ATLAS Results on B_c Production and Decay

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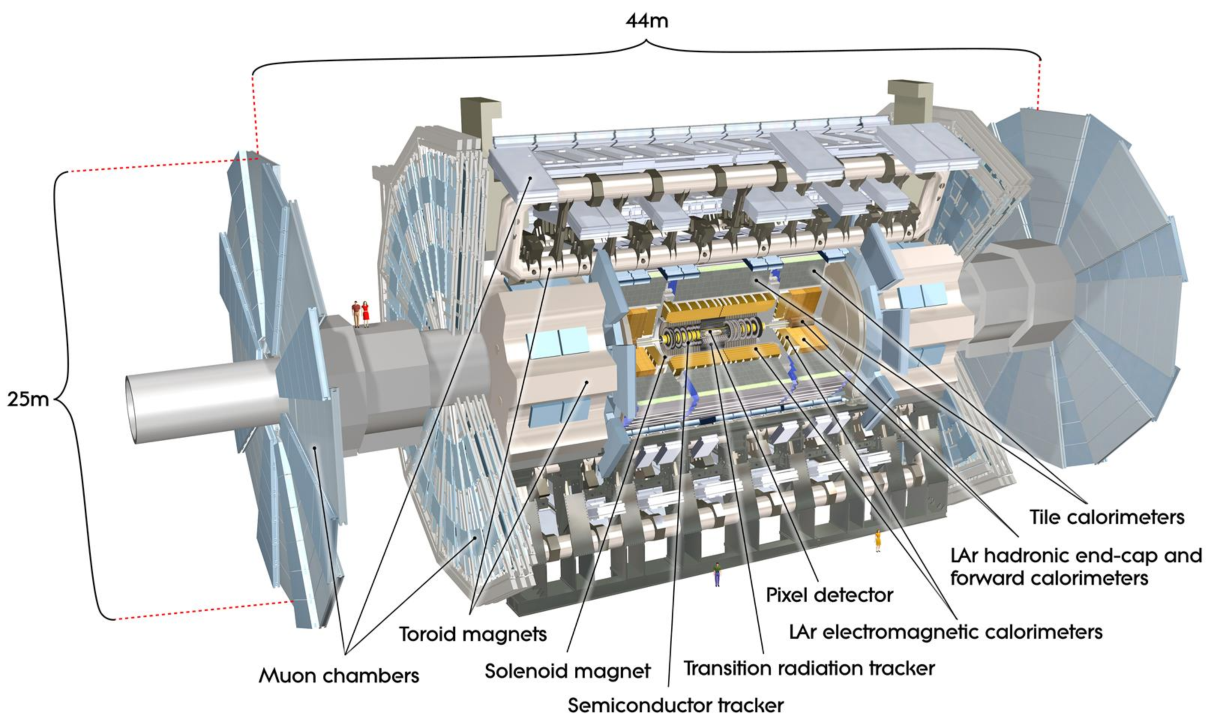
Two recent results on B_c production and decay from ATLAS, using LHC pp data.



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. Relative $B_c^{\pm}/B^{\pm}$ Production Cross Section at 8 TeV

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

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: $\frac{\sigma\left(B_c^{\pm}\right)\cdot B\left(B_c^{\pm}\rightarrow J/\psi\pi^{\pm}\right)}{\sigma\left(B^{\pm}\right)\cdot B\left(B^{\pm}\rightarrow J/\psi\pi^{\pm}\right)}$ 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.

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

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

Reconstruction details:

- require **muon p_T** > 4 GeV
- **vertex fit quality** $\chi^2 < 15$
- **dimuon invariant mass must lie in a window** that depends on the η of the muons (tighter window for more central tracks).
- **Primary vertex chosen** by extrapolating the B flight direction to the z-axis and choosing the closest vertex in the z-direction.
- **Reconstructed B candidates selections**:
  - $\chi^2/(\mathrm{dof} = 4) < 1.8$
  - $|y(B)| < 2.3$
  - $p_T^{hadron} > 2.0$ GeV
- **Impact parameter significance of the hadron track,** $d_{xy}^0 / \sigma\left(d_{xy}^0\right) > 1.2$

Unbinned maximum likelihood fit details:

- Signal – Gaussian pdf with event-by-event errors

$$F_{B_c\ \text{signal}} \propto \exp\left(-\frac{\left(m_{J/\psi\pi^\pm}-m_{B_c^\pm}\right)^2}{2\left(s\delta m_{J/\psi\pi^\pm}\right)}\right) \text{ and } F_{B^\pm\ \text{signal}} \propto \exp\left(-\frac{\left(m_{J/\psi K^\pm}-m_{B^\pm}\right)^2}{2\left(s\delta m_{J/\psi K^\pm}\right)}\right)$$

- B_c bkg – $F \propto \exp\left(a \cdot m_{J/\psi\pi^\pm}\right)+b$

- Partially-reconstructed b-hadron decays in the lower part of the $B^\pm$ spectrum fitted with the complementary error function-

$$F \propto 1-erf\left(A\right)=1-\frac{2}{\sqrt{\pi}}\int_0^A e^{-t^2}\,dt;\quad A=\frac{m_{J/\psi K^\pm}-m_0}{s_0}$$

- Cabibbo-suppressed bkg in the high part of the $B^\pm$ spectrum fitted with a Gaussian

$$F \propto \exp\left(-\frac{\left(m_{J/\psi K^\pm}-m_{B^\pm,\pi^\pm}\right)^2}{2\left(s\delta m_{J/\psi K^\pm}\right)^2}\right)$$

- Remaining bkg – due to production of J/ψ mesons from decays of b-hadrons other than $B^\pm$

$$F \propto \exp\left(d \cdot m_{J/\psi K^\pm}\right)$$

Efficiency details:

$$\varepsilon = \varepsilon^{trigger} \cdot \varepsilon^{muon\ spectrometer}\left(\mu^{+}\right) \cdot \varepsilon^{muon\ spectrometer}\left(\mu^{-}\right) \cdot \left(\varepsilon^{Inner\ Detector}\left(\mu^{\pm}\right)\right)^{2} \cdot \varepsilon^{Inner\ Detector}\left(X_{h}\right) \cdot \varepsilon^{vertex}\left(B\right) \cdot \varepsilon^{selection}\left(B\right)$$

- Efficiency correction is 8.2% - 9.9% for all differential bins in p_T and rapidity, 22% for the full range of the analysis

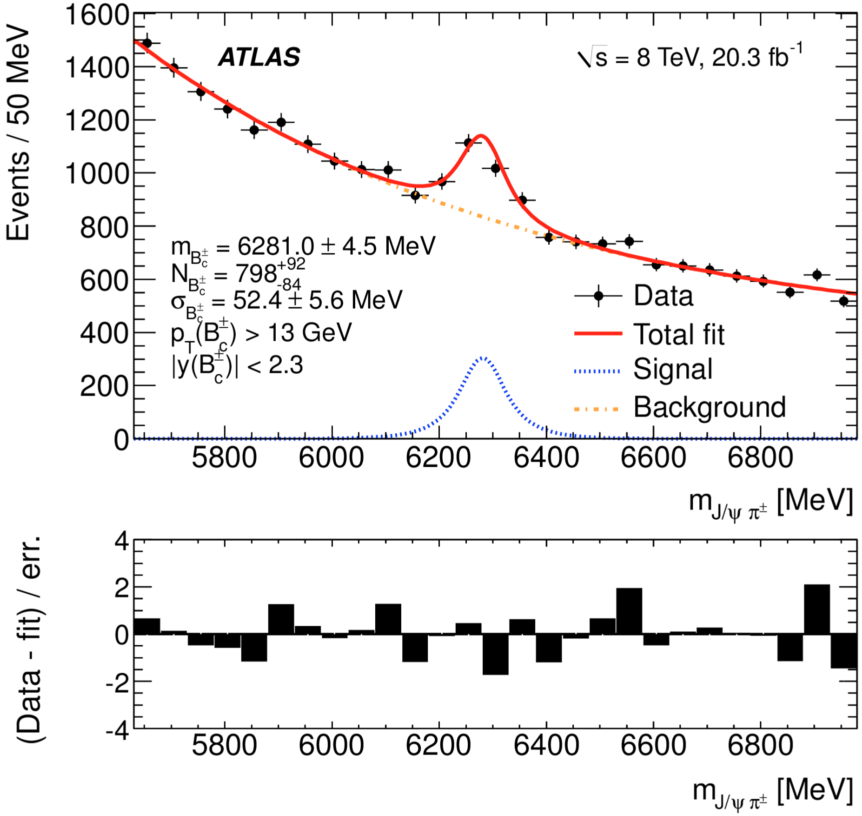
- ***Systematic uncertainties:***

- Size of the Monte Carlo samples
- Monte Carlo based reweighting procedure
- Minimal selection criteria
- Tracking uncertainty
- Choice of signal models
- Choice of background models
- Estimate of Cabibbo-suppressed decay contributions

$$B_c^{\pm} \to J/\psi K^{\pm} \text{ and } B^{\pm} \to J/\psi \pi^{\pm}$$

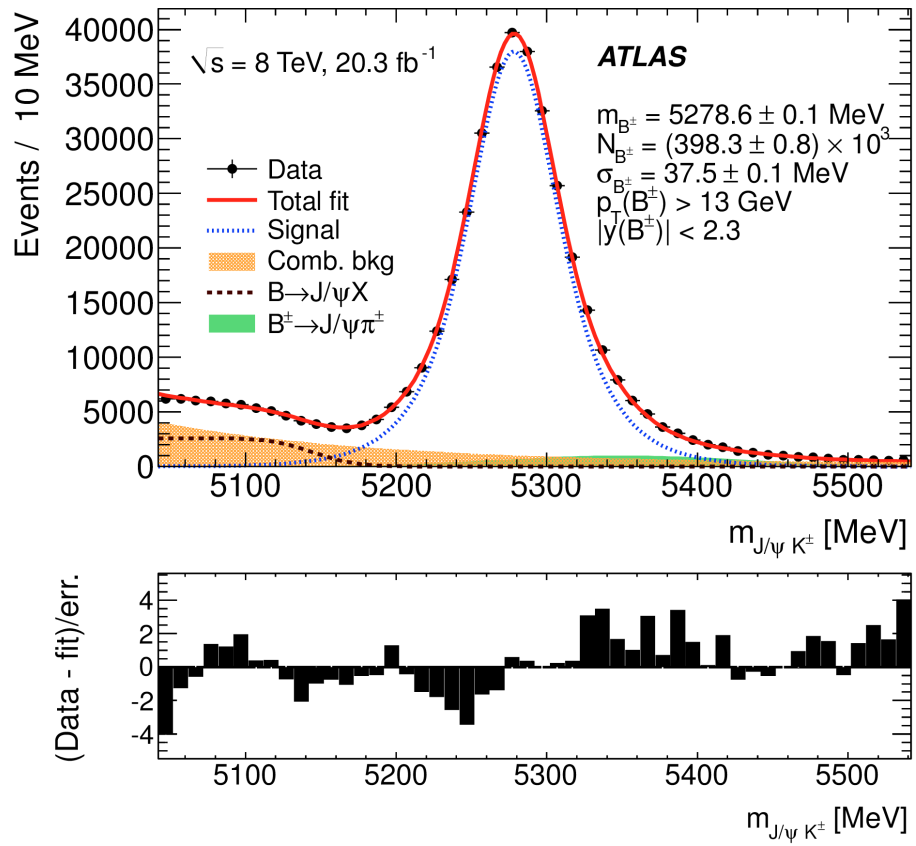
- B lifetime uncertainty
- Trigger and reconstruction effects

Example invariant mass distributions:



B_c

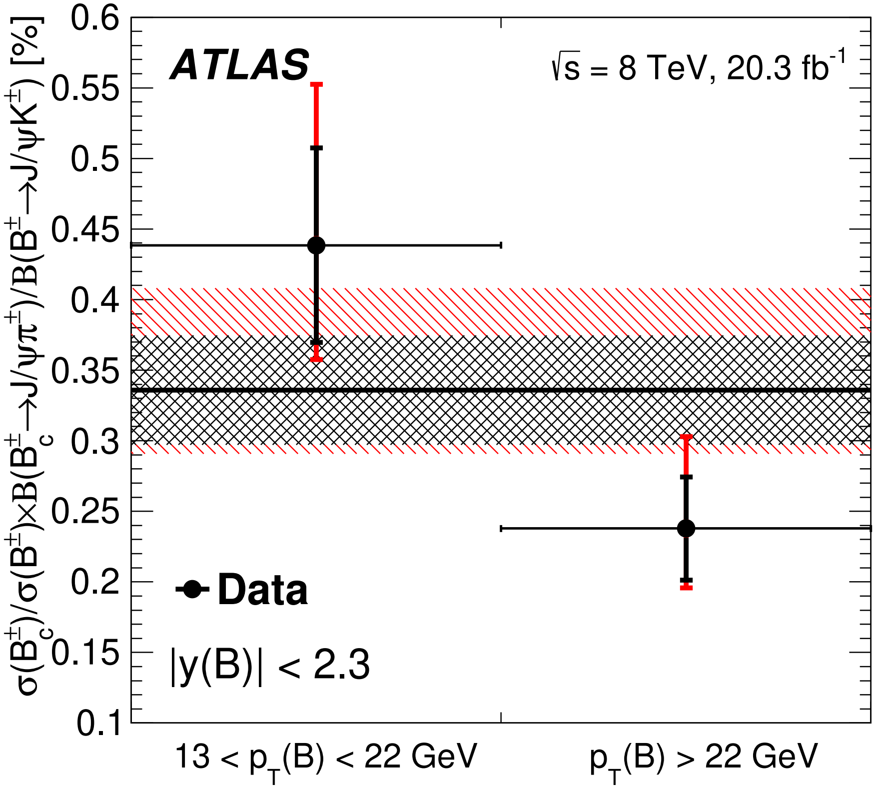
$B^{\pm}$

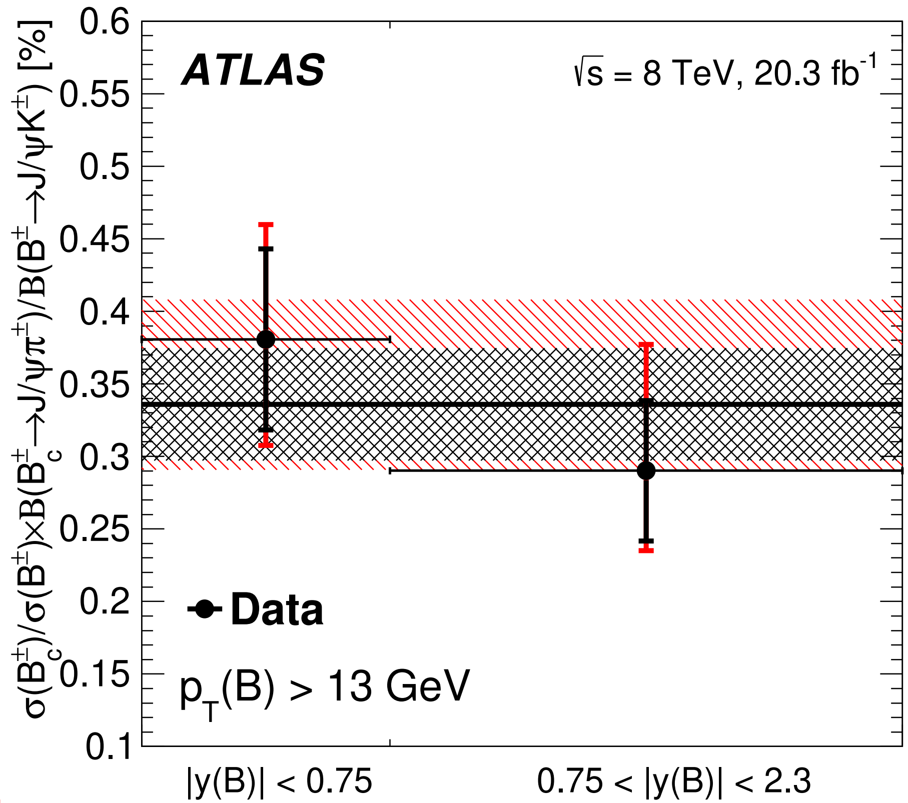


Inclusive result: For full range $p_T > 13$ GeV and $|y| < 2.3$, the production cross section ratio is $0.34 \pm 0.04(\text{stat})^{+0.06}_{-0.02}(\text{syst}) \pm 0.01(\text{lifetime})$

Differential (points) and inclusive (lines) results:

Inner error bars: statistical
Outer error bars:
stat ⊕ syst ⊕ lifetime





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 $B^{\pm}$.

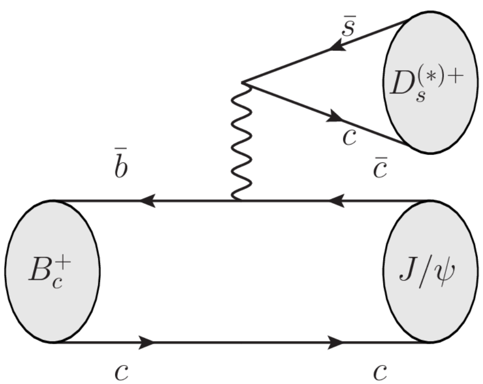
No significant dependence on rapidity is observed.

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

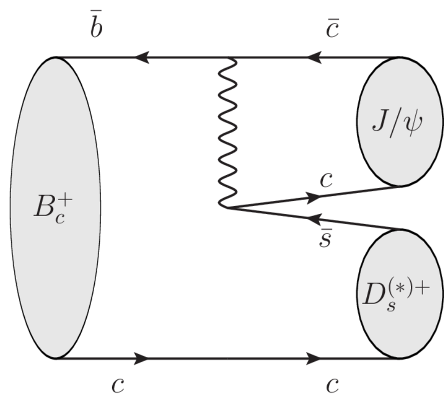
Message: Branching fractions of the decays $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ are measured relative to that of $B_c^+ \to J/\psi \pi^+$ and relative to each other.

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:

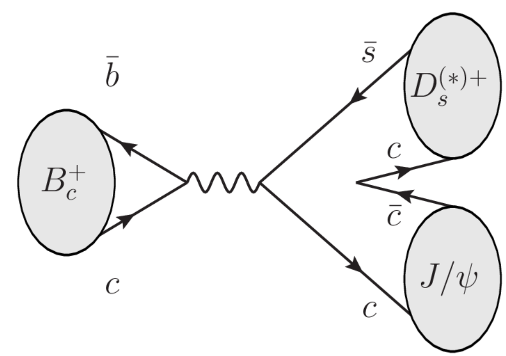
color-favored spectator:



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.

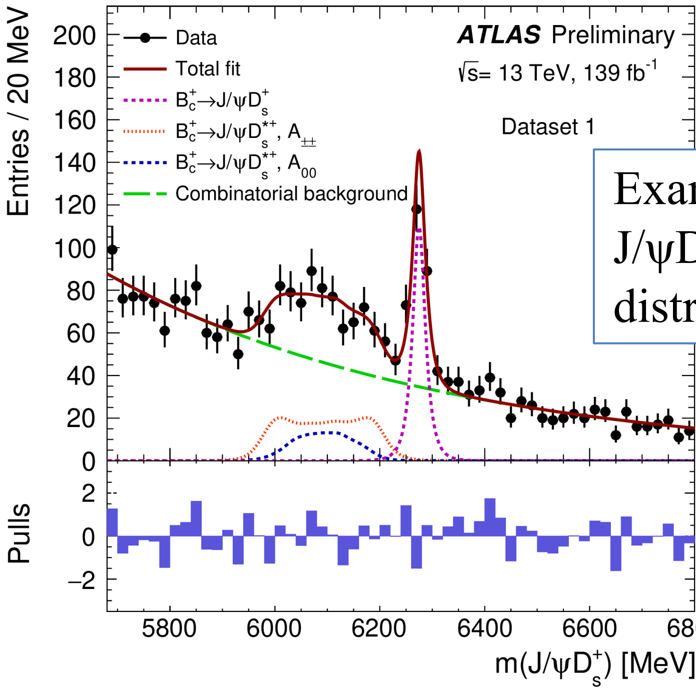
- Dataset is split to **accommodate various trigger conditions**.

- 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 $\mu^+\mu^-$.

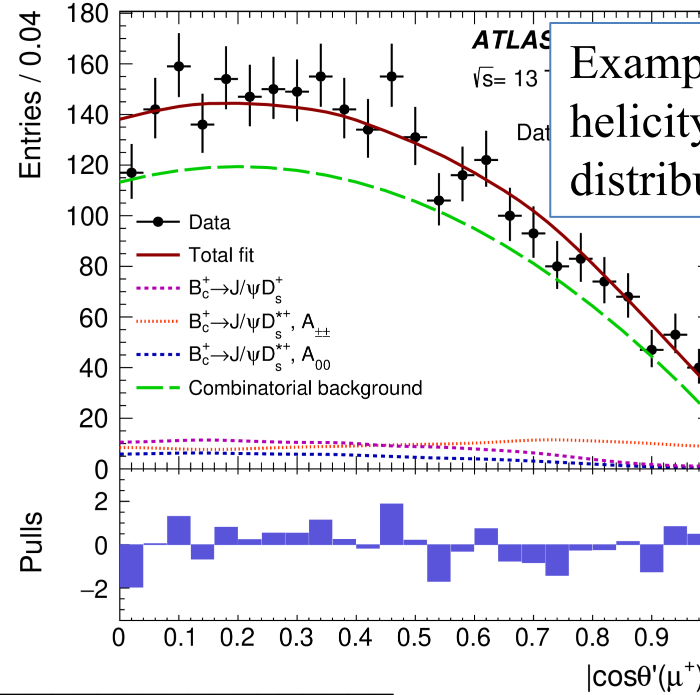
- The D_s^{*+} decays to D_s and π^0 /γ which is not reconstructed, but the mass difference between D_s^{*+} and D_s leads to **2 distinct structures** in the mass plot.

- 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.

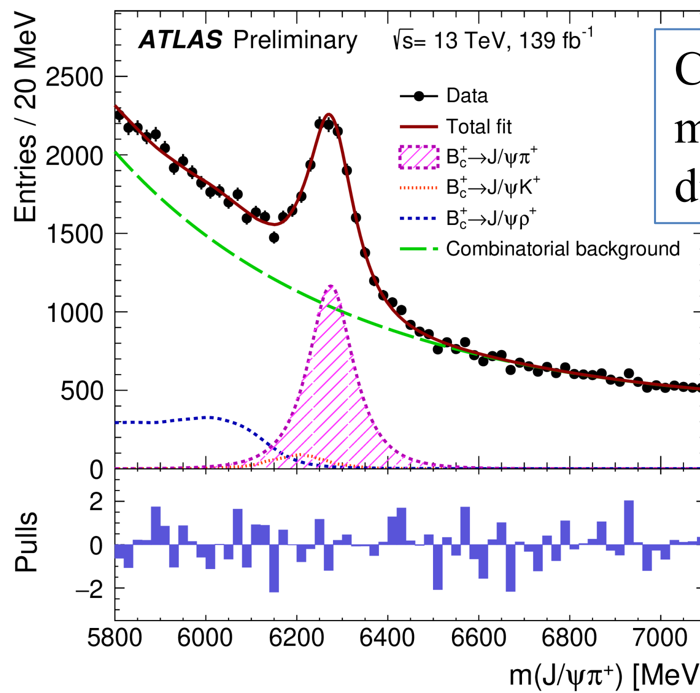


Example J/ψD$_s$ mass distribution



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:

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

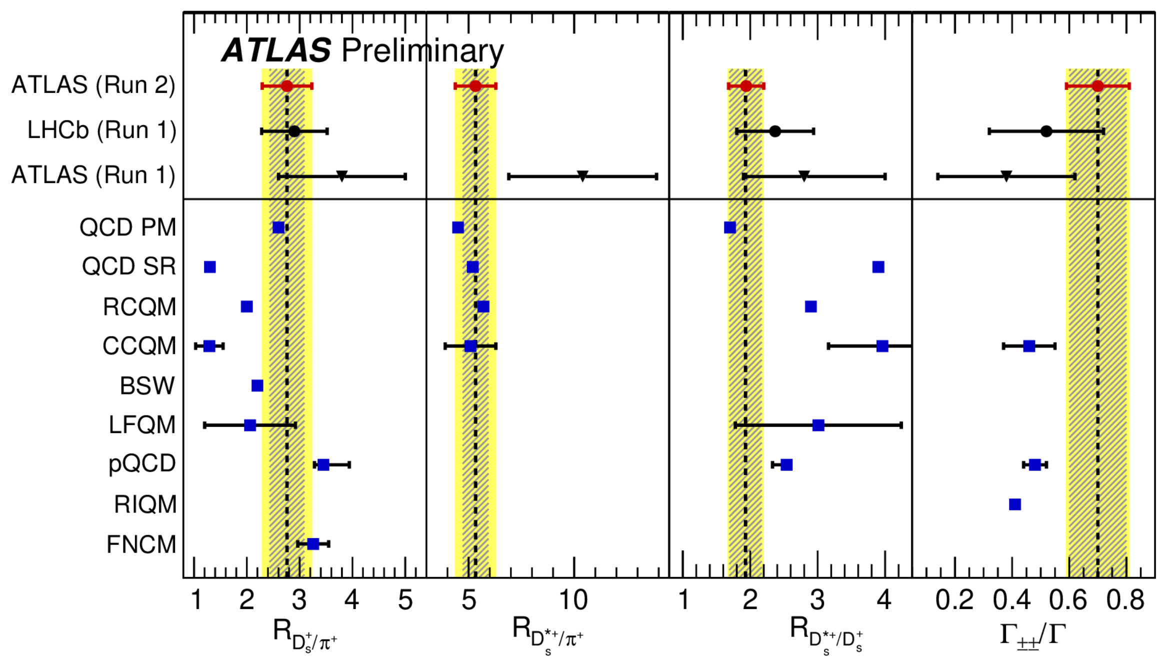
$$R_{D_s^{*+}/\pi^+} \equiv \frac{B\left(B_c^+ \to J/\psi D_s^{*+}\right)}{B\left(B_c^+ \to J/\psi \pi^+\right)} = 5.33 \pm 0.61 \pm 0.67 \pm 0.32$$

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

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 2 recent results on B_c production and decay:

- 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.*

- Study of $B_c^+ \to J/\psi D_s^{(*)+}$ 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.*