New results on $B_c(2S)$ and $B_c^*(2S)$ production

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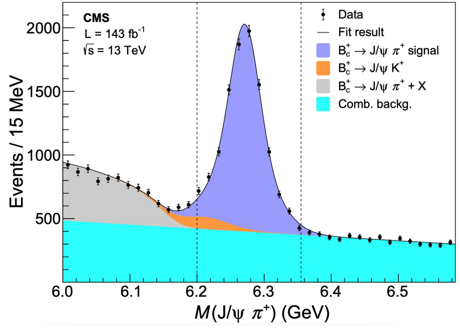
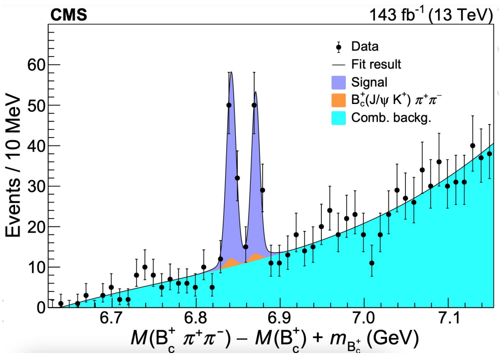
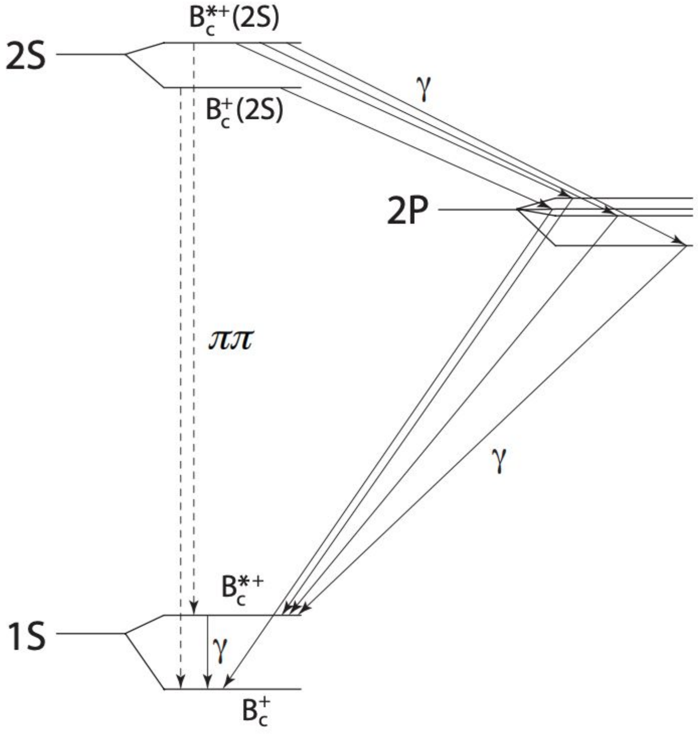




Content

Introduction



E. J. Eichten and C. Quigg, "Mesons with beauty and charm: Spectroscopy", Phys. Rev. D 49 (1994) 5845, doi:10.1103/PhysRevD.49.5845, arXiv:hep-ph/9402210.

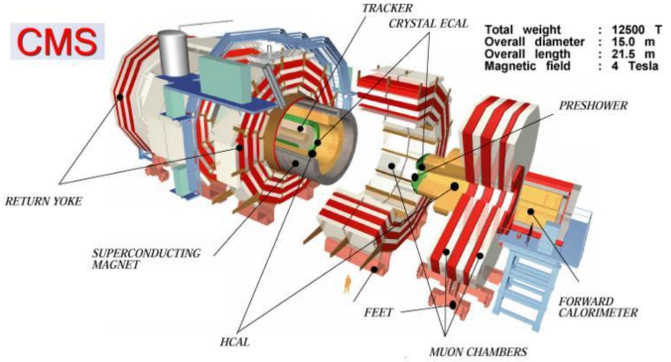
- Transitions between the lightest Bc states, with solid and dashed lines indicating the emission of photons and pion pairs, respectively.The CMS experiment recently reported the observation of $B_C(2S)^+$ and $B_C^*(2S)^+$ states.
- This new result complements the previous observation with the measurement of the $B_C(2S)^+$ to B_C^+, $B_C^*(2S)^+$ to B_C^+, and $B_C^*(2S)^+$ to $B_C(2S)^+$ cross section ratios
- The invariant mass distributions of the pair of pions emitted in the

$$B_c^{(*)}(2S)^+ \rightarrow B_c^{(*)+}\pi^+\pi^-$$

decays are also presented

Experimental Apparatus, Data Sample, and Event Selection

- Muons are measured in pseudorapidity range, $|\eta|<2.4$ by the muon subsystem.
- Single muon trigger efficiency over 90%, efficiency to reconstruct and identify muons > 96%
- Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the endcaps



$$\cos\theta = \vec{L}_{xy} \cdot \vec{p}_{\mathrm{T}} / (L_{xy}\, p_{\mathrm{T}})$$

Data of 13 TeV pp collisions corresponding to 143 fb^{-1} of integrated luminosity. Measurement in phase space region of B_C^+ p_T > 5 GeV, and $|\eta|$ < 2.4

- Dimuon Trigger: 2.8 < $m(\mu\mu)$ < 3.3 GeV, vertex fit χ^2 probability > 10%, distance of closest approach between muons < 0.5 cm, distance between dimuon vertex and beam axis L_{xy} > three time its uncertainty
- Muons: pT > 4 GeV, $|\eta|<2.5$, pT must be aligned with Lxy by $\cos\theta > 0.9$
- Trigger requires a third track: compatible with being produced at dimuon vertex (normalized χ^2 < 10), pT > 1.2GeV, $|\eta|<2.5$, significance of impact parameter > 2

Measurement of Cross Section Ratios: Introduction

- The ratios of cross sections are derived from the ratios of measured yields corrected by detection efficiencies
- The Ɓ parameters are the unknown branching fractions of the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ decays
- The $B_C^{*+} \to B_C^+ + \gamma$, decay is assumed with a branching fraction of 100%. However the low-energy photon is not reconstructed

$$R^+ \equiv \frac{\sigma(B_c(2S)^+)}{\sigma(B_c^+)}\mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-) = \frac{N(B_c(2S)^+)}{N(B_c^+)}\,\frac{\epsilon(B_c^+)}{\epsilon(B_c(2S)^+)},$$

$$R^{*+} \equiv \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c^+)}\mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-) = \frac{N(B_c^*(2S)^+)}{N(B_c^+)}\,\frac{\epsilon(B_c^+)}{\epsilon(B_c^*(2S)^+)},$$

$$R^{*+}/R^+ = \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c(2S)^+)}\,\frac{\mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-)}{\mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-)} = \frac{N(B_c^*(2S)^+)}{N(B_c(2S)^+)}\,\frac{\epsilon(B_c(2S)^+)}{\epsilon(B_c^*(2S)^+)}.$$

Measurement of Cross Section Ratios: Measurement of the B_C^+ yield

- B_C^+ candidates are required to have p_T>15GeV, |y|<2.4, kinematic vertex fit χ^2(prob)>10%, decay length>100μm.
- Unbinned maximum likelihood fit: signal=double gaussian, background=(a)combinatorial-first order poly,(b)partially reconstructed J/ψ+π+X - generalized ARGUS function, (c)J/ψ+K - fixed shape by simulation studies
- Fitted values: M(B_C^+)=6271.1±0.5 MeV, **B_C^+(yield)=7629±255 events**, σ_1= 21 MeV, σ_2= 42 MeV
- χ^2 between binned distribution and the fit function is 35 for 30 degrees of freedom

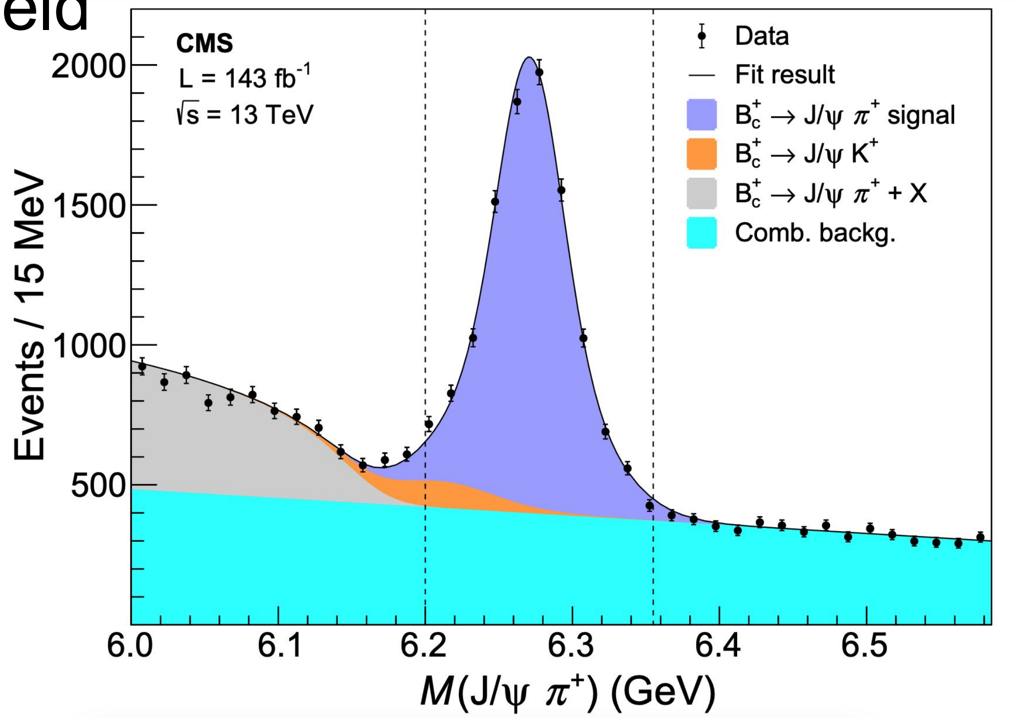


Figure 1: Invariant mass distribution of the $B_c^+ \to J/\psi\,\pi^+$ candidates, after applying all event selection criteria [1]. The fitted contributions are shown by the stacked distributions, the solid line representing their sum. The vertical dashed lines indicate the mass window used to select the B_c^+ candidates for the $B_c^{(*)}(2S)^+$ reconstruction.

Measurement of Cross Section Ratios: Measurement of the $B_C(2S)^+$ and $B_C^*(2S)^+$ yields

- $B_C\pi^+\pi^+$ candidates must have |y|<2.4, and vertex kinematic fit χ^2(prob)>10%
- Two signal peaks are fitted with double gaussians, a third-order polynomial is used for combinatorial background, and two $B_C^+ \to J/\psi+K$ contributions are fitted to double gaussians with normalization fixed by the ratio of $B_C^+ \to J/\psi+K$ to $B_C^+ \to J/\psi+\pi$ signal yields
- The fit gives **67±10 events** for the **lower-mass** peak and **52±9 for** the **higher**, with a 41/35 χ^2 per degree of freedom
- Given the unreconstructed low-energy photon, the $B_C^*(2S)^+$ peak position is at:

$$M(B_c(2S)^+) - \Delta M, \text{ where } \Delta M \equiv [M(B_c^{*+}) - M(B_c^+)] - [M(B_c^*(2S)^+) - M(B_c(2S)^+)]$$

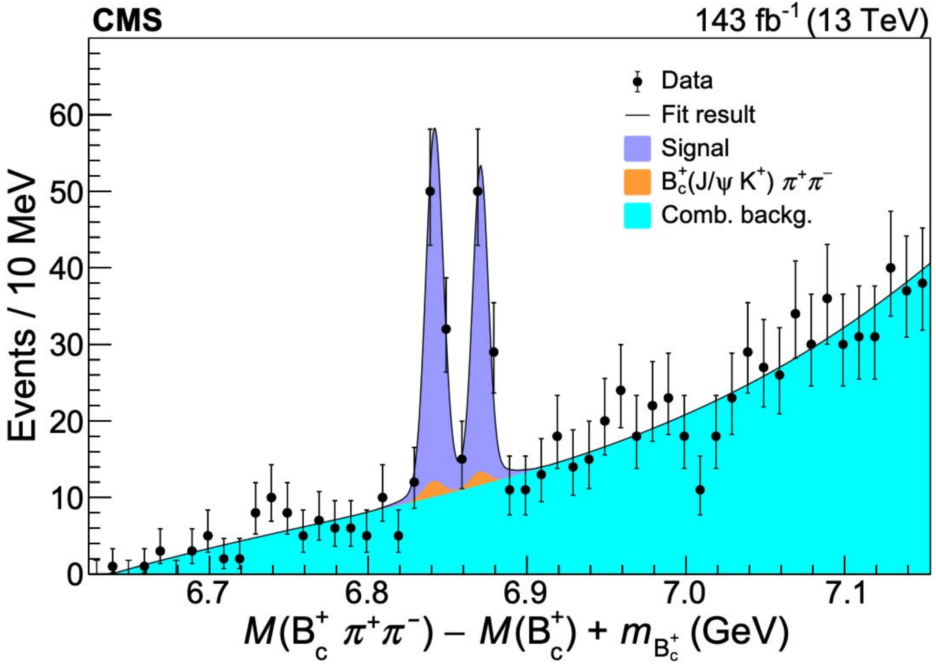


Figure 2: Invariant mass distribution of the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ candidates [1]. The $B_c^*(2S)^+$ corresponds to the lower-mass peak, the $B_c(2S)^+$ to the higher. The fitted contributions are shown by the stacked distributions, the solid line representing their sum.

Measurement of Cross Section Ratios: Reconstruction efficiencies

- Trigger efficiencies cancel in the cross section ratios. Reconstruction efficiencies are evaluated from simulated events
- Efficiencies are computed as the ratio of number of events reconstructed and the number of events generated in the phase-space region $p_T(B_C^+) > 15$ GeV and $|y(B_C^+)| < 2.4$

- Stat. uncertainty reflects the finite size of the simulated samples
- Spread uncertainty reflects the difference between the different data taking periods
- Last column reflects uncertainty in pion reconstruction

Table 1: Ratios of the reconstruction efficiencies relevant for the determination of the R^+, R^{*+}, and R^{*+}/R^+ cross section ratios. The central values are followed by the several uncertainties presented in the text.

	Central	Stat.	Spread	Pions
$\epsilon(B_c(2S)^+)/\epsilon(B_c^+)$	0.196	1.1%	1.8%	4.2%
$\epsilon(B_c^*(2S)^+)/\epsilon(B_c^+)$	0.187	1.0%	1.6%	4.2%
$\epsilon(B_c^*(2S)^+)/\epsilon(B_c(2S)^+)$	0.955	1.4%	0.9%	—

Measurement of Cross Section Ratios: Determination of the cross section ratios

- Correcting the yield ratios with their appropriate efficiency ratios leads to the following results
- Quoted uncertainties are statistical only.
- Note that the ratios include branching fractions that have not yet been measured.

$$\begin{aligned} R^{+} &= (3.47 \pm 0.63)\%, \\ R^{*+} &= (4.69 \pm 0.71)\%, \quad \text{and} \\ R^{*+}/R^{+} &= 1.35 \pm 0.32. \end{aligned}$$

Measurement of Cross Section Ratios: Dependence on the B_C^+ kinematics

- The analysis is redone by splitting the events into three B_C^+ p_T bins and (independently) into three |y| bins
- Bin edges are chosen to have similar uncertainties
- None of the ratios show significant variations, within probed kinematic regions

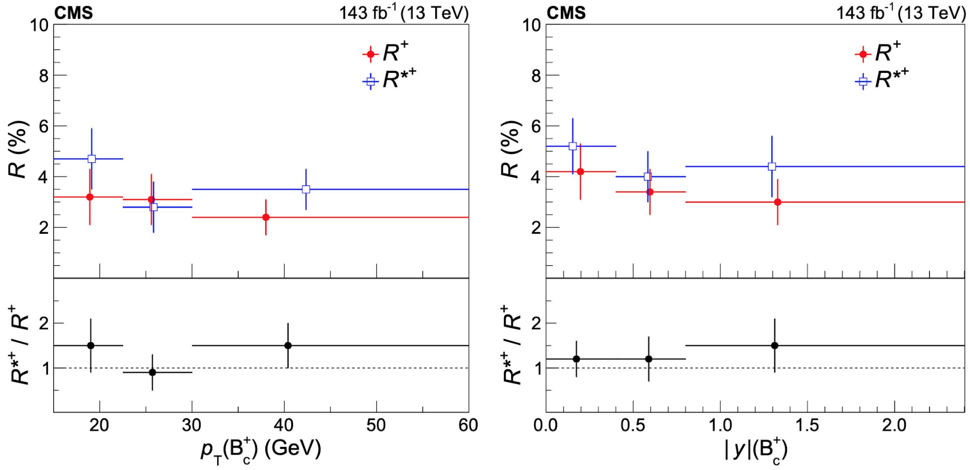


Figure 3: The R^+ and R^{*+} (upper), and R^{*+}/R^+ (lower) cross section ratios, including the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ branching fractions, as functions of the B_c^+ p_T (left) and $|y|$ (right). The horizontal bars show the bin widths. The markers are shown at the average B_c^+ p_T or $|y|$ values of the events contributing to each bin, in the background-subtracted distributions, and the vertical bars represent the statistical uncertainties only. The systematic uncertainties are essentially independent of the B_c^+ kinematics.

Measurement of Cross Section Ratios: Systematic uncertainties

Table 2: Relative systematic uncertainties (in %) in the cross section ratios, including the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ branching fractions, corresponding to the sources described in the text. The total uncertainty is the sum in quadrature of the individual terms.

	R^+	R^{*+}	R^{*+}/R^+
$J/\psi\,\pi^+$ fit model	5.5	5.5	—
$B_c^+\pi^+\pi^-$ fit model	5.9	2.9	2.9
Efficiencies: statistical uncertainty	1.1	1.0	1.4
Efficiencies: spread among years	1.8	1.6	0.9
Efficiencies: pion tracking	4.2	4.2	—
Decay kinematics	1.5	6.9	4.2
Helicity angle	1.0	6.0	3.5
Total	9.5	12.0	6.4

- For B_C^+: background model is varied to an exponential function, signal model varied to Student's t function
- For $B_C^{(*)}(2S)^+$: background varied to

$$\delta^\lambda \exp(\nu\,\delta), \text{ where } \delta \equiv M(B_c^+\pi^+\pi^-) - q_0$$

  signal variation was explored with 2 methods: using one gaussian, and sidebands fitting to background combined with event counting in signal region.

- For efficiencies: systematic uncertainties already computed translate directly to cross section ratios. $B_C^+\pi^+\pi^+$ is reconstructed assuming no kinematic correlations between the pions. The assumption is tested by reweighting the simulation to consider (a) an intermediate resonance, and (b) spin dependence

Invariant mass distribution of the dipion system

- As a complement to the cross section ratios, the dipion distribution in the $B_C^+\pi^+\pi^-$ decays may provide relevant information to the production processes of the $B_C^{(*)}(2S)^+$ states
- $B_C^{(*)}(2S)^+$ dipion mass distributions are compatible with each other, and have shapes different from the simulation

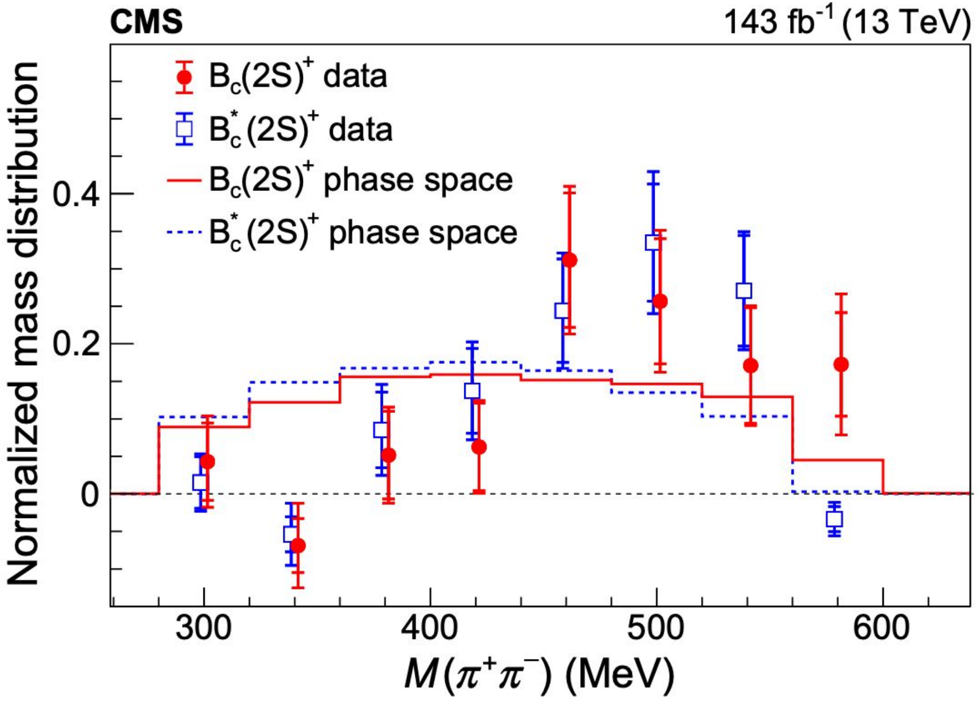


Figure 4: The dipion invariant mass distributions from $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ decays in data, normalized to unity. The inner and outer tick marks designate the statistical and total uncertainties, respectively. The lines show the corresponding predictions from phase space simulations.

Summary

- The cross section ratios of $B_C(2S)^+$ to B_C^+, $B_C^*(2S)^+$ to B_C^+, and $B_C^*(2S)^+$ to $B_C(2S)^+$ have been measured in pp collisions at $\sqrt{s}$ = 13 TeV with a dataset collected by CMS from 2015-2018 corresponding to 143 fb^{-1} of integrated luminosity.
- No significance dependence on transverse momentum or rapidity of the B_C^+ mesons is observed for any of the ratios
- The normalized dipion invariant mass distribution for the $B_C^{(*)}(2S)^+ \rightarrow B_C^+\pi^+\pi^-$ is also reported

$$R^+ = (3.47 \pm 0.63\,(\text{stat}) \pm 0.33\,(\text{syst}))\%,$$
$$R^{*+} = (4.69 \pm 0.71\,(\text{stat}) \pm 0.56\,(\text{syst}))\%, \quad \text{and}$$
$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\text{stat}) \pm 0.09\,(\text{syst}).$$