Associated quarkonium production at ATLAS as a new probe of QCD

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Motivation

Quarkonium production measurements usually focus on **inclusive** sample properties

- e.g. spin alignment, differential cross sections

The high luminosities available at the LHC make it possible to study the **rare** process of quarkonia in **association** with other particles

- e.g. other quarkonia, vector bosons, jets, top, ...

There are two possible associated production modes

- **Single Parton Scattering**: particles come from the same hard scatter
- **Double Parton Scattering**: particles come from two hard scatters within the same proton collision

Important experimental motivation for ATLAS

- We can parasitically use a high bandwidth trigger without relying on dedicated quarkonia triggers

Potential to be useful in other measurements

- Background for rare $Z \rightarrow l^+ l^- J/\psi$ decay and $H \rightarrow ZZ^*$
- Probes heavy flavour + $W/Z$ (using $J/\psi$ as b-quark proxy)
- Rare Higgs to quarkonia and associated $V$-boson
- Higgs to charm couplings
- Other new physics

Example of colour-singlet $J/\psi + W$ production

arxiv:1303.5327
Motivation

Single parton scattering (SPS)
- Both particles come from the same parton interaction
- Enhances sensitivity to a subset of matrix elements allowing tests/development of theoretical models
- This tests potential differences of the \( p_T \) spectra of singlet and octet production modes between V-boson+onia or inclusive production
- Possibility of resonant production from Higgs or New Physics

Double parton scattering (DPS)
- Each particle from independent parton interaction
- Difficult to address theoretically but is often invoked to explain observations (e.g.) rates of multiple heavy-flavour production
- To calculate \( \sigma_{\text{eff}} \), the quarkonia can be fully reconstructed; experimentally cleaner than alternative methods (e.g. \( W + 2 \) jets)
- Wider range of measurements of DPS – more realistic models, allows tests of factorisation

DPS is **indistinguishable** on per event basis. We seek observables to disentangle them e.g. \( \Delta \phi \) opening angle distributions – but can we do this well enough to be useful?
Measurement Summary

Two measurements present production of **prompt** $J/\psi$ in association with $W$ or $Z$ bosons. These studies

- establish with $> 5\sigma$ significance the observation of associated quarkonia production with electroweak bosons
- present a cross-section measurement ratio
- provisionally assess the amount of double vs single parton scattering, or present the distributions that are likely to be able to separate them

These are just the first steps, more data and different combinations of particles are needed – these studies are continuing.

<table>
<thead>
<tr>
<th></th>
<th>$\int L$</th>
<th>$\sqrt{s}$</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi + W$</td>
<td>4.6 fb-1</td>
<td>7 TeV</td>
<td>JHEP 04 (2014) 172</td>
</tr>
</tbody>
</table>
Analysis Steps Overview

1. Selection of relevant μμμμ, μμee or μμμ+MET events

2. Pile-up contamination estimation
   - W/Z and J/ψ come from two different proton-proton interactions

3. Per candidate J/ψ efficiency and acceptance corrections

4. Signal and background weights and yield extraction
   - Using an unbinned, simultaneous, maximum likelihood fit in 2D (mass & lifetime) to separate the prompt and non-prompt J/ψ components

5. Differential cross-section evaluation
   - Cross section ratios \( \sigma(J/\psi + W,Z) / \sigma(W,Z) \) presented: most uncertainties cancel

6. Generation of relevant distributions

7. DPS contribution estimation
   - DPS contribution can be estimated with a calculation using the inclusive J/ψ cross section and the DPS \( \sigma_{\text{eff}} \) measurement from \( W + 2 \) jets
Final State

Triggers: Single high $p_T$ electron/muon
$J/\psi$ fiducial cuts: The same same for both analyses (after the acceptance corrections)

$\mu$

$J/\psi$

$\mu$

$\mu$

$p_T(\mu) > 25$ GeV must match trigger

$p_T(\mu/e) > 25$ GeV

$p_T(\mu/e) > 15$ GeV

MET

01/09/15

Associated Quarkonium

D. Bertsche
Candidates

$J/\psi + W$

$J/\psi + Z$

**ATLAS**

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

\( L \text{ for } J/\psi + W \)

\( L \text{ for } J/\psi + Z \)

$\mu^+\mu^- \text{ Invariant Mass [GeV]}$

$J/\psi \text{ pseudo-proper time [ps]}$

$J/\psi \text{ pseudo-proper time [ps]}$

**ATLAS**

\( s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

$Z \rightarrow \mu\mu$

$Z \rightarrow ee$

$J/\psi \text{ invariant mass [GeV]}$

$J/\psi \text{ invariant mass [GeV]}$
Corrections and Yield Extraction

• Acceptance and efficiency corrections derived from MC and applied per candidate
  ▪ A range of acceptance corrections, covering the extremes of J/ψ polarisation scenarios

• Signal weights extracted using an 2D maximum likelihood fit with discriminants:
  ▪ J/ψ candidate mass
  ▪ J/ψ candidate pseudo-proper time

• Four categories of events are described in the fits
  ▪ W, Z candidate + real prompt J/ψ (SIGNAL)
  ▪ W, Z candidate + real non-prompt J/ψ (SIGNAL)
  ▪ W, Z candidate + two combinatorial muons forming a prompt-like lifetime distribution
  ▪ W, Z candidate + two combinatorial muons forming a non-prompt-like lifetime distribution

• Yield extracted by fitting weighted distributions
Corrections and Yield Extraction: J/ψ+W

The signal weights are extracted by applying an unbinned, simultaneous, maximum likelihood, 2D fit to the mass and lifetime distributions.

Signal significance = 5.1σ for prompt J/ψ+W
The signal weights are extracted by applying an unbinned, simultaneous, maximum likelihood, 2D fit to the mass and lifetime distributions. Signal significance > 5σ for prompt J/ψ+Z and non-prompt J/ψ+Z.
The backgrounds not covered by the fits were found to be negligible:

- **fake W/Z (from multi-jet/top)**
  
  Template fit of $m_T(W)$ estimates
  
  $0.1 \pm 4.6$ multi-jet events in
  
  $J/\psi + W$ sample

  Simulation of $t\bar{t}$ events estimates
  
  $< 0.28$ events at 95\% CL in
  
  $J/\psi + W$ sample

- **Contamination from $B_c \rightarrow J/\psi \mu^\pm \nu\mu X$**
**EXCEPT** real J/ψ and real W/Z produced in different proton-proton collisions in the same bunch crossing ("pile-up background")

\[
N_{\text{pileup\_background\_events}} = 2.3 \pm 0.2 \text{ for the } J/\psi + Z \\
N_{\text{pileup\_background\_events}} = 0.81 \pm 0.08 \text{ for the } J/\psi + W
\]
J/$\psi$+W results: azimuthal opening angle

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

- W + prompt J/$\psi$ data
- Estimated DPS contribution
- DPS uncertainty

DPS processes are expected to give a flat azimuthal opening angle ($\Delta \phi$) distribution.

Possible indication of DPS and SPS J/$\psi$+W production.
**J/ψ+W results: Cross-Section**

**Fiducial** means no J/ψ acceptance corrections.

**Inclusive** contains all corrections, also presented in $p_T^{J/\psi}$ bins.

**DPS-subtracted** to compare with theory: appears theory doesn’t fully account for SPS contribution

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DPS estimated experimentally from measurement of $\sigma_{\text{eff}}(W+2\text{jets})=15\text{mb}$

Deviations between data and theory may be due to:

- Theory underestimate of SPS rate
- Theory underestimate of DPS rate, or factorisation ansatz breakdown

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CS prediction: PL B 738 (2014) 529-529
LO CS = leading-order colour-singlet
NLO CO = next-to-leading-order colour-octet
DPS dominates the first bin.
The same pattern is observed in the azimuthal opening angle as with the J/ψ+Z.
J/ψ+Z results: total cross-sections

\[ \frac{\sigma(Z+J/\psi)}{\sigma(Z)} \times 10^6 \]

**ATLAS**, \( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} 

pp → prompt J/ψ+Z : pp → Z

\( |y_{J/\psi}| < 2.1, 8.5 < p_{T}^{J/\psi} < 100 \text{ GeV} \)

- **NLO NRQCD CS**
- **NLO NRQCD CO**
- **NLO NRQCD CO+CS**
- **LO CSM**

**Theory References:**

NRQCD: JHEP 1102 (2011) 071 (Mao et al.)
CSM: JHEP 1303 (2013) 115 (Gong et al.)

Again, theory appears to underestimate SPS production.
(Note: NLO NRQCD does feed-down a component not included in these predictions.)

NLO NRQCD CS = next-to-leading-order non-relativistic-QCD colour-singlet
NLO NRQCD CO = next-to-leading-order non-relativistic-QCD colour-octet
LO CSM = leading-order colour-singlet-mechanism
J/ψ+Z results: differential cross-sections

The lowest $p_T^{J/ψ}$ bin is mostly DPS and the highest bins are SPS dominated. The theory discrepancy becomes more pronounced with increasing $p_T^{J/ψ}$. 
J/ψ+Z results: lower limit on $\sigma_{\text{eff}}$

Again considering the first bin of this $\Delta\phi$ plot to be due to DPS…

…we set an upper limit on level of DPS contributing to the observed signal

- corresponding to a lower limit on $\sigma_{\text{eff}}$ which is in agreement with other measurements

These are early results, but they show the possibility of using quarkonia for studying DPS.

**WANTED:** models for the SPS contribution to $V+J/\psi$, particularly as a function of $\Delta\phi$

→ To allow better estimate of the DPS component
→ To allow measurement of $\sigma_{\text{eff}}$ and DPS kinematics
Outlook and conclusions

• The LHC experiments have made excellent first steps in studying the production of quarkonia in association with other particles.

• These processes will help to address issues of:
  - singlet versus octet production of quarkonia
  - double parton scattering
  - resonant production

• Given low production rates, clean experimental signatures and high mass associated particles, we should collect significant numbers of these decays in LHC Run-2 while staying within reasonable trigger thresholds.

The outlook for these studies is positive.
Additional Information
**ATLAS J/ψ +W: Event/object selection**

<table>
<thead>
<tr>
<th>Final state requirement</th>
<th>(μ^+μ^-μ^± + \text{MET} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trigger</strong></td>
<td>Single (μ &gt; 18 \text{ GeV} )</td>
</tr>
<tr>
<td><strong>Muon selections</strong></td>
<td>3 muons, 1 matched to trigger, (</td>
</tr>
<tr>
<td><strong>J/ψ selections</strong></td>
<td>(μ^+μ^-, \text{one} &gt; 4 \text{ GeV}, \text{at least one combined}, 2.5 &lt; m_{μμ} &lt; 3.5 \text{ GeV} ), (8.5 &lt; p_T(J/ψ) &lt; 30 \text{ GeV} ), (</td>
</tr>
<tr>
<td><strong>MET selections</strong></td>
<td>MET &gt; 20 GeV</td>
</tr>
</tbody>
</table>
| **W selections**        | One muon, matched to trigger: \(p_T > 25 \text{ GeV} \), \(|η|<2.4, z_0 < 1 \text{mm, } d_0/σ(d_0) < 3, \text{isolated} \)
\[m_T(W) = \sqrt[2]{2p_T(µ)\times\text{MET}\times(1-\cos(φ_µ-φ_{\text{MET}}))} \] > 40 GeV |
# ATLAS J/ψ +Z: Event/object selection

<table>
<thead>
<tr>
<th>Final state requirement</th>
<th>$\mu^+\mu^-\mu^+\mu^-$ or $\mu^+\mu^-e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>Single $\mu,e &gt; 25$ GeV</td>
</tr>
</tbody>
</table>

### Z boson selection

- $p_T$ (leading lepton) $> 25$ GeV, $p_T$ (sub-leading lepton) $> 15$ GeV
- $|\eta(\text{lepton from } Z)| < 2.5$
- $|m(Z) - 91.1876$ GeV$| < 10$ GeV

### J/ψ selection

- $8.5 < p_T(J/\psi) < 100$ GeV, $|y(J/\psi)| < 2.1$
- $p_T$ (leading muon) $> 4.0$ GeV, $|\eta(\text{leading muon})| < 2.5$

**OR**

- $p_T$ (sub-leading muon) $> 2.5$ GeV, $1.3 \leq |\eta(\text{sub-leading muon})| < 2.5$
- $p_T$ (sub-leading muon) $> 3.5$ GeV, $|\eta(\text{sub-leading muon})| < 1.3$

**must fit to vtx**

### J/ψ+Z selections

- J/ψ and Z vertices must less than 10mm apart
J/ψ kinematic acceptance depends on an uncertain spin alignment: we use extreme values to assess this uncertainty.

\[
\frac{d^2 N}{d \cos(\vartheta^*) d\varphi^*} \propto 1 + \lambda_\theta \cos^2(\vartheta^*) + \lambda_\phi \sin^2(\vartheta^*) \cos(2\varphi^*) + \lambda_{\theta\phi} \sin(2\vartheta^*) \cos(\varphi^*)
\]

<table>
<thead>
<tr>
<th>Angular coefficients</th>
<th>Isotropic (central value)</th>
<th>Longitudinal</th>
<th>Transverse positive</th>
<th>Transverse zero</th>
<th>Transverse negative</th>
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</thead>
<tbody>
<tr>
<td>(\lambda_\theta)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>+1</td>
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<tr>
<td>(\lambda_\phi)</td>
<td>0</td>
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<tr>
<td>(\lambda_{\theta\phi})</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
J/ψ Acceptance Maps

J/ψ kinematic acceptance depends on an uncertain spin alignment: we use extreme values to assess this uncertainty.

The $J/\psi$ acceptance for the extreme spin-alignment scenario transverse 0 (T+0) following Nucl. Phys. B 850 (2011) 387.
The two $J/\psi$ muons are independently efficiency weighted based on $p_T$ and pseudo-rapidity ($\eta$).

Low $p_T$ reconstruction efficiencies for combined muons.

Low $p_T$ reconstruction efficiencies for segment-tagged muons.
J/ψ pseudo-proper decay time ($\tau$)

$$\tau \equiv \frac{L_{xy} m_{J/\psi}}{p_{T,J/\psi}}$$

Allows us to distinguish between prompt and non-prompt J/ψ

Where:

- $L_{xy} = L \cdot p_{T,J/\psi} / p_{T,J/\psi}$
- $L =$ the vector from the primary decay vertex to the J/ψ decay vertex
- $m_{J/\psi} =$ the world-average mass of the J/ψ meson
- $p_{T,J/\psi} =$ the transverse momentum of the J/ψ
- $p_{T,J/\psi} =$ $|p_{T,J/\psi}|$
J/ψ+Z Theory References

- arXiv:1407.5821
- arXiv:1407.4038
- arXiv:1210.2430
- arXiv:1102.0398