Heavy Flavor Spectroscopy at CMS

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On behalf of the CMS Collaboration

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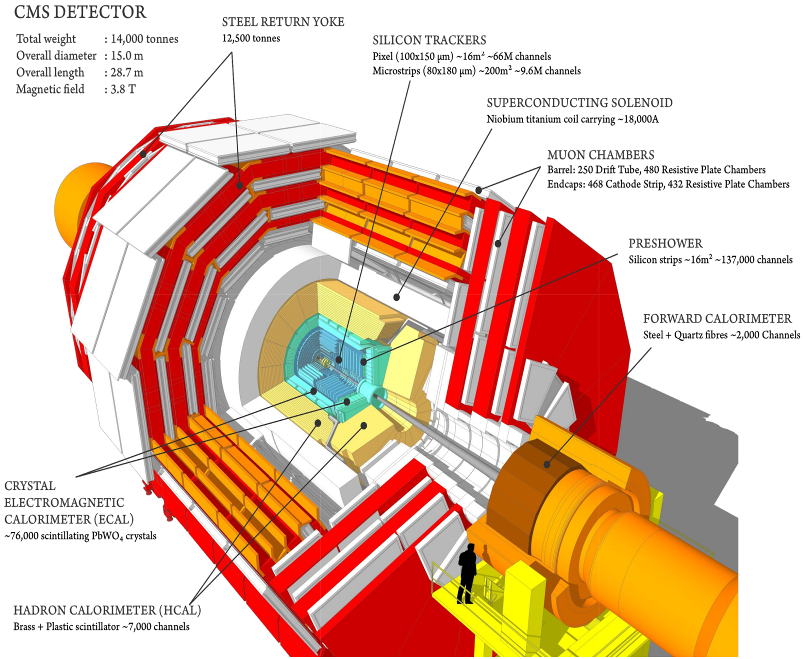
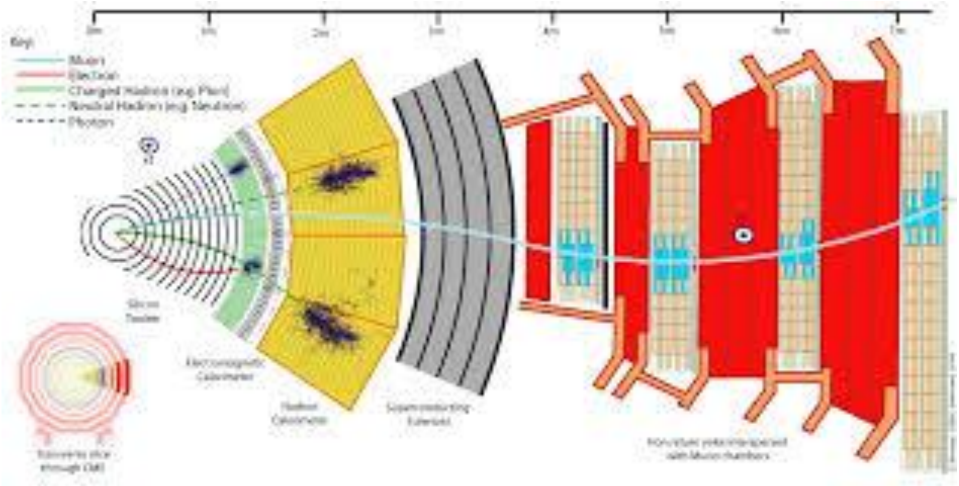
Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

CMS Detector





CMS-BPH-18-005:

Study of the $B^+ \to J/\psi \bar{\Lambda} p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV

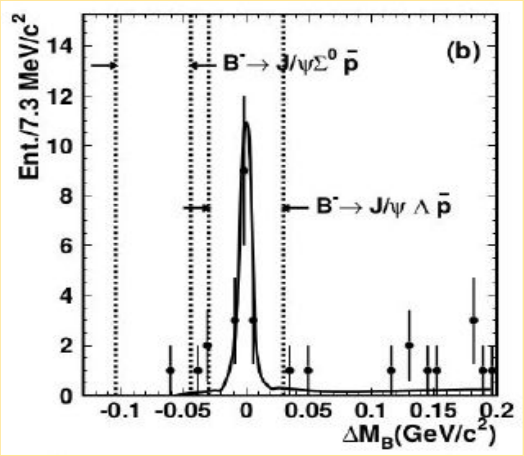
Introduction

The Belle Collaboration reported the observation of this decay in 2005, with low yield (17.2 ± 4.1 events). **Phys.Rev.D72:051105,2005**

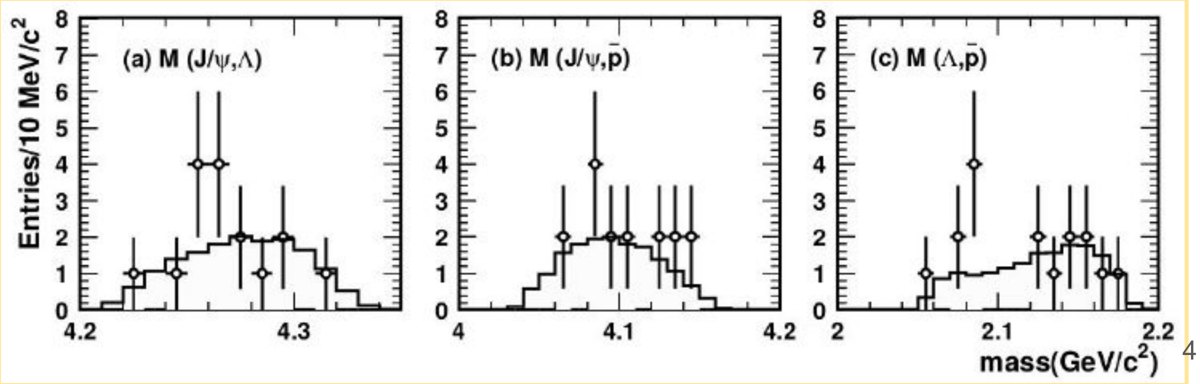
$$\beta(B \rightarrow J/\psi\Lambda p) = (11.6 \pm 2.8^{+1.8}_{-2.3})\times 10^{-6}$$

It was the first observed B meson decay into baryons and a charmonium state.

LHCb reported the first observation of the baryonic $Bc \rightarrow J/\psi pp\pi$.
Phys.Rev.Lett.113.152003



The study of new intermediate resonances in pair daughter systems is motivated by the recent **observation of P^+_c (multiquark state consistent with pentaquark)** by LHCb.
PRL 115 (2015) 072001
arXiv:1904.03947 (2019)

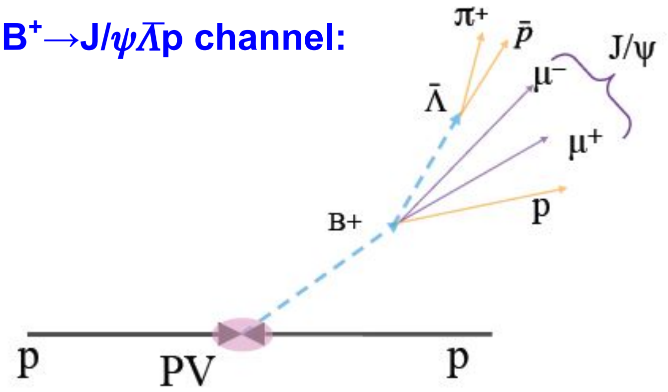


Event selection criteria

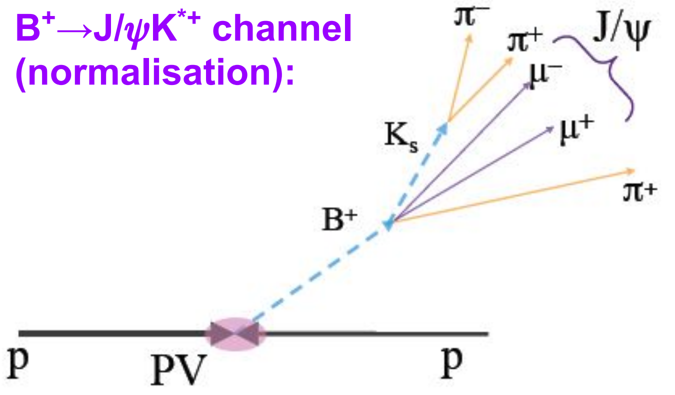
- Using data collected at 8 TeV (19.6 fb^{-1})
- The decay $B \to J/\psi K^{*}(K^{*} \to K_s^{0} \pi^{+})$ is chosen as the normalization channel, as it is measured with high precision and has similar decay topology
- The ratio of branching fractions is measured to be **(15.07 ± 0.81 (stat) ± 0.40 (syst) ± 0.86(β)) x 10^{-6}**
  This measurement is the **most precise to date** and consistent with previous Bell measurement

Kinematic cuts
$P_T(\mu^{\pm})$ > 4.0 GeV; $P_T(J/\psi)$ > 7.0 GeV;
$|M(J/\psi)-M_{PDG}(J/\psi)|$ < 100 MeV;
$P_T(p)$ > 1.0 GeV; $P_T(\Lambda)$ > 1.0 GeV; $P_T(K_S)$ > 1.0 GeV;
$P_T(B)$ > 10.0 GeV
Probability(B vertex) > 1%

$B^{+} \to J/\psi \bar{\Lambda} p$ channel:



$B^{+} \to J/\psi K^{*+}$ channel (normalisation):



Charge conjugation is implied throughout the talk

Invariant mass distribution $B^+ \to J/\psi \bar{\Lambda} p$ and $B^+ \to J/\psi K^{*+}(K_s^0 \pi^+)$ decays

Unbinned maximum-likelihood (UML) fit is performed with Gaussians shape parameters fixed to the value measured on MC

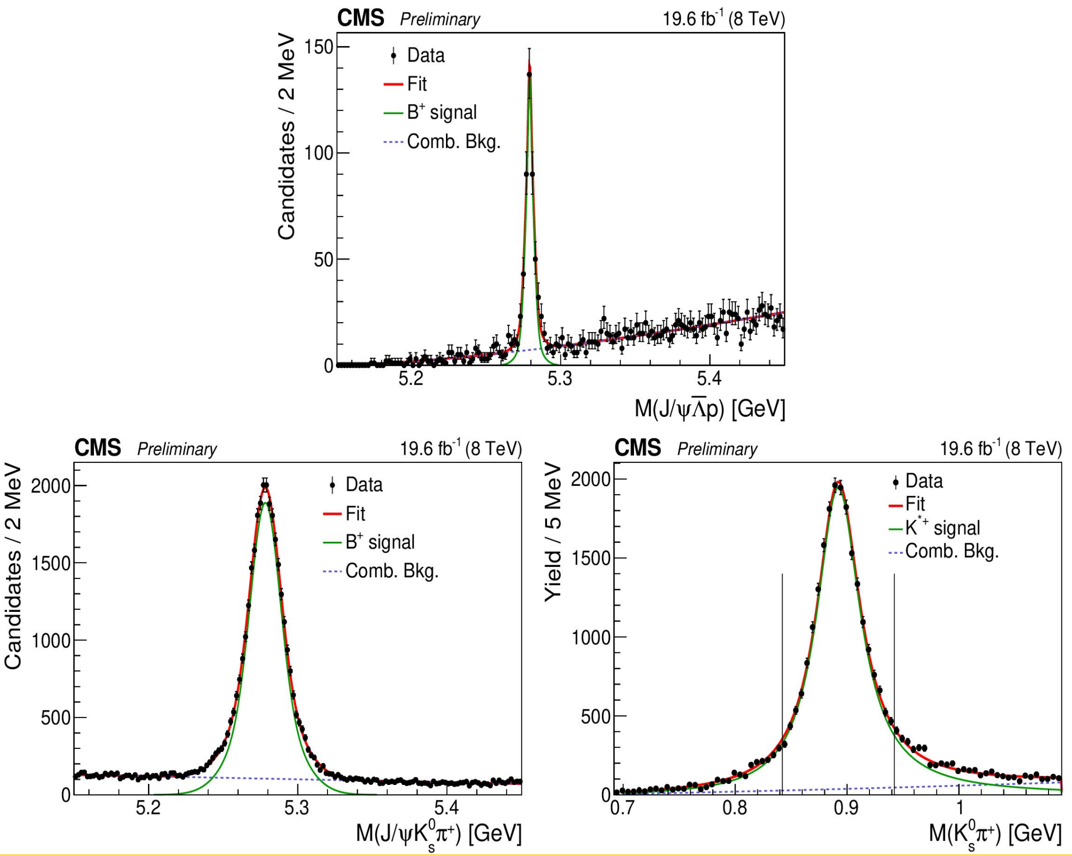
$M(B^+) = 5.27922 \pm 0.00017$ GeV

UML fit is performed with relativistic Breit-Wigner function as the signal model

Other resonances in the $K^0_s \pi^+$ were excluded

$K^0_s \pi^+$ invariant mass to be inside the ±200 MeV window around the world-average K^{*+} mass

Background subtraction using sPlot technique



BF ratio calculation

$$\frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\overline{\Lambda}\mathrm{p})}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^{*+})} = \frac{\boxed{\mathrm{N}(\mathrm{B}^+ \to \mathrm{J}/\psi\overline{\Lambda}\mathrm{p})}\boxed{\mathcal{B}(\mathrm{K}^{*+} \to \mathrm{K}^0_\mathrm{S}\pi^+)}\boxed{\mathcal{B}(\mathrm{K}^0_\mathrm{S} \to \pi^+\pi^-)}\boxed{\epsilon(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^{*+})}}{\boxed{\mathrm{N}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^{*+})}\boxed{\mathcal{B}(\overline{\Lambda} \to \overline{\mathrm{p}}\pi^+}\boxed{\epsilon(\mathrm{B}^+ \to \mathrm{J}/\psi\overline{\Lambda}\mathrm{p})}}$$

Ratio of the signal yields in data

Known branching Fractions from PDG

Ratio of total Efficiencies from MC

$$\frac{\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = (1.054 \pm 0.057(stat.) \pm 0.028(syst.) \pm 0.011(br.)) \times 10^{-2},$$

and using $\mathcal{B}(B^- \to J/\psi K^{*-}) = (1.43 \pm 0.08) \times 10^{-2}$

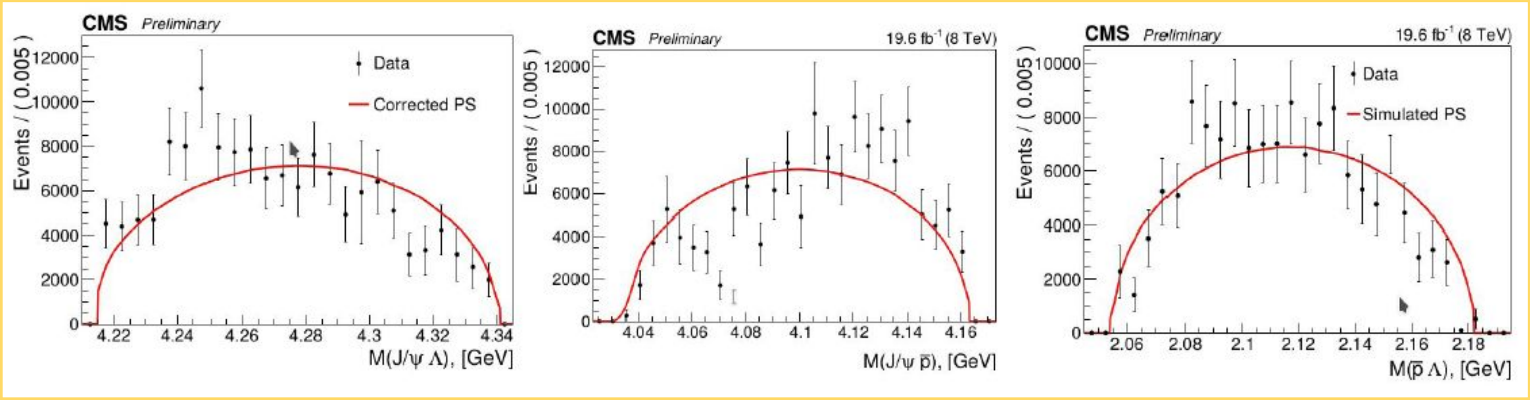
$$\boxed{\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (15.07 \pm 0.81(stat.) \pm 0.40(syst.) \pm 0.86(br.)) \times 10^{-6}}$$

PDG mean value of $\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (11.8 \pm 3.1) \times 10^{-6}$

The latest Belle measurement $\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (11.7 \pm 2.8^{+1.8}_{-2.3}) \times 10^{-6}$

Study of intermediate invariant masses in $B^+ \to J/\psi\bar{\Lambda}p$ decay

- Large signal yield allowed CMS to conduct a search for new exotic multiquark states in the two-body system
- Background subtraction is performed using the sPlot technique, with M($J/\psi\Lambda$p) as the discriminating variable
- The intermediate invariant masses are found to be inconsistent with pure 3-body phase space with a significance more than 6.1, 5.5 and 3.4 for J/ψp, $J/\psi\Lambda$ and pΛ respectively.



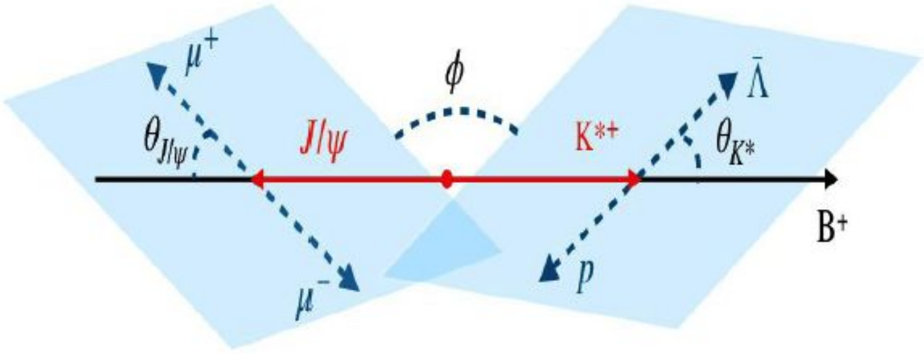
Model-independent approach: method of moments

- First introduced by BaBar [PRD 79 112001(2009)] and later used by the LHCb [PRD 92,112009 (2015), PRL 117, 082002 (2016)]
- There are at least three known K^* resonances that can decay to Λp. So, these broad excited kaon states can contribute to the two-body invariant mass distributions.
- In each M(Λp) bin, the cos(θK^*) distribution can be expressed as an expansion in terms of Legendre polynomials:

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{l_{max}} \langle P_j^U \rangle P_j(\cos\theta_{K^*})$$

cos (θK^*) helicity angle defined as the angle between Λ momentum and B+ momentum in the Λp rest frame

l_{max} equal to twice the spin of the highest-spin resonance can describe all the resonances and their interferences. From table l_{max} = 2*4=8



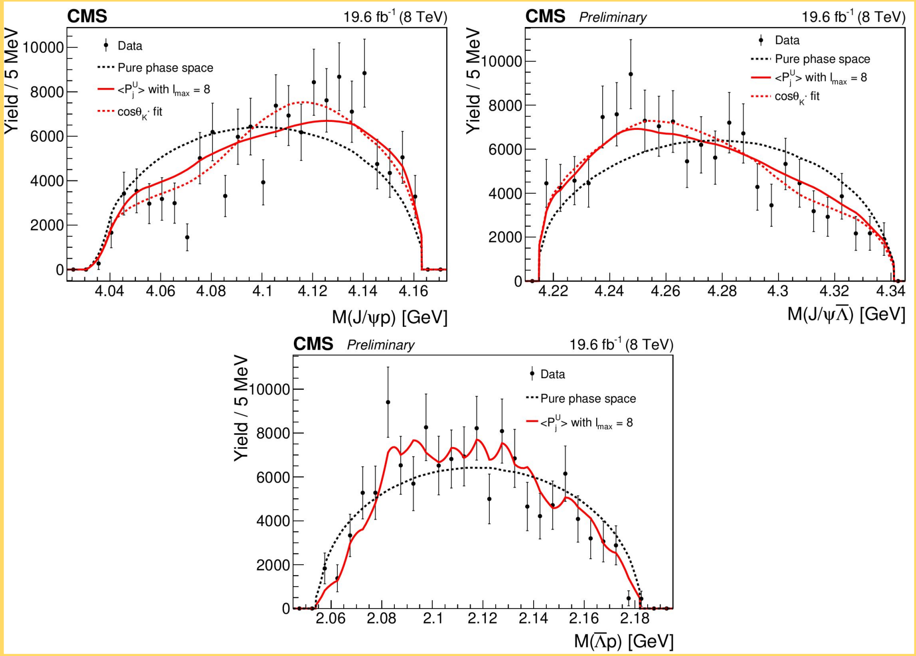
Resonance	Mass [MeV]	Natural width [MeV]	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

Simulation reweighting results

Simulation reweighing according to the observed angular structure in the Λp system

It is evident that the description of the M(J/$\psi\Lambda$) and M(J/ψp) data distributions is improved after accounting for the angular and invariant mass structure in the Λp system in simulation

Compatibility with data **eliminating the need for new resonances!**



CMS-BPH-18-007:

Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s}$ = 13 Tev

Phys. Rev. Lett. 122 (2019) 132001

Introduction

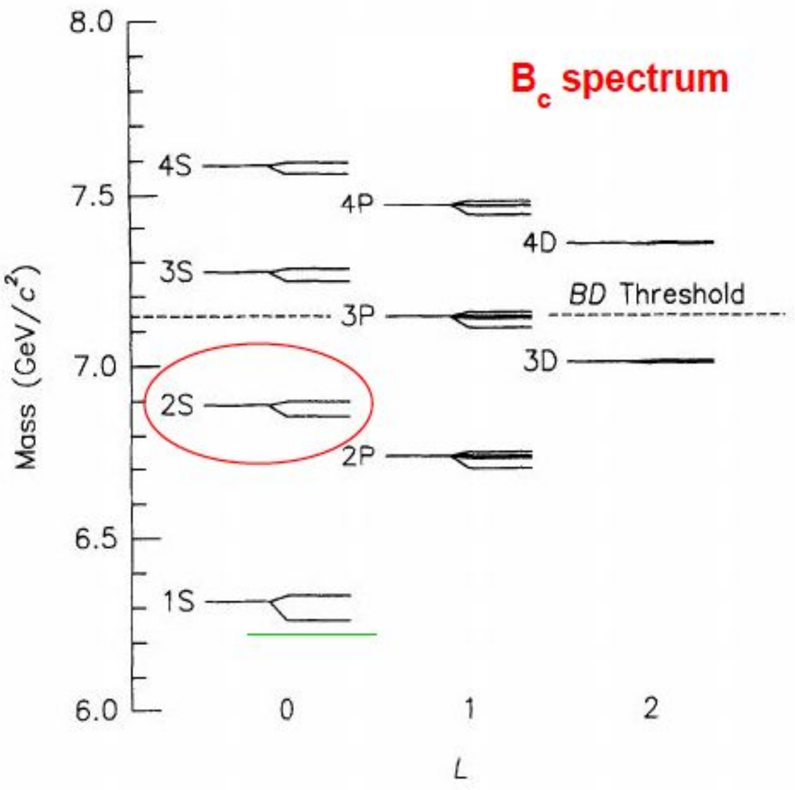
The B_C meson was discovered in 1998 by CDF. **PRL 81 (1998) 2432**

It is the lowest-mass bound state of the family of mesons composed of a charm quark and a bottom anti-quark. **PRD 49 (1994) 5845**

Experimental information is limited by rare production rate

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

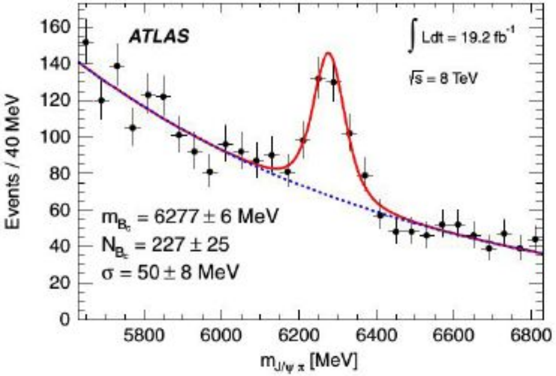


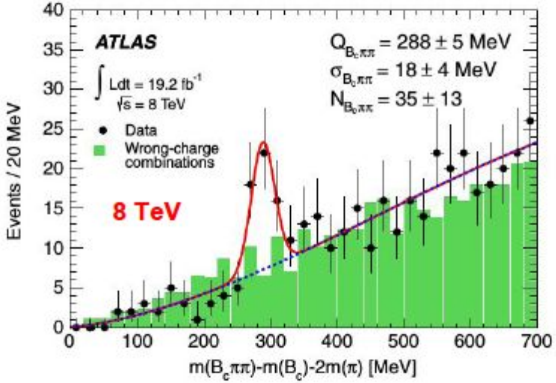
Phys. Rev. D 49 (1994) 5845

Introduction

[ATLAS reported the observation of a new state whose mass is consistent with predictions for the $B_C(2S)$](#)

PRL 113, 212004 (2014)

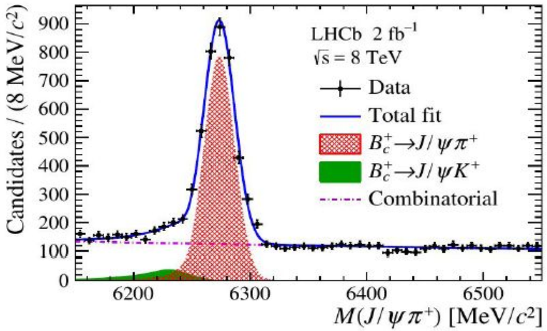




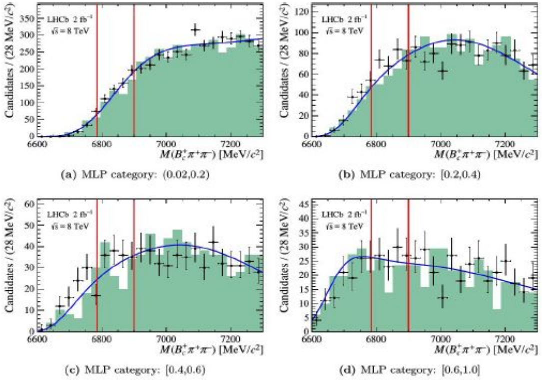
LHCb: [“No significant signal is found”](#) in the search for the excited states $B_C(2S)$ and $B_C(2S)^*$

JHEP 01 (2018) 138

kinematic ranges p_T in [0, 20] GeV/c and rapidity in [2.0, 4.5]



JHEP 01 (2018) 138



Reconstruction of the $B_c\pi\pi$

The $B_c(2S)^*$ decays to the B_c ground state through the emission of two pions and a soft photon (around 55 MeV in rest frame) :

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

Since the photon is not detected, we end up seeing

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

Same final state as

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

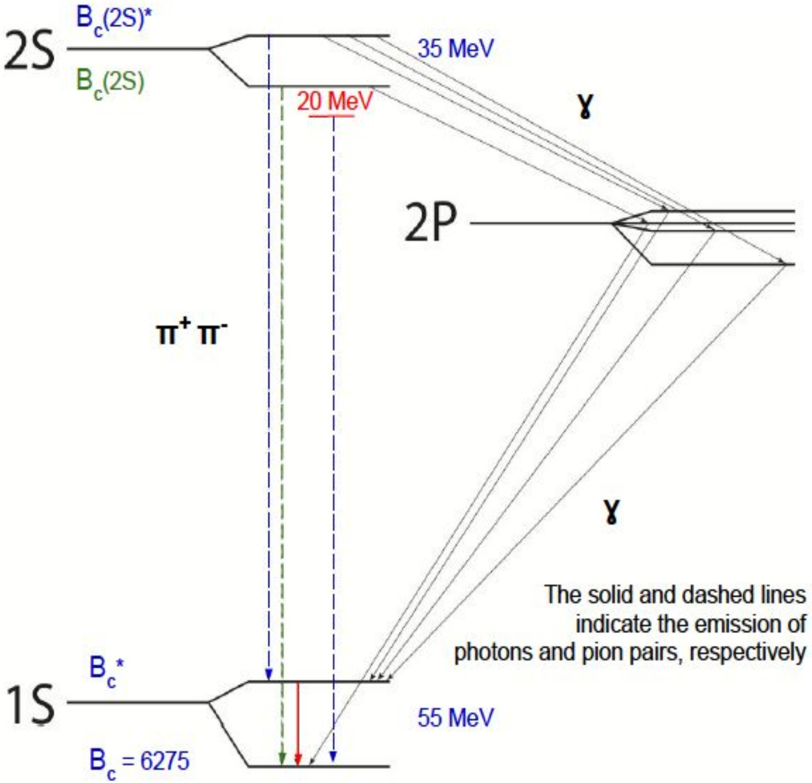
So, we see a two-peak structure in the $B_c \pi^+ \pi^-$ mass distribution, with the $B_c(2S)^*$ peak at a mass shifted by

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

which is predicted to be around 20 MeV.

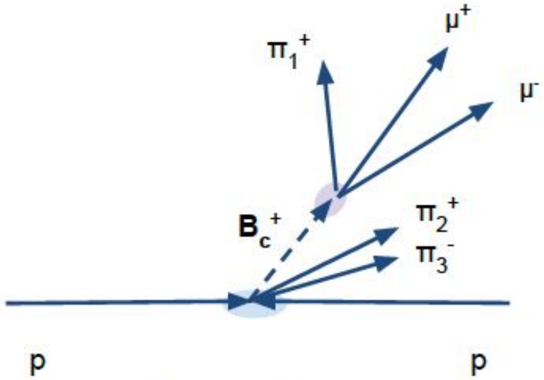
One have to notice:

$$[\ M(B_c(1S)^*) - M(B_c(1S))\ ] > [\ M(B_c(2S)^*) - M(B_c(2S))\ ]$$

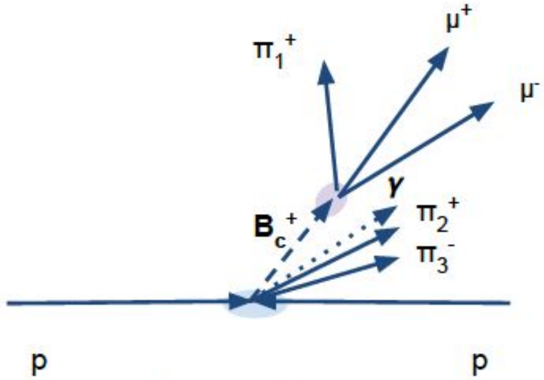


Event selection criteria

- B_c meson momentum required to point to the PV in the *xy* plane
- The PV is re-fitted excluding the three B_c decay tracks (two muons and one pion (π_1))
- π_2 and π_3 are tracks in that PV, e.g. they are prompt tracks, which are combined with B_c
- tracks and muons satisfy high-quality requirements
- When multiple $B_c \pi \pi$ candidates are found in the same event, we only keep the one with the highest p_T value



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

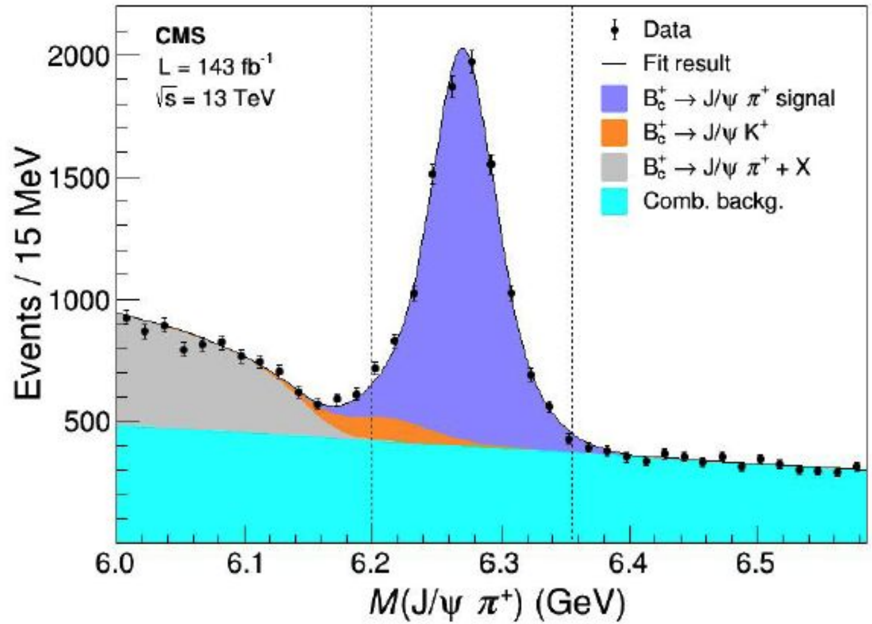


$B_c(2S)^* \rightarrow B_c^* \pi^+ \pi^-$

kinematic requirements

$p_T(\pi_1) > 3.5$ GeV
B_c prob(vtx) > 0.1
$p_T(B_c) > 15$ GeV
B_c decay length > 0.01 cm
$6.2 < M(B_c) < 6.35$ GeV
$B_c \pi \pi$ prob(vtx) > 0.1
$p_T(\pi_2) > 0.8$, $p_T(\pi_3) > 0.6$ GeV

Reconstruction of B_c



7629 ± 225 candidates

33.5 ± 2.5 MeV mass resolution

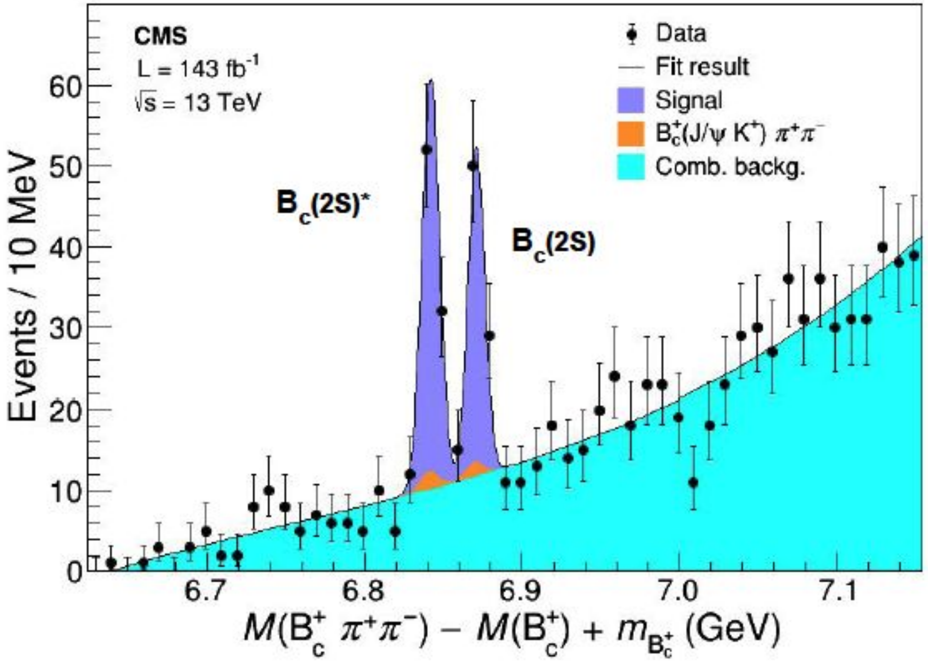
Fit details:

Unbinned ML; the signal is modeled using a double Gaussian with common mean and the background as a polynomial.
Additional background contributions from $B_c \rightarrow J/\psi\ K$ decay is modeled from the simulated sample,
while the partially reconstructed $B_c \rightarrow J/\psi\ \pi\ X$ decays are modeled with an ARGUS function convolved with a Gaussian.

Observation of the two-peak structure

The mass difference between the two states in the $B_c \pi^+\pi^-$ mass distribution is predicted to be $M(B_c(2S)) - \Delta M$, where

$$\Delta M = [\, M(B_c^*) - M(B_c)] - [\, M(B_c(2S)^*) - M(B_c(2S))] \quad \rightarrow \quad \sim 20 \text{ MeV}$$



Mass distribution fitted with Gaussian functions for the peaks and a 3rd order polynomial for the background.

Mass resolution agrees with MC expectations ~ 6 MeV

Two-peak structure observed (well resolved) :

$\Delta M = 29.1 \pm 1.5$ (stat) MeV

Local significance exceeding six σ for observing two peaks rather than one, evaluated through the ratio of likelihoods (including syst.). Each of them above five σ

Mass of $B_c(2S)$ measured to be:

$M(B_c(2S)) = 6871.0 \pm 1.2$ (stat) MeV

Natural widths : (50-90 keV predicted)

measurements consistent with zero, e.g. smaller than the resolution

Systematic uncertainty evaluation

The systematic uncertainties come from: $B_c(2S)$ fit modeling, J/ψ K uncertainties, partially reconstructed decays, and alignment of the detector.

Fit modeling:
alternative functions for the signal and the backgrounds
signal peaks: changed from two Gaussians to two Breit-Wigner functions
background: changed from a polynomial to a threshold function used in previous CMS analyses
observed differences in M and ΔM are quoted as systematic uncertainties: 0.8 and 0.7 MeV respectively

J/ψ K background contamination:
difference seen when its yield is varied by 10% (PDG BFs uncertainty): the difference is negligible

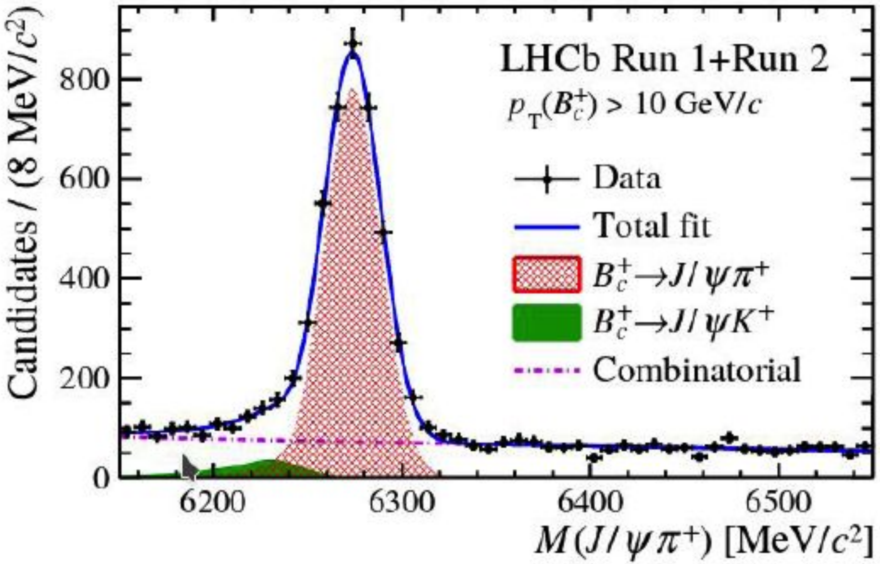
Alignment of the detector:
the possible misalignment of the detector biases the measured masses, however for studies with major detector changes (2016 vs 2017), was found to be negligible

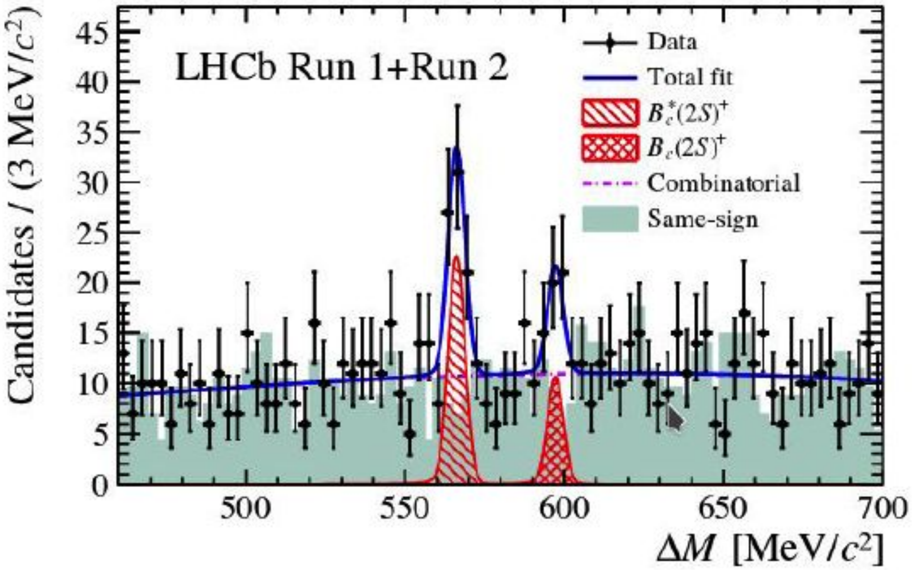
Partially-reconstructed decays:
the low-mass edge of the signal mass window was varied from 6.2 to 6.1 GeV, to increase (by 8%) this contamination;
the variations in the results are smaller than the uncorrelated stat. uncertainty: no systematic uncertainty is considered

In summary, the total systematic uncertainty is 0.8 MeV for M and 0.7 MeV for ΔM, fully determined by the choice of the fitting model for the signal peaks

Now LHCb has also confirmed the two peaks!

Observation of an excited Bc state
arXiv:1904.00081





Summary

- Using Run I data (8 TeV), the ratio of branching fractions $\frac{\mathcal{B}(B^+ \to J/\psi \bar{\Lambda} p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})}$ is measured. This measurement is the most precise to date.

- The study of two-body invariant mass distributions of the $B \to J/\psi \Lambda p$ decay products was performed.

- Model independent method is used to conclude that no new resonances are needed.

- The analysis is based on the full Run 2 data (13 TeV), corresponding to a total integrated luminosity of 143 fb^{-1}.

- Signals consistent with the $B_C(2S)$ and $B_C(2S)^*$ states have been separately observed for the first time by investigating the $B_C\pi\pi$ invariant mass spectrum measured by CMS.