Measurements of Beauty and Charmonium Production with the ATLAS Detector

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Recent Heavy Flavor Production Results

- Measurement of the prompt $J/\psi$ pair production cross-section, and measurements of the differential cross section in several kinematic variables $^1$
- Measurement of prompt and non-prompt $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ and $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ production $^2$
- Both measurements are made using $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 11.4 fb$^{-1}$

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Motivation for Studying the Prompt $J/\psi$ Pair Production

- Opportunity to test our understanding of non-perturbative QCD$^1$
- These events are also sensitive to next-to-leading-order (NLO) and higher-order perturbative QCD
- Opportunity to study and compare di-$J/\psi$ production from single parton scattering (SPS) and double parton scattering (DPS)

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Production of Prompt di-$J/\psi$ Mesons

- A differential cross section measurement is made, assuming unpolarized $J/\psi$ production, where each $J/\psi$ is required to have a transverse momentum $p_T > 8.5$ GeV and rapidity $|y| < 2.1^1$, using the equation for signal extraction:

$$\frac{\Delta \sigma_i (pp \rightarrow J/\psi J/\psi + X)}{\Delta x} = \frac{N_{sig}^i}{A_i \times \epsilon_i \times BF(J/\psi \rightarrow \mu^+ \mu^-)^2 \times \Delta x \times \mathcal{L}}$$

- where $x$ is the kinematic variable ($p_T$, mass, rapidity, azimuthal angle), $i$ is the differential cross-section bin of size $\Delta x$, $A_i$ is the kinematic acceptance correction, $\epsilon_i$ is the efficiency, and $\mathcal{L}$ is the total integrated luminosity

1 Further event selection criteria in backup slides
Production of Prompt di-$J/\psi$ Mesons

- The fraction of prompt pair events due to DPS is determined by studying kinematic correlations
- The total and DPS scattering cross-sections are compared with predictions
- The effective cross-section of DPS, which is related to the spatial separation between partons inside the proton, is measured
Extracting the DPS Fraction of Events

- The fraction of DPS events, $f_{DPS}$, is determined by fitting DPS (left figure) and SPS (right figure) templates to the data.
- The DPS sample is simulated by combining two independently produced $J/\psi$ mesons.
- The difference of rapidities, $\Delta y$, of the two $J/\psi$ mesons against the difference in the azimuthal angle, $\Delta \phi$, is shown here.
- The template for the SPS component is obtained by subtracting the DPS template from the background-subtracted data.
Cross Section of di-$J/\psi$ as a Function of $p_T (\text{di}-J/\psi)$

- Prompt-prompt di-$J/\psi$ and DPS cross sections are shown separately in the central and forward rapidity regions of the lower $p_T J/\psi$.
- This measurement is also made for the lower $J/\psi p_T$ and the di-$J/\psi$ invariant mass.
- *Forward* and *away* topology accounts for the two peaks (one near 0 $p_T$ and one at higher $p_T$) seen in the figures.

![Graphs showing cross sections of di-$J/\psi$ as a function of $p_T$]
• The total and DPS cross-sections are shown for the kinematic variables:
  • Difference in rapidity of the two $J/\psi$ mesons (left)
  • Difference in azimuthal angle of the two $J/\psi$ mesons (right)
• The shape of the leading-order (LO) DPS prediction is similar to the DPS estimate
• There is tension between the total data distribution and the SPS + DPS predictions$^1$ at large $\Delta y$

$^1$NLO* is the next to leading order color singlet non-relativistic QCD calculation without loops
• The total and DPS cross-sections are shown for the kinematic variables:
  • $J/\psi + J/\psi$ invariant mass (left)
  • $J/\psi + J/\psi p_T$ (right)

• The shape of the LO DPS prediction is similar to the DPS estimate

• There is tension between the total data distribution and the SPS + DPS predictions at large invariant mass and in the low-$p_T$ region

• Further analysis of the kinematic variables was performed and can be found in the recently published ATLAS paper

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Measurement of the effective differential cross-section of the DPS is made using:

\[ \sigma_{\text{eff}} = \frac{1}{2} \frac{\sigma^2_{J/\psi}}{\sigma_{J/\psi,J/\psi}^{DPS}} = \frac{1}{2} f_{DPS} \times \sigma_{J/\psi,J/\psi} \]

Where the prompt \( J/\psi \) differential cross-section is determined from Ref. [1], and \( f_{DPS} \) is determined through the data driven model described on slide 6.

The effective differential cross-section is measured to be:

\[ \sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat}) \pm 1.0(\text{syst}) \text{ mb} \]

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Comparison to Other Experiments

- The effective cross-section measured in this analysis is compared to measurements from other experiments.
- The ATLAS and D0\textsuperscript{1} analyses provide a hint that the effective cross-section from the prompt di-$J/\psi$ final state could be lower than that measured for the other final states.

\textsuperscript{1}D0 Collaboration, Phys. Rev. D 90 (2014) 111101, arXiv: 1406.2380
Measurement of $\psi(2S) \to J/\psi \pi^+ \pi^-$ and $X(3872) \to J/\psi \pi^+ \pi^-$ Production

- The hidden-charm state $X(3872)$ was discovered by the Belle Collaboration\(^1\) in 2003, and subsequently confirmed by CDF\(^2\), BaBar\(^3\), and D0\(^4\).
- It was the first observation of an unexpected charmonium state.
- CDF determined that the only possible quantum numbers for $X(3872)$ were $J^{PC} = 1^{++}$ and $2^{--}$ and recently LHCb\(^5\) confirmed its quantum numbers to be $1^{++}$.
- Differential cross sections are presented for the prompt and non-prompt production of $\psi(2S)$ and $X(3872)$.

Motivation for Studying $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ Production

- Interestingly, the $X(3872)$ mass ($3871 \pm 0.17$) MeV is close to the $D^0 \bar{D}^{*0}$ threshold
- CMS\(^1\) performed a cross-section measurement of promptly produced $X(3872)$ and showed the NRQCD prediction\(^2\), assuming a $D^0 \bar{D}^{*0}$ molecule, to be too high
- A later interpretation\(^3\) of $X(3872)$ as a mixed $\chi_{c1}(2P)-D^0 \bar{D}^{*0}$ state was adopted in conjunction with the NLO NRQCD model, with the production being dominated by the $\chi_{c1}(2P)$ component, and showed good agreement with the CMS data

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\(^1\) CMS Collaboration, JHEP 04 (2013) 154, arXiv:1302.3968
\(^3\) C. Meng, H. Han and K.-T. Chao, arXiv:1304.6710
Event Selection

- Events in this analysis are triggered by a pair of muons fitted to a common vertex.
- Oppositely charged muon candidates are reconstructed with the requirements $|\eta^\mu| < 2.3$ and $p_T^\mu > 4$ GeV and the dimuon system is required to fall within $\pm 120$ MeV of the $J/\psi$ mass $(3096.916 \pm 0.011)$ MeV.
- A four-track vertex fit of the two muon tracks and pairs of non-muon tracks is performed.
- The two non-muon tracks are assigned pion masses, and are required to have opposite charges and satisfy the conditions $|\eta^\pi| < 2.4$ and $p_T^\pi > 0.6$ GeV.
- The production cross-section is measured in five bins of $J/\psi \pi^+ \pi^-$ transverse momentum.
Cross Section of Prompt $\psi(2S)$

- The measured cross-section times branching fraction as a function of $p_T$ for prompt $\psi(2S)$ is shown here.
- Predictions made with NLO NRQCD describe the data well with overestimation at high $p_T$.
- A $k_T$ factorisation prediction\(^1\) includes color octet contributions and color singlet production and underestimates the data at high $p_T$.
- NNLO* color singlet model (CSM) significantly underestimates the data at high $p_T$.

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The measured cross-section times branching fraction as a function of $p_T$ for non-prompt $\psi(2S)$ is shown here.

Predictions made with fixed-order next-to-leading logarithm (FONLL) calculations\(^1\) match the data well over the whole $p_T$ range.

\(^1\)M. Cacciari et al., JHEP 10 (2012) 137, arXiv:1205.6344
The measured cross-section times branching fraction as a function of $p_T$ for prompt $X(3872)$ is shown here.

It is described within theoretical uncertainty by the prediction of the NLO NRQCD model where $X(3872)$ production is dominated by the $\chi_{c1}(2^P)$ component of the $\chi_{c1}(2^P)-D^0\bar{D}^*0$ molecular state.
Cross Section of Non-Prompt $X(3872)$

- The measured cross-section times branching fraction as a function of $p_T$ for non-prompt $X(3872)$ is shown here.
- It is compared to a calculation based on the FONLL model prediction for $\psi(2S)$, recalculated for $X(3872)$ using [1] based on the Tevatron data with large branching fraction uncertainty.
- This calculation overestimates the data by a factor increasing with $p_T$ from $\sim 4$ to $\sim 8$ over the $p_T$ range.

Kinematic Template Fit

- The measured ratio of non-prompt cross-sections times branching fractions of $X(3872)$ and $\psi(2S)$ is shown.
- The kinematic template is calculated as a ratio of the simulated $p_T$ distributions of non-prompt $X(3872)$ and non-prompt $\psi(2S)$, assuming the same mix of parent $b$-hadrons.
- The shape of the template reflects the kinematics of a $b$-hadron decay into $\psi(2S)$ or $X(3872)$.
Alternative Fit: "Two-Lifetime Fit"

- The measured ratio of non-prompt cross-sections times branching fractions of $X(3872)$ and $\psi(2S)$ is shown.
- A lifetime study was performed to separate the signal into short-lived (SL) and long-lived (LL) non-prompt components.
- The LL components were fit with the same simulated kinematic template.
- The SL components were fit with a function $a/p_T^2$, consistent with production of $B_c$ mesons dominated by non-fragmentation processes\cite{1,2}.

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Production due to $B_c$ Decays

- The fit to the ratio of short-lived non-prompt $X(3872)$ to non-prompt $\psi(2S)$ and the measured non-prompt yields of $X(3872)$ and $\psi(2S)$ are used to determine the fraction of non-prompt $X(3872)$ from short-lived sources:

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

- Since $B_c$ production is only a small fraction of the inclusive beauty production, this value indicates that the production of $X(3872)$ in $B_c$ decays is strongly enhanced compared to its production in the decays of other $b$–hadrons.
The measured non-prompt fractions of $\psi(2S)$ and $X(3872)$ are shown here. That of $\psi(2S)$ increases with $p_T$ while $X(3872)$ shows no sizeable dependence on $p_T$. The measurement agrees within errors with the CMS result obtained with $\sqrt{s} = 7$ TeV.

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Summary of the Presented Results

- The production cross-section of the prompt di-$J/\psi$ as a function of $p_T$ was shown, with forward and away topology characteristics.
- Total and DPS cross-sections of several kinematic variables were presented and match predictions well, noting exceptions in high $\Delta y$, high di-$J/\psi$ mass, and low di-$J/\psi$ $p_T$ regions.
- An effective differential cross-section measurement of the DPS fraction of prompt di-$J/\psi$ events was made and found to be lower than the cross-section for other final states.
- The prompt $\psi(2S)$ cross-section was best described by the $k_T$ factorisation prediction while NLO NRQCD overestimated and NNLO* CSM underestimated in the high $p_T$ regions and the non-prompt cross-section was well described by FONLL.
- The prompt $X(3872)$ cross-section was well described by NLO NRQCD while the non-prompt cross-section was overestimated by FONLL.
Thank You

• Thank you for your attention

• Please let me know if you have questions
Event Selection for $J/\psi$ Pair Production

- The integrated luminosity value of 11.4 fb$^{-1}$ is due to prescaling of the $J/\psi$ dimuon trigger (see ATLAS, arXiv: 1608.03953)
- $|\eta^\mu| < 2.3$ and $p_T^{\mu} > 2.5$ GeV
- $2.8 \leq m(\mu\mu) \leq 3.4$ GeV
- $|y^{J/\psi}| < 2.1$ and $p_T^{J/\psi} > 8.5$ GeV
- For the triggered $J/\psi$, both of the reconstructed muons must have an ID track matched to a MS track
- For the non-triggered $J/\psi$ candidate, at least one of the reconstructed muons must have and ID track matched to a MS track
- The distance between the two $J/\psi$ decay vertices along the beam direction is required to be $|d_z| < 1.2$ mm. This requirement aims to select two $J/\psi$ mesons that originate from the same pp collision.
- The uncertainty in the measurement of the signed transverse decay length, $L_{xy}$, is required to be less than 0.3 mm.
Cross Section of $J/\psi_2$ vs. $p_T(J/\psi_2)$

- Cross-section of the lower $p_T J/\psi$ as a function of $p_T$
Cross Section of $J/\psi + J/\psi$ vs. $m(J/\psi + J/\psi)$

- Cross Section of prompt di-$J/\psi$ as a function of $m(J/\psi + J/\psi)$
Prompt di-$J/\psi$ Kinematic Variable Studies: $\Delta y \geq 1.8$

![Graphs showing di-J/psi distributions for $\Delta y \geq 1.8$]
Prompt di-$J/\psi$ Kinematic Variable Studies: $\Delta \phi \leq \pi/2$