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# Measurement of the production cross section of prompt $J/\psi$ mesons in association with a $W^{\pm}$ boson in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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Abstract: The process $pp \to W^{\pm}J/\psi$ provides a powerful probe of the production mechanism of charmonium in hadronic collisions, and is also sensitive to multiple parton interactions in the colliding protons. Using the 2011 ATLAS dataset of 4.5 fb$^{-1}$ of $\sqrt{s} =$ 7 TeV $pp$ collisions at the LHC, the first observation is made of the production of $W^{\pm}$ + prompt $J/\psi$ events in hadronic collisions, using $W^{\pm} \to \mu\nu_{\mu}$ and $J/\psi \to \mu^{+}\mu^{-}$. A yield of $27.4^{+7.5}_{-6.5}$ $W^{\pm}$ + prompt $J/\psi$ events is observed, with a statistical significance of $5.1\sigma$. The production rate as a ratio to the inclusive $W^{\pm}$ boson production rate is measured, and the double parton scattering contribution to the cross section is estimated.

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## Contents

## 1 Introduction

Study of the production of a $W$ boson in association with a prompt $J/\psi$ meson offers new tests of Quantum Chromodynamics (QCD) at the perturbative/non-perturbative boundary as well as developing the framework for future probes of the Higgs sector and beyond-the-standard-model searches in such final states.

Perturbative calculations of heavy quarkonium production in hadronic collisions distinguish between terms that produce a heavy quark system ($Q\bar{Q}$) in a colour-singlet (CS) or a colour-octet (CO) state. The relative importance of these terms for inclusive $J/\psi$ production is a subject of debate [1–7]. In the case of prompt $J/\psi$ production in association with a $W^{\pm}$ boson, the relative contributions of CS and CO processes differ from the inclusive process. Some theoretical studies [8, 9] suggest $W^{\pm}$ + prompt $J/\psi$ production should be dominated by colour-octet processes, and thus be a distinctive test of the non-relativistic QCD (NRQCD) framework [10, 11]. In contrast, recent work [12] suggests that in 7 TeV $pp$ collisions, CO and CS (in particular, electromagnetic $W^{\pm}\gamma^{*} \rightarrow W^{\pm}J/\psi$) contributions to the $W^{\pm}$ + prompt $J/\psi$ cross section are comparable. Measurements of the production cross sections can help distinguish between these models. A search for the related processes $W^{\pm}+\Upsilon(1S)$ and $Z+\Upsilon(1S)$ performed by the CDF experiment saw no excess of events above the expected background and set upper limits on the production rate [13].

Observation and measurement of $W^{\pm}$ + prompt $J/\psi$ production for the first time represents a step in our understanding toward measurements of the Higgs boson in rare quarkonia and associated vector boson decay modes, first proposed in ref. [14]. Recent phenomenological studies [15] have emphasised the value of these rare decay modes to provide a unique probe of the Higgs boson charm couplings. Such final states can also be sensitive probes of beyond-the-standard-model (BSM) frameworks. The presence of an anomalous rate of $W^{\pm}/Z$ + prompt $J/\psi/\Upsilon$ associated production over standard model predictions can, for example, be an indication of a signature of a charged Higgs boson decay at low $\tan\beta$ in some supersymmetry models [16], or explore the possible existence of a new light scalar particle [17]. The complementarity of vector boson plus quarkonia final state measurements to ongoing BSM search programmes further emphasises the need for a robust understanding of the QCD production modes.

In addition to the single parton scattering (SPS) reaction studied as a probe of quarkonium production, double parton scattering (DPS) interactions [18–22], where the $W^{\pm}$ boson and $J/\psi$ are produced in separate parton-parton collisions from the same proton-proton interaction, can contribute to the total rate for production of a $W^{\pm}+J/\psi$ final state. These processes are not distinguishable on an event-by-event basis from SPS processes, but are expected to differ in overall kinematic features, such as angular correlations. Any measurement of the $W^{\pm}+J/\psi$ process will include both SPS and DPS contributions, and provides useful information on the DPS process as well.

This paper reports the observation of $W^{\pm}$ + prompt $J/\psi$ production in the $W^{\pm}(\rightarrow \mu^{\pm}\nu_{\mu}) + J/\psi(\rightarrow \mu^{+}\mu^{-})$ channel. Prompt $J/\psi$ candidates that are produced in decays of heavier charmonium states (e.g. $\chi_c \rightarrow \gamma + J/\psi$) are not distinguished from directly-produced $J/\psi$. $W^{\pm}$ + prompt $J/\psi$ events due to DPS are included in the measurement and their contribution to the total rate is estimated. This production mechanism (including both SPS and DPS contributions) is separated from the background of $W^{\pm}$ + $b$-hadrons with $b \rightarrow J/\psi + X$. An additional background from misidentified multi-jets is also considered. The cross-section ratio of $W^{\pm}$ + prompt $J/\psi$ production to the inclusive $W^{\pm}$ production is measured in the fiducial phase space of the $W^{\pm}$ boson and $J/\psi$. The cross-section ratio is also reported with the $J/\psi$ rate corrected for the muons that fall outside of the detector acceptance in transverse momentum and pseudorapidity for a given $J/\psi$ transverse momentum. This correction depends on the (unknown) spin-alignment of $J/\psi$ produced in association with a $W^{\pm}$ boson and so the results are provided for the full envelope of possible spin-alignment scenarios as was previously done for inclusive $J/\psi$ and $\Upsilon$ production measurements [23, 24].

The data used in this analysis were collected using the ATLAS detector during the 2011 proton-proton run of the Large Hadron Collider (LHC) at centre-of-mass energy 7 TeV and correspond to an integrated luminosity of $4.51 \pm 0.08\ \text{fb}^{-1}$ [25].

## 2 The ATLAS detector

ATLAS is a multi-purpose detector [26],[1] designed to study a variety of phenomena at the LHC. The inner detector (ID), which is surrounded by a superconducting solenoid that

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r,\phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe, referred to the $x$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$.

produces a 2 T magnetic field, performs tracking of charged particles for $|\eta| < 2.5$. The calorimeter system covers $|\eta| < 4.9$ and detects energy deposits from electrons, photons, muons and hadrons. The muon spectrometer (MS), outside the calorimeters, measures muon momenta using air-core superconducting toroidal magnets. A typical muon traverses three precision position measurement stations covering $|\eta| < 2.7$. Fast trigger chambers cover $|\eta| < 2.4$. The MS has a cylindrical barrel geometry covering $|\eta| \lesssim 1$ and an endcap disk geometry covering $|\eta| \gtrsim 1$. The combination of ID and MS tracking reconstructs muons with $p_{\mathrm{T}} \gtrsim 2.5$ GeV with resolution $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}$ better than 3% in the momentum range of interest (2.5–100 GeV).

## 3 Event selection

The data were collected using a single-muon trigger that required transverse momentum $p_{\mathrm{T}} > 18$ GeV. Muon candidates are reconstructed either by combining tracks found separately in the ID and MS ("combined" muons) or by extrapolating ID tracks to include hits in the MS ("segment-tagged" muons). Muon tracks are required to satisfy $|\eta| < 2.5$ so as to lie within the angular acceptance of both the ID and MS. Muon candidates with $p_{\mathrm{T}} > 3.5$ (2.5) GeV for $|\eta| < 1.3$ ($> 1.3$) are considered. The candidate hard scattering $pp$ collision vertex is chosen as the reconstructed vertex with the highest $\sum p_{\mathrm{T}}^2$ of associated tracks and the point of closest approach of muon candidate tracks to this vertex is required to be within 10 mm along the beam axis ($z$).

Events are required to have at least three identified muons to be considered for this analysis. One pair of oppositely charged muons is required to form a $J/\psi$ candidate, while an additional muon must combine with the event's missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ to form a $W^{\pm}$ candidate. The $W^{\pm}$ decay muon is required to match the muon reconstructed by the trigger algorithm used to collect the events. The momentum imbalance, $E_{\mathrm{T}}^{\mathrm{miss}}$, is caused by particles, such as neutrinos escaping detection, detector effects, or unaccounted physics processes [27]. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated as the negative of the vector sum of the transverse momentum of all reconstructed physics objects in the event, as well as all calorimeter energy clusters within $|\eta| < 4.9$ not associated with these objects.

At least one of the muons forming the $J/\psi$ candidate must have $p_{\mathrm{T}} > 4$ GeV and at least one must be a "combined" inner detector plus muon spectrometer muon. A vertex fit is performed to constrain the two $J/\psi$ muons to originate from a common point. The invariant mass of the dimuon system calculated with track parameters modified by the vertex fit must satisfy $2.5 < m_{\mu^+\mu^-} < 3.5$ GeV. The $J/\psi$ candidate is required to have transverse momentum $p_{\mathrm{T}}^{J/\psi}$ and rapidity $y_{J/\psi} \equiv \tanh^{-1}(p_z^{J/\psi}/E^{J/\psi})$ satisfying $p_{\mathrm{T}}^{J/\psi} > 8.5$ GeV and $|y_{J/\psi}| < 2.1$; this ensures high acceptance and efficiency for the $J/\psi$ candidate. In addition, as the signal is expected to decrease faster than background with increasing $p_{\mathrm{T}}^{J/\psi}$, $p_{\mathrm{T}}^{J/\psi} < 30$ GeV is required to improve the signal-to-background ratio.

The remaining "combined" muons are considered as $W^{\pm}$ boson decay candidates. These are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.4$ in order to be within the acceptance of the trigger. The closest distance of the $W^{\pm}$ decay muon track to the primary vertex must be within 1 mm in $z$. In order to reduce contamination from non-prompt

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muons produced in heavy flavour decays, the $W^{\pm}$ decay muon is required to have a transverse impact parameter significance $d_0/\sigma(d_0) < 3$, and it must be isolated. The impact parameter $d_0$ is defined as the distance of closest approach of the muon helix to the primary vertex in the $xy$-plane, and $\sigma(d_0)$ is the expected resolution on the measured value. The calorimetric and track isolation variables are defined as the sums of calorimeter cell $E_{\mathrm{T}}$ and track $p_{\mathrm{T}}$, respectively, within a cone of size $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon direction. The energy deposit of the muon is not included in the calorimetric isolation and only tracks (excluding the muon itself) compatible with originating at the primary vertex and with $p_{\mathrm{T}} > 1$ GeV are considered for the track isolation. A correction depending on the number of reconstructed vertices is made to the calorimetric isolation to account for energy deposits originating from additional proton-proton collisions that occur in the same bunch crossing. For the muon to be considered isolated, the two isolation variables must both be less than 5% of the muon $p_{\mathrm{T}}$. This tight selection discriminates against the multi-jet background.

In order to select events with a $W^{\pm}$ boson, $E_{\mathrm{T}}^{\mathrm{miss}}$ must exceed 20 GeV, and the $W^{\pm}$ boson transverse mass $m_{\mathrm{T}}(W)$ must exceed 40 GeV. The $W^{\pm}$ boson transverse mass is defined as

$$m_{\mathrm{T}}(W) \equiv \sqrt{2 p_{\mathrm{T}}(\mu) E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos(\phi^{\mu} - \phi^{\nu_\mu})\right)}$$

where $\phi^{\mu}$ and $\phi^{\nu_\mu}$ represent the azimuthal angles of the muon from the $W^{\pm}$ boson decay and the missing transverse momentum vector, respectively. If the invariant mass of the $W^{\pm}$ muon candidate and the $J/\psi$ candidate's oppositely charged muon is within 10 GeV of the $Z$ boson mass, the event is vetoed. After the full selection, 149 events remain, 78 with $|y_{J/\psi}| \leq 1$ and 71 with $1 < |y_{J/\psi}| < 2.1$.

Prompt $J/\psi$ candidates are distinguished from those originating from $b$-hadron decays through the separation of the primary vertex and the $J/\psi$ decay vertex. The pseudo-proper time

$$\tau \equiv \frac{\vec{L} \cdot \vec{p}_{\mathrm{T}}^{\,J/\psi}}{p_{\mathrm{T}}^{J/\psi}} \cdot \frac{m_{\mu^+\mu^-}}{p_{\mathrm{T}}^{J/\psi}},$$

is used, where $\vec{L}$ is the separation vector from the primary vertex to the $J/\psi$ decay vertex and $m_{\mu^+\mu^-}$ is the invariant mass of the $J/\psi$ candidate. Prompt $J/\psi$ decays have a pseudo-proper time consistent with zero within resolution. Non-prompt $J/\psi$ decay vertices are displaced from the primary vertex and have positive pseudo-proper time on average apart from resolution effects.

## 4 Signal extraction

The two-dimensional $J/\psi$ candidate mass and pseudo-proper time scatter distribution is shown in figure 1. These data are fit as follows: first, the two-dimensional fit described below is applied to separate the prompt $J/\psi$ component from the non-prompt $J/\psi$ component and combinatorial background. This is followed by a fit to the $W$ boson transverse mass $m_{\mathrm{T}}(W)$ to determine the contributions of $W^{\pm}$ and multi-jet background produced in association with a prompt $J/\psi$.

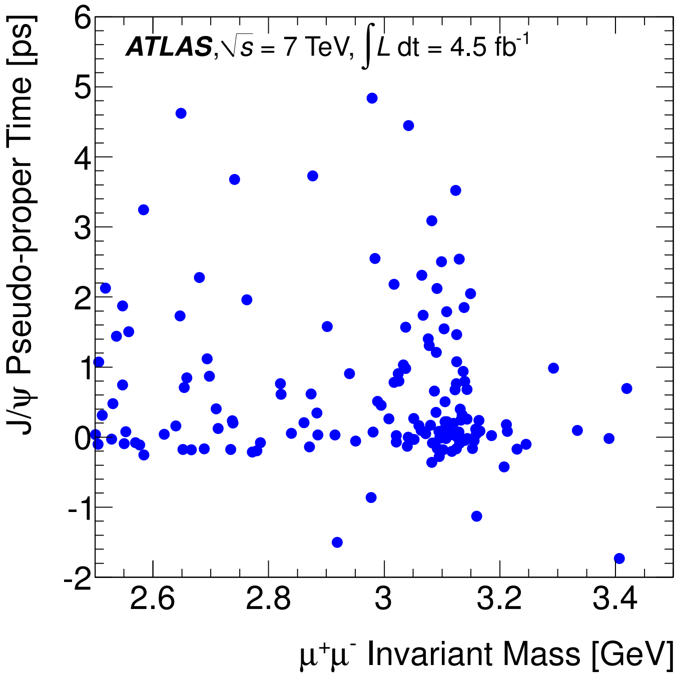


**Figure 1**. Two-dimensional plot of $W^\pm + J/\psi$ candidates in pseudo-proper time versus $\mu^+\mu^-$ invariant mass in the considered region of $J/\psi$ rapidity ($|y_{J/\psi}| < 2.1$) and transverse momentum ($8.5 < p_{\mathrm{T}}^{J/\psi} < 30$ GeV). Many candidates fall near the $J/\psi$ mass of 3.097 GeV [28] and pseudo-proper time near 0 ps, as expected from prompt $J/\psi$ production.

An unbinned maximum likelihood fit in $J/\psi$ candidate invariant mass and pseudo-proper time is used to obtain yields for prompt $J/\psi$, non-prompt $J/\psi$, and prompt/non-prompt combinatoric backgrounds. In the dimuon mass variable, the probability density functions are a Gaussian distribution for the $J/\psi$ signal and exponential functions for the combinatorial backgrounds. For the pseudo-proper time distribution, the prompt $J/\psi$ and prompt combinatoric background components are modelled by the sum of a delta-function distribution and a double-sided exponential function convolved with a Gaussian resolution function, while the non-prompt $J/\psi$ and non-prompt combinatorial background components are modelled by an exponential function (truncated to zero for $\tau < 0$) convolved with a Gaussian resolution function. The parameters that set the shapes of the fit functions, such as the mass and pseudo-proper time resolution, are considered nuisance parameters and are constrained as described below. The functional forms of the probability density functions are:

$$\begin{aligned}
M_{J/\psi}(m_{\mu^+\mu^-}) &= G(m_{\mu^+\mu^-}; m_{J/\psi}^{\mathrm{PDG}}, \sigma_m) \\
T_{\mathrm{prompt}\ J/\psi}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \Big((1-a)\delta(\tau) + aC_0 \mathrm{e}^{-|\tau|/\tau_0}\Big) \\
T_{\mathrm{non\text{-}prompt}\ J/\psi}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \Big(C_1 \theta(\tau) \mathrm{e}^{-\tau/\tau_1}\Big) \\
M_{\mathrm{prompt\ bkg}}(m_{\mu^+\mu^-}) &= C_2 \mathrm{e}^{-m_{\mu^+\mu^-}/k_0}
\end{aligned}$$

$$
\begin{aligned}
M_{\text{non-prompt bkg}}(m_{\mu^+\mu^-}) &= C_3 \mathrm{e}^{-m_{\mu^+\mu^-}/k_1} \\
T_{\text{prompt bkg}}(\tau) &= G(\tau;0,\sigma_\tau) \otimes \left((1-b)\delta(\tau) + bC_4\mathrm{e}^{-|\tau|/\tau_0}\right) \\
T_{\text{non-prompt bkg}}(\tau) &= G(\tau;0,\sigma_\tau) \otimes \left(C_5\theta(\tau)\mathrm{e}^{-\tau/\tau_2}\right).
\end{aligned}
$$

In the above, $G(x;\mu,\sigma)$ is a Gaussian function of $x$ with mean $\mu$ and width $\sigma$; $\delta$ is the Dirac delta function; $\theta$ is the step function; $a$, $b$, and the $k_i$ and $\tau_i$ are shape parameters, while the $C_i$ are appropriate normalization constants. The combined probability density function used for the fit is:

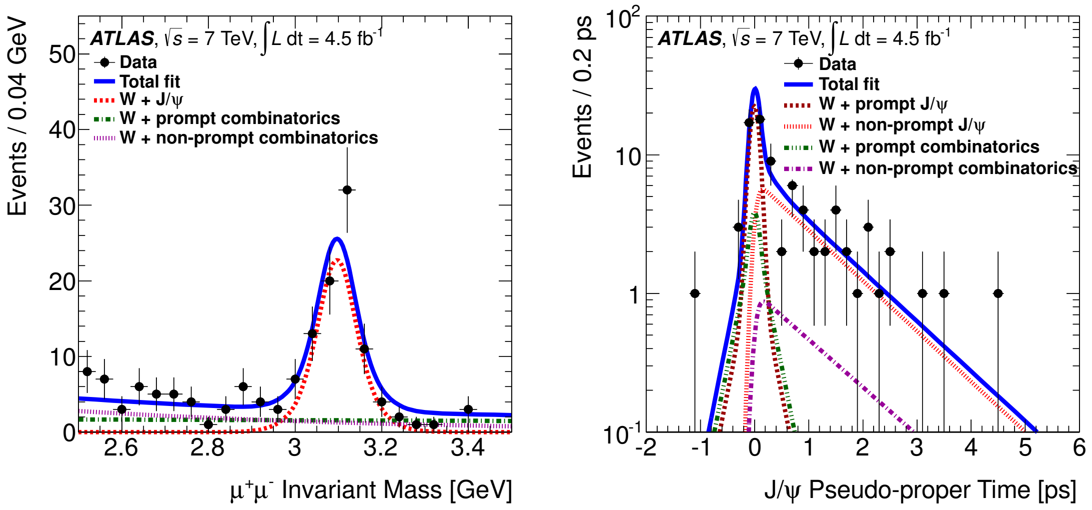
$$
\begin{aligned}
p \propto\ & N_{\text{prompt } J/\psi} \times M_{J/\psi}(m_{\mu^+\mu^-}) \times T_{\text{prompt } J/\psi}(\tau) \\
& + N_{\text{non-prompt } J/\psi} \times M_{J/\psi}(m_{\mu^+\mu^-}) \times T_{\text{non-prompt } J/\psi}(\tau) \\
& + N_{\text{prompt bkg}} \times M_{\text{prompt bkg}}(m_{\mu^+\mu^-}) \times T_{\text{prompt bkg}}(\tau) \\
& + N_{\text{non-prompt bkg}} \times M_{\text{non-prompt bkg}}(m_{\mu^+\mu^-}) \times T_{\text{non-prompt bkg}}(\tau).
\end{aligned}
$$

To account for the differences in resolution between the central and endcap detector regions, the fit is performed separately in two regions in $J/\psi$ rapidity, $|y_{J/\psi}| \leq 1$ and $1 < |y_{J/\psi}| < 2.1$. The fit is initially made on a large inclusive sample of $J/\psi$ events, selected with the same procedure as the $J/\psi$ candidates in this analysis, and the results are used to constrain the nuisance parameters $\mu$, $\sigma$, $a$, $b$, $k_i$ and $\tau_i$. The central values and uncertainties on the nuisance parameters from the inclusive fits are translated into Gaussian constraints on the parameters during the fit to the $W^\pm + J/\psi$ candidates. The values of the nuisance parameters estimated from the $W^\pm +$ prompt $J/\psi$ fits agree well with those determined in the inclusive $J/\psi$ sample, and the resulting uncertainties are similar to the uncertainty represented by the constraints. Figure 2(a) shows the mass fit in the full rapidity region ($|y_{J/\psi}| < 2.1$), whereas in figure 2(b) the pseudo-proper time fit in the $J/\psi$ mass peak region ($3.0 < m(\mu^+\mu^-) < 3.2$ GeV) is shown. Each projection shows the sum of two fits, performed separately in two regions in $J/\psi$ rapidity: $|y_{J/\psi}| \leq 1$ and $1 < |y_{J/\psi}| < 2.1$. The maximum likelihood fit permits the use of the `sPlot` procedure [29] to assign weights to each event for each component of the total probability density function (prompt $J/\psi$, non-prompt $J/\psi$, prompt combinatoric background, non-prompt combinatoric background). These weights can be used to determine the spectra of variables in the prompt $J/\psi$ signal, removing the contribution from the other sources. The procedure functions as a background subtraction technique that takes advantage of the full information available from the fit, and is used to obtain various kinematic distributions.

The robustness of the fit was tested by varying the signal and background parametrizations; changes of at most a few percent in the prompt $J/\psi$ yield were observed and are taken as systematic uncertainties (see section 7). Repeated fits to an ensemble of pseudo-experiments generated with Poisson-distributed yields and Gaussian-distributed nuisance parameters showed that the fit has no significant statistical biases, and that the uncertainties reported by the fit are accurate.

## 5 Backgrounds

A number of possible background contributions to $W^\pm +$ prompt $J/\psi$ production are considered. Production of $W^\pm$ bosons in association with $b$ quarks, with subsequent $b$-hadron



(a)

(b)

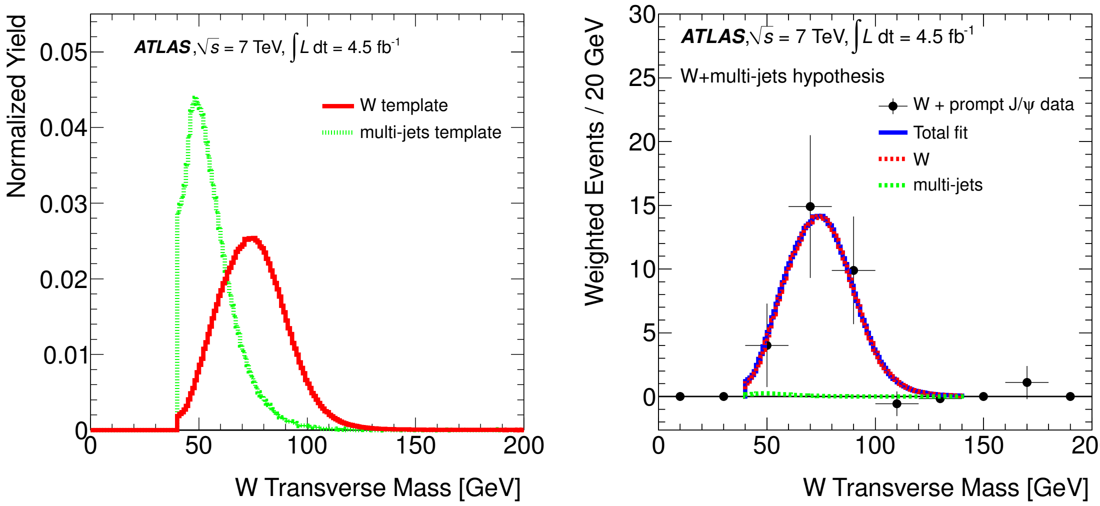
**Figure 2**. Projections in (a) invariant mass and (b) pseudo-proper time of the two-dimensional mass-pseudo-proper time fit used to extract the prompt $J/\psi$ candidates in the full rapidity region ($|y_{J/\psi}| < 2.1$). The pseudo-proper time distribution is shown for the $J/\psi$ mass peak region ($3.0 < m(\mu^+\mu^-) < 3.2$ GeV). Each projection shows the sum of two fits, performed separately in two regions in $J/\psi$ rapidity $|y_{J/\psi}| \leq 1$ and $1 < |y_{J/\psi}| < 2.1$.

decay to $J/\psi$ and other particles, produces the desired signature, except that the $J/\psi$ mesons will not be prompt. The fit will categorize these events into the non-prompt $J/\psi$ background category and the effect on the prompt signal yield is estimated to be negligible. From simulated $t\bar{t}$ events the prompt yield in our dataset is predicted to be less than 0.28 events at 95% credibility level. The ratio of $W^\pm$+$b$ to $W^\pm$ production from ATLAS measurements [30, 31] is found to be consistent (albeit with large uncertainties) with the ratio of $W^\pm$ + non-prompt $J/\psi$ to $W^\pm$ production in this analysis, when the differing phase spaces of the analyses are considered.

Decays of $B_c \to J/\psi\mu^\pm\nu_\mu X$ produce a $J/\psi$ and an additional muon. As the $B_c$ lifetime is shorter than that of other weakly-decaying $B$ hadrons, these $J/\psi$ may be mistakenly taken as prompt candidates. No candidate events are found to have a three-muon invariant mass below 12 GeV, which is far above the $B_c$ mass of 6.277 GeV [28], hence this background is negligible.

The production of $Z$ bosons, followed by the decay $Z \to \mu^+\mu^-$, can produce the signal signature if an additional muon candidate and $E_{\mathrm{T}}^{\mathrm{miss}}$ due to jet mismeasurements or neutrinos are found. This background is eliminated by vetoing events where a pairing of oppositely charged muons has an invariant mass within 10 GeV of the $Z$ boson mass.

Multi-jet production, especially of heavy-quark jets, can produce candidates with multiple reconstructed muons and $E_{\mathrm{T}}^{\mathrm{miss}}$ due to either neutrinos or mismeasurement of the jet energy. This contribution is separated from the real $W^\pm + J/\psi$ component of the observed events using the $W^\pm$ boson transverse mass $m_{\mathrm{T}}(W)$ as a discriminating variable. The



(a)

(b)

**Figure 3**. (a) Unit-normalized templates for $W$ boson transverse mass $m_{\mathrm{T}}(W)$ for multi-jet background and $W^{\pm}$ boson signal. (b) `sPlot`-weighted $W$ boson transverse mass distribution for $W^{\pm}$ + prompt $J/\psi$ candidate events with a fit to the $W^{\pm}$ boson and multi-jet components. The fit is performed in the region 40–140,GeV in $m_{\mathrm{T}}(W)$.

$m_{\mathrm{T}}(W)$ distribution of events weighted by signal (prompt $J/\psi$) `sPlot` weight is fit to a sum of a multi-jet template and a $W^{\pm}$ boson signal template (the templates are shown in figure 3(a)). The multi-jet background shape in $m_{\mathrm{T}}(W)$ is estimated using the distribution in events with non-isolated muons, which are dominated by multi-jet production. The $W^{\pm}$ template is obtained from Monte Carlo simulation. Events were produced by the Alpgen event generator [32], interfaced to Herwig [33] for parton showers and hadronization, and Jimmy [34] for simulation of the underlying event. The detector response is modelled using the Geant4-based ATLAS full simulation framework [35, 36].

The total yield for prompt $J/\psi$ production, shown in table 1, is $29.2^{+7.5}_{-6.5}$ events. The result of the $\chi^2$ fit is shown in figure 3(b). The estimate from the $m_{\mathrm{T}}(W)$ fit is that there are $0.1 \pm 4.6$ multi-jet events in the sample, providing strong support for the hypothesis that the sample is dominated by $W^{\pm}$ + prompt $J/\psi$ events. The fraction of multi-jet events is smaller than 0.31 at 95% credibility level.

The probability that a $W^{\pm}$ candidate and a $J/\psi$ candidate are produced in different proton-proton collisions that occur in the same bunch crossing ("pileup") is estimated as follows. Given the beam conditions of the dataset, the mean number of extra collisions within 10 mm of the primary vertex is calculated to be $N_{\mathrm{extra}} = 0.81 \pm 0.08$; this value is computed from the mean number of collisions per proton-proton bunch crossing $\mu$ and the geometric parameters of the interaction region. Here $\mu$ is defined as $\mu = \mathcal{L}\sigma_{\mathrm{inel}}/n_b f_r$, with $\mathcal{L}$ being the luminosity, $n_b$ the number of colliding bunch pairs, $f_r$ the accelerator revolution frequency, and $\sigma_{\mathrm{inel}}$ the $pp$ inelastic cross section, assumed to be equal to 71.5 mb [37]. For a $(|y_{J/\psi}|, p_{\mathrm{T}}^{J/\psi})$-bin, the probability for a $J/\psi$ to be produced in a $pp$ collision in that kinematic bin is determined as

$$P_{J/\psi} = \frac{\sigma^{\text{bin}}_{J/\psi}}{\sigma_{\text{inel}}} = \frac{1}{\sigma_{\text{inel}}} \int_{\text{bin}} \frac{\mathrm{d}^2\sigma(pp \to J/\psi\ X)}{\mathrm{d}y\ \mathrm{d}p_{\mathrm{T}}} \mathrm{d}y\ \mathrm{d}p_{\mathrm{T}}$$

using the double-differential $J/\psi$ production cross sections as measured [23] at $\sqrt{s} = 7\,\text{TeV}$.

Since $\mathcal{L}$ is determined independently from $\sigma_{\text{inel}}$ using van der Meer scan calibration [25], $\sigma_{\text{inel}}$ is a proportionality factor between $\mu$ and $\mathcal{L}$, and therefore $N_{\text{extra}} \propto \sigma_{\text{inel}}$. As a result the dependence on $\sigma_{\text{inel}}$ cancels in the overlap probability $N_{\text{extra}}P_{J/\psi}$. Multiplying the overlap probability by the number of $W^{\pm}$ candidates in the fiducial region, $N_{\text{pileup}} = N_{\text{extra}}P_{J/\psi}\mathcal{L}\sigma_{W^{\pm}}$, yields an estimated total of $1.8 \pm 0.2$ for such pileup overlap events in the sample. This background is subtracted when the cross-section ratios are calculated.

## 6 Double parton scattering

It is possible for the $W^{\pm}$ and $J/\psi$ to originate from two different parton interactions in the same proton-proton collision, in a double parton scattering process. The standard ansatz [18] is adopted that, for a collision in which a hard process (here $W^{\pm}$ production) occurs, the probability of an additional (distinguishable) process (here prompt $J/\psi$ production) is parameterized as

$$P_{J/\psi\,|\,W^{\pm}} = \sigma_{J/\psi}/\sigma_{\text{eff}}. \tag{1}$$

The effective area parameter $\sigma_{\text{eff}}$ accounts for the geometric size of the proton and transverse parton correlations, and is assumed to be independent of the scattering process. It is taken to be $15 \pm 3\,(\text{stat.})^{+5}_{-3}\,(\text{syst.})$ mb as measured using $W^{\pm} \to \ell\nu_{\ell} + 2$–jet events [38]. The two interactions are treated as independent and uncorrelated. This procedure relies upon an assumption of factorization between the longitudinal and transverse components of the double parton distribution functions [22, 39–41]. Recent studies [42] highlight that this assumption must fail at some level, but the current data is not sufficiently precise to allow for investigation of such effects. Studies of process and scale dependence [43] of $\sigma_{\text{eff}}$ indicate that the uncertainty on the value used here covers variation due to these effects. The prompt $J/\psi$ cross section from the ATLAS measurement [23] is used, as in the pileup estimation, corrected to the fiducial phase space of this measurement, and accounting for spin-alignment uncertainties that result from the correction. The total number of DPS events in the signal yield is estimated to be $10.8 \pm 4.2$ events.

A uniform distribution in the azimuthal angle between the $W^{\pm}$ and $J/\psi$ momenta is expected from DPS, under the assumption that the two interactions are independent. The flat DPS template is verified using PYTHIA8 [44] Monte Carlo simulation. Simulations in both the colour-singlet and colour-octet models predict a distribution strongly peaked near $\Delta\phi = \pi$ for the SPS contribution (with the exact shape dependent on kinematics and the relative size of the underlying contributions). The `sPlot`-weighted distribution of this variable for the data has a peak near $\pi$ and a tail extending towards zero, as shown in figure 4. This suggests that the observed $W^{\pm}$ + prompt $J/\psi$ candidates include both SPS and DPS events. However, this distribution is not used to separate SPS and DPS events.

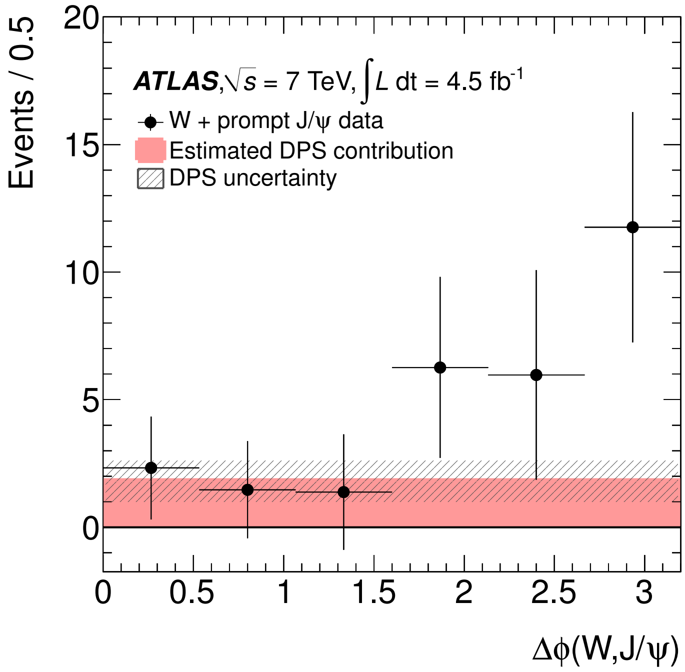


**Figure 4**. The `sPlot`-weighted azimuthal angle between the $W^\pm$ and the $J/\psi$ is shown for $W^\pm +$ prompt $J/\psi$ candidates. No efficiency or acceptance corrections are applied. The determined DPS contribution (with systematic uncertainties) is overlaid, using a flat DPS template validated using PYTHIA8 [44] Monte Carlo simulation and normalized to the total rate as estimated using the DPS ansatz in eq. (1). The hashed region shows the uncertainty on the DPS estimate.

Overlaid on figure 4 is an estimate of the DPS rate using the previously described ansatz. The determined rate is compatible with the size of the flat component of the observed $\Delta\phi$ distribution.

## 7 Results

Table 1 shows the yields resulting from the two-dimensional fit in each of the two detector regions, barrel ($|y_{J/\psi}| \leq 1.0$) and endcap ($1 < |y_{J/\psi}| < 2.1$), including the statistical uncertainty from the fit for the prompt $J/\psi$, non-prompt $J/\psi$, and combinatoric background components. The signal significance is calculated using pseudo-experiments in which events conforming with the background-only hypothesis are generated and then fit with the background-only hypothesis and the signal+background hypothesis to extract the likelihood ratio of the two hypotheses. The $p$-value shown in the table is the probability for background-only pseudo-experiments to yield a likelihood ratio value larger than the value obtained in data. The combination of the two $y_{J/\psi}$ regions rejects the background-only hypothesis at $5.1\sigma$.

To determine the ratio of the $W^\pm +$prompt $J/\psi$ cross section to the $W^\pm$ cross section, the number of inclusive $W^\pm$ events is determined from data. A sample of $W^\pm$ candidates is formed by selecting all events that satisfy the $W^\pm$ part of the $W^\pm +$ prompt $J/\psi$ re-

| Yields from two-dimensional fit | | | |
|---|---|---|---|
| Process | Barrel | Endcap | Total |
| Prompt $J/\psi$ | $10.0^{+4.7}_{-4.0}$ | $19.2^{+5.8}_{-5.1}$ | $29.2^{+7.5}_{-6.5}(*)$ |
| Non-prompt $J/\psi$ | $27.9^{+6.5}_{-5.8}$ | $13.9^{+5.3}_{-4.5}$ | $41.8^{+8.4}_{-7.3}$ |
| Prompt background | $20.4^{+5.9}_{-5.1}$ | $18.8^{+6.3}_{-5.3}$ | $39.2^{+8.6}_{-7.3}$ |
| Non-prompt background | $19.8^{+5.8}_{-4.9}$ | $19.2^{+6.1}_{-5.1}$ | $39.0^{+8.4}_{-7.1}$ |
| $p$-value | $8.0 \times 10^{-3}$ | $1.4 \times 10^{-6}$ | $2.1 \times 10^{-7}$ |
| Significance ($\sigma$) | 2.4 | 4.7 | 5.1 |

(*) of which $1.8 \pm 0.2$ originate from pileup

**Table 1**. The event yields for the prompt $J/\psi$, non-prompt $J/\psi$, and combinatorial background are shown. The errors shown include the statistical uncertainties and the systematic uncertainties from the nuisance parameters of the fit. The significance, in standard deviations, is calculated using the $p$-value from pseudo-experiments.

quirements. The $Z$+jets, $t\bar{t}$, and diboson backgrounds to inclusive $W^{\pm}$ production are estimated from Monte Carlo simulation (Alpgen [32], MC@NLO [45] and Herwig [33], respectively). The multi-jet contribution is estimated using the same technique as used for deriving the multi-jet template for the $W^{\pm}$ + prompt $J/\psi$ signal, except that the normalization is also determined by that method instead of being fit to data. The number of $W^{\pm}$ boson candidates is found to be $1.48 \times 10^7$, consistent with next-to-next-to-leading-order (NNLO) pQCD predictions [46, 47] taking into account the ATLAS detector performance.

First the fiducial cross-section ratio

$$\begin{aligned} R^{\text{fid}}_{J/\psi} &= \frac{\text{BR}(J/\psi \to \mu^+\mu^-)}{\sigma_{\text{fid}}(pp \to W^{\pm})} \cdot \frac{\mathrm{d}\sigma_{\text{fid}}(pp \to W^{\pm} + J/\psi)}{\mathrm{d}y} \\ &= \frac{N^{\text{ec}}(W^{\pm} + J/\psi)}{N(W^{\pm})} \frac{1}{\Delta y} - R^{\text{fid}}_{\text{pileup}}, \end{aligned}$$

is defined, where $N^{\text{ec}}(W^{\pm} + J/\psi)$ is the yield of $W^{\pm}$ + prompt $J/\psi$ events after correction for the $J/\psi$ muon reconstruction efficiencies, $N(W^{\pm})$ is the background-subtracted yield of inclusive $W^{\pm}$ events, $\Delta y = 4.2$ is the size of the fiducial region in $y_{J/\psi}$, and $R^{\text{fid}}_{\text{pileup}}$ is the expected pileup background contribution in the fiducial $J/\psi$ acceptance. For $R^{\text{fid}}_{J/\psi}$, corrections are not applied for the incomplete acceptance for $J/\psi$ decay muons, nor for the $W^{\pm}$ acceptance. Also, it is noted that only the cross section for $8.5 < p_{\text{T}}^{J/\psi} < 30$ GeV is considered.

The statistical uncertainties associated with the fit are calculated by fixing the nuisance parameters and performing the fit again. When the nuisance parameters are allowed to float within the Gaussian constraint, the total uncertainty on each yield is the quadratic sum of the statistical and systematic uncertainties.

The $J/\psi$ transverse momentum distribution may be different in inclusive $J/\psi$ events and $W^{\pm}$ + prompt $J/\psi$ events. Since the fit nuisance parameters from the inclusive fit are used during the $W^{\pm}$ + prompt $J/\psi$ fit, as described in section 4, this can affect the

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extracted yields, due to the different $J/\psi$ $p_{\mathrm{T}}$ spectrum of the inclusive $J/\psi$ and $W^{\pm}+J/\psi$ processes. This is estimated to have an effect of $< 1\%$ on the prompt $J/\psi$ yields extracted by the fit, by performing the fits with unconstrained nuisance parameters in different $J/\psi$ $p_{\mathrm{T}}$ ranges and comparing the yields with those from the constrained fits in the nominal $J/\psi$ $p_{\mathrm{T}}$ range. Changing the functional forms of the fit, for example by changing the single Gaussian to a double Gaussian for the signal, or the exponential function to a polynomial function for the background, results in changes in the yields of up to 4%, which is taken as a systematic uncertainty.

The efficiency and acceptance of the $W^{\pm}$ boson are assumed to be the same for inclusive $W^{\pm}$ events and $W^{\pm}+J/\psi$ events when calculating the ratio. The uncertainty due to this assumption is estimated by reweighting the $W^{\pm}$ transverse momentum spectrum in the simulated inclusive sample to match the observed spectrum from $W^{\pm}+J/\psi$ events and noting the change in efficiency, which is (2–5)%. The low-$p_{\mathrm{T}}$ muon efficiencies are determined from data and cross-checked with efficiencies measured from $J/\psi$ simulation using PYTHIA8 [44], with the difference interpreted as a systematic uncertainty of (3–5)%, while the uncertainty due to the muon momentum scale is found to be negligible.

In addition to reporting $R^{\mathrm{fid}}_{J/\psi}$, results are presented after being corrected for the fiducial acceptance of the muons from the $J/\psi$ decay, but maintaining the $J/\psi$ $p_{\mathrm{T}}$ (8.5–30 GeV) and rapidity ($-2.1$–$2.1$) range:

$$\begin{aligned} R^{\mathrm{incl}}_{J/\psi} &= \frac{\mathrm{BR}(J/\psi \to \mu^{+}\mu^{-})}{\sigma_{\mathrm{fid}}(pp \to W^{\pm})} \cdot \frac{\mathrm{d}\sigma(pp \to W^{\pm}+J/\psi)}{\mathrm{d}y} \\ &= \frac{N^{\mathrm{ec+ac}}(W^{\pm}+J/\psi)}{N(W^{\pm})}\frac{1}{\Delta y} - R_{\mathrm{pileup}}, \end{aligned}$$

where $N^{\mathrm{ec+ac}}(W^{\pm}+J/\psi)$ is the yield of $W^{\pm}+$ prompt $J/\psi$ events after $J/\psi$ acceptance corrections and efficiency corrections for both $J/\psi$ decay muons, $R_{\mathrm{pileup}}$ is the expected pileup contribution in the full $J/\psi$ decay phase space, and other variables are as for $R^{\mathrm{fid}}_{J/\psi}$. The $J/\psi$ spin-alignment, which determines the angular distribution of the muons from the $J/\psi$ decay and thus modifies the acceptance for the $J/\psi$ to be detected within the fiducial volume, is not known and is dependent on the underlying production mechanism. Five extreme scenarios that bound the possible variation are considered for the acceptance and the difference is assigned as a systematic uncertainty. These scenarios (isotropic, longitudinal, transverse+, transverse− and transverse0) depend on the $J/\psi$ spin-alignment angles, the angle between the direction of the positive muon momentum in the $J/\psi$ decay frame and the $J/\psi$ line of flight, and the angle between the $J/\psi$ production plane and the decay plane formed by the direction of the $J/\psi$ and the positive muon [23].

Table 2 summarizes the main sources of uncertainties for this analysis. Other uncertainties related to the $E_{\mathrm{T}}^{\mathrm{miss}}$ scale, luminosity, and the $W^{\pm}$ decay muon cancel in the ratio.

The isotropic spin-alignment scenario is assumed for the central result, and the variations of the result with the different spin-alignment scenarios are also reported in HEPDATA [48]. The DPS contribution to $R^{\mathrm{incl}}_{J/\psi}$ is estimated to be $(48 \pm 19) \times 10^{-8}$. Subtracting the DPS contribution from $R^{\mathrm{incl}}_{J/\psi}$ gives an estimate $R^{\mathrm{DPS\ sub}}_{J/\psi}$ of the single parton scatter-

| Source | Barrel | Endcap |
|---|---|---|
| $J/\psi$ muon efficiency | (3–5)% | (3–5)% |
| $W^{\pm}$ boson kinematics | 2% | 5% |
| Fit procedure | $^{+3}_{-2}\%$ | $^{+2}_{-1}\%$ |
| Choice of fit nuisance parameters | 1% | 1% |
| Choice of fit functional forms | 4% | 4% |
| Muon momentum scale | negligible | |
| $J/\psi$ spin-alignment | $^{+36}_{-25}\%$ | $^{+27}_{-13}\%$ |
| Statistical | $^{+47}_{-40}\%$ | $^{+30}_{-27}\%$ |

**Table 2**. Summary of the main sources of uncertainty for the measurements of $R^{\text{fid}}_{J/\psi}$ and $R^{\text{incl}}_{J/\psi}$; systematic, spin-alignment and statistical uncertainties are shown. Only uncertainties that do not cancel in the ratio of $W^{\pm}$ + prompt $J/\psi$ to $W^{\pm}$ rates are included. The spin-alignment uncertainty is not present for the $R^{\text{fid}}_{J/\psi}$ measurement.

ing rate, which can be directly compared with leading-order (LO) colour-singlet pQCD predictions [12] and next-to-leading-order (NLO) colour-octet predictions [9].

The values of the three measured ratios are shown in figure 5 and are:

$$\begin{aligned} R^{\text{fid}}_{J/\psi} &= (51 \pm 13 \pm 4) \times 10^{-8} \\ R^{\text{incl}}_{J/\psi} &= (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8} \\ R^{\text{DPS sub}}_{J/\psi} &= (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}, \end{aligned}$$

where the first uncertainty is statistical, the second is systematic and the third (where applicable) is the uncertainty due to spin-alignment. The systematic uncertainty on the DPS-subtracted ratio includes the uncertainty on the estimated DPS contribution, which itself includes a separate spin-alignment uncertainty.

**Comparisons with theoretical expectations.** For comparison of the DPS-subtracted ratio to theory, the LO colour-singlet and NLO colour-octet predictions for $W^{\pm}$ + prompt $J/\psi$ [9] are normalized to NNLO calculations of the $W^{\pm}$ production cross section (5.08 nb), derived from FEWZ 3.1.B2 [46, 47]. The expected SPS cross-section ratio $R^{\text{DPS sub}}_{J/\psi}$ from normalized next-to-leading-order colour-octet calculations is $(4.6\text{–}6.2)\times 10^{-8}$, with the range corresponding to different scales as explained below. These predictions assume that pure CO contributions dominate this process, and hence do not include any colour-singlet diagrams. The renormalization ($\mu_R$) and factorization ($\mu_F$) scales are set to the $W^{\pm}$ boson mass, $\mu_R = \mu_F = m_W$, and the NRQCD scale ($\mu_\Lambda$) is taken to be $\mu_\Lambda = m_{\text{charm}} = 1.5\,\text{GeV}$. Two sets of colour-octet long-distance matrix elements are used as input parameters to the theory, obtained from two different parameter fits to experimental data [49, 50], and the variation between the results obtained is assigned as a systematic uncertainty.

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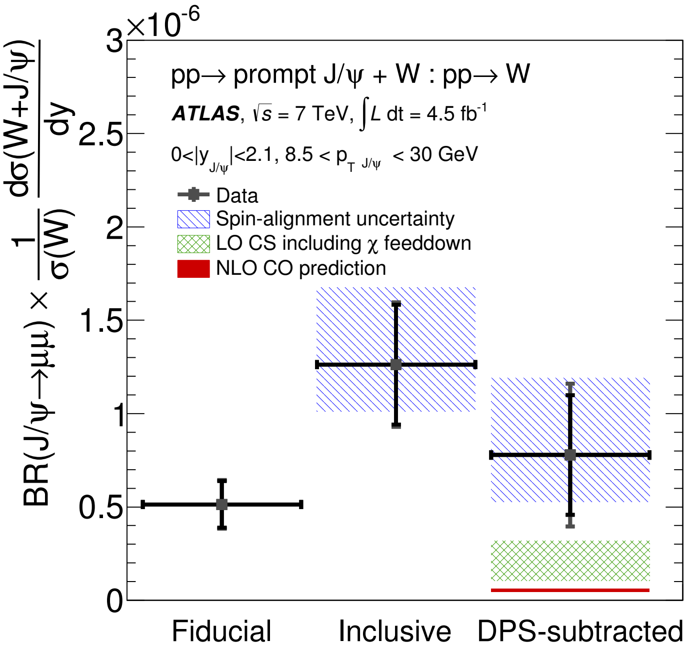

**Figure 5**. The $W^{\pm}$ + prompt $J/\psi$: $W$ production cross-section ratio in the $J/\psi$ fiducial region (Fiducial), after correction for $J/\psi$ acceptance (Inclusive), and after subtraction of the double parton scattering component (DPS-subtracted). The shaded band represents the envelope of variation due to different possible spin-alignment configurations. Inner error bars represent statistical uncertainties, outer error bars represent statistical and systematic uncertainties added in quadrature. The LO colour-singlet (CS) and NLO colour-octet (CO) predictions for SPS production are shown in comparison.

The CS model described in [12] includes contributions from $sg \to J/\psi{+}c{+}W$ and $q\bar{q}' \to \gamma^{*}W \to J/\psi W$, and accounts for indirect production in the $W^{\pm}$+prompt $J/\psi$ rate through decays of excited charmonium states of both $W^{\pm}$ + direct $\psi(2S)$ and $W^{\pm}$ + direct $\chi_{cJ}$ production. The normalized leading-order colour-singlet model predicts the SPS ratio to be (10–32) $\times\, 10^{-8}$ for the phase space region considered in this paper, with the range corresponding to different scales as explained below. The uncertainties on the colour-singlet prediction arise from varying the charm quark mass in the range $m_{\text{charm}} = (1.5 \pm 0.1)$ GeV and independently varying the factorization and renormalization scales between $0.75 \times \mu_{R,F}$ and $2 \times \mu_{R,F}$ of their central value $\mu_R = \mu_F = m_W$.

The leading-order CS contributions are nearly an order of magnitude larger than the next-to-leading-order CO contributions, with the CS prediction being consistent with the measured DPS-subtracted rate within the current experimental and theoretical uncertainties. This emphasizes that far from being a distinctive signature of CO production, this process appears to be dominated by CS production. This shortfall in the CO production prediction might be explained by the presence of large higher-order contributions [49, 50] or a possible breakdown of NRQCD universality [5]. Figure 4 supports the hypothesis of DPS factorization (within current experimental uncertainties), but possible modifications

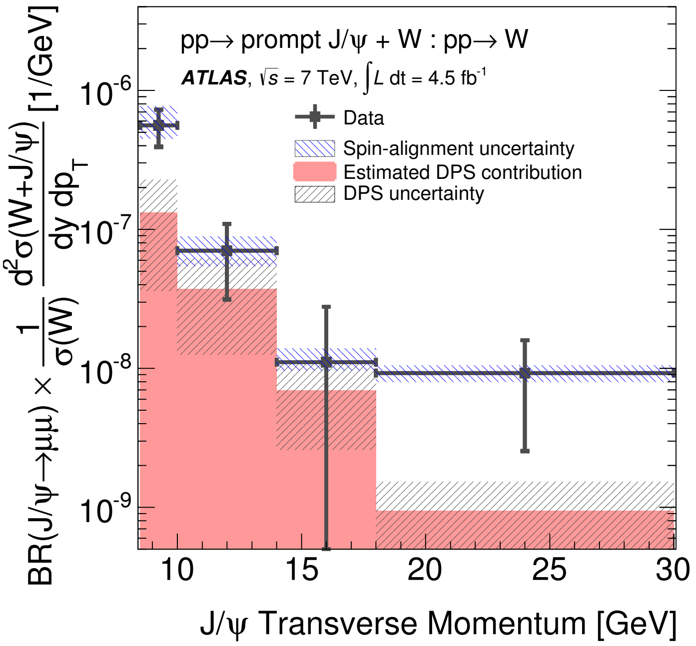

**Figure 6**. The inclusive (SPS+DPS) cross-section ratio $\mathrm{d}R^{\mathrm{incl}}_{J/\psi}/\mathrm{d}p_{\mathrm{T}}$ is shown as a function of $J/\psi$ transverse momentum. The shaded uncertainty corresponds to the variations due to the various spin-alignment scenarios. The DPS estimate is overlaid, with the uncertainty again shown by a shaded region.

| $y_{J/\psi} \times p_{\mathrm{T}}^{J/\psi}$ Bin | Inclusive (SPS+DPS) ratio $\mathrm{d}R^{\mathrm{incl}}_{J/\psi}/\mathrm{d}p_{\mathrm{T}}$ $(\times 10^{-6})$ | DPS $(\times 10^{-6})$ |
|---|---|---|
| $(0, 2.1) \times (8.5, 10)$ | $0.56 \pm 0.16(\mathrm{stat}) \pm 0.04(\mathrm{syst}) ^{+0.21}_{-0.11}(\mathrm{spin})$ | $0.13 \pm 0.10$ |
| $(0, 2.1) \times (10, 14)$ | $0.070 \pm 0.039(\mathrm{stat}) \pm 0.006(\mathrm{syst}) ^{+0.019}_{-0.016}(\mathrm{spin})$ | $0.04 \pm 0.03$ |
| $(0, 2.1) \times (14, 18)$ | $0.011 \pm 0.017(\mathrm{stat}) \pm 0.001(\mathrm{syst}) ^{+0.003}_{-0.002}(\mathrm{spin})$ | $0.007 \pm 0.004$ |
| $(0, 2.1) \times (18, 30)$ | $0.0092 \pm 0.0067(\mathrm{stat}) \pm 0.0006(\mathrm{syst}) ^{+0.0012}_{-0.0013}(\mathrm{spin})$ | $0.0009 \pm 0.0006$ |

**Table 3**. The inclusive (SPS+DPS) cross-section ratio $\mathrm{d}R^{\mathrm{incl}}_{J/\psi}/\mathrm{d}p_{\mathrm{T}}$ as a function of $J/\psi$ transverse momentum, along with the estimate of the DPS contribution.

to this formalism may also modify the DPS-subtracted rate. Nonetheless, large uncertainties on the result imply that current predictions for SPS production are compatible with the measurement at the $2\sigma$ level.

Figure 6 shows the distribution of the differential cross-section ratio $\mathrm{d}R^{\mathrm{incl}}_{J/\psi}/\mathrm{d}p_{\mathrm{T}}$ as a function of $p_{\mathrm{T}}^{J/\psi}$, with an estimate of the differential DPS contribution. The data suggest that SPS is the dominant contribution to the total rate at low $J/\psi$ transverse momenta. The results are also shown in table 3.

## 8 Conclusions

In summary, the ATLAS Collaboration has observed $W^{\pm}$ + prompt $J/\psi$ production at $5.1\sigma$ significance in 4.5 $\mathrm{fb}^{-1}$ of $\sqrt{s} = 7\,\mathrm{TeV}$ $pp$ collisions at the LHC. Additionally, the fiducial cross-section ratio of $W^\pm$ + prompt $J/\psi$ production relative to inclusive $W^\pm$ boson production in the same phase space is measured to be $R^{\rm fid}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$, where the first uncertainty is statistical, and the second systematic. The acceptance-corrected observed ratio is $R^{\rm incl}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$ where the central value is for the isotropic spin-alignment scenario, and the third uncertainty represents possible variation due to the unknown spin-alignment. The contribution to the total $W^\pm$ + prompt $J/\psi$ rate arising from single parton scattering (double parton scattering subtracted data) is estimated to be $R^{\rm DPS\ sub}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$, assuming that for DPS the $W^\pm$ and prompt $J/\psi$ production factorize completely. The distribution of the azimuthal angle between the produced $W^\pm$ and $J/\psi$ suggests the presence of both SPS and DPS contributions, and that the DPS estimate accounts for a large fraction of the observed signal. Comparing the two predictions, the colour singlet mechanism is expected to be the dominant contribution to the cross section.

Analysis of additional data will likely prove valuable in distinguishing the contributions of colour-singlet and colour-octet predictions to SPS, and to determine the relative rates of SPS and DPS production. This final state may prove to be a compelling observable for study of double parton scattering dynamics, as well as for the study of Higgs boson charm couplings and for ongoing BSM physics search programmes.

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