# Observations of double $J/\psi$ in pPb collisions and triple $J/\psi$ in pp collisions

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**Abstract.** Multi parton scattering (MPI) research has great importance in the field of high energy physics. Two recent outcomes of MPI studies conducted by the CMS collaboration at the LHC are presents. The first observation of double $J/\psi$ production in proton-lead (pPb) collisions is reported, as well as the first observation of the concurrent production of triple $J/\psi$ in proton-proton (pp) collisions. Both studies provide calculations of the effective cross section.

## 1 Introduction

Significant importance has been assigned to the study of the multi parton scattering (MPI) interaction. Investigating MPI is crucial for acquiring insights into the parton distribution function (PDF), as this process is highly related to the parton distribution [1][2]. Additionally, studying MPI is essential for measuring the effective cross section. The effective cross section is a parameter that relates a whole process to two individual processes. In a process where final state has two mesons $\psi_1\psi_2$:

$$\sigma_{\text{DPS}}^{\psi_1\psi_2} = \frac{m}{2}\frac{\sigma_{\text{SPS}}^{\psi_1}\sigma_{\text{SPS}}^{\psi_1}}{\sigma_{eff}}, \tag{1}$$

where $\sigma_{eff}$ is the effective cross section, $\sigma_{\text{SPS}}^{\psi_1}$ ($\sigma_{\text{SPS}}^{\psi_2}$) is the cross section of single parton scattering (SPS) to $\psi_1$ ($\psi_2$) and $\sigma_{\text{DPS}}^{\psi_1\psi_2}$ is the cross section of double parton scattering (DPS) to $\psi_1\psi_2$. Factor $m = 1(2)$ when $\psi_1 = (\neq)\psi_2$. The effective cross section in important for Monte Carlo generator to correctly produce MPI events. MPI also serves as the background for new physics phenomena [3][4]. Therefore, studying MPI enhances our comprehension of these new phenomena. For example, MPI $\rightarrow J/\psi J/\psi$ is the main background in the resonance $X \rightarrow J/\psi J/\psi$ searching study [4].

In the present work, two MPI studies conducted by CMS collaboration are reported: the observation of double $J/\psi$ process in proton-lead (pPb) collisions [5], and the observation of triple $J/\psi$ process in proton-proton (pp) collisions [6].

## 2 Observation of double $J/\psi$ process in the pPb collisions

The first study to investigate MPI in pPb collisions was conducted by the LHCb collaboration, which measured the DPS process with various pairs of charmed hadrons at energy of

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$\sqrt{s_{NN}}$ = 8.16 TeV [7], although the double $J/\psi$ final state has never been observed in pPb collisions. This analysis study double $J/\psi$ production in LHC pPb collisions. With possible DPS contribution, this study also provides another measurement of the effective cross section through a relationship:

$$\sigma_{eff}^{\mathrm{pPb}} = \frac{A\sigma_{eff}^{\mathrm{pp}}}{1 + \sigma_{eff}^{\mathrm{pp}} F_{\mathrm{pPb}}/A}, \tag{2}$$

where $\sigma_{eff}^{\mathrm{pPb}}$ is the effective cross section of pPb interaction, $\sigma_{eff}^{\mathrm{pp}}$ is the effective cross section of pp interation, $A = 208$ is the pPb mass and the factor $F_{\mathrm{pPb}} \approx A^{1/3}/14\pi$ mb$^{-1}$ [8].

The dataset collected during the pPb collisions in 2016 is utilized with an energy of $\sqrt{s_{NN}}$ = 8.16 TeV and an integral luminosity of 174.6 nb$^{-1}$). The primary channel of the study is $J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ due to its clearer background. Events are required to pass a series of selections in the offline reconstruction, including the presence of at least one reconstructed vertex; muons in the candidate having relatively high reconstruction quality; opposite sign (OS) muons combination having an invariant mass around the $J/\psi$ mass windows, $p_T > 6.5$ GeV and $|y| < 2.4$; and four muons are fitted to a common vertex with $\chi^2 > 0.1\%$. Additionally possible pileup events are excluded from this study.

16 candidates are observed to pass all the criteria. All candidates are found to have vertexes close to the primary vertex, within a distance of 100 $\mu$m, indicating that all candidates can be considered as promptly produced. A two dimensional ($M(J/\psi_1)$ and $M(J/\psi_2)$) unbinned extended maximum likelihood fit is applied to the 16 candidates to extract the signal yield, where a crystal ball function is utilized for the $J/\psi$ mass distribution and an exponent function to describe the combinatorial background. The fitting is illustrated by the Fig 1 [5]. From the fitting, in total 8.5 ± 3.4 candidates are regarded as the signal with a significance of 4.9 standard deviation.

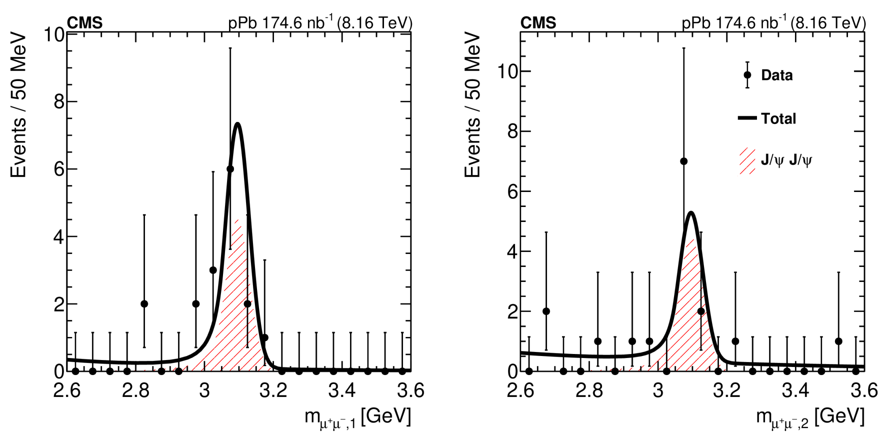


**Figure 1.** Projection of candidates passing all the criteria on the dimuon invariant mass dimensions. The solid curve represents the total fit to the data, and the red area represents the signal yield [5].

Another channel is also investigated as a cross check, where the $p_T$ subleading $J/\psi$ is reconstructed using $e^+e^-$ rather than $\mu^+\mu^-$. This method offers the advantage of a larger dataset but with a higher background. 21 candidates remain after all selections. A similar two dimensional fitter is constructed, which yields 5.7 ± 4.0 candidates assigned to the signal and a significance calculated as 2.3. The combined significance from both two channels is obtained using the Fisher formalism as 5.3 standard deviations.

The cross section for double $J/\psi$ production in pPb collisions is calculated using the $\mu^+\mu^-\mu^+\mu^-$ channel as $\sigma(\text{pPb} \to J/\psi J/\psi) = 22.0 \pm 8.9(\text{stat}) \pm 1.5(\text{syst})$ nb. Several systematic uncertainties are considered, which includes the shape of the $J/\psi$ mass distribution, the shape of the combinatorial background, the uncertainty of the integral luminosity, the uncertainty arising from the efficiency correction and the uncertainty of the branch fraction. The overall systematic uncertainty is estimated to be 6.1%.

SPS and DPS contributions to the signal are separated by a two dimensional ($|\Delta y(J/\psi_1, J/\psi_2)|$ and $\Delta\phi(J/\psi_1, J/\psi_2)$) fit as illustrated by the Fig 2 [5]. This fit is performed using a DPS template constructed by two randomly selected $J/\psi$ candidates from the dataset. From the fitting, signal events are separated into 2.1 ± 2.4 DPS candidates and 6.4 ± 4.2 SPS candidates. Based on this result, the effective cross section for pPb interaction is calculated to be $\sigma_{eff}^{\text{pPb}} = 0.53^{\infty}_{-0.2}$ b, where the cross section for SPS to single $J/\psi$ in pPb collisions is evaluated through theoretical calculations. And the effective cross section of pp interaction is derived to be $\sigma_{eff}^{\text{pp}} = 4.0^{\infty}_{-1.5}$ mb. The arbitrarily upper limit of the cross section indicates that the signal could be fully explained by SPS contribution alone. This result could be transferred into a lower limit of $\sigma_{eff}^{\text{pp}} > 1.0$ mb with 95% confidence level.

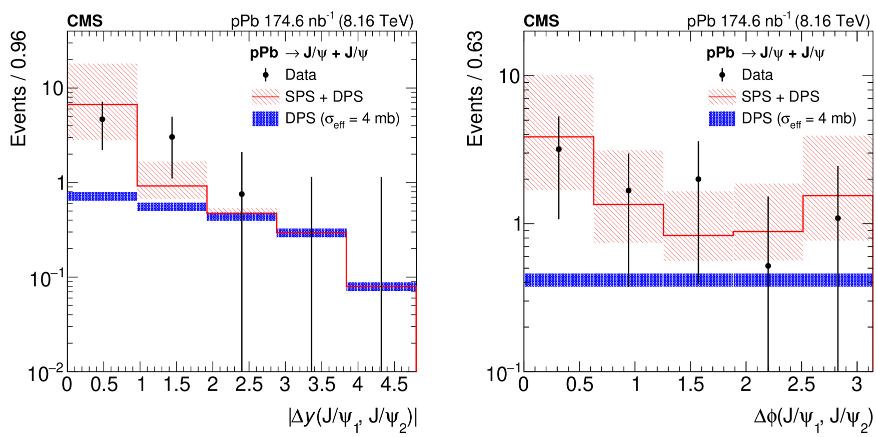


**Figure 2.** Distribution of $|\Delta y(J/\psi_1, J/\psi_2)|$ (left) and $\Delta\phi(J/\psi_1, J/\psi_2)$ (right) in data, fitted DPS template (blue histogram) normalized to the data in the DPS control region and fitted total distribution (red histogram) [5].

This study presents the first observation of double $J/\psi$ process in pPb collisions. $8.5 \pm 3.4$ and $5.7 \pm 4.0$ double $J/\psi$ candidates are identified using the channels $J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ and $J/\psi J/\psi \to \mu^+\mu^-e^+e^-$, respectively. The significance is measured to be 5.3 standard deviations by combining two channels together. The cross section of double $J/\psi$ production in pPb collisions is calculated with $\mu^+\mu^-\mu^+\mu^-$ channel as $\sigma(\text{pPb} \to J/\psi J/\psi) = 22.0 \pm 8.9(\text{stat}) \pm 1.5(\text{syst})$ nb. SPS and DPS contributions are distinguished by their kinematic differences, and a lower limit of the effective cross section of pp interaction could be obtained to be $\sigma_{eff}^{\text{pp}} > 1.0$ mb with 95% confidence level.

## 3 Observation of triple $J/\psi$ process in the pp collisions

The search for triple $J/\psi$ production has been proposed recently [9], where the SPS contribution is predicted to be small enough [10], allowing to separate more easily the DPS and triple parton scattering (TPS) processes.

The dataset of pp collisions collected during LHC RunII period is utilized, with an energy of 13 TeV and an integral luminosity of 133 fb$^{-1}$. The decay channel $J/\psi \to \mu^+\mu^-$ is chosen as to facilitate a clearer event reconstruction. Offline selection requires all six muons pass HLT $p_T$ and $\eta$ criteria, OS dimuon candidates must be within the $J/\psi$ mass windows and have $p_T > 6$ GeV and $|y| < 2.4$. Additionally, all muons in a candidate are required to share the same primary vertex.

Six triple $J/\psi$ candidates are observed after all the criteria are applied. A three dimensional ($M(J/\psi_1)$, $M(J/\psi_2)$ and $M(J/\psi_3)$) fit is conducted and the signal yield is extracted to be $5.0^{+2.6}_{-1.9}$, and the combinatorial background yield is extracted as $1.0^{+1.4}_{-0.8}$, as illustrated by the Fig 3 [6]. The significance of the signal is calculated to be 6.7 standard deviations using Wilk's theorem [11].

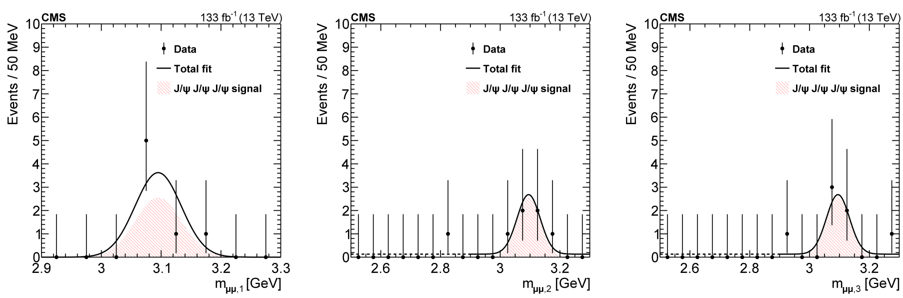


**Figure 3.** Projection of candidates passing all the criteria on the dimuon invariant mass dimensions. The solid curve represents the total fit to the data, and the red area represents the signal yield [6].

The cross section of triple $J/\psi$ production is calculated to be $\sigma(\mathrm{pp} \to \mathrm{J}/\psi\mathrm{J}/\psi) = 272^{+141}_{-104}(\mathrm{stat}) \pm 17(\mathrm{syst})$ fb. The systematic uncertainty includes the shapes of the $J/\psi$ and combinatorial background, the uncertainty from the efficiency correction, and the uncertainties associated with the luminosity and branch fraction.

$J/\psi$ candidates are not expected to arise from parton scattering alone, but also from the decay of B mesons. The $J/\psi$s origin from the former are referred to as prompt $J/\psi$s, while those from the latter are referred to as non-prompt $J/\psi$s due to their longer lifetime. Given that the cross section for B meson production at the LHC is substantial ( 0.5 mb) [9] and no lifetime requirement is applied in the offline selection, a considerable fraction of the candidates are regarded as non-promptly produced. A classification is employed based on the proper decay length $L^{J/\psi}$, with prompt $J/\psi$ being defined as those with $L^{J/\psi} < 60\ \mu$m. Using this definition, five triple $J/\psi$ candidates can be allocated to be following categories: two as "2 non-prompt + 1 prompt", one as "2 prompt + 1 non-prompt", one as "3 non-prompt", and one as "3 prompt".

The separation of different processes is implemented through a theory analysis. The SPS to single, double and triple $J/\psi$ (with various prompt and non-prompt combinations) cross sections are estimated theoretically. Subsequently, the cross section for DPS ($\sigma^{3J/\psi}_{\mathrm{DPS}}$) and TPS ($\sigma^{3J/\psi}_{\mathrm{TPS}}$) to triple $J/\psi$ are computed using the respectively formulas [6]:

$$\sigma^{3J/\psi}_{\rm DPS} = \frac{\sigma^{2p}_{\rm SPS}\sigma^{1p}_{\rm SPS} + \sigma^{2p}_{\rm SPS}\sigma^{1np}_{\rm SPS} + \sigma^{1p}_{\rm SPS}\sigma^{1p1np}_{\rm SPS} + \sigma^{1p}_{\rm SPS}\sigma^{2np}_{\rm SPS} + \sigma^{1p1np}_{\rm SPS}\sigma^{1np}_{\rm SPS} + \sigma^{2np}_{\rm SPS}\sigma^{1np}_{\rm SPS}}{\sigma^{\rm DPS}_{eff}}, \quad (3)$$

$$\sigma^{3J/\psi}_{\rm TPS} = \frac{\frac{1}{6}\left[(\sigma^{p}_{\rm SPS})^3 + (\sigma^{1np}_{\rm SPS})^3\right] + \frac{1}{2}\left[(\sigma^{1p}_{\rm SPS})^2\sigma^{1np}_{\rm SPS} + (\sigma^{1np}_{\rm SPS})^2\sigma^{1p}_{\rm SPS}\right]}{\sigma^{\rm TPS}_{eff}}, \quad (4)$$

where the $\sigma^{\rm DPS}_{eff}$ is the DPS effective cross section and the $\sigma^{\rm TPS}_{eff}$ is the TPS effective cross section. The $\sigma^{\rm DPS}_{eff}$ is predicted to be $0.82\sigma^{\rm DPS}_{eff}$ [9]. By summing $\sigma^{3J/\psi}_{\rm SPS}$, $\sigma^{3J/\psi}_{\rm DPS}$ and $\sigma^{3J/\psi}_{\rm TPS}$, the total cross section of triple $J/\psi$ production can be obtained as a function of $\sigma^{\rm DPS}_{eff}$. By comparing the value of this function to the experimental result, $\sigma^{\rm DPS}_{eff}$ can be determined to be $\sigma^{\rm DPS}_{eff} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})$ mb.

In summary, this study reports the first observation of triple $J/\psi$ process. Six candidates pass all selection criteria, with five assigned as the signal and the remaining one is regarded as combinatorial background. The significance of the signal is estimated to be 6.7 standard deviations. The cross section of the production of triple $J/\psi$ is calculated as $\sigma(\text{pp} \to J/\psi J/\psi) = 272^{+141}_{-104}(\text{stat}) \pm 17(\text{syst})$ fb, including promptly and non-promptly produced candidates. The effective cross section, derived from a theoretical study, is estimated to be $\sigma^{\rm DPS}_{eff} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})$ mb.

## 4 Summary

Study of MPI offers a great opportunity to investigate into the structure of the proton and to test our comprehension of QCD theory. Additionally, The Monte Carlo generator and the understanding of the background for new physics phenomena can also get enhanced. Two recent MPI studies conducted by the CMS collaboration are presented.

The first study reports the detection of double $J/\psi$ process in pPb collisions, where $8.5 \pm 3.4$ candidates are found in the primary channel, and a significance is estimated to be 5.3 standard deviations by combining two channels together. The first observation of triple $J/\psi$ process is reported by the second study. Five candidates are identified as triple $J/\psi$ with a significance is found to be greater than 5 standard deviations.

Both studies present the calculations of the effective cross section, which is a significant parameter in the MPI. The first study reports the lower limit of $\sigma_{eff} > 1.0$ mb with 95% confidence level, and the second study presents the result as $\sigma_{eff} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})$ mb. The results of measurements for the effective cross section from above two studies are compared with previous experimental efforts in the Fig 4 [5]. Significant deviation can be observed in the Fig 4. The results extracted from the quarkonium final state have a value of around 5 mb, which is consistent with the results obtained by the two studies presented in this paper. In contrast, the results extracted from jets, photons and W bosons have a value of around 15 mb, suggesting the breakdown in the universality of the effective cross section.

MPI has been studied in detail by the CMS collaboration, including above two analyses, a measurement of the cross section of double $J/\psi$ production in pp collisions at 7 TeV [12], a search for resonances in the double $J/\psi$ channel at 13 TeV [4] as well as a measurement of the cross section of double $\Upsilon$ production in pp collisions at 13 TeV [3], etc. The study of MPI is expected to yield further possibilities in the Run3 of the LHC, where new trigger can be implemented and new channels could become available.

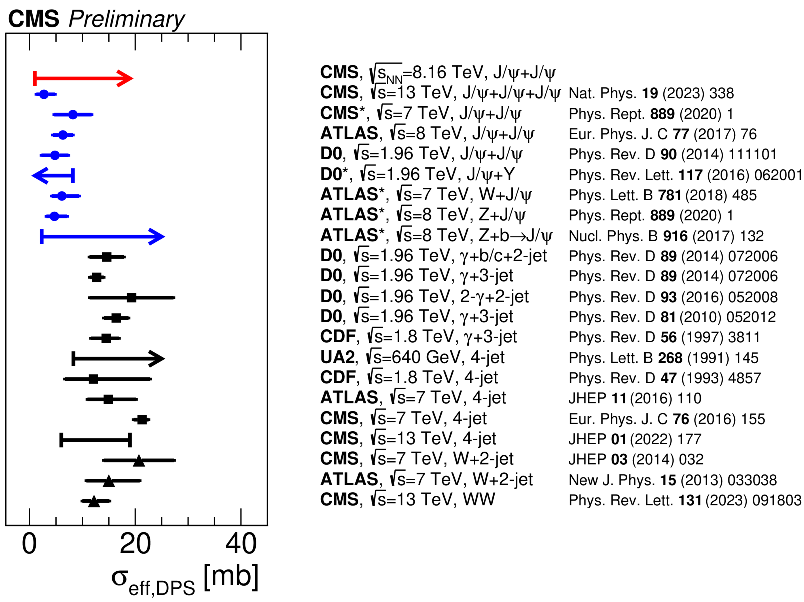


**Figure 4.** The results of measurements for the effective cross section from two studies presented in this paper and previous experimental efforts [5].

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