Overview on exotica production at CMS

Petrov Nikita
(on behalf of the CMS Collaboration)
MIPT, Moscow
nikita.petrov@cern.ch

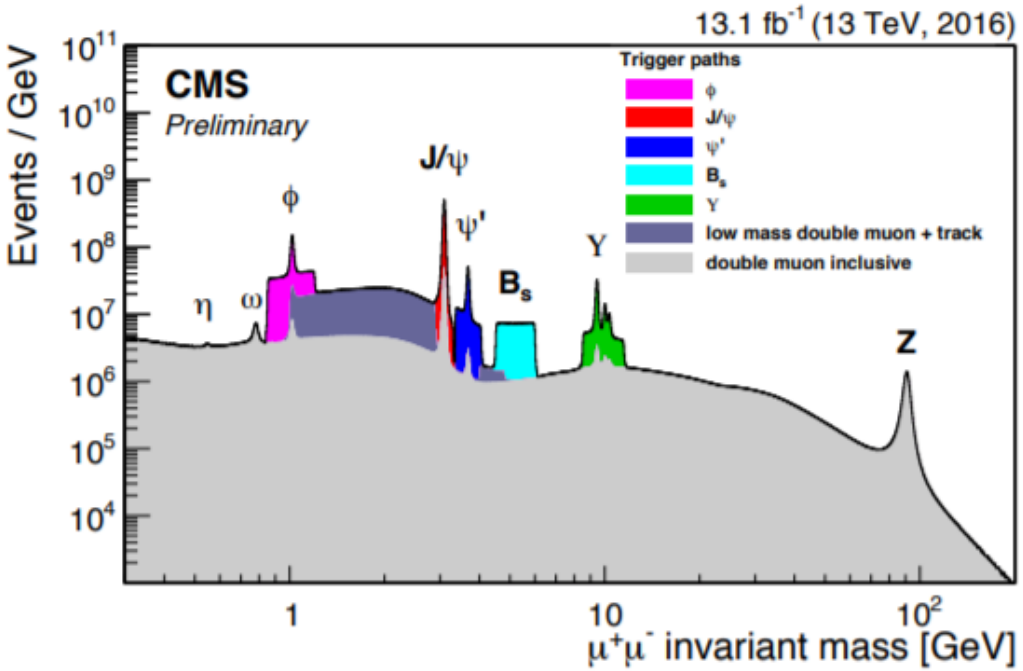
EMMI3:Workshop on anti-matter, hyper-matter and exotica production at the LHC, Wroclaw, Poland, 02.12.2019

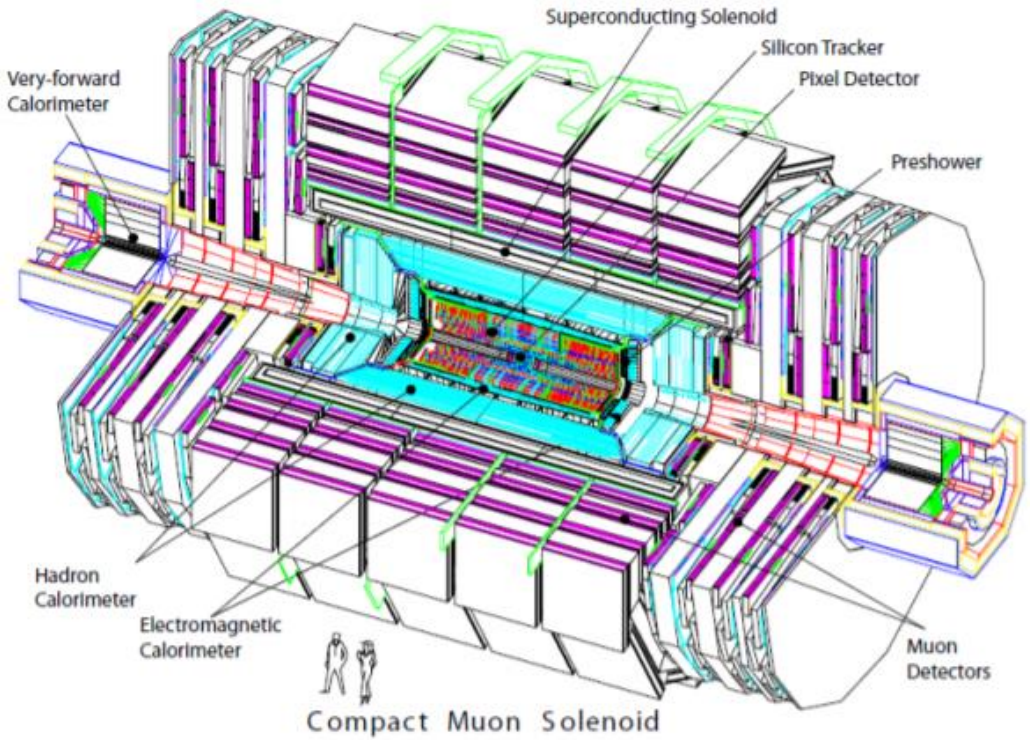
Introduction

QCD exotics production studies are very important for our understanding nonstandard forms of matter.

These studies are possible at CMS due to:

- Excellent muon system with large rapidity coverage and high-purity muon-ID
- Good resolution in $p_T \sim 1\%$ for central region of tracker
- Remarkable vertex reconstruction and impact parameter resolution down to $\approx 15\mu m$
- Efficient and very flexible set of dimuon triggers





Recent CMS results in spectroscopy and rare 3-body decays

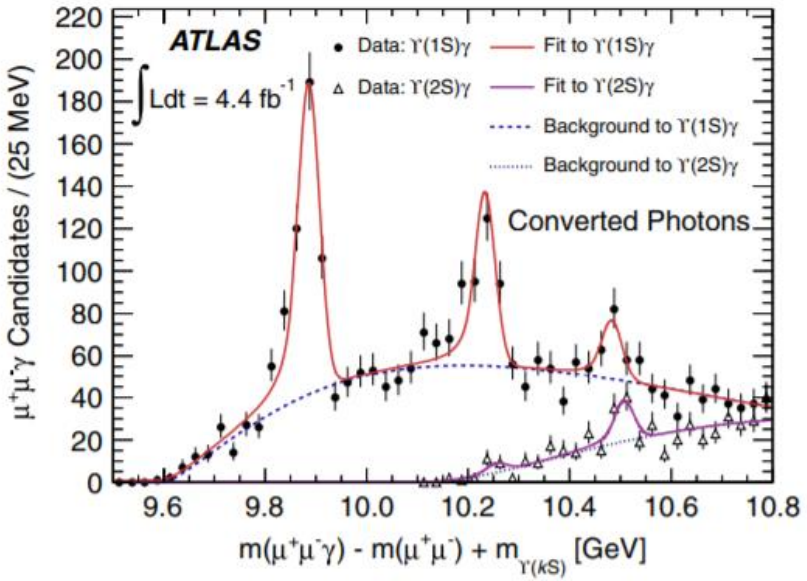
- Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ and measurement of their masses
- Observation of two exited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV
- Study of the $B^+ \to J/\psi\bar{\Lambda}p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV
- Observation of the $\Lambda_b \to J/\psi\Lambda\phi$ decay in proton-proton at $\sqrt{s} = 13$ TeV

Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ and measurement of their masses

[PRL 121 (2018) 092002]

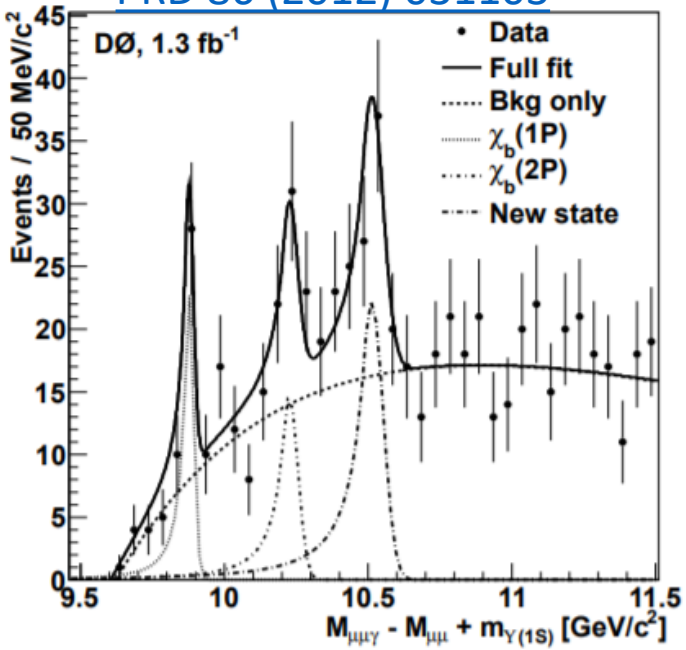
CMS: Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$

PRL 108 (2012) 152001

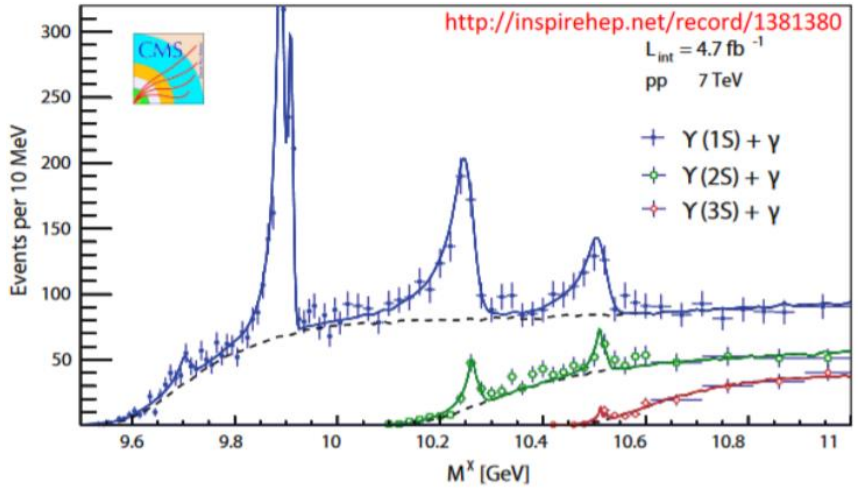


In 2011 the ATLAS Collaboration observed the $\chi_b(3P)$ state in $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ modes.

PRD 86 (2012) 031103

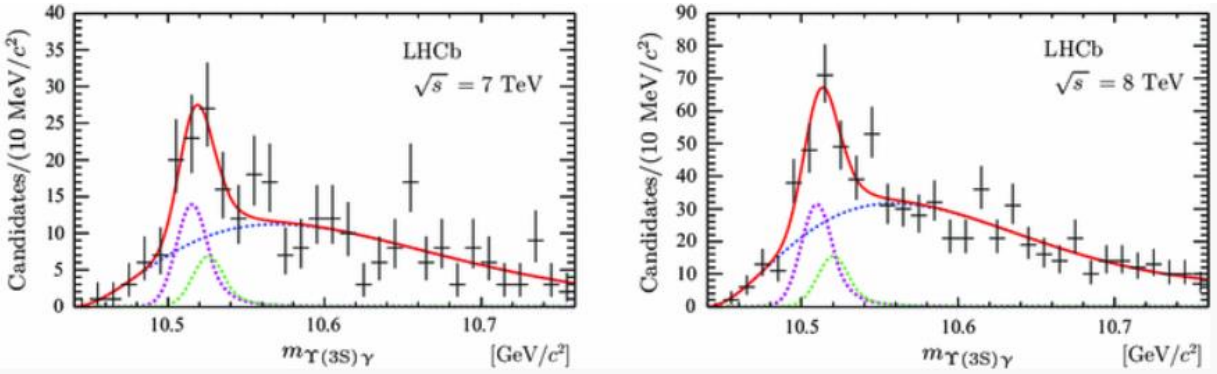


Then D0 confirmed the $\chi_b(3P) \to \Upsilon(1S)\gamma$ decay



The CMS Collaboration saw the $\chi_b(3P)$ in all modes

PRL 121 (2018) 092002

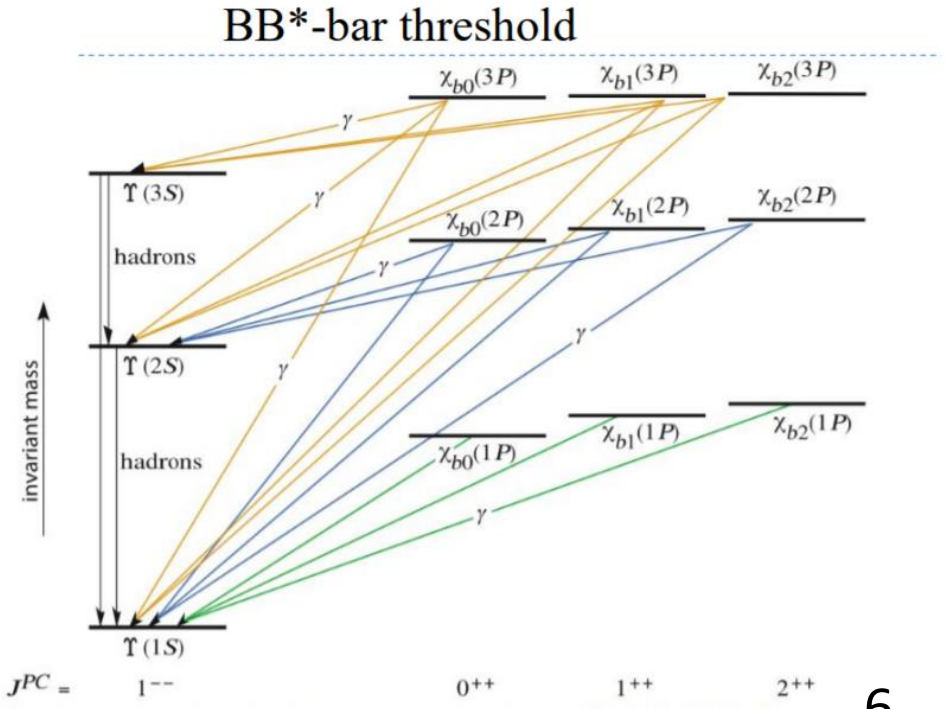


The LHCb observed new decay $\chi_b(3P) \to \Upsilon(3S)\gamma$

CMS: Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$

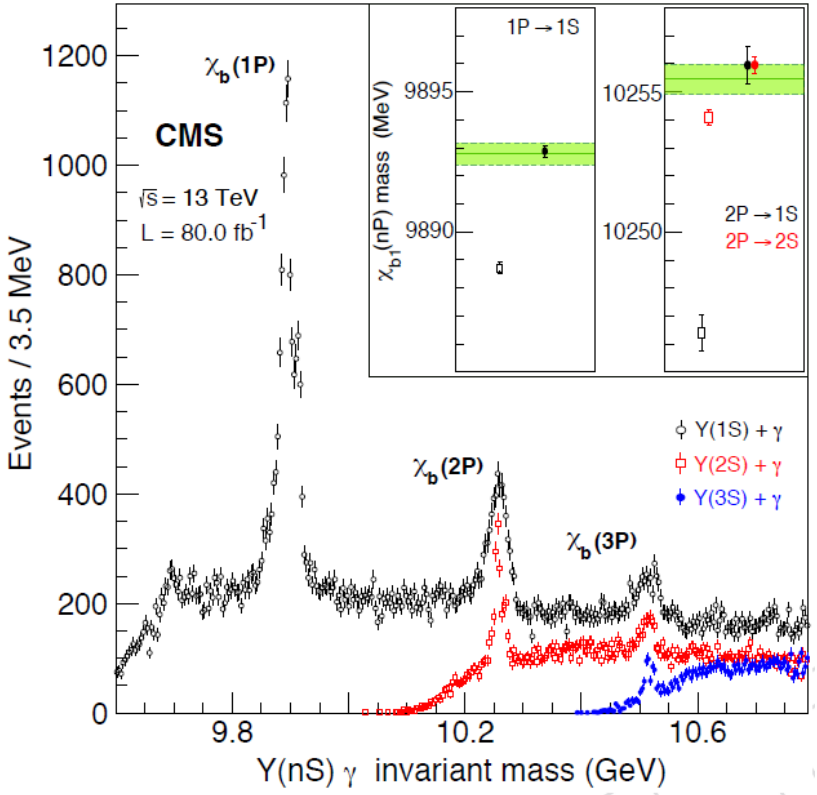
Motivation

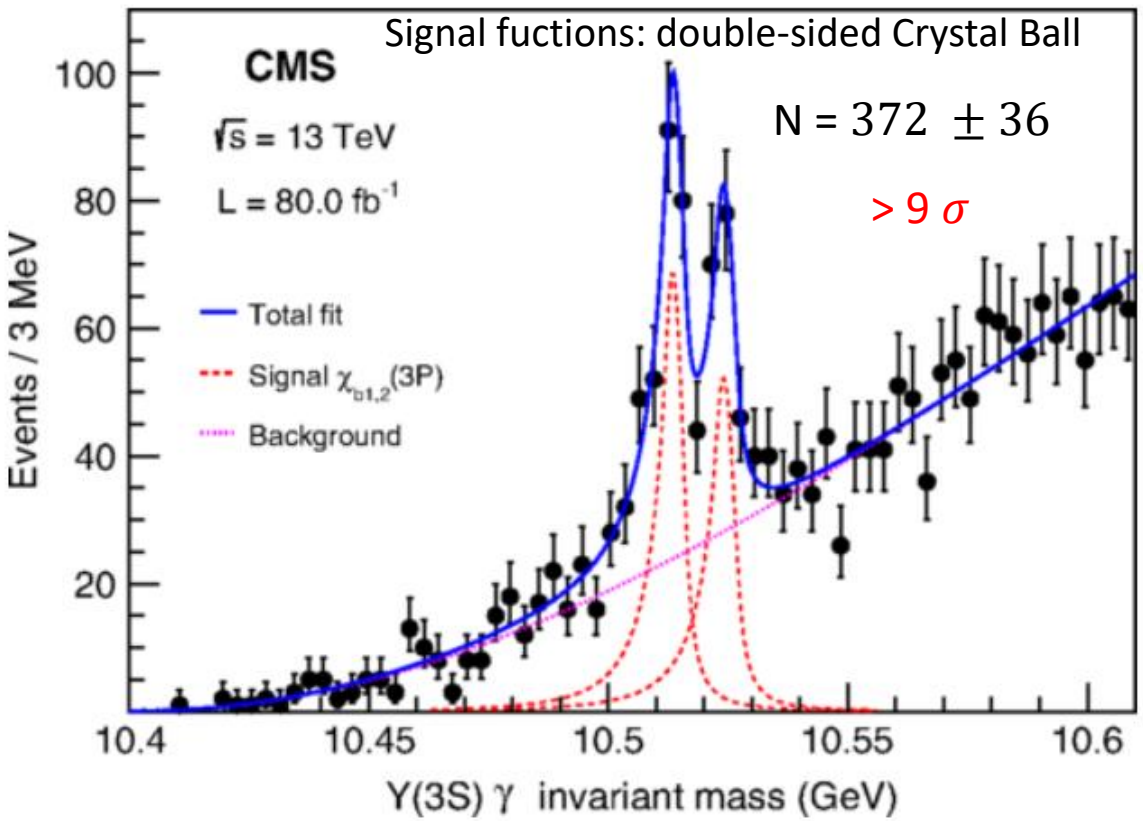
- Improve our understanding how the strong force binds quarks
- Test the influence of open-beauty threshold on the bottomonium spectrum and different theoretical models
- Search for possible X_b state (analogue of $X(3872)$) near $B\overline{B}^*$ threshold
- Check mass hierarchy of χ_b states



Picture from : V. Knünz, Measurement of Quarkonium Polarization to Probe QCD - *DOI 10.1007/978-3-319-49935-2_2*

CMS: Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$





$M_1 = 10513.42 \pm 0.41(stat.) \pm 0.18(syst.)$ MeV

$M_2 = 10524.02 \pm 0.57(stat.) \pm 0.18(syst.)$ MeV

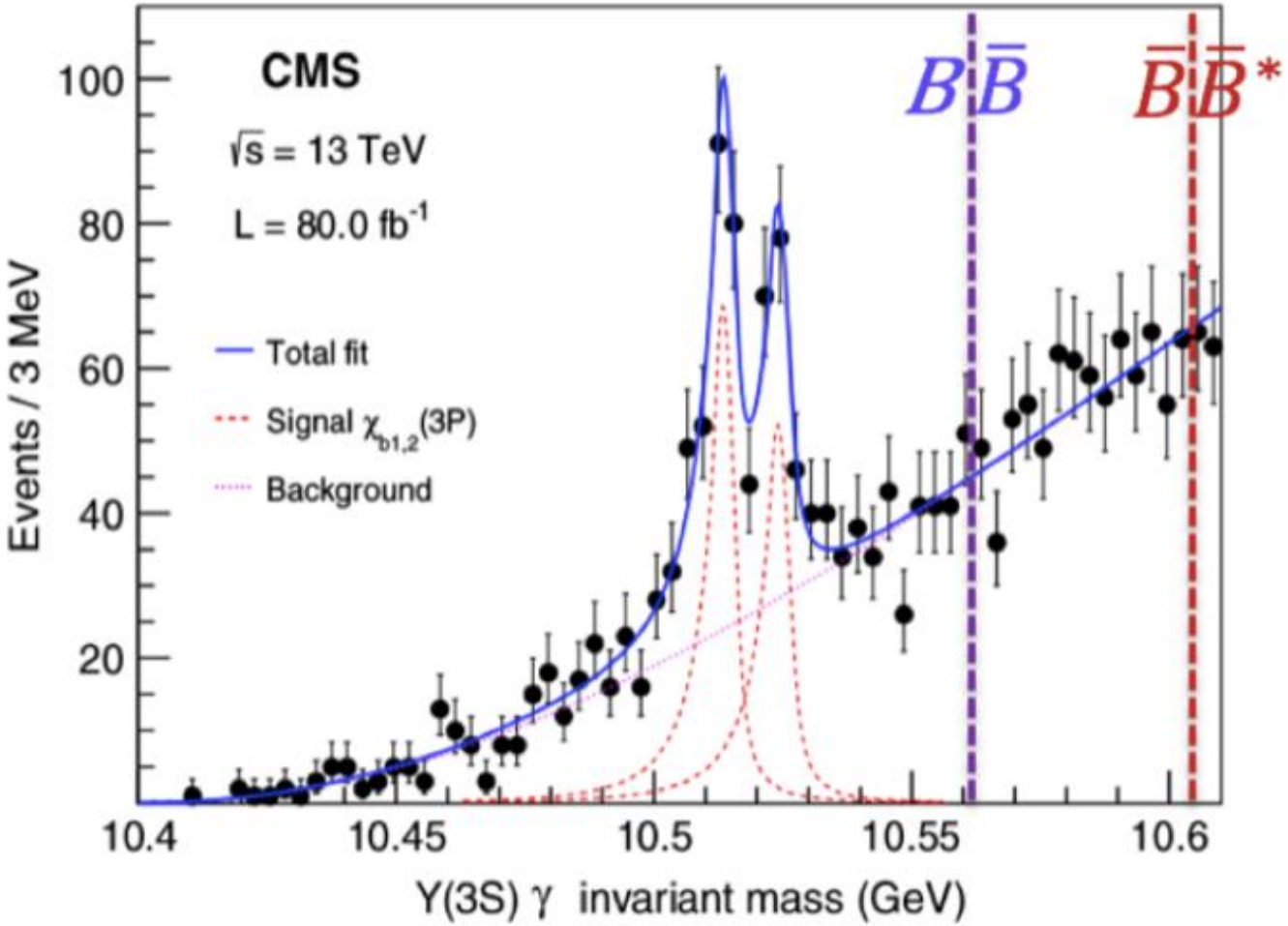
$\Delta M = 10.6 \pm 0.64(stat.) \pm 0.17(syst.)$ MeV

The χ_{b1} and χ_{b2} states are well resolved for the first time

Obtained experimental result supports natural mass hierarchy

The results of this study give important informations and significantly constraints theoretical predictions

CMS: Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$



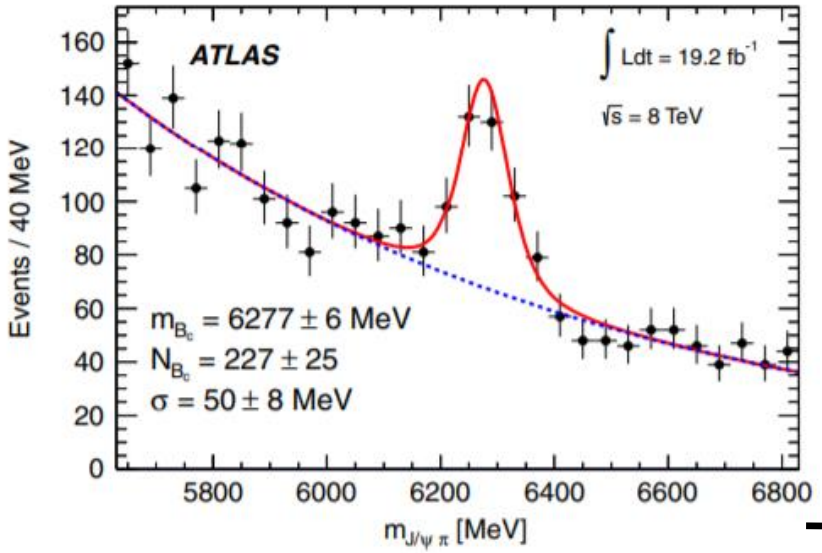
- CMS confirmed that the $\chi_{b1}(3P)$ is well below the open-beauty thresholds
- In the limit of the current statistics available there is no hint of an hypothetical X_b state, the bottomonium partner of the $X(3872)$, that might exist at masses close to the $B\bar{B}^*$ thresholds and decay to $\Upsilon(3S)\gamma$."

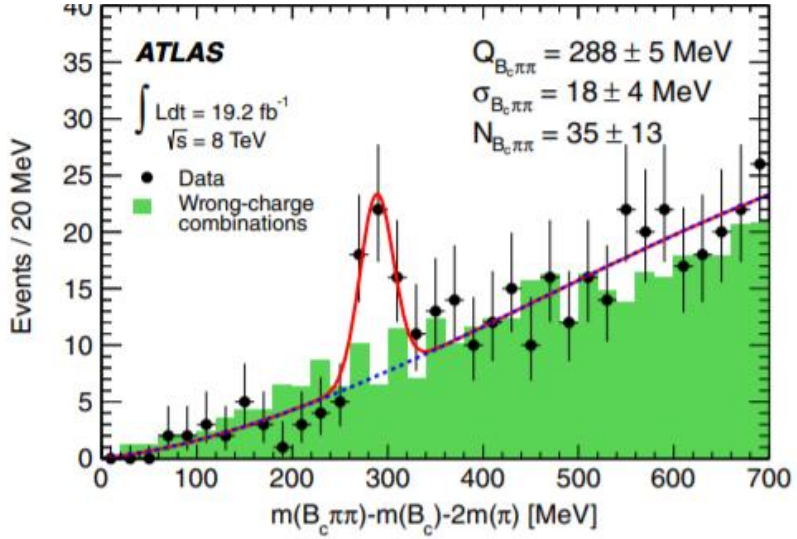
Observation of two exited $\mathbf{B_c^+}$ states and measurement of the $\mathbf{B_c^+(2S)}$ mass in pp collisions at $\sqrt{s} = \mathbf{13}$ TeV

[PRL 122 (2019) 132001]

Observation of two exited $\mathbf{B_c^+}$ states

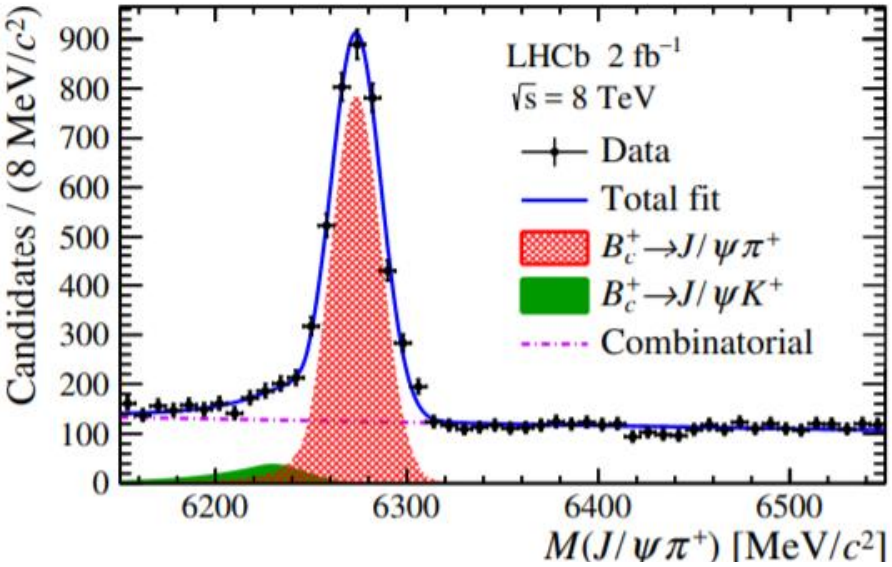
In 2014 the ATLAS Collaboration reported the observation of the new state, with mass consistient to predictions for $B_c^+(2S)$ state

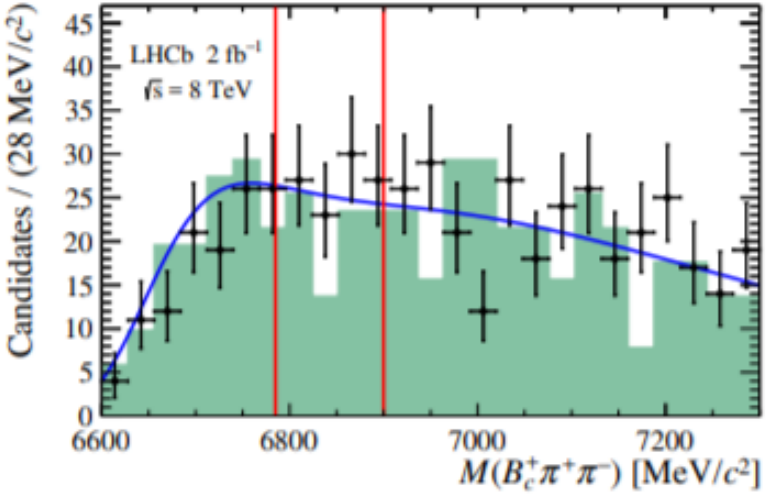




PRL 113 (2014) 212004

Than the LHCb using 8 TeV data didn't find any significant signal in the same region

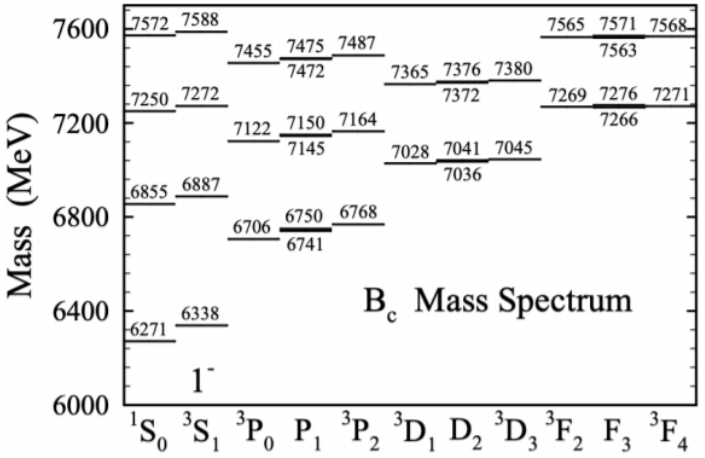




JHEP 01 (2018) 138

Observation of two exited $\mathbf{B_c^+}$ states

Motivation

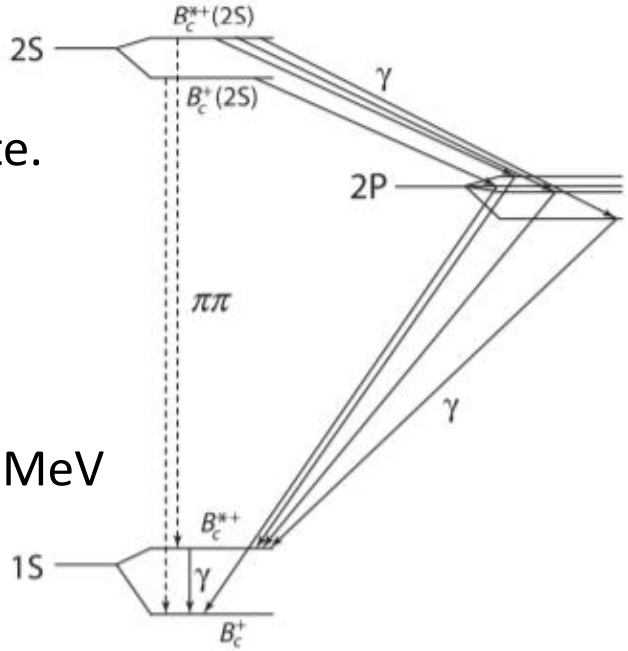


- Spectrum of B_c family is predicted to be very populated, but spectroscopic observations are poor so far
- The spectrum of B_c will help to deeply understand the dynamics of heavy-heavy quark systems.

The study is based on searching for $B_c^+(2S)$ and $B_c^{+*}(2S)$ in the $B_c^+\pi^+\pi^-$ final state.
Decay modes are:

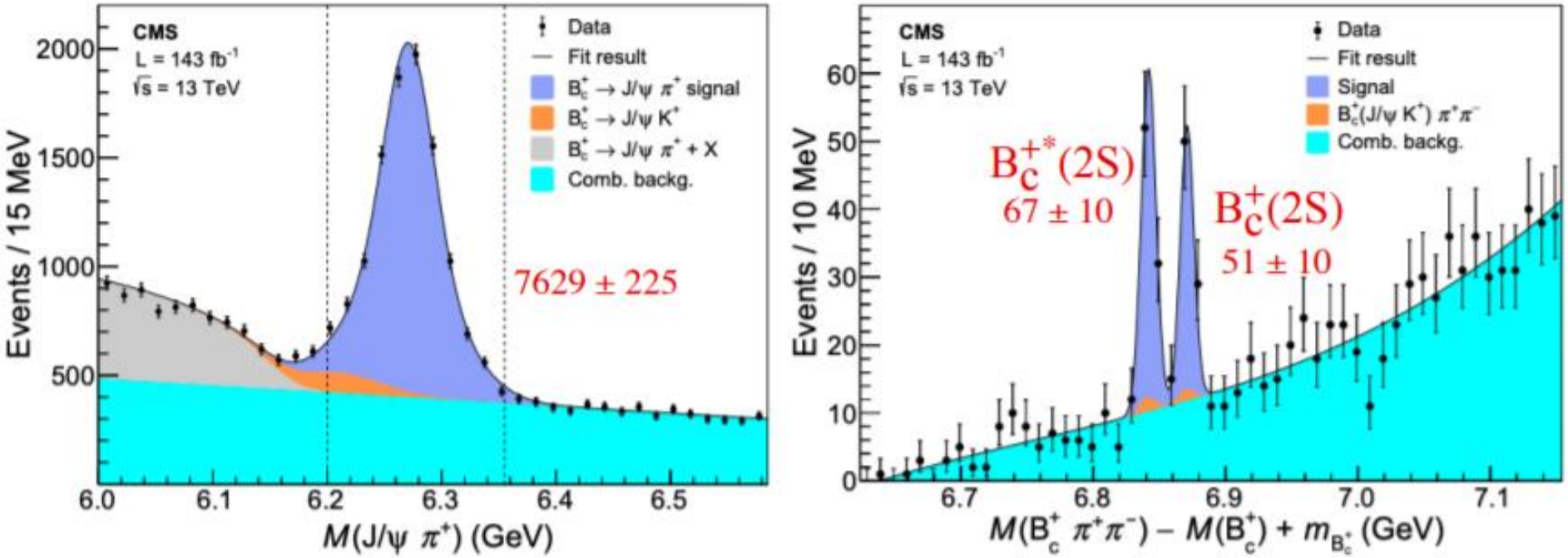
- $B_c^+(2S) \to B_c^+\pi^+\pi^-$
- $B_c^{+*}(2S) \to B_c^{+*}\pi^+\pi^-$, where $B_c^{+*} \to B_c^+\gamma$, and soft photon is lost

The theory predicts $\Delta M = [M(B_c^*) - M(B_c)] - [M(B_c^*(2S)) - M(B_c(2S))]$ = 20 MeV



Observation of two exited $\mathbf{B_c^+}$ states

Using full Run II statistics the CMS collaboration observed two well separated $B_c^+\,(2S)$ and $B_c^{+*}\,(2S)$ states



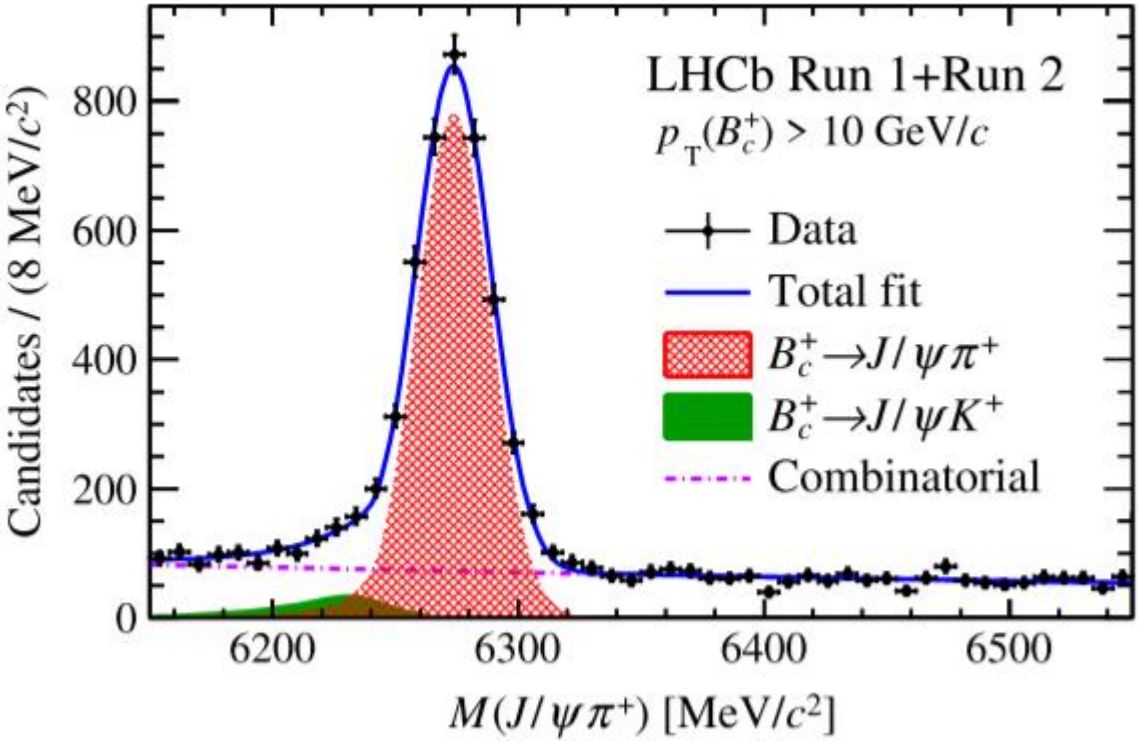
- $M\left(B_c^+(2S)\right) = 6871.0 \pm 1.2(stat.) \pm 0.8(syst.) \pm 0.8(B_c^+)$ MeV
- $\Delta M = 29.1 \pm 1.5(stat.) \pm 0.7(syst.)$ MeV

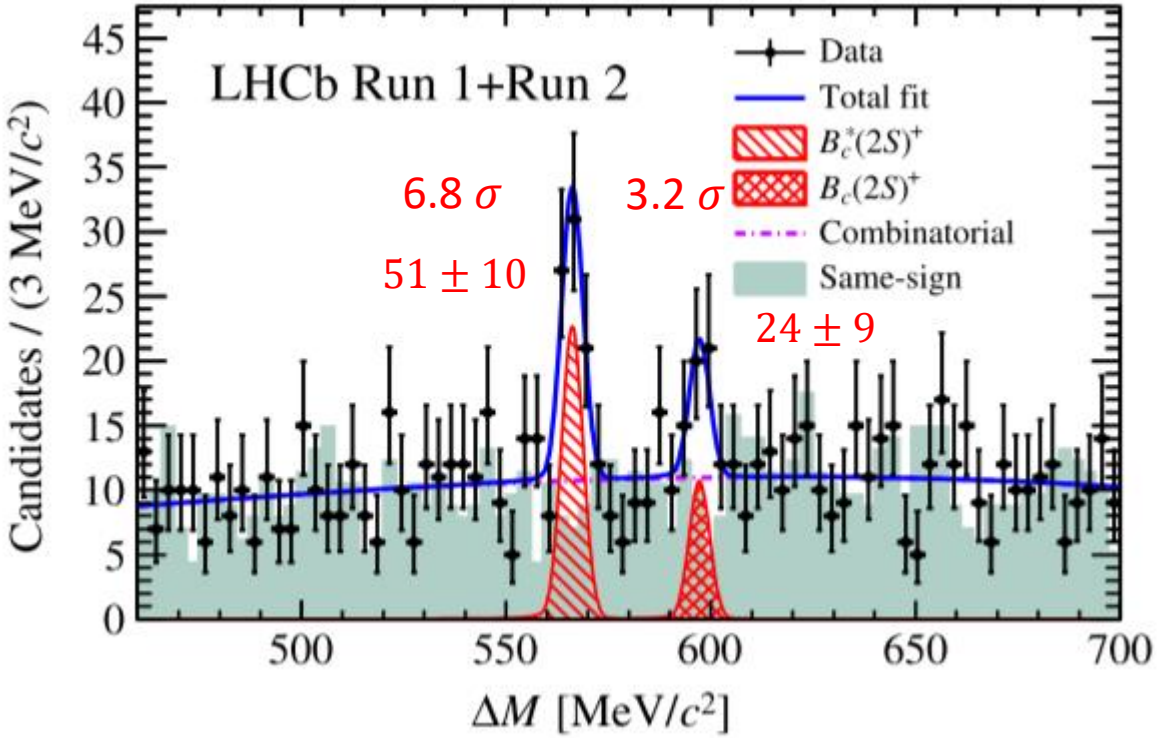
Once these yields will be corrected for detection efficiencies and acceptances we will be able to determine ratios of production cross sections to be compared with the different theoretical predictions

Observation of two excxited B_c^+ states

Recently the LHCb collaboration has confirmed the two-peaks structure using Run I and Run II statistics.

PRL 122 (2019) 232001





	$M(B_c^+(2S))$, MeV	ΔM, MeV
CMS	$6871.0 \pm 1.2 \pm 0.8 \pm 0.8$	$29.1 \pm 1.5 \pm 0.7$
LHCb	$6872.1 \pm 1.3 \pm 0.1 \pm 0.8$	$31.0 \pm 1.4 \pm 0.0$

Results of the LHCb Collaboration are in a good agreement with CMS Collaboration

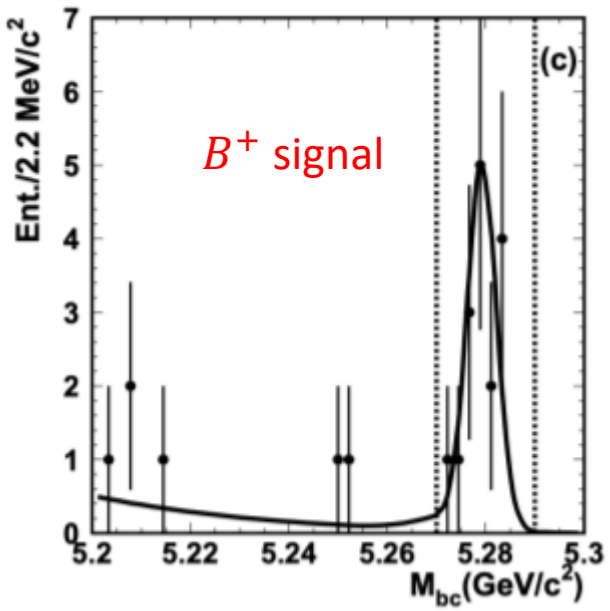
Search for exotic states in $B^+ \to J/\psi \bar{\Lambda} p$ decay

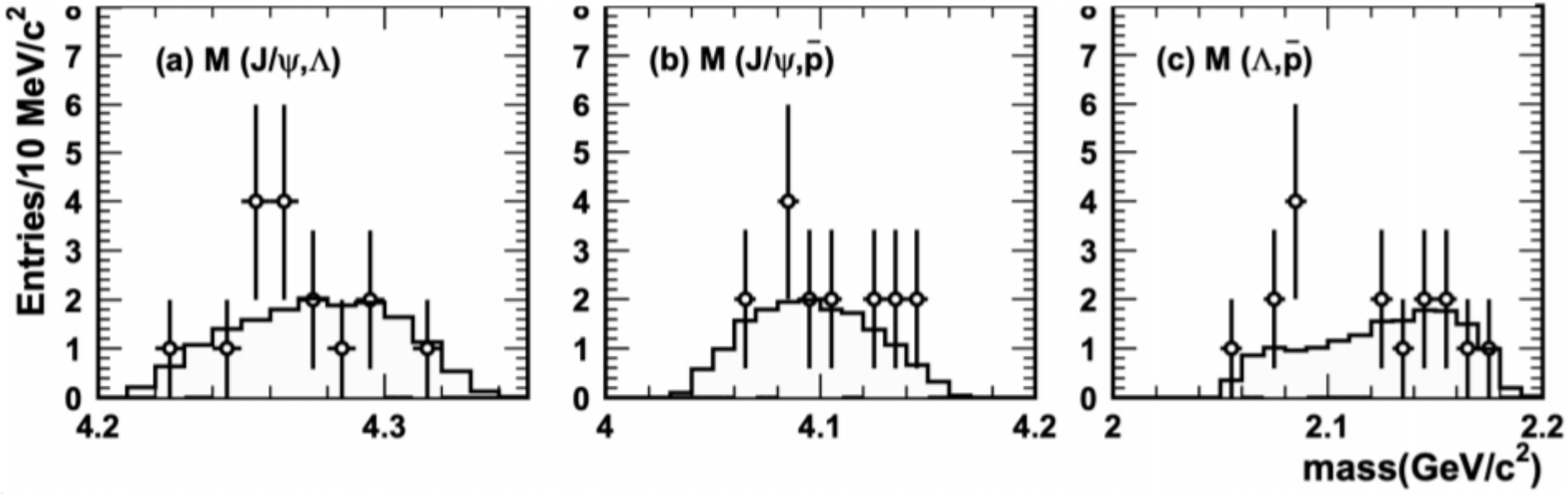
[arXiv:1907.05461] Submitted to JHEP

Study of $B^+ \to J/\psi\bar{\Lambda}p$

- In 2005 the Belle Collaboration reported the first observation of $B^+ \to J/\psi\bar{\Lambda}p$ decay.
- Since it was only 16 events in signal region $B(B^+ \to J/\psi\bar{\Lambda}p)$ was measured with large uncertainty

PRD 72 (2005) 051105





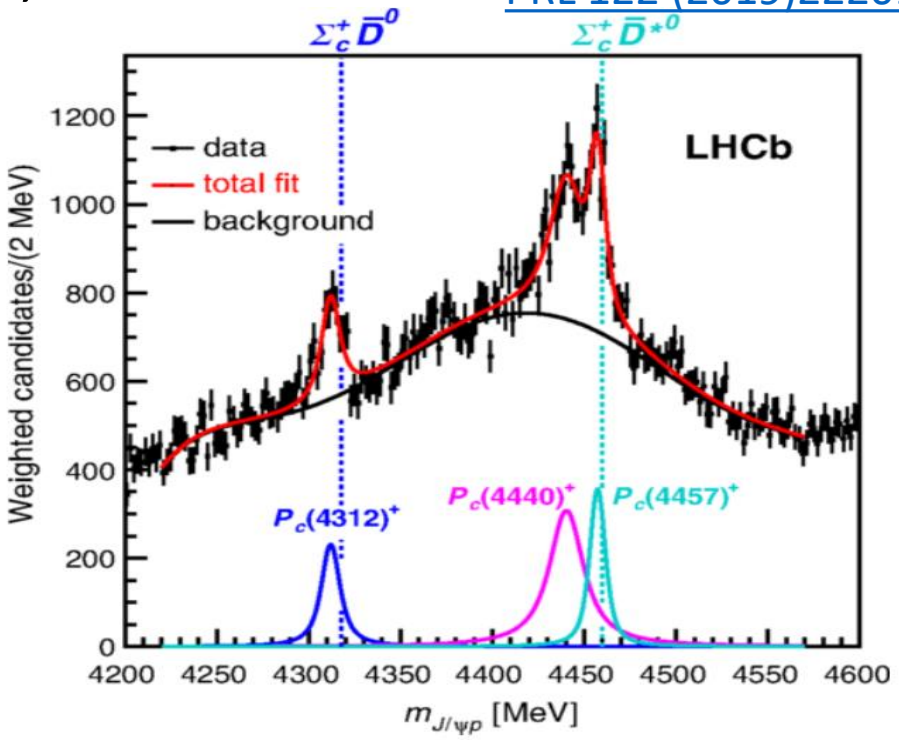
mode	Y	b	n_0	$\epsilon(\%)$	Y_{90}	$\mathcal{B}$
$B^- \to J/\psi\Lambda\bar{p}$	17.2 ± 4.1	$0.41 \pm 0.09(\text{stat.})$	16	$7.2^{+1.1}_{-1.4}$	–	$11.6 \pm 2.8(\text{stat.})^{+1.8}_{-2.3}(\text{sys.}) \times 10^{-6}$

Study of $B^+ \to J/\psi\bar{\Lambda}p$

Motivation

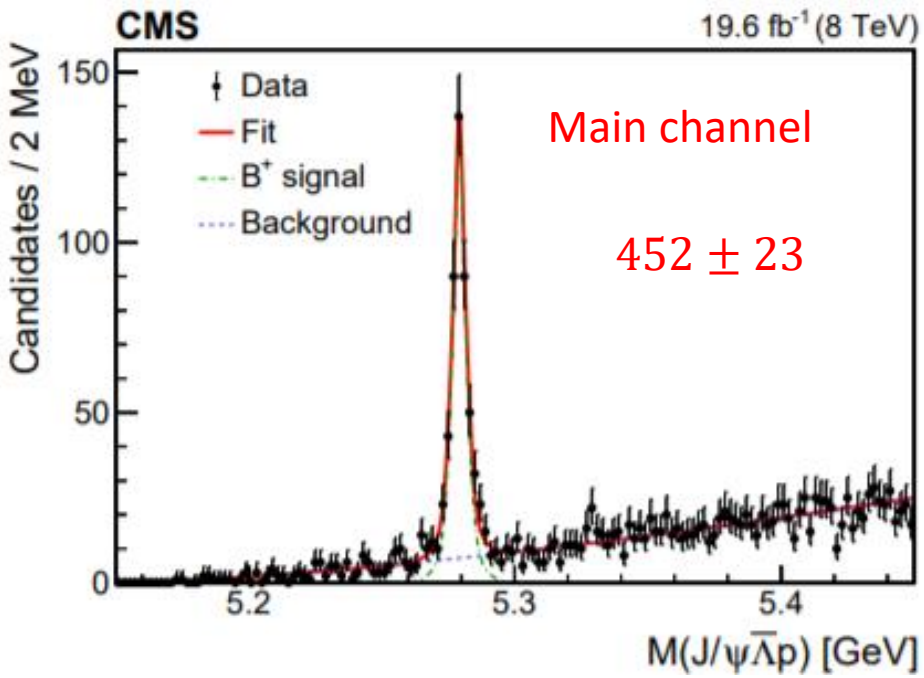
- Recently, the LHCb collaboration observed three P_c^+ states in $J/\psi p$ mass spectrum. These exotic states were referred to as charmonium-pentaquarks
- The $B^+ \to J/\psi\bar{\Lambda}p$ provides possibility to investigate mentioned before $J/\psi p$ invariant mass and also $J/\psi\bar{\Lambda}$ mass spectrum, where new "charmonium-pentaquarks" could be hidden
- In addition, such hidden pentaquark is predicted by theory. [PRD 100 (2019) 016014]

PRL 122 (2019)22201

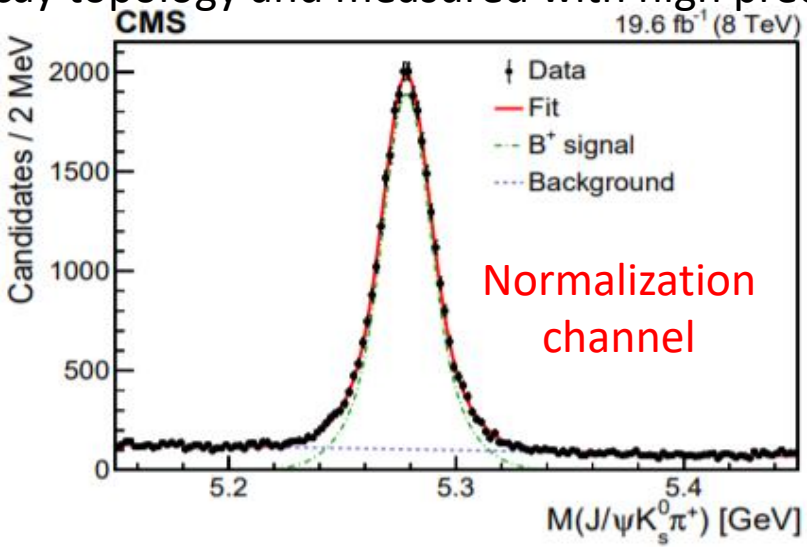


Study of $\mathbf{B^+ \to J/\psi \bar{\Lambda} p}$

The study is based on 2012 8 TeV data (19.6 fb^{-1})



The $B^+ \to J/\psi K^{*+} \to J/\psi K_S^0 \pi^+$ was chosen as a normalization channel since it has the same decay topology and measured with high precision



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

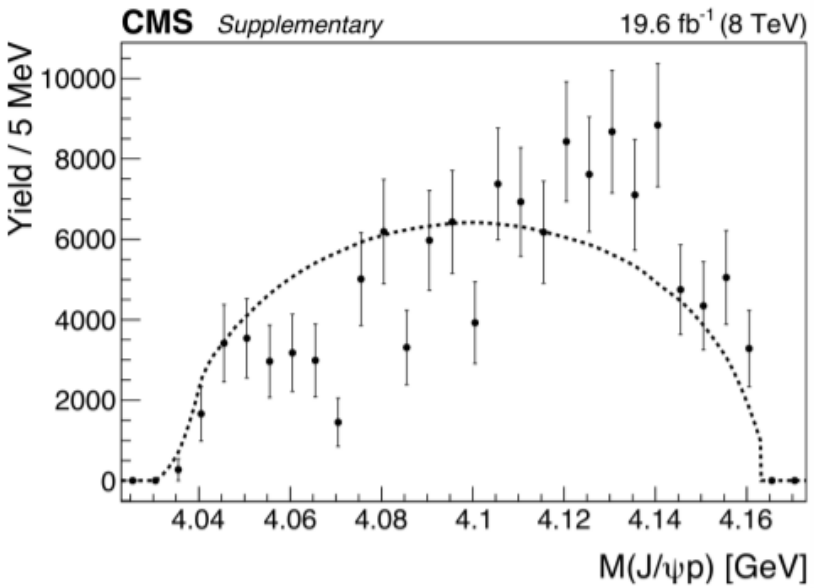
It is the most precise result to date and compatible with previous results:

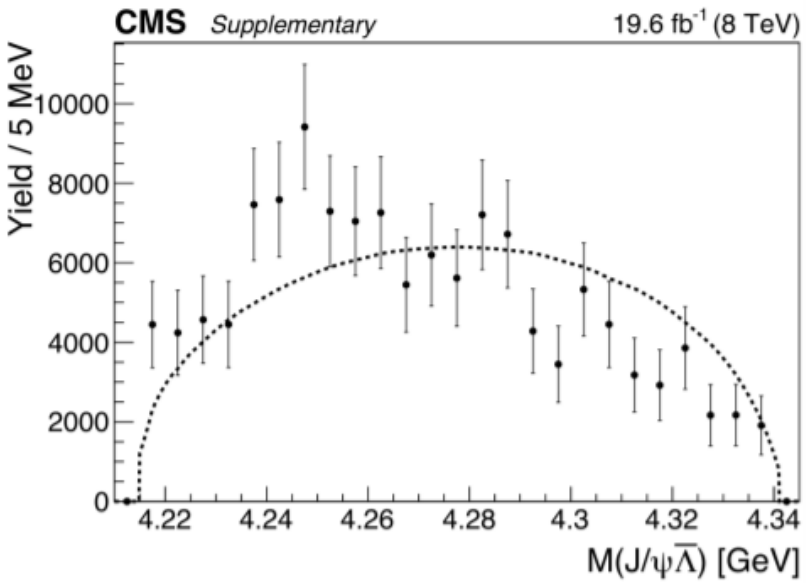
PDG: $B(B^+ \to J/\psi \bar{\Lambda} p) = (11.8 \pm 3.1) \times 10^{-6}$

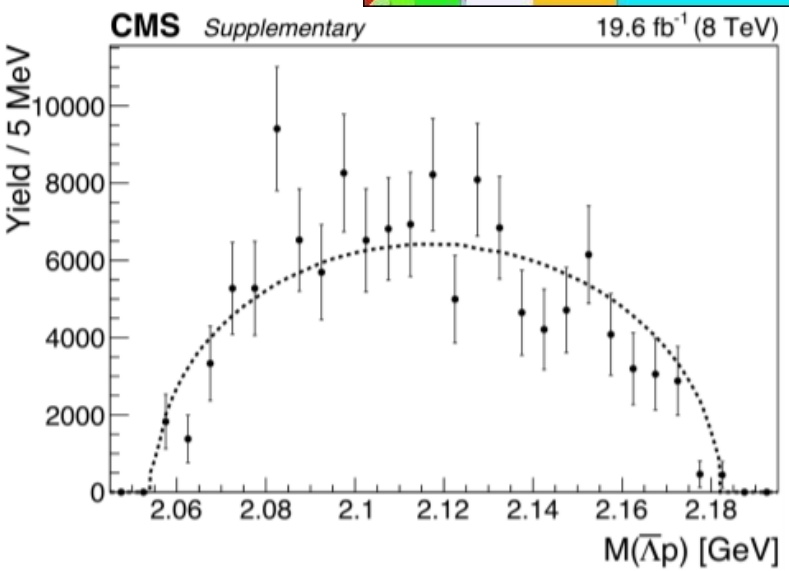
Belle: $B(B^+ \to J/\psi \bar{\Lambda} p) = (11.7 \pm 2.8^{+1.8}_{-2.3}) \times 10^{-6}$

Study of $B^+ \to J/\psi\bar{\Lambda}p$

The intermediate invariant masses are found to be inconsistent with pure 3-body PS







The significance of incompatibility data with the phase space hypotesis is > 5.5 σ for $J/\psi\bar{\Lambda}$, > 6.1 σ for $J/\psi p$ and > 3.4 σ for $\bar{\Lambda}p$ mass spectra, including systematic.

But may be it is possible to reduce this difference (see next slides)

Study of $B^+ \to J/\psi \bar{\Lambda} p$

Model independent approach

- Introduced by BaBar [Phys.Rev.D79:112001,2009] used by LHCb [Phys.Rev.D92:112009,2015]
- K^* resonances decaying to $\bar{\Lambda}$p final states can modify invariant intermediate mass distributions
- Their contributions is taken into account by measuring $\cos(\theta_{K^*})$ in each M($\bar{\Lambda}$p) bin on data:

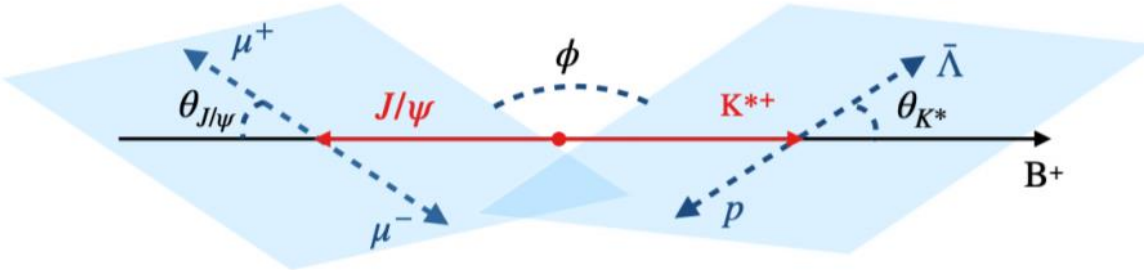
$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{l_{\max}} \langle P_j^U \rangle P_j(\cos\theta_{K^*})$$

- Then pure phase space is reweighted accordingly: $w^i = 1 + \sum_{j=1}^{l_{max}} < P_j^N > P_j(cos\theta_{K^*}^i)$

where l_{max} is 2×total spin of the highest-spin K^* decaying into $\bar{\Lambda}$p and $\langle P_j^N \rangle = 2\langle P_j^U \rangle / N_{\text{reco}}^{\text{corr}}$

Known K^* states, which can decay into $\bar{\Lambda}$p

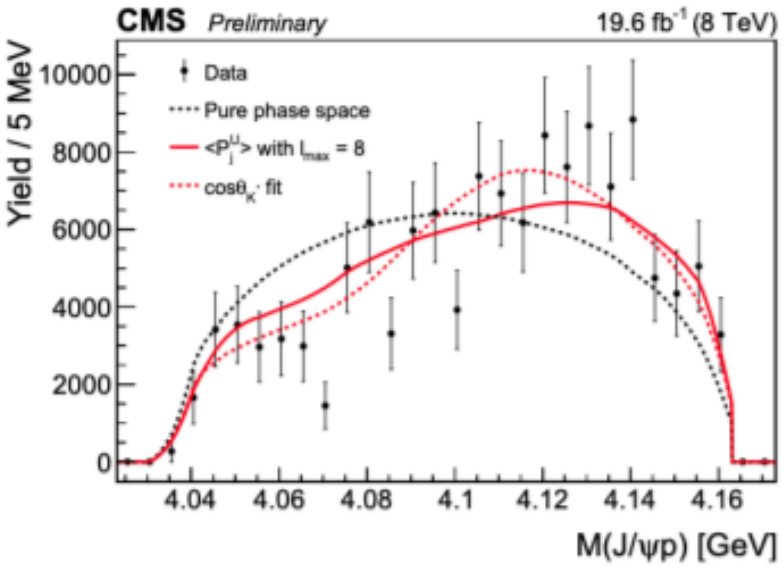
Resonance	Mass, MeV	Natural width, MeV	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

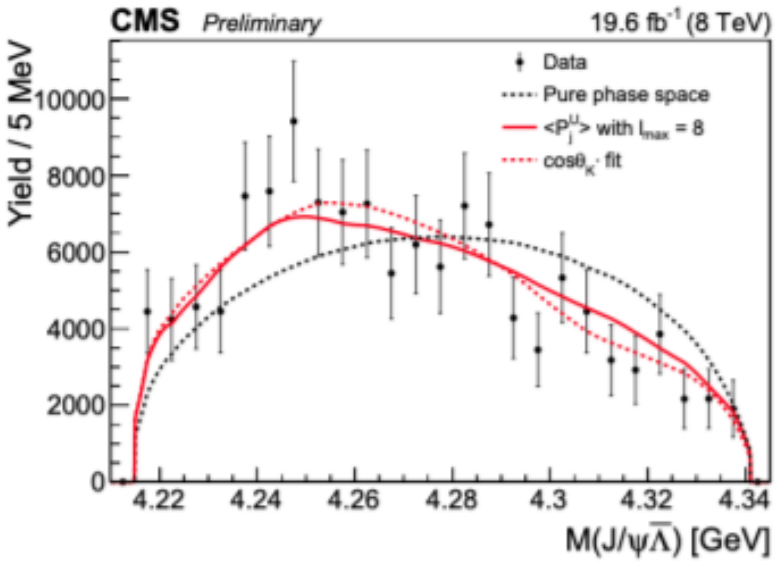


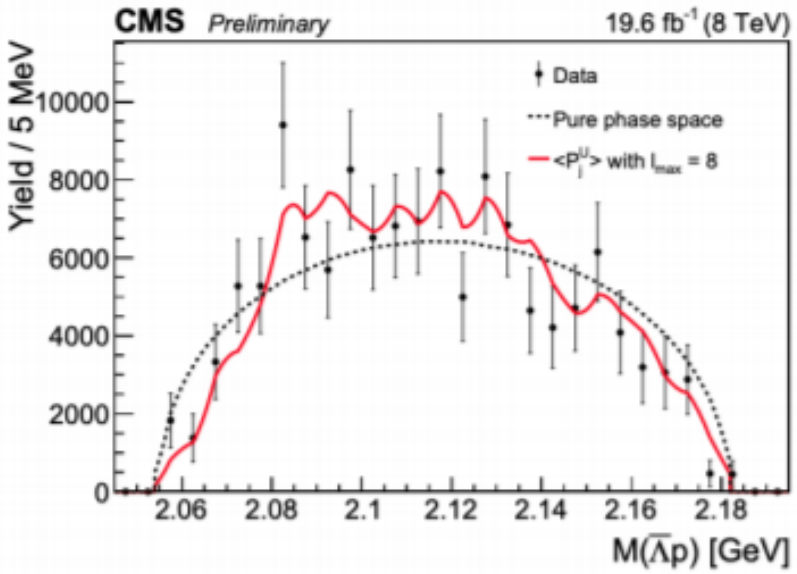
Study of $B^+ \to J/\psi\bar{\Lambda}p$

Model independent approach

After reweighting sumulation taking into account exited kaon contributions







A model independent approach improved significantly the description of the data in $J/\psi\bar{\Lambda}$ and $J/\psi p$ mass spectrum, and the significance of incompability became within 3 standard deviations including systematic.

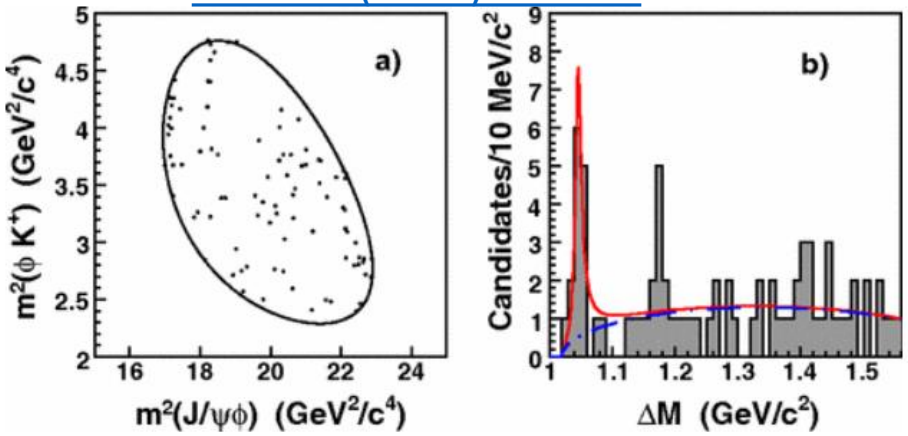
Observation of the $\Lambda_b^0 \to J/\psi\Lambda\varphi$ decay in proton-proton at $\sqrt{s} = 13$ TeV

[arXiv:1911.03789] Submitted to PLB

Observation of the $\Lambda_b \to J/\psi\Lambda\phi$ decay

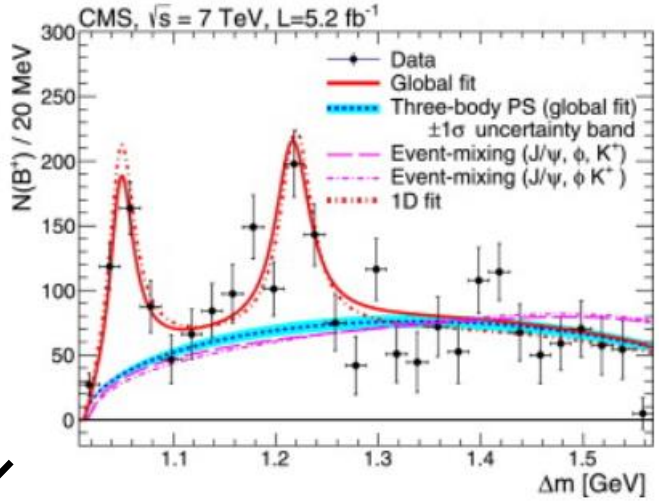
History of $B^+ \to J/\psi\phi K^+$ studies

PRL 102 (2009) 242002



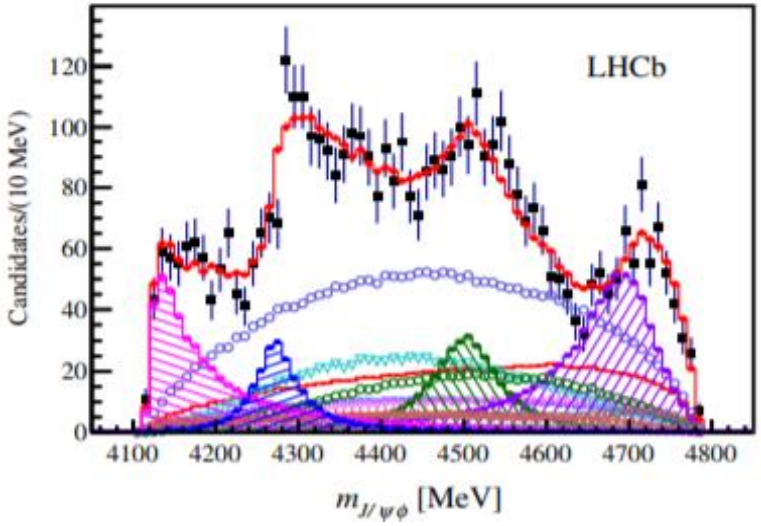
In 2008 the CDF Collaboration made an evidence of a narrow structure X(4140) near the $J/\psi\phi$ threshold in $B^+ \to J/\psi\phi K^+$ decays

PLB 734 (2014) 261



Then, in 2014 the CMS Collaboration presented observation of X(4140) and evidence of X(4274) in the same decay mode.

PRL 118 (2017) 022003



Finally, in 2016 the LHCb Collaboration performed full amplitude analysis and observed four exotic states: X(4140), X(4274), X(4500) and X(4700)

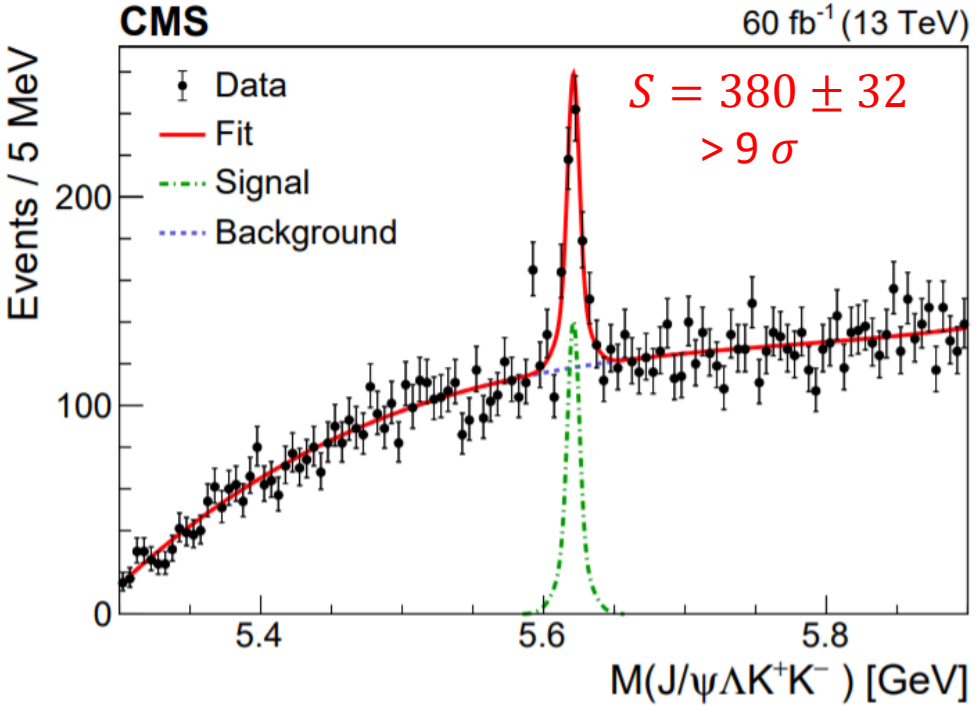
Observation of the $\Lambda_b \to J/\psi\Lambda\phi$ decay

Motivation

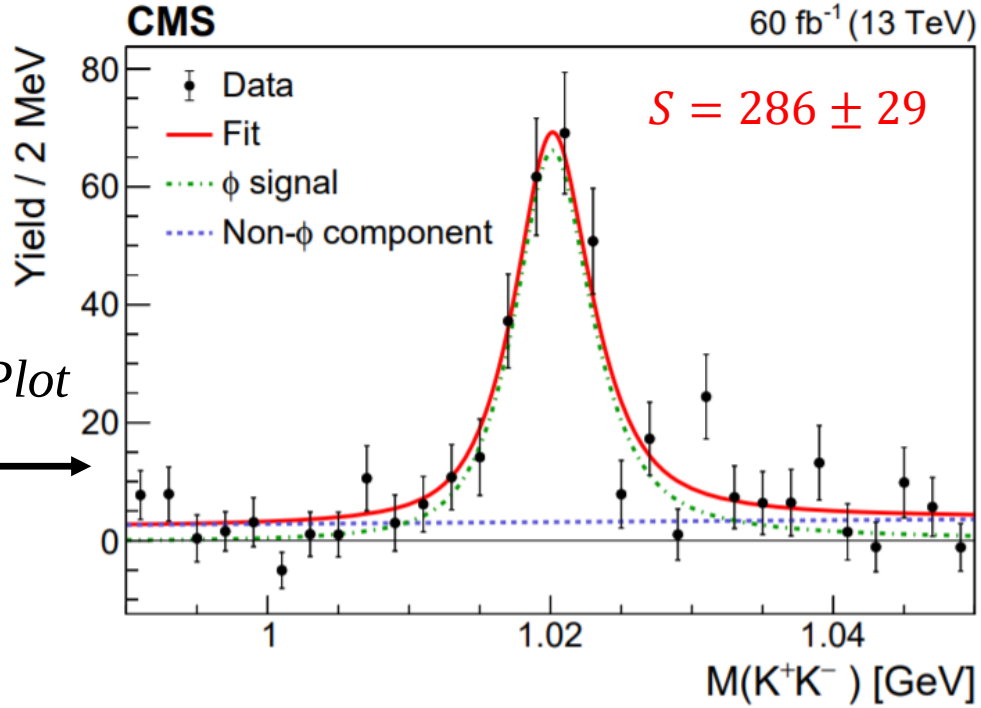
- Better understanding final-state strong interactions in b barions
- The $\Lambda_b \to J/\psi\Lambda\phi$ decay is baryonic analogue of the $B^+ \to J/\psi\phi K^+$ decay and detailed studies of the $J/\psi\phi$ spectrum produced in baryonic decays may provide an important test for the production of observed exotic states
- Also, this decay provides an opportunity to investigate $J/\psi\Lambda$ mass spectrum too, once a sufficient number of signal events is accumulated

Observation of the $\Lambda_b \to J/\psi\Lambda\phi$ decay

The study is based on 2018 13 TeV data (60 fb^{-1})

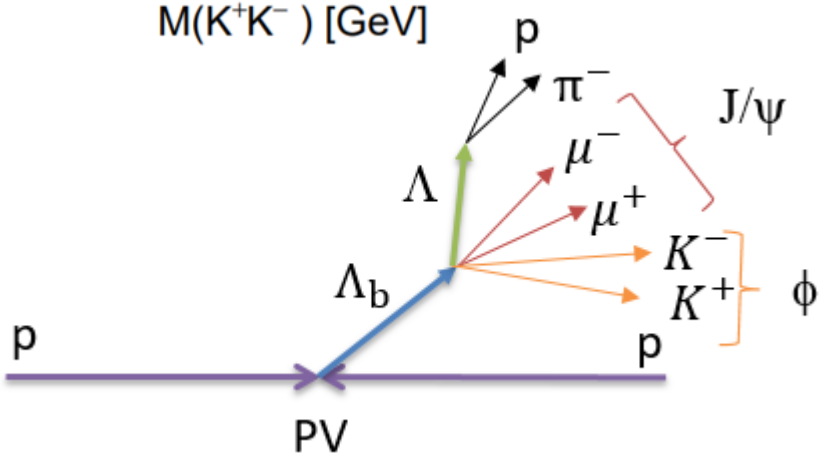


sPlot



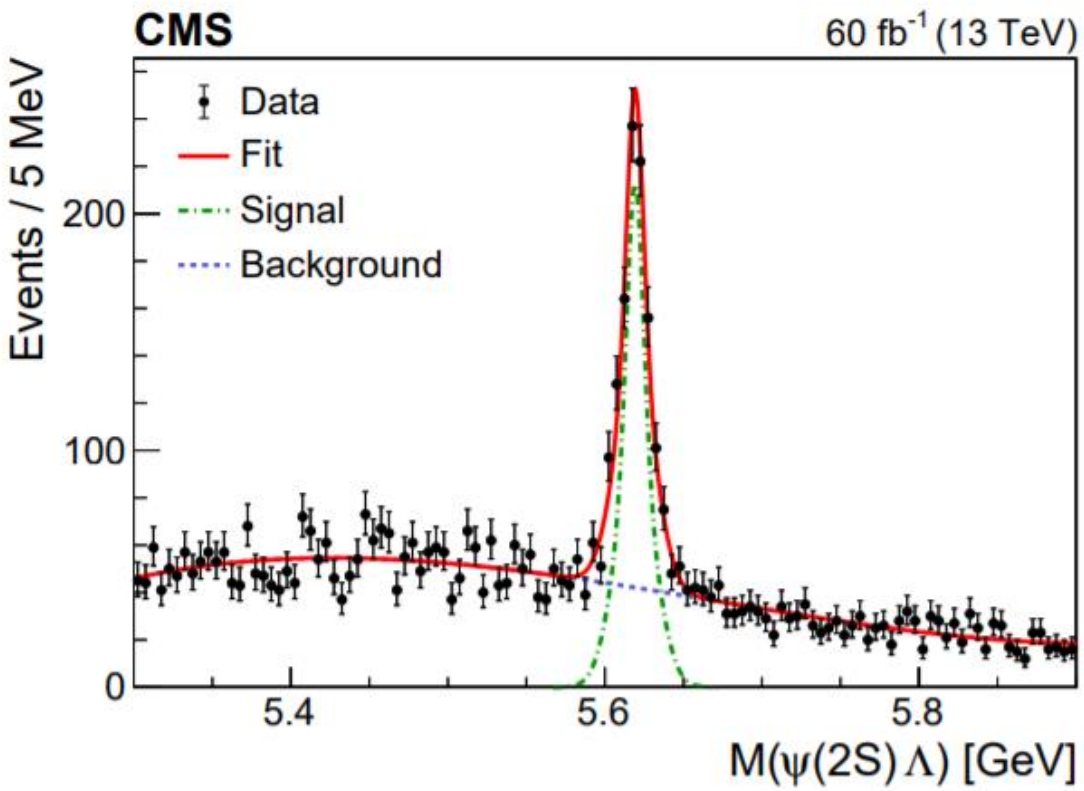
Unbinned maximum likelihood fit is applied to $J/\psi\Lambda K^+K^-$ invariant mass distribution. Than *sPlot* technique is used to obtain $M(K^+K^-)$ distribution from signal component. Finally, the $\Lambda_b \to J/\psi\Lambda\phi$ yield is obtained from fit of background-substrackted $M(K^+K^-)$ distribution.

Given the current statistics it is not still possible to investigate the $J/\psi\phi$ and $J/\psi\Lambda$ spectra yet

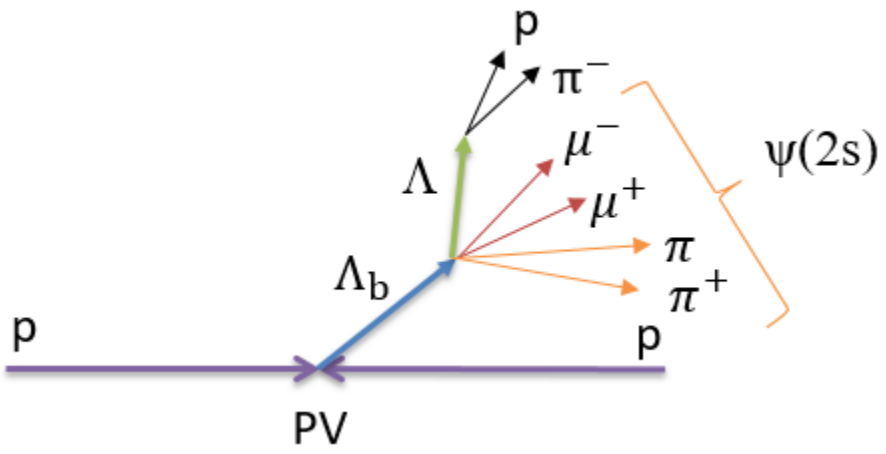


Topology of the $\Lambda_b \to J/\psi\Lambda\phi$ decay

Observation of the $\Lambda_b \to J/\psi\Lambda\phi$ decay



The $\Lambda_b^0 \to \psi(2S)\Lambda \to J/\psi\pi^+\pi^-\Lambda$ decay was chosen as a normalization channel since it has the same decay topology



The branching fraction ration is measured to be :

$$\frac{B(\Lambda_b^0 \to J/\psi\Lambda\varphi)}{B(\Lambda_b^0 \to \psi(2S)\Lambda)} = (8.26 \pm 0.90\,(\text{stat.}) \pm 0.68(\text{syst.}) \pm 0.11(\text{br.}))\%$$

Summary

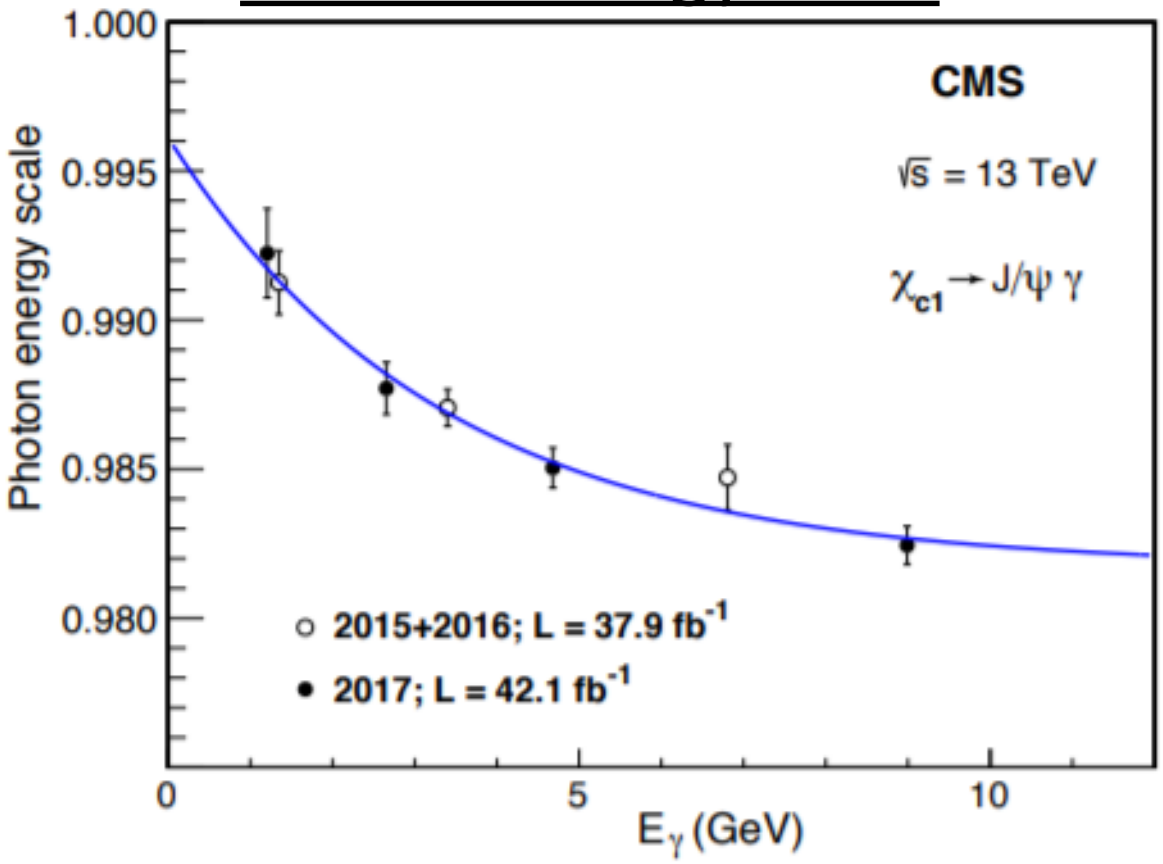
Designed for high-p_T physics, CMS is a good experiment for different exotica production studies

- Observation of two resolved states χ_{b1} and χ_{b2}
  - measured their masses and mass difference
- Observation of two exited B_c^+ states
  - first obsevation of two well resolved states $B_c^+(2S)$ and $B_c^{+*}(2S)$
  - mass measurement of $B_c^+(2S)$ state
- Study of $B^+ \to J/\psi\bar{\Lambda}p$ decay
  - the most precise branching fraction to date
  - the study of 2-body invariant mass distributions resulted in conclusion that no exotic resonances are needed
- Observation of $\Lambda_b \to J/\psi\Lambda\phi$ decay
  - measurement of $B(\Lambda_b \to J/\psi\Lambda\phi)/B(\Lambda_b^0 \to \psi(2S)\Lambda)$

Backup slides

CMS: Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$

Photon energy scale



To accurately measure the invariant mass of the $\chi_b(3P)$ candidates, the photon energy scale (PES) must be callibrated. PES defined as : $[m^2_{\mu\mu\gamma} - m^2_{\mu\mu}]/[M(\chi_{c1})^2 - M(J/\psi)]$, where $M(X)$ is the world-average X mass and $m_{\mu\mu\gamma}$ and $m_{\mu\mu}$ are invariant masses of $\mu\mu\gamma$ and $\mu\mu$, respectively. The PES values are parametrized with the function $p_0 + p_1 e^{-E_\gamma/p_2}$,where p_0, p_1, p_2 are free parameters in the fit. Finally, the resulting function is used for the event-by-event correction of the photon energy in the computation of the $\Upsilon\gamma$ invariant mass.