Associated quarkonium production at ATLAS

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On behalf of the ATLAS Collaboration

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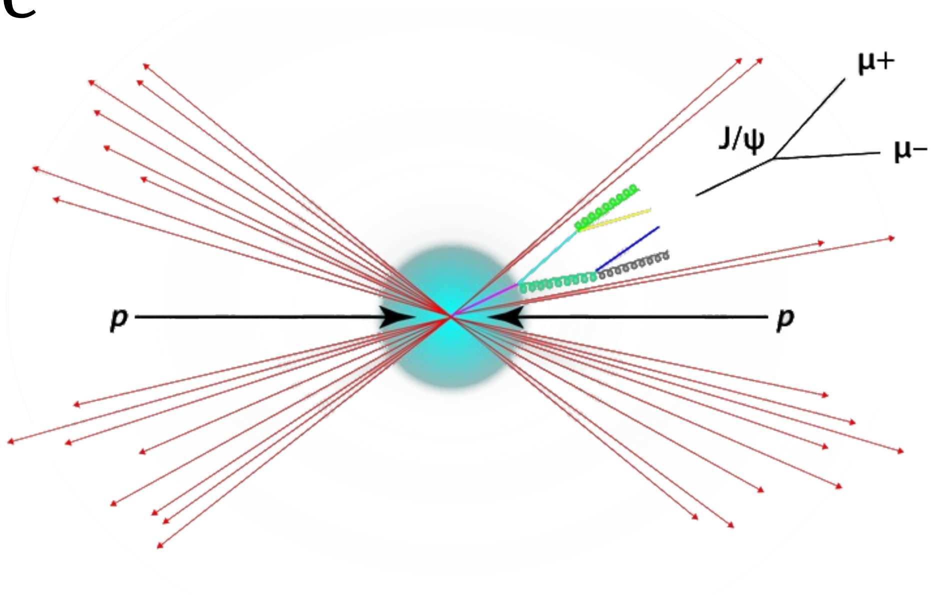
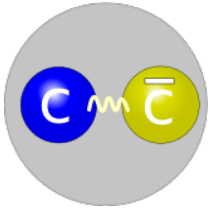
  - Prompt J/ ψ + Z^{0}
- Summary



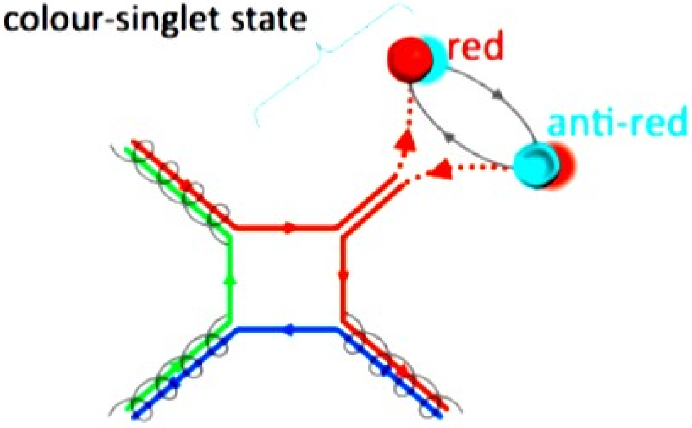
Introduction

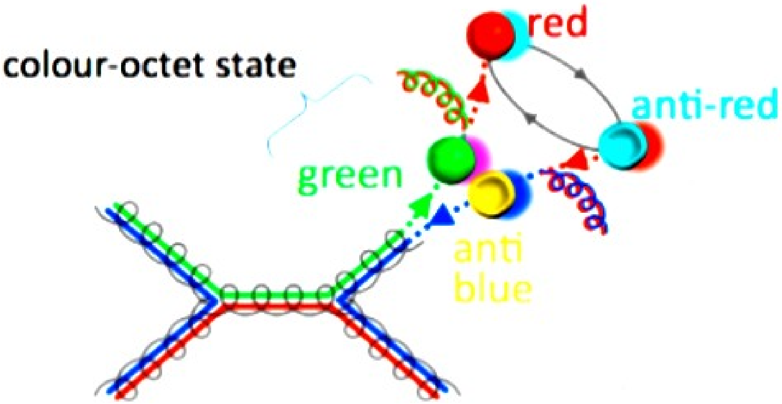


- Quarkonia are formed from a quark pair of the same flavor and should represent one of the simplest systems described by QCD theory.
- However the mechanisms responsible for the production of quarkonia, are not fully understood in hadron collisions.
- Motivation to study the production of a prompt J/ψ meson in association with a vector boson offers:
  - Tests of Quantum Chromodynamics (QCD) at the perturbative/non-perturbative boundary;
  - Useful information on the Double Parton Scattering (DPS) process along with Single Parton Scattering (SPS) process;
  - Developing the framework for future probes of the Higgs sector;
  - Beyond-the-standard-model searches in such final states.

Colour-Singlet (CS) and Colour-Octet (CO) states

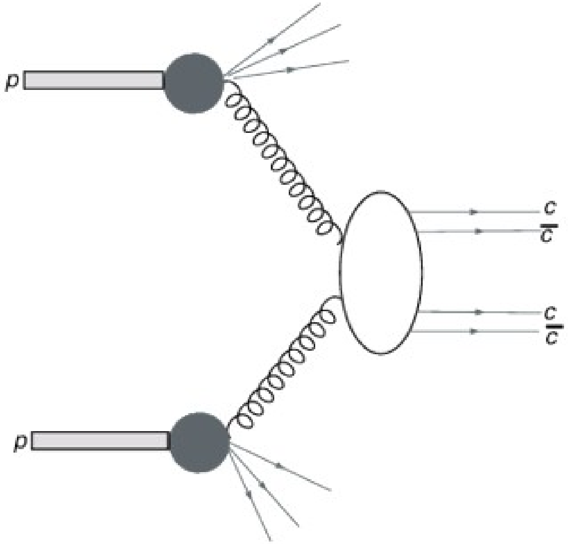
Perturbative calculations of heavy quarkonium production in hadronic collisions distinguish between terms that produce a heavy quark system ($Q\bar{Q}$) in a colour-singlet (CS) or a colour-octet (CO) state.

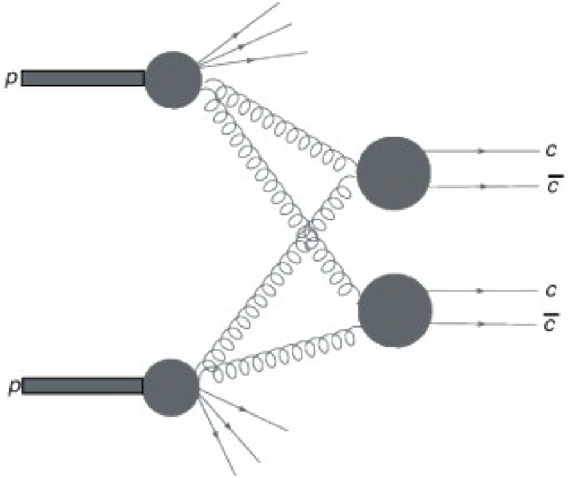




SPS and DPS

The production of two objects in the same pp collision can be due to:





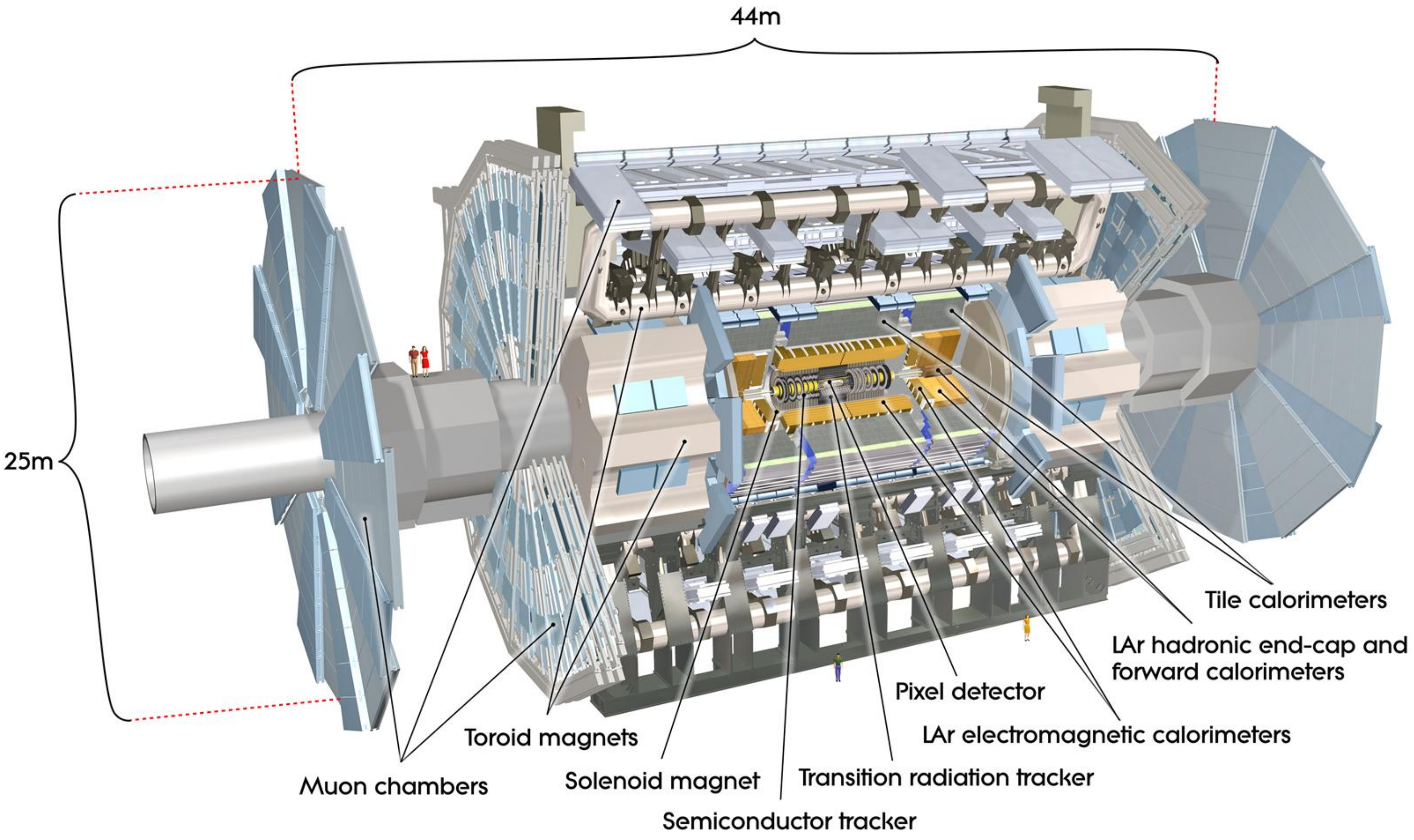
Single-Parton Scattering (SPS):

the two objects are produced via a subprocess in a single interaction of two partons.

Double-Parton Scattering (DPS):

simultaneous interaction of two pairs of partons, each producing one of the two objects, assumed to be uncorrelated.

ATLAS detector at LHC



Prompt J/ψ + W±

Measurement of the production cross section of prompt J/ψ mesons in association with a W± boson in pp collisions at √s = 7 TeV with the ATLAS detector. *JHEP 04 (2014) 172;*

Production channel in the analysis:

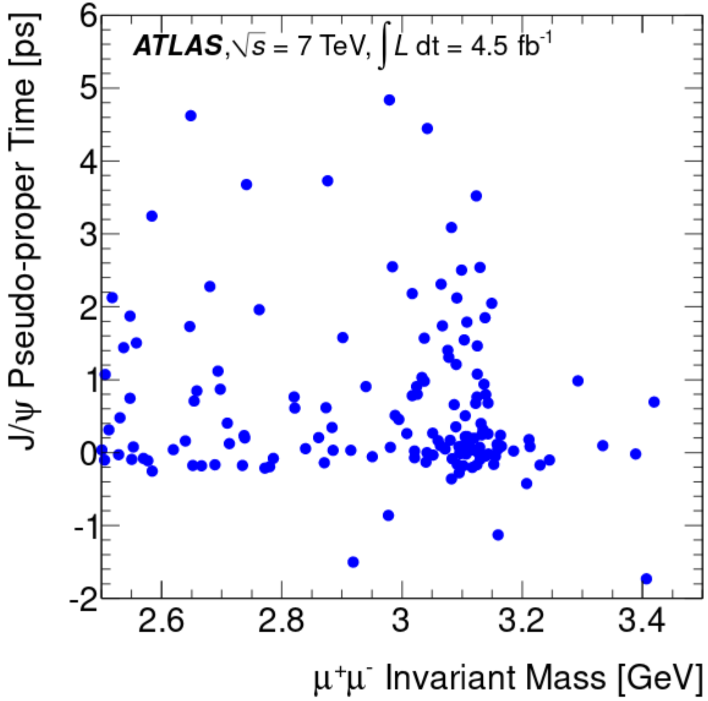
$W^{\pm}$ ($\rightarrow \mu^{\pm}\, \nu_{\mu}$) + J/ψ ($\rightarrow \mu^{+}\, \mu^{-}$)

Trigger: single muon, $p_T > 18$ GeV

Fiducial phase space: $8.5 < p_{\mathrm{T}}^{J/\psi} < 30$ GeV , $|y_{J/\psi}| < 2.1$;

$p_T^{\mu} > 3.5$ GeV $|\eta^{\mu}| < 1.3$ $|\eta^{\mu}| < 2.5$ at least one $p_T^{\mu} > 4$ GeV

$p_T^{\mu} > 2.5$ GeV $|\eta^{\mu}| > 1.3$ $p_T^{\mu(W)} > 25$ GeV $|\eta^{\mu(W)}| < 2.4$



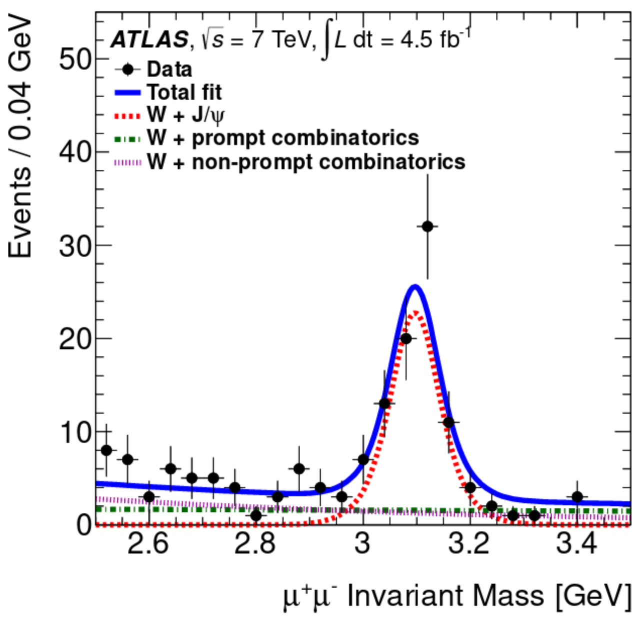
In a later analysis [*Phys.Lett. B781 (2018) 485-491*] the authors found some evidence of DPS in this measurement.

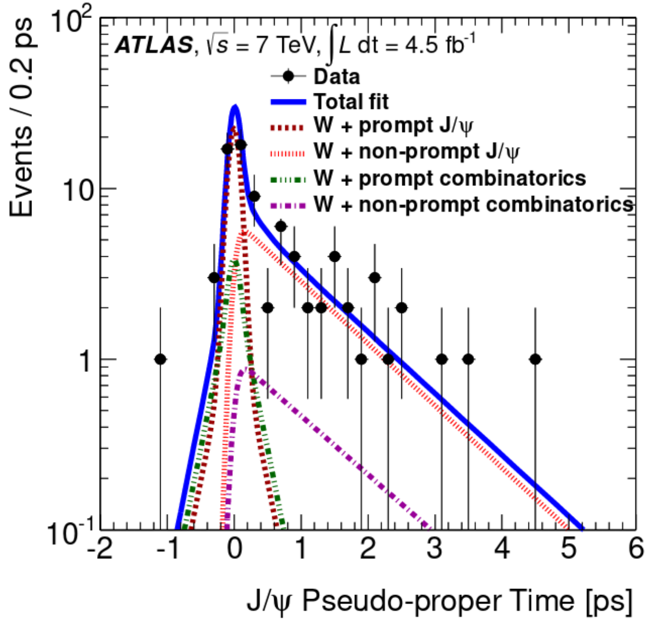
Signal extraction

Prompt production: J/ψ produced in the hard scattering process.

Non-prompt production: J/ψ produced in the decay of a B hadron, decay vertex separated from the primary vertex.

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





An unbinned maximum likelihood fit in **J/ψ candidate invariant mass** and **pseudo-proper time.**

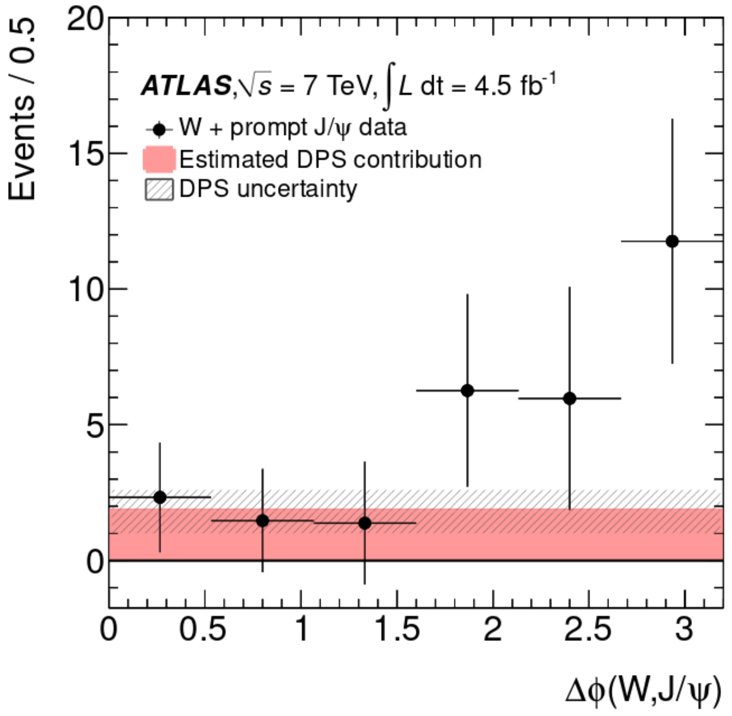
sPlot procedure (*Nucl.Instrum.Meth.A555:356-369,2005*) used to obtain yields for prompt J/ψ, non-prompt J/ψ, and background.

Double Parton Scattering - DPS

For a collision in which a hard process occurs, the probability of an additional process is parameterized as [*Paver, N. et al. Nuovo Cim. A70 (1982) 215 SISSA-7/82/EP*]:

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

σ_{eff} - the geometric size of the proton and transverse parton correlations - assumed to be **independent of the scattering process**.



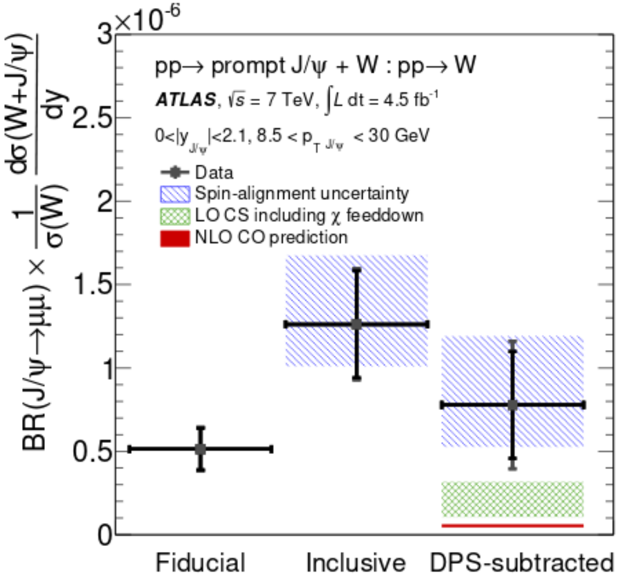
From **DPS** - a uniform distribution in the azimuthal angle between the W± and J/ψ momenta .

From **SPS -** a distribution strongly peaked near Δφ=π.

Observed W + prompt J/ψ candidates include both SPS and DPS events.

Results

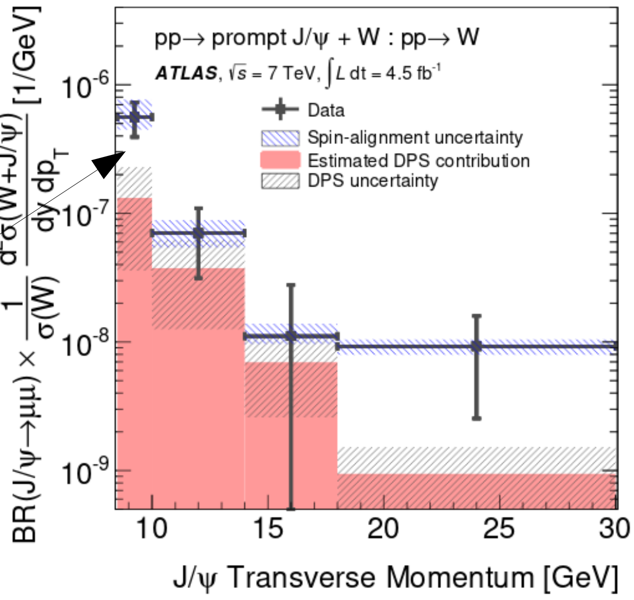
W± + prompt J/ψ:
Fiducial - W production cross-section ratio in the J/ψ fiducial region;
Inclusive - after correction for J/ψ acceptance;
DPS-subtracted - after subtraction of the double parton scattering component.



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

Uncertainty due to various spin-alignment scenarios

SPS is the dominant contribution to the total rate at low J/ψ transverse momenta



The inclusive (SPS+DPS) cross-section ratio as a function of prompt J/ψ transverse momentum.

CS prediction being consistent with the measured DPS-subtracted rate within the current experimental and theoretical uncertainties. This emphasizes that this process appears to be **dominated by CS production**.

LO CS: Lansberg, *Phys. Lett.B 726(2013) 218 – 222*;
NLO CO:Gavin, *Comput.Phys. Commun.184(2013) 209–214*.

Prompt J/ψ + Z^0

Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at √s = 8TeV with the ATLAS detector. *Eur. Phys. J. C75 (2015) 229;*

Production channel in the analysis:

Z^0 ($\to \mu^+\mu^-/e^+e^-$) + J/ψ ($\to \mu^+ \mu^-$)

Trigger: single muon or electron, p_T> 24 GeV

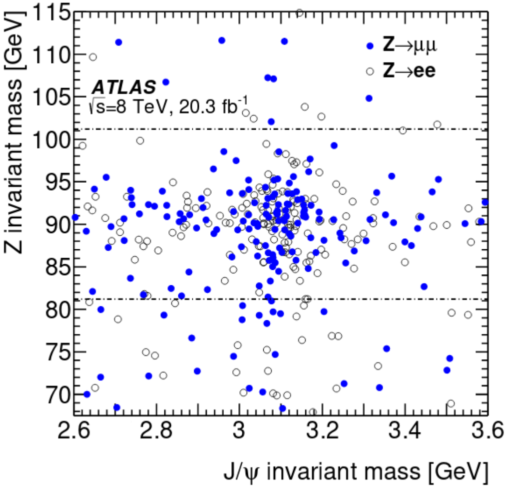
fiducial phase space $8.5 < p_T^{J/\psi} < 100$ GeV $|y^{J/\psi}| < 2.1$

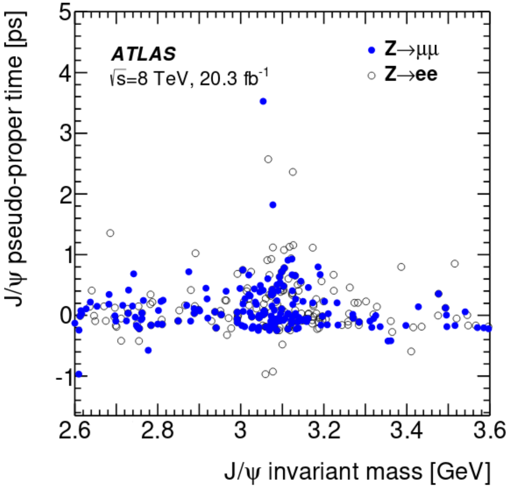
$p_T^\mu > 3.5$ GeV $|\eta^\mu| < 1.3$ $|\eta^\mu| < 2.5$

$p_T^\mu > 2.5$ GeV $|\eta^\mu| > 1.3$ at least one $p_T^\mu > 4$ GeV

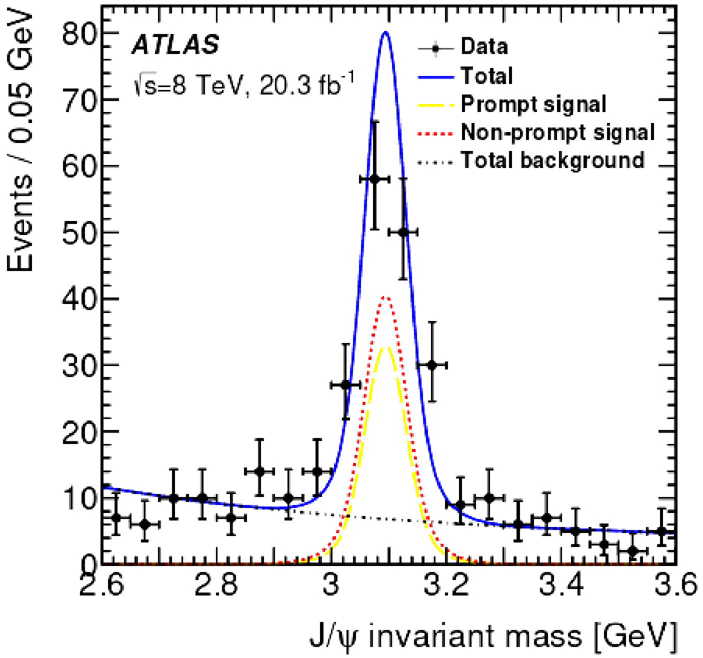
$p_T^{\mu(Z)} > 15$ GeV $|\eta^{\mu(Z)}| < 2.5$

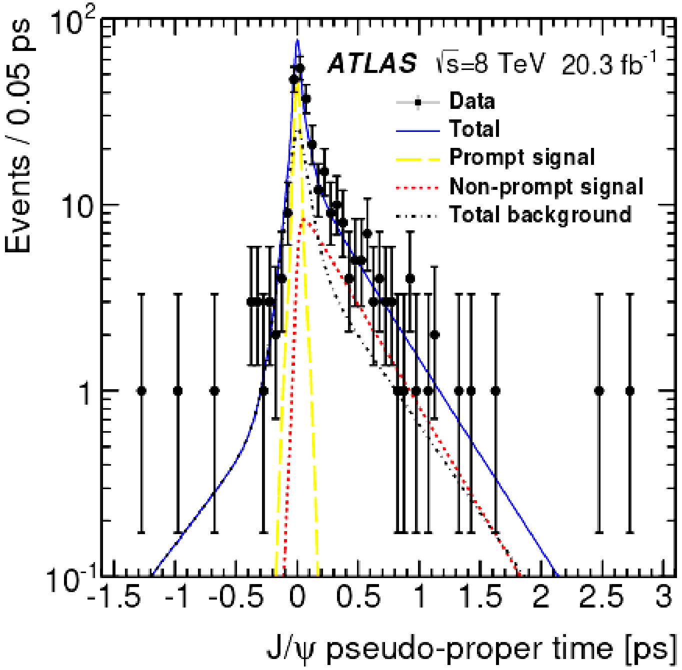
$p_T^{e(Z)} > 15$ GeV $|\eta^{e(Z)}| < 2.47$





Signal extraction





2D fit of **J/ψ candidate invariant mass** and **pseudo-proper time.**

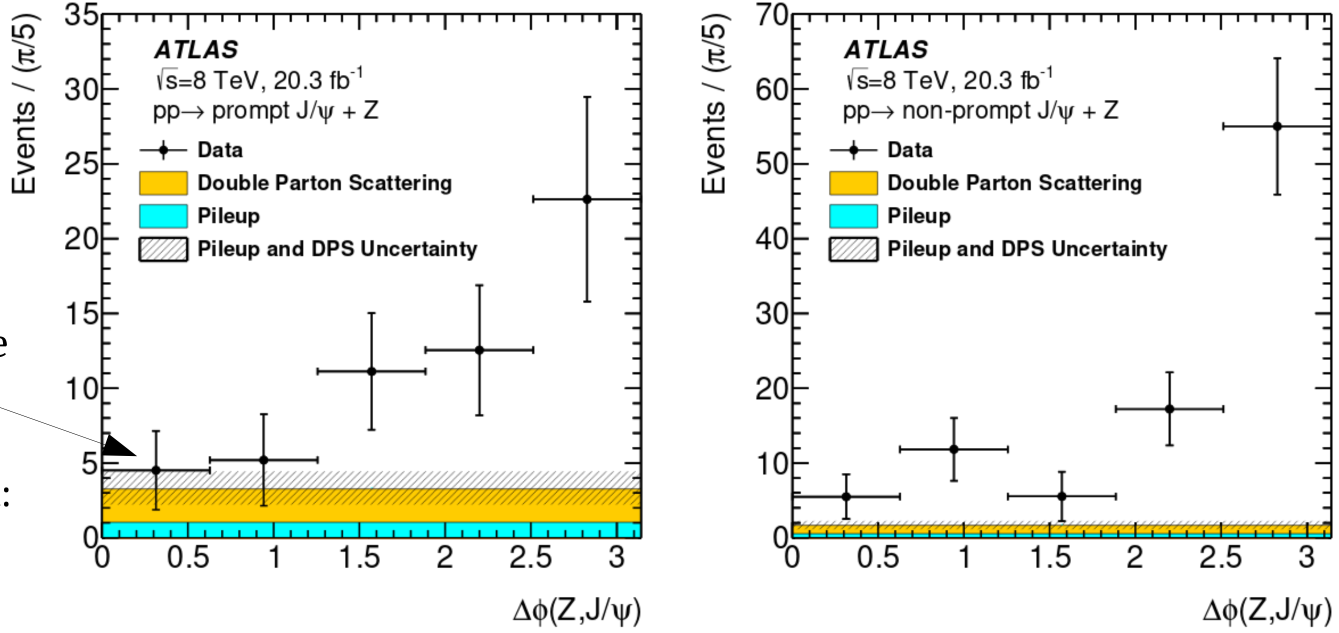
sPlot procedure (*arXiv:physics/0402083*) used to obtain yields for :

- prompt J/ψ;
- non-prompt J/ψ;
- background.

Double Parton Scattering – DPS / Yields

If all signal in the first $\Delta\varphi$ bin is due to DPS, a lower limit is set:

σ_{eff} > 5.3 mb

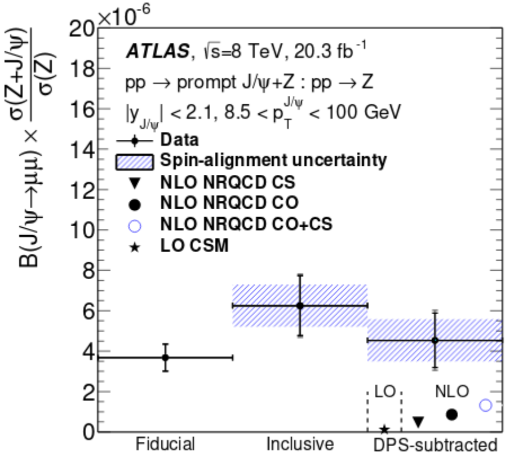


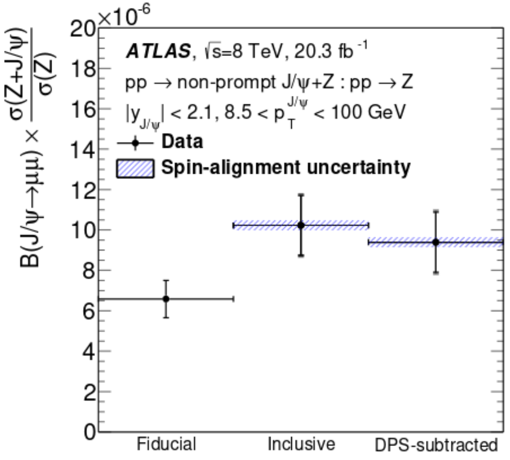
Total yield for prompt J/ψ production is 56±10 events.
Total yield for non-prompt J/ψ production is 95±12 events.
In the yields:

- estimated pile up : $5.2^{+1.8}_{-1.3}$ and $2.7^{+0.9}_{-0.6}$ for prompt and non-prompt samples respectively;
- estimated DPS: $11.1^{+5.7}_{-5.0}$ and $5.8^{+2.8}_{-2.6}$ for prompt and non-prompt samples respectively, assuming: $\sigma_{\mathrm{eff}} = 15 \pm 3\,(\mathrm{stat})\,^{+5}_{-3}\,(\mathrm{syst})\,\mathrm{mb}$, *New J. Phys. 15 (2013) 033038*
  $\sigma_{J/\psi}$ from *Nucl. Phys. B 850 (2011) 387-444*

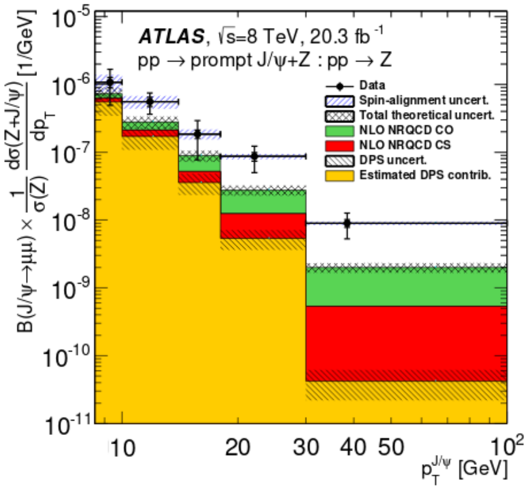
Results

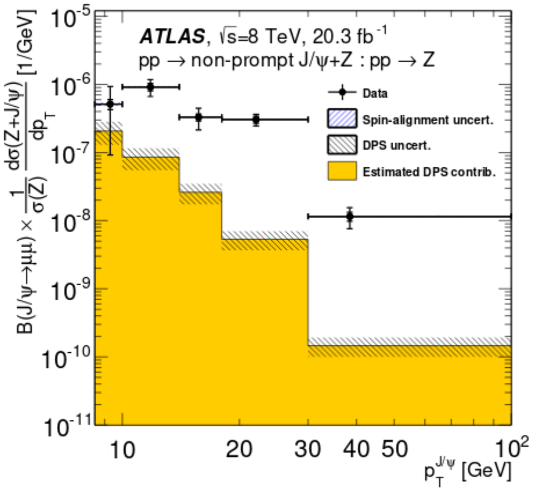
The cross-section ratio of Z^0 + prompt J/ψ to inclusive Z^0 production in the J/ψ fiducial region (**Fiducial**), after correction for J/ψ acceptance (**Inclusive**), and after subtraction of the double parton scattering component (**DPS-subtracted**).





LO: Gong, arXiv:1210.2430
NLO: Mao, arXiv:1102.0398

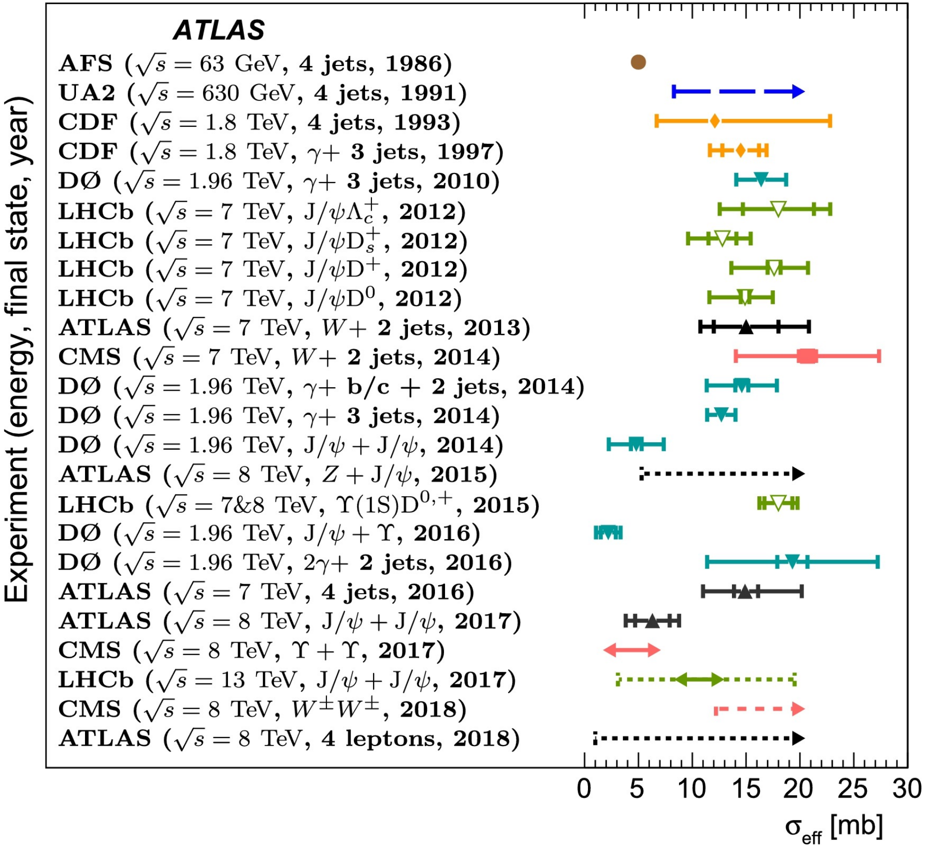




The inclusive (SPS+DPS) cross-section ratio is shown as a function of J/ψ transverse momentum.

- **A higher production rate is predicted through colour-octet transitions than through colour-singlet processes.**
- **The expected production rate from the sum of singlet and octet contributions is lower than the data by a factor of 2 to 5** in the J/ψ p_T range studied.

Summary



- ATLAS Collaboration has observed:
  - $W^\pm$ + prompt J/ψ production at 5.1σ significance in 4.5 fb^{-1} of $\sqrt{s}$ = 7 TeV pp collisions at the LHC:
    - W + prompt J/ψ candidates include both SPS and DPS events;
    - SPS is the dominant contribution to the total rate at low J/ψ p_T;
    - This process appears to be dominated by CS production.
  - Z^0 + prompt J/ψ production at 5σ significance and Z^0 + non-prompt J/ψ production at 9σ significance in 20.3 fb^{-1} of $\sqrt{s}$ = 8 TeV pp collisions at the LHC:
    - Z + prompt J/ψ candidates include both SPS and DPS events;
    - Lower limit has been set on σ_{eff} (> 5.3 mb);
    - A higher production rate is predicted through CO transitions than through CS processes;
    - The expected production rate from the sum of singlet and octet contributions is lower than the data by a factor of 2 to 5.
- The effective cross-section of double parton scattering is measured to be σ_{eff}=6.3±1.6(stat)±1.0(syst) mb [*Eur. Phys. J. C77 (2017) 76*], which is is lower than from other final states.
- Some measured SPS contributions are well above theoretical predictions.
- Theoretical predictions of the dependence of σ_{eff} on the process and energy are needed.

Backup

Triggers, fiducial cuts, integrated luminosities

$J/\psi + W^{\pm}$

Trigger: single muon, $p_T > 18$ GeV

$\sqrt{s} = 7$ TeV

$\mathcal{L} = 4.51\ \mathrm{fb}^{-1}$

$J/\psi \to \mu^+\mu^-$

$W^{\pm} \to \mu\nu_\mu$

fiducial phase space $8.5 < p_T^{J/\psi} < 30$ GeV $|y^{J/\psi}| < 2.1$

$p_T^\mu > 3.5$ GeV $|\eta^\mu| < 1.3$ $|\eta^\mu| < 2.5$ at least one $p_T^\mu > 4$ GeV

$p_T^\mu > 2.5$ GeV $|\eta^\mu| > 1.3$

$p_T^{\mu(W)} > 25$ GeV $|\eta^{\mu(W)}| < 2.4$

$J/\psi + Z^0$

Trigger: single muon or electron, $p_T > 24$ GeV

$\sqrt{s} = 8$ TeV

$\mathcal{L} = 20.3\ \mathrm{fb}^{-1}$

$J/\psi \to \mu^+\mu^-$

$Z \to \ell\ell,\ \ell = \mu, e$

fiducial phase space $8.5 < p_T^{J/\psi} < 100$ GeV $|y^{J/\psi}| < 2.1$

$p_T^\mu > 3.5$ GeV $|\eta^\mu| < 1.3$ $|\eta^\mu| < 2.5$

$p_T^\mu > 2.5$ GeV $|\eta^\mu| > 1.3$ at least one $p_T^\mu > 4$ GeV

$p_T^{\mu(Z)} > 15$ GeV $|\eta^{\mu(Z)}| < 2.5$

$p_T^{e(Z)} > 15$ GeV $|\eta^{e(Z)}| < 2.47$

2D fit model

The combined probability density function used for the fit is:

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

The functional forms of the probability density functions are:

$$
\begin{aligned}
M_{J/\psi}(m_{\mu^+\mu^-}) &= G(m_{\mu^+\mu^-}; m_{J/\psi}^{\text{PDG}}, \sigma_m) \\
T_{\text{prompt } J/\psi}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left((1-a)\delta(\tau) + aC_0 \mathrm{e}^{-|\tau|/\tau_0}\right) \\
T_{\text{non-prompt } J/\psi}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left(C_1 \theta(\tau) \mathrm{e}^{-\tau/\tau_1}\right) \\
M_{\text{prompt bkg}}(m_{\mu^+\mu^-}) &= C_2 \mathrm{e}^{-m_{\mu^+\mu^-}/k_0} \\
M_{\text{non-prompt bkg}}(m_{\mu^+\mu^-}) &= C_3 \mathrm{e}^{-m_{\mu^+\mu^-}/k_1} \\
T_{\text{prompt bkg}}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left((1-b)\delta(\tau) + bC_4 \mathrm{e}^{-|\tau|/\tau_0}\right) \\
T_{\text{non-prompt bkg}}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left(C_5 \theta(\tau) \mathrm{e}^{-\tau/\tau_2}\right).
\end{aligned}
$$

Some definitions

The cross-section ratio of $W^{\pm}$+prompt J/ψ production to the inclusive $W^{\pm}$ production:

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

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

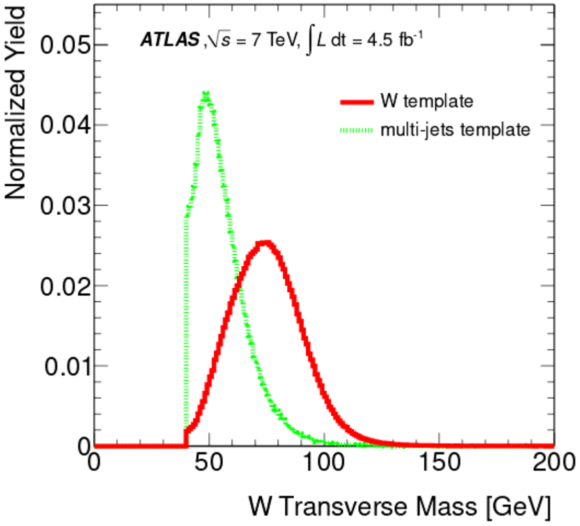
The cross-section ratio of Z^0+prompt J/ψ production to the inclusive Z^0 production:

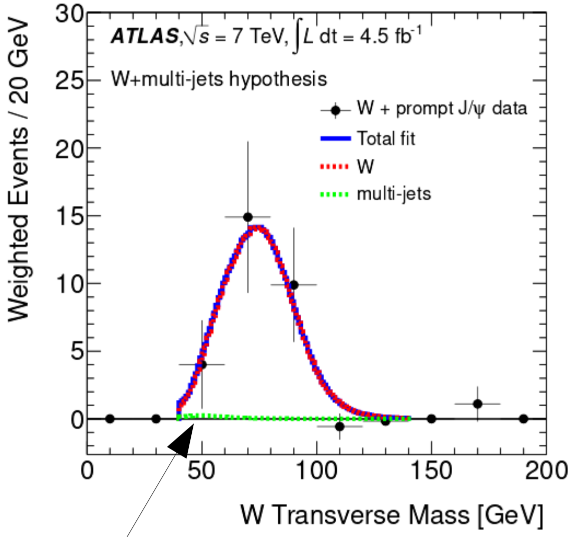
$$
\begin{aligned}
R_{Z+J/\psi}^{\mathrm{fid}} &= \mathcal{B}(J/\psi \to \mu^+\mu^-) \frac{\sigma_{\mathrm{fid}}(pp \to Z + J/\psi)}{\sigma_{\mathrm{fid}}(pp \to Z)} \\
&= \frac{1}{N(Z)} \sum_{p_{\mathrm{T}}\ \mathrm{bins}} \left[N^{\mathrm{ec}}(Z + J/\psi) - N_{\mathrm{pileup}}^{\mathrm{ec}} \right],
\end{aligned}
$$

$$
\begin{aligned}
R_{Z+J/\psi}^{\mathrm{incl}} &= \mathcal{B}(J/\psi \to \mu^+\mu^-) \frac{\sigma_{\mathrm{incl}}(pp \to Z + J/\psi)}{\sigma_{\mathrm{incl}}(pp \to Z)} \\
&= \frac{1}{N(Z)} \sum_{p_{\mathrm{T}}\ \mathrm{bins}} \left[N^{\mathrm{ec+ac}}(Z + J/\psi) - N_{\mathrm{pileup}}^{\mathrm{ec+ac}} \right],
\end{aligned}
$$

Backgrounds

- Production of $W^{\pm}$ bosons in association with b quarks, subsequent b-hadron decay to J/ψ – rejected using the fit.
- Decays of $B_c \to J/\psi\ \mu^{\pm}\ \nu\ \mu\ X$ – negligible background.
- The production of Z bosons ($Z \to \mu^+\mu^-$) – vetoing events where a pairing of muons has an invariant mass within 10 GeV of the Z boson mass.
- Multi-jet production – The $m_T(W)$ distribution of signal events is fit to a sum of a multi-jet template and a $W^{\pm}$ boson signal template.





Total yield for prompt J/ψ production is $29.2^{+7.5}_{-6.5}$ Events. In the yield:

- estimated pile up : 1.8±0.2
- estimated DPS: 10.8±4.2
  assuming: $\sigma_{\text{eff}} = 15 \pm 3\,(\text{stat})\ ^{+5}_{-3}\,(\text{syst})\ \text{mb}$, *New J. Phys. 15 (2013) 033038*
  $\sigma_{J/\psi}$ from *Nucl. Phys. B 850 (2011) 387-444*

Sample dominated by W + prompt J/ψ events.

Backgrounds

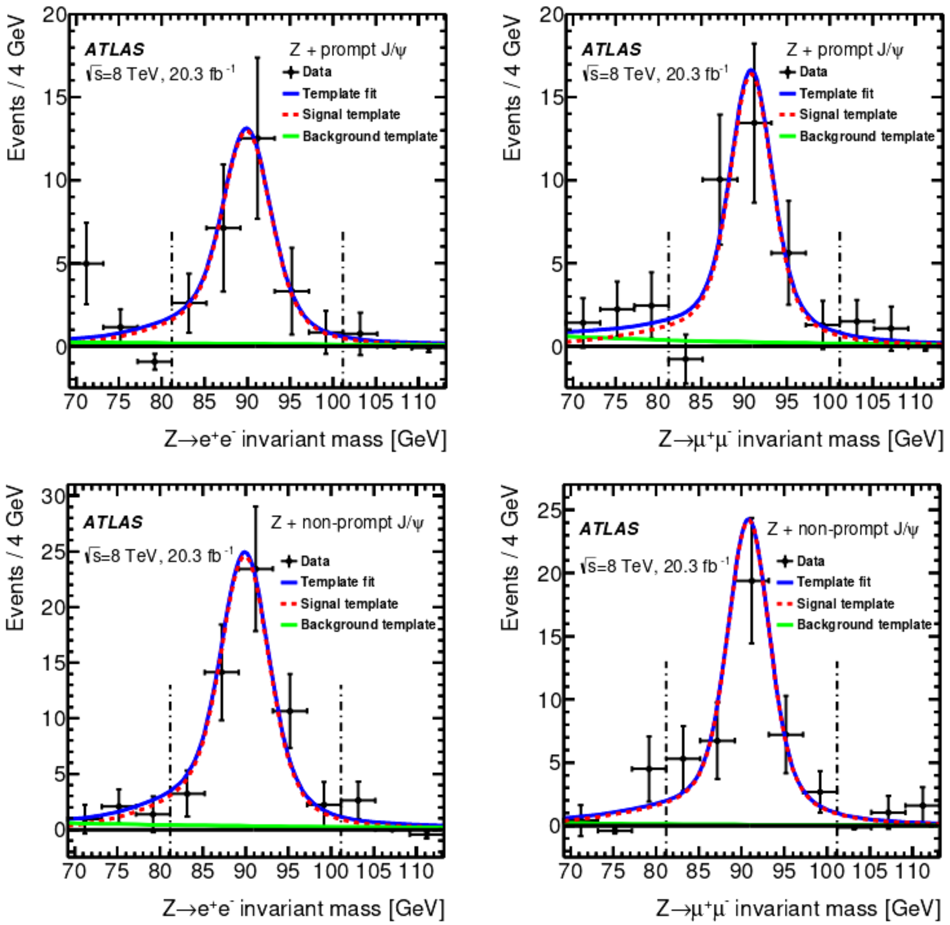
Background estimation using MC:

- $Z \to \tau\tau$ or $W \to \ell\nu$ background;
- Top quark processes involving $t\bar{t}$ or single top production;
- The single-top Wt process;
- Diboson (WZ, WW and ZZ) production.

Using data:

- Multi-jet production – Selecting non-isolated leptons.

  The m(Z) distribution of signal events is fit to a sum of a multi-jet template and a Z^0 boson signal template.



The numbers of background events estimated in the Z signal region, defined as $m_{ZPDG} \pm 10$ GeV, for the $Z \to e^+e^-(\mu^+\mu^-)$ candidates are:

- associated with prompt J/ψ: 0±4 (1±4);
- associated with non-prompt J/ψ: 1±5 (0±5).

The sample is dominated by genuine $Z + J/\psi$ events.

Measurements and limits on the effective cross section