CMS Physics Analysis Summary

Contact: cms-pag-conveners-bphysics@cern.ch 2010/07/22

J/ψ prompt and non-prompt cross sections in pp collisions at √s = 7 TeV

The CMS Collaboration

Abstract

We present a measurement of the inclusive total and differential production cross sections of J/ψ mesons and b-hadrons in pp collisions at √s = 7 TeV with the CMS experiment. The data correspond to an integrated luminosity of 100 nb⁻¹ and were collected during the first months of LHC operation. The differential production cross section of J/ψ from inclusive processes has been measured as a function of the J/ψ transverse momentum, up to 30 GeV/c, for two rapidity ranges: |y| < 1.4 and 1.4 < |y| < 2.4. The total cross section for inclusive J/ψ production, times the dimuon decay branching fraction, has been determined to be 289.1 ± 16.7(stat) ± 60.1(syst) nb for transverse momenta between 4 and 30 GeV/c and in the rapidity range |y| < 2.4. The b-hadron component has been determined from a fit to the decay length distribution of displaced J/ψ decays, and a p_T differential cross section for b-hadron decays has been derived. The total cross section times BR(J/ψ → μ⁺μ⁻) for the J/ψ production coming from B-hadrons, decaying to J/ψ mesons with transverse momenta between 4 and 30 GeV/c and in the rapidity range |y| < 2.4, is measured to be 56.1 ± 5.5(stat) ± 7.2(syst) nb. The paper ends with some comparisons between the measurements and model calculations.
1 Introduction

The production mechanism of $J/\psi$ mesons and b-hadrons in hadron collisions continues to raise interest. The production of $J/\psi$'s at hadron colliders occurs in three ways: prompt $J/\psi$'s produced directly, prompt $J/\psi$'s produced indirectly (via decay of heavier charmonium states such as $\chi_c$), and non-prompt $J/\psi$'s from the decay of a b-hadron. Prompt quarkonium production is particularly interesting in view of the present puzzling situation: although a variety of theoretical models exists for the hadronic production of prompt $J/\psi$'s [1–3], they generally fail to describe simultaneously the $J/\psi$ differential-$p_T$ cross-section measurements [3–5] and the polarization measurements [6–8] at the Tevatron. Cross-section measurements for prompt $J/\psi$'s at the Large Hadron Collider (LHC) help to clarify the production mechanism, because they allow theoretical predictions to be tested for the first time at a much higher energy and in a wider rapidity range.

Non-prompt quarkonium production can be directly related to b-hadron production via the measured $\text{BR}(b \rightarrow J/\psi)$ [9], leading to a direct measurement of the $b\bar{b}$ cross section in pp collisions. After a historical discrepancy between the Tevatron results (both from inclusive [5] and exclusive [10] measurements) and the NLO QCD theoretical results, a much better agreement was recently found using the FONLL (Fixed-Order Next-to-Leading-Log) approach [11, 12]. Measured cross-section values and spectra are also found to be in agreement with the specific Monte Carlo generators where this model is implemented, like MC@NLO [13, 14]. Studying the production of $J/\psi$'s from B-decay at the LHC is a test of these models at higher energies and is also highly relevant because it can be used to validate the QCD and the parton density function sections of the Monte Carlo.

This paper presents the first measurement of the differential $d\sigma/dp_T$ and of the total inclusive production cross section of $J/\psi$'s and b-hadrons in pp collisions at a centre-of-mass energy of 7 TeV in the rapidity range $|y| < 2.4$ with the Compact Muon Solenoid (CMS) detector. Prompt $J/\psi$ events can be separated from those coming from b-hadron decays by exploiting their decay length distribution: this allows a precise measurement of the production cross section for both channels.

The paper is organized as follows. Section 2 describes the CMS detector. Section 3 presents the data collection, the event trigger and selection, the $J/\psi$ reconstruction, and the Monte Carlo simulation. Section 4 is devoted to the evaluation of the detector acceptance and efficiencies to detect $J/\psi$ events in CMS. In Section 5 the measurement of the $J/\psi$ inclusive cross section is reported. In Section 6 the fraction of $J/\psi$ events from B-hadron decay is derived, and results are presented both for the prompt $J/\psi$ cross section and for the cross section of $J/\psi$'s from B-hadron decay. The paper finishes with some comparisons between the measurements and model calculations.

2 The CMS detector

A detailed description of the Compact Muon Solenoid (CMS) experiment can be found elsewhere [15]. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter. Within the field volume are the silicon tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are detected in the pseudorapidity window $|\eta| < 2.4$, by gaseous detectors made of three technologies: Drift Tubes (DT), Cathode Strip Chambers (CSC), and Resistive Plate Chambers (RPC), embedded in the iron return yoke. The silicon tracker is composed of pixel detectors (three barrel layers and two forward disks in either side of the detector, made of 66 million 100 × 150 $\mu$m$^2$ pix-
Data selection and event reconstruction

3.1 Data selection and Monte Carlo simulation

The analysis is based on a data sample recorded by the CMS detector in pp collisions at a centre-of-mass energy of 7 TeV. The sample corresponds to a total integrated luminosity of 100.44 ± 11.05 nb⁻¹ [16]. The parameters of the LHC were such that, on average, there were 1.6 collisions per bunch crossing. The data selection required good quality data from the Tracker, the Muon and the luminosity measurement detectors, in addition to good trigger conditions.

The current analysis is based on events triggered by two algorithms. The first, HLT_Mu3, is a single muon trigger using very loose L1 muon trigger primitives. After reconstructing the track in the HLT online farm, including information from the Silicon tracker, a $p_T$ cut of 3 GeV/c is imposed. The second, L1DoubleMuOpen, requires the detection of two muons at the hardware level, without any further processing. The coincidence of two muon signals, without any cut on $p_T$, is enough to keep the trigger rate reasonably low at the instantaneous luminosities of the LHC start-up, on which this analysis is based. All three muon systems, DT, CSC and RPC, take part in the trigger decision.

The L1DoubleMuOpen is used to measure the $J/\psi$ cross section in the region of $p_T$ smaller than 4 GeV/c, attained in the region of rapidity $1.4 < |y| < 2.4$, while the HLT_Mu3 is used for the $J/\psi$ $p_T > 4$ GeV/c range for both the $|y| < 1.4$ and $1.4 < |y| < 2.4$ regions.

Anomalous events coming from beam-gas interactions or beam scraping in the beam transport system near the interaction point, producing large activity in the pixel detector, are removed with ad-hoc filters [17]. A good primary vertex is also required, as defined in Ref. [17].

Detectors were aligned and calibrated using LHC collision data and cosmic muon events [18]. Simulated events were used to tune the selection criteria, to check the agreement with data, and to compute the acceptance and corrections to the efficiencies (see Section 4). Prompt $J/\psi$ were produced using Pythia [19], which generates events based on the leading-order singlet and octect mechanisms. Color-octet states undergo a shower evolution. We used the NRQCD matrix element tuning as obtained by comparing NRQCD calculations with CDF data [3, 20]. Non-prompt decays were also produced in Pythia and the B-hadrons decayed using the EVTGEN [21] package. Background events were generated from generic QCD events with Pythia. The simulated events were passed through the GEANT4-based [22] detector simulation, and were processed with the same reconstruction program as used for real events. Final state bremsstrahlung was implemented using PHOTOS [23, 24]. The detector simulation includes the trigger, as well as the finite precision of alignment and calibration.
3.2 Offline muon reconstruction

In this analysis, muons are defined as tracks reconstructed in the silicon tracker which are associated to a compatible signal in the muon chambers. Tracks are reconstructed using a Kalman filter technique which starts from pixel seeds and then extrapolates to the silicon strip tracker.

Two different reconstructed muon types are considered. The first one, referred to as a Global Muon, provides high-quality and high-purity muon reconstruction for tracks with $p_T \gtrsim 4$ GeV/$c$ in the central pseudo-rapidity region, and $p_T \gtrsim 1$ GeV/$c$ in the forward region. The second muon type, referred to as a Tracker Muon, achieves a better reconstruction efficiency at lower momenta.

Global Muons are built as a combined fit of silicon and muon-chamber hits, belonging to independent track segments found in the tracker and muon systems. In the muon system at least two stations must be used. The $\chi^2$ per degree of freedom of the combined fit is required to be smaller than 20. The requirements for a Tracker Muon are looser than for Global Muons: the tracks found in the Tracker must be matched to at least one muon segment in one muon station. The two muon types differ in the way the information of the muon chambers is combined with that of the tracker: requirements for Tracker Muons are less stringent, at the expense of a slightly larger background. If two (or more) tracks are close to each other, it is possible that the same muon segment or set of segments is associated to more than one track. In this case the best track is selected based on the matching between the extrapolated track and the segment in the muon detectors. More details can be found in Ref. [25].

There is an overlap between these two reconstruction methods. If a Global Muon has an associated silicon track that has also been reconstructed as Tracker Muon, then it is assigned to the Global Muon category alone, making the two categories exclusive. For either case the track momentum is determined by the fit in the Tracker only. Further cuts are applied to the tracks, mainly to reject fake muons or decays in flight from kaons or pions. The tracks must have at least 12 hits in the Tracker detector, out of which two in the pixel layers, a $\chi^2$ per degree of freedom smaller than 4, and must pass within a cylinder of radius 3 cm and length 30 cm centered at the vertex of the primary interaction and parallel to the beam line.

The momentum measurement of charged tracks in the CMS detector can be affected by systematic uncertainties due to imperfect knowledge of the magnetic field and of the material budget, to sub-detectors misalignment and to biases in the algorithms which fit the track trajectory. Studies performed with cosmic-ray muons and collision data [18, 26, 27] show a very precise control of all these possible biases. Residual effects can be spotted out by studying the dependence of the reconstructed dimuon peak shapes on the muon kinematics. The residual relative correction in the muon transverse momenta has been found to be $(0.09 \pm 0.02)\%$ [28], and has been corrected for.

3.3 $J/\psi$ event selection

To select the events with $J/\psi$ decays, muons with opposite charge are paired and their invariant mass is computed. The invariant mass of the muon pair is required to be between 2.6 and 3.5 GeV/$c^2$. The two muons helices are fitted with a common vertex constraint, and events are retained if the fit $\chi^2$ probability is larger than 0.1%. Pairs made of different muon type combinations are reconstructed: two global muons, two tracker muons or one global and one tracker muon. In case of multiple combinations in the same event, the combination with the purest muon content is chosen (global muon being purer than tracker muons). If two candidate
pairs belong to the same dimuon type combination, the one with the largest $p_T$ is chosen. On average 1.07 $J/\psi$ combinations were found per event. The analysis is then performed summing the three categories.

Same sign dimuons are also reconstructed, and are used as a check of the background level (see Section 5).

The $J/\psi$ four-momentum is computed as the vector sum of the two muon momenta. The dimuon mass spectrum is shown in Fig. 1. About 12000 $J/\psi$ candidates have been reconstructed, out of which about 19% in the two Global Muons category and 27% in the two Tracker Muons category.

![Figure 1: Dimuon invariant mass distributions for all categories (top) and for only Global Muon pairs (bottom), in the rapidity windows $|y| < 1.4$ (left) and $1.4 < |y| < 2.4$ (right). Also shown are the invariant mass widths from a fit of a Crystal Ball function plus an exponential. The worse mass resolution for large rapidities is caused by the smaller lever arm of the tracks. The non-peaking red distributions show the same sign dimuon combinations.](image)

4 Acceptance and Efficiency

The observed number of $J/\psi$ events is corrected for the detector acceptance and muon reconstruction efficiency. The acceptance accounts for purely geometrical and kinematical limitations and is taken from the simulation, while the efficiency is related to instrumental effects which can be measured from data.

4.1 Acceptance

The acceptance takes into account the finite geometrical coverage of the CMS detector and the limited kinematic acceptance of the muon trigger and reconstruction systems. Moreover, the
material in front of the muon detectors, acting as an absorber, and the curvature in the magnetic field, effectively introduce a momentum threshold.

The $J/\psi$ acceptance $A$ is defined as the fraction of detectable $J/\psi \rightarrow \mu^+\mu^-$ decays, as a function of the dimuon transverse momentum $p_T$ and rapidity $y$,

$$A(p_T, y, \lambda_\theta) = \frac{N_{\text{det}}(p_T, y, \lambda_\theta)}{N_{\text{gen}}(p_T, y, \lambda_\theta)},$$

where $N_{\text{det}}$ is the number of detectable $J/\psi$ events in a given $(p_T, y)$ bin and $N_{\text{gen}}$ is the corresponding total number of generated $J/\psi$ events in the Monte Carlo simulation. The parameter $\lambda_\theta$ reflects the fact that the acceptance has been computed for various polarization scenarios, as explained below. The large amount of simulated events available allows here the use of a much smaller bin size with respect to what is used for the cross-section determination in data.

The detectability criterion for the muons coming from the $J/\psi$ decay is that each muon should lie within the geometric acceptance of the muon detectors and have enough momentum to cross at least three active layers in any of the muon stations, since three is the minimum number of hits required for a track segment. The following kinematic cuts, defining the acceptance region, are then chosen so as to guarantee a single-muon detectability exceeding 10%:

- $|\eta_\mu| < 1.3 \rightarrow p_T^\mu > 3.3$ GeV/$c$,
- $1.3 < |\eta_\mu| < 2.2 \rightarrow p_T^\mu > 2.9$ GeV/$c$,
- $2.2 < |\eta_\mu| < 2.4 \rightarrow p_T^\mu > 0.8$ GeV/$c$.

To compute the acceptance, the $J/\psi$ events were generated with no cut in $p_T$ and within a rapidity region extending beyond the muon detectors coverage. In the actual acceptance determination, the Monte Carlo reconstructed dimuon variables are used in Eq. 1. It should be noted that the generated dimuon momentum may differ from the $J/\psi$ momentum, due to final state radiation. The difference between the acceptance computed by using the dimuon or the $J/\psi$ variables in Eq. 1 is taken as a systematic uncertainty.

The dependence on the $J/\psi$ polarization is due to the fact that different polarizations cause different muon momentum spectra in the laboratory frame.

The acceptance as a function of $p_T$ and $|y|$ is given in Fig. 2 for the combined prompt and non-prompt $J/\psi$’s, with the prompt computed as decaying isotropically, which corresponds to the unphysical case of null polarization. Also shown is the measured distribution of the $p_T$ and $|y|$ of the muon pairs within $\pm 100$ MeV/$c^2$ from the nominal $J/\psi$ mass.

Given the strong dependence of the acceptance on the prompt $J/\psi$’s polarization, it was chosen to quote final results for different polarization scenarios instead of treating this factor as a source of systematic uncertainty. For non-prompt $J/\psi$’s, however, the B-hadron events were generated with the $J/\psi$ polarization as measured from the BaBar experiment at the $Y(4S)$ [29] and the corresponding systematic uncertainty is evaluated by taking the difference with respect to the one predicted by EVTGEN.

Additional systematic uncertainties have been investigated, as described in the following paragraphs.

The $J/\psi$’s produced in b-hadron decays can, in principle, have a different acceptance with respect to the prompt ones, due to their different momentum spectra, leading to an uncertainty
coming from the unknown proportion of b-hadrons in the inclusive sample. This fraction has been varied by 20% in the Monte Carlo, giving to up 0.4% systematic uncertainty on the overall acceptance.

The distribution of the z-position of the $pp$ interaction point could potentially influence the acceptance. Several samples of $J/\psi$ have been generated, each coming from different positions along the beam line (between $-10$ and $+10$ cm with respect to the center of the collision region) and a negligible variation of the acceptance has been found.

A difference in the muon momentum scale in data and simulated events would lead to a different acceptance. The muon transverse momenta in data have been calibrated as described in [28] with an uncertainty of 0.05%. Simulated events have a bias on the $J/\psi$ mass of the order of $3 \times 10^{-4}$. As a conservative estimate the full Monte Carlo shift has been applied to the simulated muon momenta, plus a bias equivalent to the residual uncertainty on the data. The acceptance has been recomputed with shifted momenta and the difference has been taken as systematics.

A difference in the momentum resolution between data and simulated events would also give a systematics on the acceptance. The muon momentum resolution has been measured in data, and it is compatible, within the uncertainty, with what is expected from simulation[28]. The acceptance has been computed with simulated muon momenta smeared accordingly to the resolution measured on data. The uncertainty on the measured resolution has been then used to over-smear the simulated momenta and the acceptance has been recalculated. The difference has been taken as systematics.

### 4.2 Efficiency

The muon efficiency has been computed as described in [25, 30] and is based on the so-called Tag and Probe method.

The combined trigger and offline-reconstruction efficiency for a single muon is measured on data and is defined as

$$
\epsilon = \epsilon_{\text{off}} \cdot \epsilon_{\text{trig}} |_{\text{off}}
$$
where $\epsilon_{\text{off}}$ is the efficiency to reconstruct offline a muon candidate and $\epsilon_{\text{trig} | \text{off}}$ is the probability for an offline reconstructed muon to have also fired the trigger.

The efficiencies are calculated in several $(p_T^\mu, \eta^\mu)$ bins. The muon identification and the muon trigger efficiencies have a stronger $p_T^\mu$ dependence than the tracking efficiency, and are mapped with sufficient sampling to describe the turn-on curve satisfactorily. In turn, the tracking efficiency is constant for this momentum range while it varies more (though only slightly) in the $\phi - \eta$ plane [30].

The muon offline reconstruction efficiency is assumed to be given by

$$
\epsilon_{\text{off}} = \epsilon_{\text{track}} \cdot \epsilon_{\text{tag} | \text{track}}
$$

where $\epsilon_{\text{track}}$ is the tracking efficiency and $\epsilon_{\text{tag} | \text{track}}$ is the muon identification in the muon systems for a tracker-reconstructed muon, referred to as tagging efficiency.

The efficiency to detect a given $J/\psi$ event is thus dependent on the value of the muon pair kinematic variables, and is given by

$$
\epsilon(J/\psi) = \epsilon_{\text{off}}(\mu^+) \cdot \epsilon_{\text{off}}(\mu^-) \cdot \epsilon_{\text{Trigg}} \cdot \rho \cdot \epsilon_{\text{vertex}},
$$

where $\epsilon_{\text{Trigg}}$ is $\left(\epsilon_{\text{trig} | \text{off}}(\mu^+) + \epsilon_{\text{trig} | \text{off}}(\mu^-) - \epsilon_{\text{trig} | \text{off}}(\mu^+) \cdot \epsilon_{\text{trig} | \text{off}}(\mu^-)\right)$ for the HLT_Mu3 trigger and $\epsilon_{\text{trig} | \text{off}}(\mu^+) \cdot \epsilon_{\text{trig} | \text{off}}(\mu^-)$ for the L1DoubleMuonOpen trigger. The efficiency for the two muon tracks to be consistent with coming from a common vertex (see Section 3.3), $\epsilon_{\text{vertex}}$, is measured to be $(98.7 \pm 0.6)\%$, by comparing the number of two Global Muons combinations (which have a signal purity of about 95%) within $\pm 100$ MeV/$c^2$ from the nominal $J/\psi$ mass, with and without the common vertex requirement. The correction to the factorization hypothesis and the effect of the finite size of the $(p_T^\mu, \eta^\mu)$ bins are taken into account by $\rho$, which is evaluated from the Monte Carlo simulation.

When selecting the tag muon, the Tag and Probe method produces a slight bias on the distribution of the probe muon, hence a small difference arises between the measured single muon efficiencies and those of an unbiased sample. This effect is studied in the Monte Carlo simulation and corrected for.

The systematic uncertainty on $\rho$ is conservatively taken as the difference between the actual value as predicted by the Monte Carlo simulation and $\rho = 1$.

The uncertainties due to the estimated muon efficiencies were assessed by taking into account their statistical errors and by comparing in the simulation the values found with the Tag and Probe method with the true selection efficiencies. The two uncertainties were summed in quadrature.

## 5 Inclusive $J/\psi$ cross section

The measurement of the inclusive $p_T$ differential cross section is based on the following equation:

$$
\frac{d\sigma}{dp_T}(J/\psi) \cdot \text{BR}(J/\psi \to \mu^+\mu^-) = \frac{N_{\text{corr}}(J/\psi)}{\int L \cdot dt \cdot \Delta p_T}
$$

where $N_{\text{corr}}(J/\psi)$ is the $J/\psi$ yield, corrected for the $J/\psi$ selection efficiency, in a given $p_T$ bin, $\int L \cdot dt$ is the integrated luminosity, $\Delta p_T$ is the size of the $p_T$ bin, and $\text{BR}(J/\psi \to \mu^+\mu^-)$ is the branching ratio of the $J/\psi$ decay into two muons, which is $(5.88 \pm 0.10)\%$ [9].
5.1 \( J/\psi \) yields

The corrected yield, \( N_{\text{corr}}(J/\psi) \), is determined in two steps: first, in each \( J/\psi \) rapidity and \( p_T \) bin a fit to the \( \mu^+\mu^- \) invariant mass distribution is performed; the resulting yield is then corrected by a factor that takes into account the acceptance \( (A) \) and detection efficiency \( (\epsilon) \) for the particular dimuon combination. This factor, \( \langle 1/(A\epsilon) \rangle \), is obtained from the values of \( A \) and \( \epsilon \) computed in the fine-grained bins shown in Fig. 2, and the average taken over the observed data distribution in the given \( J/\psi \) rapidity and \( p_T \) bin. This effectively corresponds to measuring a differential cross section in fine-grained bins and then integrating it over larger \( J/\psi \) rapidity and \( p_T \) ranges.

The shape assumed for the signal is a Crystal Ball function [31], which takes into account the detector resolution as well as the radiative tail from internal bremsstrahlung. The shape of the background is described by an exponential. Table 1 lists the \( J/\psi \) signal yields and the corresponding statistical uncertainties from the fit, for the chosen \( p_T \) bins.

The invariant mass resolution has a strong dependence on the two muons pseudorapidities, therefore the fit is performed in two different regions in the \( J/\psi \) rapidity.

Table 1: Event yield in each \( p_T \) bin, together with the average acceptance times efficiency (computed in the null polarization scenario).

| \( p_T^{J/\psi} \) (GeV/c) | \( |y| < 1.4 \) | \( 1.4 < |y| < 2.4 \) |
|--------------------------|----------------|----------------|
| 4 – 6                    | 291 ± 21       | 923 ± 59       |
| 6 – 8                    | 457 ± 24       | 884 ± 84       |
| 8 – 10                   | 412 ± 22       | 916 ± 56       |
| 10 – 30                  | 495 ± 23       | 1316 ± 56      |

Different functions were used to assess any systematic effects coming from the fit function chosen to model the signal and the background shapes. The maximum difference in the result was taken as systematic uncertainty. For the signal, the Crystal Ball was varied to a sum of a Crystal Ball and a Gaussian, while for the background we used a second order polynomial.

A bias on the muon momentum scale can shift the events from one \( J/\psi \) \( p_T \) bin to the adjacent ones. To estimate this systematic effect a bias has been applied to the muon momenta equal to 0.02%, which is the residual uncertainty on the scale after the calibration explained in Section 3.3, and a negligible variation was found. A list of systematics can be found in Table 2.
5.2 Inclusive $J/\psi$ cross section results

Table 2: Relative uncertainties (in percent) on the corrected yield, in each $p_T$ bin: statistical, final state radiation (FSR), $p_T$ calibration, B-fraction, Non-prompt polarization, muon efficiency, $\rho$-factor, Fit functions

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5.2 Inclusive $J/\psi$ cross section results

Table 3 reports the values of the $J/\psi$ differential cross section with systematic and statistical uncertainties, for different polarization scenarios. The relative error on the luminosity determination is 11%, and is common for all bins.

Figure 3 gives the inclusive cross section $BR(J/\psi \to \mu^+\mu^-) \cdot \frac{d\sigma}{dp_T}$ in the two rapidity ranges, including statistical and systematic uncertainties, added in quadrature. It should be noticed that the first bin in the forward rapidity region extends down to $p_T^{J/\psi} = 0$ GeV/c.

The total error is dominated by the statistical uncertainty on the determination of the efficiencies from data.

The total cross section for $J/\psi$ production, obtained by integrating over $p_T$ between 4 and 30 GeV/c and over rapidity between $-2.4$ and $2.4$, gives

$$BR(J/\psi \to \mu^+\mu^-) \cdot \sigma(pp \to J/\psi + X) = (289.1 \pm 16.7\text{(stat)} \pm 60.1\text{(syst)}) \text{ nb}$$

(6)

6 Fraction of $J/\psi$ from B-hadron decay

The measurement of the fraction of $J/\psi$ coming from the decays of the B-hadrons relies on the discrimination of the $J/\psi$ produced away from the pp collision vertex (contrary to the promptly produced ones), determined by the distance between the dimuon vertex and the primary vertex in the plane orthogonal to the beam line. Given the small size of the beam spot (about 40 $\mu$m) and its careful determination even within a run, that is taken as the location of the pp collision vertex.

6.1 Separating prompt and non-prompt $J/\psi$'s.

As a rough estimate of the B-hadron decay length, for each $J/\psi$ candidate, the quantity $\ell_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_T$ is computed, where $m_{J/\psi}$ is the $J/\psi$ mass and $L_{xy}$ is the most probable transverse
| Prompt polarization | $|y| < 1.4$ | $1.4 < |y| < 2.4$ | $2.4 < |y| < 3.0$ | $3.0 < |y| < 3.4$ | $3.4 < |y| < 4.0$ | $4.0 < |y| < 6.0$ | $6.0 < |y| < 8.0$ | $8.0 < |y| < 10.0$ | $|y| > 10.0$ |
|---------------------|---------|----------------|--------|----------------|----------|----------------|----------|---------|---------|
| CS $\theta = +1$   | 1.81 ± 0.07 | 2.67 ± 0.14 | 3.69 ± 0.21 | 4.76 ± 0.29 | 5.80 ± 0.36 | 6.84 ± 0.43 | 7.86 ± 0.50 | 8.88 ± 0.57 | 9.90 ± 0.64 |
| CS $\theta = -1$   | 1.81 ± 0.07 | 2.67 ± 0.14 | 3.69 ± 0.21 | 4.76 ± 0.29 | 5.80 ± 0.36 | 6.84 ± 0.43 | 7.86 ± 0.50 | 8.88 ± 0.57 | 9.90 ± 0.64 |
| HX $\theta = +1$   | 1.81 ± 0.07 | 2.67 ± 0.14 | 3.69 ± 0.21 | 4.76 ± 0.29 | 5.80 ± 0.36 | 6.84 ± 0.43 | 7.86 ± 0.50 | 8.88 ± 0.57 | 9.90 ± 0.64 |
| HX $\theta = -1$   | 1.81 ± 0.07 | 2.67 ± 0.14 | 3.69 ± 0.21 | 4.76 ± 0.29 | 5.80 ± 0.36 | 6.84 ± 0.43 | 7.86 ± 0.50 | 8.88 ± 0.57 | 9.90 ± 0.64 |

Table 3: Differential cross sections, and average $p_T$ in the bin (in the data), for each prompt polarization considered. The default null polarization, the polarization fully longitudinal (CS), and fully transverse (HX) of the helicity projection. The helicity projection (CS) is either the Collins-Soper ($\ell^0$) or the Helicity ($\ell^0$) basis. The error is the total one. (H) frames (see Ref. [6]). Only for the null polarization case the first error is statistical and the second is systematical. For the others the error is the total one.
Figure 3: Differential cross section as a function of $p_T^{J/\psi}$ for the two different rapidity intervals and in the null polarization scenario. The error bars on the abscissa values are the RMS of the $p_T^{J/\psi}$ in each bin.

decay length in the laboratory frame \([32, 33]\), defined as

$$L_{xy} = \frac{u^T\sigma^{-1}x}{u^T\sigma^{-1}u},$$  

where \(x\) is the distance between the vertex of the two muons and the primary vertex of the event computed in the transverse plane, \(u\) is the unit vector of the $J/\psi$ $p_T$ and \(\sigma\) is the sum of the primary and secondary vertex covariance matrices.

It should be noted that negative values of $\ell_{J/\psi}$ are possible due to resolution effects which, at small decay lengths, cause the $J/\psi$ momentum vector and the one joining the primary and secondary vertices to be in opposite directions in the transverse plane.

To determine the fraction $f_B$ of $J/\psi$'s from B-hadron decays in the data, we performed an unbinned maximum-likelihood fit in bins of $p_T$, integrating over the $J/\psi$ rapidity. The dimuon mass spectrum and the $\ell_{J/\psi}$ distribution were simultaneously fitted by a log-likelihood function,

$$\ln L = \sum_{i=1}^{N} \ln F(\ell_{J/\psi}, m_{\mu\mu}),$$

where $N$ is the total number of events and $m_{\mu\mu}$ the invariant mass of the muon pair. The expression for $F(\ell_{J/\psi}, m_{\mu\mu})$ is given by

$$F(\ell_{J/\psi}, m_{\mu\mu}) = f_{\text{Sig}} \cdot F_{\text{Sig}}(\ell_{J/\psi}) \cdot M_{\text{Sig}}(m_{\mu\mu}) + (1 - f_{\text{Sig}}) \cdot F_{\text{Bkg}}(\ell_{J/\psi}) \cdot M_{\text{Bkg}}(m_{\mu\mu}),$$

where:

- $f_{\text{Sig}}$ is the fraction of events attributed to $J/\psi$ sources coming from both prompt and non-prompt components,
- $F_{\text{Sig}}(\ell_{J/\psi})$ and $F_{\text{Bkg}}(\ell_{J/\psi})$ are the functional forms describing the $\ell_{J/\psi}$ distribution for the signal and background, respectively. The signal part is given by a sum of prompt
and non-prompt components,

\[ F_{\text{Sig}}(\ell_{J/\psi}) = f_B \cdot F_B(\ell_{J/\psi}) + (1 - f_B) \cdot F_p(\ell_{J/\psi}) \]

where \( f_B \) is the fraction of \( J/\psi \) from B-hadron decays, and \( F_p(\ell_{J/\psi}) \) and \( F_B(\ell_{J/\psi}) \) are the \( \ell_{J/\psi} \) distributions for prompt and non-prompt \( J/\psi \)'s, respectively. Since \( \ell_{J/\psi} \) should be zero in an ideal detector for prompt events, \( F_p(\ell_{J/\psi}) \) is described simply by a resolution function. The shape is taken to be triple-Gaussian and its parameters are free in the nominal fit, except the very small “outlier” component which is fixed from Monte Carlo simulation. In order to evaluate systematic effects, an alternative approach uses an event-by-event error determined from the vertex covariance matrices. The \( \ell_{J/\psi} \) shape of the non-prompt component of Eq. 10 is given by convoluting the same resolution function with the true \( \ell_{J/\psi} \) distribution of the \( J/\psi \)'s from B-decay, as given by the Monte Carlo simulation. For the background \( \ell_{J/\psi} \) distribution \( F_{\text{Bkg}}(\ell_{J/\psi}) \) the same functional form was taken as employed by CDF [5], convoluted with the resolution function.

- \( M_{\text{Sig}}(m_{\mu\mu}) \) and \( M_{\text{Bkg}}(m_{\mu\mu}) \) are the functional forms describing the invariant dimuon mass distributions for the signal and background, respectively, as already mentioned (see Section 5.1).

The fit is performed in four steps:

1. A fit to the dimuon invariant mass is performed as described in the previous sections; \( f_{\text{Sig}} \) and some of the shape parameters defining the functions \( M_{\text{Sig}}(m_{\mu\mu}) \) and \( M_{\text{Bkg}}(m_{\mu\mu}) \) are then kept fixed in the next steps.

2. A fit to \( \ell_{J/\psi} \) in the prompt signal MC sample is performed to get an initial estimate of the triple-Gaussian parameters; only the small “outlier” component is then fixed for the next steps.

3. The \( \ell_{J/\psi} \) distribution in the sidebands of the dimuon invariant mass distribution, defined as the regions \([2.6,2.9]\) GeV/\(c^2\) and \([3.3,3.5]\) GeV/\(c^2\), is fitted with the \( F_{\text{Bkg}}(\ell_{J/\psi}) \) function; some of the fitted parameters are fixed for the next step.

4. The measured two-dimensional \((\ell_{J/\psi},m_{\mu\mu})\) event distribution is fitted using Eq. 8, to obtain all the parameters not fixed in the previous steps.

For the \( b \)-fraction determination we choose to keep the same rapidity splitting as in the inclusive cross section but to group some \( p_T \) bins, since more events per bin are needed to determine all fit parameters. Figure 4 shows the projection of the likelihood fits in two sample bins, while the full results are reported in Table 4.

As a control check we have performed a fit with the mean B-hadron lifetime left as a free parameter and found it to be \( \tau_B = 1.32 \pm 0.07 \) ps, where the error is statistical only, consistent with the world average [9].

### 6.1.1 Systematic uncertainties affecting the b-fraction fit

Several systematic sources have been addressed.

- **Residual misalignments in the Tracker.** The effect of uncertainties in the measured misalignment of the Tracker modules is estimated by re-reconstructing the data several times using different sets of alignment constants. These sets reflect the uncer-
6.1 Separating prompt and non-prompt $J/\psi$'s.

Figure 4: Measured $\ell_{J/\psi}$ distribution and likelihood fit result for the bins $2 < p_T^{J/\psi} < 4$ GeV/$c$, $1.4 < |y| < 2.4$ (left) and $6 < p_T^{J/\psi} < 10$ GeV/$c$, $|y| < 1.4$ (right) with their pull distributions (bottom). The blue dotted line represents the background component only, the red dashed line includes the non-prompt component and the black line represents the total fit.

Table 4: Fit results for the determination of the fraction of $J/\psi$ from B-hadrons in $p_T^{J/\psi}$ bins. The B-fraction column shows the statistical and systematic errors, while for the prompt and non-prompt fitted yields only the statistical errors are given.

<table>
<thead>
<tr>
<th>$p_T^{J/\psi}$ (GeV/$c$)</th>
<th>$N_{\text{sig}}^{\text{prompt}}$</th>
<th>$N_{\text{sig}}^{\text{non-prompt}}$</th>
<th>B-fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 − 6</td>
<td>$279 \pm 30$</td>
<td>$54 \pm 12$</td>
<td>0.162 ± 0.038 ± 0.033</td>
</tr>
<tr>
<td>6 − 10</td>
<td>$620 \pm 49$</td>
<td>$213 \pm 28$</td>
<td>0.257 ± 0.022 ± 0.011</td>
</tr>
<tr>
<td>10 − 30</td>
<td>$302 \pm 20$</td>
<td>$175 \pm 16$</td>
<td>0.369 ± 0.027 ± 0.014</td>
</tr>
<tr>
<td>1.4 &lt;</td>
<td>y</td>
<td>&lt; 2.4</td>
<td></td>
</tr>
<tr>
<td>0 − 2</td>
<td>$2530 \pm 290$</td>
<td>$277 \pm 72$</td>
<td>0.098 ± 0.022 ± 0.036</td>
</tr>
<tr>
<td>2 − 4</td>
<td>$1983 \pm 61$</td>
<td>$250 \pm 31$</td>
<td>0.112 ± 0.013 ± 0.011</td>
</tr>
<tr>
<td>4 − 6</td>
<td>$870 \pm 41$</td>
<td>$115 \pm 21$</td>
<td>0.165 ± 0.019 ± 0.010</td>
</tr>
<tr>
<td>6 − 10</td>
<td>$708 \pm 38$</td>
<td>$206 \pm 29$</td>
<td>0.203 ± 0.019 ± 0.010</td>
</tr>
<tr>
<td>10 − 30</td>
<td>$173 \pm 17$</td>
<td>$86 \pm 11$</td>
<td>0.331 ± 0.039 ± 0.018</td>
</tr>
</tbody>
</table>

The largest difference between the fitted results using the nominal configuration and the changed versions is taken as a systematic uncertainty.

- **B-hadron lifetime model.** In an alternative approach, the B-hadron pseudo-proper
decay length is described by an exponential function convoluted with a Gaussian function, which describes the smearing due to the relative motion of the $J/\psi$ with respect to the parent B-hadron. The difference between the Monte Carlo template model and this alternative is taken as a systematic uncertainty.

- **Primary vertex estimation.** In an alternative approach, the primary vertex determined event-by-event is chosen to calculate $\ell_{J/\psi}$. The difference in the fitted results is taken as a systematic uncertainty.

- **Background** The background is fitted using only the sidebands and the result is used as a fixed input to the fit in the signal region. The effect of a 100 MeV/$c^2$ variation in the sideband boundaries is taken as a systematic uncertainty.

- **$\ell_{J/\psi}$ resolution model.** The nominal (triple-Gaussian) fit model for the decay length resolution is compared to a model using two Gaussians only. The difference is taken as a systematic uncertainty.

- **Different prompt and non-prompt efficiencies** The Monte Carlo simulation predicts slightly differences between the prompt and non-prompt $J/\psi$ efficiencies. These are taken into account and the relative difference assumed as systematics.

A summary of all sources of systematic uncertainties is given in Table 5. The dominant contributions come from the description of the non-prompt component and from the resolution model, especially in the bins with few events or large background levels.

<table>
<thead>
<tr>
<th>$p_T^{J/\psi}$ (GeV/$c$)</th>
<th>Misalignment</th>
<th>$B$-lifetime model</th>
<th>Vertex estimation</th>
<th>Background fit</th>
<th>Resolution model</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>y</td>
<td>&lt; 1.4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 – 6</td>
<td>1.3</td>
<td>0.8</td>
<td>2.1</td>
<td>4.4</td>
<td>19.8</td>
<td>1.6</td>
</tr>
<tr>
<td>6 – 10</td>
<td>2.7</td>
<td>1.7</td>
<td>2.3</td>
<td>0.3</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>10 – 30</td>
<td>2.4</td>
<td>0.7</td>
<td>2.1</td>
<td>1.4</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td>$1.4 &lt;</td>
<td>y</td>
<td>&lt; 2.4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 – 2</td>
<td>1.1</td>
<td>9.4</td>
<td>22.8</td>
<td>1.9</td>
<td>22.3</td>
<td>16.4</td>
</tr>
<tr>
<td>2 – 4</td>
<td>0.4</td>
<td>0.1</td>
<td>6.3</td>
<td>2.8</td>
<td>4.3</td>
<td>5.4</td>
</tr>
<tr>
<td>4 – 6</td>
<td>2.2</td>
<td>0.8</td>
<td>2.1</td>
<td>4.4</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>6 – 10</td>
<td>3.3</td>
<td>1.7</td>
<td>2.3</td>
<td>0.3</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>10 – 30</td>
<td>3.2</td>
<td>0.7</td>
<td>2.1</td>
<td>1.4</td>
<td>3.0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

The prompt $J/\psi$ cross section and the cross section from B-hadron decays, together with their statistical and systematic uncertainties, are given in Tables 7 and 6 for the different polarization scenarios considered in Section 5.

## 7 Comparison with model calculations

The measurements summarized in Table 7 have been compared with calculations made with Monte Carlo event generators and with theoretical predictions.

The prompt $J/\psi$ differential production cross sections, in both rapidity ranges considered in the analysis, were compared with calculations made with the PYTHIA [19] and CASCADE [34] event generators, as well as with the Color Evaporation Model (CEM) theory [35–38]. These calculations include the contributions to the prompt $J/\psi$ yield due to feed-down decays from heavier charmonium states ($\chi_c$ and $\psi(2S)$) and can, therefore, be directly compared to the mea-
Table 6: Differential non-prompt $J/\psi$ cross sections, and average $p_T$ in the bin (in the data), for two non-prompt $J/\psi$ polarization considered: the polarization measured by the BaBar experiment [29] in $B_u-B_d$ mixed production and the one in the EVTGEN generator. The first error is statistical and the second is systematical.

<table>
<thead>
<tr>
<th>$p_T^{J/\psi}$ (GeV/c)</th>
<th>$\langle p_T^{J/\psi} \rangle$ (GeV/c)</th>
<th>$BR(J/\psi \rightarrow \mu^+\mu^-) \cdot \frac{d\sigma^{\text{non-prompt}}}{dp_T}$ (nb/GeV/c)</th>
<th>Non-prompt $J/\psi$ polarization</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4 – 6</td>
<td>5.59</td>
<td>5.60 ± 1.38 ± 1.49</td>
<td>5.61 ± 1.38 ± 1.50</td>
<td></td>
</tr>
<tr>
<td>6 – 10</td>
<td>7.88</td>
<td>3.06 ± 0.29 ± 0.36</td>
<td>3.07 ± 0.29 ± 0.36</td>
<td></td>
</tr>
<tr>
<td>10 – 30</td>
<td>13.53</td>
<td>0.231 ± 0.020 ± 0.035</td>
<td>0.232 ± 0.020 ± 0.036</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1.4 &lt;</td>
<td>y</td>
<td>&lt; 2.4$</td>
<td></td>
</tr>
<tr>
<td>0 – 2</td>
<td>1.23</td>
<td>28.96 ± 6.63 ± 11.63</td>
<td>28.97 ± 6.63 ± 11.64</td>
<td></td>
</tr>
<tr>
<td>2 – 4</td>
<td>2.86</td>
<td>18.32 ± 2.20 ± 2.78</td>
<td>18.34 ± 2.20 ± 2.78</td>
<td></td>
</tr>
<tr>
<td>4 – 6</td>
<td>4.89</td>
<td>8.89 ± 1.14 ± 1.71</td>
<td>8.90 ± 1.14 ± 1.72</td>
<td></td>
</tr>
<tr>
<td>6 – 10</td>
<td>7.59</td>
<td>2.07 ± 0.21 ± 0.30</td>
<td>2.08 ± 0.21 ± 0.30</td>
<td></td>
</tr>
<tr>
<td>10 – 30</td>
<td>13.14</td>
<td>0.101 ± 0.014 ± 0.017</td>
<td>0.101 ± 0.014 ± 0.017</td>
<td></td>
</tr>
</tbody>
</table>

The predictions of the Color Singlet Model (including higher-order corrections) [39–42] and of the LO NRQCD model (which includes singlet and octet components) [43, 44] are not shown in Fig. 5 because they are only available for the direct $J/\psi$ production component while the measurements include a sizeable contribution from feed-down decays, which might be of the order of 30% [45, 46] and is likely to depend on $p_T$.

The differential cross section measured at forward rapidity, $1.4 < |y| < 2.4$, is significantly higher than expected in the models represented. The discrepancy is particularly important at low $p_T$, where significantly more events are observed than predicted.

The non-prompt $J/\psi$ measurement has been compared with calculations made with the CAS-
CADE Monte Carlo generator and in the FONLL framework [12]. The measured results are given in Fig. 6 in the regions $|y| < 2.4$ (left) and $1.4 < |y| < 2.4$ (right), and show a good agreement with the predictions.

Figure 6: Differential cross section measurements for non-prompt $J/\psi$ production, as a function of the $p_T$ of $J/\psi$, compared with PYTHIA, CASCADE, and FONLL calculations in the rapidity regions $|y| < 2.4$ (left) and $1.4 < |y| < 2.4$ (right).

8 Conclusion

We have presented the first measurement of the $J/\psi$ production cross section in the dimuon channel in pp collisions at $\sqrt{s} = 7$ TeV, based on 100.44 nb$^{-1}$ of data collected by the CMS experiment during the first months of LHC operation.

The preliminary $p_T$ differential $J/\psi$ production cross section has been measured in two rapidity ranges: from 0 to 30 GeV/c in the forward $J/\psi$ rapidity ($1.4 < |y| < 2.4$) and from 4 to 30 GeV/c for $|y| < 1.4$. The total cross section for inclusive $J/\psi$ production in the dimuon decay channel has been determined to be $289.1 \pm 16.7$ (stat) $\pm 60.1$ (syst) nb for transverse momenta between 4 and 30 GeV/c in the rapidity range $|y| < 2.4$, where the systematic uncertainty is dominated by the statistical precision of the muon efficiency determination from data.

The total cross section times $BR(J/\psi \rightarrow \mu^+ \mu^-)$ for the $J/\psi$ production due to B-hadron decays, in the phase space window $4 < p_T < 30$ GeV/c and $|y| < 2.4$ is measured to be $56.1 \pm 5.5$ (stat) $\pm 7.2$ (syst) nb.

The differential prompt and non-prompt measurements have been compared with some theoretical calculations. In general, a reasonable agreement between the data and the theory curves is found, except in the case of the prompt $J/\psi$ cross section at forward rapidity and low $p_T$, where the calculations underestimate the measured yield.

Acknowledgments

We would like to thank Pierre Artoisenet, Matteo Cacciari, Jean-Philippe Lansberg, and Ramona Vogt for providing their theoretical predictions.
Table 7: Differential prompt $J/\psi$ cross sections, and average $p_T$ in the bin (in the data), for each prompt $J/\psi$ polarization considered: the default null polarization, the polarization fully longitudinal ($\lambda_\theta = -1$) and fully transverse ($\lambda_\theta = +1$) in either the Collins-Soper (CS) or the Helicity (HX) frames (see Ref. [6]). The first error is statistical and the second is systematical.

<table>
<thead>
<tr>
<th>$p_T^{J/\psi}$</th>
<th>$\langle p_T^{J/\psi} \rangle$</th>
<th>$BR(J/\psi \to \mu^+\mu^-) \cdot \frac{d\sigma_{\text{prompt}}}{dp_T}$ (nb / GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(GeV/c)</td>
<td>(GeV/c)</td>
<td>$</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>4 – 6</td>
<td>5.12</td>
<td>29.2 ± 2.5 ± 5.1</td>
</tr>
<tr>
<td>6 – 10</td>
<td>7.88</td>
<td>9.16 ± 0.45 ± 1.01</td>
</tr>
<tr>
<td>10 – 30</td>
<td>13.53</td>
<td>0.41 ± 0.03 ± 0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4 &lt; $</td>
<td>y</td>
<td>$ &lt; 2.4</td>
</tr>
<tr>
<td>0 – 2</td>
<td>1.23</td>
<td>266 ± 13 ± 45</td>
</tr>
<tr>
<td>2 – 4</td>
<td>2.86</td>
<td>147 ± 5 ± 17</td>
</tr>
<tr>
<td>4 – 6</td>
<td>4.89</td>
<td>45.6 ± 2.8 ± 8.3</td>
</tr>
<tr>
<td>6 – 10</td>
<td>7.59</td>
<td>8.29 ± 0.34 ± 1.11</td>
</tr>
<tr>
<td>10 – 30</td>
<td>13.14</td>
<td>0.21 ± 0.02 ± 0.03</td>
</tr>
</tbody>
</table>


References


