f_{b \rightarrow \psi(2S)}$  ( $f_{b \rightarrow J/\psi}$ ) indicates the production fraction of  $b \rightarrow \psi(2S)X$  ( $b \rightarrow J/\psi X$ ). The world average values are  $f_{b \rightarrow J/\psi} = (1.16 \pm 0.10) \times 10^{-2}$  and





**Figure 2.** Differential cross-section of  $\psi(2S)$  meson production as a function of (left)  $p_T$  and (right)  $y$  in  $pPb$  forward collisions. The (black) dots represent inclusive  $\psi(2S)$ , the (blue) triangles indicate prompt  $\psi(2S)$ , and the (red) squares show  $\psi(2S)$  from  $b$ . The error bars indicate the total uncertainties.



**Figure 3.** Differential cross-section of  $\psi(2S)$  meson production as a function of (left)  $p_T$  and (right)  $y$  in  $pPb$  backward collisions. The error bars indicate the total uncertainties.

$f_{b \rightarrow \psi(2S)} = (2.83 \pm 0.29) \times 10^{-3}$  [36]. The production cross-sections  $\sigma(b\bar{b})$  obtained from the results of  $J/\psi$  and  $\psi(2S)$  from  $b$  are shown in table 3. The results of the  $b\bar{b}$  cross-sections obtained from  $\psi(2S)$  from  $b$  are consistent with those from  $J/\psi$  from  $b$ .

In the combination of the results the partial correlation between  $f_{b \rightarrow \psi(2S)}$  and  $f_{b \rightarrow J/\psi}$  is taken into account. The systematic uncertainties due to the muon identification, the tracking efficiency, and the track quality are considered to be fully correlated. The systematic uncertainties due to the luminosities are partially correlated. The averaged results are also shown in table 3.

## 6.2 Cold nuclear matter effects

Cold nuclear matter effects on  $\psi(2S)$  mesons can be studied with the production cross-sections obtained in the previous section. As defined in eq. (1.2), the forward-backward production ratio,  $R_{FB}$ , can be determined with the cross-sections in the common rapidity

	$\sigma_{\text{Fwd}}(b\bar{b})$ [mb] ( $p_{\text{T}}^{\psi} < 14 \text{ GeV}/c, 1.5 < y^{\psi} < 4.0$ )	$\sigma_{\text{Bwd}}(b\bar{b})$ [mb] ( $p_{\text{T}}^{\psi} < 14 \text{ GeV}/c, -5.0 < y^{\psi} < -2.5$ )
$\psi(2S)$	$9.49 \pm 1.40 \pm 0.64 \pm 0.97$	$3.57 \pm 1.41 \pm 0.76 \pm 0.37$
$J/\psi$	$7.16 \pm 0.18 \pm 0.40 \pm 0.62$	$5.09 \pm 0.29 \pm 0.53 \pm 0.44$
Averaged	$7.43 \pm 0.56(\text{uncorr}) \pm 0.49(\text{corr})$	$4.87 \pm 0.62(\text{uncorr}) \pm 0.32(\text{corr})$

**Table 3.** Production cross-sections  $\sigma(b\bar{b})$  of  $b\bar{b}$  pairs in  $p\text{Pb}$  collisions obtained from the production cross-sections of  $J/\psi$  and  $\psi(2S)$  from  $b$ . The superscript  $\psi$  denotes  $J/\psi$  or  $\psi(2S)$ . The first uncertainties are statistical, the second are systematic, and the third are due to the production branching fractions. The last row gives the average of the  $J/\psi$  and  $\psi(2S)$  results taking account of their correlation. The correlated and uncorrelated uncertainties are provided separately.

range ( $2.5 < |y| < 4.0$ ). The results are

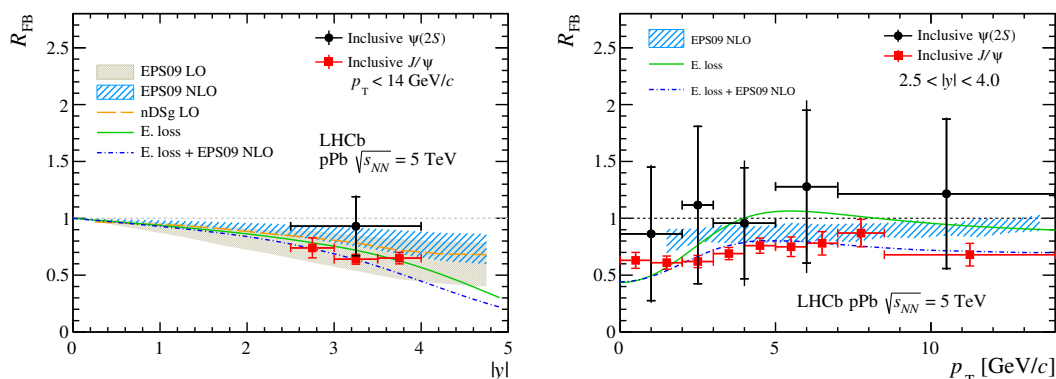
$$R_{\text{FB}}(p_{\text{T}} < 14 \text{ GeV}/c, 2.5 < |y| < 4.0) = \begin{cases} 0.93 \pm 0.29 \pm 0.08, & \text{inclusive,} \\ 0.86 \pm 0.29 \pm 0.10, & \text{prompt,} \\ 1.55 \pm 0.84 \pm 0.59, & \text{from } b, \end{cases}$$

where the first uncertainties are statistical and the second systematic. The ratios  $R_{\text{FB}}$  for inclusive  $\psi(2S)$  production as functions of  $y$  and  $p_{\text{T}}$  are shown in figure 4. For comparison, the plots also show the results for inclusive  $J/\psi$  production [19] and the theoretical predictions for  $\psi(2S)$  [3–5]. The uncertainties for the theoretical predictions are obtained by taking into account minimum and maximum nuclear shadowing effects, with many of them cancelling in the ratios. Calculations in ref. [3] are based on the Leading Order Colour Singlet Model (LO CSM) [42, 43], taking into account the modification effects of the gluon distribution function in nuclei with the parameterisation EPS09 [2] or nDSg [44]. The next-to-leading order Colour Evaporation Model (NLO CEM) [45] is used in ref. [5], considering parton shadowing with the EPS09 parameterisation. Reference [4] provides theoretical predictions of a coherent parton energy loss effect both in initial and final states, with or without additional parton shadowing effects according to EPS09. The single free parameter  $q_0$  in this model is 0.055 (0.075)  $\text{GeV}^2/\text{fm}$  when parton shadowing in the EPS09 parameterisation is (not) taken into account. Within uncertainties the measurements agree with all these calculations.

To obtain the nuclear modification factor  $R_{p\text{Pb}}$ , the  $\psi(2S)$  production cross-section in  $pp$  collisions at 5 TeV is needed, which is not yet available. However, it is reasonable to assume that

$$\frac{\sigma_{pp}^{J/\psi}(5 \text{ TeV})}{\sigma_{pp}^{\psi(2S)}(5 \text{ TeV})} = \frac{\sigma_{pp}^{J/\psi}(7 \text{ TeV})}{\sigma_{pp}^{\psi(2S)}(7 \text{ TeV})}, \tag{6.2}$$

where  $\sigma_{pp}$  indicates the production cross-section of  $J/\psi$  or  $\psi(2S)$  in  $pp$  collisions. The systematic uncertainty due to this assumption is taken to be negligible compared with the statistical uncertainties in this analysis. The ratio  $R$  of nuclear matter effects between



**Figure 4.** Forward-backward production ratios  $R_{FB}$  as functions of (left)  $|y|$  and (right)  $p_T$  for inclusive  $\psi(2S)$  mesons, together with inclusive  $J/\psi$  results [19] and the theoretical predictions [3–5], only some of which are available for  $|y|$ . For  $\psi(2S)$  results, the inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature. For  $J/\psi$  results, only total uncertainties are shown.

$\psi(2S)$  and  $J/\psi$  can then be determined as

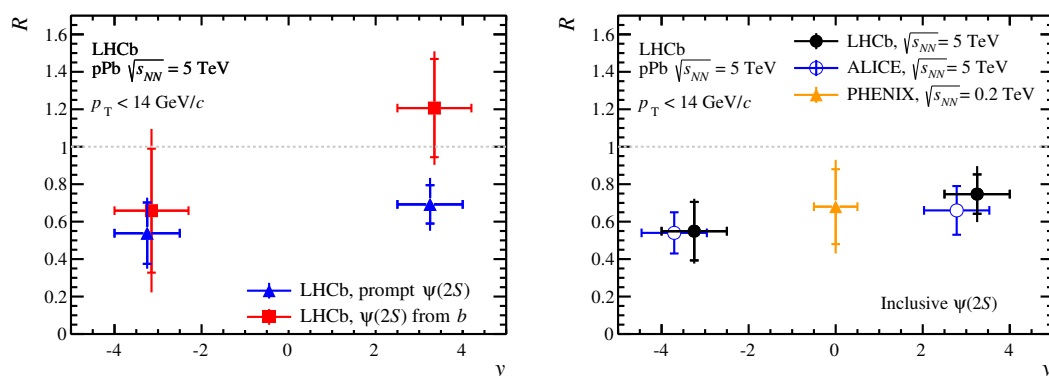
$$R \equiv \frac{R_{pPb}^{\psi(2S)}}{R_{pPb}^{J/\psi}} = \frac{\sigma_{pPb}^{\psi(2S)}(5 \text{ TeV})}{\sigma_{pPb}^{J/\psi}(5 \text{ TeV})} \times \frac{\sigma_{pp}^{J/\psi}(5 \text{ TeV})}{\sigma_{pp}^{\psi(2S)}(5 \text{ TeV})} = \frac{\sigma_{pPb}^{\psi(2S)}(5 \text{ TeV})}{\sigma_{pPb}^{J/\psi}(5 \text{ TeV})} \times \frac{\sigma_{pp}^{J/\psi}(7 \text{ TeV})}{\sigma_{pp}^{\psi(2S)}(7 \text{ TeV})}, \quad (6.3)$$

where  $R_{pPb}^{\psi(2S)}$  and  $R_{pPb}^{J/\psi}$  are the nuclear modification factors for  $\psi(2S)$  and  $J/\psi$ . The ratio  $R$  indicates whether there is relative suppression between  $\psi(2S)$  and  $J/\psi$  production in the collisions. If  $R$  is less than unity, it suggests that the suppression of  $\psi(2S)$  mesons due to nuclear matter effects in  $pPb$  collisions is stronger than that of  $J/\psi$  mesons. Using previous LHCb measurements [19, 34, 46], the values of  $R$  for prompt  $\psi(2S)$ ,  $\psi(2S)$  from  $b$  and inclusive  $\psi(2S)$  are calculated. The results are shown in figure 5, together with those from ALICE [21] and PHENIX [18]. The LHCb measurement is consistent with ALICE, which is in a comparable kinematic range. All results suggest a stronger suppression for prompt  $\psi(2S)$  mesons than that for prompt  $J/\psi$  mesons.

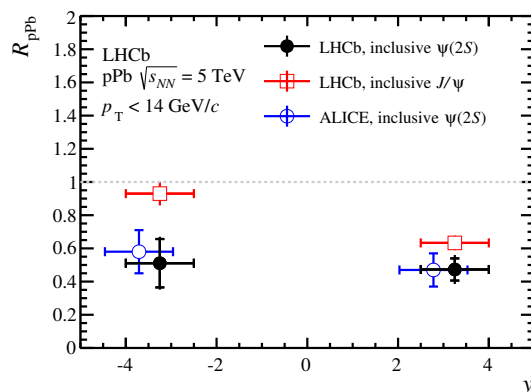
The nuclear modification factor of  $\psi(2S)$ ,  $R_{pPb}^{\psi(2S)}$ , can be expressed in terms of  $R_{pPb}^{J/\psi}$  and  $R$

$$R_{pPb}^{\psi(2S)} = R_{pPb}^{J/\psi} \times R. \quad (6.4)$$

The nuclear modification factor  $R_{pPb}^{J/\psi}$  was determined in a previous measurement [19]. The result for inclusive  $\psi(2S)$  is shown in figure 6. For comparison, the inclusive  $J/\psi$  result from previous measurements [19] and the result from ALICE [21] are also shown in the plot. The LHCb measurement is consistent with ALICE. The results for prompt  $\psi(2S)$  and  $\psi(2S)$  from  $b$  are shown in figure 7, suggesting that in  $pPb$  collisions the suppression of prompt  $\psi(2S)$  mesons is stronger than that of prompt  $J/\psi$  mesons. For  $\psi(2S)$  from  $b$ , no conclusion can be made because of the limited sample size. Figure 7 also shows several theoretical predictions [3–5, 47], where only those from ref. [47] are available for  $\psi(2S)$  from  $b$ . For prompt  $\psi(2S)$ , stronger suppression is seen in the data than expected by the



**Figure 5.** Ratio (left) between nuclear modification factors of  $\psi(2S)$  and  $J/\psi$  as a function of  $y$  for prompt  $\psi(2S)$  mesons and  $\psi(2S)$  from  $b$ . The blue triangles represent prompt  $\psi(2S)$  and the red rectangles indicate  $\psi(2S)$  from  $b$ . Ratio (right) between nuclear modification factors of  $\psi(2S)$  and  $J/\psi$  as a function of  $y$  for inclusive  $\psi(2S)$  mesons. The black dots show the LHCb result, the hollow circles indicate the ALICE result, and the yellow triangle is the PHENIX result at  $\sqrt{s_{NN}} = 0.2$  TeV. The inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature. Only total uncertainties are shown for the ALICE result.

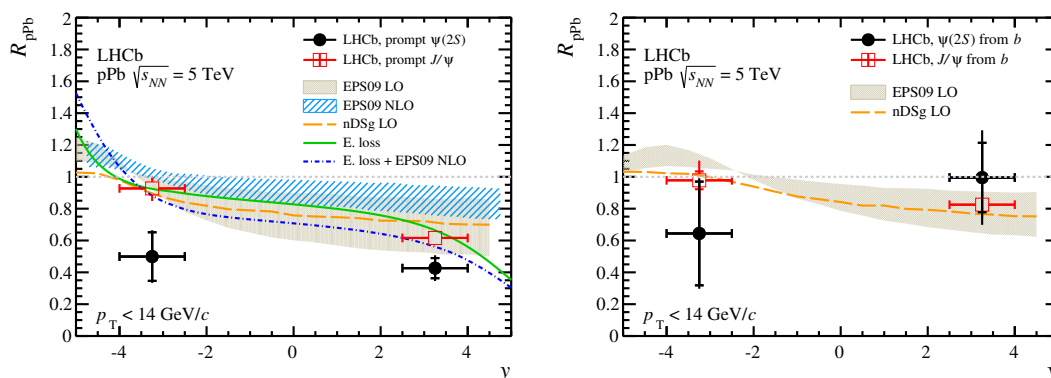


**Figure 6.** Nuclear modification factor  $R_{pPb}$  as a function of  $y$  for inclusive  $\psi(2S)$  and  $J/\psi$  mesons. The black dots represent the  $\psi(2S)$  result, the red squares indicate the  $J/\psi$  result, and the blue hollow circles show the ALICE result for  $\psi(2S)$ . The inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature. Only total uncertainties are shown for the ALICE result.

theoretical calculations mentioned above. Final-state effects, such as the interaction of the  $c\bar{c}$  pair with the dense medium created in the collisions, could be involved [48].

## 7 Conclusions

The production cross-sections of prompt  $\psi(2S)$  mesons and those from  $b$ -hadron decays are studied in  $pPb$  collisions with the LHCb detector. The nucleon-nucleon centre-of-mass energy in the collisions is  $\sqrt{s_{NN}} = 5$  TeV. The measurement is performed as a function of



**Figure 7.** Nuclear modification factor  $R_{pPb}$  as a function of  $y$  for (left) prompt  $\psi(2S)$  and (right)  $\psi(2S)$  from  $b$ , together with the theoretical predictions from (yellow dashed line and brown band) refs. [3, 47], (blue band) ref. [5], and (green solid and blue dash-dotted lines) ref. [4], where only those from ref. [47] are available for  $\psi(2S)$  from  $b$ . The inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature.

the transverse momentum and rapidity of  $\psi(2S)$  mesons in the region  $p_T < 14 \text{ GeV}/c$  and  $1.5 < y < 4.0$  (forward) and  $-5.0 < y < -2.5$  (backward). The  $b\bar{b}$  production cross-sections in  $pPb$  collisions are extracted using the results of  $\psi(2S)$  from  $b$  and  $J/\psi$  from  $b$ . The forward-backward production ratio  $R_{FB}$  is determined separately for prompt  $\psi(2S)$  mesons and those from  $b$ -hadron decays. These results show agreement within uncertainties with available theoretical predictions. The nuclear modification factor  $R_{pPb}$  is also determined separately for prompt  $\psi(2S)$  mesons and  $\psi(2S)$  from  $b$ . These results show that prompt  $\psi(2S)$  mesons are significantly more suppressed than prompt  $J/\psi$  mesons in the backward region; the results are not well described by theoretical predictions based on shadowing and energy loss mechanisms.

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## The LHCb collaboration

R. Aaij<sup>39</sup>, C. Abellán Beteta<sup>41</sup>, B. Adeva<sup>38</sup>, M. Adinolfi<sup>47</sup>, A. Affolder<sup>53</sup>, Z. Ajaltouni<sup>5</sup>, S. Akar<sup>6</sup>, J. Albrecht<sup>10</sup>, F. Alessio<sup>39</sup>, M. Alexander<sup>52</sup>, S. Ali<sup>42</sup>, G. Alkhazov<sup>31</sup>, P. Alvarez Cartelle<sup>54</sup>, A.A. Alves Jr<sup>58</sup>, S. Amato<sup>2</sup>, S. Amerio<sup>23</sup>, Y. Amhis<sup>7</sup>, L. An<sup>3,40</sup>, L. Anderlini<sup>18</sup>, G. Andreassi<sup>40</sup>, M. Andreotti<sup>17,g</sup>, J.E. Andrews<sup>59</sup>, R.B. Appleby<sup>55</sup>, O. Aquines Gutierrez<sup>11</sup>, F. Archilli<sup>39</sup>, P. d'Argent<sup>12</sup>, A. Artamonov<sup>36</sup>, M. Artuso<sup>60</sup>, E. Aslanides<sup>6</sup>, G. Auriemma<sup>26,n</sup>, M. Baalouch<sup>5</sup>, S. Bachmann<sup>12</sup>, J.J. Back<sup>49</sup>, A. Badalov<sup>37</sup>, C. Baesso<sup>61</sup>, W. Baldini<sup>17,39</sup>, R.J. Barlow<sup>55</sup>, C. Barschel<sup>39</sup>, S. Barsuk<sup>7</sup>, W. Barter<sup>39</sup>, V. Batzskaya<sup>29</sup>, V. Battista<sup>40</sup>, A. Bay<sup>40</sup>, L. Beaucourt<sup>4</sup>, J. Beddow<sup>52</sup>, F. Bedeschi<sup>24</sup>, I. Bediaga<sup>1</sup>, L.J. Bel<sup>42</sup>, V. Bellee<sup>40</sup>, N. Belloli<sup>21,k</sup>, I. Belyaev<sup>32</sup>, E. Ben-Haim<sup>8</sup>, G. Bencivenni<sup>19</sup>, S. Benson<sup>39</sup>, J. Benton<sup>47</sup>, A. Berezhnoy<sup>33</sup>, R. Bernet<sup>41</sup>, A. Bertolin<sup>23</sup>, F. Betti<sup>15</sup>, M.-O. Bettler<sup>39</sup>, M. van Beuzekom<sup>42</sup>, S. Bifani<sup>46</sup>, P. Billoir<sup>8</sup>, T. Bird<sup>55</sup>, A. Birnkraut<sup>10</sup>, A. Bizzeti<sup>18,i</sup>, T. Blake<sup>49</sup>, F. Blanc<sup>40</sup>, J. Blouw<sup>11</sup>, S. Blusk<sup>60</sup>, V. Bocci<sup>26</sup>, A. Bondar<sup>35</sup>, N. Bondar<sup>31,39</sup>, W. Bonivento<sup>16</sup>, A. Borgheresi<sup>21,k</sup>, S. Borghi<sup>55</sup>, M. Borisyak<sup>66</sup>, M. Borsato<sup>38</sup>, T.J.V. Bowcock<sup>53</sup>, E. Bowen<sup>41</sup>, C. Bozzi<sup>17,39</sup>, S. Braun<sup>12</sup>, M. Britsch<sup>12</sup>, T. Britton<sup>60</sup>, J. Brodzicka<sup>55</sup>, N.H. Brook<sup>47</sup>, E. Buchanan<sup>47</sup>, C. Burr<sup>55</sup>, A. Bursche<sup>2</sup>, J. Buytaert<sup>39</sup>, S. Cadeddu<sup>16</sup>, R. Calabrese<sup>17,g</sup>, M. Calvi<sup>21,k</sup>, M. Calvo Gomez<sup>37,p</sup>, P. Campana<sup>19</sup>, D. Campora Perez<sup>39</sup>, L. Capriotti<sup>55</sup>, A. Carbone<sup>15,e</sup>, G. Carboni<sup>25,l</sup>, R. Cardinale<sup>20,j</sup>, A. Cardini<sup>16</sup>, P. Carniti<sup>21,k</sup>, L. Carson<sup>51</sup>, K. Carvalho Akiba<sup>2</sup>, G. Casse<sup>53</sup>, L. Cassina<sup>21,k</sup>, L. Castillo Garcia<sup>40</sup>, M. Cattaneo<sup>39</sup>, Ch. Cauet<sup>10</sup>, G. Cavallero<sup>20</sup>, R. Cenci<sup>24,t</sup>, M. Charles<sup>8</sup>, Ph. Charpentier<sup>39</sup>, M. Chefdeville<sup>4</sup>, S. Chen<sup>55</sup>, S.-F. Cheung<sup>56</sup>, N. Chiapolini<sup>41</sup>, M. Chrzaszcz<sup>41,27</sup>, X. Cid Vidal<sup>39</sup>, G. Ciezarek<sup>42</sup>, P.E.L. Clarke<sup>51</sup>, M. Clemencic<sup>39</sup>, H.V. Cliff<sup>48</sup>, J. Closier<sup>39</sup>, V. Coco<sup>39</sup>, J. Cogan<sup>6</sup>, E. Cogneras<sup>5</sup>, V. Cogoni<sup>16,f</sup>, L. Cojocariu<sup>30</sup>, G. Collazuol<sup>23,r</sup>, P. Collins<sup>39</sup>, A. Comerma-Montells<sup>12</sup>, A. Contu<sup>39</sup>, A. Cook<sup>47</sup>, M. Coombes<sup>47</sup>, S. Coquereau<sup>8</sup>, G. Corti<sup>39</sup>, M. Corvo<sup>17,g</sup>, B. Couturier<sup>39</sup>, G.A. Cowan<sup>51</sup>, D.C. Craik<sup>51</sup>, A. Crocombe<sup>49</sup>, M. Cruz Torres<sup>61</sup>, S. Cunliffe<sup>54</sup>, R. Currie<sup>54</sup>, C. D'Ambrosio<sup>39</sup>, E. Dall'Occo<sup>42</sup>, J. Dalseno<sup>47</sup>, P.N.Y. David<sup>42</sup>, A. Davis<sup>58</sup>, O. De Aguiar Francisco<sup>2</sup>, K. De Bruyn<sup>6</sup>, S. De Capua<sup>55</sup>, M. De Cian<sup>12</sup>, J.M. De Miranda<sup>1</sup>, L. De Paula<sup>2</sup>, P. De Simone<sup>19</sup>, C.-T. Dean<sup>52</sup>, D. Decamp<sup>4</sup>, M. Deckenhoff<sup>10</sup>, L. Del Buono<sup>8</sup>, N. Deléage<sup>4</sup>, M. Demmer<sup>10</sup>, D. Derkach<sup>66</sup>, O. Deschamps<sup>5</sup>, F. Dettori<sup>39</sup>, B. Dey<sup>22</sup>, A. Di Canto<sup>39</sup>, F. Di Ruscio<sup>25</sup>, H. Dijkstra<sup>39</sup>, S. Donleavy<sup>53</sup>, F. Dordei<sup>39</sup>, M. Dorigo<sup>40</sup>, A. Dosil Suárez<sup>38</sup>, A. Dovbnya<sup>44</sup>, K. Dreimanis<sup>53</sup>, L. Dufour<sup>42</sup>, G. Dujany<sup>55</sup>, K. Dungs<sup>39</sup>, P. Durante<sup>39</sup>, R. Dzhelyadin<sup>36</sup>, A. Dziurda<sup>27</sup>, A. Dzyuba<sup>31</sup>, S. Easo<sup>50,39</sup>, U. Egede<sup>54</sup>, V. Egorychev<sup>32</sup>, S. Eidelman<sup>35</sup>, S. Eisenhardt<sup>51</sup>, U. Eitschberger<sup>10</sup>, R. Ekelhof<sup>10</sup>, L. Eklund<sup>52</sup>, I. El Rifai<sup>5</sup>, Ch. Elsasser<sup>41</sup>, S. Ely<sup>60</sup>, S. Esen<sup>12</sup>, H.M. Evans<sup>48</sup>, T. Evans<sup>56</sup>, A. Falabella<sup>15</sup>, C. Färber<sup>39</sup>, N. Farley<sup>46</sup>, S. Farry<sup>53</sup>, R. Fay<sup>53</sup>, D. Fazzini<sup>21,k</sup>, D. Ferguson<sup>51</sup>, V. Fernandez Albor<sup>38</sup>, F. Ferrari<sup>15</sup>, F. Ferreira Rodrigues<sup>1</sup>, M. Ferro-Luzzi<sup>39</sup>, S. Filippov<sup>34</sup>, M. Fiore<sup>17,39,g</sup>, M. Fiorini<sup>17,g</sup>, M. Firlej<sup>28</sup>, C. Fitzpatrick<sup>40</sup>, T. Fiutowski<sup>28</sup>, F. Fleuret<sup>7,b</sup>, K. Fohl<sup>39</sup>, P. Fol<sup>54</sup>, M. Fontana<sup>16</sup>, F. Fontanelli<sup>20,j</sup>, D. C. Forshaw<sup>60</sup>, R. Forty<sup>39</sup>, M. Frank<sup>39</sup>, C. Frei<sup>39</sup>, M. Frosini<sup>18</sup>, J. Fu<sup>22</sup>, E. Furfaro<sup>25,l</sup>, A. Gallas Torreira<sup>38</sup>, D. Galli<sup>15,e</sup>, S. Gallorini<sup>23</sup>, S. Gambetta<sup>51</sup>, M. Gandelman<sup>2</sup>, P. Gandini<sup>56</sup>, Y. Gao<sup>3</sup>, J. García Pardiñas<sup>38</sup>, J. Garra Tico<sup>48</sup>, L. Garrido<sup>37</sup>, D. Gascon<sup>37</sup>, C. Gaspar<sup>39</sup>, L. Gavardi<sup>10</sup>, G. Gazzoni<sup>5</sup>, D. Gerick<sup>12</sup>, E. Gersabeck<sup>12</sup>, M. Gersabeck<sup>55</sup>, T. Gershon<sup>49</sup>, Ph. Ghez<sup>4</sup>, S. Gianì<sup>40</sup>, V. Gibson<sup>48</sup>, O.G. Girard<sup>40</sup>, L. Giubega<sup>30</sup>, V.V. Gligorov<sup>39</sup>, C. Göbel<sup>61</sup>, D. Golubkov<sup>32</sup>, A. Golutvin<sup>54,39</sup>, A. Gomes<sup>1,a</sup>, C. Gotti<sup>21,k</sup>, M. Grabalosa Gándara<sup>5</sup>, R. Graciani Diaz<sup>37</sup>, L.A. Granado Cardoso<sup>39</sup>, E. Graugés<sup>37</sup>, E. Graverini<sup>41</sup>, G. Graziani<sup>18</sup>, A. Greco<sup>30</sup>, P. Griffith<sup>46</sup>, L. Grillo<sup>12</sup>, O. Grünberg<sup>64</sup>, B. Gui<sup>60</sup>, E. Gushchin<sup>34</sup>, Yu. Guz<sup>36,39</sup>, T. Gys<sup>39</sup>, T. Hadavizadeh<sup>56</sup>, C. Hadjivasiliou<sup>60</sup>, G. Haefeli<sup>40</sup>, C. Haen<sup>39</sup>, S.C. Haines<sup>48</sup>, S. Hall<sup>54</sup>, B. Hamilton<sup>59</sup>, X. Han<sup>12</sup>, S. Hansmann-Menzemer<sup>12</sup>, N. Harnew<sup>56</sup>, S.T. Harnew<sup>47</sup>, J. Harrison<sup>55</sup>, J. He<sup>39</sup>, T. Head<sup>40</sup>, V. Heijne<sup>42</sup>, A. Heister<sup>9</sup>,

K. Hennessy<sup>53</sup>, P. Henrard<sup>5</sup>, L. Henry<sup>8</sup>, J.A. Hernando Morata<sup>38</sup>, E. van Herwijnen<sup>39</sup>, M. Heß<sup>64</sup>,  
 A. Hicheur<sup>2</sup>, D. Hill<sup>56</sup>, M. Hoballah<sup>5</sup>, C. Hombach<sup>55</sup>, L. Hongming<sup>40</sup>, W. Hulsbergen<sup>42</sup>,  
 T. Humair<sup>54</sup>, M. Hushchyn<sup>66</sup>, N. Hussain<sup>56</sup>, D. Hutchcroft<sup>53</sup>, D. Hynds<sup>52</sup>, M. Idzik<sup>28</sup>, P. Ilten<sup>57</sup>,  
 R. Jacobsson<sup>39</sup>, A. Jaeger<sup>12</sup>, J. Jalocha<sup>56</sup>, E. Jans<sup>42</sup>, A. Jawahery<sup>59</sup>, M. John<sup>56</sup>, D. Johnson<sup>39</sup>,  
 C.R. Jones<sup>48</sup>, C. Joram<sup>39</sup>, B. Jost<sup>39</sup>, N. Jurik<sup>60</sup>, S. Kandybei<sup>44</sup>, W. Kanso<sup>6</sup>, M. Karacson<sup>39</sup>,  
 T.M. Karbach<sup>39,†</sup>, S. Karodia<sup>52</sup>, M. Kecke<sup>12</sup>, M. Kelsey<sup>60</sup>, I.R. Kenyon<sup>46</sup>, M. Kenzie<sup>39</sup>,  
 T. Ketel<sup>43</sup>, E. Khairullin<sup>66</sup>, B. Khanji<sup>21,39,k</sup>, C. Khurewathanakul<sup>40</sup>, T. Kirn<sup>9</sup>, S. Klaver<sup>55</sup>,  
 K. Klimaszewski<sup>29</sup>, O. Kochebina<sup>7</sup>, M. Kolpin<sup>12</sup>, I. Komarov<sup>40</sup>, R.F. Koopman<sup>43</sup>,  
 P. Koppenburg<sup>42,39</sup>, M. Kozeiha<sup>5</sup>, L. Kravchuk<sup>34</sup>, K. Kreplin<sup>12</sup>, M. Kreps<sup>49</sup>, P. Krokovny<sup>35</sup>,  
 F. Kruse<sup>10</sup>, W. Krzemien<sup>29</sup>, W. Kucewicz<sup>27,o</sup>, M. Kucharczyk<sup>27</sup>, V. Kudryavtsev<sup>35</sup>, A.  
 K. Kuonen<sup>40</sup>, K. Kurek<sup>29</sup>, T. Kvaratskheliya<sup>32</sup>, D. Lacarrere<sup>39</sup>, G. Lafferty<sup>55,39</sup>, A. Lai<sup>16</sup>,  
 D. Lambert<sup>51</sup>, G. Lanfranchi<sup>19</sup>, C. Langenbruch<sup>49</sup>, B. Langhans<sup>39</sup>, T. Latham<sup>49</sup>, C. Lazzeroni<sup>46</sup>,  
 R. Le Gac<sup>6</sup>, J. van Leerdam<sup>42</sup>, J.-P. Lees<sup>4</sup>, R. Lefèvre<sup>5</sup>, A. Leflat<sup>33,39</sup>, J. Lefrançois<sup>7</sup>,  
 E. Lemos Cid<sup>38</sup>, O. Leroy<sup>6</sup>, T. Lesiak<sup>27</sup>, B. Leverington<sup>12</sup>, Y. Li<sup>7</sup>, T. Likhomanenko<sup>66,65</sup>,  
 M. Liles<sup>53</sup>, R. Lindner<sup>39</sup>, C. Linn<sup>39</sup>, F. Lionetto<sup>41</sup>, B. Liu<sup>16</sup>, X. Liu<sup>3</sup>, D. Loh<sup>49</sup>, I. Longstaff<sup>52</sup>,  
 J.H. Lopes<sup>2</sup>, D. Lucchesi<sup>23,r</sup>, M. Lucio Martinez<sup>38</sup>, H. Luo<sup>51</sup>, A. Lupato<sup>23</sup>, E. Luppi<sup>17,g</sup>,  
 O. Lupton<sup>56</sup>, A. Lusiani<sup>24</sup>, F. Machefert<sup>7</sup>, F. Maciuc<sup>30</sup>, O. Maev<sup>31</sup>, K. Maguire<sup>55</sup>, S. Malde<sup>56</sup>,  
 A. Malinin<sup>65</sup>, G. Manca<sup>7</sup>, G. Mancinelli<sup>6</sup>, P. Manning<sup>60</sup>, A. Mapelli<sup>39</sup>, J. Maratas<sup>5</sup>,  
 J.F. Marchand<sup>4</sup>, U. Marconi<sup>15</sup>, C. Marin Benito<sup>37</sup>, P. Marino<sup>24,39,t</sup>, J. Marks<sup>12</sup>, G. Martellotti<sup>26</sup>,  
 M. Martin<sup>6</sup>, M. Martinelli<sup>40</sup>, D. Martinez Santos<sup>38</sup>, F. Martinez Vidal<sup>67</sup>, D. Martins Tostes<sup>2</sup>,  
 L.M. Massacrier<sup>7</sup>, A. Massafferri<sup>1</sup>, R. Matev<sup>39</sup>, A. Mathad<sup>49</sup>, Z. Mathe<sup>39</sup>, C. Matteuzzi<sup>21</sup>,  
 A. Mauri<sup>41</sup>, B. Maurin<sup>40</sup>, A. Mazurov<sup>46</sup>, M. McCann<sup>54</sup>, J. McCarthy<sup>46</sup>, A. McNab<sup>55</sup>,  
 R. McNulty<sup>13</sup>, B. Meadows<sup>58</sup>, F. Meier<sup>10</sup>, M. Meissner<sup>12</sup>, D. Melnychuk<sup>29</sup>, M. Merk<sup>42</sup>,  
 A. Merli<sup>22,u</sup>, E. Michielin<sup>23</sup>, D.A. Milanes<sup>63</sup>, M.-N. Minard<sup>4</sup>, D.S. Mitzel<sup>12</sup>, J. Molina Rodriguez<sup>61</sup>,  
 I.A. Monroy<sup>63</sup>, S. Monteil<sup>5</sup>, M. Morandin<sup>23</sup>, P. Morawski<sup>28</sup>, A. Mordà<sup>6</sup>, M.J. Morello<sup>24,t</sup>,  
 J. Moron<sup>28</sup>, A.B. Morris<sup>51</sup>, R. Mountain<sup>60</sup>, F. Muheim<sup>51</sup>, D. Müller<sup>55</sup>, J. Müller<sup>10</sup>, K. Müller<sup>41</sup>,  
 V. Müller<sup>10</sup>, M. Mussini<sup>15</sup>, B. Muster<sup>40</sup>, P. Naik<sup>47</sup>, T. Nakada<sup>40</sup>, R. Nandakumar<sup>50</sup>, A. Nandi<sup>56</sup>,  
 I. Nasteva<sup>2</sup>, M. Needham<sup>51</sup>, N. Neri<sup>22</sup>, S. Neubert<sup>12</sup>, N. Neufeld<sup>39</sup>, M. Neuner<sup>12</sup>, A.D. Nguyen<sup>40</sup>,  
 C. Nguyen-Mau<sup>40,q</sup>, V. Niess<sup>5</sup>, S. Nieswand<sup>9</sup>, R. Niet<sup>10</sup>, N. Nikitin<sup>33</sup>, T. Nikodem<sup>12</sup>,  
 A. Novoselov<sup>36</sup>, D.P. O’Hanlon<sup>49</sup>, A. Oblakowska-Mucha<sup>28</sup>, V. Obraztsov<sup>36</sup>, S. Ogilvy<sup>52</sup>,  
 O. Okhrimenko<sup>45</sup>, R. Oldeman<sup>16,48,f</sup>, C.J.G. Onderwater<sup>68</sup>, B. Osorio Rodrigues<sup>1</sup>,  
 J.M. Otalora Goicochea<sup>2</sup>, A. Otto<sup>39</sup>, P. Owen<sup>54</sup>, A. Oyanguren<sup>67</sup>, A. Palano<sup>14,d</sup>, F. Palombo<sup>22,u</sup>,  
 M. Palutan<sup>19</sup>, J. Panman<sup>39</sup>, A. Papanestis<sup>50</sup>, M. Pappagallo<sup>52</sup>, L.L. Pappalardo<sup>17,g</sup>,  
 C. Pappenheimer<sup>58</sup>, W. Parker<sup>59</sup>, C. Parkes<sup>55</sup>, G. Passaleva<sup>18</sup>, G.D. Patel<sup>53</sup>, M. Patel<sup>54</sup>,  
 C. Patrignani<sup>20,j</sup>, A. Pearce<sup>55,50</sup>, A. Pellegrino<sup>42</sup>, G. Penso<sup>26,m</sup>, M. Pepe Altarelli<sup>39</sup>,  
 S. Perazzini<sup>15,e</sup>, P. Perret<sup>5</sup>, L. Pescatore<sup>46</sup>, K. Petridis<sup>47</sup>, A. Petrolini<sup>20,j</sup>, M. Petruzzo<sup>22</sup>,  
 E. Picatoste Olloqui<sup>37</sup>, B. Pietrzyk<sup>4</sup>, M. Piekies<sup>27</sup>, D. Pinci<sup>26</sup>, A. Pistone<sup>20</sup>, A. Piucci<sup>12</sup>,  
 S. Playfer<sup>51</sup>, M. Plo Casasus<sup>38</sup>, T. Poikela<sup>39</sup>, F. Polci<sup>8</sup>, A. Poluektov<sup>49,35</sup>, I. Polyakov<sup>32</sup>,  
 E. Polycarpo<sup>2</sup>, A. Popov<sup>36</sup>, D. Popov<sup>11,39</sup>, B. Popovici<sup>30</sup>, C. Potterat<sup>2</sup>, E. Price<sup>47</sup>, J.D. Price<sup>53</sup>,  
 J. Prisciandaro<sup>38</sup>, A. Pritchard<sup>53</sup>, C. Prouve<sup>47</sup>, V. Pugatch<sup>45</sup>, A. Puig Navarro<sup>40</sup>, G. Punzi<sup>24,s</sup>,  
 W. Qian<sup>56</sup>, R. Quagliani<sup>7,47</sup>, B. Rachwal<sup>27</sup>, J.H. Rademacker<sup>47</sup>, M. Rama<sup>24</sup>, M. Ramos Pernas<sup>38</sup>,  
 M.S. Rangel<sup>2</sup>, I. Raniuk<sup>44</sup>, G. Raven<sup>43</sup>, F. Redi<sup>54</sup>, S. Reichert<sup>55</sup>, A.C. dos Reis<sup>1</sup>, V. Renaudin<sup>7</sup>,  
 S. Ricciardi<sup>50</sup>, S. Richards<sup>47</sup>, M. Rihl<sup>39</sup>, K. Rinnert<sup>53,39</sup>, V. Rives Molina<sup>37</sup>, P. Robbe<sup>7,39</sup>,  
 A.B. Rodrigues<sup>1</sup>, E. Rodrigues<sup>55</sup>, J.A. Rodriguez Lopez<sup>63</sup>, P. Rodriguez Perez<sup>55</sup>,  
 A. Rogozhnikov<sup>66</sup>, S. Roiser<sup>39</sup>, V. Romanovsky<sup>36</sup>, A. Romero Vidal<sup>38</sup>, J. W. Ronayne<sup>13</sup>,  
 M. Rotondo<sup>23</sup>, T. Ruf<sup>39</sup>, P. Ruiz Valls<sup>67</sup>, J.J. Saborido Silva<sup>38</sup>, N. Sagidova<sup>31</sup>, B. Saitta<sup>16,f</sup>,  
 V. Salustino Guimaraes<sup>2</sup>, C. Sanchez Mayordomo<sup>67</sup>, B. Sanmartin Sedes<sup>38</sup>, R. Santacesaria<sup>26</sup>,  
 C. Santamarina Rios<sup>38</sup>, M. Santimaria<sup>19</sup>, E. Santovetti<sup>25,l</sup>, A. Sarti<sup>19,m</sup>, C. Satriano<sup>26,n</sup>,

A. Satta<sup>25</sup>, D.M. Saunders<sup>47</sup>, D. Savrina<sup>32,33</sup>, S. Schael<sup>9</sup>, M. Schiller<sup>39</sup>, H. Schindler<sup>39</sup>,  
M. Schlupp<sup>10</sup>, M. Schmelling<sup>11</sup>, T. Schmelzer<sup>10</sup>, B. Schmidt<sup>39</sup>, O. Schneider<sup>40</sup>, A. Schopper<sup>39</sup>,  
M. Schubiger<sup>40</sup>, M.-H. Schune<sup>7</sup>, R. Schwemmer<sup>39</sup>, B. Sciascia<sup>19</sup>, A. Sciubba<sup>26,m</sup>, A. Semennikov<sup>32</sup>,  
A. Sergi<sup>46</sup>, N. Serra<sup>41</sup>, J. Serrano<sup>6</sup>, L. Sestini<sup>23</sup>, P. Seyfert<sup>21</sup>, M. Shapkin<sup>36</sup>, I. Shapoval<sup>17,44,g</sup>,  
Y. Shcheglov<sup>31</sup>, T. Shears<sup>53</sup>, L. Shekhtman<sup>35</sup>, V. Shevchenko<sup>65</sup>, A. Shires<sup>10</sup>, B.G. Siddi<sup>17</sup>,  
R. Silva Coutinho<sup>41</sup>, L. Silva de Oliveira<sup>2</sup>, G. Simi<sup>23,s</sup>, M. Sirendi<sup>48</sup>, N. Skidmore<sup>47</sup>,  
T. Skwarnicki<sup>60</sup>, E. Smith<sup>54</sup>, I.T. Smith<sup>51</sup>, J. Smith<sup>48</sup>, M. Smith<sup>55</sup>, H. Snoek<sup>42</sup>, M.D. Sokoloff<sup>58,39</sup>,  
F.J.P. Soler<sup>52</sup>, F. Soomro<sup>40</sup>, D. Souza<sup>47</sup>, B. Souza De Paula<sup>2</sup>, B. Spaan<sup>10</sup>, P. Spradlin<sup>52</sup>,  
S. Sridharan<sup>39</sup>, F. Stagni<sup>39</sup>, M. Stahl<sup>12</sup>, S. Stahl<sup>39</sup>, S. Stefkova<sup>54</sup>, O. Steinkamp<sup>41</sup>, O. Stenyakin<sup>36</sup>,  
S. Stevenson<sup>56</sup>, S. Stoica<sup>30</sup>, S. Stone<sup>60</sup>, B. Storaci<sup>41</sup>, S. Stracka<sup>24,t</sup>, M. Straticiu<sup>30</sup>,  
U. Straumann<sup>41</sup>, L. Sun<sup>58</sup>, W. Sutcliffe<sup>54</sup>, K. Swientek<sup>28</sup>, S. Swientek<sup>10</sup>, V. Syropoulos<sup>43</sup>,  
M. Szczekowski<sup>29</sup>, T. Szumlak<sup>28</sup>, S. T'Jampens<sup>4</sup>, A. Tayduganov<sup>6</sup>, T. Tekampe<sup>10</sup>, G. Tellarini<sup>17,g</sup>,  
F. Teubert<sup>39</sup>, C. Thomas<sup>56</sup>, E. Thomas<sup>39</sup>, J. van Tilburg<sup>42</sup>, V. Tisserand<sup>4</sup>, M. Tobin<sup>40</sup>, J. Todd<sup>58</sup>,  
S. Tolk<sup>43</sup>, L. Tomassetti<sup>17,g</sup>, D. Tonelli<sup>39</sup>, S. Topp-Joergensen<sup>56</sup>, E. Tournefier<sup>4</sup>, S. Tourneur<sup>40</sup>,  
K. Trabelsi<sup>40</sup>, M. Traill<sup>52</sup>, M.T. Tran<sup>40</sup>, M. Tresch<sup>41</sup>, A. Trisovic<sup>39</sup>, A. Tsaregorodtsev<sup>6</sup>,  
P. Tsopelas<sup>42</sup>, N. Tuning<sup>42,39</sup>, A. Ukleja<sup>29</sup>, A. Ustyuzhanin<sup>66,65</sup>, U. Uwer<sup>12</sup>, C. Vacca<sup>16,39,f</sup>,  
V. Vagnoni<sup>15</sup>, G. Valenti<sup>15</sup>, A. Vallier<sup>7</sup>, R. Vazquez Gomez<sup>19</sup>, P. Vazquez Regueiro<sup>38</sup>,  
C. Vázquez Sierra<sup>38</sup>, S. Vecchi<sup>17</sup>, M. van Veghel<sup>43</sup>, J.J. Velthuis<sup>47</sup>, M. Veltri<sup>18,h</sup>, G. Veneziano<sup>40</sup>,  
M. Vesterinen<sup>12</sup>, B. Viaud<sup>7</sup>, D. Vieira<sup>2</sup>, M. Vieites Diaz<sup>38</sup>, X. Vilasis-Cardona<sup>37,p</sup>, V. Volkov<sup>33</sup>,  
A. Vollhardt<sup>41</sup>, D. Voong<sup>47</sup>, A. Vorobyev<sup>31</sup>, V. Vorobyev<sup>35</sup>, C. Voß<sup>64</sup>, J.A. de Vries<sup>42</sup>, R. Waldi<sup>64</sup>,  
C. Wallace<sup>49</sup>, R. Wallace<sup>13</sup>, J. Walsh<sup>24</sup>, J. Wang<sup>60</sup>, D.R. Ward<sup>48</sup>, N.K. Watson<sup>46</sup>, D. Websdale<sup>54</sup>,  
A. Weiden<sup>41</sup>, M. Whitehead<sup>39</sup>, J. Wicht<sup>49</sup>, G. Wilkinson<sup>56,39</sup>, M. Wilkinson<sup>60</sup>, M. Williams<sup>39</sup>,  
M.P. Williams<sup>46</sup>, M. Williams<sup>57</sup>, T. Williams<sup>46</sup>, F.F. Wilson<sup>50</sup>, J. Wimberley<sup>59</sup>, J. Wishahi<sup>10</sup>,  
W. Wislicki<sup>29</sup>, M. Witek<sup>27</sup>, G. Wormser<sup>7</sup>, S.A. Wotton<sup>48</sup>, K. Wraight<sup>52</sup>, S. Wright<sup>48</sup>, K. Wyllie<sup>39</sup>,  
Y. Xie<sup>62</sup>, Z. Xu<sup>40</sup>, Z. Yang<sup>3</sup>, H. Yin<sup>62</sup>, J. Yu<sup>62</sup>, X. Yuan<sup>35</sup>, O. Yushchenko<sup>36</sup>, M. Zangoli<sup>15</sup>,  
M. Zavertyaev<sup>11,c</sup>, L. Zhang<sup>3</sup>, Y. Zhang<sup>3</sup>, A. Zhelezov<sup>12</sup>, A. Zhokhov<sup>32</sup>, L. Zhong<sup>3</sup>, V. Zhukov<sup>9</sup>,  
S. Zucchelli<sup>15</sup>

<sup>1</sup> Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

<sup>2</sup> Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

<sup>3</sup> Center for High Energy Physics, Tsinghua University, Beijing, China

<sup>4</sup> LAPP, Université Savoie Mont-Blanc, CNRS/IN2P3, Annecy-Le-Vieux, France

<sup>5</sup> Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France

<sup>6</sup> CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

<sup>7</sup> LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France

<sup>8</sup> LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France

<sup>9</sup> I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany

<sup>10</sup> Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

<sup>11</sup> Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

<sup>12</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

<sup>13</sup> School of Physics, University College Dublin, Dublin, Ireland

<sup>14</sup> Sezione INFN di Bari, Bari, Italy

<sup>15</sup> Sezione INFN di Bologna, Bologna, Italy

<sup>16</sup> Sezione INFN di Cagliari, Cagliari, Italy

<sup>17</sup> Sezione INFN di Ferrara, Ferrara, Italy

<sup>18</sup> Sezione INFN di Firenze, Firenze, Italy

<sup>19</sup> Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy

<sup>20</sup> Sezione INFN di Genova, Genova, Italy

<sup>21</sup> Sezione INFN di Milano Bicocca, Milano, Italy

<sup>22</sup> Sezione INFN di Milano, Milano, Italy

- <sup>23</sup> *Sezione INFN di Padova, Padova, Italy*
- <sup>24</sup> *Sezione INFN di Pisa, Pisa, Italy*
- <sup>25</sup> *Sezione INFN di Roma Tor Vergata, Roma, Italy*
- <sup>26</sup> *Sezione INFN di Roma La Sapienza, Roma, Italy*
- <sup>27</sup> *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
- <sup>28</sup> *AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
- <sup>29</sup> *National Center for Nuclear Research (NCBJ), Warsaw, Poland*
- <sup>30</sup> *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
- <sup>31</sup> *Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia*
- <sup>32</sup> *Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- <sup>33</sup> *Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
- <sup>34</sup> *Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
- <sup>35</sup> *Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia*
- <sup>36</sup> *Institute for High Energy Physics (IHEP), Protvino, Russia*
- <sup>37</sup> *Universitat de Barcelona, Barcelona, Spain*
- <sup>38</sup> *Universidad de Santiago de Compostela, Santiago de Compostela, Spain*
- <sup>39</sup> *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- <sup>40</sup> *Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- <sup>41</sup> *Physik-Institut, Universität Zürich, Zürich, Switzerland*
- <sup>42</sup> *Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands*
- <sup>43</sup> *Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands*
- <sup>44</sup> *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- <sup>45</sup> *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- <sup>46</sup> *University of Birmingham, Birmingham, United Kingdom*
- <sup>47</sup> *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- <sup>48</sup> *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- <sup>49</sup> *Department of Physics, University of Warwick, Coventry, United Kingdom*
- <sup>50</sup> *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- <sup>51</sup> *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- <sup>52</sup> *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- <sup>53</sup> *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- <sup>54</sup> *Imperial College London, London, United Kingdom*
- <sup>55</sup> *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- <sup>56</sup> *Department of Physics, University of Oxford, Oxford, United Kingdom*
- <sup>57</sup> *Massachusetts Institute of Technology, Cambridge, MA, United States*
- <sup>58</sup> *University of Cincinnati, Cincinnati, OH, United States*
- <sup>59</sup> *University of Maryland, College Park, MD, United States*
- <sup>60</sup> *Syracuse University, Syracuse, NY, United States*
- <sup>61</sup> *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to<sup>2</sup>*
- <sup>62</sup> *Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to<sup>3</sup>*
- <sup>63</sup> *Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to<sup>8</sup>*
- <sup>64</sup> *Institut für Physik, Universität Rostock, Rostock, Germany, associated to<sup>12</sup>*
- <sup>65</sup> *National Research Centre Kurchatov Institute, Moscow, Russia, associated to<sup>32</sup>*
- <sup>66</sup> *Yandex School of Data Analysis, Moscow, Russia, associated to<sup>32</sup>*
- <sup>67</sup> *Instituto de Física Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain, associated to<sup>37</sup>*
- <sup>68</sup> *Van Swinderen Institute, University of Groningen, Groningen, The Netherlands, associated to<sup>42</sup>*

- <sup>a</sup> *Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil*
- <sup>b</sup> *Laboratoire Leprince-Ringuet, Palaiseau, France*
- <sup>c</sup> *P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia*
- <sup>d</sup> *Università di Bari, Bari, Italy*
- <sup>e</sup> *Università di Bologna, Bologna, Italy*
- <sup>f</sup> *Università di Cagliari, Cagliari, Italy*
- <sup>g</sup> *Università di Ferrara, Ferrara, Italy*
- <sup>h</sup> *Università di Urbino, Urbino, Italy*
- <sup>i</sup> *Università di Modena e Reggio Emilia, Modena, Italy*
- <sup>j</sup> *Università di Genova, Genova, Italy*
- <sup>k</sup> *Università di Milano Bicocca, Milano, Italy*
- <sup>l</sup> *Università di Roma Tor Vergata, Roma, Italy*
- <sup>m</sup> *Università di Roma La Sapienza, Roma, Italy*
- <sup>n</sup> *Università della Basilicata, Potenza, Italy*
- <sup>o</sup> *AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland*
- <sup>p</sup> *LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
- <sup>q</sup> *Hanoi University of Science, Hanoi, Viet Nam*
- <sup>r</sup> *Università di Padova, Padova, Italy*
- <sup>s</sup> *Università di Pisa, Pisa, Italy*
- <sup>t</sup> *Scuola Normale Superiore, Pisa, Italy*
- <sup>u</sup> *Università degli Studi di Milano, Milano, Italy* † *Deceased*