Study of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays with the ATLAS detector

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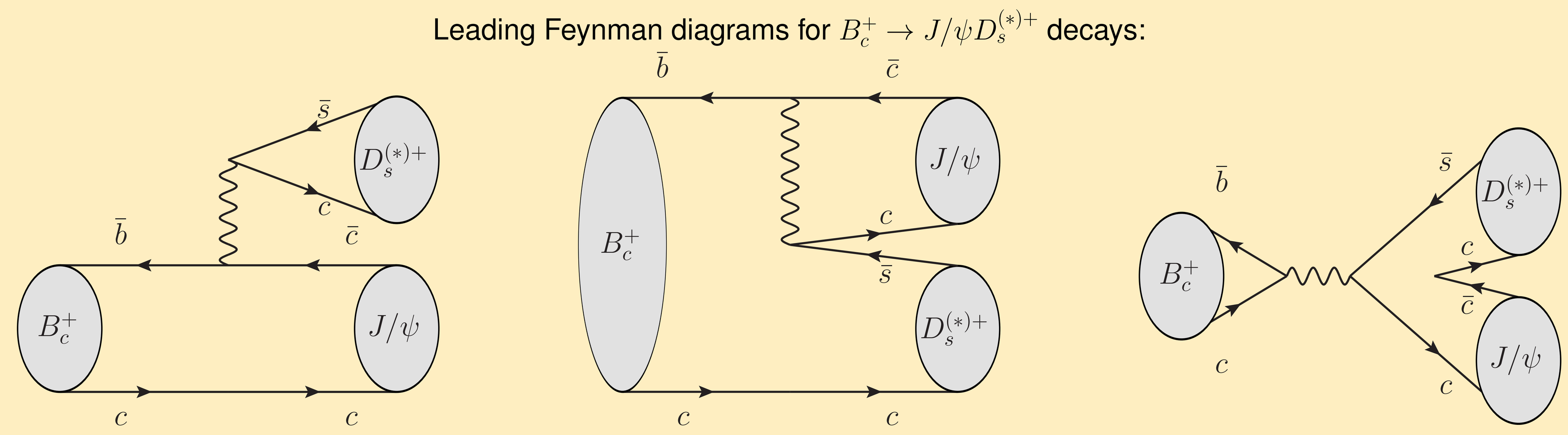
1. Introduction

The B_c^+ meson is the only known weakly decaying particle consisted of two heavy quarks. It affects theoretical calculations of its decay properties. Various model predictions are available.

Leading Feynman diagrams for $B_c^+ \to J/\psi D_s^{(*)+}$ decays:



spectator — colour-suppressed spectator — annihilation

Unlike the other B mesons, the annihilation diagram is not CKM-suppressed

Measured quantities:

- Relative branching ratios

$$\mathcal{R}_{D_s^+/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$$
$$\mathcal{R}_{D_s^{*+}/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$$
$$\mathcal{R}_{D_s^{*+}/D_s^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi D_s^+)$$

- Transverse polarisation in $B_c^+ \to J/\psi D_s^{*+}$

$$\Gamma_{\pm\pm}/\Gamma = \Gamma_{\pm\pm}(B_c^+ \to J/\psi D_s^{*+})/\Gamma(B_c^+ \to J/\psi D_s^{*+})$$

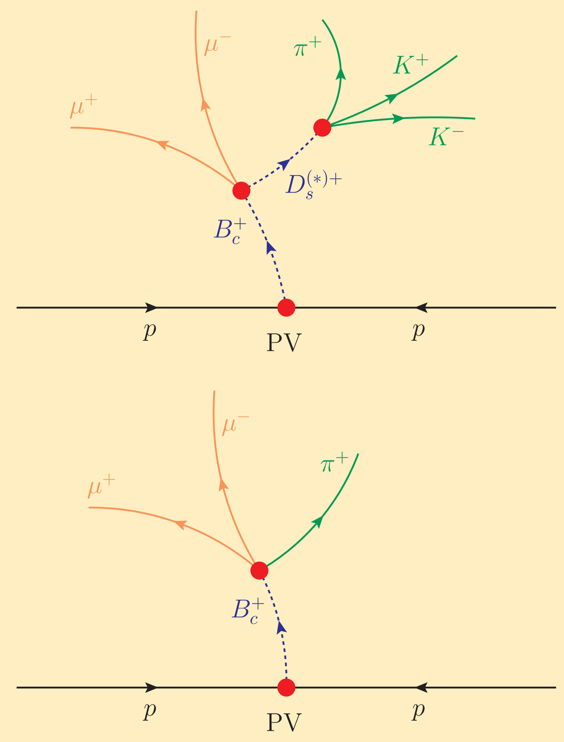
2. Reconstruction and measurement strategy

Signal modes: $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$

- Daughters are reconstructed via $J/\psi \to \mu^+\mu^-$ and $D_s^+ \to \phi\pi^+$ with $\phi \to K^+K^-$ (earlier well developed in ATLAS [1])
- 2 distinct decay vertices of B_c^+ and D_s^+ decays
- Masses of J/ψ and D_s^+ candidates are constrained in the vertex fit to their nominal values
- D_s^{*+} decays into $D_s^+\gamma$ or $D_s^+\pi^0$ with the neutral particle escaping detection, i. e. incomplete reconstruction

Reference mode: $B_c^+ \to J/\psi\pi^+$

- Observed in ATLAS earlier [2] with 2011 data
- One secondary vertex of B_c^+ decay; J/ψ candidate mass is constrained in the fit to the nominal value
- The mode provides large statistics and thus used for normalisation in the branching fractions measurement



Polarisation in $B_c^+ \to J/\psi D_s^{*+}$ decay

- Scalar B_c^+ decays into two vector particles → three possible helicity amplitudes A_{00}, A_{++}, A_{--}
- Longitudinal A_{00} and transverse $A_{\pm\pm}$ components have different kinematics: shape of $J/\psi D_s^+$ invariant mass and J/ψ helicity angle
- They can be distinguished in the fit to these variables

3. Event selection

***J/ψ* candidates**

- $p_T(\mu) > 3$ GeV, $|\eta(\mu)| < 2.3$
- Vertex $\chi^2/\mathrm{ndf} < 15$
- $2.8\ \mathrm{MeV} < m(\mu^+\mu^-) < 3.4\ \mathrm{MeV}$

D_s^+ candidates

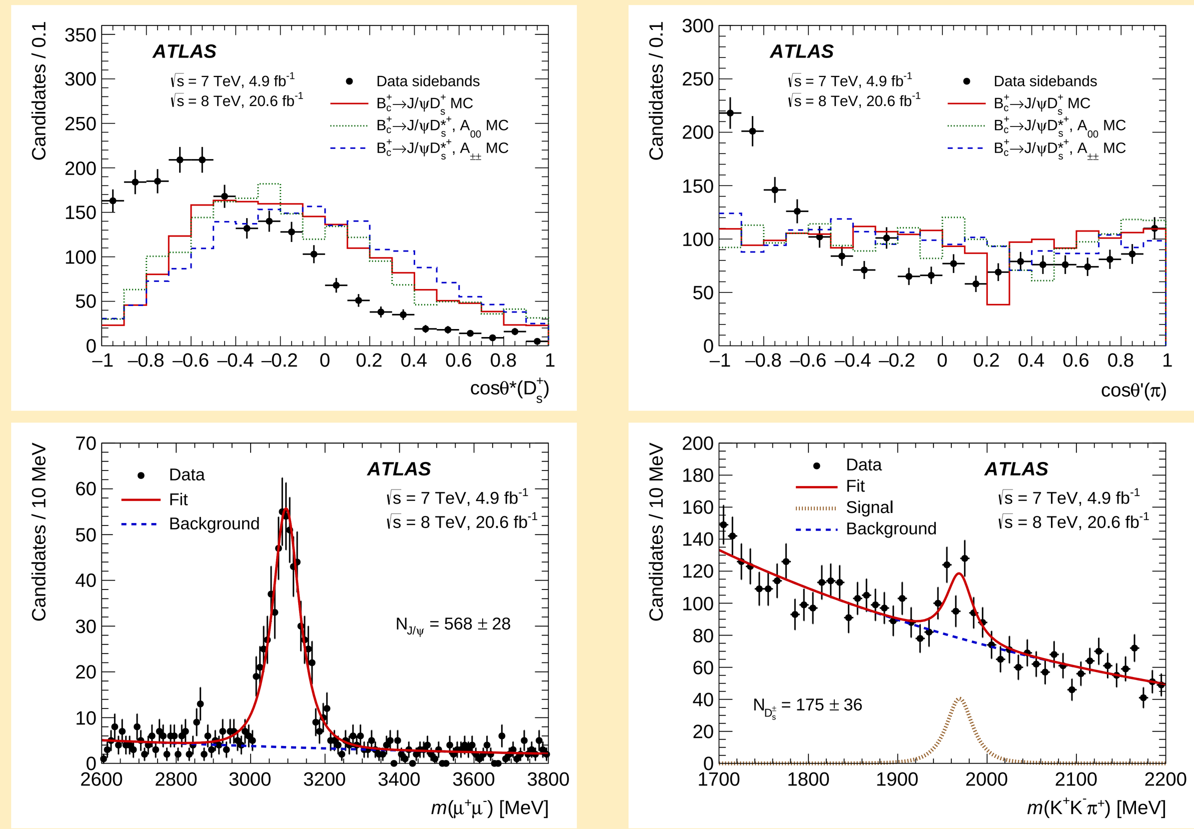
- $p_T(\mathrm{trk}) > 1$ GeV, $|\eta(\mathrm{trk})| < 2.5$
- Vertex $\chi^2/\mathrm{ndf} < 8$
- $m(\phi)$ in ± 7 MeV around nominal ϕ mass
- $\cos\theta^*(\pi) < 0.8$, $\theta^*(\pi) = \angle\left(\vec{p}_{D_s^+\ \mathrm{frame}}(\pi), \vec{p}_{\mathrm{lab.\ frame}}(D_s^+)\right)$
- $|\cos^3\theta'(K)| > 0.15$, $\theta'(K) = \angle\left(\vec{p}_{\phi\ \mathrm{frame}}(K), \vec{p}_{\phi\ \mathrm{frame}}(\pi^+)\right)$
- $1.93\ \mathrm{GeV} < m(K^+K^-\pi^+) < 2.01\ \mathrm{GeV}$

B_c^+ candidates

- $p_T(B_c^+) > 15$ GeV, $|\eta(B_c^+)| < 2.1$
- $d_0^{\mathrm{PV}} < 0.1$ mm, $z_0^{\mathrm{PV}}\sin\theta < 0.5$ mm
- Vertex $\chi^2/\mathrm{ndf} < 3$
- $L_{xy}(B_c^+) > 0.1$ mm, $L_{xy}(D_s^+) > 0.15$ mm
- Exclude $5.34\ \mathrm{GeV} < m(J/\psi\phi) < 5.40\ \mathrm{GeV}$ to suppress $B_s^0 \to J/\psi\phi$
- $\cos\theta^*(D_s^+) < 0.8$, $\theta^*(D_s^+) = \angle\left(\vec{p}_{B_c^+\ \mathrm{frame}}(D_s^+), \vec{p}_{\mathrm{lab.\ frame}}(B_c^+)\right)$
- $\cos\theta'(\pi) < 0.8$, $\theta'(\pi) = \angle\left(\vec{p}_{D_s^+\ \mathrm{frame}}(J/\psi), \vec{p}_{D_s^+\ \mathrm{frame}}(\pi^+)\right)$
- $p_T(B_c^+)/\sum p_T(\mathrm{trk}) > 0.1$ (sum over tracks from the same PV)

Full Run 1 dataset is used: **4.9 fb^{-1} @ 7 TeV + 20.6 fb^{-1} @ 8 TeV**

Trigger selection based on single-muon, di-muon and three-muon signatures



Mass spectra of J/ψ and D_s^+ candidates are shown for the vertex fit without mass constraints

6. Systematics

Systematics is dominated by uncertainties of signal extraction procedure, both for $B_c^+ \to J/\psi D_s^{(*)+}$ and $B_c^+ \to J/\psi\pi^+$ modes.

- Ratios $\mathcal{R}$ are mostly affected by signal and background mass shape variations
- $\Gamma_{\pm\pm}/\Gamma$ uncertainty is dominated by background angular modelling uncertainty

Source	Uncertainty [%]			
	$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$
Simulated $p_T(B_c^+)$ spectrum	0.4	0.9	0.5	0.4
Simulated $\lvert\eta(B_c^+)\rvert$ spectrum	1.9	2.4	0.6	0.2
Tracking efficiency	0.5	0.5	< 0.1	< 0.1
B_c^+ lifetime	1.2	1.3	< 0.1	< 0.1
D_s^+ lifetime	0.3	0.3	< 0.1	< 0.1
$B_c^+ \to J/\psi D_s^{(*)+}$ signal extraction	4.4	10.5	10.7	17.4
$B_c^+ \to J/\psi\pi^+$ signal extraction	8.5	8.5	–	–
D_s^{*+} branching fractions	< 0.1	< 0.1	< 0.1	1.1
MC sample sizes	2.3	2.4	2.7	2.2
Total	10.3	14.2	11.0	17.6
$\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$	5.9	5.9	–	–

4. Signal fits

Unbinned extended ML fit to the invariant mass $m(J/\psi D_s^+)$ and cosine helicity angle $\cos\theta'(\mu^+)$ distribution. The helicity angle $\theta'(\mu^+)$ is defined as the angle between μ^+ and D_s^+ candidate momenta in the rest frame of the muon pair.

Mass part

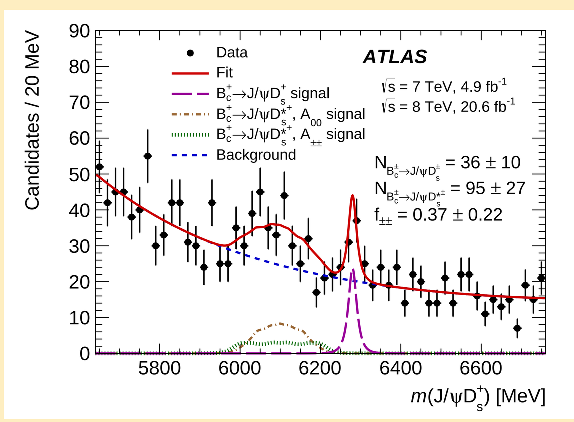
- $B_c^+ \to J/\psi D_s^+$ *signal:* modified Gaussian function

$$\mathrm{Gauss}^{\mathrm{mod}} \sim \exp\left(-\frac{x^{1+\frac{1}{1+x/2}}}{2}\right),$$

where $x = |m_0 - m|/\sigma$; width σ is fixed to MC simulation

- $B_c^+ \to J/\psi D_s^{*+}$ *signals:* sum of two templates for A_{00} and $A_{\pm\pm}$ contributions extracted from simulation with kernel estimate; fraction $f_{\pm\pm}$ is free parameter
- *Background*: two-parameter exponential function

$$\exp\left(a\cdot m + b\cdot m^2\right)$$



Statistical significance of the observed signals estimated with toy experiments is 4.9σ

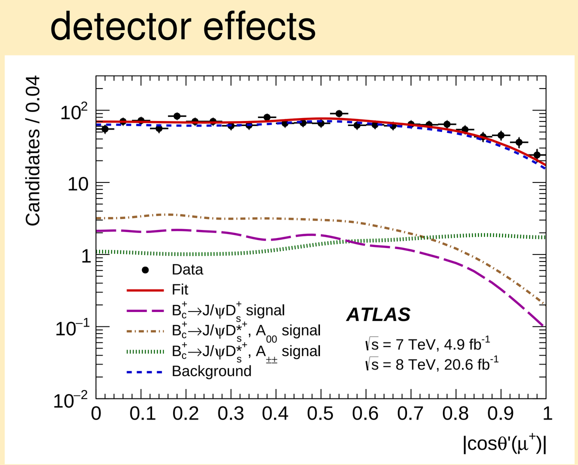
Angular part

Signals

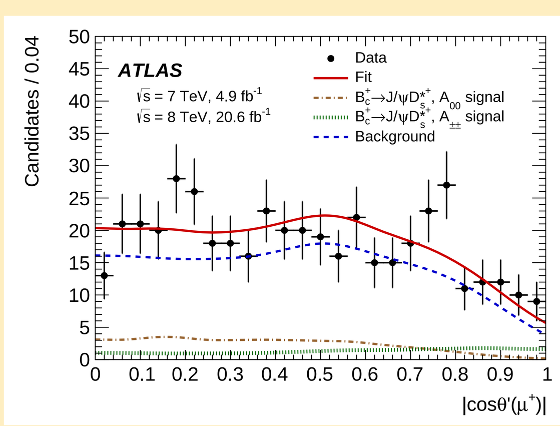
- Shapes of $\cos\theta'(\mu^+)$ can be predicted analytically:
  - $B_c^+ \to J/\psi D_s^+$: $\sim \sin^2\theta'(\mu^+)$
  - $B_c^+ \to J/\psi D_s^{*+}$, A_{00}: $\sim \sin^2\theta'(\mu^+)$
  - $B_c^+ \to J/\psi D_s^{*+}$, $A_{\pm\pm}$: $\sim (1+\cos^2\theta'(\mu^+))$
- Using kernel templates allows to account for further detector effects

Background

- Kernel templates from $J/\psi D_s^+$ mass sideband candidates are used to build the background angular PDF
- Left sideband: 5640–5900 MeV
- Right sideband: 6360–6760 MeV
- For candidates within 5770–6560 MeV – linear interpolation between two sideband templates



all candidates

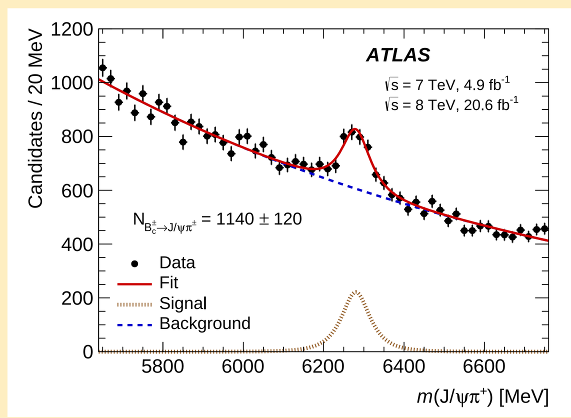


candidates with $5950\ \mathrm{MeV} < m(J/\psi D_s^+) < 6250\ \mathrm{MeV}$

5. Normalisation using reference decay

Selection of the reference decay candidates is close to that of signal for better cancellation of uncertainties

- Same J/ψ candidate selection
- Same $p_T(B_c^+)$, $|\eta(B_c^+)|$ region
- Same d_0^{PV}, $z_0^{\mathrm{PV}}\sin\theta$ cuts
- Same vertex quality cut
- $L_{xy}(B_c^+) > 0.2$ mm
- $p_T(\pi^+) > 5$ GeV, $|\eta(\pi^+)| < 2.5$
- $\cos\theta^*(\pi) > -0.8$, $\theta^*(\pi) = \angle\left(\vec{p}_{B_c^+\ \mathrm{frame}}(\pi), \vec{p}_{\mathrm{lab.\ frame}}(B_c^+)\right)$
- $|\cos\theta'(\mu^+)| > -0.8$, $\theta'(\mu^+) = \angle\left(\vec{p}_{J/\psi\ \mathrm{frame}}(\mu^+), \vec{p}_{J/\psi\ \mathrm{frame}}(\pi^+)\right)$
- Veto pion candidate tracks identified as muons to suppress $B_c^+ \to J/\psi\mu^+\nu_\mu X$



Unbinned extended ML fit to $m(J/\psi\pi^+)$ distribution

- *Signal:* modified Gaussian
- *Background:* exponential

Ratios of branching fractions:

$$\mathcal{R}_{D_s^{(*)+}/\pi^+} = \frac{1}{\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}} \times \frac{\mathcal{A}_{B_c^+\to J/\psi\pi^+}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{(*)+}}} \times \frac{N_{B_c^+\to J/\psi D_s^{(*)+}}}{N_{B_c^+\to J/\psi\pi^+}}$$

$$\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{N_{B_c^+\to J/\psi D_s^{*+}}}{N_{B_c^+\to J/\psi D_s^+}} \times \frac{\mathcal{A}_{B_c^+\to J/\psi D_s^+}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+}}}$$

- $\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$ – kaon pair mass dependent value from CLEO measurement [3]
- Acceptances $\mathcal{A}_{B_c^+\to X}$ – from MC simulation

Mode	$\mathcal{A}_{B_c^+\to X}$ [%]
$B_c^+ \to J/\psi\pi^+$	4.106 ± 0.056
$B_c^+ \to J/\psi D_s^+$	1.849 ± 0.034
$B_c^+ \to J/\psi D_s^{*+}$, A_{00}	1.829 ± 0.053
$B_c^+ \to J/\psi D_s^{*+}$, $A_{\pm\pm}$	1.712 ± 0.035

- They are different for A_{00} and $A_{\pm\pm}$ components of $B_c^+ \to J/\psi D_s^{*+}$ due to slightly different kinematics

$$\mathcal{A}_{B_c^+\to J/\psi D_s^{*+}} = \left(\frac{f_{\pm\pm}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+},A_{\pm\pm}}} + \frac{1-f_{\pm\pm}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+},A_{00}}}\right)^{-1}$$

Transverse polarisation fraction:

- $f_{\pm\pm}$ value from the fit is corrected for different acceptances of the components

$$\Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \times \frac{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{A}_{B_c^+\to J/\psi D_s^{*+},A_{\pm\pm}}}$$

7. Results

Measured ratios of branching fractions:

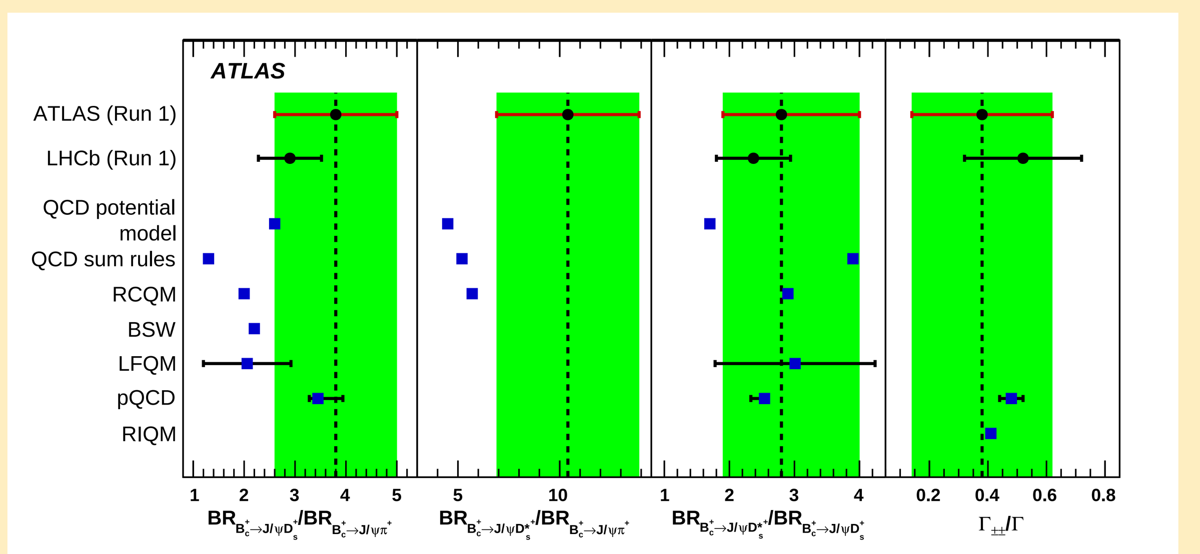
$$\mathcal{R}_{D_s^+/\pi^+} = 3.8 \pm 1.1\ (\mathrm{stat.}) \pm 0.4\ (\mathrm{syst.}) \pm 0.2\ (\mathrm{BF})$$
$$\mathcal{R}_{D_s^{*+}/\pi^+} = 10.4 \pm 3.1\ (\mathrm{stat.}) \pm 1.5\ (\mathrm{syst.}) \pm 0.6\ (\mathrm{BF})$$
$$\mathcal{R}_{D_s^{*+}/D_s^+} = 2.8^{+1.2}_{-0.8}\ (\mathrm{stat.}) \pm 0.3\ (\mathrm{syst.})$$

(BF error corresponds to the knowledge of $\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$)

Transverse polarisation fraction in $B_c^+ \to J/\psi D_s^{*+}$:

$$\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23\ (\mathrm{stat.}) \pm 0.07\ (\mathrm{syst.})$$

The results are confronted with those of LHCb measurement [4] and to expectations from various theoretical calculations.



The polarisation is found to be well described by the available theoretical approaches. The measured ratios of the branching fraction are generally well described by perturbative QCD, sum rules and relativistic quark models. However, there is an indication of underestimation of the decay rates for the $B_c^+ \to J/\psi D_s^{(*)+}$ decays by some models. The measurement results agree with those published by the LHCb experiment.

References

[1] ATLAS Collaboration, *Measurement of $D^{(*)}$ meson production cross sections in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, ATLAS-CONF-2011-017. https://cds.cern.ch/record/1336746.

[2] ATLAS Collaboration, *Observation of the $B_c^\pm$ meson in the decay $B_c^\pm \to J/\psi(\mu^+\mu^-)\pi^\pm$ with the ATLAS detector at the LHC*, ATLAS-CONF-2012-028. https://cds.cern.ch/record/1430737.

[3] CLEO Collaboration, *Absolute Measurement of Hadronic Branching Fractions of the D_s^+ Meson*, Phys. Rev. Let**100** (2008) 161804, arXiv:0801.0680 [hep-ex].

[4] LHCb Collaboration, *Observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays*, Phys. Rev. **D 87** (2013) 112012, arXiv:1304.4530 [hep-ex].