B-hadron production with the ATLAS experiment

Justas Zalieckas[†]
on behalf of the ATLAS Collaboration

[†]University of Bergen

29 April 2015 - Dallas, Texas

DIS 2015
XXIII International Workshop on
Deep-Inelastic Scattering and
Related Subjects

Overview

Outline of this talk:

- Introduction
- ATLAS detector
- *Observation of an excited $B_c^{\pm}$ meson state*
  Phys. Rev. Lett. 113, 212004 (2014) (arXiv:1407.1032)
- *Study of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays*
  ATLAS-CONF-2015-014
- Summary and future plans

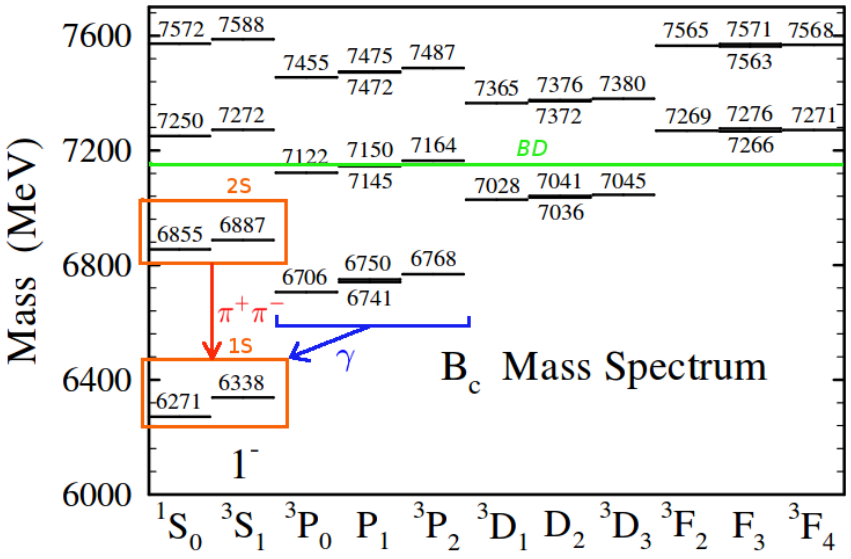
Presented studies use *pp* collisions data collected by the ATLAS experiment at $\sqrt{s} = 7$ and 8 TeV at LHC in 2011 and 2012

See also: talk by Tamsin Nooney on *New physics searches with B mesons at the ATLAS experiment*

Introduction

Excited $B_c^{\pm}$ meson state

- The $B_c^{\pm}$ $(c\bar{b})$ production at LHC via $gg \to B_c^{(*)\pm} + b + \bar{c}$ (arXiv:hep-ph/0412158)
- Below BD threshold only radiative or hadronic transitions $\to$ rich spectroscopy
- Production of $B_c^{\pm}$ at LHC: $\mathcal{O}(10^9)$ for 100 fb^{-1} (Phys. Rev. D 70 (2004) 054017)
- Study $B_c^{\pm}$ spectroscopy with ATLAS



Phys. Rev. D 70 (2004) 054017

The $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ decays

- Many possible decay modes of B_c^+
  - $c \to s(d)$
  - $\bar{b} \to \bar{c}(\bar{u})$
  - $c\bar{b} \to W^*$
- Yet only few observed
- Important probe for QCD

	Mode	Fraction (Γ_i/Γ)	Confidence level
	The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times B(\bar{b} \to B_c)$.		
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2\ ^{+2.4}_{-2.1}) \times 10^{-5}$	
Γ_2	$J/\psi(1S)\pi^+$	seen	
Γ_3	$J/\psi(1S)K^+$	seen	
Γ_4	$J/\psi(1S)\pi^+\pi^+\pi^-$	seen	
Γ_5	$J/\psi(1S)a_1(1260)$	$< 1.2 \times 10^{-3}$	90%
Γ_6	$J/\psi(1S)K^+K^-\pi^+$	seen	
Γ_7	$\psi(2S)\pi^+$	seen	
Γ_8	$J/\psi(1S)D_s^+$	seen	
Γ_9	$J/\psi(1S)D_s^{*+}$	seen	

LHCb: Phys. Rev. D 87 (2013) 112012

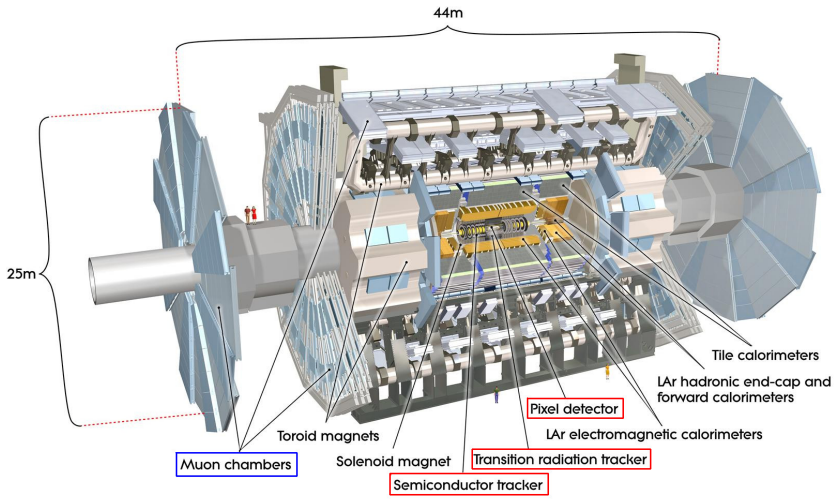
ATLAS detector

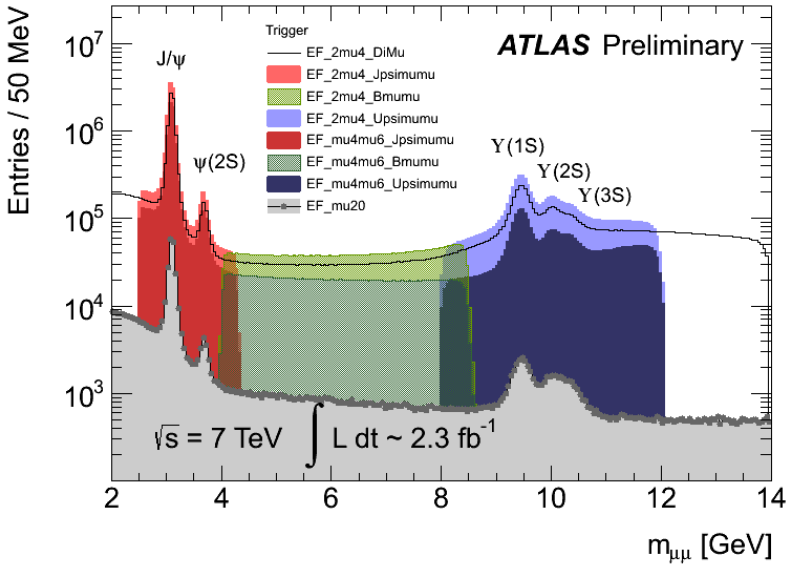
ATLAS detector

- Multipurpose, sensitive to wide range of physics problems
- Heavy flavour $\rightarrow J/\psi \rightarrow \mu^+\mu^-$ selection

Relevant subsystems:

- Inner detector (ID)
  - 2T solenoid magnetic field
  - Pixel, silicon strip (SCT), transition radiation tracker (TRT)
  - Tracking, di-muon vertexing
- Muon Spectrometer (MS)
  - Tracking chambers, detectors for triggering
  - Triggering, momentum measurement
- Muon trigger
  - Single, di-muon
  - Different p_T thresholds (4, 6 GeV)





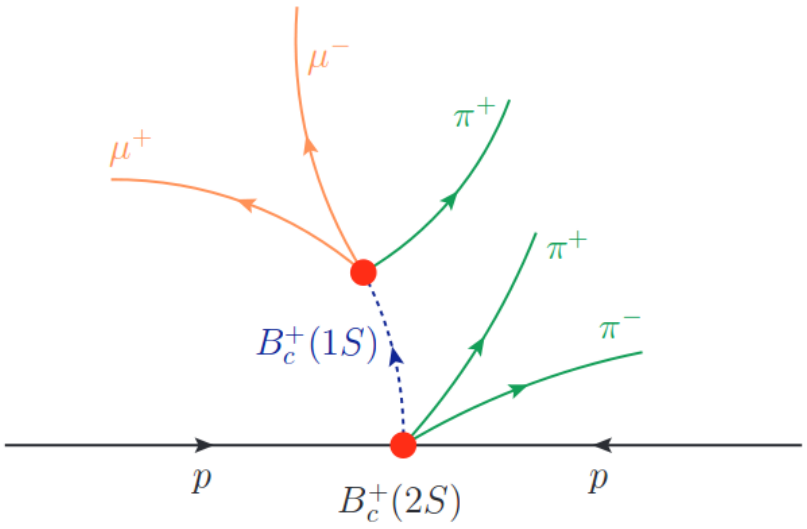
Excited B_c^+ meson state - Introduction

Introduction

- The B_c^+ observed by many experiments (CDF, D0, LHCb and ATLAS)
- Excited B_c^+ state previously not observed
  - $B_c^+(1P) \to B_c^+(1S) + \gamma$ (~ 500 MeV)
  - $B_c^+(2S_0) \to B_c^+(1S_0) + \pi^+\pi^-$
  - $B_c^+(2S_1) \to B_c^+(1S_1) + \pi^+\pi^-$ with $B_c^+(1S_1) \to B_c^+(1S_0) + \gamma$ (~ 70 MeV)
- Spectrum and properties of B_c^+ predicted by nonrelativistic potential models, perturbative QCD and lattice calculations
- Mass predictions for $B_c^+(2S)$: 6835-6917 MeV (see backup)

Analysis overview

- Data samples for 2011 and 2012: 4.9 fb^{-1} ($\sqrt{s} = 7$ TeV) and 19.2 fb^{-1} ($\sqrt{s} = 8$ TeV)
- The $B_c^+(2S)$ state reconstructed in the decay to $B_c^+(1S) + \pi^+\pi^-$



- Ground state reconstructed in $B_c^+ \to J/\psi\pi^+$ with $J/\psi \to \mu^+\mu^-$
- Selection optimized by maximizing $S/\sqrt{S+B}$ on simulations (bkg.: exclusive B_c^+ decays + $b\bar{b} \to J/\psi X$)
- Peaks sought in distribution of $Q = m(B_c^\pm\pi\pi) - m(B_c^\pm) - 2m(\pi^\pm)$

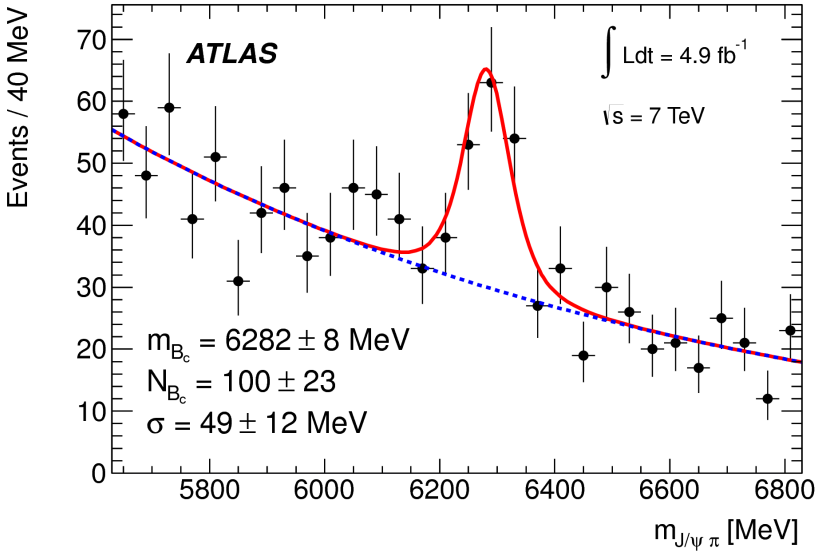
Excited B_c^+ meson state - Analysis

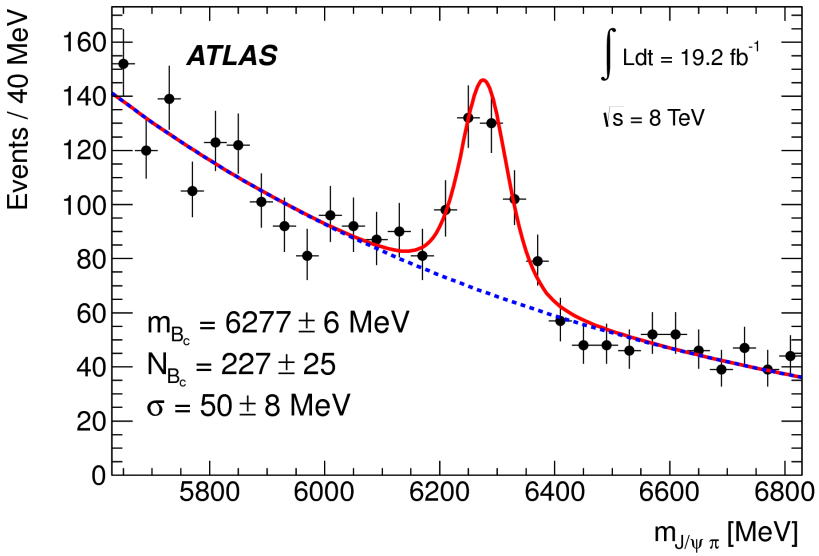
$B_c^+(1S)$ selection for 2011 (2012) data

- Muon $p_T(\mu_1, \mu_2) > 6, 4$ GeV
- J/ψ vertex fit $\chi^2/NDOF < 15$ and $m_{J/\psi}$ within $\pm 3\sigma$ (σ depends on muon η)
- $B_c^\pm$ reconstructed by fitting two muons with a pion
- $p_T(\pi) > 4$ GeV
- $d_0/\sigma(d_0)/ > 5$ (4.5)
- $J/\psi\pi^+$ vertex fit $\chi^2/NDOF < 2$ (1.5)
- $p_T(B_c^\pm) > 15$ (18) GeV

Unbinned ML fit

- Signal modelled with Gaussian and background with exponential function
- Fit in 5620-6820 MeV range
- $B_c^+(1S)$ mass consistent with world average





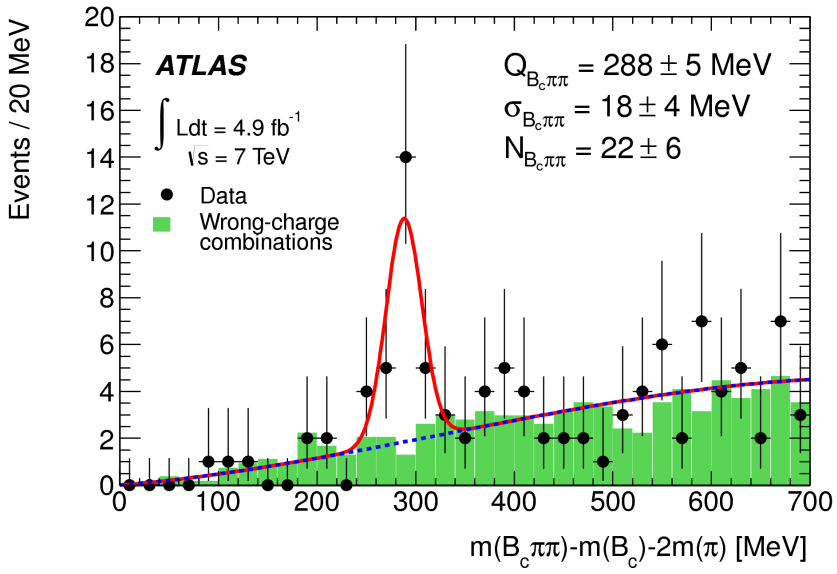
Excited B_c^+ meson state - Analysis

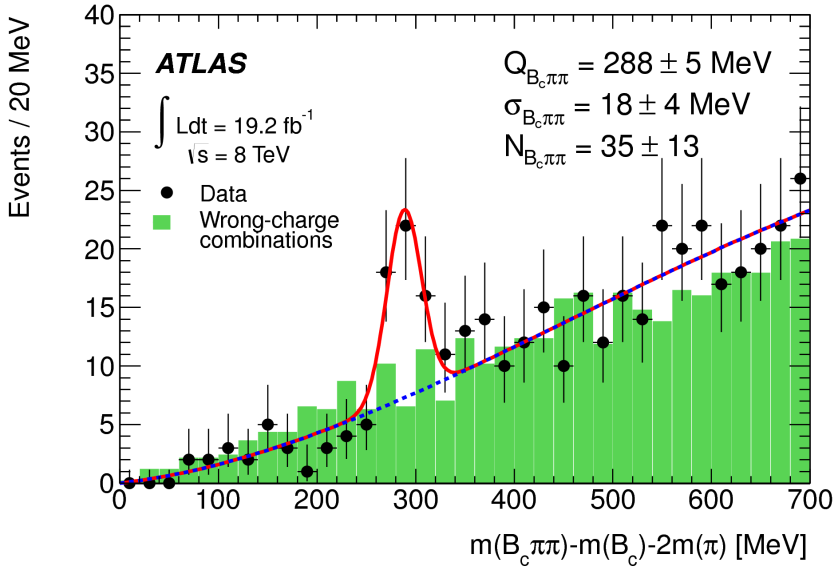
$B_c^+(2S) \to B_c^+(1S)\pi^+\pi^-$ selection

- Reconstruction of $B_c^+(2S)$ uses $B_c^+(1S)$ within $\pm 3\sigma$ of the fitted mass
- Add two pions having $p_T(\pi) > 400$ MeV
- Simultaneous cascade vertex fit of $\mu^+\mu^-\pi^+$ and $\pi^+\pi^-$ tracks
- If multiple $B_c^+(2S)$ choose with best cascade vertex fit χ^2
- Keep wrong-charge ($B^\pm\pi^\pm\pi^\pm$) combinations

ML fit to $Q = m(B_c^\pm\pi\pi) - m(B_c^\pm) - 2m(\pi^\pm)$ distribution

- Peaking structure: Gausian
- Background: 3rd order polynomial
- Wrong-charge combinations used to verify the background shape





Excited B_c^+ meson state - Results

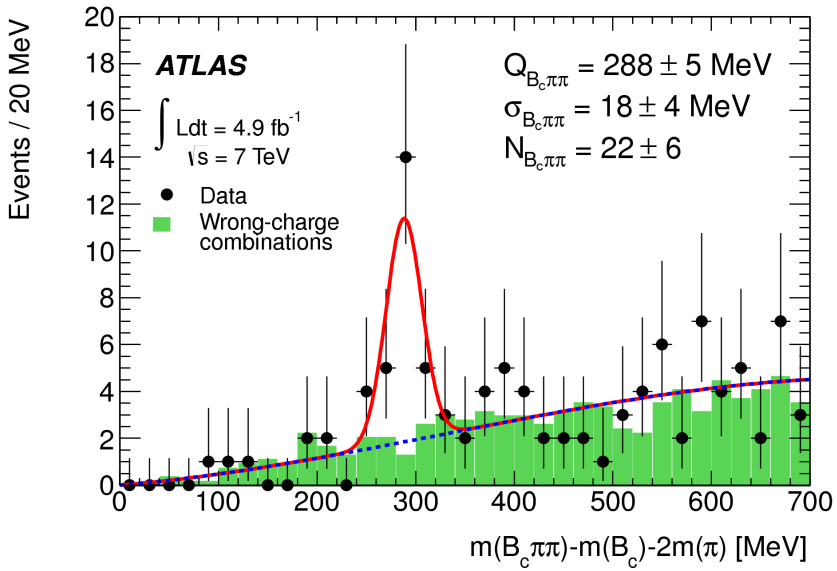
- Uncertainty on $B_c^{\pm}(2S)$ mass dominated by the fitting procedure
- The significance of a structure evaluated with pseudoexperiments (including look-elsewhere effect)

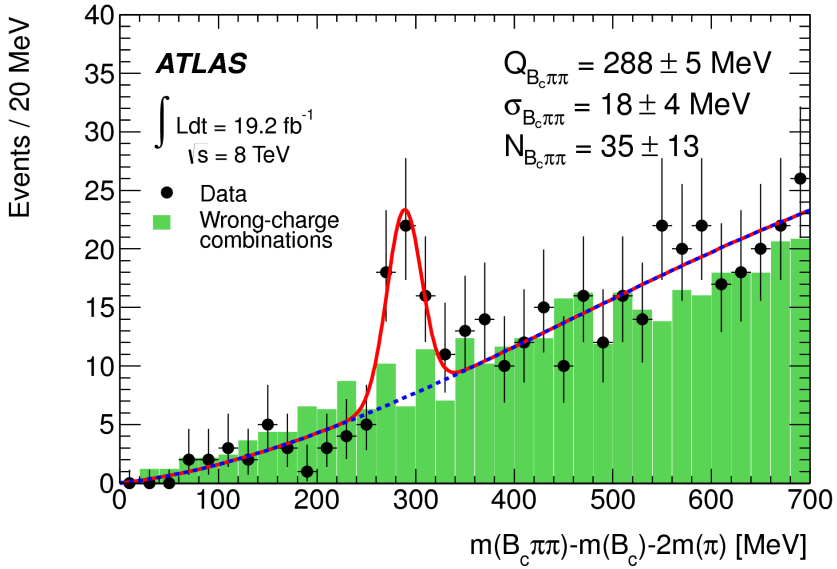
Results

- 3.7σ (4.5σ) in the 7 (8) TeV data
- Total significance: 5.2σ (local 5.4σ)
- A new state is observed at $Q = 288.3 \pm 3.5 \pm 4.1$ MeV (error weighted mean of 7 TeV and 8 TeV values)
- Corresponds to a mass of $6842 \pm 4 \pm 5$ MeV

Summary

- The mass of the observed resonance consistent with the predicted mass of the $B_c^{\pm}(2S)$ state

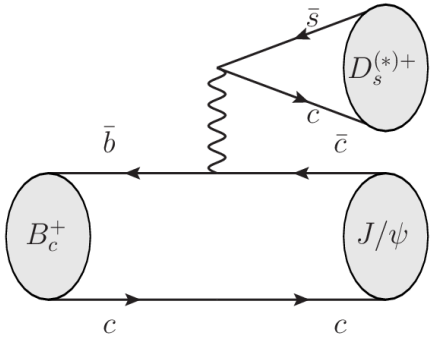


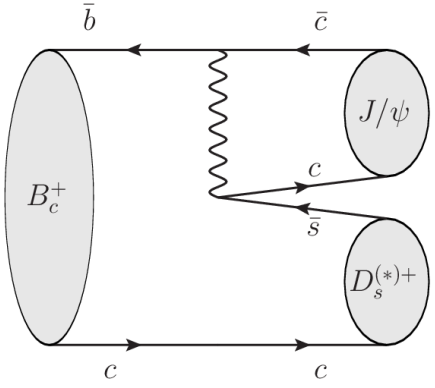


Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ - Introduction

Introduction

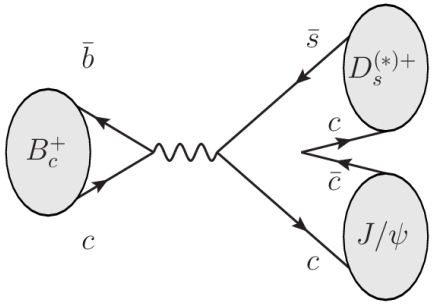
- The B_c^+ consists of two heavy quarks $\to$ affects theoretical predictions of B_c^+ decay properties
- For $\bar{b} \to \bar{c}c\bar{s}$, decays to charmonium and $D_s^{(*)+}$ occur via color-suppressed (allowed) and annihilation diagrams
- Latter not suppressed $\to$ can contribute significantly to decay amplitudes
- $B_c^+ \to J/\psi D_s^{(*)+}$ properties addressed by various models (see backup)





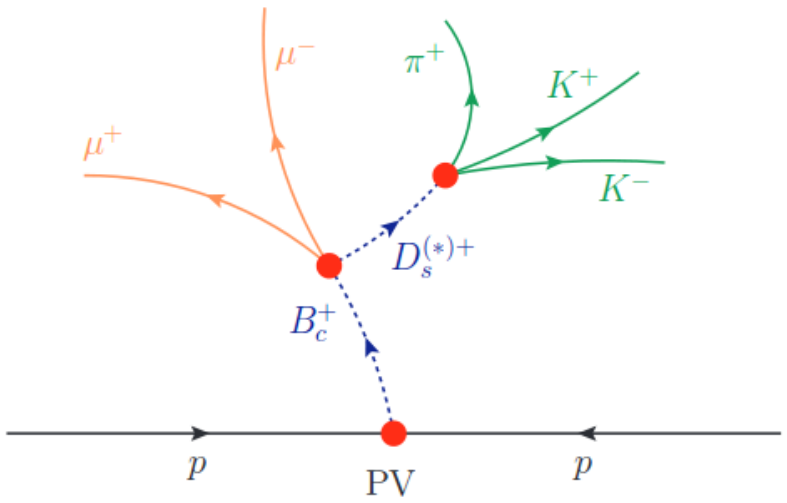
Analysis overview

- Combined data sample: 4.9 fb^{-1} ($\sqrt{s} = 7$ TeV) and 19.6 fb^{-1} ($\sqrt{s} = 8$ TeV)
- B_c^+ decays into vector-vector yielding 3 helicity final states (A_{++}, A_{--}, A_{00})
- $A_{\pm\pm}$ and A_{00} have slightly different kinematics
  $\to$ different $J/\psi D_s^+$ mass shape
  $\to$ can be distinguished in the mass fit



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

- D_s^{*+} decays into D_s^+ plus γ/π^0 (no γ/π^0 reconstruction attempt)
- The D_s^+ reconstructed via $D_s^+ \to \phi(K^+K^-)\pi^+$ and $J/\psi \to \mu^+\mu^-$
- $B_c^+ \to J/\psi\pi^+$ used as a reference channel



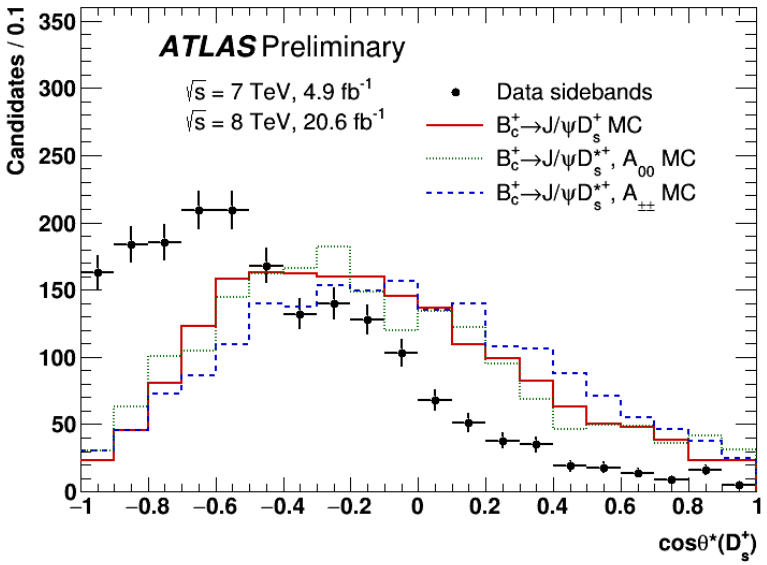
- Measurements of the rations of $\mathcal{B}$s:
  - $\mathcal{R}_{D_s^+/\pi^+} = \mathcal{B}_{B_c^+\to J/\psi D_s^+}/\mathcal{B}_{B_c^+\to J/\psi\pi^+}$
  - $\mathcal{R}_{D_s^{*+}/\pi^+} = \mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+\to J/\psi\pi^+}$
  - $\mathcal{R}_{D_s^{*+}/D_s^+} = \mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}/\mathcal{B}_{B_c^+\to J/\psi D_s^+}$
- Fraction of transverse polarization:

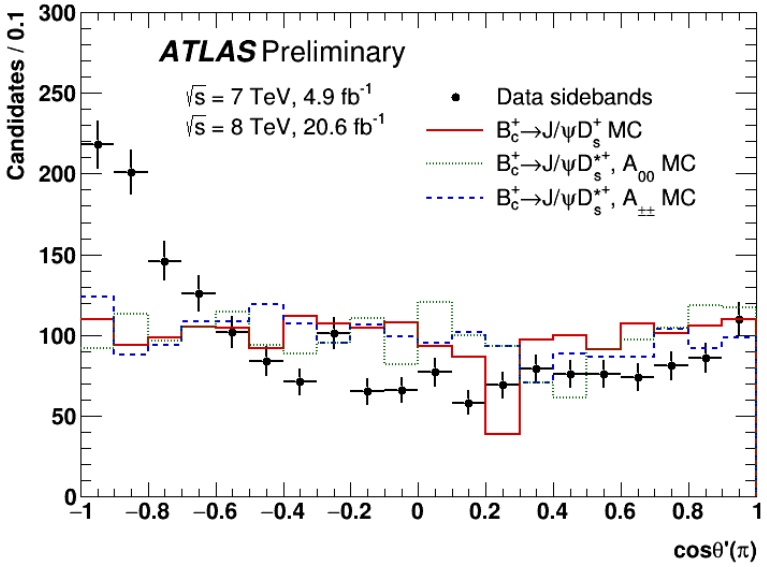
$$\frac{\Gamma_{\pm\pm}}{\Gamma} = \frac{\Gamma_{\pm\pm}(B_c^+\to J/\psi D_s^{*+})}{\Gamma(B_c^+\to J/\psi D_s^{*+})}$$

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

$\mathbf{B_c^+ \to J/\psi D_s^{(*)+}}$ candidate selection

- J/ψ and $D_s^+ \to \phi(K^+K^-)\pi^+$ selection:
  - $p_T(\mu^\pm) > 3$ GeV, $|\eta(\mu^\pm)| < 2.3$
  - $p_T(K,\pi) > 1$ GeV, $|\eta(K,\pi)| < 2.5$
  - $m(K^+K^-)$: ± 7 MeV around m(ϕ)
  - $1.93 < m(K^+K^-\pi^+) < 2.01$ GeV
- $B_c^+ \to J/\psi D_s^{(*)+}$ selection:
  - $\cos\theta^* > -0.8$ (angle between D_s^+ momentum in B_c^+ rest frame and B_c^+ line of flight in the lab. frame)
  - $\cos\theta' > -0.8$ (angle between the pion and the J/ψ in D_s^+ rest frame)
  - Remove candidates with $5.34 < m_{refit.}(J/\psi\phi) < 5.4$ GeV
- J/ψ and D_s^+ candidates are combined and a cascade vertex fit is performed:
  - Secondary vertex (B_c^+ and J/ψ decay)
  - Tertiary vertex (D_s^+ decay)

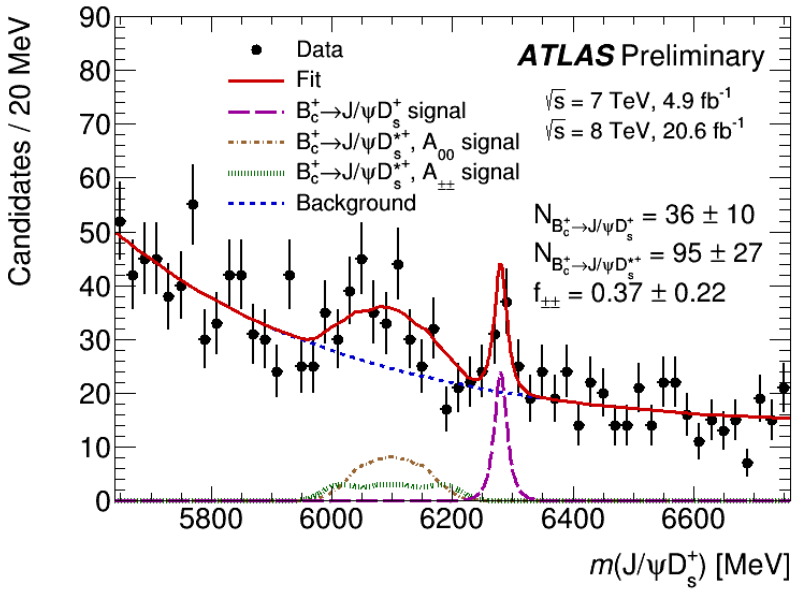


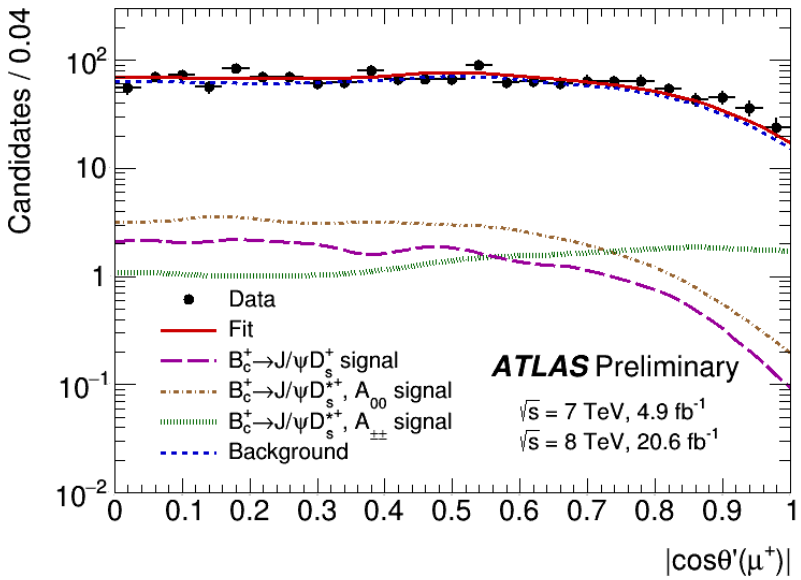


Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ - Analysis

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

- 2D unbinned ML fit: $m(B_c^+ \to J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$ (angle between μ^+ and D_s^+ momentum in the J/ψ rest frame)
- Mass components:
  - $B_c^+ \to J/\psi D_s^+$: $\sim exp\left[-\frac{x^{1+\frac{1}{1+x/2}}}{2}\right]$
  - $B_c^+ \to J/\psi D_s^{*+}$: $A_{\pm\pm}$ and A_{00} with templates from simulations
  - Background: $\sim exp\left[a \cdot x + b \cdot x^2\right]$
- Angular components:
  - Signals: templates from simulations
  - Background: data sidebands of $J/\psi D_s^+$ mass spectra
- Simultaneous 2D fit $\to$ better sensitivity w.r.t. 1D mass fit
- Signal significance 4.9σ (toy MC studies)

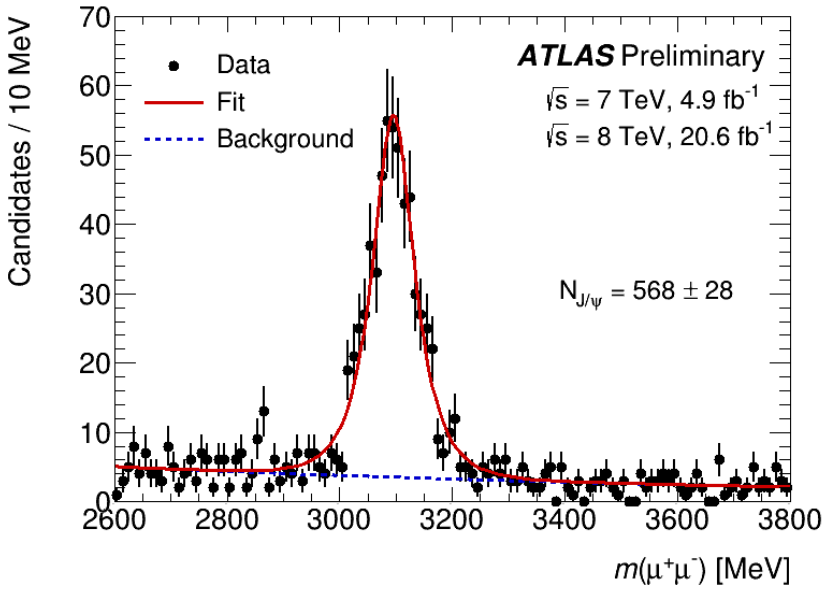


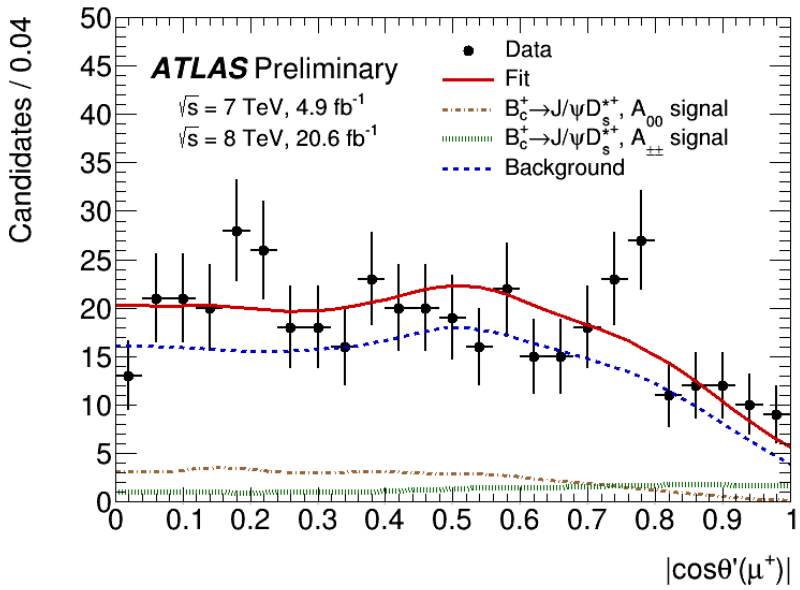


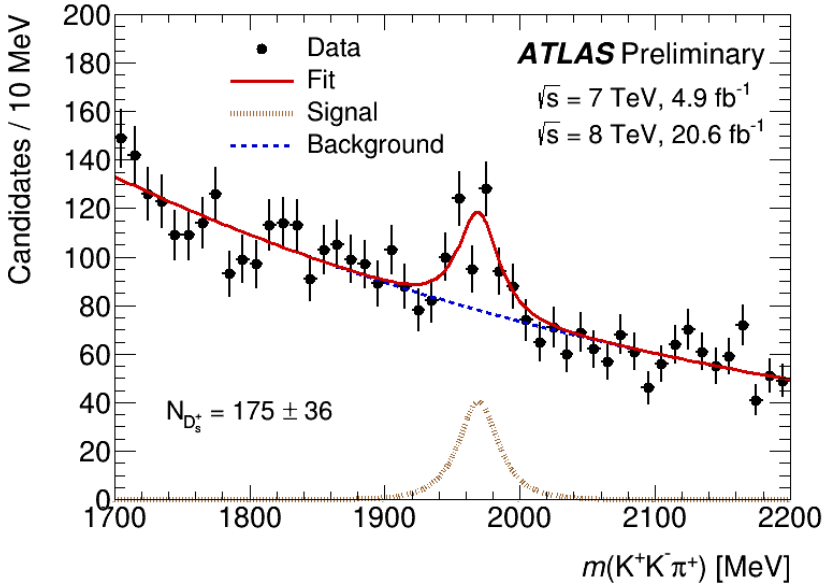
Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ - Analysis

Parameter	Value
$m_{B_c^+ \to J/\psi D_s^+}$ [MeV]	6279.9 ± 3.5
$N_{B_c^+ \to J/\psi D_s^+}$	36 ± 10
$N_{B_c^+ \to J/\psi D_s^{*+}}$	95 ± 27
$f_{\pm\pm}$	0.37 ± 0.22

- Left: mass distribution of the J/ψ and D_s^+ candidates (no mass constraints implied)
- Bottom: angular projection of the fit for $J/\psi D_s^+$ in $5.95 < m(J/\psi D_s^+) < 6.25$ GeV



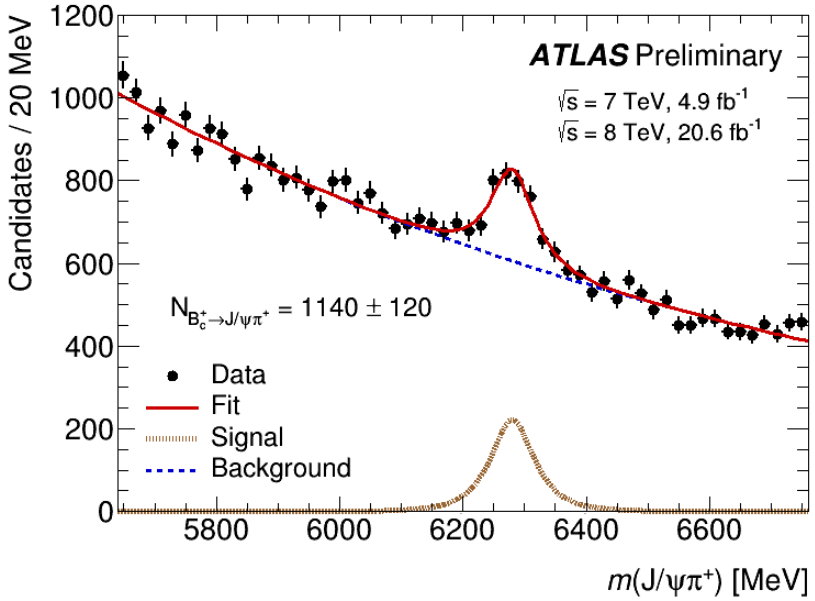




Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ - Analysis

$B_c^+ \to J/\psi\pi^+$ candidate selection and fit (reference channel)

- Event selection
  - Same J/ψ selection as for $B_c^+ \to J/\psi D_s^+$
  - $p_T(\pi^+) > 5$ GeV
  - $|\eta(\pi^+)| < 2.5$
  - veto muon tracks ($B_c^+ \to J/\psi\mu^+\nu_\mu X$)
  - $p_T(B_c^+) > 15$ GeV
  - $|\eta(B_c^+)| < 2$
  - $\chi^2/NDOF(B_c^+) < 8$
  - $0.2 < L_{xy}(B_c^+) < 10$ mm
  - $p_T(B_c^+)/\sum p_T(\mathrm{trk}) > 0.1$
  - $\cos\theta^*(\pi) > -0.8$ (angle between π momentum in $\mu^+\mu^-\pi^+$ rest frame and B_c^+ line of flight in the lab. frame)
  - $\cos\theta'(\mu^+) < 0.8$ (angle between μ^+ and π^+ momenta in $\mu^+\mu^-$ rest frame)



Unbinned ML fit

- Signal: modified Gaussian
- Background: exponential

Parameter	Value
$m_{B_c^+\to J/\psi\pi^+}$ [MeV]	6279.9 ± 3.9
$\sigma_{B_c^+\to J/\psi\pi^+}$ [MeV]	33.9 ± 4.2
$N_{B_c^+\to J/\psi\pi^+}$	1140 ± 120

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

- Measured ratios of branching fractions:

$$\mathcal{R}_{D_s^+/\pi^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^+}}{\mathcal{B}_{B_c^+\to J/\psi \pi^+}} = 3.8 \pm 1.1\ (\text{stat.})\,^{+0.2}_{-0.6}\ (\text{syst.}) \pm 0.2\ (\text{BF}),$$

$$\mathcal{R}_{D_s^{*+}/\pi^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi \pi^+}} = 10.3 \pm 3.1\ (\text{stat.})\,^{+0.8}_{-1.5}\ (\text{syst.}) \pm 0.6\ (\text{BF}),$$

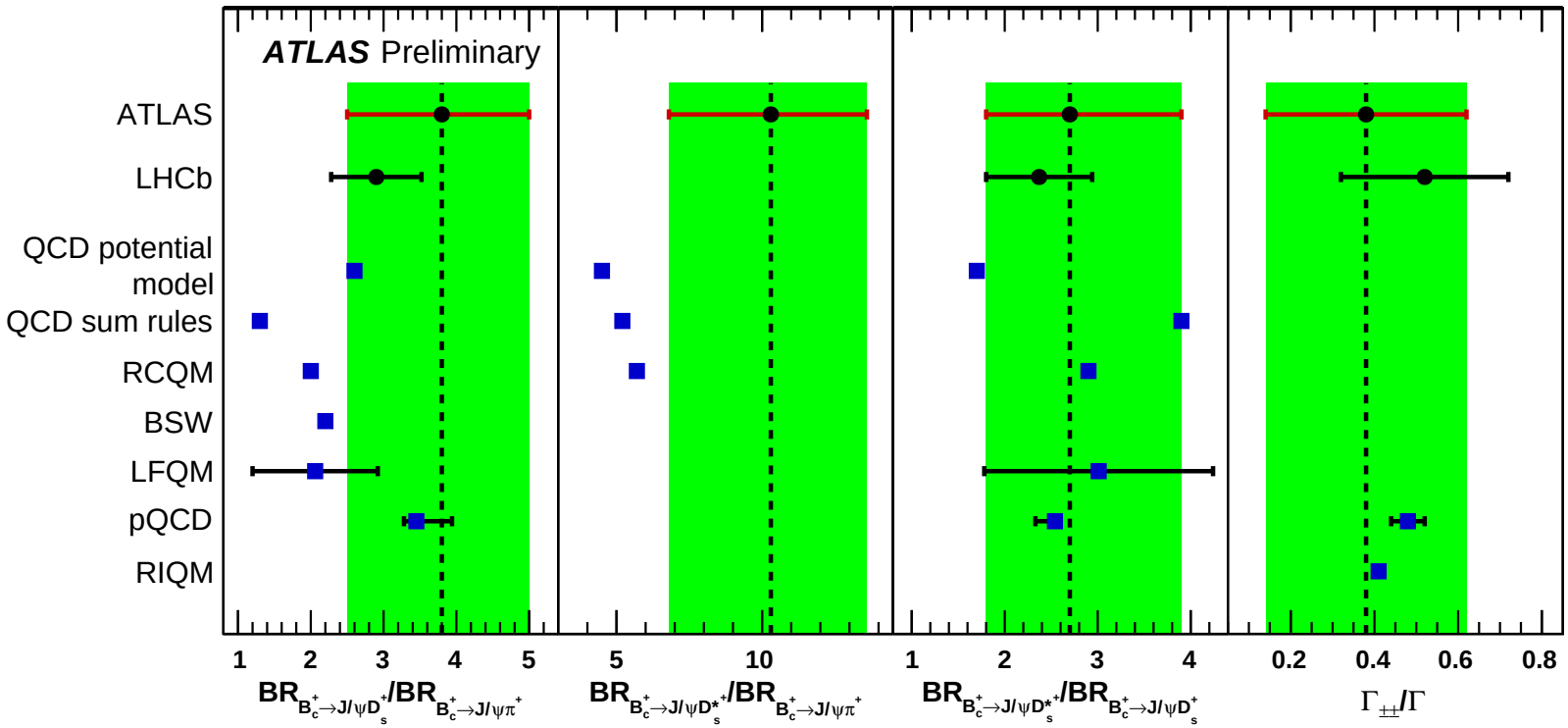
$$\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi D_s^+}} = 2.7^{+1.1}_{-0.8}\ (\text{stat.})\,^{+0.4}_{-0.3}\ (\text{syst.}),$$

- BF uncertainty corresponds to the limited knowledge of $\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)$
- Dominant uncertainty from signal and background parameterization
- Relative contribution of $A_{\pm\pm}$ amplitude to $B_c^+ \to J/\psi D_s^{*+}$ decay:

$$\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23\ (\text{stat.})\,^{+0.06}_{-0.07}\ (\text{syst.})$$

- Mostly affected by the background angular modelling

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



- Generally well described by perturbative QCD, consistent with other models
- Underestimation of $B_c^+ \to J/\psi D_s^{(*)+}$ decay rates by some models
- Results consistent with LHCb measurement (Phys. Rev. D 87 (2013) 112012)

Summary and future plans

Observation of an excited $B_c^{\pm}$ meson state

- A new state observed at $Q = 288.3 \pm 3.5 \pm 4.1$ MeV corresponding to a mass of $6842 \pm 4 \pm 5$ MeV
- Significance of observation 5.2σ (local 5.4σ)
- Consistent with predicted mass of $B_c^{\pm}(2S)$ state

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

- Measurement of ratios of branching fractions and fraction of transverse polarization: $\mathcal{R}_{D_s^+/\pi^+}$, $\mathcal{R}_{D_s^{*+}/\pi^+}$, $\mathcal{R}_{D_s^{*+}/D_s^+}$ and $\Gamma_{\pm\pm}/\Gamma$
- Polarization well described by available theoretical approaches
- Generally, predictions agree with the measurement of the ratios of branching fractions

More Run-I results to come

Looking forward to Run-II data!

BACKUP SLIDES

Excited B_c^+ meson state - References

Spectrum and properties of B_c^+ meson:

S. Narison, Phys. Lett. B 210, 238 (1988); W. Kwong and J. L. Rosner, Phys. Rev. D 44, 212 (1991); Y.-Q. Chen and Y.-P. Kuang, Phys. Rev. D 46, 1165 (1992); P. Jain and H. J. Munczek, Phys. Rev. D 48, 5403 (1993); L. P. Fulcher, Z. Chen, and K. C. Yeong, Phys. Rev. D 47, 4122 (1993); E. J. Eichten and C. Quigg, Phys. Rev. D 49, 5845 (1994); S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. V. Tkabladze, Phys. Rev. D 51, 3613 (1995); L. Motyka and K. Zalewski, Eur. Phys. J. C 4, 107 (1998); M. Baldicchi and G. M. Prosperi, Phys. Rev. D 62, 114024 (2000); N. Brambilla, A. Pineda, J. Soto, and A. Vairo, Phys. Rev. D 63, 014023 (2000); A. Pineda and A. Vairo, Phys. Rev. D 63, 054007 (2001); D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Rev. D 67, 014027 (2003); S. Godfrey, Phys. Rev. D 70, 054017 (2004); A. A. Penin, A. Pineda, V. A. Smirnov, and M. Steinhauser, Phys. Lett. B 593, 124 (2004); S. Ikhdair and R. Sever, Int. J. Mod. Phys. A 20, 4035 (2005); I. Allison, C. Davies, A. Gray, A. Kronfeld, P. Mackenzie, and J. Simone (HPQCD, Fermilab Lattice, and UKQCD Collaborations), Phys. Rev. Lett. 94, 172001 (2005); D. Ebert, R. N. Faustov, and V. O. Galkin, Eur. Phys. J. C 71, 1825 (2011); R. J. Dowdall, C. T. H. Davies, T. C. Hammant, and R. R. Horgan, Phys. Rev. D 86, 094510 (2012).

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

Theoretical predictions by:

- QCD potential model
  Phys. Rev. D 61 (2000) 034012
- QCD sum rules
  arXiv:hep-ph/0211021
- Relativistic constituent quark model (RCQM)
  Phys. Rev. D 73 (2006) 054024
- BSW relativistic quark model
  Phys. Rev. D 79 (2009) 034004
- Light-front quark model (LFQM)
  Phys. Rev. D 89 (2014) 017501
- Perturbative QCD (pQCD)
  Phys. Rev. D 90 (2014) 114030
- Relativistic independent quark model (RIQM)
  Phys. Rev. D 88 (2013) 094014

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

- $J/\psi \to \mu^+\mu^-$ selection:
  - $p_T(\mu^\pm) > 3$ GeV
  - $|\eta(\mu^\pm)| < 2.3$
  - $\chi^2/NDOF(J/\psi) < 15$
  - $2.8 < m(J/\psi) < 3.4$ GeV
  - at least one of two muons is combined
- $D_s^+ \to \phi(K^+K^-)\pi^+$ selection:
  - $p_T(K^\pm, \pi^+) > 1$ GeV
  - $|\eta(K^\pm, \pi^+)| < 2.5$
  - $\chi^2/NDOF(D_s^+) < 8$
  - $m(K^+K^-)$ within ± 7 MeV around ϕ mass
  - $1.93 < m(K^+K^-\pi^+) < 2.01$ GeV
  - $\cos\theta^*(\pi) < 0.8^\dagger$
  - $\cos^3\theta'(K) > 0.15^\dagger$

  †ATLAS-CONF-2011-017
- $B_c^+ \to J/\psi D_s^+$ selection:
  - $p_T(B_c^+) > 15$ GeV
  - $|\eta(B_c^+)| < 2.0$
  - Cascade fit $\chi^2/NDOF(B_c^+) < 3$
  - $d_0^{PV} < 0.1$ mm
  - $z_0^{PV} \sin\theta < 0.5$ mm
  - $0.1 < L_{xy}(B_c^+) < 10$ mm
  - $0.15 < L_{xy}(D_s^+ \text{ w.r.t. } B_c^+) < 10$ mm
  - $p_T(B_c^+)/\sum p_T(\text{trk}) > 0.1$
  - $\cos\theta^* > -0.8$ (angle between D_s^+ momentum in B_c^+ rest frame and B_c^+ line of flight in the lab. frame)
  - $\cos\theta' > -0.8$ (angle between the pion and the J/ψ in D_s^+ rest frame)
  - Remove candidates with $5.34 < m_{refit.}(J/\psi\phi) < 5.4$ GeV

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

Branching fractions and polarization measurement

- Ratios of the branching fractions $\mathcal{R}_{D_s^+/\pi^+}$ and $\mathcal{R}_{D_s^{*+}/\pi^+}$ are calculated as

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

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

- Acceptance for $B_c^+ \to J/\psi D_s^{*+}$ estimated as $A_{\pm\pm}$ and A_{00} average

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

- The fraction of transverse polarization:

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

- Estimated acceptance $\mathcal{A}_{B_c^+\to X}$ for all decays:

Mode	$\mathcal{A}_{B_c^+\to X}$ [%]
$B_c^+ \to J/\psi\pi^+$	4.110 ± 0.056
$B_c^+ \to J/\psi D_s^+$	1.842 ± 0.034
$B_c^+ \to J/\psi D_s^{*+}$, A_{00}	1.839 ± 0.053
$B_c^+ \to J/\psi D_s^{*+}$, $A_{\pm\pm}$	1.720 ± 0.035

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

Relative systematic uncertainties for the measured values.

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	$^{+0.4}_{-0.4}$	$^{+0.9}_{-0.9}$	$^{+0.4}_{-0.5}$	$^{+0.4}_{-0.4}$
Simulated $\lvert\eta(B_c^+)\rvert$ spectrum	$^{+1.8}_{-1.8}$	$^{+2.4}_{-2.3}$	$^{+0.6}_{-0.5}$	$^{+0.2}_{-0.1}$
Tracking efficiency	±5.0	±4.9	–	–
B_c^+ lifetime	$^{+1.1}_{-1.2}$	$^{+1.2}_{-1.3}$	–	–
D_s^+ lifetime	±0.3	±0.3	±0.1	±0.1
$B_c^+ \to J/\psi D_s^{(*)+}$ signal extraction	$^{+1.7}_{-13.5}$	$^{+3.9}_{-10.7}$	$^{+12.8}_{-10.1}$	$^{+15.2}_{-17.8}$
$B_c^+ \to J/\psi \pi^+$ signal extraction	$^{+1.5}_{-7.4}$	$^{+1.5}_{-7.4}$	–	–
D_s^{*+} branching fractions	–	$^{+0.2}_{-0.0}$	$^{+0.2}_{-0.3}$	$^{+0.8}_{-1.1}$
MC statistics	±2.3	±2.4	±2.7	±2.2
Total	$^{+6.3}_{-16.5}$	$^{+7.5}_{-14.3}$	$^{+13.1}_{-10.4}$	$^{+15.4}_{-17.9}$
$\mathcal{B}_{D_s^+\to\phi(K^+K^-)\pi^+}$	±5.9	±5.9	–	–