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Farnesina
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CMS studies of excited B_c states

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On behalf of the CMS Collaboration

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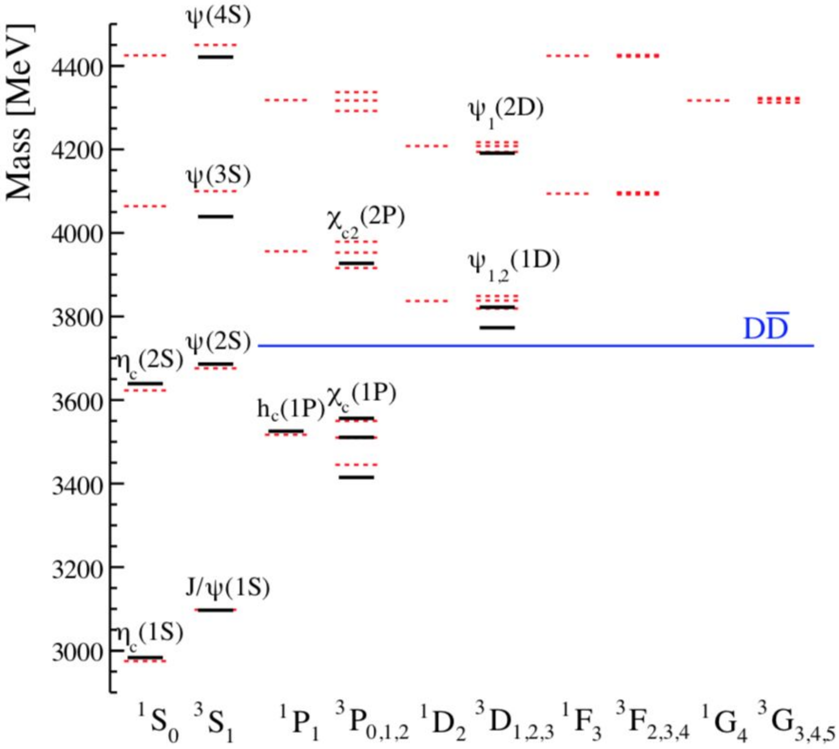
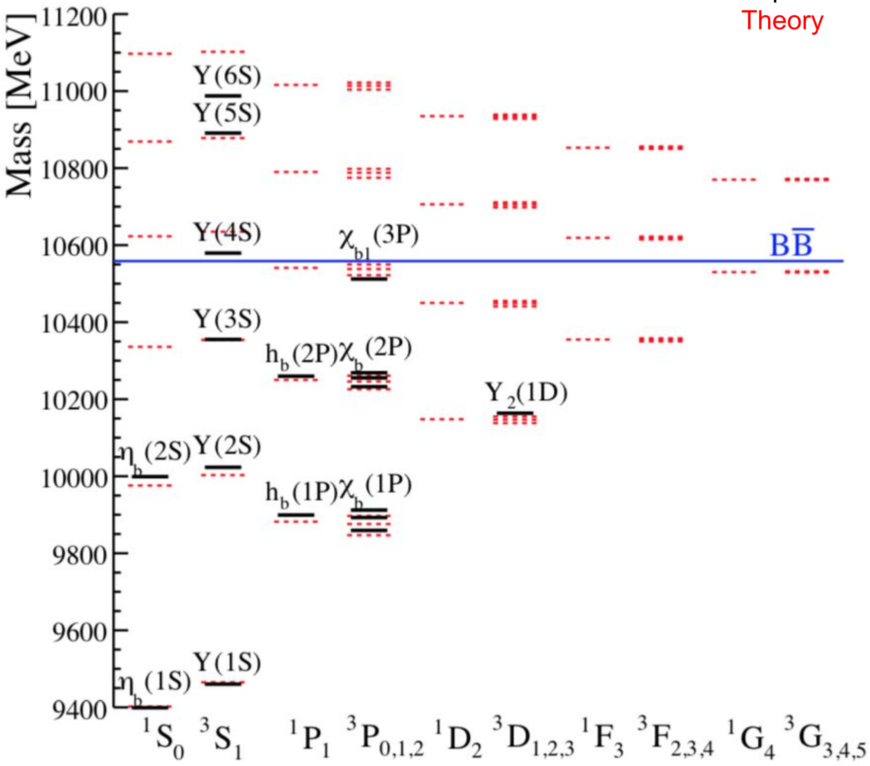
Charmonium and Bottomonium spectrum

Rev. Mod. Phys. 90, (2018) 015003

Experiment
Theory

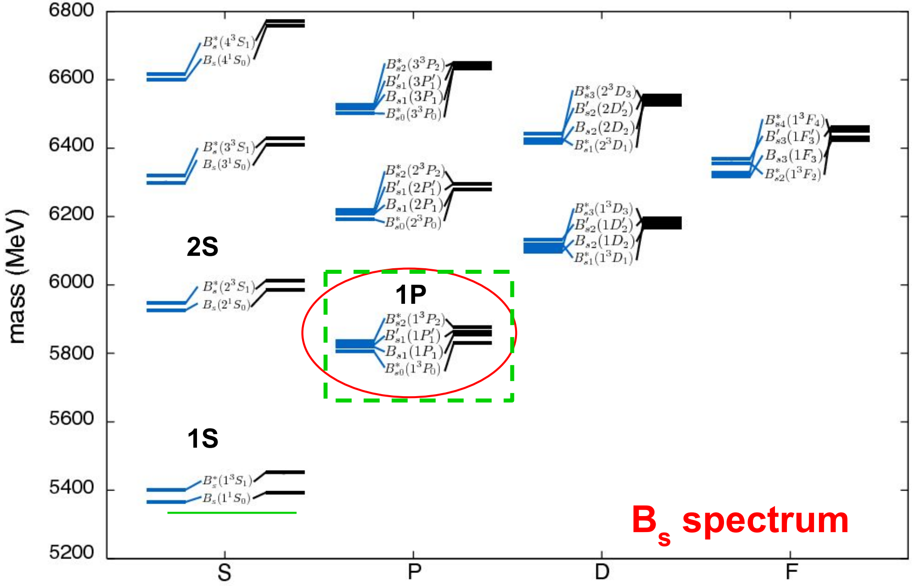


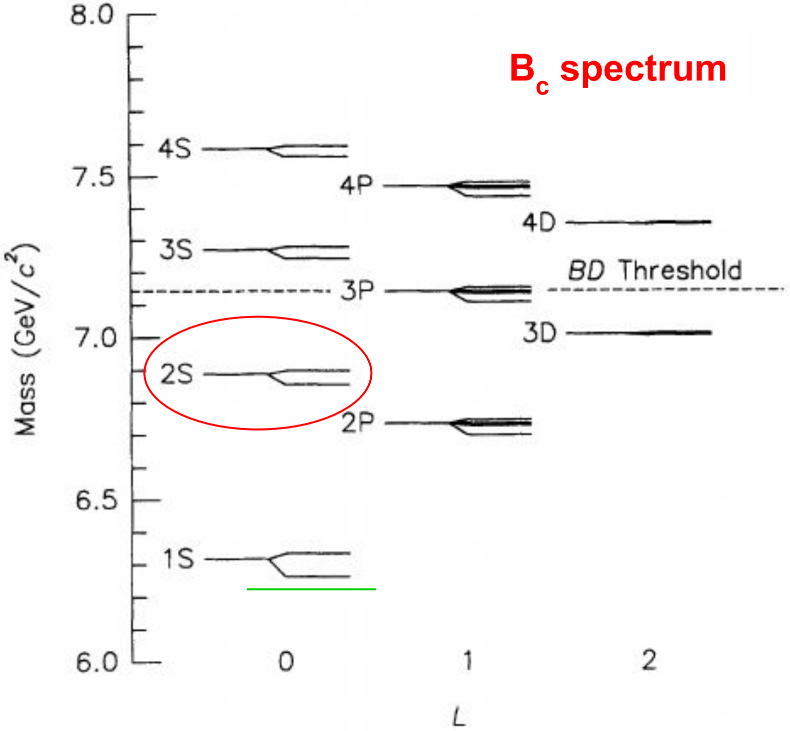


Charmonium spectrum is pretty well known, Bottomonium spectrum as well.

B meson spectrum

On the contrary, for B mesons and in particular for B_s or B_c, the knowledge is limited:





Phys.Rev. D94 (2016) 054025

Phys. Rev. D 49 (1994) 5845

Introduction

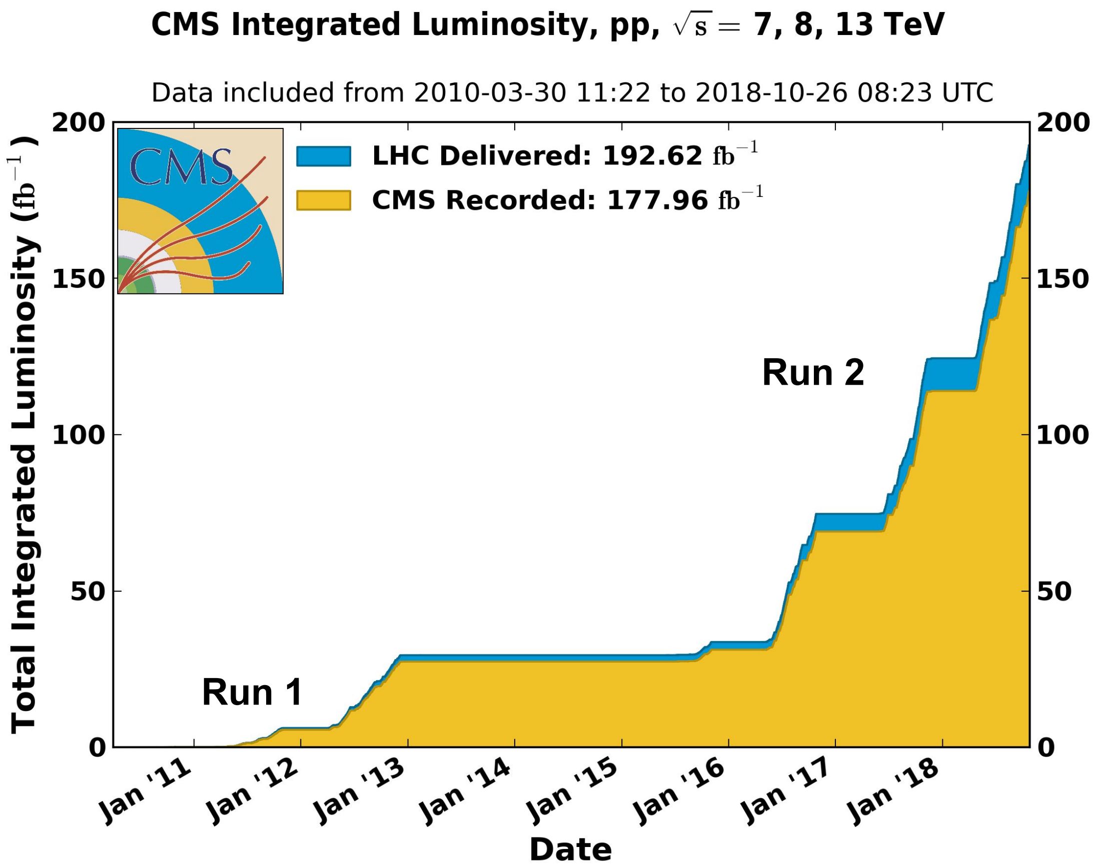
The B_c meson was discovered in 1998 by CDF (**PRL 81 (1998) 2432**).
It is the lowest-mass bound state of the family of mesons composed of a charm quark and a bottom anti-quark.

Experimental information is limited by the rare production rate, α_s^4: qqbar, gg → (c-bbar) b-cbar.

Given the different heavy quark flavors, the only allowed transitions are through photons or pion pairs

Particle	**Predicted mass (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

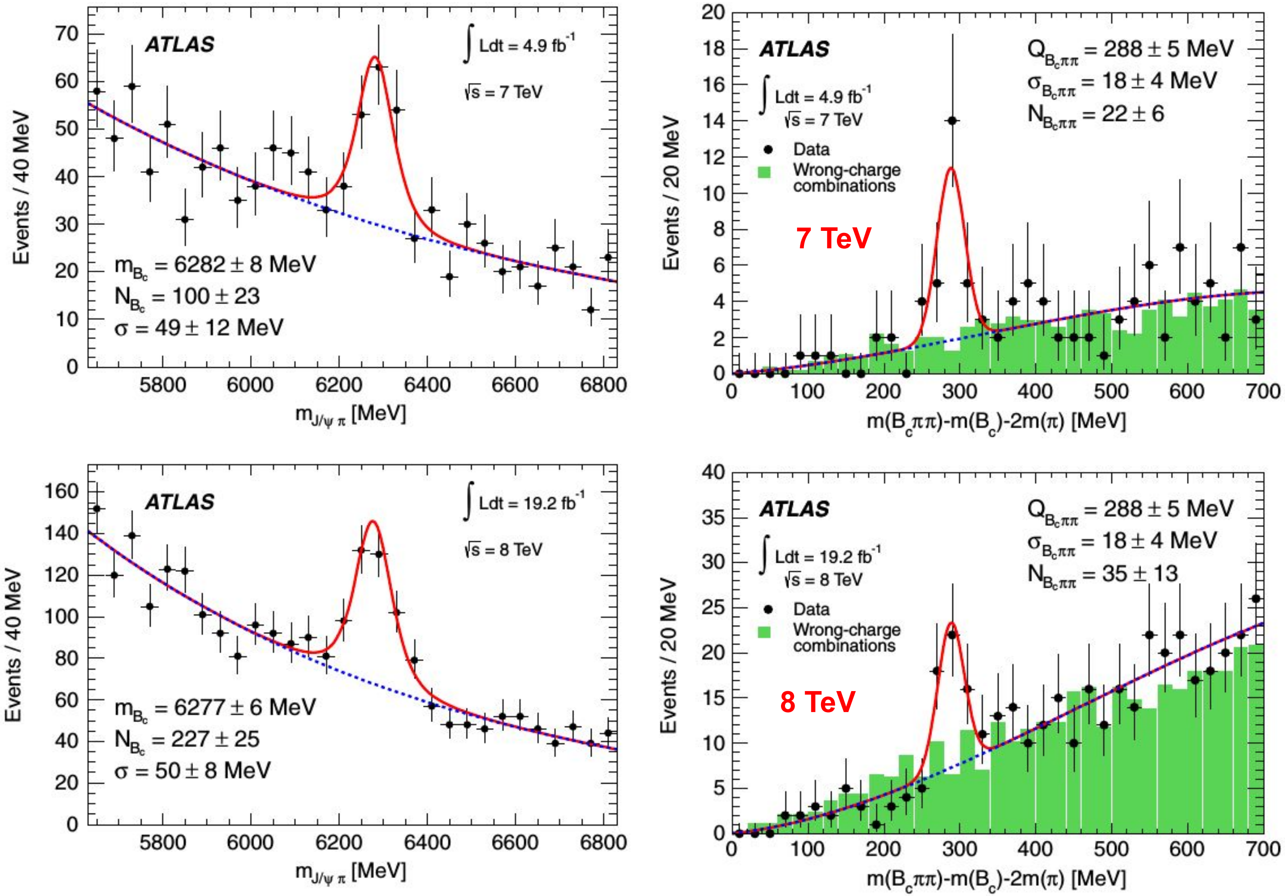


CMS has recorded ~5 fb^{-1} at √s=7 TeV, ~20 fb^{-1} at √s=8 TeV, and ~140 fb^{-1} at √s=13 TeV of data for physics analysis

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, 132001 (2019) arXiv:1902.00571

Observation of an excited B_c meson state by ATLAS



PRL 113, 212004 (2014)

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

The $B_c(2S)$ is reconstructed from the decay

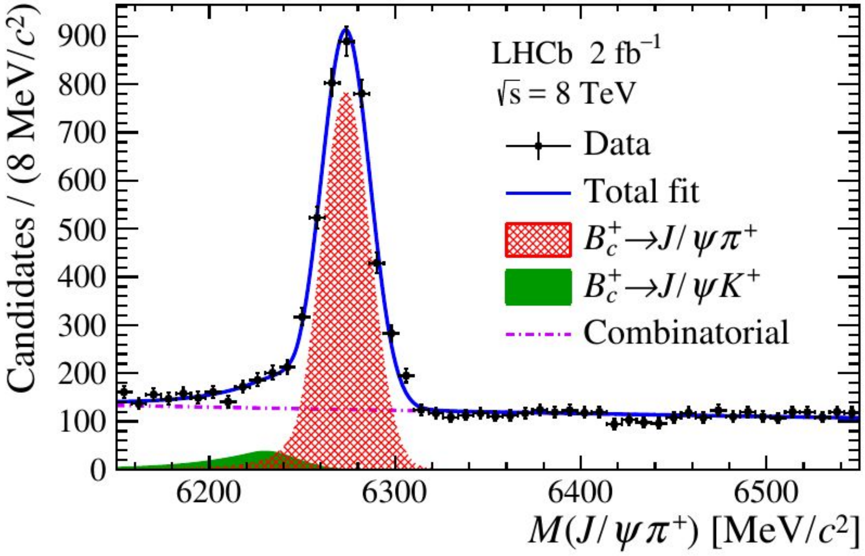
$B_c(1S)\,\pi^+\pi^-$ where $B_c \to J/\psi\,\pi$

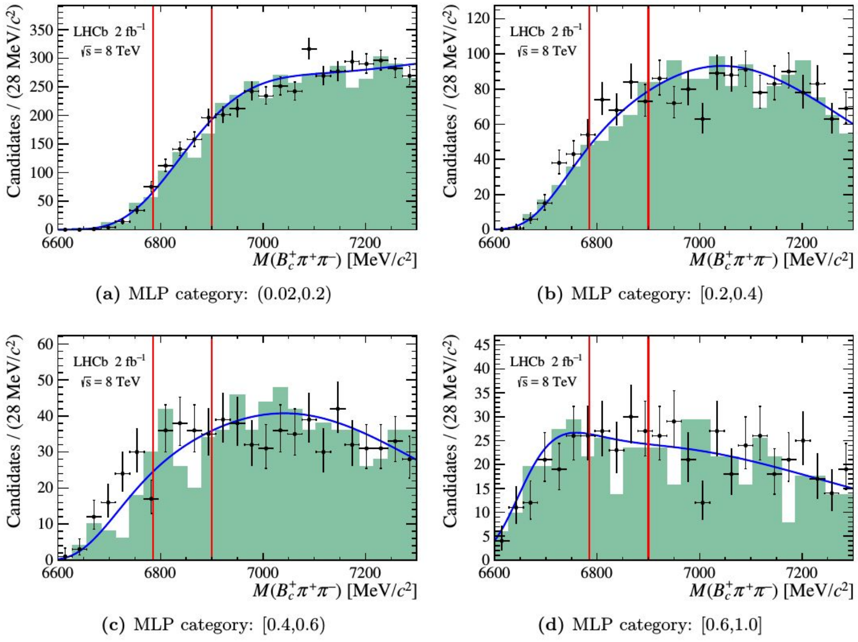
with a local significance of 5.4 σ

Search for excited B_c states by LHCb

JHEP 01 (2018) 138

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





With 3325 ± 73 B_c events:

"No significant signal is found" in the search for the excited states $B_c(2S)$ and $B_c(2S)^*$

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"

which is the same final state as

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

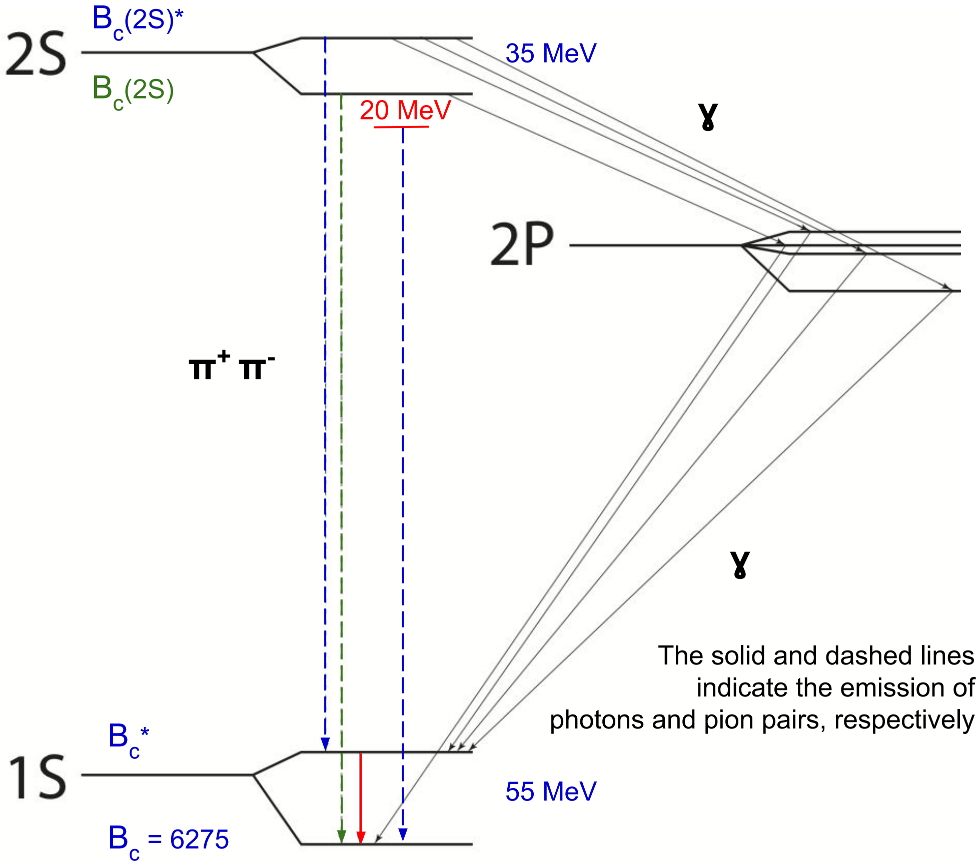
So, we see a two-peak structure in the $B_c \pi^+ \pi^-$ mass distribution, with the $B_c(2S)^*$ peak at a mass shifted by

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

which is predicted to be around 20 MeV.

Notice that

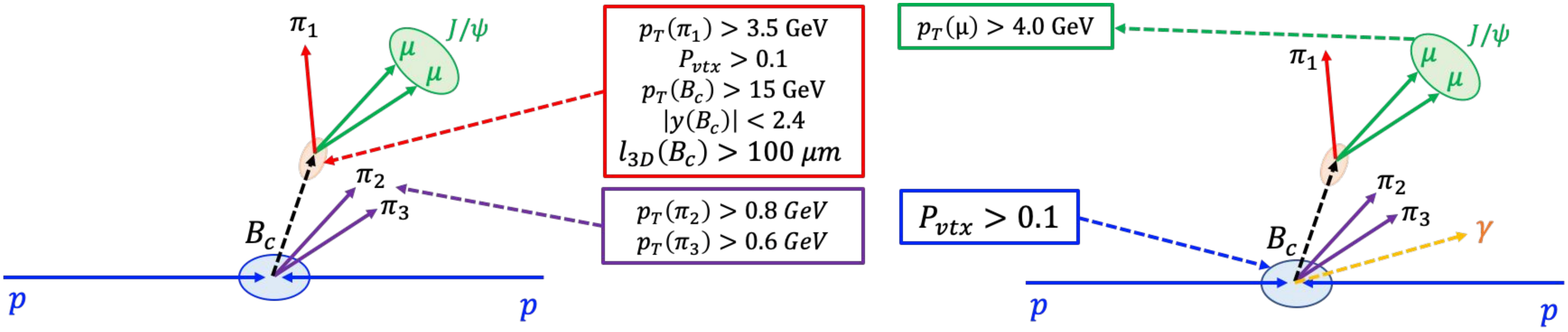
$$[\, M(B_c(1S)^*) - M(B_c(1S))\,] > [\, M(B_c(2S)^*) - M(B_c(2S))\,]$$



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

Event selection criteria

- Trigger preselection: two muons from J/ψ plus a track, with common vertex displaced from interaction point ($L_{xy}/\sigma_{Lxy} > 3$)
- 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

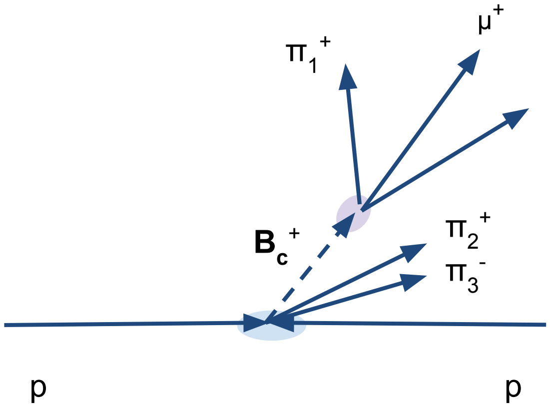


$B_c^+(2S) \to B_c^+\pi^+\pi^-$ $\qquad$ $B_c^{*+}(2S) \to B_c^{*+}\pi^+\pi^-$

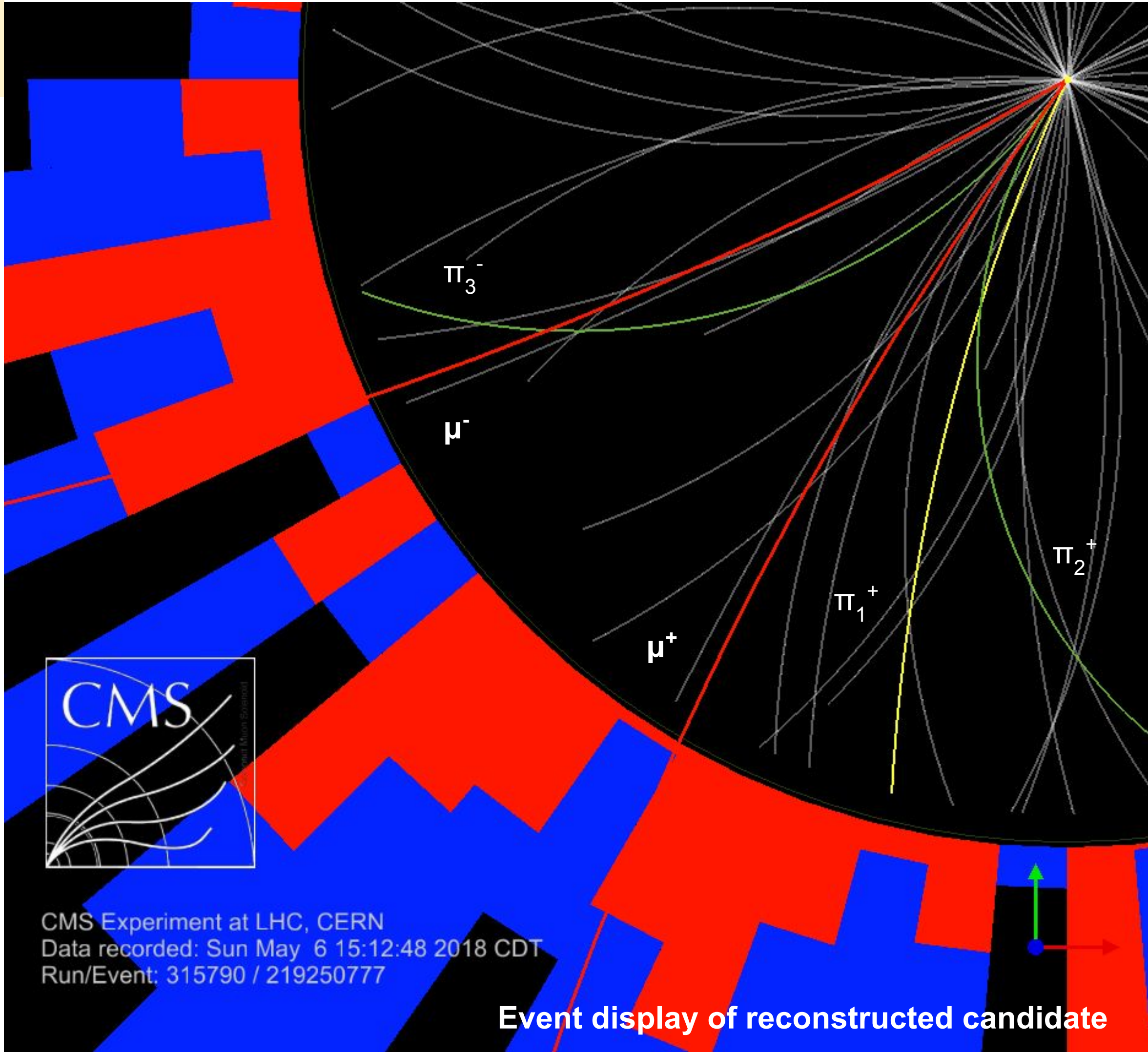
Event selection

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

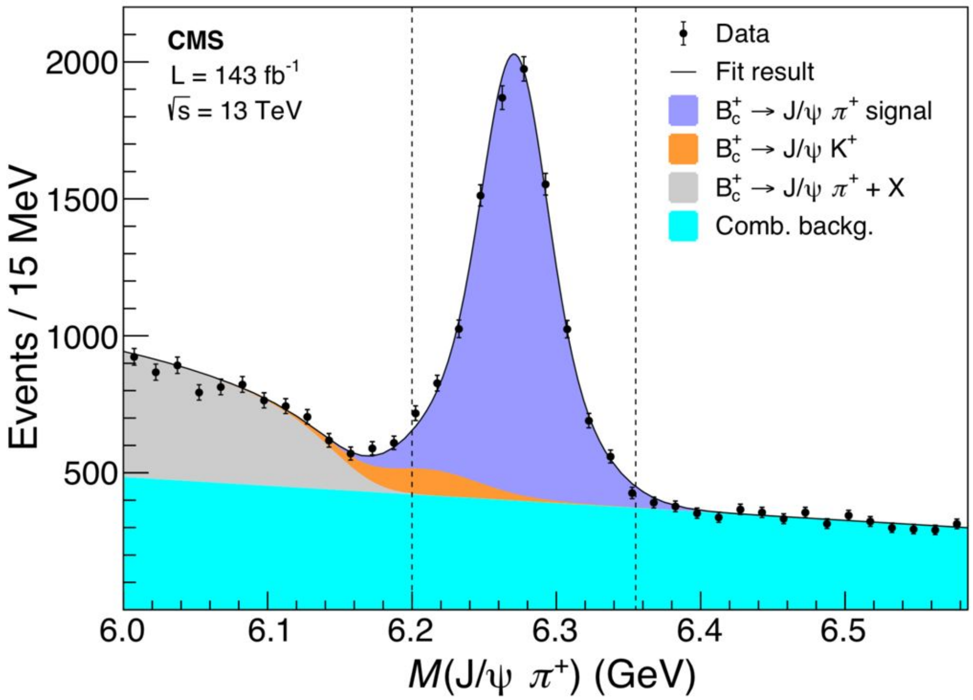


$B_c(2S) \to B_c \pi^+ \pi^-$



Event display of reconstructed candidate

Reconstruction of B_c in data: 2015 + 2016 + 2017 + 2018



7629 ± 225 candidates

~34 MeV mass resolution

Fit details:

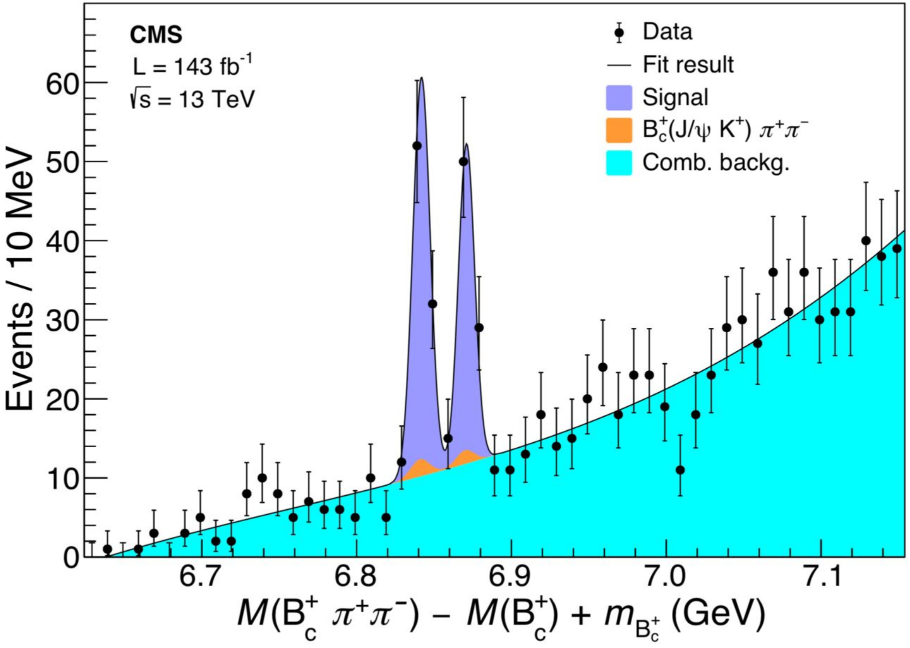
Unbinned ML; the signal is modeled using a double Gaussian with common mean and the background as a polynomial. Additional background contributions from $B_c \to J/\psi$ K decay is modeled from the simulated sample, while the partially reconstructed $B_c \to J/\psi\ \pi$ X decays are modeled with an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

Observation of a 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

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

2015+2016+2017+2018



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

- **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 evaluated 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

- **World average $M_{PDG}(B_c)$ uncertainty**: 0.8 MeV

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

Summary

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

The analysis is first LHC result based on the full usable Run 2 data of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of 143 fb^{-1}

The two-peaks are very well resolved with a measured mass difference of **ΔM = 29.1 ± 1.5 (stat) ± 0.7 (syst) MeV**

Both peaks have local significance exceeding five standard deviations

Results

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Both peaks have local significance exceeding five standard deviations

The mass of the $B_c(2S)$ state is measured to be **$M(B_c(2S))$ = 6871.0 ± 1.2 (stat) ± 0.8 (syst) ± 0.8 (B_c) MeV**

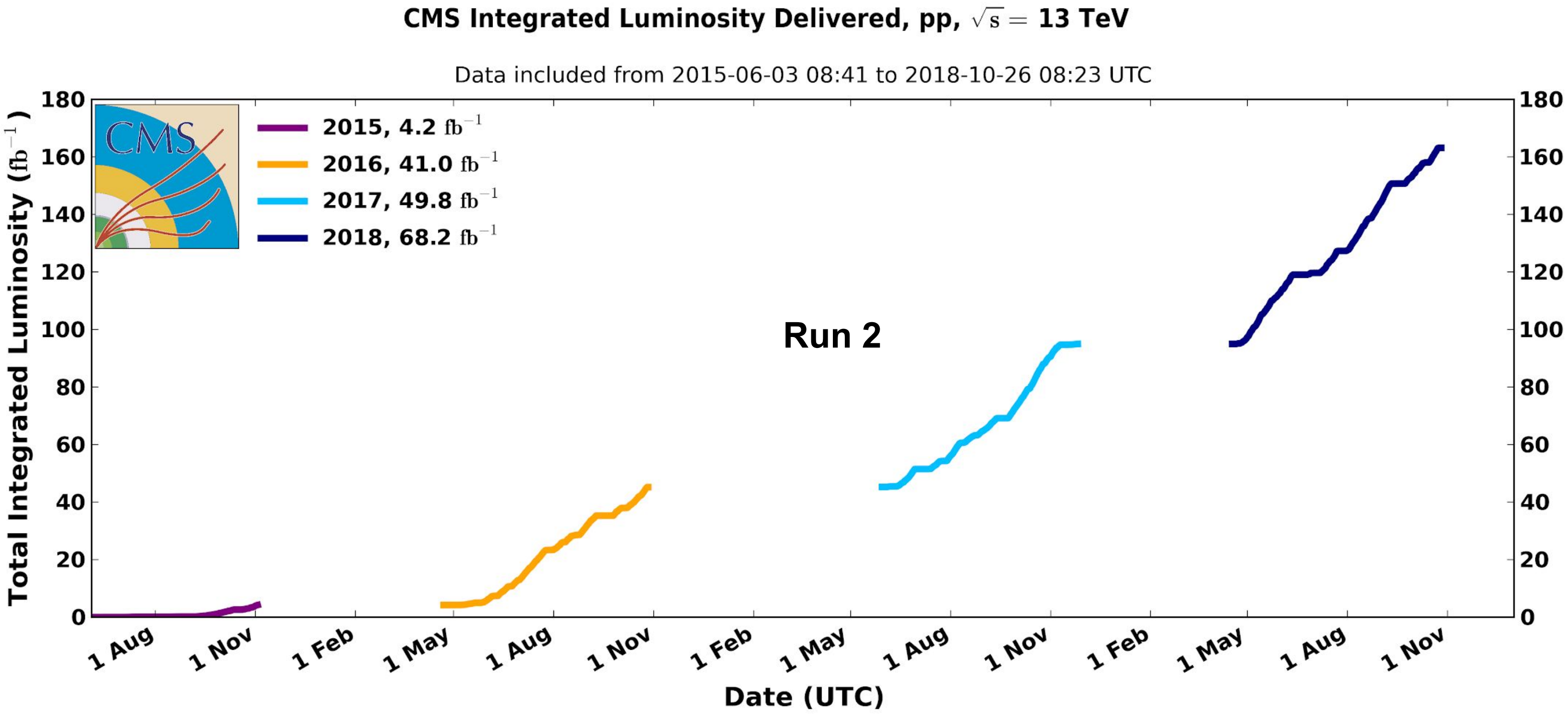
The mass of the $B_c(2S)^*$ state remains unknown because the B_c^* decays to $B_c \gamma$ and the photon is not reconstructed

Additionally two mass differences unaffected by the uncertainty of B_c world-average-mass, have been determined

$M(B_c(2S) - M(B_c) - 2m_\pi$ = 317.0 ± 1.2 (stat) ± 0.8 (syst) MeV and **$M(B_c(2S)^* - M(B_c^*)$ = 567.0 ± 1.0 (stat) MeV**

These measurements contribute significantly to the detailed characterization of the B_c family and provide a rich source of information on the non-perturbative QCD processes that bind heavy quarks into hadrons.

Backup



CMS has collected ~163 fb^{-1} of data at 13 TeV
of which ~140 fb^{-1} are good for physics

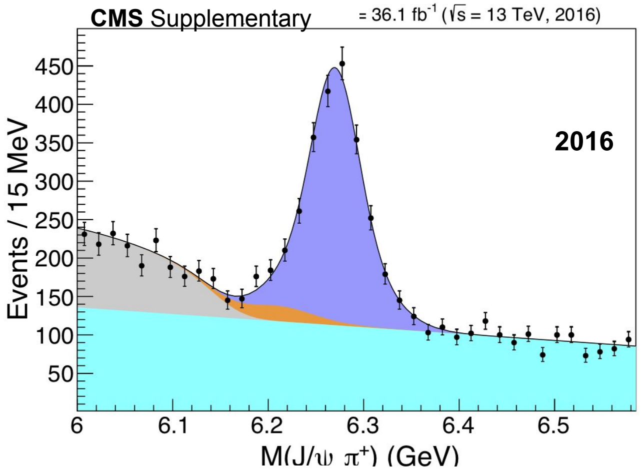
Monte Carlo generation details

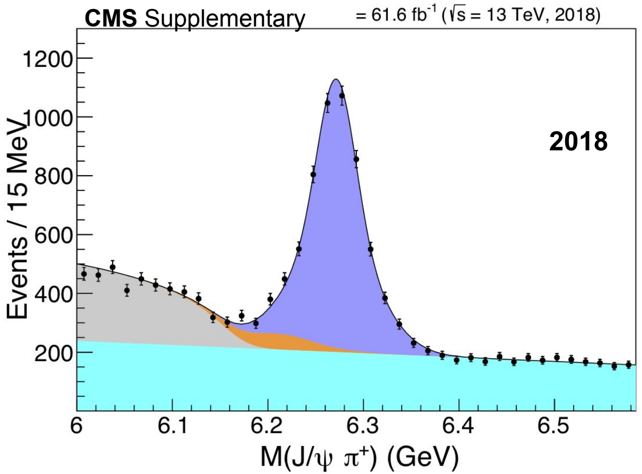
For resolution studies, background shape determination, and validation of the analysis selection criteria; we have used **BCVEGPY 2.2** to generate the (b cbar) state plus bbar and c partons. The LHE output is passed to **PYTHIA 8.230** for hadronization and to **EVTGEN 1.6** for decaying the B_c states. FSR is simulated using **PHOTOS 3.61**

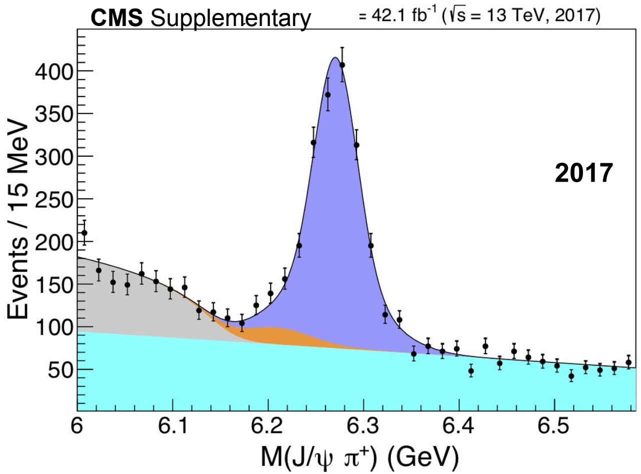
The B_c, B_c^*, $B_c(2S)$ and $B_c(2S)^*$ masses are set to 6.2749, 6.3400, 6.8630, and 6.9030 GeV, respectively

The simulated events include multiple proton-proton interactions in the same or nearby beam crossings (pileup), with a distribution matching that observed in data.

Reconstruction of B_c in data: 2016 vs 2017 vs 2018







B_c reconstruction across periods is consistent

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.

How do we compare with ATLAS observation