Production of Heavy Quarkonium States at the LHC with the ATLAS Experiment

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Heavy Quarkonium Physics

• Heavy Quarkonium, the bound state of $b$ or $c$ quark anti-quark pair, continues to challenge our understanding of QCD near to strong decay threshold
  • $J/\psi$ observed in 1974,
  • Despite being a “known” resonance its production mechanisms still uncertain.

• Onia production occurs through:
  • Prompt production -
    • Direct production,
    • Feed-down from higher quarkonium states.
  • Non-prompt production -
    • From decays of B hadrons (only charmonium).

• LHC era extends reach of the hadro-production of quarkonium to new energy regime.

• ATLAS presents results on $J/\psi$ and $\Upsilon$ production cross-sections, and observation of the $X_{c/b}$ system.
The ATLAS Detector

- Data selection begins with optimised suite of single and di-muon triggers:
  - 3-level system: 40 MHz to $O(200)$ Hz
  - Muon ID from Muon Spectrometer
  - Inner Detector provides precision momentum and lifetime measurements

- **Inner Detector**
  - $|\eta|<2.5$
  - Solenoid B=2T
  - Si Pixels,
  - Si strips,
  - Transition Radiation Tracker (TRT)
  - $\sigma/p_T \sim 3.4 \times 10^{-4} p_T + 0.015$ for $(|\eta|<1.5)$
  - Used for Tracking and Vertexing:

- **Muon Spectrometer**
  - $|\eta|<2.7$
  - Toroid B-Field, average $\sim 0.5$T
  - Muon Momentum resolution $\sigma/p < 10\%$ up to $\sim 1$ TeV
$J/\psi$ : Measurement of the differential Inclusive, Prompt and Non-Prompt Cross-Section

- $J/\psi$ candidates identified through di-muon decays:
  - Experimentally clean; BR ~ 6%
  - Separate events in to bins of pT-rapidity for differential analysis

- Per-candidate weights applied to correct for detector inefficiencies from:
  - Muon reconstruction and trigger efficiencies,
  - Detector acceptance.

\[
w^{-1} = \mathcal{A} \cdot \mathcal{M} \cdot \mathcal{E}^2_{\text{trk}} \cdot \mathcal{E}^+_{\mu}(p_T^+, \eta^+) \cdot \mathcal{E}^-_{\mu}(p_T^-, \eta^-) \cdot \mathcal{E}_{\text{trig}}
\]

- Binned $\chi^2$ fit to weighted mass-distributions determines corrected yields in each bin.
- Extract differential inclusive cross-section:
  \[
  \frac{d^2\sigma(J/\psi)}{dp_Tdy} \cdot \text{Br}(J/\psi \rightarrow \mu^+\mu^-) = \frac{N_{J/\psi}^{\text{corr}}}{L \cdot \Delta p_T \Delta y}
  \]
**J/ψ**: Spin-Alignment

- Acceptance: probability that \( J/ψ \) survives muon cuts
  - However, acceptance depends on spin-alignment,
    - Not yet well-measured under LHC conditions.

\[
\frac{dN}{d\Omega} = 1 + \lambda_{\theta^*} \cos^2 \theta^* + \lambda_{\phi^*} \sin^2 \theta^* \cos 2\phi^* + \lambda_{\theta^* \phi^*} \sin 2\theta^* \cos \phi^*
\]

- Isotropic distribution taken as central assumption
  - \( \lambda_{\theta^*} = \lambda_{\phi^*} = \lambda_{\theta^* \phi^*} = 0 \) (non-physical / pythia default)

- Take five specific working-point scenarios
  - Use as envelope of additional uncertainty on central value.
  - Relative uncertainty between different scenarios reduces at higher-pT.
Good agreement between experiments.
(including updated CMS results (not shown) - JHEP 02 (2012) 011)
**J/ψ:** Non-prompt Fraction

- Discriminate between prompt and non-prompt components from 2-d mass-lifetime fit.

- Synergy between CDF and CMS measurements:
  - No strong dependence with centre-of-mass energy, or pp vs pp.

- (also compatible with updated CMS results - not shown - JHEP 02 (2012) 011)
* Non-prompt cross-section agrees well with FONLL predictions
$J/\psi$: Prompt Cross-section

- Contributions from NNLO* compare better than NLO.
- CEM shape not quite in agreement.
Upsilon: Fiducial Cross-section

- Measurement of differential production cross-section of $\Upsilon(1S)$ in $p_T$ & rapidity.

- Similar procedure as for $J/\psi$ for weight correction
  - Candidate selection: 4 GeV $p_T$ on both muons within $|\eta|<2.5$

- Likelihood fit to $\Upsilon(1,2,3S)$ and background templates

Backgrounds more significant than in $J/\psi$, larger and more complex!

Use OS/SS $\mu+\text{trk}$ data and HF MC to model
Results are not corrected for acceptance step:
- defined within muon kinematics ($p_T > 4$ GeV, $|\eta| < 2.5$) –
- removes spin-alignment uncertainty!

Colour Singlet Model prediction is low, but contains no feed down from higher order states (NLO only)
- NRQCD shows closer agreement (within ~2x), although shape is not matched.
Spectroscopy: $\chi$ states

- Contribution to S-wave charm(bottom)-onium states through feed-down of the P-wave $\chi_c$ and $\chi_b$ states considerable ($\sim 1/3$)
- Measurement of these feed-down processes key in overall understanding of quarkonium production

- Experimentally, observe $\chi_c$ through its radiative decays to $J/\psi$.
- Challenge of reconstructing soft-photon through calorimetry or tracking (via conversions to electron pairs).
- Construct the Mass difference:
  - $\Delta m = m(\mu\mu\gamma) - m(\mu\mu)$
  - Effectively removes contribution of the di-muon resolution.

- $\chi_c$ observation using photons identified in electromagnetic calorimeter.
- Background shape determined from di-muon sideband region.
- $\chi_{c0}$ contribution neglected - small branching fraction through radiative decays.
Observation of $Xb$ system

- Observation of $Xb$ system similar to $Xc$:
  - Observed through radiative decays to upsilons.
  - Upsilons identified through di-muon decay.

- Data from 2011 at 7 TeV, corresponds to 4.4 fb$^{-1}$.
  - Events required to pass a suite of single or di-muon triggers.

- Photons identified through both:
  - Calorimetric measurement:
    - High efficiency
    - Threshold reconstruction energy 2.5 GeV.
  - Tracking-based through conversions ($\gamma \rightarrow e^+e^-$ in silicon layer of the inner detector)
    - Small probability (conversion) x reco. eff.
    - Lower threshold $p_T > 1$ GeV.
  - Photons not compatible with originating from di-muon vertex rejected.
Observation of $\chi_b(3P)$

- Di-muon candidates selected around $\Upsilon(1S)$ and $\Upsilon(2S)$:
  - Photon $p_T$ too soft in $\Upsilon(2S)$ transitions to be observed through unconverted photons.
  - Also true for the expected transitions to $\Upsilon(3S)$ (calorimetry and conversions).

- Plot $\Delta m + M(\mu\mu)$ distribution:
  - $\chi_b(1P)$ and $\chi_b(2P)$ observed.
  - **First observation of new $\chi_b$ state.**
  - Interpreted as $\chi_b(3P)$.

- Mass barycentre is estimated to be (using conversions):
  - $M(3P) = 10.530 \pm 0.005$ (stat.) $\pm 0.009$ (syst.) GeV
  - Hyperfine structure to be resolved.

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**Plot $\Delta m + M(\mu\mu)$**

- Data $\int L dt = 4.4$ fb$^{-1}$
  - Data: $\Upsilon(1S)\gamma$
  - Fit to $\Upsilon(1S)\gamma$
  - Background to $\Upsilon(1S)\gamma$

- Data: $\Upsilon(2S)\gamma$
  - Fit to $\Upsilon(2S)\gamma$
  - Background to $\Upsilon(2S)\gamma$

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**Converted Photons**

- $\chi_b \rightarrow \Upsilon(1S)\gamma$
- $\chi_b \rightarrow \Upsilon(2S)\gamma$
Conclusions

✦ Heavy Quarkonium continues to challenge current understanding:
  ✦ Data and theory gap reducing.
  ✦ ATLAS has measured:
    ✦ $J/\psi$ inclusive, prompt and non-prompt differential cross-sections.
    ✦ $\Upsilon(1S)$ fiducial differential cross-section.
    ✦ $\chi_c$ observed through radiative decays to $J/\psi$.
    ✦ $\chi_b(1P)$ and $\chi_b(2P)$ observed through radiative decays to $\Upsilon(1S)$.
    ✦ First observation of $\chi_b(3P)$ state decaying to $\Upsilon(1S)$ and $\Upsilon(2S)$:
      ✦ Each of the $\Upsilon(1, 2, 3S)$ states now subject to feed-down contributions.
    ✦ Prompt production of $\psi(2S)$, only state not contaminated by feed-down.
  ✦ Synergy across LHC experiments exploring low-pT and extending into highest pT ranges across rapidities.
  ✦ Spin-alignment measurement will reduce a dominant source of uncertainty.
  ✦ These results, and forthcoming ATLAS measurements of:
    ✦ $\Upsilon(1, 2, 3S)$, and $\psi(2S)(\rightarrow \mu\mu$ and $\rightarrow \mu\mu\pi\pi)$ production cross-sections,
    ✦ $\psi(2S)$ to $J/\psi$ production ratios, di-onia production and cross-sections of $\chi_b/c$ systems,
    ✦ will provide important input on the underlying mechanisms of Heavy Quarkonium near the strong decay threshold.
Backup
J/ψ: Sources of Uncertainties

- Sources of systematic uncertainty, and total uncertainties in each analysis bin (excluding spin-alignment)
$\chi_b$ Event Selection

- $p_T(\mu)>4$ GeV
- $|\eta| < 2.3$
- Muons identified using muon spectrometer
  - Track parameters from inner detector
- Oppositely-charged di-muon pairs forming a good vertex compatible with Upsilon mass.
- $p_T(\mu\mu)>12$ GeV (conversion)
- $p_T(\mu\mu)>20$ GeV (calorimetry)
- $|y|<2.0$
- **Photons identified through calorimetry:**
  - $E_T(\gamma) > 2.5$ GeV
  - $|\eta(\gamma)|<2.37$
  - Correction applied to photon to point back to $\mu\mu$-vertex
- **Photons identified through conversions:**
  - $p_T(\gamma) > 1$ GeV, $p_T(e)>0.5$ GeV
  - $|\eta(\gamma)|<2.5$
  - Radius of Conversion $> 40$ mm, $P(\text{conv}) > 0.01$
  - Unsigned Impact Parameter (3D) cut $< 2$ mm to reject photons not compatible with Upsilon vertex.
$\chi_b(3P)$ Calorimetry Candidate
$\chi_b(3P)$ Conversion Candidate
Bottomonium Spectroscopy through radiative decays in ATLAS
The 3D impact parameter of the converted photon with respect to the di-muon vertex, $a_0$, is a powerful variable which can be used to select photons associated with the di-muon vertex:

$\chi^2$ probability of the conversion vertex fit is required to be greater than 0.01

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Systematics: Unconverted

An extended unbinned maximum likelihood fit is performed to the
\[ m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-) + m_{T(1S)}^{PDG} \]
distribution to extract an estimate of the \( \chi_b(3P) \) mass barycentre:

**Fit Model**

- **Signal:** Single Gaussian for each \( \chi_b(nP) \) peak, each with a free mean value and width
- **Background:** Described by \( \exp(A \cdot (\Delta M) + B \cdot (\Delta M)^{-2}) \) where \( A \) and \( B \) are free parameters

**Assigned Systematic Uncertainties**

- **Unconverted** photon energy scale uncertainty (estimated at ±2% of the \( \Delta M \) position)
- Modelling of the background distribution (estimated from refitting with various alternative models)

<table>
<thead>
<tr>
<th>( \chi_b(nP) )</th>
<th>Fitted Mass (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi_b(1P) )</td>
<td>9910 ± 6 (stat.) ± 11 (syst.)</td>
</tr>
<tr>
<td>( \chi_b(2P) )</td>
<td>10246 ± 5 (stat.) ± 18 (syst.)</td>
</tr>
<tr>
<td>( \chi_b(3P) )</td>
<td>10541 ± 11 (stat.) ± 30 (syst.)</td>
</tr>
</tbody>
</table>

The statistical significance of third signal remains greater than 6\( \sigma \) with each systematic variation

A. Chisholm
Systematics: Converted

Fit Model:

- As the $J = 0$ branching fraction is significantly smaller than for $J = 1, 2$ its contribution can be neglected
- The $\chi_b(nP)$ state is therefore modelled by two Crystal Ball (CB) functions to describe the low-mass Bremsstrahlung tail
- For $n = 1, 2$, the masses of the individual $J=1,2$ states are fixed to the known PDG values, and for $n=3$ the hyperfine splitting is fixed to the theoretically predicted value of 12 MeV
- The relative normalisations of the $J=1$ and $J=2$ components are fixed to be equal
- A free parameter $\lambda$, common to all the peaks, accounts for additional energy losses and appears in the form $\Delta m \cdot \lambda$
- The background is modelled by $(\Delta m - q_0)^{\alpha} \cdot \exp\{(\Delta m - q_0) \cdot \beta\}$

Assigned Systematic Uncertainties:

- Vary relative $J = 1, 2$ signal normalisation by $\pm 0.25$ (or left free in fit): $\pm 5$ MeV
- Alternative signal and background models: $\pm 5$ MeV
- Decoupled fits to the $\Upsilon(1S)$ and $\Upsilon(2S)$ distributions: $\pm 5$ MeV
- Individually releasing constraints to the PDG values for the $\chi_b(1P)$ and $\chi_b(2P)$ masses: $\pm 3$ MeV

A. Chisholm