ATLAS Results on Charmonium Production and B_c Production and Decay

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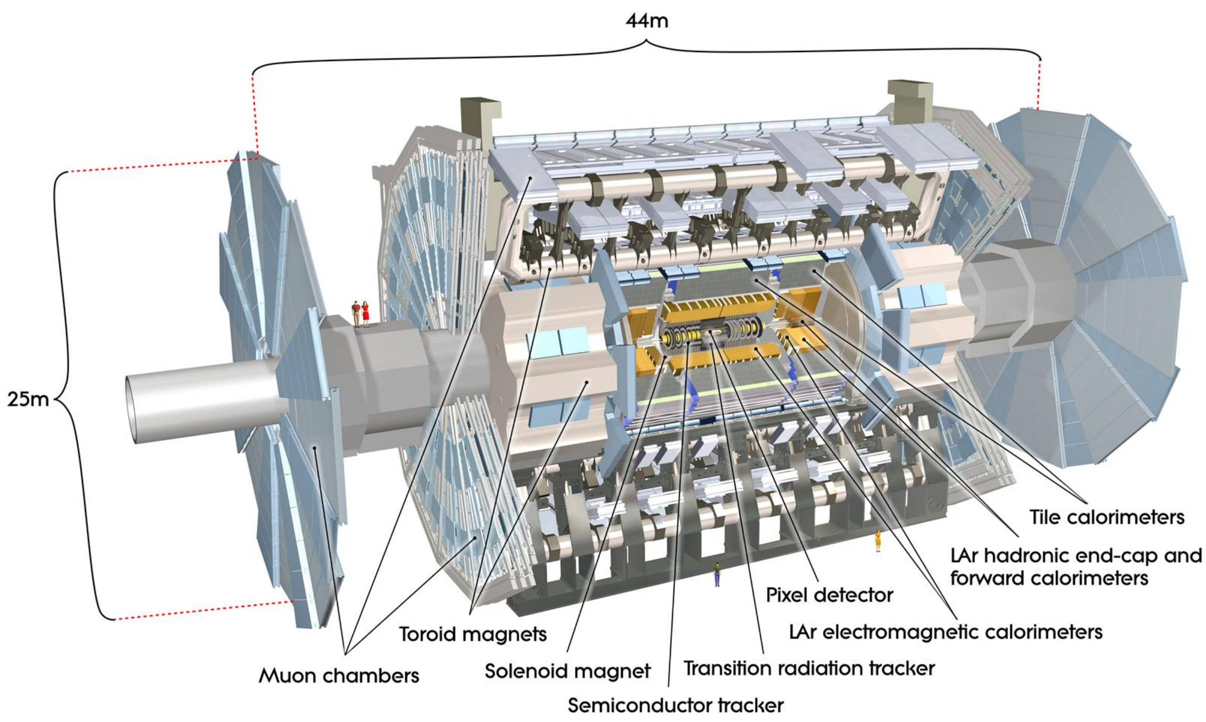
Four recent results on charmonium and B_c from ATLAS, using LHC pp data.



ATLAS from inside to out:

- Inner detector (pixel, silicon microstrips, straw-tube TRT) $|\eta| < 2.5$, surrounded by a 2T axial B field from the solenoid
- Sampling calorimeters (LAr EM $|\eta| < 3.2$; Scint tile HAD $|\eta| < 3.2$; LAr HAD $1.5 < |\eta| < 4.9$)
- Air core toroids provide B field for Muon drift tubes + cathode strip chambers (muon tracking to $|\eta| < 2.7$) and resistive plate + thin gap chambers (triggering to $|\eta| < 2.4$)

I. J/ψ Production in Association with a $W^{\pm}$ Boson at 8 TeV
II. Relative $B_c^{\pm}/B^{\pm}$ Production Cross Section at 8 TeV
III. Production Cross Section of J/ψ and $\psi(2S)$ at High p_T at 13 TeV
IV. $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ Decays at 13 TeV

Measurement of J/ψ Production in Association with a $W^{\pm}$ Boson at 8 TeV*

Message: Associated prompt production of J/ψ + $W^{\pm}$ probes the mechanism for charmonium production in hadronic collisions and is proposed to be a clear means to compare the color octet and color singlet models.

The outcome: measurements of 3 ratios, all with the form:

$$R \equiv \frac{\sigma\left(pp \to J/\psi + W^{\pm}\right)}{\sigma\left(pp \to W^{\pm}\right)} \cdot B\left(J/\psi \to \mu\mu\right)$$

- R_{fid} - "fiducial" – independent of unknown J/ψ spin alignment or J/ψ acceptance corrections
- R_{incl} - "inclusive" – accounting for J/ψ spin alignment and J/ψ acceptance corrections
- $R_{DPS\text{-}sub}$ - "inclusive with double parton scattering subtracted" – remove cases where the J/ψ and $W^{\pm}$ come from different parton pairs.

Results are compared to NLO color octet prediction for single-parton scattering.**

*JHEP 01 (2020) 095.

**M. Song et al., Chin. Phys. Lett. 30 (2013) 091201, extended to 8 TeV by original authors.

Motivation:

- **The main models for perturbative calculations of quarkonium production in hadronic collisions differ in how the system is produced:**

  - in a **color singlet** (CS) state (requires 2 hard gluons in color singlet initial state, or one gluon splitting into $Q\overline{Q}$ then one Q radiating a hard gluon)

  -or-

  - with $Q\overline{Q}$ remaining in **color octet** (CO) state and then generating color-neutral meson by low energy non-perturbative matrix elements.

- **Associated J/ψ + $W^{\pm}$ production has been presented* as a clear signature of CO processes, although higher-order CS processes have also been proposed**.**

* G. Li et al., Phys. Rev. D 83 (2011) 014001.

** B.A. Kniehl et al., Phys. Rev. D 66 (2002) 114002.

The method:

- **20.3 fb^{-1} of pp collisions at 8 TeV** – this is a factor 4 increase in dataset size over the previous ATLAS measurement*

- **Find the W's**: W is associated with the primary vertex (PV) through transverse impact parameter. Apply isolation criteria. Improve W selection through cut on transverse mass.

- **Find the J/ψ's**: If a W event has 2 additional muons, apply a J/ψ reconstruction with common-vertex constraint. Select on: $8.5 < p_{TJ/\psi} < 150$ GeV and $|y_{J/\psi}| < 2.1$.

- **Limit to prompt J/ψ's** – produced in the initial hard interaction either directly or indirectly through feed-down (including radiatively) from a heavier charmonium state. Prompt candidates have a **pseudo-proper decay time τ consistent with zero**, where

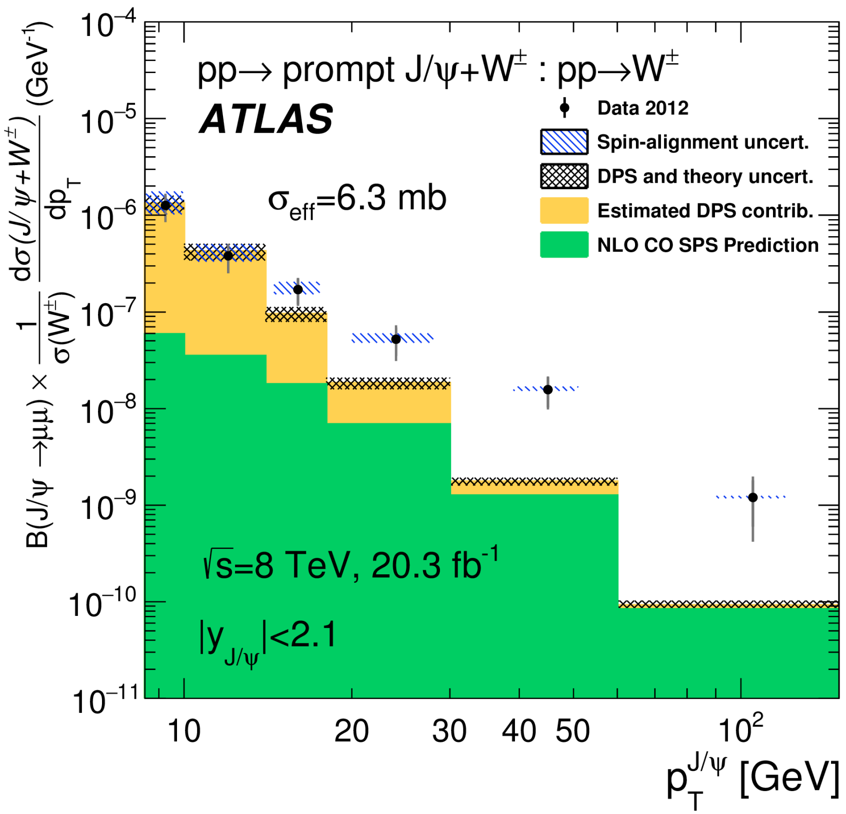
$$\tau\left(\mu^+\mu^-\right) \equiv \frac{\vec{L}\cdot\vec{p}_T^{\,J/\psi}}{p_T^{J/\psi}} \cdot \frac{m\left(\mu^+\mu^-\right)}{p_T^{J/\psi}},$$

  and $\vec{L}$ is the 2-D displacement between PV and J/ψ vertex.

- **Suppress systematic uncertainties** on W reconstruction and integrated lumi by taking the ratio of prompt cross sections to inclusive W cross section.

* ATLAS collaboration, HEP 04 (2014) 172.

- **Results binned** for $|y_{J/\psi}| < 1$ and $1 < |y_{J/\psi}| < 2$ and, for the full $|y|$ bin, differentially in $p_{T J/\psi}$.
- Measurements of the azimuthal angle between the $W^{\pm}$ and the J/ψ indicate **that double parton scattering (DPS),** in which the J/ψ and the W come from different hard interactions, **is present.**
- **The DPS contribution P^{ij} is estimated** for a process containing a $W^{\pm}$, using the measured cross-section $\sigma^{ij}_{J/\psi}$ for J/ψ production and the effective transverse overlap area of the interacting partons σ_{eff}: $P^{ij}_{J/\psi|W} = \sigma^{ij}_{J/\psi} / \sigma_{eff}$. Results are presented for σ_{eff} =15 mb and 6.3 mb.



Result:

The predicted cross section ratio is closer to data for σ_{eff} = 6.3 mb, but neither value of σ_{eff} allows a good match to the J/ψ p_T dependence. Inclusion of color singlet processes may improve the agreement.

Measurement of the Relative $B_c^{\pm}/B^{\pm}$ Production Cross Section at 8 TeV*

Message and motivation: No published calculation of the cross section at 8 TeV is available. Evidence of dependence of this ratio upon $p_T(B)$ is shown. This is the first measurement of this relative cross section for this combination of fiducial volume and energy.

The outcome: $\dfrac{\sigma\left(B_c^{\pm}\right)\cdot B\left(B_c^{\pm}\to J/\psi\pi^{\pm}\right)}{\sigma\left(B^{\pm}\right)\cdot B\left(B^{\pm}\to J/\psi\pi^{\pm}\right)}$ is measured for bins:

- **2 p_T bins** for the rapidity range $|y(b)| < 2.3$:

  $$13 \text{ GeV} < p_T(B_c^{\pm}) < 22 \text{ GeV and } p_T > 22 \text{ GeV}$$

- **2 rapidity bins** for the p_T range $p_T(B) > 13$ GeV:

  $$|y| < 0.75 \text{ and } 0.75 < |y| < 2.3$$

- **and for the full range: $p_T > 13$ GeV and $|y| < 2.3$**

* Phys. Rev. D 104 (2021) 012010.

The method:

- **Find the J/ψ**: combine every oppositely-signed pair of muons, constrain to a common vertex.

- **Find the B candidates**: fit the tracks of the 2 muons to a charged-hadron track, constrain to a common vertex. Charged hadron takes kaon (pion) mass for $B^{\pm}$ (B_c). Constrain the J/ψ mass to its world average value.

- **Remove combinatorial background** in which J/ψ is combined with unrelated light charged hadron: select on significance of impact parameter of hadron track relative to PV in transverse plane.

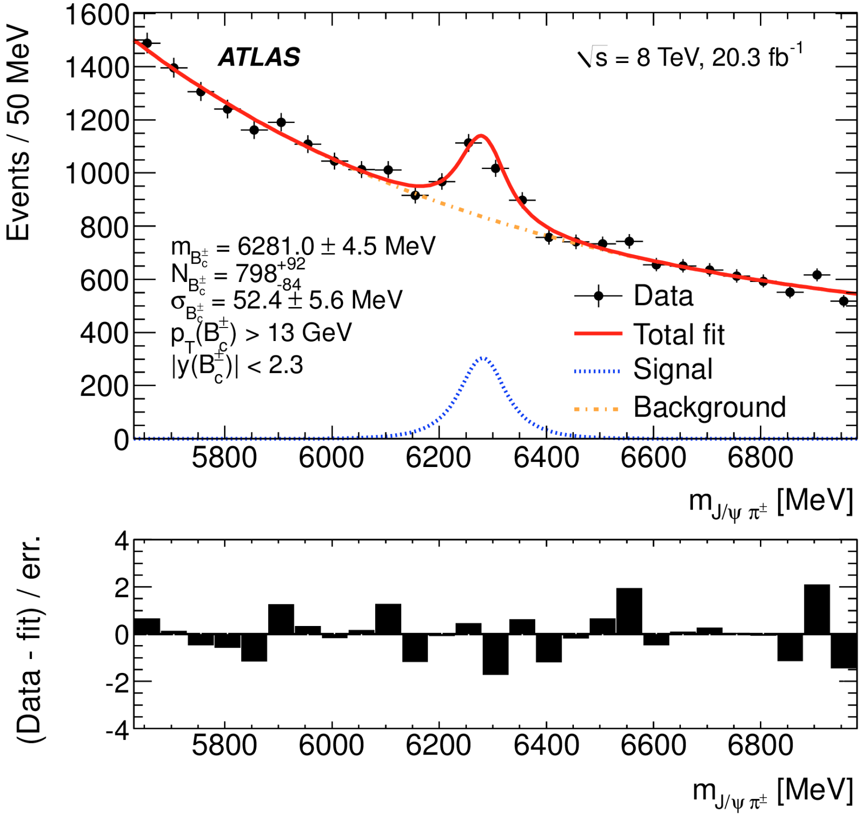
- **Remove partially-reconstructed B_c** semileptonic decays in which a muon fakes a hadron.

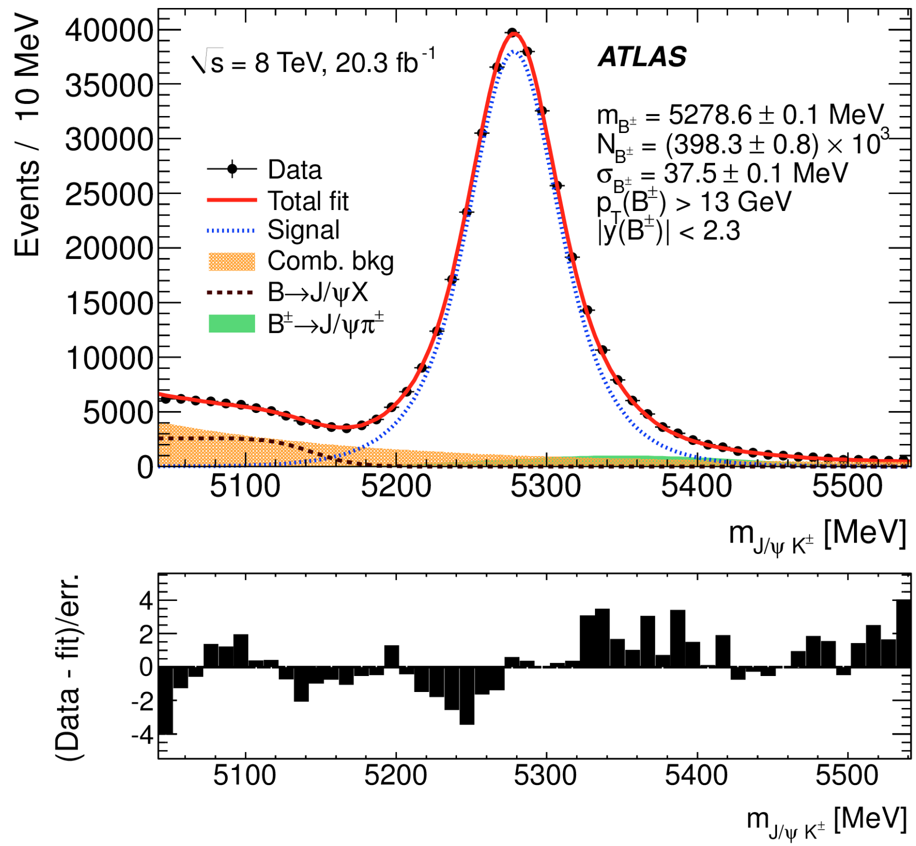
- Find $$\frac{\sigma\left(B_c^{\pm}\right)\cdot B\left(B_c^{\pm}\rightarrow J/\psi\pi^{\pm}\right)\cdot B\left(J/\psi\rightarrow\mu^{+}\mu^{-}\right)}{\sigma\left(B^{\pm}\right)\cdot B\left(B^{\pm}\rightarrow J/\psi\pi^{\pm}\right)\cdot B\left(J/\psi\rightarrow\mu^{+}\mu^{-}\right)}=\frac{N^{reco}\left(B_c^{\pm}\right)}{N^{reco}\left(B^{\pm}\right)}\cdot\frac{\varepsilon\left(B^{\pm}\right)}{\varepsilon\left(B_c^{\pm}\right)}$$

where ε's are efficiencies and N^{reco} is extracted from mass distributions by unbinned maximum-likelihood fits.

Example invariant mass distributions:

$B^{\pm}$

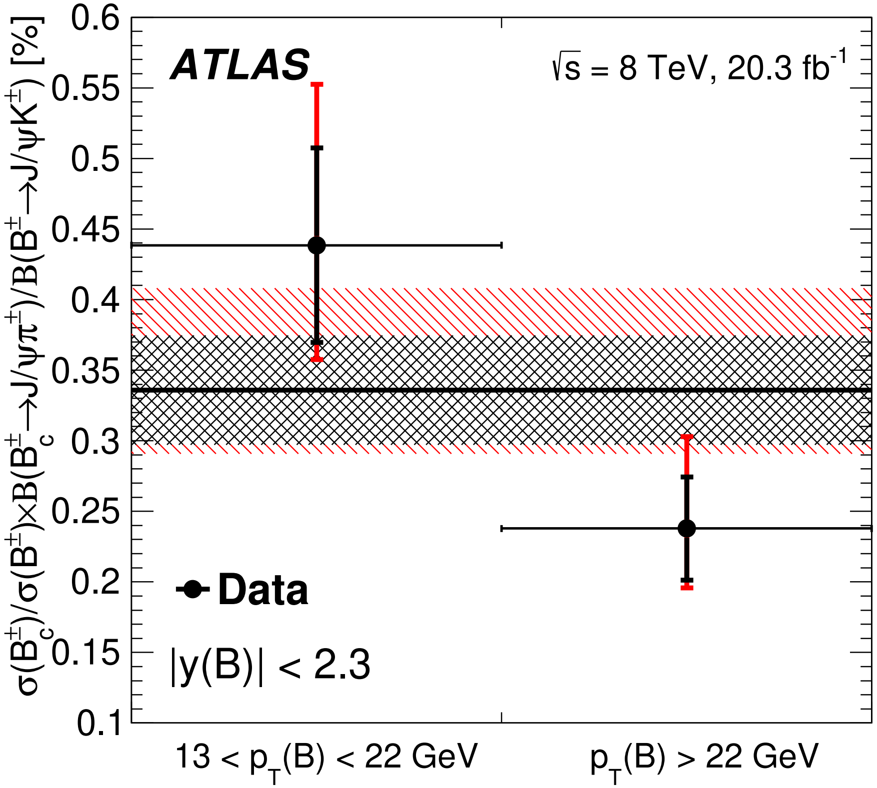


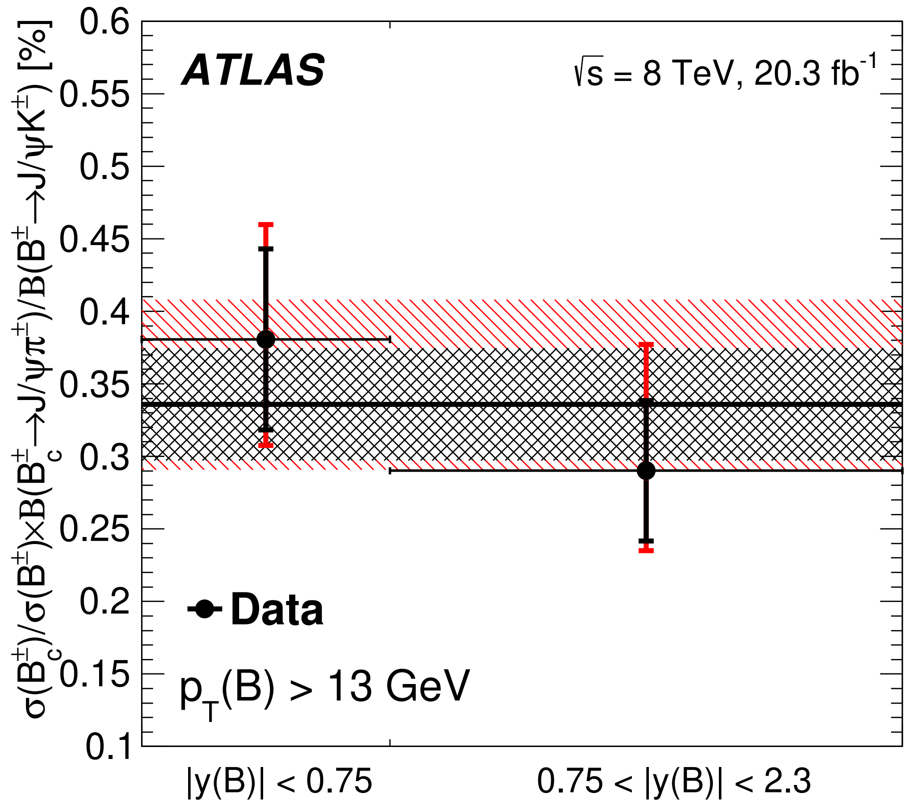


B_c

Inclusive result: For full range $p_T > 13$ GeV and $|y| < 2.3$, the production cross section ratio is $0.34 \pm 0.04(\text{stat})^{+0.06}_{-0.02}(\text{syst}) \pm 0.01(\text{lifetime})$

Differential (points) and inclusive (lines) results:





The differential measurement suggests a possible dependence on p_T: the production cross section of the B_c decreases faster with p_T than the production cross section of the $B^{\pm}$.

No significant dependence on rapidity is observed.

Measurement of the Production Cross Section of J/ψ and ψ(2S) Mesons at High Transverse Momentum at 13 TeV*

Message – This analysis broadens the scope of comparison between experiment and theory by adding a high p_T selection on the quarkonium – this is expected to improve discrimination among competing models** of vector charmonium production.

The outcome - ATLAS has measured:

- double differential production cross sections of J/ψ and ψ(2S) through their decays to $\mu^+\mu^-$.
- Prompt and non-prompt cross sections separately for both states.
- For each state, the ratio of non-prompt to total (i.e. fraction of non-prompt).
- For both prompt and non-prompt, the production ratios of ψ(2S) relative to J/ψ.

The characteristics of the measured cross sections are compared to predictions based on the FONLL model.***

*ATLAS-CONF-2019-047.
**G. Li et al., PRD 83 (2011) 014001; J.P. Lansberg and C. Lorce, Phys. Lett. B 726 (2013) 218; B. Gong et al., JHEP 03 (2013) 115; M. Song et al., JHEP 02 (2011) 071; M. Butenschoen and B.A. Kniehl, Nucl. Phys. Proc. Suppl. 222-224 (2012) 151.
***M. Cacciari et al., JHEP 0103 (2001) 006; M. Cacciari et al., JHEP 1210 (2012) 137.

The method –

- **Apply single-muon trigger with threshold $p_T > 50$ GeV.**

- **Find the J/ψ's and ψ(2S) through their decays to $\mu^+\mu^-$.** At least one muon must have $p_T > 52.5$ GeV.

- **Compute dilepton mass m(μμ) and pseudo-proper decay time τ** for each event.

- **Sort data into (12 intervals in p_T^{muon}) × (3 intervals in $|y|^{muon}$).** Correct each bin for efficiencies**, apply 2-dimensional [in m(μμ), τ] unbinned max likelihood fit to each bin.**

- **Extract yields N^{prompt} and $N^{non\text{-}prompt}$** from fits.

- **Compute double-differential cross section (*A* is acceptance, *C* is correction):**

$$\frac{d^2\sigma^{P,NP}(pp\to\psi)}{dp_T dy}\times B(\psi\to\mu^+\mu^-)=\frac{1}{A(\psi)}C_{bin-migration}C_{\substack{pileup\ and\\ angular\\ correlations}}\frac{N_\psi^{P,NP}}{\Delta p_T\Delta y\int L\,dt}$$

Method, continued –

- **Compute non-prompt fractions:**

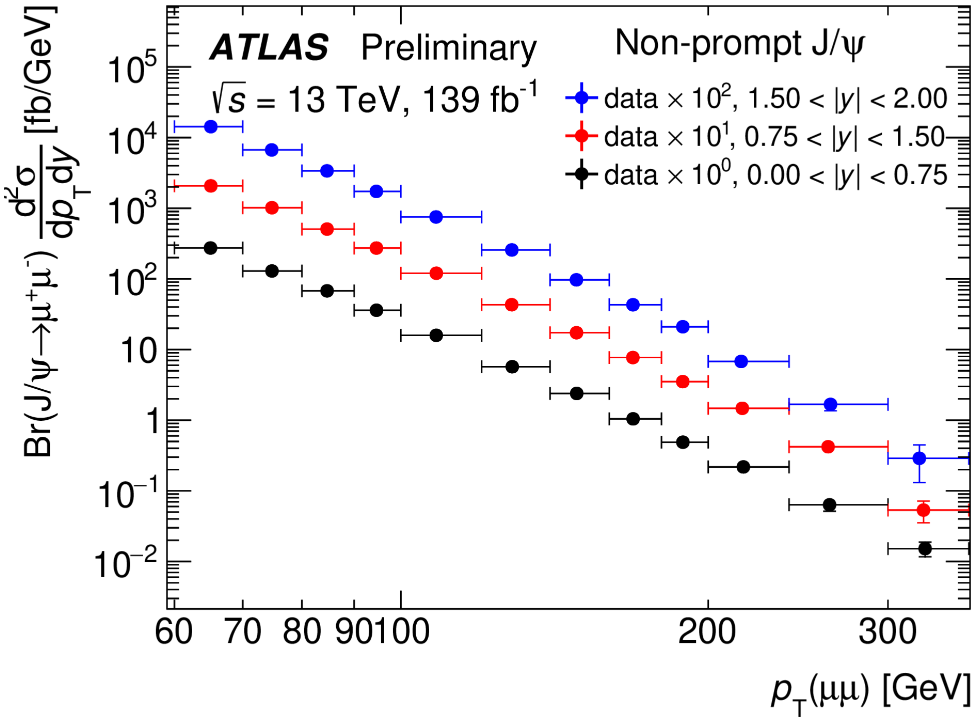
$$F^{NP}\left(p_T, y\right) = \frac{N_{\psi}^{NP}}{N_{\psi}^{P} + N_{\psi}^{NP}}$$

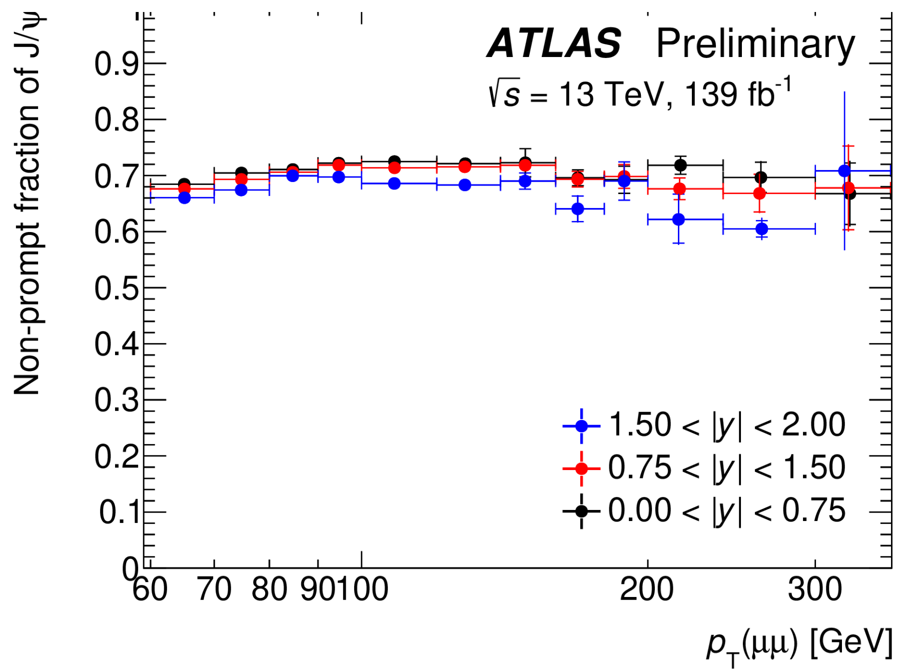
- **Compute production ratios of ψ(2S) relative to J/ψ:**

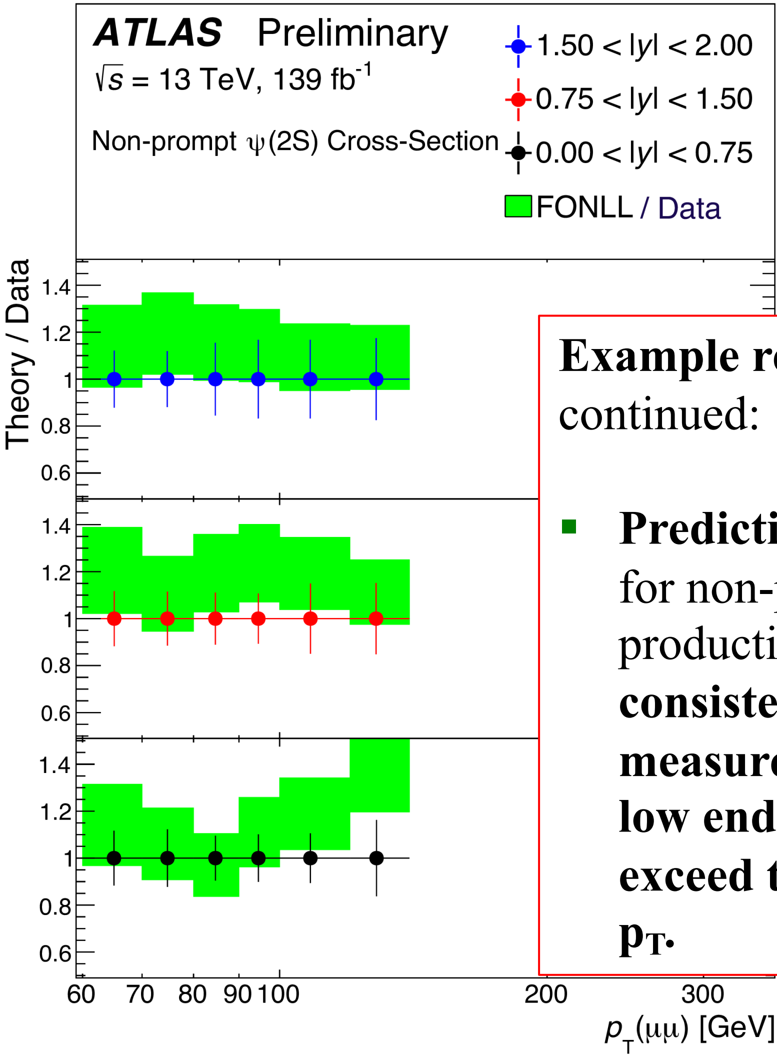
$$R^{P,NP}\left(p_T, y\right) = \left(\frac{A\left(\psi\left(2S\right)\right)}{A\left(J/\psi\right)}\right)^{-1} \frac{N_{\psi(2S)}^{P,NP}}{N_{J/\psi}^{P,NP}}$$

Example results:

- **Similar p_T dependence for prompt and non-prompt cross sections**
- **Non-prompt fraction close to constant** in this p_T range

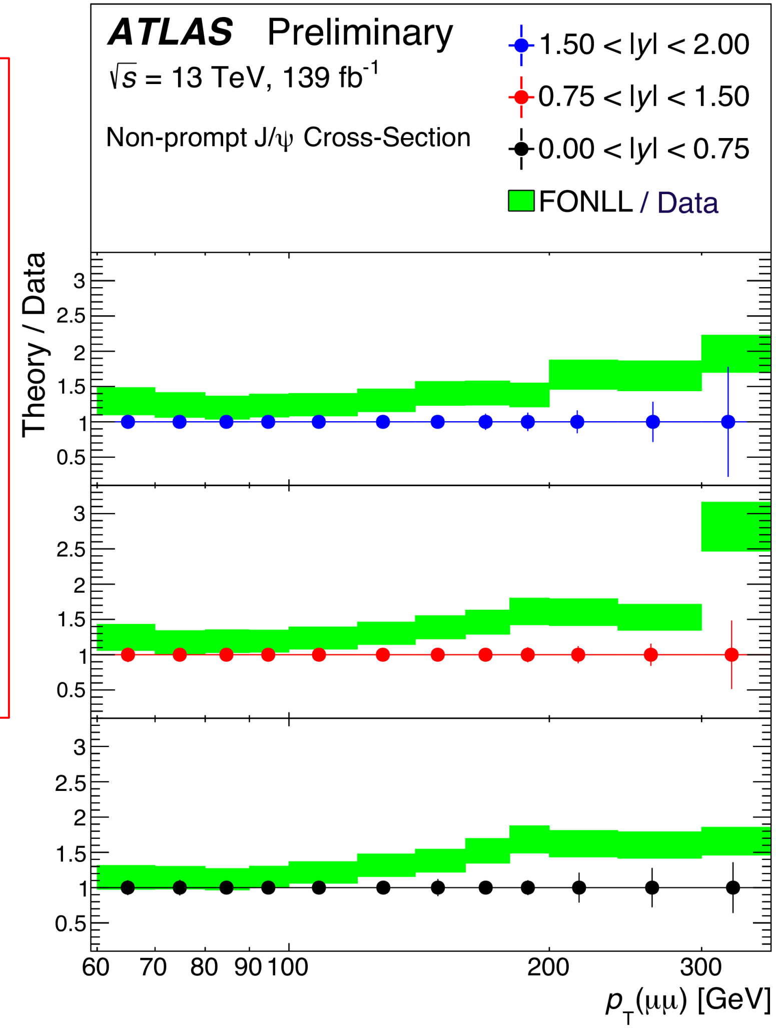


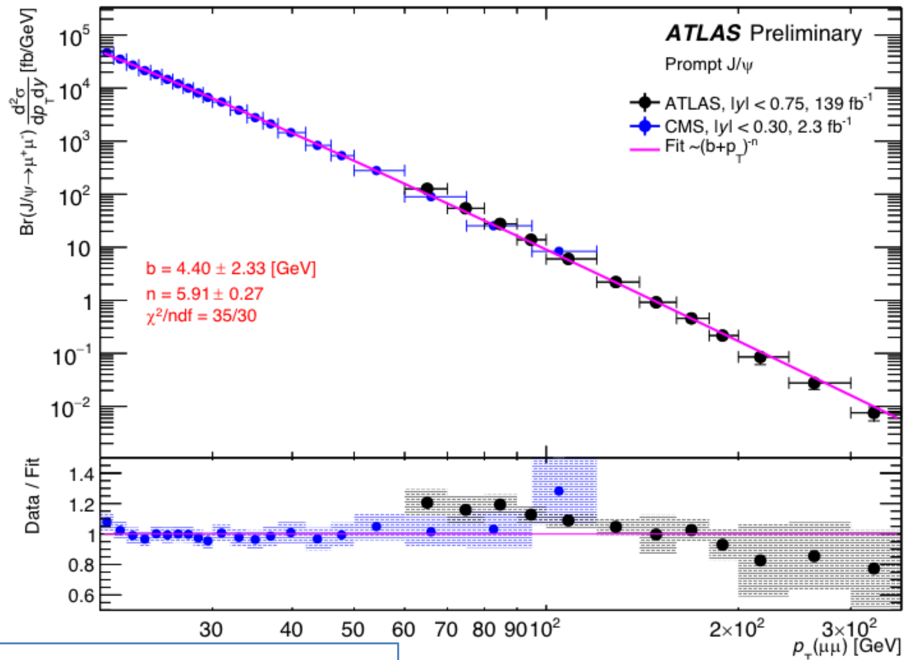




Example results, continued:

- **Predictions** at FONLL for non-prompt production **are consistent with measurement at the low end of p_T but exceed the data at high p_T.**





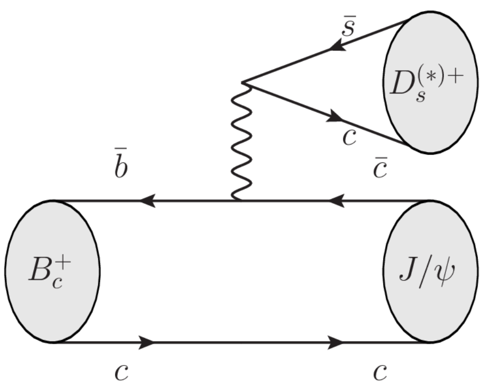
Excellent agreement between this ATLAS result for prompt J/ψ in the central rapidity range, and the CMS measurement in the closest-matching rapidity range. Both sets of data are fitted to $\sim(b+p_T)^{-n}$ for b = 4.40 ± 2.33 and n = 5.91 ± 0.27,

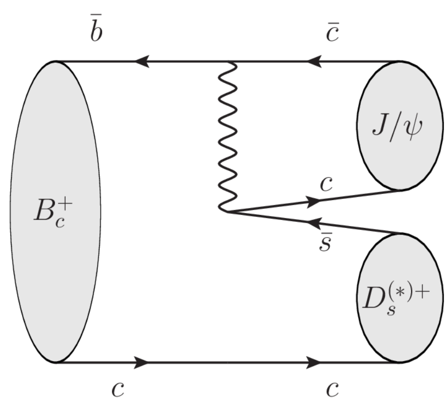
Study of $B_c^+ \to J/\psi D_s^{(*)+}$ Decays at 13 TeV*

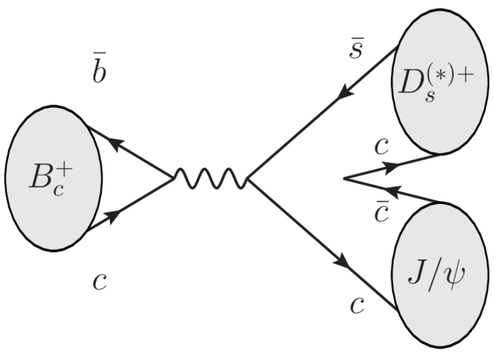
Message: Branching fractions of the decays $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ are measured relative to that of $B_c^+ \to J/\psi \pi^+$ and relative to each other.

The motivation: B_c^+ provides a unique laboratory for testing theoretical approaches to weak decays, because it is the only weakly decaying meson consisting of 2 heavy quarks. Examples of its decay modes include:

color-favored spectator: **color-suppressed spectator:** **annihilation topology:**







Outcome: The precision of the measurements exceeds that of all previous studies of these decays. The measurements are compared with 9 theoretical predictions and with LHCb† and ATLAS Run 1** results.

*ATLAS-CONF-2021-046.

† Phys. Rev. D 87 (2013) 112012 and Phys. Rev. D 89 (2014) 019901.

**Eur. Phys. J. C 76 (2016) 4.

The method:

- Use the **full Run 2 pp dataset: 139 fb^{-1}.**
- **Find the $J/\psi \rightarrow \mu^+\mu^-$.** Refit muon tracks to a common vertex.
- **Reconstruct** $D_s^+ \rightarrow \phi(\rightarrow K^+K^-)\pi^+$**.** All oppositely-charged pairs are considered for the kaon mass hypothesis. Any additional track is assigned the pion mass. Keep candidates with good vertex and masses consistent with ϕ [1019±7 MeV] and D_s^+ [1930-2010 MeV]
- **Combine the J/ψ and D_s^+ candidates.** The J/ψ and the B_c^+ share the common secondary vertex, and the D_s^+ tertiary vertex is distinct. **Require the D_s^+ momentum to point back to the B_c^+ vertex.** Constrain the J/ψ and D_s^+ candidates to world-average masses.
- Apply p_T and $|\eta|$ selections to refitted μ, K, and π tracks. **Suppress combinatorial bkg** with selections on B_c^+ vertex χ^2/N_{DOF}; transverse impact parameters of D_s^+ and B_c^+ vertices; transverse and longitudinal impact parameters of B_c^+ relative to the primary vertex; p_T cut to select hard fragmentation.
- **Suppress fake B_c^+ from $B_s^0 \rightarrow J/\psi\phi$ combined with a random track**: Exclude range $m(B_s^0) \pm 30$ MeV.
- **Further suppress combinatoric bkg: Apply boosted decision tree multivariate classifier** in TMVA, trained on D_s^+ spectrum of p_T and L_{xy} and 4 angular variables. Training uses BCVEGPY* simulation for signal and $J/\psi D_s^+$ sidebands for bkg.

The method, continued –

- **Reconstruct the reference channel** $B_c^+ \to J/\psi\pi^+$ (selections similar to those of the signal channels.) Exclude $B_c^+ \to J/\psi\mu^+\nu_\mu X$ by excluding from the pion candidates tracks identified as low-p_T muons.

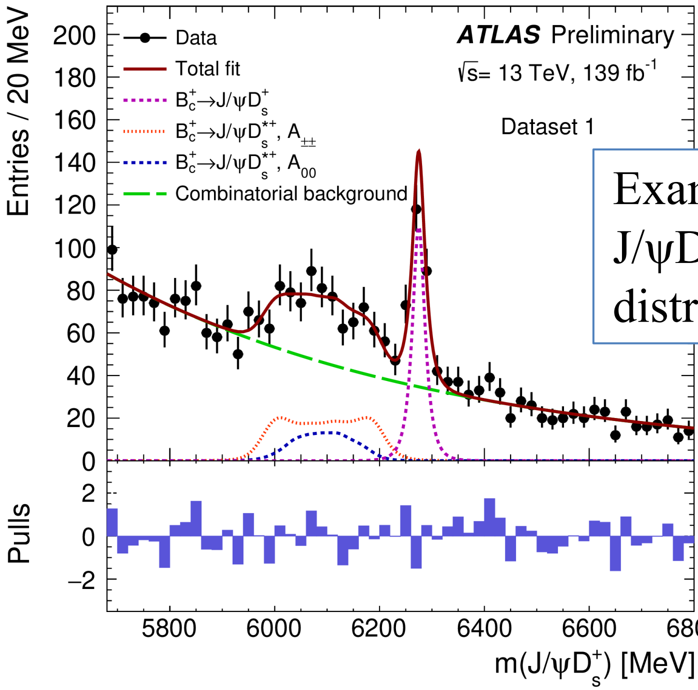
- Dataset is split to **accommodate various trigger conditions**.

- Apply an **extended unbinned maximum likelihood fit** to the 2D distribution of $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$. **The $\theta'(\mu^+)$ is the helicity angle**: the angle between the μ^+ and the D_s^+ momenta in the rest frame of the $\mu^+\mu^-$.

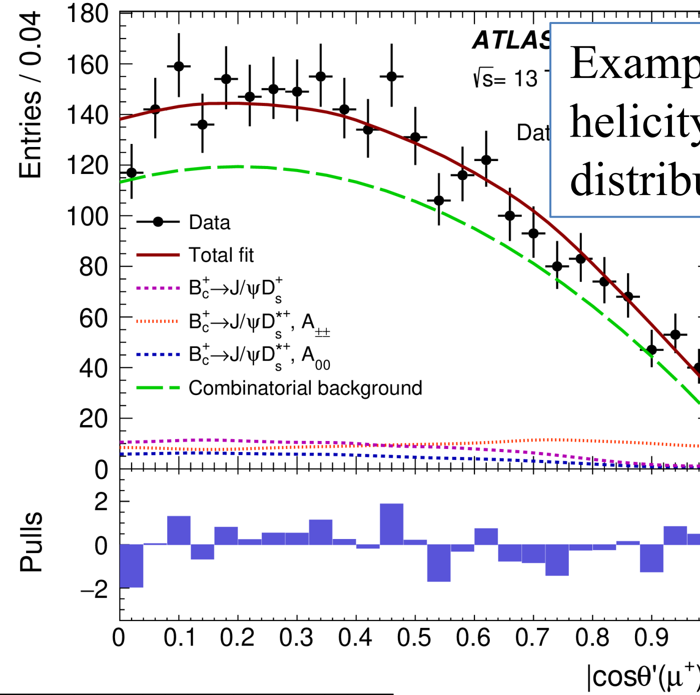
- The D_s^{*+} decays to D_s and π^0 /γ which is not reconstructed, but the mass difference between D_s^{*+} and D_s leads to **2 distinct structures** in the mass plot.

- As the $\mathbf{B_c^+ \to J/\psi D_s^{*+}}$ channel is a transition of a pseudoscalar meson into 2 vector states, it **involves 3 helicity amplitudes** ($A_{J/\psi Ds^*}$) given as A_{++}, A_{00}, A_{--}. The combination of A_{++} and A_{--} is called $A_{\pm\pm}$ and corresponds to transverse polarization. The contributions to the signal PDF for the helicity components are produced with adaptive kernel estimation technique.[†]

[*] Comput. Phys. Commun. 197 (2015) 335, arXiv: 1507.05176 [hep-ph]
[†] Comput. Phys. Commun. 136 (2001) 198, arXiv:hep-ex/0011057.

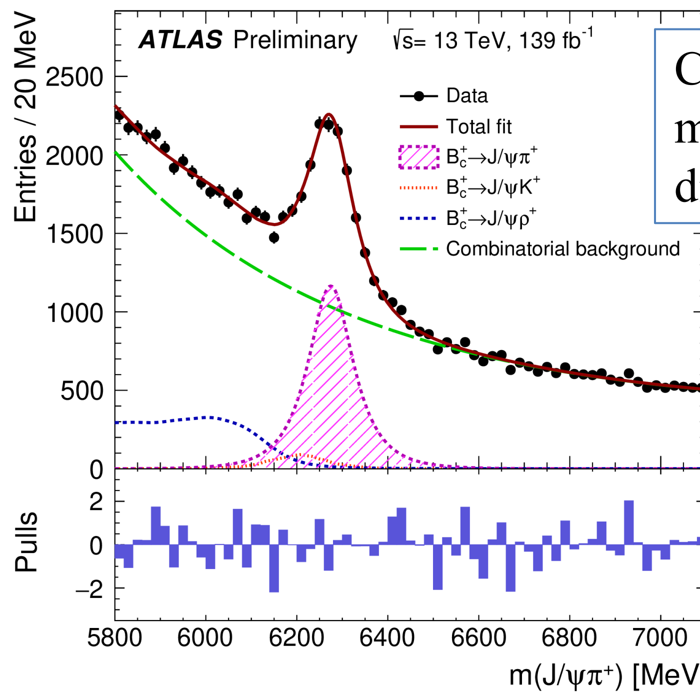


Example J/ψD$_s$ mass distribution



Example helicity angle distribution

The soft pion or gamma from the $D_s^{*+} \to D_s^+$ transition is hard enough to produce 2 distinct mass structures for the helicity components A_{00} and $A_{\pm\pm}$.



Control (J/ψπ) mass distribution

Results:

$$R_{D_s^+/\pi^+} \equiv \frac{B\left(B_c^+ \to J/\psi D_s^+\right)}{B\left(B_c^+ \to J/\psi \pi^+\right)} = 2.76 \pm 0.33 \pm 0.29 \pm 0.16$$

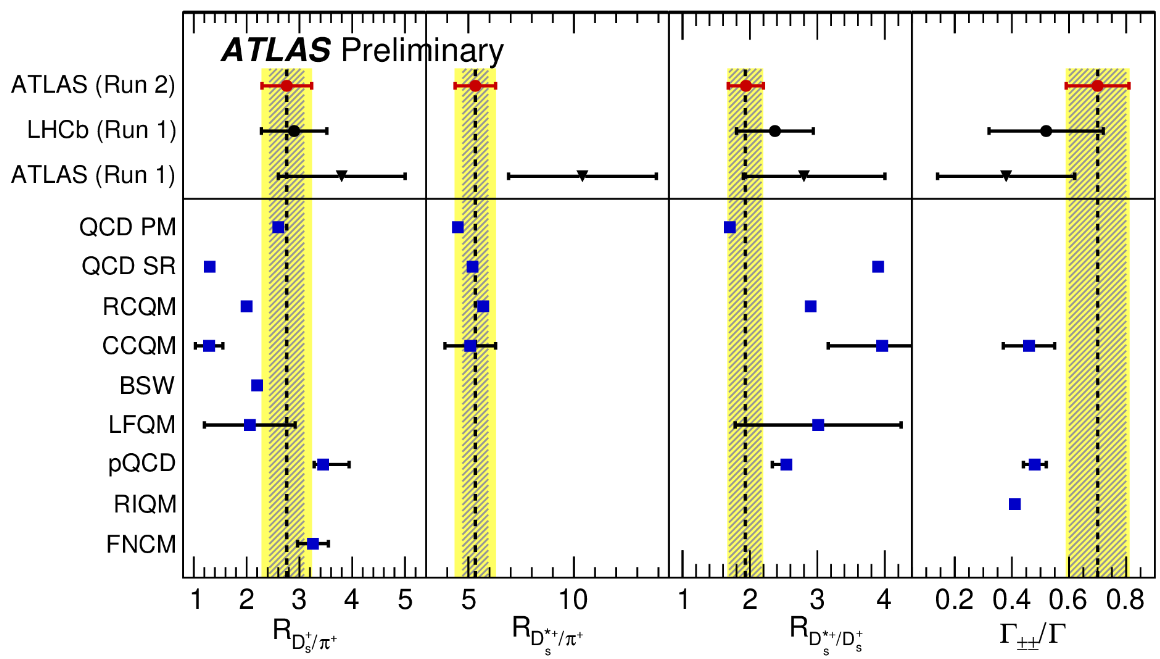
$$R_{D_s^{*+}/\pi^+} \equiv \frac{B\left(B_c^+ \to J/\psi D_s^{*+}\right)}{B\left(B_c^+ \to J/\psi \pi^+\right)} = 5.33 \pm 0.61 \pm 0.67 \pm 0.32$$

$$R_{D_s^{*+}/D_s^+} \equiv \frac{B\left(B_c^+ \to J/\psi D_s^{*+}\right)}{B\left(B_c^+ \to J/\psi D_s^+\right)} = 1.93 \pm 0.24 \pm 0.10$$

The third error derives from the uncertainty on the branching fraction of $D_s^+ \to \phi(K^+K^-)\pi^+$.

$\Gamma_{\pm\pm}/\Gamma$ = (fraction of transverse polarization in $B_c^+ \to J/\psi D_s^{*+}$) = $0.70 \pm 0.10 \pm 0.04$

- QCD PM: rel. potential model (P. Colangelo et al., arXiv:hep-h/9909423)
- QCD SR: sum rules (V. Kiselev, arXiv:hep-ph/0211021)
- RCQM: rel. constituent quark model (M. Ivanov et al., arXiv:hep-ph/0602050)
- CCQM: covariant confined quark model (S. Dubnicka et al., arXiv:1708.09607[hep-ph])
- BSW: rel. quark model (R. Dhir et al,., arXiv:0810.4284[hep-ph])
- LFQM: light-front quark model (H.W. Ke et al., arXiv:1307.5925[hep-ph])
- pQCD: pert. QCD (Z. Rui et al., arXiv:1407.5550[hep-ph])
- RIQM: rel. independent quark model (S. Kar et al., PRD 88 (2013) 094014.
- FNCM: factorization approach (B. Mohammadi, Int. J. Mod. Phys. A 33 (2018) 1850044.



Summary

ATLAS presents 4 recent results on charmonium production and B_c production and decay:

- Measurement of J/ψ production in association with a $W^{\pm}$ boson – *to assess the agreement of data with a Color Octet model; while there is reasonable agreement at low p_T, some inclusion of Color Singlet may be needed to improve the agreement at high p_T.*

- Measurement of the production cross section of B_c mesons relative to $B^{\pm}$ mesons – *new data in an energy and fiducial volume regime for which no prediction exists, and some indication of p_T dependence in the ratio.*

- Measurement of the production cross section of J/ψ and ψ(2S) mesons at high p_T – *The p_T range extends far beyond previous studies and may help discriminate among models; but the non-prompt production fraction diverges from the prediction increasingly with growing p_T.*

- Study of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays – *The precision exceeds that of all previous studies of these decays. The QCD relativistic potential model describes all three branching ratios well. Comparisons to 8 other models are also provided.*