Onia production at ATLAS

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on behalf of the ATLAS Collaboration

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## ATLAS detector

### Inner detector
- $|\eta| < 2.5$, Solenoidal B-field $= 2$ T
- Silicon: pixels, strips
- Transition Radiation Tracker
- $\sigma(p_T)/p_T \sim 3.4 \times 10^{-4} p_T \oplus 0.015$

### Muon spectrometer
- precision chambers $|\eta| < 2.7$
- trigger chambers $|\eta| < 2.4$
- Toroidal B-field, average $\sim 0.5$ T
- $\sigma(p_T)/p_T \sim 10\% p_T$ for 1 TeV track

### Dimensions
- length: 44 m
- height: 25 m
- weight: 7000 tons
- $\sim 10^8$ electronic channels

### Three level trigger system
- Level 1: hardware trigger with muon and calorimeter information $\sim 75$ kHz
- Level 2: software trigger to confirm level 1 trigger decision $\sim O(1)$ kHz
- Event Filter: event selection with more complex algorithm $\sim O(100)$ Hz
Data sample

- 2010: peak $\mathcal{L} = 2.1 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- 2011: peak $\mathcal{L} = 3.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- 2012: peak $\mathcal{L} = 6.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

LHC is performing better and better

- 2010: $\int \mathcal{L} dt = 0.045 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV}$
- 2011: $\int \mathcal{L} dt = 5.3 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV}$
- 2012: $\int \mathcal{L} dt = 3.9 \text{ fb}^{-1} \sqrt{s} = 8 \text{ TeV}$

Plenty of data available
Di-muon triggers for $B$-physics programme

- ATLAS has a $B$-physics programme with low $p_T$ dimuon signatures
  - **Onia studies**: $J/\psi \rightarrow \mu\mu, \Upsilon \rightarrow \mu\mu$
  - CP violation/mixing: $B_s \rightarrow J/\psi\phi$
  - Rare $B$ decays: $B_s \rightarrow \mu\mu$

- Trigger on low $p_T$ dimuon essential
  - 2 muons at Level 1 HW trigger
  - Confirmation with SW trigger
  - Performs vertex fit and mass cut

- “2mu4” triggers unprescaled in 2011
  - A large number of events recorded for the $B$-physics programme

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<table>
<thead>
<tr>
<th>Trigger</th>
<th>Mass range</th>
<th># of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2mu4_Jpsimumu</td>
<td>2.5 – 4.3 GeV</td>
<td>14 M</td>
</tr>
<tr>
<td>2mu4_Upsimumu</td>
<td>8 – 12 GeV</td>
<td>9.1 M</td>
</tr>
<tr>
<td>2mu4_Bmumu</td>
<td>4 – 8.5 GeV</td>
<td>3.7 M</td>
</tr>
</tbody>
</table>

figure and numbers with 2.3 fb$^{-1}$
Muon reconstruction

- **Combined**: Muon Spectrometer and Inner Detector track
- **Tagged**: Inner Detector track matched with Muon Spectrometer segment

Reconstruction efficiency in low-$p_T$ region well described by simulation

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Quarkonia

**Charmonium**

- $J/\psi$ and $\psi(2S)$ candidates
- Key signatures of $B$-meson decays through charmonium states; e.g. $B_{d(s)} \rightarrow J/\psi \; K(\phi)$
- $\sim 2.2$ millions $J/\psi$ with $240$ pb$^{-1}$

**Bottomonium**

- Three Upsilon states observed in the barrel region
- $\sim 74$ thousands $\Upsilon(1S)$ with $240$ pb$^{-1}$

**ATLAS** Preliminary

<table>
<thead>
<tr>
<th>$\sqrt{s}$ = 7 TeV</th>
<th>$\int L , dt = 0.24$ fb$^{-1}$</th>
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</table>

$N_{J/\psi} = (2.208 \pm 0.002) \times 10^6$

$m_{J/\psi} = 3.094 \pm 0.003$ GeV

$\sigma_{m_{J/\psi}} = 60 \pm 1$ MeV

$\sqrt{s} = 7$ TeV $\int L \, dt = 0.24$ fb$^{-1}$

Barrel + Barrel

$\sigma(Y_{1S}) = 0.119 \pm 0.001$ GeV

$N(Y_{1S}) = (74.1 \pm 0.5) \times 10^3$
Quarkonium physics

- $J/\psi$ and $\Upsilon$ production at the LHC offers
  - Test of perturbative QCD at new energy regime
    - Higher transverse momentum
    - Wider rapidity range
  - Production mechanism for quarkonium states not fully understood
$J/\psi \rightarrow \mu\mu$

Inclusive cross-section

\[ \frac{d^2 \sigma(J/\psi)}{dp_T dy} \cdot Br(J/\psi \rightarrow \mu^+\mu^-) = \frac{N_{\text{corr}}}{\mathcal{L} \cdot \Delta p_T \Delta y} \]

\[ N_{\text{corr}} = \Sigma w^{-1} \cdot N_{\text{reco}} \]

Event weight: \[ w^{-1} = A \cdot M \cdot \epsilon^2_{\text{trk}} \cdot \epsilon^+_{\mu}(p^+_T, \eta^+) \cdot \epsilon^-_{\mu}(p^-_T, \eta^-) \cdot \epsilon_{\text{trig}} \]

- **Detector Acceptance**: with generator level MC
- **Bin migration correction**: due to finite detector resolution
- **Reconstruction efficiencies**: with tag-and-probe method using data
- **Trigger efficiency**: determined from MC and reweighted to data

- **Result with 2.2 \, pb^{-1}**
- **Example of one rapidity bin (4 in total)**
- **variation due to 5 extreme spin alignment scenarios**
- **Agreement with CMS**
$J/\psi \rightarrow \mu\mu$

Measurement of non-prompt fraction

pseudo-proper time

$$\tau = \frac{L_{xy} \cdot m(J/\psi)}{p_T(J/\psi)}$$

- $x$-$y$ displacement of $J/\psi$ from PV
- Invariant mass of $J/\psi$
- $p_T$ of $J/\psi$

- Prompt $J/\psi$ have $\sim$ zero $\tau$ while non-prompt $J/\psi$ have positive $\tau$
- Simultaneous fit to mass and $\tau$
- Good agreement with CDF
- Fraction is $p_T$ dependent
\( J/\psi \rightarrow \mu\mu \)

Measurement of non-prompt/prompt \( J/\psi \) cross-section

**Non-prompt \( J/\psi \) cross-section**

- Good agreement with prediction by FONLL (Fixed Order Next to Leading Log)

**Prompt \( J/\psi \) cross-section**

- CEM is not describing shape
- NLO CSM is low but describing shape
- NNLO\(^*\) CSM describe the data better
$\Upsilon \rightarrow \mu\mu$

cross-section

$2 \text{ GeV} < p_T^{\mu\mu} < 4 \text{ GeV}$

$|y^{\mu\mu}| < 1.2$

$N_{\Upsilon(1S)} = 246 \pm 25$

$\chi^2/\text{ndf} = 43.3/52$

$\int L \, dt = 1.13 \text{ pb}^{-1}$

### Data 2010

- Fit result
- $\Upsilon(1S)$
- $\Upsilon(2S)$
- $\Upsilon(3S)$
- Background

### Result with $1.1 \text{ pb}^{-1}$

- Implementation of NRQCD in Pythia is higher (lower) than data at high (low) $p_T$

- CSM prediction at NLO underestimates the data. Feed-down from excited states can only account for up to a factor of two increases in predictions. NNLO corrections need to be large, or leaves more room for colour octet contributions.
Observation of $\chi_b(3P)$

- $\chi_c$ and $\chi_b$ represent spin triplet ($S=1$) P-wave ($L=1$) states of charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) spectra.

- The $\chi$ represents a triplet of states with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$

- Branching fractions for the radiative decays $\chi_b \rightarrow \Upsilon \gamma$ are large $O(10\%)$

- $\chi_b(1P)$ and $\chi_b(2P)$ already observed

- $\chi_b(3P)$ also predicted below $B\bar{B}$ threshold.

- Search for $\chi_b(3P)$ states in $\chi_b \rightarrow \Upsilon \gamma$ decays has been performed. Photon reconstructed either directly in the calorimeter or through conversion to $e^+e^-$. 

![Image of observed bottomonium radiative decays in ATLAS, $L = 4.4 \text{ fb}^{-1}$]
$\chi_b(3P)$ candidate

- $\mu\mu + \text{unconverted } \gamma$

- $m(\mu\mu\gamma) - m(\mu\mu) + m(\Upsilon(1S)) = 10.54$ GeV
$\chi_b(3P)$ candidate

- $\mu\mu + \text{converted } \gamma$

- $m(\mu\mu\gamma) - m(\mu\mu) + m(\Upsilon(1S)) = 10.54$ GeV
Observation of $\chi_b(3P)$

Unconverted photons

\[ m(\chi_b(3P)) = 10.541 \pm 0.011 \text{ (stat.)} \pm 0.030 \text{ (syst.)} \text{ GeV} \]

Converted photons

\[ m(\chi_b(3P)) = 10.530 \pm 0.005 \text{ (stat.)} \pm 0.009 \text{ (syst.)} \text{ GeV} \]

These distributions are not corrected for detector efficiencies or acceptances.

• Statistical significance of $> 6 \sigma$ in each channel
• Spin-averaged potential model prediction: 10.525 GeV


\[ m_{DØ}(\chi_b(3P)) = 10.551 \pm 0.014 \text{ (stat.)} \pm 0.017 \text{ (syst.)} \text{ GeV} \]
Summary and outlook

- ATLAS has performed measurements of Onia production
  - $J/\psi$ cross-sections
    - agreement with CDF/CMS
    - non-prompt fraction increases as $p_T$ of $J/\psi$ increases
    - Colour Singlet Model at NNLO improves agreement with measured prompt cross-sections compared to NLO
  - $\Upsilon$ cross-sections
    - NRQCD does not describe shape
    - Colour Singlet Model is describing shape but lower than data
      No feed down from higher order states are included
  - Observation of new state $\chi_b(3P)$
    - measured mass agrees well with prediction of 10.525 GeV

- ATLAS has collected a large number of di-muon sample in 2011, many new results will follow
  - Quarkonia
    - $J/\psi$ spin alignment
    - cross-sections and ratio of $\Upsilon(1S,2S,3S)$
    - $\psi(2S)$ cross-sections and ratio to $J/\psi$
    - Studies of double-quarkonium production
    - Onia $\rightarrow \pi\pi$