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

Samet Lezki [1,2] on behalf of the CMS Collaboration

(1) INFN SEZIONE DI BARI, ITALIA (2) UNIVERSITÀ DEGLI STUDI DI BARI "ALDO MORO", ITALIA

Abstract

Signals consistent with the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states are observed in proton-proton collisions at $\sqrt{s}$ = 13 TeV, in an event sample corresponding to an integrated luminosity of 143 fb^{-1}, collected by the CMS experiment during the 2015 - 2018 LHC running periods. These excited bbar-c states are observed in the $B_c^+\pi^+\pi^-$ invariant mass spectrum, with the ground state B_c^+ reconstructed through its decay to $J/\psi\pi^+$. The two states are reconstructed as two well-resolved peaks, separated in mass by 29.1 ± 1.5 (stat) ± 0.7 (syst) MeV. The observation of two peaks, rather than one, is established with a significance exceeding five standard deviations. The mass of the $B_c^+(2S)$ meson is measured to be 6871.0 ± 1.2 (stat) ± 0.8 (syst) ± 0.8 (B_c^+) MeV, where the last term corresponds to the uncertainty in the world-average B_c^+ mass.

Introduction

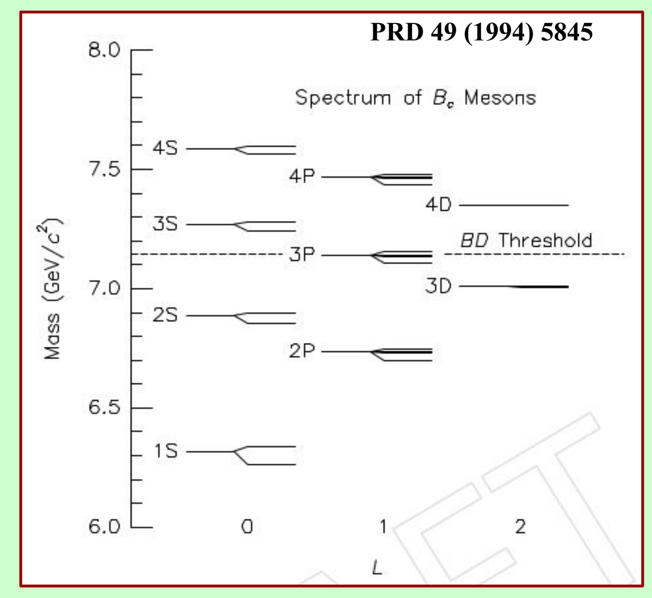
The B_c family consists of charged mesons composed of a beauty antiquark and a charm quark (or vice versa).
The ground state (B_c) was discovered in 1998 by the CDF Collaboration [PRL 81 (1998) 2432].

Experimental information is limited by low production rate: the cross section is proportional to the strong coupling constant α_S^4.
Given the different heavy quark flavors, the only allowed transitions are through photons or pion pairs.

ATLAS observed a new state with a mass consistent with predictions for the $B_c(2S)$. This state is reconstructed by its decay to $B_c\pi^+\pi^-$ followed by $B_c \rightarrow J/\psi\,\pi$ with a local significance of 5.4 σ [PRL 113, 212004 (2014)]. After the present study, the two peak structure has been observed also by LHCb [LHCb - PAPER - 2019 - 007].

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

PRD 51 (1995) 3613, PRD 53 (1996) 312, PRD 60 (1999) 074006, PRD 67 (2003) 014027, PRD 70 (2004) 054017, PRD 86 (2012) 094510, PRL 121 (2018)202002



Properties of spectrum

The $B_c(2S)$ decays directly to the B_c ground state : $B_c(2S) \rightarrow B_c\pi^+\pi^-$

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

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

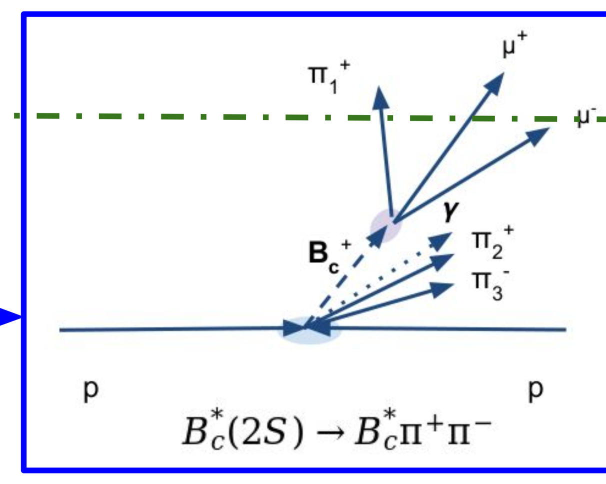
Having the emitted photon a very low energy, its detection is very challenging, and typically it is lost.
Thus:

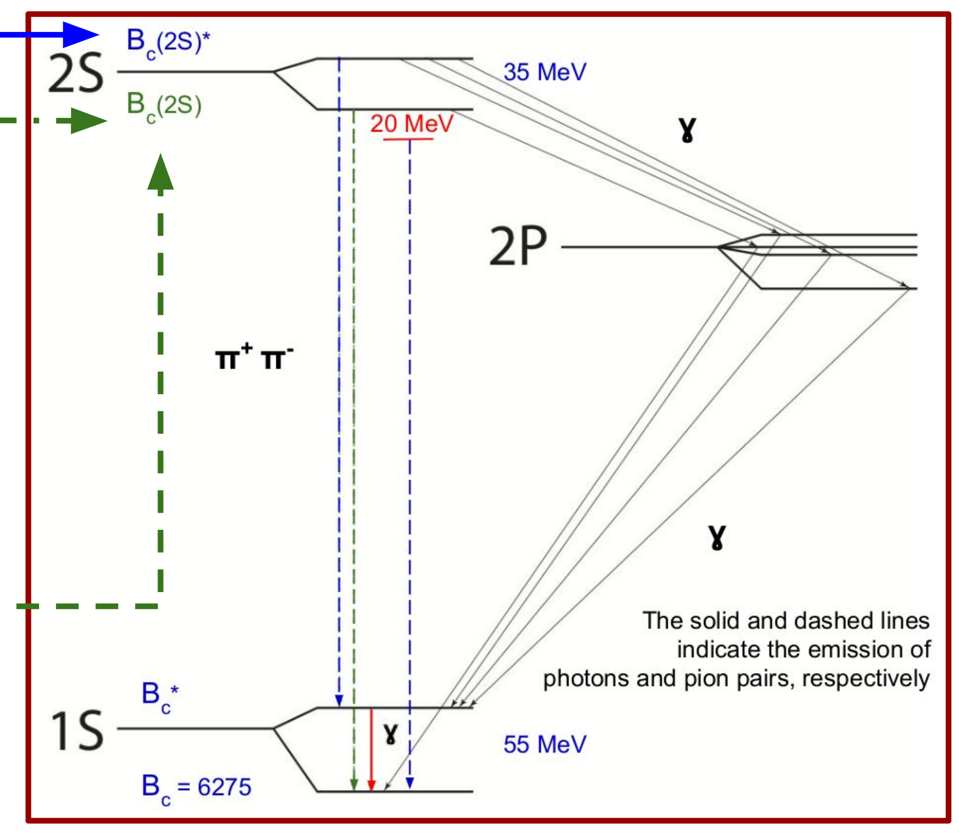
$B_c(2S) \rightarrow B_c\pi^+\pi^- + \text{"Missing Energy"}$

The $B_c(2S)^*$ peak should appear into $B_c\pi^+\pi^-$ mass spectrum at the mass $M(B_c(2S)) - \Delta M$

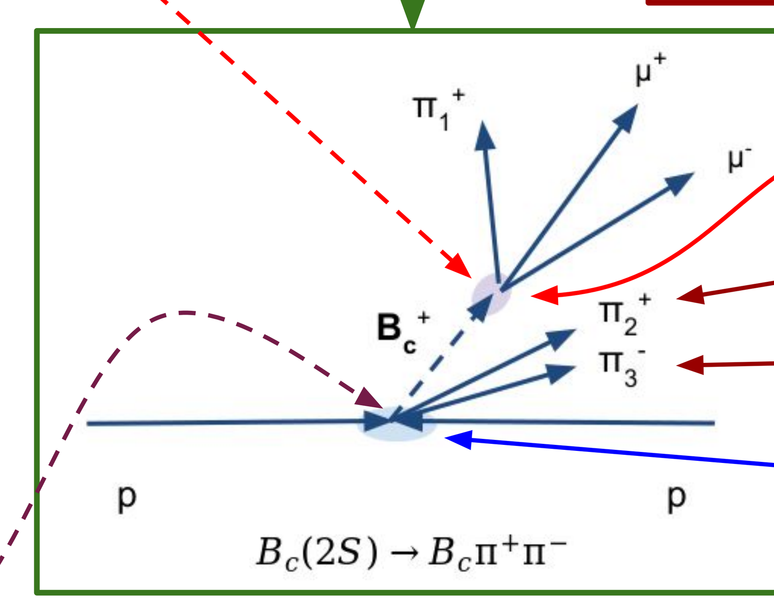
where $\Delta M = [M(B_c^*(1S)) - M(B_c(1S))] - [M(B_c^*(2S)) - M(B_c(2S))]$

which is predicted positive (ΔM~20MeV) so that the $B_c(2S)^*$ peak will be at lower masses than the $B_c(2S)$ peak



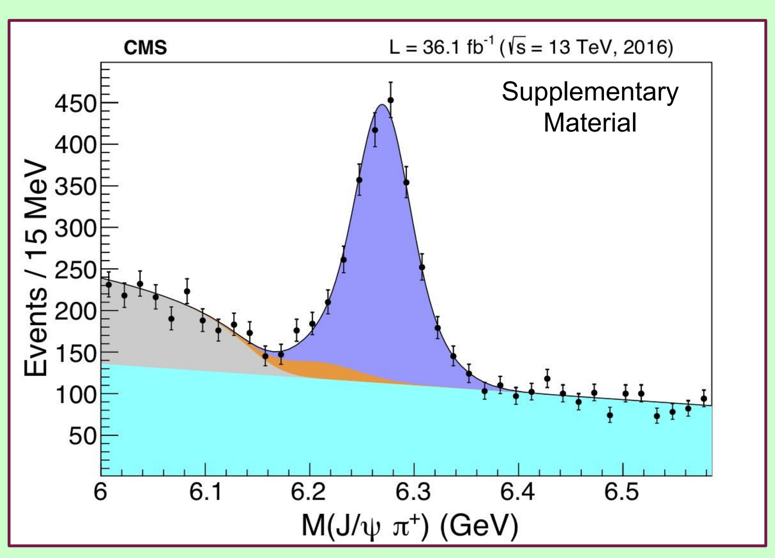


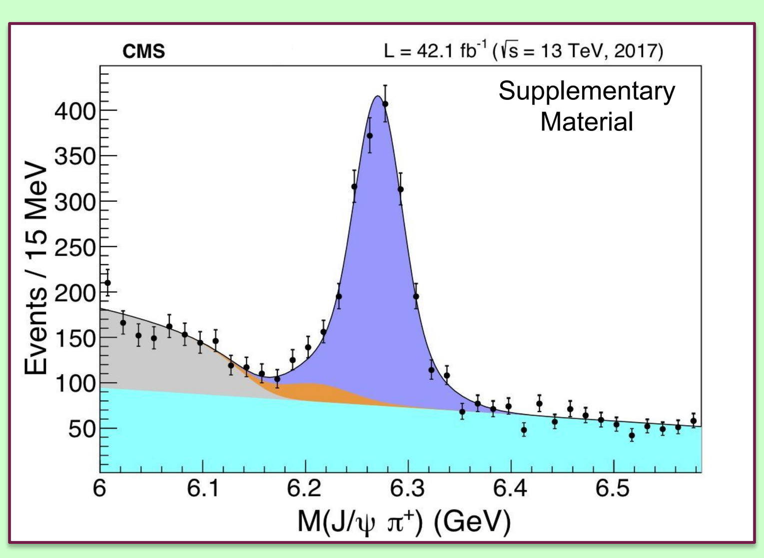
$p_T(\pi_1) >$ 3.5 GeV
$P(vtx) > 10\%$
$p_T(B_c) >$ 15 GeV
$|y(B_c)| < 2.4$
$l_{3D}(B_c) > 100\mu m$

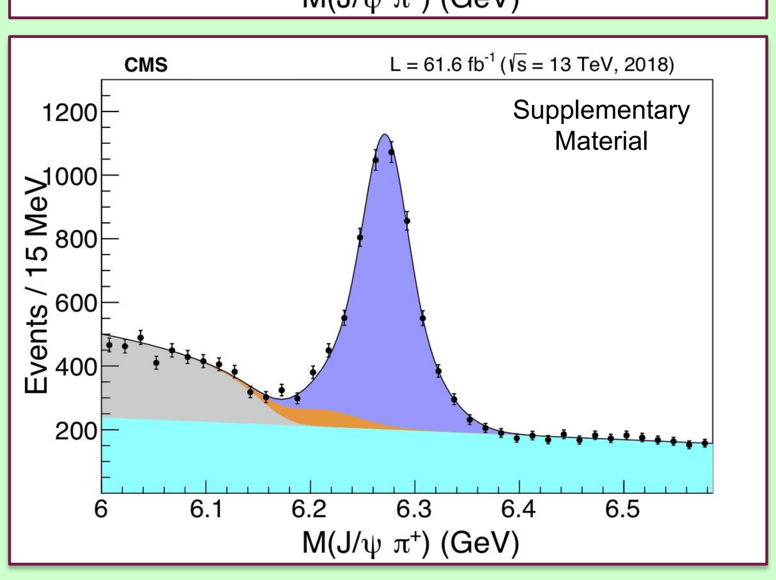


6.2 GeV $< M(B_c) <$ 6.35 GeV
$p_T(\pi_2) >$ 0.8 GeV
$p_T(\pi_3) >$ 0.6 GeV
B_c and 2 – track vtx with $P(vtx) > 10\%$

Reconstruction of B_c in 2016, 2017, 2018 and events selection criteria



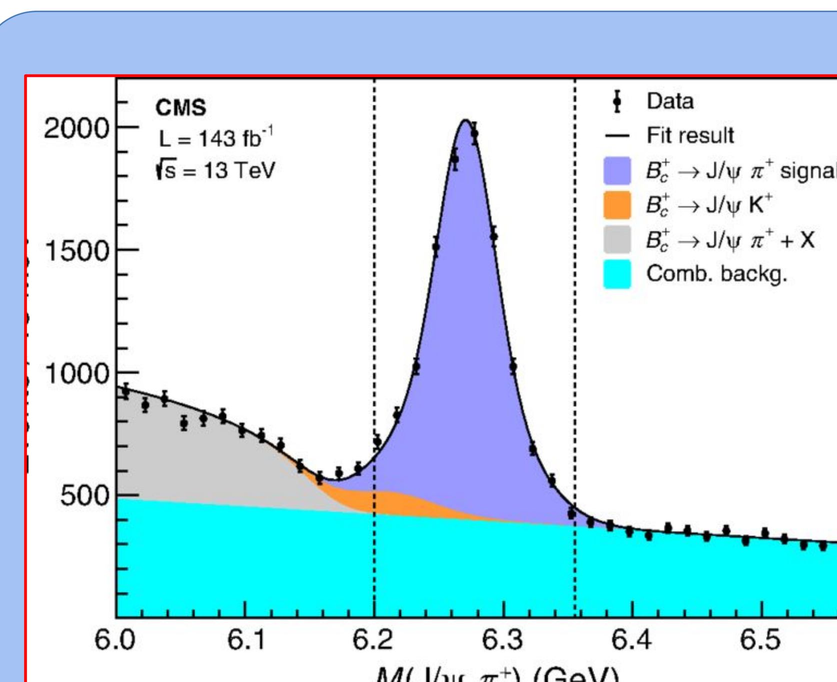




B_c reconstruction across periods is consistent

- B_c meson momentum required to point to PV in 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 going to be combined with B_c
- Tracks and muons satisfy high-quality requirements
- When multiple $B_c\pi^+\pi^-$ candidates are found in the same event, keep only the one with the highest p_T value.

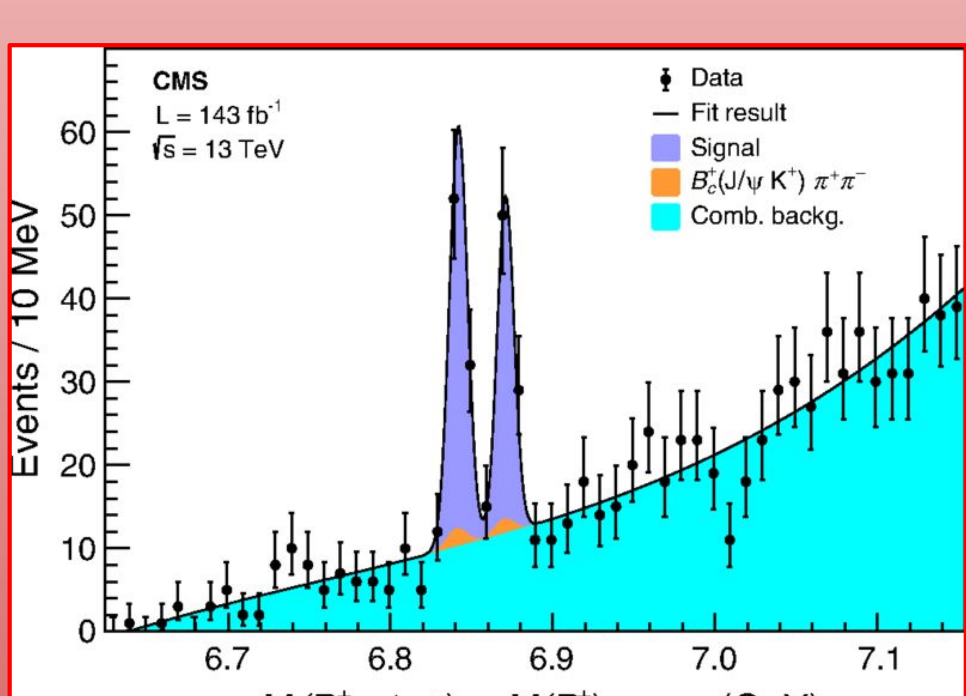
Extraction of B_c signal in full Run-II



- Unbinned ML fit; the signal is modeled using a double Gaussian with common mean and the background as a polynomial.
- Additional background contribution from $B_c \rightarrow J/\psi K$ decay is modeled taking the shape from simulation.
- Partially reconstructed $B_c \rightarrow J/\psi\pi X$ decays are modeled with an ARGUS function convolved with a Gaussian.

RESULTS [Published on Physical Review Letters 122 (2019) 132001]

- The $M(B_c\pi^+\pi^-) - M(B_c) + m_{B_c}$ distribution is fitted with Gaussian functions for the peaks and a 3rd order polynomial for the background
- Mass resolution agrees with MC expectations (~6MeV) and is much lower than ΔM thus allowing a two-peak structure to be observed; $B_c(2S)$ is assumed to be the right-most peak.
- Measured two peaks' mass difference: ΔM = [29.1 ± 1.5 (stat) ± 0.7 (syst)] MeV

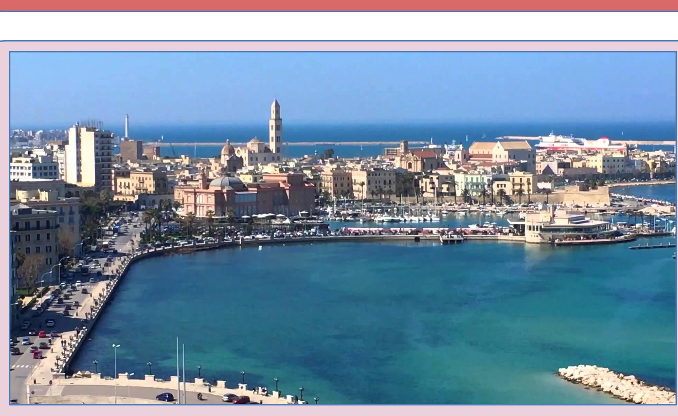


- Local significance exceeding 6.5σ for observing two peaks rather than one evaluated through a Likelihood Ratio technique (syst. un. included)
- Mass of $B_c(2S)$ measured to be: M(B_c(2S)) = 6871.0 ± 1.2(stat) ± 0.8(syst) ± 0.8(B_c) MeV
- The observed $B_c(2S)^*$ peak has a mass lower than the true value, which remains unknown (because of the unreconstructed photon).
- When fitting each signal with a Breit-Wigner convolved with the gaussian resolution function the natural width is consistent with zero: natural widths are much smaller than resolution.

Sources of systematic uncertainties

The systematic uncertainties come from:
$B_c(2S)$ fit modeling, J/ψK background, partially reconstructed decays and detector's alignment:

- 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 polynomials to a threshold function
  - Observed differences in M and ΔM are quoted as systematic uncertainties: 0.8 and 0.7 MeV respectively
- J/ψK 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 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 signal mass window was varied from 6.2 to 6.1, to increase (by 8 %) this contamination; the variations in the results are smaller than the uncertainties; no systematic uncertainty is considered



The 27th International Workshop on Weak Interactions and Neutrinos