Flavours - Classical spectroscopy

V.Mariani for the
ALICE, ATLAS, CMS, LHCb Collaborations

Heavy Flavour physics

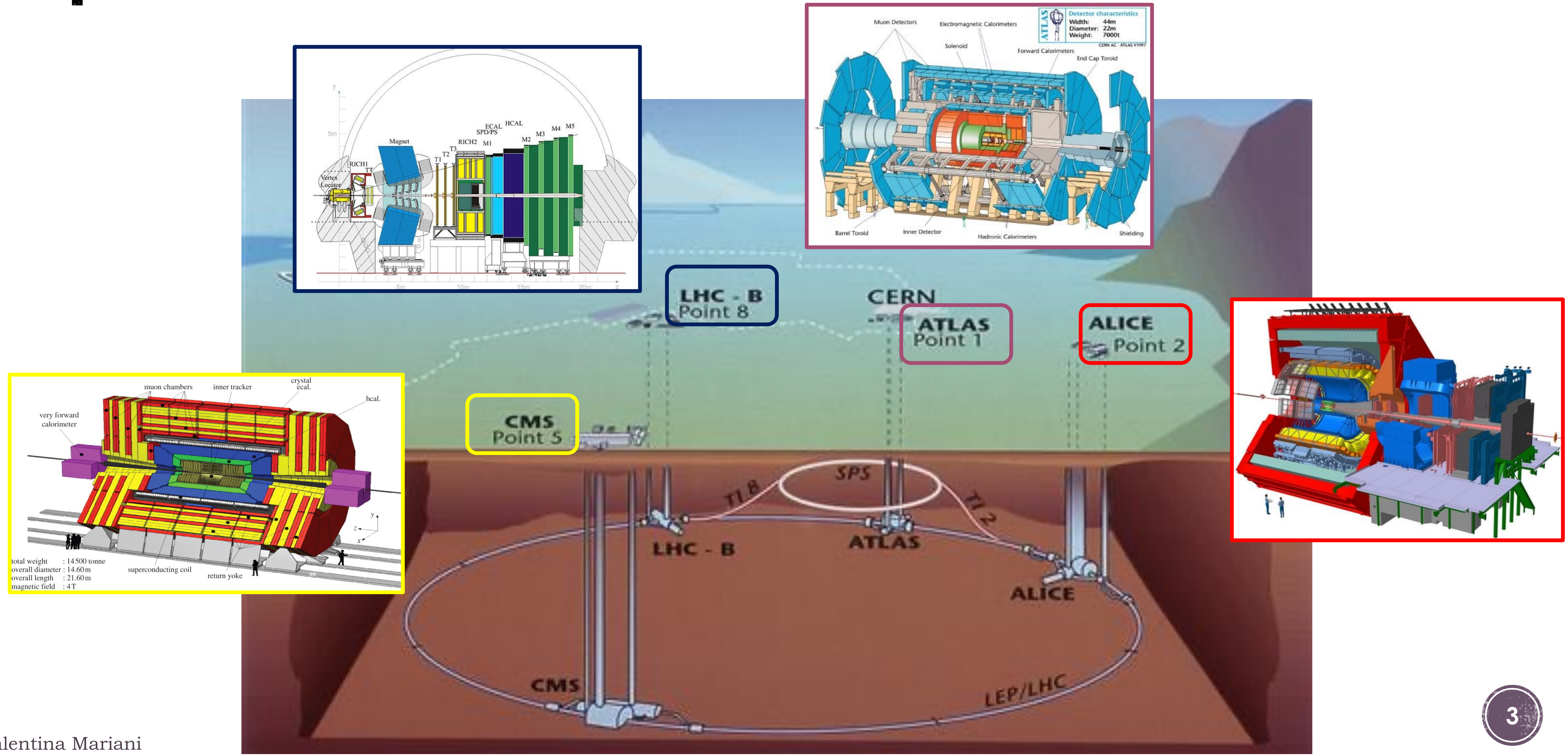
- Measurements and observations of heavy flavour production provide **important tests of QCD** and give insight into particle production at colliders

- **Hadronization challenging** to understand -> measurements needed

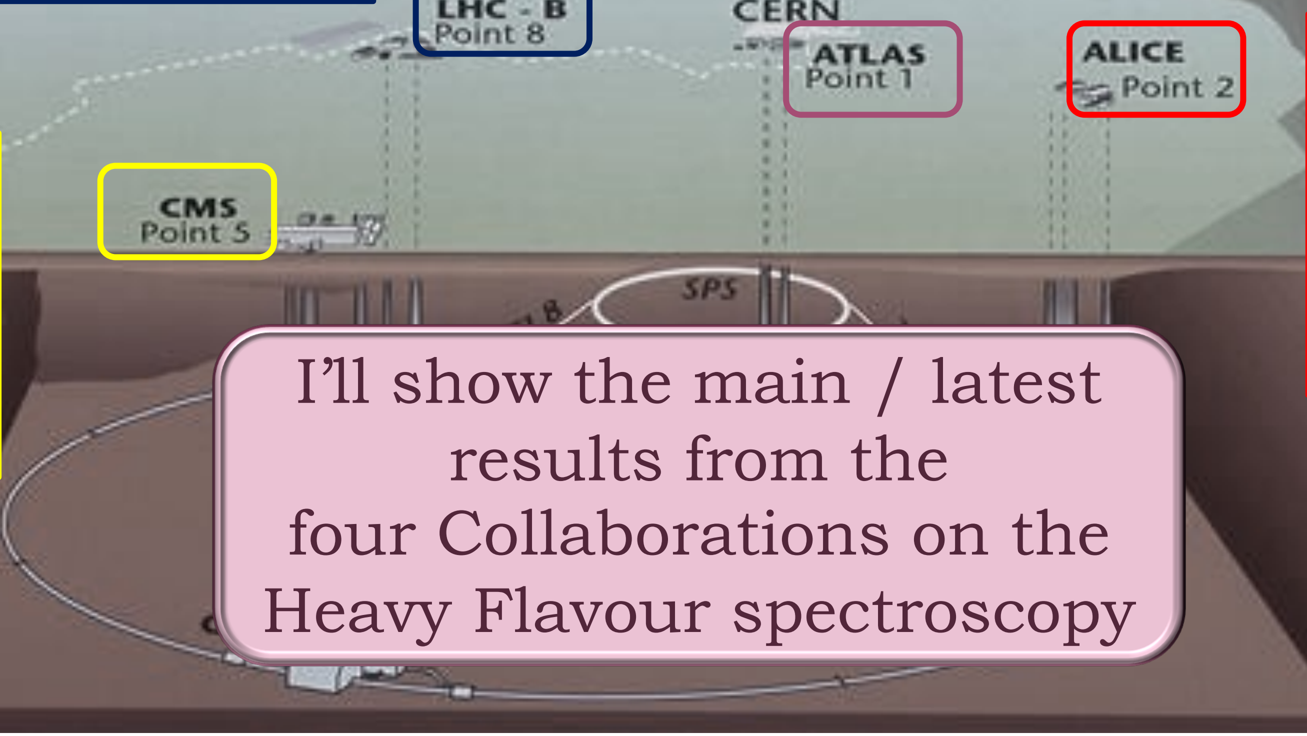
- Form **baseline or background** for other physics studies at the LHC

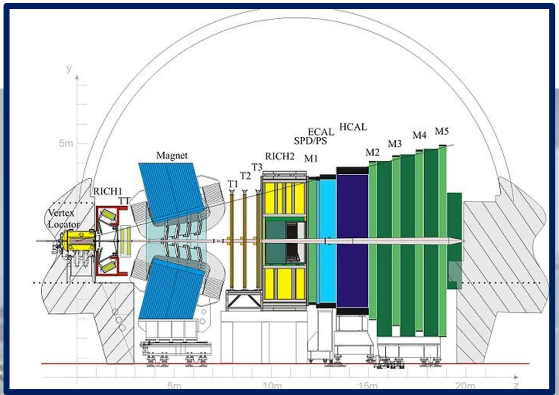
- LHC provides access to **wide kinematic range** with a **very high production cross section** if compared to e^+e^- colliders.

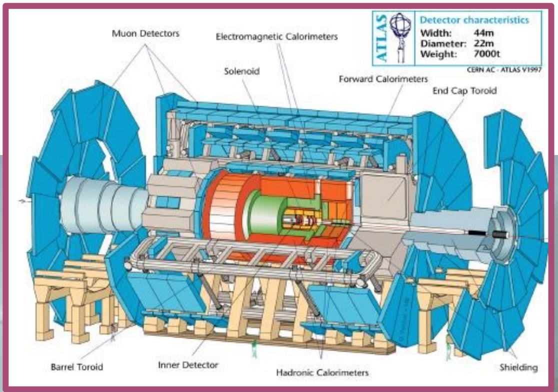
Experiments at the LHC

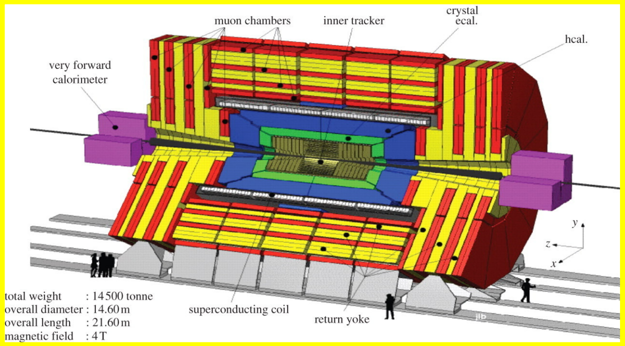


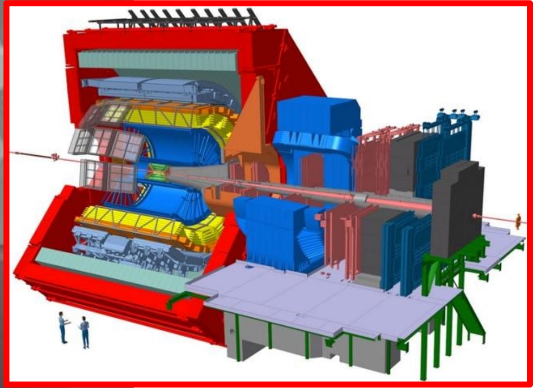
Experiments at the LHC











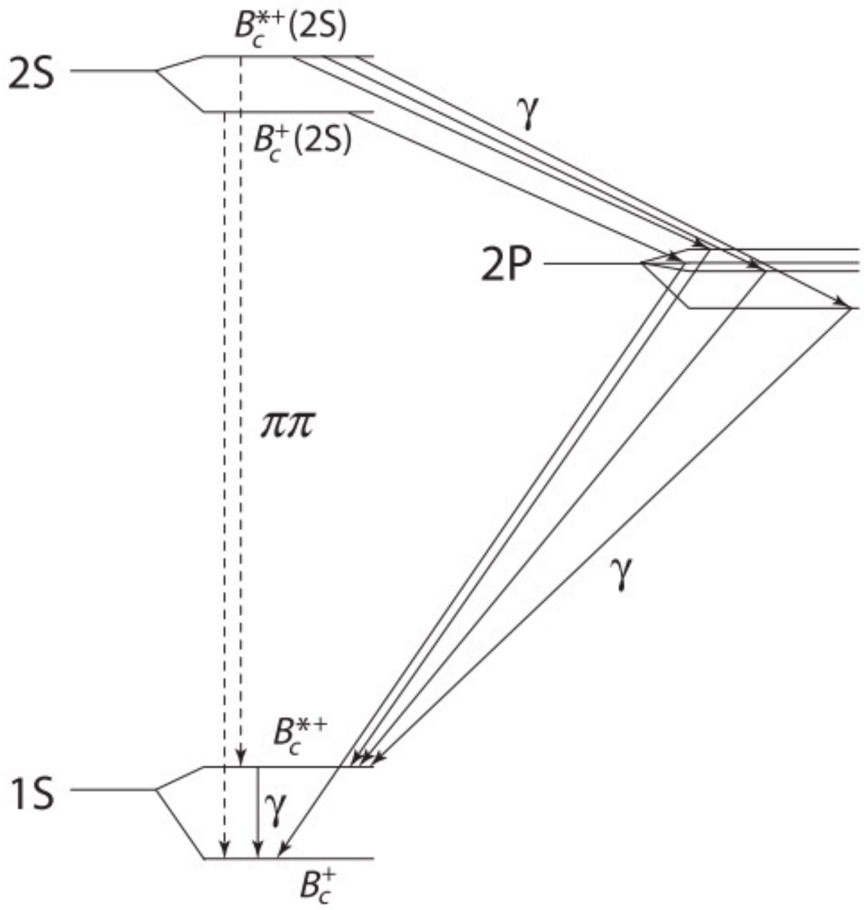
I'll show the main / latest results from the four Collaborations on the Heavy Flavour spectroscopy

$B_c^*(2S)$

- The B_c mesons ($b\bar{c}$) family is predicted to be **very populated** but the spectroscopy and property studies are still scarce.

- Less explored compared to quarkonia because of the **small production rate**: dominant mechanism requires the production of both ccbar and bbbar.

- The $b\bar{c}$ exited states decay to the ground states via the cascade emission of γ and π pairs -> total width of O(100KeV)
  -> **hard to detect**

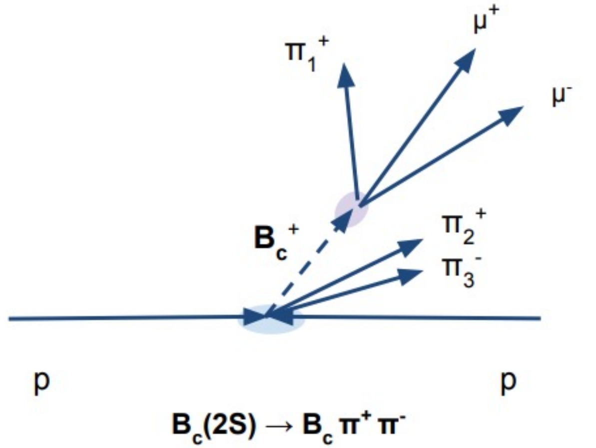


$B_c^*(2S)$

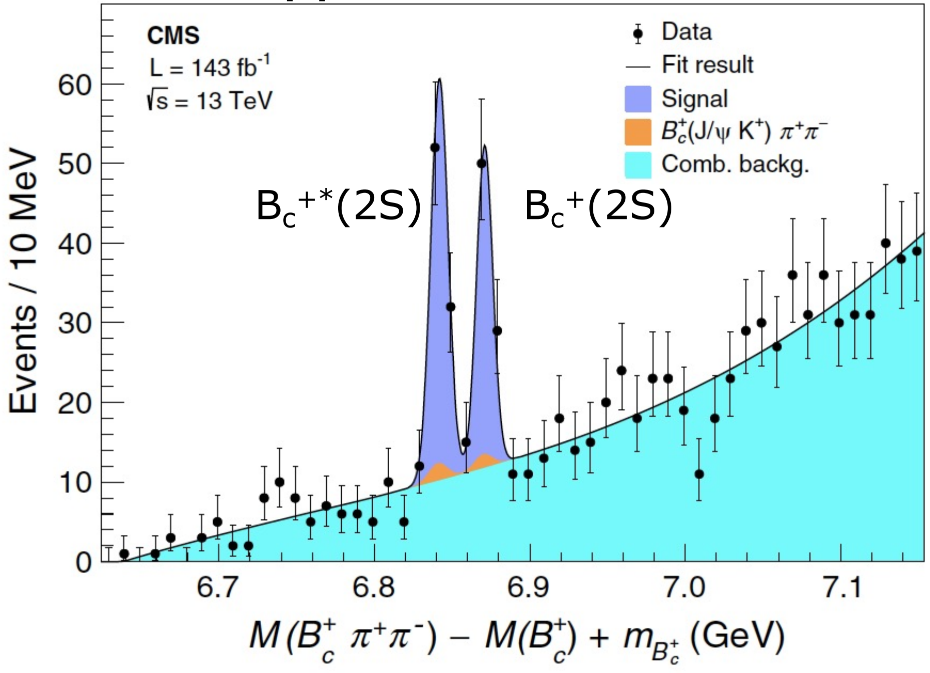
The existance of two separate states, $B_c^+(2S)$ and $B_c^{*+}(2S)$, was announced by CMS in [1], using data from Run2.

Significance of 2 peaks instead of 1 is 6.5 σ

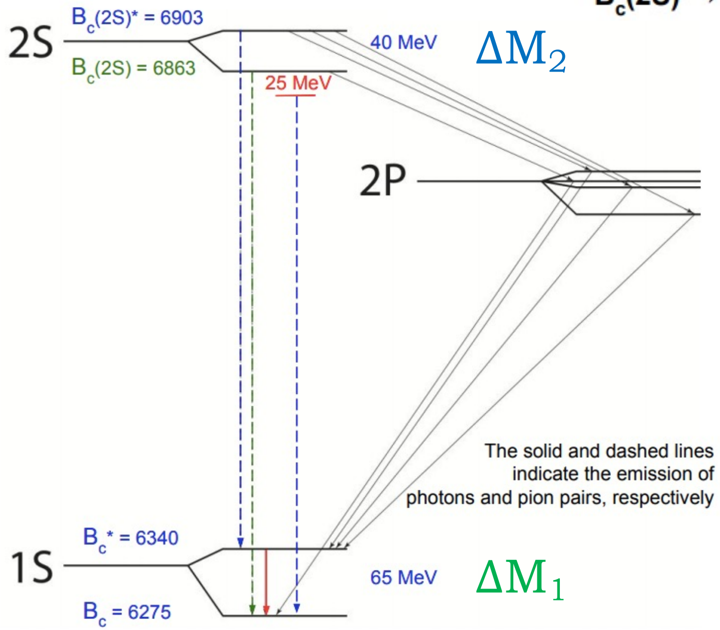
=> **First observation of two exited states**



[1] PRL **122** 132001



Consistent with ATLAS observation of one unresolved B*(2S) state [PRL 113 (2014) 212004] -> backup



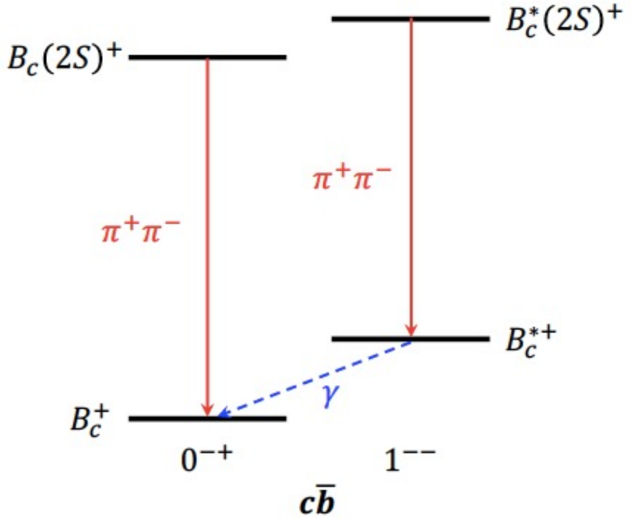
$M(B_c^+(2s)) = 6871.0 \pm 1.2\ (\text{stat}) \pm 0.8\ (\text{syst}) \pm 0.8\ (B_c^+)$ MeV

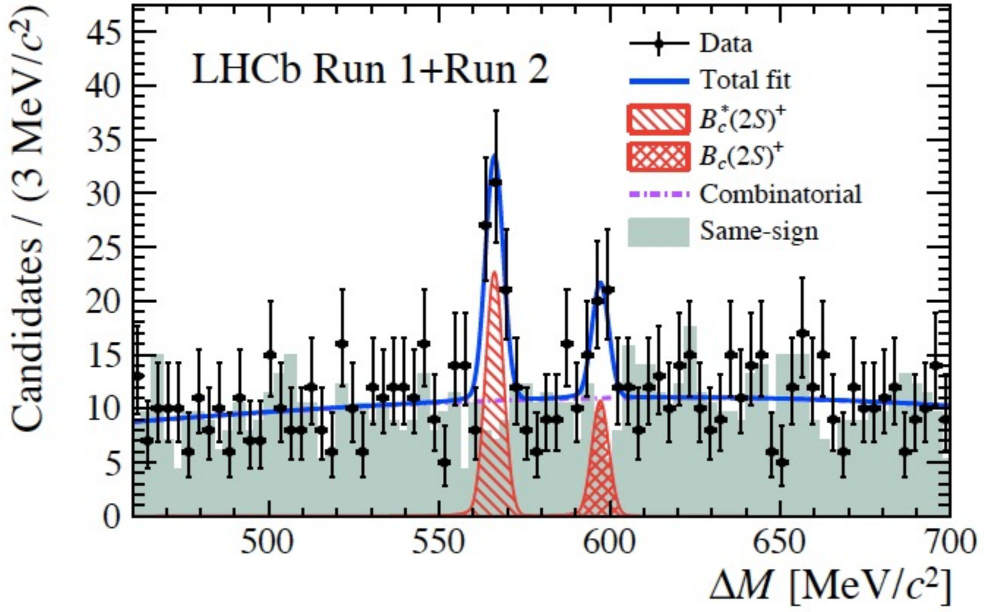
$\Delta M = \Delta M_1 - \Delta M_2 = 29.1 \pm 1.5\ (\text{stat}) \pm 0.7\ (\text{syst})$ MeV

$B_c^*(2S)$

LHCb could confirm the result using the statistics of Run1+Run2 (8.5 fb^{-1}) [2]

The second state is seen with a global (local) significance of 2.2σ (3.2σ).





$M(B_c^+(2s)) = 6872.1 \pm 1.3$ (stat) ± 0.1 (syst) ± 0.8 (B_c^+) MeV

$\Delta M = \Delta M_1 - \Delta M_2 = 31.1 \pm 1.4$ (stat) MeV

Consistent with CMS and with the theoretical predictions

[2] PRL **122** 232001

Barions with heavy-flavor quark

- Spectroscopy of baryons that contain a heavy-flavor quark can test predictions of heavy-quark effective theory.
  - Several theoretical calculations exist for various excitations of the ground state baryons containing a b quark.
- The widths and the production cross sections of various excited states are generally unknown.

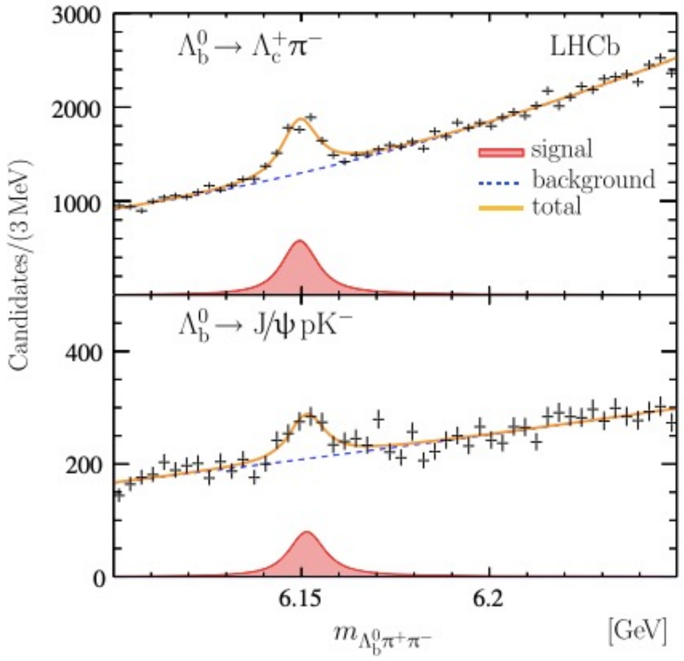
This situation makes **experimental searches** for excited heavy-quark baryons both **challenging** and **important** for testing various theoretical models.

Λ_b^0 excited states

LHCb already measured two narrow states [3] denoted as $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$

- Using data collected at 7, 8 and 13 TeV (L=9/fb) a search in the $\Lambda_b^0\pi^+\pi^-$ spectrum in the range 6.10- 6.25 GeV has been performed [4].
  Two Λ_b^0 decays: $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$

A clear excess of $\Lambda_b^0\pi^+\pi^-$ candidates around 6.15 GeV for both Λ_b^0 decay modes

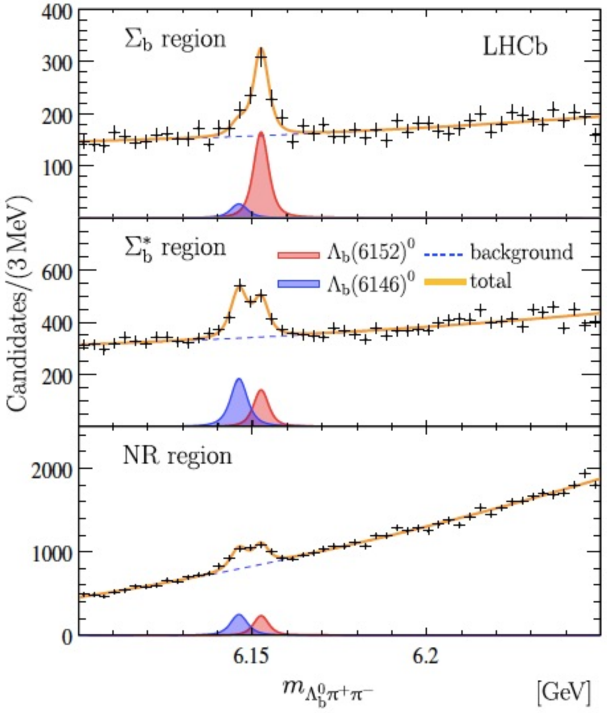


Mass above the $\Sigma_b^{*\pm}\pi^\pm$ threshold => three regions investigated:

- $\Lambda_b^0\pi^\pm$ mass within the width of $\Sigma_b^\pm$
- $\Lambda_b^0\pi^\pm$ mass within the width of $\Sigma_b^{*\pm}$
- Nonresonant region

[3] PRL **109**, 172003
[4] PRL **123**, 152001

Λ_b^0 excited states



The shapes suggest two different narrow peaks => states are called $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ and masses and widths are measured:

$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3 \text{ MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3 \text{ MeV},$$

The mass difference between the two states is 6.34 $\pm$ 0.32 $\pm$ 0.02 MeV.

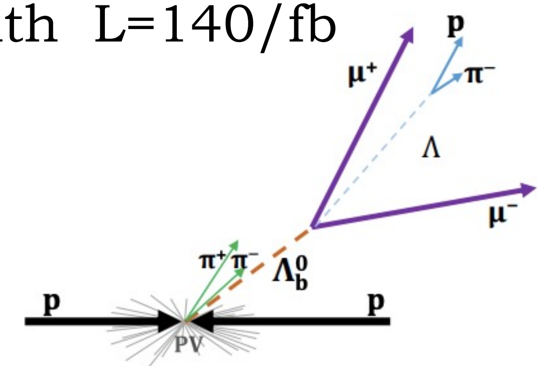
States measured are **consistent with the predictions for the doublet of $\Lambda_b(1D)^0$ states** with quantum numbers $J^P = 3/2^+$ and $5/2^+$

However, the **interpretation of these states as excited Σ_b^0 states cannot be excluded.**

[4] PRL **123**, 152001

Λ_b^0 excited states

CMS recently measured [5] exited states of the Λ_b^0 using Run2 data 16-18 with L=140/fb

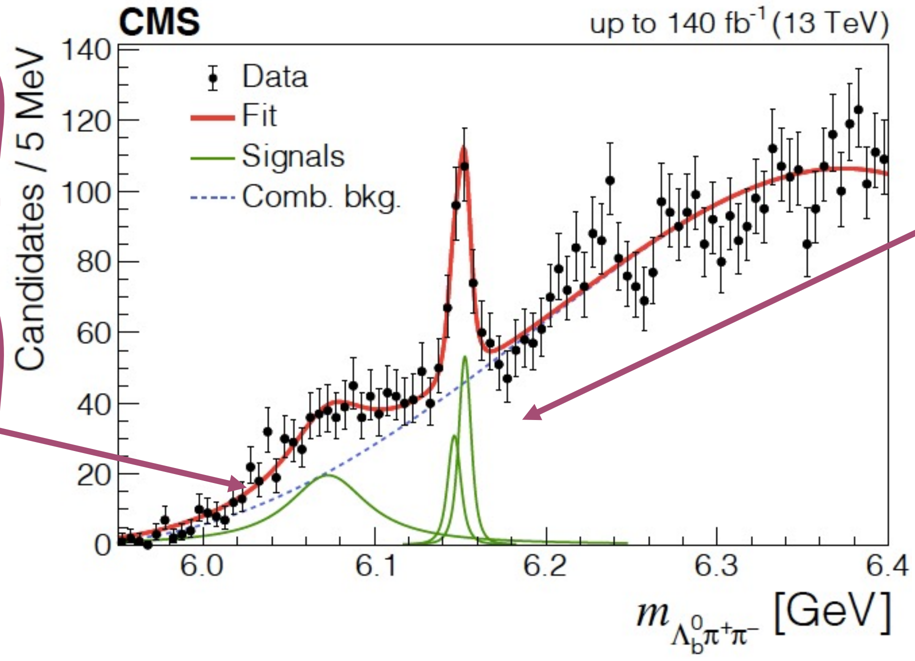


- Two Λ_b^0 decays: $\Lambda_b^0 \to \psi(2S)\Lambda \to \psi(2S)p\pi^-$ and $\Lambda_b^0 \to J/\psi\Lambda \to J/\psi p\pi^-$
- $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states have been confirmed (backup)

In the higher mass the $\Lambda_b^0\pi^+\pi^-$ spectrum show some structures

Broad excess (4σ significance) maybe related to intermediate states of $\Sigma_b^{*\pm}$ and $\Sigma_b^{\pm}$.
m=6073±5 (stat) MeV
width=55±11 (stat) MeV.
More data to better elucidate

=> LHCb also confirmed a similar structure (backup)



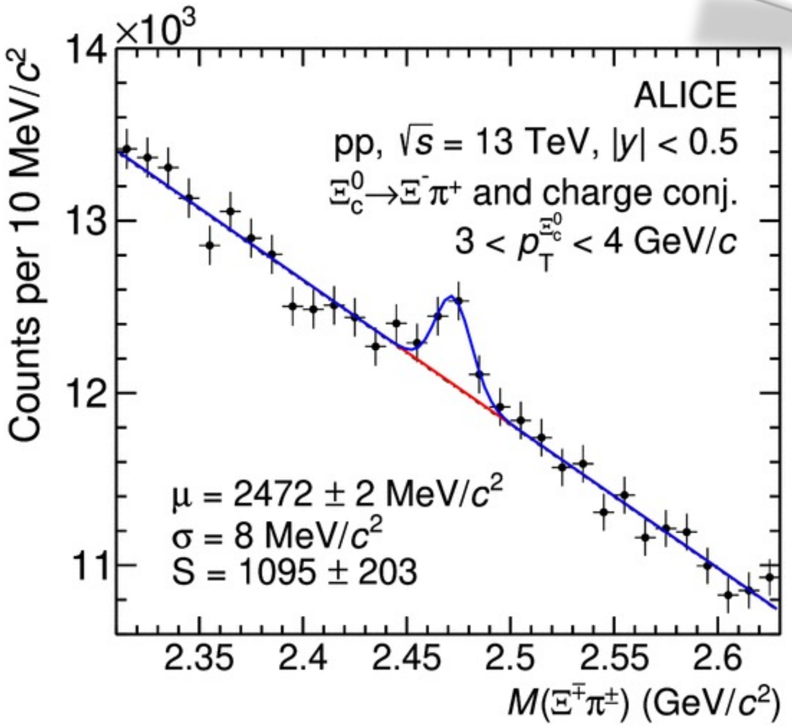
Narrow peak around 6150 MeV (more that 5σ significance) consistent with $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$, but also with a single peak hypothesis.
$m\Lambda_b(6146)^0$=6146.5±1.9±0.8±0.2 MeV
$m\Lambda_b(6152)^0$=6152.7±1.1±0.4±0.2 MeV

In agreement with the LHCb measurement

[5] PRL **803**, 135345

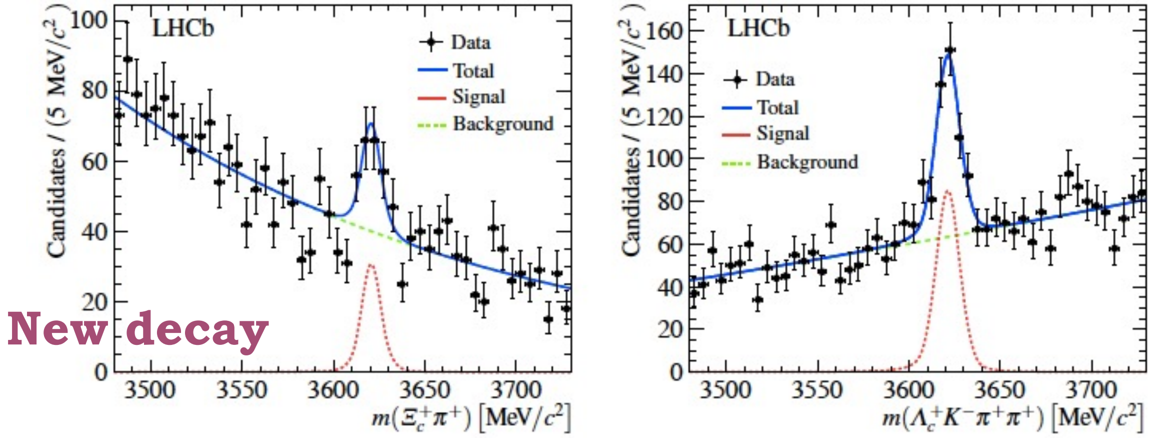
Ξ_c and Ξ_{cc} states

Results from ALICE [6] in the $\boldsymbol{\Xi_c^0 \rightarrow \Xi^{\mp}\pi^{\pm}}$ at 13 TeV



$\boldsymbol{\Xi_c^0 \rightarrow \Xi^{\mp}\pi^{\pm}}$ and charge conjugation in 3 < pT < 4 GeV in pp collisions

First measurement of $\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+}$ critical towards understanding the dynamics of weak decays of doubly heavy baryons [7]



$\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+}$ reconstruction with m(Ξ_{cc}^{++})=3620.6±1.5±0.4±0.3 MeV

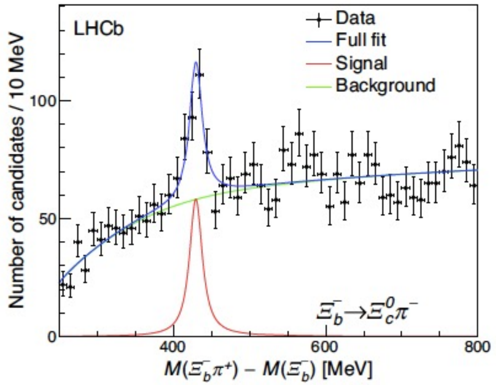
$\Xi_{cc}^{++} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$ reconstruction with m(Ξ_{cc}^{++})=3621.40±0.72±0.27±0.14MeV

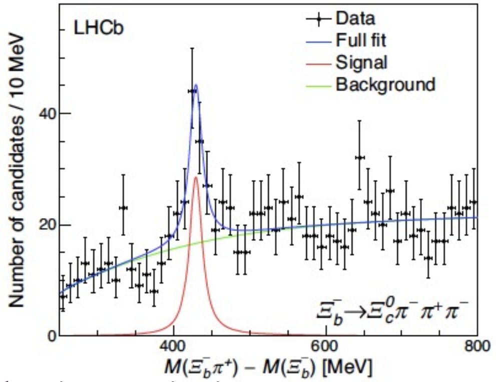
Average of the Ξ_{cc}^{++} mass: 3621.24±0.65±0.31 MeV

[6] arXiv:2105.05187
[7] PRL **121**, 162002

New $\Xi_b^{0,-}$ states

- New exited Ξ_b^0 state $\boldsymbol{\Xi_b\,(6227)^0}$ observed in the $\Xi_b^-\pi^+$ using Run1 and Run2 data (L=8.5/fb) [8]
- Two Ξ_b^- decays: $\Xi_b^- \rightarrow \Xi_c^0\pi^-$ and $\Xi_b^- \rightarrow \Xi_c^0\pi^-\pi^+\pi^-$



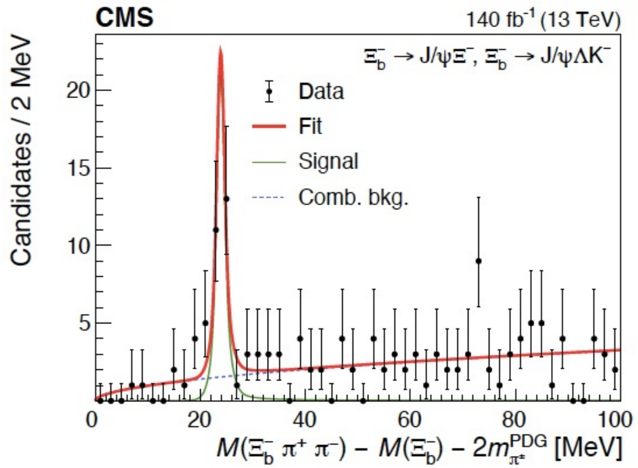


$$\delta M_\pi = M(\Xi_b^-\pi^+) - M(\Xi_b^-)$$

$\Rightarrow$ Clear peak shown in the two decays with 10σ significance

Identified as $\Xi_b\,(6227)^0$ with:
$\delta m_\pi^{peak} = 429.8^{+1.4}_{-1.5} MeV$
$m(\Xi_b\,(6227)^0) = 6227.1^{+1.4}_{-1.5} MeV$
$\Gamma(\Xi_b\,(6227)^0) = 18.6^{+5.0}_{-4.1} MeV$

- New exited Ξ_b^- state $\boldsymbol{\Xi_b\,(6100)^-}$ observed in the $\Xi_b^-\pi^+\pi^-$ using Run2 data (L=140/fb) [9]
- Two Ξ_b^- decays: $\Xi_b^- \rightarrow \Xi^- J/\psi$ and $\Xi_b^- \rightarrow J/\psi\Lambda K^-$



$$\Delta M = M(\Xi_b^-\pi^+\pi^-) - M(\Xi_b^-) + 2m_\pi^{PDG}$$

$\Rightarrow$ Clear peak shown in the two decays with > 6σ significance

Identified as $\Xi_b\,(6100)^-$ with:
$\Delta M = 24.14 \pm 0.22 \pm 0.05 MeV$
$m(\Xi_b\,(6100)^-) = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6 MeV$
Natural width consistent with 0
Consistent with J^P=3/2$^-$

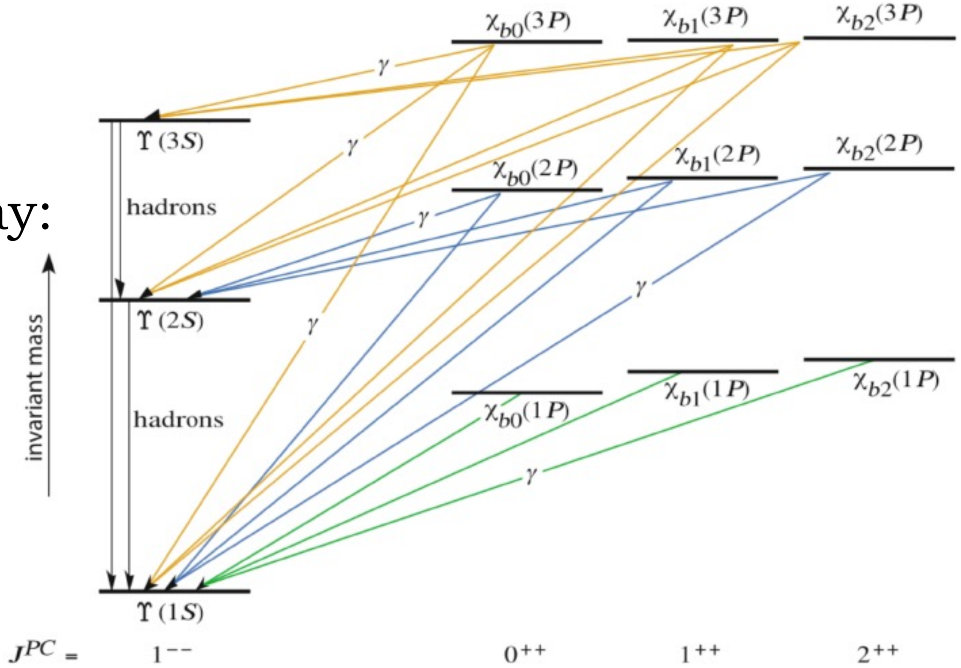
[8] PHYSICAL REVIEW D 103, 012004
[9] CMS-BPH-20-004 accepted by PRL

Bottomonium

- The bottomonium family ($b\bar{b}$) plays a special role in understanding how the QCD binds quarks into hadrons

- The χ_b(3P) state is especially interesting since its properties could be affected by the proximity of the open-beauty threshold

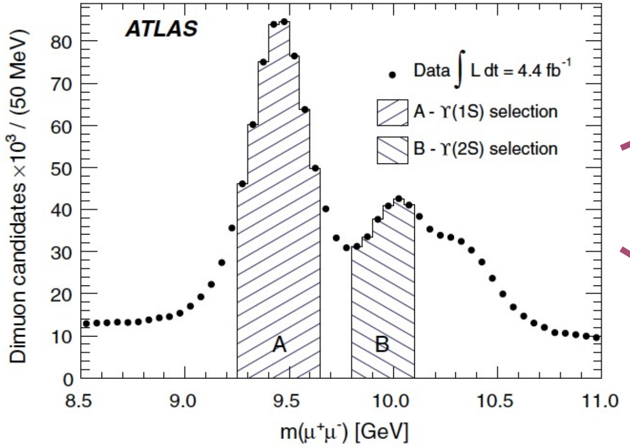
- The χ_b(3P) state is reconstructed though the decay:
  $\boldsymbol{\chi_b \rightarrow \Upsilon(nS)\gamma \rightarrow 2\mu\gamma}$ where n = 1,2,3

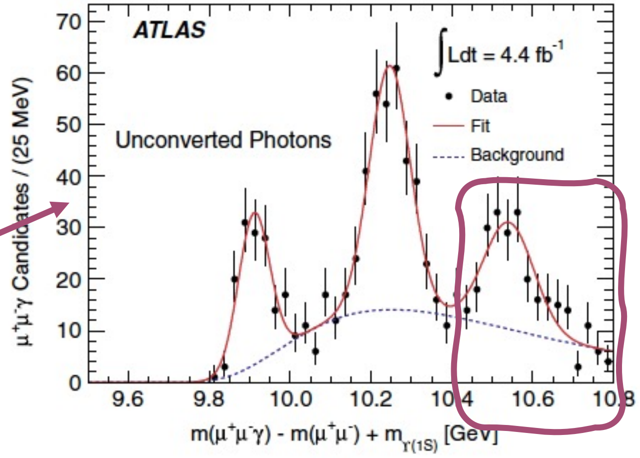


Picture from : V. Knünz, Measurement of Quarkonium Polarization to Probe QCD - *DOI 10.1007/978-3-319-49935-2_2*

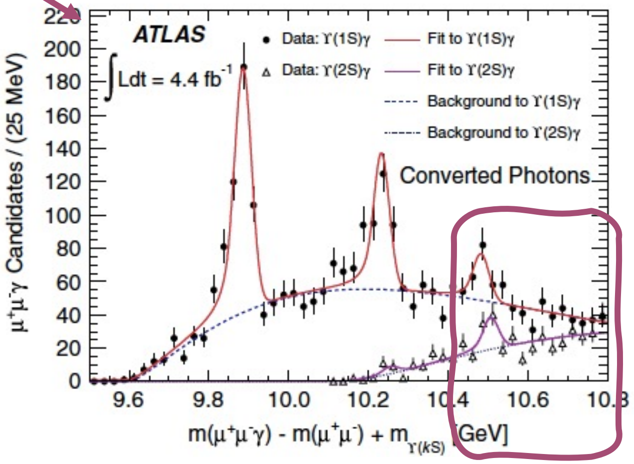
$\chi_b(3P)$

- **Firstly observed** by ATLAS in [10] at 7 TeV through the radiative decays $\chi_b(nP) \to \Upsilon(1S)\gamma$ and $\chi_b(nP) \to \Upsilon(2S)\gamma$





(a)



$\chi_b(3P)$ identified as third peak around 10.5 GeV

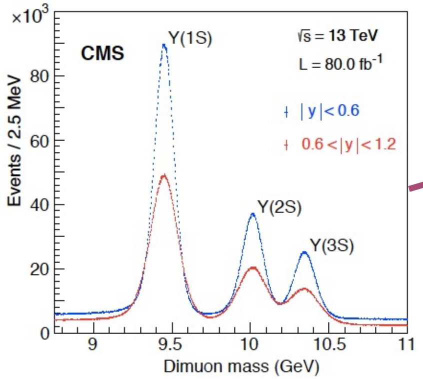
Significance of about 6σ

Mass of the $\chi_b(3P)$ baricenter
m = 10.530 $\pm$ 0.005 (stat) $\pm$ 0.009 (syst) MeV

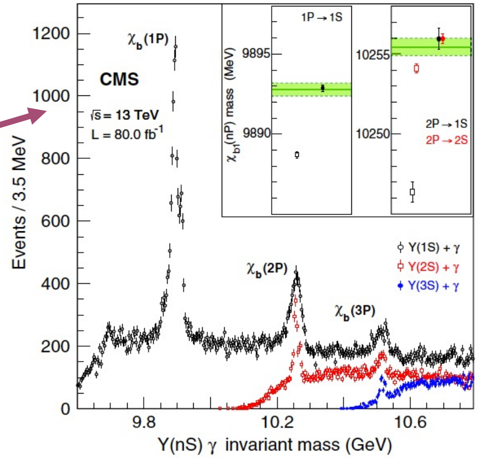
[10] PRL **108**, 152001

$\chi_b(3P)$

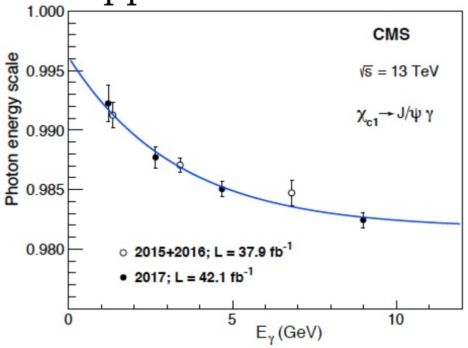
The **first observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ resolved states** performed with 13 TeV data from 2015 to 2017 (L=80/fb) [11]



Dimuon + photon



Photons energy scale calibrated in a control sample and applied event by event



[11] PRL **121**, 092002

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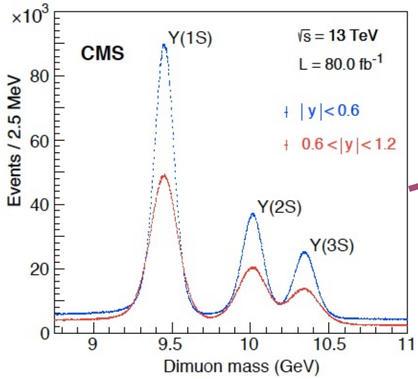

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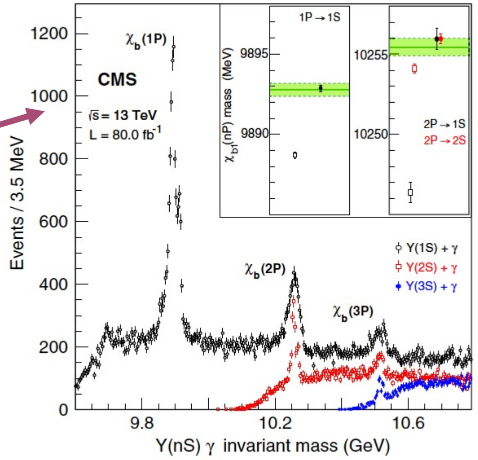

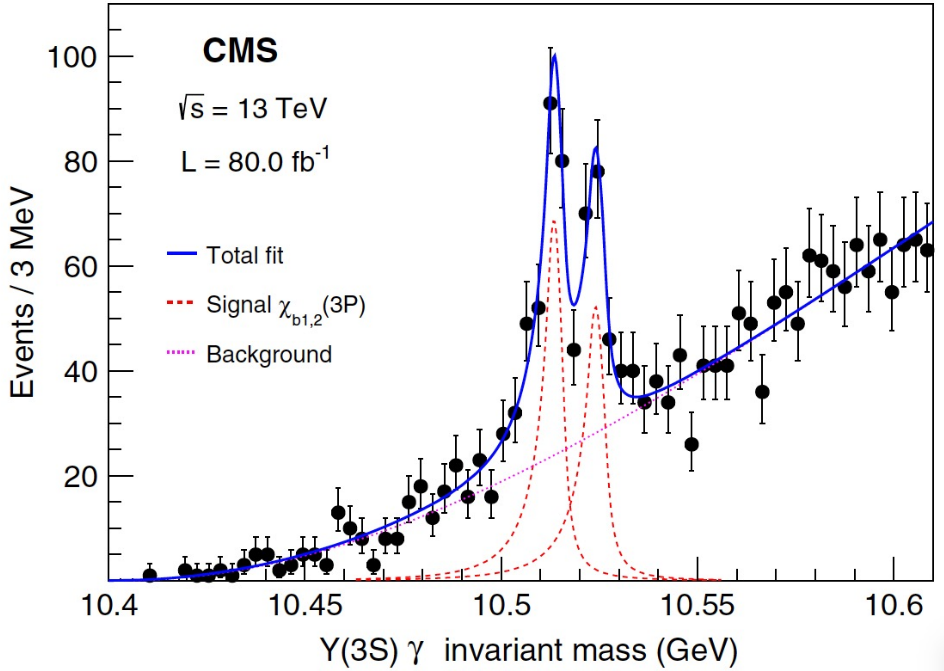

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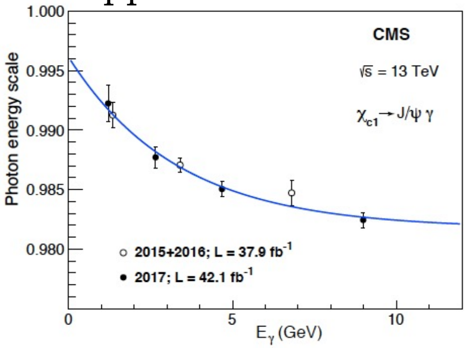

$M(\chi_{b1}(3P)) = 10513.42 \pm 0.41\ (stat) \pm 0.18\ (syst) \pm 0.5\ (\Upsilon(3S))$ MeV

$M(\chi_{b2}(3P)) = 10524.02 \pm 0.57\ (stat) \pm 0.18\ (syst) \pm 0.5\ (\Upsilon(3S))$ MeV

$\Delta M = 10.60 \pm 0.64\ (stat) \pm 0.17\ (syst)$ MeV

compatible with the theoretical expectations

[11] PRL **121**, 092002

Conclusion

- I showed the latest results on heavy flavor classical spectroscopy from the four LHC collaborations: ALICE, ATLAS, CMS and LHCb
- Hadron spectroscopy and help to shed light on the mechanisms responsible for dynamics of quarks and baryon formation.
- Very important results have been produced, mainly from Run2 data, with an impressive precision and sensitivity
- Heavy flavor spectroscopy is a very active field: much more results has to come!

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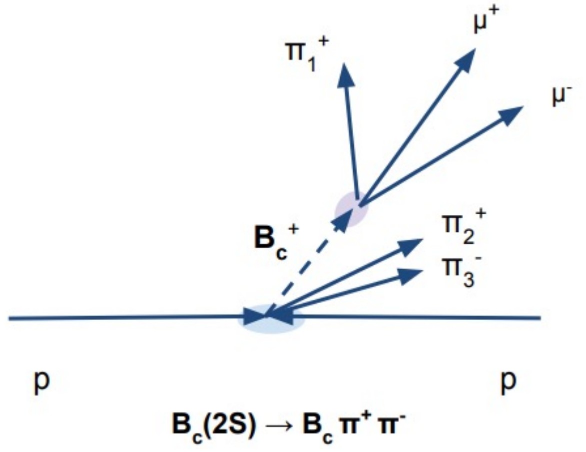
backup

$B_c^*(2S)$



Recently also the relative cross sections of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states with respect to the B_c^+ have been measured

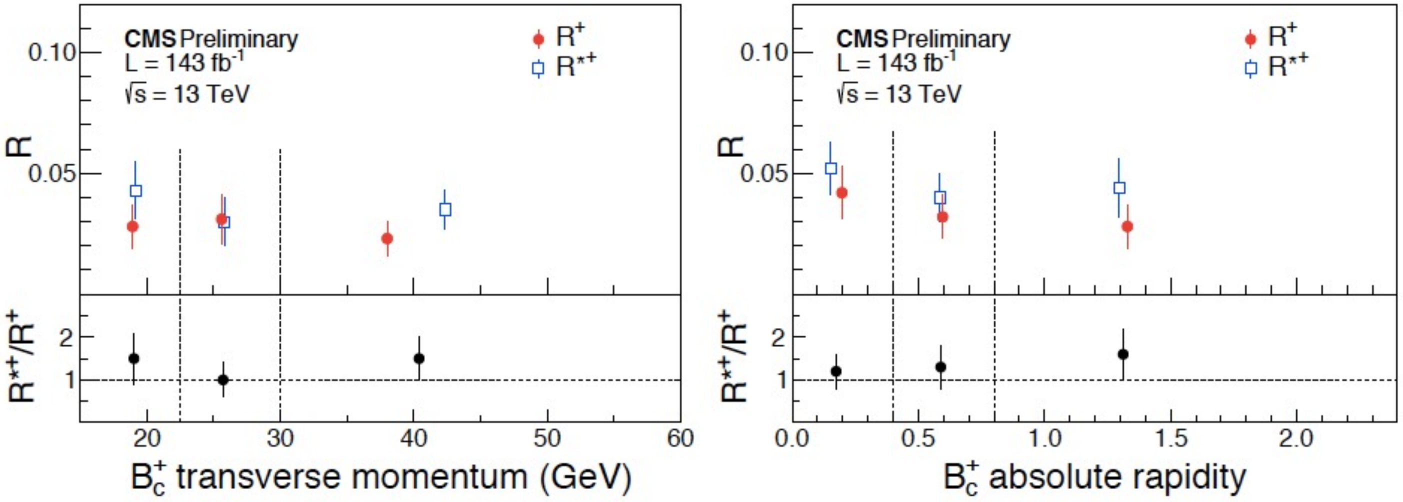
$$R^+ \equiv \frac{\sigma(B_c^+(2S))}{\sigma(B_c^+)} \cdot \mathcal{B}(B_c^+(2S) \to B_c^+ \pi^+\pi^-) = \frac{N(B_c^+(2S))}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^+(2S))},$$

$$R^{*+} \equiv \frac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+)} \cdot \mathcal{B}(B_c^{*+}(2S) \to B_c^+ \pi^+\pi^-) = \frac{N(B_c^{*+}(2S))}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^{*+}(2S))},$$

$$R^{*+}/R^+ = \frac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+(2S))} \cdot \frac{\mathcal{B}(B_c^{*+}(2S) \to B_c^+ \pi^+\pi^-)}{\mathcal{B}(B_c^+(2S) \to B_c^+ \pi^+\pi^-)} = \frac{N(B_c^{*+}(2S))}{N(B_c^+(2S))} \frac{\epsilon(B_c^+(2S))}{\epsilon(B_c^{*+}(2S))}.$$

$$R^+ = 3.57 \pm 0.69\,(\text{stat}) \pm 0.32\,(\text{syst})\,\%,$$
$$R^{*+} = 4.91 \pm 0.69\,(\text{stat}) \pm 0.57\,(\text{syst})\,\%,$$
$$R^{*+}/R^+ = 1.39 \pm 0.35\,(\text{stat}) \pm 0.09\,(\text{syst}),$$

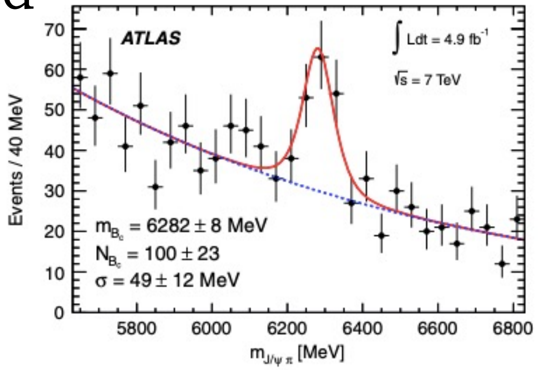
[2] CMS PAS BPH-19-001

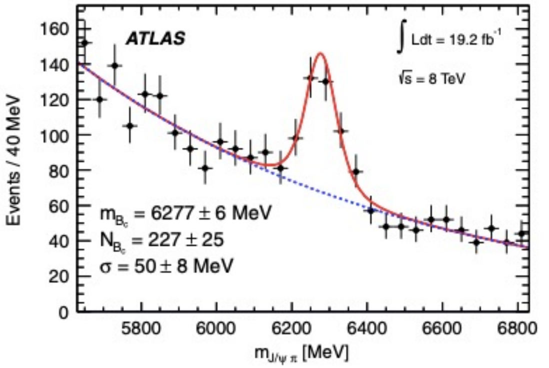


$B_c^*(2S)$

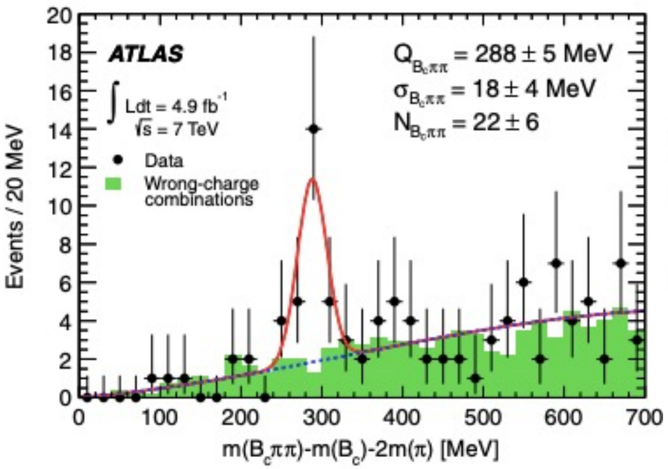
Observed for the first time by ATLAS in 2014 using Run1 data (7 + 8 TeV) [*].

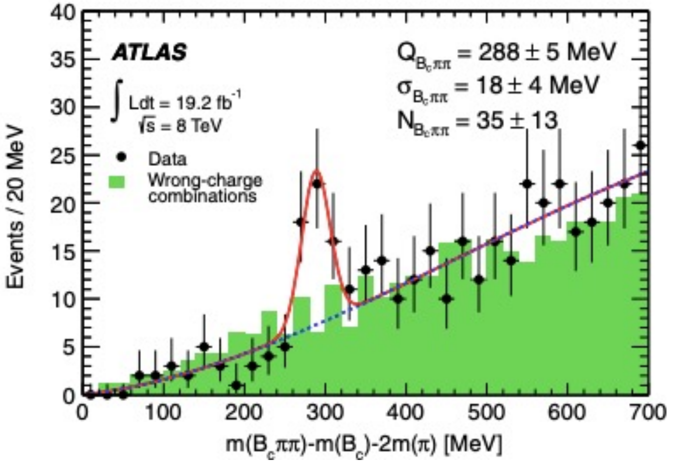
The $B_c^{\pm}$ selection criteria for the events are optimized separately for 7 and 8 TeV





[*] Phys. Rev. Lett. 113, 212004 (2014)





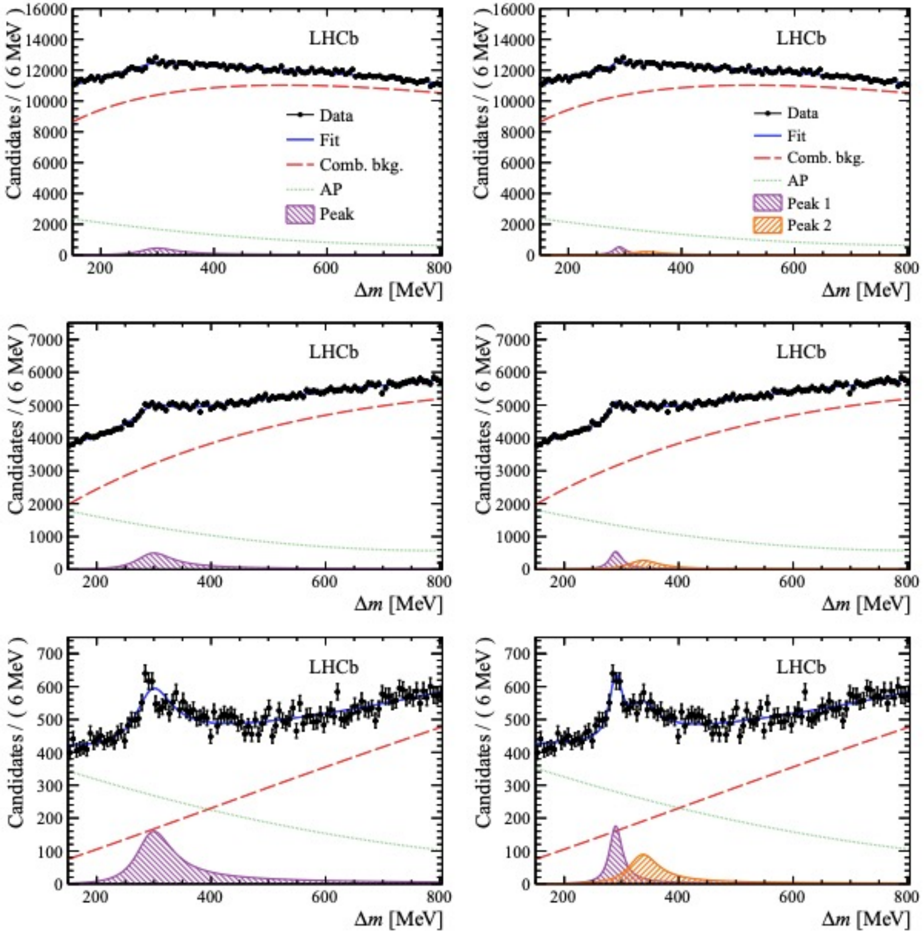
mass difference distribution:
$m(B_c^{\pm}\pi\pi) - m(B_c^{\pm}) - 2m(\pi)$

Significance of the observation: 3.7σ @7TeV and 4.5σ @8 TeV data.
Combined 7 + 8 TeV significance 5.2σ

Consistent with the predicted mass of the $B_c^{\pm}$(2S) state.

B_s^0

Structure observed in the B^+K^- mass spectrum using data from Run1+Run2 (9 fb^{-1}) [*]



K pT ∈ [0.5;1] GeV

K pT ∈ [1;2] GeV

K pT > 2 GeV

Significance of single peak wrt null hypothesis > 20 sigma, double peak wrt single 7.7 sigma

$$m_1 = 6063.5 \pm 1.2\ (\mathrm{stat}) \pm 0.8\ (\mathrm{syst})\ \mathrm{MeV},$$
$$\Gamma_1 = 26 \pm 4\ (\mathrm{stat}) \pm 4\ (\mathrm{syst})\ \mathrm{MeV},$$
$$m_2 = 6114 \pm 3\ (\mathrm{stat}) \pm 5\ (\mathrm{syst})\ \mathrm{MeV},$$
$$\Gamma_2 = 66 \pm 18\ (\mathrm{stat}) \pm 21\ (\mathrm{syst})\ \mathrm{MeV}.$$

$$\Delta m = m_{BK} - m_B - m_K$$

[*] LHCb-PAPER-2020-026

B*(2S) – CMS

Selection:

- Two muons: $|\eta| < 2.5$, pT > 4 GeV, distance of closest approach between the two muons < 0.5 cm, dimuon vertex fit $\chi2$ > 10%, dimuon invariant mass in the range 2.9–3.3 GeV, distance between the dimuon vertex and the beam axis larger than three times its uncertainty, dimuon pT aligned with the transverse displacement vector $\cos\theta > 0.98$
- third track produced at the dimuon vertex with: $|\eta| < 2.4$, pT > 3.5 GeV, $\geq$ 1 hit in the pixel layers, $\geq$ 5 hits in the tracker, transverse IP > two times its uncertainty
- $B_c^{\pm}$ candidate obtained from a kinematic fit between the 2 muons and the track: pT > 15 GeV, $|y| < 2.4$, l > 100 μm, and a kinematic fit $\chi2$ probability > 10%
- $B_c^{\pm}$(2S) and $B_c^{\pm*}$(2S) candidates reconstructed from kinematic fit between $B_c^{\pm}$ candidate with two opposite-sign tracks with a common vertex.
  Only $B_c^{\pm}$ candidates with invariant mass in the range 6.2–6.355 GeV are selected.
  One of the pion candidates must have pT > 0.8 GeV and the other pT > 0.6 GeV.
- The $B_c^{\pm}\pi^+\pi^-$ candidates must have $|y| < 2.4$ and a vertex $\chi2$ probability larger than 10%

B*(2S) - LHCb

Selection:

- Two muons with pT > 550 MeV and good track-fit quality. Required to form a common decay vertex with an invariant mass in the range 3040-3140 MeV
- Pion with pT > 1000 MeV, good track-fit quality, and be inconsistent with originating from any PV
- The J/ψ candidate is combined with a charged pion to form the $B_c^{\pm}$ candidate.
- The $B_c^{\pm}$ candidate is required to have a good-quality vertex, a trajectory consistent with coming from PV, and a decay time larger than 0.2 ps.
- A BDT is used to further suppress bkg (pt / eta / decay length / decay time / chi^2)
- $B_c^{\pm}$ candidates with M in 6200--6320 MeV are combined with a pair of oppositely charged particles identified as pions. These pion candidates are required to originate from the PV, and each have pT >300MeV, p>1500MeV, and a good track-fit quality.
- The $B_c^{\pm*}$(2S) candidate is required to have a good vertex-fit quality

Λ_b^0 - LHCb

- Samples of Λ_b^0 candidates are formed from $\Lambda_c^+\pi^-$ combinations, where the Λ_c^+ baryon is reconstructed in the $pK^-\pi^+$ final state.
- The reconstructed Λ_c^+ vertex is required to have a good fit quality and to be significantly displaced from all PVs and to have a mass of +/-25MeV wrt known value
- BDT used to reduce bkg (inputs: kinematic variables of the Λ_c^+ and Λ_b^0, the lifetime of the Λ_b^0, kinematic variables and quality of particle identification for pions, kaons, and protons, and variables describing the consistency of the selected candidates)
- Selected Λ_b^0 candidates are combined with pairs of pions originating from the same PV as the Λ_b^0. Only pion pairs with $p_T^{\pi^+\pi^-}$> 500 MeV are used, to suppress the otherwise large combinatorial

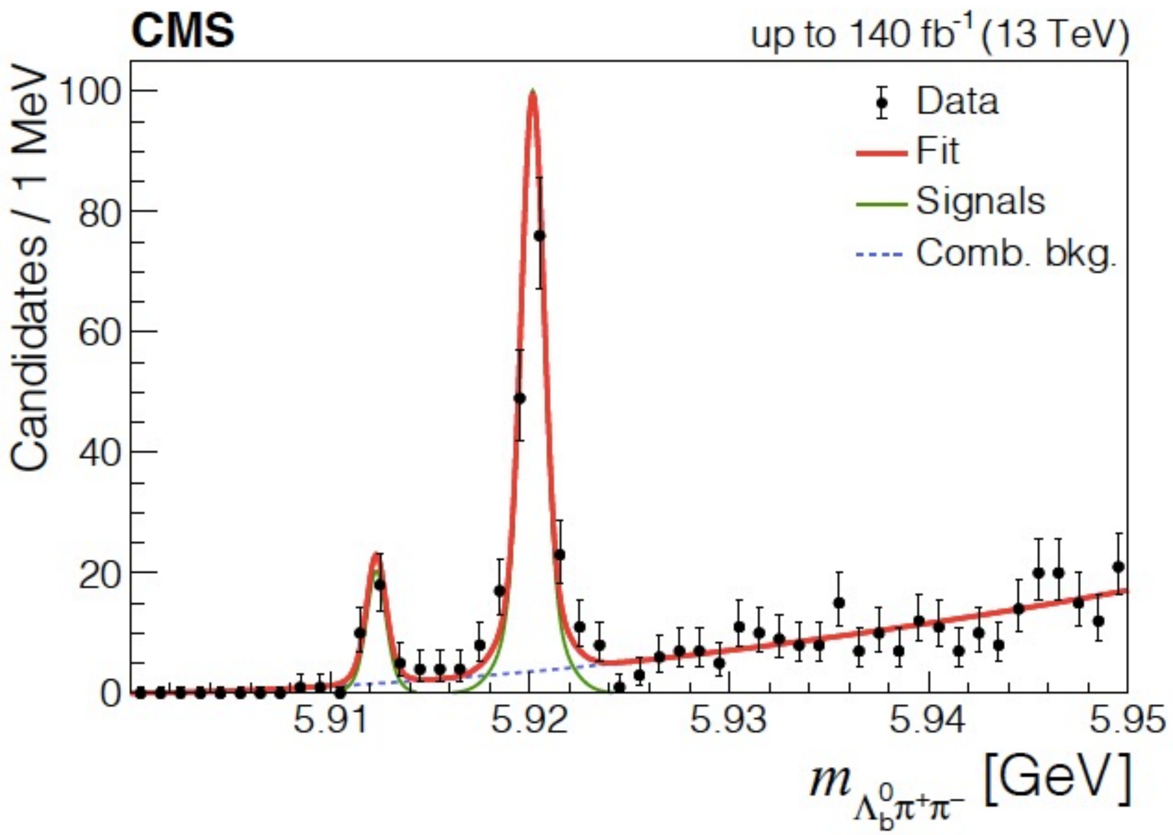
Λ_b^0 - CMS

$\Lambda_b^0 \to \psi\Lambda$ ($\mu^+\mu^-$ + $\Lambda \to p\pi^-$ from V0 collection)
Λ vtx fit probability > 1%, $p_T(\Lambda)$ > 1 GeV,
cos(3D Λ pointing angle to Λ_b^0 vertex) > 0.99,
$L_{xy}/\sigma_{Lxy}(\Lambda \text{ vtx} \to \Lambda_b^0 \text{ vtx}) > 5$
Λ mass within 10 MeV from PDG

Λ_b^0 vtx fit probability > 1%
$p_T(\Lambda_b^0)$ > 5 GeV,
cos(2D Λ_b^0 pointing angle to PV) > 0.99,
$L_{xy}/\sigma_{Lxy}(\Lambda_b^0 \text{ vtx} \to \text{PV}) > 3$

Additional channel $\Lambda_b^0 \to \psi(2S)\Lambda$, $\psi(2S) \to J/\psi\pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$: as above, additional 2 pions – high-purity tracks, p_T>0.35 GeV; Λ_b^0 obtained by vertexing $\mu^+\mu^-\pi^+\pi^-\Lambda$ with J/ψ and Λ mass constraints; $3672 < M(J/\psi\pi^+\pi^-) < 3700$ MeV

Λ_b^0 - CMS



$$M(\Lambda_b(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17\,\text{MeV},$$

$$M(\Lambda_b(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17\,\text{MeV},$$

Λ_b^0 - LHCb

Table 1: Quark-model predictions for the masses of the lightest Λ_b and $\Sigma_b^{(*)}$ states (in MeV).

Baryon	State	J^P	Ref. [15]	Ref. [16]	Ref. [17]	Ref. [18]
Λ_b^0	1S	$\frac{1}{2}^+$	5585	5612	5620	5619
	1P	$\frac{1}{2}^-$	5912	5939	5930	5911
		$\frac{3}{2}^-$	5920	5941	5942	5920
	2S	$\frac{1}{2}^+$	6045	6107	6089	
	1D	$\frac{3}{2}^+$	6145	6181	6190	6147
		$\frac{5}{2}^+$	6165	6183	6196	6153
$\Sigma_b^{(*)0}$	1S	$\frac{1}{2}^+$	5795	5833	5800	
		$\frac{3}{2}^+$	5805	5858	5834	
	1P	$\frac{1}{2}^-$	6070	6099	6101	
		$\frac{3}{2}^-$	6070	6101	6096	
		$\frac{5}{2}^-$	6090	6172	6084	
	2S	$\frac{1}{2}^+$	6200	6294	6213	
		$\frac{3}{2}^+$	6250	6308	6226	

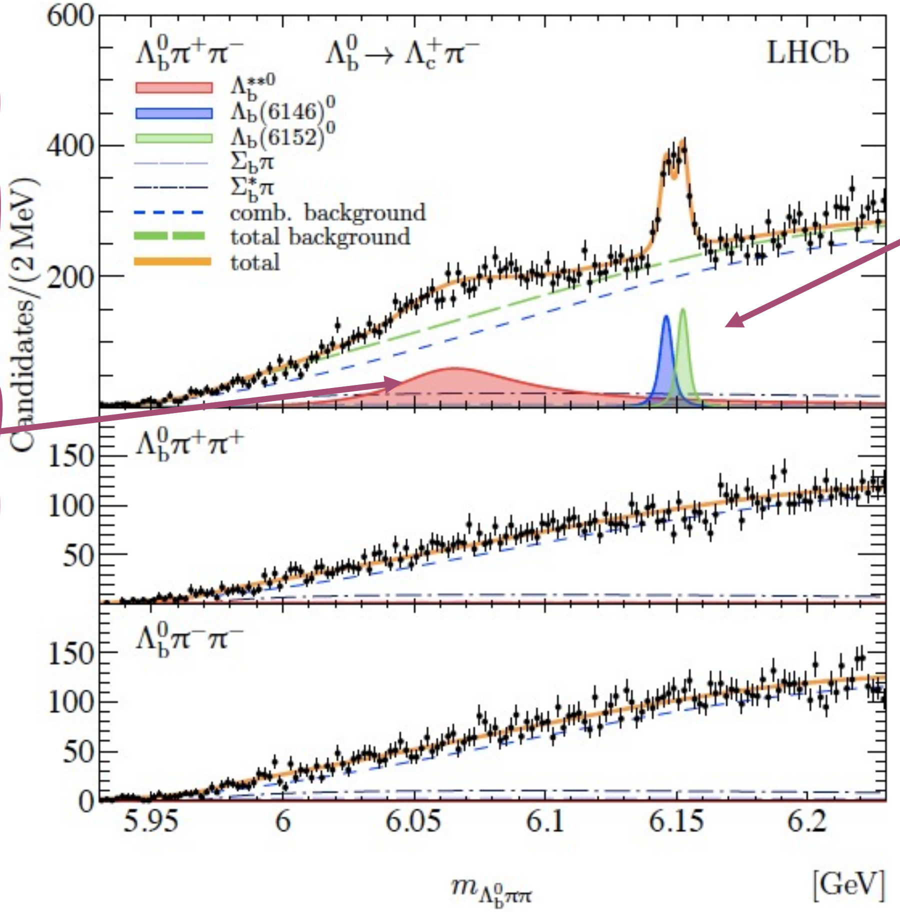
Λ_b^0 - LHCb

- Data collected at 7, 8 and 13 TeV (L=9/fb) => new state observed in the $\Lambda_b^0\pi^+\pi^-$ spectrum [*]
- Two Λ_b^0 decays: $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$
-

Broad excess referred as Λ_b^{**0}

Mass difference wrt Λ_b^0
Δm = 452.7±2.9±0.5 MeV
Width = 72±11±2 MeV

Λ_b^{**0}mass=6072.3±2.9±0.6±0.2 MeV
Consistent with the CMS measurement



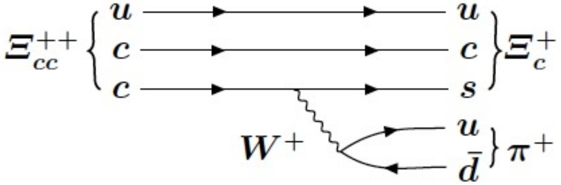
Narrow peaks already measured as $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$

Can't exclude that the broad structure corresponds to a superposition of more than one narrow states, but the interpretation of these states as excited Σ_b resonances is disfavoured.

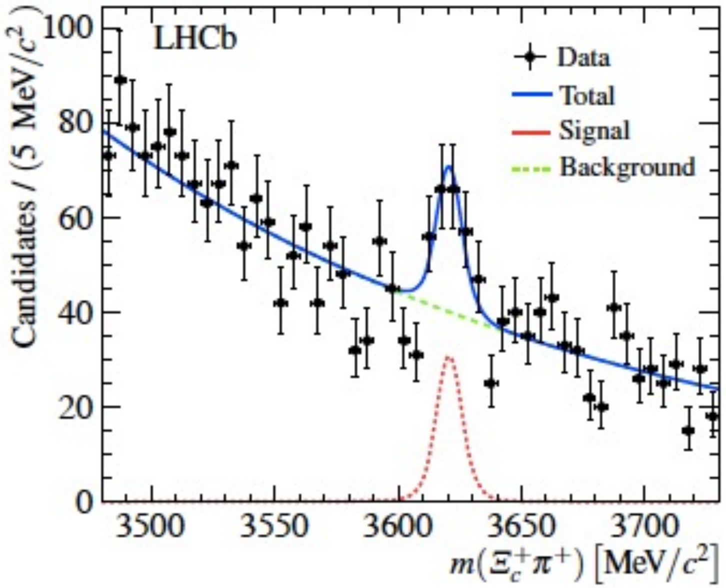
[*] JHEP 06 (2020) 136

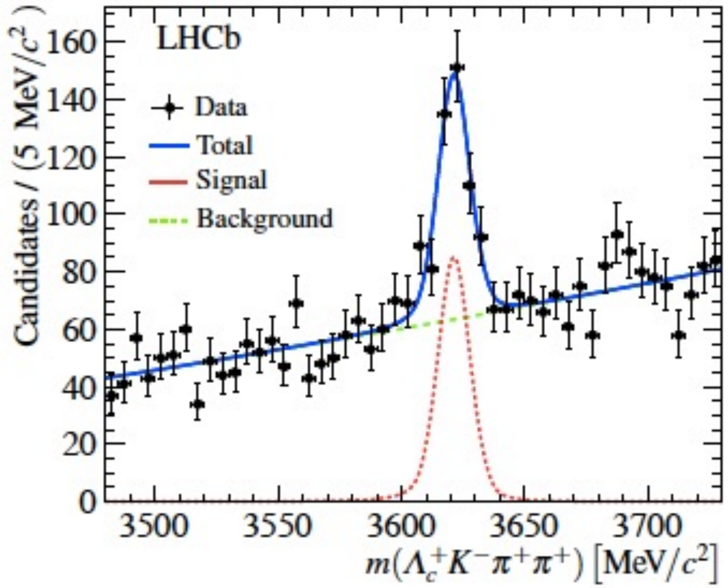
Ξ_{cc}^{++}

- Measured for the first time by LHCb in [10] in the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay with m=3621.40±0.72±0.27±0.14 MeV and its lifetime $0.256^{+0.024}_{-0.022}$ ps => compatible with a weak interacting particle
- The first measurement of the decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ is presented here [11], critical towards understanding the dynamics of weak decays of doubly heavy baryons



$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ reconstruction with m(Ξ_{cc}^{++})=3620.6±1.5±0.4±0.3 MeV





$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ reconstruction with m(Ξ_{cc}^{++})=3621.40±0.72±0.27±0.14MeV

Average of the Ξ_{cc}^{++} mass: 3621.24±0.65±0.31 MeV

[10] Phys. Rev. Lett. **119**, 112001
[11] Phys. Rev. Lett. **121**, 162002

Ξ_{cc}^{++}

Selection of $\Xi_{cc}^{++} \to \Xi_c^{+}(\to pK^{-}\pi^{+})\pi^{+}$ decay:
- three charged tracks with pT > 0.5GeV fitted to a common vertex
- Ξ_c^{+} vertex displayced with lifetime > 0.15ps and invariant mass between 2450-2488 MeV
- Additional positive track with pT > 0.2 GeV combined to the Ξ_c^{+}
- Ξ_{cc}^{++} candidate with pT > 2 GeV and originating from PV

BDT used to minimise combinatorial bkg with 3 sets of variables (particle kinematics, vertex fitting, lifetime)

Also the ratio between the two decays is measured as with $\mathcal{R}(\mathcal{B})$ = 0.035 ± 0.009 (stat) ± 0.003 (syst) in agreement with theory

$$\mathcal{R}(\mathcal{B}) \equiv \frac{\mathcal{B}\left(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}\right) \times \mathcal{B}\left(\Xi_c^{+} \to pK^{-}\pi^{+}\right)}{\mathcal{B}\left(\Xi_{cc}^{++} \to \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}\right) \times \mathcal{B}\left(\Lambda_c^{+} \to pK^{-}\pi^{+}\right)}$$

[8] Phys. Rev. Lett. 121, 162002

$\chi_b(3P)$

Selection:

- Two OS muons with pT > 4 GeV and |eta|<2.3 fitted to a common vertex
- Dimuon pT > 12 GeV and |y|<2
- 9.25 < $m_{\mu\mu}$ < 9.65 GeV for the $\Upsilon(1S)$ and 9.80 < $m_{\mu\mu}$ < 10.10 GeV for the $\Upsilon(2S)$
- Photons are reconstructed as converted (in e+e-) or unconverted

Figure of merit $\tilde{m}_k = \Delta m + m_{\Upsilon(kS)}$