Observation of double J/ψ production in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV

The LHCb Collaboration

Abstract

The production of J/ψ-J/ψ pairs in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV has been observed with the LHCb detector with an integrated luminosity of 35.2 pb$^{-1}$. The production cross section for J/ψ-J/ψ pairs with both J/ψ in the rapidity range $2 < y_{J/\psi} < 4.5$ and with transverse momentum $p_{T}^{J/\psi} < 10$ GeV/c has been measured to be

$$\sigma^{J/\psi-J/\psi} = 5.6 \pm 1.1 \pm 1.2 \text{ nb},$$

where the first uncertainty is statistical, and the second is systematic.

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$^1$Conference report prepared for 2011 Winter Conferences. Contact authors are Victor Egorychev Victor.Egorychev@cern.ch and Vanya Belyaev Ivan.Belyaev@cern.ch.
1 Introduction

QCD predicts the prompt production of two charmonia states in the same reaction to be an exceedingly rare effect. The only observation of this phenomenon in hadronic collisions to date was by the NA3 collaboration, which found evidence of J/ψJ/ψ pair production in multi-muon events in pion-platinum interactions at 150 and 280 GeV/c and in proton-platinum interactions at 400 GeV/c \[1\]. The cross-section ratio $\sigma_{J/\psi J/\psi}/\sigma_{J/\psi}$ was measured to be $(3\pm1) \times 10^{-4}$ for pion-induced production, where $\sigma_{J/\psi}$ is the inclusive J/ψ production cross section. At NA3 energies the main contribution to the cross section arises from the quark-antiquark annihilation channel \[2\]. In the case of proton-proton collisions at LHC energy, the quark-antiquark annihilation process is negligible compared to the prevailing gluon-gluon fusion process \[3\]. Theoretical calculations based on the leading order of QCD perturbation theory predict that the total cross section of J/ψ pair production in proton-proton interaction at $\sqrt{s} = 7$ TeV is equal to $\sigma_{J/\psi J/\psi} \equiv \sigma(pp \to J/\psi J/\psi + X) \sim 24.5$ nb \[4,5\]. For the J/ψ rapidity interval $2.0 < y_{J/\psi} < 4.5$ relevant to the LHCb experiment, the production cross section of J/ψJ/ψ pairs is equal to 4.34 nb, in the case initial state gluon radiation (ISR) is neglected, and drops to 4.15 nb, if ISR is taken into account.

The data used for this report comprise 35.2 pb$^{-1}$ of pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV collected by the LHCb experiment in 2010. The LHCb detector is a forward spectrometer described in detail elsewhere \[6\].

2 Event selection and signal yield

In this analysis the J/ψ is reconstructed through its decay channel into a pair of muons $J/\psi \to \mu^+\mu^-$. Well reconstructed and identified muons with transverse momentum in excess of 650 MeV/c are used. Track quality and muon identification are ensured by the cuts $\chi^2_{tr}/ndf < 5$ and $\Delta \log L_{\mu-h} > 0$, where $\chi^2_{tr}/ndf$ is the reduced $\chi^2$ from the track fit, and $\Delta \log L_{\mu-h}$ is a muon identification variable, built as the difference in logarithms of the global likelihood of the muon hypothesis with respect to the hadron one. In order to suppress the contribution from clone tracks, only tracks with the minimal symmetrised Kullback-Leibler divergency $\Delta_{KL}^{\mu\mu}$, calculated with respect to all other reconstructed tracks in the event, in excess of 5000 are considered \[7\].

The opposite-sign dimuon combinations have been required to originate from a common vertex. Only $\mu^+\mu^-$ pairs with good $\chi^2_{VX}$ of the two-prong vertex fit, $\chi^2_{VX} < 20$, are kept.

Selected $\mu^+\mu^-$ candidates with an invariant mass in the interval $3.0 < m_{\mu^+\mu^-} < 3.2$ GeV/c$^2$ have been paired to form $(\mu^+\mu^-)_1(\mu^+\mu^-)_2$ combinations. The four-muon combinations are required to originate from a common vertex compatible with one of the reconstructed primary vertices from pp collisions. This is
achieved by performing a global refit of the four-prong combination with a primary vertex constraint \([9]\), and \(\chi^2_{DTF}/ndf < 5\) is required, where \(\chi^2_{DTF}\) is the \(\chi^2\) from this global fit.

To extract the number of events with two J/\(\psi\) mesons, a double background subtraction procedure is applied. The invariant mass distributions of the first dimuon pair are obtained in bins of the invariant mass of the second dimuon pair\([9]\). These distributions are described by a double Crystal Ball function for the signal and an exponential function for the background component. The position of the J/\(\psi\) peak, the effective mass resolution and the tail parameters of the double Crystal Ball function are fixed to the values determined from analysis of the J/\(\psi\) signal shape for an inclusive J/\(\psi\) sample. The fitted yields of J/\(\psi\) \(\rightarrow (\mu^+\mu^-)_1\) in bins of the \((\mu^+\mu^-)_2\) invariant mass are presented in Fig. 1.

The distribution in Fig. 1 is fit with a double Crystal Ball function for the signal and an exponential function for the background, in the same way as previously described.

The obtained number of events with double J/\(\psi\) production is \(N^{J/\psi,J/\psi} = 139.6 \pm 17.8\), the statistical significance of this signal is determined to be \(\Delta\chi^2/ndf = 61.3/8\) and exceeds 6\(\sigma\). The fit with free mass and resolution gives the consistent results \(N^{J/\psi,J/\psi} = 140.1 \pm 21.4\), \(m^{J/\psi} = 3094.9 \pm 2.4\) MeV/c\(^2\) and \(\sigma^{J/\psi} = 14.6 \pm 2.1\) MeV/c\(^2\).

\(^2\)The transverse momentum of the \(\mu^+\mu^-\) combination has been used as an ordering criterion.

Figure 1: The fitted yields of J/\(\psi\) \(\rightarrow (\mu^+\mu^-)_1\) in bins of \((\mu^+\mu^-)_2\) invariant mass. The line represents a fit with a double Crystal Ball function for the signal and an exponential function for the background.
The raw yield of $J/\psi$ events, where both $J/\psi$ mesons are within the signal window, defined as $2 < y^{J/\psi} < 4.5$ and $p_{T}^{J/\psi} < 10 \text{ GeV}/c$, is found to be $136.7 \pm 17.5$.

The contribution to the sample from the pileup of two interactions producing each a single $J/\psi$ meson is studied using Monte Carlo simulation. Taking into account the mean number of primary proton-proton collisions per bunch crossing, equal to 2.5, as well as the measured $J/\psi$ production cross-section [11], the pileup background has been estimated to be less than 1.5 events, and has been neglected.

3 Efficiency evaluation

The total per-event efficiency for a $J/\psi$ event, $\varepsilon_{J/\psi}^{\text{tot}}$, is decomposed into three factors,

$$\varepsilon_{J/\psi}^{\text{tot}} = \varepsilon_{\text{sel\&reco\&acc}}^{J/\psi} \times \varepsilon_{\mu\text{ID}}^{J/\psi} \times \varepsilon_{\text{trg}}^{J/\psi},$$

where $\varepsilon_{\text{sel\&reco\&acc}}^{J/\psi}$ is the efficiency for acceptance, reconstruction and selection, $\varepsilon_{\mu\text{ID}}^{J/\psi}$ is the trigger efficiency for selected events, and $\varepsilon_{\text{trg}}^{J/\psi}$ is the efficiency for muon identification.

The efficiency for acceptance, reconstruction and selection for two $J/\psi$ mesons, $\varepsilon_{\text{sel\&reco\&acc}}^{J/\psi}$, is factorized into the product of efficiencies for the first and second $J/\psi$:

$$\varepsilon_{J/\psi} = \varepsilon_{\text{sel\&reco\&acc}}^{J/\psi} \times \varepsilon_{J/\psi_1} \times \varepsilon_{J/\psi_2},$$

where the efficiencies $\varepsilon_{J/\psi_1,2}$ are evaluated using Monte Carlo simulation. The efficiencies are determined as functions of the rapidity $y^{J/\psi}$, transverse momentum $p_{T}^{J/\psi}$, and $|\cos \vartheta^{*}|$, where $\vartheta^{*}$ is the angle between $\mu^{+}$ momentum in the $J/\psi$ center-of-mass frame and the $J/\psi$ flight direction in the laboratory frame.

The efficiency of muon identification is extracted from the analysis of the inclusive $J/\psi$ sample. Two efficiencies have been evaluated: the single muon identification efficiency $\varepsilon_{\mu\text{ID}}^{J/\psi}$ and the $J/\psi$ efficiency $\varepsilon_{J/\psi}$ as a function of the cut on $\Delta \log \mathcal{L}^{n-h}$, and the $J/\psi$ efficiency $\varepsilon_{J/\psi}$ as a function of the cut on $\min(\Delta \log \mathcal{L}^{n-h})$. The efficiency of muon identification for $J/\psi$ events has also been estimated from the $J/\psi$ signal itself. The results of these muon identification efficiency studies are in good agreement: $\varepsilon_{\mu\text{ID}}^{J/\psi} = (97.4 \pm 20.7)\%$, $\varepsilon_{J/\psi} = (90.9 \pm 0.1)\%$ and $\varepsilon_{J/\psi} = (91.0 \pm 0.1)\%$. The value of $\varepsilon_{J/\psi}^{\mu\text{ID}} = (91.0 \pm 0.1)\%$ has been used as a global factor for the evaluation of the total efficiency using Eq. [1].

The trigger efficiency is calculated for $J/\psi$ events, explicitly triggered by one of the $J/\psi$. The raw yield of such events is found to be $116.2 \pm 16.3$. The trigger efficiency for a single $J/\psi$ has been determined directly on data from the inclusive $J/\psi$ sample as a function of the rapidity $y^{J/\psi}$ and transverse momentum $p_{T}^{J/\psi}$ using a method that exploits the fact that $J/\psi$ events can be triggered by the $J/\psi$ daughters (trigger on signal, TOS), or by the rest of the event (trigger independent of signal, TIS) [11]. The overlap between these two cases allows to calculate the trigger efficiency directly from the data.

Global event cuts were applied in trigger to remove high multiplicity events. The effect of these cuts has been studied in detail for the inclusive $J/\psi$ events [11]. We assume the same efficiency for the global event cuts, as justified by the qualitative comparison of global event activity for $J/\psi$ and inclusive $J/\psi$ events.
4 Efficiency corrected yield and properties of J/ψ J/ψ events

The efficiency corrected number of events with two J/ψ in the signal window, $N_{\text{corr J/ψ J/ψ}}$, is extracted, using the background subtraction procedure of Sec. 2, from efficiency weighted distributions, where each event gets a weight $\omega$, defined as

$$\omega^{-1} = \varepsilon_{\text{tot J/ψ J/ψ}}^{-1},$$

where $\varepsilon_{\text{tot J/ψ J/ψ}}$ is the total efficiency of Eq. (1). The efficiency corrected fitted yields of $J/\psi \rightarrow (\mu^+\mu^-)_1$ in bins of $(\mu^+\mu^-)_2$ invariant mass are presented in Fig. 2. The distribution is fitted with a double Crystal Ball function for the signal and an exponential function for the background component with fixed position of the $J/\psi$ peak, and the effective mass resolution determined from the inclusive $J/\psi$ sample. The number of efficiency corrected events with double $J/\psi$ is found to be

$$N_{\text{corr J/ψ J/ψ}} = 667.1 \pm 127.0$$

The efficiency corrected $J/\psi$ J/ψ invariant mass spectrum is shown in Fig. 3. The bulk of events is concentrated in the low invariant mass region. The theoretical prediction
for the shape of this distribution [4] is overlayed as a red line, and it peaks sharply just above the \( J/\psi \) production threshold. The shape of \( J/\psi J/\psi \) invariant mass spectrum is sensitive to an admixture of non-direct production of \( J/\psi J/\psi \) pairs from \( J/\psi \chi_c, J/\psi \psi', \chi_c\chi_c, \psi\chi_c \) etc., etc., that are not accounted for by the model in Ref. [4]. The charm tensor tetraquark state \( \Theta_{cc} \) (if it exists) also affects the invariant mass spectrum of \( J/\psi J/\psi \) pairs [4]. With more data a signal from \( \Theta_{cc} \to J/\psi J/\psi \) as well as a signal from \( \chi_{b0,2} \to J/\psi J/\psi \) decays could be observed [15].

![Figure 3:](image)

5 Systematic uncertainties

A major source of systematic uncertainties is the determination of the per-event weight \( \omega \), defined by Eq. (2). The systematic uncertainty is obtained by varying \( \omega \) according to the uncertainties of the various factors entering Eq. (1). The systematic uncertainty on \( N_{corr}^{J/\psi J/\psi} \) associated with the uncertainty of the per-event weight \( \omega \) is found to be 3%. This contains contribution of 3% from the statistical uncertainty in determination of the trigger efficiency \( \varepsilon_{trg/TOS}^{J/\psi J/\psi} \), and a smaller contribution of 2% from the statistical uncertainty in the selection, reconstruction and acceptance efficiency \( \varepsilon_{sel&reco&acc}^{J/\psi J/\psi} \).

An additional systematic error, associated with the evaluation of trigger efficiency is estimated using several different approaches, e.g., comparison of trigger efficiencies
evaluated for events triggered only by the first and/or the second J/ψ, and found to be 8%.

The systematic error associated with the global event cuts is 2%, and that associated with the difference between data and Monte Carlo simulation for the $\chi^2_{\mathrm{DTF}} < 5$ cut is 3%. The systematic uncertainties associated with other cuts used in selection $\chi^2_{\mathrm{tr}}/\text{ndf} < 5$, $\chi^2_{\mathrm{VX}} < 20$, $\Delta_{\mathrm{KL}}^{\text{min}} > 5000$ and $\Delta \log L^{\mu-} > 0$ or the J/ψ lineshape parametrization are found to be small and have been neglected here. An additional systematic error of 1.1% per J/ψ is associated with the muon identification efficiency [11]. The largest systematic error of 4% per track is associated with the track-finding efficiency [12].

The luminosity was measured at specific periods during the data taking using both Van der Meer scans [13] and a beam-profile method [14]. Consistent results are found for the absolute luminosity scale with a precision of 10% dominated by the beam current uncertainty [11].

The relative systematic uncertainties are summarized in Table 1, where the total systematic error is defined as the quadratic sum of individual components.

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per-event efficiency</td>
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</tr>
<tr>
<td>Trigger efficiency</td>
<td>8</td>
</tr>
<tr>
<td>Global event cuts</td>
<td>2</td>
</tr>
<tr>
<td>MC-data difference</td>
<td>3</td>
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<tr>
<td>Muon identification</td>
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<tr>
<td>Tracking</td>
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<tr>
<td>Luminosity</td>
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<tr>
<td>Total</td>
<td>21</td>
</tr>
</tbody>
</table>

6 Cross-section determination

The cross-section of double J/ψ production in signal window $2 < y_{\mathrm{J/}\psi} < 4.5$ and $p_{\mathrm{T}}^{\mathrm{J/}\psi} < 10$ GeV/$c$ is computed as

$$\sigma^{\mathrm{J/}\psi \text{J/}\psi} = \frac{1}{\mathcal{L} \times B_{\mu^+\mu^-}^{\mathrm{J/\psi \to \mu^+\mu^-}}} \times N_{\mathrm{J/\psi \text{J/\psi}}}^{\text{corr}}$$

(3)

where $N_{\mathrm{J/\psi \text{J/\psi}}}^{\text{corr}}$ is the efficiency corrected number of events with two J/ψ in the signal window, $\mathcal{L} = 35.2 \pm 3.5$ pb$^{-1}$ is the integrated luminosity, and $B_{\mu^+\mu^-}^{\mathrm{J/\psi \to \mu^+\mu^-}} = (5.93 \pm 0.06)\%$ [16] is the J/ψ → $\mu^+\mu^-$ branching ratio. The result is

$$\sigma^{\mathrm{J/\psi \text{J/\psi}}} = 5.6 \pm 1.1 \pm 0.5 \pm 0.9 |_{\text{tr}} \pm 0.6 |_{\mathcal{L}} \text{ nb},$$

6
where the first uncertainty is statistical, the second is the systematic error associated with the efficiency determination, the third is the systematic error associated with the track reconstruction and the fourth arises from the uncertainty in the luminosity determination [10].

Summary

The production of $J/\psi J/\psi$ pairs in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV is observed with the LHCb detector with a statistical significance in excess of $6\sigma$. The cross-section for $J/\psi J/\psi$ events with both $J/\psi$ in the rapidity range $2 < y^{J/\psi} < 4.5$ and with transverse momentum $p_T^{J/\psi} < 10$ GeV/c is measured to be

$$\sigma^{J/\psi J/\psi} = 5.6 \pm 1.1 \pm 1.2 \text{ nb}$$
$$= 5.6 \pm 1.1 \pm 0.5 \pm 0.9 |_{\text{stat}} \pm 0.6 |_{\text{lum}} \text{ nb},$$

where the first uncertainty is statistical, the second is the systematic error associated with the efficiency determination, the third is the systematic error associated with the track reconstruction and the fourth arises from the uncertainty in the luminosity determination. The invariant mass distribution of the $J/\psi J/\psi$-events has been studied and compared with the theory predictions.

References


S. Kullback, “Information theory and statistics”, John Wiley and Sons, New York, (1959);


