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

(arXiv:1401.2831)

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DIS2014, Warsaw

April 29, 2014

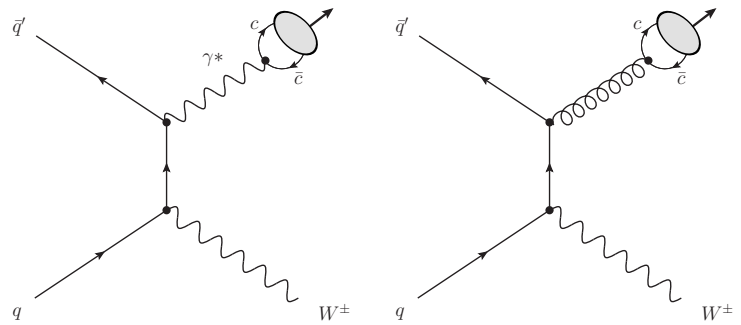
Introduction

First observation of the production of $W^{\pm}$**+prompt** J/ψ and **measurement of the cross-section ratio** relative to inclusive $W^{\pm}$ production

Production of heavy quarkonia

- **various theoretical models** (CSM, NRQCD,...) - **competing production mechanisms**
  - color-singlet (CS) process
  - color-octet (CO) process (NRQCD)
- **results of current measurements** of *inclusively* produced quarkonia (cross section, polarization) are **contradictory**

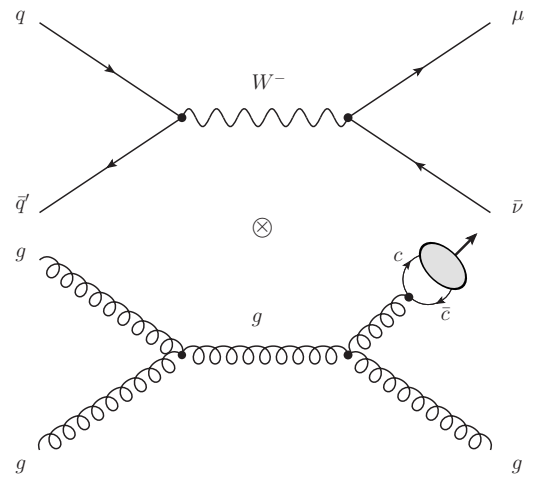
CS vs. CO



Measurement of the $W^{\pm}$+prompt J/ψ production cross section

- can help to distinguish between different production scenarios, e.g.
  1. being dominated by CO processes $\rightarrow$ test of NRQCD
  2. has comparable CS and CO contributions
- probes ***double parton scattering*** **(DPS)**
- step towards measuring Higgs boson decays into rare quarkonia
- probes BSM frameworks

DPS



Data analysis

2011 dataset $4.5\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 7$ TeV pp collisions collected by the ATLAS experiment

Event selection

J/ψ selection: $J/\psi \to \mu^+\mu^-$

- two oppositely charged muons: $p_{\mathrm{T}}^{\mu} > 4(2.5/3.5)$ GeV, $|\eta_{\mu}| < 2.5$
  - common vertex
  - invariant mass: $2.5\ \mathrm{GeV} < m_{\mu^+\mu^-} < 3.5\ \mathrm{GeV}$
- transverse momentum and rapidity of J/ψ:
  $8.5\ \mathrm{GeV} < p_{\mathrm{T}}^{J/\psi} < 30\ \mathrm{GeV}$, $|y_{J/\psi}| < 2.1$

W selection: $W \to \mu\nu$

- isolated, high p_{T} muon: $p_{\mathrm{T}}^{\mu} > 25$ GeV, $|\eta_{\mu}| < 2.4$
- missing transverse energy: $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
- transverse mass of the W boson: $m_{\mathrm{T}}^{\mathrm{W}} > 40$ GeV

Backgrounds

- W+b
- $t\bar{t}$
- Z+jets
- $B_c \to J/\psi\mu\nu X$
- multijet
- **pile-up**
- **DPS**

Additional cuts

- impact parameter cuts to suppress muons stemming from heavy flavour decays and pile-up interactions
- Z boson veto

Measurement strategy

1. Extraction of prompt J/ψ component

   = separation of **prompt** J/ψ component from **non-prompt** J/ψ component (from b-hadron decays) and **combinatorial** backgrounds

2. Extraction of $W^{\pm}$+prompt J/ψ component

   = separation of associated production with a W **boson** from **multijet** events

   = template fit to W transverse mass $m_{\mathrm{T}}^{\mathrm{W}}$ of **prompt** J/ψ component

   $\rightarrow$ multijet contamination negligible

   $\Rightarrow$ BACKUP slides

3. Determination of residual background contributions

   - **pile-up**
   - **DPS**
   - other backgrounds negligible

   to W**+prompt** J/ψ yield

Extraction of the (W+) prompt J/ψ component

2D unbinned maximum likelihood fit

1. invariant mass $m_{\mu^+\mu^-}$: J/ψ component vs. combinatorial background
2. pseudo-proper time τ: prompt vs. non-prompt components

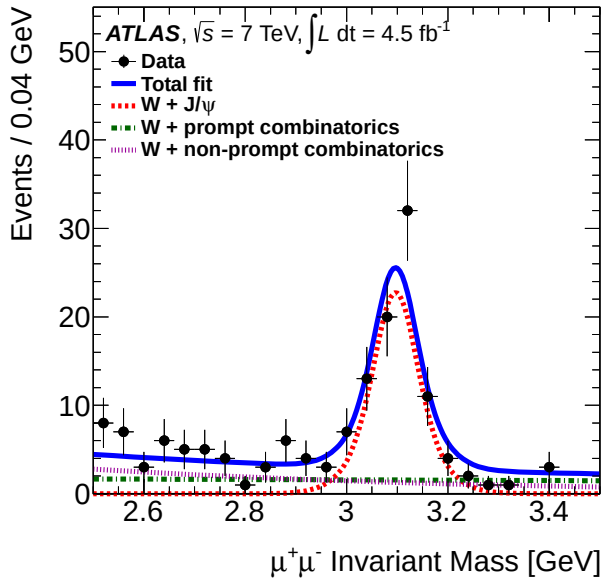
$$\tau = L_{xy} \cdot \frac{m_{\mu^+\mu^-}}{p_{\mathrm{T}}^{J/\psi}} \qquad L_{xy} : \text{distance from PV to SV}$$

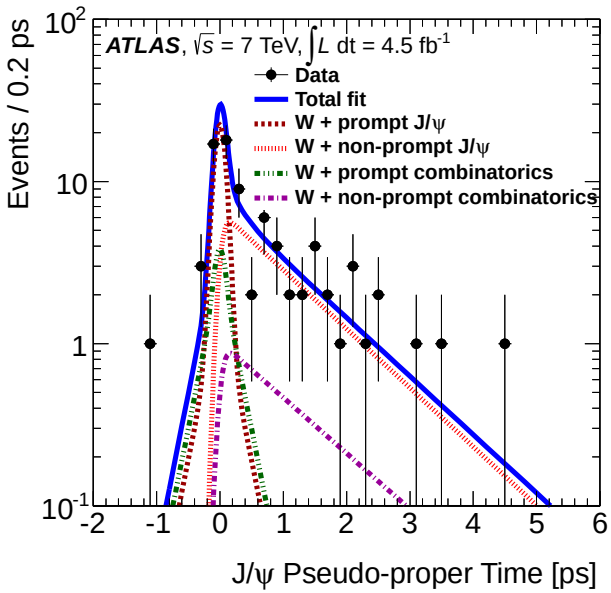
$\Rightarrow$ **prompt** J/ψ

- shape parameters, e.g. mass and pseudo-proper time resolution, are considered as **nuisance parameters**

  $\rightarrow$ initial values and constraints determined by performing a fit in an **inclusive** J/ψ **sample** selected in data

- use `sPlot` technique to extract variable distributions of the prompt J/ψ component from data





Pile-up determination

Pile-up: $W^{\pm}$ and J/ψ candidates might be produced in different pp collisions of the same bunch crossing

$$N_{\mathrm{PU}} = N_{\mathrm{vtx}}^{\mathrm{extra}} \cdot P_{J/\psi} \cdot N_{W^{\pm}}$$

- $N_{\mathrm{vtx}}^{\mathrm{extra}}$: number of extra collisions ($z_0 < 10\,\mathrm{mm}$), computed from
  - the mean number of collisions per pp bunch crossing μ
  - the geometric parameters of the interaction region
- $P_{J/\psi} = \sigma_{J/\psi}/\sigma_{inel}$: probability of producing a J/ψ meson
  - $\sigma_{J/\psi}$: cross section of inclusive J/ψ production (arXiv:1104.3038)
  - σ_{inel}: pp inelastic cross section
- $N_{W^{\pm}}$: number of $W^{\pm}$ candidates in fiducial region
- $N_{\mathrm{vtx}}^{\mathrm{extra}} \sim \sigma_{inel} \rightarrow N_{\mathrm{PU}}$ independent from σ_{inel}

$\rightarrow$ number of estimated **pile-up events**: $N_{\mathrm{PU}} = 1.8 \pm 0.2$

$\rightarrow$ subtracted from $W^{\pm}$+prompt J/ψ in cross section calculation

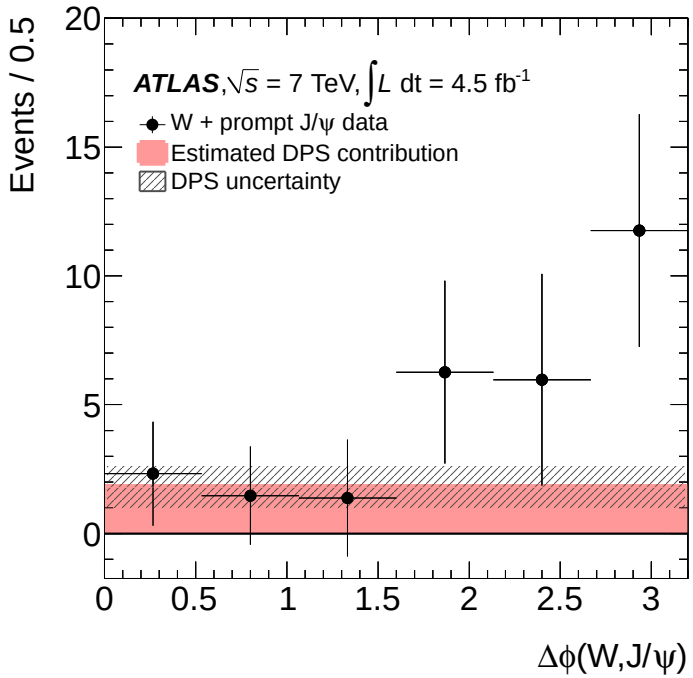
Determination of the DPS component

Double parton scattering (DPS): $W^{\pm}$ and J/ψ candidates originate from two different parton interactions in the **same** pp collision

$$N_{\mathrm{DPS}} = P_{J/\psi|W^{\pm}} \cdot N_{W^{\pm}}$$

- standard ansatz: $P_{J/\psi|W^{\pm}} = \sigma_{J/\psi}/\sigma_{\mathrm{eff}}$
- two interactions are treated as independent
- $\sigma_{\mathrm{eff}} = (15 \pm 3^{+5}_{-3})$ mb accounts for the geometric size of the proton (arXiv:1301.6872)

$\rightarrow$ number of **DPS events**: $N_{\mathrm{DPS}} = 11 \pm 4$



Cross check $\Delta\phi(W^{\pm}, J/\psi)$

- distribution for $W^{\pm}$+prompt J/ψ component extracted from data using `sPlot` technique
- DPS: **flat** distribution of $\Delta\phi(W^{\pm}, J/\psi)$ (independent processes)
- SPS: $\Delta\phi(W^{\pm}, J/\psi)$ **peaks strongly near** π

$\rightarrow$ $\Delta\phi(W^{\pm}, J/\psi)$ distribution in data suggests both DPS and SPS contributions

$\rightarrow$ determined rate is compatible

Results I: observation of $W^{\pm}$+prompt J/ψ

2D-fit results

J/ψ		background	
prompt	non-prompt	prompt	non-prompt
29^{+8}_{-7}	42^{+8}_{-7}	39^{+9}_{-7}	39^{+8}_{-7}

- combined statistical and systematic uncertainties due to nuisance parameters from the fit - statistical uncertainties dominating
- the $W^{\pm}$**+prompt** J/ψ component includes
  - 1.8 ± 0.2 pile-up events $\rightarrow$ subtracted in the following
  - 11 ± 4 DPS events

Signal significance: 5.1σ

- evaluated using pseudo-experiments for background-only hypothesis

$\rightarrow$ reject background-only hypothesis for the likelihood ratio in data

$\rightarrow$ observation

Measurement of the $W^{\pm}$+prompt J/ψ to $W^{\pm}$ cross-section ratio $R_{J/\psi}$

Cross-section ratio ($8.5\ \text{GeV} < p_{\text{T}}^{J/\psi} < 30\ \text{GeV}$, $|y_{J/\psi}| < 2.1$)

$$R_{J/\psi} = \frac{N(W^{\pm} + J/\psi)}{\varepsilon_{J/\psi} \cdot \alpha_{J/\psi} \cdot N(W^{\pm})}$$

- $N(W^{\pm} + J/\psi)$: number of $W^{\pm}$+prompt J/ψ events (normalized to fiducial region)
- $N(W^{\pm})$: number of inclusive $W^{\pm}$ events
- $\varepsilon_{J/\psi}$: **efficiency** correction factor for J/ψ decay muons
- $\alpha_{J/\psi}$: **acceptance** correction factor for J/ψ decay muons

$\rightarrow$ luminosity, BR($W \rightarrow \mu\nu$) and $W^{\pm}$ reconstruction efficiency and acceptance corrections cancel

$\rightarrow$ reduced systematic uncertainties

Number of $W^{\pm}$ events: $N(W^{\pm}) = 1.48 \times 10^7$

- $W^{\pm}$ part of event selection
- background estimation and subtraction
  - Z+jets, $t\bar{t}$ and diboson: simulations
  - multijet: data-driven (ABCD) method

Results II: cross-section ratio

Cross-section ratio results ($8.5\ \text{GeV} < p_{\text{T}}^{J/\psi} < 30\ \text{GeV}$, $|y_{J/\psi}| < 2.1$)

1. **fiducial** cross-section ratio $R_{J/\psi}^{\text{fid}} = (51 \pm 13 \pm 4) \times 10^{-8}$
   - **before** correction of the **fiducial acceptance** of J/ψ decay muon
2. **inclusive** cross-section ratio $R_{J/\psi}^{\text{incl}} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$
   - **after** correction of the **fiducial acceptance** of the J/ψ decay muons
   - assumption: isotropic spin-alignment
3. **DPS-subtracted** cross-section ratio $R_{J/\psi}^{\text{DPS sub}} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$

   $\rightarrow$ comparison to theoretical predictions

Uncertainties

1. statistical
2. systematic
3. systematic due to spin-alignment $\leftrightarrow J/\psi$ muon acceptance

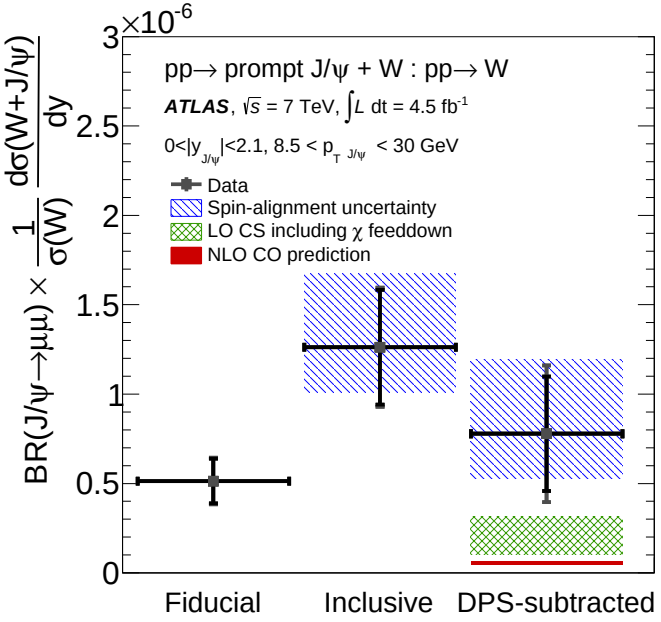
Source	Barrel	Endcap
J/ψ muon efficiency	(3-5) %	(3-5) %
$W^{\pm}$ boson kinematics	2 %	5 %
Fit	5 %	5 %
J/ψ spin alignment	$+36$ % -25 %	$+27$ % -13 %
Statistical	$+47$ % -40 %	$+30$ % -27 %

Comparison with theoretical predictions

Comparison of $R_{J/\psi}^{\text{DPS sub}} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$ to

1. LO **colour-singlet**
2. NLO **color-octet**

predictions for $W^{\pm}$+prompt J/ψ **SPS** production normalized to the NNLO $W^{\pm}$ production cross section

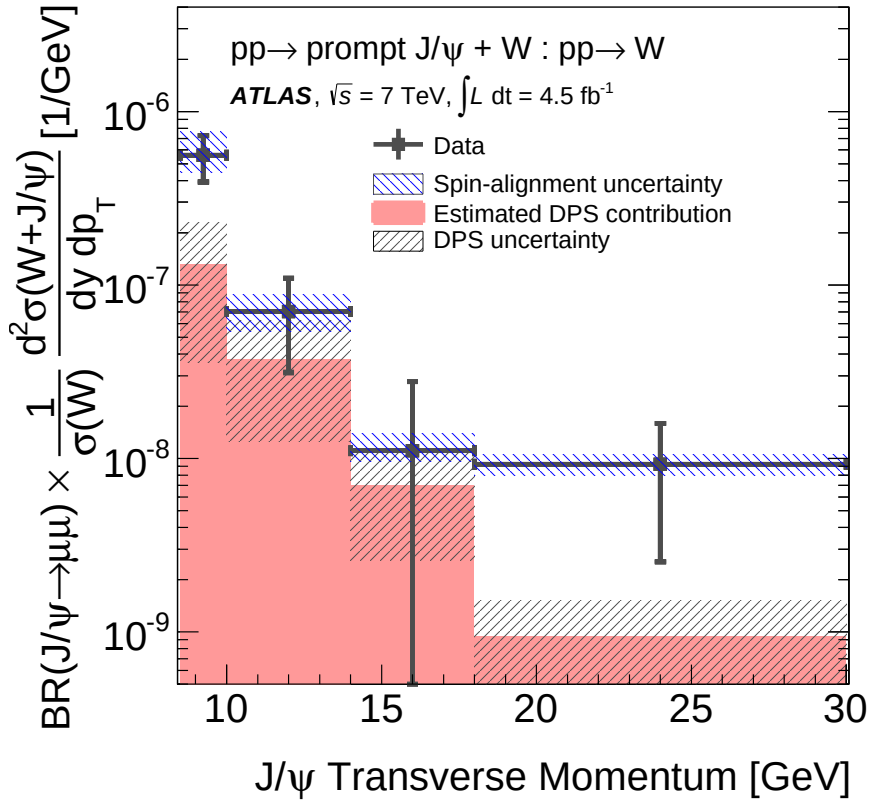


- **LO CS** contribution nearly an order of magnitude **larger than NLO CO contribution**:
  $(10 - 32) \times 10^{-8}$ vs. $(4.6 - 6.2) \times 10^{-8}$
- LO CS prediction consistent with measured $R_{J/\psi}^{\text{DPS sub}}$ within experimental *and* theoretical uncertainties
- both predictions are **compatible** with the measured result at the **2σ level**

$\Rightarrow$ **$W^{\pm}$+prompt J/ψ no distinctive signature of CO production**

Additional result

Differential cross-section ratio $\mathrm{d}R^{\mathrm{incl}}_{J/\psi}/\mathrm{d}p_{\mathrm{T}}$ as function of $p_{\mathrm{T}}^{\mathrm{J}/\psi}$



- **no DPS subtraction**

  $\rightarrow$ both SPS and DPS contributions

- estimated DPS contribution overlaid

$\rightarrow$ **SPS dominant contribution** to the total production rate of $W^{\pm}$+prompt J/ψ **at low** $p_{\mathrm{T}}^{\mathrm{J}/\psi}$

Summary

- First observation of 27^{+8}_{-7} $W^{\pm}$+prompt J/ψ events with a **statistical significance of 5.1** σ
- the measurement of the fiducial cross section ratio relative to inclusive $W^{\pm}$ production $R^{\text{fid}}_{J/\psi}$
- acceptance-corrected cross-section ratio $R^{\text{incl}}_{J/\psi}$ suffers from **unknown spin-alignment** affecting the J/ψ muon acceptance
  $\rightarrow$ will be **limiting factor** when more data is analysed
- the comparison of the DPS-subtracted cross-section ratio $R^{\text{DPS sub}}_{J/\psi}$ to LO CS and NLO CO predictions suggests $W^{\pm}$+prompt J/ψ production is **no distinctive signature of CO production**
- **DPS** contributes with a **large fraction** to the $W^{\pm}$+prompt J/ψ production
- the differential cross-section ratio $\mathrm{d}R^{\text{incl}}_{J/\psi}/\mathrm{d}p_{\mathrm{T}}$ as function of $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ suggests that **SPS** is the **dominant contribution at low** $p_{\mathrm{T}}^{\mathrm{J}/\psi}$

BACKUP

Extraction of the $W^{\pm}$+prompt J/ψ component

Multijet events can fake the W decay signature due to muons and neutrinos from heavy flavour decays and mismeasurement of the jet energy

$\rightarrow$ separate $W^{\pm}$**+prompt** J/ψ component from **multijet** events exploiting the W transverse mass distribution

Template fit to W transverse mass

- extract $m_{\mathrm{T}}^{\mathrm{W}}$ distribution of **prompt** J/ψ component from data using `sPlot` technique
- multijet template: non-isolated muons in data using ABCD method
- W+prompt J/ψ template: MC simulation

$\rightarrow$ number of estimated **multijet events**: 0.1 ± 4.6