PRODUCTION OF QUARKONIUM STATES AT THE ATLAS EXPERIMENT

PHENO2014

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(on behalf of the Atlas Collaboration)
INTEREST IN QUARKONIA PRODUCTION

- Quarkonia are a $q\bar{q}$ bound state.

- A lot to learn from Quarkonium production:
  - Dynamics of strong interaction, and hadron formation.
  - Presence of multiple energy scales (hard scale, soft scale, and ultra soft scale).
  - Higgs decays to quarkonia provide a unique probe to the Higgs Bosons charm couplings.
  - Ideal probe of beyond-the-standard-model (BSM) frameworks.

- Observed in the past large disagreements between experimental results and theoretical production models (Tevatron):
  - Color Singlet Model (CM), Color Octet Model (COM), Color Evaporation Model (CEM),...
RESULTS IN TALK

In this talk I will focus on the three most recent ATLAS Quarkonia results.

• Measurement of $W + \text{prompt } J/\psi$ production at $\sqrt{s} = 7$ TeV: arXiv:1401.2831 [hep-ex], accepted for publication in JHEP.

• Measurement of $\chi_{c1}$ and $\chi_{c2}$ production at $\sqrt{s} = 7$ TeV: arXiv:1404.7035 [hep-ex], submitted to JHEP.

• Cross-Section Measurement of $\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ at $\sqrt{s} = 7$ TeV: ATLAS-CONF-2013-094.
W + PROMPT J/ψ PRODUCTION

- 4.5 fb$^{-1}$ of 2011 $\sqrt{s} = 7$ TeV ATLAS data, select $W \rightarrow \mu \nu, J/\psi \rightarrow \mu \mu$.

- Single high $p_T$ muon trigger ($p_T > 18$ GeV) with:
  - $J/\psi$: one muon with $p_T > 4$ GeV, $p_T > 3.5$ (2.5) GeV for $|\eta| < 1.3$ (> 1.3), and $|y_{J/\psi}| < 2.1$.
  - $W$ Boson: $p_T > 25$ GeV, $|\eta| < 2.4$, MET > 20 GeV, and $m_T(W) > 40$ GeV.

- Expected Background:
  - Pileup (multiple pp collisions in a bunch crossing, estimated to be $1.8 \pm 0.2$ events).
  - W+b-quark.
    - Separated from prompt production with unbinned maximum likelihood fit.
    - W+b production in itself is of similar magnitude as that of the signal, this is the first such measurement.
  - Top pair production (predicted to be less than 0.28 events at 95% CL).
  - Z+jets (negligible after vetoing opposite charged muons with invariant mass within 10 GeV of Z mass).
  - Multijet production (found to be smaller than 0.31 events at a 95% CL after fitting $m_T(W)$).

- Corrected for experimental efficiency and detector acceptance.
A Maximum Likelihood fit of the Di-muon invariant mass and $J/\psi$ pseudo-proper time are used to extract prompt $J/\psi$ events. Then $m_T(W)$ is fit to separate the QCD multijet background. The background-only hypothesis is rejected at $5.1\sigma$. 

![Graphs showing data, fit, and hypothesis]

- **Yields from two-dimensional fit**

<table>
<thead>
<tr>
<th>Process</th>
<th>Barrel</th>
<th>Endcap</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Prompt $J/\psi$</td>
<td>10.0$^{+4.7}_{-4.6}$</td>
<td>19.2$^{+5.8}_{-5.1}$</td>
<td>29.2$^{+7.1}_{-6.5}$ (*)</td>
</tr>
<tr>
<td>Non-prompt $J/\psi$</td>
<td>27.9$^{+5.8}_{-5.3}$</td>
<td>13.9$^{+5.3}_{-4.5}$</td>
<td>41.8$^{+7.3}_{-6.4}$</td>
</tr>
<tr>
<td>Prompt background</td>
<td>20.4$^{+5.5}_{-5.1}$</td>
<td>18.8$^{+5.3}_{-4.3}$</td>
<td>39.2$^{+7.6}_{-6.3}$</td>
</tr>
<tr>
<td>Non-prompt background</td>
<td>19.8$^{+5.6}_{-5.0}$</td>
<td>19.2$^{+6.1}_{-5.1}$</td>
<td>39.0$^{+7.4}_{-6.1}$</td>
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- **p-value** $8.0 \times 10^{-3}$, $1.4 \times 10^{-6}$, $2.1 \times 10^{-7}$
- **Significance ($\sigma$)** 2.4, 4.7, 5.1

(*) of which 1.8 $\pm$ 0.2 originate from pileup
Double Parton Scattering (DPS): two parton-parton interactions in a single hadron-hadron collision.

\[ \sigma_{DPS} = \frac{\sigma_W \sigma_{J/\psi}}{2 \sigma_{Eff}}. \]

In a DPS event the W boson and J/\(\psi\) should be independent of each other which leads to a flat \(\Delta \phi\) distribution.

The data indicate the presence of both DPS and Single Parton Scattering (SPS).
The differential cross-section ratio as a function of $p_T$, $dR_{J/\psi}^{incl}/dp_T$.

- A DPS estimate is shown and the data suggests DPS is a large fraction of the signal, $f_{DPS} \sim 37\%$.

- NLO Color Octet contributions are an order of magnitude smaller than LO Color Singlet contributions.

- Color singlet dominance in contradiction to color octet enhancement in other quarkonium production processes. Breakdown of NRQCD universality? Modifications to DPS ansatz?

- Due to the large uncertainties SPS prediction are compatible with results at the $2\sigma$ level.

LO: arXiv:1303.5327
NLO: arXiv:1012.3798
\( \chi_{c1} \) AND \( \chi_{c2} \) PRODUCTION

- Prompt \( J/\psi \) can be produced directly, or from decays of other states such as \( \chi_c \).
- 4.5 fb\(^{-1}\) of 2011 \( \sqrt{s} = 7 \) TeV ATLAS data, select \( \chi_c \rightarrow J/\psi \gamma, J/\psi \rightarrow \mu \mu \).
- Di-muon trigger with \( p_T > 4 \) GeV.
  - \( J/\psi \): \( p_T(\mu) > 4 \) GeV, \( |\eta| < 2.3 \).
  - \( \gamma \): opp. charged tracks with \( p_T > 400 \) MeV, \( |\eta| < 2.3 \). \( p_T(\gamma) > 4 \) GeV, \( |\eta(\gamma)| < 2.3 \).
- An unbinned simultaneous Maximum Likelihood fit of \( \Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-) \) and the pseudo-proper lifetime.
  - Corrected for experimental efficiency and detector acceptance.
First absolute measurement of differential cross-section of prompt $\chi_{c1}$ and $\chi_{c2}$.

- Compared with NLO NRQCD (from the Tevatron), $k_T$ factorization, and LO CSM.
- NRQCD is in good agreement. The $k_T$ factorization approach predicts an excess and LO CSM underestimates the results.

First absolute measurement of differential cross-section of non-prompt $\chi_{c1}$ and $\chi_{c2}$.

- The results are compared to FONLL predictions for $b$-hadron production.
- Measurements found to be in good agreement.

$k_T$: arXiv:1108.2856
LO CSM: http://superchic.hepforge.org/chigen.html
\( \chi_{c1} \) AND \( \chi_{c2} \) PRODUCTION RATES

- **(Left)** Fraction of prompt \( J/\psi \) produced from \( \chi_c \) decay.
  - Results compared to LHCb data and NLO NRQCD, and are in good agreement and are between 20-30%.
  - LHCb: arXiv:1204.1462

- **(Right)** Ratio of prompt \( \chi_{c2} \) relative to \( \chi_{c1} \) as a function of \( p_T^{J/\psi} \).
  - Compared with CMS data and NLO NRQCD predictions. Good agreement especially at low \( p_T^{J/\psi} \), but hints of overestimate at high \( p_T \).
  - The LO CSM consistently underestimates the measurements.
  - CMS: arXiv:1210.0875

- **(Bottom)** Ratio of non-prompt \( \chi_{c2} \) relative to \( \chi_{c1} \) as a function of \( p_T^{J/\psi} \).
  - Compared with one data point from CDF. The results are consistent.
  - CDF: hep-ex/0703028
  - The Branching Fraction \( B(B^\pm \to \chi_{c1} K^\pm) \) is measured. It is found to be:
    \[
    B(B^\pm \to \chi_{c1} K^\pm) = (4.9 \pm 0.9 \text{ (stat.)} \pm 0.6 \text{ (syst.)}) \times 10^{-4}.
    \]
    (Details in Backup Slides).
$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)\pi^+ \pi^-$

- $\psi(2S)$ has no significant feed down, higher charmonium states decay predominately to $D\bar{D}$. Expands on previous measurements to the range $|y| < 2.0$ and $10 < p_T < 100$ GeV.

- 2.1 fb$^{-1}$ of 2011 $\sqrt{s} = 7$ TeV ATLAS data.

- Di-muon trigger with $p_T > 4$ GeV.
  - $J/\psi$: $p_T(\mu) > 4$ GeV, $|\eta| < 2.3$. $p_T(J/\psi) > 8$ GeV, $|y(J/\psi)| < 2.0$.
  - $\pi^\pm$: opp. charged tracks with $p_T > 0.5$ GeV, $|\eta| < 2.5$, and assigning pion mass hypothesis. A four-particle vertex fit is performed with $M(\mu^+ \mu^-)$ constrained to the pdg value for the $J/\psi$ (3096.916 MeV).

- An unbinned simultaneous Maximum Likelihood fit of the $J/\psi\pi\pi$ mass and the pseudo-proper lifetime are in bins of $p_T$.
  - Split into three rapidity bins: $|y| < 0.75$, 0.75$<|y| < 1.5$, 1.5$<|y| < 2.0$.
  - Corrected for trigger efficiency, muon reconstruction, pion reconstruction, and detector acceptance.
PRODUCTION CROSS-SECTION FOR $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$

- (Left) Prompt and (Right) non-prompt $\psi(2S)$ cross-section as a function of $p_T$.
  - Compared to earlier LHCb and CMS results in similar rapidity ranges. The common $p_T$ range values are in good agreement.
  - LHCb: arXiv:1204.1258

- (Left) Prompt $\psi(2S)$ cross-section compared with LO and NLO NRQCD, and $k_T$ factorization.
  - LO predictions are in agreement with large uncertainties.
  - NLO are in good agreement until high $p_T$, where it overestimates and predicts a harder spectrum.
  - $k_T$ factorization underestimates the data and has a $p_T$ dependent shape.

- (Right) Non-Prompt $\psi(2S)$ cross-section compared with FONLL and fixed-order NLO predictions.
  - FONLL shows better agreement than NLO, but both overestimate at high $p_T$.

CSM: Phys.Rev. D18 (1978) 1501,
NRQCD: arXiv:1009.3655
$k_T$: arXiv:1108.2856
SUMMARY

  - Measured for the first time. Background-only hypothesis rejection at 5.1σ.
  - NLO CO contributions are nearly an order of magnitude less than LO CS contributions.
    - Novel observables with which to test QCD, including DPS contributions, as well as a source of rare/BSM physics.

- **χ𝑐1** and **χ𝑐2** production (arXiv:1404.7035 [hep-ex]):
  - **χ𝑐** absolute cross-section is measured for the first time.
    - Prompt production found to be in agreement with NRQCD predictions. kT factorisation approach predicts an excess.
    - Non-prompt production in agreement with FONLL at low pT, with slight overestimates developing toward high pT.

- **ψ(2S) → J/ψ(→ μ⁺μ⁻)π⁺π⁻ (ATLAS-CONF-2013-094):**
  - The cross-section for ψ(2S) → J/ψ(→ μ⁺μ⁻)π⁺π⁻ is consistent with previous measurements.
    - For prompt production, NLO NRQCD describes the data well except at high pT where it overestimates. kT factorization noticeably undershoots the data, this is correlated with the overestimate in χ𝑐 and can be used to help tune the model.
    - For non-prompt production, both NLO and FONLL describe the data well over a wide range of pT, but have a significant overestimation at high pT. Possible cause is sharing of energy with B→ψ(2S)+X? The same overestimate in FONLL is seen in χ𝑐.
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: $\sigma_{DPS}^{(A,B)} = \frac{m}{2} \sigma_A \sigma_B \sigma_{Eff}$.
  - $m = 1$ if A and B are distinguishable and $m = 2$ if they are indistinguishable.
  - $\sigma_{Eff} = \left[ \int \left[ f(b_1) f(b_2) \right] d^2b_1 d^2b_2 \right]^{-1}$ 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 $x_F$. 

1. The differential cross-section of non-prompt $\chi_{c1}$ and $\chi_{c2}$ as a function of the $J/\psi$ transverse momentum.

2. The results are compared with NLO NRQCD (from the Tevatron), $k_T$ factorization, and LO CSM.

3. NRQCD is in good agreement with the results. The $k_T$ factorization approach predicts an excess and LO CSM underestimates the results.

4. The differential cross-section of prompt $\chi_{c1}$ and $\chi_{c2}$ as a function of the $J/\psi$ transverse momentum.

5. The results are compared to FONLL predictions for $b$-hadron production.

6. Measurements found to be in good agreement but discrepancies emerge toward higher $p_T$. 
The fraction of non-prompt $\chi_{c1}$ and $\chi_{c2}$ as a function of $p_T$. The non-prompt fraction increases with $p_T$ as seen with $J/\psi$ and $\psi(2s)$, but is dominated by prompt production unlike the other two systems.
BRANCHING FRACTION $B(B^\pm \rightarrow \chi_{c1}K^\pm)$

- $B(B^\pm \rightarrow \chi_{c1}K^\pm) = A_B \frac{N^B_{\chi_{c1}}}{N^B_{J/\psi}} \frac{B(B^\pm \rightarrow J/\psi K^\pm)}{B(\chi_{c1} \rightarrow J/\psi \gamma)}$

- (Top) Fit of $m(\mu^+\mu^-K^\pm) - m(\mu^+\mu^-\gamma) + m_{\chi_{c1}}$ used to extract the corrected yields for the $\chi_{c1}$ signal.

- (Bottom) Fit of $m(\mu^+\mu^-K^\pm) - m(\mu^+\mu^-\gamma) + m_{J/\psi}$ used to extract the corrected yields for the $J/\psi$ signal.

- $B(B^\pm \rightarrow \chi_{c1}K^\pm) = (4.9 \pm 0.9 \text{ (stat.)} \pm 0.6 \text{ (syst.)}) \times 10^{-4}$.

- World average is $(4.79 \pm 0.23) \times 10^{-4}$ and is dominated by Belle and BaBar measurements.
**ψ(2S) SIMULTANEOUS FITS**

- $\vert y \vert < 0.75$

- $0.75 < \vert y \vert < 1.5$

- $1.5 < \vert y \vert < 2.0$
NON-PROMPT $\psi(2S)$ PRODUCTION FRACTION
MEASURED $\psi(2S)$ DIFFERENTIAL CROSS-SECTION RATIOS