



# Study of $\Upsilon$ production in $p\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

LHCb collaboration<sup>†</sup>

## Abstract

The production of  $\Upsilon(nS)$  mesons ( $n = 1, 2, 3$ ) in  $p\text{Pb}$  and  $\text{Pb}p$  collisions at a centre-of-mass energy per nucleon pair  $\sqrt{s_{\text{NN}}} = 8.16$  TeV is measured by the LHCb experiment, using a data sample corresponding to an integrated luminosity of  $31.8 \text{ nb}^{-1}$ . The  $\Upsilon(nS)$  mesons are reconstructed through their decays into two opposite-sign muons. The measurements comprise the differential production cross-sections of the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  states, their forward-to-backward ratios and nuclear modification factors. The measurements are performed as a function of the transverse momentum  $p_{\text{T}}$  and rapidity in the nucleon-nucleon centre-of-mass frame  $y^*$  of the  $\Upsilon(nS)$  states, in the kinematic range  $p_{\text{T}} < 25 \text{ GeV}/c$  and  $1.5 < y^* < 4.0$  ( $-5.0 < y^* < -2.5$ ) for  $p\text{Pb}$  ( $\text{Pb}p$ ) collisions. In addition, production cross-sections for  $\Upsilon(3S)$  are measured integrated over phase space and the production ratios between all three  $\Upsilon(nS)$  states are determined. Suppression for bottomonium in proton-lead collisions is observed, which is particularly visible in the ratios. The results are compared to theoretical models.

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# 1 Introduction

Existing experimental results in collisions of ultra-relativistic heavy nuclei are consistent with the formation of a deconfined state of hot partonic matter, referred to as Quark-Gluon Plasma (QGP) [1, 2]. One of the signatures of QGP is the suppression of heavy-quarkonia production in the collisions of heavy nuclei (AA collisions) with respect to  $pp$  collisions, an effect that is enhanced for states with lower binding energies, such as the  $\Upsilon(3S)$  meson [3]. However, the suppression of heavy-quarkonia production can also occur in the collisions of protons with heavy nuclei ( $pA$  collisions), where traditionally it was assumed that there was no QGP created.

In  $pA$  collisions, this suppression is caused by nuclear phenomena unrelated to deconfinement, commonly called cold nuclear matter (CNM) effects. The CNM effects that are expected to affect quarkonia production are of two types, “initial-state” effects happening at an early stage of the collision, such as nuclear effects on parton densities [4–7] or coherent energy losses [8–10], and “final-state” effects, as quarkonia absorption by nucleons [11], expected to be negligible at LHC energies [12–15]. Another final-state effect is the breaking of the  $q\bar{q}$  pair caused by collisions with comoving particles with similar rapidities (the so-called “comovers” model [16–20]), whose density is determined from the particle multiplicity measured in that region of rapidity. This model could explain the relative suppression observed among the  $\Upsilon(nS)$  states both in AA [21] and in  $pA$  collisions [22]. The size of nuclear effects can be quantified by measuring the nuclear modification factor  $R_{pA}$ , which is defined as the ratio of the cross-section in  $pA$  collisions to that in  $pp$  collisions scaled by the number of nucleons in the nucleus. In the absence of modifications,  $R_{pA}$  is unity.

Previous measurements in  $pA$  and AA collisions at RHIC [23] and LHC [22, 24–27] have revealed sizable nuclear modification factors for the  $\Upsilon(nS)$  states and a suppression which seems to be more pronounced for the higher states. Using a data sample corresponding to an integrated luminosity of about  $1.5 \text{ nb}^{-1}$ , the LHCb collaboration measured the production of  $\Upsilon(nS)$  mesons in  $pPb$  collisions at a per-nucleon centre-of-mass energy of  $\sqrt{s_{NN}} = 5 \text{ TeV}$  [28]. Moreover, the measurement of nuclear modification and forward-backward production ratios for  $\Upsilon(1S)$ , as well as  $\Upsilon(nS)$  to  $\Upsilon(1S)$  ratios, were performed.

In this paper, the production of  $\Upsilon(nS)$  mesons is studied in  $pPb$  collisions using data collected at  $\sqrt{s_{NN}} = 8.16 \text{ TeV}$  with the LHCb detector, corresponding to a total integrated luminosity of  $31.8 \text{ nb}^{-1}$ . This dataset has been used already for the study of the production of prompt  $J/\psi$  and  $J/\psi$  coming from  $b$ -hadron decays (called nonprompt  $J/\psi$  in the following) [29]. The measurements presented in this work comprise the differential production cross-sections of the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  states, their forward-to-backward ratios and nuclear modification factors, and the production ratios between all three  $\Upsilon(nS)$  states. In addition, the ratio of  $\Upsilon(1S)$  to nonprompt  $J/\psi$  cross-sections is determined as a function of proton-nucleon centre-of-mass rapidity,  $y^*$ , integrated over the transverse momenta,  $p_T$ , of the mesons, a measurement that allows direct comparison of open heavy-flavour and quarkonia production in the environment of heavy-nuclei collisions.

## 2 Detector description and data samples

The LHCb detector [30,31] is a single-arm forward spectrometer 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 beam-beam interaction region [32], 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 [33] placed downstream of the magnet. The tracking system provides a measurement of the momentum 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 (PV), the impact parameter (IP), is measured with a resolution of  $(15 + 29/p_T) \mu\text{m}$ , where  $p_T$  is in GeV/ $c$ . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [34]. 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 [35].

The trigger [36] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, in which all charged particles with  $p_T > 300 \text{ MeV}/c$  are reconstructed. The alignment and calibration of the detector is performed in near real-time [37]. This alignment is also used later in the offline reconstruction, ensuring consistent and high-quality particle identification (PID) information in the online and offline processing. The identical performance of the online and offline reconstruction offers the opportunity to perform physics analyses directly using candidates reconstructed in the trigger [36,38] as well as storing information about all reconstructed particles in the event [39]. The storage of only the triggered candidates enables a reduction of the event size by an order of magnitude.

For this analysis, at least one muon with  $p_T > 500 \text{ MeV}/c$  is required at the hardware trigger stage and at the software trigger stage, two muon tracks with  $p_T > 300 \text{ MeV}/c$  and a high-quality reconstructed decay vertex are required to form an  $\Upsilon(nS)$  candidate with invariant mass  $m(\mu^+\mu^-) > 4.7 \text{ GeV}/c^2$ . In addition, a small fraction of events with a large number of tracks in the vertex detector are rejected to avoid potential problems at the reconstruction stage.

Simulation is used in the determination of efficiencies. The  $p\text{Pb}$  collisions are simulated with EPOS-LHC [40] and the  $\Upsilon(nS) \rightarrow \mu^+\mu^-$  decays with PYTHIA 8.1 [41] in  $pp$  collisions where the proton energy is equal to that in  $p\text{Pb}$  collisions. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [42], as described in Ref. [43]. The  $\Upsilon(nS)$  mesons are produced unpolarised, justified by the fact that the polarisation of  $\Upsilon(nS)$  mesons has been measured by LHCb in  $pp$  collisions at similar energies and found to be small [44]. Consistently with what was done in previous LHCb analyses [29], no systematic uncertainty is associated with this assumption.

The asymmetric layout of the LHCb experiment [30], which covers the pseudorapidity range of  $2 < \eta < 5$ , results in two configurations: in the *forward*  $p\text{Pb}$  (*backward*  $\text{Pb}p$ ) configuration, the proton (lead) beam travels from the VELO detector to the muon chambers, taking advantage of the inversion of the proton and lead beams during the  $p\text{Pb}$  data-taking run. The energy of the proton beam is 6.5 TeV, while that of the lead beam is 2.56 TeV per nucleon, resulting in a centre-of-mass energy of the proton-nucleon system of 8.16 TeV. Since the energy per nucleon in the proton beam is significantly larger

than that in the lead beam, the proton-nucleon centre-of-mass system has a rapidity in the laboratory frame of +0.465 (−0.465) for  $p\text{Pb}$  ( $\text{Pb}p$ ) collisions, resulting in a shift of the effective detector acceptance. In this analysis,  $\Upsilon(nS)$  mesons are measured in the kinematic range of  $p_{\text{T}} < 25$  GeV/ $c$ , and  $1.5 < y^* < 4.0$  for  $p\text{Pb}$  forward and  $-5.0 < y^* < -2.5$  for  $p\text{Pb}$  backward collisions. This is the first measurement of  $\Upsilon(3S)$  production in  $p\text{Pb}$  collisions in this kinematic range. The data samples correspond to an integrated luminosity of  $12.5 \pm 0.3 \text{ nb}^{-1}$  in the forward configuration and  $19.3 \pm 0.5 \text{ nb}^{-1}$  in the backward configuration. The luminosities are determined using van der Meer scans [45], which were performed for both beam configurations.

### 3 Definition of the observables

The observables are measured in bins of  $p_{\text{T}}$  and  $y^*$  of the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  mesons, where both  $p_{\text{T}}$  and  $y^*$  are defined with respect to the direction of the proton beam in the centre-of-mass frame. For the  $\Upsilon(3S)$  meson, due to the limited signal yield, only integrated observables are measured.

The differential cross-section is measured in a fixed bin size of 0.5 units for  $y^*$  and variable bin sizes for  $p_{\text{T}}$  in the 0–25 GeV/ $c$  range. The  $\Upsilon(nS)$  meson double-differential production cross-section in the proton-lead collisions is defined as

$$\frac{d^2\sigma}{dp_{\text{T}}dy^*} = \frac{N(\Upsilon(nS) \rightarrow \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_{\text{tot}}^{\Upsilon(nS)} \times \mathcal{B}_{\mu\mu}^{\Upsilon(nS)} \times \Delta p_{\text{T}} \times \Delta y^*}, \quad (1)$$

where  $N(\Upsilon(nS) \rightarrow \mu^+\mu^-)$  is the raw yield of the  $\Upsilon(nS)$  decays reconstructed in the given rapidity and transverse momentum bin,  $\varepsilon_{\text{tot}}^{\Upsilon(nS)}$  is the total efficiency in that bin, including acceptance,  $\mathcal{B}_{\mu\mu}^{\Upsilon(nS)}$  is the branching fraction of the  $\Upsilon(nS)$  state to the  $\mu^+\mu^-$  final state, and  $\mathcal{L}$  is the integrated luminosity of the data sample. The values of the branching fractions used in this measurement are  $(2.48 \pm 0.05)\%$  for  $\Upsilon(1S) \rightarrow \mu^+\mu^-$ ,  $(1.93 \pm 0.17)\%$  for  $\Upsilon(2S) \rightarrow \mu^+\mu^-$ , and  $(2.18 \pm 0.21)\%$  for  $\Upsilon(3S) \rightarrow \mu^+\mu^-$  [46].

The nuclear modification factor for  $^{208}\text{Pb}$  is defined for the  $p\text{Pb}$  and  $\text{Pb}p$  configurations as

$$R_{p\text{Pb}}(p_{\text{T}}, y^*) = \frac{1}{208} \frac{d^2\sigma_{p\text{Pb}}(p_{\text{T}}, y^*)/dp_{\text{T}}dy^*}{d^2\sigma_{pp}(p_{\text{T}}, y^*)/dp_{\text{T}}dy^*}, \quad (2)$$

where  $\sigma_{pp}$  is the reference cross-section from  $pp$  collisions interpolated to  $\sqrt{s} = 8.16$  TeV using the LHCb measurements at  $\sqrt{s} = 2.76, 7, 8,$  and  $13$  TeV.

The forward-to-backward ratio is defined as

$$R_{\text{FB}}(p_{\text{T}}, |y^*|) = \frac{d^2\sigma_{p\text{Pb}}(p_{\text{T}}, +|y^*|)/dp_{\text{T}}dy^*}{d^2\sigma_{\text{Pb}p}(p_{\text{T}}, -|y^*|)/dp_{\text{T}}dy^*}, \quad (3)$$

and is evaluated in the rapidity range of  $2.5 < |y^*| < 4.0$ , which is common to  $p\text{Pb}$  and  $\text{Pb}p$  collisions.

The ratio of excited  $\Upsilon(2S)$  and  $\Upsilon(3S)$  states to the  $\Upsilon(1S)$  ground state in proton-lead collisions is defined as

$$R(\Upsilon(nS)) = \frac{[d^2\sigma/dp_{\text{T}}dy^*](\Upsilon(nS))}{[d^2\sigma/dp_{\text{T}}dy^*](\Upsilon(1S))}. \quad (4)$$

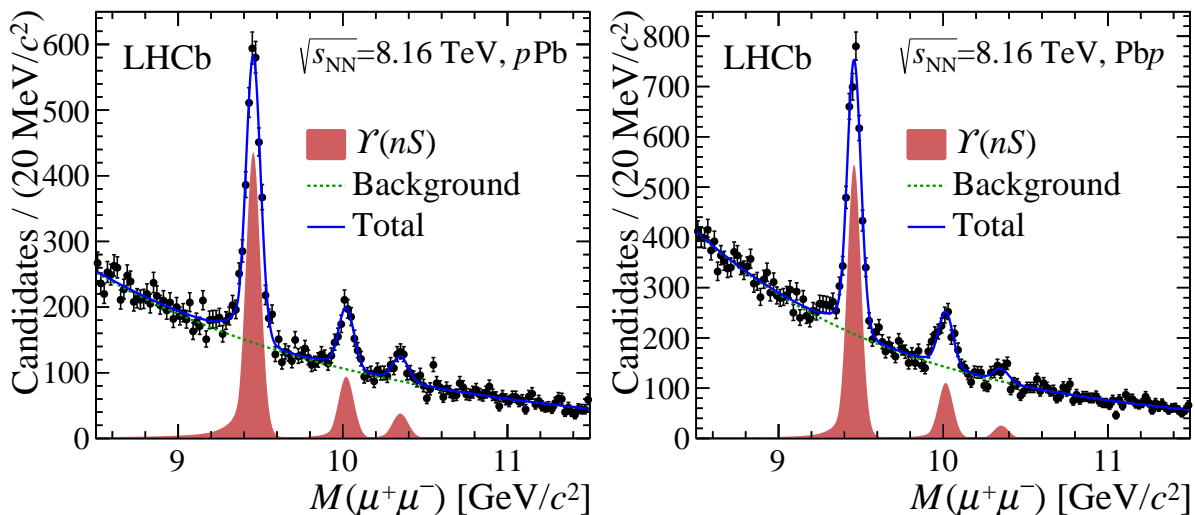


Figure 1: Invariant-mass distribution of  $\mu^+\mu^-$  pairs from the (left)  $p\text{Pb}$  and (right)  $\text{Pbp}$  samples after the trigger and offline selections.

In addition, the ratio of  $\Upsilon(1S)$  to non-prompt  $J/\psi$  cross-sections in proton-lead collisions is measured in the same way. The double ratio

$$\mathfrak{R}_{(p\text{Pb}|\text{Pbp})/pp}^{\Upsilon(nS)/\Upsilon(1S)} = \frac{R(\Upsilon(nS))_{p\text{Pb}|\text{Pbp}}}{R(\Upsilon(nS))_{pp}} \quad (5)$$

compares the ratio  $R(\Upsilon(nS))$  in  $p\text{Pb}$  or  $\text{Pbp}$  collisions to  $R(\Upsilon(nS))$  in  $pp$  collisions.

## 4 Event selection

The candidates reconstructed in the trigger are further filtered by means of an offline selection. In the offline selection, there must be at least one PV reconstructed and each PV must have at least four tracks measured in the vertex detector. For events with multiple PVs, the PV that has the smallest  $\chi_{\text{IP}}^2$  with respect to the  $\Upsilon(nS)$  candidate is chosen. Here,  $\chi_{\text{IP}}^2$  is defined as the difference between the vertex-fit  $\chi^2$  calculated with the  $\Upsilon(nS)$  meson candidate included in or excluded from the PV fit. Each muon track is required to have  $p_{\text{T}} > 1 \text{ GeV}/c$ , to be in the geometrical acceptance of the spectrometer ( $2.0 < \eta < 5.0$ ), to satisfy PID requirements, and to have a good track-fit quality. The dimuon invariant-mass distribution of offline-selected candidates is shown in Fig. 1 for the  $p\text{Pb}$  and  $\text{Pbp}$  samples.

The dimuon invariant-mass distribution is fitted with an exponential function for the background and three separate peaking functions, each consisting of the sum of two Crystal Ball functions [47] for the  $\Upsilon(nS)$  peaks. The shape parameters of the double Crystal Ball functions ( $n$  and  $\alpha$ ) are fixed to the values obtained in the simulation. The yields of  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)$  mesons in the  $p\text{Pb}$  and  $\text{Pbp}$  samples are summarised in Table 1. The probability that the background can produce a fluctuation greater than or equal to the excess observed in data is calculated as the local  $p$ -value. For the exponential-

Table 1: Yields of  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)$  mesons in  $p\text{Pb}$  and  $\text{Pb}p$  samples as given by the fit. The uncertainties are statistical only.

Samples	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\mathcal{L}$
$p\text{Pb}$	$2705 \pm 87$	$584 \pm 49$	$262 \pm 44$	$12.5 \text{ nb}^{-1}$
$\text{Pb}p$	$3072 \pm 82$	$679 \pm 54$	$159 \pm 39$	$19.3 \text{ nb}^{-1}$

background-only fits in the range of  $\pm 100 \text{ MeV}/c^2$  around the expected  $\Upsilon(3S)$  mass peak, the local  $p$ -values are below  $10^{-13}$  in  $p\text{Pb}$  sample and below  $10^{-7}$  in  $\text{Pb}p$  sample.

## 5 Efficiencies

The signal yields are corrected bin-by-bin by the total efficiencies to obtain the cross-section measurements. The total efficiency  $\varepsilon_{\text{tot}}$  includes contributions from the geometrical acceptance, the tracking and trigger efficiencies, and the efficiency of the selection including the requirement on the PID of the muons. All efficiencies are determined from simulation apart from the tracking and particle-identification efficiencies, where data are used to correct the efficiencies obtained from the simulation. The same procedure is used for each of the three  $\Upsilon(nS)$  states.

The muon tracking efficiency is calculated using simulated  $\Upsilon(nS)$  events in  $p\text{Pb}$  and  $\text{Pb}p$  collisions, and the efficiency in simulation is calibrated using efficiencies estimated from  $J/\psi$  candidates selected in  $p\text{Pb}$  data using a tag-and-probe method similar to that adopted in the measurement of  $J/\psi$  production using the same data set [29].

The PID efficiency for muons is measured using statistically independent samples of  $J/\psi$  decays in  $p\text{Pb}$ ,  $\text{Pb}p$  and  $pp$  data. In regions where the number of  $J/\psi$  decays is small, the efficiency is determined using weighted data from  $pp$  collisions to reproduce the kinematics and detector occupancies of  $p\text{Pb}$  collisions.

The total efficiency for the  $\Upsilon(1S)$  state is shown in Fig. 2. The efficiencies for the  $\Upsilon(2S)$  and  $\Upsilon(3S)$  states are similar. The uncertainties shown are statistical, due to the limited size of the simulated samples, and systematic, which will be discussed in the next section. The difference in efficiencies as a function of rapidity is largely due to acceptance effects.

## 6 Systematic uncertainties

Table 2 summarises the systematic uncertainties, which are different for each of the  $\Upsilon(nS)$  states. The finite size of the simulation samples leads to an uncertainty on the efficiency estimation, which is uncorrelated among bins and  $\Upsilon(nS)$  states and contributes to the uncertainties in acceptance, offline selection and trigger efficiencies. These uncertainties are small compared to the other systematic uncertainties and barely affect the overall systematic uncertainty. All other uncertainties are correlated among bins.

The choice of the fit model for the mass distributions affects the signal yields. The uncertainty associated with the choice of the fit functions is estimated using different

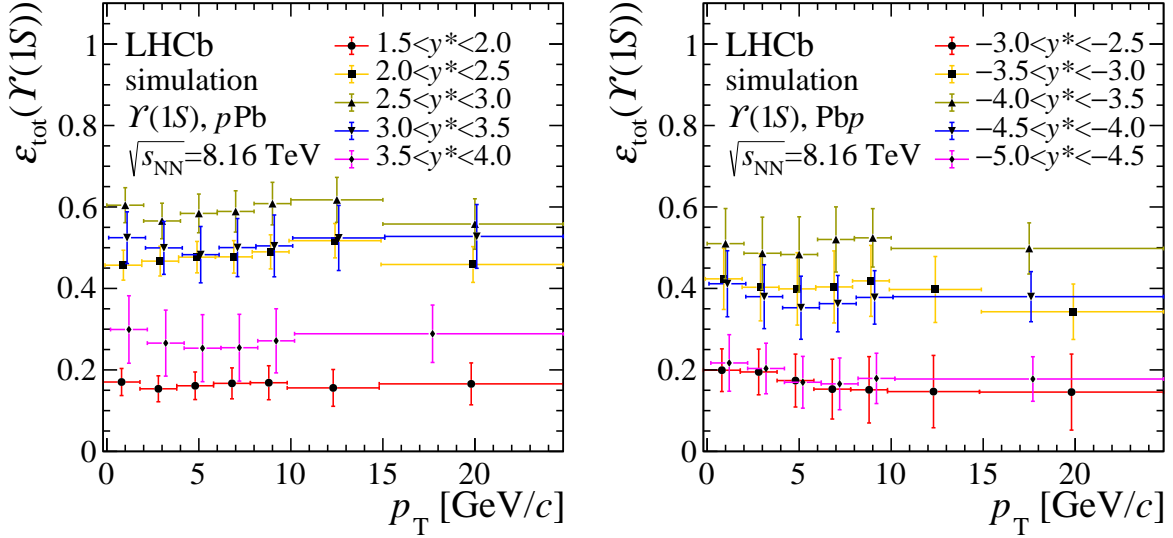


Figure 2: Total efficiency  $\varepsilon_{\text{tot}}$  of the  $\Upsilon(1S)$  meson as a function of its  $p_T$  in different  $y^*$  bins in (left)  $p\text{Pb}$  and (right)  $\text{Pb}p$  collisions. The horizontal locations of the markers are roughly the centroids of the bins, with offsets from centre to aid in readability.

Table 2: Systematic uncertainties (in percent) on the cross-section measurements. The ranges indicate the minimum and maximum values in different bins, among all  $\Upsilon(nS)$  states.

Source	$p\text{Pb}$	$\text{Pb}p$
Signal determination	5.7%	5.7%
Acceptance	0.7% – 3.4%	0.5% – 3.5%
Reconstruction efficiency	2.1% – 7.9%	2.5% – 8.1%
Offline selection efficiency	0.1% – 0.8%	0.1% – 1.4%
PID efficiency	1.1% – 4.4%	1.9% – 6.0%
Trigger efficiency	2.0% – 2.8%	2.0% – 2.4%
Luminosity	2.6%	2.5%
Branching ratio	2.0% – 9.6%	2.0% – 9.6%

functions (single Crystal Ball functions for signal, and a second-order polynomial for background), and by modifying the fit range for the signal fit to account for the uncertainty due to the radiative tail. The uncertainty due to the choice of the fit models is estimated to be 5.7%.

The track reconstruction efficiency calibration has uncertainties from three sources: the size of the calibration samples, the selection efficiency, and the signal yield determination of the calibration data sample. Considering all these effects, the total uncertainty from the reconstruction of the tracks varies from 2.1% to 7.9% for the  $p\text{Pb}$  sample and from 2.5% to 8.1% for the  $\text{Pb}p$  sample.

The uncertainty on the offline selection efficiency is only due to the finite size of the simulation sample, varying from 0.1% to 1.4%.



The PID uncertainties are related to the limited size of the  $pp$  and  $p\text{Pb}$  ( $\text{Pb}p$ ) calibration samples, and to the difference between the  $pp$  and  $p\text{Pb}$  ( $\text{Pb}p$ ) PID calibration samples. The latter effects lead to an uncertainty on the PID efficiency varying from 1.1% to 3.9% for the  $p\text{Pb}$  sample and from 1.9% to 2.8% for the  $\text{Pb}p$  sample. The total PID uncertainty including all effects varies from 1.1% to 4.4% for the  $p\text{Pb}$  sample and from 1.9% to 6.0% for the  $\text{Pb}p$  sample.

The trigger efficiency is obtained from simulation. The limited size of the simulated samples contributes to kinematic-bin-dependent uncertainties that vary between 0.2% and 2.0% for the  $p\text{Pb}$  sample and between 0.2% and 1.2% in the  $\text{Pb}p$  sample. An additional uncertainty of 2.0% is assigned based on a study of the trigger efficiency on a calibration data sample.

The relative uncertainty on the  $p\text{Pb}$  luminosity determined by the van der Meer scan is 2.6% and that on the  $\text{Pb}p$  luminosity is 2.5%.

The uncertainties from the decay branching fractions of the  $\Upsilon(nS)$  states contribute to the systematic uncertainty for values between 2.0 and 9.6% [46].

## 7 Results

The total  $\Upsilon(nS)$  cross-sections in the kinematic region  $p_{\text{T}} < 25$  GeV/c and  $1.5 < y^* < 4.0$  ( $-5.0 < y^* < -2.5$ ) for  $p\text{Pb}$  ( $\text{Pb}p$ ) sample are measured to be

$$\begin{aligned}\sigma_{p\text{Pb}}^{\Upsilon(1S)} &= 22.8 \pm 0.9 \text{ (stat)} \pm 2.1 \text{ (syst)} \mu\text{b}, \\ \sigma_{p\text{Pb}}^{\Upsilon(2S)} &= 6.4 \pm 0.6 \text{ (stat)} \pm 0.8 \text{ (syst)} \mu\text{b}, \\ \sigma_{p\text{Pb}}^{\Upsilon(3S)} &= 2.5 \pm 0.4 \text{ (stat)} \pm 0.3 \text{ (syst)} \mu\text{b}, \\ \sigma_{\text{Pb}p}^{\Upsilon(1S)} &= 20.3 \pm 0.8 \text{ (stat)} \pm 2.6 \text{ (syst)} \mu\text{b}, \\ \sigma_{\text{Pb}p}^{\Upsilon(2S)} &= 6.0 \pm 0.5 \text{ (stat)} \pm 0.9 \text{ (syst)} \mu\text{b}, \\ \sigma_{\text{Pb}p}^{\Upsilon(3S)} &= 1.2 \pm 0.3 \text{ (stat)} \pm 0.2 \text{ (syst)} \mu\text{b}.\end{aligned}$$

The cross-sections are also evaluated as a function of  $p_{\text{T}}$  and  $y^*$  for the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  states. The double-differential cross-section for the  $\Upsilon(1S)$  state is shown in Fig. 3. It is integrated over  $p_{\text{T}}$  to form a differential cross-section as a function of  $y^*$ , as shown in Fig. 4 (left), and integrated over  $y^*$  to form a differential cross-section as a function of  $p_{\text{T}}$ , as shown in Fig. 5 (left).<sup>1</sup> Similarly, for the  $\Upsilon(2S)$  state the differential cross-section as a function of  $y^*$  and  $p_{\text{T}}$  are shown in Fig. 4 (right) and Fig. 5 (right), respectively. For the  $\Upsilon(3S)$  state, due to the limited sample size, only the cross-section integrated over  $p_{\text{T}}$  and  $y^*$  is measured.

To measure the nuclear modification factor, a measurement of the  $pp$  cross-section at the same centre-of-mass energy is needed. In the absence of a direct measurement, the value of the  $\Upsilon(nS)$  cross-section in  $pp$  collisions at  $\sqrt{s} = 8.16$  TeV is obtained by interpolating between the values measured in  $pp$  collisions by LHCb at 2.76, 7, 8 and 13 TeV [48–50] using a second-order polynomial function. The differences between the scale factors obtained using the nominal second-order polynomial fits and alternative fits

<sup>1</sup> The numerical results of all cross-section measurements shown in this section can be found in Appendix A.

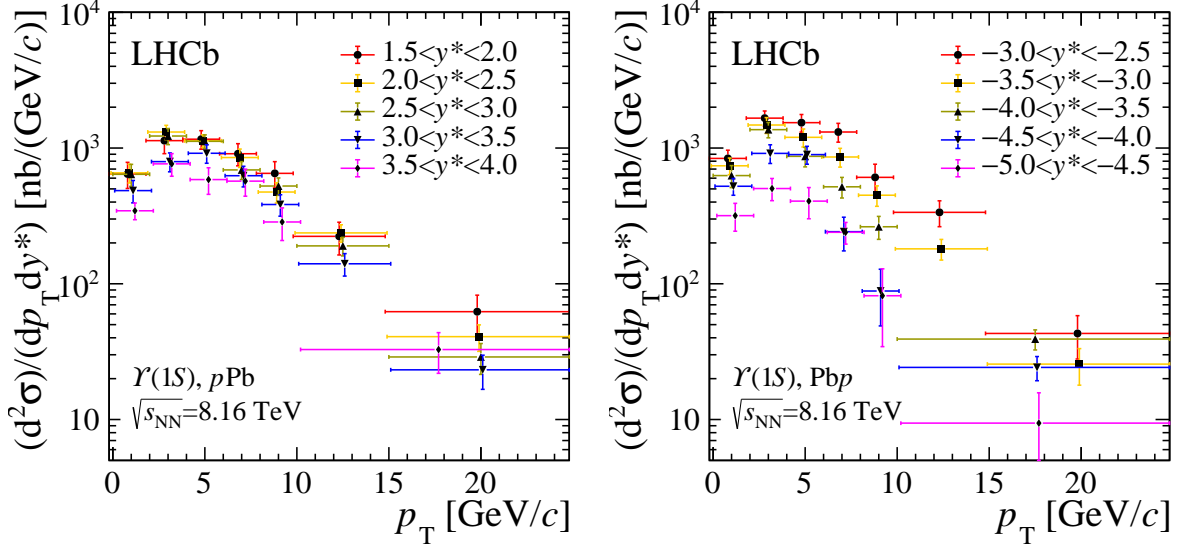


Figure 3: Double-differential cross-section for the  $\Upsilon(1S)$  meson as a function of  $p_T$  for different values of  $y^*$  for the (left) forward  $p\text{Pb}$  and (right) backward  $\text{Pb}p$  samples. The uncertainties are the sums in quadrature of the statistical and systematic components. The horizontal locations of the markers are roughly the centroids of the bins, with offsets from centre to aid in readability.

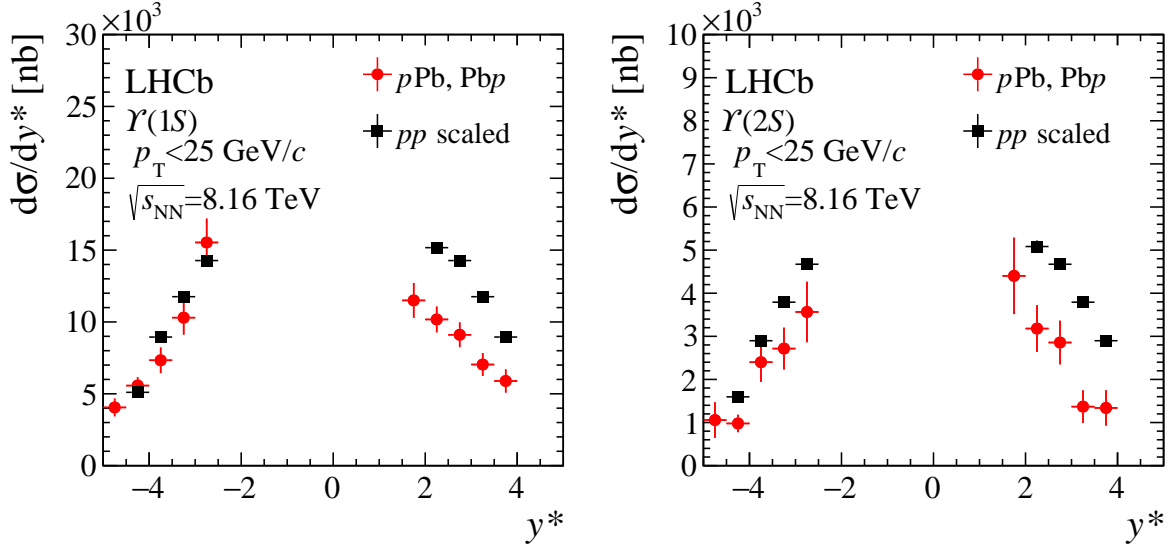


Figure 4: Cross-section of (left)  $\Upsilon(1S)$  and (right)  $\Upsilon(2S)$  production as a function of  $y^*$  integrated over  $p_T$  for the backward (negative  $y^*$ ) and forward (positive  $y^*$ ) samples, compared to the cross-section measured in  $pp$ , interpolated to  $\sqrt{s_{\text{NN}}} = 8.16$  TeV. In this and subsequent figures, the uncertainties shown are the sums in quadrature of the statistical and systematic components.

using exponential functions are assigned as systematic uncertainties on the interpolated cross-sections. The values of the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  differential cross-sections in  $p_T$  ( $y^*$ ) integrated over  $y^*$  ( $p_T$ ) in  $pp$  collisions at  $\sqrt{s} = 8.16$  TeV are shown in Figs. 4 to 5, and their numerical values are provided in Appendix B. The production of both  $\Upsilon(1S)$  and

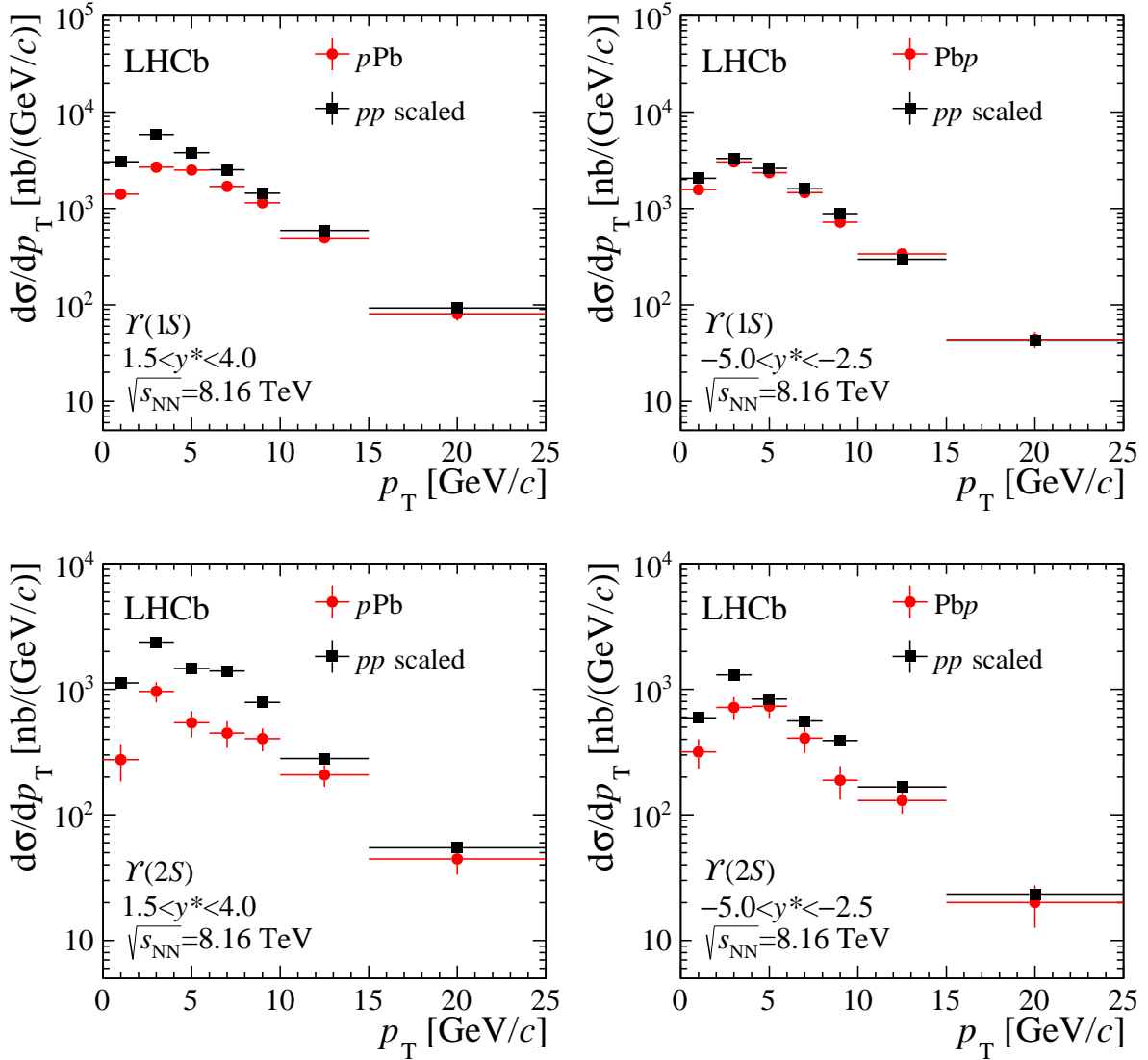


Figure 5: Cross-section of (top)  $\Upsilon(1S)$  and (bottom)  $\Upsilon(2S)$  production as a function of  $p_T$  integrated over  $y^*$  for the (left) forward and (right) backward samples compared to the cross-section measured in  $pp$ , interpolated to  $\sqrt{s_{NN}} = 8.16$  TeV.

$\Upsilon(2S)$  is suppressed in the forward  $pPb$  region with respect to the scaled value from  $pp$  collisions, as already observed in the prompt  $J/\psi$  measurement [29], while no significant suppression is visible in the backward  $Pbp$  region. The nuclear modification factors are evaluated as functions of  $p_T$  and  $y^*$  for the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  states,<sup>2</sup> and compared with different theoretical calculations:

1. A calculation based on the “HELAC-Onia” framework [51–53], where the modification of the parton flux due to CNM is treated within the collinear factorisation framework using two different nuclear parton distribution functions (nPDFs), the EPPS16 [54] and nCTEQ15 nPDFs set [7].

<sup>2</sup> In the nuclear modification factors, the systematic uncertainty related to branching ratios cancels.

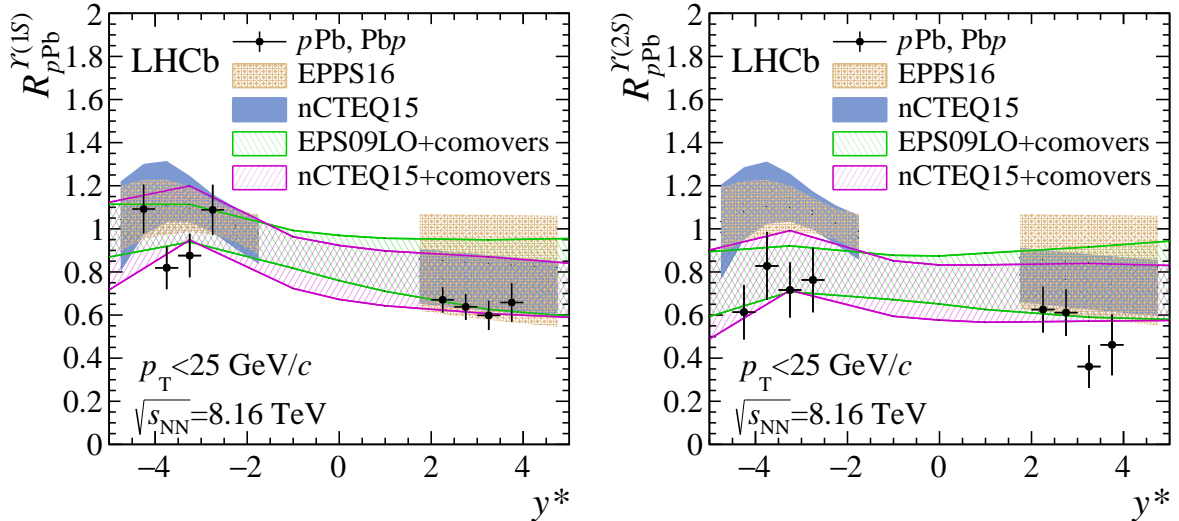


Figure 6: Nuclear modification factors of the (left)  $\Upsilon(1S)$  and (right)  $\Upsilon(2S)$  mesons as a function of  $y^*$  integrated over  $p_T$  for the forward and backward samples. The bands correspond to the theoretical predictions for the nCTEQ15 and EPPS16 nPDFs sets, and the comovers model as reported in the text.

2. Calculations based on the *comovers* model of  $\Upsilon(nS)$  production [17, 18], which implements final state interaction of the quarkonia states and nuclear parton distribution function modification via EPS09 at leading order [6], and the nCTEQ15 set already described.

The measurements and the calculations are shown in Figs. 6 and 7. For the  $\Upsilon(1S)$  state the nuclear modification factor is about 0.5 (0.8) at low  $p_T$  in the forward (backward) region, and is consistent with unity for  $p_T$  larger than 10 GeV/c, as predicted by the models. As a function of rapidity,  $R_{pPb}$  is consistent with unity in the PbP region at negative  $|y^*|$ , while a suppression is observed in the pPb region, where it averages around 0.7, consistent with the models analysed. The nuclear modification factor for  $\Upsilon(2S)$  is smaller than  $\Upsilon(1S)$ , which is consistent with the comovers models. The corresponding numerical results can be found in Appendix C. The same trend as for the  $\Upsilon(1S)$  state is observed for the  $\Upsilon(2S)$  state, although the suppression seems more pronounced for the  $\Upsilon(2S)$  state, as already observed by other experiments [22], especially in the backward region.

The forward-backward asymmetry is evaluated only for the  $\Upsilon(1S)$  meson as a function of  $p_T$  and  $y^*$ , see Fig. 8, whereas for the  $\Upsilon(2S)$  meson it is integrated over both  $y^*$  and  $p_T$  as shown in Fig. 9. The corresponding numerical results can be found in Appendix D.<sup>3</sup>

The ratio of the cross-sections of  $\Upsilon(2S)$  and  $\Upsilon(1S)$  mesons as a function of  $p_T$ , integrated over  $y^*$ , and as function of  $y^*$ , integrated over  $p_T$ , are shown in Fig. 10. The corresponding numerical results can be found in Appendix E. The ratios confirmed a larger suppression for the excited states with respect to the ground state observed in proton-lead collisions compared to  $pp$  collisions [49]. For the  $\Upsilon(3S)$  state, due to the

<sup>3</sup>In the forward-backward ratio, the systematic uncertainty related to branching ratios cancels.

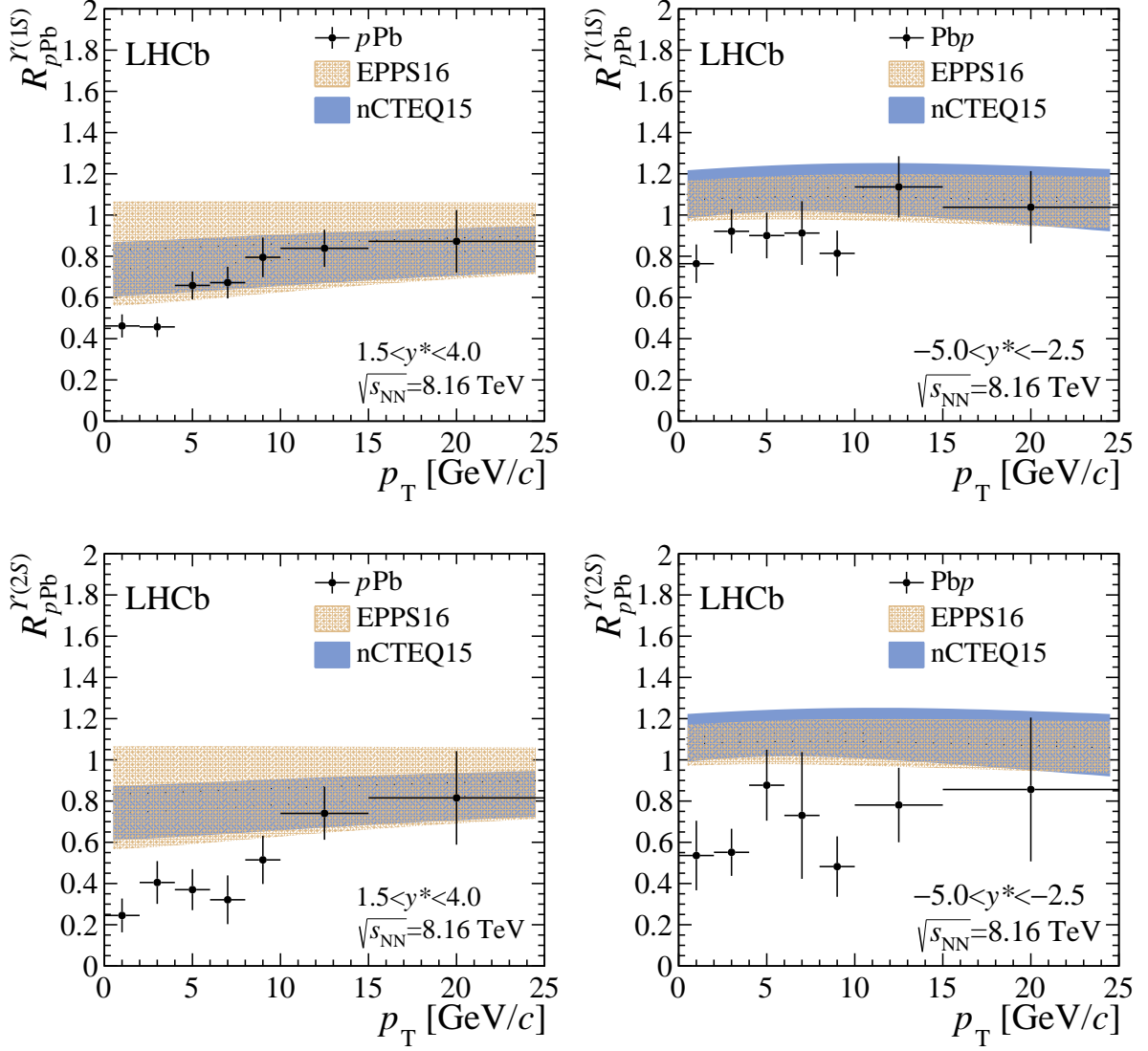


Figure 7: Nuclear modification factors of the (top)  $\Upsilon(1S)$  and (bottom)  $\Upsilon(2S)$  mesons as a function of  $p_T$  integrated over  $y^*$  for the (left) forward and (right) backward samples. The bands correspond to the theoretical predictions for the nCTEQ15 and EPPS16 nPDFs sets as reported in the text.

limited size of the data sample, only an integral ratio is measured. In the determination of the ratio  $R(\Upsilon(nS))$ , most of the systematic uncertainties cancel, except that related to branching ratios.

The integrated ratios are summarised in Table 3, where values are also reported for  $pp$  collisions. The corresponding double-ratio results are shown in Fig. 11 (left), together with the comovers model calculations, and the numerical results are

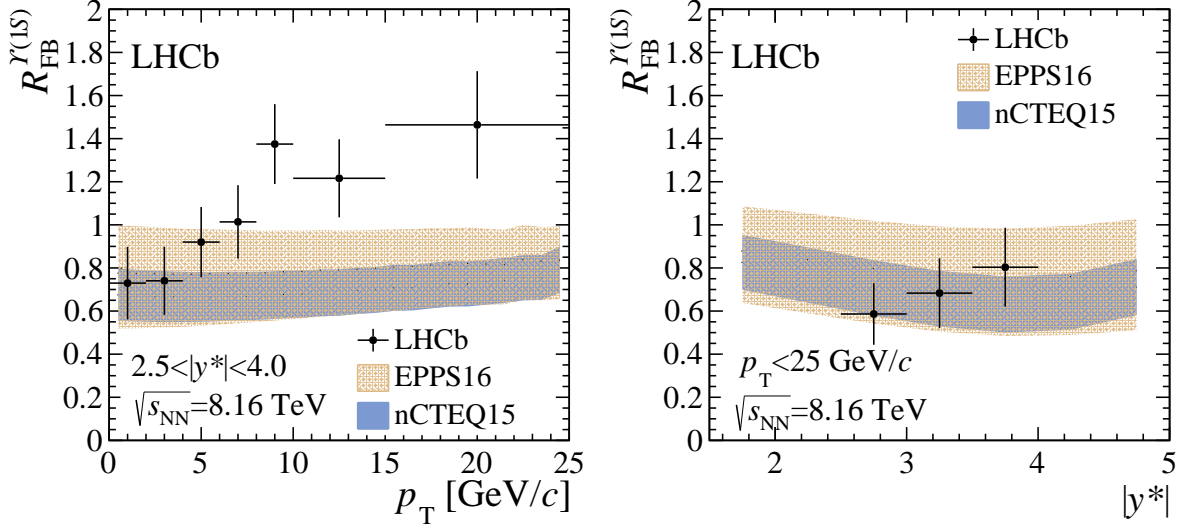


Figure 8: Forward-backward ratio for the  $\Upsilon(1S)$  as a function of (left)  $p_T$  integrated over  $y^*$  and (right) as a function of  $|y^*|$  integrated over  $p_T$ . The bands correspond to the theoretical calculations for the nCTEQ15 and EPPS16 nPDFs sets as reported in the text.

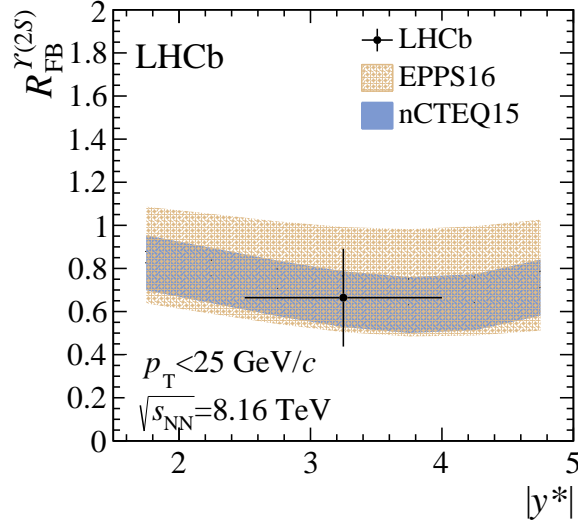


Figure 9: Forward-backward ratio for the  $\Upsilon(2S)$  compared with theoretical calculations for the nCTEQ15 and EPPS16 nPDFs sets as reported in the text.

$$\mathfrak{R}_{p\text{Pb}/pp}^{\Upsilon(2S)/\Upsilon(1S)} = 0.86 \pm 0.15,$$

$$\mathfrak{R}_{p\text{Pb}/pp}^{\Upsilon(3S)/\Upsilon(1S)} = 0.81 \pm 0.15,$$

$$\mathfrak{R}_{\text{Pb}p/pp}^{\Upsilon(2S)/\Upsilon(1S)} = 0.91 \pm 0.21,$$

$$\mathfrak{R}_{\text{Pb}p/pp}^{\Upsilon(3S)/\Upsilon(1S)} = 0.44 \pm 0.15.$$

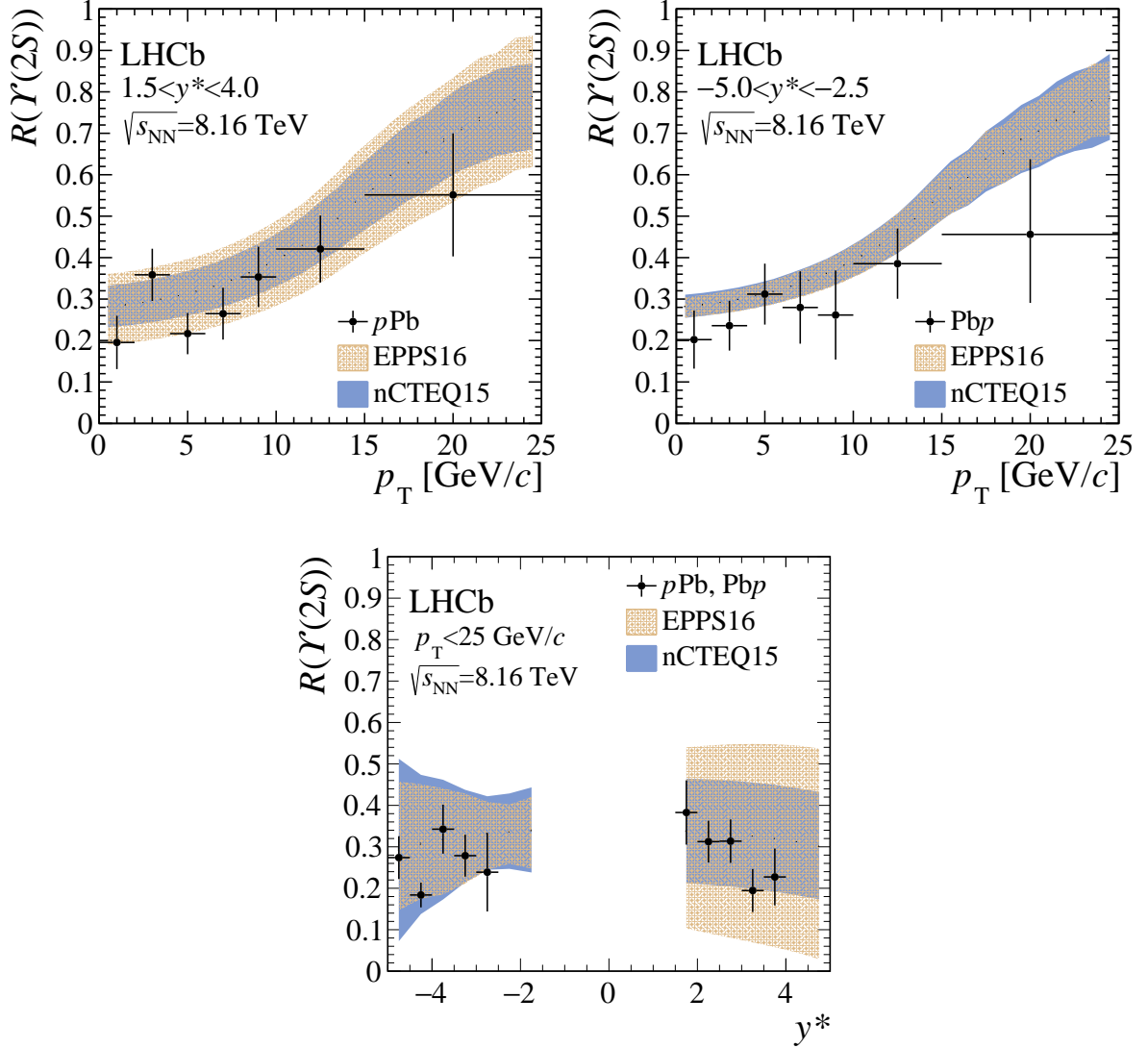


Figure 10: Ratios between  $\Upsilon(2S)$  and  $\Upsilon(1S)$  cross-sections as a function of (top)  $p_T$  integrated over  $y^*$ , and as function of (bottom)  $y^*$  integrated over  $p_T$ , for  $pPb$  and  $Pbp$  collisions. The bands correspond to the theoretical predictions for the nCTEQ15 and EPPS16 nPDFs sets as reported in the text.

For the double ratio of the  $\Upsilon(3S)$  over  $\Upsilon(1S)$  in the backward a clear indication of stronger suppression is observed, in agreement with the comovers model as shown in Fig. 11 (right). The ratio of the  $\Upsilon(1S)$  and nonprompt  $J/\psi$  cross-sections in  $pPb$  and  $Pbp$  collisions is also measured, where the nonprompt  $J/\psi$  cross-section was measured previously by LHCb [29] using the same data sample. The ratio is shown in Fig. 12 compared to the corresponding result observed in  $pp$  collisions. The numerical results are reported in Appendix F. A small suppression is visible, which could be attributed to final-state CNM effects. More data are needed in order to have a more definite indication of a different suppression mechanism for bottomonium and open beauty, such as  $\Upsilon(1S)$  and nonprompt  $J/\psi$  states, as indicated by Refs. [55, 56].

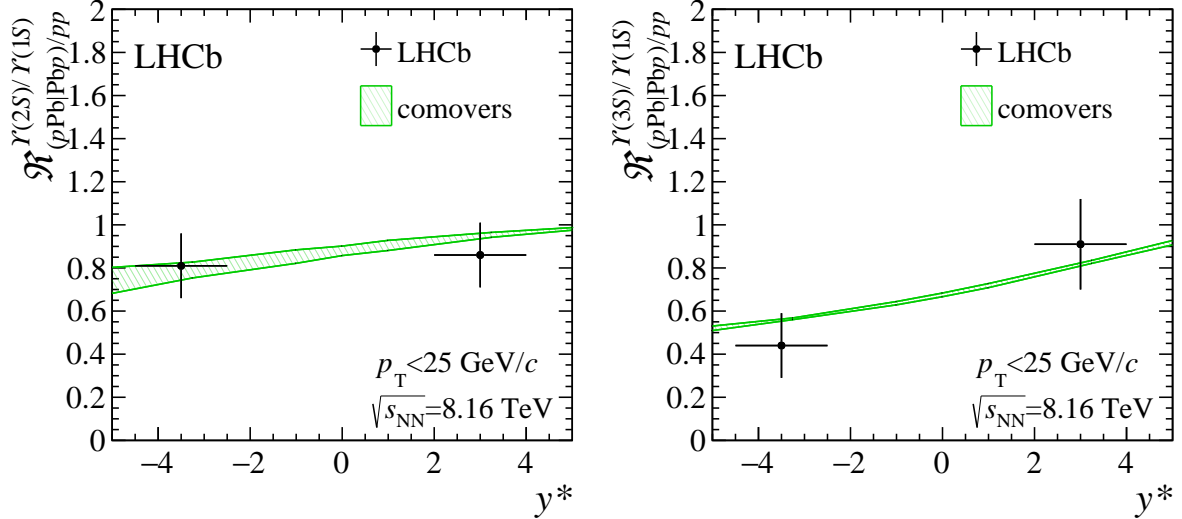


Figure 11: Double ratios for (left)  $\Upsilon(2S)$  and (right)  $\Upsilon(3S)$ . The bands correspond to the theoretical prediction for the comovers model as reported in the text.

Table 3: Ratio  $R(\Upsilon(nS))$  in  $pp$ ,  $pPb$ , and  $PbP$  samples. The uncertainties are combinations of statistical and systematical components.

	Sample	$R(\Upsilon(2S))$	$R(\Upsilon(3S))$
$pp$	$2.0 < y^* < 4.0$	$0.328 \pm 0.004$	$0.137 \pm 0.002$
$pp$	$-4.5 < y^* < -2.5$	$0.325 \pm 0.004$	$0.137 \pm 0.002$
$pPb$	$2.0 < y^* < 4.0$	$0.282 \pm 0.050$	$0.11 \pm 0.02$
$PbP$	$-4.5 < y^* < -2.5$	$0.296 \pm 0.070$	$0.06 \pm 0.02$

## 8 Summary

The production of  $\Upsilon(nS)$  states is studied in proton-lead collisions at  $\sqrt{s_{NN}} = 8.16$  TeV using data collected by the LHCb detector in 2016. The cross-sections, nuclear modification factors and forward-backward ratios are measured double-differentially ( $\Upsilon(1S)$ ) and single-differentially ( $\Upsilon(2S)$ ). The ratios of the production cross-sections of the different  $\Upsilon(nS)$  states are also measured as functions of transverse momentum and rapidity in the nucleon-nucleon centre-of-mass frame. The results are consistent with previous observations and with the theoretical model calculations, indicating a suppression of  $\Upsilon(nS)$  production in proton-lead collisions up to about 40%, more pronounced for the excited  $\Upsilon$  states, particularly in the region of negative rapidity.

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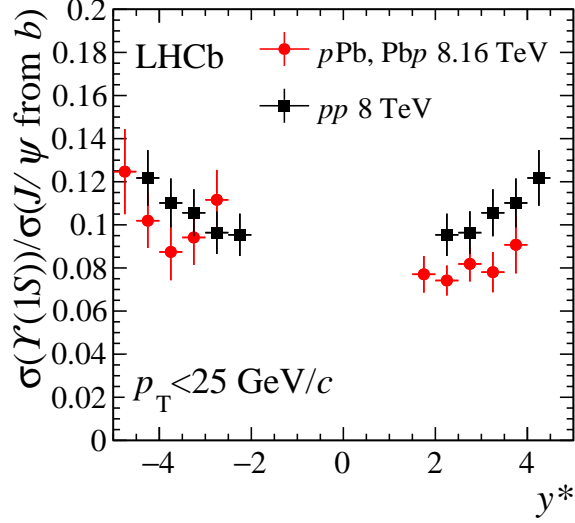


Figure 12: Ratio of  $\Upsilon(1S)$  to nonprompt  $J/\psi$  cross-sections as a function of  $y^*$  integrated over  $p_T$ , for  $p\text{Pb}$  and  $\text{Pb}p$  collisions.

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# Appendices

## A Cross-section

Tables 4 and 5 list the double-differential cross-section for  $\Upsilon(1S)$  in  $p\text{Pb}$  forward and backward samples. Tables 6 and 7 list the differential cross-section for  $\Upsilon(1S)$  in bins of transverse momentum and rapidity. The corresponding values for the  $\Upsilon(2S)$  state are listed in Tables 8 and 9. In all tables, the quoted uncertainties are the sum in quadrature of the statistical and systematic components.

Table 4:  $\Upsilon(1S)$  production cross-section in  $p\text{Pb}$ , as a function of  $p_{\text{T}}$  and  $y^*$ .

$p_{\text{T}}$ [GeV/c]	$y^*$	$\frac{d^2\sigma}{dp_{\text{T}}dy^*}$ [nb/(GeV/c)]
$0 < p_{\text{T}} < 2$	$1.5 < y^* < 2.0$	$644 \pm 142$
$0 < p_{\text{T}} < 2$	$2.0 < y^* < 2.5$	$656 \pm 106$
$0 < p_{\text{T}} < 2$	$2.5 < y^* < 3.0$	$641 \pm 119$
$0 < p_{\text{T}} < 2$	$3.0 < y^* < 3.5$	$486 \pm 92$
$0 < p_{\text{T}} < 2$	$3.5 < y^* < 4.0$	$345 \pm 50$
$2 < p_{\text{T}} < 4$	$1.5 < y^* < 2.0$	$1134 \pm 227$
$2 < p_{\text{T}} < 4$	$2.0 < y^* < 2.5$	$1312 \pm 163$
$2 < p_{\text{T}} < 4$	$2.5 < y^* < 3.0$	$1226 \pm 171$
$2 < p_{\text{T}} < 4$	$3.0 < y^* < 3.5$	$794 \pm 129$
$2 < p_{\text{T}} < 4$	$3.5 < y^* < 4.0$	$765 \pm 147$
$4 < p_{\text{T}} < 6$	$1.5 < y^* < 2.0$	$1162 \pm 184$
$4 < p_{\text{T}} < 6$	$2.0 < y^* < 2.5$	$1130 \pm 128$
$4 < p_{\text{T}} < 6$	$2.5 < y^* < 3.0$	$1121 \pm 135$
$4 < p_{\text{T}} < 6$	$3.0 < y^* < 3.5$	$915 \pm 147$
$4 < p_{\text{T}} < 6$	$3.5 < y^* < 4.0$	$586 \pm 132$
$6 < p_{\text{T}} < 8$	$1.5 < y^* < 2.0$	$908 \pm 171$
$6 < p_{\text{T}} < 8$	$2.0 < y^* < 2.5$	$851 \pm 135$
$6 < p_{\text{T}} < 8$	$2.5 < y^* < 3.0$	$690 \pm 106$
$6 < p_{\text{T}} < 8$	$3.0 < y^* < 3.5$	$625 \pm 111$
$6 < p_{\text{T}} < 8$	$3.5 < y^* < 4.0$	$570 \pm 131$
$8 < p_{\text{T}} < 10$	$1.5 < y^* < 2.0$	$651 \pm 145$
$8 < p_{\text{T}} < 10$	$2.0 < y^* < 2.5$	$474 \pm 83$
$8 < p_{\text{T}} < 10$	$2.5 < y^* < 3.0$	$525 \pm 79$
$8 < p_{\text{T}} < 10$	$3.0 < y^* < 3.5$	$384 \pm 71$
$8 < p_{\text{T}} < 10$	$3.5 < y^* < 4.0$	$285 \pm 79$
$10 < p_{\text{T}} < 15$	$1.5 < y^* < 2.0$	$224 \pm 61$
$10 < p_{\text{T}} < 15$	$2.0 < y^* < 2.5$	$237 \pm 36$
$10 < p_{\text{T}} < 15$	$2.5 < y^* < 3.0$	$190 \pm 30$
$10 < p_{\text{T}} < 15$	$3.0 < y^* < 3.5$	$140 \pm 28$
$10 < p_{\text{T}} < 25$	$3.5 < y^* < 4.0$	$33 \pm 11$
$15 < p_{\text{T}} < 25$	$1.5 < y^* < 2.0$	$62 \pm 20$
$15 < p_{\text{T}} < 25$	$2.0 < y^* < 2.5$	$41 \pm 9$
$15 < p_{\text{T}} < 25$	$2.5 < y^* < 3.0$	$29 \pm 8$
$15 < p_{\text{T}} < 25$	$3.0 < y^* < 3.5$	$23 \pm 7$

Table 5:  $\Upsilon(1S)$  production cross-section in Pb $p$ , as a function of  $p_T$  and  $y^*$ .

$p_T$ [GeV/c]	$y^*$	$\frac{d^2\sigma}{dp_T dy^*}$ [nb/(GeV/c)]
$0 < p_T < 2$	$-3.0 < y^* < -2.5$	$839 \pm 130$
$0 < p_T < 2$	$-3.5 < y^* < -3.0$	$740 \pm 114$
$0 < p_T < 2$	$-4.0 < y^* < -3.5$	$627 \pm 129$
$0 < p_T < 2$	$-4.5 < y^* < -4.0$	$523 \pm 90$
$0 < p_T < 2$	$-5.0 < y^* < -4.5$	$318 \pm 77$
$2 < p_T < 4$	$-3.0 < y^* < -2.5$	$1661 \pm 228$
$2 < p_T < 4$	$-3.5 < y^* < -3.0$	$1478 \pm 225$
$2 < p_T < 4$	$-4.0 < y^* < -3.5$	$1366 \pm 216$
$2 < p_T < 4$	$-4.5 < y^* < -4.0$	$913 \pm 164$
$2 < p_T < 4$	$-5.0 < y^* < -4.5$	$503 \pm 99$
$4 < p_T < 6$	$-3.0 < y^* < -2.5$	$1538 \pm 243$
$4 < p_T < 6$	$-3.5 < y^* < -3.0$	$1199 \pm 204$
$4 < p_T < 6$	$-4.0 < y^* < -3.5$	$869 \pm 165$
$4 < p_T < 6$	$-4.5 < y^* < -4.0$	$895 \pm 152$
$4 < p_T < 6$	$-5.0 < y^* < -4.5$	$406 \pm 107$
$6 < p_T < 8$	$-3.0 < y^* < -2.5$	$1313 \pm 222$
$6 < p_T < 8$	$-3.5 < y^* < -3.0$	$859 \pm 149$
$6 < p_T < 8$	$-4.0 < y^* < -3.5$	$518 \pm 99$
$6 < p_T < 8$	$-4.5 < y^* < -4.0$	$242 \pm 69$
$6 < p_T < 8$	$-5.0 < y^* < -4.5$	$240 \pm 45$
$8 < p_T < 10$	$-3.0 < y^* < -2.5$	$608 \pm 156$
$8 < p_T < 10$	$-3.5 < y^* < -3.0$	$449 \pm 83$
$8 < p_T < 10$	$-4.0 < y^* < -3.5$	$263 \pm 53$
$8 < p_T < 10$	$-4.5 < y^* < -4.0$	$88 \pm 40$
$8 < p_T < 10$	$-5.0 < y^* < -4.5$	$82 \pm 47$
$10 < p_T < 15$	$-3.0 < y^* < -2.5$	$336 \pm 75$
$10 < p_T < 15$	$-3.5 < y^* < -3.0$	$181 \pm 33$
$10 < p_T < 25$	$-4.0 < y^* < -3.5$	$39 \pm 7$
$10 < p_T < 25$	$-4.5 < y^* < -4.0$	$24 \pm 5$
$10 < p_T < 25$	$-5.0 < y^* < -4.5$	$9 \pm 6$
$15 < p_T < 25$	$-3.0 < y^* < -2.5$	$43 \pm 15$
$15 < p_T < 25$	$-3.5 < y^* < -3.0$	$26 \pm 8$

Table 6:  $\Upsilon(1S)$  production cross-section in  $p\text{Pb}$  and  $\text{Pb}p$ , as a function of  $p_{\text{T}}$ .

$p_{\text{T}}$ (GeV/ $c$ )	$\frac{d\sigma}{dp_{\text{T}}}$ in $p\text{Pb}$ [nb/(GeV/ $c$ )]	$\frac{d\sigma}{dp_{\text{T}}}$ in $\text{Pb}p$ [nb/(GeV/ $c$ )]
$0 < p_{\text{T}} < 2$	$1409 \pm 164$	$1570 \pm 234$
$2 < p_{\text{T}} < 4$	$2683 \pm 287$	$3040 \pm 437$
$4 < p_{\text{T}} < 6$	$2500 \pm 268$	$2349 \pm 341$
$6 < p_{\text{T}} < 8$	$1693 \pm 197$	$1461 \pm 203$
$8 < p_{\text{T}} < 10$	$1145 \pm 142$	$721 \pm 107$
$10 < p_{\text{T}} < 15$	$495 \pm 61$	$338 \pm 48$
$15 < p_{\text{T}} < 25$	$81 \pm 13$	$44 \pm 9$

Table 7:  $\Upsilon(1S)$  production cross-section in  $p\text{Pb}$  and  $\text{Pb}p$ , as a function of  $y^*$ .

$y^*$	$\frac{d\sigma}{dy^*}$ [nb]
$-5.0 < y^* < -4.5$	$4050 \pm 646$
$-4.5 < y^* < -4.0$	$5572 \pm 720$
$-4.0 < y^* < -3.5$	$7333 \pm 1109$
$-3.5 < y^* < -3.0$	$10300 \pm 1399$
$-3.0 < y^* < -2.5$	$15531 \pm 1868$
$1.5 < y^* < 2.0$	$11500 \pm 1266$
$2.0 < y^* < 2.5$	$10175 \pm 955$
$2.5 < y^* < 3.0$	$9107 \pm 908$
$3.0 < y^* < 3.5$	$7038 \pm 843$
$3.5 < y^* < 4.0$	$5891 \pm 862$

Table 8:  $\Upsilon(2S)$  production cross-section in  $p\text{Pb}$  and  $\text{Pb}p$ , as a function of  $p_{\text{T}}$ .

$p_{\text{T}}$ [GeV/ $c$ ]	$\frac{d\sigma}{dp_{\text{T}}}$ in $p\text{Pb}$ [nb/(GeV/ $c$ )]	$\frac{d\sigma}{dp_{\text{T}}}$ in $\text{Pb}p$ [nb/(GeV/ $c$ )]
$0 < p_{\text{T}} < 2$	$275 \pm 91$	$317 \pm 83$
$2 < p_{\text{T}} < 4$	$962 \pm 179$	$717 \pm 148$
$4 < p_{\text{T}} < 6$	$542 \pm 129$	$733 \pm 142$
$6 < p_{\text{T}} < 8$	$448 \pm 109$	$409 \pm 97$
$8 < p_{\text{T}} < 10$	$405 \pm 86$	$189 \pm 57$
$10 < p_{\text{T}} < 15$	$208 \pm 42$	$130 \pm 28$
$15 < p_{\text{T}} < 25$	$45 \pm 11$	$20 \pm 7$

Table 9:  $\Upsilon(2S)$  production cross-section in  $p\text{Pb}$ , as a function of  $y^*$ .

$y^*$	$\frac{d\sigma}{dy^*}$ [nb]
$-5.0 < y^* < -4.5$	$1058 \pm 414$
$-4.5 < y^* < -4.0$	$979 \pm 202$
$-4.0 < y^* < -3.5$	$2400 \pm 458$
$-3.5 < y^* < -3.0$	$2716 \pm 485$
$-3.0 < y^* < -2.5$	$3565 \pm 702$
$1.5 < y^* < 2.0$	$4402 \pm 898$
$2.0 < y^* < 2.5$	$3180 \pm 551$
$2.5 < y^* < 3.0$	$2856 \pm 515$
$3.0 < y^* < 3.5$	$1369 \pm 381$
$3.5 < y^* < 4.0$	$1339 \pm 416$

## B Scaled $\Upsilon(1S)$ and $\Upsilon(2S)$ differential cross-sections in $pp$ collisions

Tables 10 and 11 show the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  differential cross-sections scaled to the cross-section in  $pp$  collisions at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV in  $p_{\text{T}}$  integrated over  $y$  in region  $2.0 < y < 4.5$  and in  $y$  over  $p_{\text{T}}$  in region  $p_{\text{T}} < 25$  GeV/ $c$ .

Table 10: Scaled  $pp$  differential cross-section in  $p_{\text{T}}$  at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV. The first uncertainty is statistical, the second is systematic, which includes the systematic uncertainty from the  $pp$  measurement and that estimated by changing the interpolation function.

$p_{\text{T}}$ [GeV/ $c$ ]	$\Upsilon(1S) \frac{d\sigma}{dp_{\text{T}}}$ [nb/(GeV/ $c$ )]	$\Upsilon(2S) \frac{d\sigma}{dp_{\text{T}}}$ [nb/(GeV/ $c$ )]
$0 < p_{\text{T}} < 2$	$1995 \pm 14 \pm 31$	$555 \pm 9 \pm 11$
$2 < p_{\text{T}} < 4$	$3626 \pm 18 \pm 51$	$1052 \pm 11 \pm 19$
$4 < p_{\text{T}} < 6$	$2898 \pm 16 \pm 40$	$910 \pm 11 \pm 15$
$6 < p_{\text{T}} < 8$	$1786 \pm 12 \pm 28$	$634 \pm 9 \pm 14$
$8 < p_{\text{T}} < 10$	$1009 \pm 9 \pm 15$	$394 \pm 7 \pm 7$
$10 < p_{\text{T}} < 15$	$382 \pm 5 \pm 7$	$169 \pm 4 \pm 4$
$15 < p_{\text{T}} < 25$	$54 \pm 2 \pm 1$	$29 \pm 1 \pm 1$

Table 11: Scaled  $pp$  differential cross-section in  $y$  at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV. The first uncertainty is statistical, the second is systematic, which includes the systematic uncertainty from the  $pp$  measurement and that estimated by changing the interpolation function.

$y$	$\Upsilon(1S) \frac{d\sigma}{dy}$ [nb]	$\Upsilon(2S) \frac{d\sigma}{dy}$ [nb]
$2.0 < y < 2.5$	$15171 \pm 143 \pm 250$	$5083 \pm 105 \pm 110$
$2.5 < y < 3.0$	$14273 \pm 82 \pm 193$	$4672 \pm 60 \pm 79$
$3.0 < y < 3.5$	$11758 \pm 66 \pm 170$	$3792 \pm 49 \pm 71$
$3.5 < y < 4.0$	$8950 \pm 65 \pm 137$	$2898 \pm 46 \pm 61$
$4.0 < y < 4.5$	$5103 \pm 73 \pm 90$	$1596 \pm 50 \pm 42$

## C Nuclear modification factor

Tables 12 and 13 list the nuclear modification factors  $R_{p\text{Pb}}^{\Upsilon(1S)}$  for  $\Upsilon(1S)$  in transverse momentum bins and in rapidity bins. Tables 14 and 15 listed the nuclear modification factors for  $\Upsilon(1S)$   $R_{p\text{Pb}}^{\Upsilon(2S)}$  for  $\Upsilon(2S)$  in transverse momentum bins and in rapidity bins. In all tables, the quoted uncertainties are the sum in quadrature of the statistical and systematic components.

Table 12:  $\Upsilon(1S)$  nuclear modification factor,  $R_{p\text{Pb}}^{\Upsilon(1S)}$ , in  $p\text{Pb}$  and  $\text{Pb}p$  as a function of  $p_{\text{T}}$  integrated over  $y^*$  in the range  $1.5 < y^* < 4.0$  for  $p\text{Pb}$  and  $-5.0 < y^* < -2.5$  for  $\text{Pb}p$ .

$p_{\text{T}}$ [GeV/ $c$ ]	$R_{p\text{Pb}}^{\Upsilon(1S)}$ in $p\text{Pb}$	$R_{p\text{Pb}}^{\Upsilon(1S)}$ in $\text{Pb}p$
$0 < p_{\text{T}} < 2$	$0.46 \pm 0.06$	$0.76 \pm 0.11$
$2 < p_{\text{T}} < 4$	$0.46 \pm 0.05$	$0.92 \pm 0.13$
$4 < p_{\text{T}} < 6$	$0.66 \pm 0.07$	$0.90 \pm 0.13$
$6 < p_{\text{T}} < 8$	$0.67 \pm 0.08$	$0.91 \pm 0.17$
$8 < p_{\text{T}} < 10$	$0.79 \pm 0.10$	$0.81 \pm 0.12$
$10 < p_{\text{T}} < 15$	$0.84 \pm 0.10$	$1.14 \pm 0.16$
$15 < p_{\text{T}} < 25$	$0.87 \pm 0.16$	$1.04 \pm 0.18$

Table 13:  $\Upsilon(1S)$  nuclear modification factor,  $R_{p\text{Pb}}^{\Upsilon(1S)}$ , in  $p\text{Pb}$  and  $\text{Pb}p$  as a function of  $y^*$  integrated over  $p_{\text{T}}$  in the range  $0 < p_{\text{T}} < 25$  GeV/ $c$ .

$y^*$	$R_{p\text{Pb}}^{\Upsilon(1S)}$
$-4.5 < y^* < -4.0$	$1.09 \pm 0.14$
$-4.0 < y^* < -3.5$	$0.82 \pm 0.12$
$-3.5 < y^* < -3.0$	$0.88 \pm 0.12$
$-3.0 < y^* < -2.5$	$1.09 \pm 0.13$
$2.0 < y^* < 2.5$	$0.67 \pm 0.06$
$2.5 < y^* < 3.0$	$0.64 \pm 0.06$
$3.0 < y^* < 3.5$	$0.60 \pm 0.07$
$3.5 < y^* < 4.0$	$0.66 \pm 0.10$



Table 14:  $\Upsilon(2S)$  nuclear modification factor,  $R_{p\text{Pb}}^{\Upsilon(2S)}$ , in  $p\text{Pb}$  and  $\text{Pb}p$  as a function of  $p_{\text{T}}$  integrated over  $y^*$  in the range  $1.5 < y^* < 4.0$  for  $p\text{Pb}$  and  $-5.0 < y^* < -2.5$  for  $\text{Pb}p$ .

$p_{\text{T}}$ [GeV/c]	$R_{p\text{Pb}}^{\Upsilon(2S)}$ in $p\text{Pb}$	$R_{p\text{Pb}}^{\Upsilon(2S)}$ in $\text{Pb}p$
$0 < p_{\text{T}} < 2$	$0.22 \pm 0.08$	$0.54 \pm 0.17$
$2 < p_{\text{T}} < 4$	$0.38 \pm 0.10$	$0.55 \pm 0.11$
$4 < p_{\text{T}} < 6$	$0.35 \pm 0.09$	$0.88 \pm 0.17$
$6 < p_{\text{T}} < 8$	$0.30 \pm 0.11$	$0.73 \pm 0.31$
$8 < p_{\text{T}} < 10$	$0.49 \pm 0.11$	$0.48 \pm 0.15$
$10 < p_{\text{T}} < 15$	$0.69 \pm 0.12$	$0.78 \pm 0.18$
$15 < p_{\text{T}} < 25$	$0.78 \pm 0.22$	$0.86 \pm 0.35$

Table 15:  $\Upsilon(2S)$  nuclear modification factor,  $R_{p\text{Pb}}^{\Upsilon(2S)}$ , in  $p\text{Pb}$  and  $\text{Pb}p$  as a function of  $y^*$  integrated over  $p_{\text{T}}$  in the range  $0 < p_{\text{T}} < 25$  GeV/c.

$y^*$	$R_{p\text{Pb}}^{\Upsilon(2S)}$
$-4.5 < y^* < -4.0$	$0.61 \pm 0.13$
$-4.0 < y^* < -3.5$	$0.83 \pm 0.16$
$-3.5 < y^* < -3.0$	$0.72 \pm 0.13$
$-3.0 < y^* < -2.5$	$0.76 \pm 0.15$
$2.0 < y^* < 2.5$	$0.63 \pm 0.11$
$2.5 < y^* < 3.0$	$0.61 \pm 0.11$
$3.0 < y^* < 3.5$	$0.36 \pm 0.10$
$3.5 < y^* < 4.0$	$0.46 \pm 0.14$

## D Forward-to-backward ratios

Tables 16 and 17 list the forward-to-backward ratios  $R_{\text{FB}}^{\Upsilon(1S)}$  for  $\Upsilon(1S)$  in transverse momentum bins and in rapidity bins. In all tables, the quoted uncertainties are the sum in quadrature of the statistical and systematic components. The ratio  $R_{\text{FB}}^{\Upsilon(2S)}$  integrated over  $|y^*|$  in the range  $2.5 < |y^*| < 4.0$ , and over  $p_{\text{T}}$  in the range  $0 < p_{\text{T}} < 25$  GeV/ $c$  is  $0.66 \pm 0.23$ .

Table 16:  $\Upsilon(1S)$  forward-to-backward ratio,  $R_{\text{FB}}^{\Upsilon(1S)}$ , as a function of  $p_{\text{T}}$  integrated over  $|y^*|$  in the range  $2.5 < |y^*| < 4.0$ .

$p_{\text{T}}$ [GeV/ $c$ ]	$R_{\text{FB}}^{\Upsilon(1S)}$
$0 < p_{\text{T}} < 2$	$0.73 \pm 0.19$
$2 < p_{\text{T}} < 4$	$0.74 \pm 0.18$
$4 < p_{\text{T}} < 6$	$0.92 \pm 0.19$
$6 < p_{\text{T}} < 8$	$1.01 \pm 0.19$
$8 < p_{\text{T}} < 10$	$1.37 \pm 0.20$
$10 < p_{\text{T}} < 15$	$1.22 \pm 0.20$
$15 < p_{\text{T}} < 25$	$1.46 \pm 0.26$

Table 17:  $\Upsilon(1S)$  forward-to-backward ratio,  $R_{\text{FB}}^{\Upsilon(1S)}$ , as a function of  $|y^*|$  integrated over  $p_{\text{T}}$  in the range  $0 < p_{\text{T}} < 25$  GeV/ $c$ .

$ y^* $	$R_{\text{FB}}^{\Upsilon(1S)}$
$2.5 <  y^*  < 3.0$	$0.59 \pm 0.16$
$3.0 <  y^*  < 3.5$	$0.68 \pm 0.18$
$3.5 <  y^*  < 4.0$	$0.80 \pm 0.21$

## E Ratios between excited states

Tables 18 and 19 list the  $\Upsilon(2S)$  to  $\Upsilon(1S)$  ratios in bins of transverse momentum bins and rapidity. In all tables, the quoted uncertainties are the sum in quadrature of the statistical and systematic components.

Table 18:  $\Upsilon(2S)$  to  $\Upsilon(1S)$  ratio,  $R(\Upsilon(2S))$ , in  $p\text{Pb}$  and  $\text{Pb}p$  as a function of  $p_{\text{T}}$  integrated over  $y^*$  in the range  $1.5 < y^* < 4.0$  for  $p\text{Pb}$  and  $-5.0 < y^* < -2.5$  for  $\text{Pb}p$ .

$p_{\text{T}}$ [GeV/c]	$R(\Upsilon(2S))$ in $p\text{Pb}$	$R(\Upsilon(2S))$ in $\text{Pb}p$
$0 < p_{\text{T}} < 2$	$0.20 \pm 0.06$	$0.21 \pm 0.07$
$2 < p_{\text{T}} < 4$	$0.36 \pm 0.06$	$0.25 \pm 0.06$
$4 < p_{\text{T}} < 6$	$0.22 \pm 0.05$	$0.33 \pm 0.08$
$6 < p_{\text{T}} < 8$	$0.26 \pm 0.06$	$0.29 \pm 0.09$
$8 < p_{\text{T}} < 10$	$0.35 \pm 0.07$	$0.28 \pm 0.11$
$10 < p_{\text{T}} < 15$	$0.42 \pm 0.08$	$0.41 \pm 0.09$
$15 < p_{\text{T}} < 25$	$0.55 \pm 0.15$	$0.49 \pm 0.19$

Table 19:  $\Upsilon(2S)$  to  $\Upsilon(1S)$  ratio,  $R(\Upsilon(2S))$ , in  $p\text{Pb}$  and  $\text{Pb}p$  as a function of  $y^*$  integrated over  $p_{\text{T}}$  in the range  $0 < p_{\text{T}} < 25$  GeV/c.

$y^*$	$R(2S)$
$-5.0 < y^* < -4.5$	$0.27 \pm 0.05$
$-4.5 < y^* < -4.0$	$0.18 \pm 0.03$
$-4.0 < y^* < -3.5$	$0.34 \pm 0.06$
$-3.5 < y^* < -3.0$	$0.28 \pm 0.05$
$-3.0 < y^* < -2.5$	$0.24 \pm 0.09$
$1.5 < y^* < 2.0$	$0.38 \pm 0.08$
$2.0 < y^* < 2.5$	$0.31 \pm 0.05$
$2.5 < y^* < 3.0$	$0.31 \pm 0.05$
$3.0 < y^* < 3.5$	$0.19 \pm 0.05$
$3.5 < y^* < 4.0$	$0.23 \pm 0.07$

## F $\Upsilon(1S)$ to nonprompt $J/\psi$ ratios

Table 20 lists the  $\Upsilon(1S)$  to nonprompt  $J/\psi$  ratios in rapidity bins.

Table 20:  $\Upsilon(1S)$  to nonprompt  $J/\psi$ , in  $p\text{Pb}$  and  $\text{Pb}p$  as a function of  $y^*$  integrated over  $p_T$  in the range  $0 < p_T < 25$  GeV/ $c$ . The quoted uncertainties are the sum in quadrature of the statistical and systematic components.

$y^*$	$\Upsilon(1S)$ to $J/\psi$ -from-b
$-5.0 < y^* < -4.5$	$0.125 \pm 0.020$
$-4.5 < y^* < -4.0$	$0.102 \pm 0.013$
$-4.0 < y^* < -3.5$	$0.087 \pm 0.013$
$-3.5 < y^* < -3.0$	$0.094 \pm 0.013$
$-3.0 < y^* < -2.5$	$0.112 \pm 0.014$
$1.5 < y^* < 2.0$	$0.077 \pm 0.008$
$2.0 < y^* < 2.5$	$0.074 \pm 0.007$
$2.5 < y^* < 3.0$	$0.082 \pm 0.008$
$3.0 < y^* < 3.5$	$0.078 \pm 0.009$
$3.5 < y^* < 4.0$	$0.091 \pm 0.013$

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## LHCb collaboration

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Billoir<sup>9</sup>, A. Birnkraut<sup>11</sup>, A. Bizzeti<sup>18,u</sup>, M. Bjørn<sup>58</sup>, M.P. Blago<sup>43</sup>, T. Blake<sup>51</sup>, F. Blanc<sup>44</sup>, S. Blusk<sup>62</sup>, D. Bobulska<sup>54</sup>, V. Bocci<sup>27</sup>, O. Boente Garcia<sup>42</sup>, T. Boettcher<sup>59</sup>, A. Bondar<sup>39,w</sup>, N. Bondar<sup>34</sup>, S. Borghi<sup>57,43</sup>, M. Borisyak<sup>38</sup>, M. Borsato<sup>42</sup>, F. Bossu<sup>8</sup>, M. Boubdir<sup>10</sup>, T.J.V. Bowcock<sup>55</sup>, C. Bozzi<sup>17,43</sup>, S. Braun<sup>13</sup>, M. Brodski<sup>43</sup>, J. Brodzicka<sup>30</sup>, A. Brossa Gonzalo<sup>51</sup>, D. Brundu<sup>23,43</sup>, E. Buchanan<sup>49</sup>, A. Buonauro<sup>45</sup>, C. Burr<sup>57</sup>, A. Bursche<sup>23</sup>, J. Buytaert<sup>43</sup>, W. Byczynski<sup>43</sup>, S. Cadeddu<sup>23</sup>, H. Cai<sup>67</sup>, R. Calabrese<sup>17,g</sup>, R. Calladine<sup>48</sup>, M. Calvi<sup>21,i</sup>, M. Calvo Gomez<sup>41,m</sup>, A. 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Esen<sup>28</sup>, T. Evans<sup>60</sup>, A. Falabella<sup>16</sup>, N. Farley<sup>48</sup>, S. Farry<sup>55</sup>, D. Fazzini<sup>21,43,i</sup>, L. Federici<sup>26</sup>, P. Fernandez Declara<sup>43</sup>, A. Fernandez Prieto<sup>42</sup>, F. Ferrari<sup>16</sup>, L. Ferreira Lopes<sup>44</sup>, F. Ferreira Rodrigues<sup>2</sup>, M. Ferro-Luzzi<sup>43</sup>, S. Filippov<sup>37</sup>, R.A. Fini<sup>15</sup>, M. Fiorini<sup>17,g</sup>, M. Firlej<sup>31</sup>, C. Fitzpatrick<sup>44</sup>, T. Fiutowski<sup>31</sup>, F. Fleuret<sup>8,b</sup>, M. Fontana<sup>43</sup>, F. Fontanelli<sup>20,h</sup>, R. Forty<sup>43</sup>, V. Franco Lima<sup>55</sup>, M. Frank<sup>43</sup>, C. Frei<sup>43</sup>, J. Fu<sup>22,q</sup>, W. Funk<sup>43</sup>, C. Färber<sup>43</sup>, M. Féo Pereira Rivello Carvalho<sup>28</sup>, E. Gabriel<sup>53</sup>, A. Gallas Torreira<sup>42</sup>, D. Galli<sup>16,e</sup>, S. Gallorini<sup>24</sup>, S. Gambetta<sup>53</sup>, Y. Gan<sup>3</sup>, M. Gandelman<sup>2</sup>, P. 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 A. Grecu<sup>33</sup>, R. Greim<sup>28</sup>, P. Griffith<sup>23</sup>, L. Grillo<sup>57</sup>, L. Gruber<sup>43</sup>, B.R. Gruberg Cazon<sup>58</sup>,  
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 X. Han<sup>13</sup>, T.H. Hancock<sup>58</sup>, S. Hansmann-Menzemer<sup>13</sup>, N. Harnew<sup>58</sup>, S.T. Harnew<sup>49</sup>,  
 T. Harrison<sup>55</sup>, C. Hasse<sup>43</sup>, M. Hatch<sup>43</sup>, J. He<sup>65</sup>, M. Hecker<sup>56</sup>, K. Heinicke<sup>11</sup>, A. Heister<sup>11</sup>,  
 K. Hennessy<sup>55</sup>, L. Henry<sup>75</sup>, E. van Herwijnen<sup>43</sup>, J. Heuel<sup>10</sup>, M. Heß<sup>70</sup>, A. Hicheur<sup>63</sup>,  
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 Z.C. Huard<sup>60</sup>, W. Hulsbergen<sup>28</sup>, T. Humair<sup>56</sup>, M. Hushchyn<sup>38</sup>, D. Hutchcroft<sup>55</sup>, D. Hynds<sup>28</sup>,  
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 A. Jawahery<sup>61</sup>, F. Jiang<sup>3</sup>, M. John<sup>58</sup>, D. Johnson<sup>43</sup>, C.R. Jones<sup>50</sup>, C. Joram<sup>43</sup>, B. Jost<sup>43</sup>,  
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 M. Kecke<sup>13</sup>, F. Keizer<sup>50</sup>, M. Kelsey<sup>62</sup>, M. Kenzie<sup>50</sup>, T. Ketel<sup>29</sup>, E. Khairullin<sup>38</sup>, B. Khanji<sup>43</sup>,  
 C. Khurewathanakul<sup>44</sup>, K.E. Kim<sup>62</sup>, T. Kirn<sup>10</sup>, S. Klaver<sup>19</sup>, K. Klimaszewski<sup>32</sup>,  
 T. Klimkovich<sup>12</sup>, S. Koliiev<sup>47</sup>, M. Kolpin<sup>13</sup>, R. Kopecna<sup>13</sup>, P. Koppenburg<sup>28</sup>, I. Kostyuk<sup>28</sup>,  
 S. Kotriakhova<sup>34</sup>, M. Kozeiha<sup>6</sup>, L. Kravchuk<sup>37</sup>, M. Kreps<sup>51</sup>, F. Kress<sup>56</sup>, P. Krokovny<sup>39,w</sup>,  
 W. Krupa<sup>31</sup>, W. Krzemien<sup>32</sup>, W. Kucewicz<sup>30,l</sup>, M. Kucharczyk<sup>30</sup>, V. Kudryavtsev<sup>39,w</sup>,  
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 J. Lefrançois<sup>8</sup>, R. Lefèvre<sup>6</sup>, F. Lemaitre<sup>43</sup>, O. Leroy<sup>7</sup>, T. Lesiak<sup>30</sup>, B. Leverington<sup>13</sup>, P.-R. Li<sup>65</sup>,  
 Y. Li<sup>4</sup>, Z. Li<sup>62</sup>, X. Liang<sup>62</sup>, T. Likhomanenko<sup>72</sup>, R. Lindner<sup>43</sup>, F. Lionetto<sup>45</sup>, V. Lisovskyi<sup>8</sup>,  
 G. Liu<sup>66</sup>, X. Liu<sup>3</sup>, D. Loh<sup>51</sup>, A. Loi<sup>23</sup>, I. Longstaff<sup>54</sup>, J.H. Lopes<sup>2</sup>, G.H. Lovell<sup>50</sup>, D. Lucchesi<sup>24,o</sup>,  
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 F. Machefert<sup>8</sup>, F. Maciuc<sup>33</sup>, V. Macko<sup>44</sup>, P. Mackowiak<sup>11</sup>, S. Maddrell-Mander<sup>49</sup>, O. Maev<sup>34,43</sup>,  
 K. Maguire<sup>57</sup>, D. Maisuzenko<sup>34</sup>, M.W. Majewski<sup>31</sup>, S. Malde<sup>58</sup>, B. Malecki<sup>30</sup>, A. Malinin<sup>72</sup>,  
 T. Maltsev<sup>39,w</sup>, G. Manca<sup>23,f</sup>, G. Mancinelli<sup>7</sup>, D. Marangotto<sup>22,q</sup>, J. Maratas<sup>6,v</sup>,  
 J.F. Marchand<sup>5</sup>, U. Marconi<sup>16</sup>, C. Marin Benito<sup>8</sup>, M. Marinangeli<sup>44</sup>, P. Marino<sup>44</sup>, J. Marks<sup>13</sup>,  
 P.J. Marshall<sup>55</sup>, G. Martellotti<sup>27</sup>, M. Martin<sup>7</sup>, M. Martinelli<sup>43</sup>, D. Martinez Santos<sup>42</sup>,  
 F. Martinez Vidal<sup>75</sup>, A. Massafferri<sup>1</sup>, M. Materok<sup>10</sup>, R. Matev<sup>43</sup>, A. Mathad<sup>51</sup>, Z. Mathe<sup>43</sup>,  
 C. Matteuzzi<sup>21</sup>, A. Mauri<sup>45</sup>, E. Maurice<sup>8,b</sup>, B. Maurin<sup>44</sup>, A. Mazurov<sup>48</sup>, M. McCann<sup>56,43</sup>,  
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 S. Petrucci<sup>53</sup>, M. Petruzzo<sup>22,q</sup>, B. Pietrzyk<sup>5</sup>, G. Pietrzyk<sup>44</sup>, M. Pikiés<sup>30</sup>, M. Pili<sup>58</sup>, D. Pinci<sup>27</sup>,  
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