Heavy flavor production and spectroscopy at ATLAS

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For the ATLAS collaboration
Introduction

• **Charmonium/Open Charm Production**

• **B Baryons/Bc**
  – “Measurement of the branching ratio $\Gamma(Λ_b^0 → ψ(2S)Λ^0) / \Gamma(Λ_b^0 → J/ψΛ^0)$ with the ATLAS detector”, arXiv: 1507.08202 (Phys Lett B 751 (2015) 63-80)

• **b Quark Fragmentation**

• **13 TeV Results**

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

Muon Spectrometer
TrIGGERING $|\eta| < 2.4$
Precision Tracking $|\eta| < 2.7$

Inner Detector
$P_T > 0.4$ GeV $|\eta| < 2.5$
New for Run2: Insertable B-Layer (IBL)
Additional inner-most pixel layer ($r=33$mm) and lower $x/X_0$ beam pipe

Resolution in $m_{\mu^+\mu^-}$ $\sim 50$ MeV for $J/\psi$ and $150$ MeV for $\Upsilon(nS)$
Resolution in b-hadron proper decay time $\sim 100$ fs (no IBL, $\sim 30\%$ improvement expected)
Data

Datasets (pp):

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

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

13 TeV data, 3.9 fb\(^{-1}\)
50/25 ns bunch spacing
Peak: \(5.0 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)
Triggering for Heavy Flavor physics

20/40 MHz collision rate $\rightarrow$ ~400 Hz recorded

HF physics concentrates on low $p_T$ di-muon signatures

**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
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 Next-to-Leading Logarithm

~35% of prompt J/ψ come from feed-down, ψ(2S) are almost all direct
J/$\psi$ and $\psi(2S)$ 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/$\psi$ and $\psi(2S)$ yields are determined from an unbinned fit to the 2-D dimuon mass and pseudo-proper decay time ($\tau$) distribution

2-D fits performed in 22 $p_T \times 8$ rapidity bins

\[ \tau = \frac{L_{xy} m(J/\psi)}{P_T(J/\psi)} \]
**J/ψ and ψ(2S) Production at 7 and 8 TeV**

Prompt J/ψ compared to NRQCD - good agreement across range of $P_T$, no $y$ dependence
J/ψ and ψ(2S) Production at 7 and 8 TeV

Prompt ψ(2S) (no significant feed-down) compared to NRQCD. Generally describes data well but deteriorates at higher $p_T$. 

[Graphs showing ATLAS data and theory predictions for $B(\psi(2S) \rightarrow \mu^+\mu^-)$]
J/ψ and ψ(2S) Production at 7 and 8 TeV

Non-prompt compared to FONLL- predicts slightly harder $p_T$ spectra

Seen consistently across charmonium, open charm and open beauty measurements compared to FONLL
J/ψ and ψ(2S) Production at 7 and 8 TeV

Ratio of $\psi(2S)/J/\psi$
Prompt: slight increase as function of $p_T$
Non-prompt: 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 $\sim20$ GeV
D* production

Charm production studied through the reconstruction of exclusive D meson decays

Valuable tool for tuning and validation of MC generators used for LHC physics

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, $|\eta| < 2.1$) extrapolated to a measurement of the total charm cross section

$$\sigma^{tot}_{c\bar{c}} = 8.6 \pm 0.3\,(stat) \pm 0.7\,(syst) \pm 0.3\,(lum) \pm 0.2\,(ff)^{+3.8\,(extr)}_{-3.4}\,mb$$

$ff \equiv$ fragmentation function
extr $\equiv$ extrapolation procedure
Extracted strangeness suppression factor in charm fragmentation

\[ 0.26 \pm 0.05 \text{(stat)} \pm 0.02 \text{(syst)} \pm 0.02 \text{(br)} \pm 0.01 \text{(extr)} \]

Extracted fraction of charged non-strange D-mesons produced in a vector state

\[ 0.56 \pm 0.03 \text{(stat)} \pm 0.01 \text{(syst)} \pm 0.01 \text{(br)} \pm 0.02 \text{(extr)} \]
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 $B^0 \rightarrow J/\psi K^{*0}$

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

Perturbative QCD prediction

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

\[
\frac{f_s}{f_d} = 0.240 \pm 0.004(stat) \pm 0.010(syst) \pm 0.017(th)
\]
B-quark Fragmentation Fractions $f_s/f_d$

Measured as a function of $p_T$ and $\eta$ (no evidence of dependence found)
Observation of $\Lambda_b \rightarrow \psi(2S)\Lambda$

First observation of the decay mode $\Lambda_b \rightarrow \psi(2S)\Lambda$ (8 TeV pp collisions)

Measured relative BR to $\Lambda_b \rightarrow J/\psi \Lambda^0$

In kinematic range $p_T(\Lambda_b) > 10$ GeV and $|\eta(\Lambda_b)| < 2.1$

Modeling $B^0 \rightarrow \psi(nS)K^0_s$ reflection

< 0.5% bias to ratio from $\Lambda_b \rightarrow \Lambda^0\mu\mu$

\[
\frac{\Gamma(\Lambda_b^0 \rightarrow \psi(2S)\Lambda^0)}{\Gamma(\Lambda_b^0 \rightarrow J/\psi\Lambda^0)} = 0.501 \pm 0.033 \text{(stat)} \pm 0.016 \text{(syst)} \pm 0.011 \text{(Br)}
\]

Prediction: $0.8 \pm 0.1$ **

0.5-0.8 in analogous B meson decays

** T. Gutsche et. al. PRD 88 (2013) 114018
BR and Angular Analysis of $B_c \rightarrow J/\psi \ D_s^{+\ast}$

Two heavy quarks, both can decay weakly, affects theoretical prediction of $B_c$ properties.

$B_c \rightarrow J/\psi \ D_s^{+\ast}$ 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 $\Gamma^{\pm\pm}/\Gamma^{00}$

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

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

$D_s^{+\ast} \rightarrow D_s^{+}[\pi^0/\gamma]_{\text{soft}}$

(not detected)

MC based templates
$\mathbf{B}_c \rightarrow J/\psi \ D^{+}_S \ (+) \ Results$

\[
\frac{B_{B_c^+ \rightarrow J/\psi D_S^+}}{B_{B_c^+ \rightarrow J/\psi \pi^+}} = 3.8 \pm 1.1\text{(stat)} \pm 0.4\text{(syst)} \pm 0.2\text{(BF)}
\]

Ratios of BR

\[
\frac{B_{B_c^+ \rightarrow J/\psi D_s^{*+}}}{B_{B_c^+ \rightarrow J/\psi \pi^+}} = 10.4 \pm 3.1\text{(stat)} \pm 1.5\text{(syst)} \pm 0.6\text{(BF)}
\]

\[
\frac{B_{B_c^+ \rightarrow J/\psi D_s^{*+}}}{B_{B_c^+ \rightarrow J/\psi D_s^+}} = 2.8^{+1.2}_{-0.8}\text{(stat)} \pm 0.3\text{(syst)}
\]

Transverse polarization fraction

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

Comparison to LHCb and Theoretical predictions

![Graph comparing ATLAS, LHCb, and theoretical predictions for BR and $\Gamma_{\pm\pm}$.](image)
Measurement of $B^+$ mass with 13 TeV data

Initial performance study using full (3.2 fb$^{-1}$) 2015 pp dataset at $\sqrt{s}=13$ TeV in preparation for further detailed $b$-hadron measurements

Reconstruct $B^\pm \rightarrow J/\psi K^\pm$ decay with simple selection $P_T^{\mu}>4$ GeV and $P_T^K>3$ GeV

Perform three-track ($\mu^+\mu^-K^\pm$) vertex fit with $\chi^2$/dof<3

$B^+$ mass extracted from 16 separate unbinned fits to $M(J/\psi K^\pm)$ distributions binned in $y(J/\psi K^\pm)$

Systematic uncertainty (0.25 MeV) dominated by fit model (momentum scale not yet included)

<table>
<thead>
<tr>
<th>Fit</th>
<th>$B^\pm$ mass [MeV]</th>
<th>Fit error [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default Fit</td>
<td>5279.31</td>
<td>0.11 (stat.)</td>
</tr>
<tr>
<td>$L_{xy}&gt;0.2$ mm</td>
<td>5279.34</td>
<td>0.09 (stat.)</td>
</tr>
<tr>
<td>World Average fit</td>
<td>5279.29</td>
<td>0.15</td>
</tr>
<tr>
<td>LHCB</td>
<td>5279.38</td>
<td>0.11 (stat.) ± 0.33 (syst.)</td>
</tr>
</tbody>
</table>

Good agreement with world average
Non Prompt J/ψ fraction at 13 TeV

First ATLAS quarkonium production measurement at 13 TeV. Similar to Run-1 study
Early data sample of 6.4 pb\(^{-1}\) collected with di-muon triggers

Yields extracted from an un-weighted and unbinned fit to 2D dimuon mass and pseudo proper decay time

Efficiencies and acceptance cancel to a good approximation in the non-prompt fraction. Assign small (3%) uncertainty

Little dependence on \(\sqrt{s}\) when moving from 7 to 13 GeV

Minimal dependence on rapidity, similar to Run-1 results
Conclusions

• Number of new results in production and decay properties using full Run-1 data set. Important input for theory MC generator tuning

• First studies of 2015 pp collision data at $\sqrt{s}=13$ TeV. $J/\psi$ production and b-hadron reconstruction

• ATLAS will continue its B-physics program in Run 2, 3 and the HL LHC era. 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