

# ATLAS results on $B_c^+$ production and decays

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# Introduction

- ▶  $B_c^+$  meson family is unique in the Stand Model
  - ▶ Formed by two open heavy flavor quarks:  $\bar{b}c$
  - ▶ Ground state weakly decay only
  - ▶ Rich structures in the spectrum of  $(\bar{b}c)$  system
- ▶ Rich decay modes
  - ▶ Either  $\bar{b}$  or  $c$  quark can decay with the other as spectator
  - ▶  $\bar{b}$  and  $c$  quarks can annihilate to a  $W^+$  boson
- ▶ This talk covers a selection of ATLAS results
  - ▶ Relative  $B_c/B^+$  production measurement at 8 TeV – [Phys. Rev. D 104, 012010](#)
  - ▶ Study of the  $B_c^+ \rightarrow J/\psi D_s^+$  and  $B_c^+ \rightarrow J/\psi D_s^{*+}$  decays in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector [JHEP 08 \(2022\) 087](#)

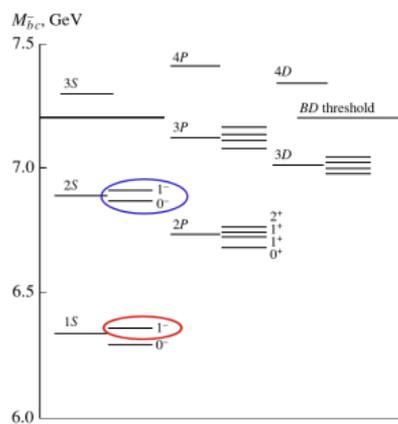


Fig. 1. The mass spectrum of  $(\bar{b}c)$  with account of the spin-dependent splittings.

Table 1. The mass spectrum of  $(\bar{b}c)$  with account of the spin-dependent splittings

| State    | Martin [8] | BT [9] | State    | Martin [8] | BT [9] |
|----------|------------|--------|----------|------------|--------|
| $1^1S_0$ | 6.253      | 6.264  | $3^1P_0$ | 7.088      | 7.108  |
| $1^1S_1$ | 6.317      | 6.337  | $3P1^+$  | 7.113      | 7.135  |
| $2^1S_0$ | 6.867      | 6.856  | $3P1'^+$ | 7.124      | 7.142  |
| $2^1S_1$ | 6.902      | 6.899  | $3^3P_2$ | 7.134      | 7.153  |
| $2^1P_0$ | 6.683      | 6.700  | $3D2^-$  | 7.001      | 7.009  |
| $2P1^+$  | 6.717      | 6.730  | $3^5D_3$ | 7.007      | 7.005  |
| $2P1'^+$ | 6.729      | 6.736  | $3^3D_1$ | 7.008      | 7.012  |
| $2^3P_2$ | 6.743      | 6.747  | $3D2'^-$ | 7.016      | 7.012  |

[Phys.Atom.Nucl. 67 \(2004\) 1559](#)

# Relative $B_c^+ / B^+$ production measurement at 8 TeV

## ► Motivation:

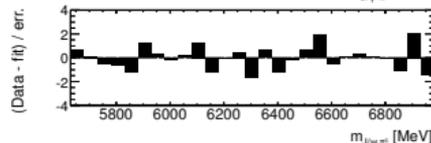
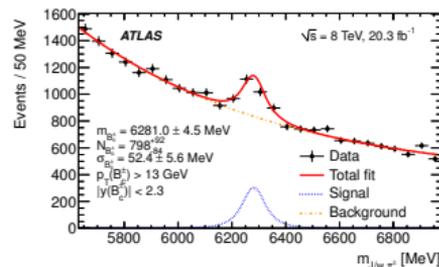
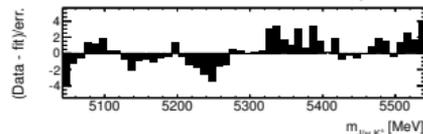
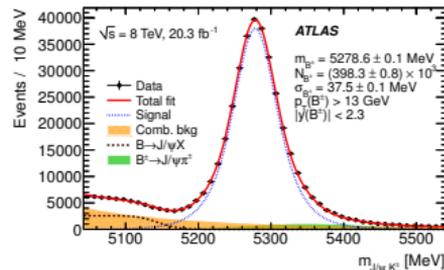
- Unique probe for heavy quark dynamics
- test of the QCD prediction;
- important input for heavy quark production models;
- complements CMS and LHCb measurements;

## ► Measure the ratio: $\frac{\sigma(B_c^+) \cdot \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}{\sigma(B^+) \cdot \mathcal{B}(B^+ \rightarrow J/\psi K^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}$

- Common systematic uncertainties mostly cancel

## ► Fiducial region of the measurement:

- $p_T(B) > 13 \text{ GeV}$ ,  $|y(B)| < 2.3$
- In addition to the full bin two bins in  $p_T$  ( $13 < p_T(B) < 22 \text{ GeV}$  and  $p_T > 22 \text{ GeV}$ ) and two bins in rapidity ( $|y| < 0.75$  and  $0.75 < |y| < 2.3$ ) were defined



# $B_c^+ / B^+$ production: results

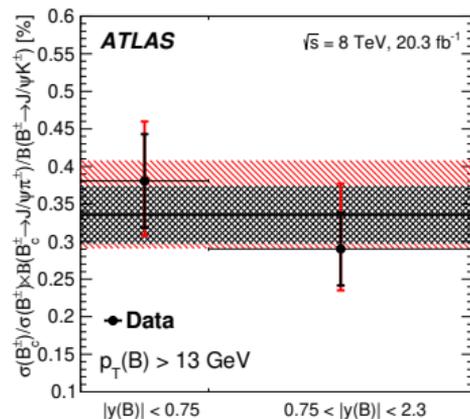
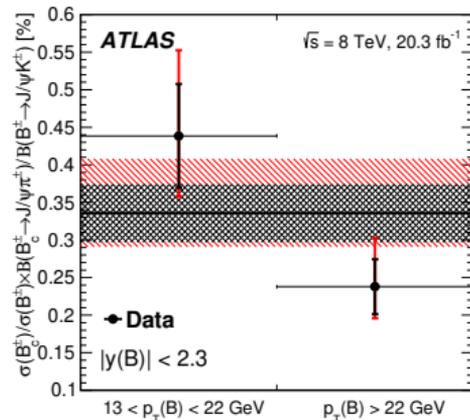
- Production ratio in the fiducial region

$$\frac{\sigma(B_c^+) \cdot \mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{\sigma(B^+) \cdot \mathcal{B}(B^+ \rightarrow J/\psi K^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)} =$$

$$(0.34 \pm 0.04(\text{stat.})_{-0.02}^{+0.06}(\text{syst.}) \pm 0.01(\text{lifetime}))\%$$

- $B_c^+$  production decreases faster with  $p_T$  than that for  $B^+$
- No evident rapidity dependence

| Analysis bin                                   | $\sigma(B_c^\pm)/\sigma(B^\pm) \times \mathcal{B}(B_c^\pm \rightarrow J/\psi\pi^\pm)/\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)$ |
|--|---|
| $p_T(B) > 13 \text{ GeV},  y(B)  < 2.3$        | $(0.34 \pm 0.04_{\text{stat}}^{+0.06} -0.02_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$  |
| $13 < p_T(B) < 22 \text{ GeV},  y(B)  < 2.3$   | $(0.44 \pm 0.07_{\text{stat}}^{+0.09} -0.04_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$  |
| $p_T(B) > 22 \text{ GeV},  y(B)  < 2.3$        | $(0.24 \pm 0.04_{\text{stat}}^{+0.05} -0.01_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$  |
| $p_T(B) > 13 \text{ GeV},  y(B)  < 0.75$       | $(0.38 \pm 0.06_{\text{stat}}^{+0.05} -0.04_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$  |
| $p_T(B) > 13 \text{ GeV}, 0.75 <  y(B)  < 2.3$ | $(0.29 \pm 0.05_{\text{stat}}^{+0.07} -0.02_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$  |



## $B_c^+ / B^+$ production: results

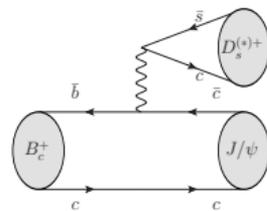
| Measurement | $p_T(B)$    | $ y(B) $  | Result [%]                                     |
|-------------|-------------|-----------|--|
| ATLAS 8 TeV | $> 13$ GeV  | $< 2.3$   | $(0.34 \pm 0.04^{+0.06}_{-0.02} \pm 0.01)$     |
| bin 1       | 13 – 22 GeV | $< 2.3$   | $(0.44 \pm 0.07 \pm_{-0.04}^{+0.09} \pm 0.01)$ |
| bin 2       | $> 22$ GeV  | $< 2.3$   | $(0.24 \pm 0.04 \pm_{-0.01}^{+0.05} \pm 0.01)$ |
| LHCb 8 TeV  | $< 20$ GeV  | 2.0 – 4.5 | $(0.683 \pm 0.018 \pm 0.009)$                  |
| CMS 7 TeV   | $> 15$ GeV  | $< 1.6$   | $(0.48 \pm 0.05 \pm 0.03 \pm 0.05)$            |

- ▶ Lower than the [LHCb result](#)  for more forward and lower- $p_T$  fiducial volume:
- ▶ Fairly consistent with the [CMS result](#)  in a similar (but not identical) fiducial volume:

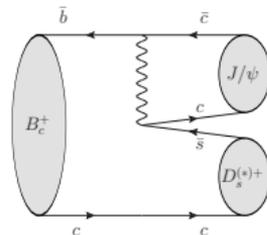
# Study of the $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays: analysis outline

- ▶  $B_c^+ \rightarrow J/\psi D_s^{(*)+}$  decays observed earlier by LHCb (PRD 87 (2013) 112012) and ATLAS (EPJC 76 (2016) 4).
- ▶ This analysis aims at more precise measurement of  $B_c^+ \rightarrow J/\psi D_s^{(*)+}$  branching fraction and polarization with full Run-2 data
  - ▶ Test various approaches predicting these (perturbative QCD calculation, relativistic potential models...)
- ▶ Decays  $B_c^+ \rightarrow J/\psi D_s^{(*)+}$  can occur through  $b$  decay with  $c$  as spectator, or through annihilation diagram
- ▶  $B_c^+ \rightarrow J/\psi(\mu^+\mu^-)D_s^+(\rightarrow \phi(\rightarrow K^+K^-)\pi^+)$
- ▶  $B_c^+ \rightarrow J/\psi(\mu^+\mu^-)D_s^{*+}(\rightarrow D_s^+\gamma/\pi^0)$ 
  - ▶ Same reconstructed final state, soft neutral particle escapes detection
  - ▶ Transition of a pseudoscalar meson into two vector states (can be described in terms of three helicity amplitudes:  $A_{++}$ ,  $A_{--}$ ,  $A_{00}$ )
- ▶ **Reference channel:**  $B_c^+ \rightarrow J/\psi\pi^+$  (use it for  $\mathcal{B}$  measurement)
- ▶ Define fiducial range of the measurement:  $p_T(B_c^+) > 15 \text{ GeV}$ ,  $|\eta(B_c^+)| < 2.0$
- ▶ Measured quantities:
  - ▶ Ratios b/w  $\mathcal{B}$  of signal channels and  $\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)$
  - ▶ Ratios b/w  $\mathcal{B}$ 's of signal channels (to cancel some of the uncertainties)
  - ▶ Transverse polarisation fraction  $\Gamma_{\pm\pm}/\Gamma$  for  $B_c^+ \rightarrow J/\psi D_s^{*+}$

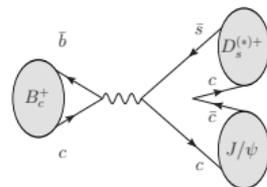
color-favored spectator:



color-suppressed spectator:

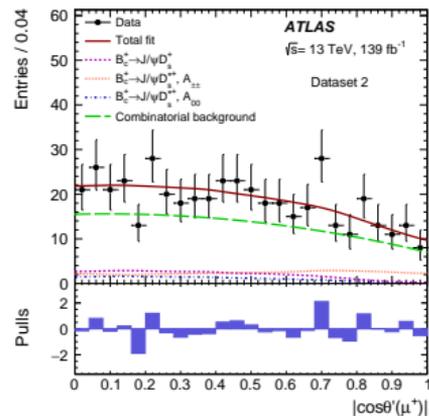
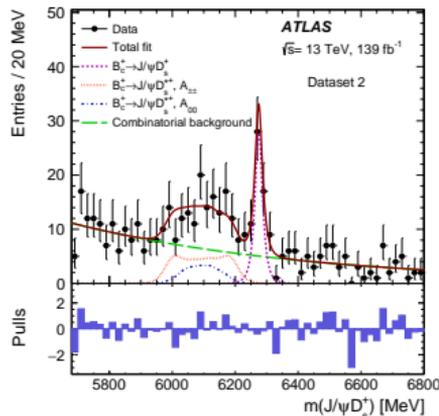
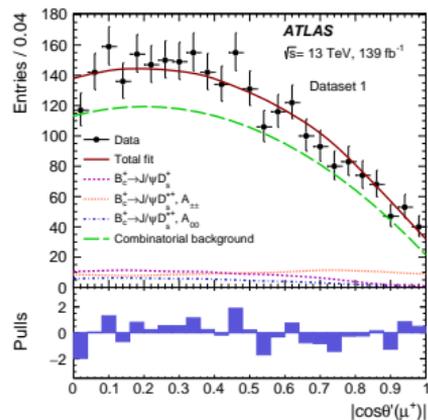
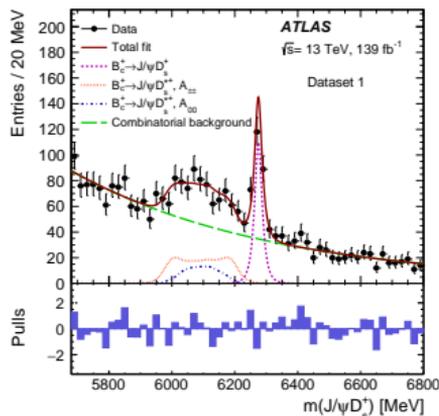


annihilation topology:



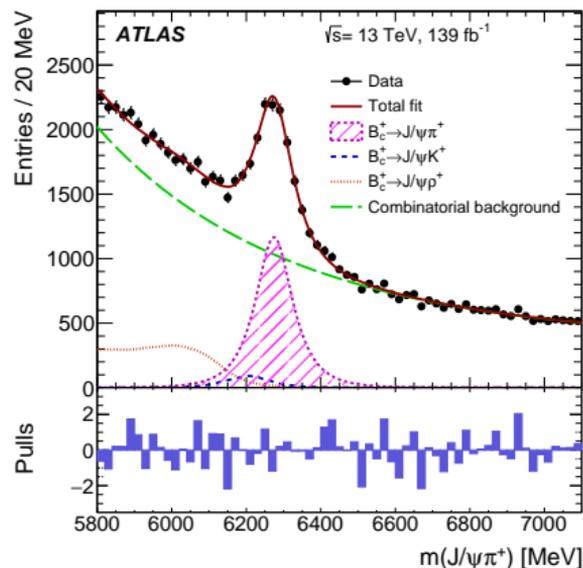
# Study of the $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays

- ▶ 2D fit to extract the signal parameters:  $m(J/\psi D_s^+)$  and the  $J/\psi$  helicity angle ( $\theta'(\mu^+)$ )
  - ▶ angle between the  $\mu^+$  and  $D_s^+$  candidate momenta in the rest frame of the muon pair
  - ▶ both sensitive to polarization
- ▶ *Dataset 1*: candidates in the events collected by the standard dimuon or three-muon triggers without requirements on additional ID track.
  - ▶ can be safely used to measure  $R_{D_s^+/\pi^+}$ ,  $R_{D_s^{*+}/\pi^+}$
- ▶ *Dataset 2*: candidates collected only by the dedicated  $B_s^0 \rightarrow \mu^+ \mu^- \phi$  triggers and not by other ones used in the analysis.
  - ▶ improve sensitivity to  $R_{D_s^{*+}/D_s^+}$ ,  $\Gamma_{\pm\pm}/\Gamma$
- ▶  $N_{B_c^+ \rightarrow J/\psi D_s^+} = 241 \pm 28$
- ▶  $N_{B_c^+ \rightarrow J/\psi D_s^{*+}} = 424 \pm 46$



# Study of the $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays: $B_c^+ \rightarrow J/\psi \pi^+$

- ▶ Selections similar to those of the signal channels
  - ▶ To suppress combinatorial background additional requirements are used
- ▶ The yield of the  $B_c^+ \rightarrow J/\psi \pi^+$  decay signal is extracted with an extended unbinned maximum-likelihood fit to the distribution of  $J/\psi \pi^+$  mass.



| Parameter                            | Value                |
|--------------------------------------|----------------------|
| $m_{B_c^+}$ [MeV]                    | $6274.5 \pm 1.5$     |
| $\sigma_{B_c^+}$ [MeV]               | $47.5 \pm 2.5$       |
| $N_{B_c^+ \rightarrow J/\psi \pi^+}$ | $8440^{+550}_{-470}$ |

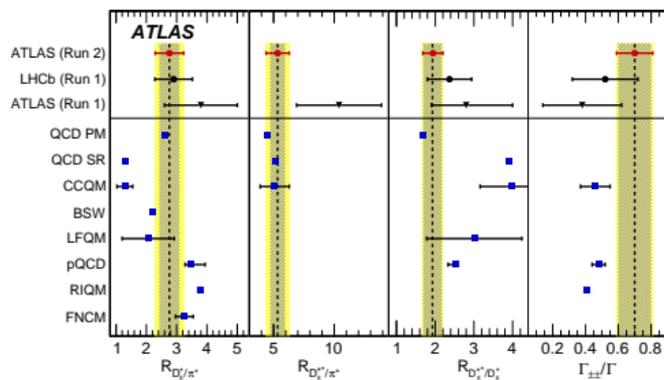
# $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ : results

$$R_{D_s^+/\pi^+} = 2.76 \pm 0.33(\text{stat.}) \pm 0.29(\text{syst.}) \pm 0.16(\text{br.f.})$$

$$R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61(\text{stat.}) \pm 0.67(\text{syst.}) \pm 0.32(\text{br.f.})$$

$$R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24(\text{stat.}) \pm 0.09(\text{syst.})$$

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



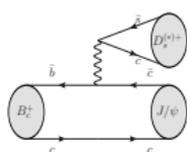
- ▶ All results are consistent with the earlier measurements of ATLAS and LHCb.
- ▶  $R_{D_s^{*+}/\pi^+}$  described well by the predictions
- ▶  $R_{D_s^+/\pi^+}$  and  $R_{D_s^{*+}/D_s^+}$  predictions consistently deviate from data – except QCD PM (PRD 61 (2000) 034012W) perfectly agreeing
- ▶  $\Gamma_{\pm\pm}/\Gamma$  agrees with naive spin-counting estimate of 2/3 and larger than the dedicated predictions
- ▶ The precision of the measurement exceeds that of all previous studies of these decays

# $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ : results

- The measured ratios of branching fractions and the transverse polarization fraction can be compared to the corresponding quantities of the other B mesons.

$$R_{D_s^+/\pi^+} \approx \frac{\Gamma(B \rightarrow \bar{D}^* D_s^+)}{\Gamma(B \rightarrow \bar{D}^* \pi^+)}$$

Assuming that the colour-favoured spectator diagram dominates the decay amplitudes

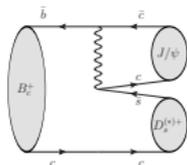


$$R_{D_s^{*+}/\pi^+} \approx \frac{\Gamma(B \rightarrow \bar{D}^* D_s^{*+})}{\Gamma(B \rightarrow \bar{D}^* \pi^+)}$$

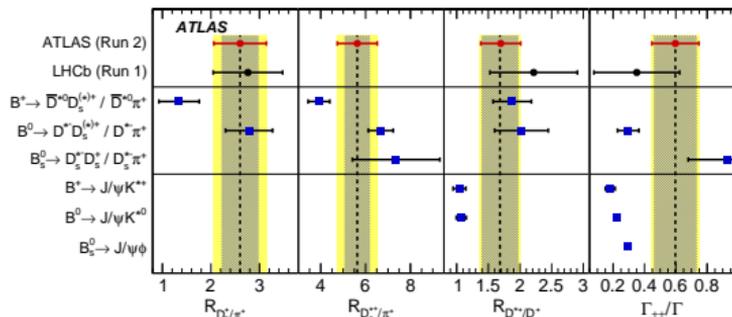
$$R_{D_s^{*+}/D_s^+} \approx \frac{\Gamma(B \rightarrow \bar{D}^* D_s^+)}{\Gamma(B \rightarrow \bar{D}^* D_s^{*+})}$$

- $B$  stands for  $B^0$ ,  $B^+$ , or  $B_s^0$  and  $\bar{D}^*$  is  $\bar{D}^{*0}$ ,  $D^{*-}$ , or  $D_s^{*-}$

Assuming that the colour-suppressed spectator diagram dominates the decay amplitudes



- $B$  stands for  $B^+$  or  $B^0$  and  $K^{(*)}$  is  $K^{(*)+}$  or  $K^{(*)0}$



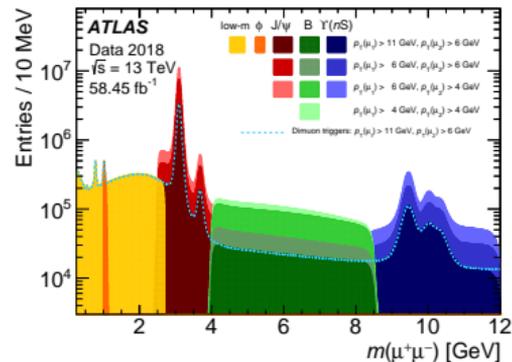
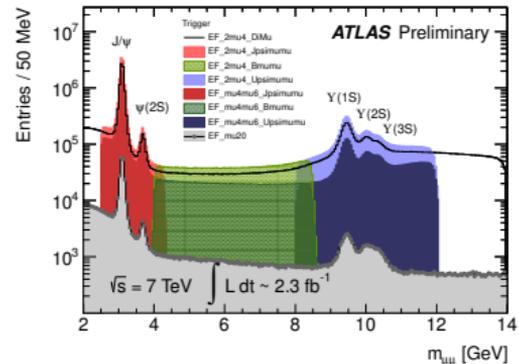
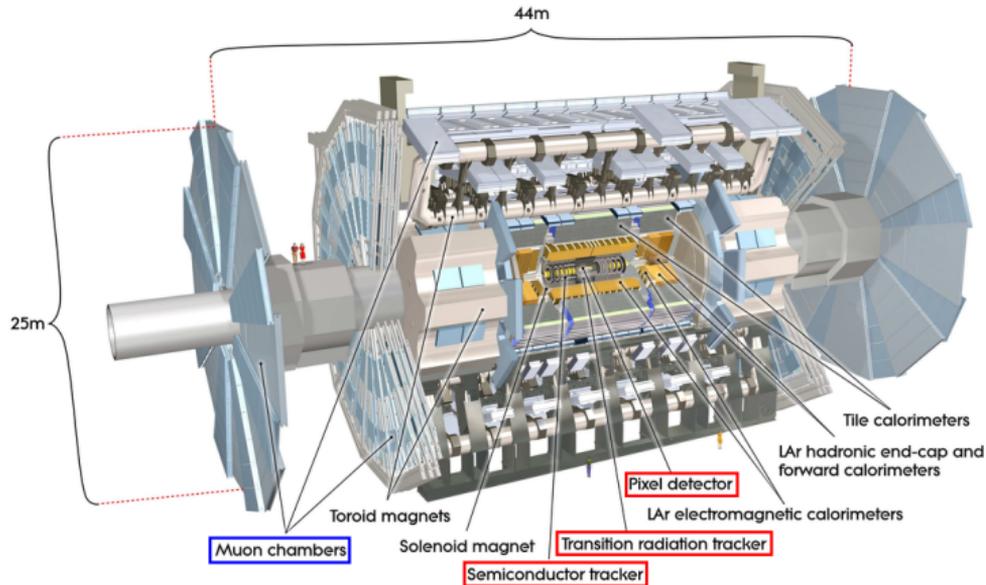
- Supports the assumption that the colour-favoured spectator diagram dominates the decay amplitudes

# Summary

- ▶ Two recent ATLAS results on  $B_c^+$  production and decay was presented:
  - ▶ Relative  $B_c/B^+$  production measurement at 8 TeV – 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  $B_c^+ \rightarrow J/\psi D_s^{(*)+}$  decays – the precision exceeds that of all previous studies of these decays.
- ▶ For  $B_c^+$  physics, Run 2 provides more than order-of-magnitude higher yields
- ▶ Lots of further possible measurements on production, decays, and spectroscopy of  $B_c^+$  mesons – **many interesting results are still to come!**

Backup slides

# ATLAS detector and trigger



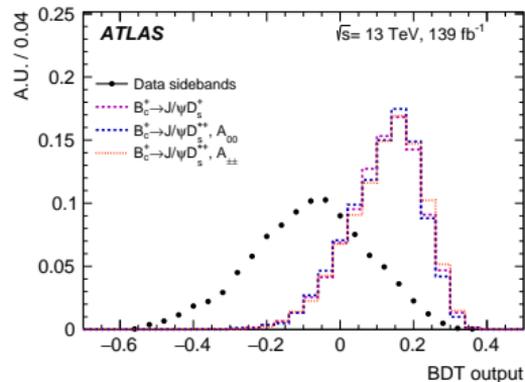
# $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ : $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ selection

## ► Preselection

- $p_T(\mu) > 4 \text{ GeV}$ ,  $|\eta(\mu)| < 2.3$ ,  $p_T(\text{trk}) > 1 \text{ GeV}$ ,  $|\eta(\text{trk})| < 2.5$
- Loose muon identification WP
- $m(K^+K^-)$  within  $\pm 7 \text{ MeV}$  around PDG
- $\chi^2/n.d.f.(B_c^+) < 2$
- $L_{xy}(B_c) > 0.3 \text{ mm}$ ,  $L_{xy}(D_s^+) > 0$
- $|d_0^{\text{PV}}(B_c^+)/\sigma_{d_0^{\text{PV}}}(B_c^+)| < 5$  and  $|z_0^{\text{PV}}(B_c^+)/\sigma_{z_0^{\text{PV}}}(B_c^+)| < 5 \text{ mm}$  w.r.t the PV
- $p_T(B_c^+)/\sum p_T(\text{trk}) > 0.1$  (sum over all tracks from the PB)
- remove  $5340 < m(J/\psi\phi) < 5400 \text{ MeV}$  range

## ► BDT

- Signal – candidates from simulated samples
- Background – sidebands of  $J/\psi D_s^+$  system mass distribution defined as the unification of [5680, 5900] MeV and [6400, 6800] MeV
- 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  $B_c^+$ )



- **Dataset 1:** candidates in the events collected by the standard dimuon or three-muon triggers without requirements on additional ID track.
  - can be safely used to measure  $R_{D_s^+/\pi^+}$ ,  $R_{D_s^{*+}/\pi^+}$
- **Dataset 2:** candidates collected only by the dedicated  $B_s^0 \rightarrow \mu^+\mu^-\phi$  triggers and not by other ones used in the analysis.
  - improve sensitivity to  $R_{D_s^{*+}/D_s^+}$ ,  $\Gamma_{\pm\pm}/\Gamma$

# $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ : fit

- ▶ 2D fit to extract the signal parameters –  $m(J/\psi D_s^+)$  and the  $J/\psi$  helicity angle

## ▶ $B_c^+ \rightarrow J/\psi D_s^+$ signal

- ▶ *mass*: modified Gaussian
- ▶  $|\cos\theta'(\mu^+)|$ : MC kernel template (same in DS1 and DS2)

## ▶ $B_c^+ \rightarrow J/\psi D_s^{*+}$ signals, separately $A_{\pm\pm}$ and $A_{00}$ components

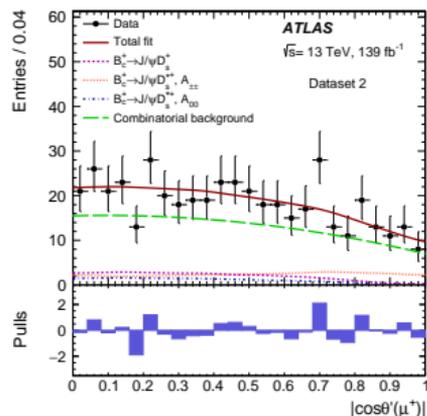
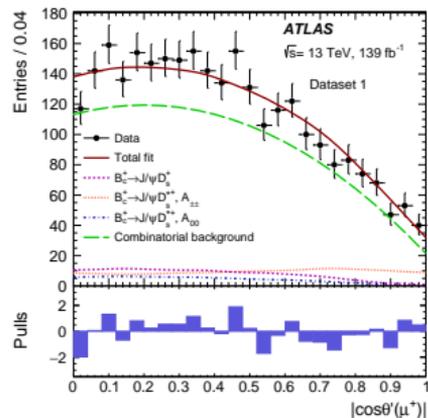
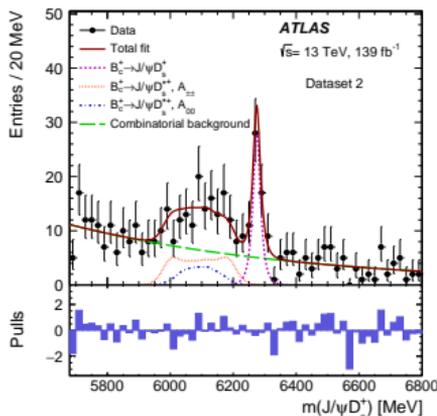
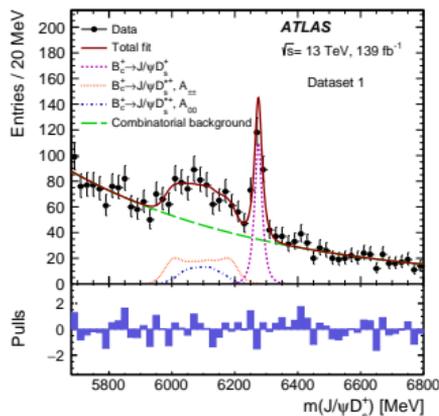
- ▶ *mass*: MC kernel templates (same in DS1 and DS2)
- ▶  $|\cos\theta'(\mu^+)|$ : MC kernel templates (same in DS1 and DS2)

## ▶ Background

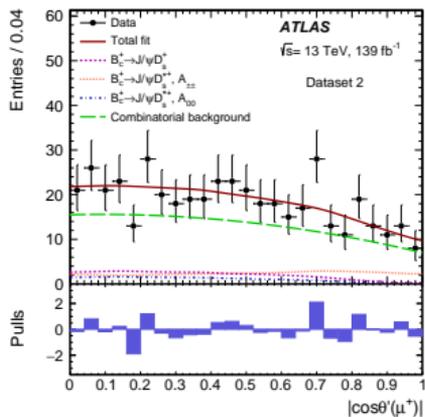
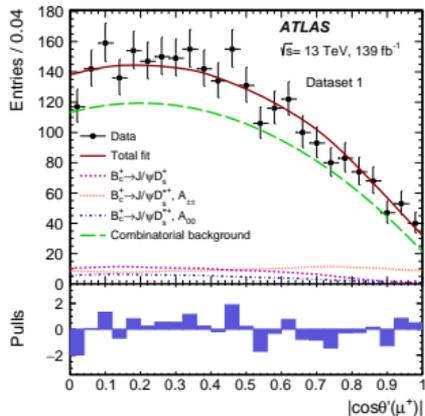
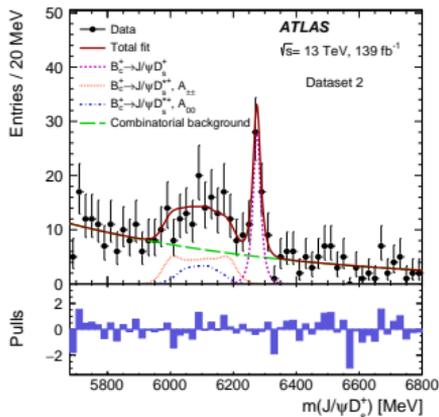
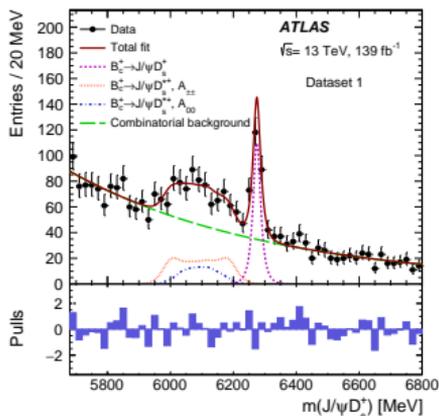
- ▶ *mass*: exponential (same slope in DS1 and DS2)
- ▶  $|\cos\theta'(\mu^+)|$ : 2nd order polynomial (same parameters in DS1 and DS2)

## ▶ Total yields

- ▶  $N_{B_c^+ \rightarrow J/\psi D_s^+} = 241 \pm 28$
- ▶  $N_{B_c^+ \rightarrow J/\psi D_s^{*+}} = 424 \pm 46$



# $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ fit result



$$G_{mod} \propto \exp\left(-0.5 \times t^1 + 1/(1 + t/2)\right)$$

where  $t = |m(J/\psi D_s^+) - m_{B_c^+}| / \sigma_{B_c^+}$

| Parameter  | Value            |
|--|------------------|
| $m_{B_c^+}$ [MeV]                                | $6274.8 \pm 1.4$ |
| $\sigma_{B_c^+}$ [MeV]                           | $11.5 \pm 1.5$   |
| $r_{D_s^{*+}/D_s^+}$                             | $1.76 \pm 0.22$  |
| $f_{\pm\pm}$                                     | $0.70 \pm 0.10$  |
| $N_{B_c^+ \rightarrow J/\psi D_s^+}^{DS1}$       | $193 \pm 20$     |
| $N_{B_c^+ \rightarrow J/\psi D_s^+}^{DS2}$       | $49 \pm 10$      |
| $N_{B_c^+ \rightarrow J/\psi D_s^{*+}}^{DS1}$    | $338 \pm 32$     |
| $N_{B_c^+ \rightarrow J/\psi D_s^{*+}}^{DS1\&2}$ | $241 \pm 28$     |
| $N_{B_c^+ \rightarrow J/\psi D_s^{*+}}^{DS1\&2}$ | $424 \pm 46$     |

# $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ : $B_c^+ \rightarrow J/\psi \pi^+$ selection and fit

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

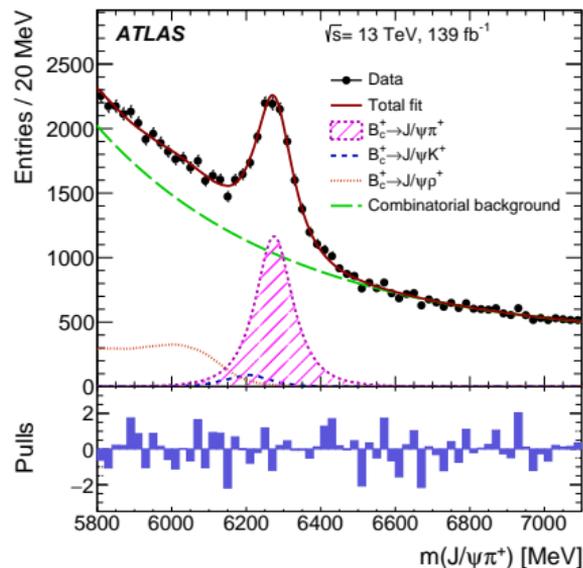
- ▶  $p_T(\mu)$ ,  $|\eta(\mu)|$ ,  $|\eta(\text{trk})|$
- ▶  $p_T(B_c^+)/\sum p_T(\text{trk})$
- ▶  $L_{xy}(B_c^+)$

## ▶ Further cuts

- ▶  $|d_0^{\text{PV}}(B_c^+)/\sigma_{d_0^{\text{PV}}}(B_c^+)| < 3$  and  $|z_0^{\text{PV}}(B_c^+)/\sigma_{z_0^{\text{PV}}}(B_c^+)| < 3$
- ▶  $\chi^2/n.d.f.(B_c^+) < 1.8$
- ▶  $p_T(\pi^+) > 3.5 \text{ GeV}$
- ▶ Veto  $\pi^+$  candidate tracks identified as *low- $p_T$*  muons

## ▶ Fit model

- ▶ Signal: **modified Gaussian**
- ▶  $B_c^+ \rightarrow J/\psi K^+$ : MC template (relative rate to the signal fixed to PDG\*efficiency ratio)
- ▶ Combinatorics: **2-parameter exponential**,  $\exp(-a_0 m \cdot (1 + a_1 m))$
- ▶ PRD component:
  - ▶ MC suggests it'd dominated by  $B_c^+ \rightarrow J/\psi \rho^+$
  - ▶ 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



| Parameter                            | Value                |
|--------------------------------------|----------------------|
| $m_{B_c^+}$ [MeV]                    | $6274.5 \pm 1.5$     |
| $\sigma_{B_c^+}$ [MeV]               | $47.5 \pm 2.5$       |
| $N_{B_c^+ \rightarrow J/\psi \pi^+}$ | $8440^{+550}_{-470}$ |

# Ratios calculation

$$R_{D_s^{(*)+}/\pi^+} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{(*)+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = \frac{N_{B_c^+ \rightarrow J/\psi D_s^{(*)+}}^{\text{DS1}}}{N_{B_c^+ \rightarrow J/\psi \pi^+}} \times \frac{\epsilon_{B_c^+ \rightarrow J/\psi \pi^+}^{\text{DS1}}}{\epsilon_{B_c^+ \rightarrow J/\psi D_s^{(*)+}}^{\text{DS1}}} \times \frac{1}{\mathcal{B}(D_s^+ \rightarrow \phi(K^+ K^-)\pi^+)}, \quad (1)$$

►  $\mathcal{B}(D_s^+ \rightarrow \phi(K^+ K^-)\pi^+)$  taken as  $m(K^+ K^-)$ -dependent, using CLEO measurement, recalculated to  $\pm 7$  MeV

$$R_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)} = \frac{N_{B_c^+ \rightarrow J/\psi D_s^{*+}}^{\text{DS1\&2}}}{N_{B_c^+ \rightarrow J/\psi D_s^+}^{\text{DS1\&2}}} \times \frac{\epsilon_{B_c^+ \rightarrow J/\psi D_s^+}^{\text{DS1\&2}}}{\epsilon_{B_c^+ \rightarrow J/\psi D_s^{*+}}^{\text{DS1\&2}}} = r_{D_s^{*+}/D_s^+} \times \frac{\epsilon_{B_c^+ \rightarrow J/\psi D_s^+}^{\text{DS1\&2}}}{\epsilon_{B_c^+ \rightarrow J/\psi D_s^{*+}}^{\text{DS1\&2}}}, \quad (2)$$

$$\epsilon_{B_c^+ \rightarrow J/\psi D_s^{*+}} = \frac{1}{f_{\pm\pm}/\epsilon_{B_c^+ \rightarrow J/\psi D_s^{*+}, A_{\pm\pm}} + (1 - f_{\pm\pm})/\epsilon_{B_c^+ \rightarrow J/\psi D_s^{*+}, A_{00}}}, \quad (3)$$

$$\Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \times \frac{\epsilon_{B_c^+ \rightarrow J/\psi D_s^+}^{\text{DS1\&2}}}{\epsilon_{B_c^+ \rightarrow J/\psi D_s^{*+}, A_{\pm\pm}}^{\text{DS1\&2}}}. \quad (4)$$

| Mode  | $\epsilon_{B_c^+ \rightarrow J/\psi X}^{\text{DS1}}$ [%] | $\epsilon_{B_c^+ \rightarrow J/\psi X}^{\text{DS1\&2}}$ [%] |
|---|--|---|
| $B_c^+ \rightarrow J/\psi D_s^+$                | $0.971 \pm 0.012$  | $1.163 \pm 0.013$   |
| $B_c^+ \rightarrow J/\psi D_s^{*+}, A_{00}$     | $0.916 \pm 0.012$  | $1.088 \pm 0.012$   |
| $B_c^+ \rightarrow J/\psi D_s^{*+}, A_{\pm\pm}$ | $0.868 \pm 0.010$  | $1.049 \pm 0.011$   |
| $B_c^+ \rightarrow J/\psi \pi^+$                | $2.169 \pm 0.018$  | -   |

# $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ : 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 $ \eta(B_c^+) $ 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               | –                 | –                        |
| $\chi^2/N_{\text{dof}}$ cut efficiency             | 3.2               | 3.2               | –                 | –                        |
| Impact parameter cuts efficiency                   | 0.2               | 0.2               | –                 | –                        |
| BDT cut efficiency                                 | 1.3               | 1.3               | –                 | –                        |
| Trigger efficiency                                 | 0.6               | 0.6               | –                 | –                        |
| Other $D_s^+$ decay modes                          | 1.6               | 1.6               | –                 | –                        |
| $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ 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                      |
| $B_s^0 \rightarrow \mu^+ \mu^- \phi$ triggers      | 0.8               | 0.5               | 1.3               | 4.0                      |
| $D_s^{*+}$ branching fractions                     | < 0.1             | < 0.1             | < 0.1             | 0.7                      |
| $B_c^+ \rightarrow J/\psi \pi^+$ 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  | 10.8              | 12.6              | 5.0               | 5.9                      |
| $\mathcal{B}(D_s^+ \rightarrow \phi(K^+K^-)\pi^+)$ | 5.9               | 5.9               | –                 | –                        |