QUARKONIA PRODUCTION WITH THE ATLAS EXPERIMENT
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(on behalf of the ATLAS Collaboration)
In this talk I will focus on two different methods of studying quarkonium at ATLAS.

• The first is trying to understand exotic quarkonium through searches for the bottomonium counterpart for $X(3872)$.

• The second is through studying rare production models of quarkonium.
  • “Observation and measurements of the production of prompt and non-prompt $J/\psi$ mesons in association with a $Z$ boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”: arXiv:1412.6428 [hep-ex], submitted to EPJC.
X(3872) and X_b

- X(3872) is the first and best-studied hidden-charm state in the last decade. First observed by Belle in $B^\pm \to K^\pm X(\to \pi^+\pi^-J/\psi)$ (arXiv:hepex/0309032v2).

- CMS has measured the product of the cross section of prompt X(3872) times $BF(X(3872)\to \pi^+\pi^-J/\psi)$ to be $(6.56 \pm 0.29 \pm 0.65)\%$ of the value for the product of the cross section of $\psi(2S)$ and $BF(\psi(2S)\to \pi^+\pi^-J/\psi)$ (arXiv:1302.3968).

- Due to the mass, small width, and $J^{PC}=1^{++}$ (LHCb: arXiv:1504.0633) it is unlikely to be a conventional quarkonium state.
  - $D^0\bar{D}^{*0}$ molecular models (arXiv:hep-ph/0311229) and tetraquark states (arXiv:hep-ph/0412098) are popular.

- Heavy-quark symmetry suggests the presence of hidden-beauty partner $X_b$. We will look at the analogous decay to $\pi^+\pi^-\Upsilon(1S)$.
  - CMS found no signal and set an upper limit on the cross section times $BF(X_b\to \pi+\pi^-\Upsilon(1S))$ at values between 0.9-5.4% of the $\Upsilon(2S)$ rate (arXiv:1309.0250).
  - Using this decay we also search for $\Upsilon(1^{3}D_j)$, $\Upsilon(10860)$, and $\Upsilon(11020)$. 


$X_b \rightarrow \pi^+\pi^-\Upsilon(1S)$

- 16.2 fb$^{-1}$ of $\sqrt{s} = 8$ TeV ATLAS Data.
- Each event passes a trigger requiring two opposite-sign muons with $p_T > 4$ GeV and $8 \text{ GeV} < M(\mu\mu) < 12$ GeV.
  - $\Upsilon(1S)$: $|\eta\mu| < 2.3$, $|M(\mu\mu) - M(\Upsilon(1S))| < 350$ MeV.
  - $\pi$: opposite charge, $|\eta\pi| < 2.5$, $p_T > 400$ MeV.
  - $\pi^+\pi^-\Upsilon(1S)$: $M(\pi^+\pi^-\Upsilon(1S)) < 11.2$ GeV, $p_T > 5$ GeV, $|y| < 2.4$.

- ATLAS measurements of $\Upsilon(nS)$ production cross sections at $\sqrt{s} = 7$ TeV (in the di-muon channel) are reweighted using Pythia 8 MC to provide predictions for $\Upsilon(nS)$ cross sections at $\sqrt{s} = 8$ TeV.

- The data are split into 8 kinematic bins and the signal is extracted via three splitting functions and their complements.
  - Bins are at $|y| = 1.2$, $p_T = 20$ GeV, and $\cos(\vartheta^*) = 0$. Determined by the $S/\sqrt{B}$ significance.
The $\Upsilon(2S)$ and $\Upsilon(3S)$ peaks are fit to validate the measurement techniques.

The signal shape parameters are fixed to the simulated values.

The expected yield (calculated in the backup) is compared to the total fitted yield.

- $\Upsilon(2S)$: $N_{2S} = 34,300 \pm 800$. ✔
  - $N_{2S}^{\text{expect.}} = 33,300 \pm 2,500$.

- $\Upsilon(3S)$: $N_{3S} = 11,600 \pm 1,300$. ✔
  - $N_{3S}^{\text{expect.}} = 11,400 \pm 1,500$. 
The data is fit every 10 MeV excluding the range around \( \Upsilon(2S) \) and \( \Upsilon(3S) \). The range is:
- 10.05–10.31 and 10.40–11.00 GeV.
- No excess with a local significance of 3\( \sigma \) or greater is observed.

\[ N = N_{2S} \cdot R \cdot \frac{A}{A_{2S}} \cdot \frac{\epsilon}{\epsilon_{2S}}. \]
\[ R \equiv \frac{\sigma_{BF}}{\sigma_{BF}}_{2S}. \]

Upper limits on \( R = 0.8\text{-}4.0\% \) at 95\% CL.
- Excludes analogous \( R = 6.56\% \) from \( X(3872) \).

Upper limit is more restrictive than the CMS results above \( \sim 10.1 \) GeV.

If \( X_b \) exists in this range:
- The BF or production cross section relative to \( \Upsilon(2S) \) is smaller than \( X(3872) \) relative to \( \psi(2S) \).
- There are no strong isospin-violating effects present as in \( X(3872) \rightarrow \pi^+\pi^-J/\psi \).
- If so \( X_b \) would have more prominent decays to \( \pi^+\pi^-\chi_{b1} \) or \( \pi^+\pi^-\pi^0 \Upsilon(1S) \).
\(\Upsilon(1^3D_J), \Upsilon(10860), \text{ and } \Upsilon(11020)\)

- To fit the \(\Upsilon(1^3D_J)\) triplet two extra peaks are added.
  - CLEO (arXiv:hep-ex/0404021) and BaBar (arXiv:1004.0175) measured an average \(M(\Upsilon(1^3D_2)) = (10163.7 \pm 1.4)\) MeV.
  - Averaging over multiple models gives 10156, 10164, and 10170 MeV.
  - Assuming a common lineshape model for \(J=0,1,2\), no significant signals are observed.
  - Assuming \(J = 2\) dominates or the mass splitting is larger than the resolution and BF(\(\Upsilon(1^3D_2) \rightarrow \pi^+\pi^-\Upsilon(1S)\)) (arXiv:1004.0175) gives:
    - \(\sigma(\Upsilon(1^3D_2))/\sigma(\Upsilon(2S)) \leq 0.55\).

- Broader range for \(\Upsilon(10860)\), and \(\Upsilon(11020)\).
  - Assuming the world average for the mass and width, significances of 0.6\(\sigma\) and 0.3\(\sigma\) are found for \(\Upsilon(10860)\) and \(\Upsilon(11020)\).
  - If the mass and width are calculated in a grid with \(m\pm20\) MeV and \(\Gamma\pm\Delta\Gamma\):
    - \(\Upsilon(10860):\) Significance of 1.1\(\sigma\) at \(m = 10856\) MeV and \(\Gamma = 55\) MeV.
    - \(\Upsilon(11020):\) Significance of 0.6\(\sigma\) at \(m = 11039\) MeV and \(\Gamma = 95\) MeV.
**Z+J/ψ**

- The first measurement of Z+J/ψ.
  - 20.3 fb\(^{-1}\) of \(\sqrt{s} = 8\) TeV ATLAS Data.
  - Look at both di-electron and di-muon decay modes of Z boson.

- **Interests:**
  - Spin-alignment of charmonium and distinguish between color octet and singlet models.
  - Improve perturbative convergence of calculations.
  - Heavy flavor production in association with a Z boson.
  - ZZ* and a background to Z\(\rightarrow l^+l^-J/ψ\).
  - Rare Higgs decay, charm couplings, and CP properties.
  - Double Parton Scattering.

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### Z boson selection

- \(p_T\) (trigger lepton) > 25 GeV,  \(p_T\) (sub-leading lepton) > 15 GeV
- \(|\eta\text{(lepton from } Z)| < 2.5\)
- \(|m(Z) - 91.1876\text{ GeV}| < 10\text{ GeV}\)

### J/ψ selection

- \(2.6 < m(J/ψ) < 3.6\text{ GeV}\)
- \(8.5 < p_T(J/ψ) < 100\text{ GeV}, \ |\eta(J/ψ)| < 2.1\)
- \(p_T\) (leading muon) > 4.0 GeV, \(|\eta\text{(leading muon)}| < 2.5\)
- either \(p_T\) (sub-leading muon) > 2.5 GeV, \(|\eta\text{(sub-leading muon)}| < 2.5\)
- or \(p_T\) (sub-leading muon) > 3.5 GeV, \(|\eta\text{(sub-leading muon)}| < 1.3\)

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**arXiv:**1102.0398  **arXiv:**1210.2430
Extracting Signal

- $Z \rightarrow \tau \tau$, $W \rightarrow l \nu$, $t \bar{t}$, single top and diboson backgrounds are modeled by MC.
- Multijet and misidentified leptons are modelled by reversing isolation req.
- Pileup background events are estimated (backup).
Double Parton Scattering (DPS): two parton-parton interactions in a single hadron-hadron collision.

\[ \sigma_{DPS} = \frac{\sigma_Z \sigma_{J/\psi}}{\sigma_{Eff}}. \]

\[ \sigma_{Eff} = 15 \pm 3 \text{(stat)} \pm 5 \text{(sys)} \text{ mb taken from ATLAS W+2j results (arXiv:1301.6872[hep-ex]) for DPS estimates.} \]

DPS events are distributed uniformly in \( \Delta \phi(Z,J/\psi) \).

Single Parton Scattering (SPS) events preferentially produced back-to-back, peaking at \( \Delta \phi = \pi \).

We set a conservative lower limit on the effective cross-section (upper limit on DPS production) by assuming \( |\Delta \phi|<\pi/5 \) is purely DPS.

\[ \sigma_{Eff} > 5.3 \text{ mb (3.7 mb) at 68\% (95\%) CL.} \]

Results are measured in the fiducial volume, then the inclusive volume, and finally after DPS subtraction.
Results: $Z + J/\psi$

- First measurement of $Z + J/\psi$. Null hypothesis excluded at 5$\sigma$ for prompt and 9$\sigma$ for non-prompt.

\[
R_{Z+J/\psi} = \frac{\text{BF}(J/\psi \rightarrow \mu^+\mu^-) \frac{\sigma(pp \rightarrow Z+J/\psi)}{\sigma(pp \rightarrow Z)}}{\sigma(pp \rightarrow Z)}
\]

- $R_{Z+J/\psi}^{fid} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7}$ (prompt).
- $R_{Z+J/\psi}^{fid} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7}$ (non-prompt).

- $f_{DPS} = (29\pm9)$% prompt, $(8\pm2)$% non-prompt.

- Theory underestimates SPS production.
  - Does not include feed-down from excited charmonium states, but only accounts for about 20%.


Prompt differential cross section ratio is compared to NLO SPS predictions and DPS expectations.

Theory predicts CO > 2*CS with CO increasing with $p_T$.

DPS + NLO SPS predictions underestimate the data by a factor of 4-5 for $p_T^{J/\psi} > 18$ GeV.

Significant SPS contribution to $Z +$ non-prompt $J/\psi$ is expected from $Z + b$-jet production.

The data presents the opportunity to test $Z + b$-jet production at low $p_T$.
Summary

- Search for $X_b$ and other hidden beauty states ([arXiv:1410.4409 [hep-ex]]):
  - No evidence of new states for masses 10.05–10.31 GeV and 10.40–11.00 GeV.
  - Upper limit set on $R = (\sigma_{BF})/(\sigma_{BF})_{2S}$ ranging from 0.8 – 4.0%. The $X_b$ limit is the most stringent in this channel to-date.
    - Excludes the analogous $R = 6.56\%$ of $X(3872)$ for all masses.
  - No significant signal for the $\Upsilon(1^{3}D_{1})$ triplet, $\Upsilon(10860)$, or $\Upsilon(11020)$.
  - 95% CLs upper limit of 0.55 is set on $\sigma(\Upsilon(1^{3}D_{2}))/\sigma(\Upsilon(2S))$.

  - Measured for the first time. Background-only rejection at 5$\sigma$ for prompt and 9$\sigma$ for non-prompt.
  - DPS plays a large role (~29% for prompt $J/\psi$). A lower limit on the effective cross section (upper limit on the rate of DPS) is measured:
    - $\sigma_{Eff} > 5.3$ mb (3.7 mb) at 68% (95%) CL.
  - NLO SPS + DPS predictions underestimate the $Z +$ prompt $J/\psi$ data.
  - Large $Z +$ non-prompt $J/\psi$ SPS component is expected from $Z+b$-jet.
Splitting Functions

- Splitting functions are used to calculate the signal yield in any particular ($|y|$, $p_T$, $\cos\theta^*$) bin.
  - $S_{|y|} = 0.606 \pm 0.004$ for $|y|<1.2$.
  - $S^{b(\text{ec})}_{p_T}(m) = a/(1+e^{-b(m-c)})$ for $p_T < 20$ GeV.
  - $S_{\cos\theta^*}(m) = a + bm + cm^2$ for $\cos\theta^* < 0$.

- Multiplying the splitting functions and their complements gives the signal yield. For example in the bin ($|y|< 1.2$, $p_T > 20$ GeV, $\cos\theta^* < 0$) the function is:
  - $S_{|y|} \cdot (1 - S^{b}_{p_T}(m)) \cdot S_{\cos\theta^*}(m)$. 
Calculation of Expected $\Upsilon(2S)$

- $N_2^{exp} = (\sigma BF)_{2S} \cdot L \cdot A \cdot \epsilon$
  - $(\sigma BF)_{2S} \equiv$ The product of the cross section and branching fraction estimated from the extended cross section measurement using world averaged values for $BF(\Upsilon(1S) \rightarrow \mu^+ \mu^-)$ and $BF(\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S))$.

- $L \equiv$ Luminosity.

- $A \equiv$ The acceptance calculated from the shape of the doubly differential cross section. $A = (1.442 \pm 0.004)\%$ assuming the CLEO dipion mass spectrum (arXiv:hep-ex/9802024) and isotropic signal decays.

- $\epsilon \equiv$ The reconstruction efficiency for decays within the acceptance is taken from the $\Upsilon(2S)$ simulation, $\epsilon = 0.283 \pm 0.002$. 
The $\Upsilon(10860)$ (left) and $\Upsilon(11020)$ (right). simultaneous fits projected onto the most sensitive bin.

The dashed line is a strong signal with $\sigma=10\sigma_{2S}$ for $\Upsilon(10860)$ and $\sigma B = (\sigma B)_{2S}$ for $\Upsilon(11020)$.

No attempt is made to explain the large partial width of $\Upsilon(10860)$ compared to $\Upsilon(3S)$ and $\Upsilon(4S)$.

No strong signal is observed for either state.
## Systematic Uncertainty: Search for $X_b$

### Signal shape parameters

| Source | $\sigma_b$ [%] | $\sigma_{\text{ec}}$ [%] | $f_b$ [%] | $f_{\text{ec}}$ [%] | $r_b$ [%] | $r_{\text{ec}}$ [%] | $S_{|y|}$ [%] | $S^b_{\text{PT}}$ [%] | $S^c_{\text{PT}}$ [%] | $S^{(1)}_{\cos\theta^*}$ [%] | $S^{(2)}_{\cos\theta^*}$ [%] | $S^{(3)}_{\cos\theta^*}$ [%] | $S^{(4)}_{\cos\theta^*}$ [%] |
|--------|----------------|----------------|-----------|----------------|---------|---------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Extracting $f, r$ | 0.5 | 1.1 | 1.2 | 1.4 | | | | | | | | | |
| Extrapolating $\sigma$ | 0.1 | 0.2 | | | | | | | | | | | |
| Data/MC difference in $\sigma$ | 1.9 | 4.2 | | | | | | | | | | | |
| $|y|$ scale factors | | | | | | | | | | | | | 5.8 |
| Production weighting | 0.3 | 8.4 | 7.0 | 0.9 | 2.8 | 2.1 | 3.4 | | | | | | |
| Bin splittings: fit | 0.2 | 0.5 | 0.8 | 2.4 | 4.2 | 2.8 | 6.0 | | | | | | |
| Bin splittings: parameterisation | 1.8 | 1.0 | 1.2 | 0.2 | 0.2 | 0.4 | 0.2 | | | | | | |
| $m_{\pi^+\pi^-}$ shape | 0.2 | 8.0 | 11.5 | 34.7 | 16.2 | 15.9 | 15.0 | | | | | | |
| **Total** | 2.0 | 4.2 | 0.5 | 1.1 | 1.2 | 1.4 | 6.1 | 11.6 | 13.6 | 34.8 | 17.0 | 16.3 | 16.6 |

### Signal bin splitting functions

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<th>$N_{2S}$ [%]</th>
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<td><strong>Total</strong></td>
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<td>1.5</td>
<td>11.7</td>
<td>17.3</td>
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Z + Non-prompt J/ψ Mass fits
# Z + J/ψ Fit Results

| Process               | $|y_{J/ψ}| < 1.0$ | $1.0 < |y_{J/ψ}| < 2.1$ | Total                  |
|-----------------------|-----------------|-----------------------------|-------------------------|
|                       | Events found    | From pileup                 |                         |
| Prompt signal         | 24 ± 6 ± 2      | 32 ± 8 ± 5                  | 56 ± 10 ± 5             |
| Non-prompt signal     | 54 ± 9 ± 3      | 41 ± 8 ± 7                  | 95 ± 12 ± 8             |
| Background            | 61 ± 11 ± 6     | 77 ± 13 ± 7                 | 138 ± 17 ± 9            |
|                       | 5.2$^{+1.8}_{-1.3}$ | 2.7$^{+0.9}_{-0.6}$         |                         |
“Pile-up”: Double Interactions

- Cut on $|d_z|>10$ mm between J/ψ and Z boson limits DI background without biasing the signal.
  - Need to calculate number of DI events that make it into cut.

- $N_{\text{DI}} = N_{\text{extra}} N_{Z} P_{J/\psi}^{ij} = N_{\text{extra}} N_{Z} \frac{\sigma_{J/\psi}^{ij}}{\sigma_{\text{inel}}}$.  
  - $N_{\text{extra}} = 2.3 \pm 0.2$. The number of additional vertices within 10 mm of a randomly selected vertex.
  - $N_{Z} \equiv$ number of Z candidates.
  - $P_{J/\psi}^{ij} \equiv$ the probability for a J/ψ to be produced at a given pileup vertex.
  - $\sigma_{\text{inel}} = 73$ mb (arXiv:1101.2185 [hep-ex]).

- $N_{\text{DI}} = 5.2^{+1.8}_{-1.3}$ (prompt), $2.7^{+0.9}_{-0.6}$ (non-prompt).
Double Parton Scattering: Features

- Double Parton Scattering (DPS) requires large c.m. energies and low values of incoming fractional momenta ($x_F$). This is possible to achieve at a non-negligible rate at the LHC.

- Because it is dependent on the transverse distance between interactions regions, the DPS cross section decreases quickly as a function of transverse energy.

- Assuming that the two processes ($\sigma_A, \sigma_B$) are independent of each other, DPS cross section can be written as: $\sigma_{DPS}^{(A,B)} = \frac{m \sigma_A \sigma_B}{2 \sigma_{Eff}}$.
  - $m = 1$ if A and B are indistinguishable and $m = 2$ if they are distinguishable
  - $\sigma_{Eff} = \left[\int [f(b) f(b_1 - b)]^2 d^2b_1 d^2b\right]^{-1}$ where $f(b)$ parton density in the transverse plane and is assumed to be a universal function, same for both protons.
  - $\frac{\sigma_B}{\sigma_{Eff}}$ is the probability for scattering B to occur given scattering A has already occurred.
  - $\sigma_{Eff}$ measures the size in impact parameter space of the incident hadron’s partonic core.
  - $\sigma_{Eff} \sim \frac{1}{4} \sigma_{Inel}$.
    - If the effective cross section was equal to the inelastic cross section, it would imply uncorrelated scatterings.
    - This result indicates a correlation (“clumpiness”) in the hadron structure.

- A constant value of $\sigma_{Eff}$ has been able to describe results in different kinematical regions. CDF has also tested the dependence of $\sigma_{Eff}$ on $x_F$ and had compatible results with being independent of $x_F$. 
Double Parton Scattering

- $b_1, b_2$ are the transverse positions of the two partons.
- $b$ is the impact parameter (distance between the centers of the colliding hadrons).
- $pp \rightarrow A \oplus pp \rightarrow B$.
- A and B with a clean signature, and large rates.
- Example: $A = \gamma + j, \ B = j + j$. 
Effective Cross Section
# Systematic Uncertainty: Z+J/ψ Production

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