Spectroscopy of new heavy baryons

Paolo Gandini
INFN - Sezione di Milano

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INFN MILANO
Istituto Nazionale di Fisica Nucleare
Sezione di Milano

LHCb

Outline

- I will concentrate on the spectroscopy of new heavy baryons
- A detailed description of hundreds of analyses is of course beyond the scope of this talk
- The idea is to describe the journey so far, what we learned, and what we can do in the future
- Different approaches to the analyses and how the analysis techniques improved

    - **Shopping list**
        - General Introduction on heavy baryons
        - Timeline of spectroscopy studies → example
        - Types of analysis
        - Double heavy baryons
        - $\Xi_b\pi\pi$ states → most recent observations

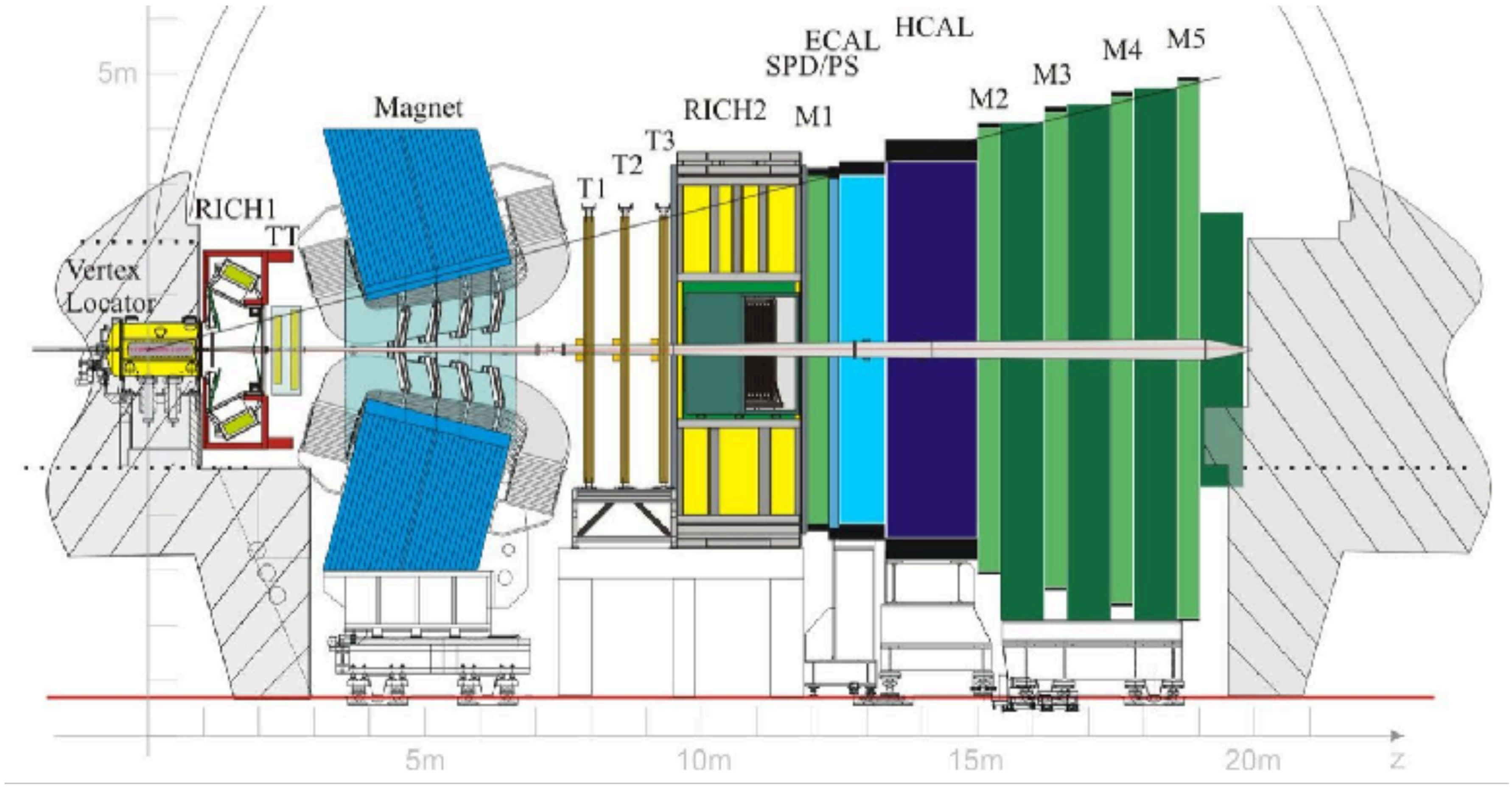
Spoiler Alert
The talk will be full of images generated with AI

The LHCb detector

You've seen this detector before…

Ingredients for good spectroscopy measurements

- **Excellent tracking** → mass and lifetime resolutions
- **Particle Identification** → important when dealing with charged hadrons in final states
- **Trigger efficiency** → use of muons & topological trigger give excellent efficiency



LHCb Detector Performance
Int. J. Mod. Phys. A 30 (2015) 1530022

Baryon Multiplets - Status of the art

- Multiplets: Still a lot of expected states not observed experimentally, yet
- I will concentrate on conventional hadrons, but we can have extra states
- **Also beyond so-called "conventional hadrons" we have so-called exotic states**

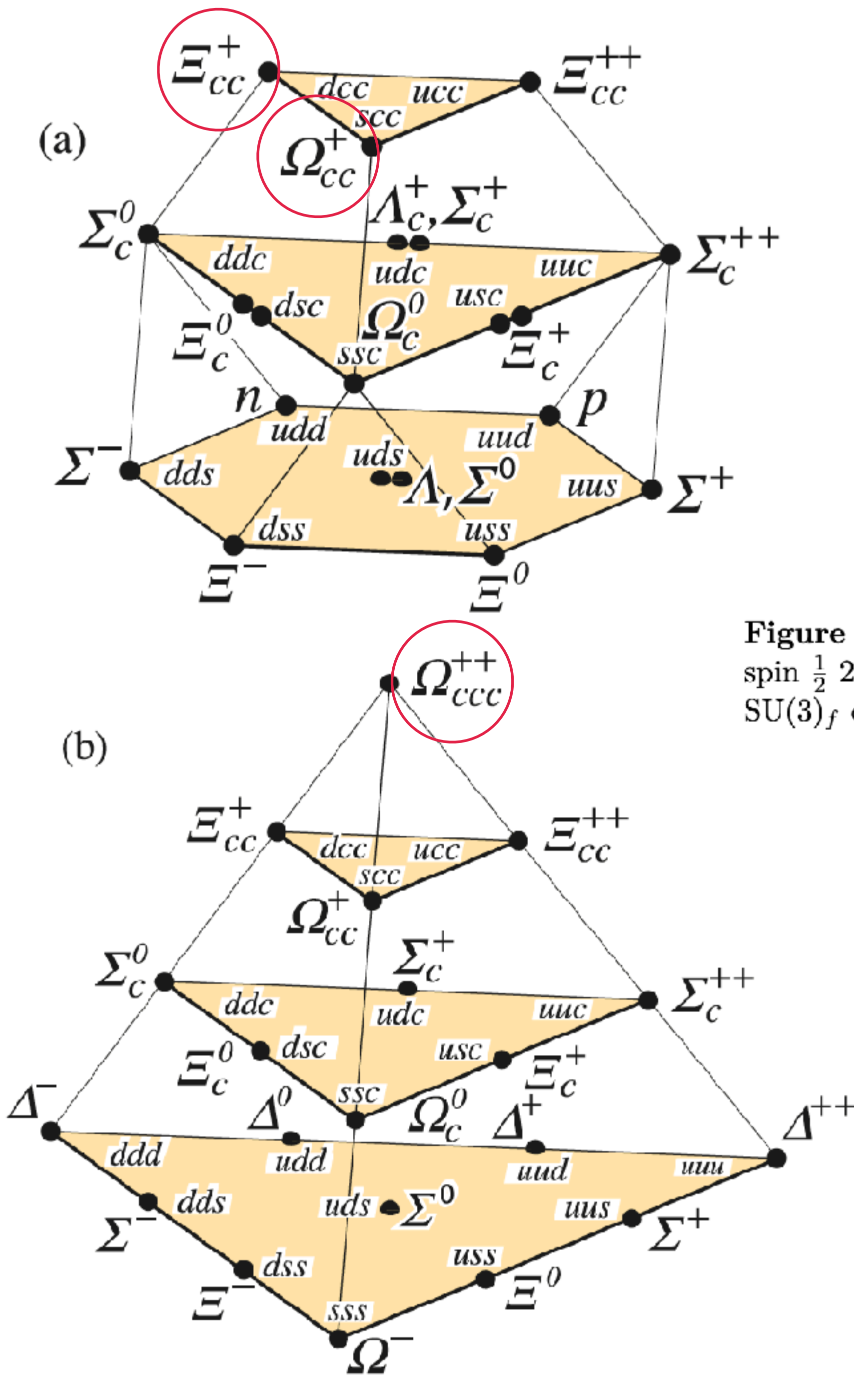
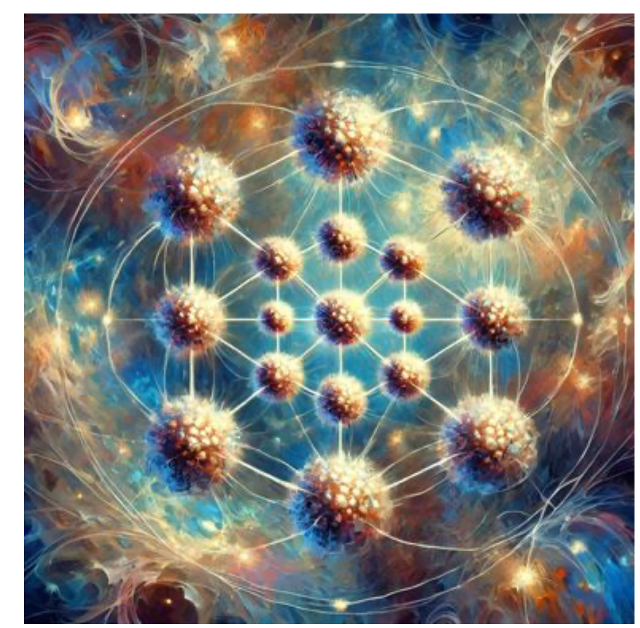
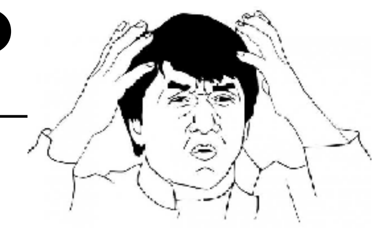


Image taken from PDG
[*Review of Particle Physics*]

Figure 15.5: $SU(4)_f$ multiplets of ground state baryons made of u, d, s, and c quarks. (a) The spin $\frac{1}{2}$ 20-plet extends the charmless $SU(3)_f$ octet to $C = 1,2$; (b) the spin $\frac{3}{2}$ 20-plet extends the $SU(3)_f$ decuplet to $C = 1, 2, 3$.

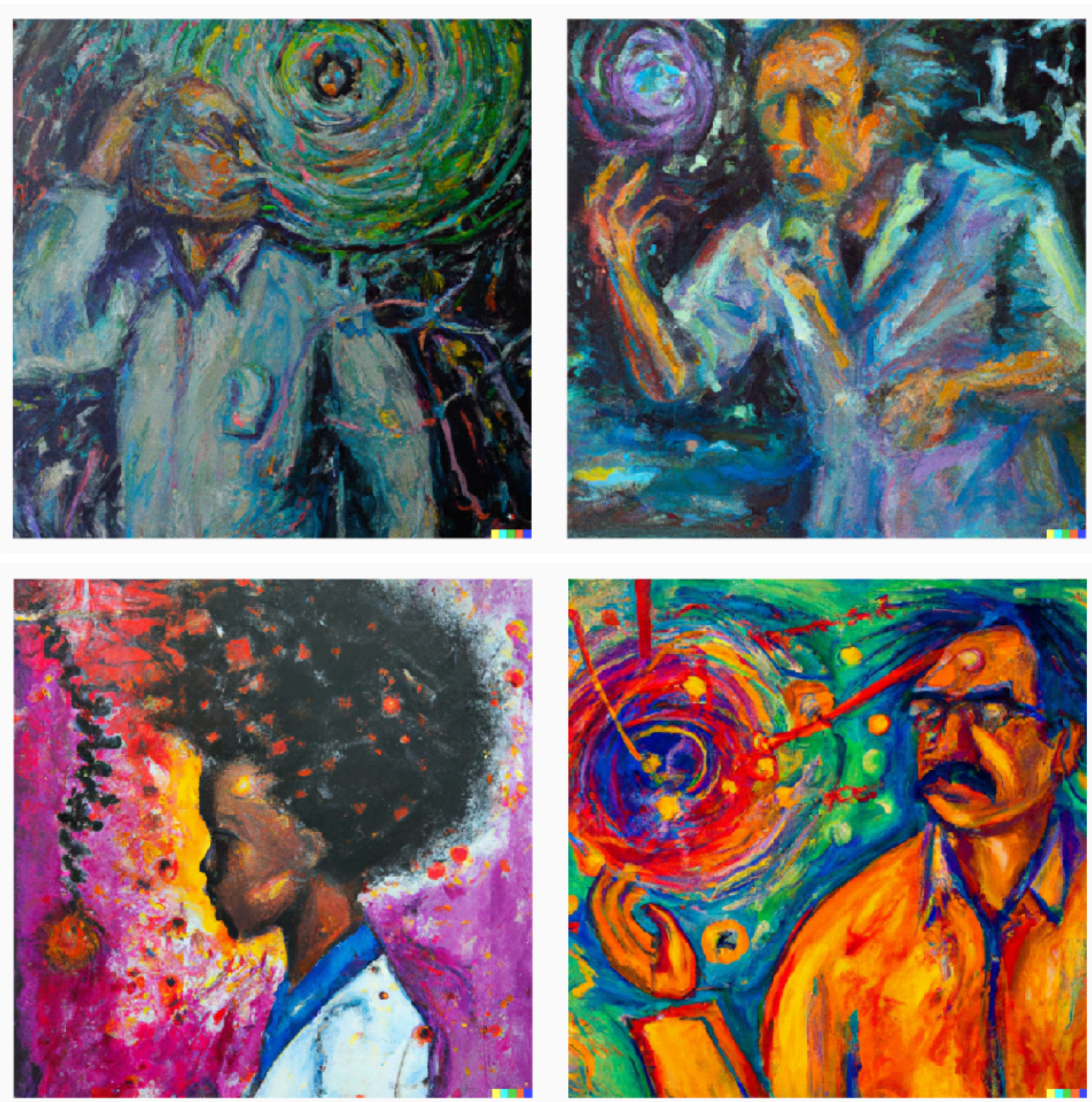


Scientists discovering new particles in 2023



This is what happens when you ask to a modern AI

Images generated
by DALL-E
artificial intelligence



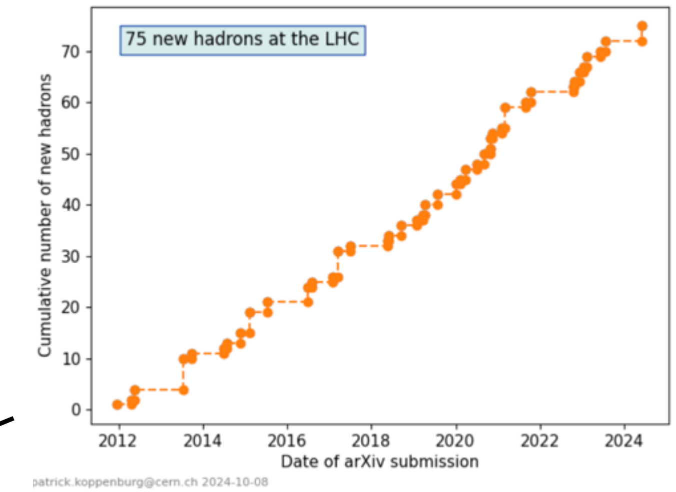
And using Midjourney
More oniric...
less inclusive

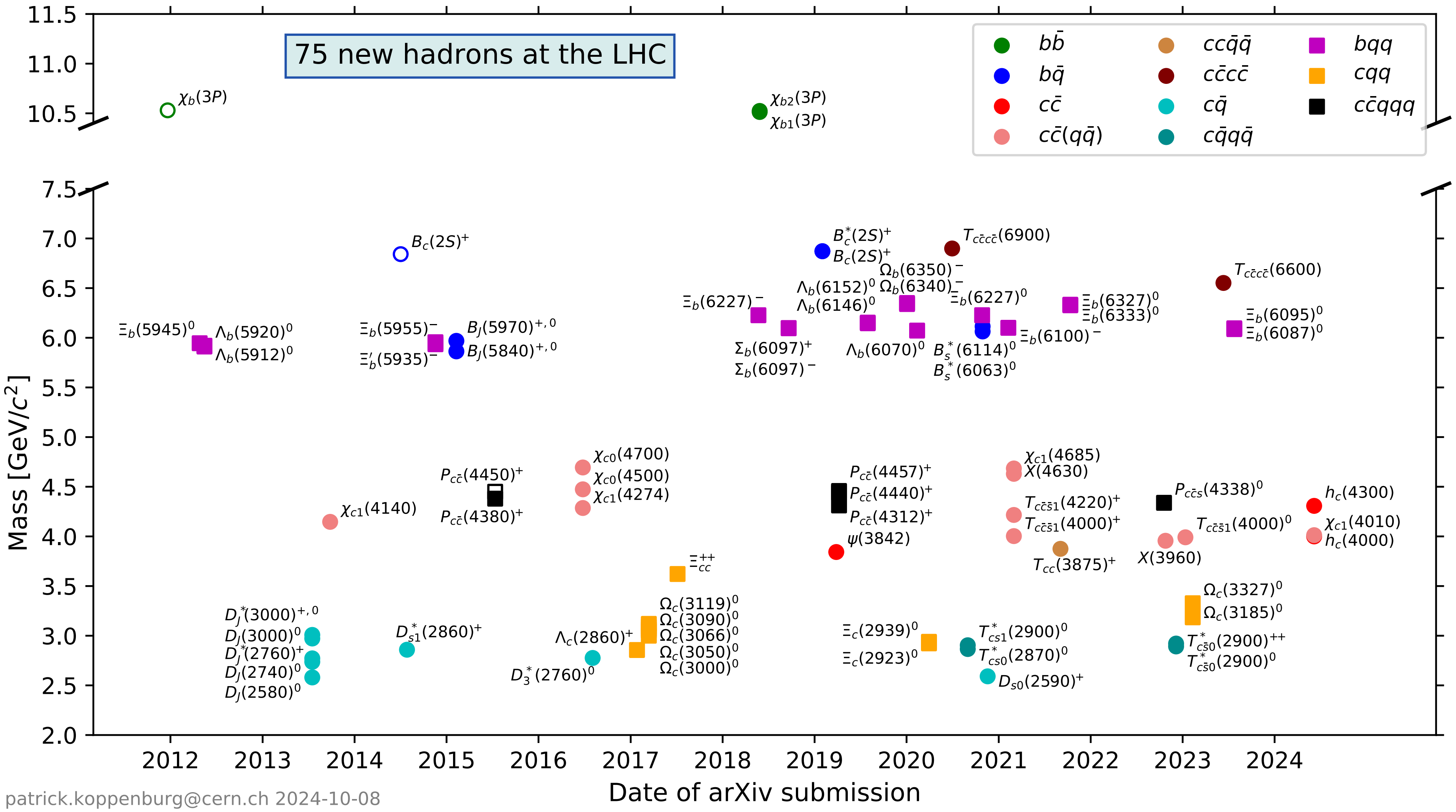
Scientists discovering new particles in 2024

I asked baryons at CERN → now detectors included

New observations at LHC

- **Spectroscopy is a super-active field at LHC and all the experiments are contributing!**
- So far 75 hadrons have been discovered at the LHC, of which 64 by LHCb
- The list is growing… All sector represented





LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2024 updates.

New observations at LHC

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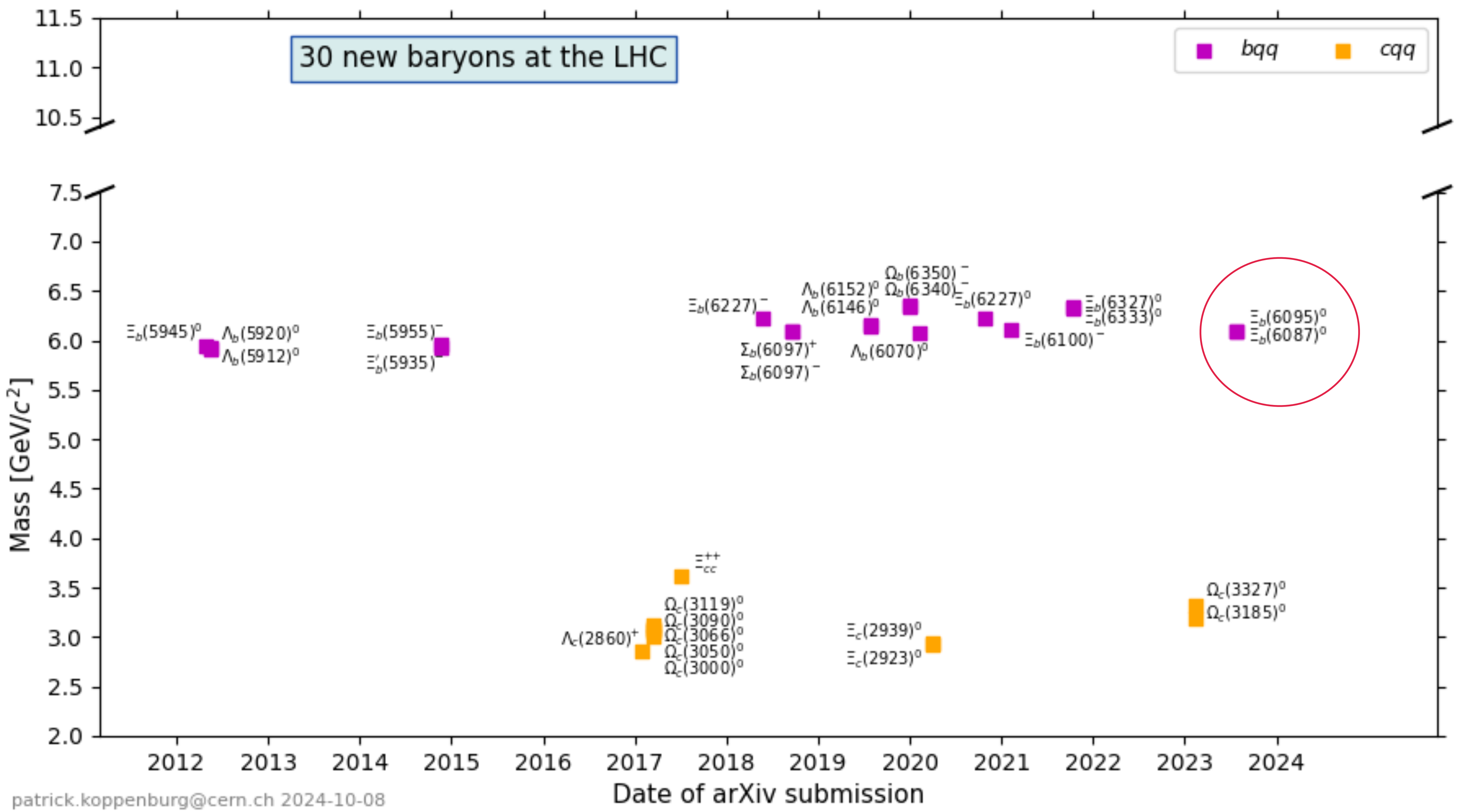


LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2024 updates.

Names & Decays

- Baryons have probably a less known nomenclature
- Decay patterns depend on mass and spin properties

CHARMED BARYONS ($C = +1$)

$\Lambda_c^+ = udc\,,\ \Sigma_c^{++} = uuc\,,\ \Sigma_c^+ = udc\,,\ \Sigma_c^0 = ddc\,,$
$\Xi_c^+ = usc\,,\ \Xi_c^0 = dsc\,,\ \Omega_c^0 = ssc$

BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = udb\,,\ \Xi_b^0 = usb\,,\ \Xi_b^- = dsb\,,\ \Omega_b^- = ssb$

- Ground states + Orbital excitations
- Ground states usually decay weakly
- Excitations usually decay strongly to ground states
- Ladder of expected excitations →

PHYSICAL REVIEW D **98,** 031502(R) (2018)

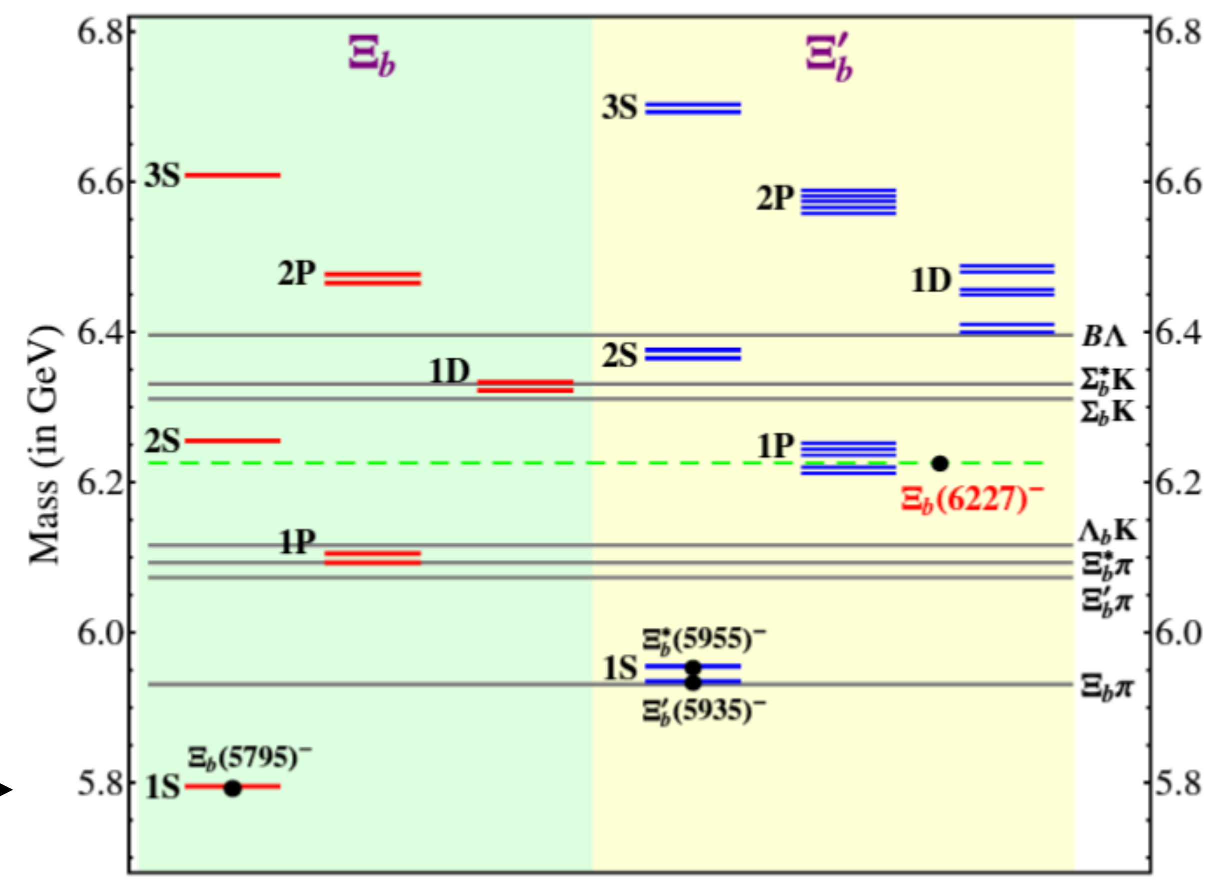


FIG. 2. The obtained masses for the bottom-strange baryons. The red solid lines (left) correspond to the predicted masses of Ξ_b states which are composed of a good diquark and a bottom quark, while the blue solid lines (right) correspond to the Ξ'_b states which contain a bad diquark. Here, we also listed the measured masses of the ground states [1] and the $\Xi_b(6227)^-$ [9], which are marked by "filled circle".

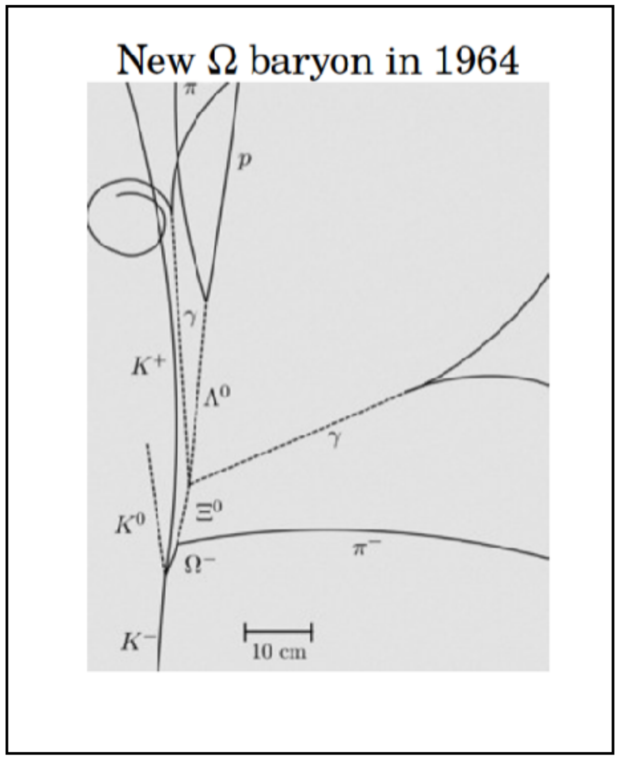
Most ground states are known
But not all yet!

Observation of five new narrow Ω^0_c states → $\Xi_c^+K^-$

- Example with the Ω and its heavier counterparts → surprises even in “conventional” baryon spectroscopy

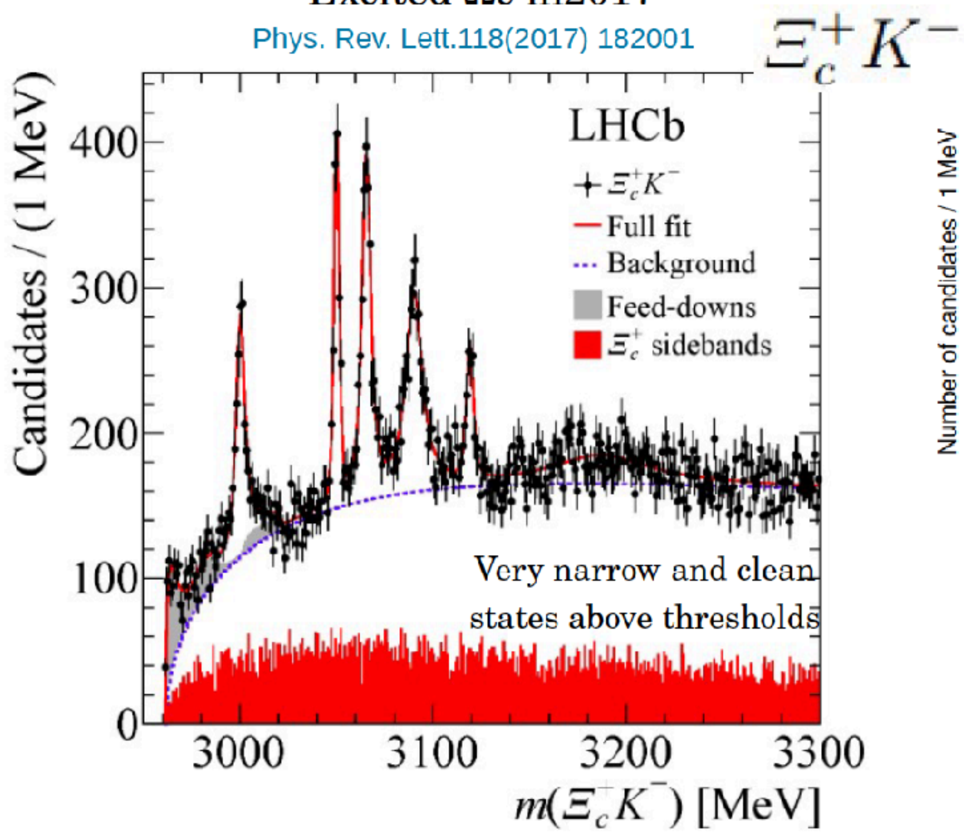
1964 → 2017 → 2020

First observation of sss state



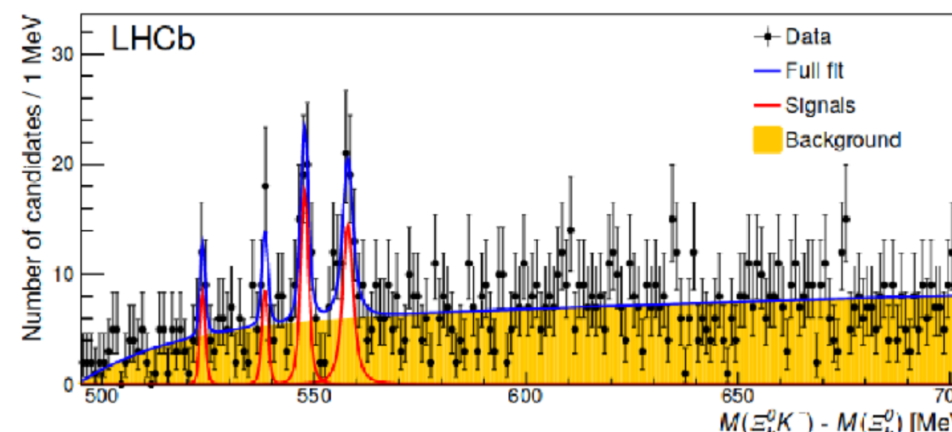
Excited Ωc in2017

Phys. Rev. Lett.118(2017) 182001

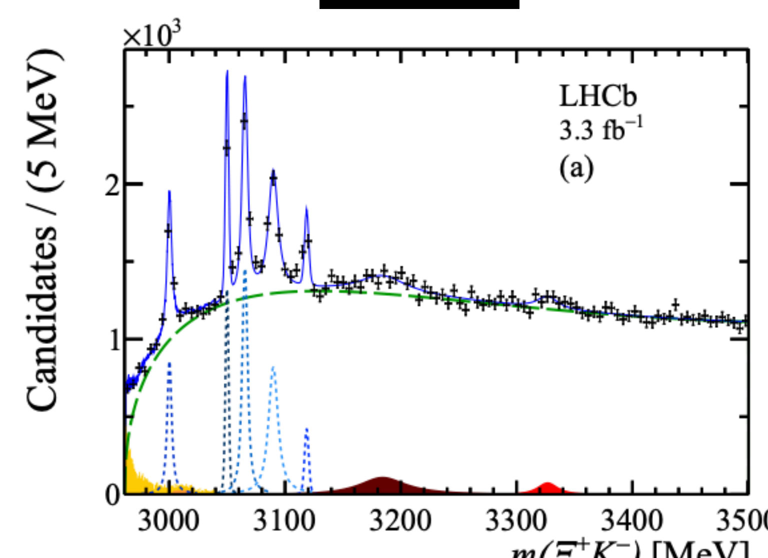


Ω_b^- states → $\Xi_b^0K^-$

Phys. Rev. Lett. 124, 082002 (2020)



2023



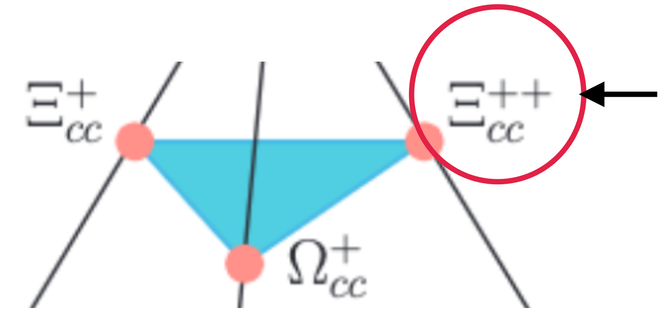
- Observation of two new broad states
- Two new excited states, $\Omega_c^0(3185)0$ and $\Omega_c^0(3327)$
- Still debate on the spin-state assignment

Doubly heavy Ξ_{cc}^{+}

2017

- Not only strong decays → first observation of double-heavy baryons
- Start of a new field of spectroscopy → double heavy spectroscopy is now a fact in LHCb

Ξ_{cc}^{++}



- Well established in 2 different modes (as required by PDG)
- Lifetime measured as well

3621.6 ± 0.4 MeV

$(2.56 \pm 0.27) \times 10^{-13}$ s

	Mode
Γ_1	$\Lambda_c^+ K^- \pi^+ \pi^+$
Γ_2	$\Xi_c^+ \pi^+$, $\Xi_c^+ \to p K^- \pi^+$
Γ_3	$D^+ p K^- \pi^+$

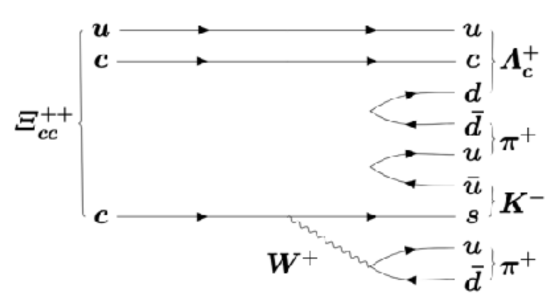
+

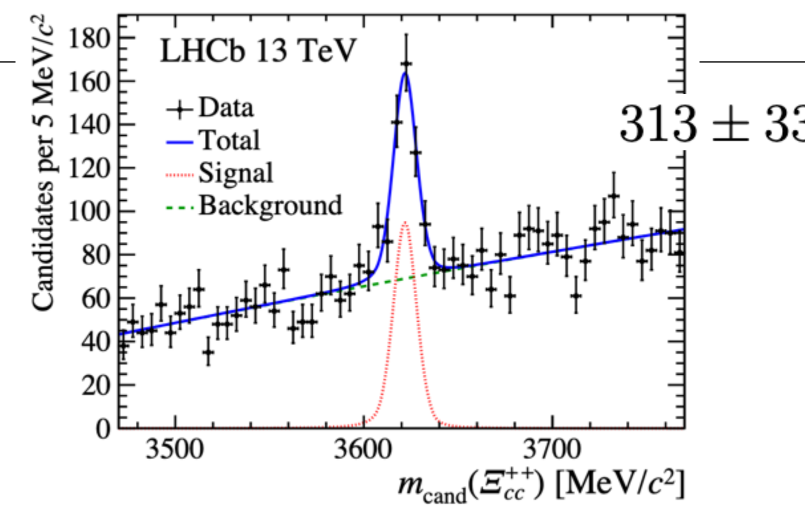
$\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+$

JHEP 05 (2022) 038

Phys. Rev. Lett. 119, 112001 **(2017)**

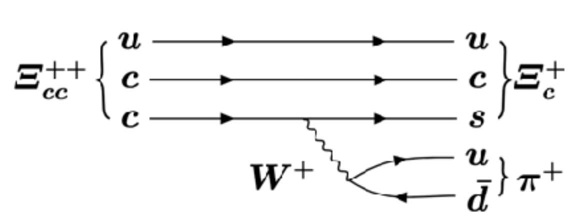
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

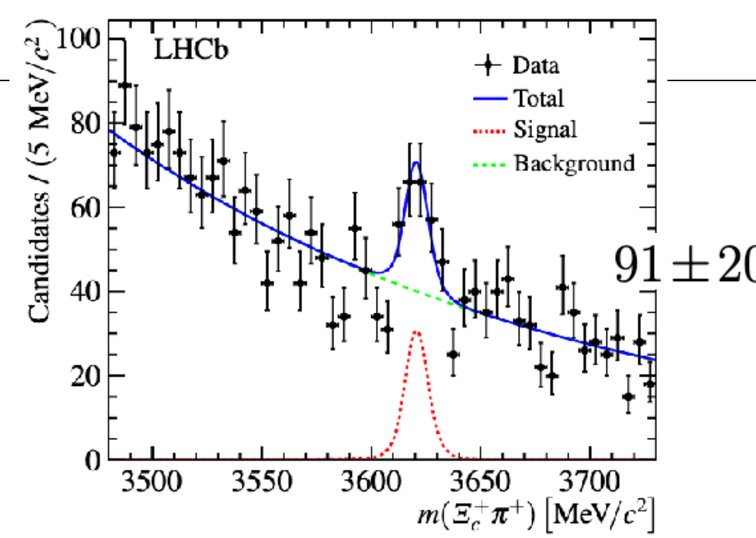




Phys. Rev. Lett. 121, 162002 (2018)

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$





Ingredients for a successful analysis
An example…

- High yields + Clean samples
- Good momentum resolution (for m_0 and Γ)
- Good ideas and guestimations

- Example on how things evolve with data becoming available

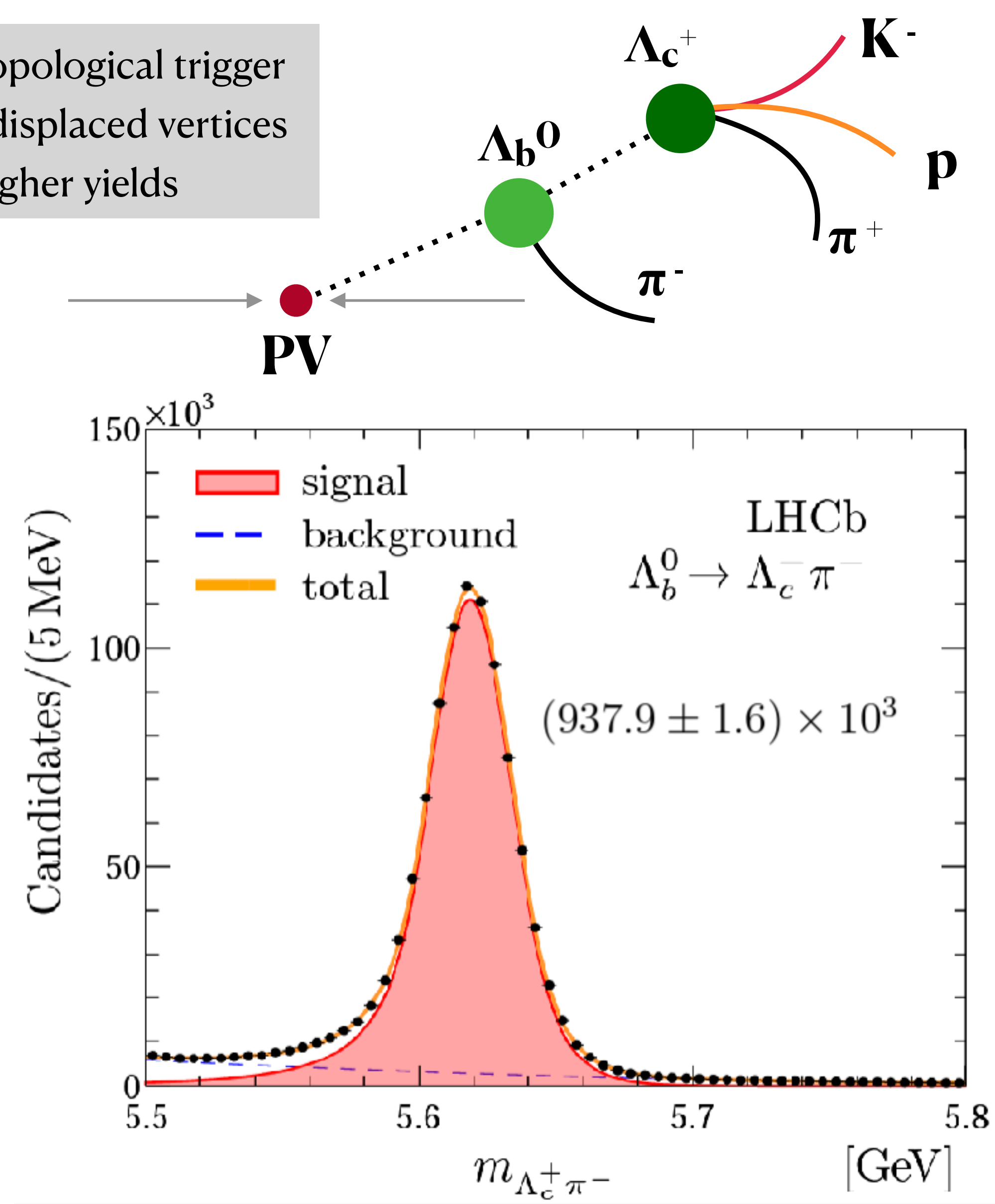
Di-Muon vs Topological triggers

JHEP 06 (2020) 136

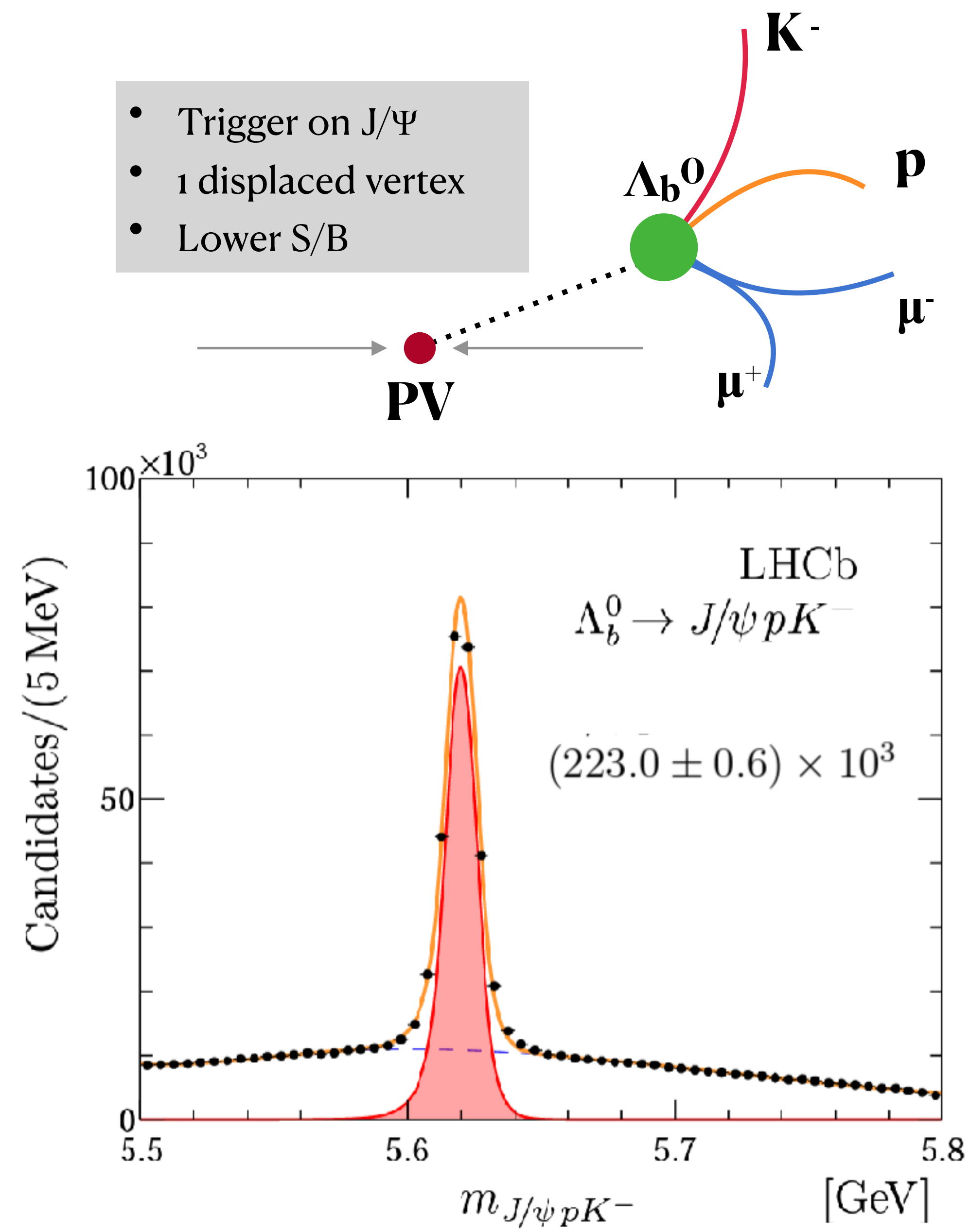
- **First job is to gather high yields to access rare states**
- Also, S/B ratio is important, especially for the most intricate analyses
- **As an example we can consider the Λ_b baryon. Standard candle for many b-baryon analyses**
- Also a clean control sample for many different tasks (calibration/BF measurements)
- **Use Λ_b to show Pros and Cons of Di-Muon vs Fully hadronic triggers**

Most abundant b-baryon

- Topological trigger
- 2 displaced vertices
- Higher yields



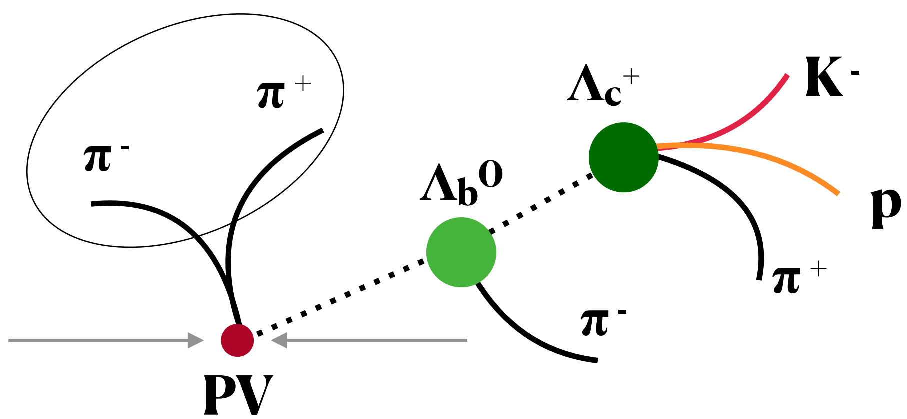
- Trigger on J/Ψ
- 1 displaced vertex
- Lower S/B

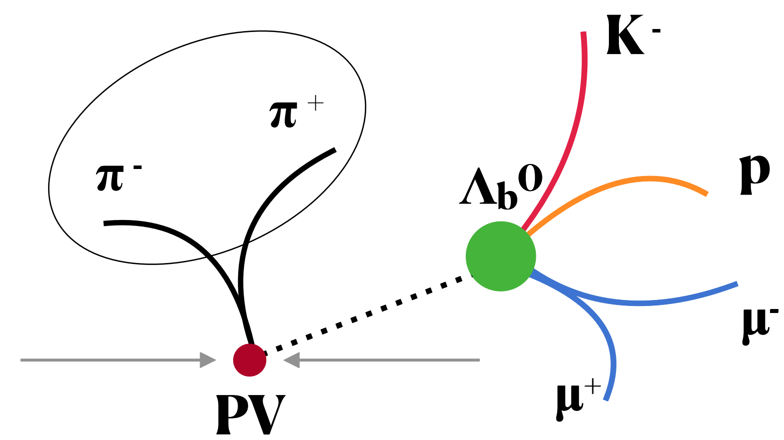


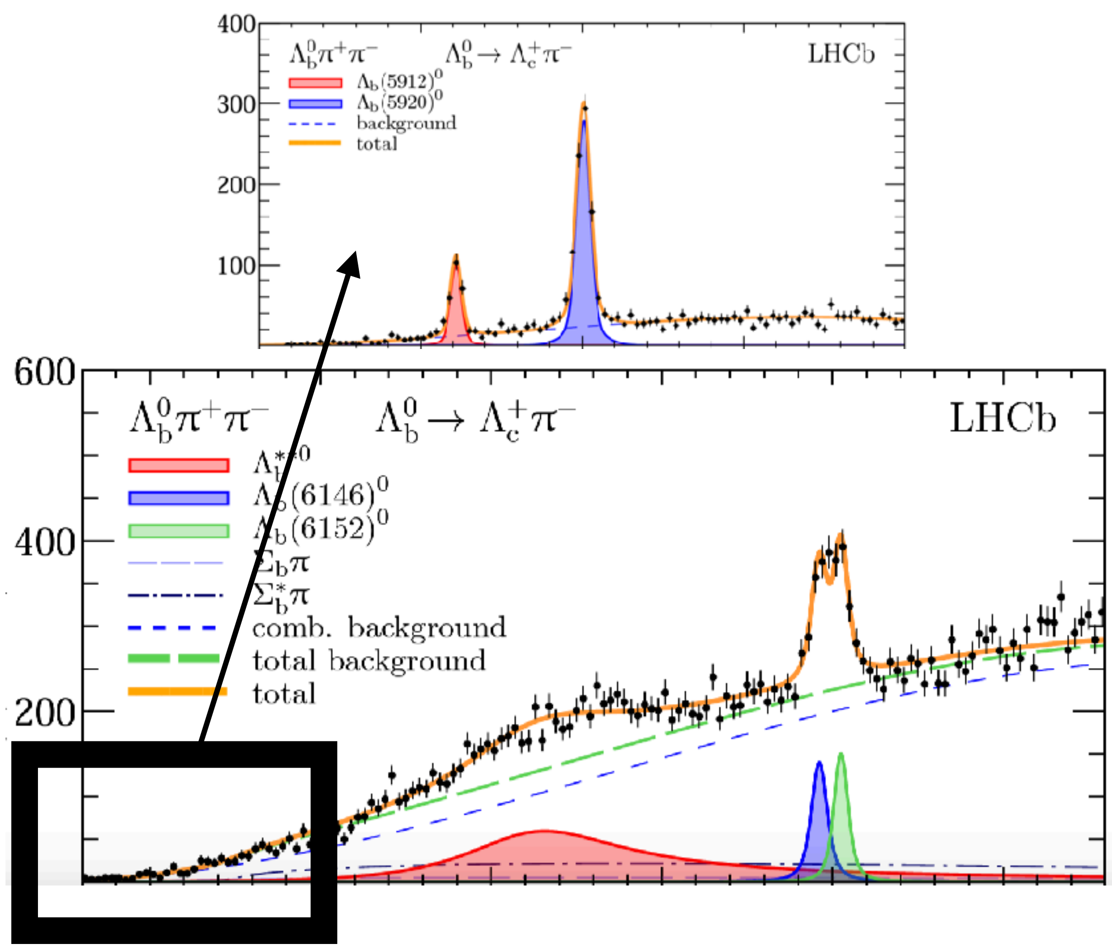
Extending the Q value regions

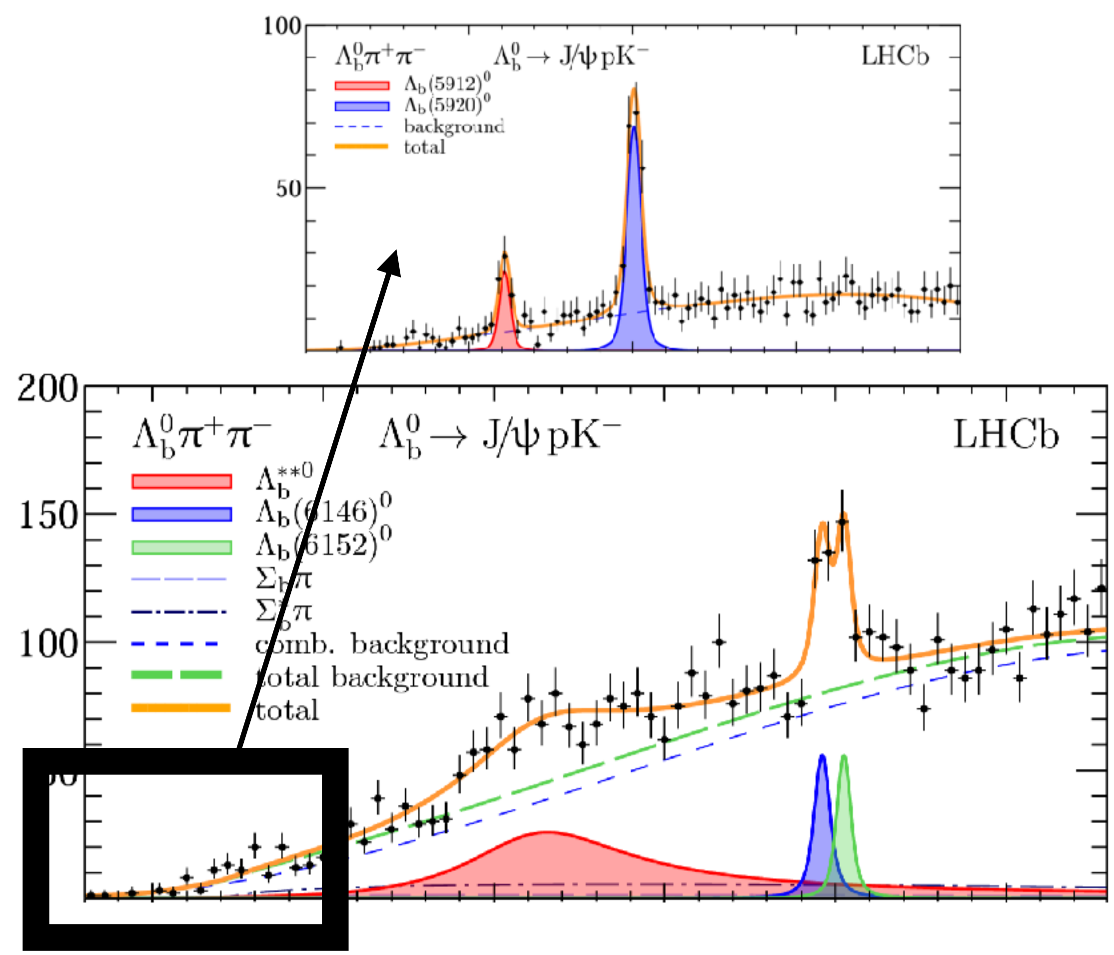
JHEP 06 (2020) 136

- **Again.. as an example one can look for resonances above threshold → Strong decays**
- Rich system of resonances!
- Actually interesting to show the time evolution of observation









Observations vs Data available

JHEP 06 (2020) 136

- **Again.. as an example one can look for resonances above threshold → Strong decays**
- Rich system of resonances!
- Actually interesting to show the time evolution of observation

3.	LHCb	$\Lambda_b(5920)^0$	5919.8 ± 0.7	*bud*	15 May 2012	Phys. Rev. Lett. 109 (2012) 172003
4.	LHCb	$\Lambda_b(5912)^0$	5912.0 ± 0.7	*bud*	15 May 2012	Phys. Rev. Lett. 109 (2012) 172003

1 fb^{-1}

- Then more data → extend the Q value range to search for higher mass resonances

41.	LHCb	$\Lambda_b(6152)^0$	6152.5 ± 0.4	*bud*	31 Jul 2019	Phys. Rev. Lett. 123 (2019) 152001
42.	LHCb	$\Lambda_b(6146)^0$	6146.2 ± 0.4	*bud*	31 Jul 2019	Phys. Rev. Lett. 123 (2019) 152001
45.	LHCb	$\Lambda_b(6070)^0$	6072.3 ± 3.0	*bud*	12 Feb 2020	JHEP 06 (2020) 136

9 fb^{-1}

?

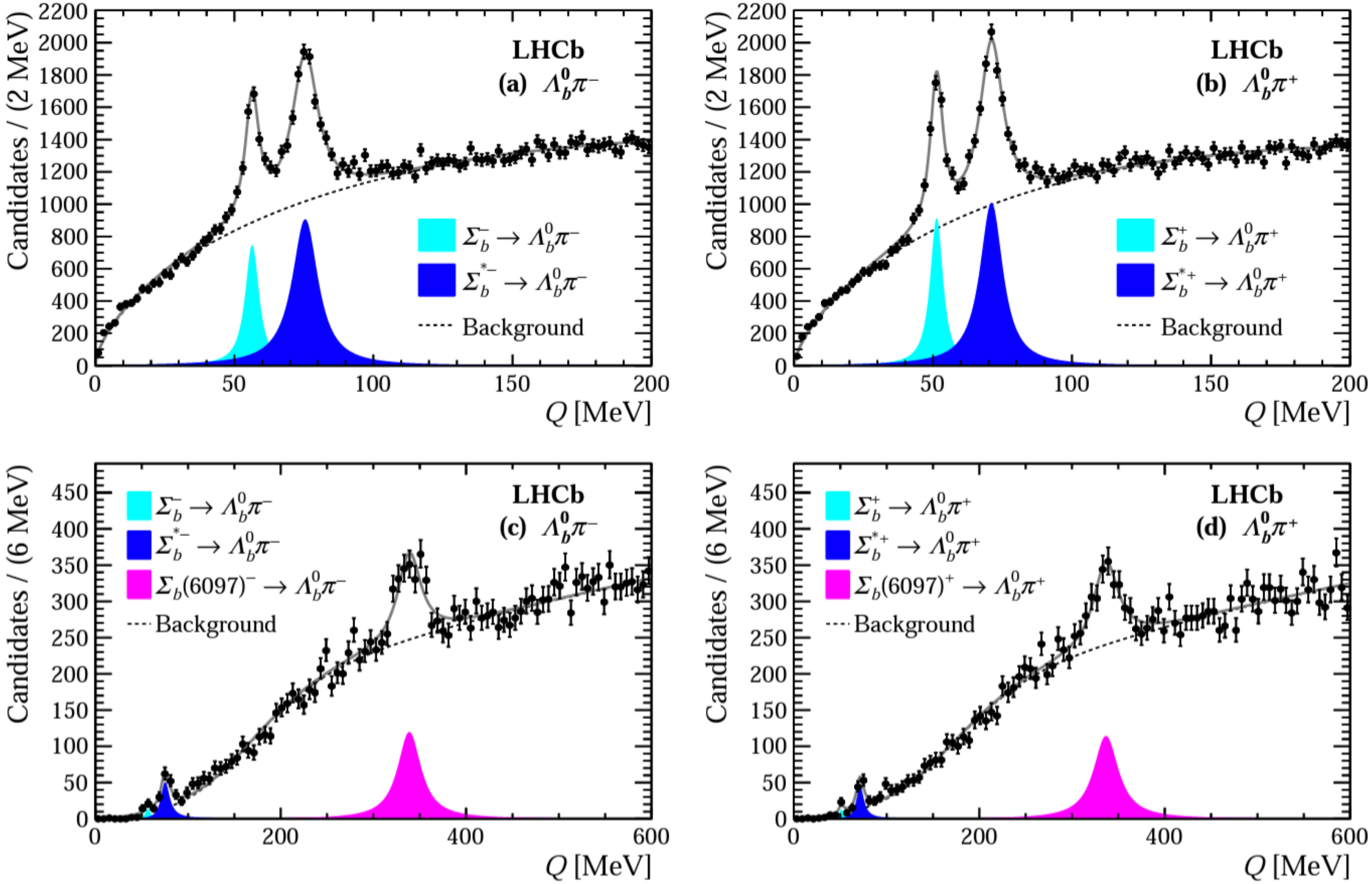
Missing Ground States: example Σ_b^0

(buu, bdd, bud)

- **Some states still eluding experimental observation**
- E.g. neutral Σ_b states are likely to decay strongly in $\Lambda_b\pi^0$
- Experimentally challenging to reconstruct prompt π^0
- One could look at charged case and guesstimate
- Combinatorial of photons too severe…

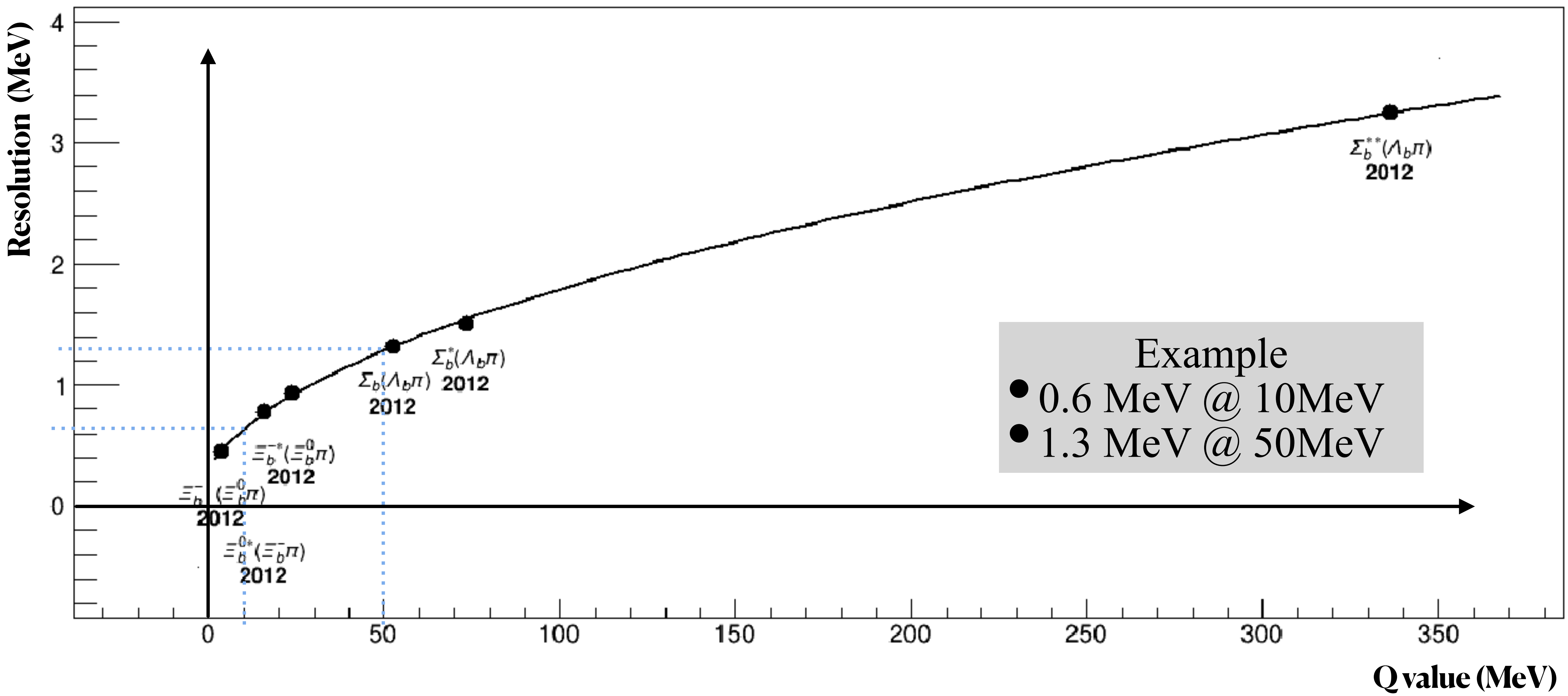
First observed by CDF
Searches then extended by LHCb

Phys. Rev. Lett. 122, 012001 (2019)



Resolution studies

- Essential to have good resolution to extract the physical parameters of resonances
- Experimental resolution should be ideally << natural width
- Convolve BW with resolution function
- Resolution is now well understood, checked with simulation and data-driven strategies
- Dependence wrt Qvalue = $m(\Lambda_b \pi\pi) - m(\Lambda_b) - 2m(\pi)$



Observation of new baryons in $\Xi_b^- \pi^+ \pi^-$ and $\Xi_b^0 \pi^+ \pi^-$

Phys. Rev. Lett. **131**, 171901

Phys. Rev. Lett. **131**, 171901

New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

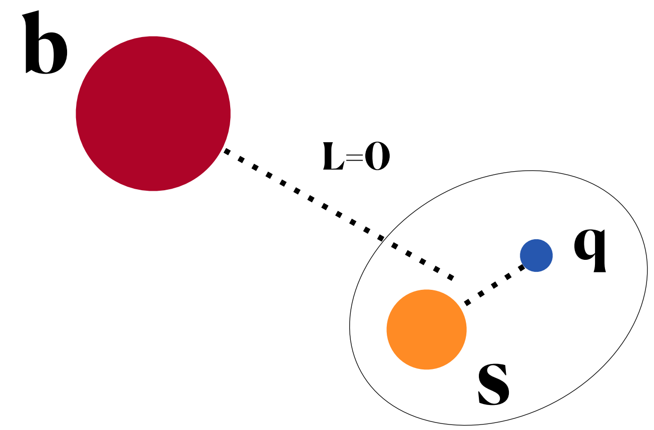
- At LHCb, we look both for charged and neutral states $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

- Ξ_b baryons form an isospin doublet (*bsu, bsd*)
- The ground states have L=0 between *b* and lighter *sq* diquark

- Three isospin doublets of such non-excited states are expected
- Different spin parity J^P and J_{sq}

- One state still unobserved $\Xi_b'^0$
- Experimentally challenging:
  - Its mass may be below the $\Xi_b^-\pi^+$
  - Thus it is expected → $\Xi_b^0\pi^0$, $\Xi_b^0\gamma$

- A number of excited states of higher mass is expected



$$(J_{sq},\ J^P)$$

$$(0, (\tfrac{1}{2})^+),\ (1, (\tfrac{1}{2})^+) \text{ and } (1, (\tfrac{3}{2})^+)$$

$$\Xi_b^{(-,0)},\ \Xi_b'^{(0,-)} \text{ and } \Xi_b^{*(0,-)}$$

From PDG live

Ξ_b^-	$1/2^+$	***
Ξ_b^0	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***

New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

Phys. Rev. Lett. **131**, 171901

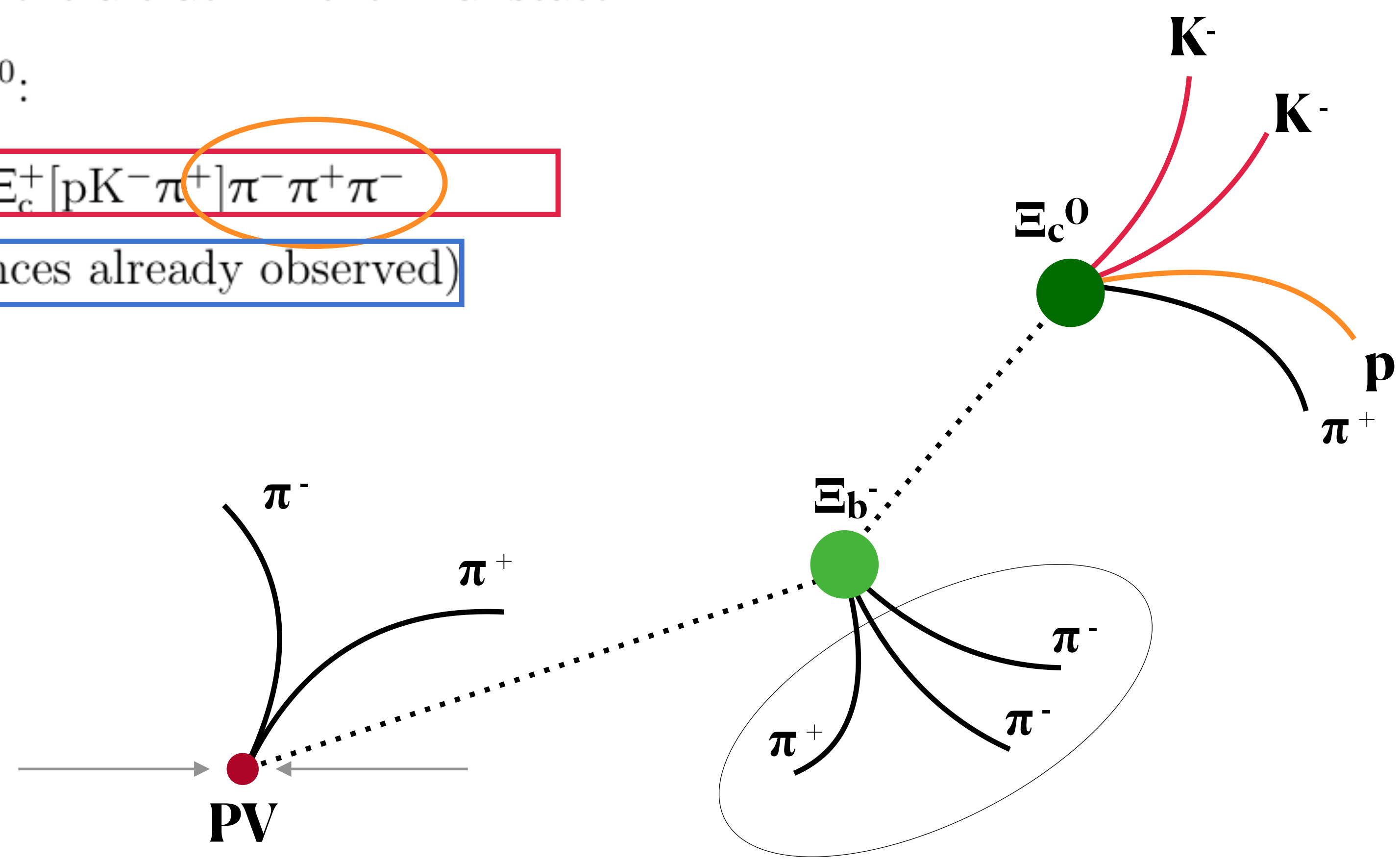
- The idea is to use different final states
- Look for single bachelor and three bachelor final states
- More experimentally challenging (more tracks, more background) but we can get easily a 50% more signal

- Charged resonance temporarily referred to as Ξ_b^{**-}:
  - ☐ Start with $\Xi_b^- \to \Xi_c^0[pK^-K^+\pi^+]\pi^-$ and $\Xi_b^- \to \Xi_c^0[pK^-K^+\pi^+]\pi^-\pi^+\pi^-$
  - ☐ $\Xi_b^{*0} \to \Xi_b^-\pi^+$ (one intermediate resonance already observed)
  - ☐ $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$
  - ☐ The final state is thus $\Xi_b^-\pi^+\pi^-$
  - ☐ The yield is expected lower here due to the extra track in the final state

Final state

- Neutral resonance temporarily referred to as Ξ_b^{**0}:
  - ☐ Start with $\Xi_b^0 \to \Xi_c^+[pK^-\pi^+]\pi^-$ and $\Xi_b^0 \to \Xi_c^+[pK^-\pi^+]\pi^-\pi^+\pi^-$
  - ☐ $\Xi_b'^-, \Xi_b^{*-} \to \Xi_b^0\pi^-$ (two intermediate resonances already observed)
  - ☐ $\Xi_b^{**0} \to \Xi_b'^-\pi^+, \Xi_b^{**0} \to \Xi_b^{*-}\pi^+$
  - ☐ The final state is thus $\Xi_b^0\pi^-\pi^+$

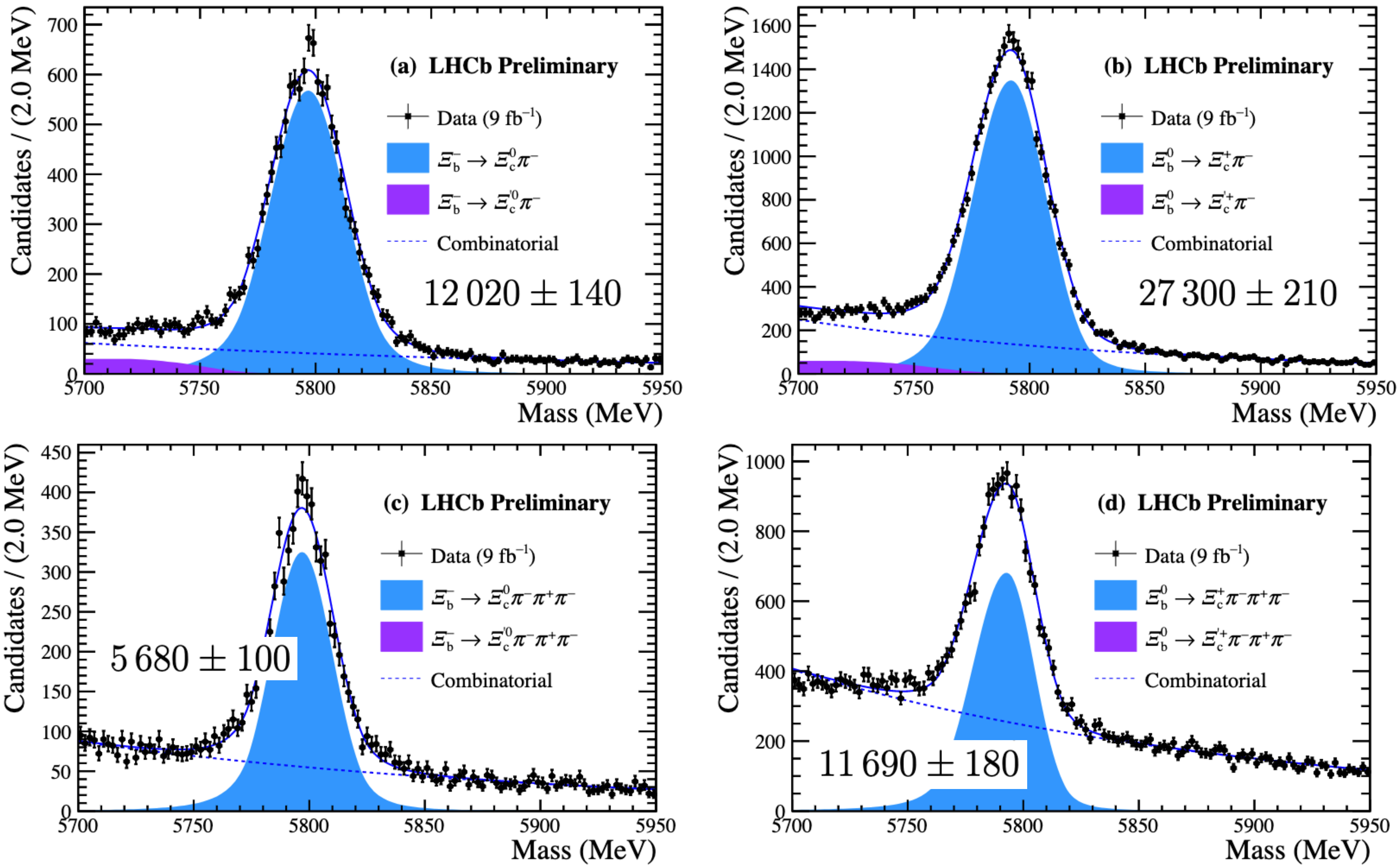
Final state



Up to 9 tracks in the final state

New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

- Reconstruct nice samples of Ξ_b charged and neutral
- Selection based on BDT algorithms trained on simulation for signal and DATA sidebands for background
- Additional vetoes to suppress contributions from Λ_b, where required



Phys. Rev. Lett. **131**, 171901

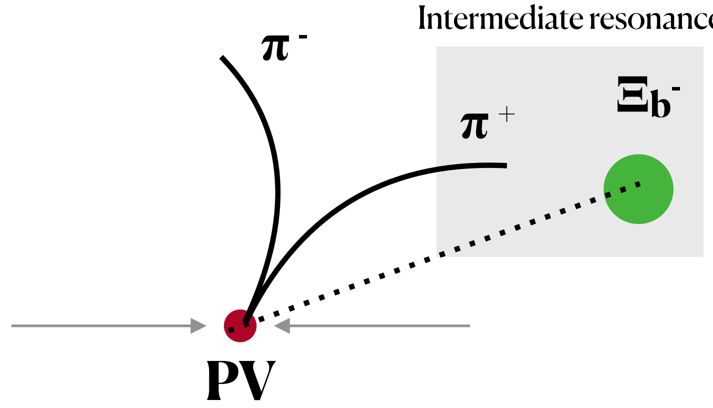
New baryons in $\Xi_b^- \pi^+ \pi^-$ and $\Xi_b^0 \pi^+ \pi^-$

- We fit Q value (mass differences) → resolution effects cancel out
- Resolution curves obtained from simulation, but validated with extensive cross-checks on data
- Fit models: Signal + Background + Reflections (where needed)

$\mathrm{PDF_{sig}}(m_0, \Gamma) = \mathrm{DCB_{res}} \otimes \mathrm{BW_{rel}}(m_0, \Gamma)$

power-like function $(Q - d)^n$

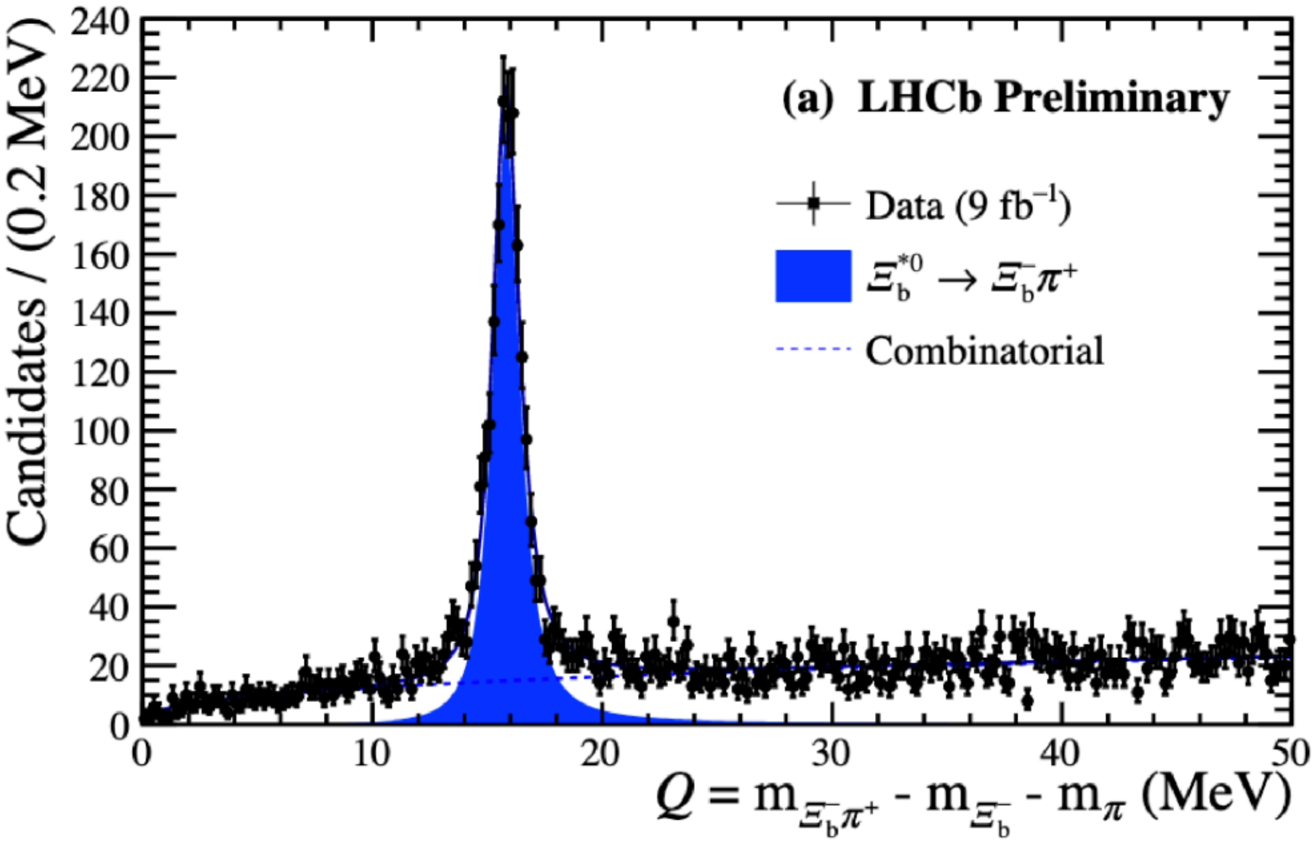
partially reconstructed candidates coming from higher-mass resonances

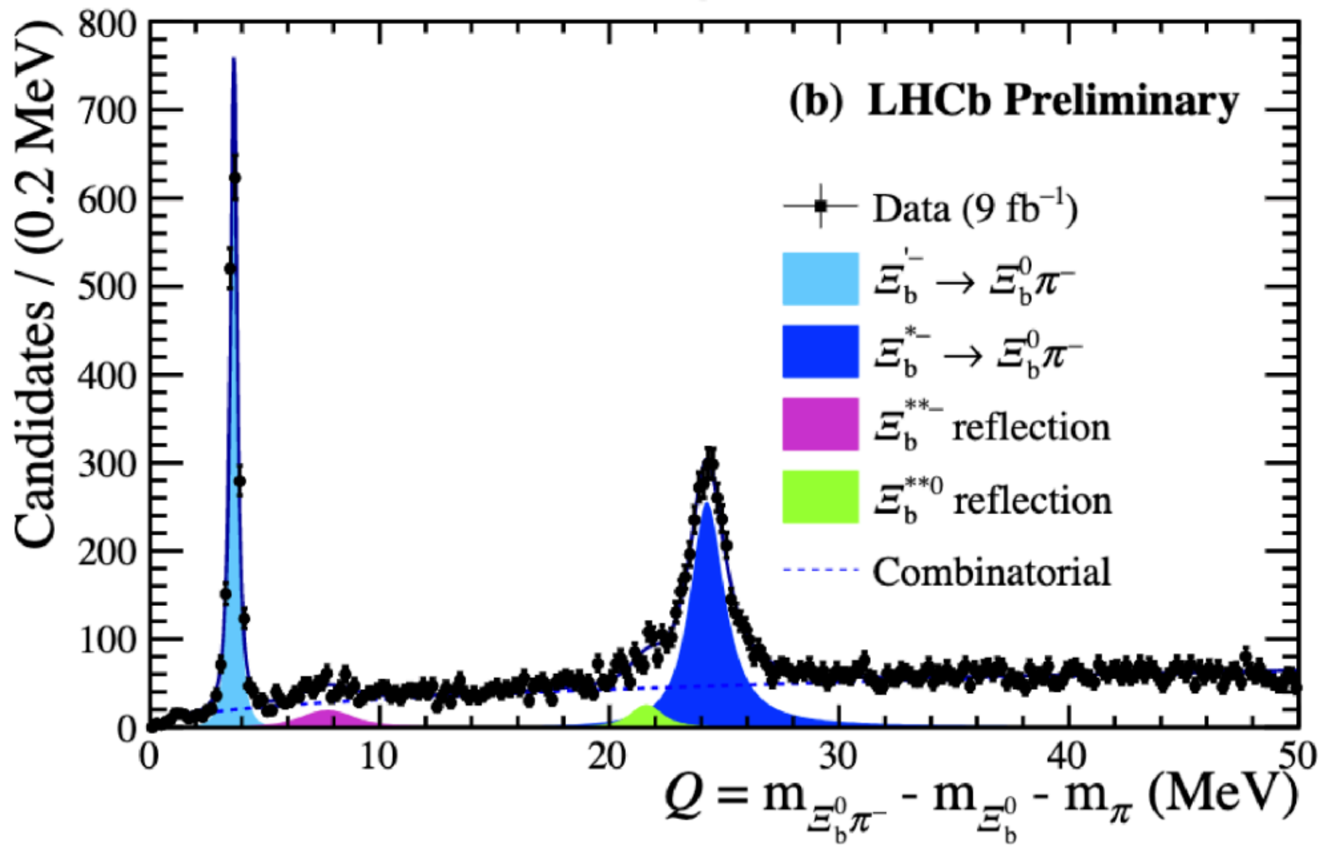


$\Xi_b^- \pi^+$

Those are the intermediate resonances
Nice mass distributions and signals

$\Xi_b^0 \pi^-$

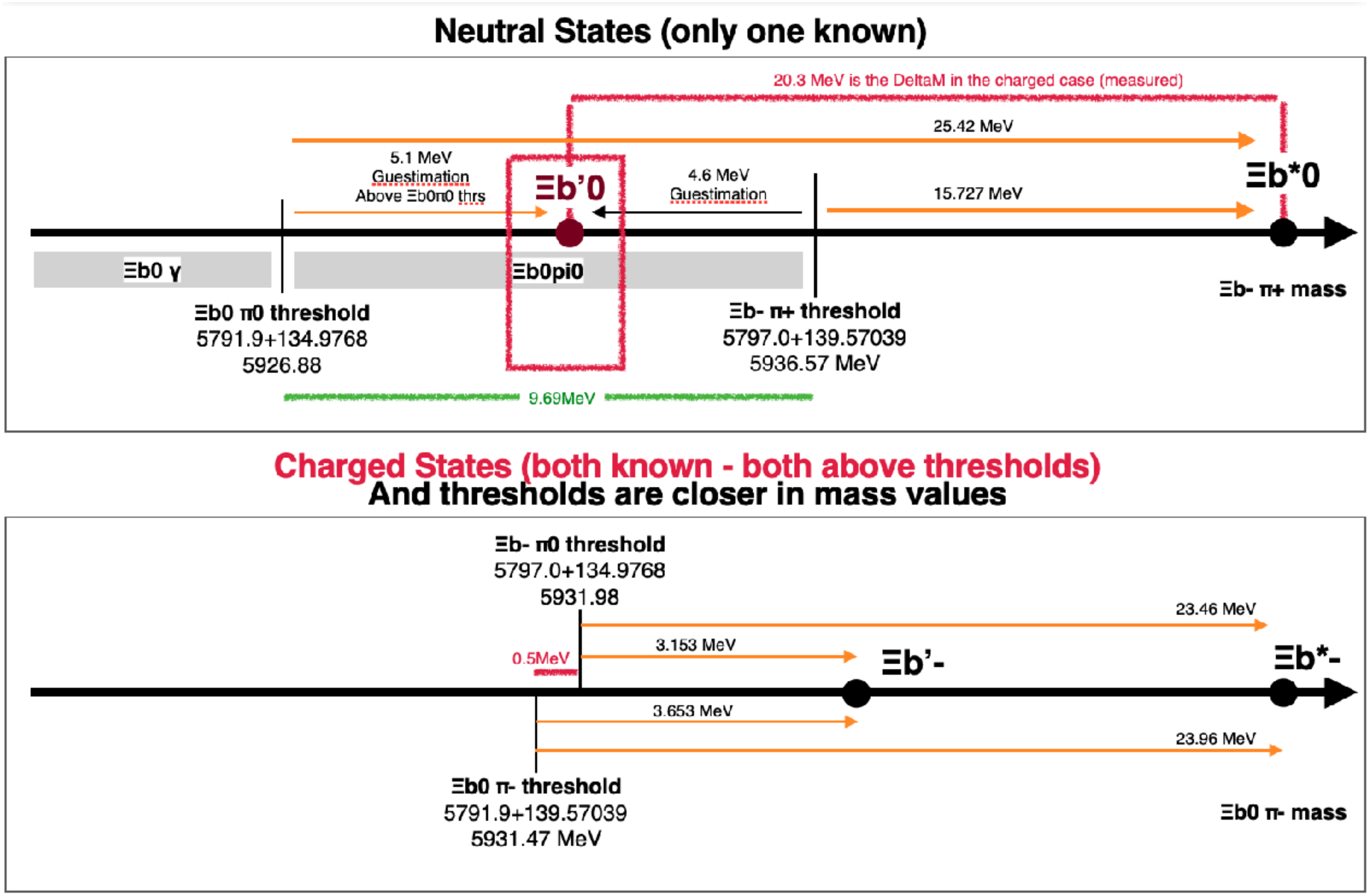




Phys. Rev. Lett. **131**, 171901

New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

- Experimental situation quite interesting: **4 states expected but only 3 observed**



One could guesstimate the mass of the unobserved state from the charged case

Ξ_b^- Ξ_b^0

$\Xi_b'^-$ $\Xi_b'^0$?

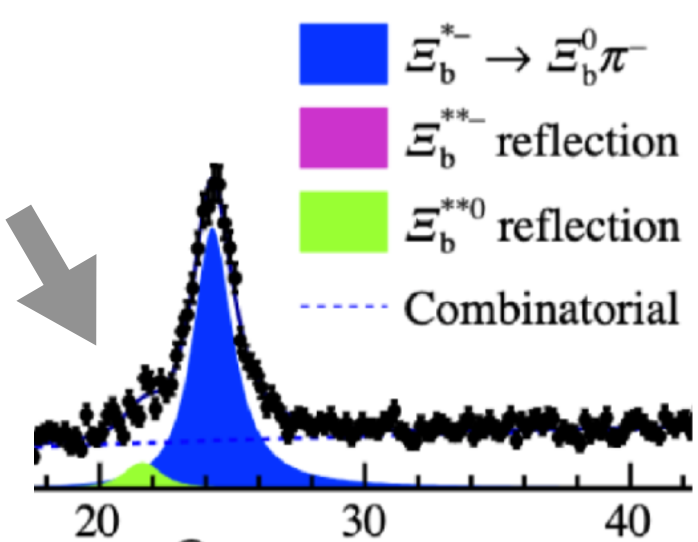
Ξ_b^{*-} Ξ_b^{*0}

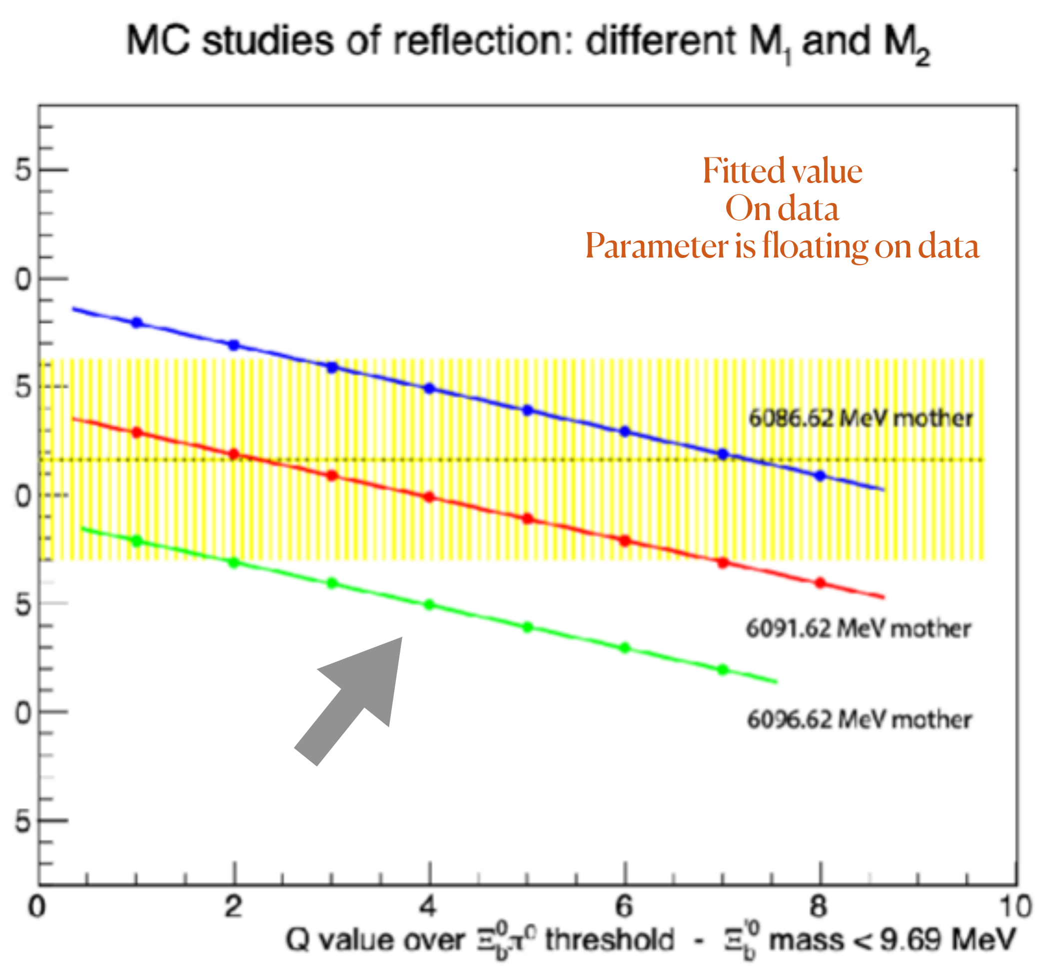
- Studied all possible ways in which new peaks could appear in the intermediate spectra
- E.g if a neutral particle is lost [$\Xi_b^0\pi^0$]
- **Studies on simulation and DATA to identify *so-called reflections***

Phys. Rev. Lett. **131**, 171901

New baryons in $\Xi_b^- \pi^+ \pi^-$ and $\Xi_b^0 \pi^+ \pi^-$

- Additional components are added in the fit to the $\Xi_b^0 \pi^-$ spectrum to describe partially reconstructed candidates coming from higher-mass resonances
- The reflections of the newly observed states in $\Xi_b \pi\pi$ (reflecting into the $\Xi_b \pi$ spectrum) are studied with simulation + data cross-checks
- The means of the reflection components are free parameters in the fits to data and their fitted values are consistent with expectations
- **The fit also confirms the presence of partially reconstructed** $\Xi_b^-(6100) \rightarrow \Xi_b^{*0}(\Xi_b^0 \pi^0)\pi^-$
- **Hints of a possible contribution from the decay chains** $\Xi_b^-(1P, 1/2) \rightarrow \Xi_b'^0(\Xi_b^0 \pi^0)\pi^-$

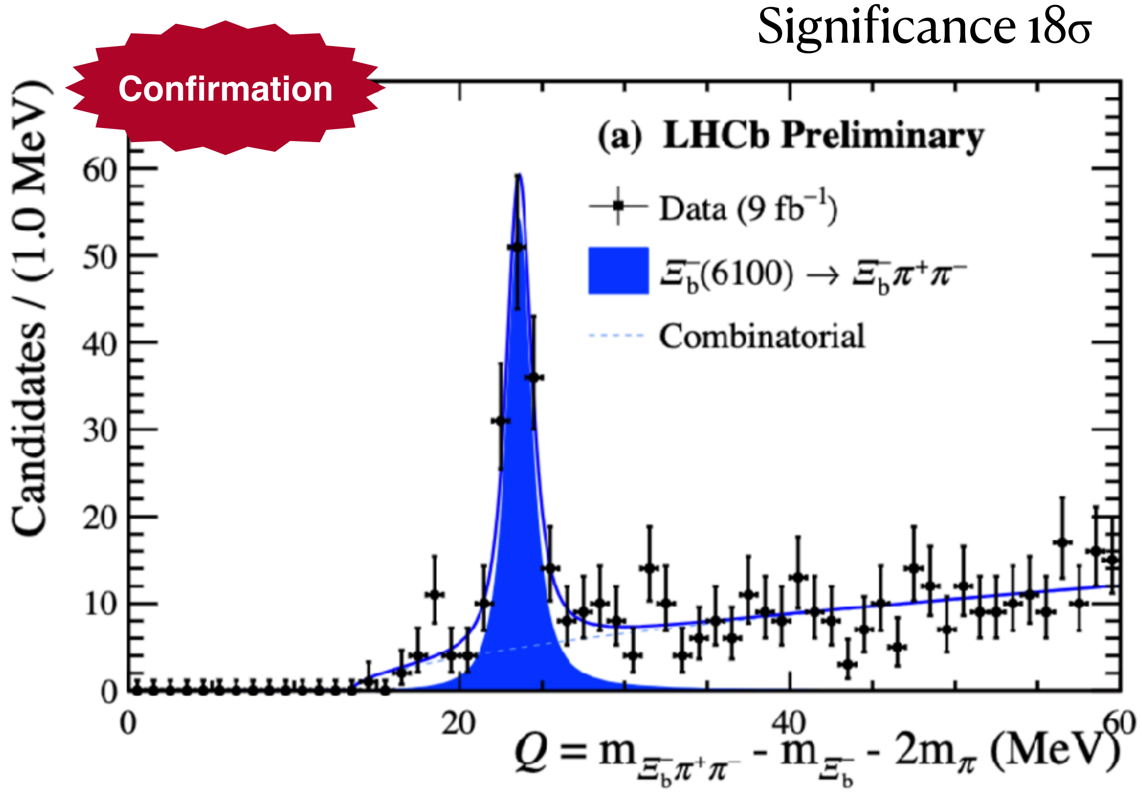




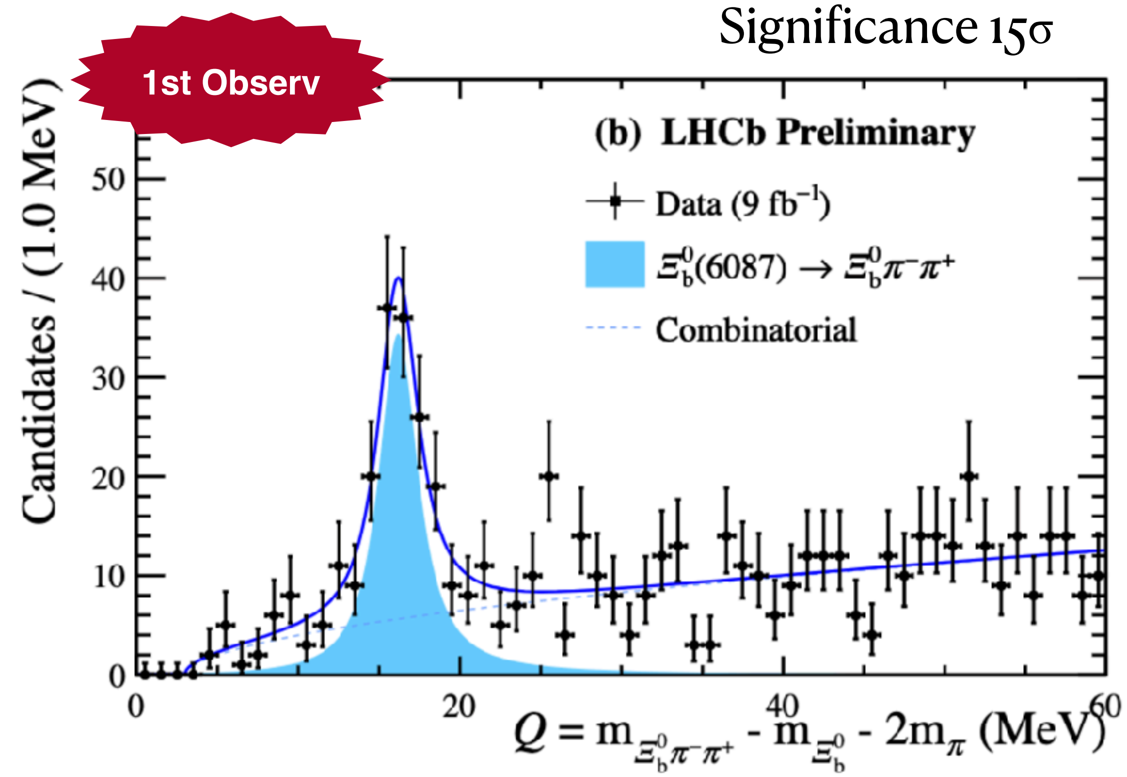
However, a precise estimation of the two states properties is not possible due to the limited yield available and the **presence of two unknown mass values.**

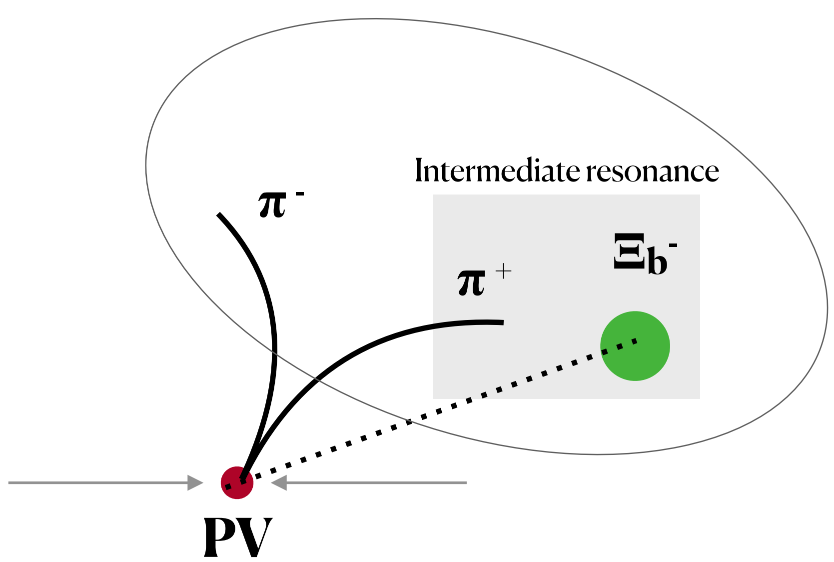
New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

Significance 18σ

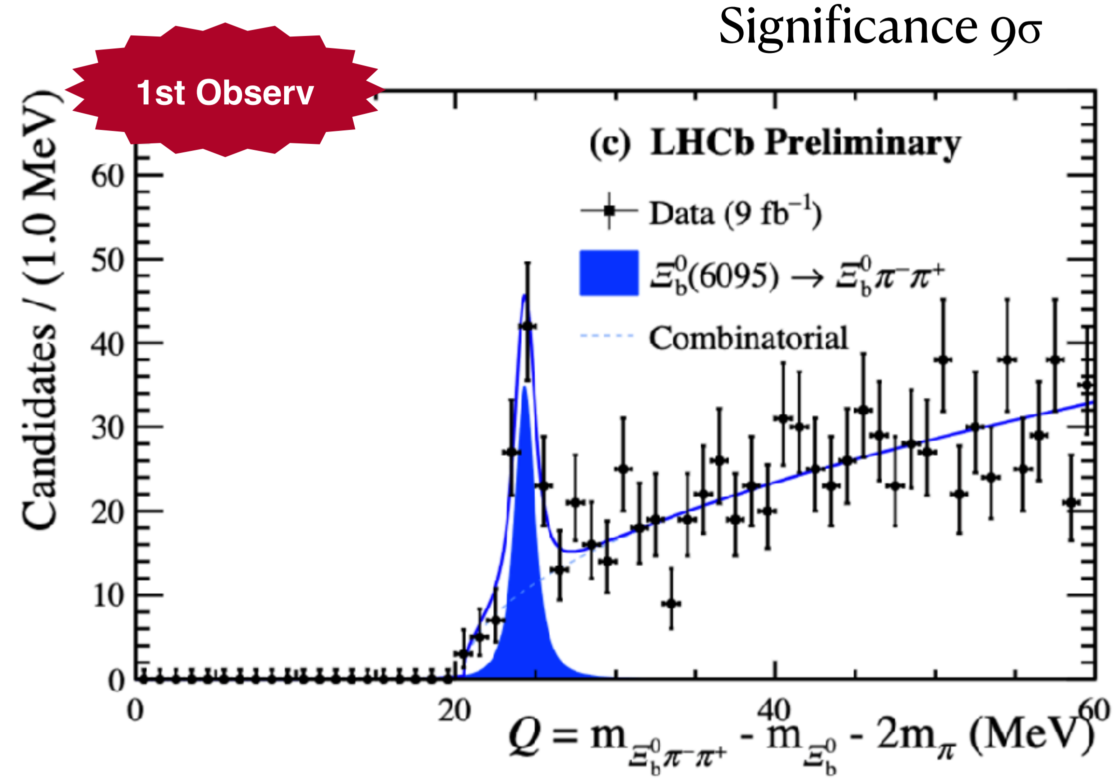


Significance 15σ





Significance 9σ



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New baryons in $\Xi_b^- \pi^+ \pi^-$ and $\Xi_b^0 \pi^+ \pi^-$

- Analysis is statistically limited
- Investigated several sources of systematics
- Numerical results below

	Value [MeV]
$Q_0\ (\Xi_b^-(6100))$	$23.60 \pm 0.11 \pm 0.02$
$\Gamma\ (\Xi_b^-(6100))$	$0.94 \pm 0.30 \pm 0.08$
$m_0\ (\Xi_b^-(6100))$	$6099.74 \pm 0.11 \pm 0.02\ \pm 0.6\ (\Xi_b^-)$
$Q_0\ (\Xi_b^0(6087))$	$16.20 \pm 0.20 \pm 0.06$
$\Gamma\ (\Xi_b^0(6087))$	$2.43 \pm 0.51 \pm 0.10$
$m_0\ (\Xi_b^0(6087))$	$6087.24 \pm 0.20 \pm 0.06\ \pm 0.5\ (\Xi_b^0)$
$Q_0\ (\Xi_b^0(6095))$	$24.32 \pm 0.15 \pm 0.03$
$\Gamma\ (\Xi_b^0(6095))$	$0.50 \pm 0.33 \pm 0.11$
$m_0\ (\Xi_b^0(6095))$	$6095.36 \pm 0.15 \pm 0.03\ \pm 0.5\ (\Xi_b^0)$
$Q_0\ (\Xi_b^{*0})$	$15.80 \pm 0.02 \pm 0.01$
$\Gamma\ (\Xi_b^{*0})$	$0.87 \pm 0.06 \pm 0.05$
$m_0\ (\Xi_b^{*0})$	$5952.37 \pm 0.02 \pm 0.01\ \pm 0.6\ (\Xi_b^-)$
$Q_0\ (\Xi_b^{\prime -})$	$3.66 \pm 0.01 \pm 0.00$
$\Gamma\ (\Xi_b^{\prime -})$	$0.03 \pm 0.01 \pm 0.03$
$m_0\ (\Xi_b^{\prime -})$	$5935.13 \pm 0.01 \pm 0.00\ \pm 0.5\ (\Xi_b^0)$
$Q_0\ (\Xi_b^{*-})$	$24.27 \pm 0.03 \pm 0.01$
$\Gamma\ (\Xi_b^{*-})$	$1.43 \pm 0.08 \pm 0.08$
$m_0\ (\Xi_b^{*-})$	$5955.74 \pm 0.03 \pm 0.01\ \pm 0.5\ (\Xi_b^0)$

$\Xi_b(6100)^-$ — Confirmation

$\Xi_b(6087)^0$, $\Xi_b(6095)^0$ — 1st Observ

Improvements

	Ξ_b^{*0}		$\Xi_b^{\prime -}$		Ξ_b^{*-}	
Source	Q_0	Γ	Q_0	Γ	Q_0	Γ
Momentum scale	0.006	0.001	0.001	0.001	0.008	0.001
Background	0.003	0.029	0.000	0.006	0.004	0.073
Reflections			0.000	0.000	0.002	0.007
Resolution	0.001	0.038	0.002	0.027	0.000	0.033
BW param.	0.001	0.001	0.000	0.000	0.001	0.002
Total	0.007	0.048	0.002	0.028	0.010	0.081

	$\Xi_b^-(6100)$		$\Xi_b^0(6087)$		$\Xi_b^0(6095)$	
Source	Q_0	Γ	Q_0	Γ	Q_0	Γ
Momentum scale	0.008	0.002	0.007	0.001	0.009	0.006
Background	0.004	0.035	0.022	0.089	0.023	0.025
Resolution	0.004	0.054	0.001	0.035	0.006	0.073
BW param.	0.016	0.050	0.056	0.007	0.001	0.079
Total	0.019	0.081	0.060	0.096	0.026	0.111

States are confirmed to be narrow

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In summary:

- **Observation of two new *bsq* baryons is reported: $\Xi_b(6100)^-$**
- **One state is confirmed (and measured): $\Xi_b(6087)^0$ $\Xi_b(6095)^0$**
- Best measurement on the known Ξ_b' and Ξ_b^* states
- This measurement uses final states with up to 9 tracks (record in LHCb
- Possible thanks to the excellent performance of the LHCb tracking, PID and trigger systems
- First observation of $\Xi_b^0 \to \Xi_c^+\pi\pi\pi$
- Seems like resonances go predominantly via their intermediate resonances
- Situation similar in the charm sector (but threshold there are different and so e.m. decays)

A naive interpretation would be that the new states are P-wave states ($l = 1$ between b and qs diquark) coupling to the b quark ($s = \frac{1}{2}$) to give a pair of states $J^P = (\frac{1}{2})^-$ and $(\frac{3}{2})^-$, respectively. One might expect the dominant decay mode of the lighter one to be $\Xi_b^{\prime(0,-)}\pi$ and for the heavier one $\Xi_b^{*(0,-)}\pi$. The lighter $\Xi_b^-(1\mathrm{P},1/2)$ state is not observed as it would likely decay primarily through the intermediate $\Xi_b^{\prime 0}$ resonance which is below threshold to decay to $\Xi_b^-\pi^+$. However, hints of such $\Xi_b^-(6100) \to \Xi_b^{\prime 0}(\Xi_b^0\pi^0)\pi^-$ decay could be observed in the $\Xi_b^0\pi^-$ spectrum as a partially reconstructed feed-down component.

Conclusions

- LHC has proven to be a wonderful playground for heavy flavour physics!
- I tried to highlight the milestones and experimental challenges
- Bright future ahead as more data will be available with the upgraded detector!
- Higher statistics → Access to states with lower production rates