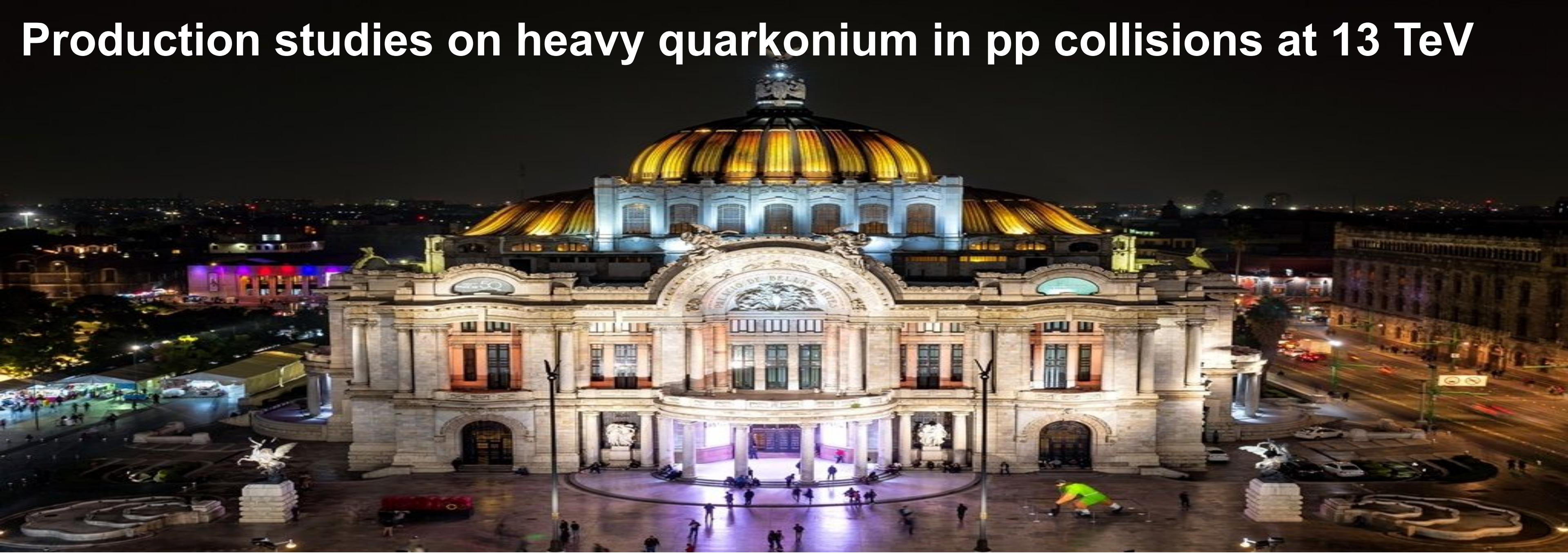
Production studies on heavy quarkonium in pp collisions at 13 TeV



Jhovanny Andres Mejia Guisao
On behalf of the CMS collaboration
UNIVERSIDAD DE ANTIOQUIA, COLOMBIA

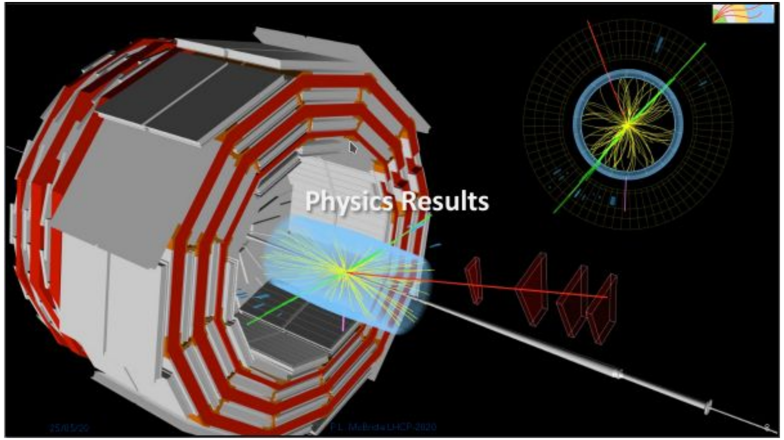
Annual Meeting, Division of Particles and Fields of the Mexican Physical Society (DPyC-SMF). 9-10 July 2020, Mexico City

Outline

- **Observation of the $B_s \to X(3872)\varphi$ decay mode.**
  CMS-BPH-17-005; arXiv:2005.04764 (Submitted to Phys. Rev. Lett).

- **Measurement of the CP violating phase ϕ_s in the $B_s \to J/\psi\varphi(1020) \to \mu+\mu-K+K-$ channel in proton-proton collisions at 13 TeV.**
  CMS-BPH-20-001; arXiv:2007.02434 (Submitted to PLB).

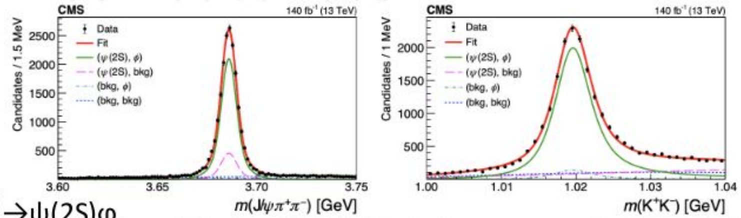
- **Relative cross sections of the $B_c(2S)$ and $B_c(2S)^*$ states with respect to the B_c state in proton-proton collisions at 13 TeV.**
  CMS-PAS-BPH-19-001.



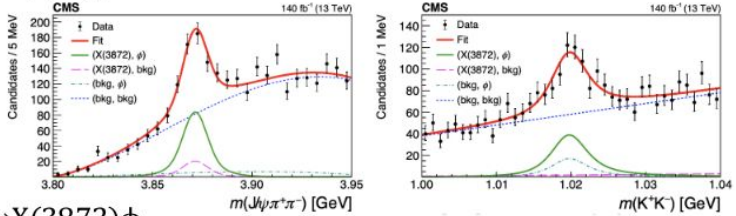
First observation of the $B_s^0 \to X(3872)\varphi$ decay mode

$B_s^0 \to X(3872)\varphi$ decay

- observation of X(3872) in different B-hadron decays is important for understanding the nature of this state
- Channel analyzed: $X(3872) \to J/\psi(\to \mu\mu)\pi\pi$
  - normalization to the analogous $\psi(2S)$ channel (cancellation of many systematic effects)
- significance from 2D fit > 6σ



$B_s^0 \to \psi(2S)\varphi$



$B_s^0 \to X(3872)\phi$

$J/\psi\pi\pi$ and KK masses for the reference and signal channels

$$R = \frac{B(B_s^0 \to X(3872)\phi) \times B(X(3872) \to J/\psi\pi\pi)}{B(B_s^0 \to \psi(2S)\phi) \times B(\psi(2S) \to J/\psi\pi\pi)} = (2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst}))$$

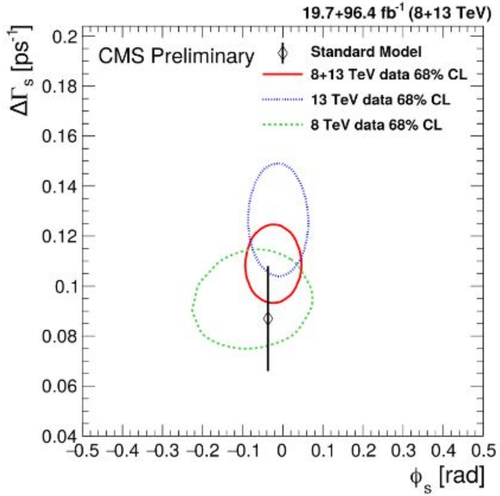
- measured branching fraction for B_s^0 is similar to the one for B^0, but only about 1/2 the one for B^+

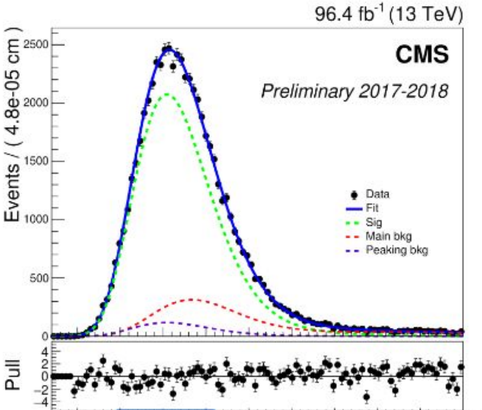
CMS-BPH-17-005
arXiv:2005.04764
(submitted to PRL)

Measurement of the CP violating phase Φ_S in $B_S \rightarrow J/\psi$ KK

Measurement of ϕ_S and the decay width difference between the two B_S mass eigenstates, $\Delta\Gamma_S$, in decays to $J/\psi(\rightarrow\mu\mu)$KK

- time-dependent, flavor-tagged angular analysis using a dedicated trigger (2017&2018)
- improved opposite-side tagging using ML techniques, incl. event-by-event estimate of the mistag probability
- substantial improvement w.r.t. 8 TeV measurement

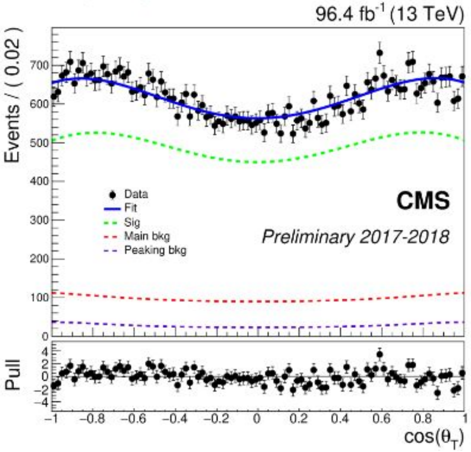


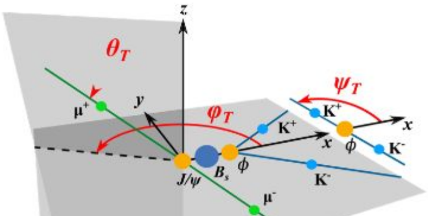


15μm

Uncertainty in cτ

Decay angle θ_T





CMS-BPH-20-001
arXiv:2007.02434
(Submitted to PLB)

CMS-PAS-BPH-19-001:

Relative cross sections of the $B_c(2S)$ and $B_c(2S)^*$ states with respect to the B_c state in proton-proton collisions at 13 TeV.

Introduction

Particle	Predicted M(MeV)
B_c	6247-6286
B_c^*	6308-6341
$B_c(2S)$	6835-6882
$B_c(2S)^*$	6881-6914

[*] PRD 49 (1994) 5845, PRD 51 (1995) 3613, PRD 52 (1995) 5229, PRD 53 (1996) 312, PLB 382 (1996) 131, PRD 160 (1999) 074006, PRD 67 (2003) 014027 PRD 70 (2004) 054017, PRL 104 (2010) 022001, PRD 86 (2012) 094510, PRL 121 (2018) 202002

$B_c(2S)^* \rightarrow B_c^* \pi^+ \pi^-$ followed by $B_c^* \rightarrow B_c \gamma_{lost}$

Since the photon is not detected, we end up seeing

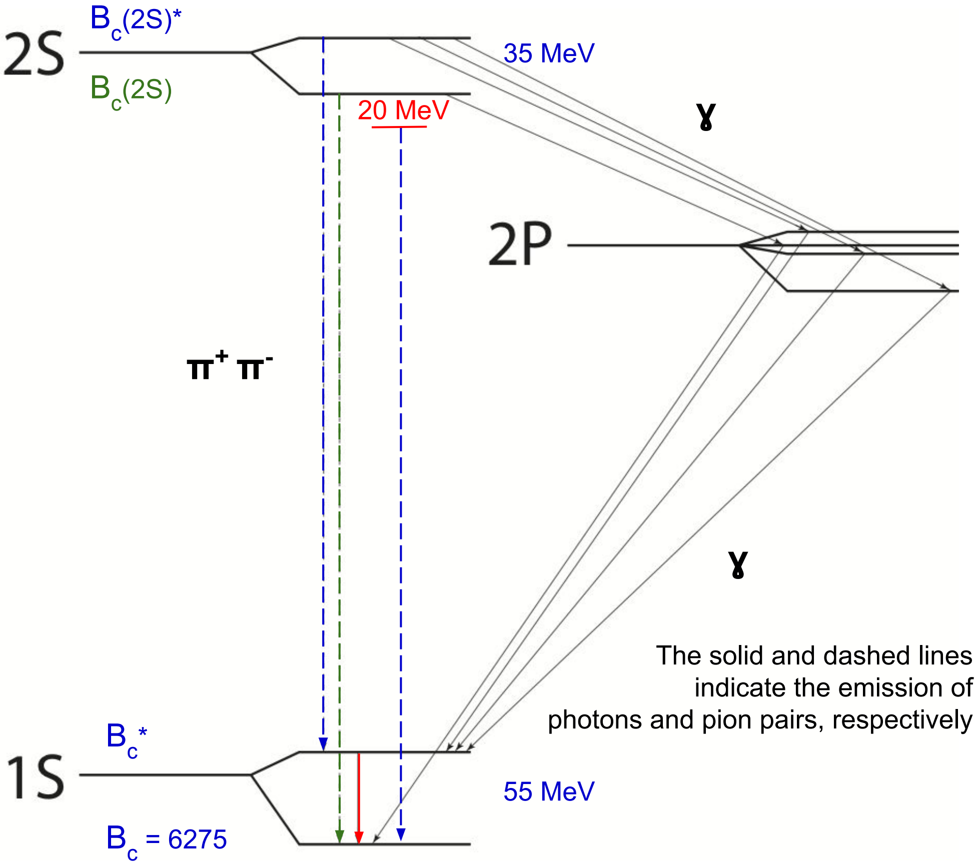
$B_c(2S)^* \rightarrow B_c \pi^+ \pi^-$ plus "missing energy"

Same final state as

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

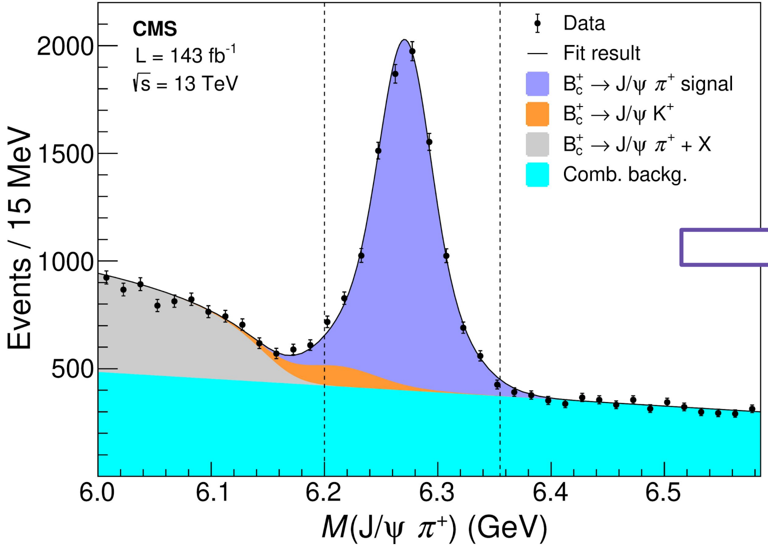
So, we see a two-peak structure in the $B_c \pi^+ \pi^-$ mass distribution, with the $B_c(2S)^*$ peak at a mass shifted by

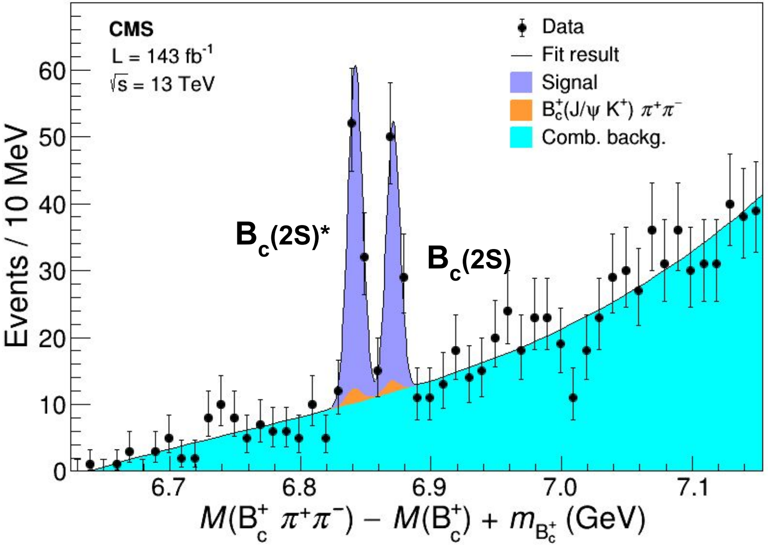
$$\Delta M = [\, M(B_c^*) - M(B_c)\,] - [\, M(B_c(2S)^*) - M(B_c(2S))\,]$$



The solid and dashed lines indicate the emission of photons and pion pairs, respectively

Observation of the two-peak structure





7629 ± 225 candidates

33.5 ± 2.5 MeV mass resolution

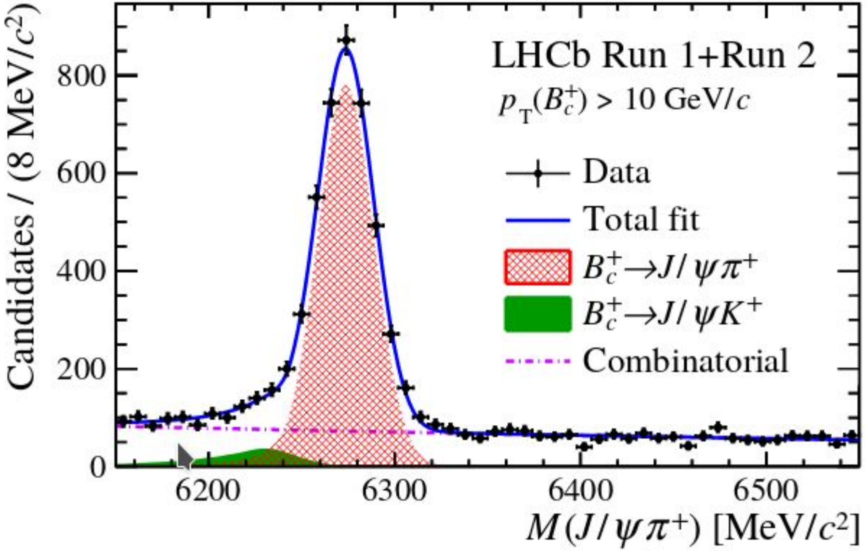
$\Delta M = [\,M(B_c^*) - M(B_c)] - [\,M(B_c(2S)^*) - M(B_c(2S))]$

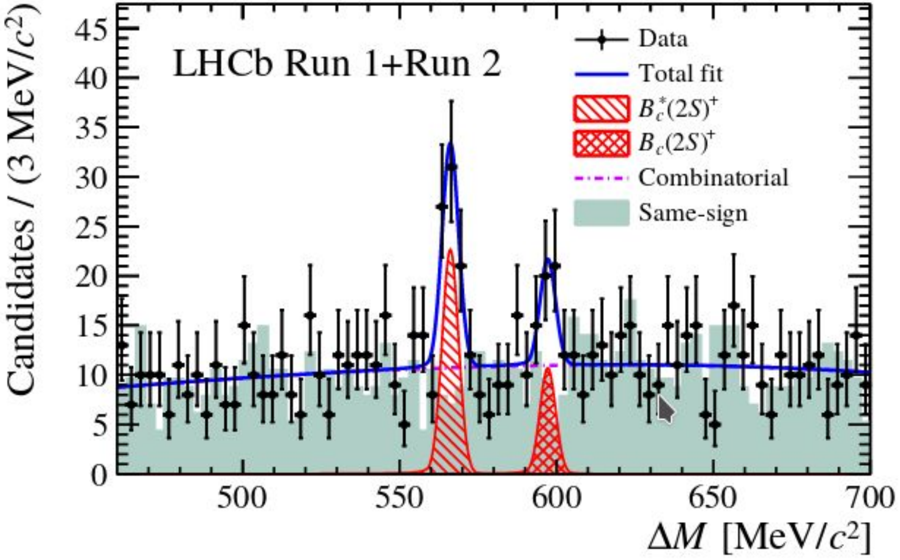
Observation of Two Excited B_c States and Measurement of the $B_c(2S)$ Mass in pp Collisions at $\sqrt{s}$ = 13 TeV : **PRL 122 (2019) 132001**

Two-peak structure observed (well resolved) :
ΔM = 29.1 ± 1.5 (stat) ± 0.7 (sys) MeV

Mass of $B_c(2S)$ measured to be:
$M(B_c(2S))$ = 6871.0 ± 1.2 (stat) ± 0.8 (sys) ± 0.8 (B_c)MeV

Right after, LHCb also reported the observation of the Bc(2S)* and a hint of the Bc(2S).





Observation of an excited B_c state: **PRL 122 (2019) 232001**

Two-peak structure observed (well resolved) :

$M(B_c(2S)^*) = 6841.2 \pm 0.6$ (stat) ± 0.1 (sys) ± 0.8 (B_c)MeV

Mass of B_c(2S) measured to be:

$M(B_c(2S)) = 6872.1 \pm 1.3$ (stat) ± 0.1 (sys) ± 0.8 (B_c)MeV

Motivation

ATLAS was to first one who provides hints about these excited states **Phys. Rev. Lett. 113 (2014) 212004**

LHCb and CMS confirms these and separate the spin states. However, not information about the production rates of these states has been reported so far.

- These discoveries have stimulated the theoretical studies for understanding the properties of these mesons: **Phys.Rev. D99 (2019) 054025 or Mod.Phys.Lett. A34 (2019) 1950331** among others. They suggest further experimental studies for determining
    - relative production ratios of the two observed states
    - relative production ratio respect to the base state
    - study of the dipion invariant mass distribution
- The studies are needed to test calculations of production and decay rates and shed light on the nature of a possible intermediate structure, similar to that observed in charmonium and bottomonium transitions of the 2S to 1S states.

$$\mathcal{R} = \frac{\sigma_{\mathrm{B_c(2S)^{(*)+}}}}{\sigma_{\mathrm{B_c^+}}} \times \mathcal{B}(\mathrm{B_c(2S)^{(*)+}} \to \mathrm{B_c^+}\pi^+\pi^-) = \frac{\mathrm{N}_{\mathrm{B_c(2S)^{(*)+}}}}{\mathrm{N}_{\mathrm{B_c^+}}} \frac{\epsilon_{\mathrm{B_c^+}}}{\epsilon_{\mathrm{B_c(2S)^{(*)+}}}}$$

$$\frac{\sigma_{\mathrm{B_c^{*+}(2S)}}}{\sigma_{\mathrm{B_c^+(2S)}}} \times \frac{\mathcal{B}(\mathrm{B_c^{*+}(2S)} \to \mathrm{B_c^+}\pi^+\pi^-)}{\mathcal{B}(\mathrm{B_c^+(2S)} \to \mathrm{B_c^+}\pi^+\pi^-)} = \frac{\mathrm{N}_{\mathrm{B_c^{*+}(2S)}}}{\mathrm{N}_{\mathrm{B_c^+(2S)}}} \frac{\epsilon_{\mathrm{B_c^+(2S)}}}{\epsilon_{\mathrm{B_c^{*+}(2S)}}}$$

Efficiencies for B_c^+, $B_c(2S)^+$ and $B_c(2S)^{+*}$:

We must know the total reconstruction efficiency, i.e. the “ratio efficiencies” between B_c (2S) and B_c. To obtain those, we use the MC simulation samples.

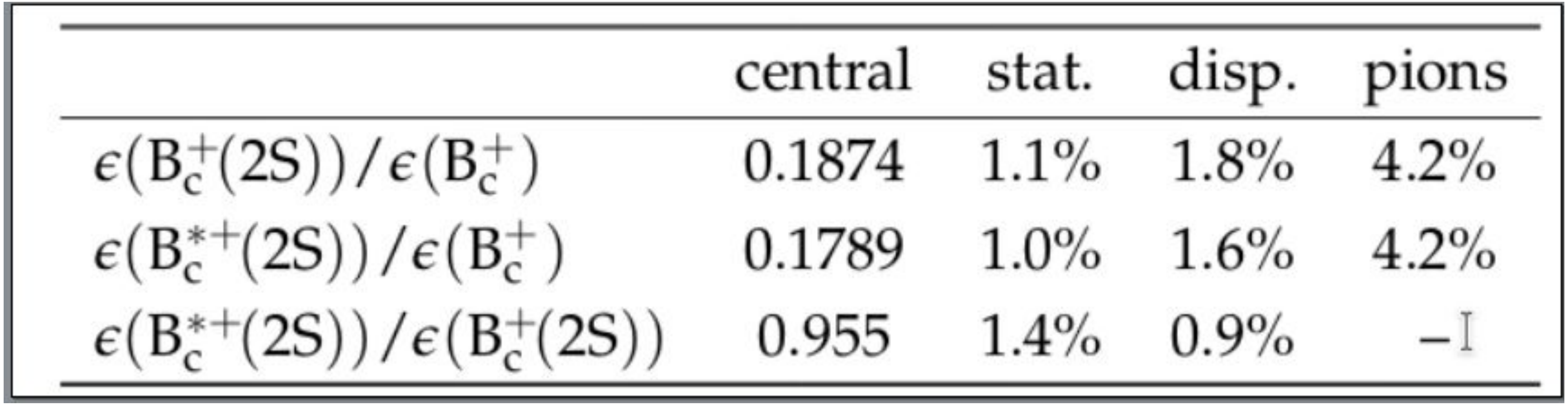
$$\epsilon_{B_c(2S)^+} = \frac{N^{\text{rec}}_{B_c(2S)^+\to B_c^+\pi^+\pi^-}}{N^{\text{gen}}_{B_c(2S)^+\to B_c^+\pi^+\pi^-}}$$

CMS-PAS-BPH-19-001

where $N^{\text{rec}}_{B_c(2S)^+\to B_c^+\pi^+\pi^-}$ is the number of reconstructed $B_c(2S) \to B_c \pi^+\pi^-$ events after the full selection and is $N^{\text{gen}}_{B_c(2S)^+\to B_c^+\pi^+\pi^-}$ the number of generated $B_c(2S) \to B_c \pi^+\pi^-$ decays in the fiducial region of the analysis specified by the B_c kinematic window $pT(B_c)>15$ GeV and $|y(B_c)|<2.4$. Analogous efficiency definitions apply for B_c and $B_c(2S)$

Efficiencies

CMS-PAS-BPH-19-001



	central	stat.	disp.	pions
$\epsilon(B_c^+(2S))/\epsilon(B_c^+)$	0.1874	1.1%	1.8%	4.2%
$\epsilon(B_c^{*+}(2S))/\epsilon(B_c^+)$	0.1789	1.0%	1.6%	4.2%
$\epsilon(B_c^{*+}(2S))/\epsilon(B_c^+(2S))$	0.955	1.4%	0.9%	–

Ratio efficiencies average for the whole data taking period.

Ratio of cross sections

- The ratio of the $B_c(2S)^{\pm}$ production cross-section times the branching fraction of $B_c(2S)^{\pm} \rightarrow B_c^{\pm}\pi^{+}\pi^{-}$ to the production cross-section of the $B_c^{\pm}$ state, is given by

$$\mathcal{R} = \frac{\sigma_{B_c(2S)^{(*)+}}}{\sigma_{B_c^+}} \times \mathcal{B}(B_c(2S)^{(*)+} \rightarrow B_c^+\pi^+\pi^-) = \frac{N_{B_c(2S)^{(*)+}}}{N_{B_c^+}} \frac{\epsilon_{B_c^+}}{\epsilon_{B_c(2S)^{(*)+}}}$$

CMS

$$\boxed{\begin{aligned} R^{+} &= 3.57 \pm 0.69\,\%, \\ R^{*+} &= 4.91 \pm 0.69\,\%, \\ R^{*+}/R^{+} &= 1.39 \pm 0.35\,. \end{aligned}}$$

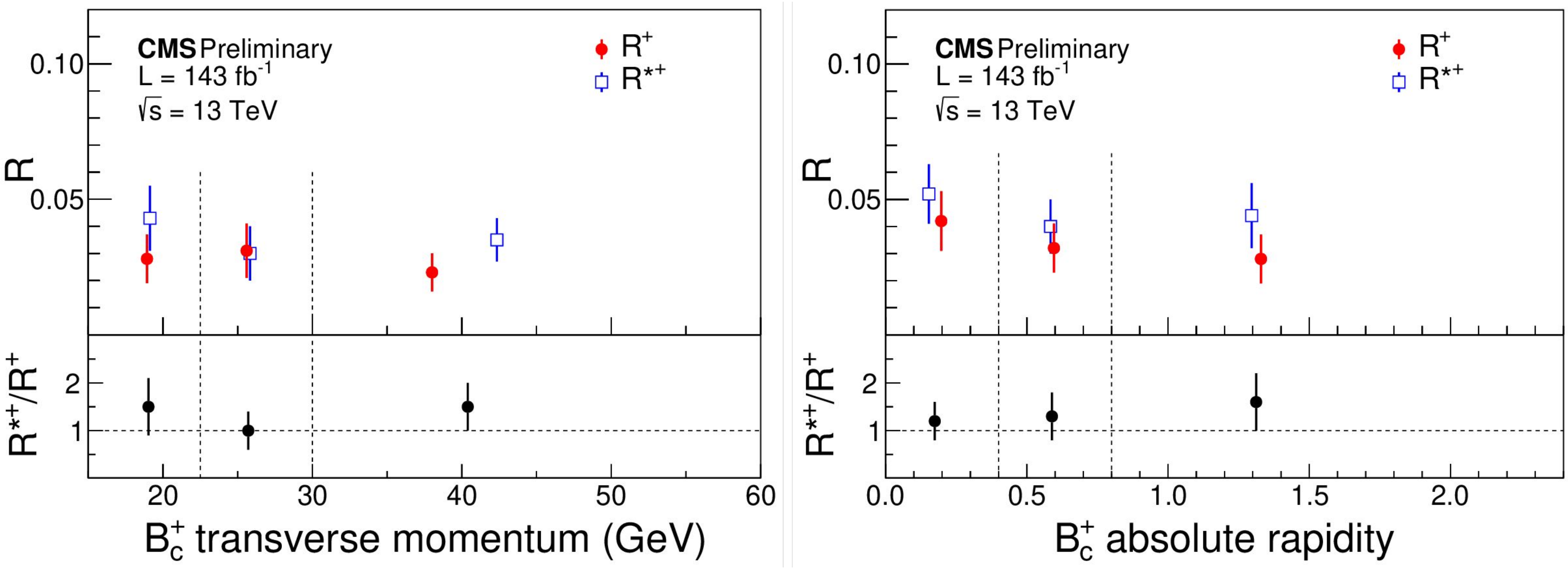
CMS-PAS-BPH-19-001

ATLAS $(0.22 \pm 0.08)/\epsilon_7$ $(0.15 \pm 0.06)/\epsilon_8$

LHCb $< [0.04, 0.09]$

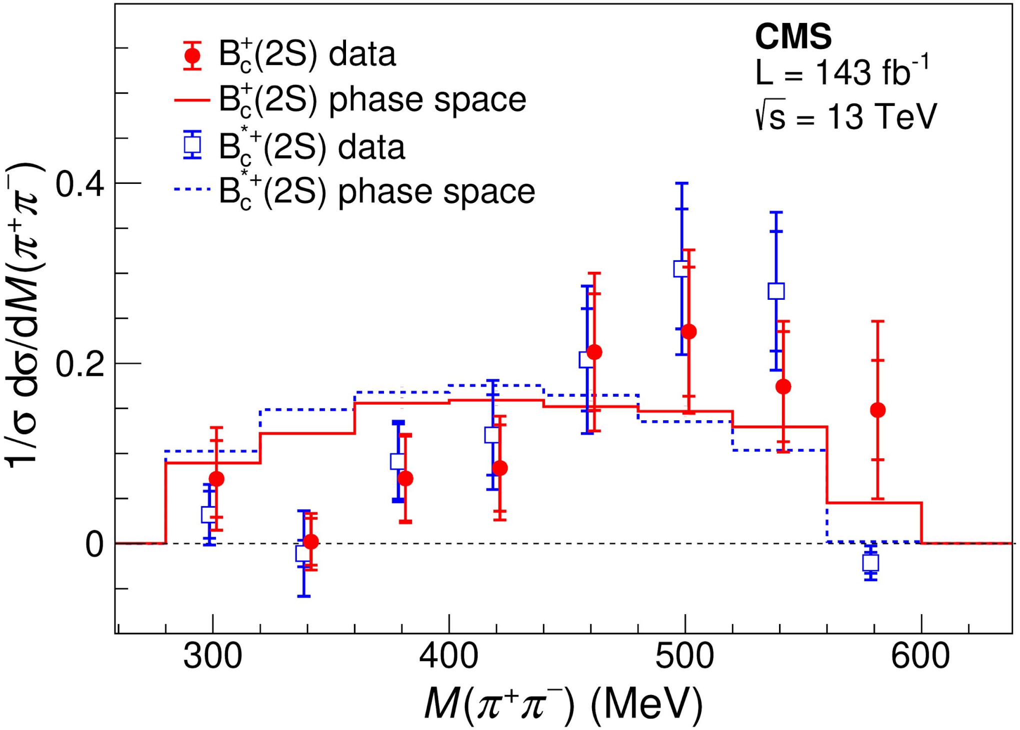
Note: LHCb Run-I limits are under the interpretation of ΔM equal to 0. However they are mostly insensitive. ATLAS result is clearly incompatible with LHCb and CMS results.

Production ratio as a function of pT and rapidity



CMS-PAS-BPH-19-001

Dipion mass spectra



The vertical bars on the points of those distributions represent the statistical uncertainty in the data.

Distribution was obtained using an sPlot. Variations using a background subtracted method has been taken as systematic uncertainty.

CMS-PAS-BPH-19-001

Adimensional reduced dipion mass distribution of Bc(2S)$^{(*)}$ candidates

Systematic uncertainty evaluation

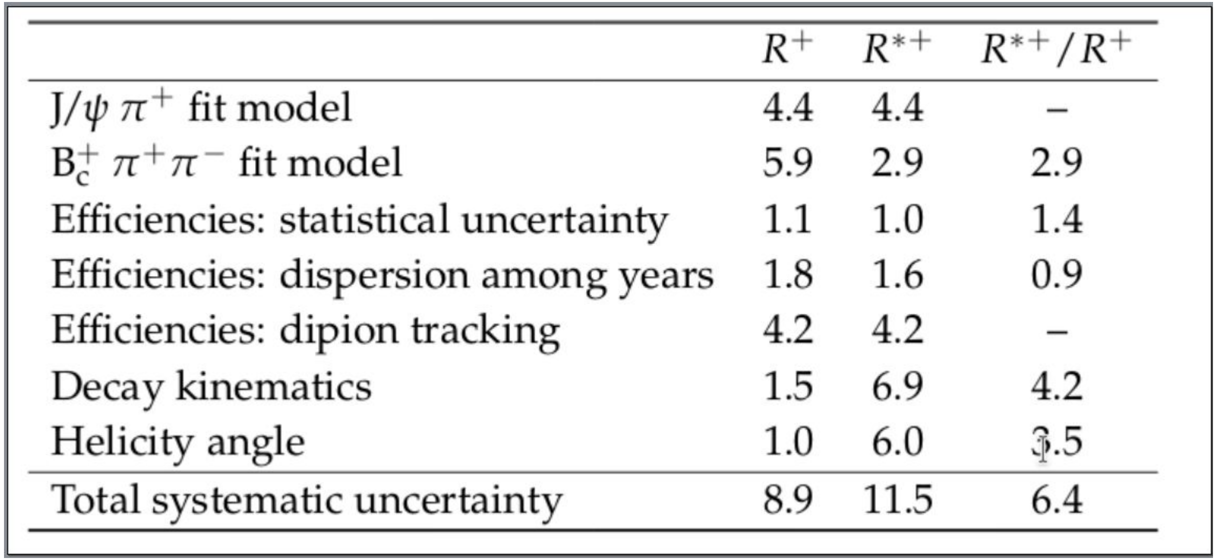
The systematics on cross sections ratios, comes from: B_c modeling, $B_c(2S)$ modeling and efficiency determination (for the ratio). The systematic assigned to the efficiency are those due to the MC sample size, and those from the difference observed between the data taking periods respect to the average .

For B_c modelling we have used alternative modelling for signal and background:
Signal, was changed from two Gaussians to Gaussian + Crystal Ball, and the background shape from polynomial to exponential. Observed difference in yields are quote as systematic uncertainties.

The changes in the $B_c(2S)$ modelling: Signal, was changed from Gaussians to Double Gaussian functions parametrizations for each peak, with the resolution parameters fixed from MC. The background shape from polynomial to a threshold function, used in other analysis . In addition, a toy test with the simulated distributions and the background distribution was performed. Observed difference in yields are quote as systematic uncertainties.

Dipion mass distribution systematic studies

Systematic uncertainties on dipion mass distribution from different sources. The total systematic uncertainty is the sum in quadrature of the individual uncertainties. Values are in %.



	R^{+}	R^{*+}	R^{*+}/R^{+}
$J/\psi\,\pi^{+}$ fit model	4.4	4.4	–
$B_c^{+}\,\pi^{+}\pi^{-}$ fit model	5.9	2.9	2.9
Efficiencies: statistical uncertainty	1.1	1.0	1.4
Efficiencies: dispersion among years	1.8	1.6	0.9
Efficiencies: dipion tracking	4.2	4.2	–
Decay kinematics	1.5	6.9	4.2
Helicity angle	1.0	6.0	3.5
Total systematic uncertainty	8.9	11.5	6.4

CMS-PAS-BPH-19-001

To determinate the systematic uncertainties on the dipion mass distribution of $B_c(2S)$ candidates, it have been evaluate the impact of the signal, and background modeling and the J/ψK and partial reconstructed B_c decays contributions.

Besides, instead of the sPlot determination, we used the wrong-sign dipion invariant mass spectrum as background shape to subtract it from the dipion invariant mass distribution

Summary

CMS-PAS-BPH-19-001

Using 2015-2018 full dataset for RunII (143 fb^{-1}), we studied the excited states $B_c(2S)^{(*)\pm}$

$B_c(2S)^\pm \rightarrow B_c^\pm\pi^+\pi^-$

$B_c(2S)^{*\pm} \rightarrow B_c^{*\pm}\pi^+\pi^- \rightarrow (B_c^\pm\gamma)\pi^+\pi^-$, with

$B_c^\pm \rightarrow J/\psi\pi^\pm$ and $J/\psi \rightarrow \mu^+\mu^-$

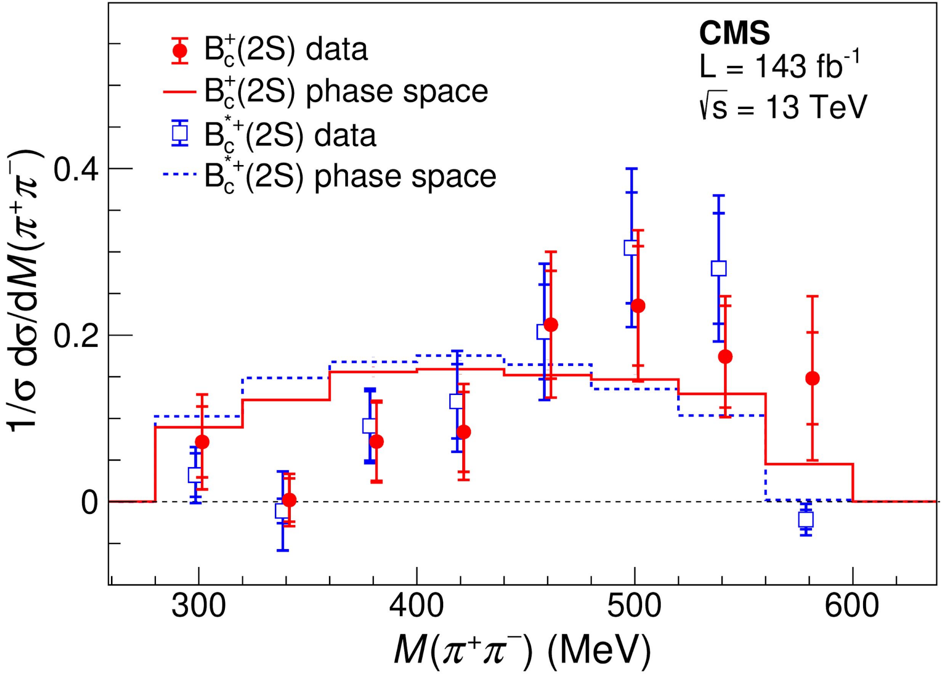
And measured the production ratios

$R(B_c(2S)^+) = 3.57 \pm 0.69$ (stat) ± 0.32 (syst) %

$R(B_c(2S)^{*+}) = 4.91 \pm 0.69$ (stat) ± 0.57 (syst) %

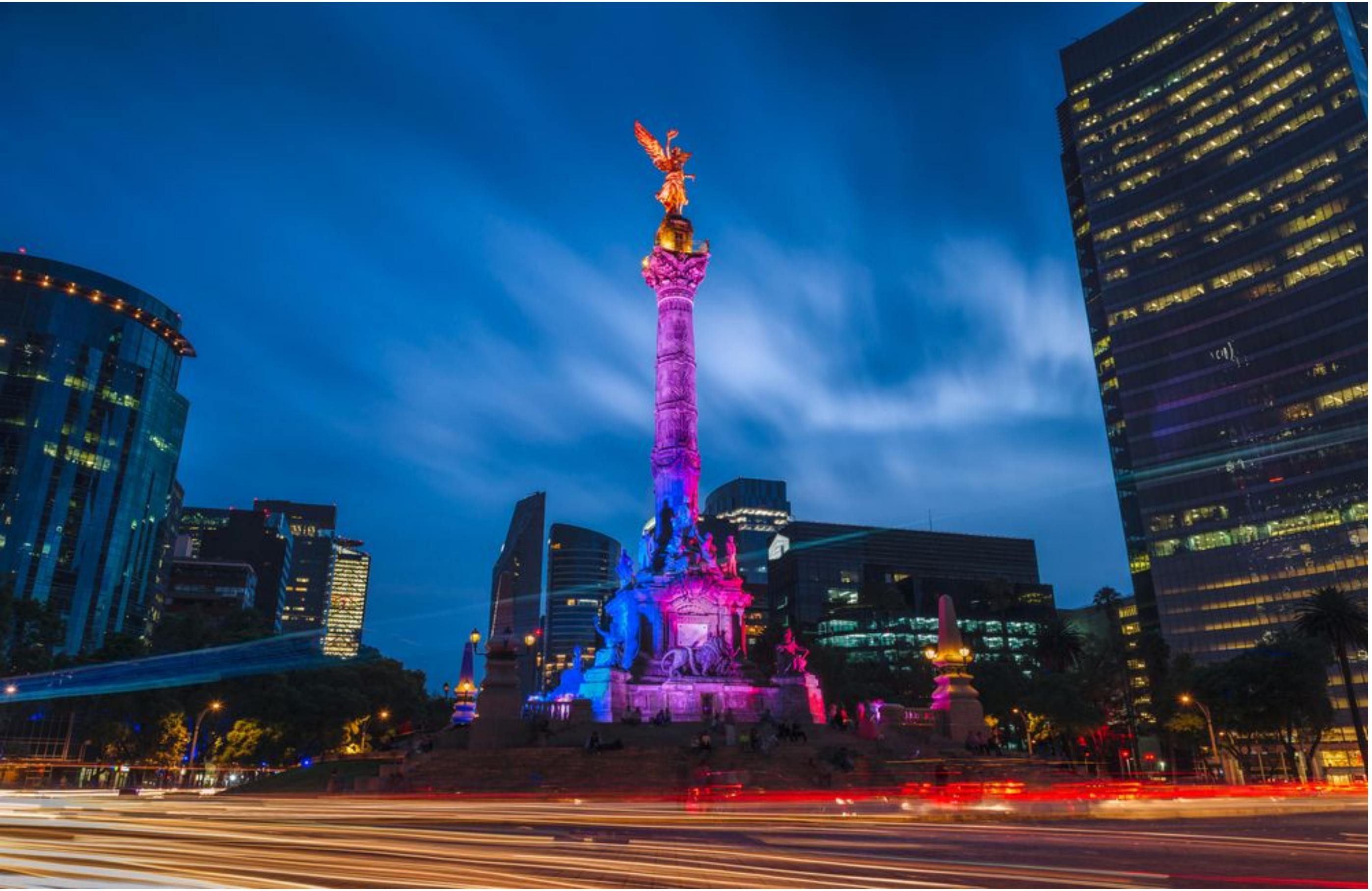
$R(B_c(2S)^{*+}/B_c(2S)^+) = 1.39 \pm 0.35$ (stat) ± 0.09 (syst)

for $p_T(B_c) > 15$ GeV and $|y(B_c)| < 2.4$



These cross section production ratios and studies on the dipion mass distribution of $B_c(2S)^{(*)\pm}$ could provide essential information on the nature and production mechanism of the (c bbar) system.

Thanks!



LHCb limits on R

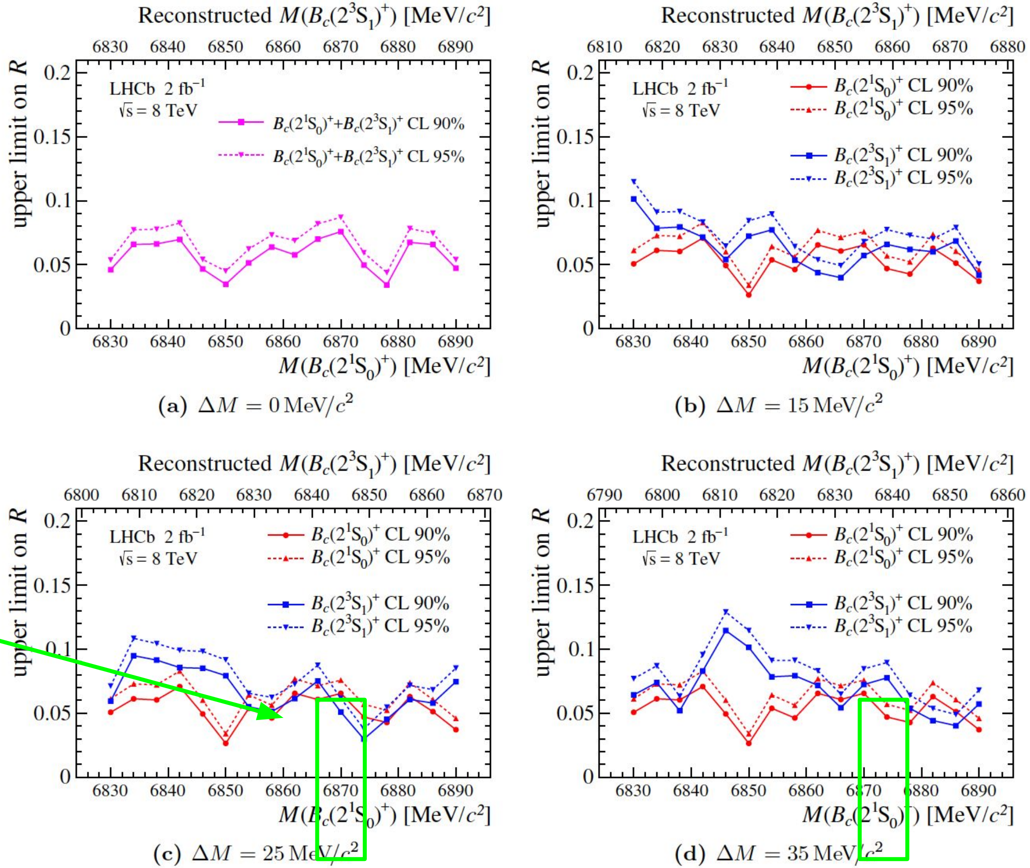
CMS measurement:

$R(B_c(2^1S_0)^+) = 0.024 \pm 0.006$ (stat) ± 0.004 (syst)

$R(B_c(2^3S_1)^+) = 0.020 \pm 0.005$ (stat) ± 0.002 (syst)

assuming not kinematical dependency,

Notice: for most of the cases $B_c(2^3S_1)^+$ rate is higher than $B_c(2^1S_0)^+$, but the rate change for the region around $M(B_c(2^1S_0)^+)$~6870 MeV



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

Figure 4. The upper limits on the ratio $\mathcal{R}(B_c^{(*)}(2S)^+)$ at 95% and 90% confidence levels under different mass splitting ΔM hypotheses.

JHEP01(2018)138