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Observation of simultaneous production of three J/ψ mesons in pp collisions

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This writeup presents the first observation of the simultaneous production of three J/ψ mesons in proton-proton (pp) collisions, based on a data sample collected by the CMS experiment at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 133 fb^{-1}. The $pp \to J/\psi\, J/\psi\, J/\psi\, X$ process is observed with a significance above five standard deviations in final states with three $\mu^+\mu^-$ pairs. The measured inclusive fiducial cross section of $\sigma(\text{pp} \to J/\psi\, J/\psi\, J/\psi\, X) = 272^{+141}_{-104}(\text{stat}) \pm 17(\text{syst})$ fb is compared to theoretical expectations for the production of three J/ψ mesons in single- (SPS), double- (DPS), and triple- (TPS) parton scatterings. Assuming factorization of multiple hard-scattering probabilities in terms of SPS cross sections, the measured process is found to be dominated by DPS and TPS contributions, and an effective DPS cross section, related to the transverse distribution of partons in the proton, of $\sigma_{\text{eff,DPS}} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})$ mb is determined.

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1. Introduction

The analysis described in this contribution presents the first observation of the simultaneous production of three J/ψ mesons in pp collisions [1]. High-energy particle accelerators are unique tools to study the structure of matter at the shortest distances. Protons are used in energy-frontier colliders because they are relatively easy to accelerate and keep in a circular orbit to enable high collision rates. However, protons are not fundamental particles and, in fact, have a complicated quantum mechanical structure. In the modern picture known as the parton model [2], individual "parts" of the two protons undergo a hard scattering with one another, with the remainders of each proton only slightly disturbed in the process. As the energy of the colliding protons increases, the collisions probe shorter and shorter distances within the proton, and the density of gluons and sea quarks grows rapidly. Thus, at high enough energies, more than one pair of partons can undergo a hard scattering in a single proton-proton (pp) collision, leading to the simultaneous and independent production of two or more particles with large transverse momentum (p_T) and/or mass (m), above a few GeV. Double-parton scatterings (DPS) were first observed at the CERN Intersecting Storage Rings some 35 years ago [3, 4] and have been a subject of intense theoretical and experimental investigations ever since [5]. Triple-parton scatterings (TPS), where three hard parton interactions take place simultaneously, have only been proposed for study recently [6], and have not been experimentally explored yet.

In the simplest approach, ignoring any correlations between the individual partons, the probability to produce n high-p_T particles in a given pp collision must be proportional to the n^{th}-product of probabilities to independently produce each of them. Thus, the probability to produce two or three high-p_T particles in DPS and TPS scales with the square and cube, respectively, of the corresponding single-parton scattering (SPS) probabilities [7]. The occurrence of DPS and TPS processes is therefore more likely for final states with large SPS cross sections, such as quarkonia states (e.g., J/ψ and Υ mesons), than for rarer heavier particles such as, e.g., electroweak (EW) bosons [8]. In the DPS case, the cross section to produce two charmonium mesons ψ_1 and ψ_2 can be written as the product of the SPS cross sections for the production of each individual meson divided by an effective cross section to warrant the proper units of the final result,

$$\sigma_{\text{DPS}}^{\text{pp}\to\psi_1\,\psi_2+\text{X}} = \left(\frac{\mathfrak{m}}{2}\right) \frac{\sigma_{\text{SPS}}^{\text{pp}\to\psi_1+\text{X}}\ \sigma_{\text{SPS}}^{\text{pp}\to\psi_2+\text{X}}}{\sigma_{\text{eff,DPS}}}, \tag{1}$$

Where $\mathfrak{m}$ is a combinatorial factor to avoid double counting, $\mathfrak{m} = 1\ (2)$ if $\psi_1 = \psi_2$ ($\psi_1 \neq \psi_2$), and $\sigma_{\text{eff,DPS}}$ is an effective cross section that, in a purely geometric approach, can be determined from the pp transverse overlap [7]. A *smaller* value of $\sigma_{\text{eff,DPS}}$, which is proportional to the average (squared) transverse separation of the partons participating in the two hard scatterings, implies *larger* DPS yields.

There is an equivalent of Eq. (1) for the production of three charmonium mesons in a TPS process [1], and the effective cross section $\sigma_{\text{eff,TPS}}$ is closely related to its DPS counterpart via $\sigma_{\text{eff,TPS}} = \kappa\,\sigma_{\text{eff,DPS}}$, with κ value close to one. In the absence of parton correlations, a value of $\kappa = 0.82 \pm 0.11$ has been derived in [6] for a variety of proton transverse parton profiles. A theoretical study of the production of three prompt-J/ψ mesons [9], based on the nonrelativistic quantum chromodynamics (NRQCD) approach at leading-order (LO) accuracy as implemented in the HELAC-Onia code [10], has demonstrated that the pure SPS contributions are negligible compared to those from DPS and TPS. The experimental measurement of pp $\rightarrow J/\psi\, J/\psi\, J/\psi\, X$ is thus a golden channel for the study of TPS and, in addition, provides an alternative extraction of $\sigma_{\text{eff,DPS}}$, thereby shedding new light into the underlying dynamics of hard n-parton scattering (NPS).

2. Selection and cross section measurement

The present analysis employs an trigger that requires three muons, each having $p_T > 3.5$ GeV for $|\eta| < 1.2$ (barrel) or $p_T > 2.5$ GeV for $1.2 < |\eta| < 2.4$ (endcap). In addition, the event must have at least one pair of oppositely charged muons with invariant mass between 2.80 and 3.35 GeV that originate from a common vertex with a probability greater than 0.5%.

The data analysis starts by selecting events with six reconstructed muons. The muons are combined into opposite-sign (OS) pairs, originate from a common vertex with a probability greater than 0.5%. All selected muon pairs are further required to share the same primary pp interaction vertex. The analysis thereby includes prompt-J/ψ mesons coming directly from the pp interaction and nonprompt ones coming from the decays of beauty hadrons. A more detailed description of the selection can be found in Ref. [1].

The signal yield is extracted with a three-dimensional unbinned extended maximum likelihood fit of the $m_{\mu^+\mu^-}$ distributions of all J/ψ candidates in the event over the $2.9 < m_{\mu^+\mu^-} < 3.3$ GeV range. The extracted signal yield (red shaded areas in the $m_{\mu^+\mu^-}$ distributions of Fig. 1) corresponds to $N_{\text{sig}}^{3J/\psi} = 5.0^{+2.6}_{-1.9}$ triple-J/ψ events, with $1.0^{+1.4}_{-0.8}$ background events. The statistical significance of the signal is found to be above 5 standard deviations.

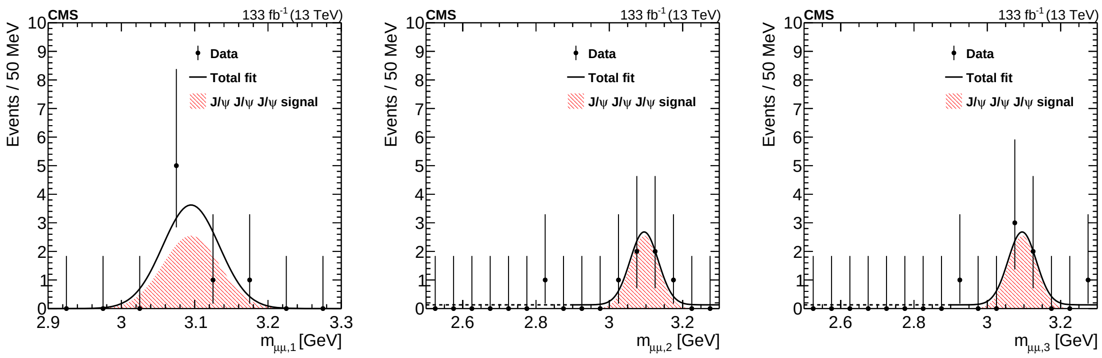

Figure 1: Invariant mass distributions for the three $\mu^+\mu^-$ pairs, ordered (left to right) by decreasing pair p_T, in the selected events. The data are represented by the points with the vertical bars showing the (Poisson) statistical uncertainties. The solid (dotted) curve shows the overall fit to the data (in the extended mass range), and the red shaded area the fitted signal yield.

$\sigma(\text{pp} \rightarrow J/\psi\, J/\psi\, J/\psi\, X) = N_{\text{sig}}^{3J/\psi}/(\epsilon\, L_{\text{int}}\, \mathcal{B}^3_{J/\psi\rightarrow\mu^+\mu^-})$ is the cross section for inclusive triple-J/ψ, where $N_{\text{sig}}^{3J/\psi}$ is the number of signal events, L_{int} the total integrated luminosity, $\mathcal{B}_{J/\psi\rightarrow\mu^+\mu^-}$

the dimuon branching fraction, and $\epsilon = \epsilon_{\text{trig}}\,\epsilon_{\text{id}}\,\epsilon_{\text{reco}}$ the total efficiency composed of trigger, identification, and reconstruction components. The J/ψ muon identification and reconstruction efficiencies are extracted with the tag-and-probe method, yielding $\epsilon_{\text{id}}\,\epsilon_{\text{reco}} = 0.78$. The trigger efficiency is found to be $\epsilon_{\text{trig}} = 0.84$ from a study of the MC samples. The measured cross section for triple-J/ψ production is $\sigma(\text{pp} \to J/\psi J/\psi J/\psi\, X) = 272^{+141}_{-104}(\text{stat}) \pm 17(\text{syst})$ fb.

3. Discussion

The total inclusive triple-J/ψ cross section is expected to correspond to the sum of the contributions from the SPS, DPS, and TPS processes, each of which contains various combinations of prompt (p) and nonprompt (np) J/ψ contributions. Under the simplest assumption of factorization of multiple hard-scattering probabilities in terms of SPS cross sections, the DPS and TPS contributions to triple-J/ψ production can be written (for example, through Eqs. (1)) as a combination of products of single- and double-J/ψ SPS cross sections. Therefore, from the individual SPS cross sections for single-, double-, and triple-J/ψ production, one can determine the total triple-J/ψ production cross section. The values of the relevant SPS cross sections can be found in table 4 of Ref. [1]. Using those SPS values, and assuming that the effective DPS and TPS cross sections are related by $\sigma_{\text{eff,TPS}} = (0.82 \pm 0.11)\,\sigma_{\text{eff,DPS}}$ [6] in a baseline approach that ignores parton correlations, one can extract the value of the effective DPS cross section that yields the experimentally measured $\sigma^{3J/\psi}_{\text{tot}}$ value. Following such a procedure, the value $\sigma_{\text{eff,DPS}} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})$ mb is derived, where the first uncertainty is due to the experimental $\sigma^{3J/\psi}_{\text{tot}}$ precision and the second is due to the propagation of all sources of theoretical uncertainties.

Process:	3 prompt	2 prompt+1 nonprompt	1 prompt+2 nonprompt	3 nonprompt	Total
$\sigma^{3J/\psi}_{\text{SPS}}$ (fb)	< 0.005	5.7	0.014	12	18
$N^{3J/\psi}_{\text{SPS}}$	0.0	0.10	0.0	0.22	0.32
$\sigma^{3J/\psi}_{\text{DPS}}$ (fb)	8.4	8.9	90	95	202
$N^{3J/\psi}_{\text{DPS}}$	0.15	0.16	1.65	1.75	3.7
$\sigma^{3J/\psi}_{\text{TPS}}$ (fb)	6.1	19.4	20.4	7.2	53
$N^{3J/\psi}_{\text{TPS}}$	0.11	0.36	0.38	0.13	1.0
$\sigma^{3J/\psi}_{\text{tot}}$ (fb)	15	34	110	114	272
$N^{3J/\psi}_{\text{tot}}$	0.3	0.6	2.0	2.1	5.0

Figure 2: Central values of the predictions for triple-J/ψ production cross sections (in fb) and yields from SPS, DPS (for $\sigma_{\text{eff,DPS}} = 2.7$ mb), and TPS (for $\sigma_{\text{eff,TPS}} = 0.82\,\sigma_{\text{eff,DPS}} = 2.2$ mb) processes, and their total sum. The values are given in columns for combinations of n prompt and $(3-n)$ nonprompt J/ψ mesons, the last column giving their corresponding sums. The expected yield, $N^{3J/\psi}_{\text{NPS}}$, is given for an effective integrated luminosity of $\epsilon_{\text{int}} = 87\ \text{fb}^{-1}$ for each contributing process. The last column lists the total cross sections and yields for SPS, DPS, TPS and their sums. More details can be found in Ref. [1].

The inclusive triple-J/ψ theoretical cross sections and yields for each individual process contributing to the total production are listed in Fig. 2. The expected contributions from SPS, DPS, and TPS processes to the total triple-J/ψ cross section amount to about 6, 74, and 20%, respectively. This confirms the conclusion of Ref. [9] that triple-J/ψ production is a golden channel to study DPS and TPS, with minimal SPS contamination.

In Fig. 3, the $\sigma_{\text{eff,DPS}}$ value extracted here (red circle) is compared to the world data on effective DPS cross sections derived from midrapidity measurements with quarkonium final states (blue circles), as well as from processes with jets, photons, and/or W bosons (black squares and triangles). The effective cross sections obtained from quarkonium measurements favor a smaller value of $\sigma_{\text{eff,DPS}} \approx$ 3–10 mb compared to the $\sigma_{\text{eff,DPS}} \approx$ 10–20 mb derived from harder or heavier final states. Such an apparent process-dependent $\sigma_{\text{eff,DPS}}$ value is suggestive of different parton transverse profiles, and/or presence of correlations, probed inside the proton at varying fractional momenta.

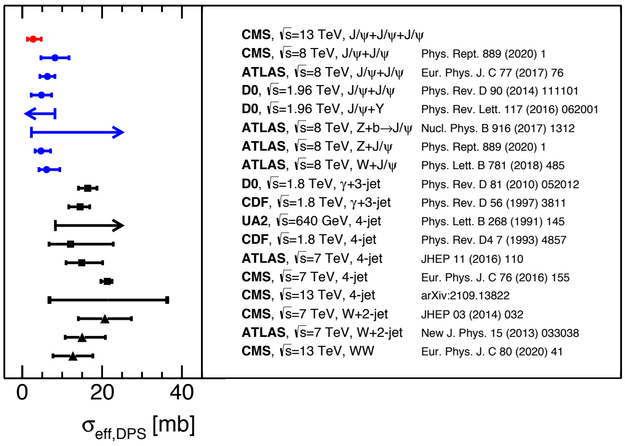

Figure 3: Comparison of the $\sigma_{\text{eff,DPS}}$ parameter extracted here (upper red circle) to those derived in midrapidity measurements of double-quarkonium and EW boson plus quarkonium production (blue circles), as well as in final states with jets, γ+ jets , and same-sign W bosons (black squares and triangles) [1].

4. Summary

The first observation of the simultaneous production of three J/ψ mesons in proton-proton (pp) collisions has been reported. The cross section for inclusive triple-J/ψ production is $\sigma(\text{pp} \rightarrow J/\psi J/\psi J/\psi\ X) = 272^{+141}_{-104}(\text{stat})\pm 17(\text{syst})$ fb. This result is compared to the theoretical expectations for triple-J/ψproduction via a sum of contributions from single- (SPS), double- (DPS), and triple- (TPS) parton scatterings. Under the simplest assumption of factorization of multiple hard-scattering probabilities in terms of SPS cross sections, the measured triple-J/ψ cross section is consistent with the production via DPS (≈74%), TPS (≈20%), and SPS (≈6%) processes for a value of the effective DPS cross section parameter, closely related to the transverse distribution of partons in the proton, of $\sigma_{\text{eff,DPS}} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})$ mb. Within its large uncertainty, this parameter is consistent with those extracted from double-quarkonium measurements, but significantly smaller than the $\sigma_{\text{eff,DPS}}$ values derived from DPS studies based on high-p_T jets and/or electroweak bosons. This work presents a novel approach to study multiple hard-scatterings in pp collisions exploiting, for the first time, the simultaneous production of three heavy particles.

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