First measurement of associated vector boson plus prompt charmonium production at the ATLAS experiment

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Associated vector boson plus prompt charmonium production

Introduction

- J/ψ meson is a bound state of $\bar{c}c$
- Production mechanism of prompt J/ψ not well understood
- Production mechanisms:
  - Colour singlet process (CS): quarkonia produced is determined by the state of the original quarks
  - Colour octet process (CO): proposes that the quark pairs produced by the hard process are not produced with the quantum numbers of the physical quarkonia but evolve into the quarkonia state through radiation of soft gluons.

- $W^\pm +$ prompt J/ψ is a quark-initiated process with different production mechanisms than the inclusive J/ψ
- Possible scenarios considered prior to ATLAS measurement
  - being dominated by CO processes $\Rightarrow$ test of NRQCD (Phys.Rev. D66 (2002) 114002)
  - First measurement of the associated production of $W^\pm +$ prompt J/ψ (arxiv.org/1401.2831)
    - $W^\pm \rightarrow \mu\nu_\mu$ and $J/\psi \rightarrow \mu\mu$ with ATLAS detector at $\sqrt{s} = 7$ TeV
The ATLAS detector

- General purpose detector at the LHC
- Tracking
  - Silicon (Pixel+SemiConductor Tracker) and Transition Radiation Tracker
  - 2 T solenoidal field
- Muon identification:
  - Dedicated tracking chambers
  - 0.5-2T toroidal field
- Neutrinos
  - Not detected
  - Imbalance of transverse momentum
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Data analysis

- 2011 dataset, 4.5 fb\(^{-1}\) of \(\sqrt{s} = 7\) TeV pp collisions
- Single muon trigger \(p_T > 18\) GeV
- \(J/\psi \rightarrow \mu^+\mu^-\)
  - \(p_T^\mu > 3.5\) (2.5) GeV with |\(\eta| < 1.3\) (>1.3)
  - common vertex
  - invariant mass 2.5 < \(m_{\mu\mu}\) < 3.5 GeV
- 8.5 < \(p_T^{J/\psi}\) < 30 GeV and |\(y_{J/\psi}\)|<2.1
- \(W^\pm \rightarrow \mu^0\mu^-\)
  - isolated muon \(p_T > 25\) GeV and |\(\eta| < 2.4\)
  - missing transverse energy > 20 GeV
  - transverse mass of the \(W^\pm\) boson > 40 GeV
- Remove events with |\(m_{\mu\mu} - m_Z\)|<10 GeV

\[\begin{array}{c|c|c|c|c|c|c|c|c|c}
\text{Invariant Mass [GeV]} & 2.6 & 2.8 & 3 & 3.2 & 3.4 \\
\hline
\text{ATLAS, }\sqrt{s} = 7\text{ TeV, }\int L dt = 4.5\text{ fb}^{-1}
\end{array}\]
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Extraction of prompt $J/\psi$ component

- 2D unbinned maximum likelihood fit in $J/\psi$ invariant mass and pseudo-proper time
- Mass
  - signal: gaussian
  - background: exponential
- Pseudo-proper time
  - prompt: gaussian + double sided exponential
  - non-prompt: single sided exponential

shape parameters taken from a fit in an inclusive $J/\psi$ sample from data
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### Extraction of prompt $J/\psi$ component

| 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        |

$p$-value evaluated with pseudo-experiments with B-only hypothesis to determine how often it fluctuates to S+B hypothesis.

extract $m_T^W$ events based on the prompt $J/\psi$ yield using sPlot
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$W^\pm$ events associated with prompt $J/\psi$s

- Confirming the $W^\pm$
- Weighted $W^\pm$ transverse mass distribution using $J/\psi$ signal yield compared with
  - $W^\pm$ signal template
  - data-driven multi-jet template
- Multi-jet yield < 0.3 events at 95% credibility

![Graph of $W$ transverse mass distribution]

**ATLAS, $\sqrt{s} = 7$ TeV, $\int L \, dt = 4.5$ fb$^{-1}$**

Normalized Yield

- $W$ template
- multi-jets template

Weighted Events / 20 GeV

- $W +$ prompt $J/\psi$ data
- Total fit
- $W$
- multi-jets

**ATLAS, $\sqrt{s} = 7$ TeV, $\int L \, dt = 4.5$ fb$^{-1}$**

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Backgrounds

- $W^\pm + b$
  - rejected from the fit
- $B_c \rightarrow J/\psi \mu^\pm \nu_\mu X$
  - check the three-muon invariant mass below 12 GeV
- $Z + \text{jets}$
  - $|m_{\mu\mu} - m_z| < 10$ GeV
- Pileup
  - $W^\pm + J/\psi$ candidates might be produced in different pp collisions of the same bunch crossing
  - $N = N_{\text{extra vtx}} \times P_{J/\psi} \times N_{W^\pm}$
    - $N_{\text{extra vtx}}$: Number of extra vertices near the $W^\pm$
    - $P_{J/\psi}$: Probability of producing a $J/\psi$ meson
    - $N_{W^\pm}$: number of $W^\pm$ candidates in fiducial region
  - Estimated $\sim 1.8 \pm 0.2$ events (subtracted from the cross section measurement)
• W± and J/ψ candidates originate from two different parton interactions in the same pp collision

\[ N_{\text{DPS}} = P_{J/\psi|W^\pm} N_{W^\pm} \]

\[ P_{J/\psi|W^\pm} = \frac{\sigma_{J/\psi}}{\sigma_{\text{eff}}} \]

- Probability of an additional process to occur (along with the J/ψ)
- \( \sigma_{\text{eff}} = 15^{+3}_{-3.3} \) mb (ATLAS measurement arXiv:1301.6872)
- \( N_{W^\pm} \): number of W± candidates in fiducial region
- \( N_{\text{DPS}} = 11 \pm 4 \)
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Cross section ratio $W^{\pm}+J/\psi : W^{\pm}$

$$\frac{\sigma(pp \rightarrow W + \text{prompt } J/\psi)}{\sigma(pp \rightarrow W)} = \frac{\frac{N_{W+J/\psi}}{\epsilon_{J/\psi} \cdot \alpha_{J/\psi} \cdot \epsilon_{W} \cdot \mathcal{L}}}{\frac{N_{W}}{\epsilon_{W} \cdot \mathcal{L}}}$$

- Ratio reduces (cancels) systematic uncertainties associated with luminosity and the $W$ boson
- Ingredients missing
  - efficiency $\epsilon(J/\psi)$
  - acceptance $\alpha(J/\psi)$
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**Efficiency - acceptance corrections**

- Muon reconstruction efficiencies calculated using $J/\psi$ “tag-and-probe” method
- Decay muons can follow different paths (depending on the spin-alignment)
- The efficiency for these muons to fall in the fiducial region - acceptance
  - Following different $J/\psi$ spin-alignment scenarios

#### Longitudinal acceptance

![Diagram showing longitudinal acceptance](image)

#### Isotropic acceptance

![Diagram showing isotropic acceptance](image)
• Inclusive differential cross section
• Rare process
• Estimation for DPS contribution
  • 40% of the total signal
• SPS dominated low $p_T^{J/\psi}$ production rate

$$\frac{d^2\sigma(W+J/\psi)}{dy dp_T}$$

$pp \to$ prompt $J/\psi + W : pp \to W$

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Conclusions

\[ R_{J/\psi}^{\text{fid}} = (51 \pm 13 \pm 4) \times 10^{-8} \]
\[ R_{J/\psi}^{\text{incl}} = (126 \pm 32 \pm 9) \times 10^{-8} \]
\[ R_{J/\psi}^{\text{DPS sub}} = (78 \pm 32 \pm 41 \pm 25) \times 10^{-8} \]

LO CSM contributions: \((10 \pm 32) \times 10^{-8}\)

NLO COM contributions \((4.6 \pm 6.2) \times 10^{-8}\)

- First observation of charmonium + vector boson production with a statistical significance of \(5.1\sigma\)
- Measurement of cross-section ratio \(W^\pm + J/\psi : W^\pm\)
- CSM theories revisited
  - CSM contributions larger than COM
- Differential cross section ratio as a function of \(p_T^{J/\psi}\) suggests big single parton scattering contribution

\[ \text{pp} \rightarrow \text{prompt } J/\psi + W : \text{pp} \rightarrow W \]

\(\textcolor{blue}{\text{ATLAS}}, \sqrt{s} = 7 \text{ TeV}, \int L \, dt = 4.5 \text{ fb}^{-1}\)

\(0 < \Delta y_{J/\psi} < 2.1, 8.5 < p_T^{J/\psi} < 30 \text{ GeV}\)

- Data
- Spin-alignment uncertainty
- LO CS including \(\chi\) feeddown
- NLO CO prediction

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Back up
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#### Uncertainties

| 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                                 | $^{+47\%}_{-40\%}$ | $^{+30\%}_{-27\%}$ |