ATLAS results on charmonium production and B_c^+ production and decays

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EPS-HEP Conference 2021
26-30 July 2021

Introduction

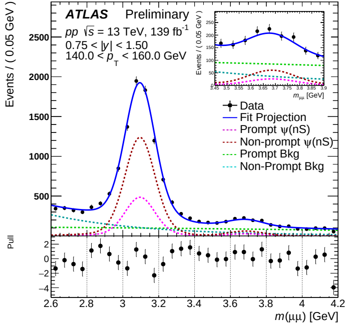
B-physics at ATLAS

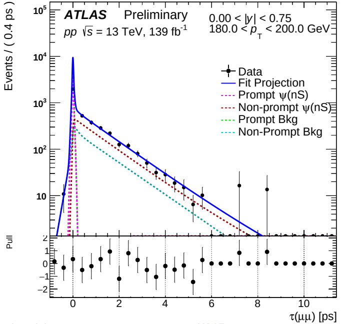
- Possible to measure heavy flavour (HF) production at *high energy*
- Much *higher HF yields* in pp environment compared to B-factories
- Extended spectroscopy studies are possible
- ATLAS and CMS, although not specially optimized for B-physics, provide *complementary kinematic region to LHCb*
  - Benefit from *higher statistics* in certain analyses

- This talk covers a selection of ATLAS results
  - High-p_{T} J/ψ and $\psi(2S)$ production at 13 TeV ATLAS-CONF-2019-047
  - Relative B_c/B^+ production measurement at 8 TeV – Phys. Rev. D 104, 012010
  - Study of the $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector ATLAS-CONF-2021-046

High-p_T J/ψ and $\psi(2S)$ production measurement

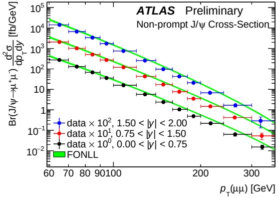
- Two different mechanisms for charmonium production:
  - *Prompt*: directly in *pp* interaction or via feed-down from heavier states
  - *Non-prompt*: from decays of *b* hadrons
    - Can be distinguished by fitting the pseudo proper lifetime
  - FONLL calculations within the framework of perturbative QCD have been reasonably successful in describing the non-prompt contributions
  - Satisfactory understanding of the prompt production mechanisms is still to be achieved
- Previous ATLAS measurement: J/ψ and $\psi(2S)$ differential x-sections at 7, 8 TeV– Eur. Phys. J. C 76 (2016) 283
  - Overall reasonable agreement with theoretical predictions for prompt and non-prompt production
  - Di-muon triggers with low thresholds – could not reach beyond p_T of $\sim$ 100 GeV
- New measurement focuses on high-p_T charmonia
  - Help to discriminate various theoretical models
  - Use *single-muon* triggers (50 GeV muon p_T thershold) to cover the range 60 – 360 GeV
  - Full Run-2 dataset, 139 fb^{-1} at 13 TeV

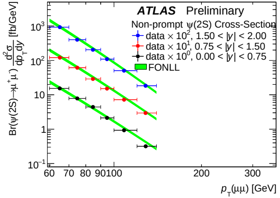


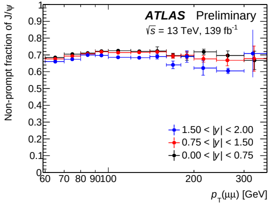


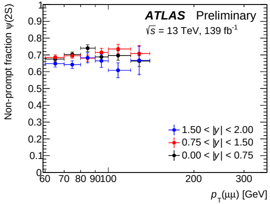
High-p_T J/ψ and $\psi(2S)$ measurement

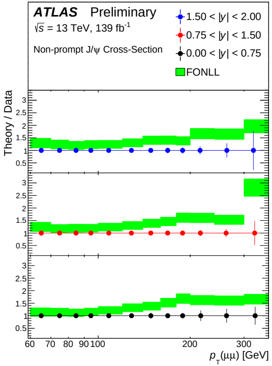
- Measured are
  - Prompt and non-prompt J/ψ and $\psi(2S)$ double-differential x-sections
  - Non-prompt fraction for J/ψ and $\psi(2S)$
  - $\psi(2S)/J/\psi$ production ratio for prompt and non-prompt

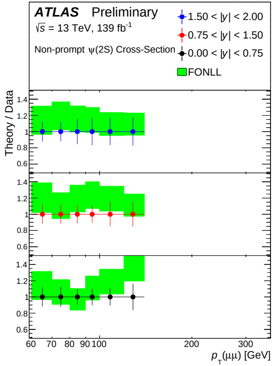


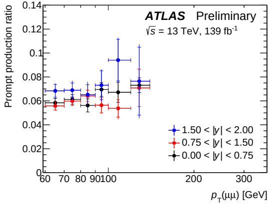


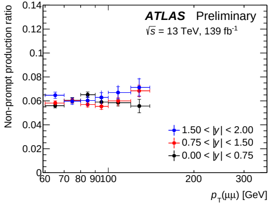








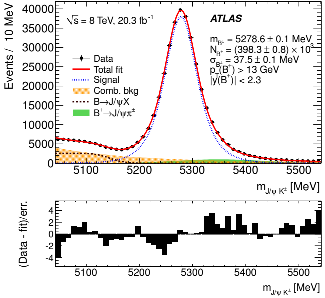


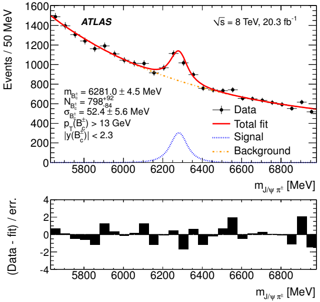


- p_T ranges extend significantly
- FONLL consistent at low-p_T, over-estimates high-p_T production

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

- B_c^+ is the only known weakly decaying particle made of two heavy quarks
- Motivation:
  - test of the QCD prediction;
  - important input for heavy quark production models;
  - complements CMS and LHCb measurements;
- Measure the ratio: $\frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)}$
  - Common systematic uncertainties mostly cancel
- Fiducial region of the measurement:
  - $p_{\mathrm{T}}(B) > 13\,\mathrm{GeV}$, $|y(B)| < 2.3$
  - In addition to the full bin two bins in p_{T} ($13 < p_{\mathrm{T}}(B) < 22\,\mathrm{GeV}$ and $p_{\mathrm{T}} > 22\mathrm{GeV}$) and two bins in rapidity ($|y| < 0.75$ and $0.75 < |y| < 2.3$) were defined





B_c^+/B^+ production: results

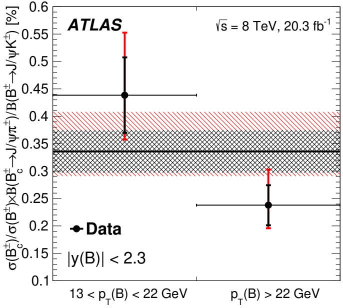
- Production ratio in the fiducial region

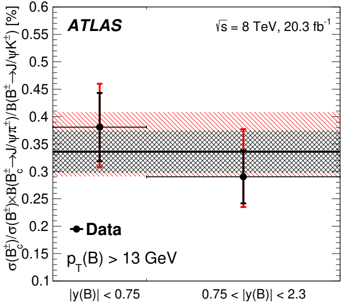
$$\frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)} =$$

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

  - Lower than the LHCb result for more forward and lower-p_T fiducial volume: $(0.683 \pm 0.018 \pm 0.009)\%$, $0 < p_T(B) < 20\,\text{GeV}$, $2 < y(B) < 4.5$
  - Fairly consistent with the CMS result in a similar (but not identical) fiducial volume: $(0.48 \pm 0.05(\text{stat.}) \pm 0.03(\text{syst.}) \pm 0.05(\text{lifetime}))\%$ at $\sqrt{s} = 7$ TeV, $p_T(B) > 15\,\text{GeV}$, $|y(B)| < 1.6$
- B_c^+ production decreases faster with p_T than that for B^+
- No evident rapidity dependence

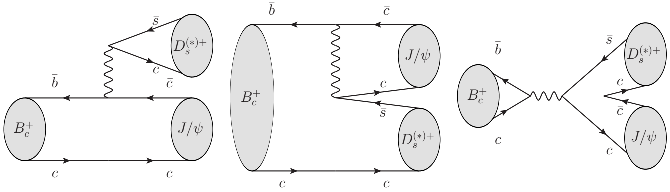
Analysis bin	$\sigma(B_c^\pm)/\sigma(B^\pm)\times\mathcal{B}(B_c^\pm\to J/\psi\pi^\pm)/\mathcal{B}(B^\pm\to J/\psi K^\pm)$
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$	$(0.34 \pm 0.04_{\text{stat}}\,{}^{+0.06}_{-0.02}{}_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$
$13 < p_T(B) < 22$ GeV, $\lvert y(B)\rvert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





New: Study of the $B_c^+ \to J/\psi D_s^{(*)+}$

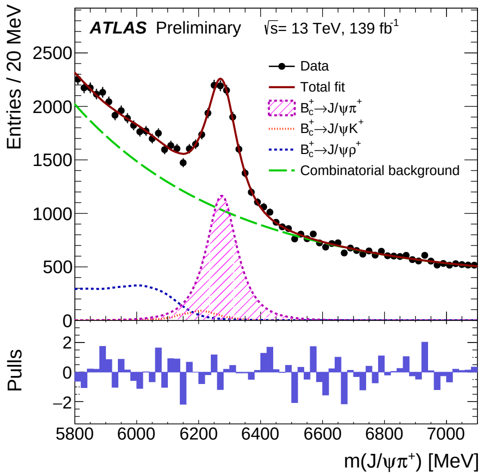
- Decays $B_c^+ \to J/\psi D_s^{(*)+}$ can occur through b decay with c as spectator, or through annihilation diagram



- Only $B_c^+ \to J/\psi D_s^{(*)+}$ decays observed earlier by LHCb (PRD 87 (2013) 112012) and ATLAS (EPJC 76 (2016) 4).
- This analysis aims at more precise measurement of $B_c^+ \to J/\psi D_s^{(*)+}$ branching fraction and polarization with full Run-2 data
  - Test various approaches predicting these (perturbative QCD calculation, relativistic potential models, sum rules calculations...)

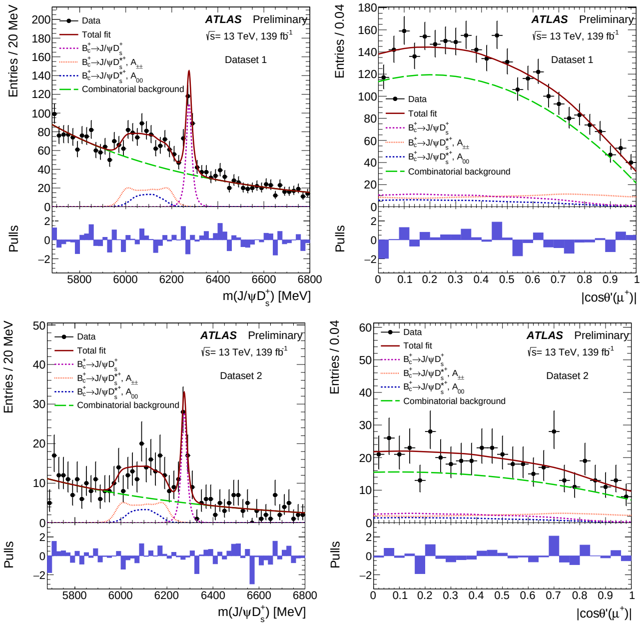
Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ decays

- $B_c^+ \to J/\psi(\mu^+\mu^-)D_s^+(\to \phi(\to K^+K^-)\pi^+)$
- $B_c^+ \to J/\psi(\mu^+\mu^-)D_s^{*+}(\to D_s^+\gamma/\pi^0)$
  - Same reconstructed final state, soft neutral particle escapes detection
- **Reference channel:** $B_c^+ \to J/\psi\pi^+$
  - Use it for $\mathcal{B}$ measurement
- Define fiducial range of the measurement: $p_T(B_c^+) > 15$ GeV, $|\eta(B_c^+)| < 2.0$
- Measured quantities:
  - Ratios b/w $\mathcal{B}$ of signal channels and $\mathcal{B}(B_c^+ \to J/\psi\pi^+)$: $R_{D_s^{(*)+}/\pi^+}$
  - Ratios b/w $\mathcal{B}$'s of signal channels (to cancel some of the uncertainties): $R_{D_s^{*+}/D_s^+}$
  - Transverse polarisation fraction $\Gamma_{\pm\pm}/\Gamma$ for $B_c^+ \to J/\psi D_s^{*+}$



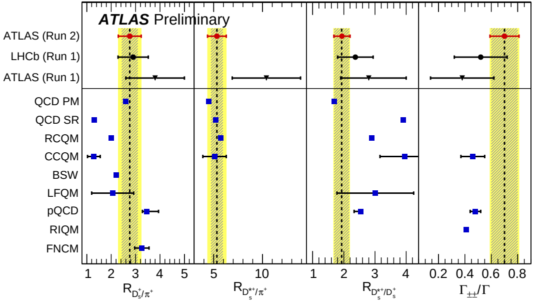
Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ decays

- *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 $B_s^0 \to \mu^+\mu^-\phi$ triggers and not by other ones used in the analysis.
  - improve sensitivity to $R_{D_s^{*+}/D_s^+}$, $\Gamma_{\pm\pm}/\Gamma$



Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ decays: results

$$R_{D_s^+/\pi^+} = 2.76 \pm 0.33(\text{stat.}) \pm 0.29(\text{syst.}) \pm 0.16(\text{br.f.})$$
$$R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61(\text{stat.}) \pm 0.67(\text{syst.}) \pm 0.32(\text{br.f.})$$
$$R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24(\text{stat.}) \pm 0.10(\text{syst.})$$
$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$



- All results are consistent with the earlier measurements of ATLAS and LHCb.
- The precision of the measurement exceeds that of all previous studies of these decays

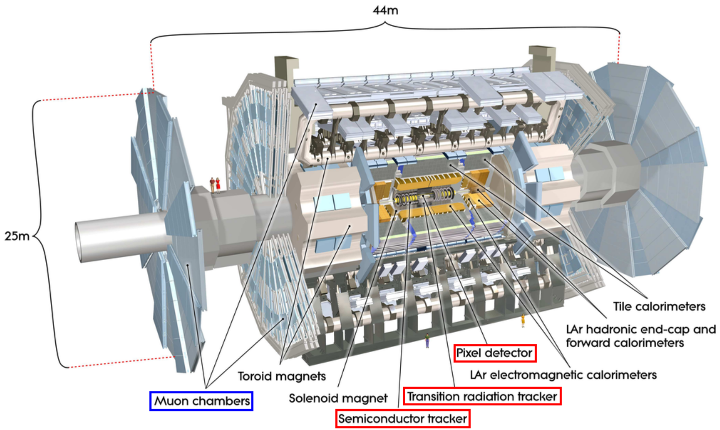
$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$	Ref.
2.76 ± 0.47	5.33 ± 0.96	1.93 ± 0.26	0.70 ± 0.11	ATLAS Run 2
2.90 ± 0.62	–	2.37 ± 0.57	0.52 ± 0.20	LHCb Run 1
3.8 ± 1.2	10.4 ± 3.5	$2.8^{+1.2}_{-0.9}$	0.38 ± 0.24	ATLAS Run 1
2.6	4.5	1.7	–	QCD potential model
1.3	5.2	3.9	–	QCD sum rules
2.0	5.7	2.9	–	RCQM
1.29 ± 0.26	5.09 ± 1.02	3.96 ± 0.80	0.46 ± 0.09	CCQM
2.2	–	–	–	BSW
2.06 ± 0.86	–	3.01 ± 1.23	–	LFQM
$3.45^{+0.49}_{-0.17}$	–	$2.54^{+0.07}_{-0.21}$	0.48 ± 0.04	pQCD
–	–	–	0.410	RIQM
3.257 ± 0.293	–	–	–	FNCM

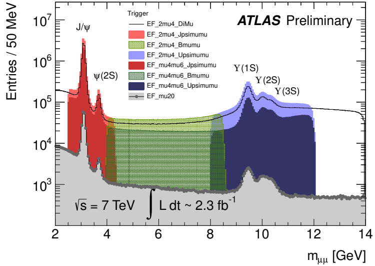
Summary

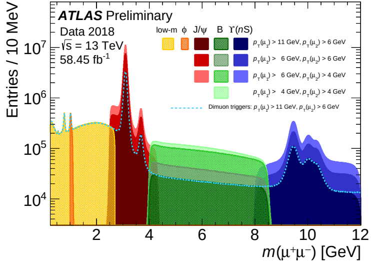
- A selection of ATLAS results on heavy flavour production was presented
  - Production of hidden charm
  - Physics of B_c^+ mesons
- More can be found here:
  - ATLAS B-physics public results page
- Many interesting results are still to come!

Backup slides

ATLAS detector and trigger



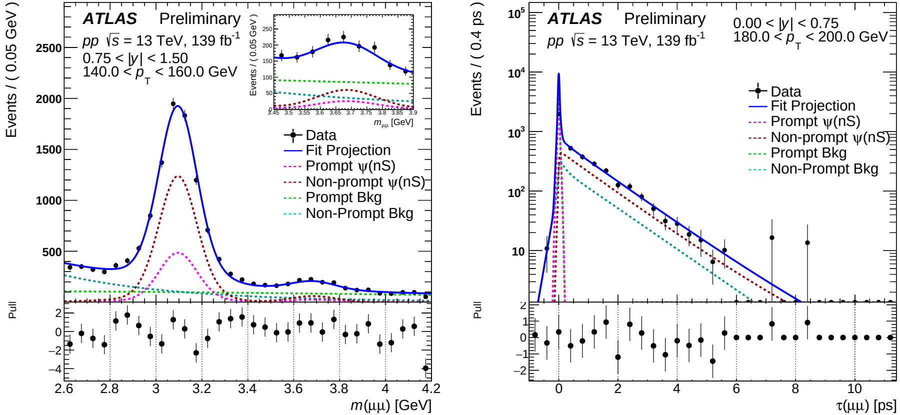




J/ψ and $\psi(2S)$ fits

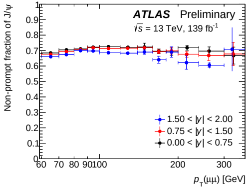
i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega G_1(m) + (1-\omega)CB_1(m)$	$\delta(\tau)$
2	J/ψ	NP	$\omega G_1(m) + (1-\omega)CB_1(m)$	$E_1(\tau)$
3	$\psi(2S)$	P	$\omega G_2(m) + (1-\omega)CB_2(m)$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega G_2(m) + (1-\omega)CB_2(m)$	$E_2(\tau)$
5	Bkg	P	B	$\delta(\tau)$
6	Bkg	NP	$E_4(m)$	$E_5(\tau)$
7	Bkg	NP	$E_6(m)$	$E_7(\lvert\tau\rvert)$

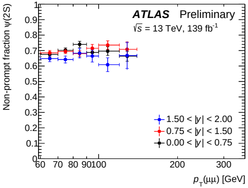
Notation	Function
G	Gaussian
CB	Crystal Ball
E	Exponential
B	Bernstein polynomials

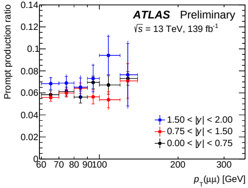


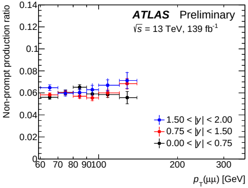
High-p_T J/ψ and $\psi(2S)$ measurement

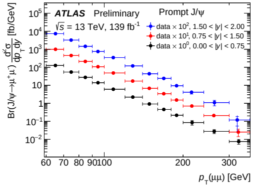
- Measured are
  - Prompt and non-prompt J/ψ and ψ(2S) double-differential x-sections
  - Non-prompt fraction for J/ψ and ψ(2S)
  - ψ(2S)/J/ψ production ratio for prompt and non-prompt
- p_T ranges extend significantly
- FONLL consistent at low-p_T, over-estimates high-p_T production

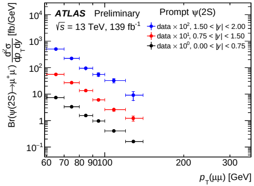


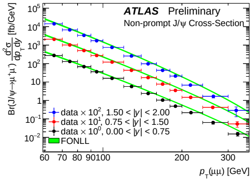


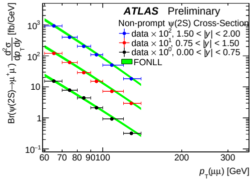


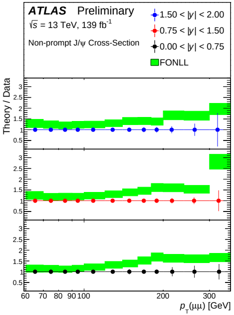


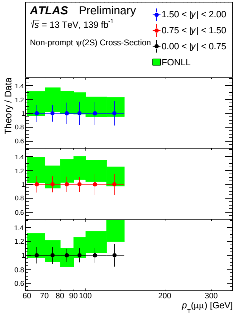






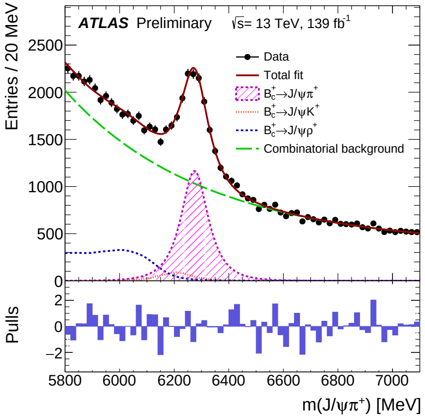






$B_c^+ \to J/\psi\pi^+$ fit

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

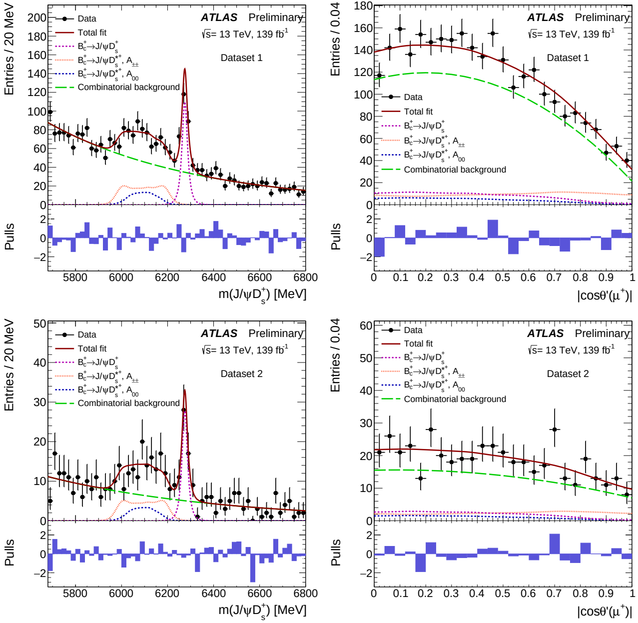


$B_c^+ \to J/\psi D_s^{(*)+}$ fit PDF

- 2D unbinned ML fit of $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$; mass and angular PDF are factorized
- ratio between $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ yield and $f_{\pm\pm}$ are the same in DS1 and DS2
- $B_c^+ \to J/\psi D_s^+$ signal
  - *mass:* modified Gaussian[1]
  - $|\cos\theta'(\mu^+)|$: MC kernel template (same in DS1 and DS2)
- $B_c^+ \to J/\psi D_s^{*+}$ 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)

[1] $Gauss^{mod} \propto \exp(-0.5 \times t^{1+1/(1+t/2)})$, where $t = |m(J/\psi D_s^+) - m_{B_c^+}|/\sigma_{B_c^+}$

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



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

Ratios calculation

- $$R_{D_s^{(*)+}/\pi^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{(*)+})}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = \frac{N^{\text{DS1}}_{B_c^+ \to J/\psi D_s^{(*)+}}}{N_{B_c^+ \to J/\psi \pi^+}} \times \frac{\varepsilon_{B_c^+ \to J/\psi \pi^+}}{\varepsilon^{\text{DS1}}_{B_c^+ \to J/\psi D_s^{(*)+}}} \times \frac{1}{\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)}, \quad (1)$$
- $\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)$ taken as $m(K^+K^-)$-dependent, using CLEO measurement, recalculated to ± 7 MeV
- $$R_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)} = \frac{N^{\text{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}}{N^{\text{DS1\&2}}_{B_c^+ \to J/\psi D_s^+}} \times \frac{\varepsilon^{\text{DS1\&2}}_{B_c^+ \to J/\psi D_s^+}}{\varepsilon^{\text{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}} = r_{D_s^{*+}/D_s^+} \times \frac{\varepsilon^{\text{DS1\&2}}_{B_c^+ \to J/\psi D_s^+}}{\varepsilon^{\text{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}}, \quad (2)$$
- $$\varepsilon_{B_c^+ \to J/\psi D_s^{*+}} = \frac{1}{f_{\pm\pm}/\varepsilon_{B_c^+ \to J/\psi D_s^{*+}, A_{\pm\pm}} + (1 - f_{\pm\pm})/\varepsilon_{B_c^+ \to J/\psi D_s^{*+}, A_{00}}}, \quad (3)$$
- $$\Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \times \frac{\varepsilon^{\text{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}}{\varepsilon^{\text{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}, A_{\pm\pm}}}. \quad (4)$$

Mode	$\epsilon^{\text{DS1}}_{B_c^+ \to J/\psi X}$ [%]	$\epsilon^{\text{DS1\&2}}_{B_c^+ \to J/\psi X}$ [%]
$B_c^+ \to J/\psi D_s^+$	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	–

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	–	–

- Effect of muon reconstruction and identification efficiency uncertainty affects individual channel efficiencies by about 1–2%. However, for the measured quantities, due to cancellation in the efficiency ratios, it is found to be negligible.