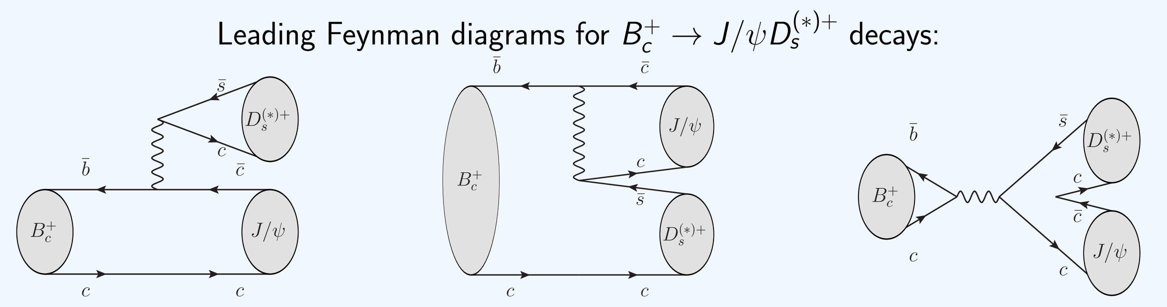
Study of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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

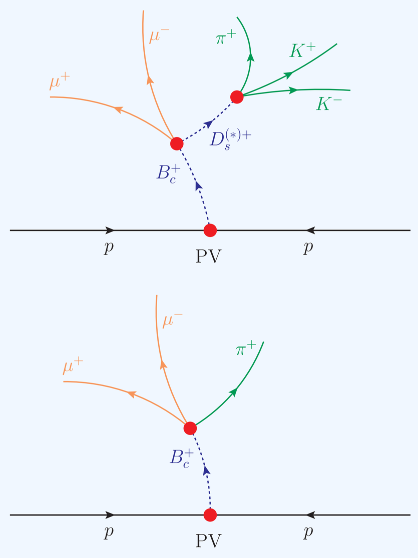
$$\mathcal{R}_{D_s^+/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$$
$$\mathcal{R}_{D_s^{*+}/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$$
$$\mathcal{R}_{D_s^{*+}/D_s^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+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

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

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 $\phi \to K^+K^-$
- 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: $B_c^+ \to J/\psi\pi^+$

- 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

Preselection

J/ψ candidates

The J/ψ candidates are built from pairs of oppositely charged muon candidates that are reconstructed using information from the MS and the ID. Muon candidates must satisfy the *Loose* identification working point

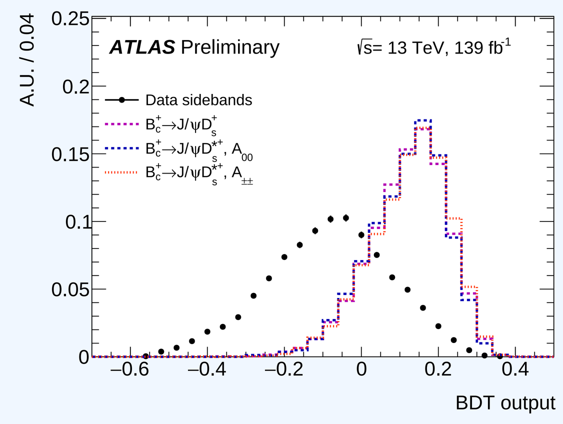
D_s^+ candidates

- $p_T(\mathrm{trk}) > 1$ GeV, $|\eta(\mathrm{trk})| < 2.5$
- $L_{xy}(D_s^+) > 0$ mm (w.r.t the B_c^+ vertex)
- $m(\phi)$ in $\pm$7MeV around nominal ϕ mass
- 1.93GeV $< m(K^+K^-\pi^+) <$ 2.01GeV

B_c^+ candidates

- $p_T(B_c^+) > 15$ GeV, $|\eta(B_c^+)| < 2.1$
- $|d_0^{PV}(B_c^+)/\sigma_{d_0^{PV}}(B_c^+)| < 5$ and $|z_0^{PV}(B_c^+)/\sigma_{z_0^{PV}}(B_c^+)| < 5$ w.r.t the PV
- Vertex χ^2/n.d.f. < 2, n.d.f. $= 8$
- $L_{xy}(B_c^+) > 0.3$ mm, $L_{xy}(B_c^+) < 10$ mm
- Exclude 5.34GeV $< m(J/\psi\phi) <$ 5.40GeV to suppress $B_s^0 \to J/\psi\phi$

To further suppress the combinatorial background, a multivariate classifier based on boosted decision trees (BDT) as implemented in the TMVA framework is employed.



BDT input variables

- $p_T(D_s^+)$, $L_{xy}(D_s^+)$
- $\cos\theta^*(\pi^+)$, $|\cos^3\theta'(K^+)|$ (for D_s^+)
- $\cos\theta^*(D_s^+)$, $\cos\theta'(\pi^+)$ (for B_c^+)

4. Signal fits

An extended unbinned maximum-likelihood fit to the two-dimensional distribution of $m(J/\psi D_s^+)$ and $\cos\theta'(\mu^+)$ is performed to extract the signal yields as well as the transverse polarization fraction in the $B_c^+ \to J/\psi D_s^{*+}$ decay. 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

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

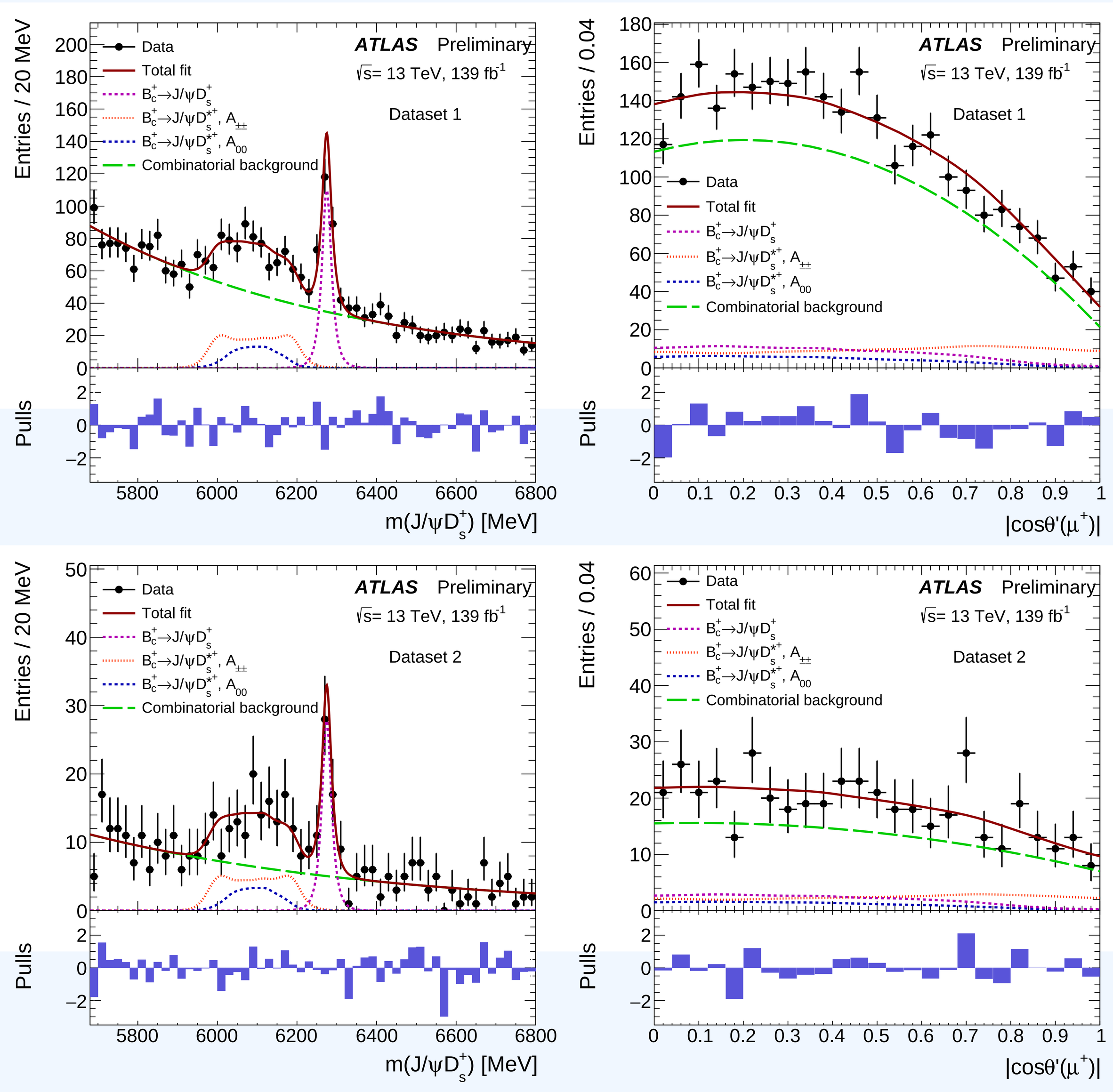
where $x = |m_0 - m|/\sigma$; width σ is fixed to MC simulation
- *$B_c^+ \to J/\psi D_s^{*+}$ signals:* sum of two templates for A_{00} and $A_{\pm\pm}$ contributions extracted from simulation with kernel estimate; fraction $f_{\pm\pm}$ is free parameter
- *Background*: exponential function

Angular part

- 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: Second-order polynomial shapes

- *Dataset 1*: candidates in the events collected by the standard dimuon or three-muon triggers – can be safely used to measure $R_{D_s^+/\pi^+}$, $R_{D_s^{*+}/\pi^+}$.
- *Dataset 2*: candidates collected only by the dedicated bBmumux_Bsmumuphi triggers – improve sensitivity to $R_{D_s^{*+}/D_s^+}$, $\Gamma_{\pm\pm}/\Gamma$.



5. Normalisation using reference decay

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

Same cuts as in $B_c^+ \to J/\psi D_s^{(*)+}$:

- J/ψ candidate selection
- $p_T(B_c^+)$, $|\eta(B_c^+)|$ region, $L_{xy}(B_c^+)$

Further cuts

- $|d_0^{PV}(B_c^+)/\sigma_{d_0^{PV}}(B_c^+)| < 3$ and $|z_0^{PV}(B_c^+)/\sigma_{z_0^{PV}}(B_c^+)| < 3$
- $\chi^2/n.d.f.(B_c^+) < 1.8$, $p_T(\pi^+) > 3.5$ GeV
- Veto π^+ candidate tracks identified as *low-p_T* muons to suppress $B_c^+ \to J/\psi\mu^+\nu_\mu X$

Ratios of branching fractions:

$$R_{D_s^{(*)+}/\pi^+} = \frac{N^{\mathrm{DS1}}_{B_c^+\to J/\psi D_s^{(*)+}}}{N_{B_c^+\to J/\psi\pi^+}} \times \frac{\epsilon_{B_c^+\to J/\psi\pi^+}}{\epsilon^{\mathrm{DS1}}_{B_c^+\to J/\psi D_s^{(*)+}}} \times \frac{1}{\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)},$$

$$R_{D_s^{*+}/D_s^+} = \frac{N^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^{*+}}}{N^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^+}} \times \frac{\epsilon^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^+}}{\epsilon^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^{*+}}} = r_{D_s^{*+}/D_s^+} \times \frac{\epsilon^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^+}}{\epsilon^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^{*+}}},$$

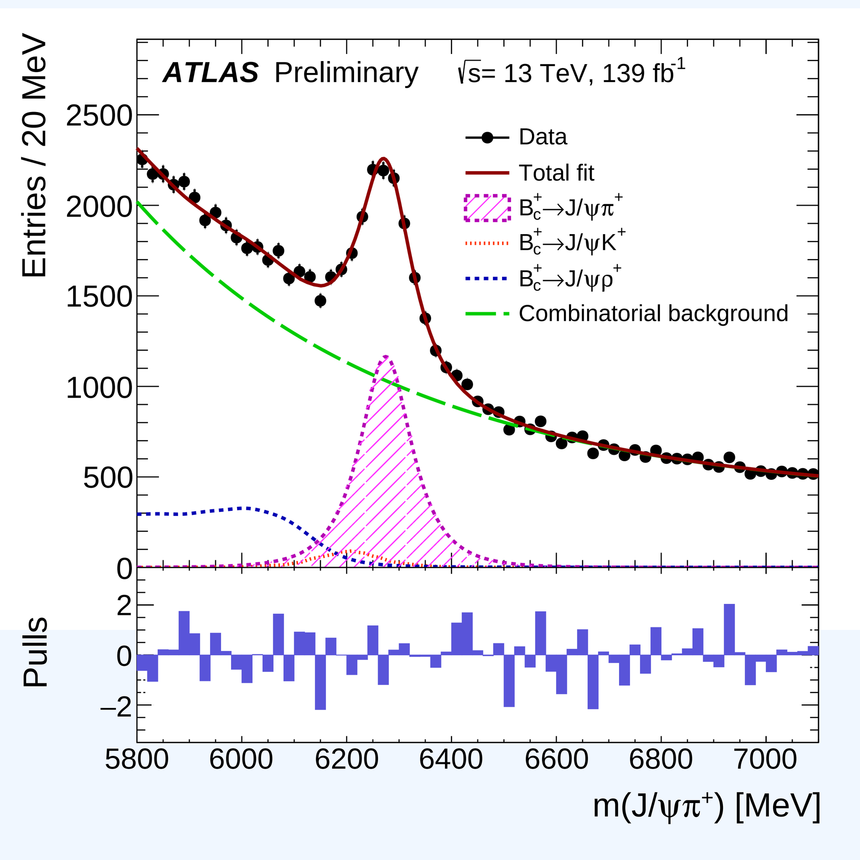
$$\Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \times \frac{\epsilon^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^{*+}}}{\epsilon^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^{*+},A_{\pm\pm}}}$$

- $\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$ – kaon pair mass dependent value from CLEO measurement [1]
- The total efficiencies – from MC simulation

Mode	$\epsilon^{\mathrm{DS1}}_{B_c^+\to J/\psi X}$ [%]	$\epsilon^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi X}$ [%]
$B_c^+ \to J/\psi D_s^+$	0.971 ± 0.012	1.163 ± 0.013
$B_c^+ \to J/\psi D_s^{*+}$, A_{00}	0.916 ± 0.012	1.088 ± 0.012
$B_c^+ \to J/\psi D_s^{*+}$, $A_{\pm\pm}$	0.868 ± 0.010	1.049 ± 0.011
$B_c^+ \to J/\psi\pi^+$	2.169 ± 0.018	–

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

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



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

- *Signal:* modified Gaussian
- *$B_c^+ \to J/\psi K^+$:* MC template (relative rate to the signal fixed to PDG*efficiency ratio)
- *PRD component:*
  - MC suggests it'd dominated by $B_c^+ \to J/\psi\rho^+$
  - It has $A_{\pm\pm}$ and A_{00} components with different mass shapes
  - Fit with a sum of two MC templates, leaving the f_{00} floating
- *Combinatorics:* 2-parameter exponential, $\exp(-a_0 m \cdot (1 + a_1 m))$

6. Systematics

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	1.5	1.9	0.4	0.1
Simulated $\lvert\eta(B_c^+)\rvert$ spectrum	0.7	0.7	0.1	0.2
B_c^+ lifetime	0.1	< 0.1	–	–
D_s^+ lifetime	0.4	0.4	–	–
Tracking efficiency	1.0	1.0	< 0.1	< 0.1
Pile-up effects	1.0	1.0	–	–
χ^2/ndf cut efficiency	3.2	3.2	–	–
Impact parameter cuts efficiency	0.2	0.2	–	–
BDT cut efficiency	1.3	1.3	–	–
Trigger efficiency	1.0	1.0	–	–
$B_c^+ \to J/\psi D_s^{(*)+}$ signal fit:				
D_s^+ signal mass modelling	1.8	0.5	1.3	0.8
D_s^{*+} signal mass modelling	0.6	1.2	1.7	2.7
signal angular modelling	0.4	< 0.1	0.4	0.6
background mass modelling	6.0	9.0	3.2	1.0
background angular modelling	0.9	1.3	2.1	2.4
$B_s^0 \to \mu^+\mu^-\phi$ triggers	0.8	0.5	1.3	4.0
$B_c^+ \to J/\psi\pi^+$ signal fit				
signal modelling	4.2	4.2	–	–
PRD/comb. background modelling	5.8	5.8	–	–
CKM-suppr. background modelling	1.0	1.0	–	–
MC statistics	1.5	1.5	1.7	1.5
Total	10.7	12.6	5.0	5.8
$\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)$	5.9	5.9	–	–

7. Results

Measured ratios of branching fractions:

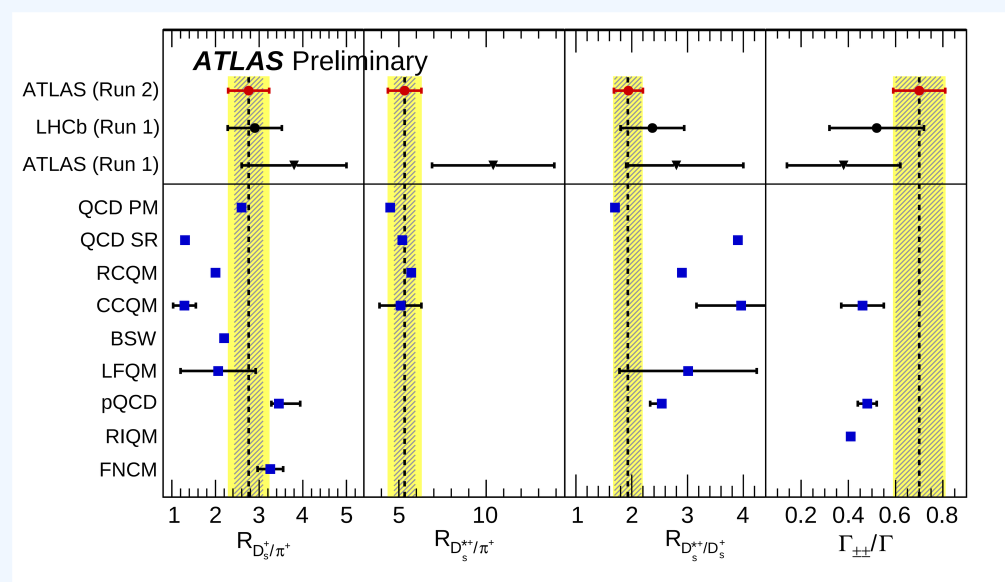
$$\mathcal{R}_{D_s^+/\pi^+} = 2.76 \pm 0.33(\mathrm{stat.}) \pm 0.29(\mathrm{syst.}) \pm 0.16(\mathrm{BF})$$
$$\mathcal{R}_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61(\mathrm{stat.}) \pm 0.67(\mathrm{syst.}) \pm 0.32(\mathrm{BF})$$
$$\mathcal{R}_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24(\mathrm{stat.}) \pm 0.1(\mathrm{syst.})$$

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

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

$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$$

The measurements of $R_{D_s^+/\pi^+}$ and $R_{D_s^{*+}/D_s^+}$ agree with ATLAS Run 1 [2] and LHCb [3] results. The obtained value of the $R_{D_s^{*+}/\pi^+}$ is smaller and $\Gamma_{\pm\pm}/\Gamma$ is larger than the ATLAS Run 1 measurement, although in both cases the difference does not exceed 1.5 standard deviations taking the Run 1 uncertainty. All the ratios of branching fractions are well described by the QCD relativistic potential model predictions [4].



References

[1] CLEO Collaboration, *Absolute Measurement of Hadronic Branching Fractions of the $D^+_{(s)}$ Meson*, Phys. Rev. Let**100** (2008) 161804, arXiv:0801.0680 [hep-ex].

[2] ATLAS Collaboration, *Study of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays with the ATLAS detector*, Eur. Phys. J. C **76** (2016) no.1, 4, arXiv:1507.07099 [hep-ex].

[3] 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].

[4] P. Colangelo and F. De Fazio, *Using heavy quark spin symmetry in semileptonic B_c decays, Phys. Rev. D* **61** *(2000), 034012, arXiv:hep-ph/9909423 [hep-ph]*.

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