Quarkonium and heavy flavour production measurements at the ATLAS experiment

S. Leontsinis$^{1,2}$
on behalf of the ATLAS Collaboration

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## Quarkonium and heavy flavour production measurements at ATLAS

### Introduction

| Search for \( X_b \) and other hidden-beauty states using \( π^+π^−\gamma(1S) \) channel | Phys. Lett. B 740 (2015) 199-217 |
| Cross-section measurement of \( ψ(2S) \rightarrow J/ψ \rightarrow \mu^+\mu^- \) \( π^+π^- \) at \( \sqrt{s} = 7\text{TeV} \) | JHEP 09 (2014) 079 |
| \( φ_s \) and \( ΔΓ_s \) from flavour tagged time dependent angular analysis of \( B_{0s} \rightarrow J/ψ \ φ \) | Phys. Rev. D 90 (2014) 052007 |
| Observation of an excited \( B_{c}^+ \) meson state with the ATLAS detector | Phys. Rev. Lett. 113 (2014) |
| √ | Branching fractions of \( B_{c}^+ \rightarrow J/ψ D_{s}^+ \) and \( B_{c}^+ \rightarrow J/ψ D_{s}^{−+} \) and transverse polarization fraction in the latter decay | ATLAS-CONF-2015-014 |
| √ | Study of \( J/ψ \) and \( ψ(2S) \) production in \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) p+Pb and \( \sqrt{s} = 2.76 \text{ TeV} \) pp collisions with the ATLAS detector | ATLAS-CONF-2015-023 |
| √ | Differential cross-sections of prompt and non-prompt \( J/ψ \) and \( ψ(2S) \) at \( \sqrt{s} = 7 \) and 8 \( \text{TeV} \) | ATLAS-CONF-2015-024 |
| √ | Measurement of the differential non-prompt \( J/ψ \) production fraction in \( \sqrt{s} = 13 \text{ TeV} \) pp collisions at the ATLAS experiment | ATLAS-CONF-2015-030 |
| √ | Observation of \( Λ_b \) in the decay \( Λ_{b}^{0} \rightarrow ψ(2S) \ Λ^{0} \) | |

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Study of the $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$ decays

- $B_c^+$ consists of a $b$ and $c$ quark $\bar{b} \rightarrow \bar{c} c \bar{s}$ processes occur via
  - colour-allowed and colour-suppressed spectator diagrams
  - weak annihilation diagrams
- Study $B_c^+$ decay to $J/\psi D_s^+$ and $J/\psi D_s^{*+}$
  - $D_s^+ \rightarrow \phi \pi^+ (\phi \rightarrow K^+K^-)$
  - $D_s^{*+} \rightarrow D_s^+ +$ soft photon or pion
- $B_c^+ \rightarrow J/\psi D_s^{*+}$
  - pseudoscalar meson to a pair of vector states transition
  - described by three helicity amplitudes
  - $A_{++}, A_{--}, A_{00}$

$$\mathcal{B}_{B_c^+ \rightarrow J/\psi D_s^+} \quad \mathcal{B}_{B_c^+ \rightarrow J/\psi D_s^{*+}}$$

- Two dimensional extended unbinned ML fit
  - mass and helicity angle
- Both $\sqrt{s} = 7$ and 8 TeV data sets
  - 4.9 and 20.6 fb$^{-1}$
- Use an ensemble of single, di-muon and three-muon triggers
Observation of $\Lambda_b$ in the decay $\Lambda_b^0 \rightarrow \psi(2S) \Lambda^0$

- First observation of $\Lambda_b^0 \rightarrow \psi(2S) \Lambda^0$
- Measurement of branching ratio $\Gamma(\Lambda_b^0 \rightarrow \psi(2S) \Lambda^0) / \Gamma(\Lambda_b^0 \rightarrow J/\psi \Lambda^0)$
  - Quarkonium reconstructed in the di-muon mode
  - $\Lambda^0 \rightarrow p \pi^+$
  - $= 0.501 \pm 0.033$ (stat.) $\pm 0.016$ (syst.) $\pm 0.011$ (B)
- Theory prediction: $0.8 \pm 0.1$
- $\sqrt{s} = 8$ TeV data set
- $20.6 \text{ fb}^{-1}$
Quarkonium and heavy flavour production measurements at ATLAS

Prompt and non-prompt $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 2.76, 7$ and $8$ TeV

- Quarkonia provide a unique opportunity to study QCD
- Hidden flavour presents significant challenges
  - theory and experiment
- Many theoretical models available
  - Colour Singlet Model
    - NNLO contributions calculated without introducing new phenomenological parameters
    - impossible to extend the calculation to P-wave states
  - Non-relativistic QCD (NRQCD)
    - parameters included, determined from fits to experimental data
    - good description of cross-sections - fail on polarisation
  - excuse me if your favourite one is not listed here
- Quarkonia are produced
  - QCD sources (prompt)
  - subsequent decays of $b$-hadrons (non-prompt)
    - $\psi(2S)$ has no significant feed-down from higher states
  - $4$ pb$^{-1}$ of $\sqrt{s}=2.76$ TeV, $2.1$ fb$^{-1}$ of $\sqrt{s}=7$ TeV and $11.4$ fb$^{-1}$ of $\sqrt{s}=8$ TeV
- $J/\psi$ and $\psi(2S)$ to di-muon final state
  - di-muon trigger
  - Differential cross-section
    $$\frac{d^2\sigma(pp \rightarrow \psi)}{dp_Tdy} \times B(\psi \rightarrow \mu^+\mu^-) = \frac{N^p_{\psi}}{\Delta p_T \Delta y \times \int L dt}$$
Quarkonium and heavy flavour production measurements at ATLAS

Prompt and non-prompt $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 2.76$, 7 and 8 TeV

- Correcting for
  - trigger and reconstruction efficiencies
  - acceptance (depending on spin-alignment)
    - isotropic scenario considered for main result
- Double differential cross-section
  - 22 $p_T$ bins: 8-110 GeV
  - 8 $y$ bins: 0-2

7 TeV prompt

8 TeV

7 TeV non-prompt

8 TeV

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- No significant rapidity dependence
- Slight overestimation of non-prompt $\psi(2S)$ production compared with $J/\psi$ predictions
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Quarkonium and heavy flavour production measurements at ATLAS
Prompt and non-prompt $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 2.76, 7$ and $8$ TeV

- Comparison with CMS$^1$ and LHCb$^2$ results
  - overlapping regions of $p_T$ and $|y|$ shows good agreement
- Combination of LHC measurements provide a wide coverage on $p_T$ and $|y|$
Quarkonium and heavy flavour production measurements at ATLAS

Prompt and non-prompt $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 2.76$, 7 and 8 TeV

- Measurement of the non-prompt fraction
  - $J/\psi$ and $\psi(2S)$ at $\sqrt{s} = 7$ and 8 TeV
  - cancellation of acceptance and efficiency corrections

\[ f_{\psi}^{\text{np}} \equiv \frac{pp \rightarrow b + X \rightarrow \psi + X'}{pp \text{ Inclusive}} = \frac{N_{\psi}^{\text{np}}}{N_{\psi}^{\text{np}} + N_{\psi}^{\text{p}}}. \]
Quarkonium and heavy flavour production measurements at ATLAS

Prompt and non-prompt $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 2.76$, 7 and 8 TeV and 13 TeV

- Measurement of the non-prompt fraction
  - $J/\psi$ and $\psi(2S)$ at $\sqrt{s} = 7$ and 8 TeV + 13 TeV
  - low $p_T$ (4 GeV) di-muon or higher $p_T$ (14 GeV) single muon trigger requirement
  - integrated luminosity of 6 pb$^{-1}$

$$f^\psi_B \equiv \frac{pp \rightarrow b + X \rightarrow \psi + X'}{pp \rightarrow \psi + X'} = \frac{N^\text{np}_\psi}{N^\text{np}_\psi + N^p_\psi}$$

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**Non-prompt Fraction**

ATLAS Preliminary

- $J/\psi$, $|y_{J/\psi}| < 0.75$
- $\psi(2S)$, $0.25 < |y_{\psi(2S)}| < 0.50$
- $\psi(2S)$, $1.96$ TeV, 39.7 pb$^{-1}$
- CDF ($p\bar{p}$), 1.96 TeV, 39.7 pb$^{-1}$

**Candidates**

- ATLAS 13 TeV, 6.4 pb$^{-1}$, $|y_{\mu\mu}| < 0.75$
- ATLAS 7 TeV, 2.1 fb$^{-1}$, $0.25 < |y_{\mu\mu}| < 0.50$
- ATLAS 2.76 TeV, 4 pb$^{-1}$, $|y_{\mu\mu}| < 0.75$
- CDF ($p\bar{p}$), 1.96 TeV, 39.7 pb$^{-1}$, $|y_{\mu\mu}| < 0.75$

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Associated production of $Z$ bosons with prompt and non-prompt $J/\psi$ mesons

- $J/\psi + Z$ can occur
  - single parton scattering (SPS)
  - double parton scattering (DPS)
- $J/\psi$ can be produced
  - prompt
  - non-prompt
- Additional observables and new final states provides further constraints on the contributions from colour-singlet and colour-octet production processes
- Using 20.3 fb$^{-1}$ of $\sqrt{s} = 8$ TeV data
  - high-$p_T$ single muon trigger
- Two dimensional unbinned maximum likelihood fit to separate prompt and non-prompt component
Quarkonium and heavy flavour production measurements at ATLAS

Associated production of $Z$ bosons with prompt and non-prompt $J/\psi$ mesons

- Single parton scattering
  - both objects from the same interaction
- Double parton scattering
  - each object from independent scatter
- Indistinguishable on an event-by-event basis
- Use of discriminating variables
  - azimuthal angle between the two particles $[\Delta\phi(Z,J/\psi)]$
  - flat contribution from DPS
  - peak at $\Delta\phi=\pi$, from SPS back-to-back production
    - smeared due to detector effects
- DPS governed by a “universal” effective cross-section, $\sigma_{\text{eff}}$
- Estimation follows:
  - $N_{\text{DPS}}=P_{\text{DPS}}^{J/\psi} N_{\text{fid}}^{Z}$
  - $P_{\text{DPS}}^{J/\psi} = \frac{\sigma_{\text{bin}}^{J/\psi}}{\sigma_{\text{eff}}}$
  - $\sigma_{\text{eff}}$ taken from ATLAS W+2jets measurement
- Prompt: $11.1^{+5.7}_{-5.0}$
- Non prompt: $5.8^{+2.8}_{-2.6}$
- Extraction of lower limit on $\sigma_{\text{eff}}>5.3$ mb

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Ma. Yeh"uu-Wei
 Associated production of $Z$ bosons with prompt and non-prompt $J/\psi$ mesons

- First observation of $Z+J/\psi$
  - prompt 5σ significance
  - non-prompt 9σ significance
- One of the most rare processes
  - occurs 10 times every million $Z$ bosons
- Total cross sections
  - theory is underestimating the SPS production
- Differential cross sections
  - low $p_T$ dominated by DPS
  - SPS drops off less steeply with $p_T$ than DPS
  - Theory discrepancy more pronounced with higher $p_T$
- DPS fraction is
  - 29% for the prompt $J/\psi + Z$
  - 8% for the non-prompt $J/\psi + Z$
## Quarkonium and heavy flavour production measurements at ATLAS

### Conclusions

| √  | Search for $X_0$ and other hidden-beauty states using $\pi^+\pi^- Y(1S)$ channel | Phys. Lett. B 740 (2015) 199-217 |
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https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

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### Conclusions

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| ✓ | Observation of an excited $B_c^+$ meson state with the ATLAS detector | Phys. Rev. Lett. 113 (2014) |

- Don’t miss the talks from
  - Cristiano Alpigiani
  - New physics searches with heavy flavour observables at ATLAS
- James Walder
  - Measurements of production and decay of exotic mesons at the ATLAS and CMS experiments

| ✓ | Branching ratios of $B_c^+$ mesons | ATLAS-CNF-2015-014 |
| ✓ | Study of $b\bar{b}$ events at ATLAS | ATLAS-CNF-2015-023 |
| ✓ | Different perspectives on heavy flavour production at ATLAS | ATLAS-CNF-2015-024 |
| ✓ | Measurements of production and decay of exotic mesons in p+p collisions at the ATLAS experiment | ATLAS-CNF-2015-XXX |
| ✓ | Observation of $\Lambda_b$ in the decay $\Lambda_b^0 \rightarrow \psi(2S) \Lambda^0$ | ATLAS-CNF-2015-030 |

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BACKUP
## Quarkonium and heavy flavour production measurements at ATLAS

Prompt and non-prompt $J/\psi$ and $\psi(2S)$ production at $\sqrt{s} = 7$ and 8 TeV

### Systematics

<table>
<thead>
<tr>
<th>Systematic Type</th>
<th>7 TeV [%]</th>
<th>8 TeV [%]</th>
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</thead>
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<tr>
<td></td>
<td>Min Median Max</td>
<td>Min Median Max</td>
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<td>Luminosity</td>
<td>1.8  1.8  1.8</td>
<td>2.8  2.8  2.8</td>
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<td>Inner Detector tracking efficiency</td>
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<td>1.0  1.0  1.0</td>
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<td>Muon reconstruction efficiency</td>
<td>0.7  1.2  4.7</td>
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<td>Muon trigger efficiency</td>
<td>3.2  4.7  35.9</td>
<td>2.9  7.0  23.4</td>
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<td>Fit model parameterizations</td>
<td>0.9  3.7  39.1</td>
<td>0.9  3.7  86.2</td>
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<td>Bin migrations</td>
<td>0.01 0.1  1.4</td>
<td>0.01 0.3  1.5</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>4.3  7.4  43.2</strong></td>
<td><strong>5.2  9.1  87.1</strong></td>
</tr>
</tbody>
</table>
## Systematics

| Source                  | Prompt $|y_{J/\psi}| < 1.0$ | Prompt $1.0 < |y_{J/\psi}| < 2.1$ | Non-prompt $|y_{J/\psi}| < 1.0$ | Non-prompt $1.0 < |y_{J/\psi}| < 2.1$ |
|-------------------------|-------------|-----------------|-----------------|-------------------|
| Fit procedure           | 3%          | 3%              | 4%              | 8%                |
| $Z$ boson kinematics    | 1%          | 1%              | 1%              | 1%                |
| $\mu_{J/\psi}$ efficiency | 1%          | 1%              | 1%              | 1%                |
| Vertex separation       | 7%          | 16%             | 2%              | 15%               |
Quarkonium and heavy flavour production measurements at ATLAS

Study of the $B_{c}^{+}\rightarrow J/\psi D_{s}^{+}$ and $B_{c}^{+}\rightarrow J/\psi D_{s}^{+*}$ decays

Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{D_{s}^{+}/\pi^{+}}$</th>
<th>$R_{D_{s}^{*+}/\pi^{+}}$</th>
<th>$R_{D_{s}^{*+}/D_{s}^{+}}$</th>
<th>$\Gamma_{\pm\pm}/\Gamma$</th>
</tr>
</thead>
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<tr>
<td>Simulated $p_{T}(B_{c}^{+})$ spectrum</td>
<td>+0.4</td>
<td>+0.9</td>
<td>+0.4</td>
<td>+0.4</td>
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<tr>
<td></td>
<td>-0.4</td>
<td>-0.9</td>
<td>-0.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>Simulated $</td>
<td>\eta(B_{c}^{+})</td>
<td>$ spectrum</td>
<td>+1.8</td>
<td>+2.4</td>
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<td>-1.8</td>
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<td>Tracking efficiency</td>
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<td>$B_{c}^{+}$ lifetime</td>
<td>+1.1</td>
<td>+1.2</td>
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<td>-</td>
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<tr>
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<td>-1.3</td>
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<td>$D_{s}^{+}$ lifetime</td>
<td>±0.3</td>
<td>±0.3</td>
<td>±0.1</td>
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<td>$B_{c}^{+}\rightarrow J/\psi D_{s}^{(*)+}$ signal extraction</td>
<td>+1.7</td>
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<td>-10.1</td>
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<td>$B_{c}^{+}\rightarrow J/\psi\pi^{+}$ signal extraction</td>
<td>+1.5</td>
<td>+1.5</td>
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<td>$D_{s}^{*+}$ branching fractions</td>
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<td>-0.3</td>
<td>-1.1</td>
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<td>±2.4</td>
<td>±2.7</td>
<td>±2.2</td>
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<td>Total</td>
<td>+6.3</td>
<td>+7.5</td>
<td>+13.1</td>
<td>+15.4</td>
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<tr>
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<td>-14.3</td>
<td>-10.4</td>
<td>-17.9</td>
</tr>
<tr>
<td>$\mathcal{B}<em>{D</em>{s}^{+}\rightarrow\phi(K^{+}K^{-})\pi^{+}}$</td>
<td>±5.9</td>
<td>±5.9</td>
<td>-</td>
<td>-</td>
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</table>