Heavy flavor production and spectroscopy at ATLAS

PHENO 2016

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for the ATLAS collaboration

May 10th 2016
Introduction

- **Charmonium/Open Charm Production**
  - “Measurement of the differential cross-sections of prompt and non-prompt production of J/ψ and ψ(2S) in pp collisions at √s = 7 and 8 TeV with the ATLAS detector”  
    arXiv:1512.03657 (To appear in EPJC)
  - “Measurement of D*±, D± and D_s± meson production cross sections in pp collisions at √s=7 TeV with the ATLAS detector”
    arXiv:1512.02913 (To appear in EPJC)

- **B Baryons/B_c**
  - “Measurement of the branching ratio $\frac{\Gamma(\Lambda_b^0 \rightarrow J/\psi(2S)\Lambda^0)}{\Gamma(\Lambda_b^0 \rightarrow J/\psi\Lambda^0)}$ with the ATLAS detector” (at √s = 8 TeV)  
  - “Study of the $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$ decays with the ATLAS detector” (at √s = 7 and 8 TeV)

- **b Quark Fragmentation**
  - “Determination of the ratio of b-quark fragmentation fractions $f_s/f_d$ in pp collisions at √s=7 TeV with the ATLAS detector”

All ATLAS Heavy Flavor results can be found at:  
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
### Muon Spectrometer

**Triggering** \( |\eta| < 2.4 \)

**Precision Tracking** \( |\eta| < 2.7 \)

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### Inner Detector

- \( p_T > 0.4 \text{ GeV} \), \( |\eta| < 2.5 \)
- **New for Run 2:** Insertable B-Layer (IBL)
- Additional inner-most pixel layer \((r=33\text{mm})\) and lower \(x/X_0\) beam pipe

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### Resolution in \( m_{\mu^+\mu^-} \)

- \( \sim 50 \text{ MeV} \) for \( J/\psi \)
- \( 150 \text{ MeV} \) for \( \Upsilon(nS) \)

Resolution in \( b \)-hadron proper decay time \( \sim 100 \text{ fs} \)
Datasets (pp)

\( \sqrt{s} = 7 \text{ TeV} \)

- **8 TeV data, 21.3 fb\(^{-1}\)**
  - 50 ns bunch spacing
  - Peak: \( 7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)

\( \sqrt{s} = 8 \text{ TeV} \)

- Total Delivered: 22.8 fb\(^{-1}\)
- Total Recorded: 21.3 fb\(^{-1}\)

\( \sqrt{s} = 7 \text{ TeV} \)

- **7 TeV data, 5.08 fb\(^{-1}\)**
  - 50 ns bunch spacing
  - Peak: \( 3.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)

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Heavy Flavor at ATLAS

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Triggering for Heavy Flavor Physics

Quarkonia: $J/\psi \rightarrow \mu\mu, \ Upsilon \rightarrow \mu\mu$

Exclusive: $B \rightarrow J/\psi(\mu\mu) \times$ decays

Rare decays: $B \rightarrow \mu\mu(X)$ decays

- Trigger on low-$p_T$ 4,6 GeV dimuons
- Large gain in yields w.r.t single muon triggers
- 20 MHz collision rate, ~400 Hz recorded
- HF physics concentrates on low $p_T$ di-muon signatures
Charmonium Production at the LHC

Quarkonium production at the LHC offers unique windows on our understanding of the strong interaction.

Two distinct charmonium production mechanisms at the LHC:

**Prompt**: Produced directly in the pp interaction or through feed-down from heavier (directly produced) states

**Theory**: Non-relativistic QCD

**Non-Prompt**: produced in decays of b-hadrons, can be separated experimentally due to the “long” b-hadron lifetime.

**Theory**: Fixed Order and Next-to-Leading Logarithm

~35% of prompt J/ψ come from feed-down, ψ(2S) are almost all direct

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Also:

- Bottomonium measurements
- Exotic state searches
J/ψ and ψ(2S) Production at 7 and 8 TeV

Data (2.1 fb\(^{-1}\) at 7 TeV and 11.4 fb\(^{-1}\) at 8 TeV) collected with dimuon triggers

- Basic muon kinematic selection: \(p_T(\mu_{1,2}) > 4\) GeV and \(|\eta(\mu_{1,2})| < 2.3\) and vertex fit of dimuon tracks

Each dimuon candidate is weighted to correct for trigger efficiency, muon identification, and reconstruction and geometrical acceptance.

Corrected prompt and non-prompt J/ψ and ψ(2S) yields are determined from an unbinned fit to the 2-D dimuon mass and pseudo-proper decay time (τ) distribution

2-D fits performed in up to 22 \(p_T\) x 8 rapidity bins
Prompt $J/\psi$ compared to NRQCD

good agreement across range of $p_T$

no $y$ dependence

Prompt $\psi(2S)$ (no significant feed-down)

compared to NRQCD

Generally describes data well but deteriorates at higher $p_T$
J/ψ and ψ(2S) Production at 7 and 8 TeV

Non-prompt compared to FONLL - predicts slightly harder \( p_T \) spectra
Production Ratio of prompt $\psi(2S)/J/\psi$ consistent with flat across the whole $p_T$ range studied.

Prompt $J/\psi$ fraction dominates at low $p_T$ but non-prompt exceeds prompt at ~20 GeV.

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arXiv:1512.03657
**D*±, D±, D_s± production at 7 TeV**

Charm production studied through the reconstruction of exclusive D meson decays

- Valuable tool for **tuning** and **validation** of MC generators used for LHC physics (e.g. fragmentation tests)
- Total and differential cross sections compared to a range of theory predictions and MC generators
- Results within fiducial space (3.5<p_T<100 GeV, |η|<2.1) extrapolated to a measurement of the total charm cross section

\[
\sigma_{cc}^{tot} = 8.6 \pm 0.3(stat) \pm 0.7(syst) \pm 0.3(lum) \pm 0.2(ff^{3.8}_{extr}) \text{mb}
\]

xff ≡ fragmentation function
extr ≡ extrapolation procedure
$D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$ production at 7 TeV

Differential cross sections

**Extracted strangeness suppression factor in charm fragmentation ($\gamma_{s/d}$)**

$0.26 \pm 0.05\,(stat) \pm 0.02\,(syst) \pm 0.02\,(br) \pm 0.01\,(extr)$

**Extracted fraction of charged non-strange $D$-mesons produced in a vector state ($P_v^d$)**

$0.56 \pm 0.03\,(stat) \pm 0.01\,(syst) \pm 0.01\,(br) \pm 0.02\,(extr)$
Observation of $\Lambda_b^0 \rightarrow \psi(2S)\Lambda^0$

- First observation of the decay mode: $\Lambda_b^0 \rightarrow \psi(2S)\Lambda^0$ (8 TeV pp collisions)
- Measured relative BR to $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$:
  - In kinematic range $p_T(\Lambda_b^0) > 10$ GeV and $|\eta(\Lambda_b^0)| < 2.1$
  - Modeling $B^0 \rightarrow \psi(nS)K^0_s$ reflection
  - $< 0.5\%$ bias to ratio from $\Lambda_b \rightarrow \Lambda^0\mu\mu$

Exceeded by available prediction: $0.80 \pm 0.1$

Within range of analogous $B$ meson decays: $0.5$-$0.8$
Two heavy quarks, both can decay weakly, affects theoretical prediction of $B_c$ properties

$B_c \rightarrow J/\psi D_{s}^{+*}$ decay is a transition of $PS \rightarrow V+V$ described by 3 helicity amplitudes

Simplified angular analysis, distinguishing $A_{00}$ from $(A_{++}$ and $A_{--})$

Measuring fraction of transverse polarization $\Gamma^{++}/\Gamma^{00}$

Measurement of relative BR of $B_c \rightarrow J/\psi D_{s}^{+}$ w.r.t $B_c \rightarrow J/\psi D_{s}^{+*}$ and of both the decay modes w.r.t BR of $B_c \rightarrow J/\psi \pi^+$

$D_{s}^{+} \rightarrow \phi(K^+K^-)\pi^+$

$D_{s}^{+*} \rightarrow D_{s}^{+}[\pi^0/\gamma]_{soft}$

(not detected)

MC based templates
$B_c \rightarrow J/\psi \, D_s^{(*)}$ Results

Ratios of the BR of the decay modes:

Transverse polarization fraction

$$\frac{\Gamma_{\perp\perp}}{\Gamma} = 0.38 \pm 0.23(\text{stat}) \pm 0.07(\text{syst})$$

Comparison to LHCb and theoretical predictions

Shows good agreement with LHCb results
b-quark Fragmentation Fractions $f_s/f_d$

Important for studies such as $B_s \rightarrow \mu\mu$

Using decay modes $B_s \rightarrow J/\psi\phi$ and $B^0 \rightarrow J/\psi K^{*0}$

$$\frac{f_s}{f_d} \frac{B(B_s^0 \rightarrow J/\psi\phi)}{B(B_d^0 \rightarrow J/\psi K^{*0})} = 0.199 \pm 0.004 \text{(stat)} \pm 0.008 \text{(syst)}$$


$$\frac{B(B_s^0 \rightarrow J/\psi\phi)}{B(B_d^0 \rightarrow J/\psi K^{*0})} = 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.01}(f_M)^{+0.02}_{-0.01}(a_i)^{+0.01}_{-0.02}(m_c)$$

$$\frac{f_s}{f_d} = 0.240 \pm 0.004 \text{(stat)} \pm 0.010 \text{(syst)} \pm 0.017 \text{(th)}$$

Measured as a function of $p_T$ and $\eta$ (no evidence of dependence found)

Agrees with LHCb results and improves the world average arXiv:1507.08925

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Conclusions

• The presented results in production and decay properties using the full Run-1 data set are important input for theory MC generator tuning.

• The presented results show good agreement with theory and other measurements.

• ATLAS will continue its B-physics program. Focusing on precision measurements, rare decays and heavy flavor production and spectroscopy.

• Detector upgrades (tracking and muon system) and new trigger strategies will help to cope with high luminosity environment.
Backup
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<tr>
<th>Short Title</th>
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<tbody>
<tr>
<td>Study of the rare decays $B_{s}^{0}$ and $B^{0}$ into muon pairs from data collected during the LHC Run 1 with the ATLAS detector</td>
<td>25 fb⁻¹</td>
<td>Submitted to Eur. Phys. J. C.</td>
<td>arXiv:1604.04263</td>
<td>Link</td>
<td>-</td>
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<td>NEW Measurement of the CP-violating phase $\phi_{s}$ and the $B_{s}^{0}$ meson decay width difference with $B_{s}^{0} \rightarrow J/\psi \phi$ decays in ATLAS</td>
<td>14.3 fb⁻¹</td>
<td>Submitted to JHEP</td>
<td>arXiv:1601.03297</td>
<td>Link</td>
<td>-</td>
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<td>Measurement of $D^{+}, D^{0}$ and $D_{s}^{+}$ meson production cross sections in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector</td>
<td>280 nb⁻¹</td>
<td>Submitted to Nucl. Phys. B</td>
<td>arXiv:1512.02913</td>
<td>Link</td>
<td>-</td>
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<td>Observation and branching fraction of $\Lambda_{c} \rightarrow \psi(2S)\Lambda^{0}$ decay</td>
<td>20.6 fb⁻¹</td>
<td>Physics Letters B 751 (2015) 63-80</td>
<td>arXiv:1507.08202</td>
<td>Link</td>
<td>-</td>
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<td>Branching fractions of $B_{c} \rightarrow J/\psi D_{s}^{+}$ and $B_{c} \rightarrow J/\psi D_{s}^{-}$ and transverse polarization fraction in the latter decay</td>
<td>(4.9 + 20.6) fb⁻¹</td>
<td>Eur. Phys. J. C, 76(1), 1 (2016)</td>
<td>arXiv:1507.07099</td>
<td>Link</td>
<td>ATLAS-CONF-2015-014</td>
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<td>Search for $X_{b}$ and other hidden-beauty states using $\pi^{+}\pi^{-}Y(1S)$ channel</td>
<td>16.2 fb⁻¹</td>
<td>Phys. Lett. B740 (2015) 199-217</td>
<td>arXiv:1410.4490</td>
<td>Link</td>
<td>-</td>
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<td>Cross-section measurement of $\psi(2S) \rightarrow J/\psi (\rightarrow \mu^{+}\mu^{-}) \pi^{+}\pi^{-}$ at $\sqrt{s} = 7$ TeV</td>
<td>2.1 fb⁻¹</td>
<td>JHEP.09 (2014) 079</td>
<td>arXiv:1407.5532</td>
<td>Link</td>
<td>ATLAS-CONF-2013-094</td>
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<td>$\phi_{s}$ and $\Delta \Gamma_{s}$ from flavour tagged time dependent angular analysis of $B_{s}^{0} \rightarrow J/\psi \phi$</td>
<td>4.9 fb⁻¹</td>
<td>Phys. Rev. D 90 (2014) 052007</td>
<td>arXiv:1407.1796</td>
<td>Link</td>
<td>ATLAS-CONF-2013-039</td>
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<td>Observation of an excited $B_{s}$ meson state with the ATLAS detector</td>
<td>(4.9 + 19.2) fb⁻¹</td>
<td>Phys. Rev. Lett. 113 (2014) 212004</td>
<td>arXiv:1410.1032</td>
<td>Link</td>
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<td>Measurement of $X_{c1}$ and $X_{c2}$ production at $\sqrt{s} = 7$ TeV</td>
<td>4.5 fb⁻¹</td>
<td>JHEP.07 (2014) 154</td>
<td>arXiv:1404.7035</td>
<td>Link</td>
<td>ATLAS-CONF-2013-095</td>
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<td>Parity violating asymmetry parameter $\alpha_{b}$ and the helicity amplitudes for the decay $\Lambda_{b}^{0} \rightarrow J/\psi \Lambda^{0}$</td>
<td>4.6 fb⁻¹</td>
<td>Phys. Rev. D 89 (2014) 092009</td>
<td>arXiv:1404.1071</td>
<td>Link</td>
<td>ATLAS-CONF-2013-071</td>
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<td>Production cross section of $B^{+}$ at $\sqrt{s} = 7$ TeV</td>
<td>2.4 fb⁻¹</td>
<td>JHEP.10 (2013) 042</td>
<td>arXiv:1307.0126</td>
<td>Link</td>
<td>ATLAS-CONF-2013-008</td>
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