Reviewing a decade of spectroscopy at LHCb
and
the observation of new baryonic structures

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On behalf of the LHCb collaboration

25th April 2023
CERN Seminar

Image celebrating the observation of Tcc in 2021
by the LHCb collaboration… an intrinsic exotic state!

Outline

- The title is a bit ambitious… Reviewing a decade of spectroscopy… Risk of being tedious…
- A detailed description of hundreds of analyses is of course beyond the scope of this talk

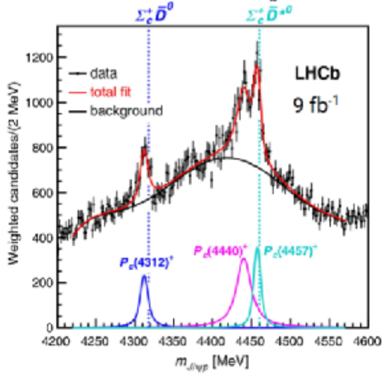
- The idea is to describe the journey so far and what we learned
- Different approaches to the analyses and how the analysis techniques improved

- The talk will be divided in two

• A decade of spectroscopy at LHCb

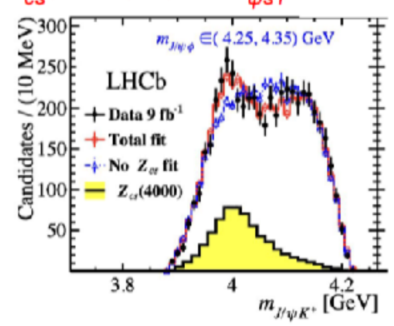
Pentaquarks

by LHCb in 2015 in $\Lambda_b \to J/\psi pK$

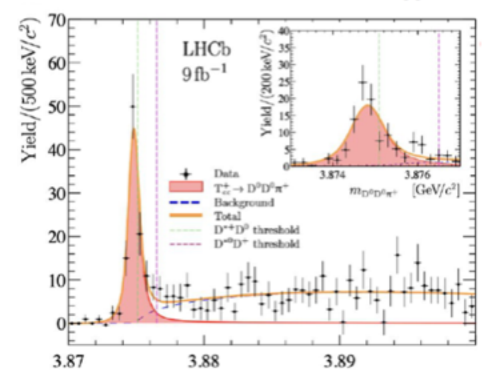


Tetraquarks

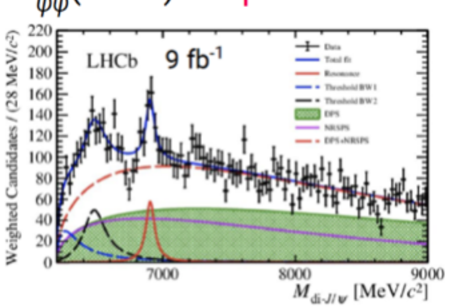
$Z_{cs}(4000)^+$ ($\to T^{\theta}_{\psi s1}$)



Doubly-charm tetraquark $T_{cc}(3875)^+$



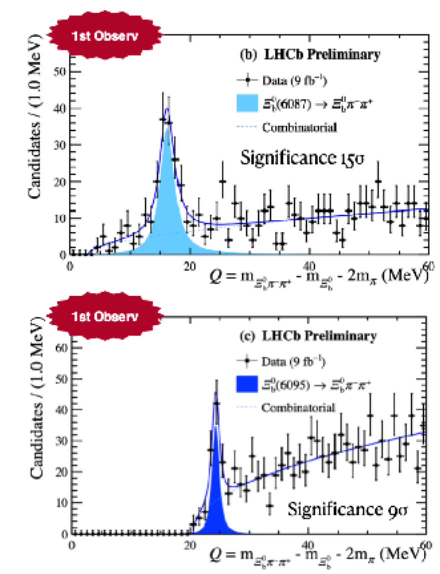
$T_{\psi\psi}(6900)$: di-ψ resonance



• The observation of new baryonic structures

New!

First time presented
At Moriond QCD 2023

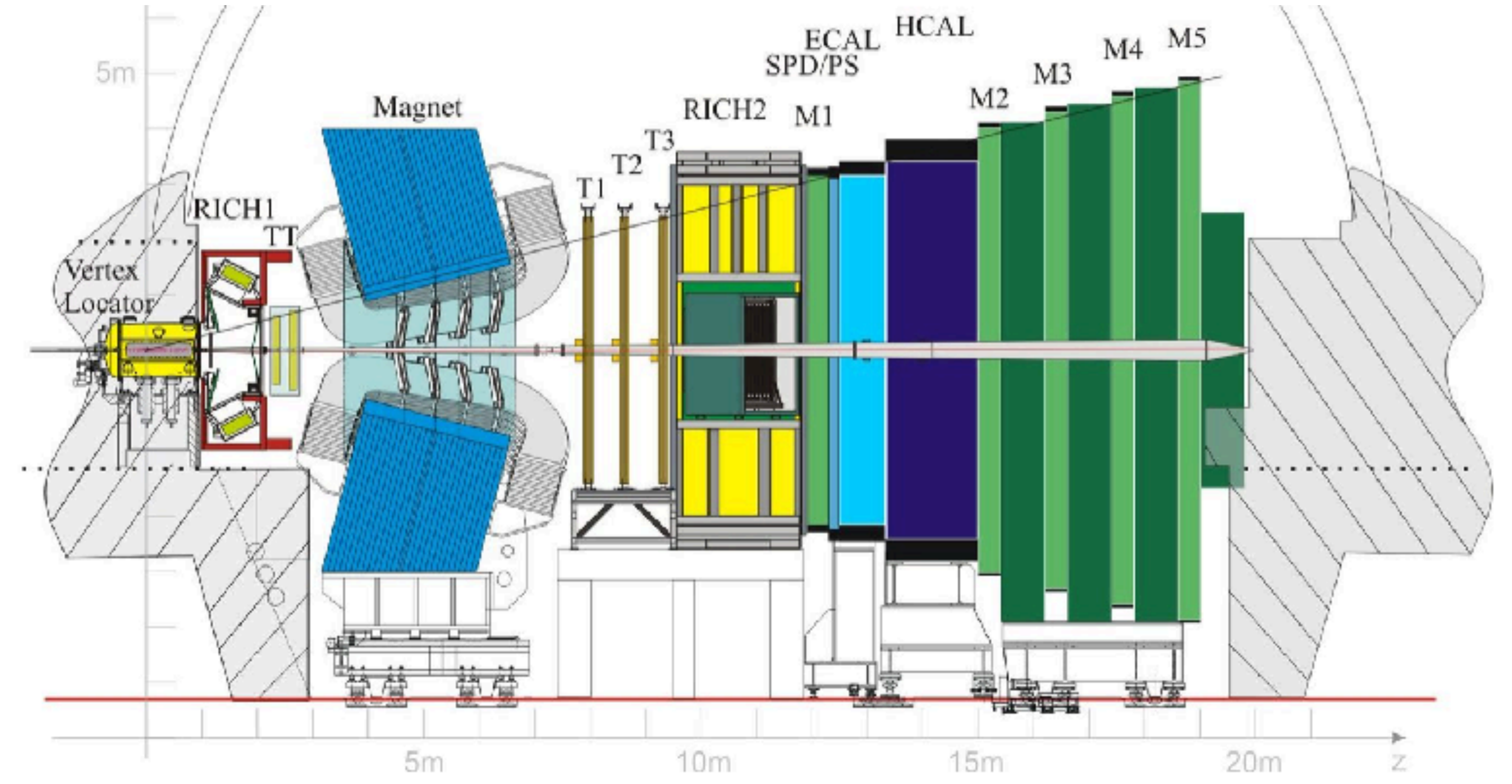


Observation of new baryons in the $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ systems

LHCb -PAPER-2023-008
In preparation

The LHCb detector

- LHCb designed as forward spectrometer covering the pseudo rapidity range $2<\eta<5$
- The LHCb experiment is an extraordinary spectroscopy gym both for “conventional” and “exotic” states
- At LHC *b* and *c* baryons are produced in unprecedented quantities (high cross sections & luminosity)
- Perfect conditions for both precision measurements & observations of new states
- Drawbacks: reconstructing neutrals is experimentally challenging (but doable)

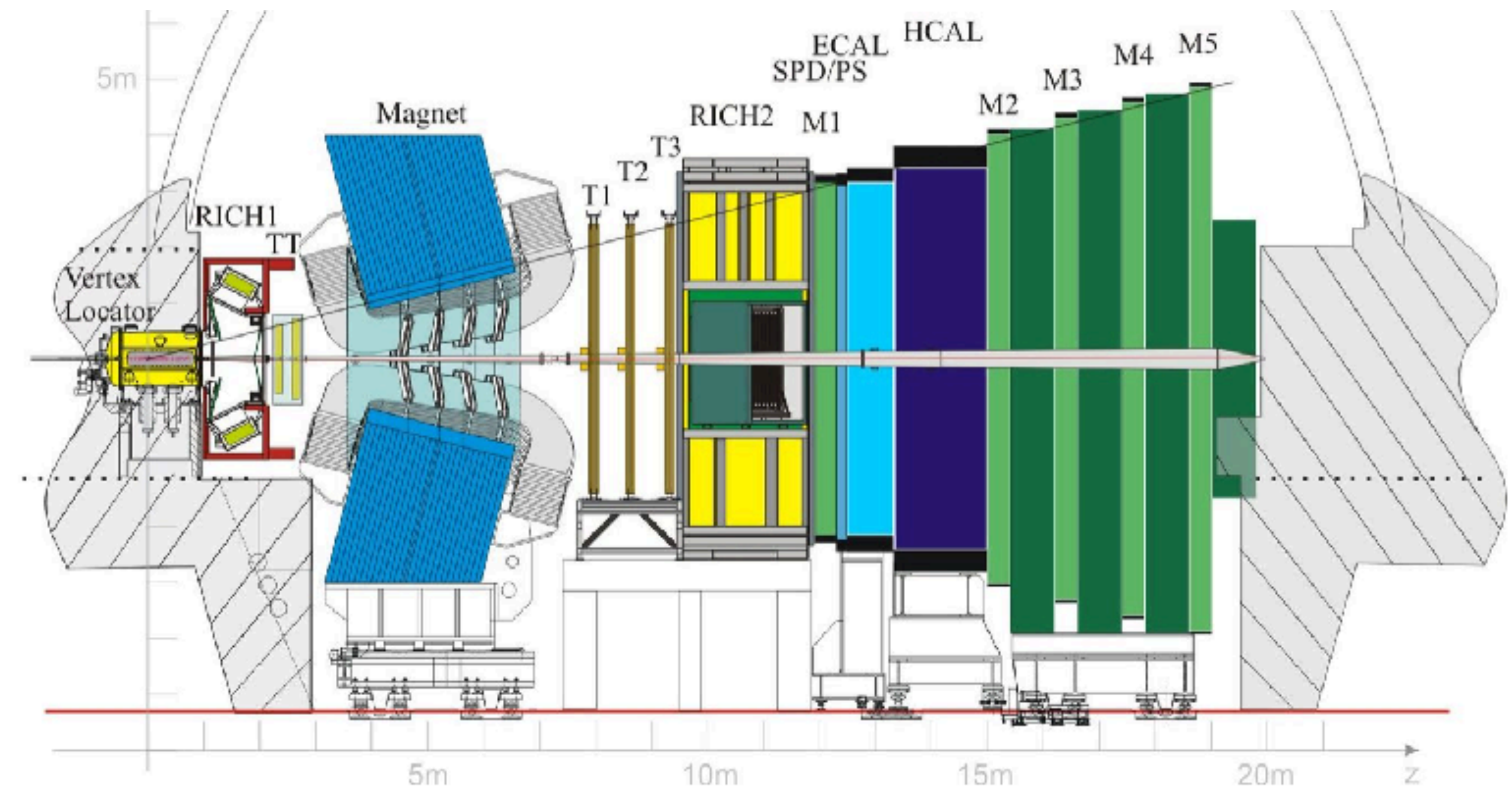


LHCb Detector Performance
[Int. J. Mod. Phys. A 30 (2015) 1530022]

The LHCb detector

Ingredients for good spectroscopy measurements

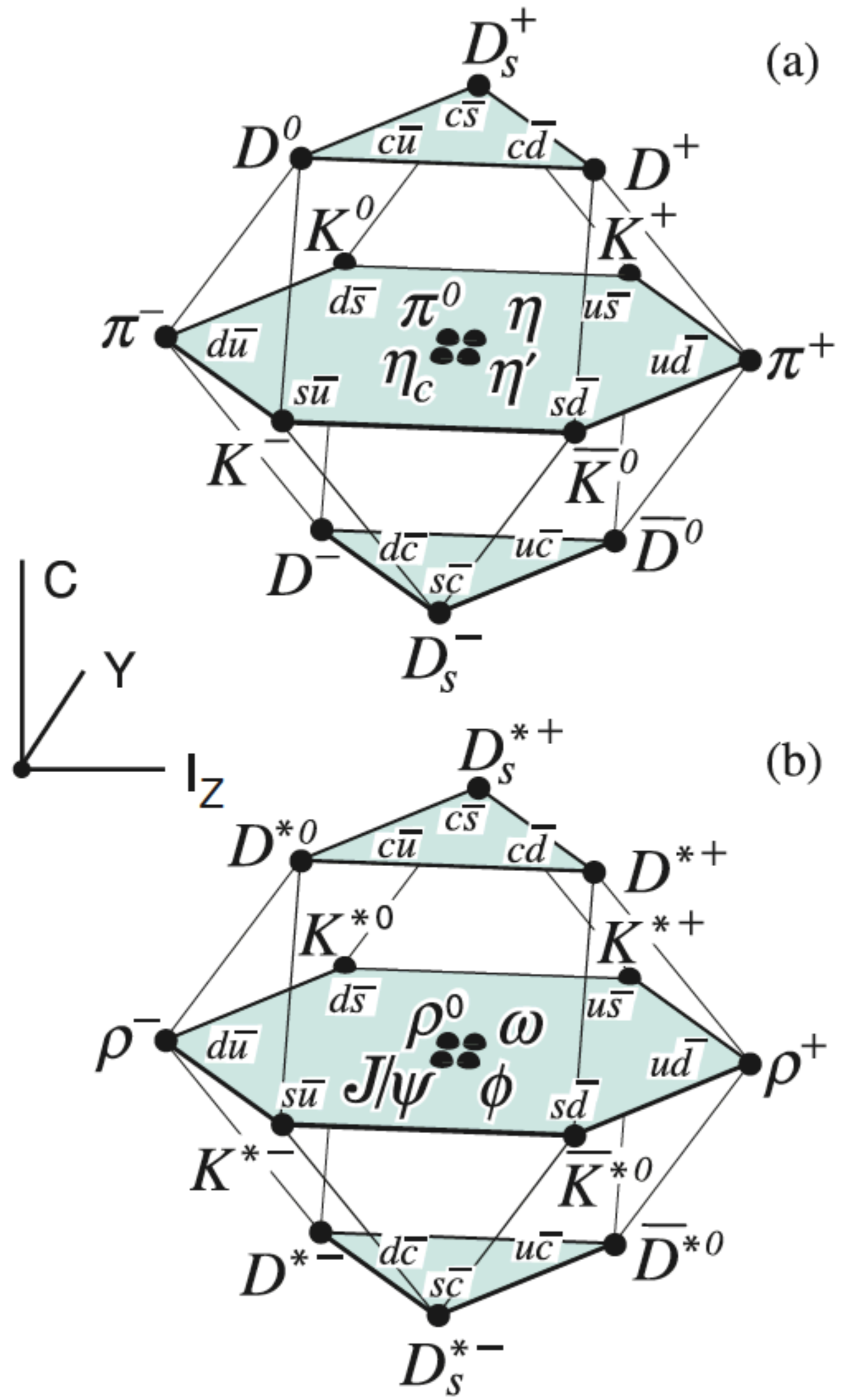
- **Excellent tracking** → mass and lifetime resolutions
- **Particle Identification** → important when dealing with charged hadrons in final states
- **Trigger efficiency** → use of muons & topological trigger give excellent efficiency



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

Spectroscopy multiplets

- I cannot start without showing the hadron multiplets and the "eightfold way"
- Still a lot of expected states not observed experimentally, yet
- **Also beyond so-called "conventional hadrons" we have so-called exotic states**



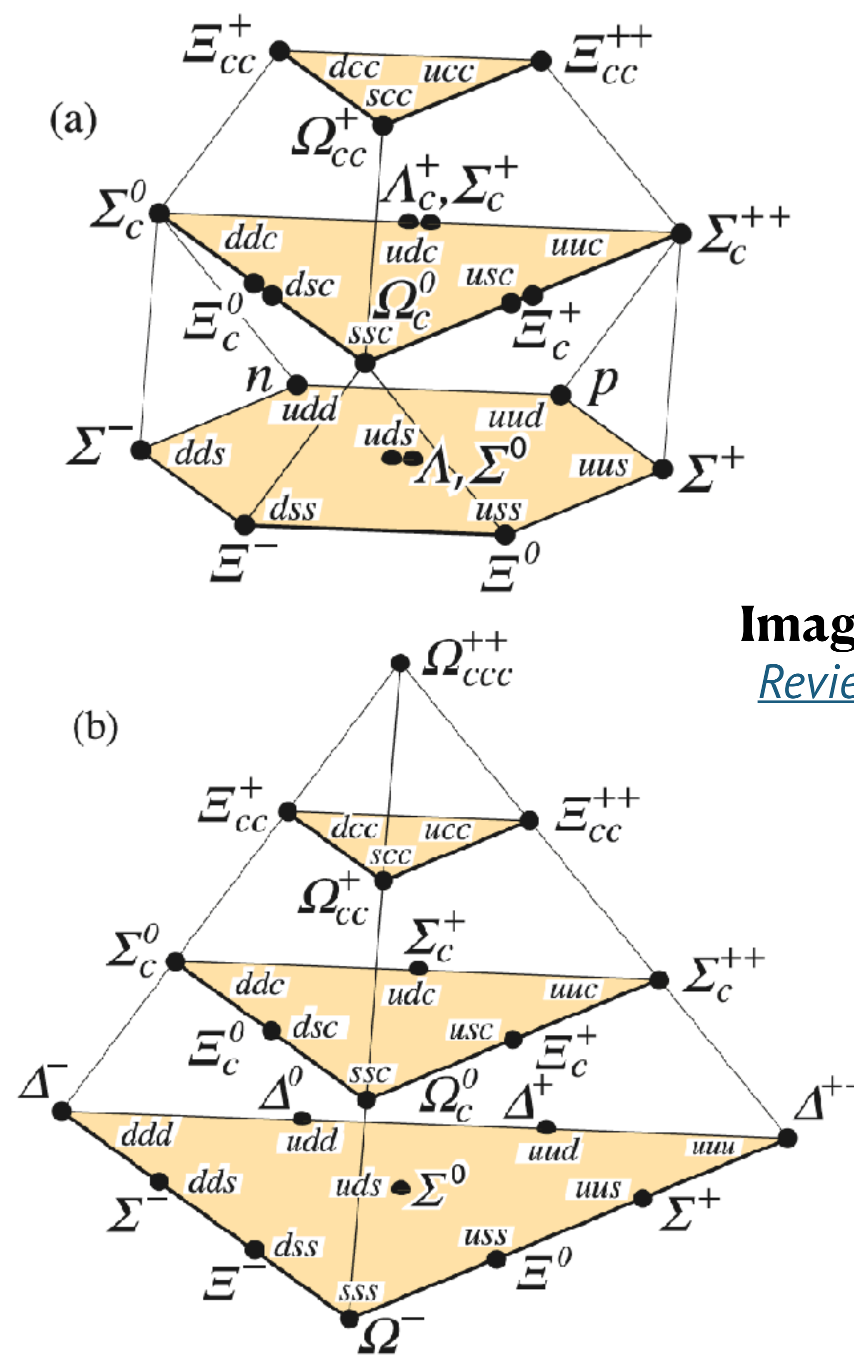


Image taken from PDG
Review of Particle Physics

"Conventional" and "Exotic"

- Jargon terminology: "exotic" is whatever does not fit in the qqq or $q\bar{q}$ scheme
- Actually even "exotic" combinations were predicted while ago, along with their "conventional" counterparts
- I will not go into the details of molecular/compact object… (still debate ongoing)

SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

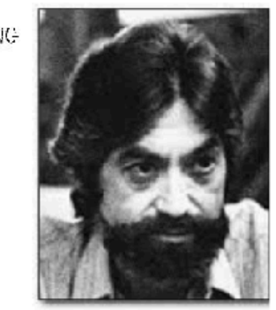
Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), (qqqq$\bar{q}$), etc., while mesons are made out of (q$\bar{q}$), (qq$\bar{q}\bar{q}$), etc. It is assuming that the lowes

Interesting to note the rise of citations since LHC start

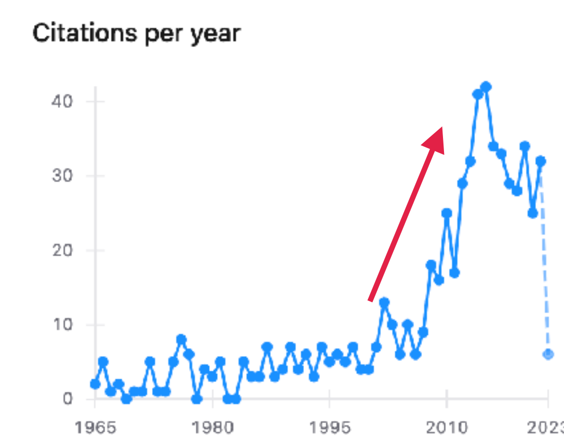
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva



In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}$AAAA, $\bar{A}\bar{A}$AAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}$A, $\bar{A}\bar{A}$AA etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}$A and AAA, that is, "deuces and treys".

Mostly cited together…



Scientists discovering new particles…

DALL·E History Collections

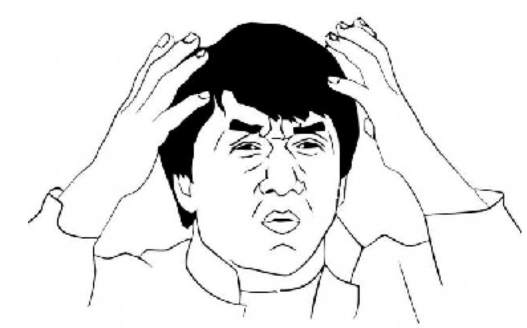
This is what happens when you ask to a modern AI

Images generated by DALL-E artificial intelligence

Edit the detailed description

an expressionist painting of a CERN physicist discovering new particles

Generate



NB

Fortunately
Everyone is represented

All have a
Lab coat!

Scientists discovering new particles…

And using Midjourney
More oniric… less inclusive

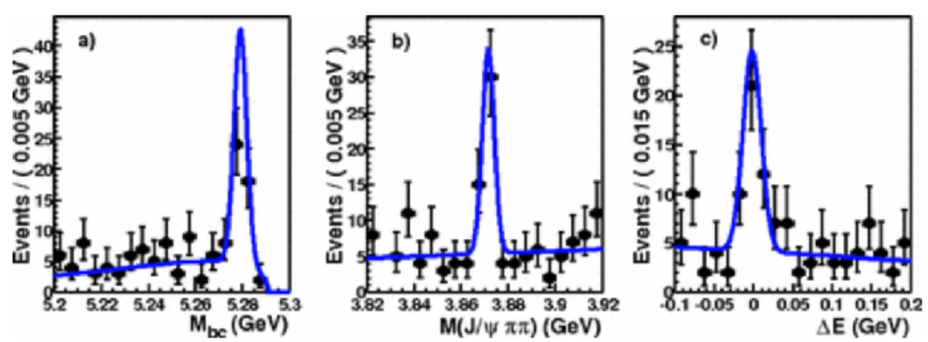
Belle - Belle2 - Babar - BESIII

- This talk focuses on experimental results at LHC
- But we cannot forget the contributions from other experiments!
- Pioneering work on X, Y, Z states
- E.g. the then-called X(3872) was observed for the first time by Belle in 2003 Phys. Rev. Lett. 91, 262001
- Still debate ongoing on its nature
- 2013: LHCb has determined the quantum numbers to be 1^{++} Phys. Rev. Lett. 110, 222001

Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

S.-K. Choi *et al.* (Belle Collaboration)
Phys. Rev. Lett. **91**, 262001 – Published 23 December 2003

Phys. Rev. Lett. 91, 262001

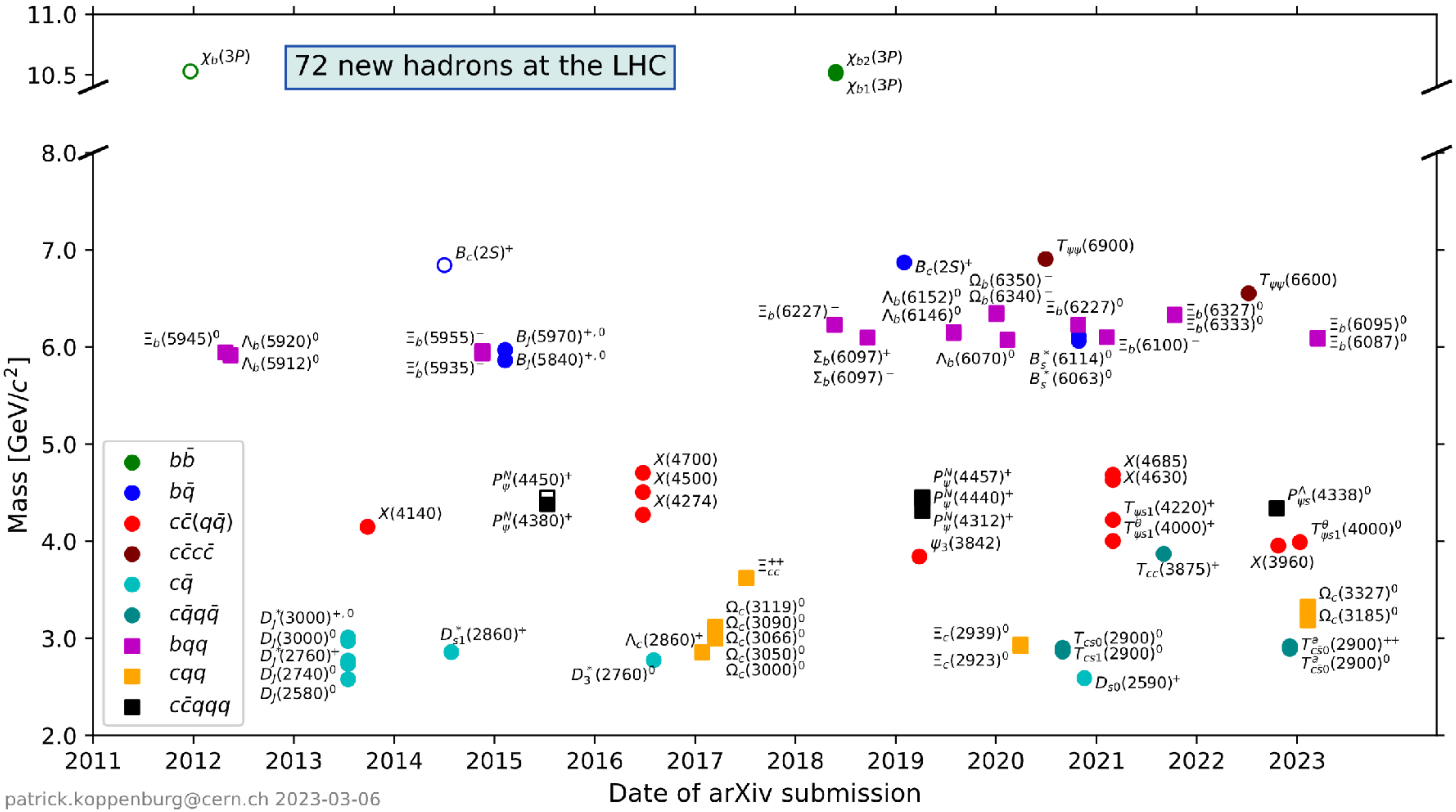


Determination of the $X(3872)$ Meson Quantum Numbers

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **110**, 222001 – Published 29 May 2013

New observations at LHC

- **Spectroscopy is a super-active field at LHC and all the experiments are contributing!**
- So far 72 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 2023 updates.

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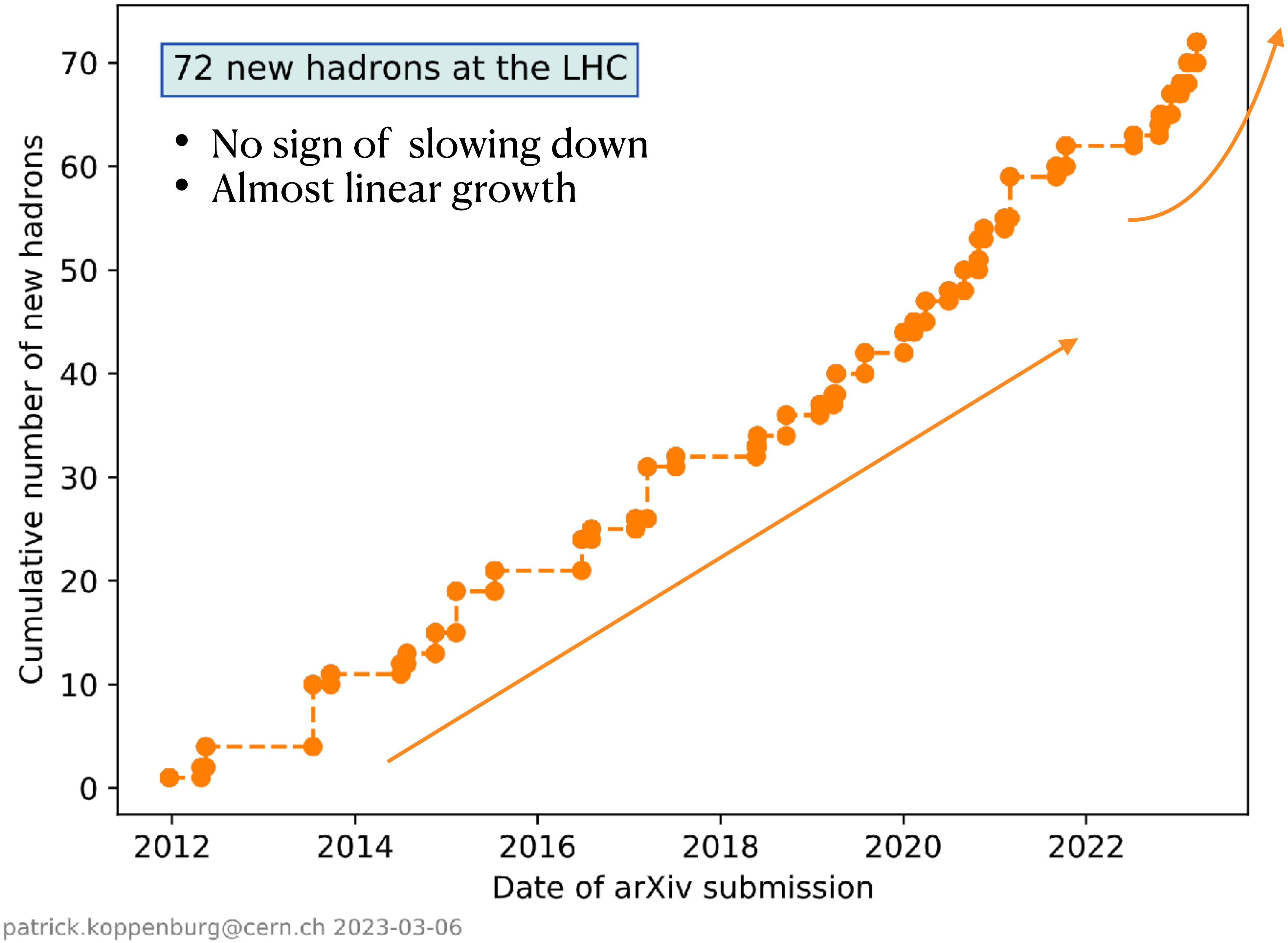

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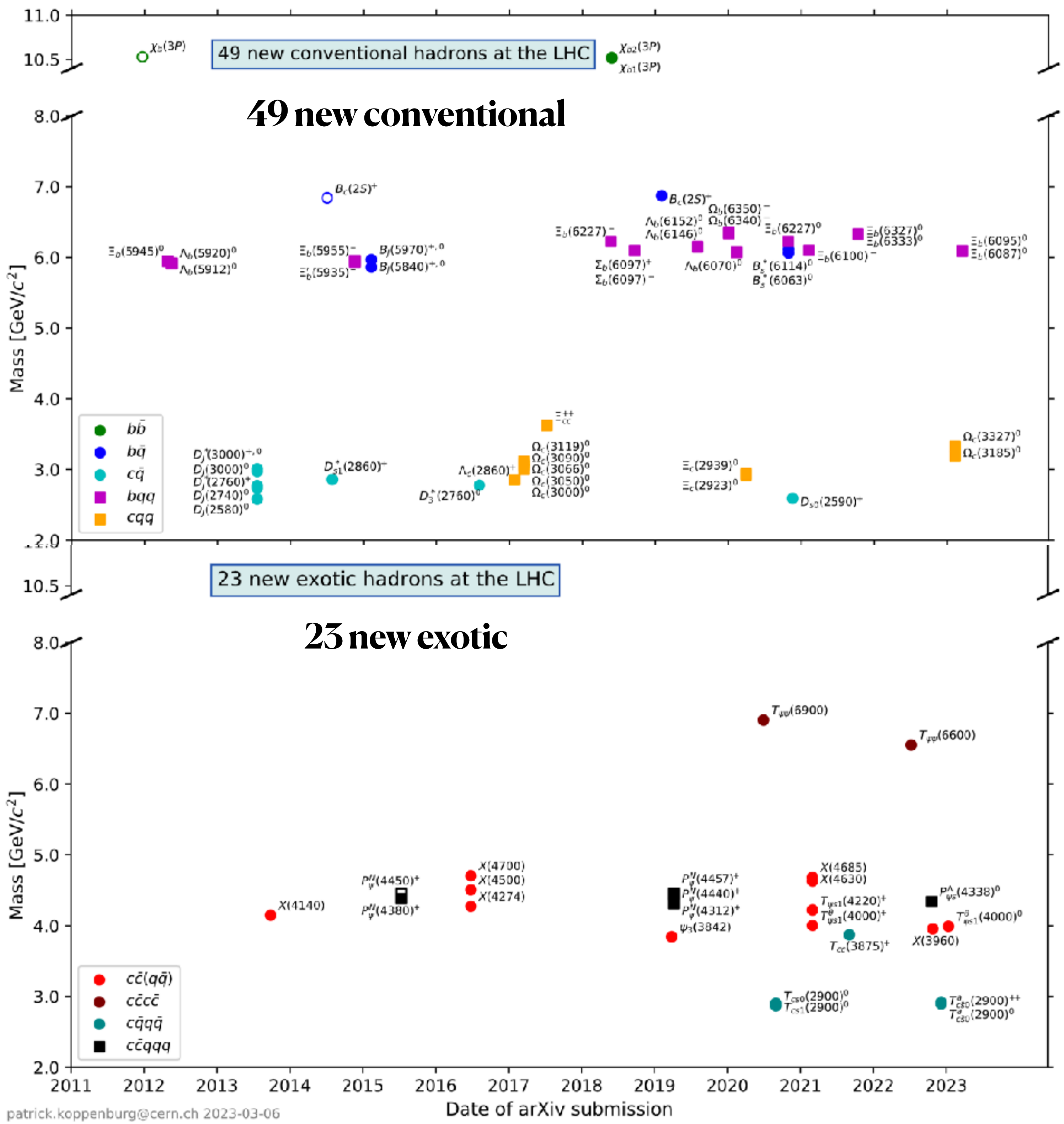
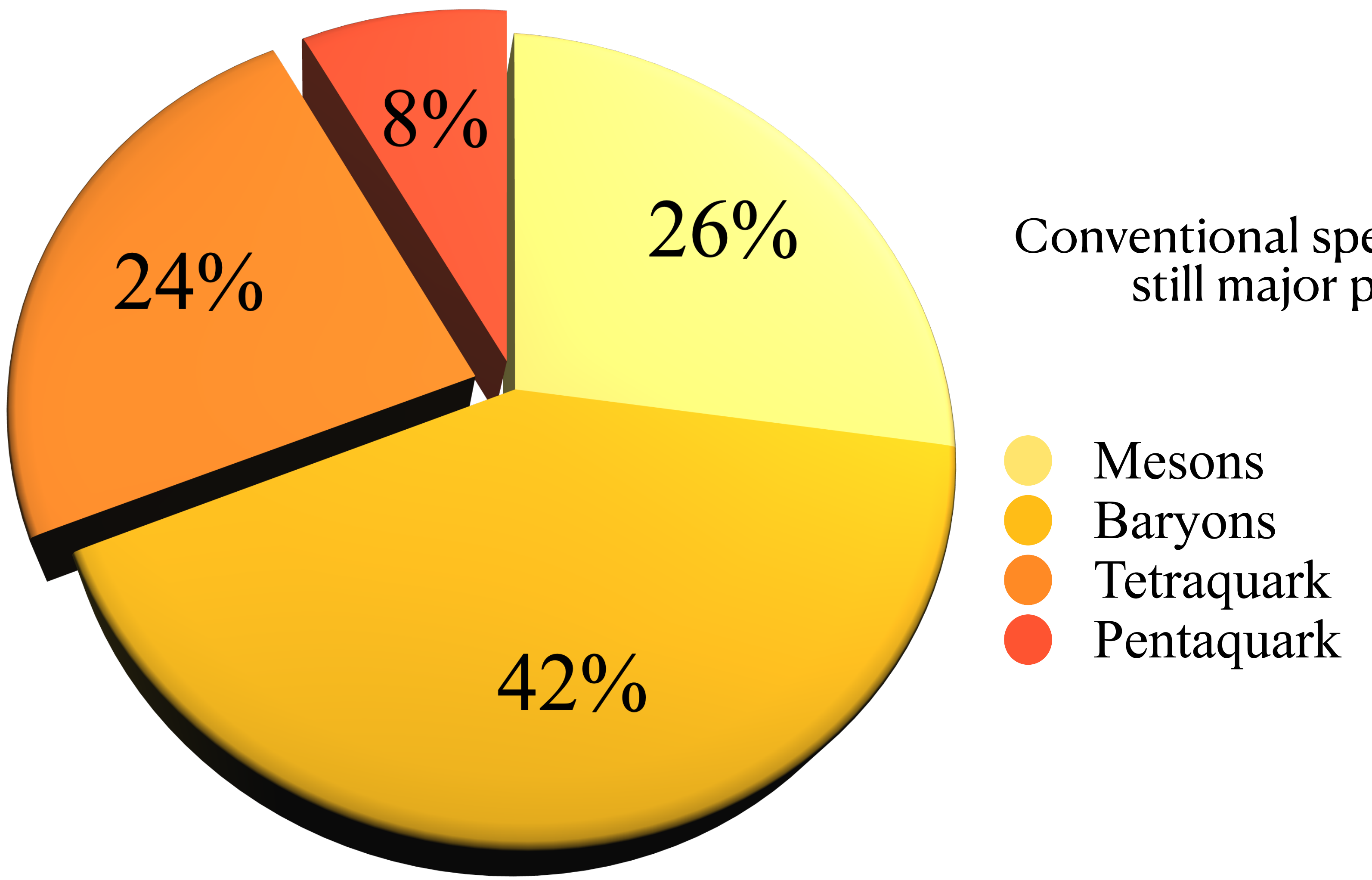


LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.

New observations at LHC

- Observations in both the charm and the bottom sector
- Baryons represented quite abundantly → no competition from other sources than LHC
- Exotics are being observed copiously in channels not available before
- Also different analysis methods (in production, in decay)



Conventional spectroscopy still major player

LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.

A recap on naming convention

- Baryons have probably a less known nomenclature

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)

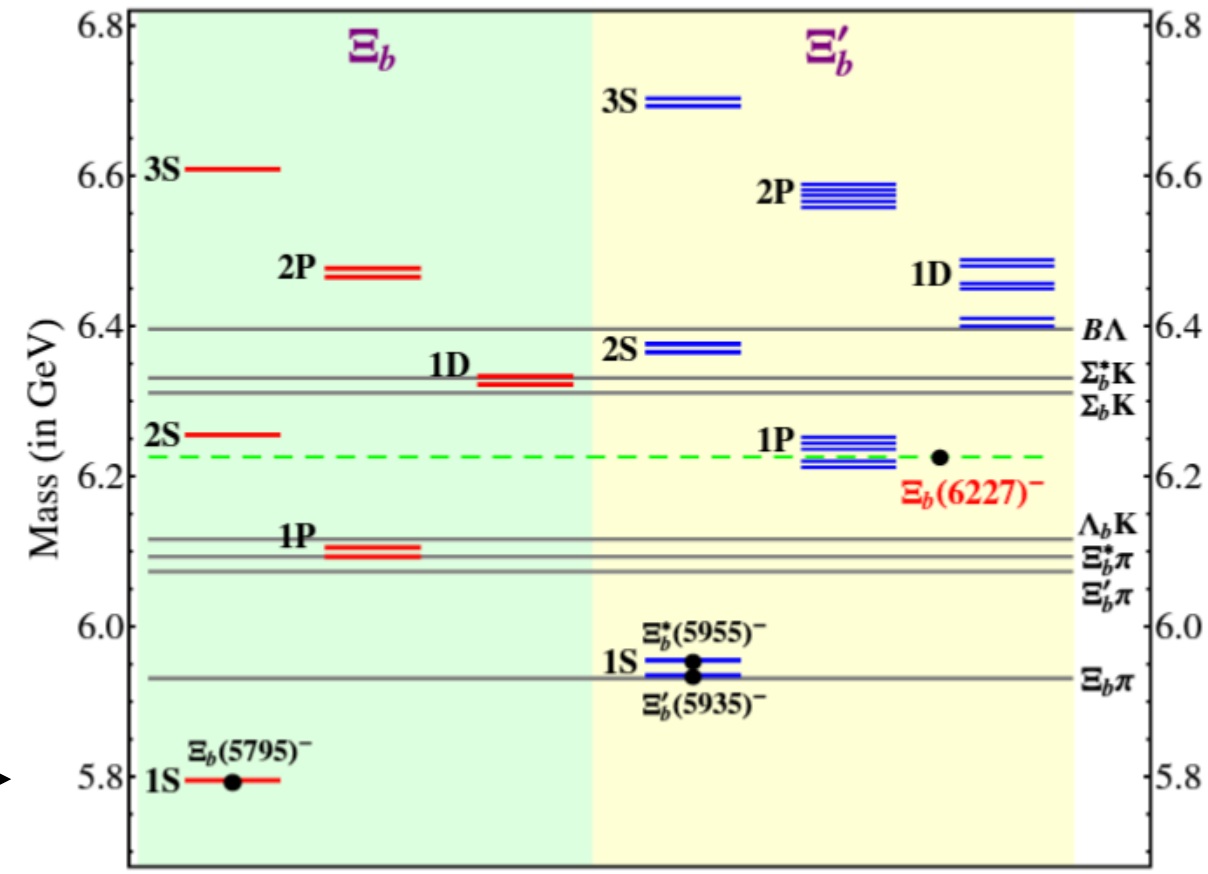


FIG. 2. The obtained masses for the bottom-strange baryons. The red solid lines (left) correspond to the predicted masses of Ξ_b states which are composed of a good diquark and a bottom quark, while the blue solid lines (right) correspond to the Ξ'_b states which contain a bad diquark. Here, we also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

New naming convention

arXiv 2206.15233

- **Many new exotic hadrons observed → some do not fit in the existing naming scheme for hadrons**
- Active discussion with PDG ongoing (and other experiments)
- Current scheme does not fully cover states with manifestly exotic quantum numbers
- LHCb proposed a new scheme extending the existing protocol to provide a consistent naming convention
- Future proof for new discoveries (hopefully…)

The impact on various recently discovered hadrons

Minimal quark content	Current name	$I^{(G)}, J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+,\ J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+, J^{PC} = 1^{++}$	$\chi_{c1}(4140)$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2},\ J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2},\ J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+,\ J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$

- **T for tetraquark**
- **P for pentaquark**
- **Clever system of**
  - Superscript for isospin parity and Parity
  - Subscript for the quark content (open or hidden)

New naming convention

arXiv 2206.15233

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- Active discussion with PDG ongoing (and other experiments)
- Current scheme does not fully cover states with manifestly exotic quantum numbers
- LHCb proposed a new scheme extending the existing protocol to provide a consistent naming convention
- **Future proof for new discoveries (hopefully...)**

Actually,

I received a comment from a colleague stating that

“Your slide looks good, although personally I hope that the new scheme is ***not*** future-proof for new discoveries, as that would mean we have discovered something not covered in the scheme (e.g. a heavy-flavoured dibaryon). Of course if that happens the scheme can be extended ..."

And this shows how we are impatiently looking for new data and ready for new searches!

Some history…

This talk is not meant to be just a chronological collection of results
Rather and organic description of highlights and some successful techniques
+
A few selected results

Pentaquarks and Tetraquarks

- Several results drew attention in press
- Some results were actually unforeseen from the initial LHCb roadmap → LHCb is truly a GPD
- Here is just a small recap: milestones

2015

Phys. Rev. Lett. 115, 072001

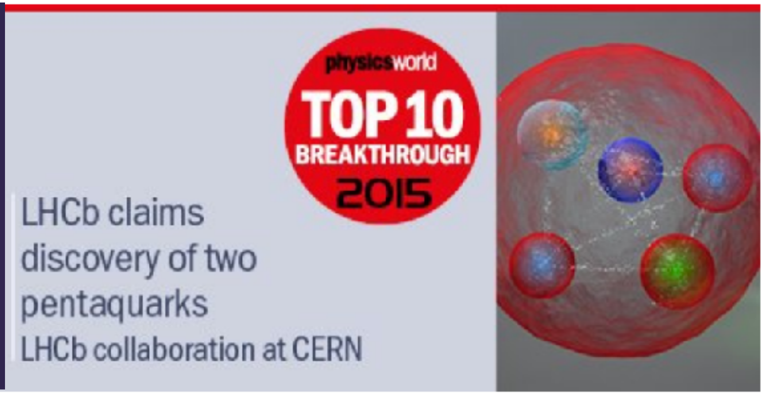
Featured in Physics · Editors' Suggestion · Open Access

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **115**, 072001 – Published 12 August 2015

Physics See Viewpoint: Elusive Pentaquark Comes into View

Was $P_c(4450)^+$. Later resolved into $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$.



2016

Phys. Rev. Lett. 118, 022003

Editors' Suggestion · Open Access

Observation of $J/\psi\phi$ Structures Consistent with Exotic States from Amplitude Analysis of $B^+ \to J/\psi\phi K^+$ Decays

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **118**, 022003 – Published 11 January 2017

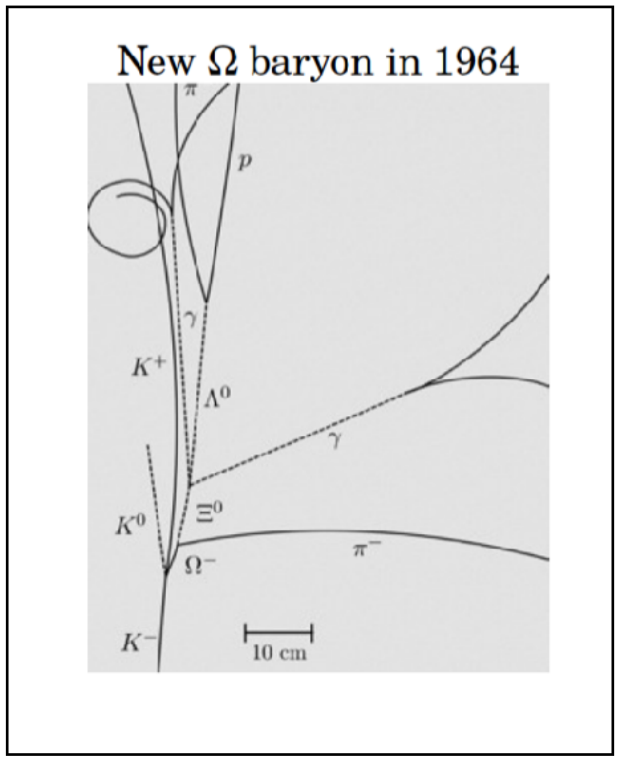
\+ **many other more recent observations**

Really difficult to make justice to so many nice results

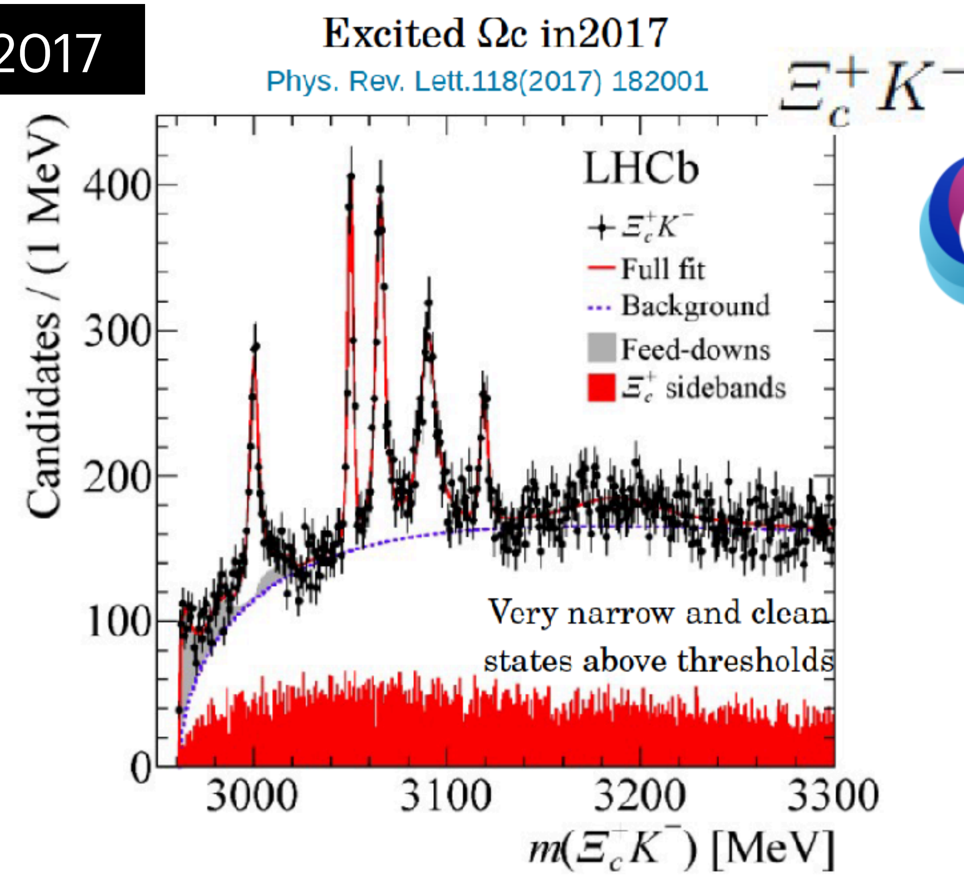
Observation of five new narrow Ω^0_c states $\rightarrow \Xi_c^+ K^-$

- Surprises even in "conventional" baryon spectroscopy… 5 states at the same time!

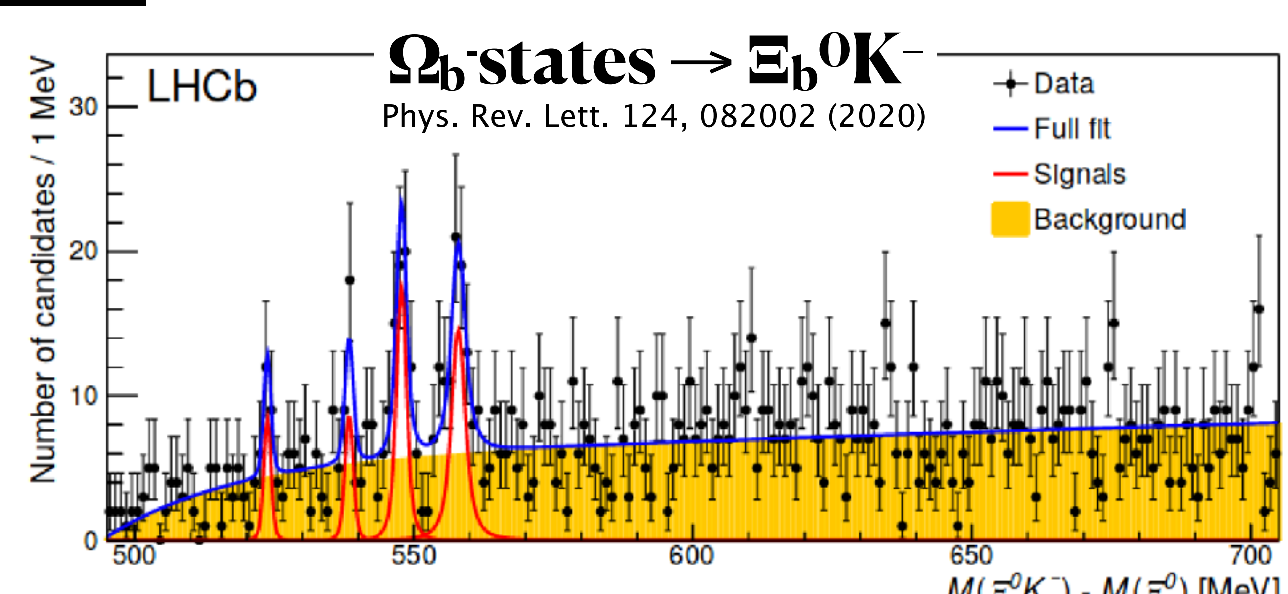
First observation of sss state



2017



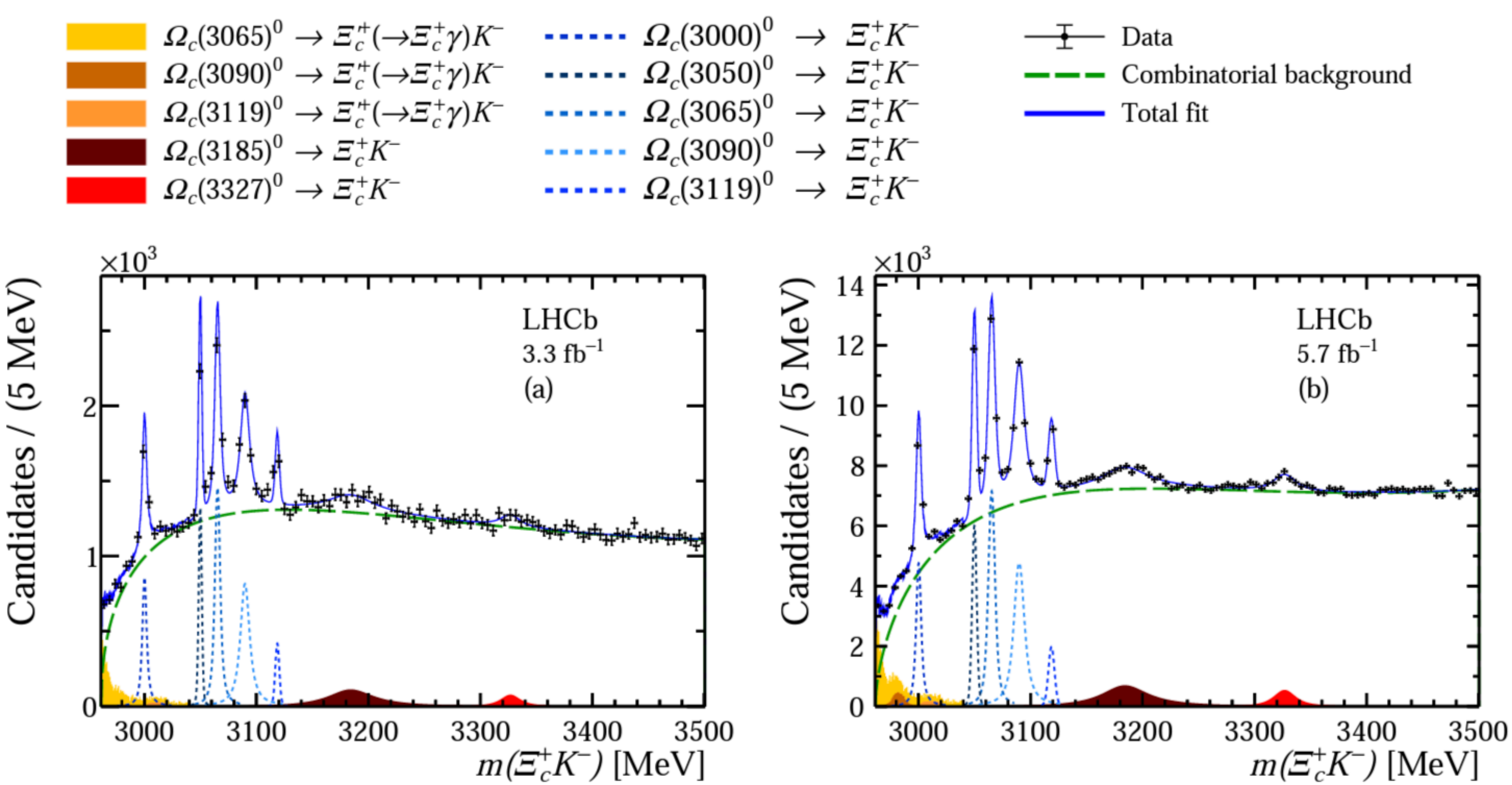
2020



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

2023 arXiv:2302.04733

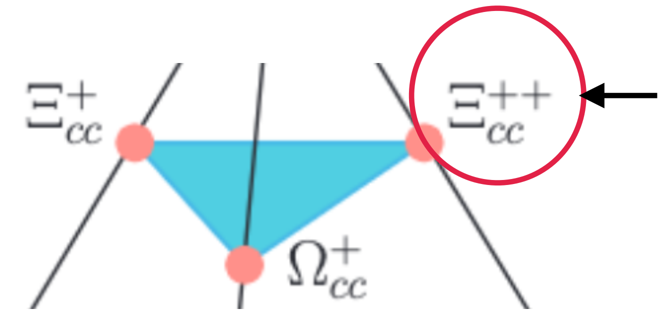
- Very recent paper with the observation of two new broad states
- Two new excited states, $\Omega_c^0(3185)0$ and $\Omega_c^0(3327)$, are observed
- Still debate on the spin-state assignment
- Several studies of possible feed-downs from higher mass resonances are considered



Doubly heavy Ξcc^{++}

2017

- Not only strong decays → first observation of double-heavy baryons
- Start of a new field of spectroscopy…



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	$D^+ p K^- \pi^+$

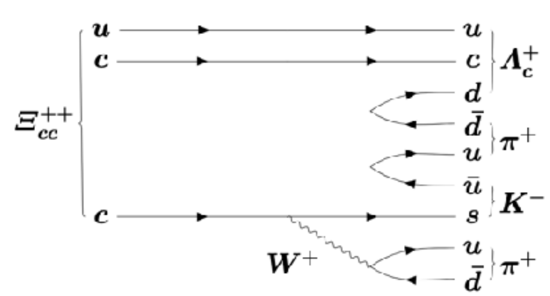
+

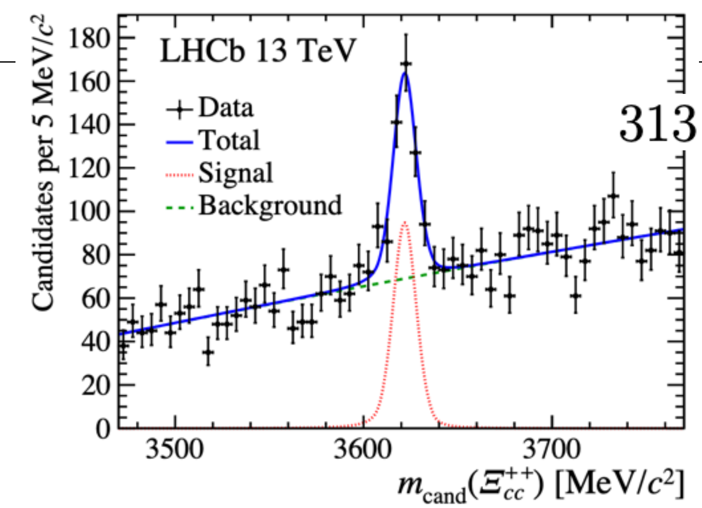
$\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+$

JHEP 05 (2022) 038

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

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

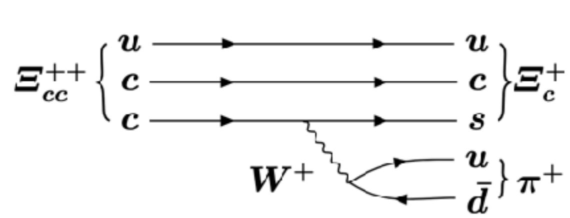


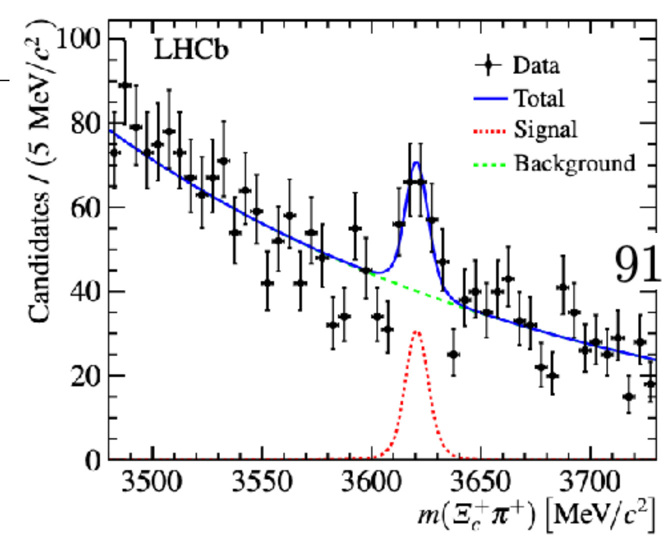


313 ± 33

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

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



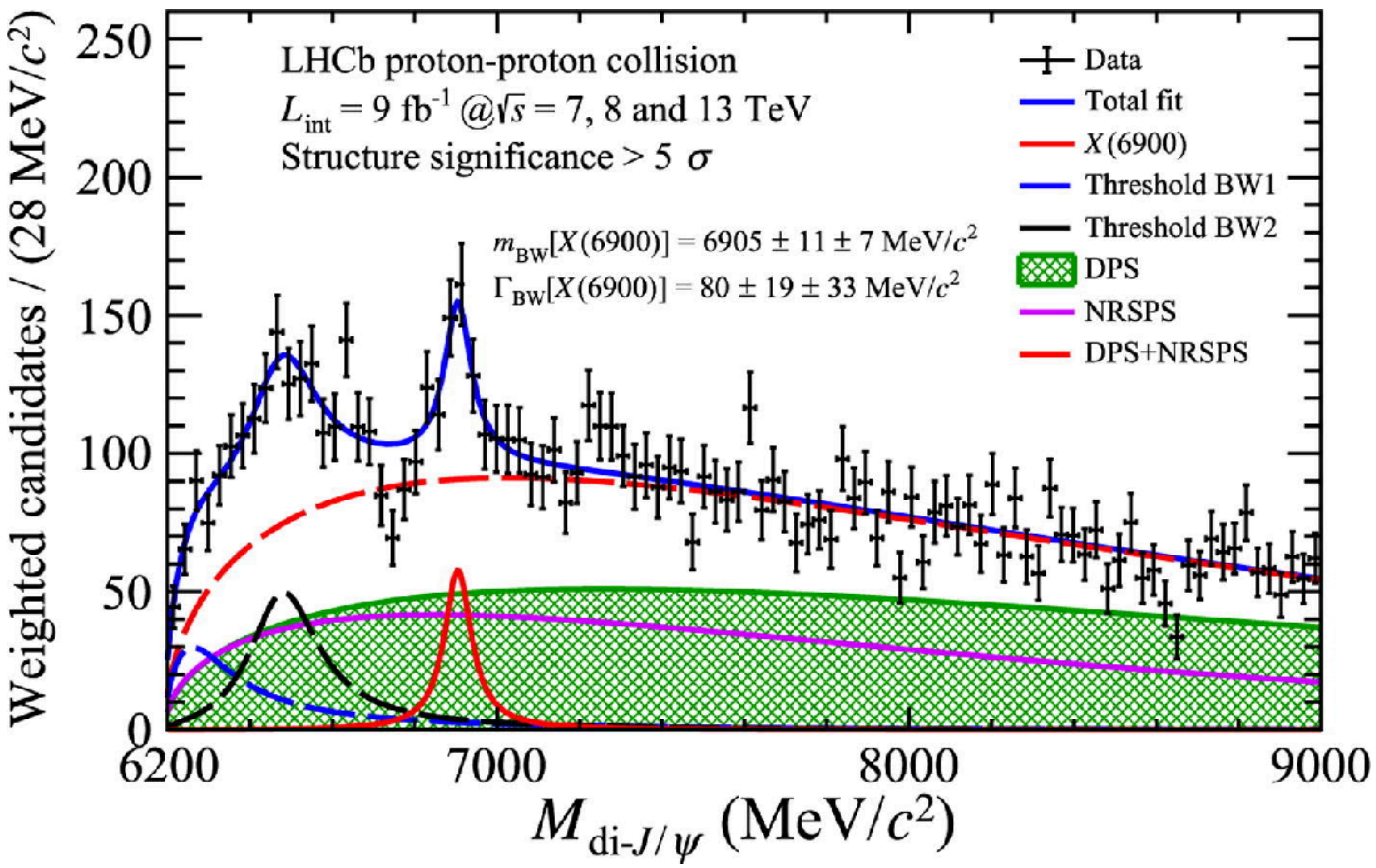


91 ± 20

Observation of a J/ΨJ/Ψ resonance

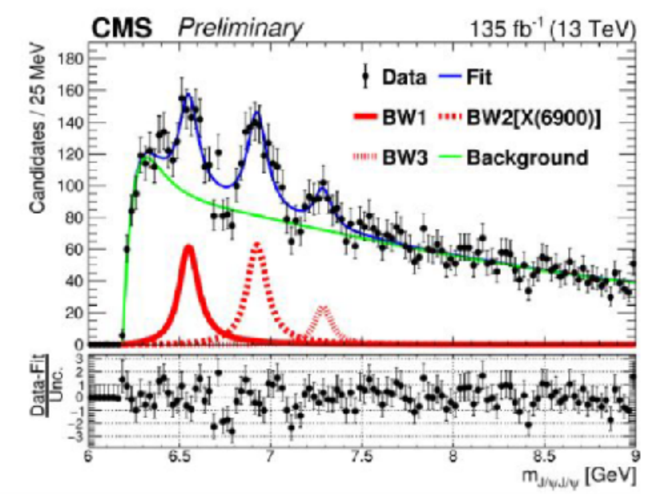
2020 Science Bulletin 65 (2020) 1983

- LHCb announced the possible discovery of a four-charm quark tetraquark in J/ΨJ/Ψ
- LHCb observation of X(6900) confirmed both by CMS and ATLAS
- Discussion on how to interpret the states and spectrum still ongoing



CMS-PAS-BPH-21-003

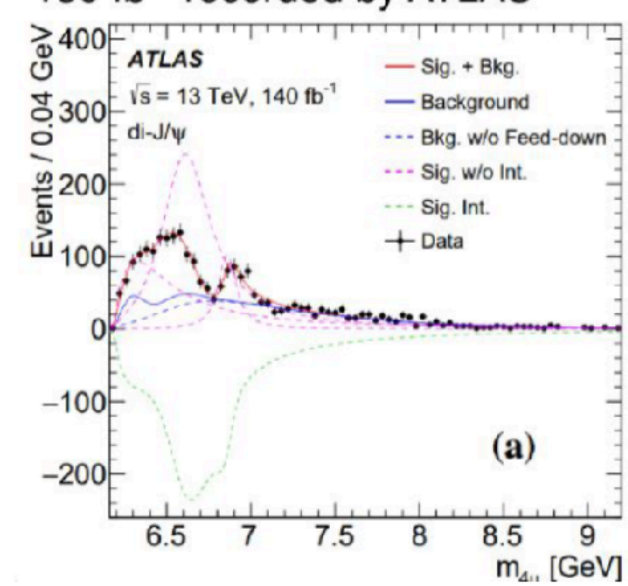
135 fb^{-1} recorded with the CMS



[Submitted on 18 Apr 2023]

arXiv:2304.08962

139 fb^{-1} recorded by ATLAS



Observation of a new T_{cc}^{+} state

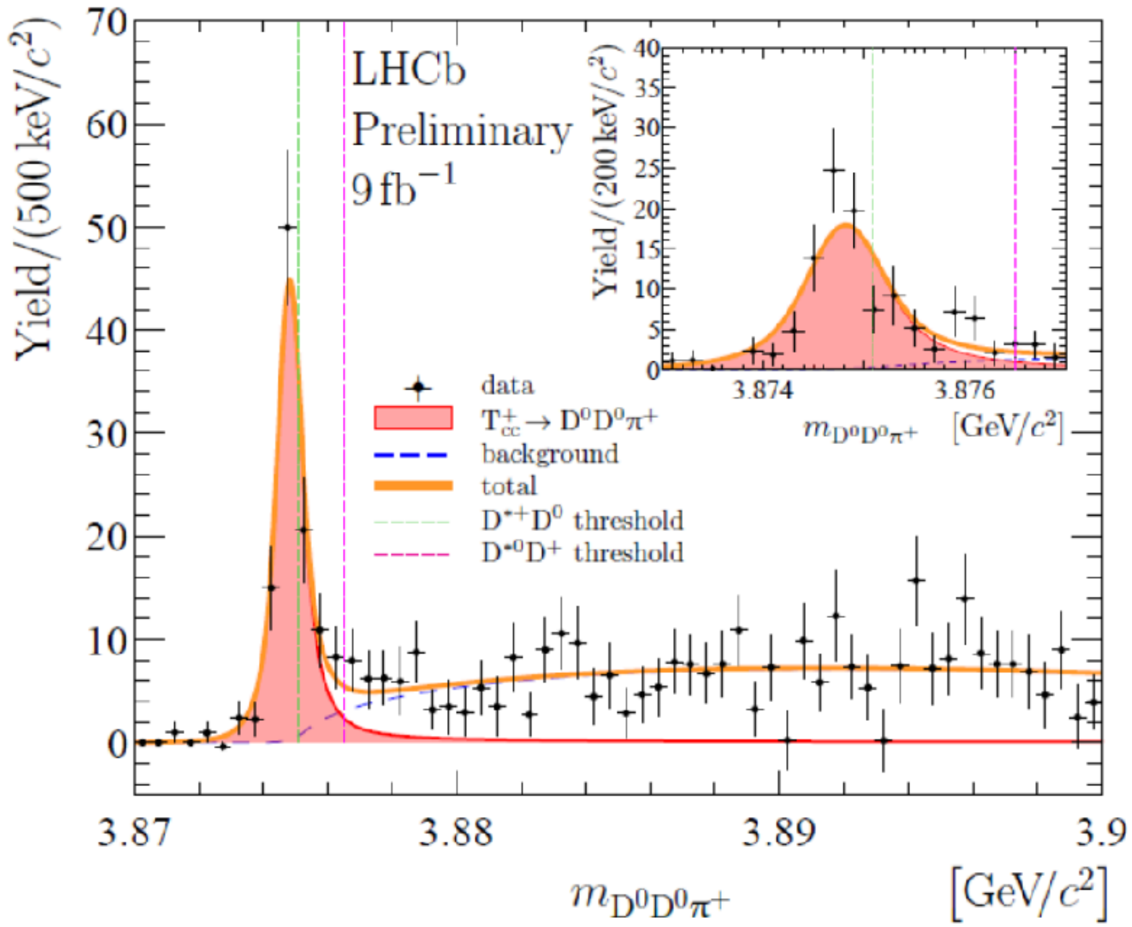
2021

Nature Physics volume 18, pages 751–754 (2022)

- Charged state with double charm content (two D meson with same "charge" in the same final state)
- Flavour not "hidden"
- Very narrow peak just above the threshold with striking significance over background

29 July 2021: Observation of an exceptionally charming tetraquark.

This week at the European Physical Society conference on high energy physics, EPS-HEP 2021 the LHCb Collaboration presented the first observation of a doubly charmed tetraquark, T_{cc}^{+}, with a new quark content $cc\bar{u}\bar{d}$. The newly discovered particle containing two heavy charm quarks is manifestly exotic, *i.e.* beyond the conventional pattern of hadron formation found in mesons and baryons. The tetraquark particle manifests itself as a narrow peak in the $D^0D^0\pi^+$ meson mass spectrum, just below $D^{*+}D^0$ mass threshold, with a statistical significance exceeding 20 standard deviations. The full Run 1 and Run 2 dataset was used to obtain this discovery.



- T_{cc}^{+}, with a new quark content $cc\bar{u}\bar{d}$
- Charged double-charmed state is manifestly exotic
- **Narrow peak in the $D^0D^0\pi^+$ meson mass spectrum**
- The new state is just below $D^{*+}D^0$ mass threshold
- Sample is extremely pure

- Subtract fake-D background using 2D fit to ($m_{K\pi}$, $m_{K\pi}$)
- No evidence in opposite sign sample

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

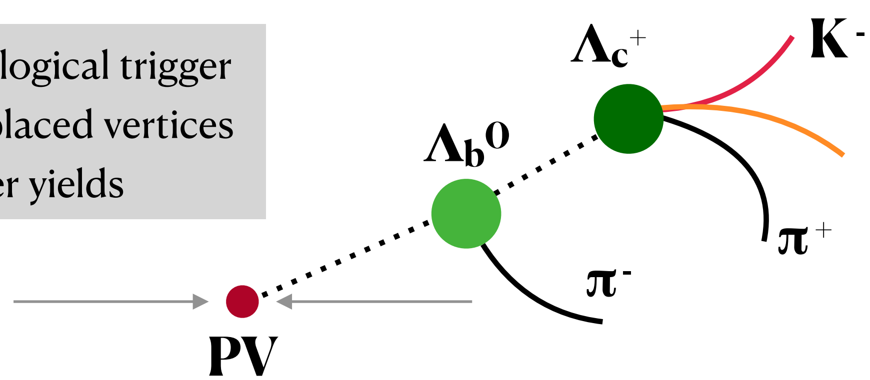
Di-Muon vs Topological triggers

JHEP 06 (2020) 136

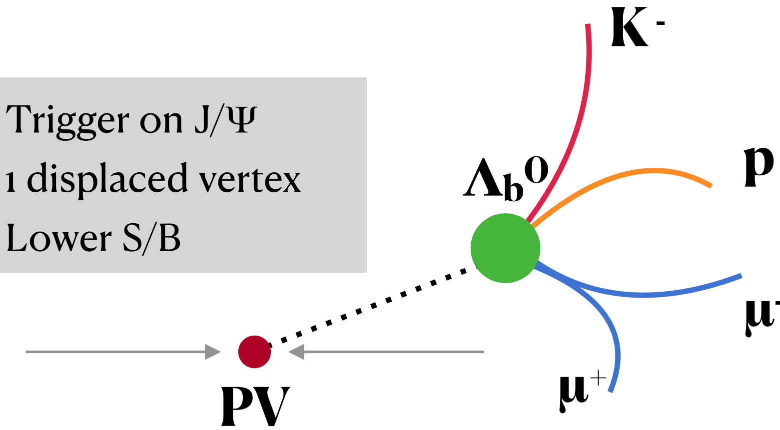
- **First job is to gather high yields to access rare states**
- Also, S/B ratio is important, especially for the most intricate analyses
- **As an example we can consider the Λ_b baryon. Standard candle for many b-baryon analyses**
- Also a clean control sample for many different tasks (calibration/BF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

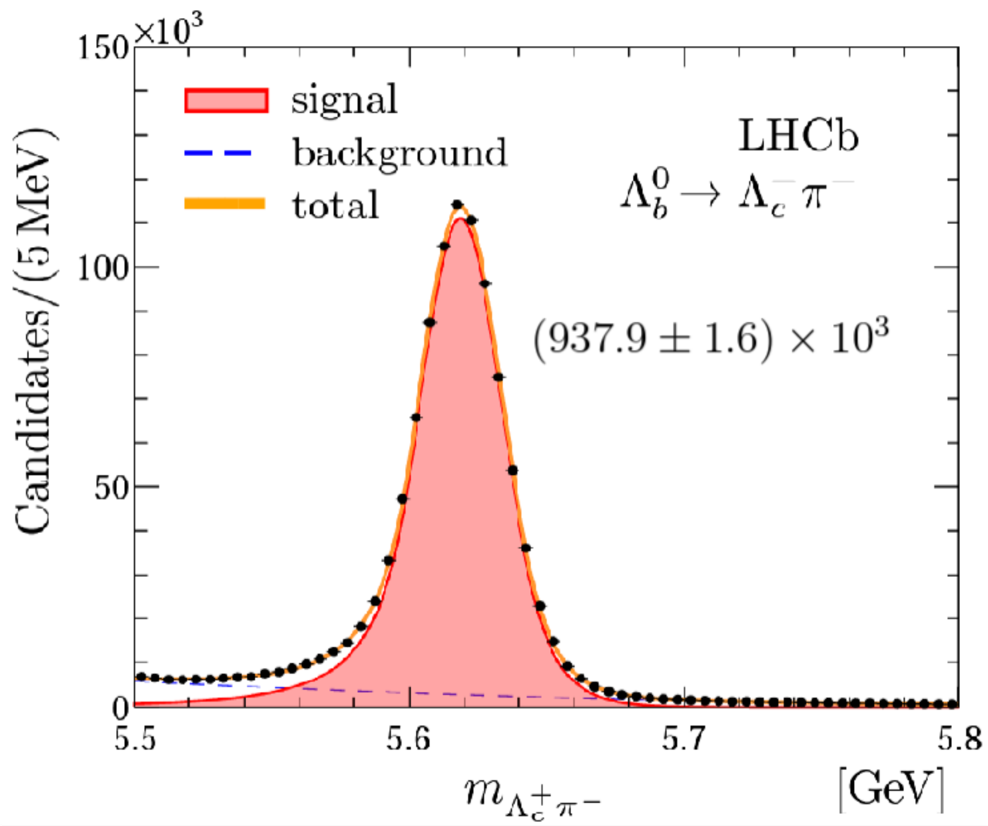
Most abundant b-baryon

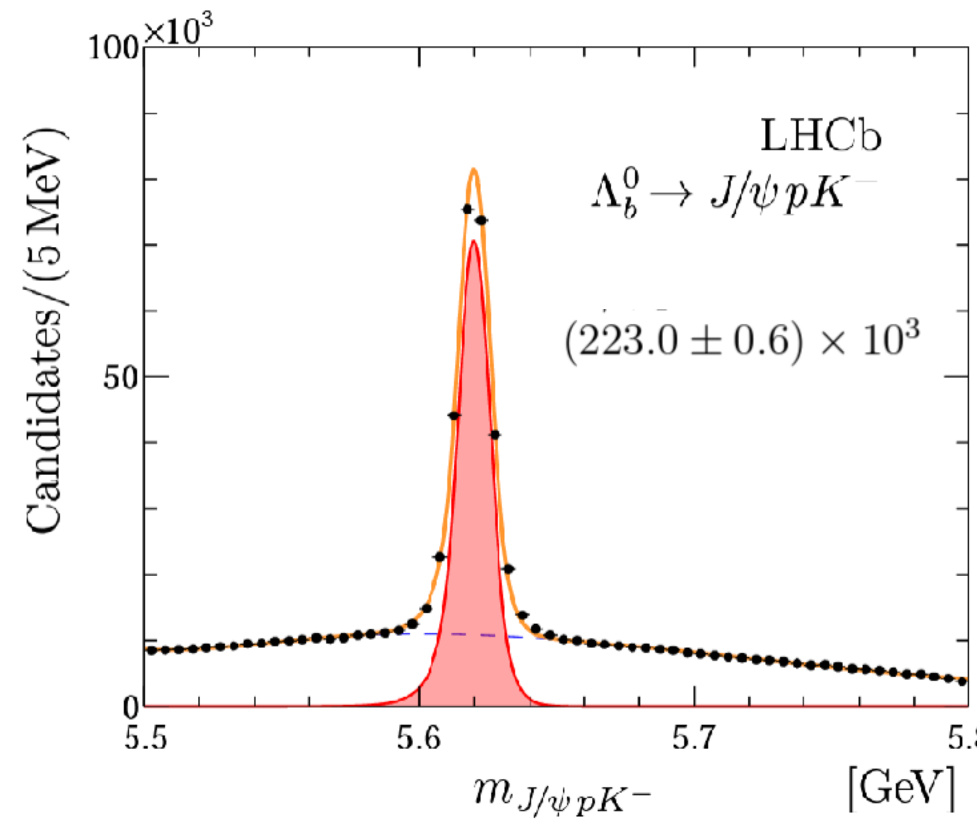
- Topological trigger
- 2 displaced vertices
- Higher yields



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



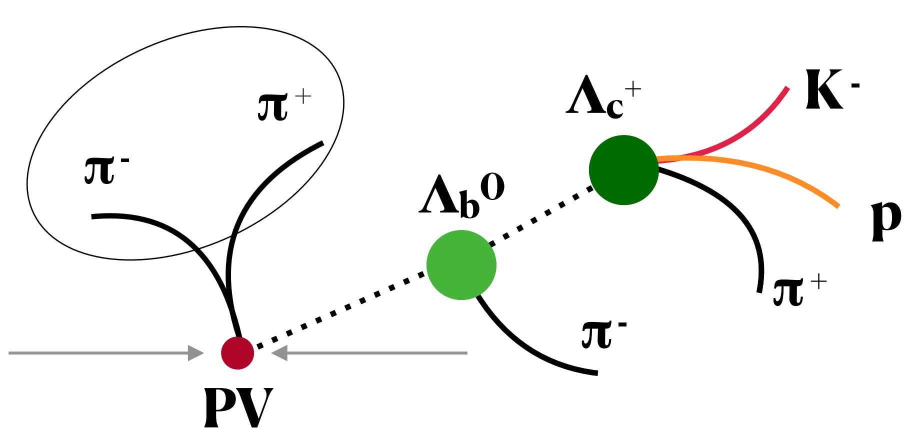


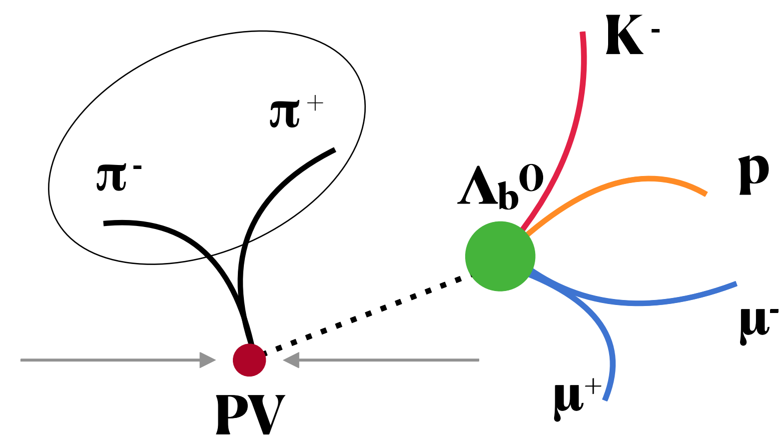


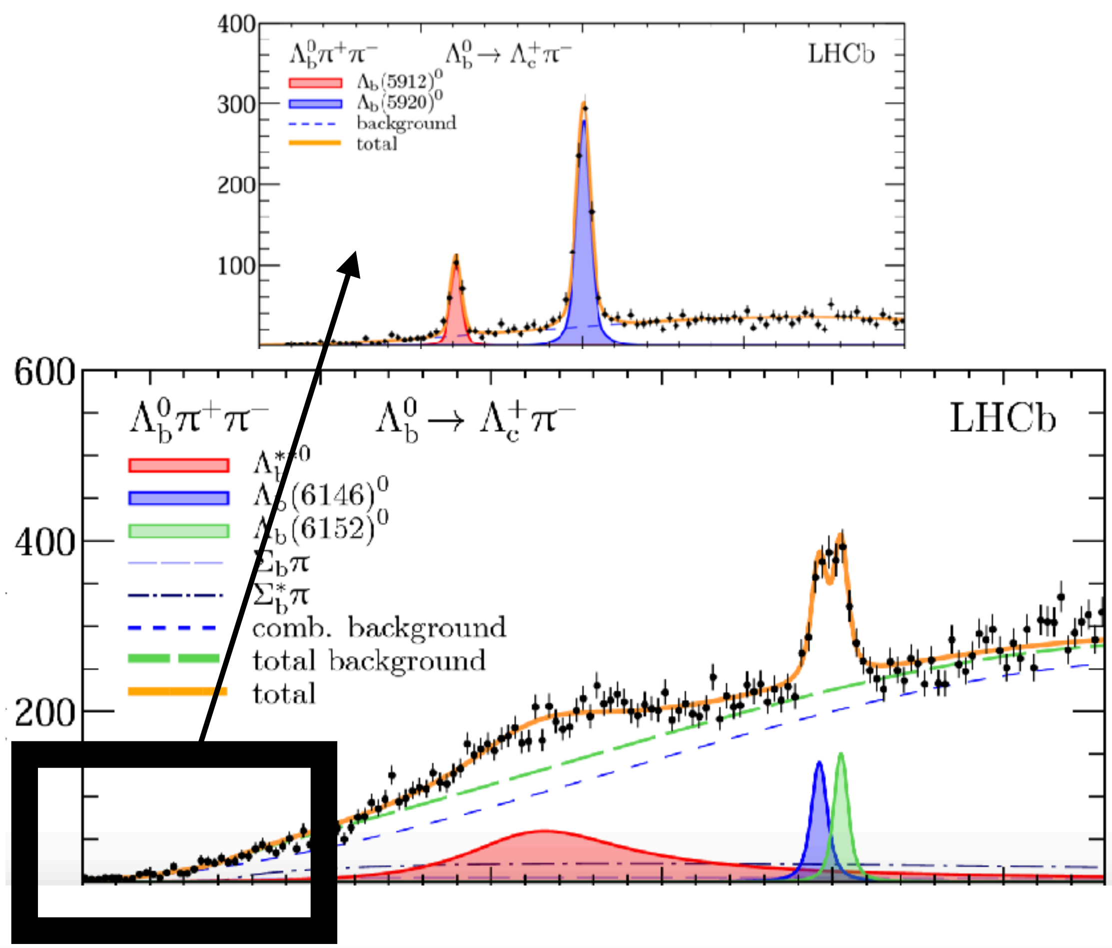
Extending the Q value regions

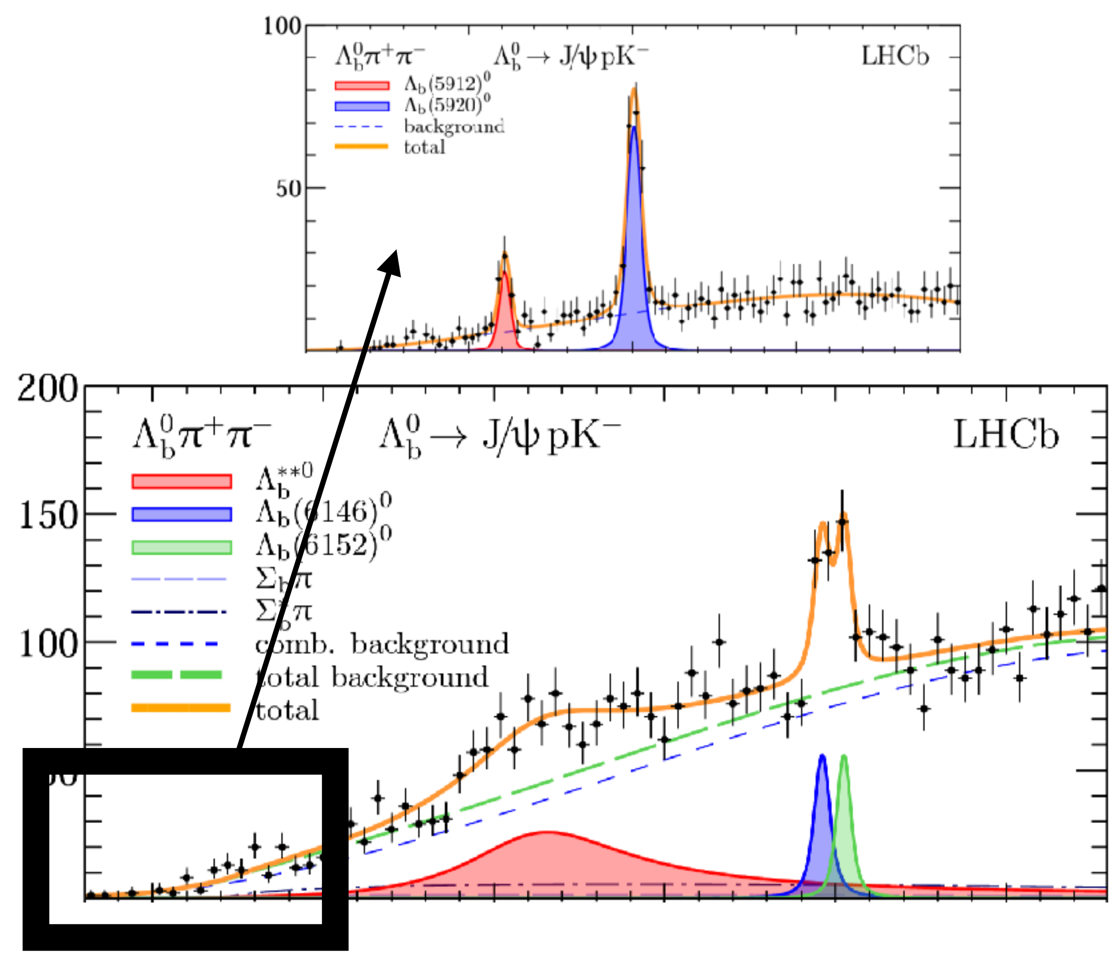
JHEP 06 (2020) 136

- **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}

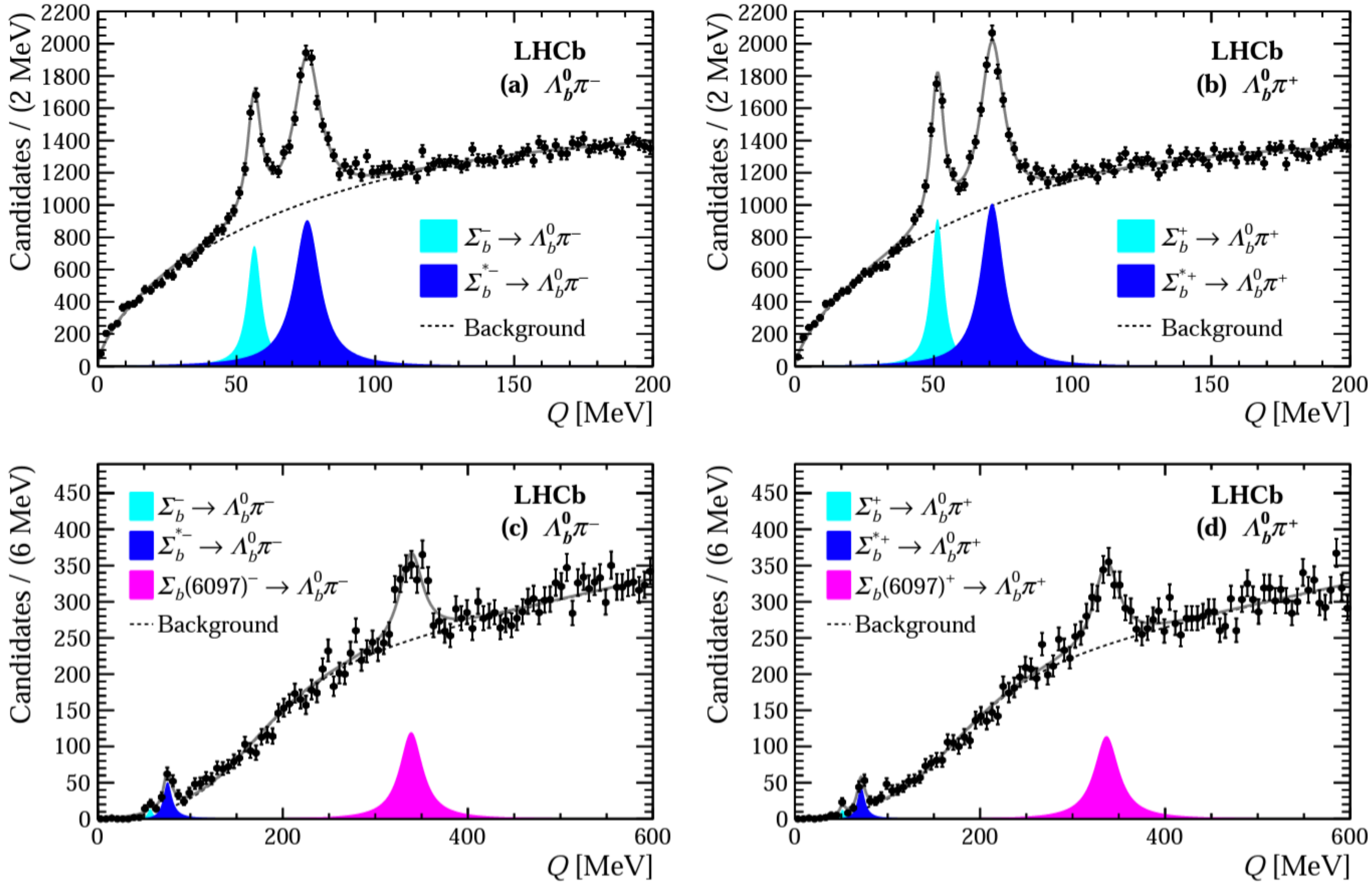
Missing States: example Σ_b^0

(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…

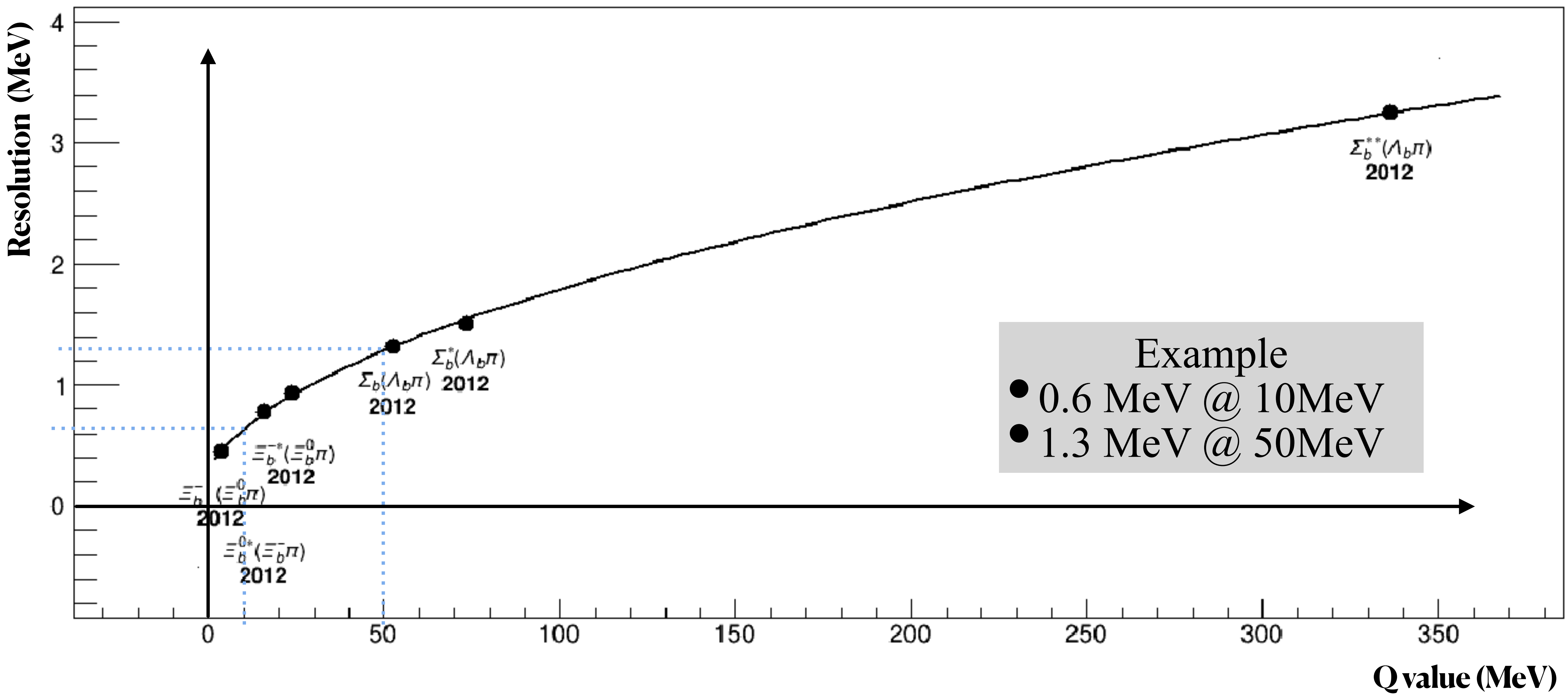
First observed by CDF
Searches then extended by LHCb

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 = $m(\Lambda_b\pi\pi) - m(\Lambda_b) - 2m(\pi)$



Latest search on baryon spectroscopy…

New!

First time presented
At Moriond QCD 2023

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

LHCb-PAPER-2023-008
In preparation

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

LHCb-PAPER-2023-008
In preparation

New!

- First investigation in LHCb of the final states $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$
- **Interesting physics system with still missing unobserved states**
- Masses expected close to threshold → experimental resolutions are small
- The CMS collaboration has reported the observation of the new $\Xi_b(6100)$ state in 2021

Phys. Rev. Lett. 126, 252003

Measurement using final states containing J/Ψ
Small yield (Γ not measured)
We usually use fully hadronic modes for this searches

Good example of complementarity of different experiments

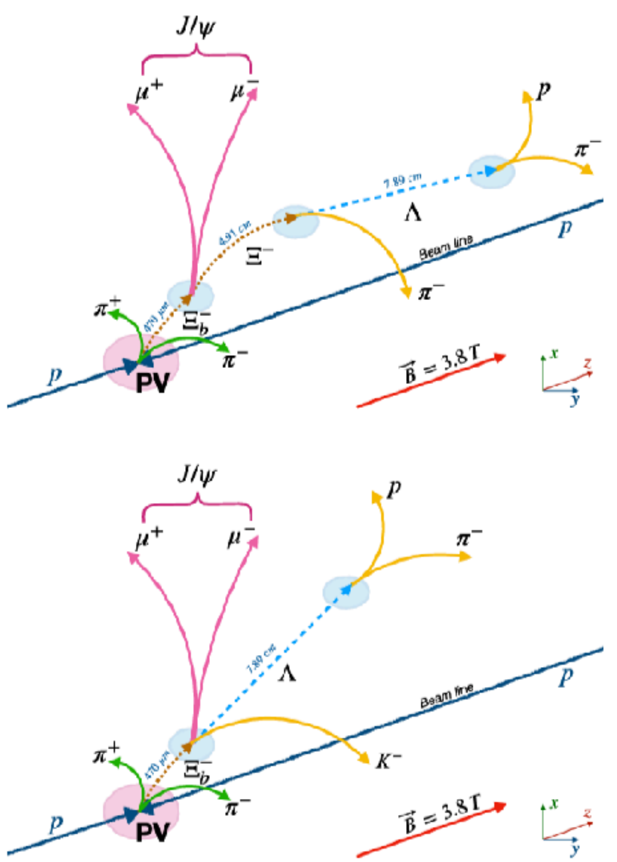
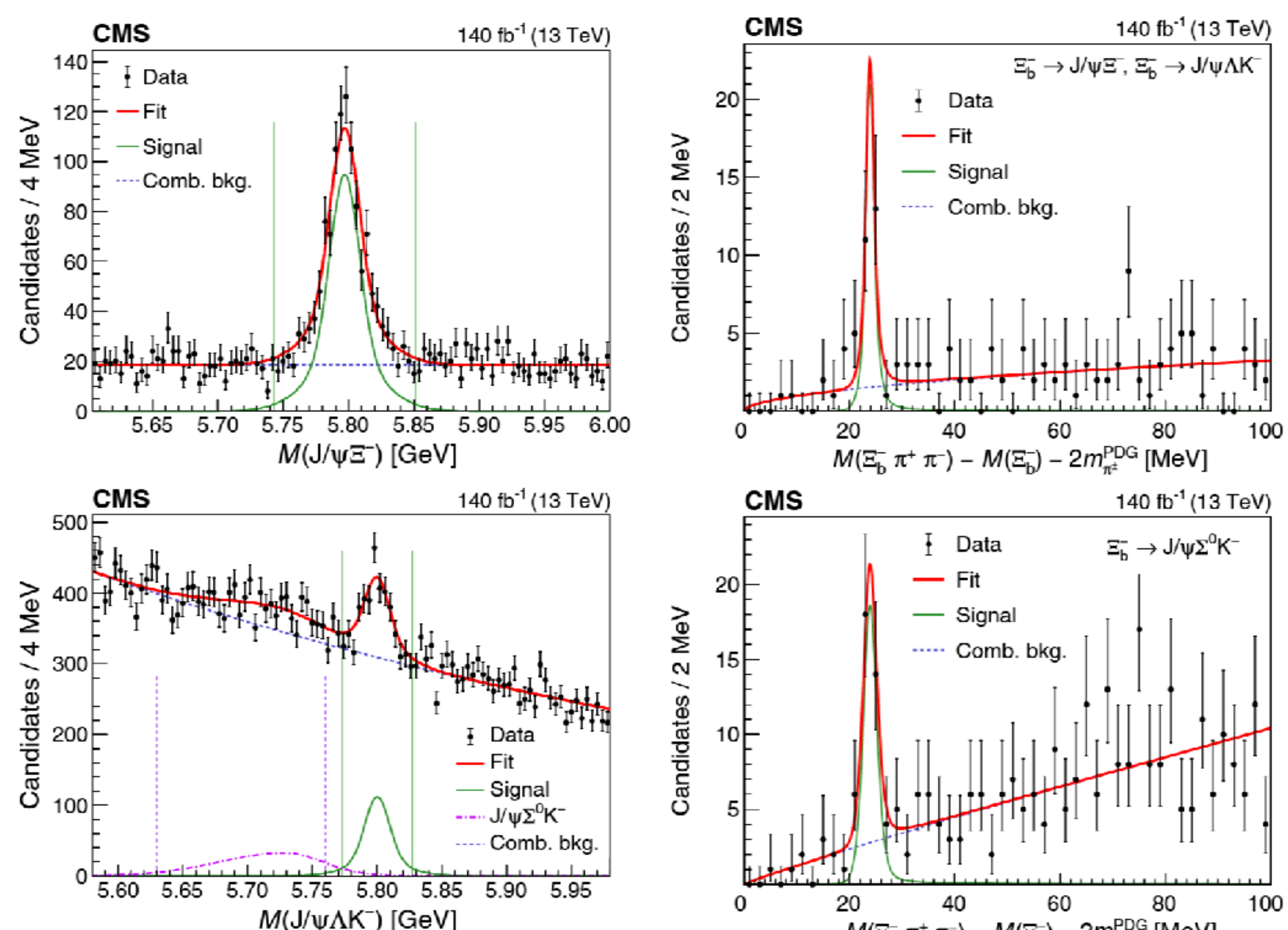


FIG. 1. The $\Xi_b(6100)^- \to \Xi_b^-\pi^+\pi^-$ decay topology, where the Ξ_b^- decays to $J/\psi\Xi^-$ (upper) or to $J/\psi\Lambda K^-$ (lower). The numbers in blue are average decay lengths.



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

LHCb-PAPER-2023-008
In preparation

New!

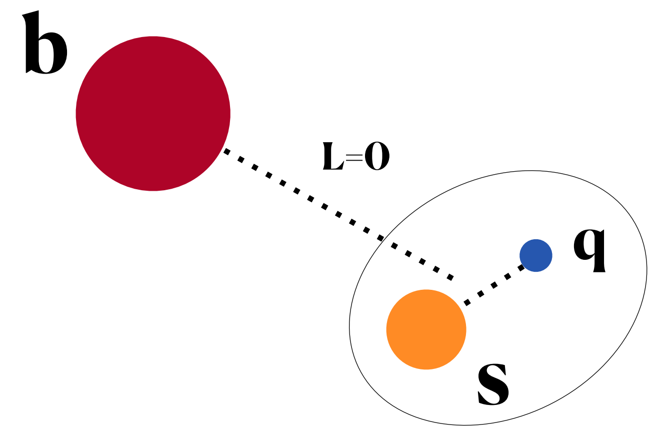
- At LHCb, we look both for charged and neutral states $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

- 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 $\Xi_b^0\pi^+\pi^-$

LHCb-PAPER-2023-008
In preparation

New!

- 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

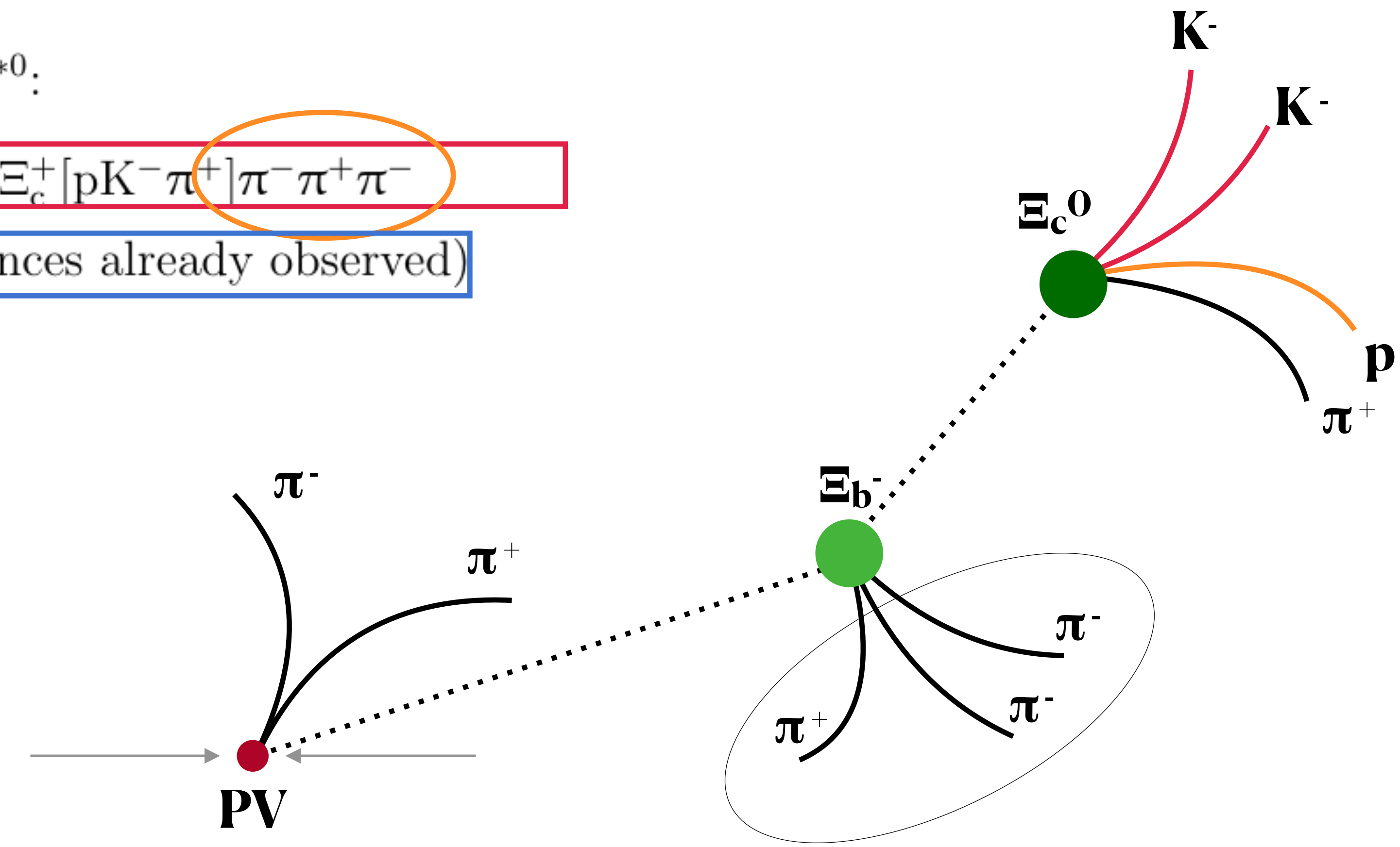
- Charged resonance temporarily referred to as Ξ_b^{**-}:
  - ☐ Start with $\Xi_b^- \to \Xi_c^0[pK^-K^+\pi^+]\pi^-$ and $\Xi_b^- \to \Xi_c^0[pK^-K^+\pi^+]\pi^-\pi^+\pi^-$
  - ☐ $\Xi_b^{*0} \to \Xi_b^-\pi^+$ (one intermediate resonance already observed)
  - ☐ $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$
  - ☐ The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

Final state

Up to 9 tracks in the final state

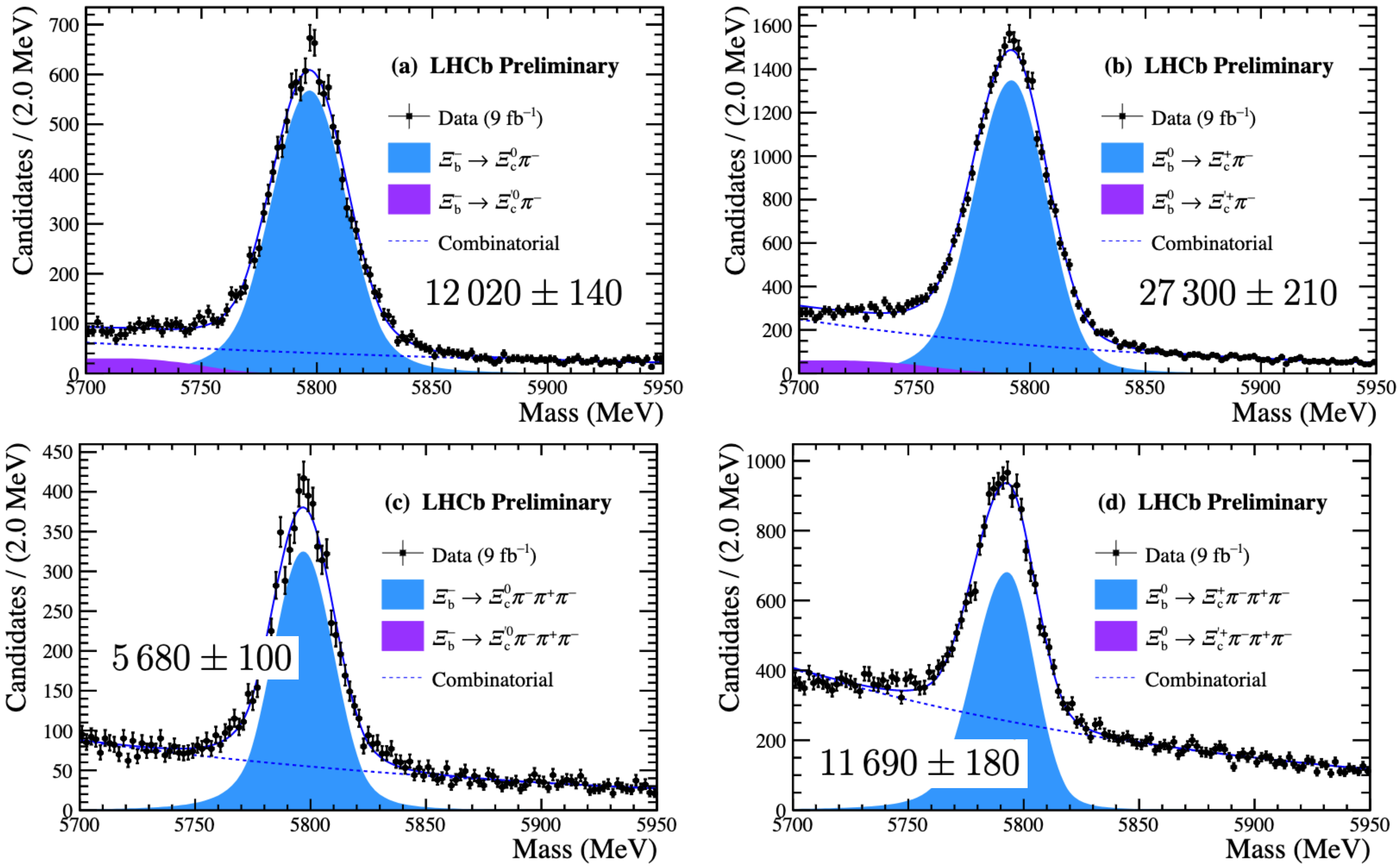


New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

LHCb-PAPER-2023-008
In preparation

New!

- 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



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

LHCb-PAPER-2023-008
In preparation

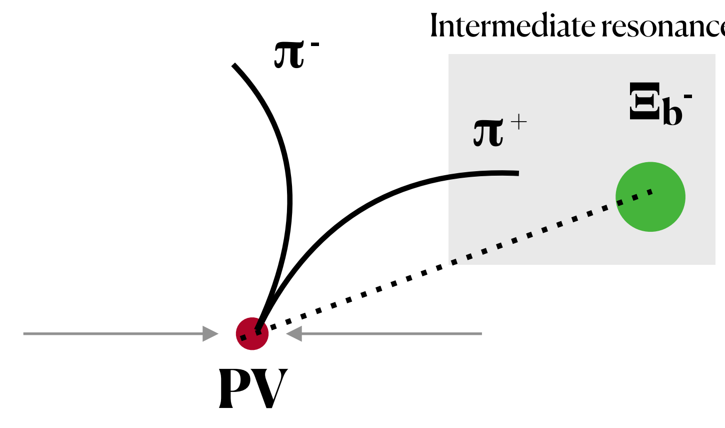
New!

- 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 $(Q - d)^n$

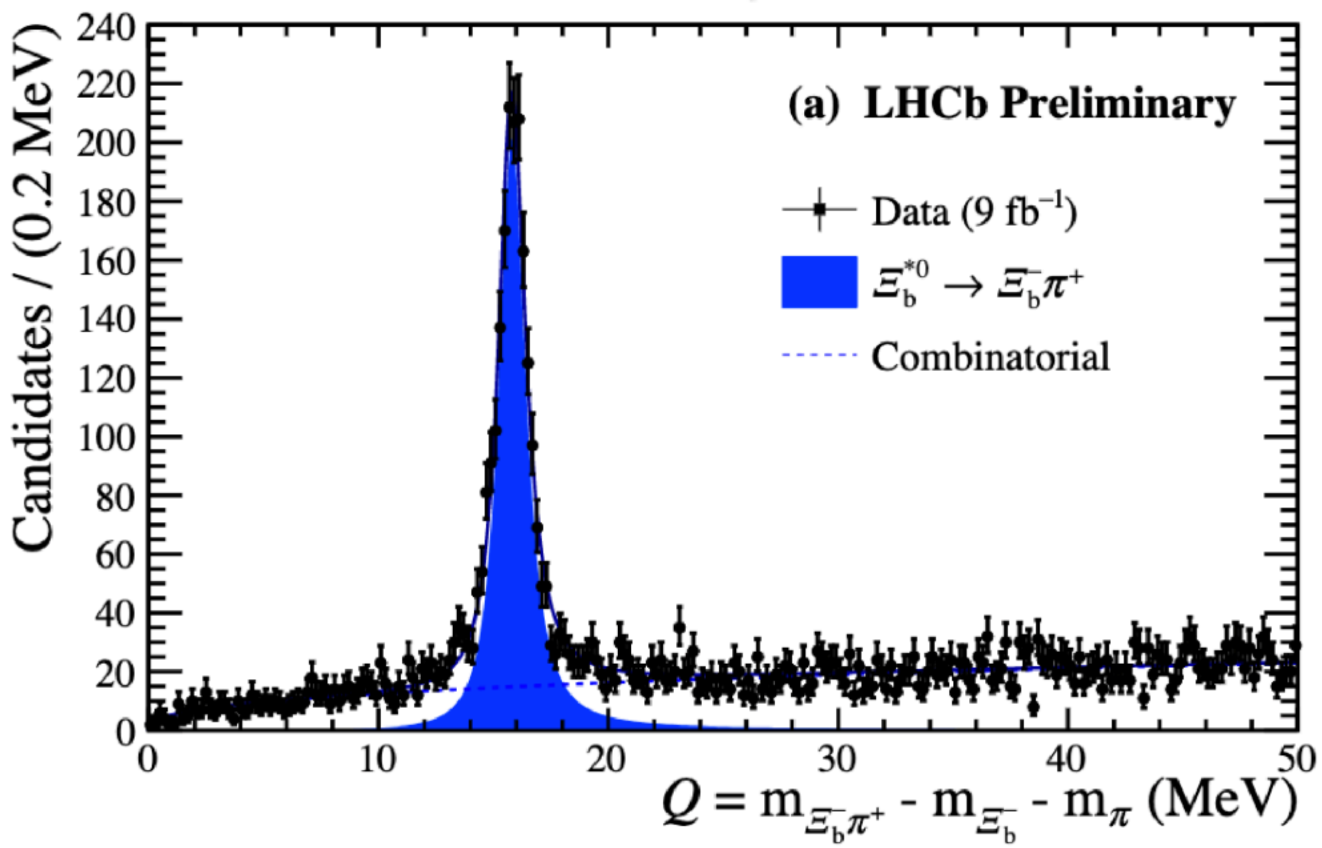
partially reconstructed candidates coming from higher-mass resonances

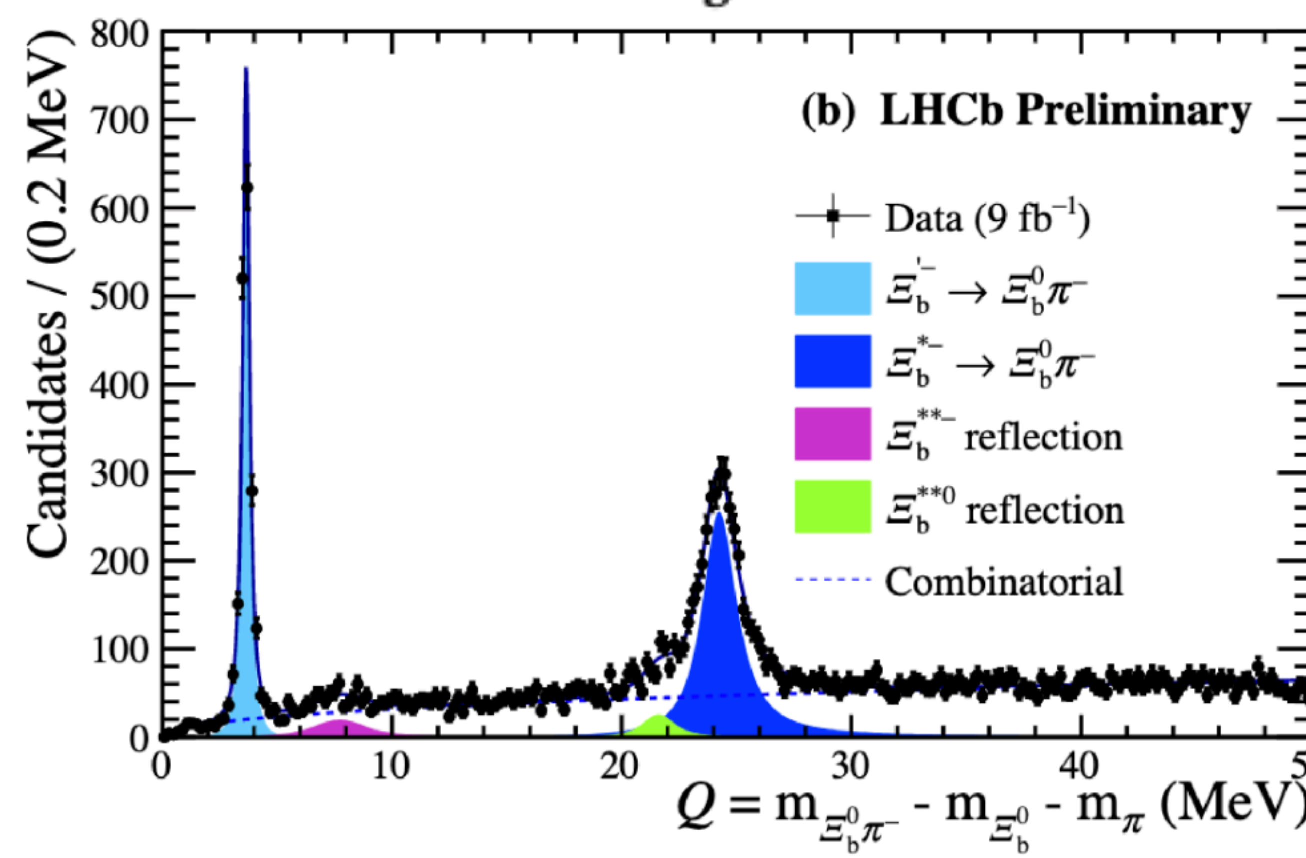


$\Xi_b^- \pi^+$

Those are the intermediate resonances
Nice mass distributions and signals

$\Xi_b^0 \pi^-$



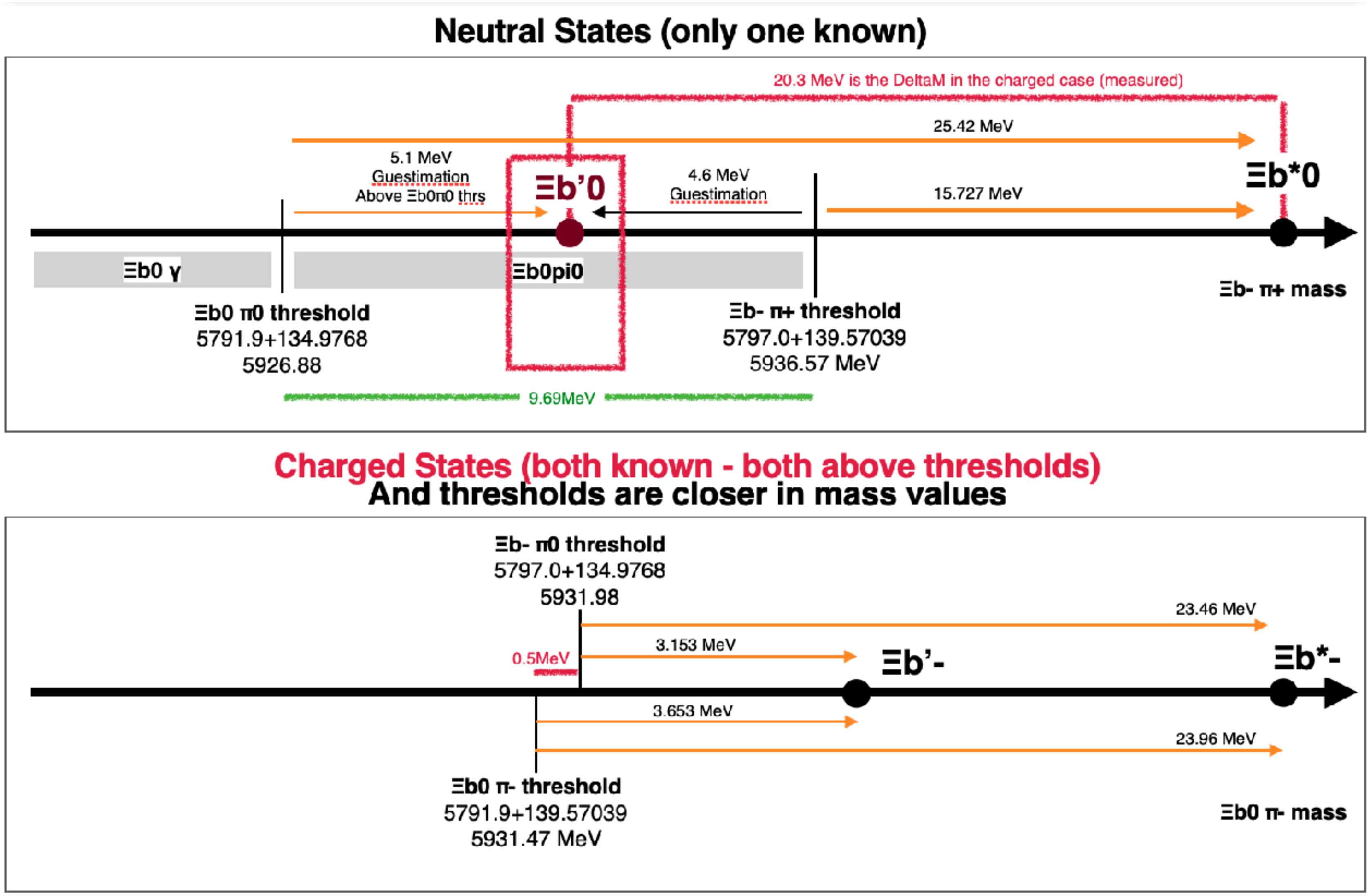


New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

LHCb-PAPER-2023-008
In preparation

New!

- 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***

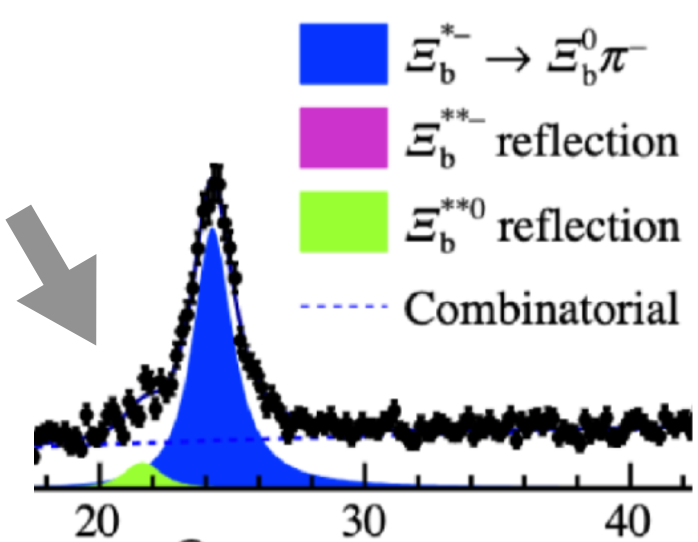
New baryons in $\Xi_b^- \pi^+\pi^-$ and $\Xi_b^0 \pi^+\pi^-$

LHCb-PAPER-2023-008
In preparation

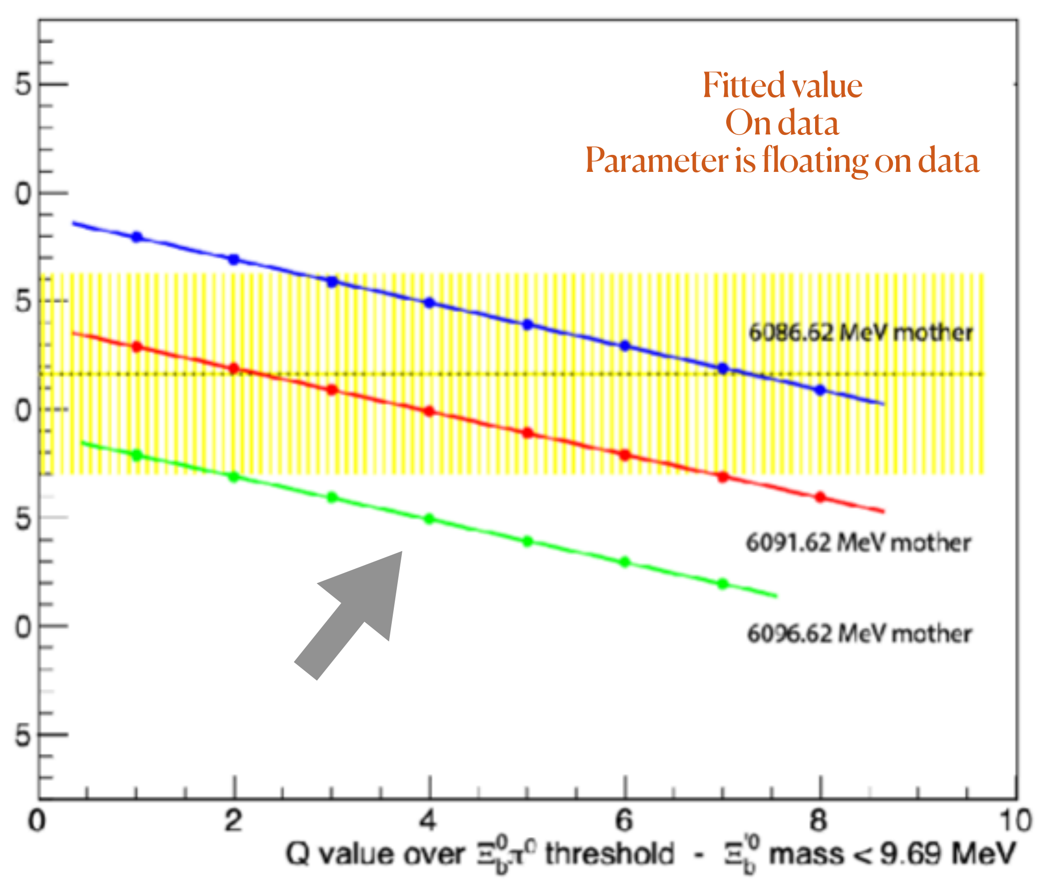
New!

- 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** $\Xi_b^-(6100) \to \Xi_b^{*0}(\Xi_b^0\pi^0)\pi^-$
- **Hints of a possible contribution from the decay chains** $\Xi_b^-(1P, 1/2) \to \Xi_b^{\prime 0}(\Xi_b^0\pi^0)\pi^-$



MC studies of reflection: different M_1 and M_2



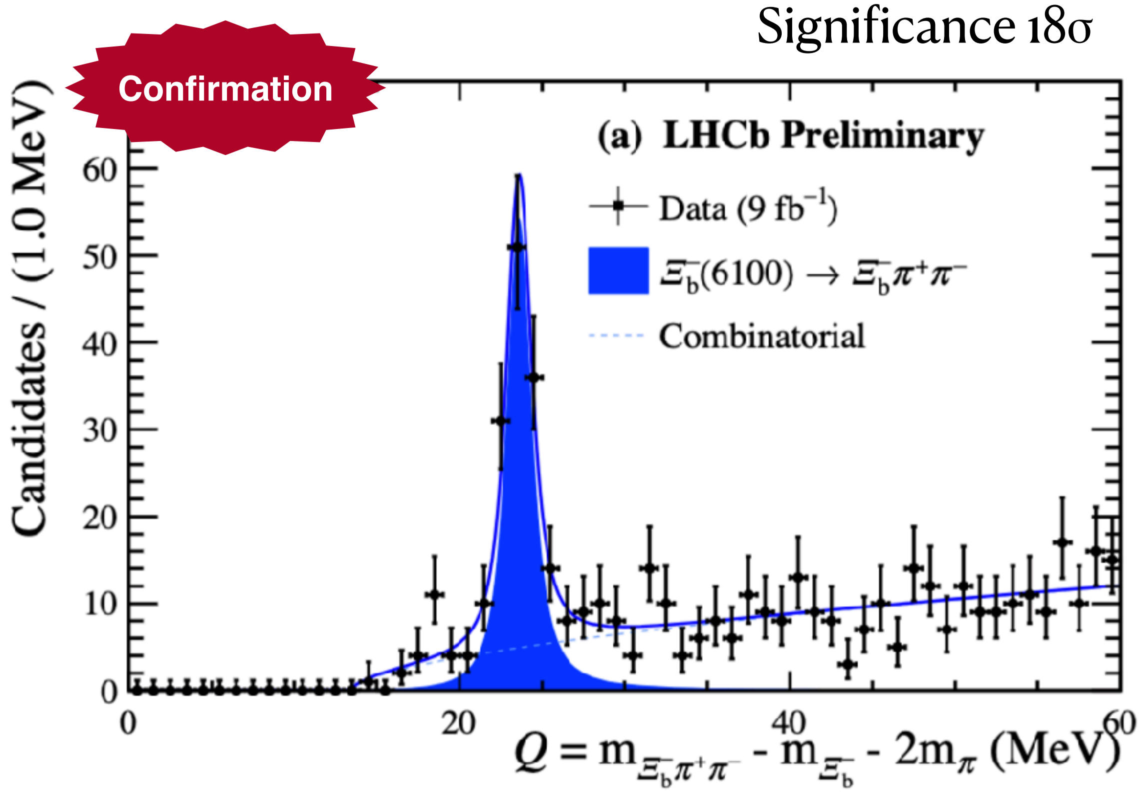
However, a precise estimation of the two states properties is not possible due to the limited yield available and the **presence of two unknown mass values.**

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

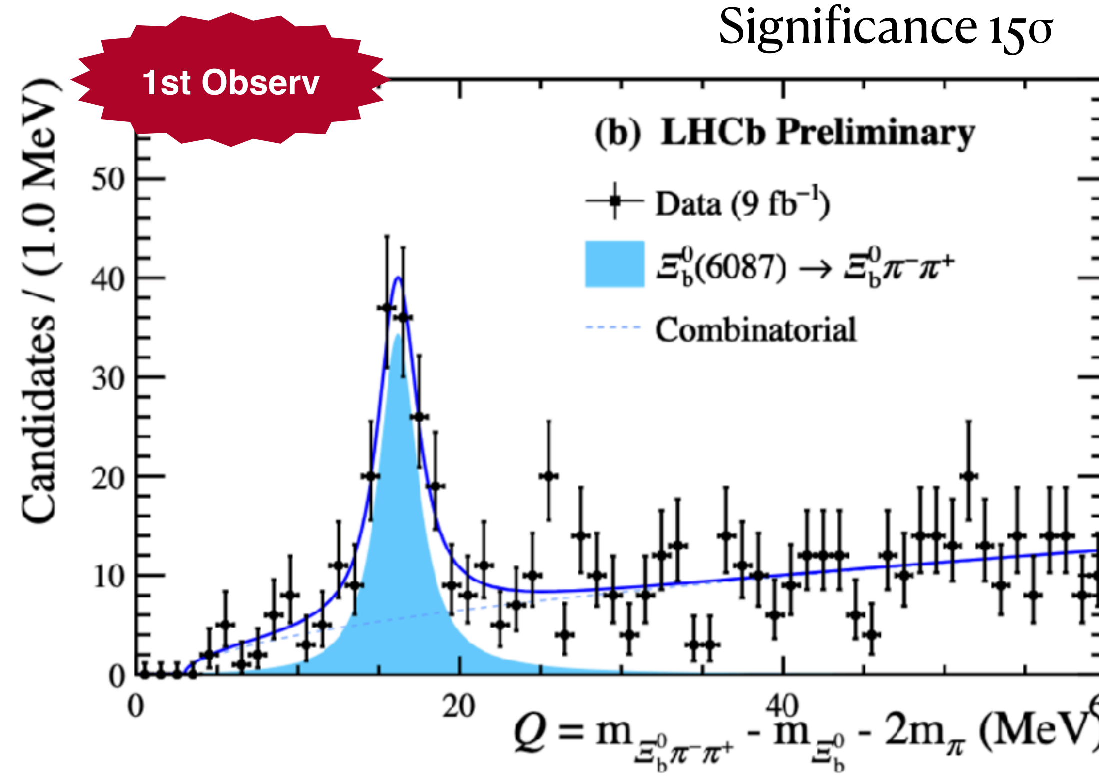
LHCb-PAPER-2023-008
In preparation

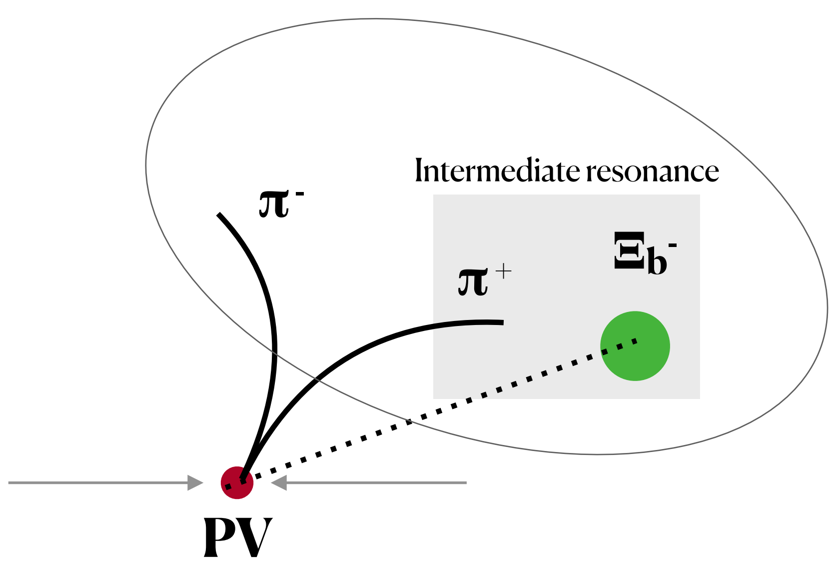
New!

Significance 18σ

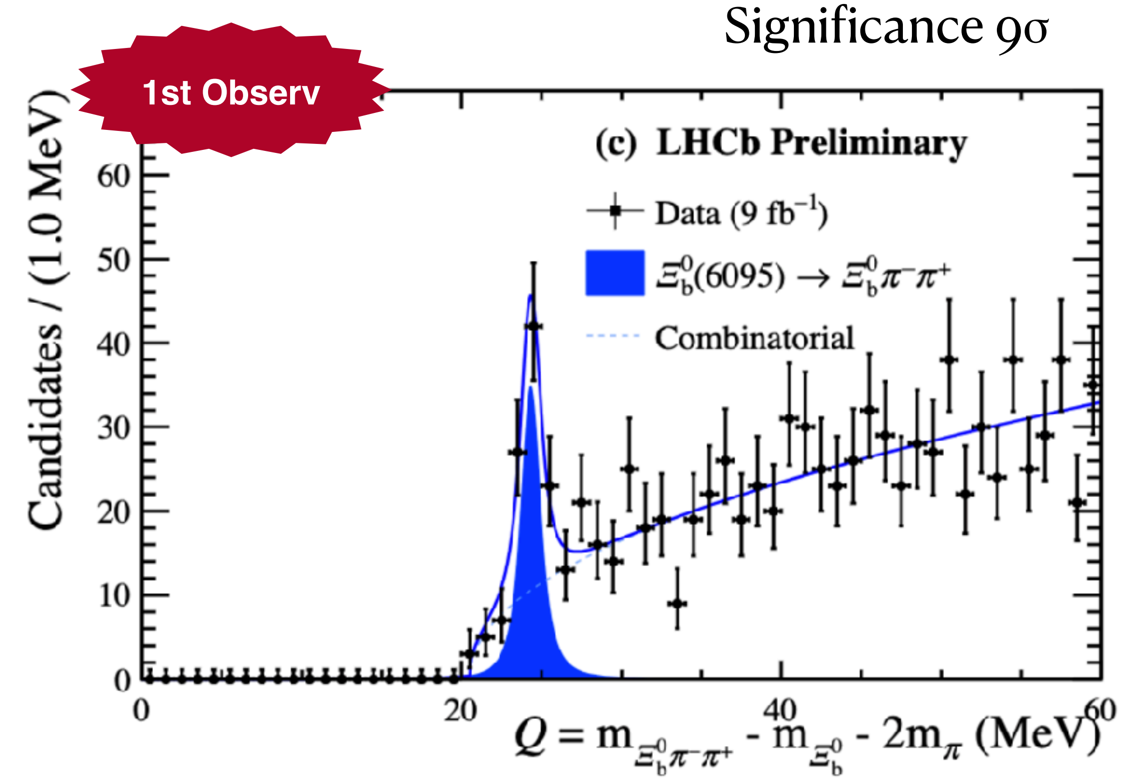


Significance 15σ





Significance 9σ



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

LHCb-PAPER-2023-008
In preparation

New!

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

		Value [MeV]
$\Xi_b(6100)^-$ (Confirmation)	Q_0 $(\Xi_b^-(6100))$	$23.60 \pm 0.11 \pm 0.02$
	Γ $(\Xi_b^-(6100))$	$0.94 \pm 0.30 \pm 0.08$
	m_0 $(\Xi_b^-(6100))$	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6$ (Ξ_b^-)
$\Xi_b(6087)^0$ (1st Observ)	Q_0 $(\Xi_b^0(6087))$	$16.20 \pm 0.20 \pm 0.06$
	Γ $(\Xi_b^0(6087))$	$2.43 \pm 0.51 \pm 0.10$
	m_0 $(\Xi_b^0(6087))$	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5$ (Ξ_b^0)
$\Xi_b(6095)^0$ (1st Observ)	Q_0 $(\Xi_b^0(6095))$	$24.32 \pm 0.15 \pm 0.03$
	Γ $(\Xi_b^0(6095))$	$0.50 \pm 0.33 \pm 0.11$
	m_0 $(\Xi_b^0(6095))$	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5$ (Ξ_b^0)
Improvements	Q_0 (Ξ_b^{*0})	$15.80 \pm 0.02 \pm 0.01$
	Γ (Ξ_b^{*0})	$0.87 \pm 0.06 \pm 0.05$
	m_0 (Ξ_b^{*0})	$5952.37 \pm 0.02 \pm 0.01 \pm 0.6$ (Ξ_b^-)
	Q_0 $(\Xi_b^{\prime -})$	$3.66 \pm 0.01 \pm 0.00$
	Γ $(\Xi_b^{\prime -})$	$0.03 \pm 0.01 \pm 0.03$
	m_0 $(\Xi_b^{\prime -})$	$5935.13 \pm 0.01 \pm 0.00 \pm 0.5$ (Ξ_b^0)
	Q_0 (Ξ_b^{*-})	$24.27 \pm 0.03 \pm 0.01$
	Γ (Ξ_b^{*-})	$1.43 \pm 0.08 \pm 0.08$
	m_0 (Ξ_b^{*-})	$5955.74 \pm 0.03 \pm 0.01 \pm 0.5$ (Ξ_b^0)

	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

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

LHCb-PAPER-2023-008
In preparation

New!

In summary:

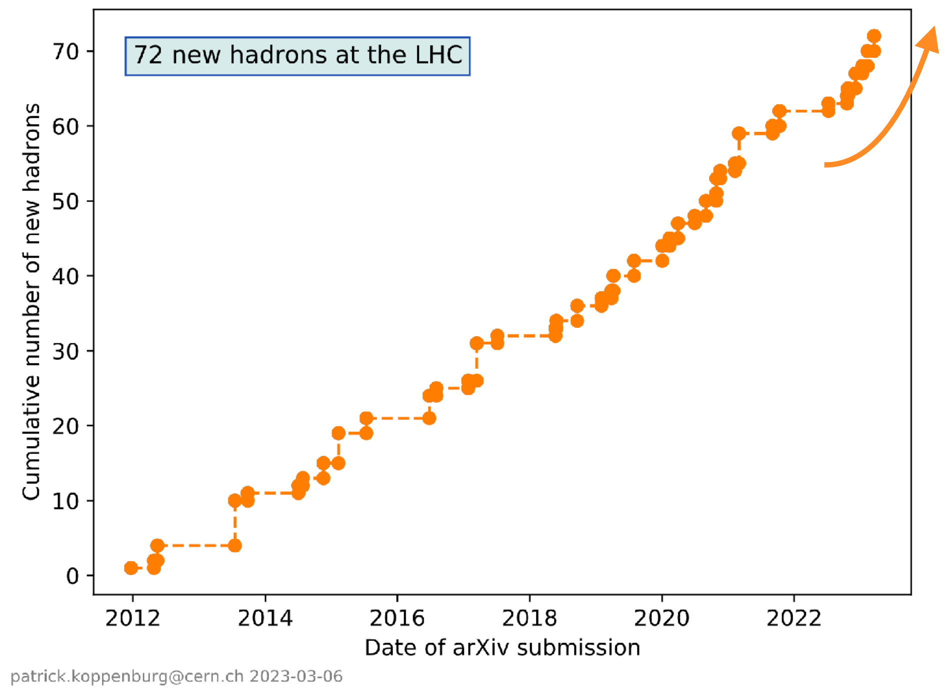
- **Observation of two new *bsq* baryons is reported: $\Xi_b(6100)^-$**
- **One state is confirmed (and measured): $\Xi_b(6087)^0$ $\Xi_b(6095)^0$**
- Best measurement on the known Ξ_b' and Ξ_b^* states
- This measurement uses final states with up to 9 tracks (record in LHCb
- Possible thanks to the 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

- I reviewed briefly a decade of analysis and observations
- LHC has proven to be a wonderful playground for heavy flavour physics!
- I tried to highlight the milestones and experimental challenges
- Also presented the latest observations of new baryons in $\Xi_b^- \pi^+ \pi^-$ and $\Xi_b^0 \pi^+ \pi^-$

- Bright future ahead as more data will be available with the upgraded detector!
- Higher statistics → Access to states with lower production rates



The LHCb Upgrade

- Let me take the opportunity to introduce the upgraded detector
- Spectroscopy analyses will benefit both for increased luminosity and performance
- Full software trigger improves efficiency and flexibility

Upstream Tracker closing completes installation of the LHCb Upgrade 1 detector

First plots with Run3 data