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Measurement of prompt J/ψ pair production in pp collisions at $\sqrt{s} = 7\,\text{Tev}$

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ABSTRACT: Production of prompt J/ψ meson pairs in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ is measured with the CMS experiment at the LHC in a data sample corresponding to an integrated luminosity of about $4.7\,\text{fb}^{-1}$. The two J/ψ mesons are fully reconstructed via their decays into $\mu^+\mu^-$ pairs. This observation provides for the first time access to the high-transverse-momentum region of J/ψ pair production where model predictions are not yet established. The total and differential cross sections are measured in a phase space defined by the individual J/ψ transverse momentum ($p_\text{T}^{J/\psi}$) and rapidity ($|y^{J/\psi}|$): $|y^{J/\psi}| < 1.2$ for $p_\text{T}^{J/\psi} > 6.5\,\text{GeV}/c$; $1.2 < |y^{J/\psi}| < 1.43$ for a p_T threshold that scales linearly with $|y^{J/\psi}|$ from 6.5 to $4.5\,\text{GeV}/c$; and $1.43 < |y^{J/\psi}| < 2.2$ for $p_\text{T}^{J/\psi} > 4.5\,\text{GeV}/c$. The total cross section, assuming unpolarized prompt J/ψ pair production is $1.49 \pm 0.07\,(\text{stat}) \pm 0.13\,(\text{syst})\,\text{nb}$. Different assumptions about the J/ψ polarization imply modifications to the cross section ranging from -31% to $+27\%$.

Contents

1 Introduction

The measurement of J/ψ meson pairs that are directly created in the primary interaction (prompt) in proton-proton (pp) collisions at $\sqrt{s} = 7$ TeV provides general insight into how particles are produced during proton collisions at the CERN LHC. Owing to the high flux of incoming partons at the LHC energy, it is expected that more than one parton pair will often scatter in a pp collision [1]. These multiparton scattering contributions are difficult to address within the framework of perturbative quantum chromodynamics (QCD), hence the need for experimental studies (see e.g., ref. [2] and references therein). The general assumption is that single-parton scattering (SPS) is the dominant process. Double-parton scattering (DPS) and higher-order multiple-parton interactions are widely invoked to account for observations that cannot be explained otherwise, such as the rates for multiple heavy-flavor production [3]. New measurements will help the creation of more realistic particle production models. The production of J/ψ meson pairs provides a clean signal in a parton-parton interaction regime that is complementary to the one probed by studies based on hadronic jets. Multiple-parton interactions can lead to distinct differences in event variables that probe pair-wise balancing, such as the absolute rapidity difference $|\Delta y|$ between the two J/ψ mesons [1, 4, 5]. The strong correlation of two J/ψ mesons produced via SPS interaction results in small values of $|\Delta y|$, whereas large values of $|\Delta y|$ are possible for production due to DPS.

In contrast to earlier experiments where quark-antiquark annihilation dominated [6, 7], the dominant J/ψ production process in pp collisions at the LHC is gluon-gluon fusion [8].

At the parton level, the two J/ψ mesons are either produced as color-singlet states or color-octet states that turn into singlets after emitting gluons. Color-octet contributions for J/ψ pair production at transverse momentum (p_{T}) of a pair below 15 GeV/c and low invariant mass are considered to be negligible, but play a greater role as p_{T} increases [9, 10]. Next-to-leading-order QCD calculations also indicate enhanced contributions from color-singlet heavy-quark pair production at higher p_{T} [11–14]. The CMS experiment provides access to p_{T} measurements above 15 GeV/c.

Recently, the LHCb experiment measured the cross section for J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV to be $5.1 \pm 1.0 \pm 1.1$ nb (where the first uncertainty is statistical and the second systematic) within the LHCb phase space (defined as $2 < y^{\mathrm{J}/\psi} < 4.5$ and $p_{\mathrm{T}}^{\mathrm{J}/\psi} < 10$ GeV/c) [15]. Theoretical calculations of J/ψ pair production via SPS based on leading-order color-singlet states predict a cross section of 4 nb, with an uncertainty of about 30% [9, 16]. This prediction is consistent with the measured value. The CMS experiment samples a J/ψ production regime complementary to LHCb, with coverage at higher p_{T} and more central rapidity. Hence, J/ψ pair production cross section measurements by CMS provide new information for the development of production models that include higher-order corrections and DPS.

Model descriptions of J/ψ pair production are also a crucial input to quantify nonresonant contributions in the search for resonances. States can be searched for with CMS in a wider J/ψ pair invariant-mass range as compared to previous experiments. For example, the bottomonium ground state η_b is expected to decay into two J/ψ mesons in analogy to the η_c charmonium ground state that decays into two ϕ mesons [17]. However, explicit calculations based on nonrelativistic QCD (NRQCD) [18, 19] predict this decay mode to be highly suppressed, so any observation of this process could indicate possible shortcomings of present NRQCD approaches. Other predicted resonant states that could decay into two J/ψ mesons are exotic tetraquark charm states [9]. A CP-odd Higgs boson, e.g., in the next-to-minimal supersymmetric standard model [20], is predicted with a mass near the η_b. Mixing with a CP-odd Higgs boson could alter the behavior of the η_b with respect to QCD predictions [21, 22]. The BaBar experiment first observed the η_b state in radiative Υ transitions [23] and published an upper limit on the effective coupling of a CP-odd Higgs boson with mass below 9.3 GeV/c^2 to b quarks [24]. No evidence for a CP-odd Higgs boson was found by CMS in the $\mu^+\mu^-$ invariant-mass spectrum for masses between 5.5 and 14 GeV/c^2 [25].

This Letter presents a measurement of the cross section for prompt J/ψ pair production with data recorded with the CMS experiment in pp collisions at a center-of-mass energy of 7 TeV . Acceptance corrections are calculated based on the measured J/ψ meson kinematics, and efficiency corrections are calculated based on the measured decay-muon kinematics of each event thereby minimizing the dependence on production models. Monte Carlo (MC) simulation samples for different production models with either strongly correlated J/ψ mesons (SPS model) or less correlated J/ψ mesons (DPS model) are only used to define the phase-space region and validate the correction method. They also provide guidance for the parameterization of various kinematic distributions in the events. The SPS generator is a color-singlet model [9] implemented in PYTHIA 6 [26], and the DPS generator is implemented in PYTHIA 8 [27] using color-singlet and -octet production models.

The cross section measurement is evaluated in a predefined region of the J/ψ phase space that, in turn, is constrained by the muon identification and reconstruction capabilities of CMS. The differential cross section of J/ψ pair production is calculated as

$$\frac{\mathrm{d}\sigma(\mathrm{pp} \to \mathrm{J}/\psi\,\mathrm{J}/\psi + X)}{\mathrm{d}x} = \sum_i \frac{s_i}{a_i \cdot \epsilon_i \cdot (BF)^2 \cdot \Delta x \cdot \mathcal{L}}. \tag{1.1}$$

The sum is performed over events i in an interval Δx, where x represents a kinematic variable describing the J/ψ pair. In this analysis, x is taken as the invariant mass of the J/ψ pair ($M_{\mathrm{J}/\psi\,\mathrm{J}/\psi}$), the absolute difference in J/ψ meson rapidities ($|\Delta y|$), and the transverse momentum of the J/ψ pair ($p_\mathrm{T}^{\mathrm{J}/\psi\,\mathrm{J}/\psi}$). The quantity s_i is the signal weight per event. The acceptance value a_i calculated for each event represents the probability that the muons resulting from the J/ψ decays pass the muon acceptance. The detection efficiency ϵ_i is the probability for the four muons in an event to be detected and pass the trigger and reconstruction quality requirements. The integrated luminosity of the dataset is $\mathcal{L}$, and BF is the branching fraction for the J/ψ decay into two muons. The total cross section in the J/ψ phase-space window is determined by summing over all events.

2 CMS detector

A detailed description of the CMS detector can be found elsewhere [28]. The primary components used in this analysis are the silicon tracker and the muon systems. The tracker operates in a 3.8 T axial magnetic field generated by a superconducting solenoid with an internal diameter of 6 m. The innermost part of the tracker consists of three cylindrical layers of pixel detectors complemented by two disks in the forward and backward directions. The radial region between 20 and 116 cm is occupied by several layers of silicon strip detectors in barrel and disk configurations. Multiple overlapping layers ensure a sufficient number of hits to precisely reconstruct tracks in the pseudorapidity range $|\eta| < 2.4$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle of the track measured from the positive z axis. The coordinate system is defined to have its origin at the center of the detector, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis aligned with the counterclockwise-beam direction. An impact parameter resolution around 15 μm and a p_T resolution around 1.5% are achieved for charged particles with p_T up to 100 GeV/c. Muons are identified in the range $|\eta| < 2.4$, with detection planes made of drift tubes, cathode strip chambers, and resistive-plate chambers embedded in the steel flux-return yoke of the solenoid. The CMS detector response is determined with MC simulations using GEANT4 [29].

3 Event selection and efficiencies

This analysis uses an unprescaled muon trigger path designed to achieve the highest possible signal-to-noise ratio and efficiency for J/ψ pair searches during the 2011 data taking. This trigger requires the presence of at least three muons, two of which must be oppositely charged, have a dimuon invariant mass in the interval between 2.8 and 3.35 GeV/c^2, and a

vertex fit probability greater than 0.5%, as determined by a Kalman filter algorithm [30]. Reconstruction of muons proceeds by associating measurements in the muon detectors with tracks found in the silicon tracker, both called segments. A given muon segment can be associated with more than one silicon track at the time of reconstruction, allowing reconstructed muons to share segments in the muon system. An arbitration algorithm then assigns each muon segment to a unique muon track. Muons are further required to pass the following quality criteria: (i) the associated track segment must have hits in at least two layers of the pixel tracker and at least 11 total silicon tracker hits (pixel and strip detectors combined), and (ii) the silicon track fit χ^2 divided by the number of degrees of freedom must be less than 1.8. Three of the muons are required to fulfill the criteria

$$
\begin{aligned}
p_{\mathrm{T}}^{\mu} &> 3.5\,\mathrm{GeV}/c && \text{if} && |\eta^{\mu}| < 1.2, \\
p_{\mathrm{T}}^{\mu} &> 3.5 \to 2\,\mathrm{GeV}/c && \text{if} && 1.2 < |\eta^{\mu}| < 1.6, \\
p_{\mathrm{T}}^{\mu} &> 2\,\mathrm{GeV}/c && \text{if} && 1.6 < |\eta^{\mu}| < 2.4,
\end{aligned}
\tag{3.1}
$$

where the p_{T} threshold scales linearly downward with $|\eta^{\mu}|$ in the range $1.2 < |\eta^{\mu}| < 1.6$. They must further be matched to the muon candidates that triggered the event. The fourth muon (not required to match to the trigger muon candidates) is allowed to pass the looser acceptance criteria

$$
\begin{aligned}
p_{\mathrm{T}}^{\mu} &> 3\,\mathrm{GeV}/c && \text{if} && |\eta^{\mu}| < 1.2, \\
p^{\mu} &> 3\,\mathrm{GeV}/c && \text{if} && 1.2 < |\eta^{\mu}| < 2.4,
\end{aligned}
\tag{3.2}
$$

where p^{μ} is the magnitude of the total muon momentum.

Candidate events must have two pairs of opposite-sign muons each with an invariant mass close to the J/ψ mass [31]. Each J/ψ candidate is further required to be within the phase space

$$
\begin{aligned}
p_{\mathrm{T}}^{\mathrm{J}/\psi} &> 6.5\,\mathrm{GeV}/c && \text{if} && |y^{\mathrm{J}/\psi}| < 1.2, \\
p_{\mathrm{T}}^{\mathrm{J}/\psi} &> 6.5 \to 4.5\,\mathrm{GeV}/c && \text{if} && 1.2 < |y^{\mathrm{J}/\psi}| < 1.43, \\
p_{\mathrm{T}}^{\mathrm{J}/\psi} &> 4.5\,\mathrm{GeV}/c && \text{if} && 1.43 < |y^{\mathrm{J}/\psi}| < 2.2,
\end{aligned}
\tag{3.3}
$$

where the $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ threshold scales linearly with $|y^{\mathrm{J}/\psi}|$ in the range $1.2 < |y^{\mathrm{J}/\psi}| < 1.43$. The boundaries are optimized to obtain maximum coverage of the J/ψ phase space within the muon acceptance. If there are more than two J/ψ candidates in an event, the candidates with the highest vertex fit probabilities are selected. For signal MC simulation samples in which multiple collision events per bunch crossing (pileup events) are included, this selection process finds the correct dimuon combinations for 99.7% of the selected events.

In addition to the invariant mass of each dimuon candidate, $m^{\mathrm{J}/\psi}$, two event variables sensitive to the prompt J/ψ pair topology are defined: (i) the proper transverse decay length, ct_{xy}, of the higher-p_{T} J/ψ, and (ii) the separation significance, δd, between the J/ψ mesons. Calculating the proper transverse decay length requires identification of the primary vertex in an event, defined as the vertex formed by charged-particle tracks with the highest sum of p_{T} squared that can be fit to a common position, excluding the muon tracks from the two J/ψ candidates. The transverse decay length in the laboratory frame is given as $L_{xy} = (\vec{r}_{\mathrm{T}} \cdot \vec{p}_{\mathrm{T}}^{\,\mathrm{J}/\psi})/p_{\mathrm{T}}^{\mathrm{J}/\psi}$, where $\vec{r}_{\mathrm{T}}$ is the vector pointing from the primary vertex to the

J/ψ vertex in the transverse plane. The proper transverse decay length is then calculated as $ct_{xy} = (m^{\text{J}/\psi}/p_{\text{T}}^{\text{J}/\psi}) \cdot L_{xy}$ and is required to be in the range from -0.05 to $0.1\,\text{cm}$. The separation significance is defined as the ratio of the magnitude of the three-dimensional vector $\Delta\vec{r}$ between the two reconstructed J/ψ vertices and the uncertainty of the distance measurement, $\sigma_{\Delta\vec{r}}$ (which includes the uncertainty in the vertex position, as determined by the Kalman filter technique, and the uncertainty of the muon track fit): $\delta d \equiv |\Delta\vec{r}|/\sigma_{\Delta\vec{r}}$. The requirement $\delta d < 8$ is imposed. From a data sample of pp collisions corresponding to an integrated luminosity of $4.73\,\text{fb}^{-1}$ [32], 1043 candidate events containing a J/ψ pair are found.

The kinematics of the J/ψ J/$\psi \to 4\mu$ final state is sensitive to the underlying physics of production and decay, and this analysis probes a higher-p_{T} region of J/ψ pair production than previous experiments. Therefore, the dependence on production model assumptions is minimized. Given the relatively small number of events in the final-analysis event sample it was affordable to calculate acceptance and efficiency corrections on an event-by-event basis using the measured J/ψ and muon momenta. The procedure has the merit of not depending on assumptions regarding correlations between production observables.

The muon acceptance is evaluated by generating a large number of simulated decays starting from the reconstructed four momenta of the two J/ψ mesons in an event. The acceptance correction, a_i, for a given event i is the number of times all four muons survive the acceptance criteria, listed in eqs. (3.1) and (3.2), divided by the total number of trials for the event. The angle of the decay muons with respect to the direction of flight of the parent J/ψ, in the J/ψ rest frame, is assumed to be isotropically distributed. Deviations from this assumption are considered and discussed later. The event-by-event acceptance-correction procedure is evaluated with both SPS and DPS MC simulation samples. For each sample of N events within the J/ψ phase space, the muon acceptance criteria are applied to obtain a sample of accepted events. For each of the surviving events i, the corresponding a_i is obtained as described above. The corrected number of signal events within the J/ψ phase space, N', is then calculated as a sum over the survivors, $N' = \sum_i 1/a_i$. The difference between N and N' is used to estimate the systematic uncertainty in the method.

The efficiency correction is also determined on a per-event basis by repeatedly generating J/ψ pair events where the generated muon momenta are the measured muon momenta from the reconstructed event. The event is then subjected to the complete CMS detector simulation and reconstruction chain. The efficiency correction, ϵ_i, for a measured event i is the fraction of simulated events that pass the trigger and reconstruction requirements. The number of efficiency-corrected events is then given as $\sum_i 1/\epsilon_i$, summed over the events that survive the trigger and reconstruction requirements. An average efficiency for the sample in bins of the observables, Δx, is obtained as the number of events that survive the trigger and reconstruction requirements, divided by the number of efficiency-corrected events. The method is evaluated with samples of reconstructed SPS and DPS J/ψ pair MC simulation events. For comparison, the average efficiency is alternatively determined from the SPS and DPS MC simulation samples with simulated muon momenta. The average efficiency is then given as the number of events surviving the trigger and reconstruction criteria, divided by the number of events originally generated in the J/ψ phase space and muon acceptance

region. In contrast to the first method, this efficiency calculation is based on true muon momenta. The difference between these two average efficiencies is due to the resolution of the detector and is accounted for by a scaling factor which is in close agreement between the two production models.

4 Signal yield

An extended maximum likelihood method is performed to separate the signal from background contributions in the data sample. The signal weights s_i in eq. (1) are derived with the sPlot technique [33]. The signal yield resulting from the fit is equal to the sum of the s_i. These weights are used to obtain the signal distribution in bins of kinematic variables that quantify the J/ψ pair production. Correlations between fit variables and production observables are found to be negligible from simulated samples. Four kinematic variables are selected to discriminate the J/ψ pair signal from the background: (i) the $\mu^+\mu^-$ invariant mass of the higher-$p_{\rm T}$ J/ψ, $M_{\mu\mu}^{(1)}$, (ii) the $\mu^+\mu^-$ invariant mass of the lower-$p_{\rm T}$ J/ψ, $M_{\mu\mu}^{(2)}$, (iii) the proper transverse decay length of the higher-$p_{\rm T}$ J/ψ, ct_{xy}, and (iv) the separation significance, δd, between the two J/ψ candidates. Five categories of events are identified:

1. events containing a real prompt J/ψ pair (sig),

2. background from at least one nonprompt J/ψ meson, mostly from B-meson decays (nonprompt),

3. the higher-$p_{\rm T}$ prompt J/ψ and two unassociated muons that have an invariant mass within the J/ψ mass window,

4. the lower-$p_{\rm T}$ prompt J/ψ and two unassociated muons that have an invariant mass within the J/ψ mass window, and

5. four unassociated muons (combinatorial-combinatorial).

The categories 3 and 4 have a common yield (J/ψ-combinatorial), and the parameter f is defined as their relative fraction. The likelihood function for event j is obtained by summing the product of the yields n_i and the probability density functions (PDFs) for the four kinematic variables $P_i(M_{\mu\mu}^{(1)})$, $Q_i(M_{\mu\mu}^{(2)})$, $R_i(ct_{xy})$, $S_i(\delta d)$ with the shape parameters for each of the five event categories i. The likelihood for each event j is given as:

$$
\begin{aligned}
\ell_j =\, & n_{\rm sig}\left[P_1 \cdot Q_1 \cdot R_1 \cdot S_1\right] + n_{\rm nonprompt}\left[P_2 \cdot Q_2 \cdot R_2 \cdot S_2\right] \\
& + n_{\rm J/\psi\text{-}combinatorial}[f \cdot P_3 \cdot Q_3 \cdot R_3 \cdot S_3 + (1-f) \cdot P_4 \cdot Q_4 \cdot R_4 \cdot S_4] \\
& + n_{\rm combinatorial\text{-}combinatorial}\left[P_5 \cdot Q_5 \cdot R_5 \cdot S_5\right].
\end{aligned}
\tag{4.1}
$$

The yields n_i are determined by minimizing the quantity $-\ln\mathcal{L}$ [34], where $\mathcal{L} = \prod_j \ell_j$.

According to the signal MC simulation, the invariant mass and ct_{xy} of the higher-$p_{\rm T}$ J/ψ are correlated by about 13%. All other correlations between event variables are below 5%. Therefore, the parameterization for each variable is independently determined. Several parameterizations for each distribution are considered, and the simplest function with the

least number of parameters necessary to adequately describe the observed distribution is selected as the PDF. For parameterizations that result in equally good descriptions of the data (as measured by the χ^2 of the fit of the distribution in data for a given variable), the difference in signal yields is used as a measure of the systematic uncertainty.

For the likelihood fit, the sum of two Gaussian functions with a common mean is used to parameterize the signal J/ψ invariant mass PDFs P_1 and Q_1; the same parameters are used to describe the nonprompt components P_2 and Q_2, and the J/ψ part of the J/ψ-combinatorial cases P_3 and Q_4. The widths of the Gaussian functions are fixed to the best-fit values obtained in simulation samples. A sum of two Gaussians is also used to describe the signal ct_{xy} PDF R_1. The nonprompt background distribution R_2 is fit by an exponential function convolved with a single Gaussian. The separation significance PDFs for the signal and nonprompt components, S_1 and S_2, are parameterized with a single Gaussian convolved with an exponential function. Simulated event samples are used to parameterize the prompt and nonprompt ct_{xy} and δd distributions. The distributions of the signal variables as predicted by the simulation of SPS production agree with those from DPS production.

Combinatorial background shapes are obtained directly from data. Two $M_{\mu\mu}$ sideband regions are defined in the ranges $[2.85, 3]$ and $[3.2, 3.35]$ GeV/c^2, adjacent to the signal region defined as $[3, 3.2]$ GeV/c^2, and PDF parameters are estimated from fits to combinations of samples in data where only one or neither of the J/ψ candidates originate from the signal region. The mass distributions are parameterized under the assumption that they only contain contributions from true J/ψ candidates and combinatorial background. Third-order Chebyshev polynomial functions are used to describe the combinatorial components of each invariant mass PDF Q_3 and P_4 in the partially combinatorial and completely combinatorial category. In the latter case, it is required that P_5 equals P_4 and Q_5 equals Q_3. A sum of two Gaussians is used for R_{3-5}, and a Landau function plus a first-order Chebyshev polynomial is used to parameterize S_{3-5}.

The final fit is performed on the full data sample. The mean values of the central Gaussian functions of the two $\mu^+\mu^-$ invariant-mass distributions are left free, as is the proper decay time of the nonprompt component. The fit yields $n_{\text{sig}} = 446 \pm 23$ signal events. Figure 1 shows the distributions of the event variables from data with the fit result superimposed. The fit is validated by repeatedly generating simulated samples from the PDFs for all components and no bias is found. Furthermore, the robustness of the fit is probed by adding combinations of simulated signal and background events to the data set. To ensure that the cross section determination is insensitive to changing conditions, the distributions of the variables used in the likelihood fit are compared in subsets of events. Event variable distributions from events containing six reconstructed primary vertices or fewer agree with distributions in events containing more than six primary vertices (within statistical uncertainties). The behavior is confirmed with MC simulation signal samples generated with and without pileup contributions. The variable distributions also agree between the two major 2011 data-taking periods.
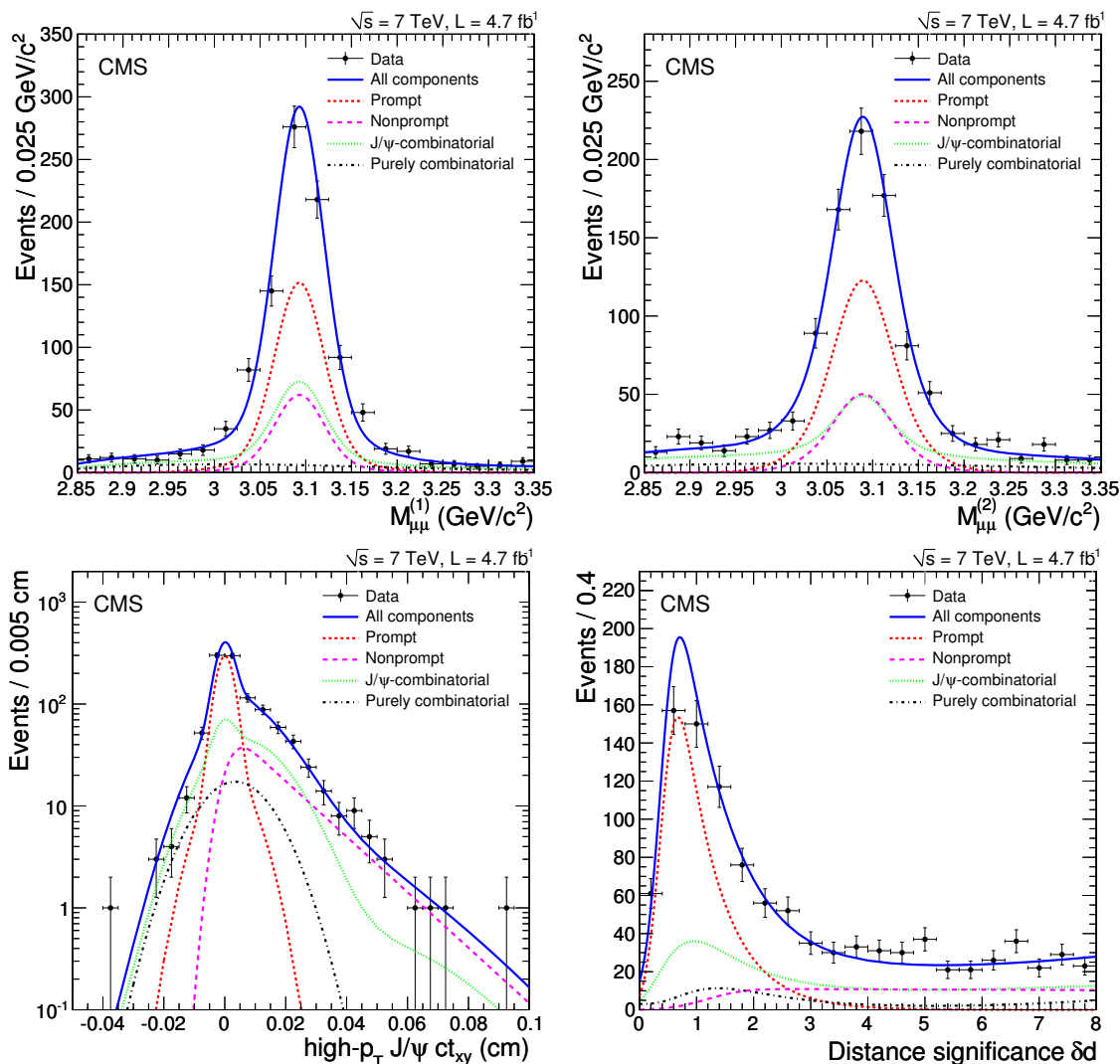
Figure 1. Distributions of $M_{\mu\mu}^{(1)}$ (top left), $M_{\mu\mu}^{(2)}$ (top right), ct_{xy} (bottom left), and distance significance δd (bottom right) for the candidate events and the projections of the fit results. The data are shown as points with the vertical error bars representing the statistical uncertainty. The fit result to the full sample is shown as a solid line. Individual contributions from the various categories are shown in different line styles: signal (short dashes), nonprompt background (long dashes), J/ψ-combinatorial components (dots), and the pure combinatorial component (dashes and dots).

5 Systematic uncertainties

The uncertainty in the J/ψ dimuon branching fraction is taken from the world average [31] (2% when added linearly). The systematic uncertainty corresponding to the integrated luminosity normalization is estimated in previous studies (2.2%) [32]. Simulated event samples based on SPS and DPS production models are used to estimate the uncertainty in the event-by-event acceptance correction method: N simulated events are subjected to

the acceptance criteria, and the event-based acceptance correction is applied to arrive at a corrected yield, N'. The uncertainty is taken as half of the relative difference between the two yields, N and N'. The larger value among the SPS- and DPS-based samples is quoted (1.1%). The precision of the event-based efficiency correction is limited by the number of reconstructed events, $n_{\text{reco},i}$, found after the substitution process for each event i. The cross section is recalculated by repeatedly varying $n_{\text{reco},i}$ according to Gaussian functions with standard deviation $\sqrt{n_{\text{reco},i}}$. The standard deviation of the resulting cross section distribution is used as an estimate of the uncertainty in the efficiency calculation (4.4%). The relative efficiency scaling factor is determined from SPS and DPS MC simulation samples, representing very different scenarios of J/ψ pair kinematics. The uncertainty due to model dependence of the scaling factor is defined as the difference in the cross section between either model and the average of the two (0.2%). The small uncertainty demonstrates that there is little overall model dependence.

The muon track reconstruction efficiency is derived from simulated events. The uncertainty is estimated from data and simulation samples that contain at least one reconstructed J/ψ. For each muon in an event, the tracking efficiency in data and simulation is obtained as a function of the measured muon pseudorapidity [35]. The relative uncertainty is defined as the absolute difference between the data- and simulation-based values divided by the data-based value. Individual muon uncertainties are added linearly per event (3.0%) since correlations between the muons are not taken into account.

The efficiency to trigger and reconstruct J/ψ pair events relies on detector simulation. To evaluate the uncertainty event-based efficiency values are instead constructed from single-muon efficiencies. The single-muon efficiencies are determined by applying a "tag-and-probe" method [36] to control samples in data and simulation that contain single J/ψ decays to muons. Hence, correlations among the two J/ψ mesons in the event are neglected. The difference in the signal yield in data when corrected with efficiencies found from either data or simulation is used to measure the uncertainty. The event-based efficiency correction is defined as the product of the event's trigger efficiency, given that all muons are found offline, and the event efficiency for reconstructing, identifying, and selecting offline all four muons in an event. The trigger efficiency is calculated from the single-muon trigger efficiencies and the dimuon vertexing efficiency as the trigger requires at least three reconstruced muons, two of which must be fit to a J/ψ vertex. The offline reconstruction efficiency for a single muon is given as the product of the tracking efficiency, muon identification efficiency, and the efficiency to pass the offline quality criteria. All muon efficiencies are obtained as a function of muon p_{T} and η from previous studies [36]. The probability to successfully fit both vertices in an event is greater than 99.9% for SPS and 99.6% for DPS simulation samples. Therefore, the offline event reconstruction efficiency is considered to be entirely a product of the muon reconstruction efficiencies. The largest deviation of the corrected signal yield using the single-muon efficiency values from data control samples compared to simulation is chosen as a conservative measure of the uncertainty (6.5%).

All PDF parameters that are fixed for the maximum likelihood fit are varied by their uncertainty, as determined from the fits to the data sidebands and MC simulation samples. The prompt ct_{xy} distribution is also parameterized using a sum of three Gaussians.

Source	Relative uncertainty [%]
Branching fraction	2.0
Integrated luminosity	2.2
Acceptance correction	1.1
Efficiency correction	4.4
Efficiency scaling factor	0.2
Muon track reconstruction	3.0
Detector simulation	6.5
PDF parameters	0.6
Production model	0.1
Total	9.0

Table 1. Summary of relative systematic uncertainties in the J/ψ pair total cross section.

Alternative fit shapes such as third-order polynomials or exponential functions are used for the background models. A Crystal Ball function [37] is considered as an alternative to the parameterization of the J/ψ invariant-mass distribution. A resolution function convolved with an exponential function is considered for the separation significance of the combinatorial background components. The largest difference in signal yields between fits with different shape parameterizations is taken as the uncertainty from the PDFs (0.6%). To evaluate the dependence of the PDF parameterization on the production model, both reconstructed DPS and SPS samples are used. The difference in signal yields between fits with those two PDF sets is considered as an uncertainty (0.1%). The total systematic uncertainty is calculated as the sum in quadrature of the individual uncertainties (9.0%). The individual relative uncertainties for the total cross section are listed in table 5. The systematic uncertainty for each differential cross section is also evaluated on a per-bin basis for all uncertainties due to the acceptance and efficiency corrections.

To study the effect of nonisotropic J/ψ decay into muons on the measured cross section, the event-based acceptance is determined using extreme scenarios. Defining θ as the angle between the μ^+ direction in the J/ψ rest frame and the J/ψ direction in the pp center-of-mass frame, the angular distribution of decay muons is parameterized as: $f(\theta) = 1 + \lambda \cos^2 \theta$, where λ is a polarization observable [38], with $\lambda = 0$ corresponding to an isotropic J/ψ decay. Compared to the $\lambda = 0$ case, the total cross section is 31% lower for $\lambda = -1$ and 27% higher for $\lambda = +1$. The differential cross section measurements for $\lambda = \pm 1$ lie within the statistical uncertainties of the $\lambda = 0$ case when scaled to the same total cross section, indicating that different polarization assumptions do not affect the shapes of the cross section distributions. Once the value of λ has been measured, it can be used in the acceptance calculation to mitigate this source of uncertainty.

6   Results

The total cross section obtained by summing over the sample on an event-by-event basis and assuming unpolarized prompt J/ψ pair production is

$$\sigma(\text{pp} \to \text{J}/\psi \, \text{J}/\psi + X) = 1.49 \pm 0.07 \pm 0.13 \, \text{nb}, \tag{6.1}$$

$M_{\mathrm{J}/\psi\,\mathrm{J}/\psi}$ (GeV/c^2)	$\mathrm{d}\sigma/\mathrm{d}M_{\mathrm{J}/\psi\,\mathrm{J}/\psi}$ (nb/(GeV/c^2))
6–8	$0.208 \pm 0.018 \pm 0.069$
8–13	$0.107 \pm 0.011 \pm 0.025$
13–22	$0.019 \pm 0.002 \pm 0.001$
22–35	$0.008 \pm 0.001 \pm 0.001$
35–80	$0.007 \pm 0.001 \pm 0.001$

Table 2. Differential cross section in bins of the J/ψ pair invariant mass ($M_{\mathrm{J}/\psi\,\mathrm{J}/\psi}$). The uncertainties shown are statistical first, then systematic.

$|\Delta y|$	$\mathrm{d}\sigma/\mathrm{d}|\Delta y|$ (nb)
0–0.3	$2.06 \pm 0.14 \pm 0.25$
0.3–0.6	$1.09 \pm 0.13 \pm 0.16$
0.6–1	$0.421 \pm 0.057 \pm 0.077$
1–1.6	$0.040 \pm 0.006 \pm 0.006$
1.6–2.6	$0.025 \pm 0.005 \pm 0.005$
2.6–4.4	$0.205 \pm 0.033 \pm 0.058$

Table 3. Differential cross section in bins of the absolute rapidity difference between J/ψ mesons ($|\Delta y|$). The uncertainties shown are statistical first, then systematic.

$p_{\mathrm{T}}^{\mathrm{J}/\psi\,\mathrm{J}/\psi}$ (GeV/c)	$\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{\mathrm{J}/\psi\,\mathrm{J}/\psi}$ (nb/(GeV/c))
0–5	$0.056 \pm 0.007 \pm 0.012$
5–10	$0.048 \pm 0.006 \pm 0.010$
10–14	$0.108 \pm 0.013 \pm 0.012$
14–18	$0.089 \pm 0.009 \pm 0.012$
18–23	$0.019 \pm 0.002 \pm 0.003$
23–40	$0.003 \pm 0.001 \pm 0.001$

Table 4. Differential cross section in bins of the transverse momentum of the J/ψ pair ($p_{\mathrm{T}}^{\mathrm{J}/\psi\,\mathrm{J}/\psi}$). The uncertainties shown are statistical first, then systematic.

with statistical and systematic uncertainties shown, respectively. For the measurement, the values $\mathcal{L} = 4.73 \pm 0.10\,\mathrm{fb}^{-1}$ [32] and $BF(\mathrm{J}/\psi \to \mu^+\mu^-) = (5.93 \pm 0.06)\%$ [31] are used. The differential cross section as a function of the J/ψ pair invariant mass ($M_{\mathrm{J}/\psi\,\mathrm{J}/\psi}$), the absolute rapidity difference between J/ψ mesons ($|\Delta y|$), and the J/ψ pair transverse momentum ($p_{\mathrm{T}}^{\mathrm{J}/\psi\,\mathrm{J}/\psi}$) is shown in figure 2. The observed differential cross section is not only a result of the kinematics of J/ψ pair production, but also of the J/ψ phase-space window (given in the figures) available for measurement. The corresponding numerical values are summarized in tables 2, 3, and 4, respectively.

A search for the η_b is performed by examining the J/ψ pair invariant-mass distribution around the nominal η_b mass [31], before efficiency and acceptance corrections. From samples of simulated J/ψ pair events produced via SPS or DPS, the acceptance times efficiency
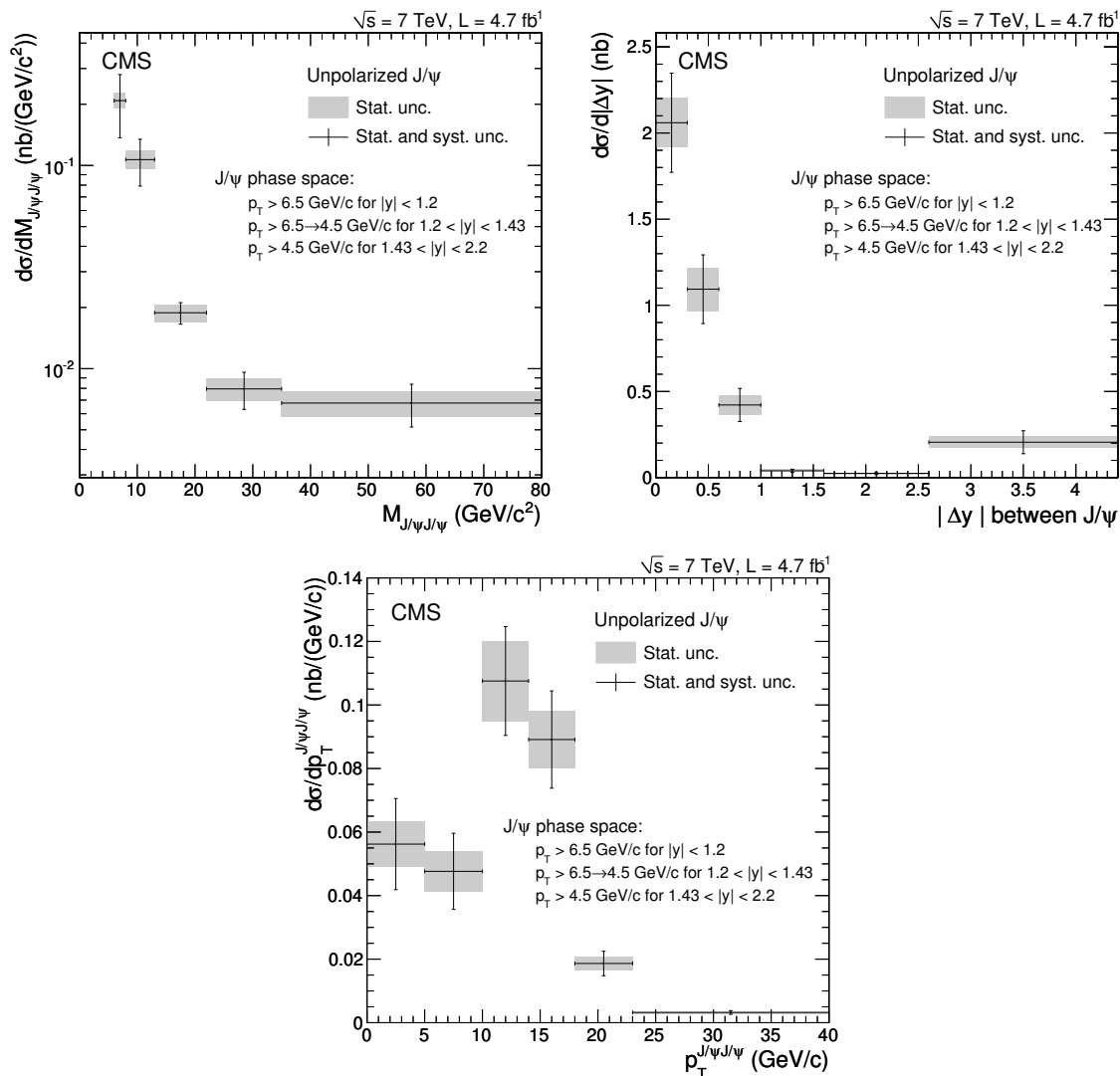
Figure 2. Differential cross section for prompt J/ψ pair production as a function of the J/ψ pair invariant mass ($M_{\mathrm{J/\psi\,J/\psi}}$, top left), the absolute rapidity difference between J/ψ mesons ($|\Delta y|$, top right), and the J/ψ pair transverse momentum ($p_{\mathrm{T}}^{\mathrm{J/\psi\,J/\psi}}$, bottom), over the J/ψ phase space given in the figure, assuming unpolarized J/ψ production. The shaded regions represent the statistical uncertainties only, and the error bars represent the statistical and systematic uncertainties added in quadrature.

is found to be nearly linear in the mass interval 8.68–10.12 GeV/c^2. The reconstructed Gaussian width of the η_b is 0.08 GeV/c^2, as determined from a J/ψ pair MC simulation sample generated according to a Breit-Wigner function with the nominal η_b mass and width [31]. The signal search interval 9.16–9.64 GeV/c^2 corresponds to three standard deviations on each side of the mean mass value. Two sideband regions of the same width as the signal region are defined as the intervals 8.68–9.16 GeV/c^2 and 9.64–10.12 GeV/c^2. A first-degree polynomial is used to fit the number of events in the sideband regions. Extrapolating these

yields to the signal region predicts 15 ± 4 nonresonant events. The total number of J/ψ pair events in this region in data is 15. Hence, no significant η_b contribution is observed.

7 Summary

A signal yield of 446 ± 23 events for the production of prompt J/ψ meson pairs has been observed with the CMS detector in pp collisions at $\sqrt{s} = 7$ TeV from a sample corresponding to an integrated luminosity of $4.73 \pm 0.10 \, \text{fb}^{-1}$. A data-based method has been used to correct for the acceptance and efficiency, minimizing the model dependence of the cross section determination. The total cross section of prompt J/ψ pair production measured within a phase-space region defined by the individual J/ψ p_T and rapidity is found to be $1.49 \pm 0.07 \, (\text{stat}) \pm 0.13 \, (\text{syst}) \, \text{nb}$, where unpolarized production is assumed. Differential cross sections have been obtained in bins of the J/ψ pair invariant mass, the absolute rapidity difference between the two J/ψ mesons, and the J/ψ pair transverse momentum. These measurements probe J/ψ pair production at higher J/ψ p_T and more central rapidity than the LHCb measurement [15], providing for the first time information about a kinematic region where color-octet J/ψ states and higher-order corrections play a greater role in production. The differential cross section in bins of $|\Delta y|$ is sensitive to DPS contributions to prompt J/ψ pair production. The differential cross section decreases rapidly as a function of $|\Delta y|$. However, a non-zero value is measured in the $|\Delta y|$ bin between 2.6 and 4.4. Current models predict that this region can be populated via DPS production [1, 4, 5].

There is no evidence for the η_b resonance in the J/ψ pair invariant-mass distribution above the background expectations derived from the η_b sideband regions. Since models describing the nonresonant J/ψ pair production in the CMS J/ψ phase-space window are not available, an upper limit on the production cross section times branching fraction for $\eta_b \to \text{J}/\psi \, \text{J}/\psi$ cannot be obtained.

Model descriptions of J/ψ pair production at higher p_T are crucial input to quantify nonresonant contributions in the search for new states at different center-of-mass energies. The cross section measurements presented here provide significant new information for developing improved theoretical production models.

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