Conventional hadron spectroscopy at LHCb

The 23rd International Conference on Few-Body Problems in Physics
Beijing, China
Sept.22-27, 2024

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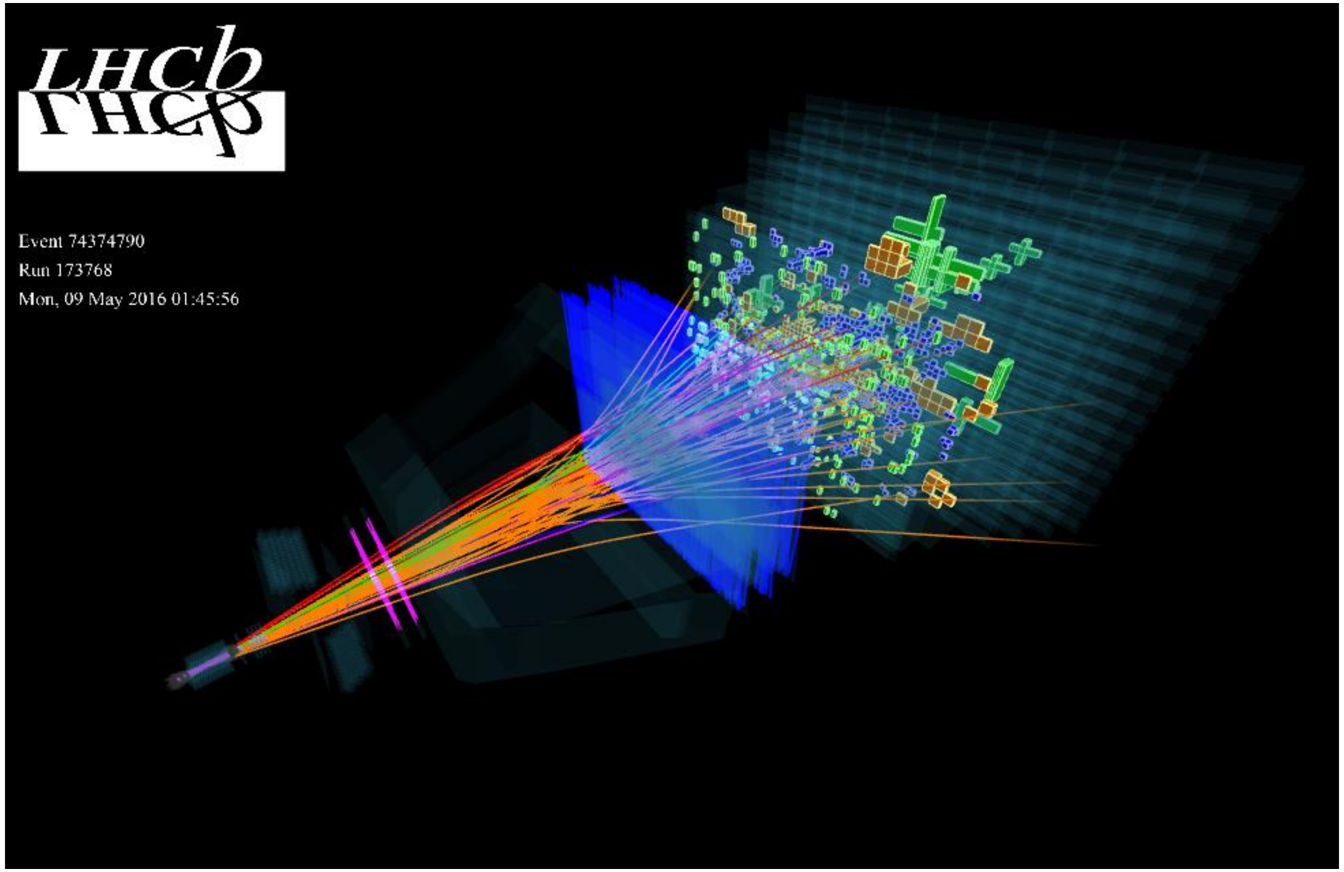
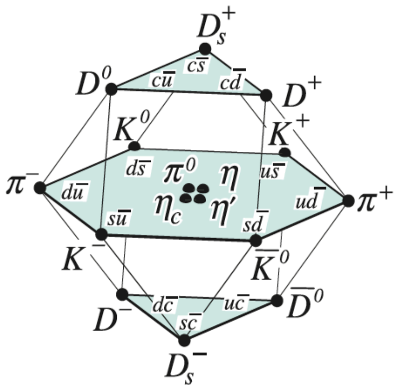
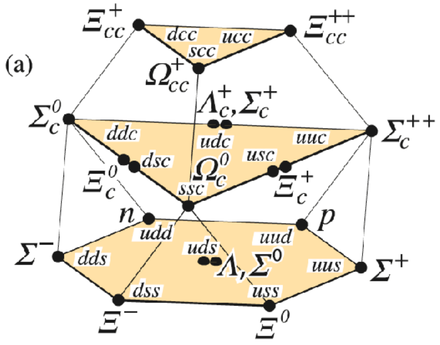
On behalf of the LHCb collaboration



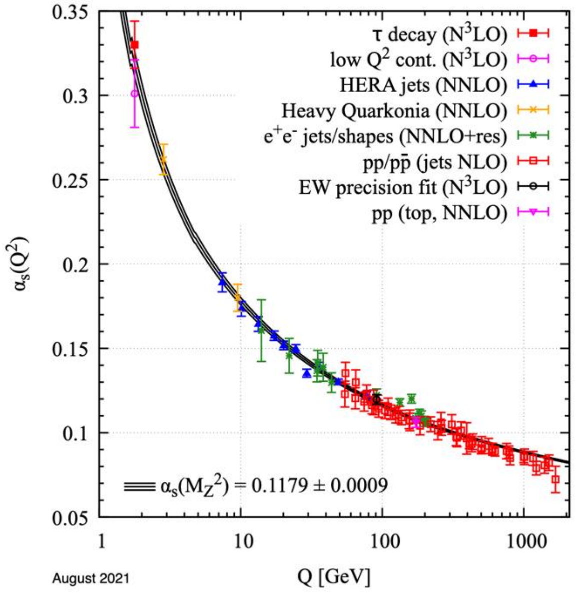
Conventional hadrons

- Conventional hadrons: color-singlet
  - Meson: $\bar{q}q$
  - Baryon: qqq
- $\mathcal{L}_{QCD}$ is in principle expected to fully describe the spectrum and properties of hadrons
- **Experimental measurements in hadron spectroscopy**
  - Extend the knowledge of QCD
  - Provide crucial inputs to reduce the uncertainties in theory
  - Help to understand the ways in which QCD forms bound states and about their internal structure

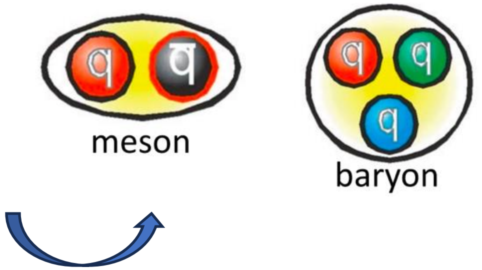




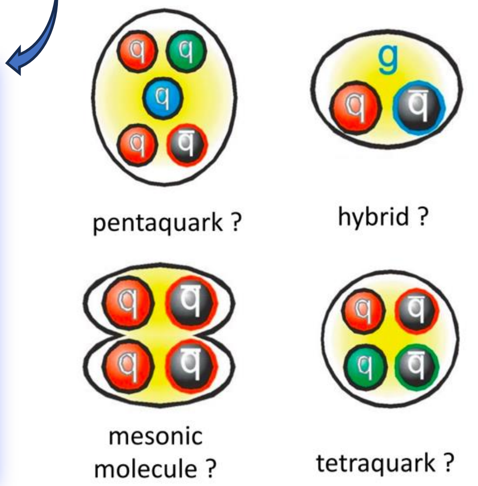
[PDG Appendix]



CONVENTIONAL



EXOTIC

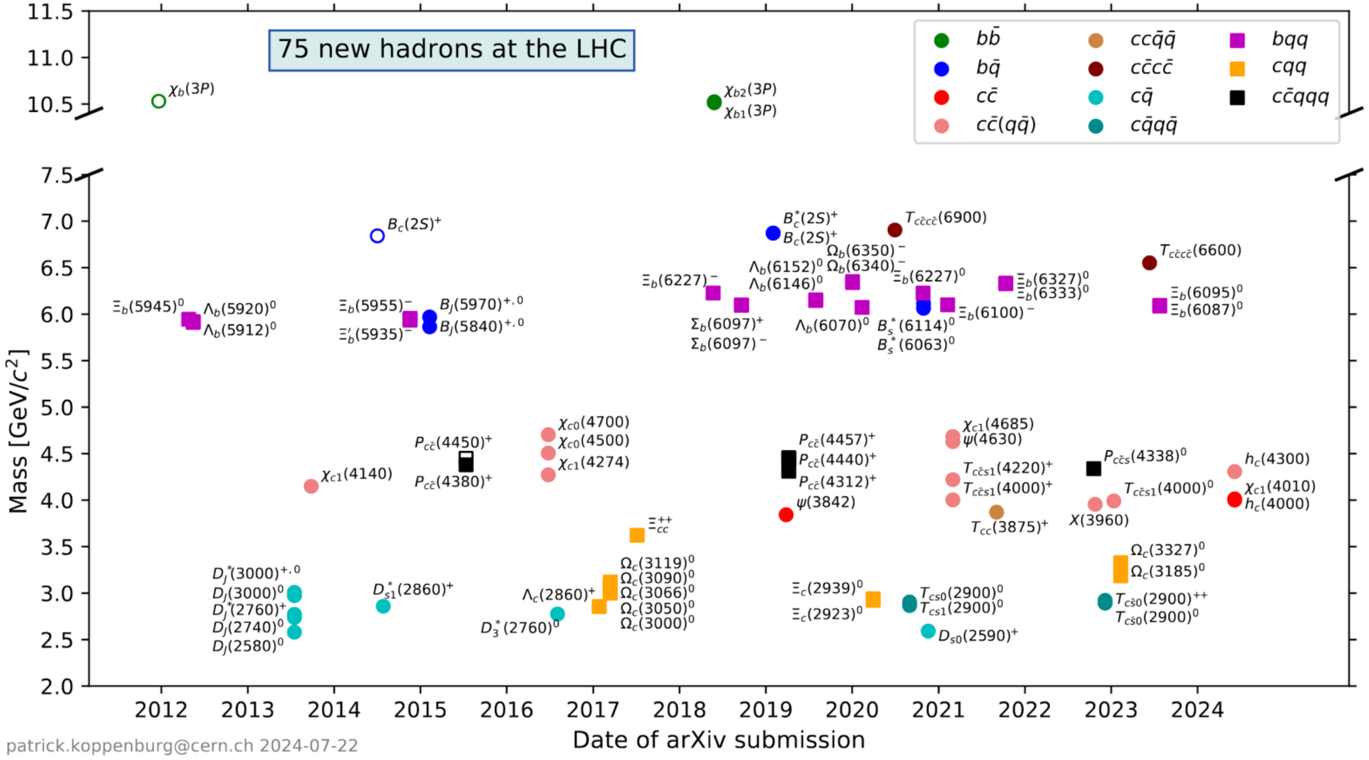


Properties

- New state
- New decay
- Mass & Width (lifetime)
- Production
- Branching ratio
- Quantum numbers
- ……

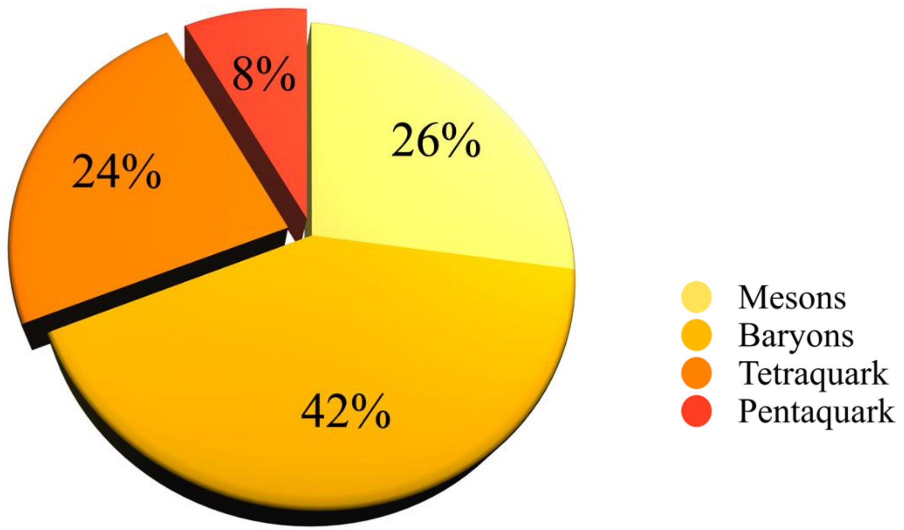
Conventional Hadron Spectroscopy at LHCb

- The world's largest samples of reconstructed conventional heavy flavour hadrons are collected with LHCb during LHC RunI and RunII
- So far 75 hadrons have been discovered at the LHC, of which 67 by LHCb
- The list is still growing…



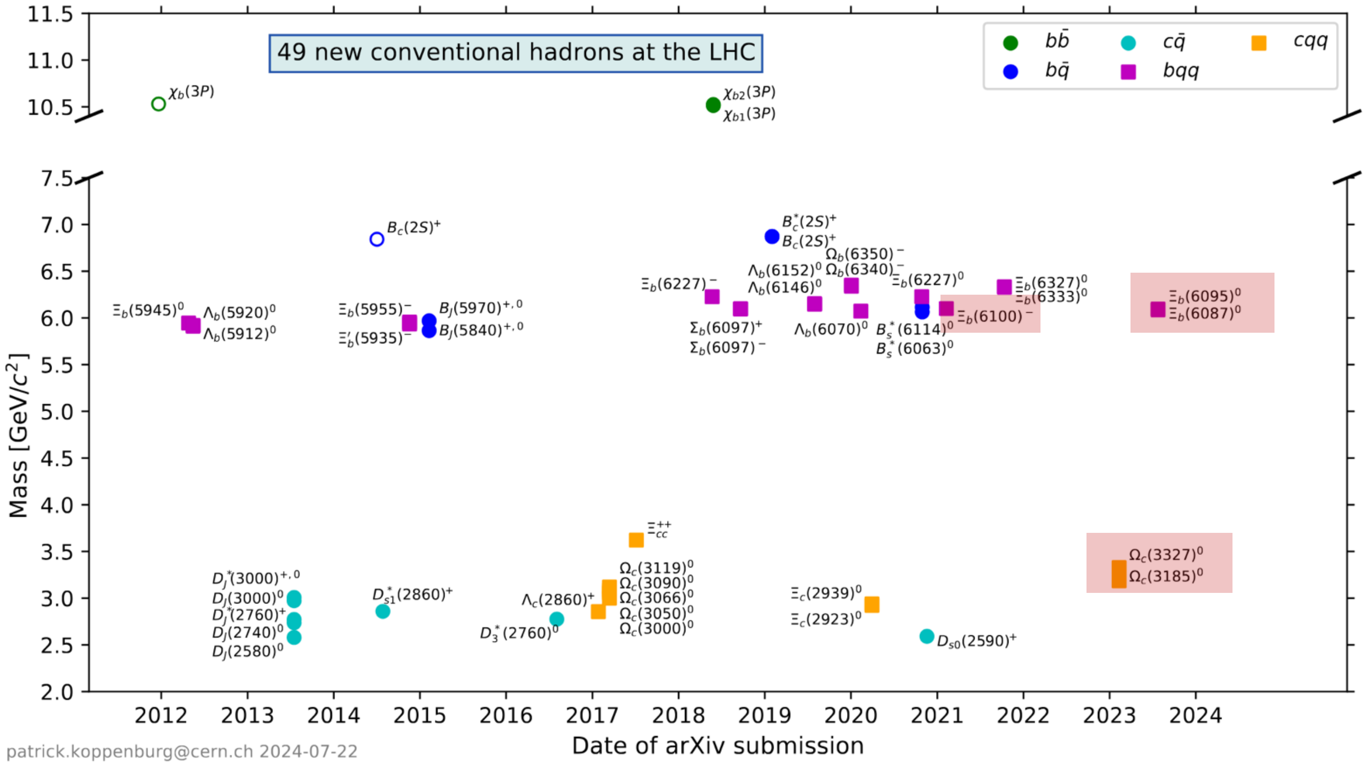
[https://www.nikhef.nl/~pkoppenb/hadrons//Masses.pdf]

The conventional spectroscopy still major player



Conventional Hadron Spectroscopy at LHCb

- This talk will focus on the selected topics of conventional hadron spectroscopy, includes:
  - Recent observations of new hadron
  - Recent measurements of hadron property

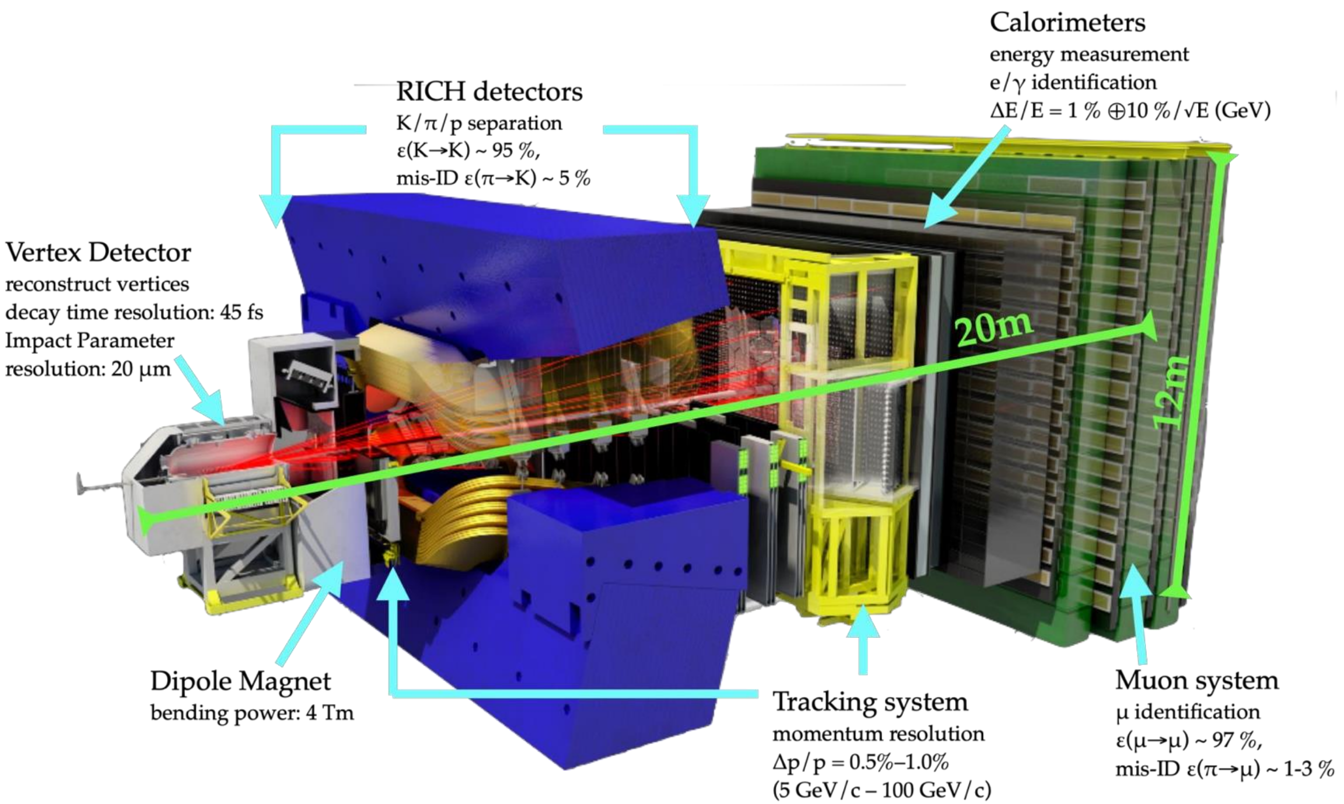


[https://www.nikhef.nl/~pkoppenb/hadrons//Masses_conventional_hadrons.pdf]

- Observation of $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$
  [Phys. Rev. Lett. 118, 182001]
- Observation of $\Xi_b(6100)^-, \Xi_b(6087)^0$ and $\Xi_b(6095)^0$
  [Phys. Rev. Lett. 131 (2023) 171901]
- Study of hidden beauty spectroscopy
  [arXiv:2408.05134]
- Determination of the spin-parities of $\Xi_c(3055)^{+(0)}$
  [arXiv:2409.05440]

The LHCb detector

- A general purpose detector covering the forward region: $2 < \eta < 5$
- Unprecedented b and c samples delivered by the LHC → designed for heavy flavor physics
- **Perfect conditions for both precision measurements & observations of new states**
- Successful operation in RunI and RunII with various collision systems (pp, p-Pb, Pb-Pb)

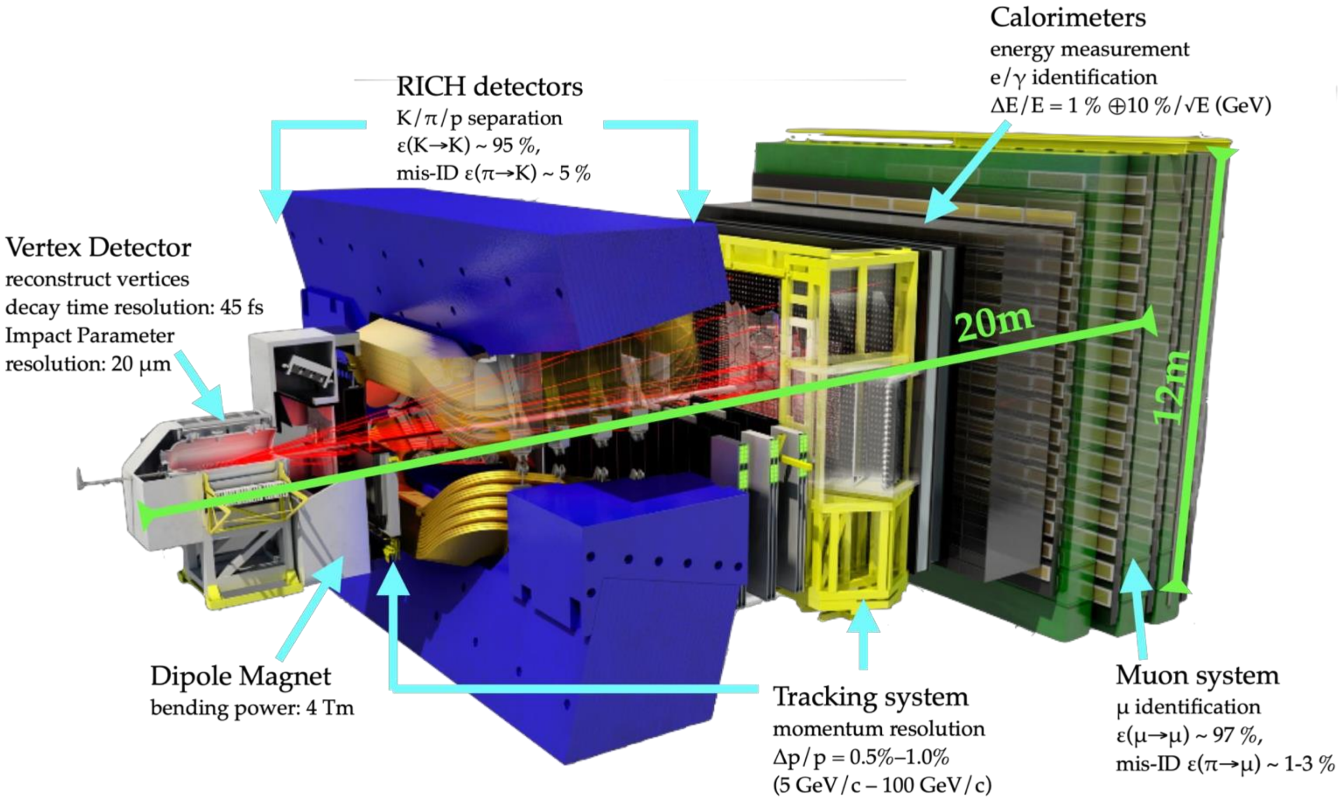


[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

The LHCb detector

Ingredients for good spectroscopy measurement

- **Excellent tracking** → mass and lifetime resolutions
- **Particle identification** → important when dealing with charged hadrons in the final states
- **Trigger system** → give excellent efficiency



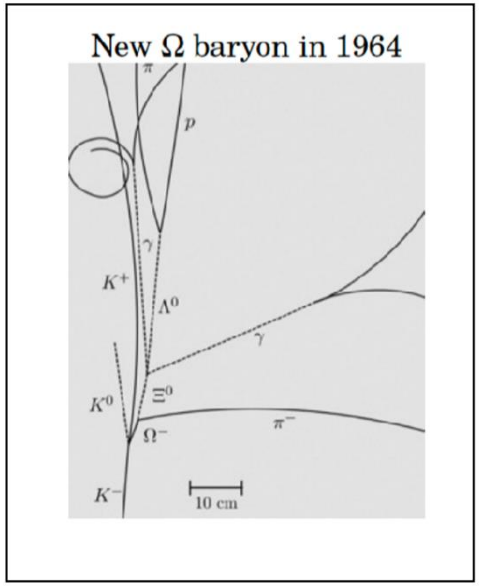
[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

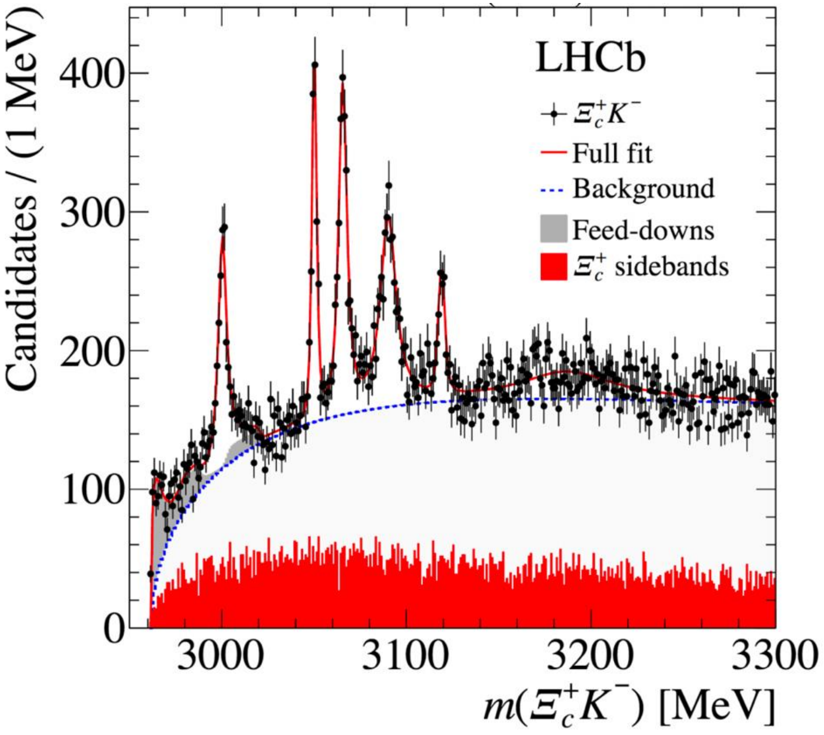
Observation of new Ω_c^0 states in $\Xi_c^+ K^-$ spectrum

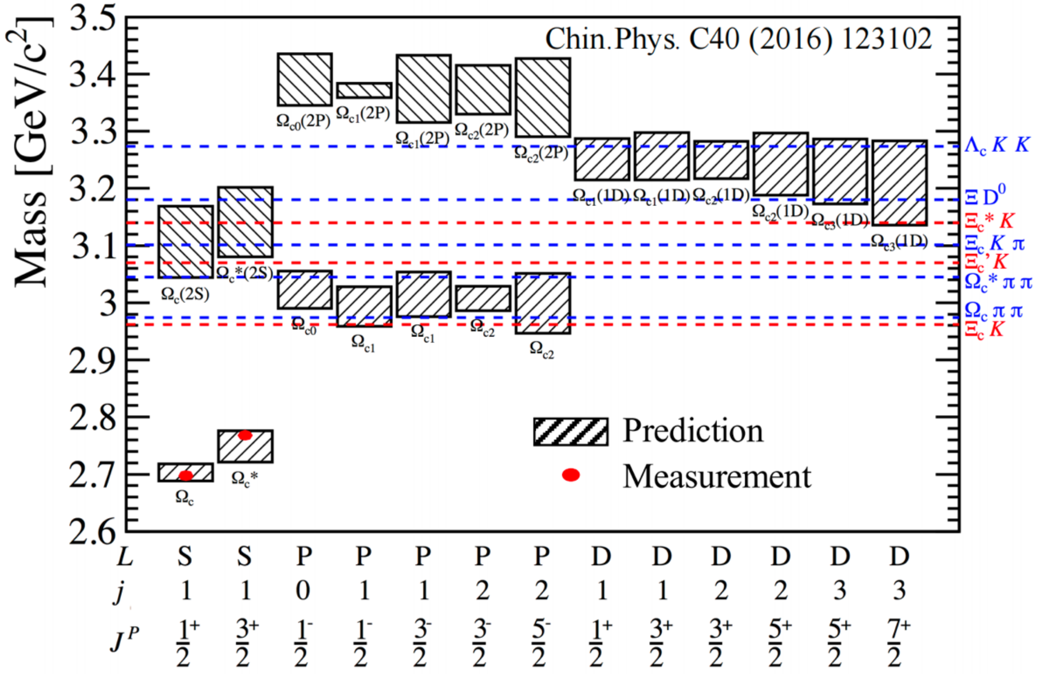
[Phys. Rev. Lett. 118, 182001]

- Study status in 2017:
  - $\Omega_c^0 \to \Xi_c^+ K^-, \Xi_c^+ \to p K^- \pi^+$
  - The LHCb studied $\Xi_c^+ K^-$ spectrum up to 3450 MeV using RunI data
  - There are 5 new states observed: $\Omega_c(3000)^0, \Omega_c(3050)^0, \Omega_c(3066)^0, \Omega_c(3090)^0, \Omega_c(3119)^0$
  - There are 1 hint on another broad structure around 3200 and 3300 MeV

First observation of sss state



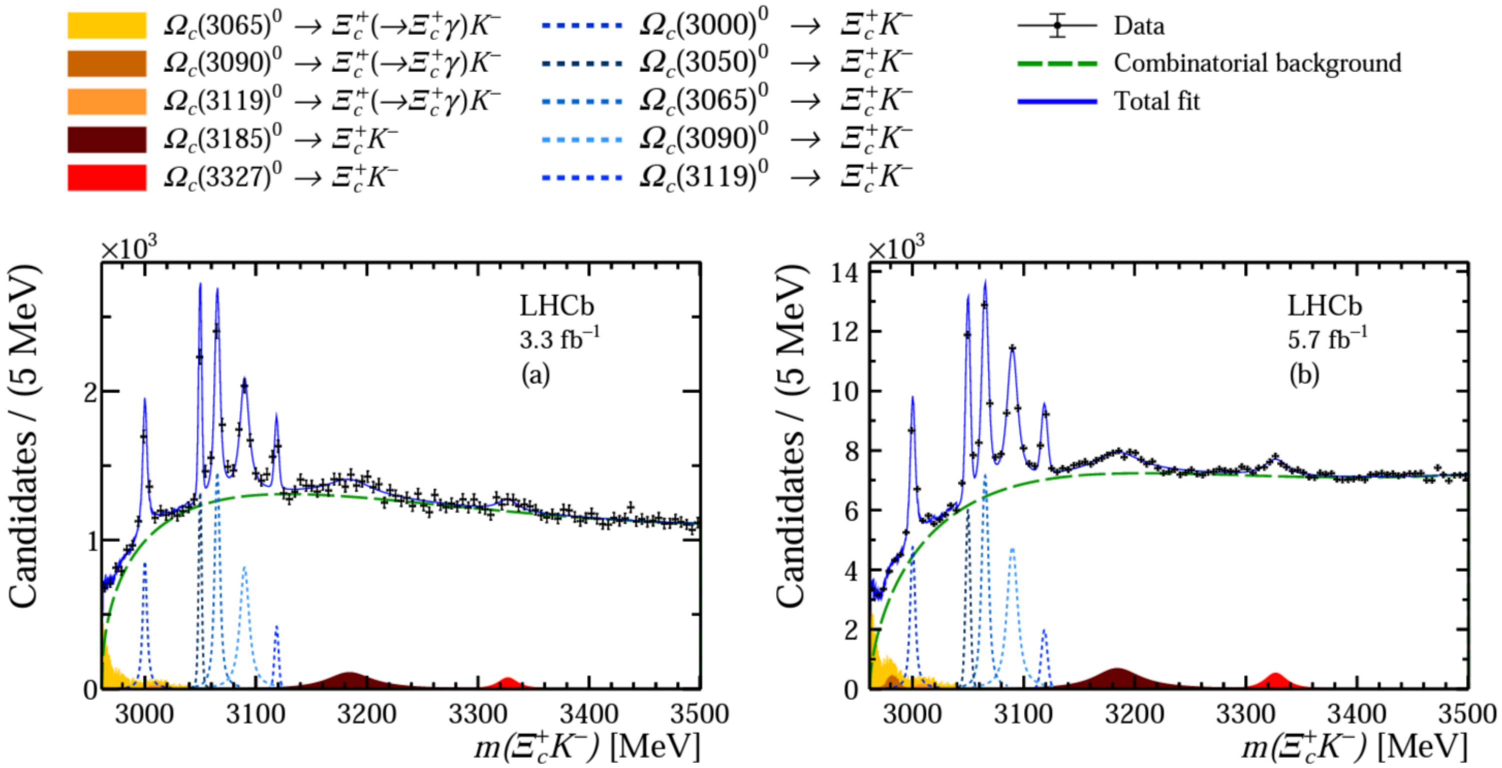




Observation of new Ω_c^0 states in $\Xi_c^+ K^-$ spectrum

[Phys. Rev. Lett. 131, 131902]

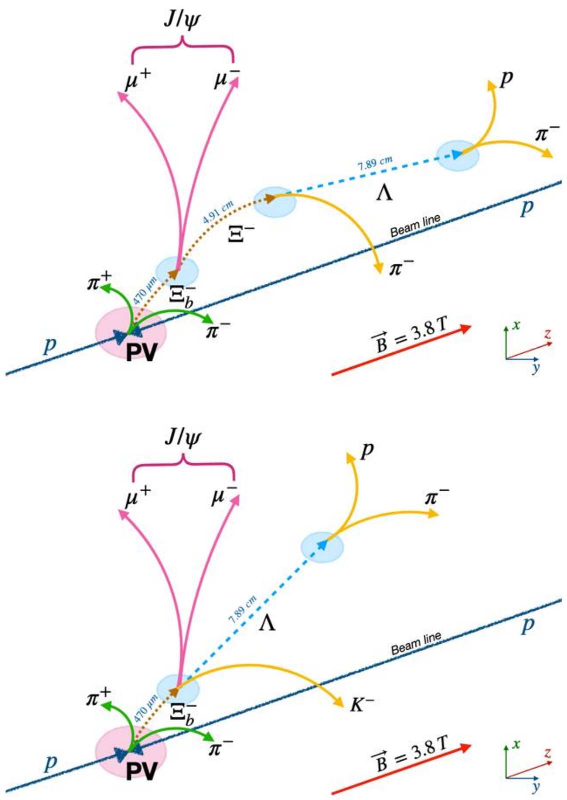
- Newly added 2016-2018 data
- Dedicated selection and BDT training per sample
- In total 7 states are reported, including 2 broad new states $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$

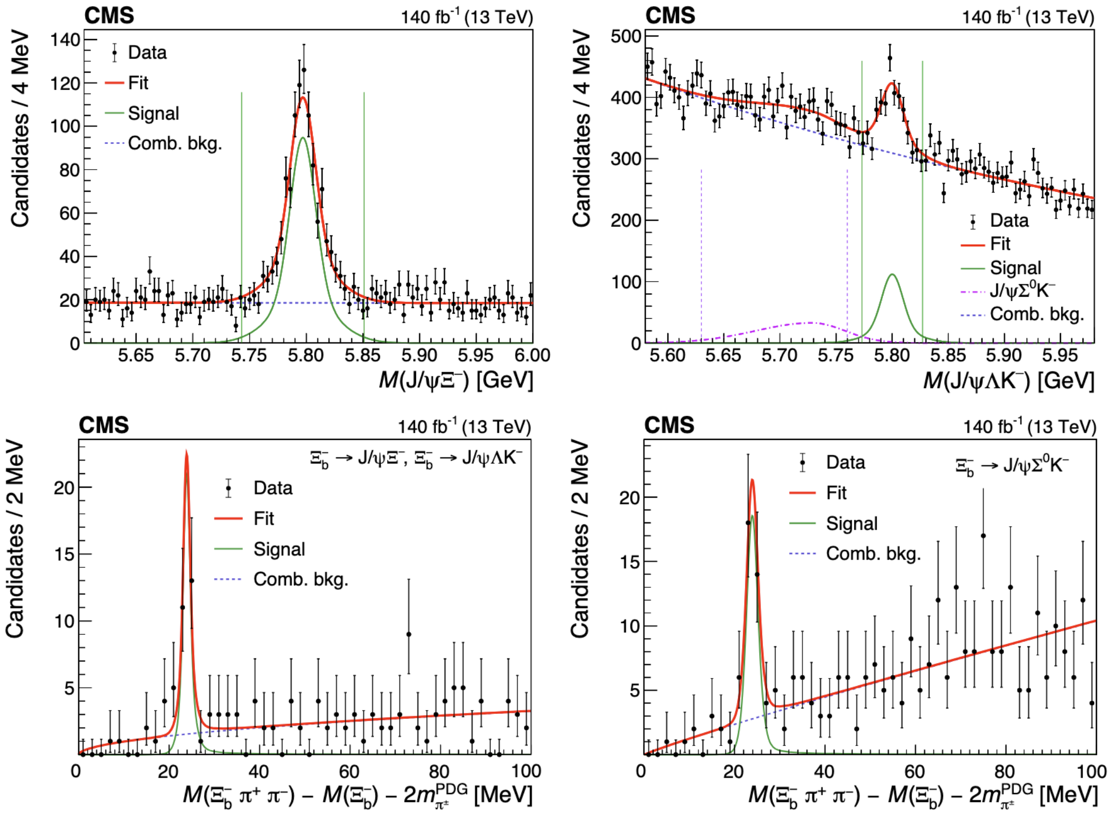


Observation of new baryons in $\Xi_b^{-(0)}\pi^-\pi^+$ spectrum

- In 2021, the CMS collaboration has reported the observation of the new $\Xi_b(6100)^-$ state [Phys. Rev. Lett. 126, 252003]
  - ❒ $\Xi_b(6100)^- \to \Xi_b^- \pi^+\pi^-$
  - ❒ Using the final states containing $J/\psi \to$ Di-muon trigger
  - ❒ limited statistics

Good example of complementarity :)

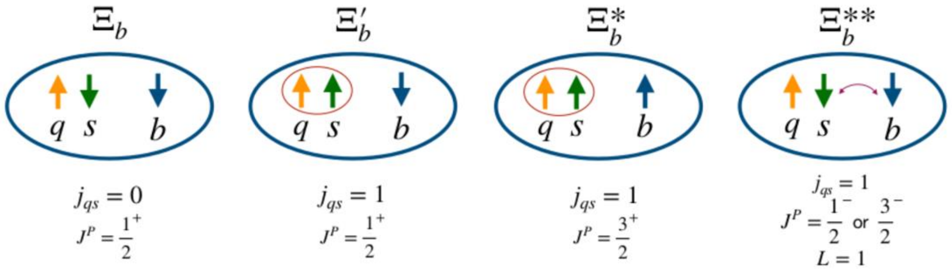




Observation of new baryons in $\Xi_b^{-(0)}\pi^-\pi^+$ spectrum

[Phys. Rev. Lett. 131 (2023) 171901]

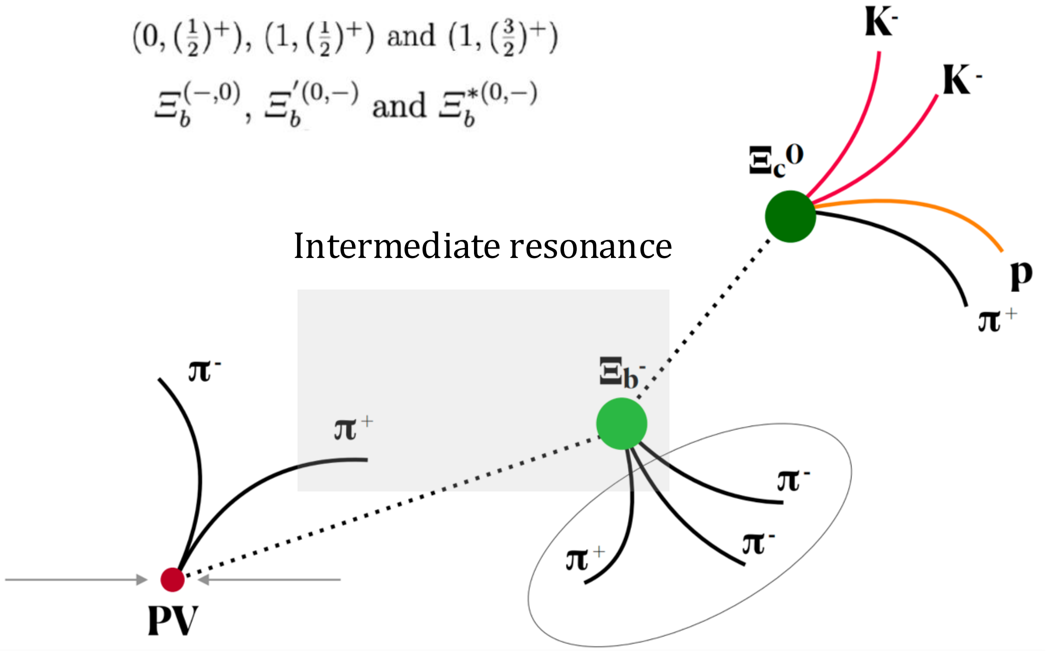
- The Ξ_b baryons form an isospin doublet (bsu, bsd)
- First investigation in LHCb using $\Xi_b^-\pi^-\pi^+$ and $\Xi_b^0\pi^-\pi^+$ final states
  - Different decay modes were used to look for single or three pions
  - Most abundant b-baryon
  - Hadronic final states with topological trigger → **Higher yields, S/B**



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

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

- New 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 known)
  - $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$
  - The final state is thus $\Xi_b^-\pi^+\pi^-$ **Charged final states**
  - The yield is expected lower here due to the extra track in the final state
- New 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 known)
  - $\Xi_b^{**0} \to \Xi_b'^-\pi^+, \Xi_b^{**0} \to \Xi_b^{*-}\pi^+$
  - The final state is thus $\Xi_b^0\pi^-\pi^+$ **Neutral final states**

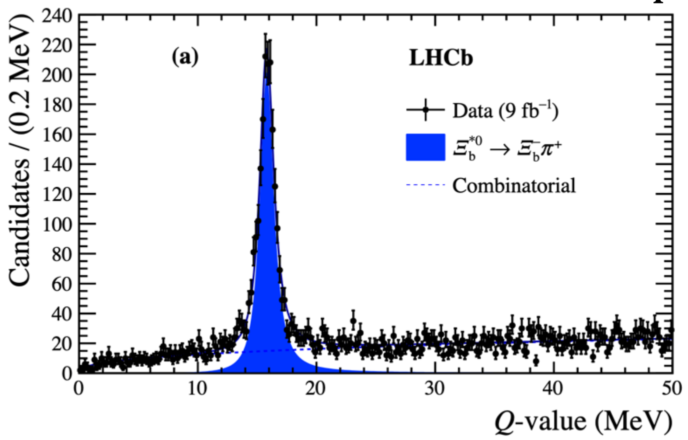


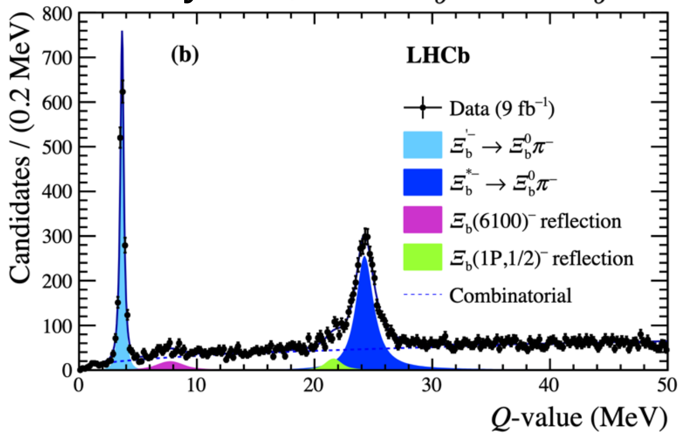
⇒ Up to 9 tracks in the final states

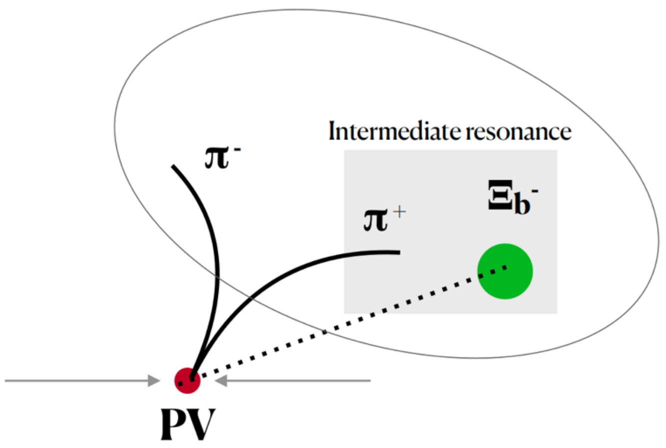
Observation of new baryons in $\Xi_b^{-(0)}\pi^-\pi^+$ spectrum

[Phys. Rev. Lett. 131 (2023) 171901]

- The Q value(mass differences) is fitted to cancel out the resolution effect
- The intermediate resonances presented nicely $Q = m_{\Xi_b\pi} - m_{\Xi_b} - m_\pi$

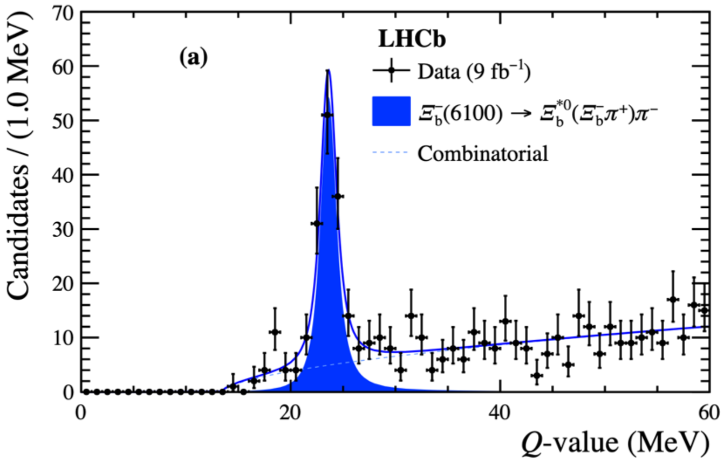


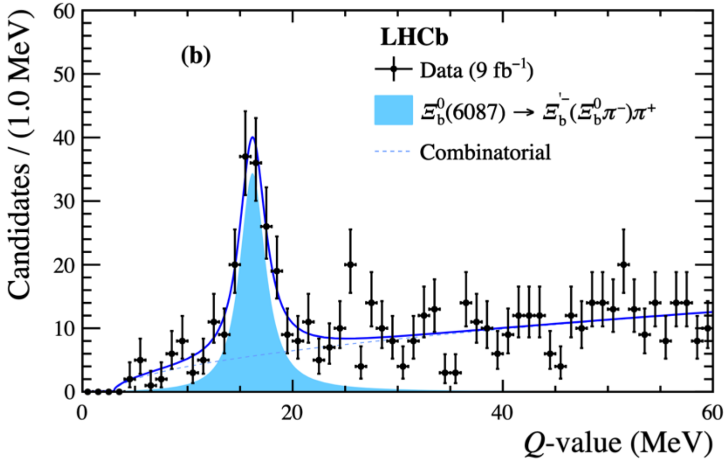


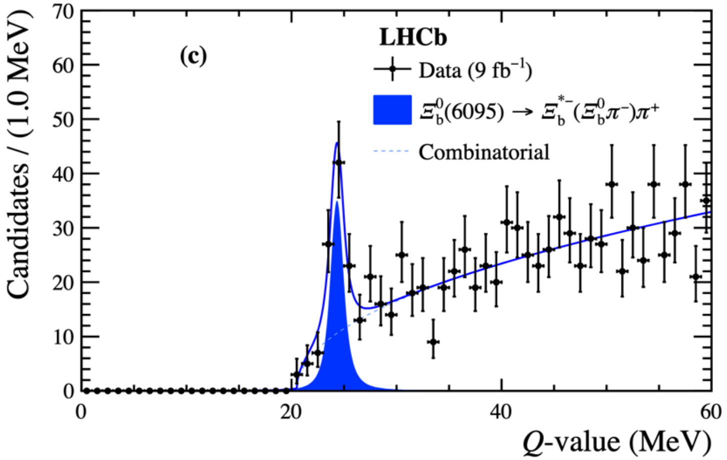


- Combine the intermediate state with the second opposite-charged pion

$$Q = m_{\Xi_b\pi\pi} - m_{\Xi_b} - 2m_\pi$$



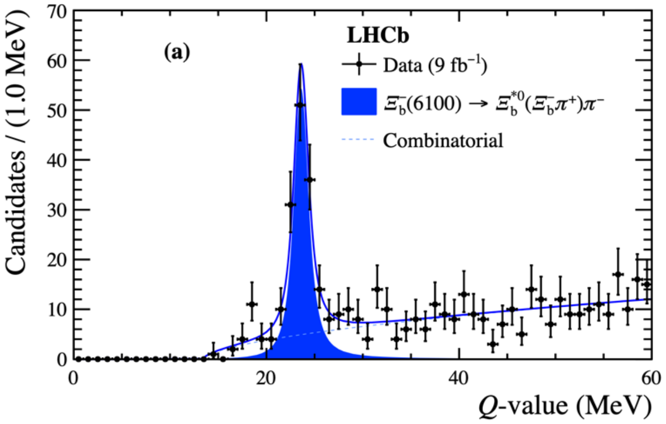


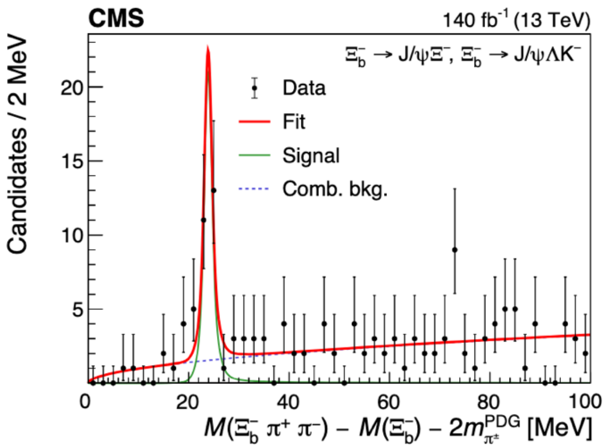


Observation of new baryons in $\Xi_b^{-(0)}\pi^-\pi^+$ spectrum

[Phys. Rev. Lett. 131 (2023) 171901]

- The $\Xi_b(6100)^-$ is confirmed by LHCb with significance > 12 σ
  - ❒ The decay mainly through $\Xi_b^{*0}\pi^-$ state
- First observation of $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$
  - ❒ Significance > 10 σ (7 σ)
  - ❒ Main decay processes: $\Xi_b^{\prime-}\pi^+$ and $\Xi_b^{*-}\pi^+$
- The best measurement on the known $\Xi_b^{\prime-}$ and Ξ_b^{*-} states
- First observation of $\Xi_b^0 \to \Xi_c^+\pi^-\pi^+\pi^-$ (New decay)





State	Observ.	Value (MeV)	
$\Xi_b(6100)^-$	Q_0	$23.6 \pm 0.11 \pm 0.02$	
	Γ	$0.94 \pm 0.30 \pm 0.08$	
	m_0	$6099.74 \pm 0.11 \pm 0.02$	
$\Xi_b(6087)^0$	Q_0	$16.20 \pm 0.20 \pm 0.06$	
	Γ	$2.43 \pm 0.51 \pm 0.10$	
	m_0	$6087.24 \pm 0.20 \pm 0.06$	± 0.5 (Ξ_b^0)
$\Xi_b(6095)^0$	Q_0	$24.32 \pm 0.15 \pm 0.03$	
	Γ	$0.50 \pm 0.33 \pm 0.11$	
	m_0	$6095.36 \pm 0.15 \pm 0.03$	
Ξ_b^{*0}	Q_0	$15.80 \pm 0.02 \pm 0.01$	
	Γ	$0.87 \pm 0.06 \pm 0.05$	
	m_0	$5952.37 \pm 0.02 \pm 0.01$	± 0.6 (Ξ_b^-)
$\Xi_b^{\prime-}$	Q_0	$3.66 \pm 0.01 \pm 0.00$	
	Γ	$0.03 \pm 0.01 \pm 0.03$	
	m_0	$5935.13 \pm 0.01 \pm 0.00$	± 0.5 (Ξ_b^0)
Ξ_b^{*-}	Q_0	$24.27 \pm 0.03 \pm 0.01$	
	Γ	$1.43 \pm 0.08 \pm 0.08$	
	m_0	$5955.74 \pm 0.03 \pm 0.01$	± 0.5 (Ξ_b^0)

Confirmation

Observation

Improvement

Study of hidden beauty spectroscopy

- Υ states [arXiv:2408.05134]
  - Masses measured in 1990s (CESR, DORIS, VEPP) , relied on photon energy of $\Upsilon(2S)$ and $\Upsilon(3S)$
    → standing tensions between CESR and DORIS on $\Upsilon(1S)$ mass
  - Shamov et al resolved by reanalysing the data with interference and radiative corrections considered correctly
  - Quoted error in PDG 2024 for $\Upsilon(1S)$ decreased: 0.26 MeV → 0.1 MeV ☺ [Phys. Lett. B839 (2023), 137766]
  - DORIS data is removed for $\Upsilon(2S)$, error increased: 0.31 MeV → 0.5 MeV ☹
- χ_b states
  - Mass knowledge largely comes from study of photon energy in feed-down from Υ decays
  - Measurement of mass splitting are dominated by BarBar experiment

$m_{\chi_{b2}(1P)} - m_{\chi_{b1}(1P)}$ PDGID:M078DM2 INSPIRE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
19.10 ± 0.25 OUR AVERAGE Error includes scale factor of 1.1.				
19.81 ±0.65 ±0.20	[1] AAIJ	2014BG	LHCB	$p\,p \to \gamma\mu^+\mu^- X$
19.01 ±0.24	LEES	2014M	BABR	$\Upsilon(2S) \to \gamma\gamma\mu^+\mu^-$

[1] From the $\chi_{bj}(1P) \to \Upsilon(1S)\gamma$ transition.

References:

AAIJ	2014BG	JHEP 1410 088	Measurement of the $\chi_b(3P)$ Mass and of the Relative Rate of $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ Production
LEES	2014M	PR D90 112010	Bottomonium Spectroscopy and Radiative Transitions Involving the $\chi_{bJ}(1P, 2P)$ States at BABAR

State	Measured mass $[\mathrm{MeV}/c^2]$ PDG2024	Measured mass $[\mathrm{MeV}/c^2]$ PDG2022
$\Upsilon(1S)$	9460.4 ± 0.1	9460.30 ± 0.26
$\Upsilon(2S)$	10023.4 ± 0.5	10023.26 ± 0.31
$\Upsilon(3S)$	10355.2 ± 0.5	10355.2 ± 0.5

Study of hidden beauty spectroscopy

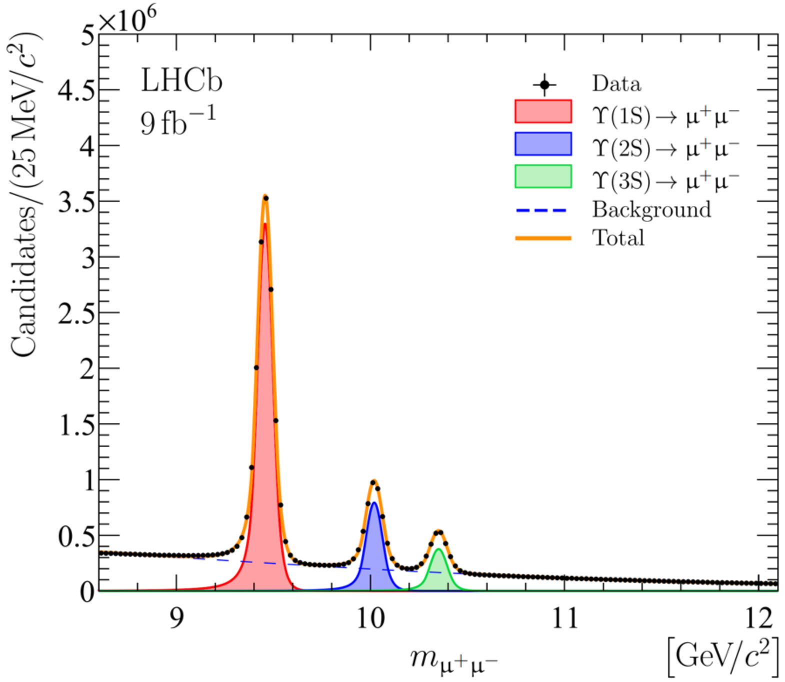
- Measurement of the mass and mass splittings using [arXiv:2408.05134]
  - Di-muon mode: $\Upsilon \to \mu^-\mu^+$
  - Di-pion mode: $\Upsilon(2S) \to \Upsilon(1S)\pi^-\pi^+$, $\Upsilon(3S) \to \Upsilon(2S)\pi^-\pi^+$

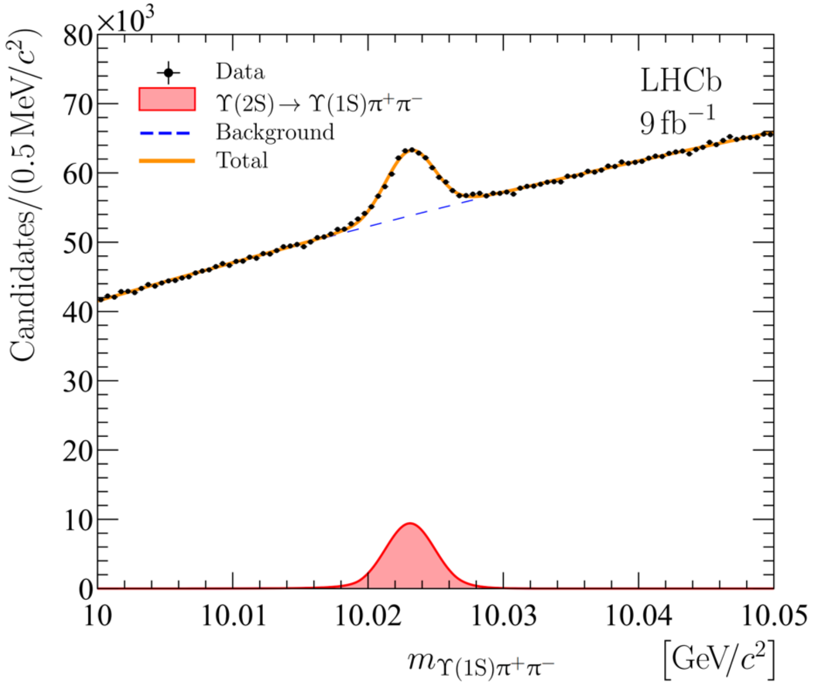
Agree with PDG. Most precise result for $\Upsilon(2S)$

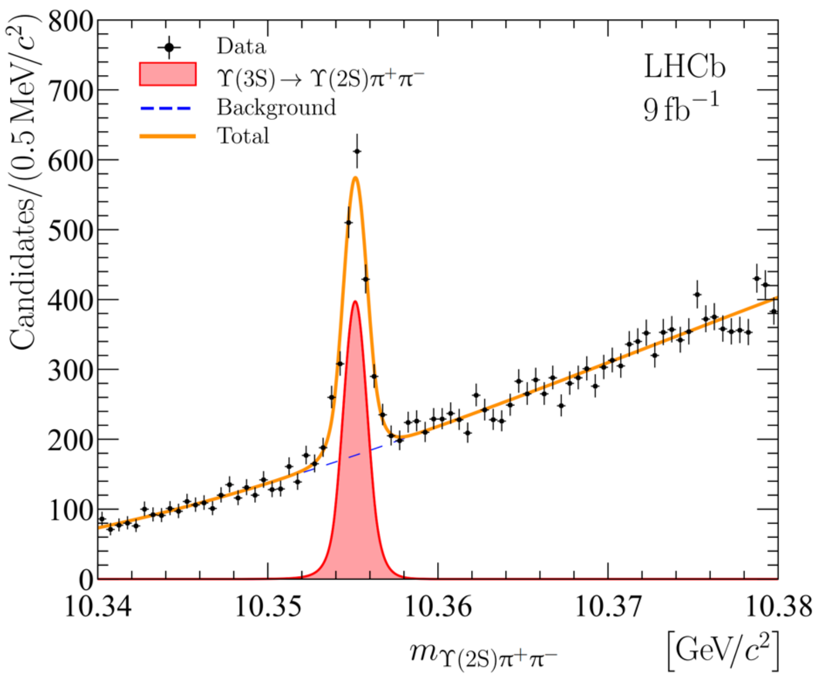
$$m_{\Upsilon(2S)} = 10\,023.25 \pm 0.03 \pm 0.12 \pm 0.09\ \text{MeV}/c^2$$
$$m_{\Upsilon(3S)} = 10\,355.28 \pm 0.03 \pm 0.04 \pm 0.48\ \text{MeV}/c^2$$

Similar precision to BaBar, $2-4\,\sigma$ tension

$$m_{\Upsilon(2S)} - m_{\Upsilon(1S)} = 562.84 \pm 0.02 \pm 0.13\ \text{MeV}/c^2,$$
$$m_{\Upsilon(3S)} - m_{\Upsilon(2S)} = 331.86 \pm 0.03 \pm 0.05\ \text{MeV}/c^2.$$







Study of hidden beauty spectroscopy

[arXiv:2408.05134]

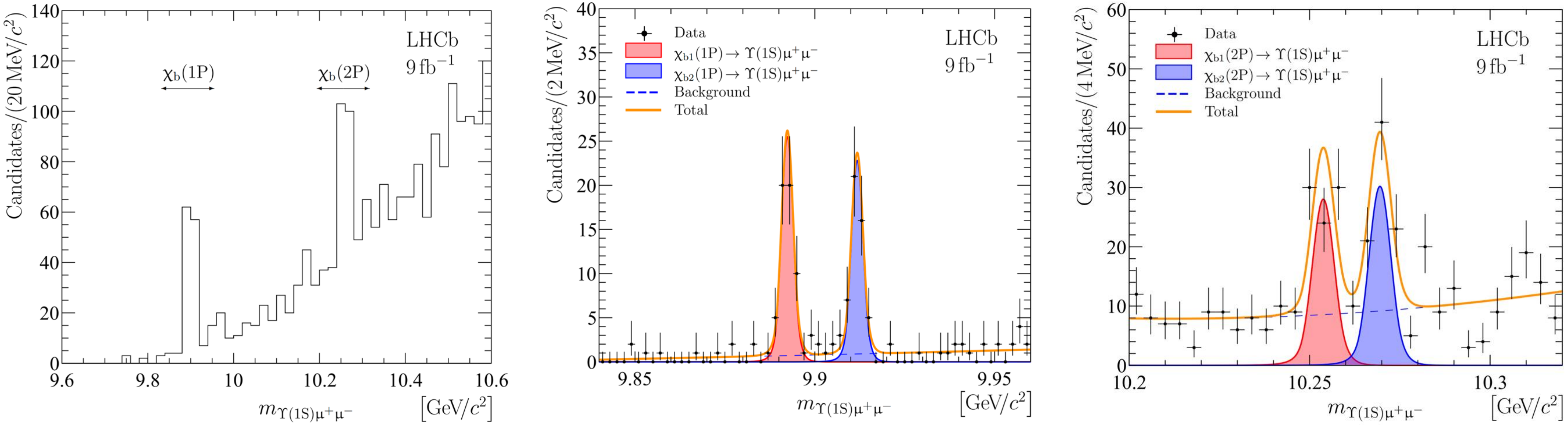
- First observation of muonic Dalitz decay $\chi_b \to \Upsilon(1S)\mu^-\mu^+$
  - Measured masses agree with PDG

$$
\begin{aligned}
m_{\chi_{b1}(1P)} &= 9\,892.50 \pm 0.26 \pm 0.10 \pm 0.10\,\mathrm{MeV}/c^2 \\
m_{\chi_{b2}(1P)} &= 9\,911.92 \pm 0.29 \pm 0.11 \pm 0.10\,\mathrm{MeV}/c^2
\end{aligned}
$$

World best value

$$
\begin{aligned}
m_{\chi_{b1}(2P)} &= 10\,253.97 \pm 0.75 \pm 0.22 \pm 0.09\,\mathrm{MeV}/c^2 \\
m_{\chi_{b2}(2P)} &= 10\,269.67 \pm 0.67 \pm 0.22 \pm 0.09\,\mathrm{MeV}/c^2
\end{aligned}
$$

Not so precise yet but competitive statistics limited

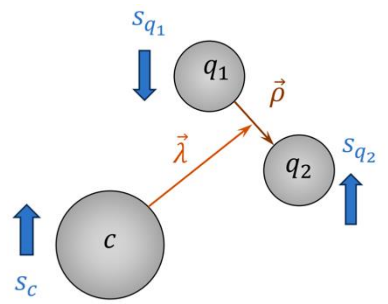


Determination of the spin-parity of $\Xi_c(3055)^{+(0)}$

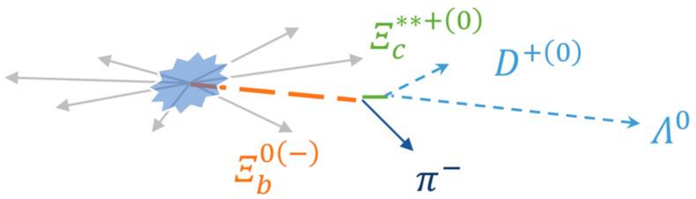
[arXiv:2409.05440]

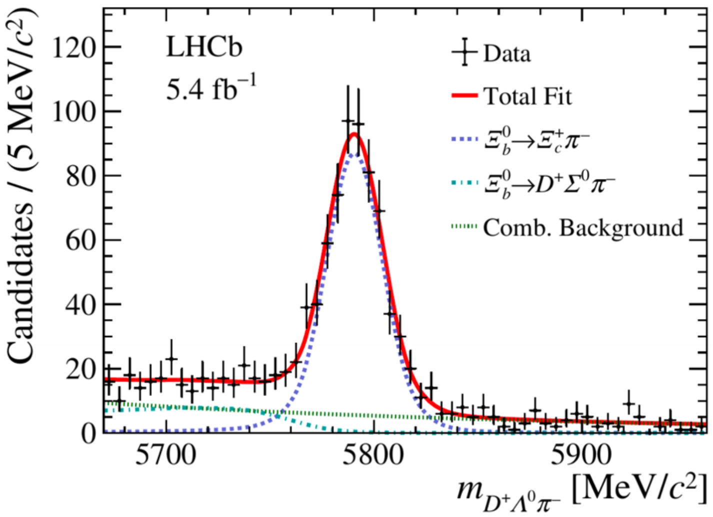
- $\Xi_c(3055)^{+(0)}$ observed for the first time by Babar(Belle)
- Excitation modes of $\Xi_c(3055)^{+(0)}$ extensively studied
- Many proposed interpretations, including $J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$

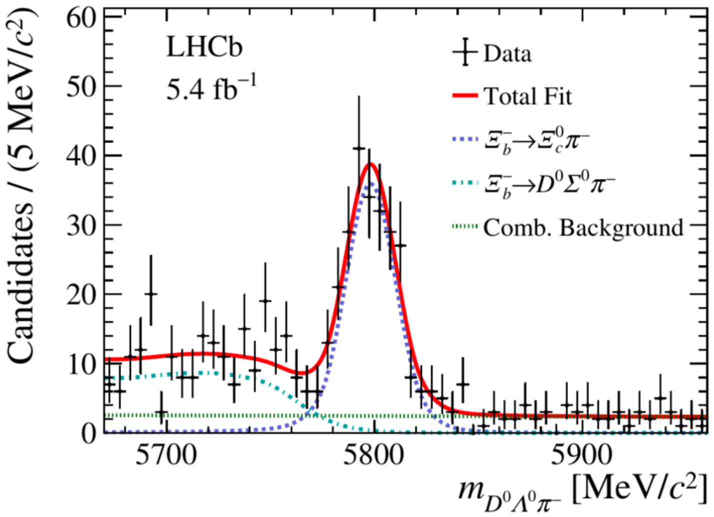
  ⇒ **determination of J^P is an important information for charm baryon spectroscopy**

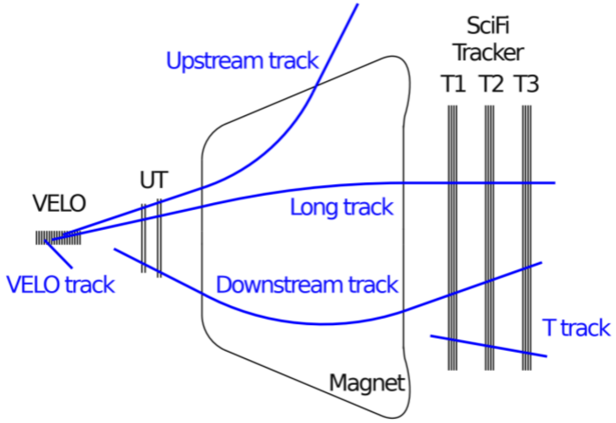


- Strategy
  - ❒ In $\Xi_b^{0(-)} \to \Xi_c^{**+(0)}\pi^-$ decay, where $\Xi_c^{**+(0)} \to D^{+(0)}\Lambda^0$
  - ❒ The Λ^0 can be both Long-Long and Down-Down tracks





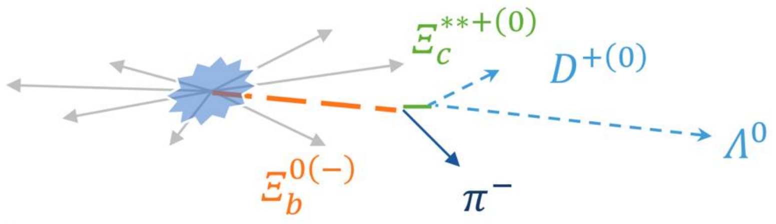




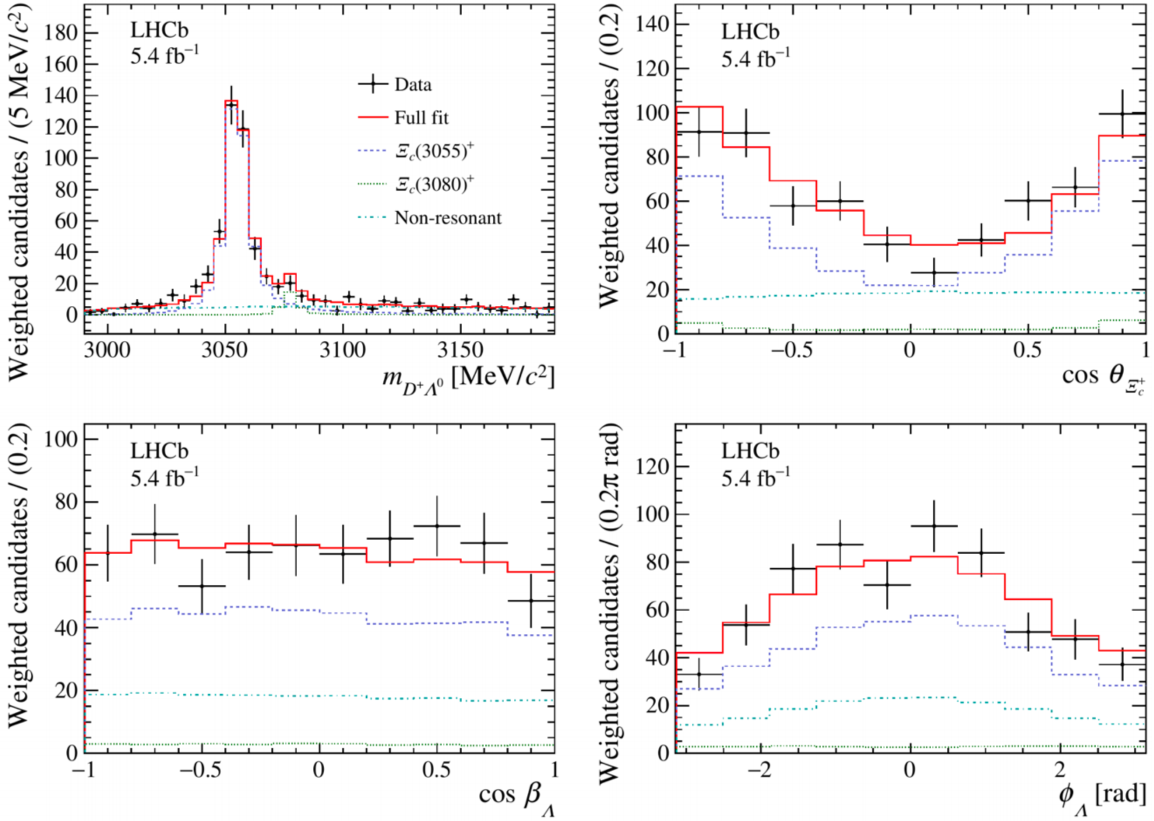
Determination of the spin-parity of $\Xi_c(3055)^{+(0)}$

[arXiv:2409.05440]

- Amplitude analysis
  - Helicity formalism
  - Free parameters: mass, width, helicity couplings



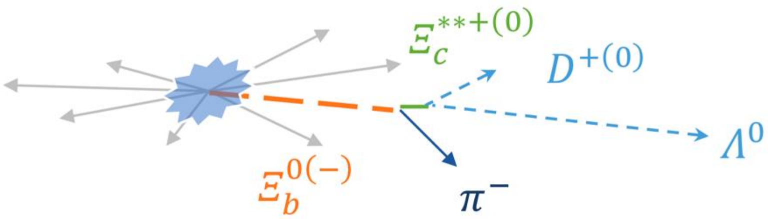
- **Best fit corresponds to $J^P = \frac{3}{2}^+$**

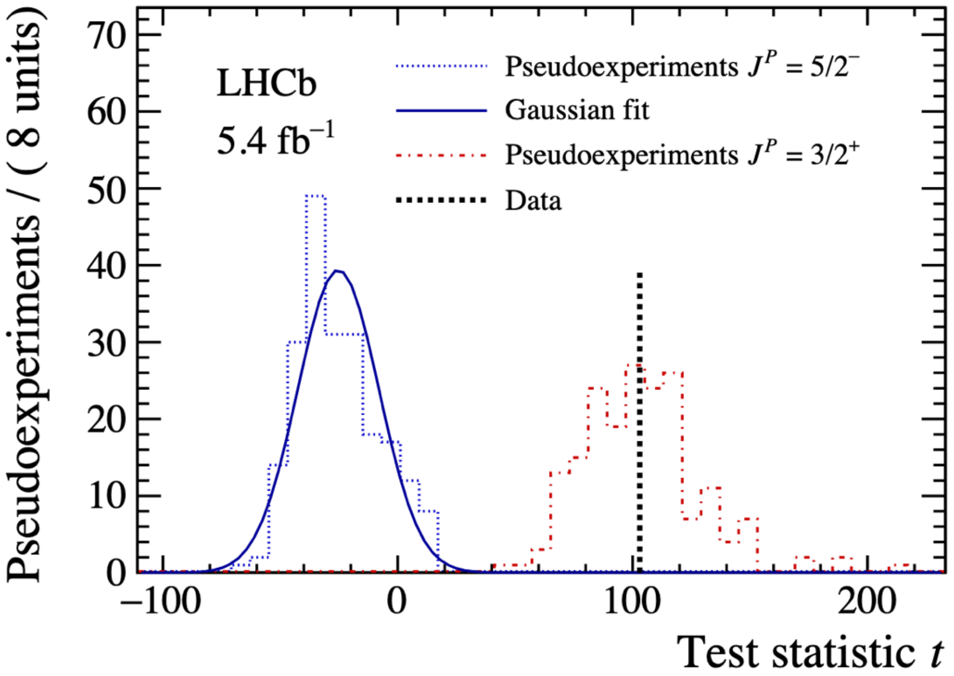


Determination of the spin-parity of $\Xi_c(3055)^{+(0)}$

[arXiv:2409.05440]

- Amplitude analysis
  - Helicity formalism
  - Free parameters: mass, width, helicity couplings
- **Best fit corresponds to $J^P = \frac{3}{2}^+$**
- **With rejection significance of other hypotheses $n_\sigma > 6.5\,\sigma$**





$J^P_{\Xi_c(3055)^+}$	n_σ
$1/2^-$	12.9σ
$1/2^+$	11.0σ
$3/2^-$	7.3σ
$5/2^-$	6.5σ
$5/2^+$	9.8σ
$7/2^-$	10.7σ
$7/2^+$	10.9σ

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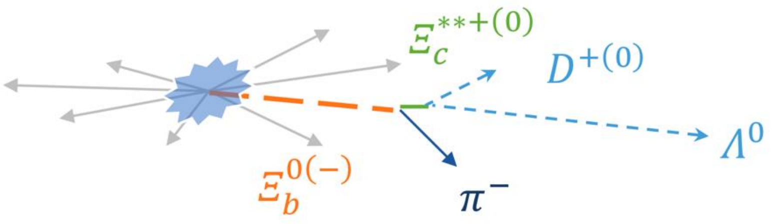
- **With rejection significance of other hypotheses $n_\sigma > 6.5\,\sigma$**
- **Measured the up-down asymmetries α of $\Xi_b^{0(-)} \to \Xi_c(3055)^{+(0)}\pi^-$ decays**
  - Consistent with a complete parity violation
  - First measurement for the transition of the Ξ_b to Ξ_c baryon with a pseudoscalar meson
- **Measured the relative branching fraction $B_{\Xi_c(3080)^+}/B_{\Xi_c(3055)^+}$**



$$\alpha \equiv \frac{|H_{\lambda_{\Xi_b^0}=+1/2}|^2 - |H_{\lambda_{\Xi_b^0}=-1/2}|^2}{|H_{\lambda_{\Xi_b^0}=+1/2}|^2 + |H_{\lambda_{\Xi_b^0}=-1/2}|^2}$$

Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
$m\,[\mathrm{MeV}/c^2]$	$3054.52 \pm 0.36 \pm 0.17$	$3061.00 \pm 0.80 \pm 0.23$
$\Gamma\,[\mathrm{MeV}]$	$8.01 \pm 0.76 \pm 0.34$	$12.4 \pm 2.0 \pm 1.1$
α	$-0.92 \pm 0.10 \pm 0.05$	$-0.92 \pm 0.16 \pm 0.22$
$R_{\mathcal{B}}$	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$

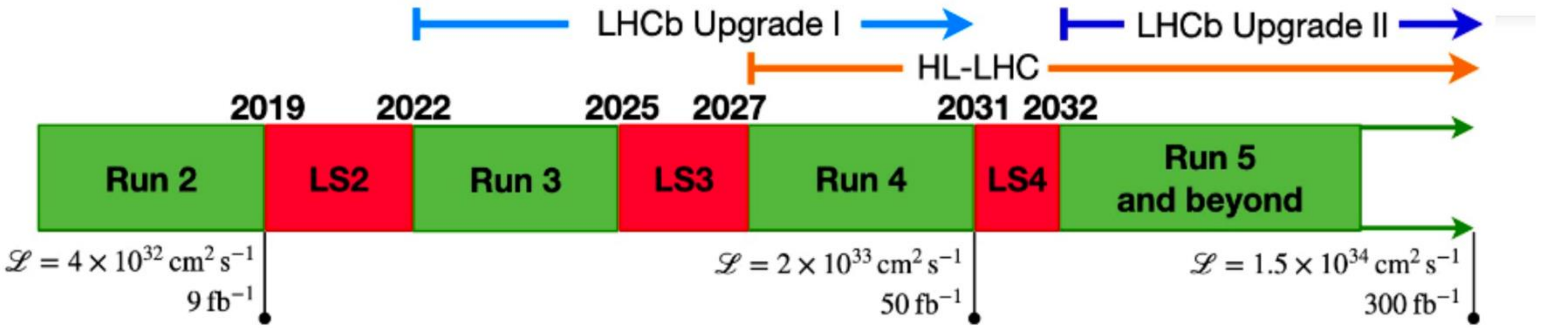
Summary and prospect

- Recent interesting results presented in this talk
  - ✓ Observation of $\Xi_b(6100)^-$, $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$
  - ✓ Observation of $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$
  - ✓ New decay modes: $\chi_b \to \Upsilon(1S)\mu^-\mu^+$, $\Xi_b^0 \to \Xi_c^+\pi^-\pi^+\pi^-$
  - ✓ Mass measurement: Υ, χ_b
  - ✓ Spin-parity determination: $\Xi_c(3055)^+$, $\Xi_c(3055)^0$

Just one more conventional hadron away from completing the spectroscopy puzzle ……

Today's discovery, tomorrow's precision tool to test QCD!

- In RunIII, the LHCb experiment will keep making important contributions to heavy hadron spectroscopy with
  - ❒ Higher luminosity
  - ❒ Upgraded detector
  - ❒ Improved techniques
  - ❒ …

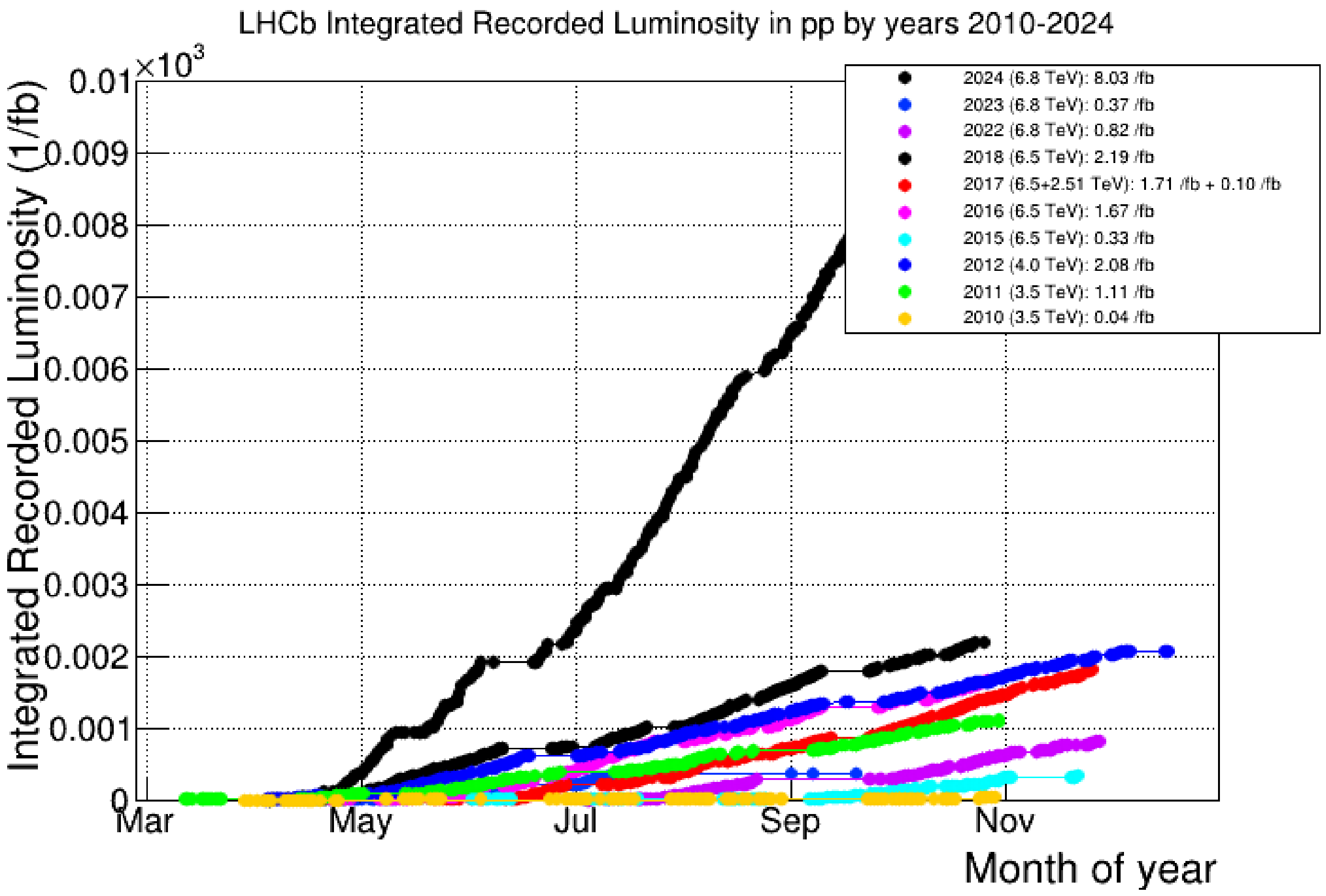


Thanks a lot for your attention!

Backup

LHCb dataset

- RunI: 3 fb^{-1} pp collision @ 7,8 TeV
- RunII: 6 fb^{-1} pp collision @ 13 TeV

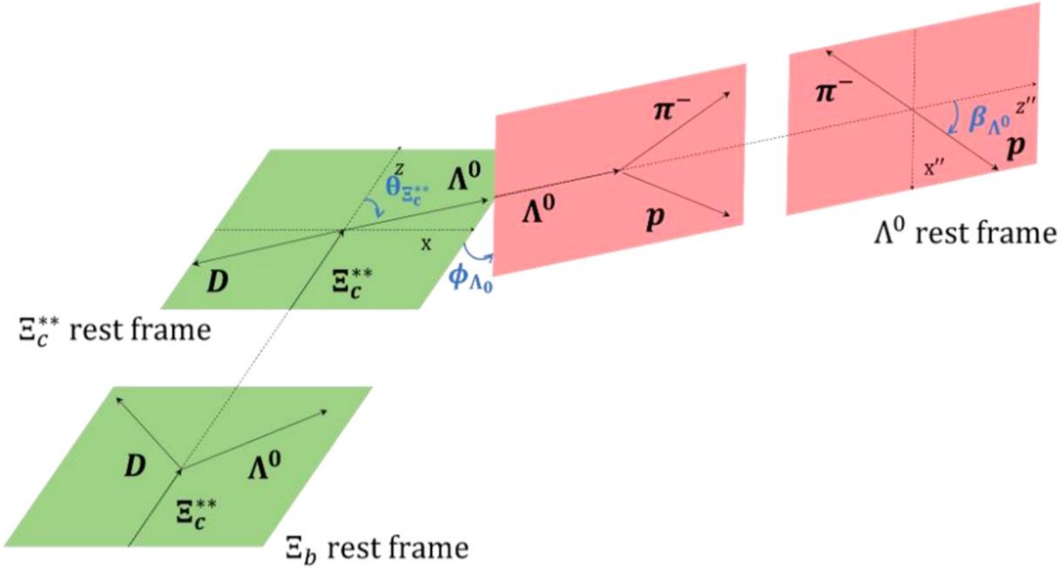


https://lbgroups.cern.ch/online/OperationsPlots/index.htm

Helicity amplitude

- Helicity couplings in the $\Xi_b \to \Xi_c \pi,\ \Xi_c^{**} \to D\Lambda,\ \Lambda \to p\pi$ decay chain

  - $\Xi_b \to \Xi_c^{**}\pi^-$ $\quad A^{\Xi_b\to\Xi_c\pi^-}_{\lambda_{\Xi_b},\lambda_{\Xi_c},\lambda_\pi} = H^{\Xi_b\to\Xi_c\pi^-}_{\lambda_{\Xi_c}}\delta_{\lambda_{\Xi_b},\lambda_{\Xi_c}}$ $\quad$ Floated for each resonance
  - $\Xi_c^{**} \to D\Lambda$ $\quad A^{\Xi_c\to D\Lambda}_{\lambda_{\Xi_c},\lambda_D,\lambda_\Lambda} = H^{\Xi_c\to D\Lambda}_{\lambda_\Lambda} d^{J_{\Xi_c}}_{\lambda_{\Xi_c},\lambda_\Lambda}(\theta)$ $\quad$ Strong decay, only phase term: $\eta^{P_{\Xi_c}}(-1)^{J_{\Xi_c}+1/2}$
  - $\Lambda \to p\pi^-$ $\quad A^{\Lambda\to p\pi^-}_{\lambda_\Lambda,\lambda_p,\lambda_\pi} = H^{\Lambda\to p\pi^-}_{\lambda_p} D^{j_\Lambda}_{\lambda_\Lambda,\lambda_p}(\phi,\beta,0)$ $\quad$ Fixed from input



Theoretical interpretations of $\Xi_c(3055)$

- Summarized in Rept.Prog.Phys. 80 (2017) no.7, 076201

References	Theoretical model	J^P of $\Xi_c(3055)$
Eur. Phys. J. A 37 (2008) 217–225	Faddeev method	$5/2^+$ (1D)
Phys. Rev. D 78 (2008) 056005	Regge phenomenology	$5/2^+$ (1D)
Phys. Rev. D 84 (2011) 014025	QCD-motivated relativistic quark model	$3/2^+$ (1D)
Phys. Rev. D 86 (2012) 034024	Chiral quark model	$3/2^+$ (1D)
Eur. Phys. J. A 82 (2015) 51	Relativistic flux tube model	$3/2^+$ (1D)
Phys. Rev. D 94 (2016) 114016	QCD sum rules within HQET	$3/2^+$ (1D)
Phys. Rev. D 96 (2017) 114003	3P0 model	$1/2^+(\bar{3}_F),\ 3/2^+(6_F)$ (2S)
Eur. Phys. J. C 79 (2019)167	Hadron molecular state	$1/2^-, 3/2^-$ (molecular)