Production of $b$ & $c$ hadrons with the ATLAS detector

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On behalf of the ATLAS Collaboration
ATLAS: a particle detector at the LHC

- **Inner tracker**
  - 2T solenoid
  - \(|\eta|<2.5\)
  - Silicon pixel
  - Silicon strips
  - straw tracker

- **Muon system**
  - 0.5-2T toroid
  - \(|\eta|<2.7\)
  - Precision & trigger chambers

\[ \sigma_{Pt}/Pt \sim 0.05\%Pt[GeV] \oplus 1.5\% \]
\[ \sim 10 \mu m \text{ impact parameter resolution} \]
LHC performance

- Excellent LHC performance
- Collected
  - 7 TeV: 4.5 fb⁻¹
  - 8 TeV: 20.3 fb⁻¹
  - 13 TeV: 3.9+35.6+9.6 fb⁻¹
- B-physics relies largely on (di-) muon triggers
- Some analysis use partial datasets
bb-cross section

- Can identify jets with b-hadrons from lifetime
- Difficult (large uncertainties) for charm
- Composition from template fit

**ATLAS Simulation**

\[ 110 < m_{bb} < 130 \text{ GeV} \]

- \( \Sigma \log(p_b/p_c) \)

**ATLAS**

\[ 90 < p_{T,bb} < 110 \text{ GeV} \]

- Data 2011
- \( f_{bb} = 0.540 \pm 0.020 \)
- \( \chi^2/\text{DoF} = 32.1/34 \)
- \( s=7 \text{ TeV}, 4.2 \text{ fb}^{-1} \)
bb-cross section

- 2 b-jets pT>20 GeV, leading jet pT> 270 GeV
- Measured bb-cross section reasonably modeled
- Observed problems:
  - Deviations for MC@NLO
  - Description of non-hard bb (gluon splitting)

EPJC (2016) 76:670
B-hadron pair production

- Small $\Delta R$ bb production difficult to probe with jets
- Important background for $H\rightarrow bb$
- Utilise $B\rightarrow J/\psi + X$ & $B\rightarrow \mu + X$ decays
- Use lifetime fit to extract $J/\psi$ from b-hadrons

3rd muon: Impact parameter $d_0$+Boosted Decision Tree
B-hadron pair production

- Differential x-section compared with MC (many more distrib., see bkp)
- Best description: Pythia with pT based gluon splitting kernel

<table>
<thead>
<tr>
<th>Option label</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt. 1</td>
<td>The same splitting kernel, ((1/2)(z^2 + (1-z)^2)), for massive as massless quarks, only with an extra (\beta) phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO ([34]) method.</td>
</tr>
<tr>
<td>Opt. 4</td>
<td>A splitting kernel (z^2 + (1-z)^2 + 8r_q z(1-z)), normalised so that the (z)-integrated rate is ((\beta/3)(1+r/2)), and with an additional suppression factor ((1-m_{qq}^2/m_{dipole}^2)), which reduces the rate of high-mass (q\bar{q}) pairs. This is the default setting in PYTHIA8.2.</td>
</tr>
<tr>
<td>Opt. 5</td>
<td>Same as Option 1, but reweighted to an (\alpha_s(km_{qq}^2)) rather than the normal (\alpha_s(p_T^2)), with (k = 1).</td>
</tr>
<tr>
<td>Opt. 5b</td>
<td>Same as Option 5, but setting (k = 0.25).</td>
</tr>
<tr>
<td>Opt. 8</td>
<td>Same as Option 4, but reweighted to an (\alpha_s(km_{qq}^2)) rather than the normal (\alpha_s(p_T^2)), with (k = 1).</td>
</tr>
<tr>
<td>Opt. 8b</td>
<td>Same as Option 8, but setting (k = 0.25).</td>
</tr>
</tbody>
</table>

hep-ex:1705.03374
Charm production cross section

- Reliable inclusive charm identification difficult
- Worry about b- feed down
- Reconstruct open charm
  - D meson decays
- Reconstruct hidden charm/Quarkonia
  - J/ψ
  - ψ(2s)
  - Exotic X(3872) state
J/ψ ψ(2s) X(3872) cross section

Quarkonia states

 thresholds:

\[ J^{PC} = \begin{align*}
0^{-+} & \quad 1^{--} & \quad 1^{+-} & \quad 0^{++} & \quad 1^{++} & \quad 2^{++}
\end{align*} \]

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J/ψ ψ(2s) cross sections

- non-prompt component from b-feed down
- Reconstruct di-muon decay
- Use displaced vertex & lifetime to fit components

EPJC (2016) 76:283
J/ψ ψ(2s) cross sections

- Prompt & non-prompt cross sections
- Good agreement between experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>s (TeV)</th>
<th>lumi (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>7</td>
<td>2.1</td>
</tr>
<tr>
<td>CMS</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>8</td>
<td>1.75</td>
</tr>
<tr>
<td>LHCb</td>
<td>2.0</td>
<td>1.75</td>
</tr>
</tbody>
</table>

**EPJC (2016) 76:283**
J/ψ cross sections at 13 TeV

- Measure non-prompt J/ψ fraction from lifetime fit
- Strong pT dependence
- Some variations
  - With rapidity
  - With energy

ATLAS-CONF-2015-030
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ψ(2s) & X(3872) production

- Utilise → J/ψππ → μμππ decays, measure (non)prompt
- Two lifetime fit, to account for Bc component
- m consistent with ρ → ππ

D^0–D^{*−} “molecule”
Diquark–diantiquark

Utilise → J/ψππ → μμππ decays, measure (non)prompt

Two lifetime fit, to account for Bc component

m_ππ consistent with ρ → ππ

ATLAS
εs=8 TeV, 11.4 fb^{-1}

Data
Fit
X(3872) Sig
ψ(2S) Sig
Background

J/ψππ candidates / 4 MeV

10^{-6}
0.20
0.15
0.10
0.05
0.00
3.7
3.8
3.9
m(J/ψππ) [GeV]

ATLAS
εs=8 TeV, 11.4 fb^{-1}

Data
Sum of Fits
Data_{LL} Template Fit
Data_{SL} p_τ^2 Fit

X(3872) → J/ψππ MC (phase space)

P → J/ψππ MC (phase space)
X(3872) cross section

- Utilise $\rightarrow J/\psi \pi \pi \rightarrow \mu \mu \pi \pi$ decays, measure (non)prompt

$$\sigma(pp \rightarrow B_c + \text{any}) \frac{\mathcal{B}(B_c \rightarrow X(3872) + \text{any})}{\sigma(pp \rightarrow \text{non-prompt} \ X(3872) + \text{any})} = (25 \pm 13\,\text{(stat)} \pm 2\,\text{(sys)} \pm 5\,\text{(spin)})\%$$

- Two lifetime fit, to account for Bc component

- NLO prediction using DD molecule, $\chi c_1(2P)$ mixture

- FONNL model

hep-ph:1304.6710

JHEP01 (2017) 117

Non-Prompt

Prompt

ATLAS $\sqrt{s}=8\,\text{TeV}, 11.4\,\text{fb}^{-1}$ Prompt X(3872)

ATLAS $\sqrt{s}=8\,\text{TeV}, 11.4\,\text{fb}^{-1}$ Non-Prompt X(3872)

NLO NRQCD

FONNL rescaled to X(3872)

Branching fraction uncertainty

JHEP10(2012)137

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Prompt $J/\psi$ pair production

- Testing higher order perturbative QCD
- Effects of single (SPS) and dual parton scattering (DPS)

Leading order  
SPS  
next-to-leading-order  
DPS
Prompt $J/\psi$ pair production

- Use Lifetime to separate prompt
- Two regions:
  - Low $p_T$ away: $J/\psi$ back-to-back
  - High $p_T$ forward: $J/\psi$ close by

EPJC (2017) 77:76
**Prompt J/ψ pair production**

- Extract DPS cross section &

\[
\sigma_{\text{eff}} = \frac{1}{2} \frac{\sigma_{J/\psi}}{\sigma_{DPS}} = \frac{1}{2} \sigma_{J/\psi} = 6.3 \pm 1.6(\text{stat}) \pm 1.0(\text{syst}) \text{ mb}
\]

- Discrepancies at low pT & high mass

**EPJC (2017) 77:76**

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**ATLAS**

\(\sqrt{s} = 8 \text{ TeV}, 11.4 \text{ fb}^{-1}\)

- \(f_{\text{dps}} = 9.5\% \pm 2.2\%\)
- Data
- DPS Estimate
- NLO* SPS+DPS Pred.

**ATLAS**

\(\sqrt{s} = 8 \text{ TeV}, 11.4 \text{ fb}^{-1}\)

- \(f_{\text{dps}} = 9.5\% \pm 2.1\%\)
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- NLO* SPS+DPS Pred.

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Summary and Conclusion

- ATLAS has an active B-physics program
- Measured production of
  - b-jets
  - B-hadrons
  - Charm (J/\(\psi\), \(\psi(2s)\), X(3872)) cross sections
  - J/\(\psi\) \(\psi(2s)\) pair production
- Testing QCD
  → improving description
  → improving Monte Carlo
Bonus Slides
B-hadron pair production

ATLAS

Data
Pythia8 Opt. 1
Stat.
Pythia8 Opt. 4
Stat.+Syst.
Pythia8 Opt. 5
Pythia8 Opt. 8
Pythia8 Opt. 5b
Pythia8 Opt. 8b

\( f_0 = 8 \text{ TeV}, 11.4 \text{ fb}^{-1} \)

\( \frac{d\sigma}{d\Delta R(J/\psi \mu)} \)

\( \Delta R(J/\psi \mu) \)

\( \Delta R(J/\psi \mu) \)

Relative uncertainty [%]

ATLAS

\( f_0 = 8 \text{ TeV}, 11.4 \text{ fb}^{-1} \)

Total
Statistical
\( \mu \text{ Trig} + \text{Reco} \)
J/\psi fit model
BDT
Fake J/\psi
B_{c}
obc Hadron

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ψ(2s) & X(3872) production

- Utilise $\rightarrow J/\psi \pi \pi \rightarrow \mu \mu \pi \pi$ decays

$\psi(2s)$ & $X(3872)$ production

$\bar{D}^{0} - D^{0}$ molecule

Diquark–diantiquark

$D^0 - \bar{D}^{0}$

$\psi(2S)$ → $J/\psi \pi \pi$ MC (phase space)

$X(3872)$ → $J/\psi \phi$ ($\rightarrow \pi \pi$)

$X(3872)$ → $J/\psi \pi \pi$ MC (phase space)

$\frac{1}{\Gamma} \frac{d\Gamma}{dm_{\pi \pi}} (\psi(2S) \rightarrow J/\psi \pi \pi)$

$\frac{1}{\Gamma} \frac{d\Gamma}{dm_{\pi \pi}} (X(3872) \rightarrow J/\psi \phi)$

$\frac{1}{\Gamma} \frac{d\Gamma}{dm_{\pi \pi}} (X(3872) \rightarrow J/\psi \pi \pi)$

$\bar{D}^{0}$

$D^{0}$

$\bar{D}^{0}$

$D^{0}$

$\pi$

$\mu$

μπππ

$\mu \mu \pi \pi$

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$\psi(2s)$ & X(3872) production

- Utilise $\rightarrow J/\psi\pi\pi \rightarrow \mu\mu\pi\pi$ decays