PROCEEDINGS OF SCIENCE

Associated J/ψ production measurements at ATLAS

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The associated production of quarkonium with a vector boson or an additional quarkonium state are rare processes that provide new insight into QCD models of quarkonium production, but also provide new opportunities to study double parton scattering. We present new measurements of J/ψ production in association with a vector boson or another J/ψ, in pp collisions using the ATLAS detector at the LHC. Differential production cross-sections of these processes are measured, and a data-driven approach is used to estimate the single parton scattering and double parton scattering contributions to these rates.

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1. Introduction

Associated production of charmonia and a vector boson or another onium state at the LHC offers the ability to test our understanding of non-perturbative Quantum Chromodynamics (QCD), in addition to providing an opportunity to study charmonium production models. These events can be produced from a single gluon–gluon collision via single parton scattering (SPS) or from two independent parton–parton scatters in a single proton–proton collision, known as double parton scattering (DPS).

Although SPS is the dominant process, it is expected that DPS plays a larger role at high energies [1]. Testing possible correlations of non-perturbative origin between the partons in DPS events could lead to a better comprehension of non-perturbative QCD. A parameter of interest in DPS studies is the effective cross-section which is sensitive to the spatial distribution of partons in the proton.

A simplified ansatz [2] for defining the DPS cross-section in terms of the production cross-sections of the two final states (A, B) and an effective cross-section is:

$$\sigma_{\rm DPS} = \frac{m}{2}\frac{\sigma_{\rm A}\sigma_{\rm B}}{\sigma_{\rm eff}}. \qquad (1.1)$$

In this equation m is a symmetrisation parameter where $m = 1(2)$ if the processes A and B are (in)distinguishable. The effective cross-section, $\sigma_{\rm eff}$, measures the inner structure of the proton in the impact parameter space. In the derivation of Eq. 1.1, $\sigma_{\rm eff}$ is assumed to be process and energy independent to first-order approximations in perturbative QCD predictions. There is no theoretical proof of these assumptions and therefore experimental confirmation is necessary.

We present the recent results of the production of a prompt J/ψ meson in association with a $W^\pm$ boson [3], a J/ψ meson in association with a Z boson [4], and the prompt pair production of J/ψ mesons [5] using the ATLAS detector [6] at the LHC. In all of these results J/ψ mesons are reconstructed using the $J/\psi \to \mu^+\mu^-$ decay mode

2. Associated production of a J/ψ meson with a vector boson

The associated production of $W^\pm + J/\psi$ [3] provides a distinctive test of non-relativistic QCD. A $W^\pm + J/\psi$ sample, with $W \to e\nu, \mu\nu$, was selected from a dataset corresponding to an integrated luminosity of 4.51 ± 0.08 fb^{-1} [7] of proton–proton collisions at $\sqrt{s}$ = 7 TeV. The data were collected by the ATLAS detector at the LHC in 2011 in proton–proton collisions at $\sqrt{s}$ = 7 TeV. Early theoretical studies [8, 9] suggested that this final state should be dominated by colour-octet processes, in which a $c\bar{c}$ pair is produced in the colour-octet state and evolves into a J/ψ meson. More recent predictions [10] suggest that the colour-octet and colour-singlet processes should be of the same magnitude.

The main sources of background for this process are non-prompt J/ψ mesons which are produced via the decay of a b-hadron, $t\bar{t}$ events, the production of Z bosons, and multi-jet events. To extract the signal, a simultaneous unbinned maximum likelihood fit of the J/ψ invariant mass and pseudo-proper time is performed. The resulting likelihood is used as a signal weight (prompt J/ψ events) in the fit of the W boson transverse mass using the sPlot procedure [11]. The effective

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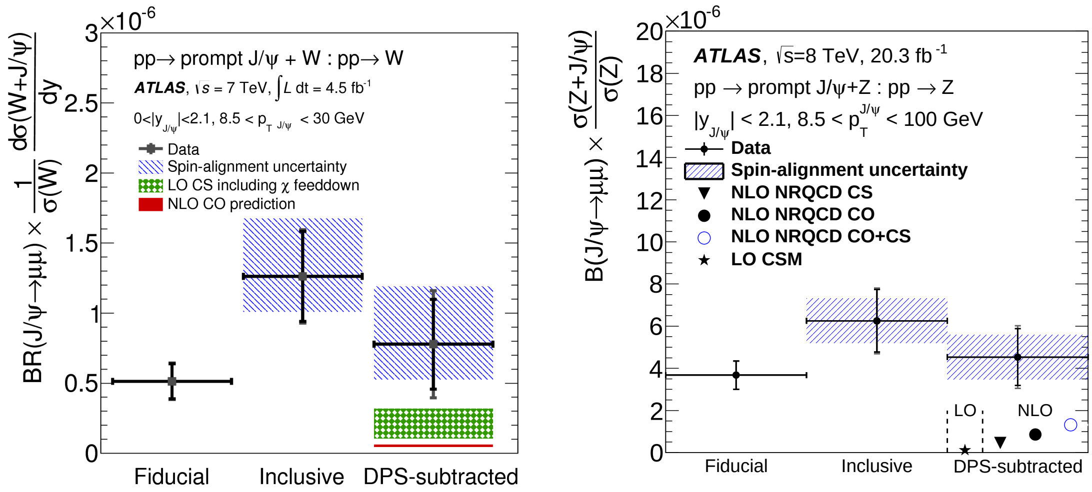
cross-section of DPS, σ_{eff} = 15 ± 3 (stat.) $^{+5}_{-3}$ (syst.) mb, is taken from the ATLAS $W^{\pm} \to l\nu_l$ + 2 jets measurement [12].

The $W^{\pm} + J/\psi$ to $W^{\pm}$ cross-section ratio is shown in Figure 1(a) and is compared to leading-order (LO) colour-singlet pQCD predictions [10] and next-to-leading-order (NLO) colour-octet predictions [9]. DPS was found to make up a large fraction of the data. The LO colour-singlet contributions are nearly an order of magnitude larger than the colour-octet contributions.

For the $Z(\to ee, \mu\mu) + J/\psi$ analysis [4], a sample was selected from a dataset corresponding to an integrated luminosity of 20.3 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 8 TeV. The main sources of background for this process are $Z \to \tau\tau$, $W \to l\nu$, diboson events, and events from pile-up. The same method to extract the signal as in the $W^{\pm} + J/\psi$ analysis was used.

The fraction of inclusive events from DPS using the effective cross-section measured in Ref. [12] was found to be (29 ± 9)% for prompt production and (8 ± 2)% for non-prompt production. By fitting the distribution of the azimuthal angle between the Z boson and J/ψ meson with a DPS template which is not normalised to the value in Ref. [12], a lower limit on the effective cross-section was measured to be 5.3 mb (3.7 mb) at 68% (95%) confidence level.

In Figure 1(b) the cross-section ratio of a prompt J/ψ meson in association with a Z boson to inclusive Z boson production is shown and is compared with LO [13] and NLO [14] colour-singlet and colour-octet predictions. The colour-octet processes are found to have a higher production rate than colour-singlet processes. The sum of the colour-singlet and colour-octet predictions underestimate the data in the transverse momentum range studied.



(a) (b)

Figure 1: The production cross-section ratios of (a) $W^{\pm} + J/\psi$ to $W^{\pm}$ [3] and (b) $Z + J/\psi$ to Z [4] in the J/ψ fiducial region, after correction for J/ψ acceptance, and after subtraction of the double parton scattering component.

3. Prompt pair production of J/ψ mesons

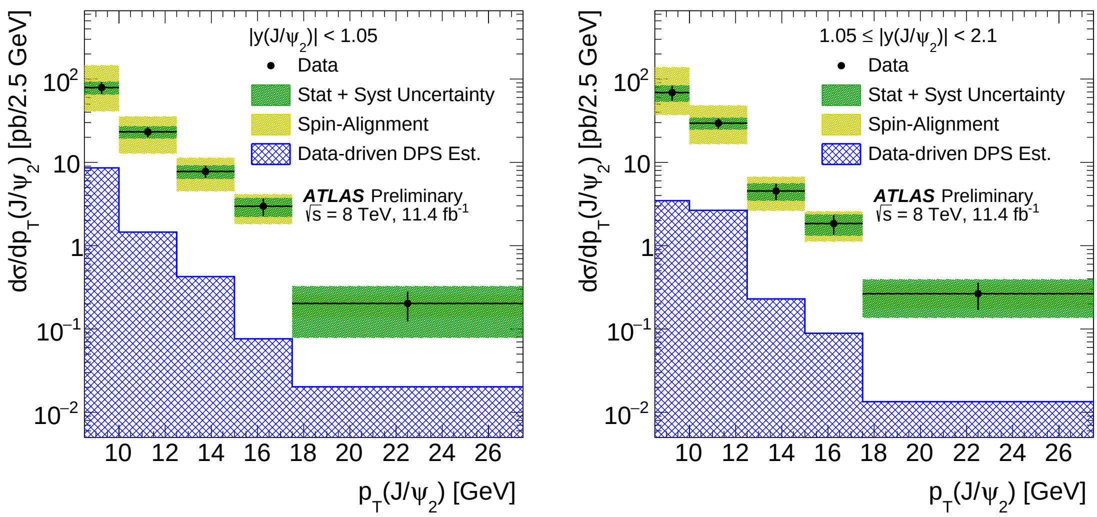
In this analysis [5], a di-J/ψ sample was selected from a dataset corresponding to an integrated luminosity of 11.4 ± 0.3 fb^{-1} [15]. The data were collected by the ATLAS detector at the LHC in 2012 in proton–proton collisions at $\sqrt{s}$ = 8 TeV. The main sources of background to di-J/ψ production, where both J/ψ mesons are produced promptly (PP), are non-J/ψ events, non-prompt J/ψ events, and events from pile-up. To extract the PP di-J/ψ signal a two-dimensional fit of the mass and transverse decay length distributions is performed sequentially in four rapidity regions after which pile-up background is subtracted.

The inclusive PP di-J/ψ cross-section under the assumption of unpolarised J/ψ mesons and with the kinematic requirements of $p_{\mathrm{T}} > 8.5$ GeV, $|y| < 2.1$ is measured to be:

$$\sigma(pp \to J/\psi J/\psi + X) = \begin{cases} 82.2 \pm 8.3\,(\mathrm{stat}) \pm 6.3\,(\mathrm{syst}) \pm 0.9\,(\mathrm{BF}) \pm 2.3\,(\mathrm{lumi})\,\mathrm{pb}, & |y| < 1.05 \\ 78.3 \pm 9.2\,(\mathrm{stat}) \pm 6.6\,(\mathrm{syst}) \pm 0.9\,(\mathrm{BF}) \pm 2.2\,(\mathrm{lumi})\,\mathrm{pb}, & 1.05 \leq |y| < 2.1. \end{cases}$$

The above rapidity regions are defined in terms of the sub-leading J/ψ meson. The systematic uncertainties for the branching fraction of $J/\psi \to \mu^+\mu^-$ and luminosity are quoted separately.

The PP differential cross-sections as a function of the sub-leading J/ψ p_{T} are shown for the central and forward rapidity regions in Figure 2. A data-driven method of modelling DPS by combining re-sampled J/ψ mesons from two random events in the di-J/ψ sample was used. The template is normalised to a DPS-dominated region of the data, $\Delta y \geq 1.8$ and $\Delta\phi \leq \pi/2$, and avoids dependence on perturbative QCD corrections and on J/ψ production models. The DPS-weighted distributions are included in the figure. These results are obtained assuming unpolarised J/ψ mesons and exclude the J/ψ spin-alignment uncertainty which is shown separately in the figure.



(a) (b)

Figure 2: The differential cross-section of PP di-J/ψ production [5] as a function of the sub-leading J/ψ p_{T}, $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}(J/\psi_2)$, in the (a) central and (b) forward rapidity regions. The uncertainty due to the choice of J/ψ spin-alignment is shown separately.

In Figure 3, total and DPS di-J/ψ distributions extracted from data are compared to the LO DPS [16] and sum of the LO DPS and NLO SPS [17, 18] predictions in the fiducial volume assuming unpolarised J/ψ production. The DPS and SPS predictions are normalised to the f_{DPS} value measured with the data-driven model.

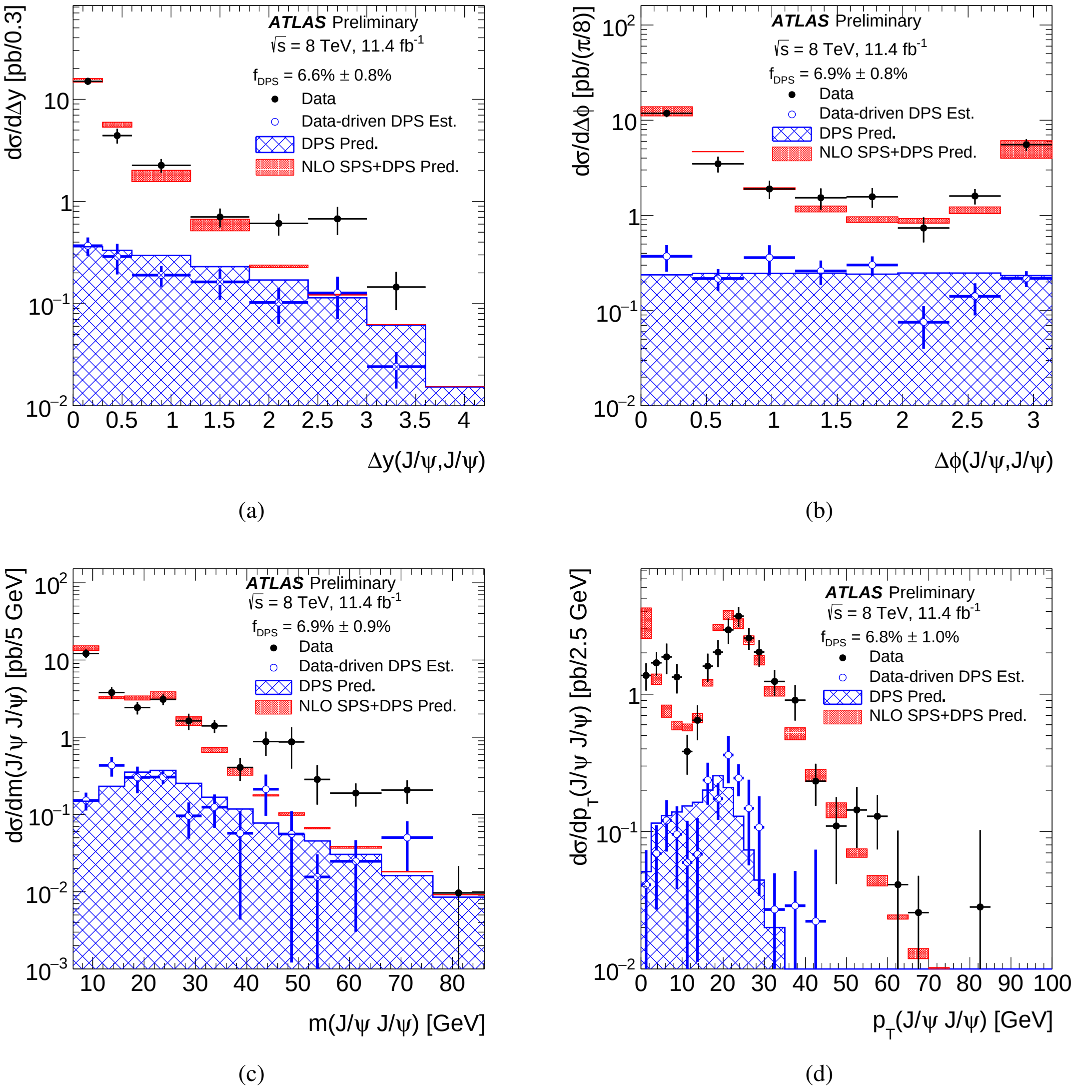


Figure 3: The total and DPS differential cross-sections of PP di-J/ψ production [5] as a function of (a) the difference in rapidity between the two J/ψ mesons, (b) the azimuthal angle between the two J/ψ mesons, (c) the invariant mass of the di-J/ψ, and (d) the transverse momentum of the di-J/ψ. Shown are the data as well as the LO DPS [16] + NLO SPS [17, 18] predictions. The DPS and NLO SPS predictions are normalised to the value of f_{DPS} found in the data.

The measured DPS distributions agree quite well with the DPS predictions. The distributions reveal that a significant fraction of events have a topology in which the NLO SPS contributions dominate, when the J/ψ pair is produced back-to-back with respect to an additional gluon. Therefore LO predictions alone, which do not include this topology, are not enough to describe PP di-J/ψ production.

A disagreement between the total data distribution and the total theory predictions is observed at large differences in rapidity between the two J/ψ mesons (Δy), large invariant mass, and in the low-p_{T} region that corresponds to di-J/ψ production in a back-to-back topology. A plausible explanation for the excesses is the presence of a non-constant contribution to the di-J/ψ final state from feed-down of back-to-back SPS pair production from excited charmonium states which could change the kinematic properties of the SPS distribution [19, 20]. The wide peak seen at low di-J/ψ p_{T} can be explained either by a large effect due to the inclusion of the intrinsic parton transverse momentum, smearing due to a non-constant feed-down component, or a combination of the two.

The effective cross-section obtained from these inputs is $\sigma_{\mathrm{eff}} = 8.7 \pm 1.1(\mathrm{stat}) \pm 1.4(\mathrm{syst}) \pm 0.1(\mathrm{BF}) \pm 0.3(\mathrm{lumi})$ mb. It is compared to measurements from other experiments and processes in Figure 4. The ATLAS and D0 experiment analyses provide a hint that the effective cross-section measured from the prompt di-J/ψ final state could be lower than that measured from the other final states. It is interesting to note that the di-J/ψ, J/ψ+Υ, and 4-jet processes are each dominated by gluon interactions and therefore should directly probe the gluon distribution in the proton [21, 22, 23]. The pion cloud model [24] predicts a smaller average transverse distance between gluons in the nucleon than between quarks. Such a difference could produce a lower effective cross-section for gluon-dominated processes. The final results can be found in Ref. [25].

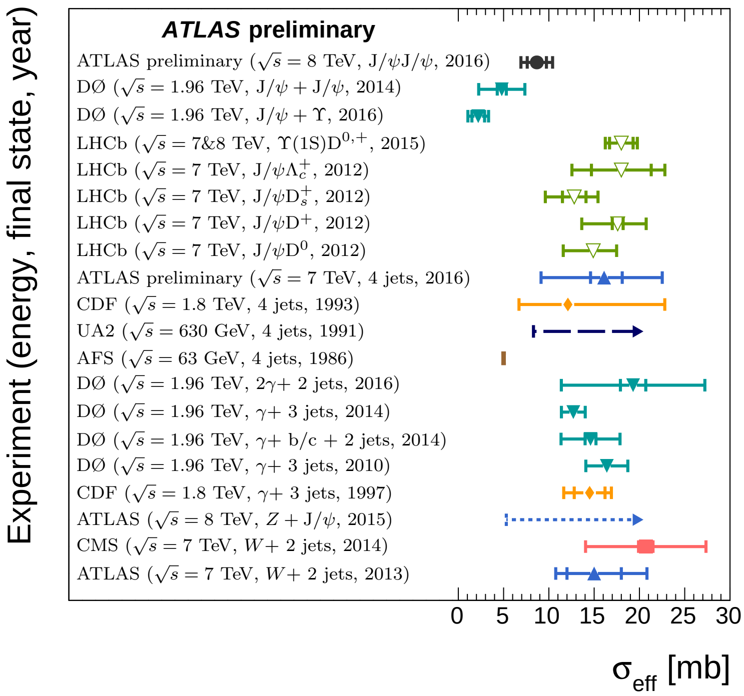


Figure 4: The effective cross-section of DPS from different energies and final states. The full list of papers is cited in Ref. [5].

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