B_c spectroscopy at ATLAS

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On behalf of ATLAS collaboration

The 7th International Workshop on Charm Physics

Detroit, Michigan

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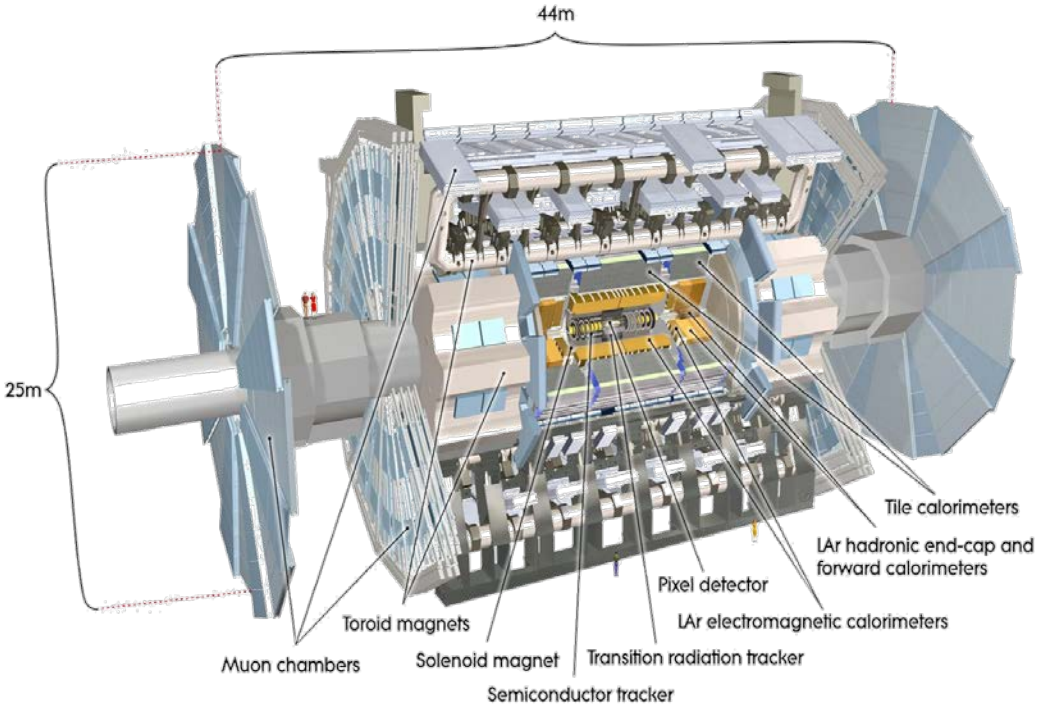
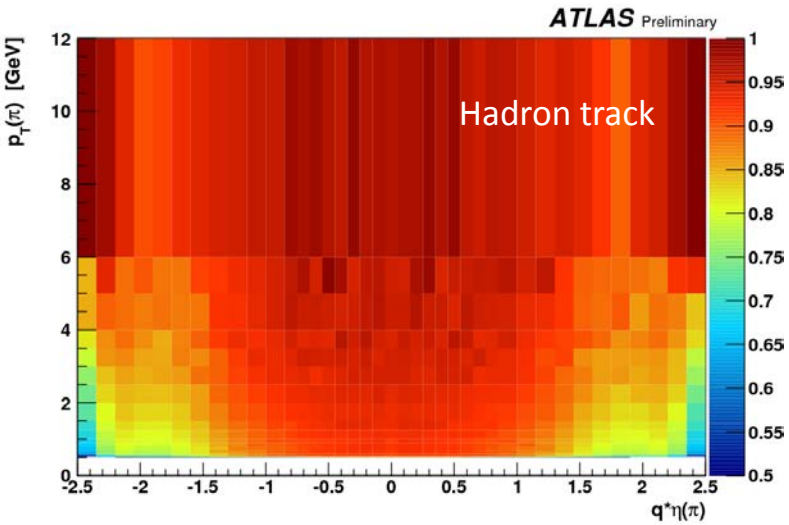
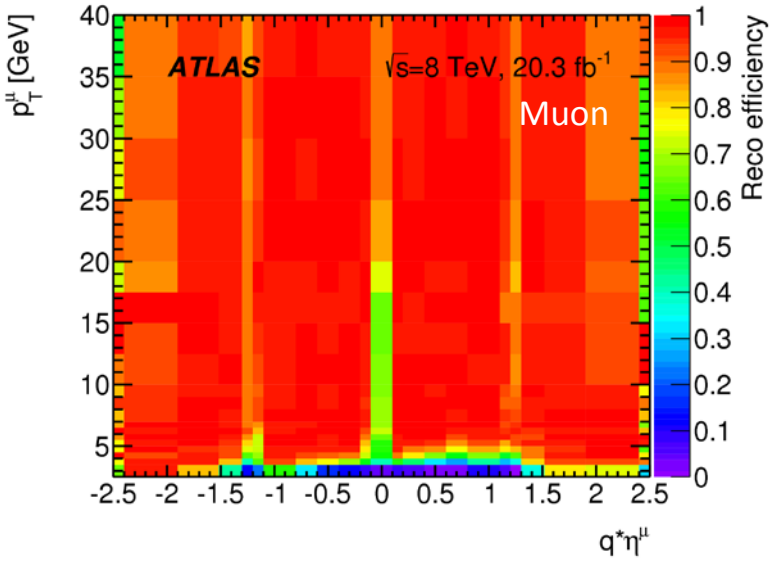
ATLAS - detector

- Inner detector
  - Silicon (Pixel+Semiconductor tracker) and Transition Radiation Tracker
  - 2T solenoidal field
- Muon detector
  - Muon chambers
  - 0.5 -2T toroidal field

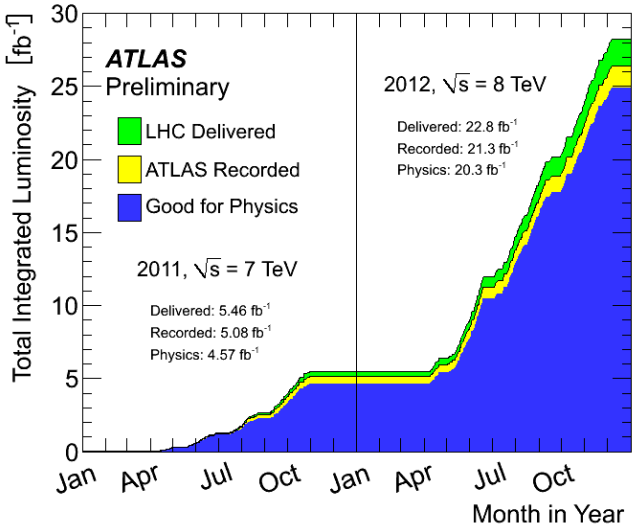


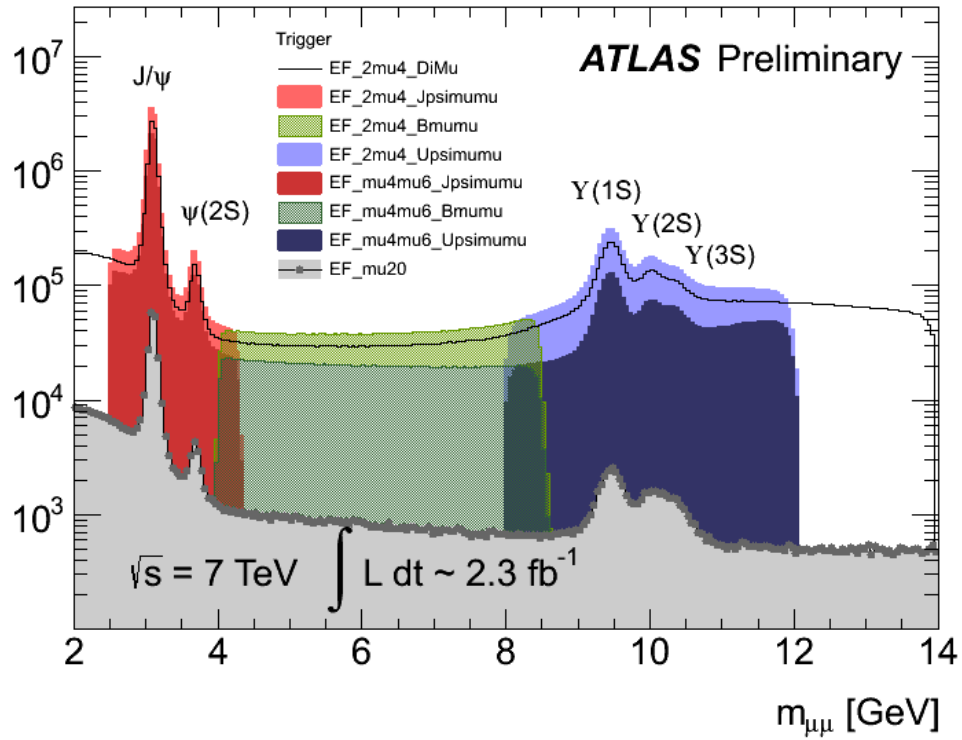




ATLAS - data

Total 5.08 fb^{-1} + 21.3 fb^{-1}

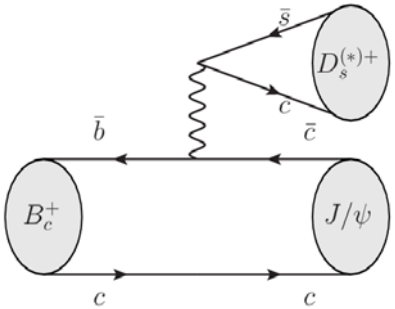




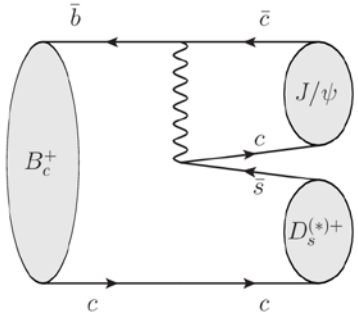
- B-phyics triggers
  - Single muon and di-muon triggers with different p_T thresholds and dimuon invariant mass ranges.
  - J/ψ Topological triggers J/ψ ->$\mu^+\mu^-$: 2.5 – 4.3 GeV
- Triple muon triggers
  - require one L1 muon then search for second and third muon in inner detector tracks.

B_c->$J/\psi D_s^{(*)+}$ branching ratio

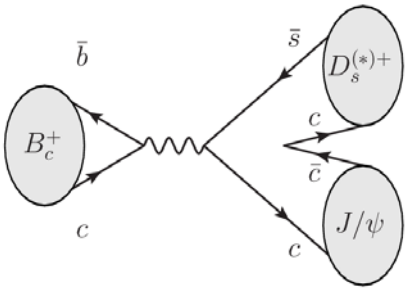
- Decays with a charmonium and a $D_s^{(*)+}$ meson
  - Represent $\bar{b}$ -> $\bar{c}c\bar{s}$ processes
  - Or annihilation process
  - First observed by LHCb.



Color favor Spectator



Colour-suppressed spectator

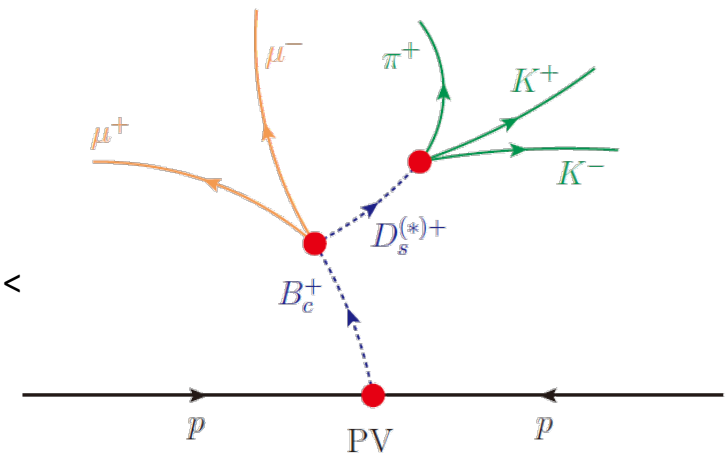


Annihilation

- Branching ratio measured
  - B_c->$J/\psi D_s$
  - B_c->$J/\psi D_s^*$
  - B_c->$J/\psi\pi$ is used as reference channel

B_c->$J/\psi D_s^{(*)+}$ branching ratio - selection

- Combination of 2011 and 2012 sample, 4.9 + 20.6 fb^{-1}
- Data collected using single muon, di-muon and three muon triggers.
- J/ψ selection
  - μ $|\eta| < 2.3$, $p_T > 3$GeV *(for single muon trigger events)*
- D_s selection
  - $D_s \to \phi(K^+K^-)\pi$
  - K^+,K^- and π^+ $p_T > 1$GeV, $|\eta| < 2.5$
  - $\cos\theta^*(\pi) < 0.8$ *(between π and D_s in the D_s rest frame)*
  - $|\cos^3\theta'(K)| > 0.15$ *(between K and π in the ϕ rest frame)*
- B_c selection
  - $1.93 < m(K^+K^-\pi) < 2.01$GeV, $2.8 < m(\mu^+\mu^-) < 3.4$GeV
  - Cascade fit, point back to PV
  - B_c $p_T > 15$GeV, $|\eta| < 2.0$, $p_T/\Sigma\, p_T(trk) > 0.1$, 0.1mm < Lxy < 10mm
  - 0.15mm < Lxy(D_s^+wrtB_c) < 10mm
  - $\cos\theta'(\pi) > -0.8$ *(between π and J/ψ in D_s rest frame)*
  - $\cos\theta^*(D_s^+) > -0.8$ *(between D_s and B_c in B_c rest frame)*



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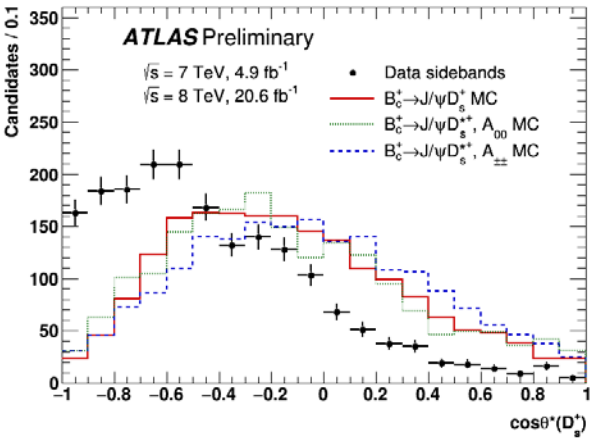
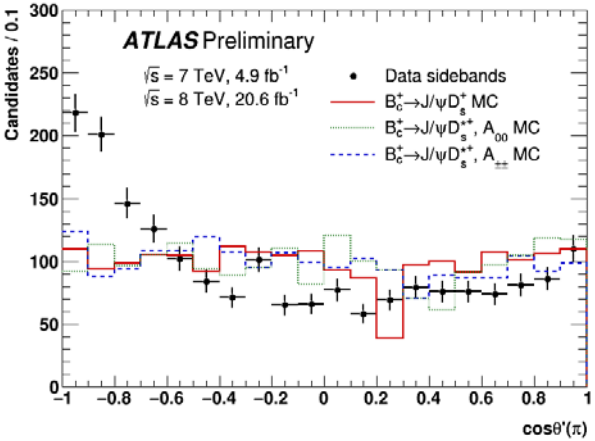


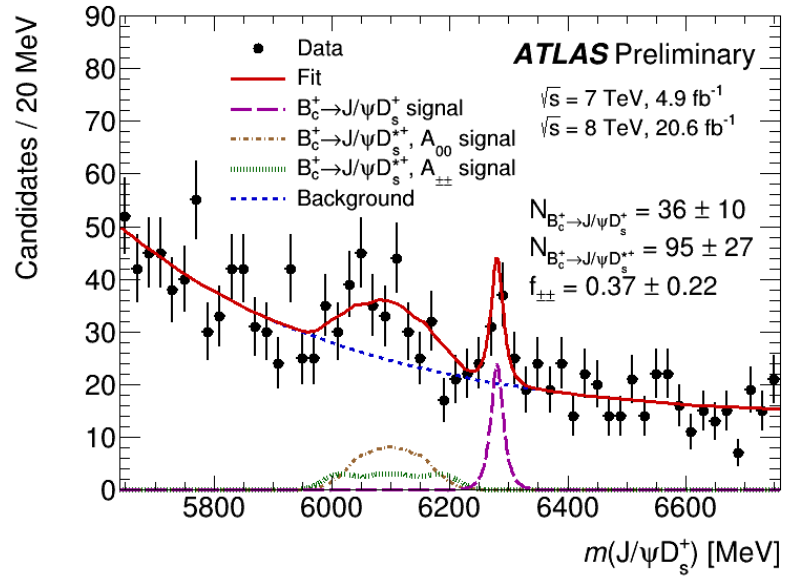


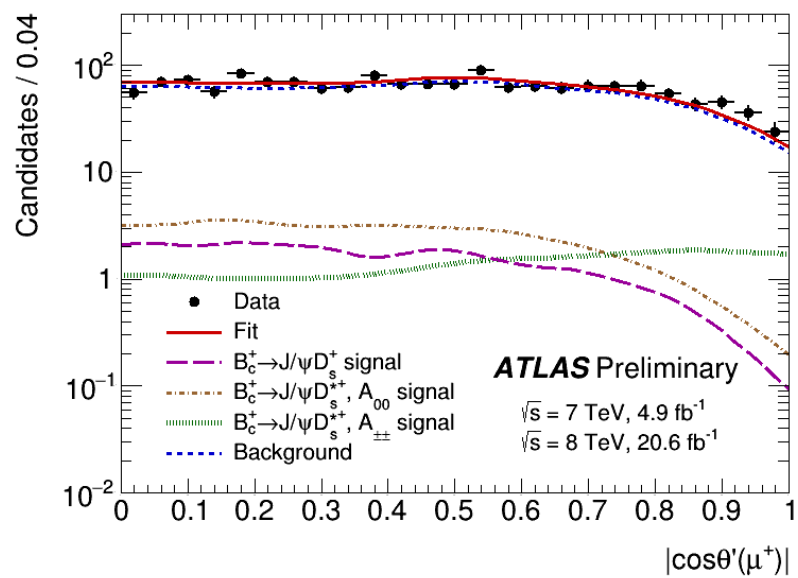
B_c->$J/\psi D_s^{(*)+}$ branching ratio - fit

- B_c->$J/\psi D_s^{(*)+}$, D_s^*->$D_s+\gamma/\pi^0$
  - γ/π^0 is too soft to be detected
    -> partially reconstructed B_c
    -> different mass shape in $J/\psi D_s^+$
  - 3 helicity final states A_{++}, A_{--}, A_{00}
    -> different kinematics
    -> different distribution of helicity angle
- Two-dimensional extended unbinned maximum likelihood fit

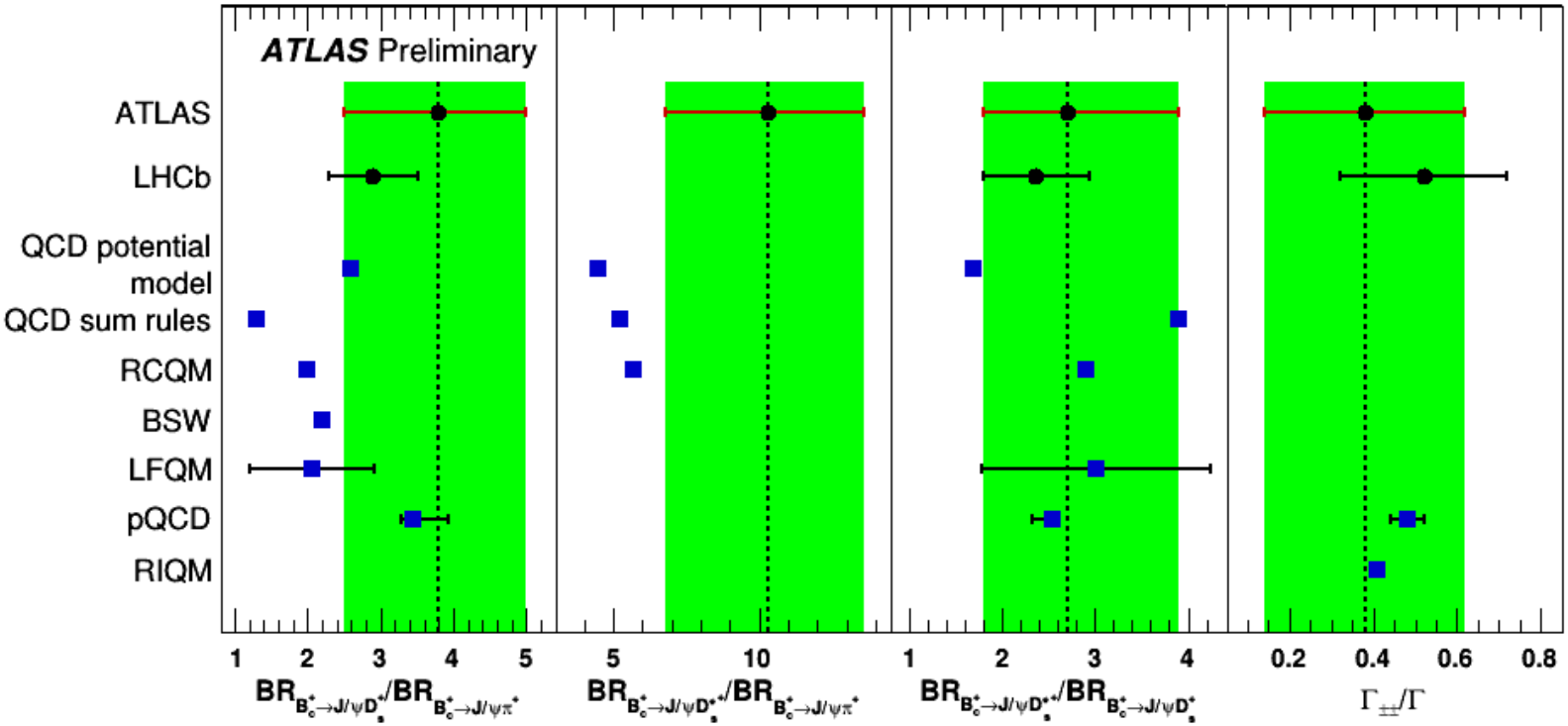
Parameter	Value
$m_{B_c^+ \to J/\psi D_s^+}$ [MeV]	6279.9 ± 3.5
$N_{B_c^+ \to J/\psi D_s^+}$	36 ± 10
$N_{B_c^+ \to J/\psi D_s^{*+}}$	95 ± 27
$f_{\pm\pm}$	0.37 ± 0.22

  - $f_{\pm\pm}$ is the relative contribution of the $A_{\pm\pm}$ amplitude





B_c->$J/\psi D_s^{(*)+}$ branching ratio



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

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

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

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

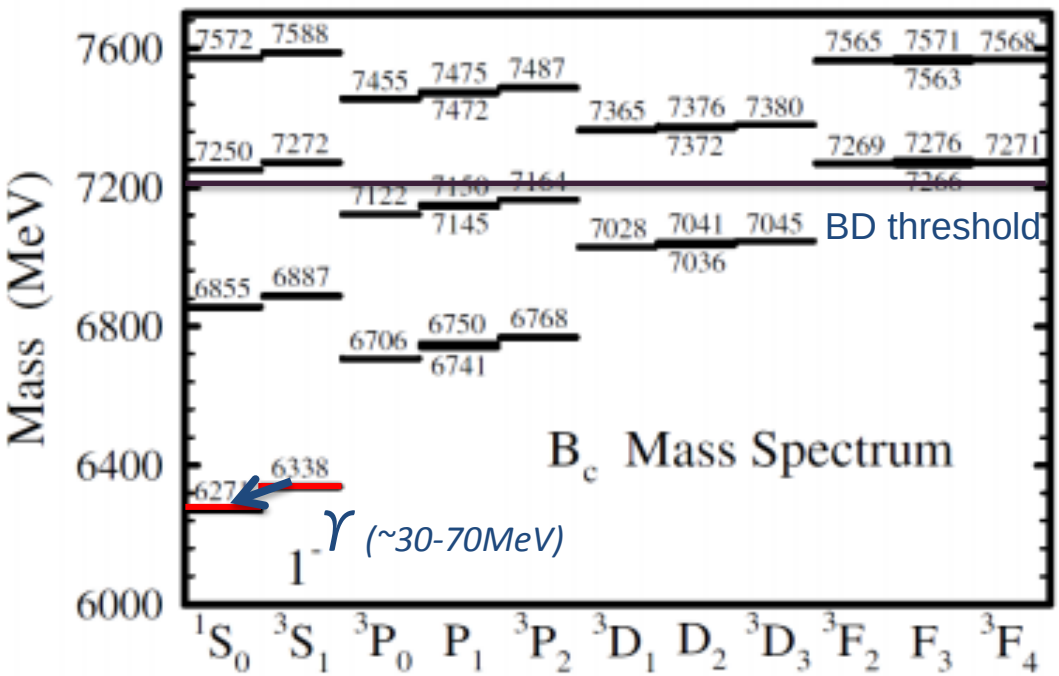
ATLAS-CONF-2015-014

$B_c(2S)$ meson – B_c mass spectroscopy

- Many theoretical predictions for the bc-family spectroscopy and properties.
- 1S - ground state
  - Pseudoscalar 1^1S_0 and vector 1^3S_1
  - Mass difference ~30-70 MeV
  - Transition via soft photon

    -> too soft to be detected
  - Can not be separate due

    to detector resolution



S. Godfrey, PRD 70, 054017(2004)

Phys. Rev. Lett. 113 (2014) 212004

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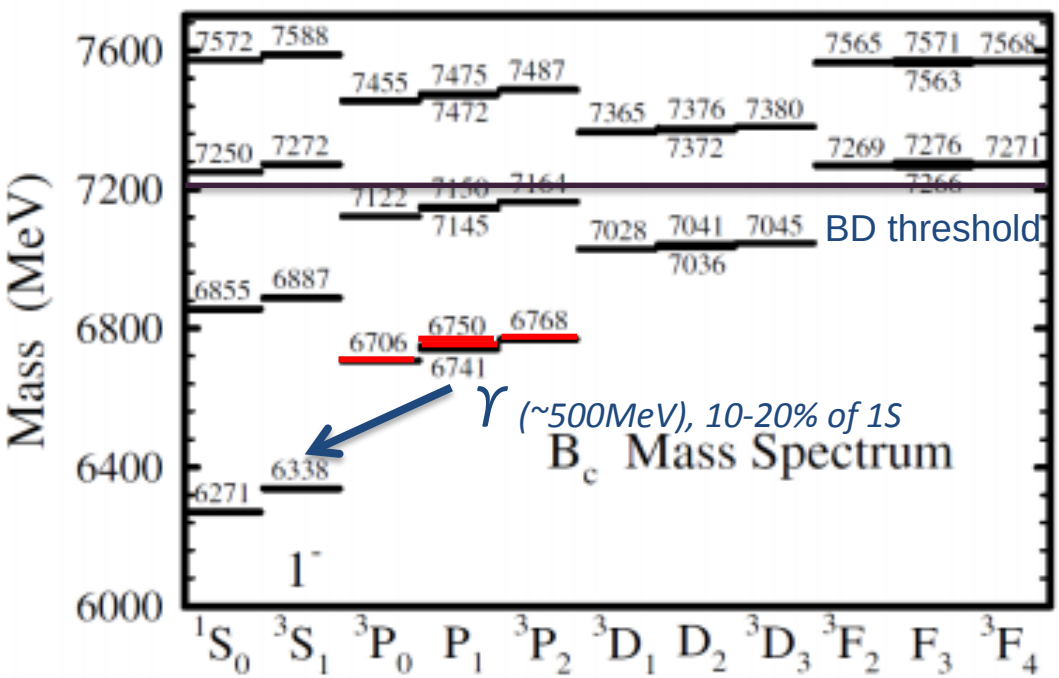
- 2P states
  - decay radiative to 1S state
  - E_γ ~500 MeV
  - Potentially detectable



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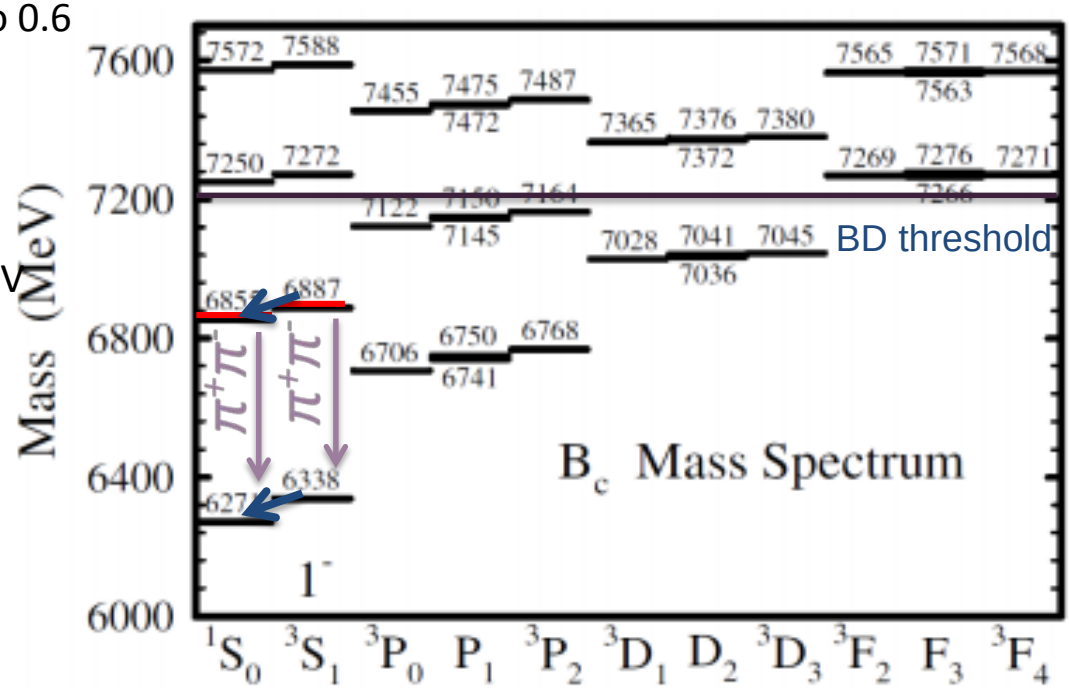
$B_c(2S)$ meson – B_c mass spectroscopy

- Many theoretical predictions for the bc-family spectroscopy and properties.
- 2S state
  - $B_c(2S_0) \rightarrow B_c(1S_0) + \pi^+\pi^-$

    $B_c(2S_1) \rightarrow B_c(1S_1) + \pi^-\pi^+$, $B_c(1S_1) \rightarrow B_c(1S_0) + \gamma_{invisible}$
  - Predicted $\sigma(2S)/\sigma(1S)$ up to 0.6
  - Br(2S → 1S ππ) ~ 75-95%.
  - Predicted mass:

    $m(B_c(2S))$ ~ 6835-6917 MeV



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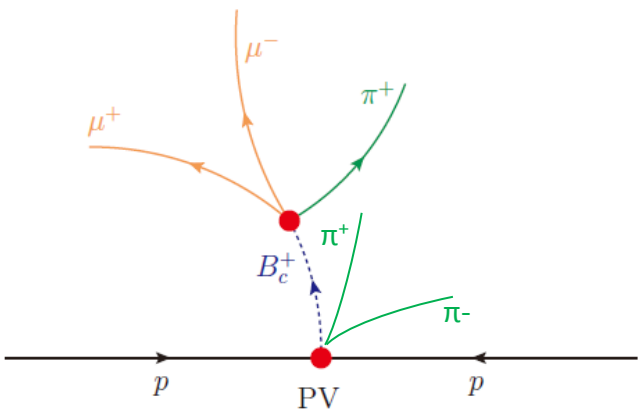
$B_c(2S)$ meson - selection

- Using both 2011 7 TeV and 2012 8 TeV data, 4.9 fb^{-1} and 19.2 fb^{-1}
- Data collected using Di-muon trigger *($p_T(\mu_{high}) > 6GeV$, $p_T(\mu_{low}) > 4GeV$)*
- Selection optimized separately for 7 TeV and 2012 8 TeV data.
- B_c selection
  - $B_c \to J/\psi\pi$
  - J/ψ muons $p_T > (6,4)$ GeV, π $p_T > 4$ GeV.
  - $d^0_{xy}/\sigma(d^0_{xy}) > 4.5_{(7\ TeV)} > 5.0_{(8\ TeV)}$
  - $p_T(B) > 15_{(7\ TeV)} > 18_{(8\ TeV)}$ GeV.



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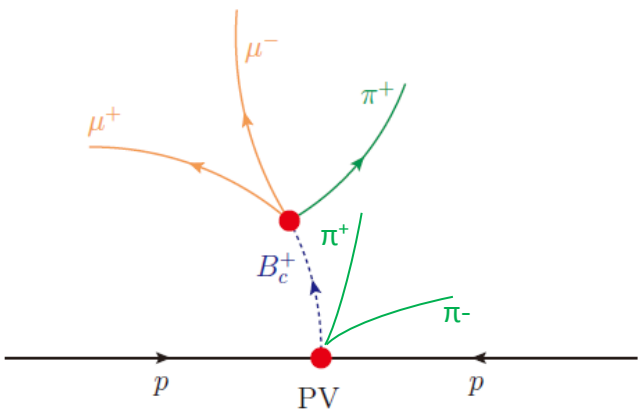
  - $p_T(B) > 15_{(7\ TeV)} > 18_{(8\ TeV)}$ GeV.
- $B_c(2S)$ candidates:
  - B_c mass with in 3σ around the PDG mass
  - π $p_T > 400$ MeV.
  - Cascade fit, no mass constraint
  - Keeping only one candidate with the best χ^2
  - Momentum pointing to the same primary vertex as the B_c
  - $\Delta z < 1mm$ (difference in z between π and leading muon) for 8 TeV data to reduce tracks associated with the reconstructed primary vertex due to pile-up .



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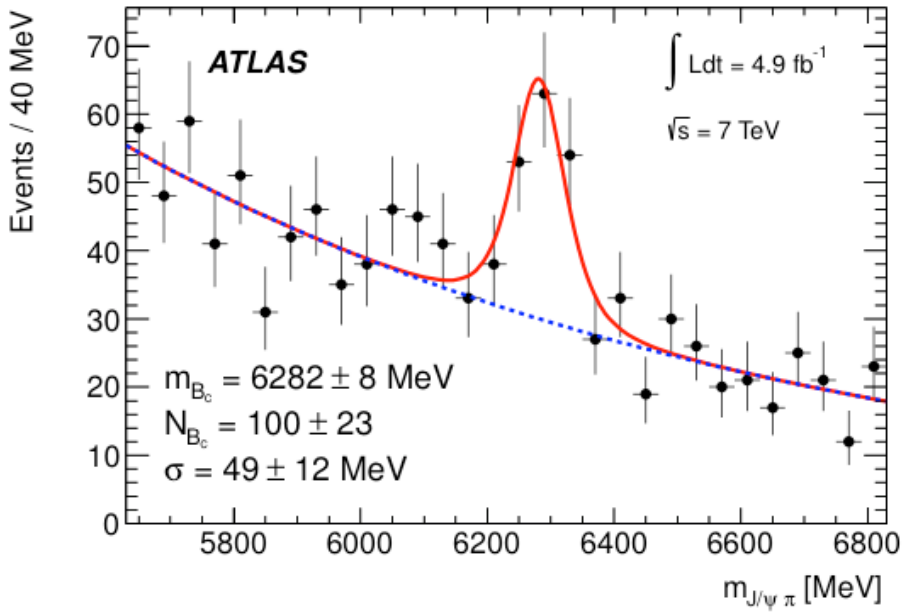
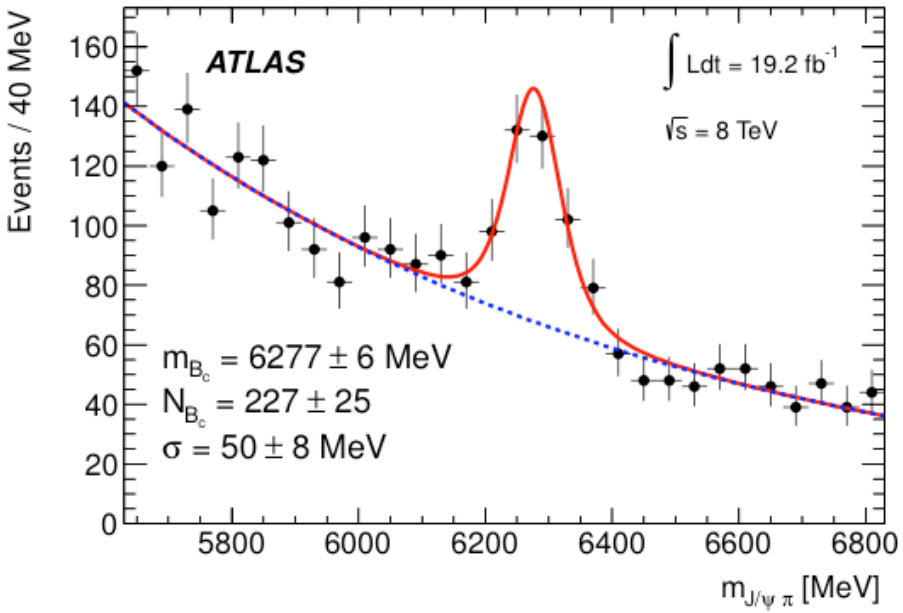
$B_c(2S)$ meson – B_c mass fit

- Extended unbinned maximum likelihood fit with per event error
- The mass of B_c is consistent in two year
- The relative yield is lower for 8 TeV data due to changes in both trigger and selections.





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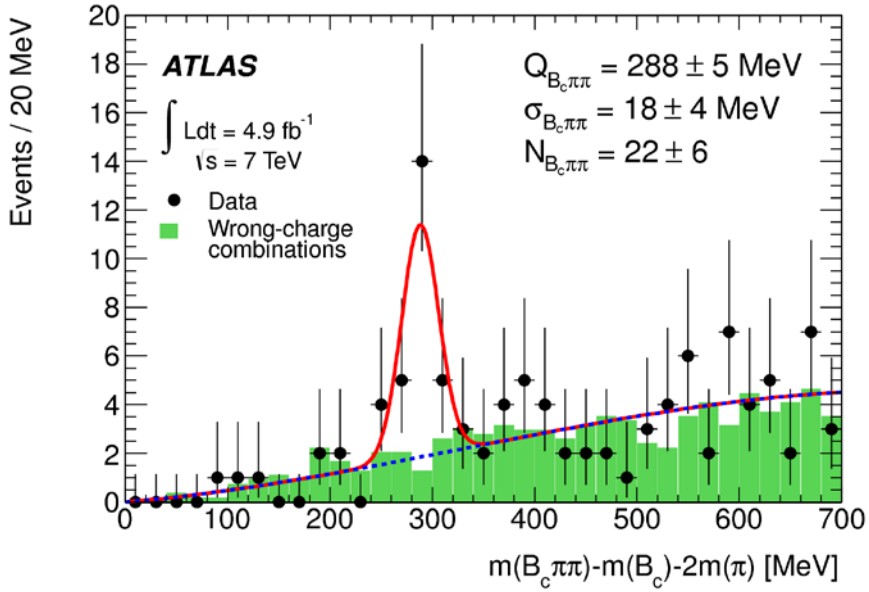
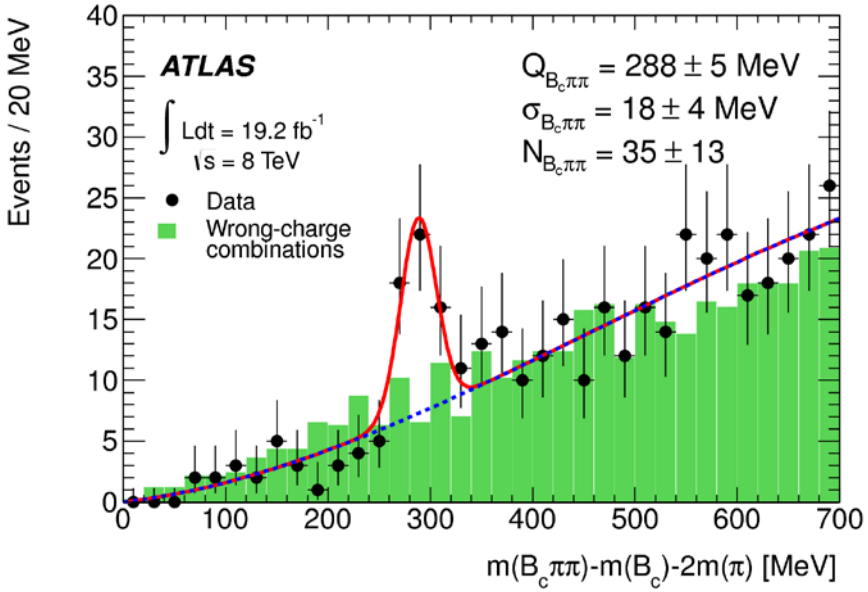
$B_c(2S)$ meson - $B_c(2S)$ mass fit

- $Q_{B_c\pi\pi} = m(B_c\,\pi^+\pi^-) - m(B_c) - m(\pi^+\pi^-)$
  - Peak at 288±5 MeV on both 7 TeV and 8 TeV data
  - No structure can be seen in the same signed combination of the pions
  - Combined significance of 5.2σ.
    - 7 TeV alone: 3.7σ
    - 8 TeV alone: 4.5σ.
  - Predicted Q value for B_c (2S) is ~300MeV
- $B_c(2S)$ is observed with mass of $6842 \pm 4_{stat} \pm 5_{syst}$ MeV.





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Summary

- The branching ratio of $B_c \to J/\psi D_s^{(*)+}$ has been measured.
  - Relative branching ratio of $B_c \to J/\psi D_s^{(*)+}/B_c \to J/\psi\pi$, $B_c \to J/\psi D_s^{*}/B_c \to J/\psi D_s$
  - Fraction of transvers polarization in $B_c \to J/\psi D_s^{*}$ decay
  - Result is consistent with LHCb and various predictions.

- B_c meson has a rich spectroscopy predicted.
  - Only the 1S state has been observed before.
  - ATLAS made the first observation of $B_c(2S)$ state
  - $m = 6842 \pm 4_{stat} \pm 5_{syst}$ MeV, 5.2σ significance.