Measurement of the $J/\psi$ cross section in $pp$ collisions at $\sqrt{s} = 13$ TeV

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The double-differential cross sections of the promptly-produced $J/\psi$ mesons, in transverse momentum, $p_T$, and absolute rapidity, $|y|$, are measured in $pp$ collisions at $\sqrt{s} = 13$ TeV, using a dimuon sample collected by CMS in 2015, corresponding to an integrated luminosity of 2.4 fb$^{-1}$. The results are based on a two–dimensional analysis of the dimuon invariant mass and decay length, and cover a broad $p_T$ range, extending from 20 to 120 GeV, in the $|y| < 1.2$ region.

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Abstract. The double-differential cross-sections of the promptly-produced $J/\psi$ mesons, in transverse momentum, $p_T$, and absolute rapidity, $|y|$, are measured in pp collisions at $\sqrt{s} = 13$ TeV, using a dimuon sample collected by CMS in 2015, corresponding to an integrated luminosity of 2.4 $fb^{-1}$. The results are based on a two-dimensional analysis of the dimuon invariant mass and decay length, and cover a broad $p_T$ range, extending from 20 to 120 GeV, in the $|y| < 1.2$ region.

1. Introduction
The study of quarkonium production in hadronic collisions has been the subject of a large number of experiments since the discovery of heavy-quark bound states. The theoretical treatment of the subject is nowadays based on an effective field theory, Non-Relativistic QCD (NRQCD) [1-3] which assumes factorization of the production process into two phases. The perturbative part of the process generates the heavy $Q\bar{Q}$ pair in a given spin and orbital angular momentum state in either a color singlet or color octet configuration. The subsequent hadronization producing the bound state is controlled by so-called Long Distance Matrix Elements (LDMEs) that are process-independent. Run-1 experiments at the LHC provided precise measurements for $J/\psi$. These measurements include the differential cross-sections [5] and polarizations [6] at $\sqrt{s} = 7$ TeV calculations by several groups [6-10]. The most recent theory calculations have shown improved agreement with the experimental observation that the polarization at production for all the quarkonium states remains small for transverse momenta up to 70 GeV. Comparison of the pp collision results with Run-2 data at 13 TeV to the corresponding 7 TeV measurements provides a good opportunity to test the factorization hypotheses of NRQCD by using the same LDMEs and perturbative calculations appropriate to the two center-of-mass energies. In addition, the extended $p_T$ reach obtained with the higher center-of-mass energy and production cross section, together with the improved statistical precision, can provide further comparisons with theoretical calculations.

We used the data taken by CMS [4] in the so-called RUN-2 in 2015. This analysis uses the same techniques previously employed by CMS [5] cross-sections of promptly produced quarkonium states, which are calculated in several dimuon $p_T$ and $|y|$ bins, using the formula:
where \( Br(J/\psi \to \mu^+ \mu^-) \) is the branching fraction of the \( J/\psi \) into two muons, \( N^{cc}(p_T, y) \) is the number of signal events from likelihood fit in the \((p_T, y)\) bin under consideration. \( \mathcal{L} \) is the integrated luminosity \( 2.4 \, fb^{-1} \), \( \Delta y \) and \( \Delta p_T \) are the widths of the bin, and \( \left\langle \frac{1}{A(p_T, y) \varepsilon(p_T, y)} \right\rangle \) is the average of the inverse acceptance times efficiency for all the events in the bin. The acceptance is calculated using simulation, while the efficiency is derived using a data-driven approach. The non-prompt components for \( J/\psi \), due to decays of b-hadrons, are separated using the pseudo-proper decay length (PPDL). The analysis does not distinguish feed-down from decays of heavier quarkonium states and direct production of quarkonia. The results obtained by CMS at \( \sqrt{s} = 7 \) TeV [12] are shown in Fig. 1. The polarization of \( J/\psi \) has been measured in a previous CMS work and it is found consistent with zero. In this analysis the acceptance is calculated in the hypothesis of null polarization, presently theoretical. Models are being improved to describe simultaneously \( J/\psi \) differential cross section and polarization measurements.

**Figure 1.** The \( J/\psi \) and \( \psi(2S) \) differential \( p_T \) cross-sections times the dimuon branching fractions for four rapidity bins and integrated over the range \(|y| < 1.2\). Taken from Phys. Rev. Lett. 114, 191802.

### 2. Dataset and event selection

\( J/\psi \) candidates are formed by pairing opposite-sign muons. In this analysis, to ease the calculation of efficiency, we considered only the case in which the two muons bend away from each other in the CMS magnetic field. This measurement was performed in the kinematical region \( 20 < p_T(J/\psi) < 120 \, GeV \) and \(|y(J/\psi)| < 1.2\). A fit of the two muon tracks to a common vertex is performed, and the fit \( \chi^2 \) probability required to be above 0.5%. Both muons have to be identified as reconstructed tracks with at least five measurements in the silicon tracker, and at least one in the pixel detector. The track is required to match at least one muon segment identified by a station in the muon detector. Loose cuts are applied on the longitudinal and transverse impact parameter in order to reject cosmic rays and in-flight decays. Opposite-sign muons are then paired and the dimuon vertex-\( \chi^2 \) probability requires to be greater than 1%.

### 3. Determination of the yields

The yields are measured using an extended unbinned maximum likelihood fit to the mass distribution. The \( J/\psi \) mass is modelled with a Crystall Ball and a Gaussian function. An exponential is used to describe the dimuon mass background.

An additional non-prompt component originating from the decay of b-hadrons must be taken
into account. The prompt and non-prompt yields are measured by simultaneously fitting the mass and the PPDL [13] distribution. The PPDL distribution is modelled by a prompt signal component represented by a resolution function, which uses the event-by-event uncertainty information, a non-prompt term given by an exponential function convoluted with the resolution function, and the continuum background term represented by the empirical sum of two Gaussian functions centered at zero plus an exponential decay function to take into account prompt and non-prompt background components. The resolution function was modelled by two Gaussians, with gaussianly-constrained parameters derived from fits to $p_T$-integrated data. Fig. 2 shows the maximum likelihood fit projected onto the mass and PPDL dimensions, for a particular $(p_T,y)$ bin as an example.

Figure 2. Fits of $J/\psi$ mass (right) and lifetime (left) in a particular $(p_T,y)$ bin. Taken from CMS-PAS-BPH-15-005.

4. Acceptance
The acceptance is calculated using simulated events produced by Monte Carlo. The simulation takes into account final-state photon radiation. The acceptance for events in a given $(p_T,y)$ range is defined as:

$$A = \frac{N_{\text{gen}}^\varepsilon(p_T,y)}{N_{\text{gen}}^\varepsilon(p_T,y)},$$

(2)

where $N_{\text{kin}}^\varepsilon(p_T,y)$ is the number of generated events which pass the kinematic selections described above for data events and $N_{\text{gen}}^\varepsilon(p_T,y)$ is the total of the simulated events in that $p_T$ and $y$ range.

5. Efficiency
The muon reconstruction, identification and trigger efficiencies were measured individually from data as a function of muon $p_T$ and pseudorapidity,

$$\epsilon_{\mu\mu}(p_T,y) = \epsilon(p_{T1},\eta_1) \cdot \epsilon(p_{T2},\eta_2) \cdot \rho(p_T,y) \cdot \epsilon_{tk}^2.$$  

(3)

Efficiencies are measurement from data. $\epsilon(p_{T1},\eta_1)$ and $\epsilon(p_{T2},\eta_2)$ are obtained from Tag-and-Probe [14] technique that takes advantage of dedicated efficiency triggers, $\rho(p_T,y)$ is the correlation factor and $\epsilon_{tk}^2$ is the tracking efficiency. The dimuon efficiency is, similarly to the acceptance, calculated on a event-by-event basis and stored in $(p_T,y)$ histograms.
6. Systematic Uncertainties

Systematic uncertainties include uncertainties on dimuon acceptance and efficiencies, and the determination of the signal yields. A 2.7% uncertainty on the luminosity measurement is assigned. We considered the systematics uncertainties:

- Uncertainties in the estimation of the yield.
- Statistical.
- Non-prompt fraction statistical.
- Acceptance statistical.
- $\rho$ statistical.
- Conditional single efficiency.
- L3 scale factor.
- Single efficiency.
- Non-prompt fraction systematical.
- Yield systematic.
- $\rho$ Systematical.

As an example, we explain two of them.

6.1. Uncertainties in the measurement of the yields

Uncertainties on the estimation of yields were evaluated by changing the signal and background models used in the maximum likelihood fits. To assess the systematic uncertainty in the signal modeling, $n$ (a parameters of the Crystall Ball function) was varied by $\pm 5\sigma$. The systematic uncertainty originating from a possibly imperfect description of the background was evaluated by changing the background model from an exponential to a linear function. The observed differences from the nominal were taken as systematic uncertainty. The uncertainty on the estimation of the non-prompt fraction arises from the choice of primary vertex and from the modeling of the signal and background in the transverse decay length distribution. Similarly, we assess the impact of modeling the non-prompt signal by fixing the parameterization of the exponential. The systematic uncertainty contribution from the primary vertex choice was added in quadrature with half of the difference between the maximum deviation observed from the nominal fit to the other contributions.

6.2. Uncertainties in the acceptance and efficiency correction

To take into account statistical uncertainties in the measurement of the single-muon efficiencies, we varied the three parameters of the parameterization function within their uncertainties and repeated the efficiency calculation.

7. Results

The cross-sections for the $J/\psi$ is computed using Eq. (1). Results are presented in Fig. 3 in for rapidity range. Fig. 4 shows the comparison of cross section measured by CMS at 7 TeV [5] with the respective analysis. Both 7 TeV and 13 TeV data are presented for the rapidity-integrated range $|y| < 1.2$, which was obtained as the weighted average of the individual rapidity ranges at $\sqrt{s} = 13$ TeV. As shown in the bottom panel of Fig. 4, the 13 TeV cross-sections of the meson is factor of 2 to 3 larger than the corresponding 7 TeV cross-sections, changing slowly as a function of dimuon $p_T$. A detailed comparison with theory awaits an updated NRQCD calculation for 13 TeV.
8. Conclusions
The double differential production cross-sections of $J/\psi$ has been measured in pp collisions at $\sqrt{s} = 13$ TeV with CMS detector at LHC. The measurement has been performed in the central rapidity region ($|y| < 1.2$) as a function of $p_T$ in several rapidity ranges, extending up to 120 GeV. Ratios of cross-sections measured at 13 TeV and 7 TeV are included in this report. These results shall contribute to consolidate the underlying hypotheses of NRQCD and provide further input to constrain the theory parameters.

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