Measurements of Beauty and Charmonium Production with the ATLAS Detector

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Recent Heavy Flavor Production Results

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

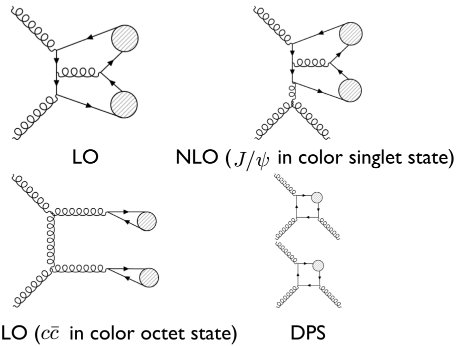
[1] ATLAS Collaboration, Eur. Phys. J. C (2017) 77: 76, arxiv:1612.02950v2

[2] ATLAS Collaboration, JHEP 1701 (2017) 117, arxiv:1610.09303v1

Motivation for Studying the Prompt J/ψ 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/ψ production from single parton scattering (SPS) and double parton scattering (DPS)

Feynman diagrams for different production models



[1] L. P. Sun, H. Han and K. T. Chao, Phys. Rev. D 94 (2016) 074033, arXiv: 1404.4042

Production of Prompt di-J/ψ Mesons

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

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

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

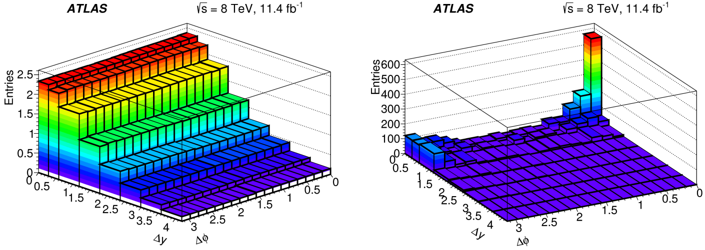
[1] Further event selection criteria in backup slides

Production of Prompt di-J/ψ 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

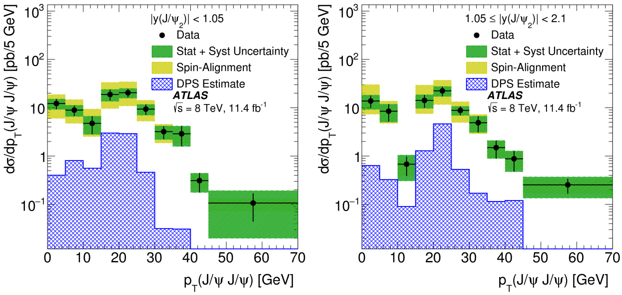
Extracting the DPS Fraction of Events

- 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/ψ mesons
- The difference of rapidities, Δy, of the two J/ψ 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

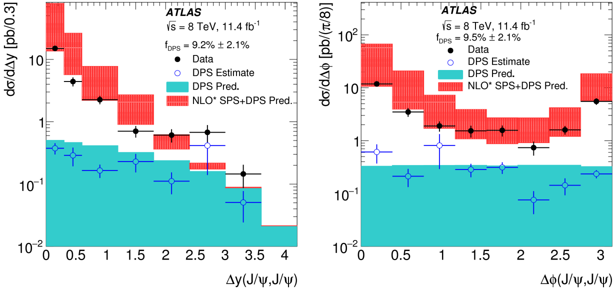


Cross Section of di-J/ψ as a Function of p_T(di-J/ψ)

- Prompt-prompt di-J/ψ and DPS cross sections are shown separately in the central and forward rapidity regions of the lower p_T J/ψ
- This measurement is also made for the lower J/ψ p_T and the di-J/ψ 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

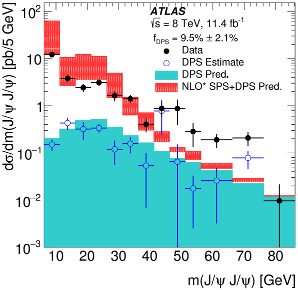


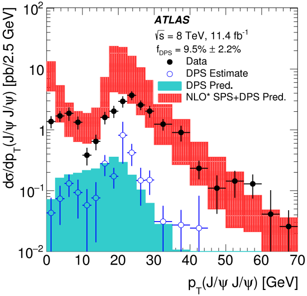
- The total and DPS cross-sections are shown for the kinematic variables:
  - Difference in rapidity of the two J/ψ mesons (left)
  - Difference in azimuthal angle of the two J/ψ mesons (right)
- The shape of the leading-order (LO) DPS prediction is similar to the DPS estimate
- There is tension between the total data distribution and the SPS + DPS predictions[1] at large Δy



[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 [1]

[1] ATLAS Collaboration, Eur. Phys. J. C (2017) 77: 76, arxiv:1612.02950v2

Effective Differential Cross Section

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

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

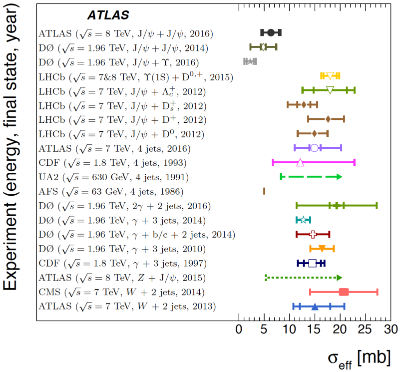
- Where the prompt J/ψ differential cross-section is determined from Ref. [1], and f_{DPS} is determined through the data driven model described on slide 6
- The effective differential cross-section is measured to be:

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

[1] ATLAS Collaboration, Eur. Phys. J. C 76 (2016) 283, arXiv: 1512.03657

Comparison to Other Experiments

- The effective cross-section measured in this analysis is compared to measurements from other experiments
- The ATLAS and D0[1] analyses provide a hint that the effective cross-section from the prompt di-J/ψ final state could be lower than that measured for the other final states



[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 $X(3872)$

[1] Belle Collaboration, Phys. Rev. Lett. 91 (2003) 262001, arXiv:hep-ex/0309032

[2] CDF Collaboration, Phys. Rev. Lett. 93 (2004) 072001, arXiv:hep-ex/0312021

[3] BaBar Collaboration, Phys. Rev. D 71 (2005) 071103, arXiv:hep-ex/0406022

[4] D0 Collaboration, Phys. Rev. Lett. 93 (2004) 162002, arXiv:hep-ex/0405004

[5] LHCb Collaboration, Phys. Rev. D 92 (2015) 011102, arXiv:1504.06339

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

- Interestingly, the $X(3872)$ mass (3871 ± 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

[1] CMS Collaboration, JHEP 04 (2013) 154, arXiv:1302.3968

[2] P. Artoisenet and E. Braaten, Phys. Rev. D 81 (2010) 114018, arXiv:0911.2016

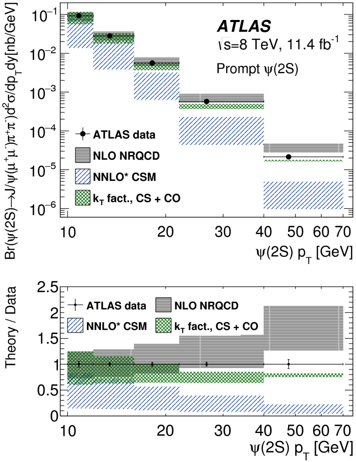
[3] C. Meng, H. Han and K.-T. Chao, arXiv:1304.6710

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 ± 120 MeV of the J/ψ mass (3096.916 ± 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 $\psi(2S)$

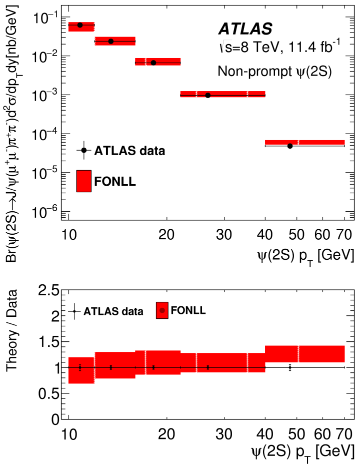
- The measured cross-section times branching fraction as a function of p_T for prompt $\psi(2S)$ is shown here
- Predictions made with NLO NRQCD describe the data well with overestimation at high p_T
- A k_T factorisation prediction[1] includes color octet contributions and color singlet production and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



[1] S. P. Baranov, A. V. Lipatov and N. P. Zotov, Eur. Phys. J. C 75 (2015) 455, arXiv:1508.05480

Cross Section of Non-Prompt $\psi(2S)$

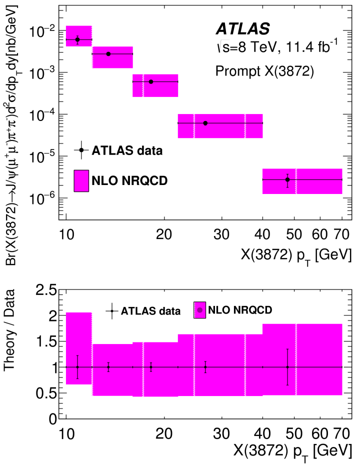
- The measured cross-section times branching fraction as a function of p_T for non-prompt $\psi(2S)$ is shown here
- Predictions made with fixed-order next-to-leading logarithm (FONLL) calculations[1] match the data well over the whole p_T range



[1] M. Cacciari et al., JHEP 10 (2012) 137, arXiv:1205.6344

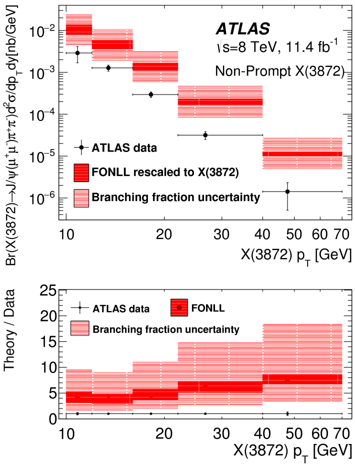
Cross Section of Prompt $X(3872)$

- 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 $\chi_{c1}(2P)$ component of the $\chi_{c1}(2P)$-$D^0\bar{D}^{*0}$ molecular state



Cross Section of Non-Prompt $X(3872)$

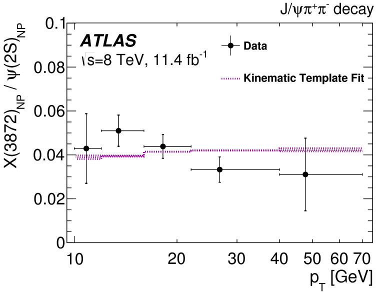
- The measured cross-section times branching fraction as a function of p_T for non-prompt $X(3872)$ is shown here
- It is compared to a calculation based on the FONLL model prediction for $\psi(2S)$, recalculated for $X(3872)$ using [1] based on the Tevatron data with large branching fraction uncertainty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



[1] P. Artoisenet and E. Braaten, Phys. Rev. D 81 (2010) 114018, arXiv:0911.2016

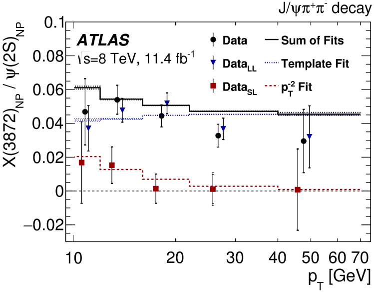
Kinematic Template Fit

- 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[1, 2]



[1] A. V. Berezhnoy and A. K. Likhoded, arXiv:1309.1979

[2] M. Cacciari et al., JHEP 10 (2012) 137, arXiv:1205.6344

Production due to B_c Decays

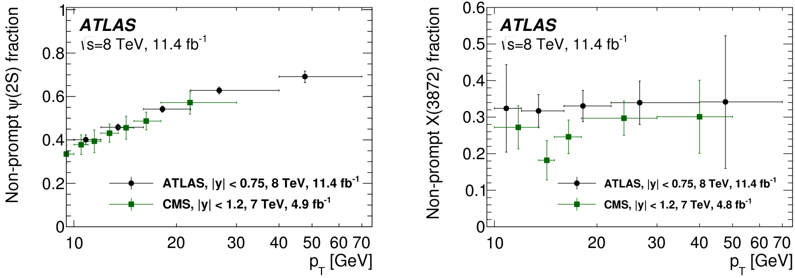
- The fit to the ratio of short-lived non-prompt $X(3872)$ to non-prompt $\psi(2S)$ and the measured non-prompt yields of $X(3872)$ and $\psi(2S)$ are used to determine the fraction of non-prompt $X(3872)$ from short-lived sources:

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

- 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

Measured Non-Prompt Fractions of $\psi(2S)$ and $X(3872)$

- 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[1] obtained with $\sqrt{s} = 7$ TeV



[1] CMS Collaboration, JHEP 04 (2013) 154, arXiv:1302.3968

Summary of the Presented Results

- The production cross-section of the prompt di-J/ψ 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 Δy, high di-J/ψ mass, and low di-J/ψ p_T regions
- An effective differential cross-section measurement of the DPS fraction of prompt di-J/ψ 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

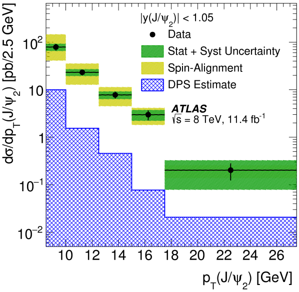
Backup Slides

Event Selection for J/ψ Pair Production

- The integrated luminosity value of 11.4 fb^{-1} is due to prescaling of the J/ψ 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/ψ, both of the reconstructed muons must have an ID track matched to a MS track
- For the non-triggered J/ψ candidate, at least one of the reconstructed muons must have and ID track matched to a MS track
- The distance between the two J/ψ decay vertices along the beam direction is required to be $|d_z| < 1.2$ mm. This requirement aims to select two J/ψ 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.

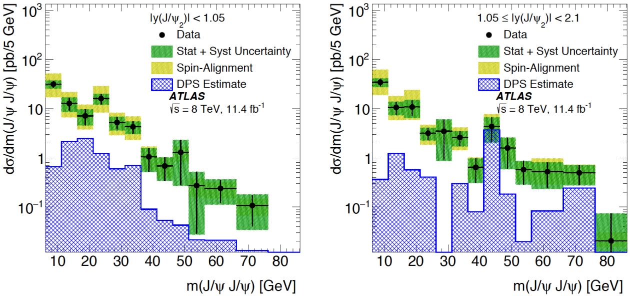
Cross Section of J/ψ_2 vs. $p_T(J/\psi_2)$

- Cross-section of the lower p_T J/ψ as a function of p_T

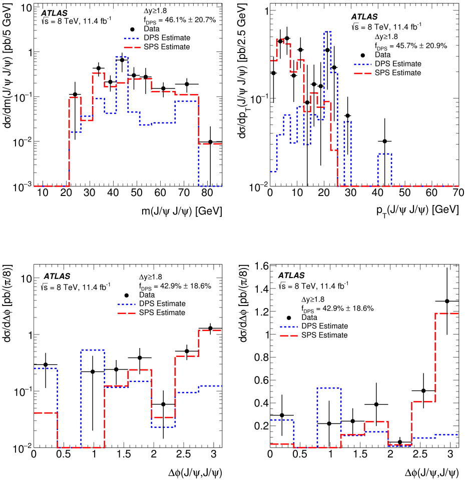


Cross Section of $J/\psi + J/\psi$ vs. $m(J/\psi + J/\psi)$

- Cross Section of prompt di-J/ψ as a function of $m(J/\psi + J/\psi)$



Prompt di-J/ψ Kinematic Variable Studies: $\Delta y \geq 1.8$



Prompt di-J/ψ Kinematic Variable Studies: $\Delta\phi \leq \pi/2$