ATLAS and CMS measurements on spectroscopy

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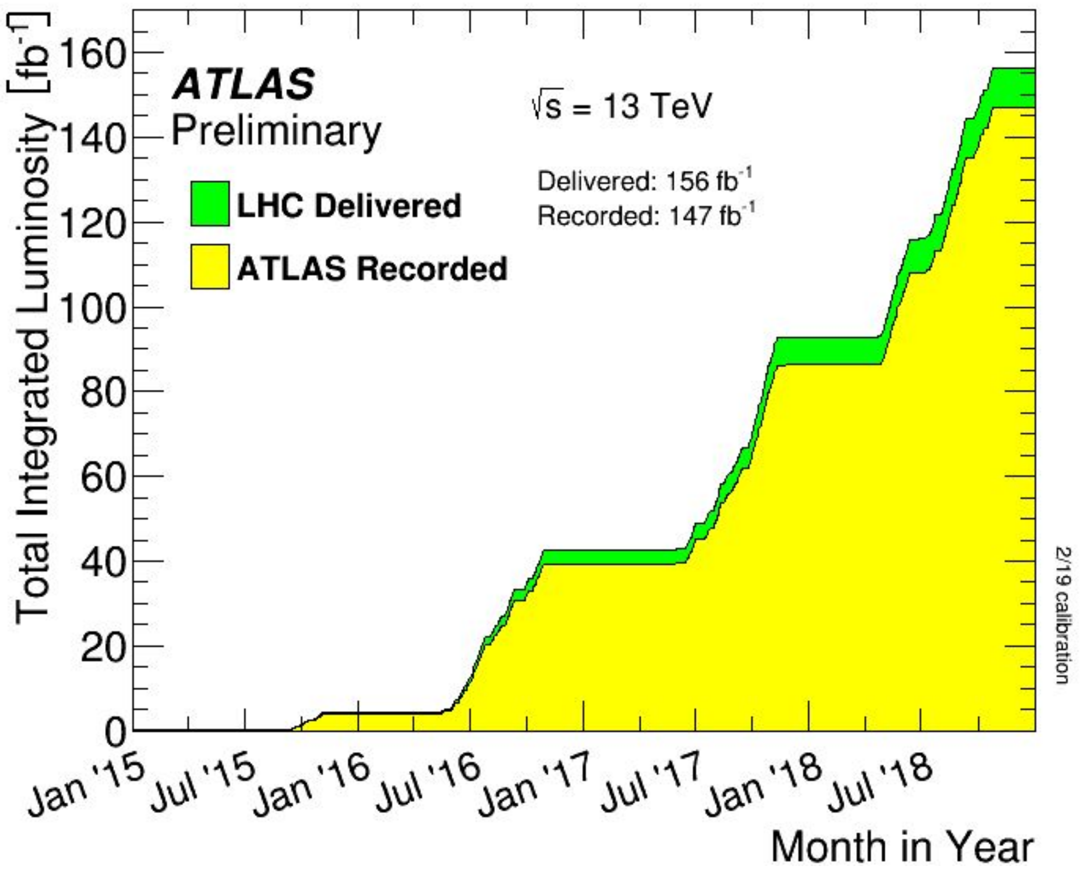
Outline

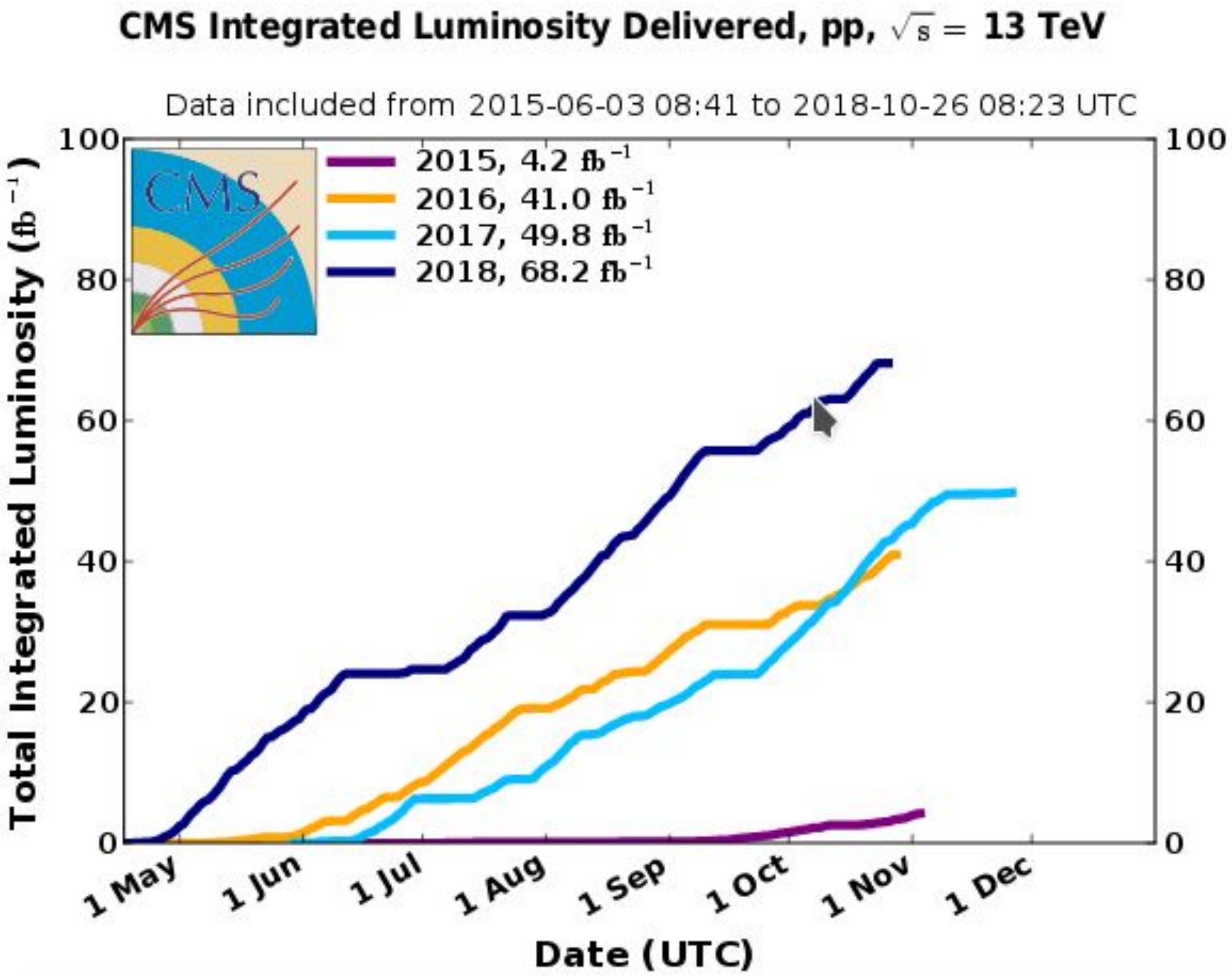
- **Observation of an Excited B_c Meson State with the ATLAS Detector.**
  CERN-PH-EP-2014-137
  Phys. Rev. Lett. 113, 212004 (2014)

- **Observation of two excited B_c states and measurement of the B_c(2S) mass in pp collisions at $\sqrt{s}$ = 13 TeV.**
  CMS-BPH-18-007; CERN-EP-2019-014
  Phys. Rev. Lett. 122 (2019) 132001

- **Search for a Structure in the $B_s^0\pi$ Invariant Mass Spectrum with the ATLAS Experiment.**
  CERN-EP-2017-333
  Phys. Rev. Lett. 120 (2018) 202007

- **Study of the $B \rightarrow J/\psi \Lambda p$ decay in proton-proton collisions at $\sqrt{s}$ = 8 TeV.**
  CMS-PAS-BPH-18-005





Exceeding the original integrated luminosity projections, 150 fb^{-1} has been delivered by the LHC in Run 2 (2015−2018).
Congratulations LHC, for a great performance!

ATLAS/CMS has accumulated over 140 fb^{-1} at 13 TeV of data for physics.

CERN-PH-EP-2014-137:

Observation of an Excited B_c Meson State with the ATLAS Detector.

Phys. Rev. Lett. 113, 212004 (2014)

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.

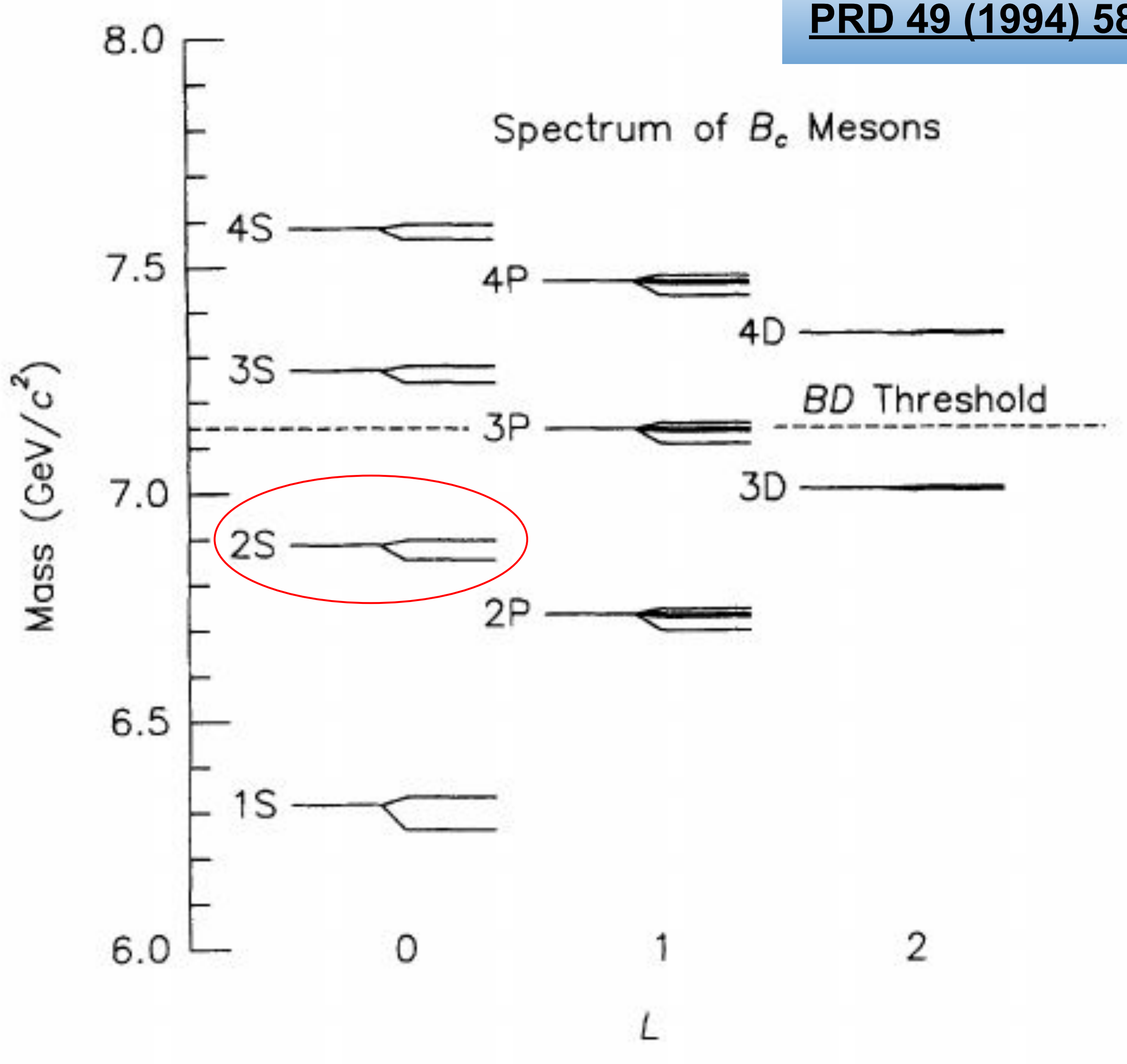
Experimental information is limited by rare production rate, α_s^4 : qqbar, gg → (c-bbar) b-cbar.

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

Particle	Predicted 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

PRD 49 (1994) 5845

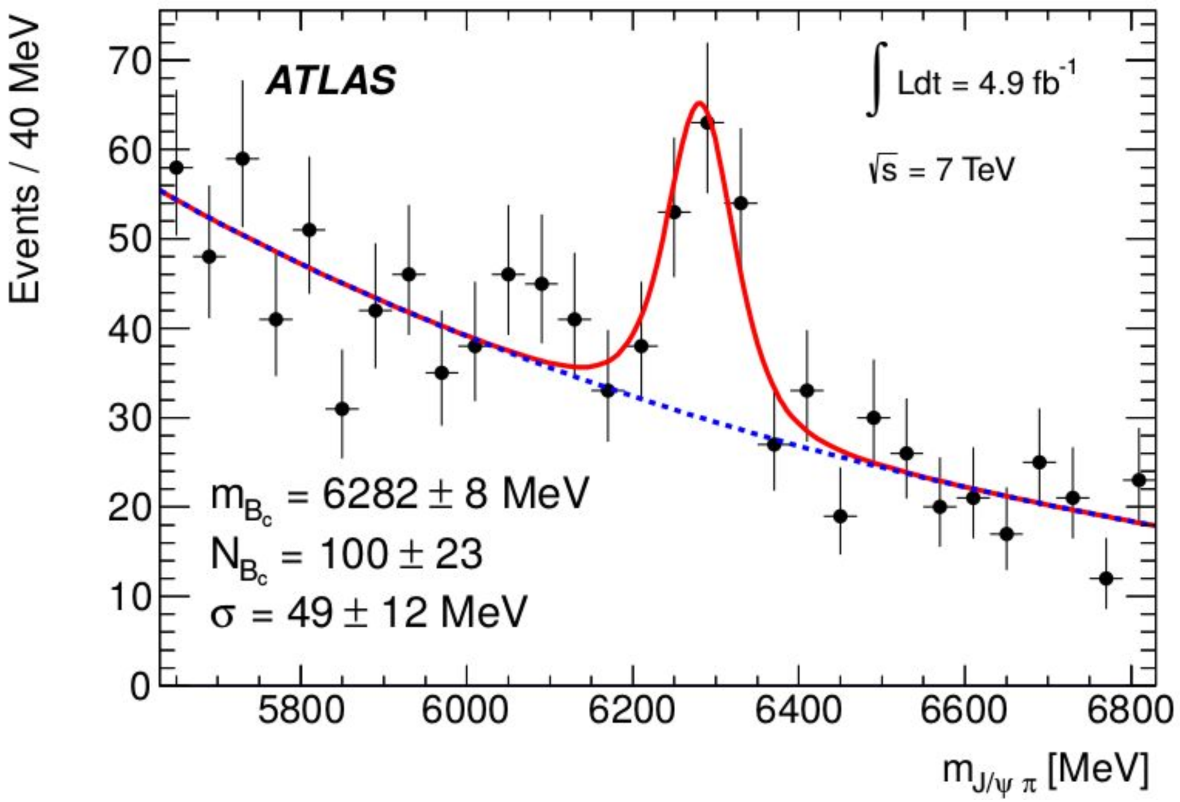


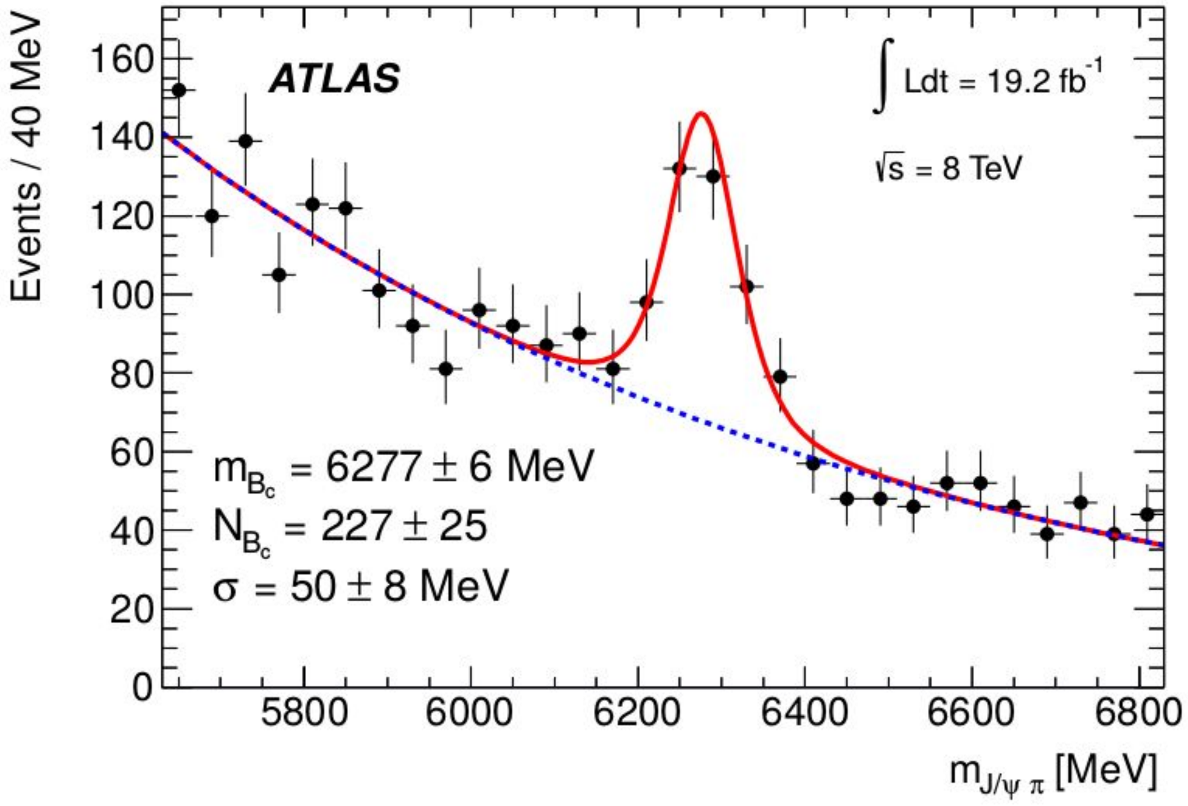
Observation of an Excited Bc Meson at ATLAS

- **Ground state: $B_c \longrightarrow J/\Psi(\mu\mu)\pi$**

- The B_c selection criteria for the events are optimized separately for 7 and 8 TeV
  $p_T(B_c) > 15$ GeV (7 TeV) and $p_T(B_c) > 15$ GeV (8 TeV)

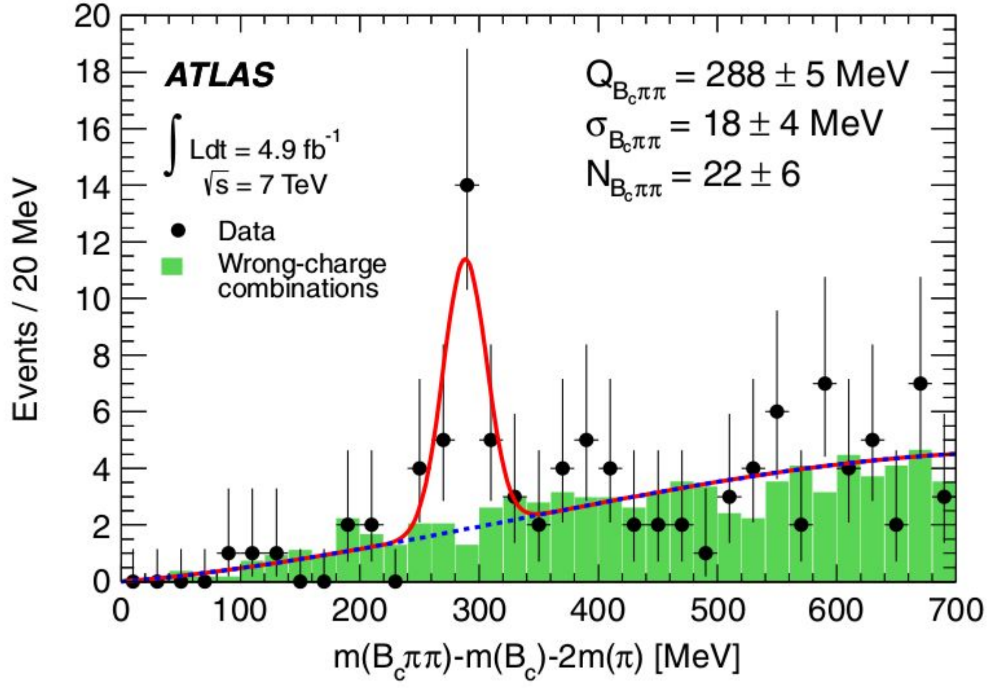
- Extended unbinned maximum likelihood fit, with a Gaussian function modeling the signal and an exponential modeling the background shape.

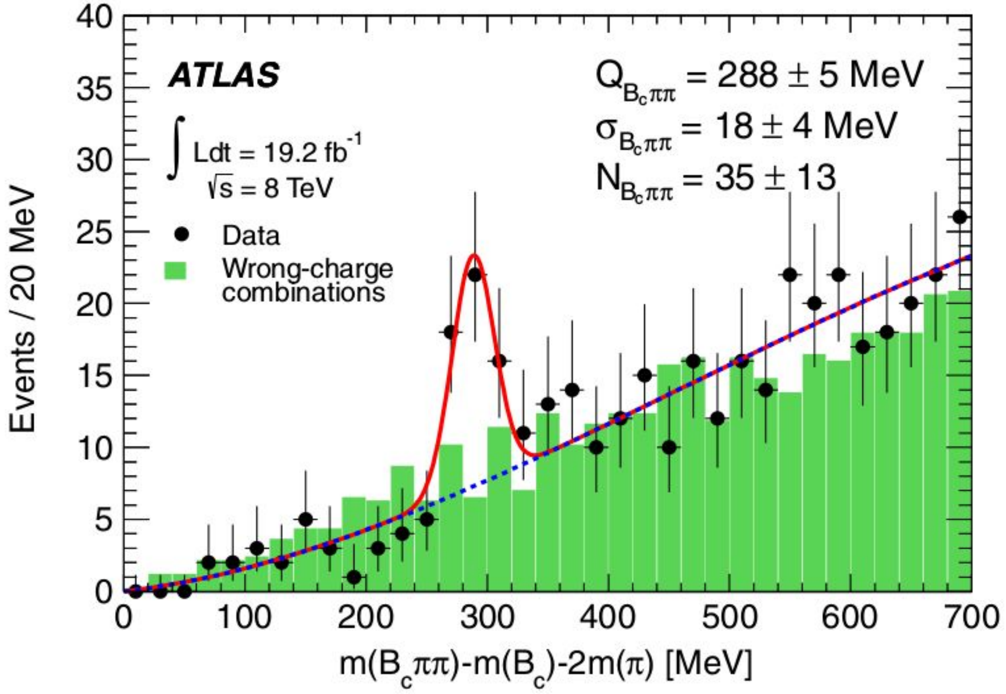




More details in the next slides

Observation of an Excited Bc Meson at ATLAS





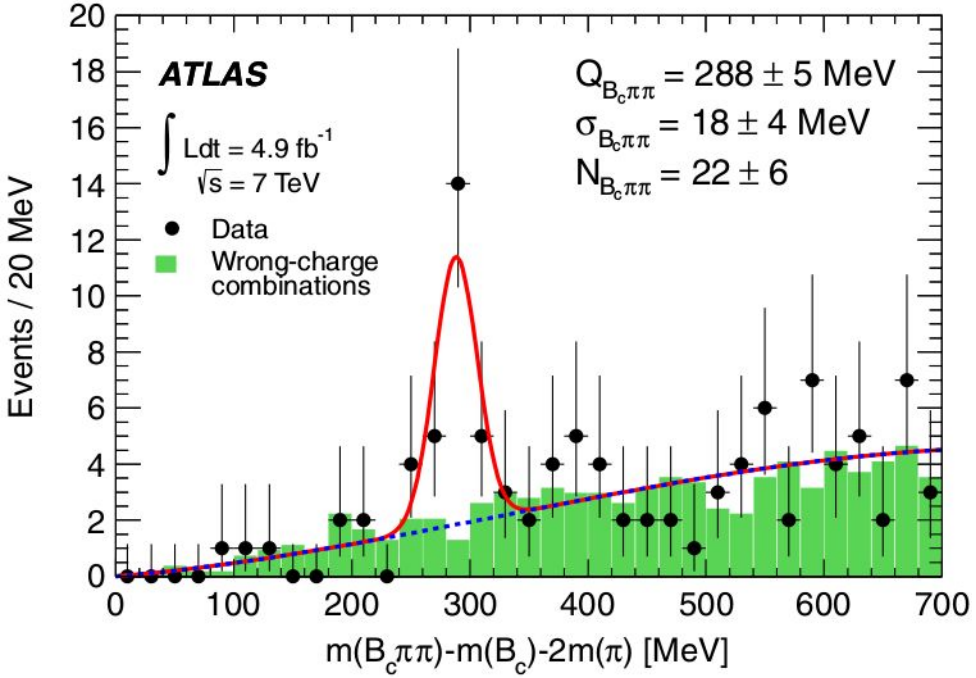
- Select B_c ground state candidates within 3σ of the fitted mass value.
  - The three tracks from the secondary vertex and the two tracks from the primary vertex are refitted simultaneously.
  - Momentum of Bc candidate must point to the pions vertex.

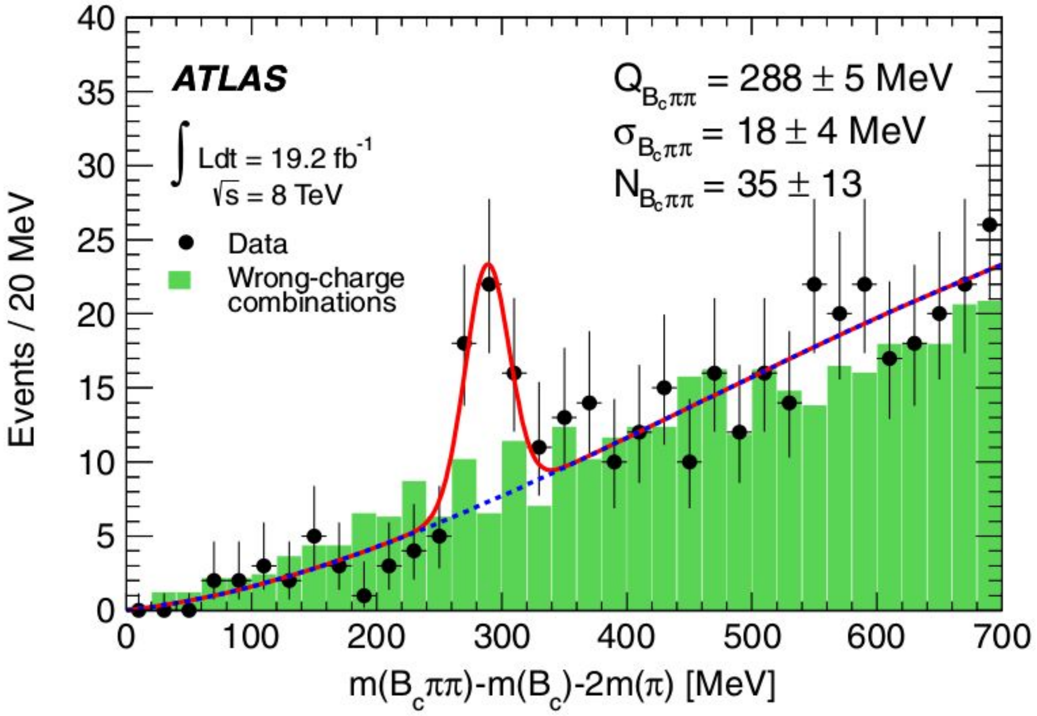
- Extended unbinned maximum likelihood fit. The fit includes a third-order polynomial to model the background and a Gaussian function for the structure.

- To improve the resolution, peaks are sought in the distribution of the variable:
  $Q = m(B_c\pi\pi) - m(B_c) - 2m(\pi)$

More details in the next slides

Observation of an Excited B_c Meson at ATLAS





- A new state is observed at
  Q = 288.3±3.5 stat ±4.1 syst MeV

  Corresponding to a mass of
  6842±4 stat ±5 syst MeV

- The significance of the observation is 5.2σ

- **The observed structure is consistent with the predicted mass of the B_c(2S) excited state.**

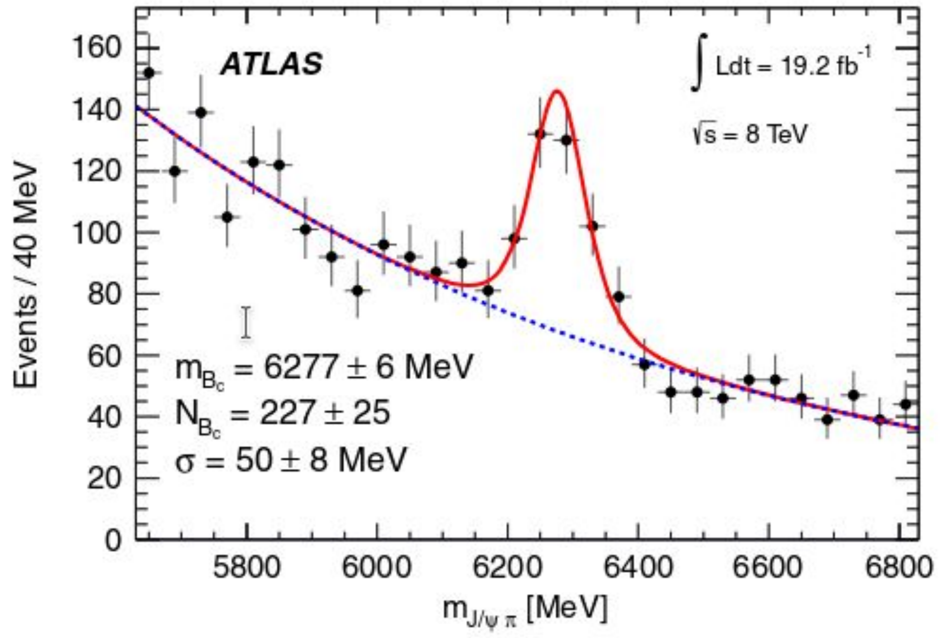
- **This analysis "open the door" to more studies and results in this sector.**

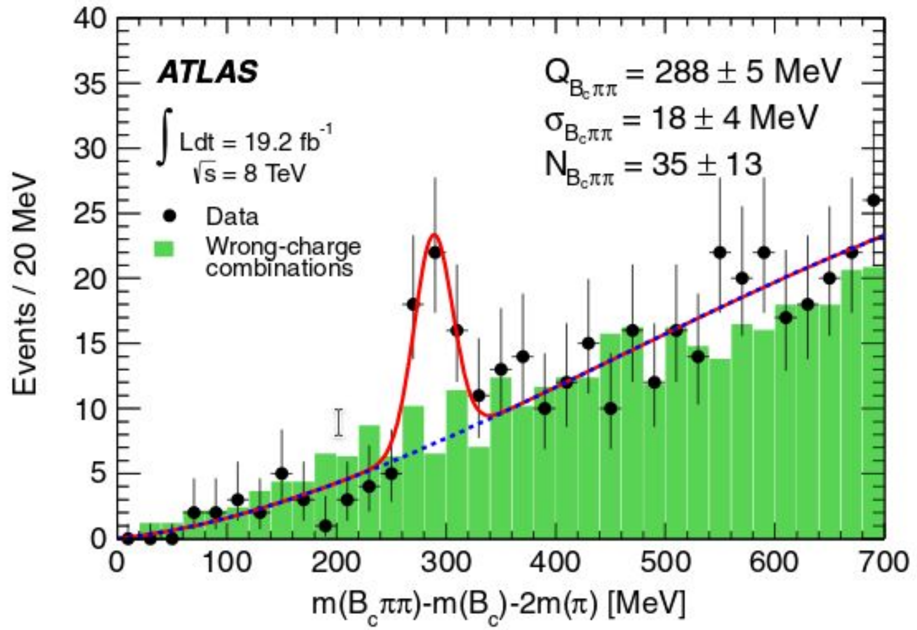
CMS-BPH-18-007:

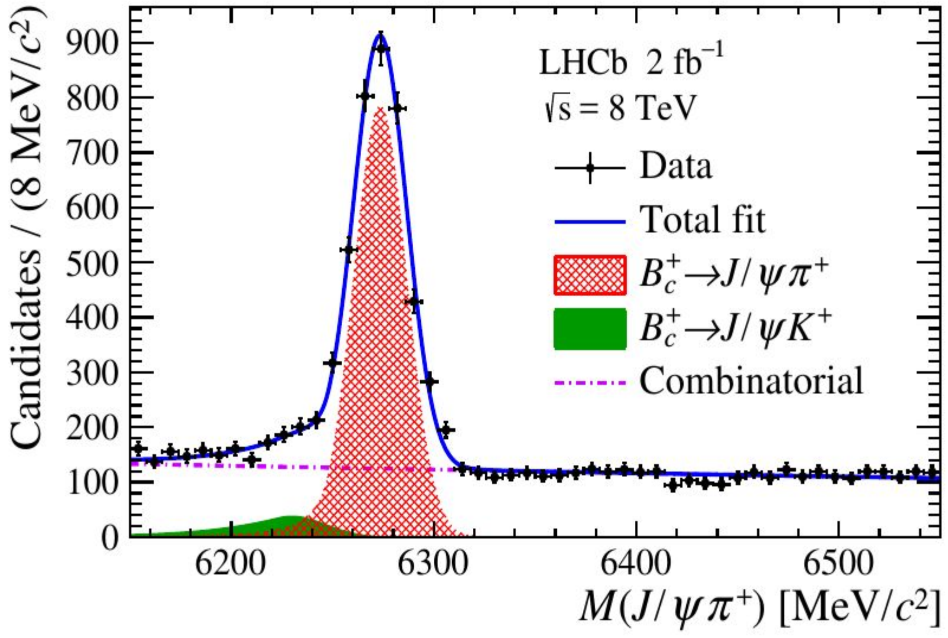
Observation of two excited B_c states and measurement of the $B_c(2S)$ mass in pp collisions at $\sqrt{s}$ = 13 TeV

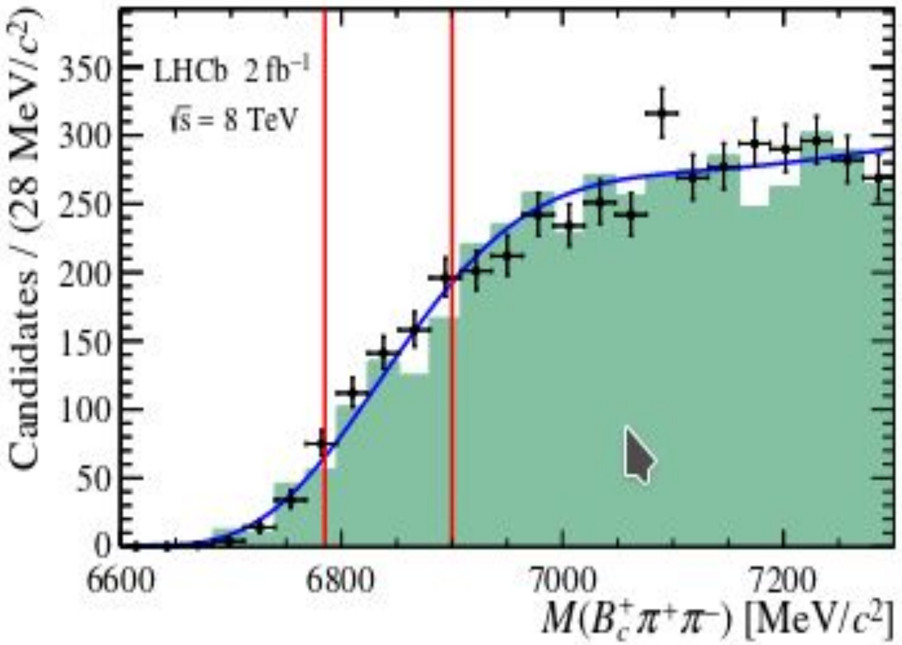
PRL 122 (2019) 132001

Excitate B_c meson









PRL 113, 212004 (2014)

They report 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 $B_c\pi\pi$ followed by $B_c \to J/\psi\pi$ with a local significance of 5.4 σ

JHEP 01 (2018) 138

With 3325 ± 73 B_c events :
"No significant signal is found" in the search for the excited states $B_c(2S)$ and $B_c(2S)^*$ in 8 TeV data

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) :

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

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

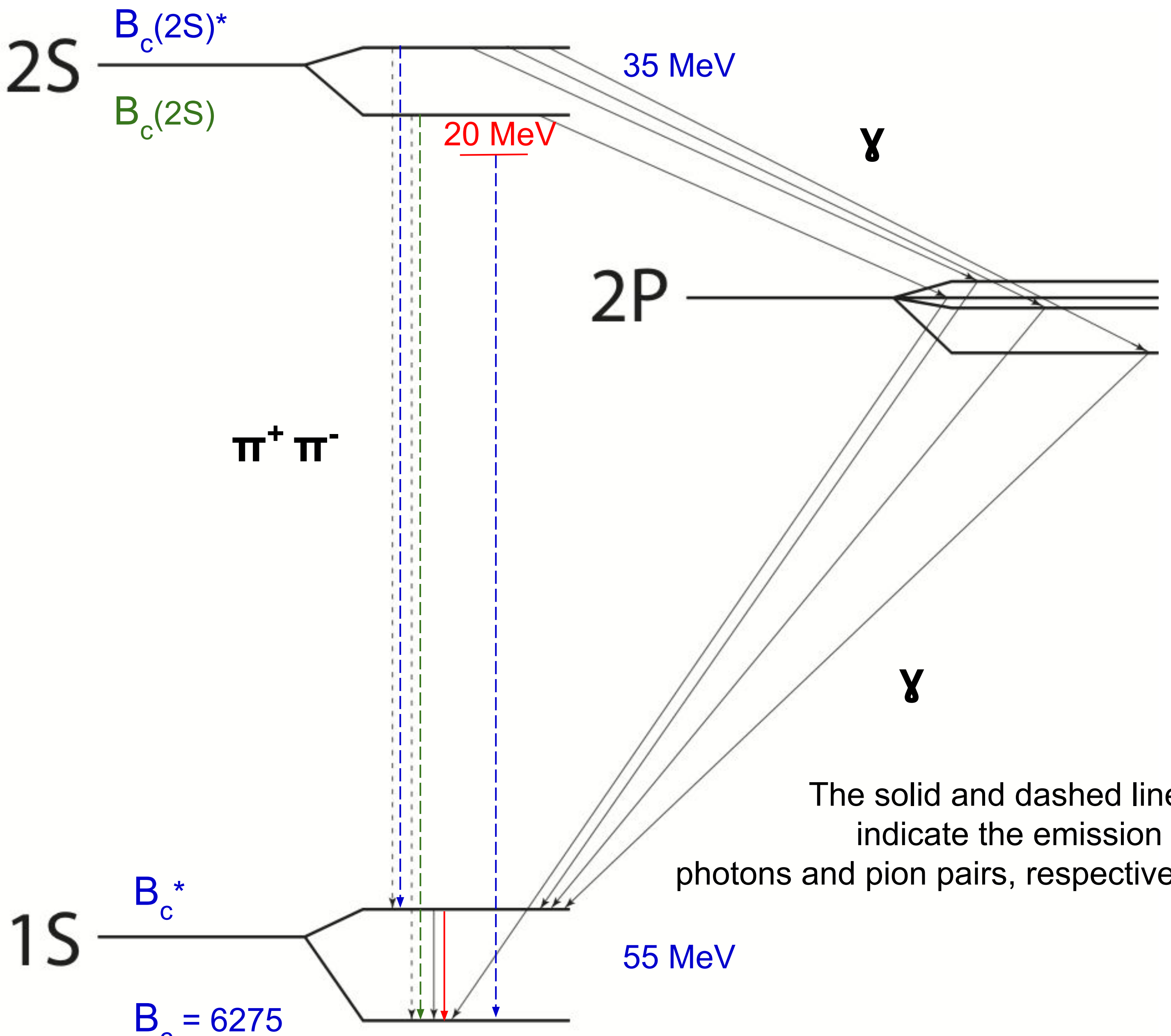
So, we see a two-peak structure in the $B_c \pi^+ \pi^-$ mass distribution, with the $B_c(2S)^*$ peak at a mass shifted by

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

which is predicted to be around 20 MeV.

One have to notice:

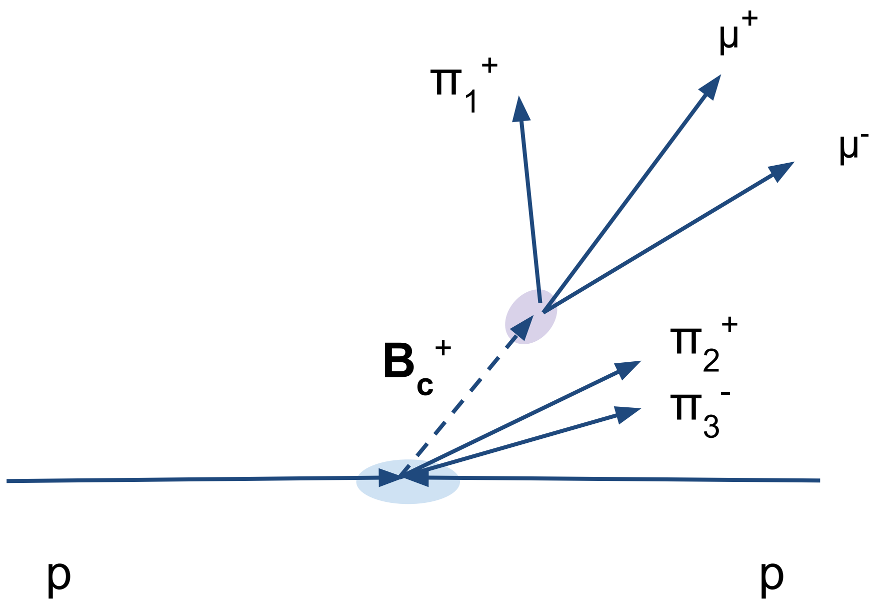
$$[\, M(B_c(1S)^*) - M(B_c(1S)) \,] > [\, M(B_c(2S)^*) - M(B_c(2S) \,]$$



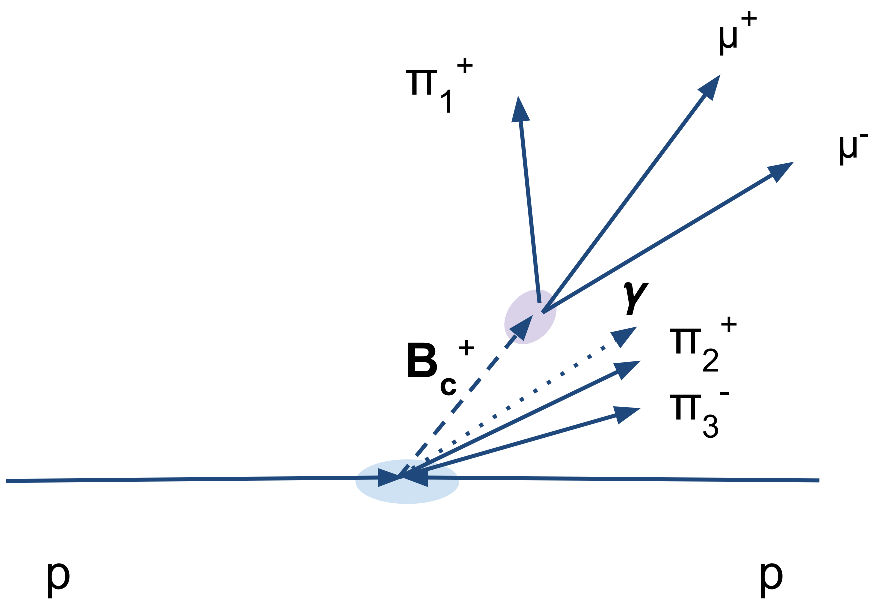
The solid and dashed lines indicate the emission of photons and pion pairs, respectively

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 pT value

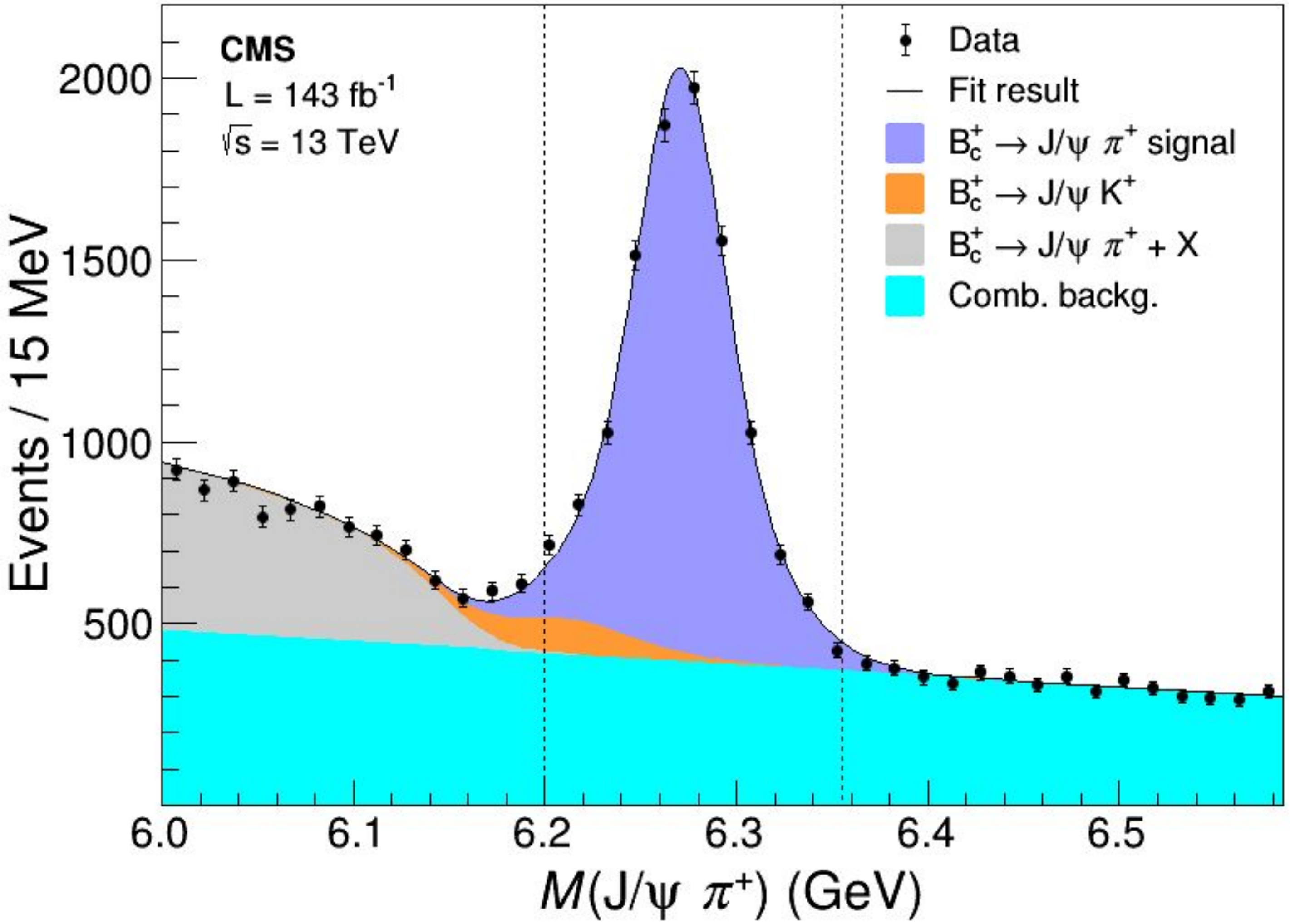


$B_c(2S) \to B_c \pi^+ \pi^-$



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

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



7629 ± 225 candidates

33.5 ± 2.5 MeV mass resolution

Fit details:

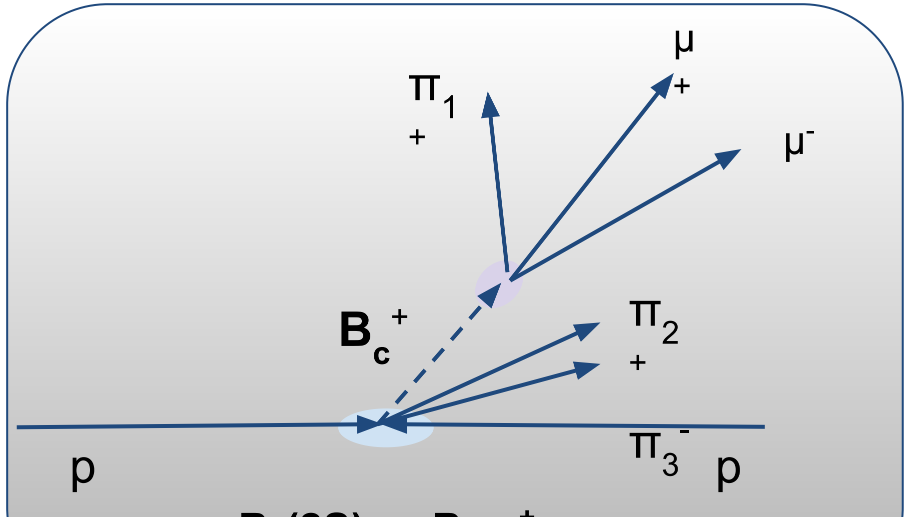
Unbinned ML; the signal is modeled using a double Gaussian with common mean and the background as a polynomial.
Additional background contributions from $B_c \to J/\psi$ K decay is modeled from the simulated sample,
while the partially reconstructed $B_c \to J/\psi\ \pi$ X decays are modeled with an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

Event selection

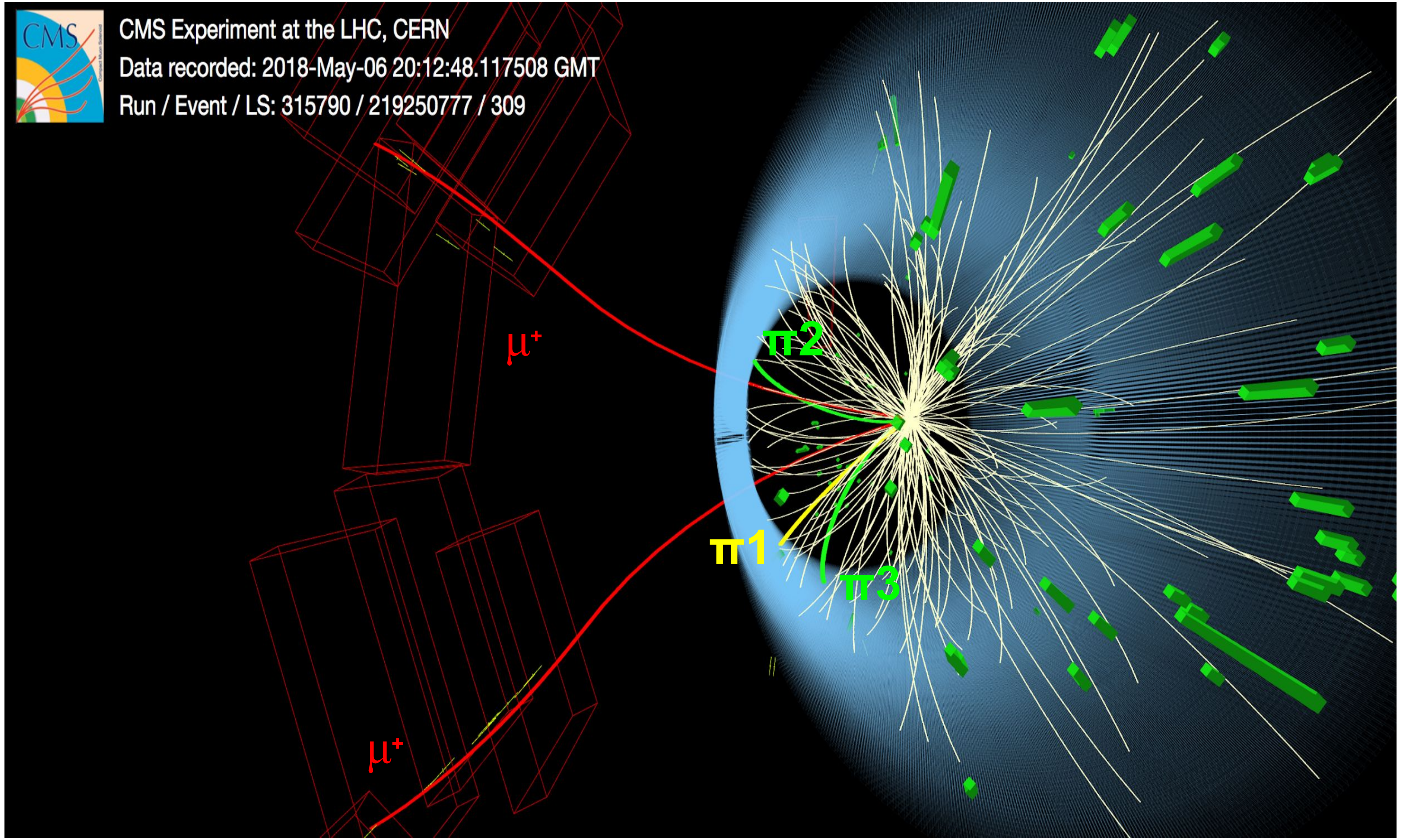
kinematic requirements

$p_T(\pi_1) > 3.5$ 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



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

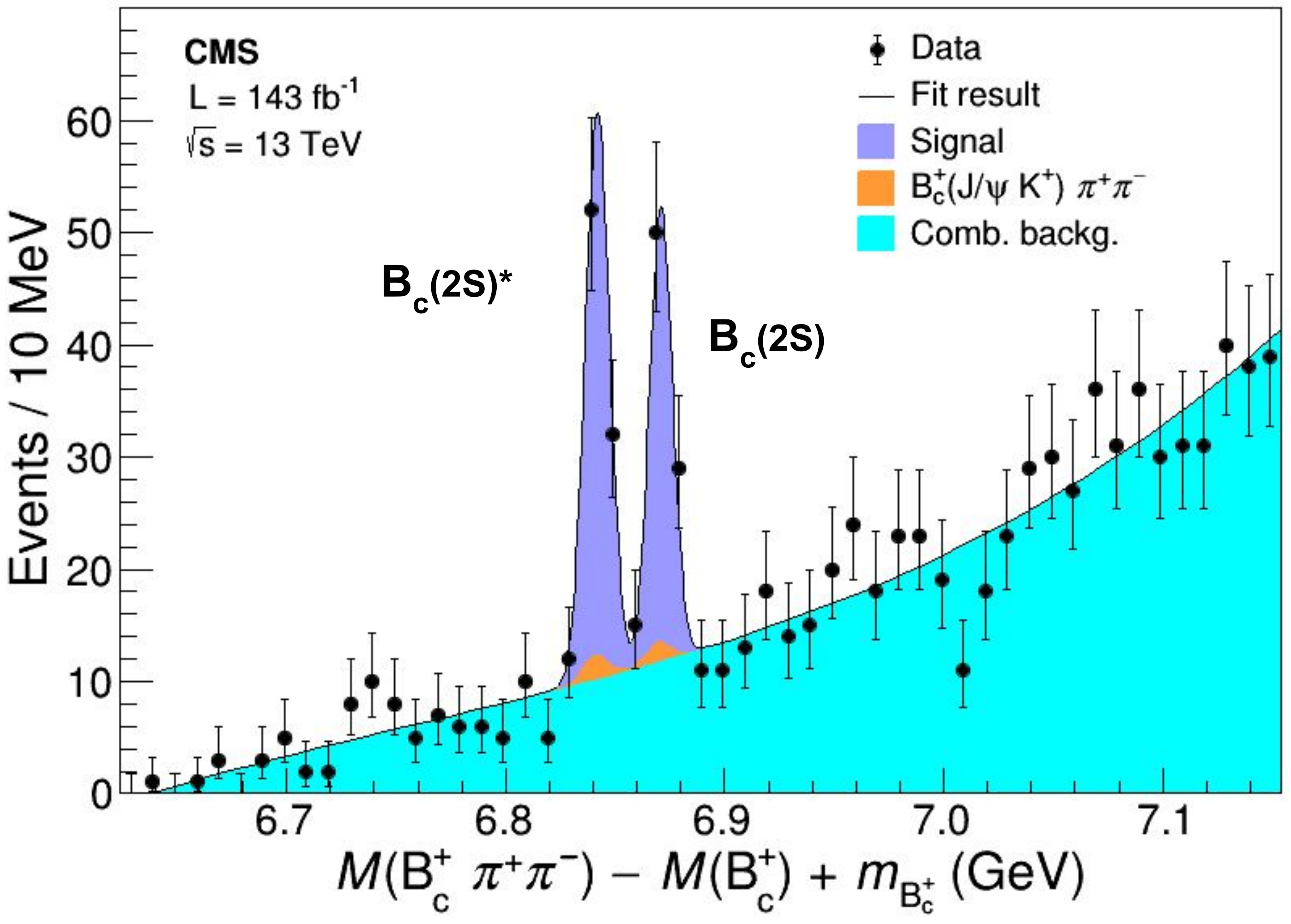


Event display of reconstructed candidate

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)) - ΔM, 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) :

ΔM = 29.1 ± 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 ± 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

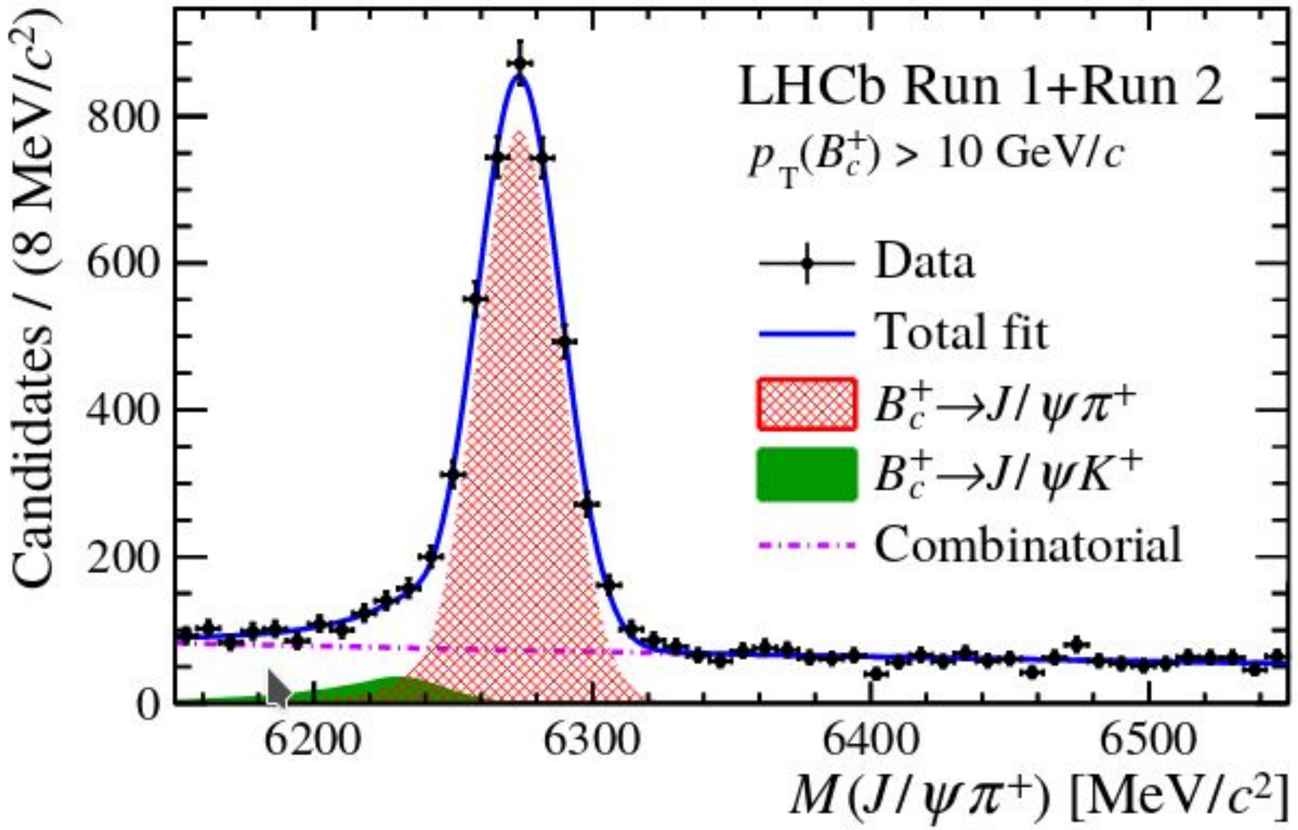
Alignment of the detector:
the possible misalignment of the detector biases the measured masses, however for studies with major detector changes (2016 vs 2017), was found to be negligible

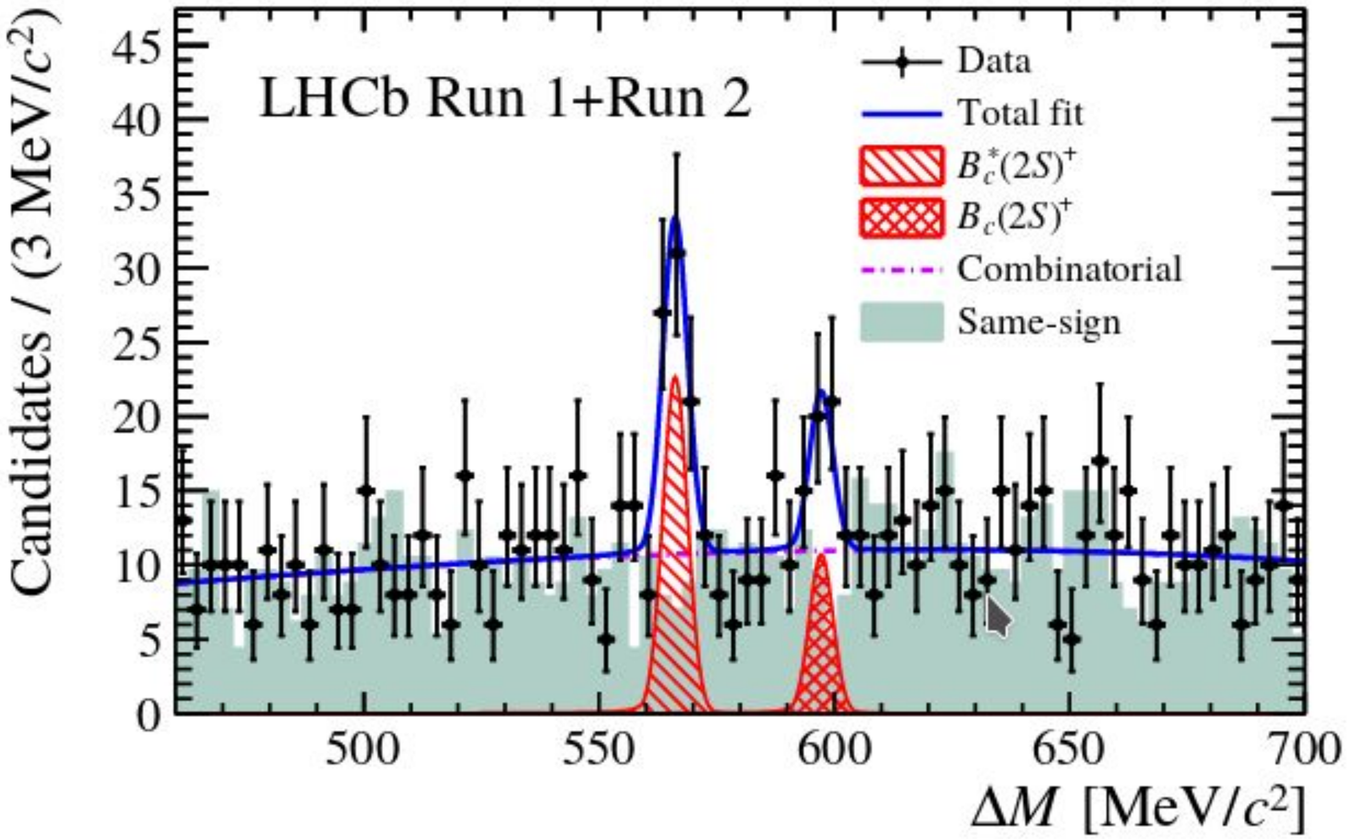
Partially-reconstructed decays:
the low-mass edge of the signal mass window was varied from 6.2 to 6.1 GeV, to increase (by 8%) this contamination;
the variations in the results are smaller than the uncorrelated stat. uncertainty: no systematic uncertainty is considered

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





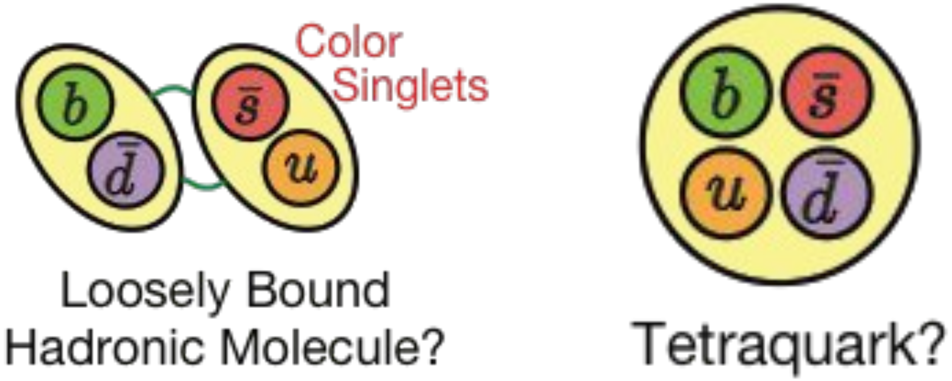
CERN-EP-2017-333:

Search for a Structure in the $B_s^0\pi$ Invariant Mass Spectrum with the ATLAS Experiment.

PRL 120 (2018) 202007

Search for resonance-like structures in the $B_s^0\pi$ invariant mass spectrum

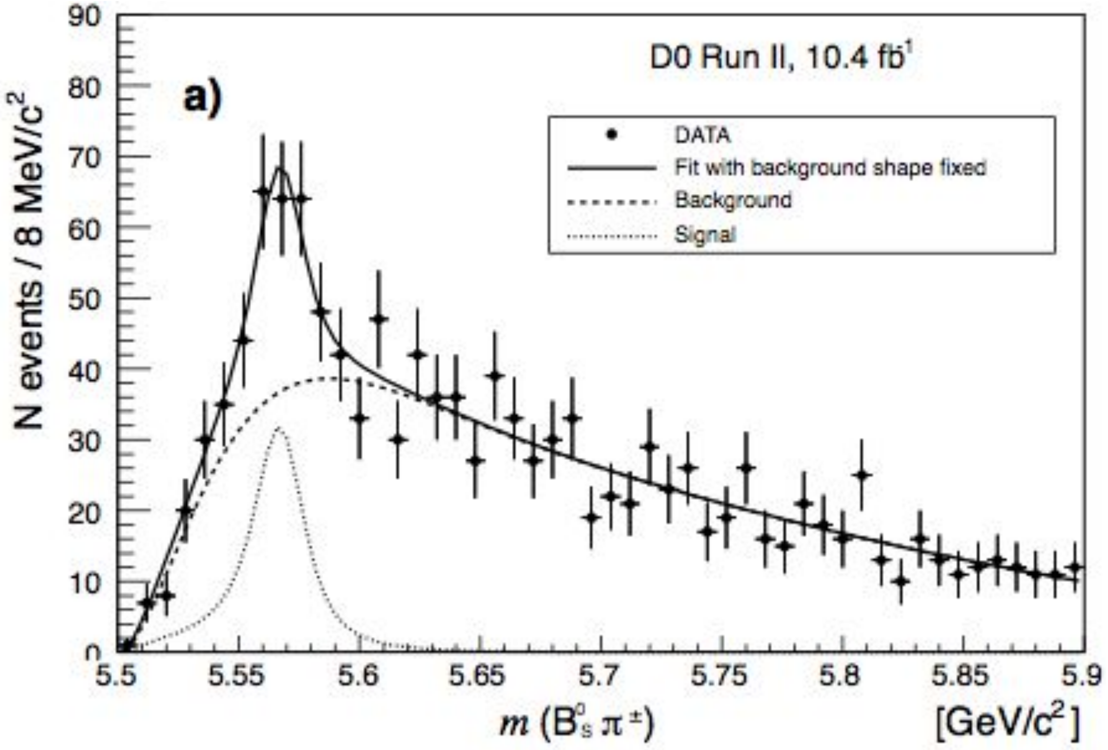
- D0 observed an unexpected narrow structure, named X(5568), in the $B_s^0\pi$ system.
- State w/ **4 different flavors of quarks**



Given the large difference between Mx and the B^0 $K^{\pm}$ mass threshold, a molecular hypothesis is unlikely

If confirmed, Tetraquark interpretation would be favored. However, Theory predicts more states.

arXiv:1602.07588



Phys. Rev. Lett. 117, 022003 (2016)

$$M_X = 5567.8 \pm 2.9\,^{+0.9}_{-1.9}\ \mathrm{MeV}$$

$$\Gamma_X = 21.9 \pm 6.4\,^{+5.0}_{-2.5}\ \mathrm{MeV}$$

Strong decay!

$$N_X = 133 \pm 31 \pm 15\ \mathrm{cand.}$$

- If $X(5568)^- \to B_s^0\pi^-$ then $J^P = 0^+$
- If $X(5617)^- \to B_s^{0*}\pi^-$, $\hookrightarrow B_s^0\gamma$ miss! then $J^P = 1^+$

Not confirmed by LHCb

Not confirmed by CMS

Not confirmed by CDF

Search for $X^+(5568) \rightarrow B_s^0\pi^+$: ATLAS

- ATLAS has recollected several thousands of Bs→J/ψφ decays on what to look for.

Model:

- 2 gaussians for signal.
- An exponential for Bkg.

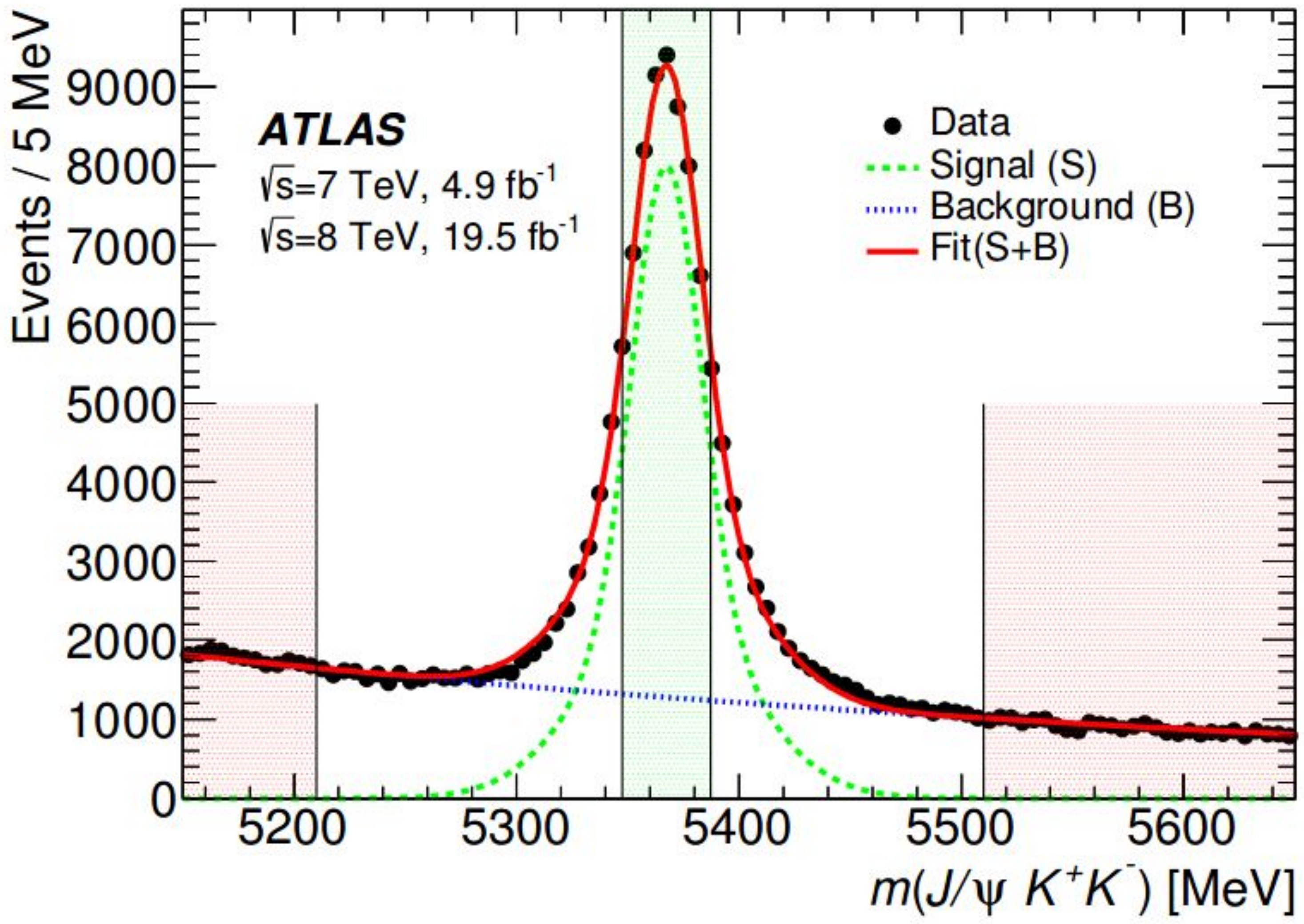
Two regions of interest are defined with σ_{eff} ~ 14 MeV:

- **Signal region. Keep events in [5346.6,5386.6] MeV range for further investigation.**

  N_{Bs0} = 52 750 ± 280

- **SideBands.**

  5150 < m(J/ψKK) < 5210 MeV and
  5510 < m(J/ψKK) <5650 MeV

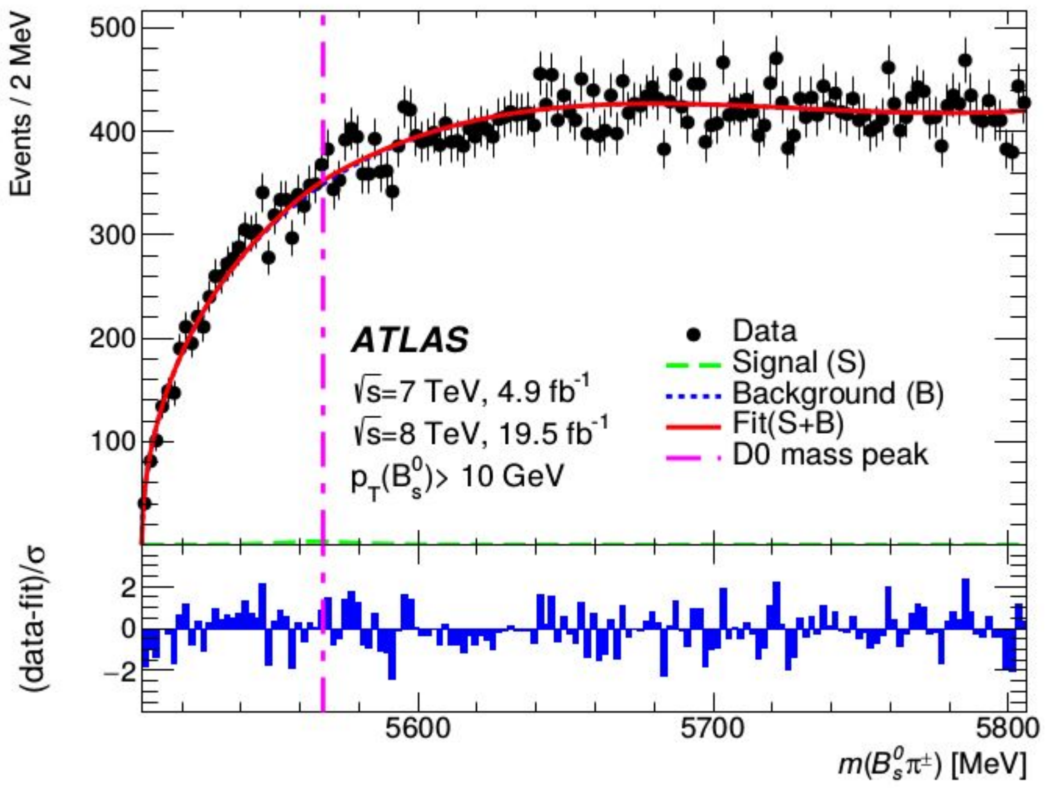


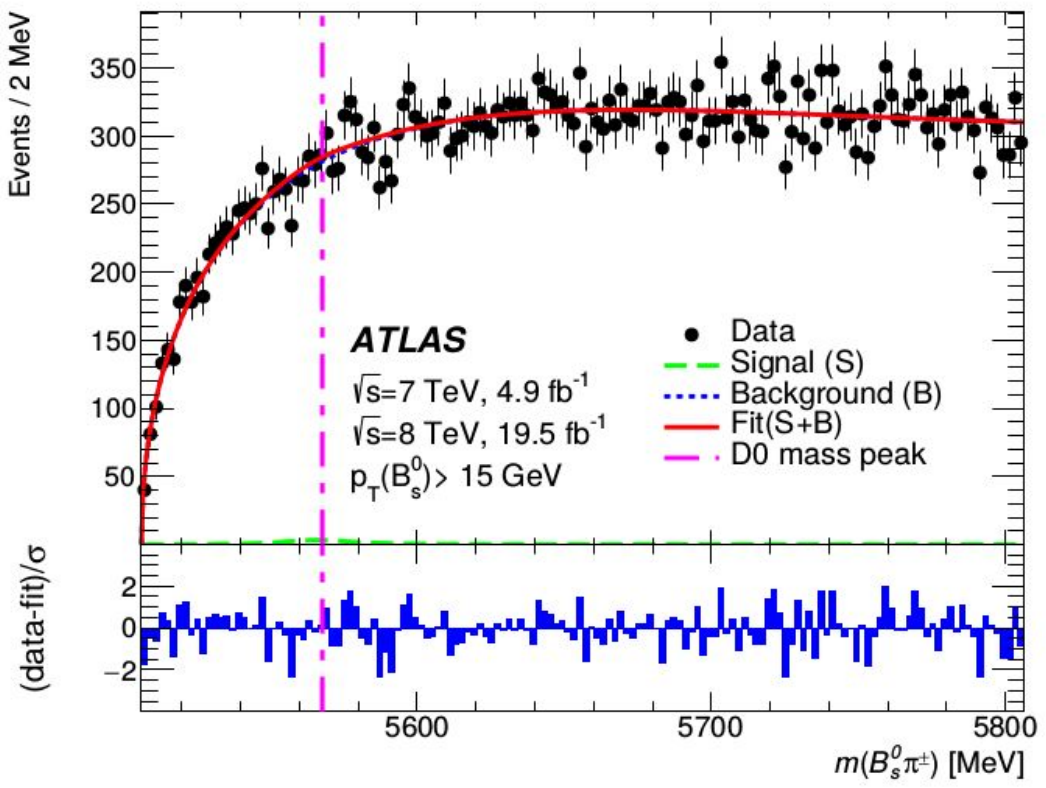
Search for $X^+(5568) \rightarrow B_s^0\pi^+$: ATLAS

- The $B_s\pi^+$ candidates are constructed by combining each of the tracks forming the selected PV with the selected Bs candidate.

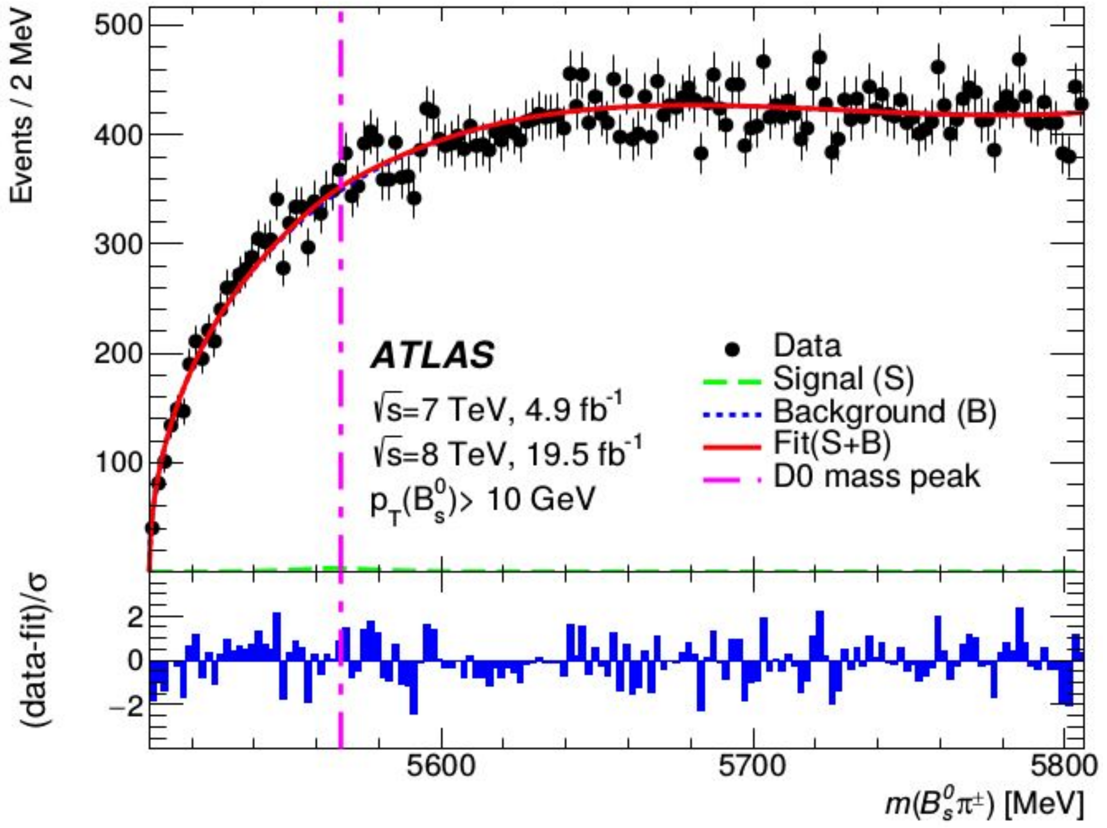
- Mass variable:
  m(J/ΨKKπ) - m(J/ΨKK) + mfit(Bs) where, mfit(Bs) = 5366.6 MeV

- Following other experiments extended unbinned maximum likelihood fits are performed for two subsets of $B_s^0\pi^+$ candidates: **$pT(B_s^0)$>10 GeV and $pT(B_s^0)$>15 GeV**





Search for $X^+(5568) \rightarrow B_s^0 \pi^+$: ATLAS



$N(B_s^0)/10^3$	$p_T(B_s^0) > 10$ GeV	52.75 ± 0.28
	$p_T(B_s^0) > 15$ GeV	43.46 ± 0.24
$N(X)$	$p_T(B_s^0) > 10$ GeV	60 ± 140
	$p_T(B_s^0) > 15$ GeV	-30 ± 150
$\epsilon^{rel}(X)$	$p_T(B_s^0) > 10$ GeV	0.53 ± 0.09
	$p_T(B_s^0) > 15$ GeV	0.60 ± 0.10

- **No significant signal is observed**
- 95%CL upper limits

  N(X) < 382 (pT(B) > 10 GeV)
  N(X) < 356 (pT(B) > 15 GeV)

  Systematic uncertainties affecting these limits are included in the determination of N(X)

- Efficiency

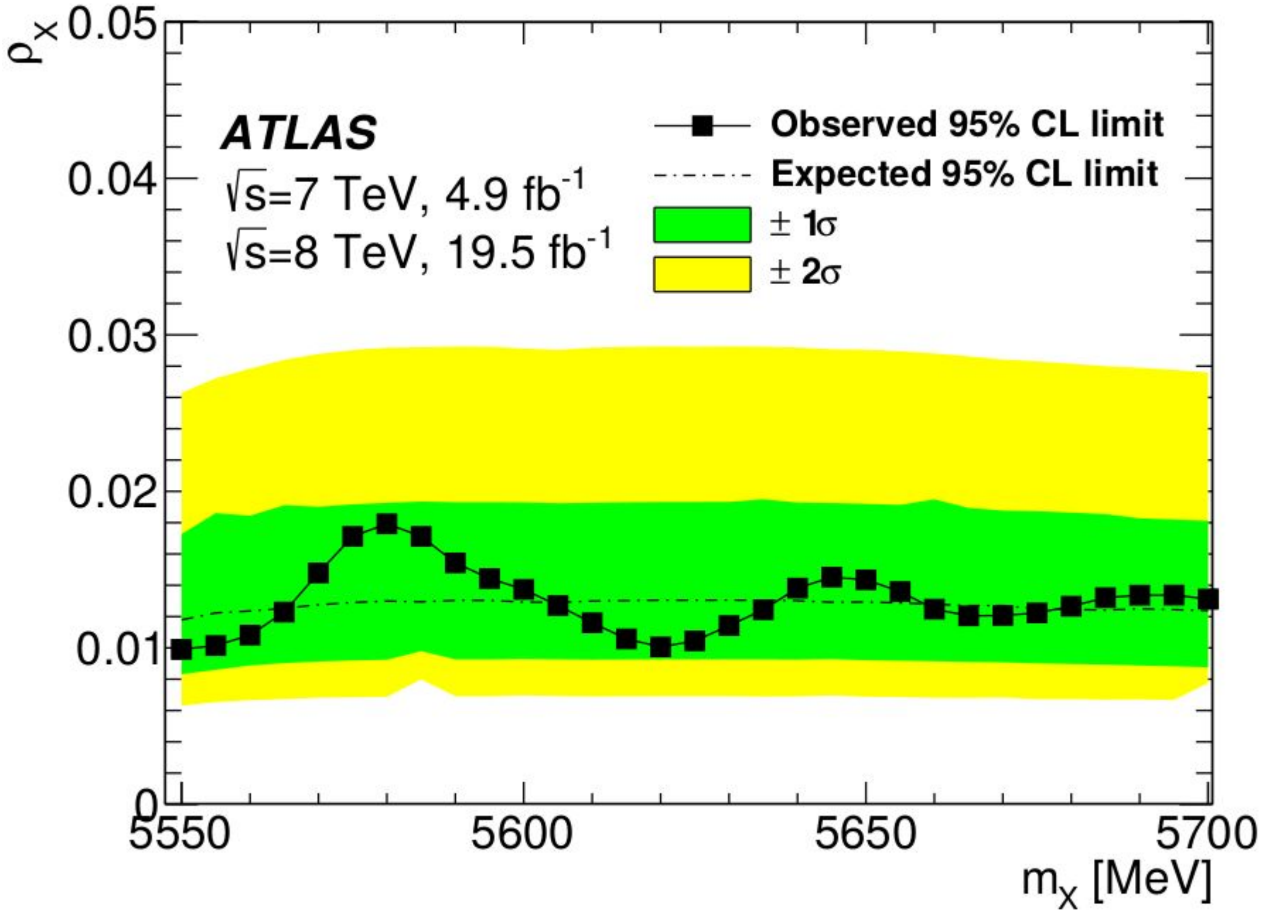
$$\epsilon^{rel}(X) = \epsilon(X)/\epsilon(B_s^0)$$

In the ratio, the acceptance of the Bs decay cancels, so the value to be determined is the pion reconstruction efficiency

Search for $X^+(5568) \to B_s^0 \pi^+$: ATLAS

- Extract 95% CL upper limits on production rate

$$\rho_X \equiv \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0 \pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})} = \frac{N(X)}{N(B_s^0)} \times \frac{1}{\epsilon^{\text{rel}}(X)}$$



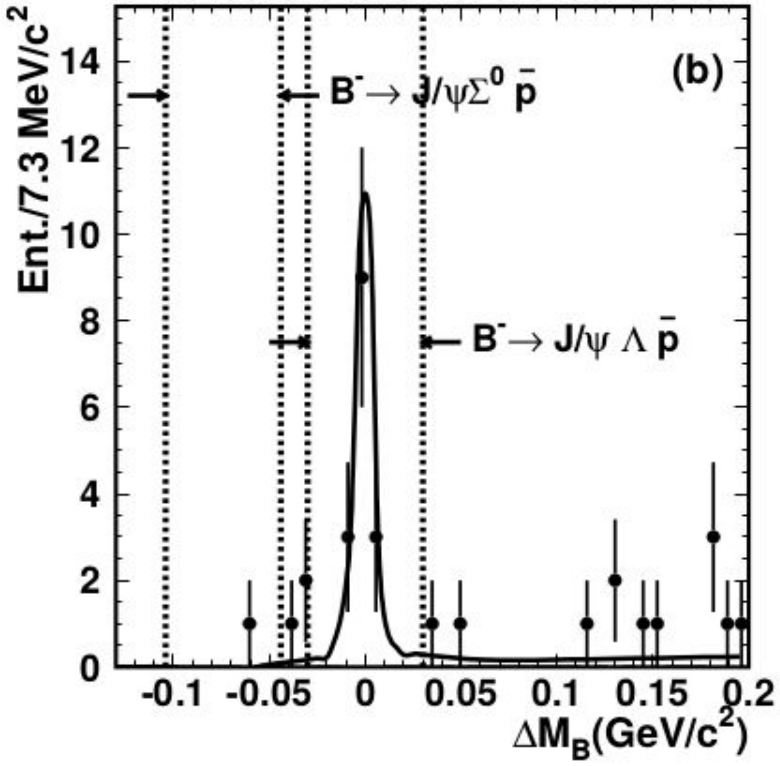
- **Signal: Breit-Wigner (assuming a resonant state as described by D0 observation).**
- Systematic uncertainties affecting these limits are included.
- Scan range 5550 - 5700 MeV every 5 MeV

CMS-PAS-BPH-18-005:

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

First example of a B meson decay into baryons

Phys.Rev.D72:051105,2005

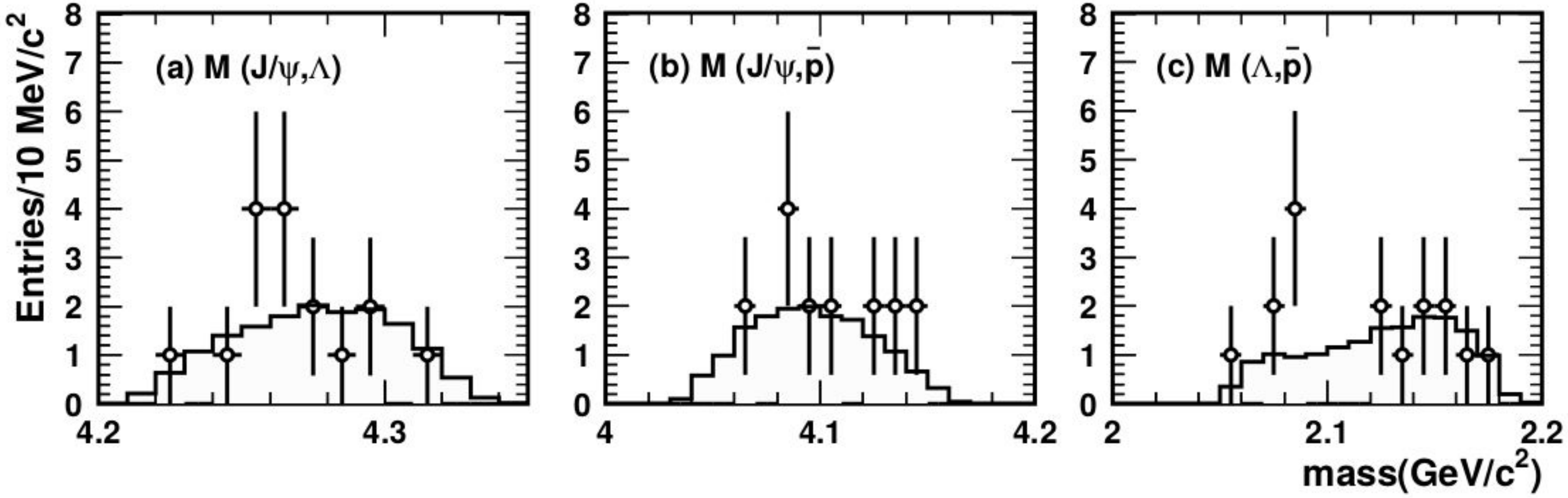


Observed in 2005 by Belle with very low yield (17.2 ± 4.1 events)

$\beta(B \rightarrow J/\psi\Lambda p) = (11.6 +/- 2.8^{+1.8}_{-2.3})\times10^{-6}$

Recently, the LHCb Collaboration reported the first observation of the baryonic Bc→J/ψppπ. 10.1103/PhysRevLett.113.152003

Motivation to study this decay is to search for new intermediate resonances in the **J/ψΛ, J/ψp and Λp** systems

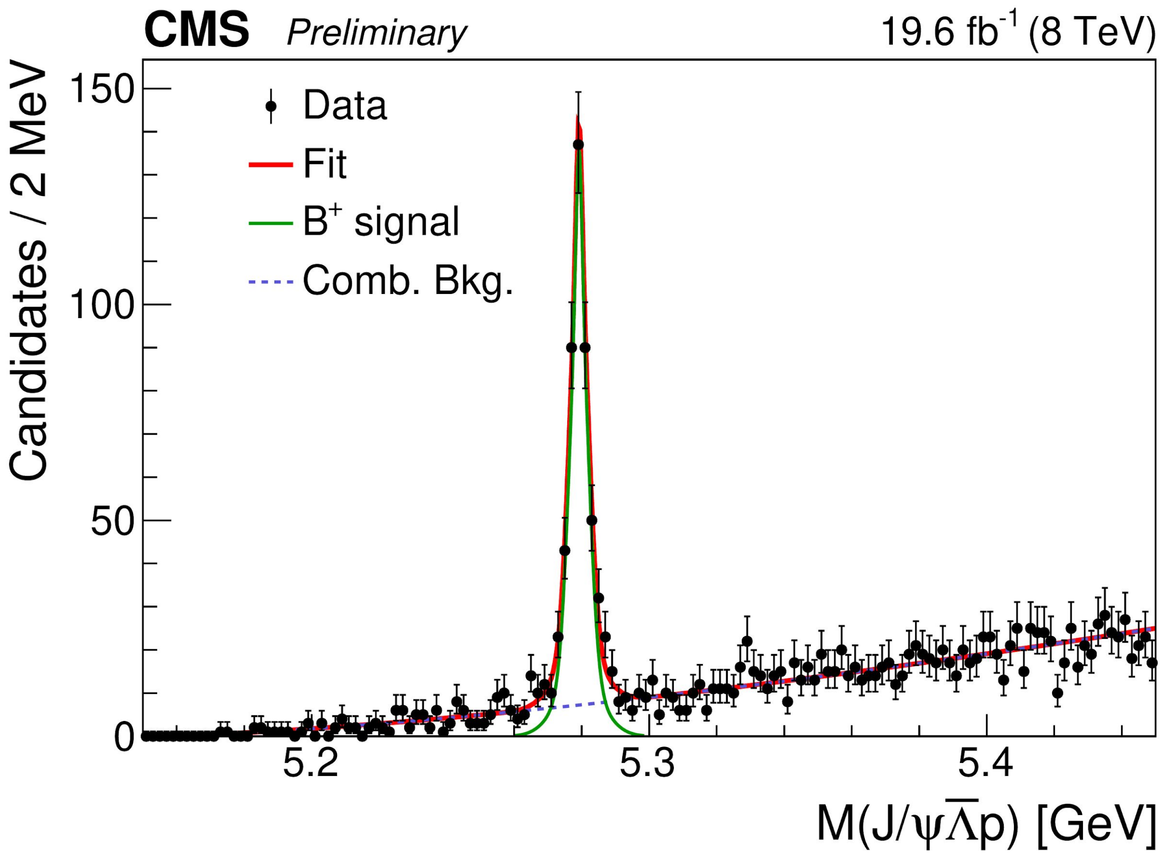


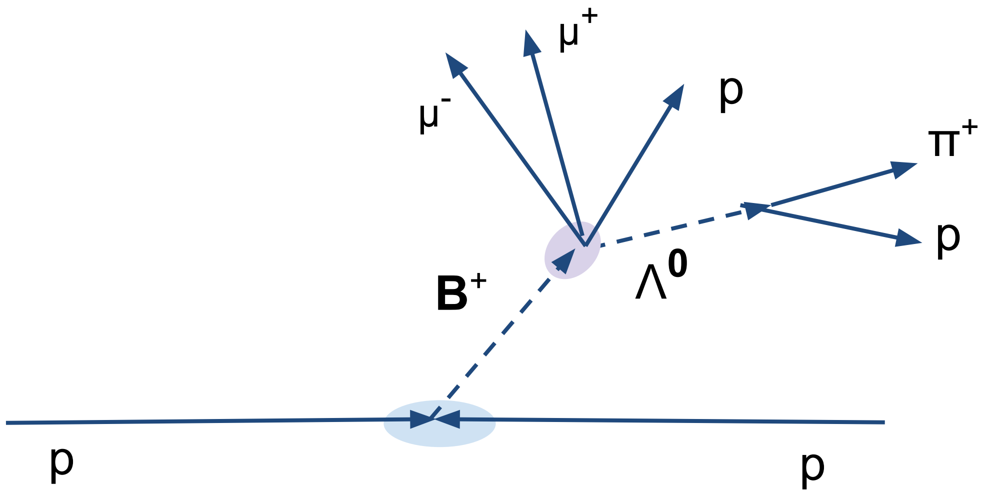
Such a study in the Λb → J/ψpK decay resulted in the observation by the LHCb Collaboration of new multiquark states consistent with pentaquarks. 10.1103/PhysRevLett.115.072001, arXiv:1904.00081 (2019)

B → J/ψΛp production at CMS

- Using data collected at 8 TeV, corresponding to an integrated luminosity of 19.6 fb^{-1}

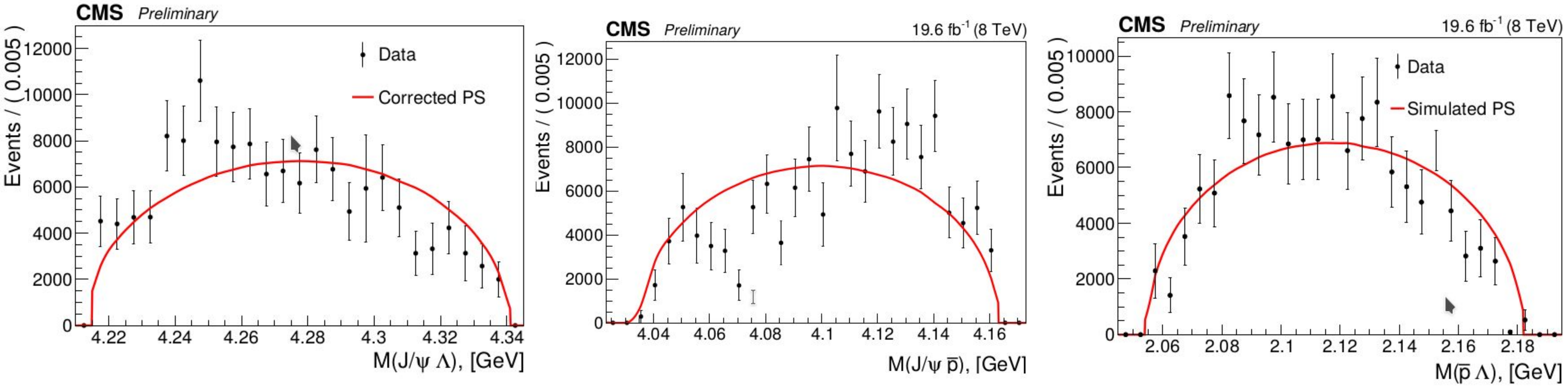
- The decay $B \to J/\psi K^{*}(K^{*} \to K_s^0 \pi^+)$ is chosen as the normalization channel, as it is measured with high precision and has a similar decay topology.
  The ratio of branching fractions is measured to be
  (15.07 ± 0.81 (stat) ± 0.40 (syst) ± 0.86(β))x10^{-6}
  This measurement is the most precise to date & consistent with previous Belle measurement





J/ψΛ, J/ψp and Λp systems

- Large signal yield allowed CMS to conduct a search for new exotic multiquark states in the two-body systems
- The three two-body systems show incompatibility with the phase space hypothesis



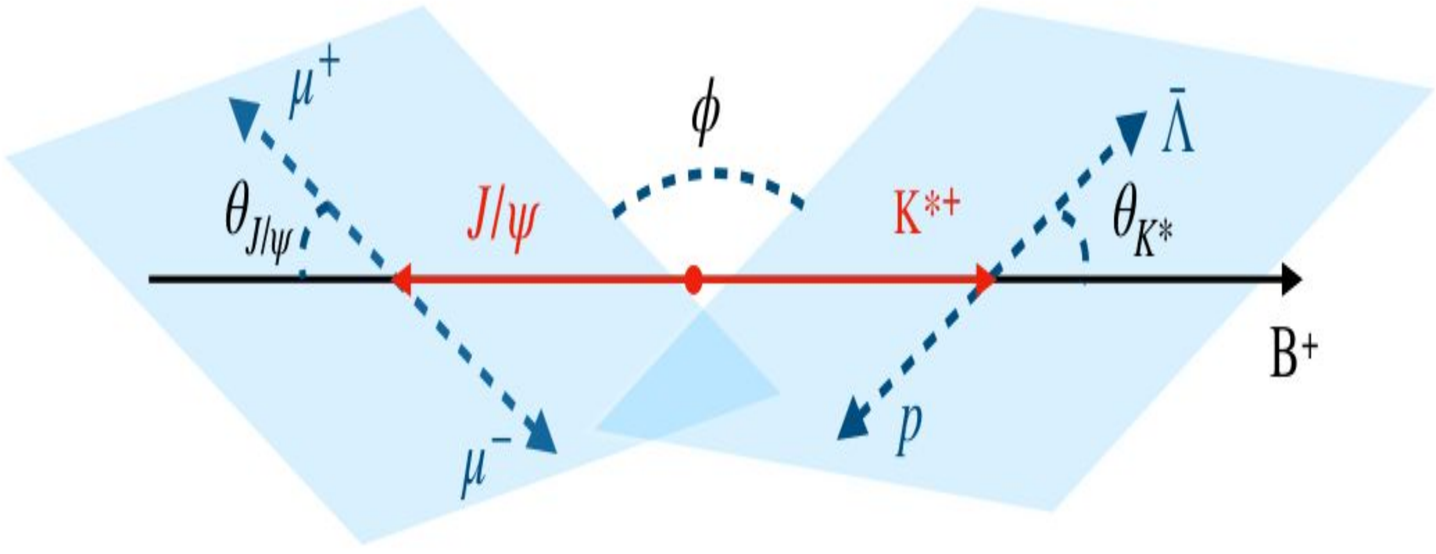
Model-independent approach: method of moments

- First introduced by the 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 resonace can describe all the resonaces and their interferences. From table L_{max}= 2*4=8.



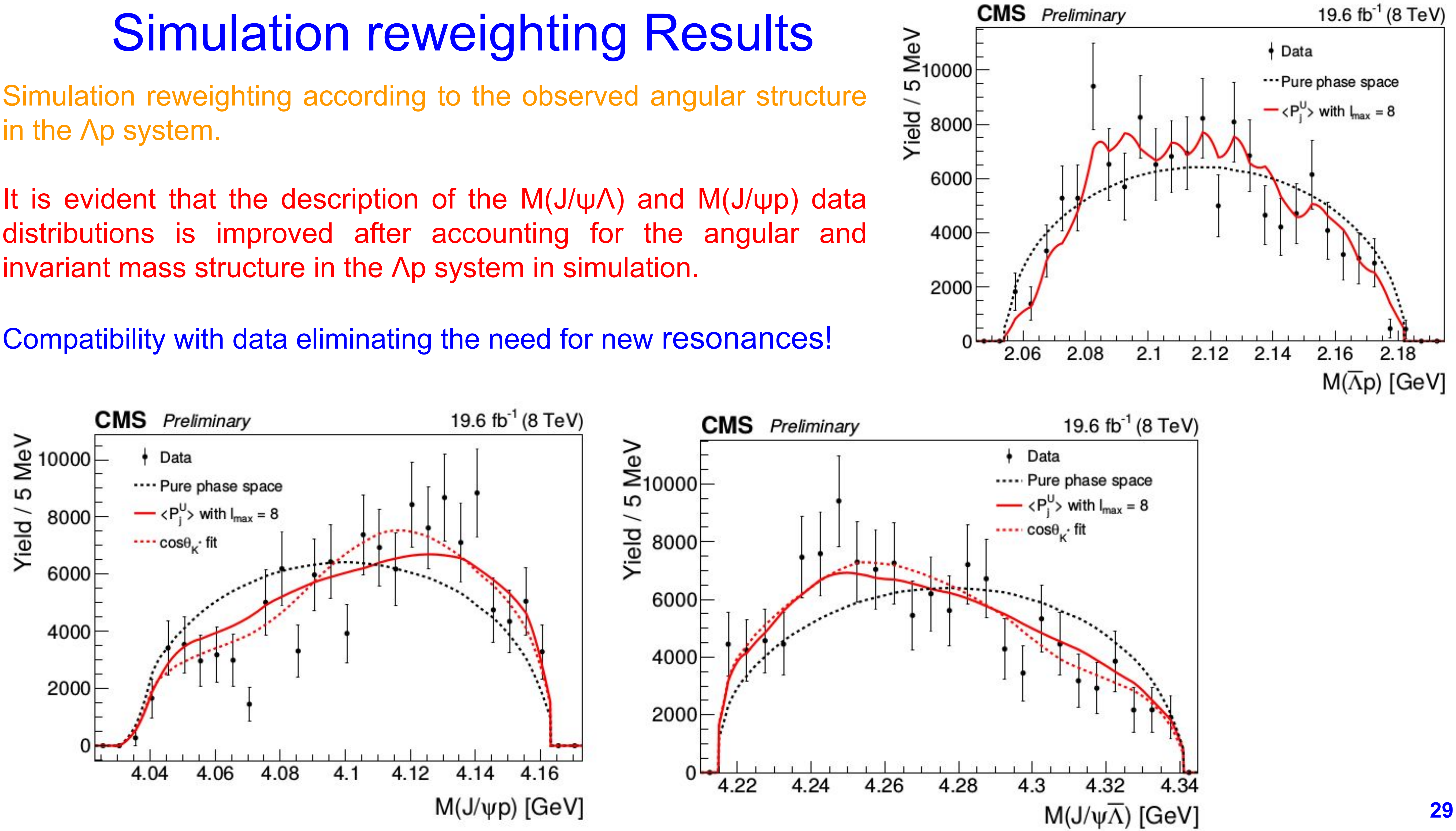
Resonance	Mass [MeV]	Natural width [MeV]	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

Simulation reweighting Results

Simulation reweighting according to the observed angular structure in the Λp system.

It is evident that the description of the M(J/ψΛ) 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!



Summary

Considerable LHC data sets collected in Run 2 by ATLAS and CMS offers future opportunities in searches for new resonances .

For both experimentally and theoretically point of view, Heavy-flavor spectroscopy continues to be very fruitful.

Using full Run 1 data (7 Tev and 8 TeV), a B_c meson excited state was observed at ATLAS.

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 based on the full Run 2 data (13 TeV), corresponding to a total integrated luminosity of 143 fb-1

ATLAS has searched for the new structure reported by D0, so called X(5568). No significant signal observed, upper limits was set.

The ratio of branching fractions $\frac{\mathcal{B}(B^+\to J/\psi\overline{\Lambda}p)}{\mathcal{B}(B^+\to J/\psi K^{*+})}$ 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. A model Independent approach was used to conclude that no new resonances are needed.

THANKS for listening!