Associated production of $J/\psi$ pairs with the ATLAS detector

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A recent measurement of prompt $J/\psi$ pair production is presented, using a sample of 11.4 fb$^{-1}$ of proton-proton collision data collected at $\sqrt{s} = 8$ TeV in the ATLAS detector. The differential cross-section is measured as a function of kinematic distributions for the lower-$p_T$ $J/\psi$ meson and for the di-$J/\psi$ system. A data-driven approach is used to extract the fraction of prompt $J/\psi$ pair events due to double parton scattering and an effective cross-section of double parton scattering is measured to be $\sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat}) \pm 1.0(\text{syst}) \pm 0.1(\text{BF}) \pm 0.1(\text{lumi})$ mb.
1. Introduction

The simultaneous production of quarkonium with vector bosons or with other quarkonium states allows the mechanism for quarkonium production to be probed in a new regime. These final states are sensitive to non-perturbative quantum chromodynamics (QCD) and to higher-order QCD corrections, and also allow the contribution from multiple parton interactions to be studied.

The ATLAS collaboration has published several measurements of the associated production of quarkonia, including $J/\psi + W$ production in the 7 TeV data [2] and $J/\psi + Z$ production in the 8 TeV data [3]. The current presentation will describe the recent measurement of $J/\psi$ pair production in the 8 TeV dataset [4], using 11.4 fb$^{-1}$ of proton-proton collision data recorded in the ATLAS detector [1] during the 2012 running period. Each $J/\psi$ candidate is selected in the $J/\psi \rightarrow \mu^+ \mu^-$ decay mode.

In the following, the $J/\psi$ candidates are separated into prompt decays, where the $J/\psi$ is produced directly in the p-p interaction or through feed-down decays from higher-mass charmonium states, or non-prompt decays, where the charmonium candidate is produced in the decay chain of a $b$-hadron and typically has a displaced decay vertex. Di-$J/\psi$ candidates can be produced either from a single parton scattering (SPS) process, where the two mesons are produced from a single gluon-gluon collision, or from double parton scattering (DPS), where two independent pairs of partons scatter in a single p-p collision. The aim of this measurement is to extract the prompt-prompt di-$J/\psi$ candidates, and to compare contributions arising from SPS and DPS processes.

2. Analysis

Events are selected using dimuon triggers and a set of kinematic selection cuts, including transverse momentum and rapidity requirements on each $J/\psi$ candidate: $p_T > 8.5$ GeV and $|y| < 2.1$. Corrections are applied for the trigger, reconstruction and event selection efficiencies, and the muon fiducial region is corrected with a kinematic acceptance factor.

The prompt di-$J/\psi$ signal is separated from background processes using a sequence of fits: non-$J/\psi$ background is removed using a two-dimensional fit to the $J/\psi$ invariant masses; non-prompt background from $b$-hadron decays is removed in a two-dimensional fit to the $J/\psi$ transverse decay lengths; and pile-up background is removed using a one-dimensional vertex separation fit. Figure 1 illustrates the one-dimensional projections of the 2D fit to the transverse decay length, $L_{xy}$, of each $J/\psi$ candidate. Resolution functions are determined from an inclusive $J/\psi$ sample and four fits are performed, depending on whether each $J/\psi$ candidate lies in the central or forward rapidity region. Extracting the prompt-prompt di-$J/\psi$ fraction in four coarse rapidity regions can lead to a possible bias in the prompt-prompt event weights when applied to differential kinematic distributions (e.g. as a function of $J/\psi$ $p_T$). A bias correction is extracted from Monte Carlo samples generated with PYTHIA8 [5] and is shown in Figure 2 for all the kinematic variables considered in this analysis.

The double parton scattering (DPS) contribution is extracted using a data-driven procedure, in which pairs of $J/\psi$ candidates are chosen randomly from two different events in the di-$J/\psi$ sample. This procedure assumes that the $J/\psi$ candidates in genuine DPS events are produced independently. A 2D template of the absolute difference in $J/\psi$ rapidities, $|\Delta y|$, against the azimuthal
Figure 1: The transverse decay length spectra $L_{xy}$ of the leading and sub-leading $J/\psi$ mesons in the central-central rapidity region [4].

Figure 2: Bias correction for the prompt-prompt fraction $f_{pp}$: central (left) and forward (right) rapidity [4].

angle difference, $|\Delta \phi|$, is used to derive DPS event weights. The DPS-dominated region $|\Delta y| > 1.8$ and $|\Delta \phi| > \pi/2$ is normalised to the data, then the SPS template is obtained by subtracting the DPS contribution from the background-subtracted data. Figure 3 shows the data-driven DPS and SPS template distributions.

3. Results

Figure 4 shows two differential prompt-prompt di-$J/\psi$ cross-section measurements in the $J/\psi$ fiducial volume ($p_T > 8.5$ GeV and $|y| < 2.1$), as a function of the $p_T$ of the sub-leading $J/\psi$ and of the $p_T$ of the di-$J/\psi$ system. The central values assume unpolarised $J/\psi$ mesons and the yellow bands indicate the maximal spin-alignment variation on the measurements. The DPS-weighted distributions are also shown. In the second plot, the peak at low $p_T(J/\psi J/\psi)$ corresponds to back-to-back $J/\psi$ mesons (the “away” region), while the second peak at higher $p_T$ is due to $J/\psi$ mesons produced in the same direction, recoiling against a gluon, and hence is a next-to-leading order effect.
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Figure 3: Data-driven templates of $|\Delta y|$ against $|\Delta \phi|$ for DPS (left) and SPS (right) [4].

Figure 4: Differential cross-sections in the central rapidity region as a function of the $p_T$ of the sub-leading $J/\psi$ (left) and $p_T$ of the di-$J/\psi$ system (right) [4].

Further differential cross-section measurements are shown in Figure 5 within the muon fiducial volume, without acceptance corrections. The data are compared with a leading-order DPS prediction [6], normalised to the measured DPS fraction, and a partial next-to-leading order SPS calculation, denoted NLO* [7, 8]. The SPS prediction has been scaled by a constant feed-down correction factor of 1.85, to allow for feed-down from $\psi(2S)$. Although there is reasonable agreement between the data and predictions, it can be seen that the NLO* SPS + LO DPS cross-section shows some discrepancy with data at large di-$J/\psi$ invariant mass, $m(J/\psi J/\psi)$, and at low $p_T(J/\psi J/\psi)$. These regions correspond to di-$J/\psi$ production in an away topology, and may indicate that a non-constant feed-down correction or other effects need to be included in the predictions.

An inclusive prompt-prompt di-$J/\psi$ cross-section can be measured in the $J/\psi$ fiducial volume $p_T > 8.5$ GeV, $|y| < 2.1$ for two rapidity regions of the sub-leading $J/\psi$ meson, assuming unpolarised $J/\psi$ mesons:

$$\sigma(pp \rightarrow J/\psi J/\psi + X) = \begin{cases} 82.2 \pm 8.3 \text{ (stat) } \pm 6.3 \text{ (syst) } \pm 0.9 \text{ (BF) } \pm 1.6 \text{ (lumi) pb, } |y| < 1.05, \\ 78.3 \pm 9.2 \text{ (stat) } \pm 6.6 \text{ (syst) } \pm 0.9 \text{ (BF) } \pm 1.5 \text{ (lumi) pb, } 1.05 \leq |y| < 2.1, \end{cases}$$

where the contributions to the uncertainty are the statistical, systematic, branching fraction and luminosity uncertainties, respectively.

The effective DPS cross-section $\sigma_{\text{eff}}$ can be derived using the formula

$$\sigma_{\text{eff}} = \frac{1}{2} \frac{\sigma^2_{J/\psi}}{\sigma_{\text{DPS}}} = \frac{1}{2} \frac{\sigma^2_{J/\psi}}{\sigma_{\text{DPS}} \times \sigma_{J/\psi J/\psi}},$$

(3.1)
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Figure 5: Total and DPS cross-sections as a function of the di-$J/\psi$ invariant mass (left) and $p_T$ (right) [4].

where $\sigma_{J/\psi J/\psi}$ is measured in the current analysis, $\sigma_{J/\psi}$ is taken from the ATLAS prompt $J/\psi$ cross-section measurement at 8 TeV [9] and the DPS fraction $f_{\text{DPS}} = (9.2 \pm 2.1 \text{ (stat)} \pm 0.5 \text{ (syst)})\%$ is taken from the $\Delta y$ distribution. This gives a value of

$$\sigma_{\text{eff}} = 6.3 \pm 1.6 \text{(stat)} \pm 1.0 \text{(syst)} \pm 0.1 \text{(BF)} \pm 0.1 \text{(lumi)} \text{ mb}, \quad (3.2)$$

where the uncertainties are as described above. A summary of $\sigma_{\text{eff}}$ measurements from different centre-of-mass energies and different final states is presented in Figure 6. The current measurement lies somewhat lower than many of the previous values, and is close to the D0 di-quarkonia results [10, 11]. The di-$J/\psi$, $J/\psi$-$\Upsilon$ and 4-jet processes are dominated by gluon interactions and should therefore probe the gluon distribution in proton; however, other measurements of these processes give higher effective cross-sections. In addition, a recent LHCb measurement of the $J/\psi$ pair production cross-section at 13 TeV [12] measures $\sigma_{\text{eff}}$ in the range $9.2 - 14.4 \text{ mb for } p_T(J/\psi) < 10 \text{ GeV}, 2.0 < y(J/\psi) < 4.5$. More detailed measurements of the DPS contribution will help to test the assumptions of process and energy dependence that are implicit in determining $\sigma_{\text{eff}}$.

4. Summary

A study of prompt di-$J/\psi$ production has been presented, using 11.4 $\text{fb}^{-1}$ of data recorded by the ATLAS detector at $\sqrt{s} = 8 \text{ TeV}$. Differential cross-section measurements are shown for $J/\psi$ and di-$J/\psi$ observables, including a data-driven estimate of the double-parton scattering contribution. A substantial dataset has already been recorded at $\sqrt{s} = 13 \text{ TeV}$, which will allow further measurements of the di-$J/\psi$ final state at higher precision in the near future.

References


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![Graph: Figure 6](image)

**Figure 6**: The effective cross-section of DPS from different energies and final states. The full list of journal references is cited in Ref. [4].


