



CERN-EP-2019-014  
12 May 2019

## Inclusive $J/\psi$ production at mid-rapidity in pp collisions at $\sqrt{s} = 5.02$ TeV

ALICE Collaboration\*

### Abstract

Inclusive  $J/\psi$  production is studied in minimum-bias proton-proton collisions at a centre-of-mass energy of  $\sqrt{s} = 5.02$  TeV by ALICE at the CERN LHC. The measurement is performed at mid-rapidity ( $|y| < 0.9$ ) in the dielectron decay channel down to zero transverse momentum  $p_T$ , using a data sample corresponding to an integrated luminosity of  $L_{\text{int}} = 19.4 \pm 0.4 \text{ nb}^{-1}$ . The measured  $p_T$ -integrated inclusive  $J/\psi$  production cross section is  $d\sigma/dy = 5.64 \pm 0.22(\text{stat.}) \pm 0.33(\text{syst.}) \pm 0.12(\text{lumi.}) \mu\text{b}$ . The  $p_T$ -differential cross section  $d^2\sigma/dp_T dy$  is measured in the  $p_T$  range 0 – 10 GeV/ $c$  and compared with state-of-the-art perturbative QCD calculations. The  $J/\psi$   $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$  are extracted and compared with results obtained at other collision energies.

arXiv:1905.07211v1 [nucl-ex] 17 May 2019

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\*See Appendix A for the list of collaboration members

## 1 Introduction

At LHC energies, charmonium is mainly produced from gluon–gluon scatterings producing  $c\bar{c}$  pairs [1] which form a bound state. While the hard gluon–gluon scattering can be described within perturbative Quantum Chromodynamics (QCD), the hadronisation of the  $c\bar{c}$  pair into charmonium is essentially non-perturbative and cannot be yet calculated from the QCD Lagrangian. There are several phenomenological approaches for the description of charmonium production: the Colour Evaporation Model (CEM) [2, 3], the Colour Singlet Model (CSM) [4] and the Non-Relativistic QCD model (NRQCD) [5] which differ mainly in the way the charmonium states are formed in the hadronisation process. In the CEM model, the production rate of a given charmonium state is proportional to the production cross section of  $c\bar{c}$  pairs integrated between the mass of the bound state and twice the mass of the lightest D-meson. In the CSM model, the pre-resonant  $c\bar{c}$  state is assumed to be directly produced colourless and with the same quantum numbers as the final-state charmonium. The NRQCD model includes all possible colour and quantum number states for the pre-resonant  $c\bar{c}$  pair, with each configuration having a probability to transform into a given bound state, described by a set of universal long-distance matrix elements determined from global fits to experimental data. Detailed reviews of the state-of-the-art calculations for charmonium production can be found in Refs. [6–8].

$J/\psi$  production is a probe of the hot and dense medium created in ultrarelativistic heavy-ion collisions [9, 10]. Moreover, it is also sensitive to nuclear effects not related to the creation of deconfined matter, called cold-nuclear-matter effects, such as modification of the parton distribution functions [11, 12]. In order to gauge both the hot and cold medium effects, precise knowledge of the  $J/\psi$  production rates in the absence of a nucleus in the initial state is of paramount importance. The  $J/\psi$  measurement in pp collisions constitutes a baseline for the quantification of nuclear effects in both nucleus–nucleus and proton–nucleus collisions.

In this paper, results for the transverse momentum ( $p_T$ ) dependence of the inclusive  $J/\psi$  production cross section at mid-rapidity ( $|y| < 0.9$ ) in pp collisions at the centre-of-mass energy  $\sqrt{s} = 5.02$  TeV are presented. In addition to the directly produced  $J/\psi$  contribution, the inclusive cross section also contains feed-down contributions from the decay of heavier charmonium states (mainly  $\psi(2S)$  and  $\chi_c$ ) and from the decay of beauty hadrons (non-prompt  $J/\psi$ ).

The  $J/\psi$  production is measured in the dielectron decay channel using the ALICE central barrel detectors. The  $p_T$ -differential cross section is measured for  $p_T < 10$  GeV/ $c$  supplementing the existing mid-rapidity measurements at high  $p_T$  by ATLAS [13] and CMS [14] down to zero  $p_T$ . Thus, ALICE can measure the  $p_T$ -integrated inclusive  $J/\psi$  production cross section, the mean transverse momentum  $\langle p_T \rangle$  and the second moment of the transverse momentum  $\langle p_T^2 \rangle$ . Similar measurements in pp collisions were performed by ALICE at  $\sqrt{s} = 2.76$  TeV [15] and at  $\sqrt{s} = 7$  TeV [16] at mid- and forward rapidity ( $2.5 < y < 4.0$ ), and at  $\sqrt{s} = 5.02, 8$  and  $13$  TeV at forward-rapidity [17–19]. Prompt  $J/\psi$  production cross sections were measured at  $\sqrt{s} = 7$  TeV by ALICE [20] and LHCb [21] and at  $\sqrt{s} = 8$  and  $13$  TeV by LHCb [22, 23].

The paper is organised as follows: the ALICE apparatus and the data sample are described in Section 2, the data analysis is detailed in Section 3 and the results are discussed in Section 4 in comparison with other measurements and theoretical calculations. Conclusions are given in Section 5.

## 2 Apparatus and data sample

The central barrel of the ALICE detector [24, 25] allows the reconstruction of  $J/\psi$  in the  $e^+e^-$  decay channel at mid-rapidity. The entire setup is placed in a solenoidal magnetic field of  $B = 0.5$  T oriented along the beam direction.

In this analysis, the Inner Tracking System (ITS) [26] and the Time Projection Chamber (TPC) [27] are

used for tracking whereas the TPC provides the electron identification. The ITS is subdivided into six cylindrically-shaped layers of silicon detectors around the beam pipe with radii from 3.9 to 43.0 cm. The two innermost layers form the high granularity Silicon Pixel Detector (SPD), the two intermediate layers the Silicon Drift Detector (SDD), and the outermost layers the Silicon Strip Detector (SSD). The ITS provides precise tracking close to the interaction point and collision vertex position determination. The TPC is a large drift detector with a cylindrical geometry which extends radially between  $85 < r < 250$  cm and longitudinally between  $-250 < z < 250$  cm, where  $z = 0$  and  $r = 0$  correspond to the nominal interaction point. It is the main tracking device, with a full azimuthal acceptance for tracks in the pseudorapidity range  $|\eta| < 0.9$ . Additionally, the TPC can be used for the particle identification of charged particles via the measurement of the specific ionisation energy loss  $dE/dx$  in the TPC gas.

The minimum bias (MB) trigger is provided by the V0 detector which consists of two forward scintillator arrays [28] placed on both sides of the nominal interaction point at  $z = -90$  and  $+340$  cm covering the  $\eta$  range  $-3.7 < \eta < -1.7$  and  $2.8 < \eta < 5.1$ . The trigger signal consists of a coincident signal on both sides and is fully efficient in inelastic collisions containing a  $J/\psi$ .

For this analysis, the data recorded by ALICE in the 2017 LHC pp run at a centre-of-mass collision energy of  $\sqrt{s} = 5.02$  TeV are used. A total of 987 million MB events are used in this analysis corresponding to an integrated luminosity of  $L_{\text{int}} = 19.4 \pm 0.4 \text{ nb}^{-1}$ . The integrated luminosity is obtained following a procedure [29] which employs the Van der Meer technique [30].

### 3 Analysis, corrections, and systematic uncertainties

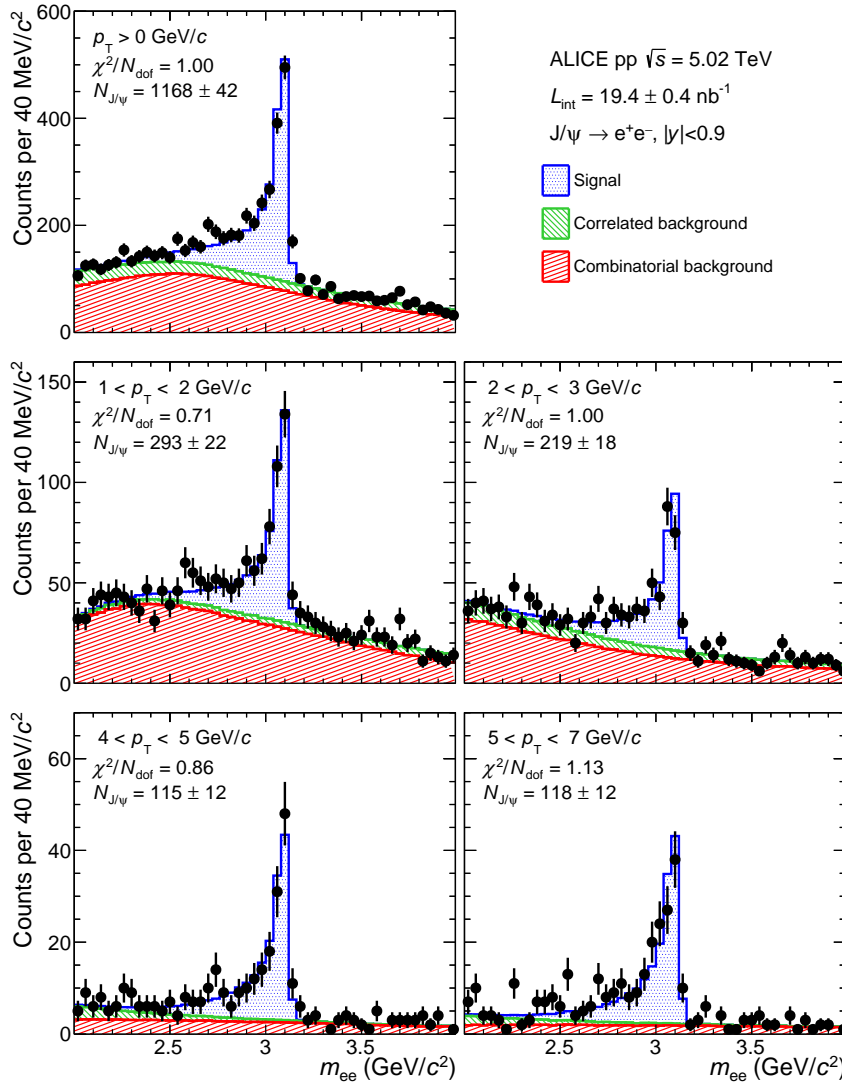
#### 3.1 Event and track selection

The  $J/\psi$  candidates are searched in the dielectron decay channel, with the electron tracks being reconstructed in the ITS and the TPC. The events fulfill the MB trigger condition and have the collision vertex within the longitudinal interval  $|z_{\text{vtx}}| < 10$  cm to ensure uniform detector acceptance. Beam-gas events are rejected using offline timing cuts with the V0 detector. The probability for collision pile-up was  $\leq 1\%$  during the entire data taking period and these events are rejected using a vertex finding algorithm based on SPD tracklets [25].

Electron candidates are required to have a minimum transverse momentum of  $1 \text{ GeV}/c$  and a pseudorapidity range of  $|\eta| < 0.9$ . Due to the short decay time of the  $J/\psi$  and its decay mothers, if any, the daughter electrons are reconstructed as primary particles [31]. The candidate daughter tracks are required to have a maximum distance-of-closest-approach to the reconstructed collision vertex of  $0.2$  cm in the radial direction and  $0.4$  cm along the beam-axis direction. Monte Carlo (MC) simulations are used to verify that this requirement does not reject electrons from the decays of non-prompt  $J/\psi$ . Tracks which originate from long-lived weak decays of charged particles (e.g.  $\pi^\pm \rightarrow \mu^\pm \nu$  or  $K^\pm \rightarrow \mu^\pm \nu$ ) are rejected from the analysis. A hit in at least one of the two SPD layers is required for both electron candidates to improve the tracking resolution and reduce the number of electrons from photon conversions. Electron candidates are required to have at least 70 out of a maximum of 159 attached clusters and a  $\chi^2/N_{\text{dof}} < 2$  in the TPC.

Electron candidates are selected such that their specific ionisation energy loss  $dE/dx$  in the TPC lies within the interval  $[-2, +3] \sigma_e$  relative to the expectation for electrons with same momentum as the candidate, where  $\sigma_e$  is the specific energy-loss resolution for electrons in the TPC. Similarly, to further reject contamination, particles compatible within  $3\sigma$  with being a proton or a pion, according to the measured  $dE/dx$ , are rejected.

The dominant source of background electrons is photon conversions. Electrons from conversions in the material at large radii (typically beyond the SPD layers) are removed using the requirement on the SPD hits described above. Electrons from conversions occurring in the beam pipe or in the SPD material



**Fig. 1:** (Colour online) Same-event opposite-sign dielectron invariant mass distributions for several  $p_T$ -intervals with signal (blue), correlated background (green), and combinatorial background (red) components.

can pass the primary track selection criteria. Therefore, further rejection of this background is done by employing a method which relies on a second set of electrons selected with looser criteria. Electrons from the first (primary) set are paired with those of the second set. For pairs with an invariant mass below the threshold of  $50 \text{ MeV}/c^2$ , the corresponding electron from the primary set is excluded from further analysis. The looser selection criteria of the second set are optimized in a data driven way such that the signal to background ratio is improved, but the loss of signal with respect to not applying this procedure remains negligible.

### 3.2 Signal extraction

The  $J/\psi$  signal is extracted from the invariant mass distribution of all opposite-sign pairs obtained by making all possible combinations with the electrons and positrons selected with the criteria described above. Examples of invariant mass distributions of opposite-sign (OS) electron pairs are shown in Fig. 1 for the  $p_T$ -integrated case and for a few selected  $p_T$  intervals. These distributions contain contributions from the  $J/\psi$  signal and the combinatorial and the correlated background. For the combinatorial background, kinematic correlations do not play a significant role and this component can be modelled using a

mixed event technique, while the correlated background in the  $J/\psi$  mass region originates mainly from semi-leptonic decays of correlated open heavy-flavour hadrons [32]. The signal component corresponds to the dielectron pairs from  $J/\psi$  decays and has an asymmetric shape due to the radiative component and to the energy lost by the electrons in the detector material via brehmsstrahlung.

In order to obtain the raw number of  $J/\psi$  counts, a two-step procedure is employed. First, the combinatorial background is obtained using a mixed event (ME) technique and scaled such that the invariant mass distribution of like-sign (LS) pairs from ME matches the same-event LS distribution in the invariant mass range  $1.2 < m_{ee} < 5.0$  GeV/ $c^2$ . Second, the combinatorial background is subtracted and the remaining distribution is fit with a two-component function, an exponential (or a second order polynomial) for the correlated background and the MC template of the  $J/\psi$  signal shape. This strategy provides a good fit quality for all the  $p_T$  intervals, as indicated by the  $\chi^2/N_{\text{dof}}$  values shown in the panels of Fig. 1. The number of  $J/\psi$  candidates is obtained by counting the bin entries in the mass interval  $2.92 < m_{ee} < 3.16$  GeV/ $c^2$  after subtracting all background components. The background-subtracted signal distribution is also fit with a Crystal Ball function [33] and the  $p_T$ -integrated dielectron mass resolution at the  $J/\psi$  peak region obtained from the Gaussian core of the function is found to be 23 MeV/ $c^2$ .

Alternative fit strategies for the same event OS invariant mass distribution are considered. A first strategy is to make a template fit to the total OS invariant mass distribution, where the mixed event LS background is used as the template for the combinatorial background with the normalisation used as a free parameter, while the correlated background and signal components are defined similarly as for the standard method. A second alternative is to fit the OS mass distribution with the MC template for the signal component, while for the sum of the combinatorial and correlated background an ad-hoc function is used (ratio of small order polynomials). These alternative methods produce compatible results.

### 3.3 Corrections

In order to correct the observed  $J/\psi$  signal for detector effects and the selection procedure, MC events are generated by adding a single  $J/\psi$  meson to a simulated MB pp collision. PYTHIA 6.4 [34] is used to simulate the MB events and the non-prompt  $J/\psi$  component, while the prompt component is produced uniformly distributed in rapidity with a  $p_T$  spectrum based on a phenomenological interpolation of measurements at RHIC, CDF, and the LHC [35]. The  $J/\psi$  decays, including the radiative component, are handled by PHOTOS [36]. The transport through the ALICE detector material is handled by GEANT3 [37] with tracks being reconstructed from the simulated hits using the same algorithm as for the real data. The  $p_T$ -integrated acceptance times efficiency  $\langle A \times \varepsilon \rangle$  is 9.9%, varying between 8.1% and 13% as a function of  $p_T$ , and is the product of the acceptance factor, the reconstruction efficiency including the track quality cuts, the electron identification cuts and the fraction of the signal within the mass counting interval of  $2.92 < m_{ee} < 3.16$  GeV/ $c^2$ . Due to the variation of  $\langle A \times \varepsilon \rangle$  with the  $J/\psi$  transverse momentum in the considered  $p_T$  intervals, the calculated correction factors have a mild dependence on the shape of the  $p_T$  distribution and the fraction of non-prompt  $J/\psi$ ,  $f_B$ , used in the simulation. In order to correct for this effect, the corrected  $J/\psi$  cross-section, obtained initially using efficiencies weighted with the  $J/\psi$  spectrum from simulations, is used to reweight the acceptance times efficiency factor and obtain an updated cross-section. This procedure can be iteratively employed until the variation of the  $J/\psi$  cross section between two iterations is smaller than a desired precision. Already after the first iteration, the inclusive  $J/\psi$   $p_T$ -integrated cross section varied by less than 1%, while for the  $p_T$ -differential cross section the changes were even smaller, so the procedure is stopped after one iteration. Due to the fact that in our analysis there is a 1–2% difference in acceptance times efficiency between prompt and non-prompt  $J/\psi$  and that the  $f_B$  value in simulation is larger with respect to existing measurements at Tevatron [38] and LHC [20, 39, 40] energies, the acceptance times efficiency factors are reweighted to account for these differences. The largest impact from this correction is obtained at high  $p_T$ , where the difference between simulation and existing  $f_B$  measurements is largest, and shifts the cross section upwards by 0.3%.

The differential cross section in a rapidity interval  $\Delta y$  and transverse momentum interval  $\Delta p_T$  is calculated as

$$\frac{d^2\sigma_{J/\psi}}{dy dp_T} = \frac{N_{J/\psi}(\Delta y, \Delta p_T)}{\text{BR}(J/\psi \rightarrow e^+e^-) \cdot \langle A \times \varepsilon \rangle(\Delta y, \Delta p_T) \cdot \Delta y \cdot \Delta p_T \cdot L_{\text{int}}}, \quad (1)$$

where  $N_{J/\psi}$  is the number of reconstructed  $J/\psi$  candidates,  $\text{BR}(J/\psi \rightarrow e^+e^-)$  is the branching ratio of the  $J/\psi$  mesons decaying into dielectrons [41], and  $L_{\text{int}}$  is the integrated luminosity of the data sample.

### 3.4 Systematic uncertainties

The sources of systematic uncertainties are related to the ITS-TPC tracking, electron identification, signal extraction procedure, the  $J/\psi$  input kinematic distributions used in the MC production, the integrated luminosity determination, and the branching ratio of the dielectron decay channel. A summary of all the systematic uncertainties is provided in Table 1.

The dominant source of systematic uncertainty is related to the ITS-TPC tracking and has two components, one related to the ITS-TPC matching efficiency and the other to the track quality requirements. The component due to the ITS-TPC matching efficiency is the largest and is determined by comparing the probability to match the TPC tracks to hits in the ITS in both data and simulation [42]. After propagation to the  $J/\psi$  candidate pairs, this uncertainty is found to vary between 4.3% at low  $p_T$  up to 5.4% at high  $p_T$ . The uncertainty due to the track quality requirements amounts to approximately 2% in all  $p_T$  intervals and was obtained by varying the selection criteria and computing the RMS of the cross-section distribution obtained after these variations. This tracking uncertainty is considered to be correlated over  $p_T$ .

The systematic uncertainty due to the electron identification is estimated by comparing the response of the TPC electron identification of a clean sample of electrons from tagged photon conversions in data to true electrons from the MC simulation. Half the difference between the selection efficiency in data and simulation is taken as the systematic uncertainty on the single electron PID efficiency and propagated to that on the  $J/\psi$  selection using a toy MC simulating  $J/\psi$  decays in the dielectron channel. The uncertainty due to the TPC PID ranges between 0.1% at intermediate and 2.5% at high  $p_T$  and is considered to be correlated over  $p_T$ .

The uncertainty on the signal extraction procedure has contributions from the choice of the  $J/\psi$  invariant mass shape and from the fit procedure used to describe the correlated background. It is estimated by

**Table 1:** Summary of the contributions to the systematic uncertainty (in percentage) for the inclusive  $p_T$ -integrated cross section  $d\sigma/dy$  and in the different  $p_T$  intervals. All sources of systematic uncertainty are considered to be highly correlated over  $p_T$ , except for the background fit which is considered fully uncorrelated.

Source	$p_T$ (GeV/c)							
	$p_T > 0$	0–1	1–2	2–3	3–4	4–5	5–7	7–10
Tracking	5.3	4.8	5.1	5.4	5.5	5.2	5.6	5.7
PID	0.43	0.21	0.42	0.17	0.04	0.40	1.1	2.5
Signal shape	1.9	1.8	1.8	1.8	1.8	1.8	2.9	2.9
Background fit	0.21	1.0	0.30	0.36	0.18	0.27	0.21	0.21
MC input	1.4	0.24	0.35	0.10	0.15	0.11	0.15	0.69
Luminosity	2.1							
Branching ratio	0.53							
Total uncorrelated syst.	0.21	1.0	0.30	0.36	0.18	0.27	0.21	0.21
Total correlated syst.	5.8	5.1	5.5	5.7	5.8	5.6	6.4	6.9
Global syst.	2.2							
Total	6.2	5.6	5.9	6.1	6.2	6.1	6.8	7.3

varying the mass interval used for the signal counting and the mass range used for the fitting. The value of the uncertainty is determined as the RMS of the distribution of cross sections obtained from the cases which give statistically significant variations, similar to the procedure described by Barlow [43]. The uncertainty on the  $J/\psi$  signal shape ranges between 1.8% in the low- and 2.9% in the high- $p_T$  intervals and is treated to be correlated over  $p_T$ . The uncertainty due to the background fitting is 1% in the lowest  $p_T$ -interval and less than 0.5% otherwise. It is considered as uncorrelated.

The uncertainty from the  $J/\psi$   $p_T$ -distribution which is used to compute the corrections is related to the precision of the fit to the measured  $J/\psi$  spectrum which is used in the iterative procedure described in Section 3.3. The fit parameters are varied randomly within their allowed fit uncertainty taking into account their correlation matrix. The resulting uncertainty amounts to 1.4% for the  $p_T$ -integrated cross section and less than 1% in each of the considered  $p_T$ -intervals.

The systematic uncertainty on the integrated beam luminosity is described in detail in Ref. [29] and amounts to 2.1%. This uncertainty is taken as a global uncertainty for the  $p_T$ -integrated and the  $p_T$ -differential cross sections.

The uncertainty on the branching ratio  $\text{BR}(J/\psi \rightarrow e^+e^-) = (5.97 \pm 0.03)\%$  [41] is treated as fully correlated between all bins.

## 4 Results

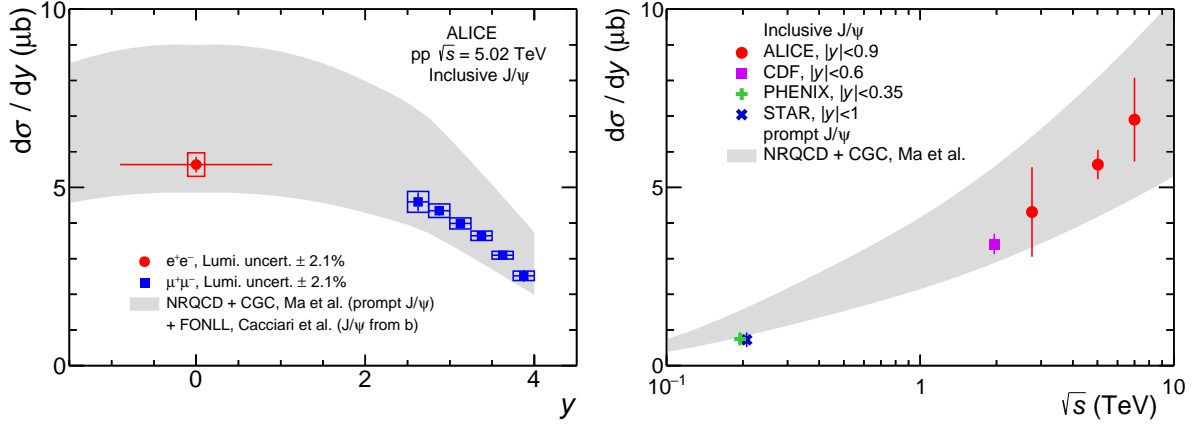
The inclusive  $J/\psi$  cross section in pp collisions at  $\sqrt{s} = 5.02$  TeV measured at mid-rapidity in the interval  $|y| < 0.9$  is

$$d\sigma_{J/\psi}/dy = 5.64 \pm 0.22(\text{stat.}) \pm 0.33(\text{syst.}) \pm 0.12(\text{lumi.}) \mu\text{b}.$$

The systematic uncertainty contains all the sources described in Section 3 added in quadrature, assuming that the  $J/\psi$  is produced unpolarised. Although the existing measurements in pp collisions at LHC energies indicate a null or only a small polarisation [44–46], there are no polarisation measurements for  $J/\psi$  at low  $p_T$  and mid-rapidity at LHC energies. In order to estimate the impact on the measured inclusive  $J/\psi$  cross section, the acceptance and efficiency factors are reweighted to take into account various polarisation scenarios. In the most extreme cases of a fully transversal ( $\lambda_{\text{HE}} = +1$ ) or a fully longitudinal ( $\lambda_{\text{HE}} = -1$ ) polarisation, the  $p_T$ -integrated cross section would increase by 15% or decrease by 24%, respectively.

In the left panel of Fig. 2, the inclusive  $p_T$ -integrated cross section  $d\sigma/dy$  is compared with the ALICE measurements at forward rapidity in the dimuon channel [19]. The systematic uncertainties are represented as boxes and the statistical uncertainties are shown by vertical error bars. The reported  $J/\psi$  cross sections are inclusive and contain a prompt and non-prompt component. The rapidity-dependent cross section is compared with results for prompt  $J/\psi$  from Leading Order (LO) NRQCD calculations coupled to a Colour Glass Condensate (CGC) description of the gluon distributions in the proton from Ma and Venugopalan [47]. The non-prompt component is calculated with Fixed-Order Next-to-Leading Logarithm (FONLL) [48] from beauty quarks with a  $J/\psi$  in the final state. The prompt component from Ref. [47] and the non-prompt component from Ref. [48] are then added together in order to generate the inclusive  $J/\psi$  cross section shown in the left panel of Fig. 2. The uncertainties of the prompt and non-prompt component are assumed to be uncorrelated when calculating the error band of the sum. The non-prompt contribution to the inclusive cross section is of the order of 10–20% in the considered low- $p_T$  regime. Good agreement between the model and data is observed over the full rapidity range, however the model uncertainties are much larger compared to the data.

The energy dependence of the  $J/\psi$  cross section in pp collisions at mid-rapidity is shown in the right panel of Fig. 2. The results are compared with the PHENIX [49] and STAR [50] measurements at  $\sqrt{s} = 0.2$  TeV, the CDF measurement at  $\sqrt{s} = 1.96$  TeV [38], and previous ALICE measurements at

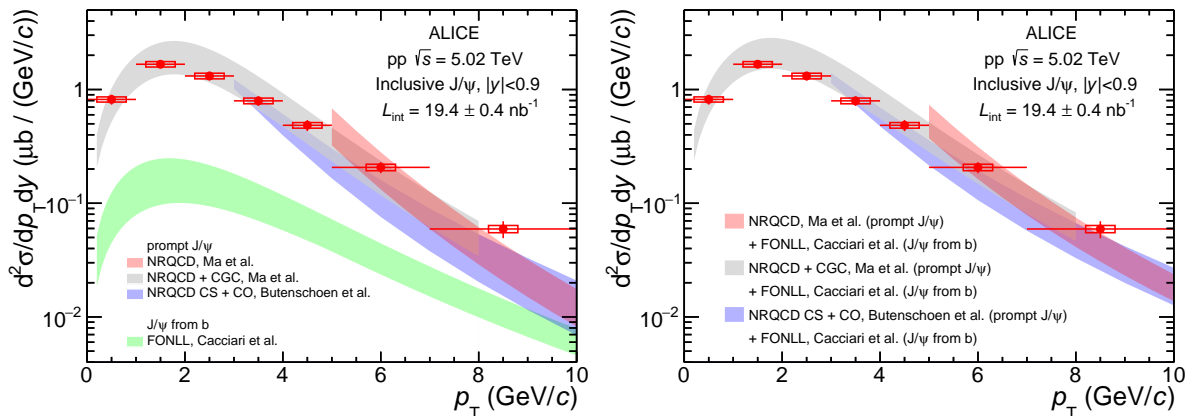


**Fig. 2:** Left: Inclusive  $J/\psi$  cross-section as a function of rapidity compared to the ALICE results at forward rapidity [19] and to calculations from [47] to which a non-prompt component is added as computed in [48]. Right: Inclusive  $J/\psi$  cross section at mid-rapidity [15, 16, 38, 49, 50] as a function of collision energy compared to the calculations from [47]. The data points from PHENIX and STAR, both at  $\sqrt{s} = 0.2$  TeV, are slightly shifted for visibility.

$\sqrt{s} = 2.76$  [15] and 7 TeV [16], where statistical and systematic uncertainties are added in quadrature. A steady increase, approximately logarithmic in  $\sqrt{s}$ , of  $d\sigma/dy$  at mid-rapidity is observed. The data are compared with the calculated prompt  $J/\psi$  cross section from Ref. [47]. Since the non-prompt component is known to be of the order of 10% of the inclusive cross-section, the qualitative agreement remains good.

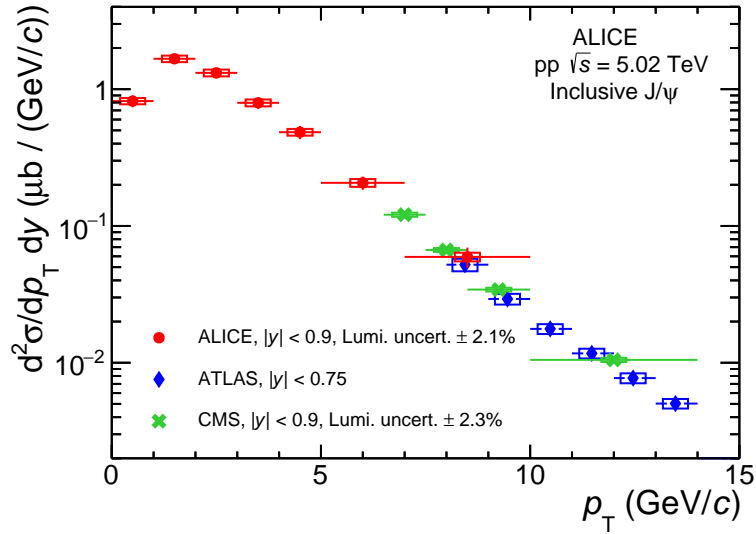
In the left panel of Fig. 3, the  $p_T$ -differential cross section  $d^2\sigma/dp_T dy$  is compared to three calculations: the prompt  $J/\psi$  cross section of NLO NRQCD calculations from Ma et al. [51], Butenschoen and Kniehl [52], and the above-mentioned calculations for NRQCD+CGC [47]. The non-prompt component calculated from FONLL [48] is shown separately. In the right panel of Fig. 3, the prompt and non-prompt components are added and compared with results of the present analysis. The agreement between all models and data is good in the measured  $p_T$ -range.

In Fig. 4, the  $p_T$ -differential cross section  $d^2\sigma/dp_T dy$  is compared with the high- $p_T$  measurements from ATLAS [13] and CMS [14] at mid-rapidity and same collision energy. It should be noted that the ATLAS and CMS measurements extend to higher  $p_T$  but are truncated to a region which is relevant for the



**Fig. 3:**  $p_T$ -differential inclusive  $J/\psi$  cross section compared with prompt  $J/\psi$  calculations from NLO NRQCD [51, 52] and LO NRQCD+CGC [47] and non-prompt  $J/\psi$  calculations from FONLL [48]. The calculations for the prompt and non-prompt components are shown separately in the left panel while in the right panel the FONLL calculation is added to the prompt  $J/\psi$  calculations.





**Fig. 4:**  $p_T$ -differential inclusive  $J/\psi$  cross section compared with ATLAS [13] and CMS [14] results at mid-rapidity. Luminosity uncertainties are indicated in the legend, except in the case of ATLAS for which these are included in the boxes.

comparison to ALICE. The ATLAS and CMS measurements of the prompt and non-prompt contributions were summed in order to obtain the inclusive cross section needed to compare with our measurement. Good agreement is observed between the results in the overlapping  $p_T$  region.

The energy dependence of the  $p_T$ -differential  $J/\psi$  cross section can be studied by using its moments, the average transverse momentum  $\langle p_T \rangle$  and the squared average transverse momentum  $\langle p_T^2 \rangle$ . In this analysis, the inclusive  $J/\psi$   $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$  are obtained by fitting the measured spectrum with a power law function of the form

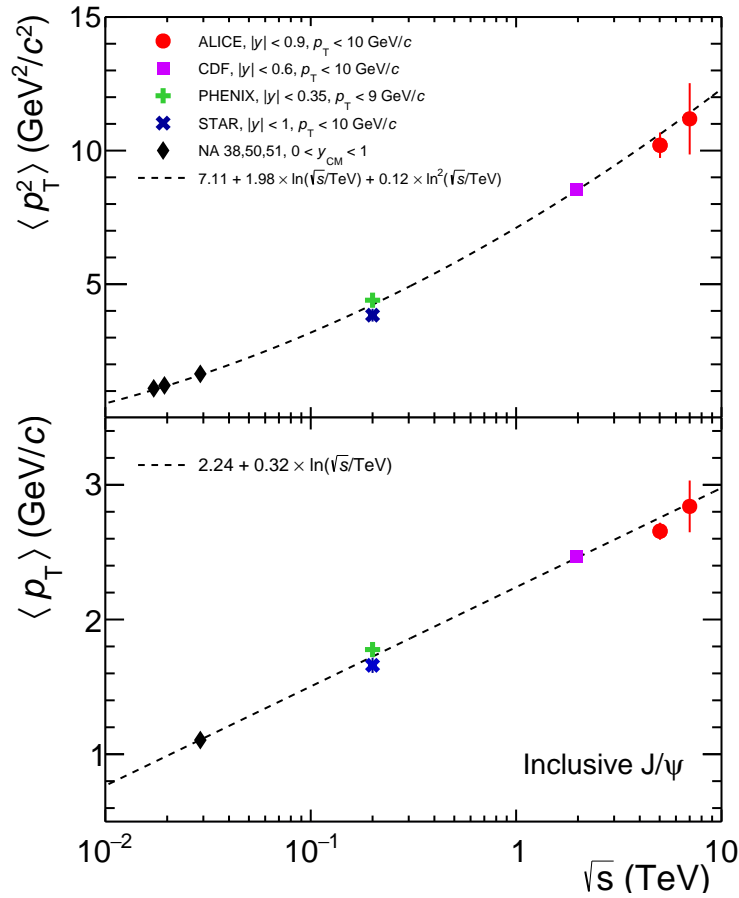
$$f(p_T) = C \times \frac{p_T}{\left\{1 + (p_T/p_0)^2\right\}^n}, \quad (2)$$

where  $C$ ,  $p_0$ , and  $n$  are free fit parameters. In the interval  $p_T < 10$  GeV/ $c$ , the first two moments of the fitted function are

$$\begin{aligned} \langle p_T \rangle &= 2.66 \pm 0.06(\text{stat.}) \pm 0.01(\text{syst.}) \text{ GeV}/c, \\ \langle p_T^2 \rangle &= 10.2 \pm 0.5(\text{stat.}) \pm 0.1(\text{syst.}) \text{ GeV}^2/c^2. \end{aligned}$$

The systematic uncertainty is obtained by fitting the measured  $J/\psi$  spectrum only with the systematic uncertainty of the  $p_T$ -differential cross section. The statistical uncertainty on the  $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$  takes into account the correlation matrix of the parameters from the fit procedure. A cross check of these results is performed considering a fit to the dielectron  $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$  distribution as a function of the invariant mass. A polynomial fit function is used to parameterise the background  $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$  as a function of invariant mass, and the signal-over-background ratio obtained from the signal extraction procedure as discussed in Section 3.2. The values obtained with this cross check are found to be compatible with the ones obtained from the spectrum fit.

The energy dependence of the  $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$  are shown in Fig. 5. A steady increase with energy is observed for both  $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$  over a wide collision energy range which includes results from SPS [53], RHIC [49, 50], Tevatron [38], and LHC [16, 20]. Statistical and systematic uncertainties are added in quadrature. This behaviour is a consequence of the opening of the phase space with increasing collision energy, i.e. for a fixed Bjorken- $x$  the momentum-exchange  $Q^2$  grows with increasing collision energy leading to a hardening of the  $J/\psi$   $p_T$  spectrum. Also, the faster increase with energy of the  $b\bar{b}$  cross section compared to the  $c\bar{c}$  cross section leads to a growth of the non-prompt  $J/\psi$  fraction, which further



**Fig. 5:** The  $\langle p_T \rangle$  (lower panel) and  $\langle p_T^2 \rangle$  (upper panel) of inclusive  $J/\psi$  at mid-rapidity as a function of the collision energy. These results are compared to previous results from ALICE [16, 20], Tevatron [38], RHIC [49, 50] and SPS [53].

hardens the  $J/\psi$   $p_T$  spectrum. In order to quantify the energy dependence of the  $J/\psi$   $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$ , we performed similar fits to those used in Ref. [49, 54], where linear or quadratic functions of the logarithm of the centre-of-mass collision energy were used. These simple parametrisations describe the existing measurements over nearly three orders of magnitude in collision energy.

## 5 Conclusions

The  $p_T$ -differential and  $p_T$ -integrated inclusive  $J/\psi$  production cross section in proton–proton collisions at  $\sqrt{s} = 5.02$  TeV in the rapidity range  $|y| < 0.9$  is measured down to zero  $p_T$  and represents a strong constraint for state-of-the-art model calculations.

Comparisons of the inclusive  $p_T$ -integrated and  $p_T$ -differential cross section with various NRQCD calculations for prompt  $J/\psi$  summed with a non-prompt  $J/\psi$  component calculated with FONLL show good agreement.

A hardening of the  $p_T$ -differential cross section is observed with increasing collision energy. This is well described by a linear and squared logarithmic increase of  $\langle p_T \rangle$  and  $\langle p_T^2 \rangle$  with  $\sqrt{s}$ , respectively.

## Acknowledgements

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable con-

tributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Universidade Federal do Rio Grande do Sul (UFRGS), Financiadora de Estudos e Projetos (Finep) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil; Ministry of Science & Technology of China (MSTC), National Natural Science Foundation of China (NSFC) and Ministry of Education of China (MOEC), China; Croatian Science Foundation and Ministry of Science and Education, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research — Natural Sciences, the Carlsberg Foundation and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l’Energie Atomique (CEA), Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS) and Région des Pays de la Loire, France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi and Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology, Nagasaki Institute of Applied Science (IIST), Japan Society for the Promotion of Science (JSPS) KAKENHI and Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Académico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Science and Higher Education and National Science Centre, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics and Ministry of Research and Innovation and Institute of Atomic Physics, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; National Science and Technology Development Agency (NSDTA), Suranaree University of Technology (SUT) and Office of the Higher Education Commission under NRU project of Thailand, Thailand; Turkish Atomic Energy Agency (TAEK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

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