Search for excited B_c^+ states at LHCb

Liupan An
On behalf of the LHCb collaboration
Tsinghua University

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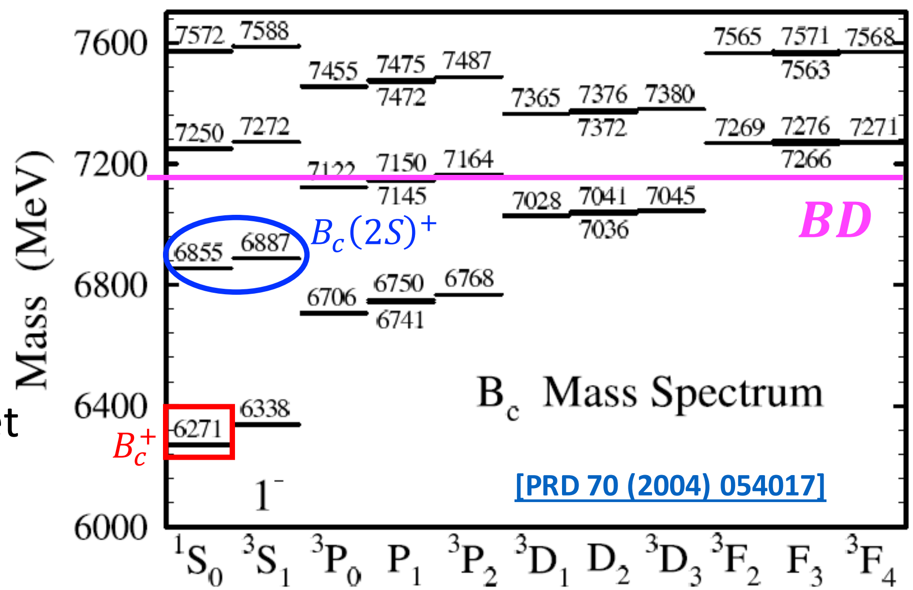
Outline

https://arxiv.org/abs/1712.04094

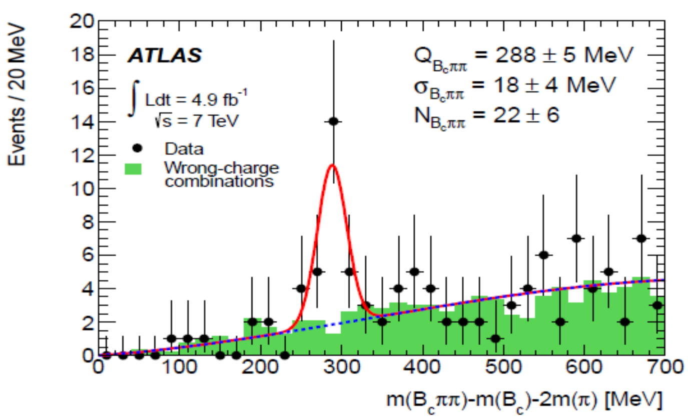
- Introduction
- The LHCb detector
- Analysis strategy
- Selection
- Upper limits
- Summary

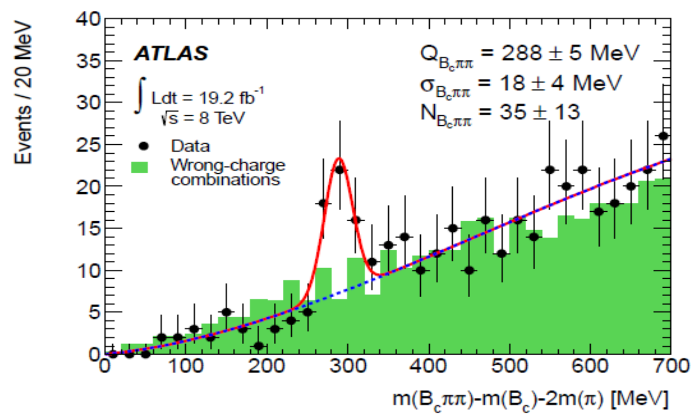
Introduction

- B_c^+: the only meson family containing two different heavy flavor quarks
  - ✓A rich mass spectrum predicted by various QCD potential models and Lattice QCD
  - ✓States below BD threshold can only undergo radiative or hadronic transitions to the ground state B_c^+ which decays weakly
  - ✓Only B_c^+ and $B_c(2S)^+$ observed so far



- ATLAS observed $B_c(2S)^+$ using $B_c^+\pi^+\pi^-$
  - ✓No discrimination between
    - $B_c(2^1S_0)^+ \rightarrow B_c^+\pi^+\pi^-$
    - $B_c(2^3S_1)^+ \rightarrow B_c^{*+}(\rightarrow B_c^+\gamma)\pi^+\pi^-$
  - ✓No confirmation from other experiments yet
- Important to perform the search at LHCb!

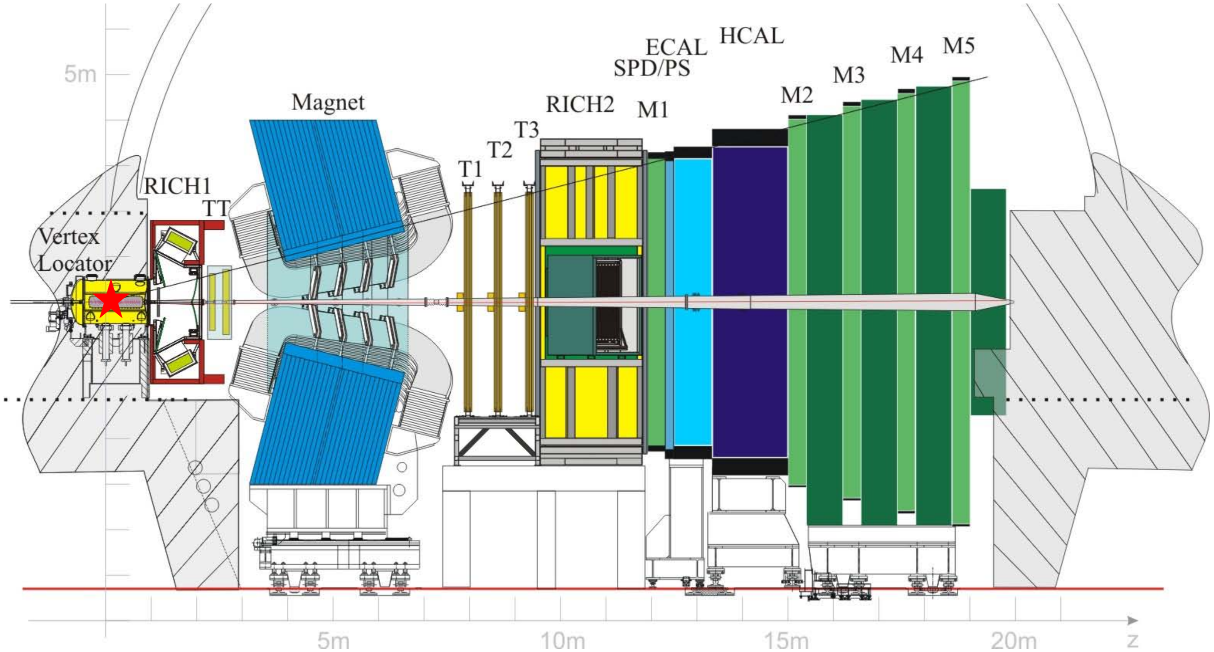


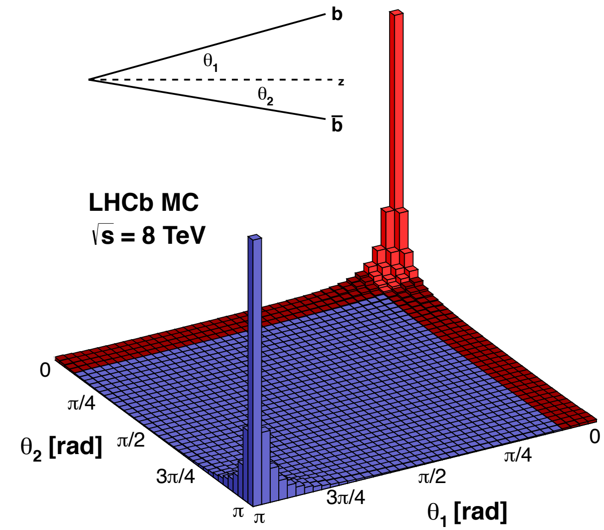


[PRL 113 (2014) 12004]

The LHCb detector

- A single-arm forward region spectrometer covering $2 < \eta < 5$
  - ✓ Collected the largest B_c^+ sample so far
  - ✓ Has a better mass resolution providing larger possibility to distinguish $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$ if they don't overlap





[JINST 3 (2008) S08005]

- ✓ **Vertex Locator:** $\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
- ✓ **Tracking (TT, T1-T3):** $\Delta p/p = 0.5 - 0.6\%$ for $5 < p < 100\ \mathrm{GeV}/c$
- ✓ **RICHs:** $\varepsilon(K \to K) \sim 95\%$ @ misID rate $(\pi \to K) \sim 5\%$
- ✓ **Muon system (M1-M5):** $\varepsilon(\mu \to \mu) \sim 97\%$ @ misID rate $(\pi \to \mu) \sim 1 - 3\%$
- ✓ **ECAL:** $\sigma_E/E \sim 10\%/\sqrt{E} \otimes 1\%$ (E in GeV)
- ✓ **HCAL:** $\sigma_E/E \sim 70\%/\sqrt{E} \otimes 10\%$ (E in GeV)

Analysis strategy

❖Data sample: pp collision data at $\sqrt{s} = 8$ TeV corresponding to 2 fb^{-1}

❖MC sample: BcVegPy generator used to simulate the production of B_c^+ mesons
[CPC 174 (2006) 241]

➢ $B_c^{(*)}(2S)^+$ reconstructed using $B_c^+\pi^+\pi^-$ with $B_c^+ \to J/\psi\pi^+, J/\psi \to \mu^+\mu^-$

- $B_c(2^1S_0)^+ \to B_c^+\pi^+\pi^-$
- $B_c(2^3S_1)^+ \to B_c^{*+}(\to B_c^+\gamma)\pi^+\pi^-$ with γ not reconstructed

⇒ $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$ mass peak difference is

$$\Delta M = \Delta M(1S) - \Delta M(2S)$$
$$= \left(M(1^3S_1) - M(1^1S_0)\right) - \left(M(2^3S_1) - M(2^1S_0)\right)$$

➢ Mass region of interest for $B_c^{(*)}(2S)^+$ search

✓Theories predict

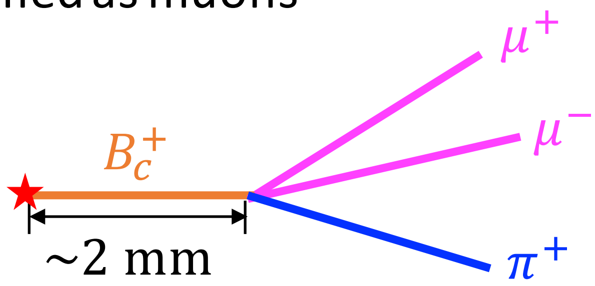
$M(B_c(2^1S_0)^+) \in (6830{,}6890)\ \text{MeV}/c^2$ & $\Delta M \in [0{,}35]\,\text{MeV}/c^2$

$M(B_c(2^3S_1)^+)_{\text{rec}} \in (6795{,}6890)\ \text{MeV}/c^2$

✓ATLAS measurement $M(B_c(2S)^+) = 6842 \pm 4(\text{stat}) \pm 5(\text{syst})\text{MeV}/c^2$

Selection of B_c^+

- **Trigger requirement**
  - ✓Hardware: at least one muon with high p_{T} or a hadron with high E_{T}
  - ✓Software: two muon tracks or three charged tracks with high p_{T} forming a secondary vertex with significant displacement from the interaction point
- **Offline cuts**
  - ✓$\mu^{\pm}$: $p_{\mathrm{T}} > 0.55\ \mathrm{GeV}/c$, good track-fit quality, identified as muons
  - ✓$J/\psi \to \mu^+\mu^-$: $M(\mu^+\mu^-) \in [3040,3140]\ \mathrm{MeV}/c^2$, muons originate from a common vertex
  - ✓π^+: $p_{\mathrm{T}} > 1.0\ \mathrm{GeV}/c$, good track-fit quality, isolated from primary vertex
  - ✓$B_c^+ \to J/\psi\pi^+$: J/ψ and π^+ form a common vertex, come from PV, $\tau > 0.2$ ps

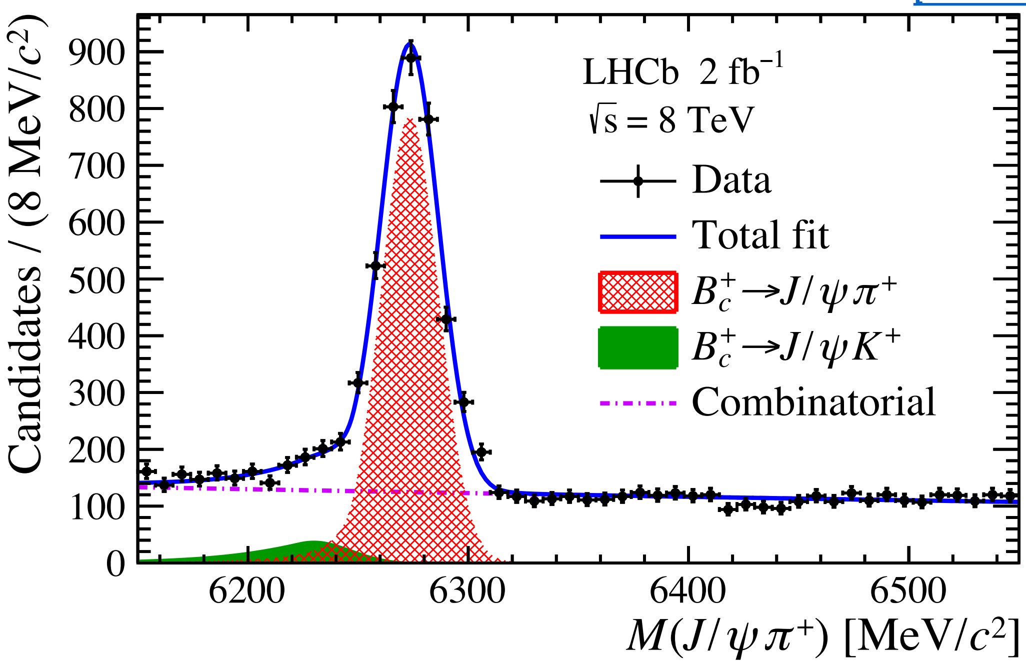


- **BDTG classifier applied**
  - ✓ Input variables: χ^2_{IP} of all particles;
    p_{T} of $\mu^{\pm}$, J/ψ and π^+;
    decay length, decay time and χ^2_{vtx} of B_c^+
  - ✓ BDTG threshold chosen to maximize the signal significance $S/\sqrt{S+B}$

B_c^+ signal yield

- ➢Determined with unbinned maximum likelihood fit to $J/\psi\pi^+$ invariant mass spectrum
  - ✓Signal: parameterized DSCB functions (Gaussian function with power tails)
  - ✓Combinatorial background: exponential function
  - ✓Contamination from $B_c^+ \to J/\psi K^+$: sum of 2 CB functions; fixed to MC

[arXiv:1712.04094]



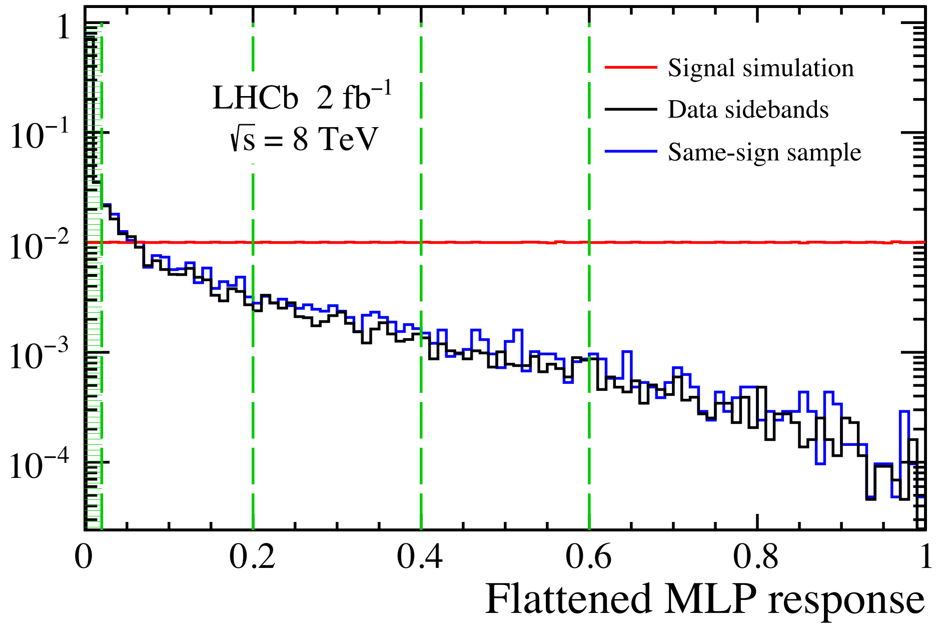
- ➢Signal yield 3325 ± 73, compared to 327 ± 34 in the ATLAS measurement

Selection of $B_c^{(*)}(2S)^+$

- Cuts
  - ✓ B_c^+: selected B_c^+ with $M(J/\psi\pi^+) \in [6200,6340]$ MeV$/c^2$
  - ✓ $\pi^\pm$: $p_\mathrm{T} > 0.25$ GeV$/c$, $p > 2$ GeV$/c$, good track-fit quality, identified as pions
  - ✓ $B_c^{(*)}(2S)^+$: good vertex-fit quality
- MLP classifier
  - ✓ Input variables: $p_\mathrm{T}(B_c^+)$; $B_c^{(*)}(2S)^+$ χ^2_vtx;
    decay angle of B_c^+ and $\pi^\pm$;
    angle in XY-plane between daughters of $B_c^{(*)}(2S)^+$;
    minimum cosine value of the angles between daughters.
  - ✓ Inputs have similar distributions for $B_c(2^1S_0)^+$ & $B_c(2^3S_1)^+$
  - ✓ Signal sample: $B_c(2^1S_0)^+$ & $B_c(2^3S_1)^+$ MC
    Background sample: sidebands in $M(B_c^+\pi^+\pi^-) \in [6555,6785] \cup [6900,7500]$ MeV$/c^2$

MLP response

- ➢The MLP output of signal sample is flattened, making the background candidates cluster near zero
- ➢Data split into 4 Categories: (0.02,0.2), [0.2,0.4), [0.4,0.6) and [0.6,1.0], with 98% of the signal retained

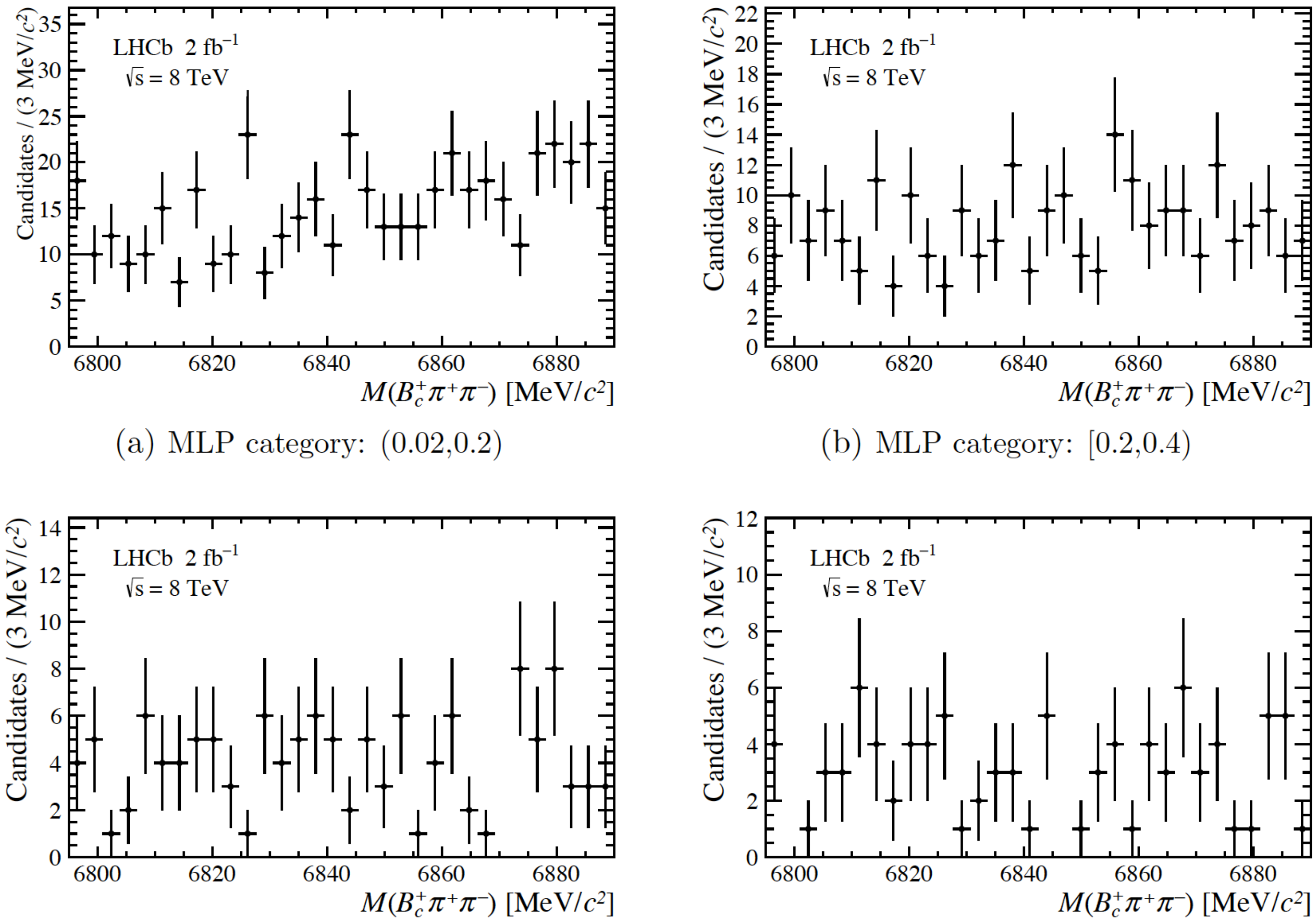


✓Clear discrimination between signal and background

✓Good agreement between data sidebands and same-sign sample, which is later used to control the background shape

$B_c^+\pi^+\pi^-$ mass spectrum

- No evidence of $B_c^{(*)}(2S)^+$ signal. Upper limits to be given.



(a) MLP category: (0.02,0.2)

(b) MLP category: [0.2,0.4)

(c) MLP category: [0.4,0.6)

(d) MLP category: [0.6,1.0]

[arXiv:1712.04094]

Upper limits

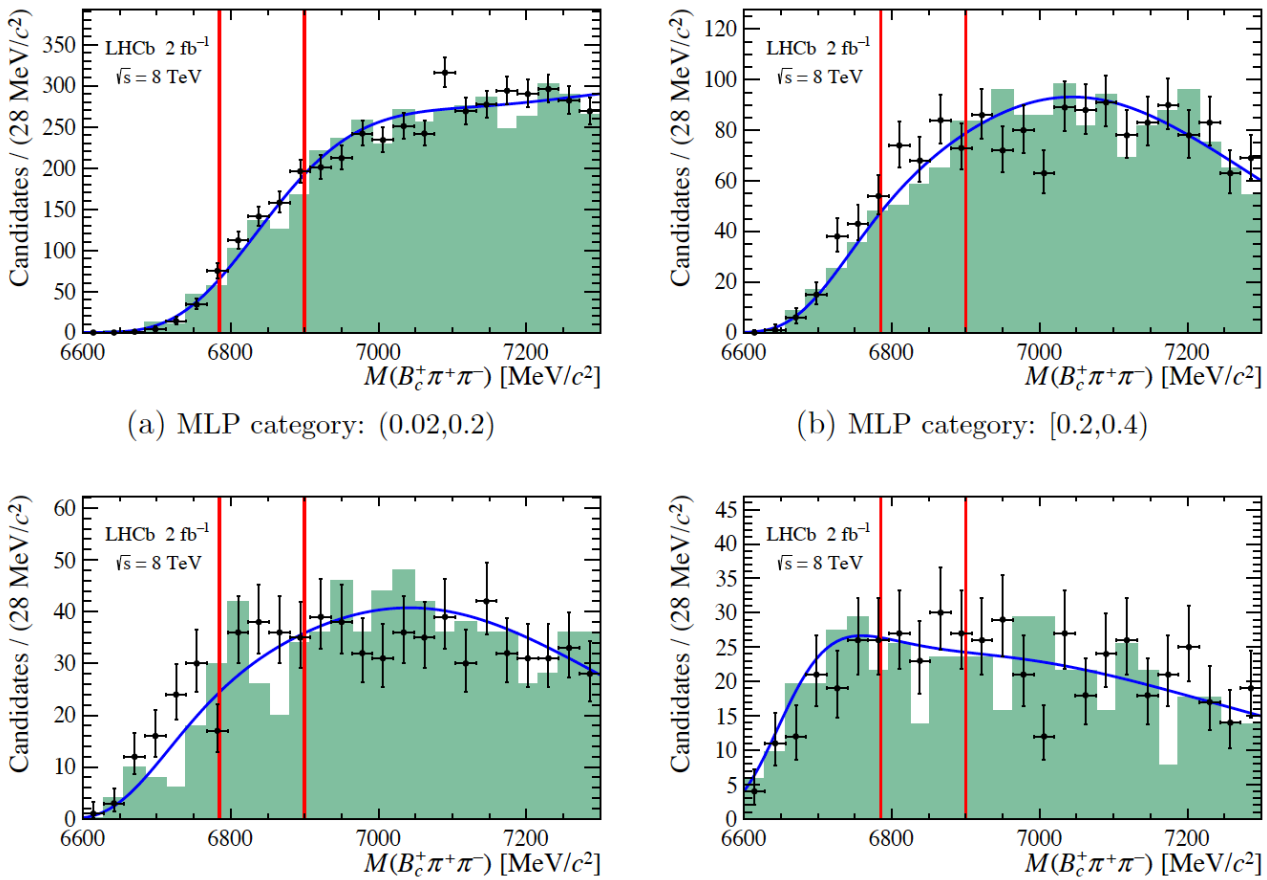
- Set upper limits to for two cases

$$\mathcal{R} = \frac{\sigma\left(B_c^{(*)+}(2S)\right)\cdot\mathcal{B}\left(B_c^{(*)+}(2S)\to B_c^+\pi^+\pi^-\right)}{\sigma(B_c^+)}$$
$$= \frac{N\left(B_c^{(*)+}(2S)\right)}{N(B_c^+)}\times\frac{\varepsilon(B_c^+\to J/\psi\pi^+)}{\varepsilon\left(B_c^{(*)+}(2S)\to B_c^+\pi^+\pi^-\right)\cdot\varepsilon'(B_c^+\to J/\psi\pi^+)}$$

  - ✓ $\Delta M = 0$; fully overlapping; upper limits for $\mathcal{R}(B_c(2^1S_0)^+) + \mathcal{R}(B_c(2^3S_1)^+)$
  - ✓ $\Delta M \neq 0$; fully separated; $\Delta M = 15\ /\ 25\ /\ 35\ \mathrm{MeV}/c^2$
- Scan region: $M(B_c(2^1S_0)^+) \in (6830, 6890)\ \mathrm{MeV}/c^2$
- Scan window: $\left[M - 1.4\times\sigma\left(B_c^{(*)}(2S)^+\right), M + 1.4\times\sigma\left(B_c^{(*)}(2S)^+\right)\right]$
  - ✓ Gives the best sensitivity
  - ✓ σ determined from MC and scaled according to $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$
  - ✓ $\sigma(B_c(2^1S_0)^+)\sim 2\ \mathrm{MeV}; B_c(2^3S_1)^+\sim 3\ \mathrm{MeV}$
- CLs method: upper limits determined from the CL_s vs. $\mathcal{R}$ curve
  - ✓ Statistical test $\mathcal{Q} = \frac{\mathcal{L}(N_{\mathrm{obs}};N_S+N_B)}{\mathcal{L}(N_{\mathrm{obs}};N_B)}$; $\mathcal{L}(n;x) = \frac{e^{-x}}{n!}x^n$; $\mathcal{Q}_{\mathrm{tot}} = \prod_i^{\mathrm{Nbins}}\mathcal{Q}_i$
  - ✓ $CL_{\mathrm{s+b}} = P_{\mathrm{s+b}}(ln\mathcal{Q} \leq ln\mathcal{Q}_{\mathrm{obs}})$; $CL_{\mathrm{b}} = P_{\mathrm{b}}(ln\mathcal{Q} \leq ln\mathcal{Q}_{\mathrm{obs}})$
  - ✓ $CL_{\mathrm{s}} = CL_{\mathrm{s+b}}/CL_{\mathrm{b}}$

Background determination

- Determined by extrapolating from sidebands
  - ✓Model: sum of two $(x-\mathrm{offset})^{\mathrm{power}} \times \exp(-\mathrm{coeff}\cdot(x-\mathrm{offset}))$ parameters fixed to fit of same-sign distribution



(a) MLP category: (0.02,0.2)

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[arXiv:1712.04094]

Efficiencies

- Estimated using simulated samples
  - ✓Pion PID efficiency calibrated according to data sample
  - ✓Tracking efficiency of two pions corrected according to data sample
- The efficiency of reconstructing B_c^+ cancel well between the $B_c^{(*)}(2S)^+$ and B_c^+ channels

[arXiv:1712.04094]

MLP category	(0.02, 0.2)	[0.2, 0.4)	[0.4, 0.6)	[0.6, 1.0]
		Efficiencies in %		
$B_c(2S)^+$	0.148 ± 0.006	0.140 ± 0.006	0.130 ± 0.006	0.256 ± 0.008
$B_c^*(2S)^+$	0.118 ± 0.003	0.140 ± 0.004	0.144 ± 0.004	0.288 ± 0.005

Before MLP: $\varepsilon(B_c(2^1S_0)^+) = 0.0091 \pm 0.0002, \varepsilon(B_c(2^3S_1)^+) = 0.0086 \pm 0.0001$
$\varepsilon(B_c^+) = 0.0931 \pm 0.0005$

- Variation of efficiency with respect to $B_c^{(*)}(2S)^+$ mass studied using simulated samples with different mass settings

Systematic uncertainties

MLP category	(0.02, 0.2)	[0.2, 0.4)	[0.4, 0.6)	[0.6, 1.0]
$N_{B_c^+}$	1.0%			
$\varepsilon_{B_c^+}$	0.5%			
N_B	4.2%	9.0%	15.0%	6.9%
$B_c(2S)^+ \to B_c^+ \pi^+ \pi^-$				
$\varepsilon_{B_c(2S)^+}$	4.6%	4.7%	4.9%	3.6%
Efficiency variation *vs.* $M(B_c(2S)^+)$	0.6%	1.3%	1.8%	2.7%
$B_c^*(2S)^+ \to B_c^{*+} \pi^+ \pi^-$				
$\varepsilon_{B_c^*(2S)^+}$	3.5%	3.3%	3.3%	2.7%
Efficiency variation *vs.* $M(B_c^*(2S)^+)$	1.0%	1.8%	2.5%	4.3%

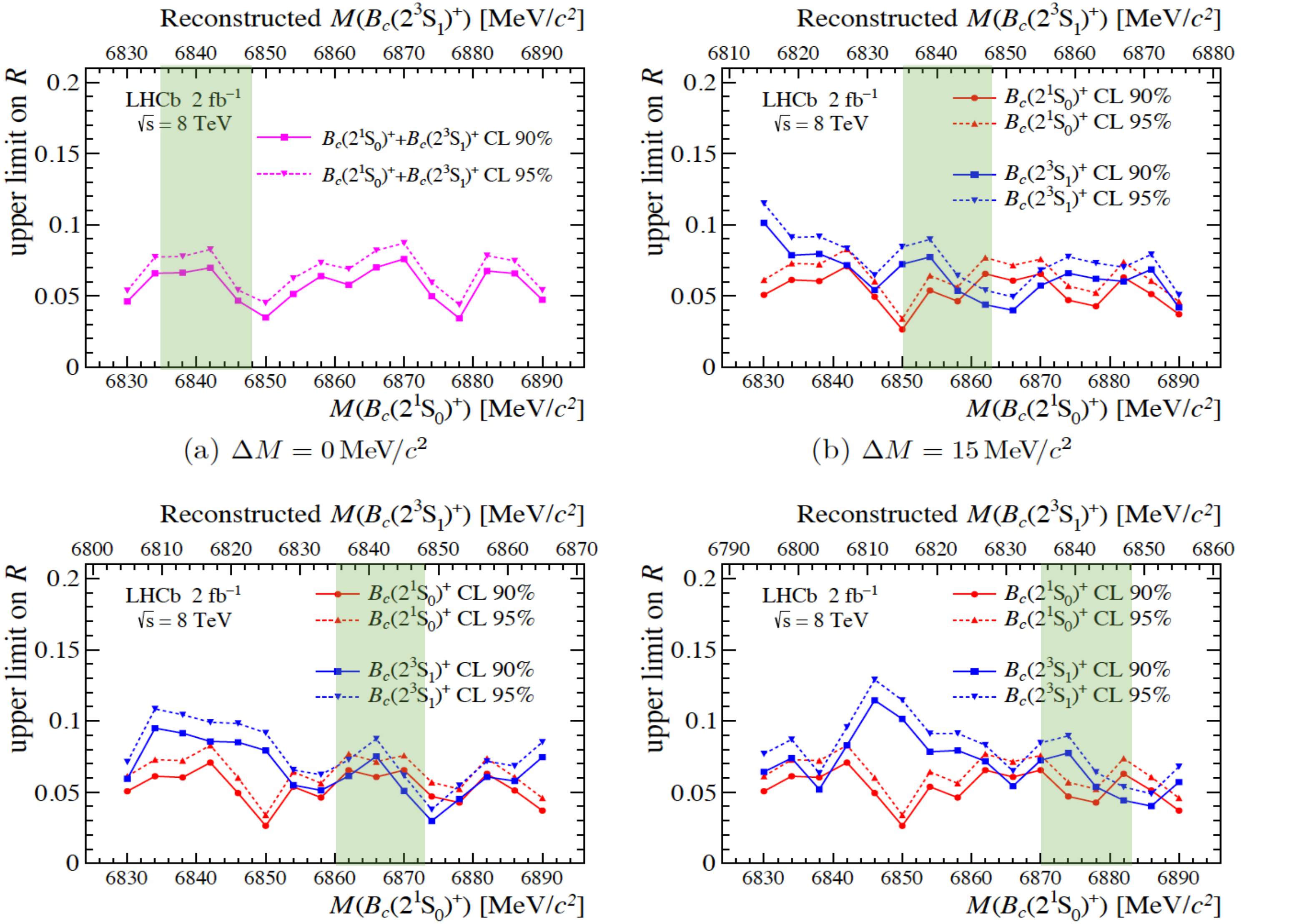
[arXiv:1712.04094]

Largest contribution is systematic uncertainty of N_B

1) Disagreement between data and same-sign: generating toy MC samples with sidebands of real data and signal region taken from same-sign sample
2) Imperfect modelling: using alternative empirical model

Results

➢ Theories predict $\mathcal{R}(B_c(2^3S_1)^+) > 2\times\mathcal{R}(B_c(2^1S_0)^+) \Rightarrow$ overlapped or $B_c(2^3S_1)^+$



(a) $\Delta M = 0\,\mathrm{MeV}/c^2$

(b) $\Delta M = 15\,\mathrm{MeV}/c^2$

(c) $\Delta M = 25\,\mathrm{MeV}/c^2$

(d) $\Delta M = 35\,\mathrm{MeV}/c^2$

[arXiv:1712.04094]

Comparison to ATLAS

- LHCb: forward y and smaller p_{T} ⇔ ATLAS: central y and larger p_{T}
- $\mathcal{R}$ has no significant dependence on p_{T} and y of B_c^+ according to theories, so the upper limits can be compared with the ATLAS measurement
- Comparison with ATLAS

	$\sqrt{s} = 7\,\mathrm{TeV}$	$\sqrt{s} = 8\,\mathrm{TeV}$	
ATLAS	$(0.22 \pm 0.08\,(\mathrm{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\mathrm{stat}))/\varepsilon_8$	[PRL 113 (2014) 12004]
LHCb	–	$< [0.04, 0.09]$	[arXiv:1712.04094]

  - ✓ $\varepsilon_{7,8}$ is the efficiency to reconstruct $B_c^{(*)}(2S)^+$ w.r.t. the B_c^+ signals; ≤ 1 but much larger than that of LHCb due to the larger p_{T}
  - ✓ LHCb upper limits at 95% CL in the vicinity of the ATLAS peak at $\sim 6842\ \mathrm{MeV}/c^2$

- The LHCb and ATLAS measurements are compatible only in case of very large values of $\varepsilon_{7,8}$

Summary

- Search for $B_c^{(*)}(2S)^+ \to B_c^+\pi^+\pi^-$ using 2 fb^{-1} data at $\sqrt{s} = 8$ TeV
  - ✓ No evidence of signal
  - ✓ Upper limits set for different mass hypotheses
  - ✓ No argument of clear discrepancy with the ATLAS observation

- A good chance to confirm the $B_c^{(*)}(2S)^+$ observation with the full dataset
  - ✓ RunI (2011-2012): $\mathcal{L}_{\mathrm{int}} = 1\ \mathrm{fb}^{-1}$ @ 7 TeV & 2 fb^{-1} @ 8 TeV; $\sigma(b\bar{b}) \approx 250\ \mu\mathrm{b}^{-1}$ @ 7 TeV
  - ✓ RunII (2015-2018): $\mathcal{L}_{\mathrm{int}} = 5\ \mathrm{fb}^{-1}$ @ 13 TeV ; $\sigma(b\bar{b}) \approx 500\ \mu\mathrm{b}^{-1}$ @ 13 TeV

Thank you!