HADRON 2023

New results on conventional heavy baryon spectroscopy from LHCb

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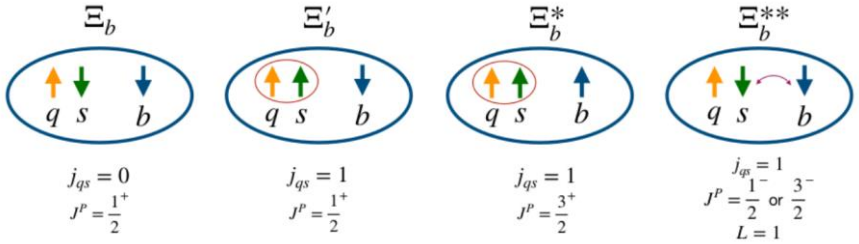
(on behalf of the LHCb collaboration)

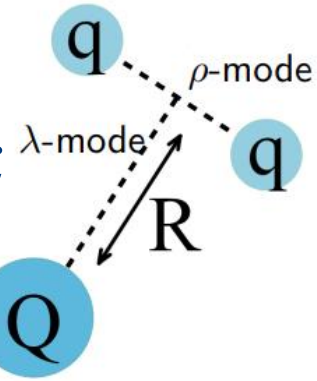
University of Chinese Academy of Sciences

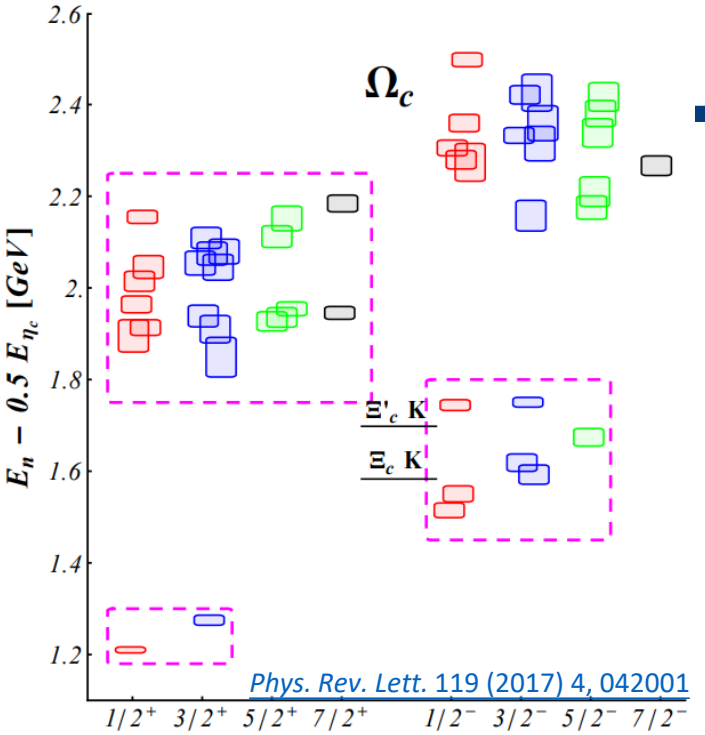
Hadron 2023
June 5 to 9, 2023

Motivation - I

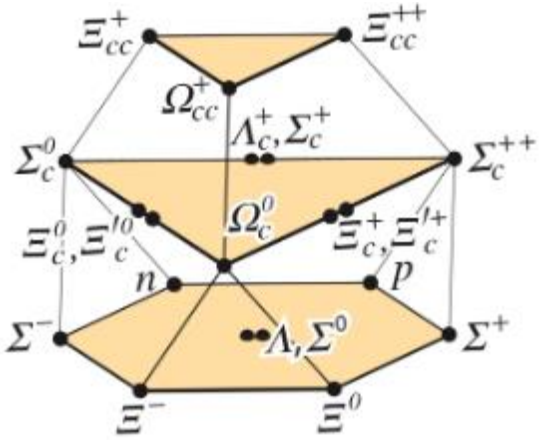


- **Why we do spectroscopy?**
- Missing particles in hadron multiplets;
  - Ground QQq, QQQ states
  - Excited Qqq states
- Complex inner structure of excited states;
  - Molecular? Pentaquark? (hidden $q\bar{q}$?)
  - Radially mode? Orbital mode?

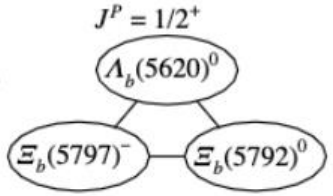




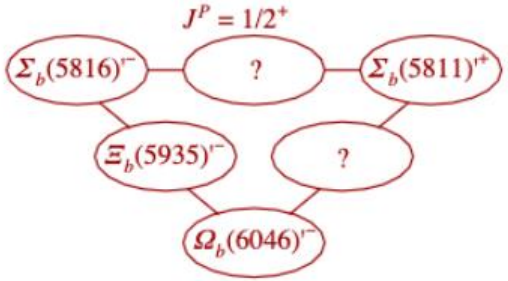
Phys. Rev. Lett. 119 (2017) 4, 042001



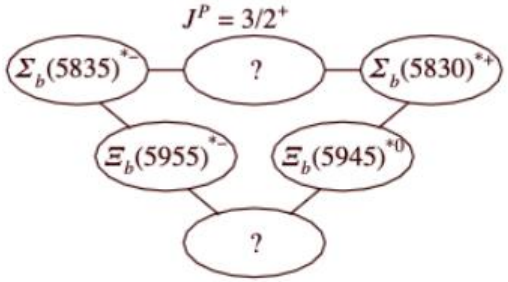
1S



$s_{qq'} = 0$



$s_{qq'} = 1$



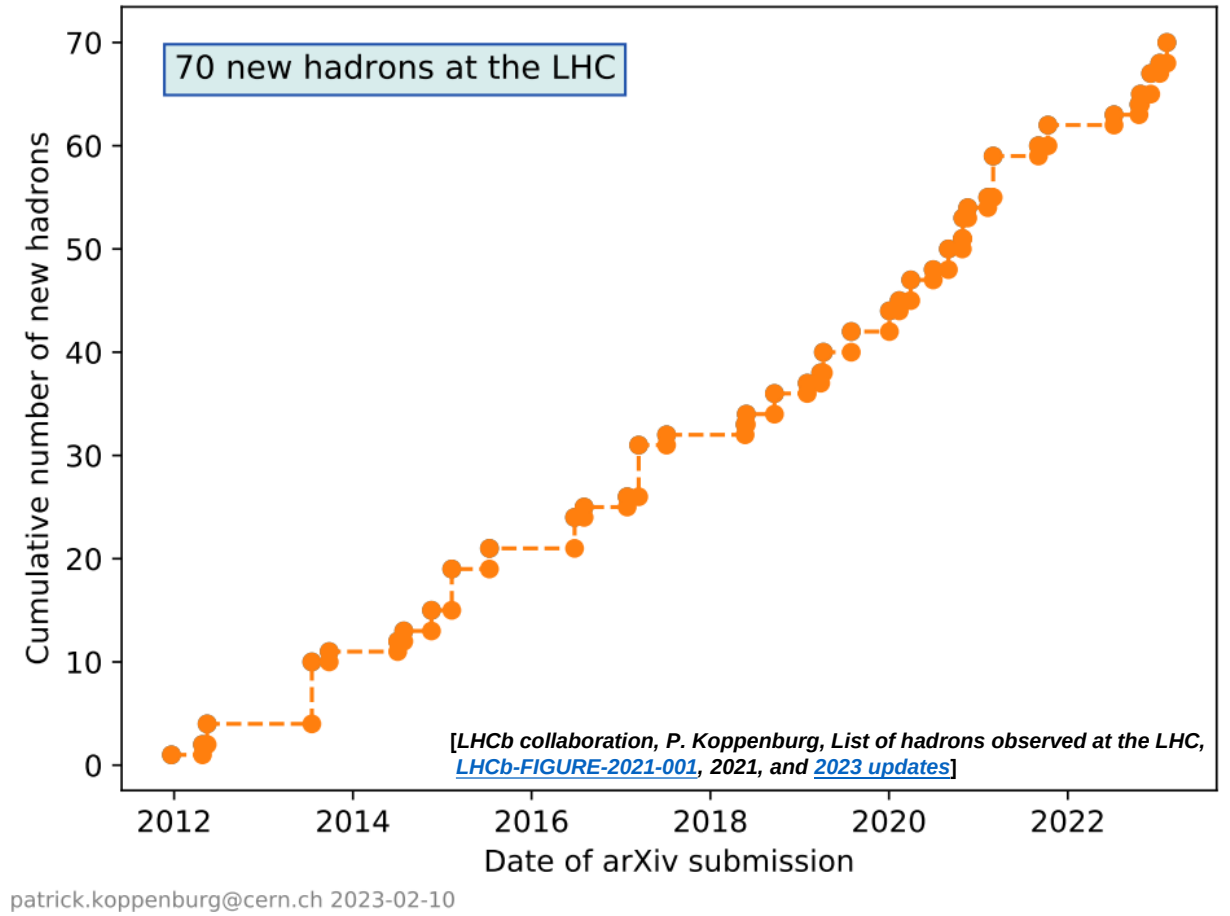
$s_{qq'} = 1$

Motivation - II

- **What can we do?**

- Searching for new decays.
- Expanding known decays.

- Mass, width (lifetime);
- Production;
- Branching ratio;
- Quantum numbers ($I^G J^{PC}$).

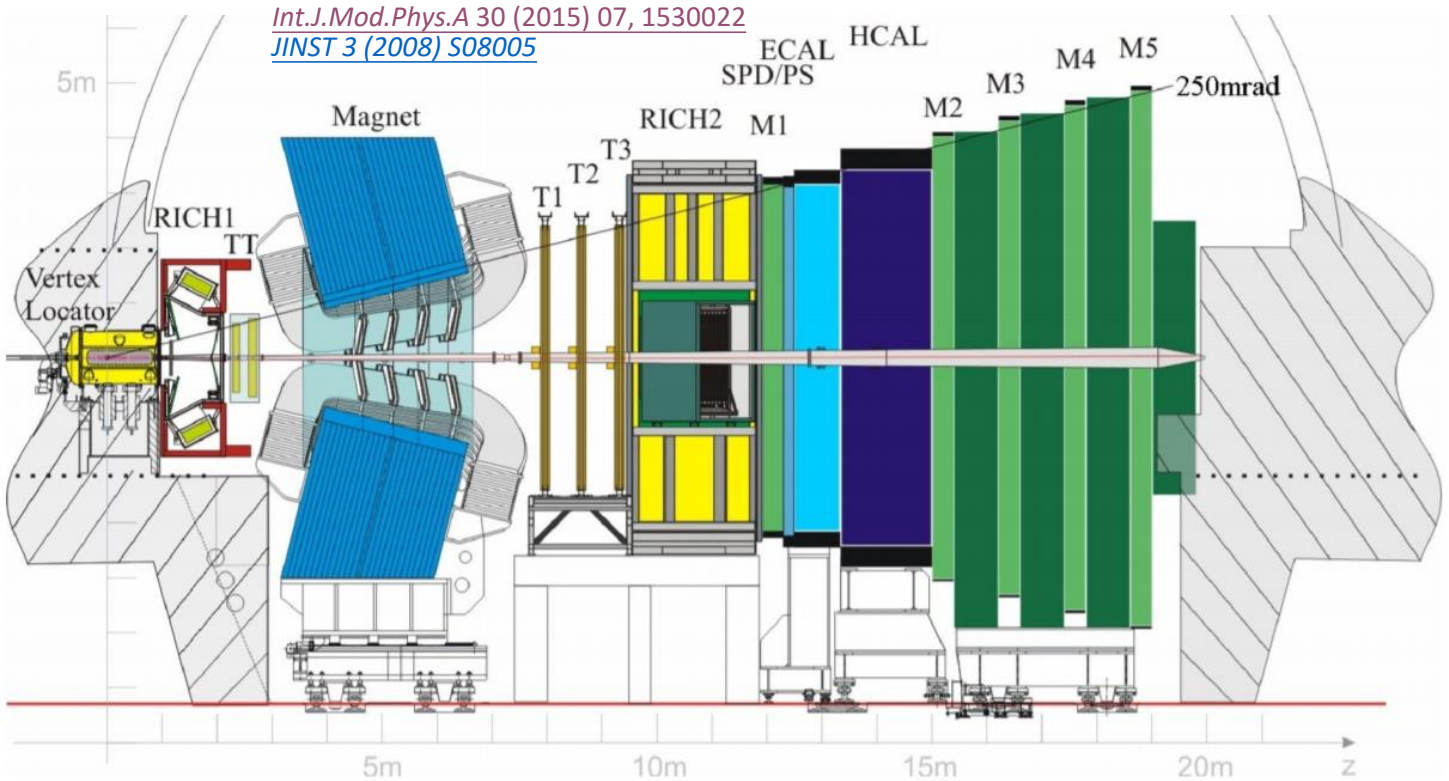


LHCb experiment - I

$\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$
$\sigma_\tau = 45\ \mathrm{fs}$

$\sigma_p/p \sim 0.5\% - 1.0\%$
$\sigma_E/E = \frac{10\%}{\sqrt{E}} \pm 1\%$

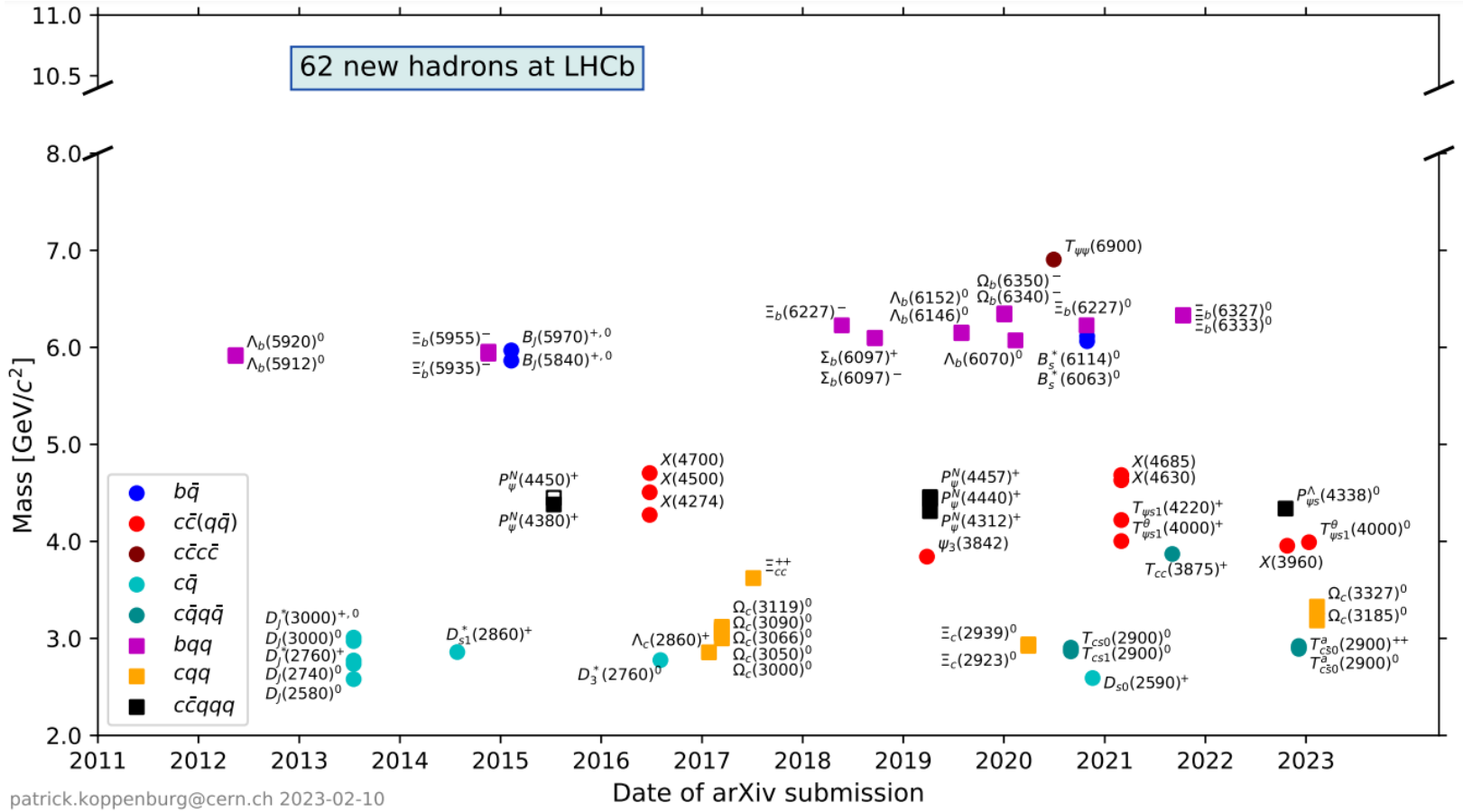
$\epsilon(K \to K) \sim 95\%$
Mis-ID $\epsilon(\pi \to K) \sim 5\%$



- LHCb designed for study charmed and beauty hadron.
- Excellent vertex, tracking and PID performance.

LHCb experiment - II

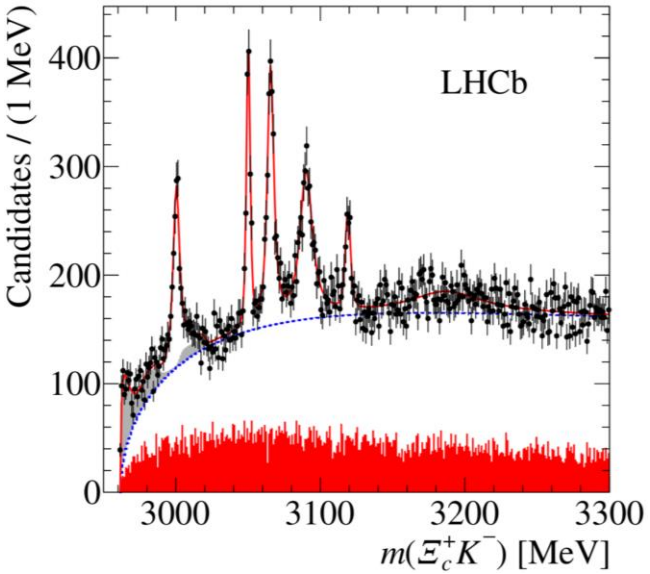
- LHCb collected the largest samples of reconstructed heavy hadrons during LHC Run 1 and Run 2.



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

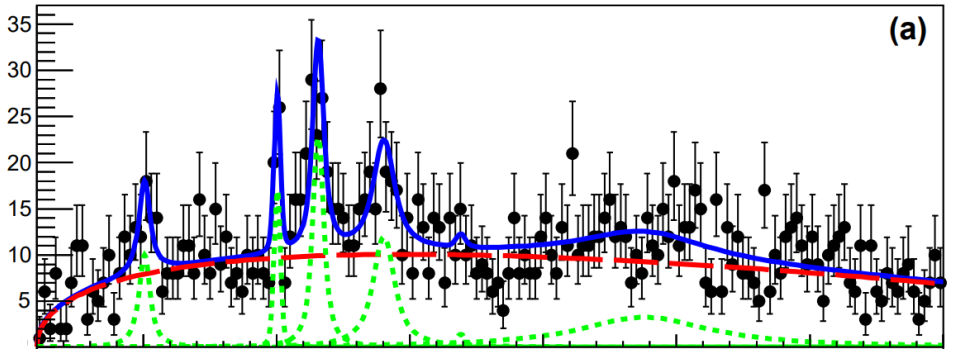
Excited Ω_c^0 states - I

- **Starting of the story…**
- In 2017, LHCb observed five new excited Ω_c^0 in $m(\Xi_c^+ K^-)$.
- **Four** of them confirmed by Belle.



2017 LHCb result

PHYS. REV. LETT. 118 (2017) 182001



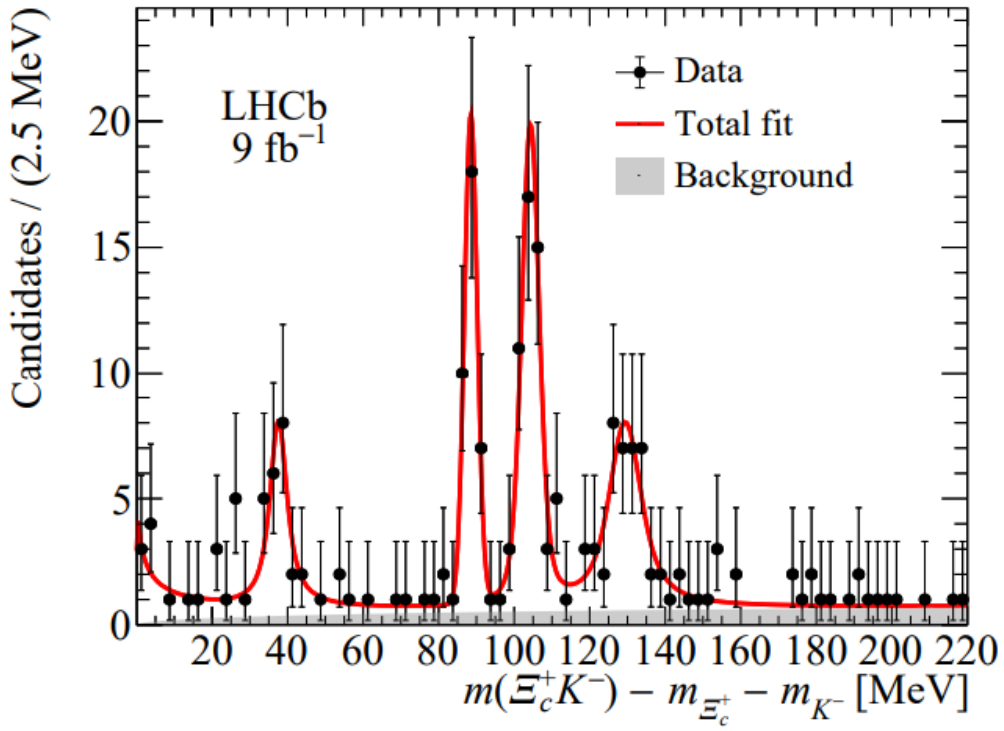
2018 Belle result

PHYS. REV. D 97 (2018) 5, 051102

Excited Ω_c^0 states - II

- In 2021, LHCb observed **four** of them from $\Omega_b^- \to \Omega_c^{(**)0}\pi^-$
- Spin test done, but no solid conclusion.

PHYS. REV. D 104 (2021) 9, 9.



State	Observable	Measurement
Ω_b^-	m	$6044.3 \pm 1.2 \pm 1.1^{+0.19}_{-0.22}$ MeV
	$\mathcal{R}$	$1.35 \pm 0.11 \pm 0.05$
Threshold structure	Significance	$4.3\,\sigma$
$\Omega_c(3000)^0$	Significance	$6.2\,\sigma$
	ΔM	$37.6 \pm 0.9 \pm 0.9$ MeV
	m	$2999.2 \pm 0.9 \pm 0.9^{+0.19}_{-0.22}$ MeV
	Γ	$4.8 \pm 2.1 \pm 2.5$ MeV
	$\mathcal{P}$	$0.11 \pm 0.02 \pm 0.04$
	J rejection	$0.5\,\sigma\,(J=1/2), 0.8\,\sigma\,(J=3/2), 0.4\,\sigma\,(J=5/2)$
$\Omega_c(3050)^0$	Significance	$9.9\,\sigma$
	ΔM	$88.5 \pm 0.3 \pm 0.2$ MeV
	m	$3050.1 \pm 0.3 \pm 0.2^{+0.19}_{-0.22}$ MeV
	Γ	< 1.6 MeV, 95% CL
	$\mathcal{P}$	$0.15 \pm 0.02 \pm 0.02$
	J rejection	$2.2\,\sigma\,(J=1/2), 0.1\,\sigma\,(J=3/2), 1.2\,\sigma\,(J=5/2)$
$\Omega_c(3065)^0$	Significance	$11.9\,\sigma$
	ΔM	$104.3 \pm 0.4 \pm 0.4$ MeV
	m	$3065.9 \pm 0.4 \pm 0.4^{+0.19}_{-0.22}$ MeV
	Γ	$1.7 \pm 1.0 \pm 0.5$ MeV
	$\mathcal{P}$	$0.23 \pm 0.02 \pm 0.02$
	J rejection	$3.6\,\sigma\,(J=1/2), 0.6\,\sigma\,(J=3/2), 1.2\,\sigma\,(J=5/2)$
$\Omega_c(3090)^0$	Significance	$7.8\,\sigma$
	ΔM	$129.4 \pm 1.1 \pm 1.0$ MeV
	m	$3091.0 \pm 1.1 \pm 1.0^{+0.19}_{-0.22}$ MeV
	Γ	$7.4 \pm 3.1 \pm 2.8$ MeV
	$\mathcal{P}$	$0.19 \pm 0.02 \pm 0.04$
	J rejection	$0.3\,\sigma\,(J=1/2), 0.8\,\sigma\,(J=3/2), 0.5\,\sigma\,(J=5/2)$
$\Omega_c(3120)^0$	$\mathcal{P}$	< 0.03, 95% CL

Stat. Sys.

New

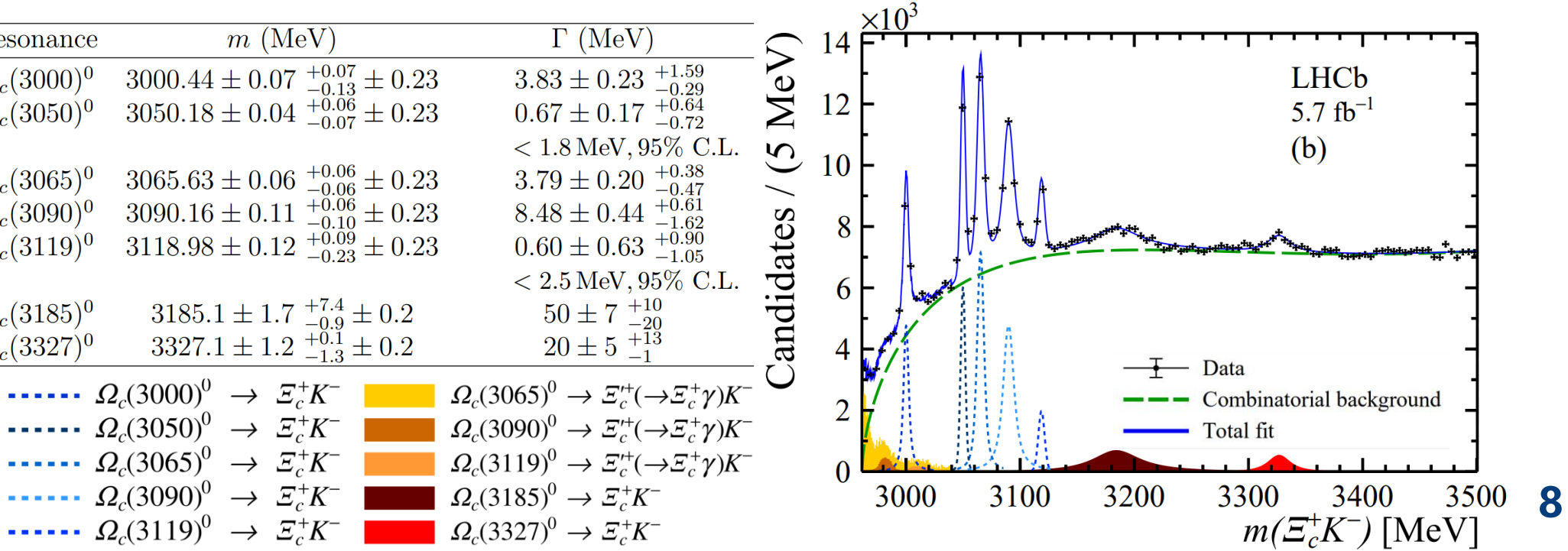
New excited Ω_c^0 states - I

ARXIV: 2302.04733.

- **New states observed: $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$**
- **All previous states confirmed**, and masses and widths measured with the highest precision.
- Detailed study of the threshold enhancement.
- Detailed study of the $\Omega_c(3185)^0$ with alternative model.

} **as systematics**

Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\ ^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\ ^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\ ^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\ ^{+0.64}_{-0.72}$
		< 1.8 MeV, 95% C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\ ^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\ ^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\ ^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\ ^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\ ^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\ ^{+0.90}_{-1.05}$
		< 2.5 MeV, 95% C.L.
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\ ^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\ ^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\ ^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\ ^{+13}_{-1}$

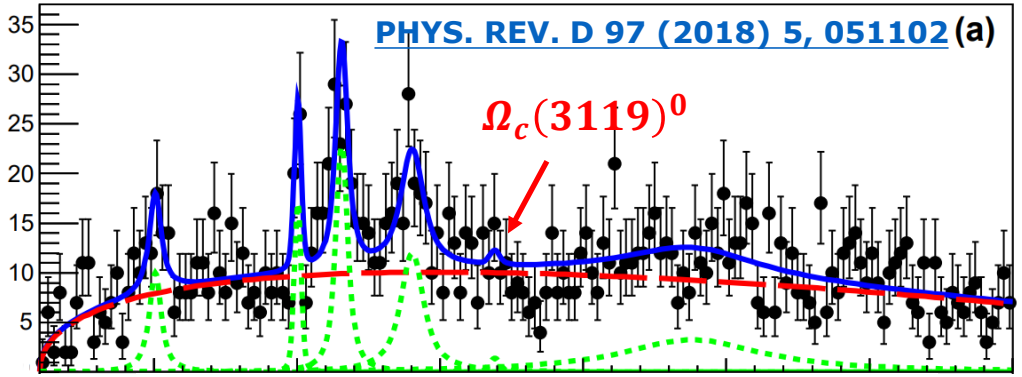


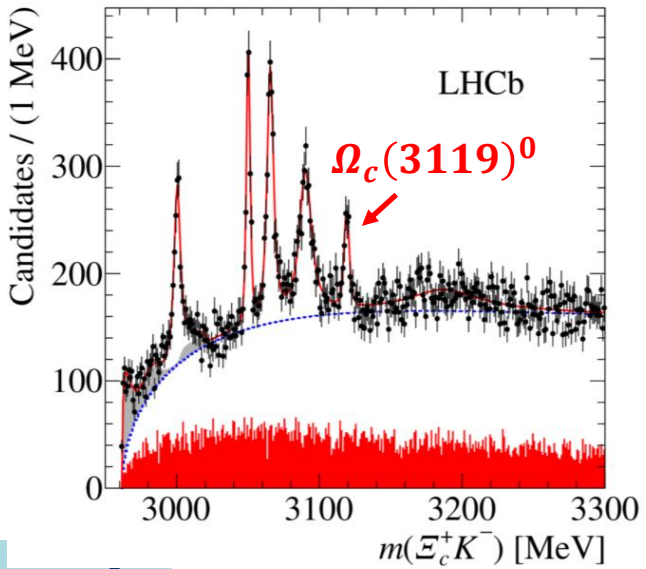
New

New excited Ω_c^0 states - II

- Three $m(\Xi_c^+ K^-)$ studies from LHCb…
- And one $m(\Xi_c^+ K^-)$ study from Belle…

- **What happens on $\Omega_c(3119)^0$?**
- **What exactly happens on threshold?**





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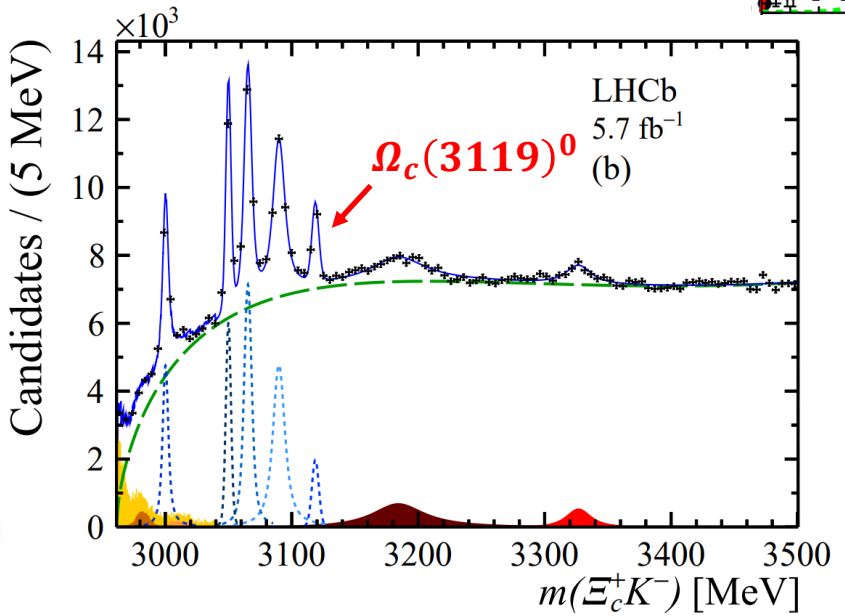

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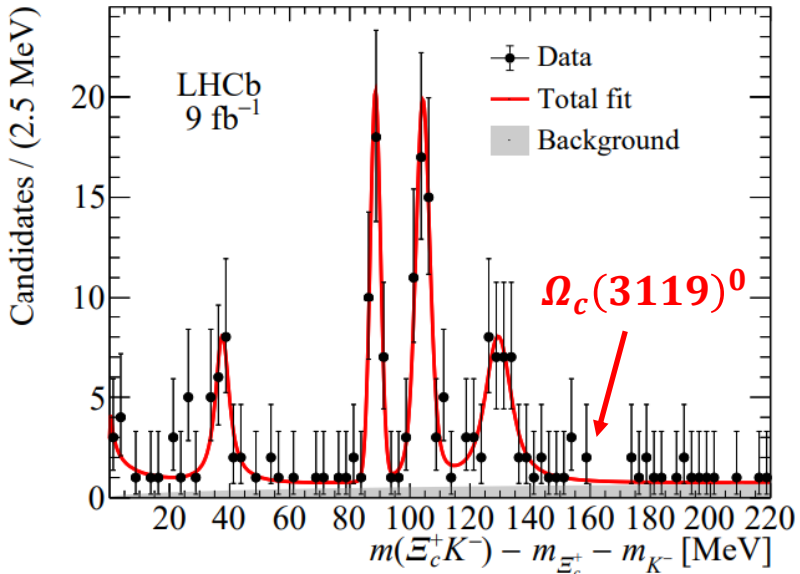

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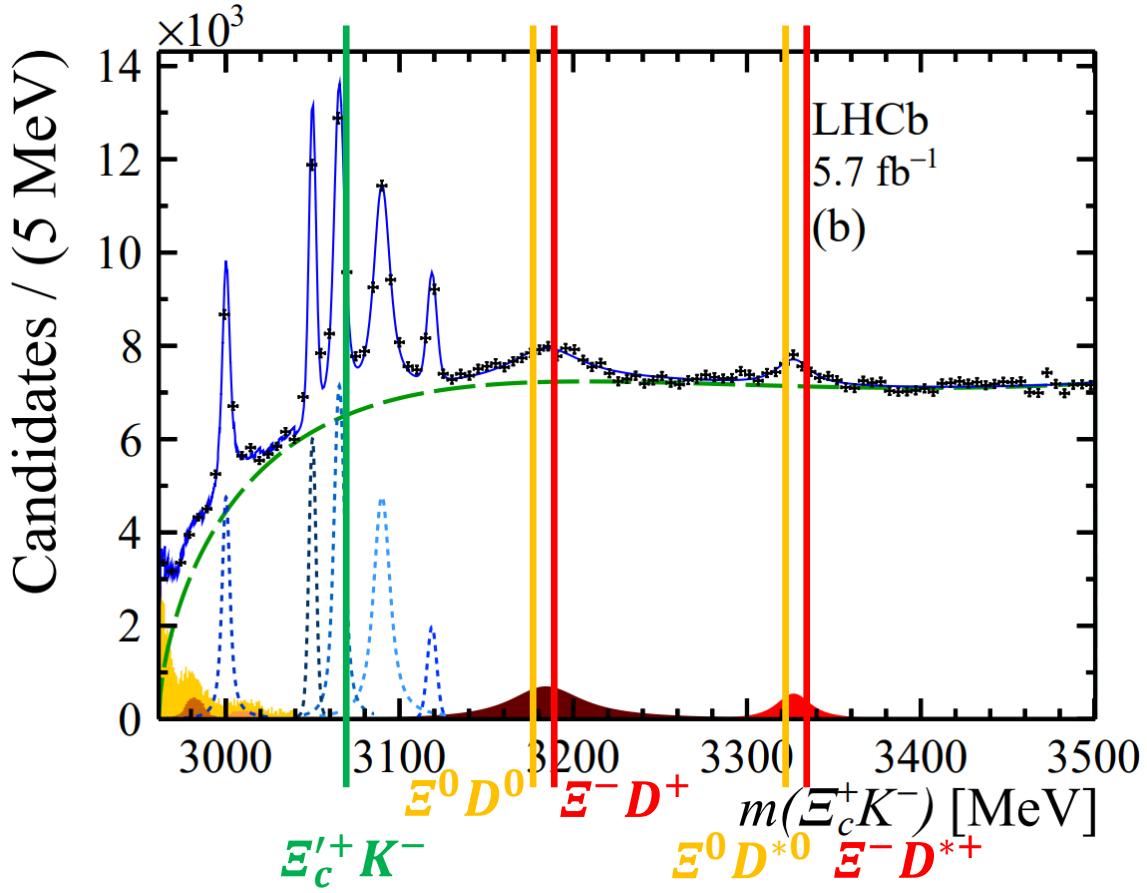
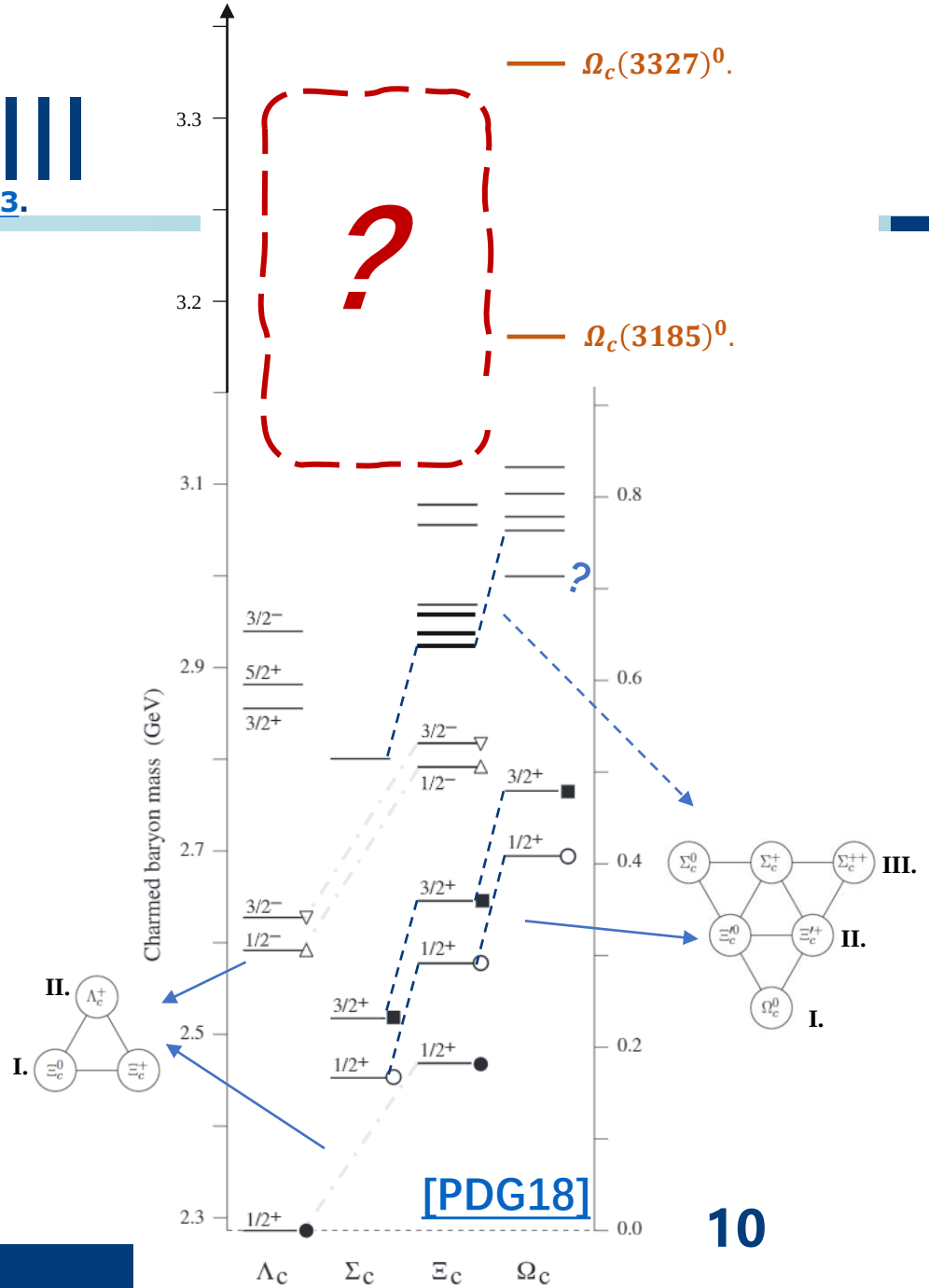
New

New excited Ω_c^0 states - III

ARXIV: 2302.04733.

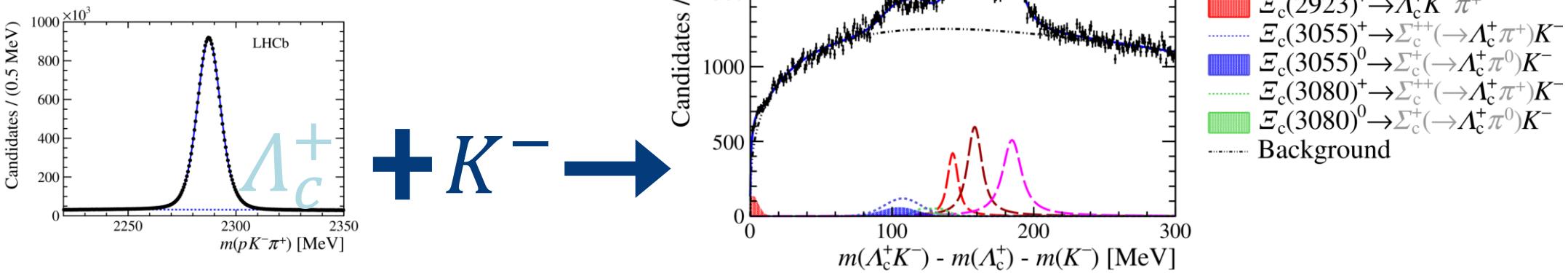




Excited Ξ_c^0 states - I

PHYS. REV. LETT. 124 (2020) 222001

- Three excited Ξ_c^0 were observed in prompt $m(\Lambda_c^+ K^-)$.
- Using LHCb 2016-2018 data, at 13 TeV and 5.4 fb^{-1}.



Resonance	Peak of ΔM [MeV]	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$
		Stat. Sys. input	

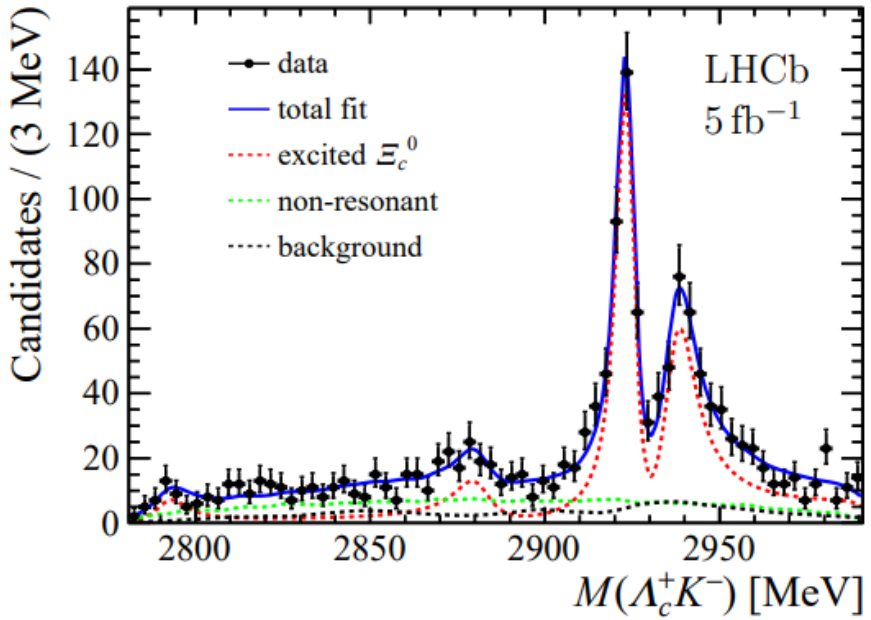
Excited Ξ_c^0 states - II

ARXIV: 2211.00812

- $B^- \to \Lambda_c^+ \Lambda_c^- K^-$ decay is studied.
- Confirmed $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$, consistent with prompt result.
- **Evidence of $\Xi_c(2880)^0 \to \Lambda_c^+ K^-$ observed ($3.8\,\sigma$).**
- No structure on $m(\Lambda_c^+ \Lambda_c^-)$ and $m(\Lambda_c^- K^-)$

State	Mass (MeV)	Width (MeV)
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$

$$\frac{\mathcal{B}(B^- \to \Lambda_c^+ \Lambda_c^- K^-)}{\mathcal{B}(B^- \to D^+ D^- K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25$$

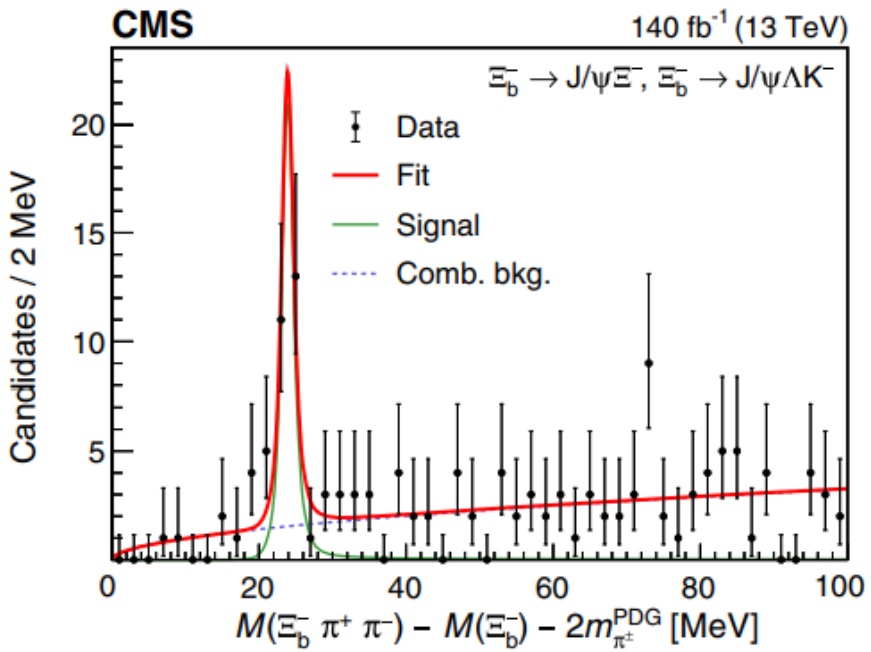


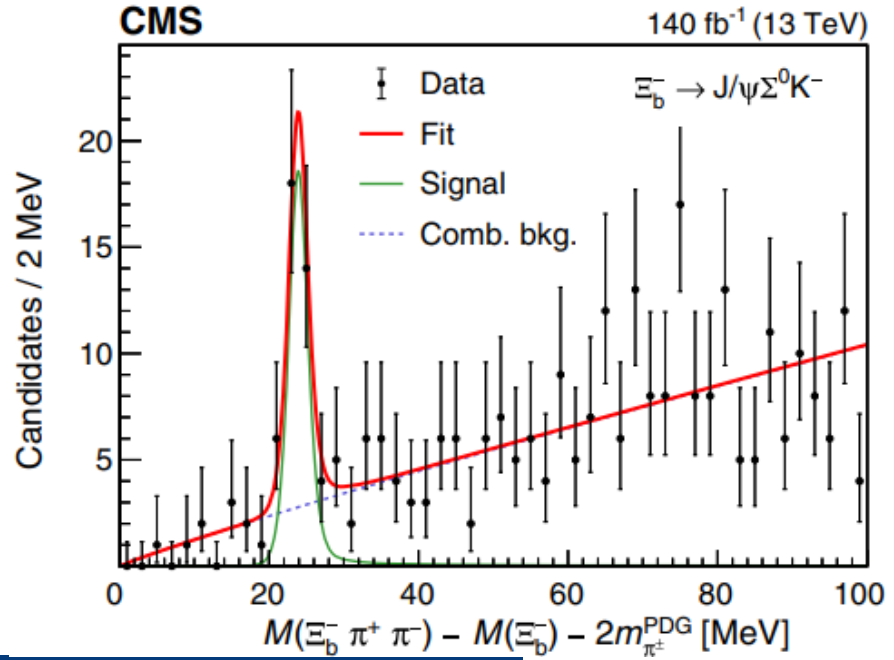
Excited Ξ_b^- states

PHYS. REV. LETT. 126, 252003

- $\Xi_b(6100)^-$ observed by CMS in $m(\Xi_b^-\pi^+\pi^-)$
- Two channels used to reconstruct Ξ_b^-

$$m(\Xi_b(6100)^-) = 6100 \pm 0.2(\text{stat.}) \pm 0.1(\text{syst}) \pm 0.6\ (\Xi_b^-)\ \text{MeV}$$
$$\Gamma(\Xi_b(6100)^-) < 1.9\ \text{MeV, C.L. } 95\%$$





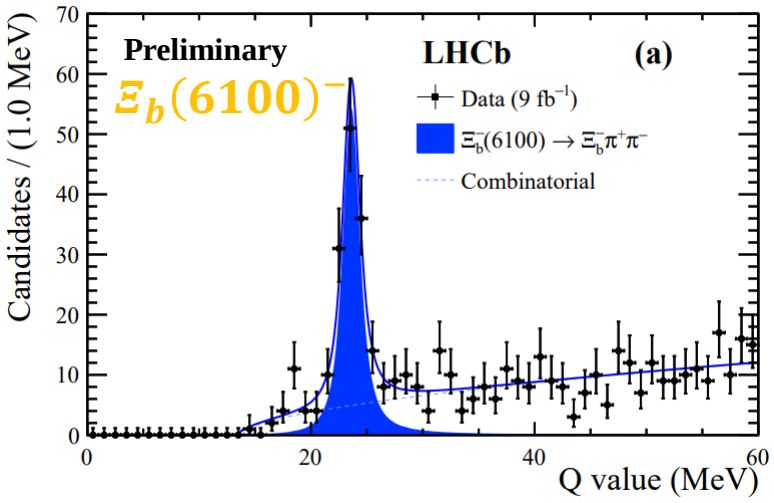
New

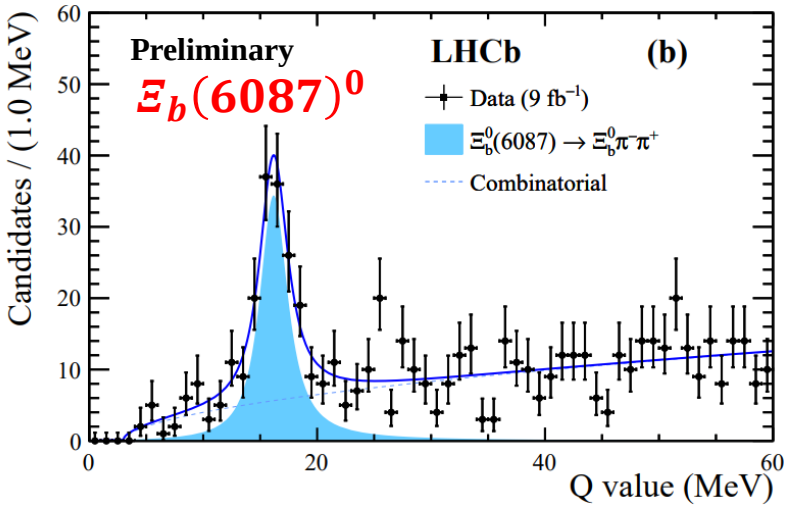
New excited Ξ_b^0 states

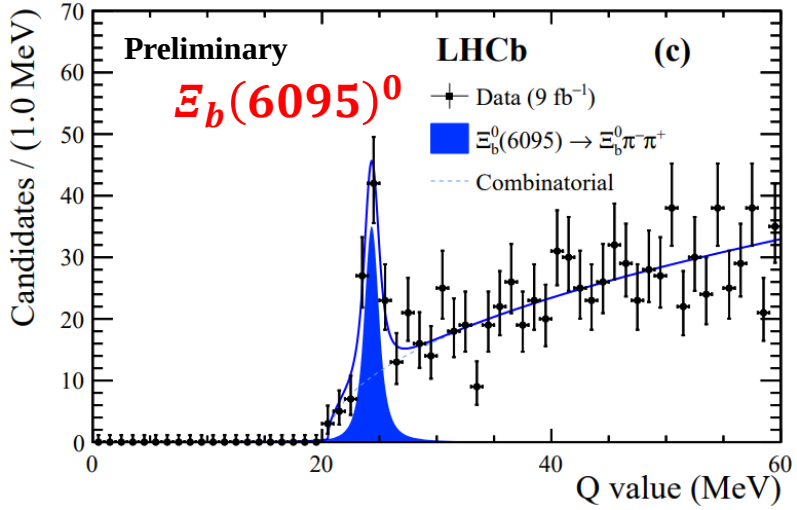
LHCB-PAPER-2023-008 (IN PREPARATION)

- **Observation of two new excited Ξ_b^0 baryons: $\Xi_b(6087)^0, \Xi_b(6095)^0$.**
- **One state is confirmed: $\Xi_b(6100)^-$.**
- First observation of $\Xi_b^0 \to \Xi_c^+ \pi\pi\pi$
- Best measurement on known $\Xi_b'^-$ and Ξ_b^{*-} states.

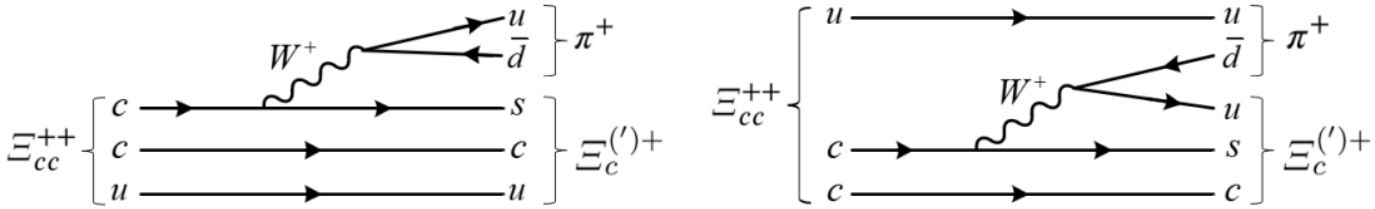
$Q_0\ (\Xi_b^0(6087))$	$16.20 \pm 0.20 \pm 0.06$
$\Gamma\ \ (\Xi_b^0(6087))$	$2.43 \pm 0.51 \pm 0.10$
$m_0\ (\Xi_b^0(6087))$	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5\ (\Xi_b^0)$
$Q_0\ (\Xi_b^0(6095))$	$24.32 \pm 0.15 \pm 0.03$
$\Gamma\ \ (\Xi_b^0(6095))$	$0.50 \pm 0.33 \pm 0.11$
$m_0\ (\Xi_b^0(6095))$	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5\ (\Xi_b^0)$







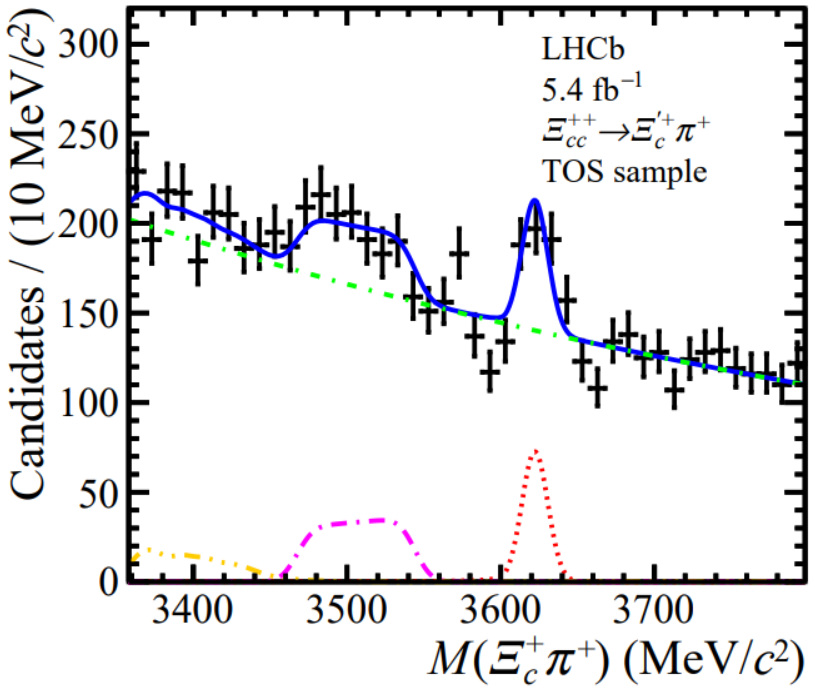
$\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$

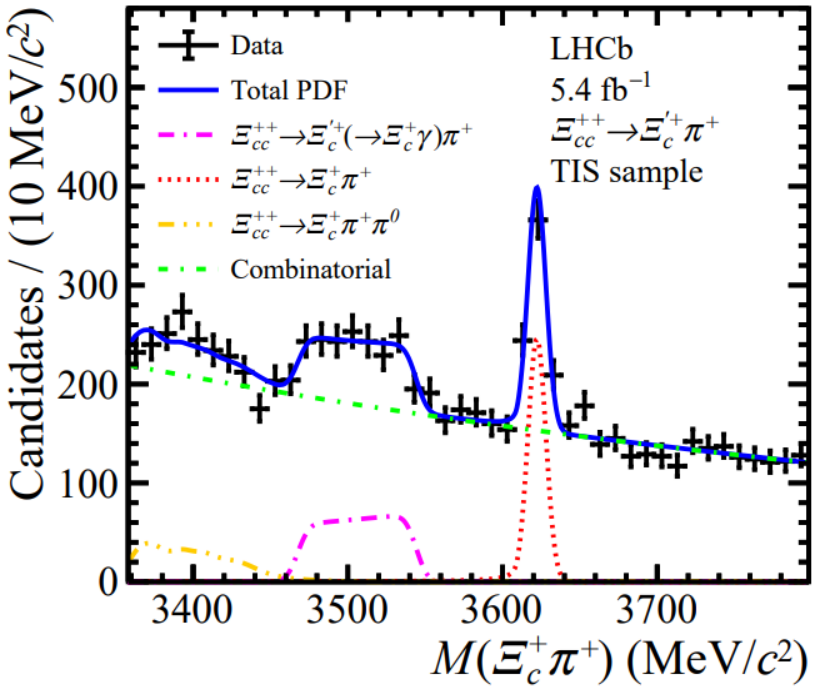


JHEP 05 (2022) 038

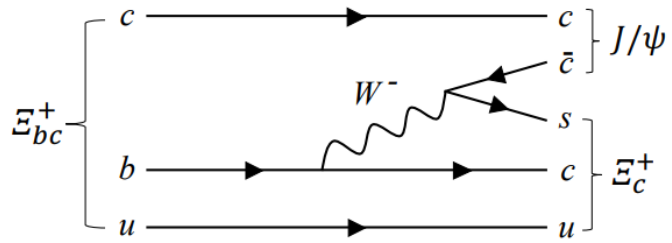
- $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$ observed with LHCb run-2 data.
- $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$ is reconstructed partially.

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+})} = 1.41 \pm 0.17 \pm 0.10$$



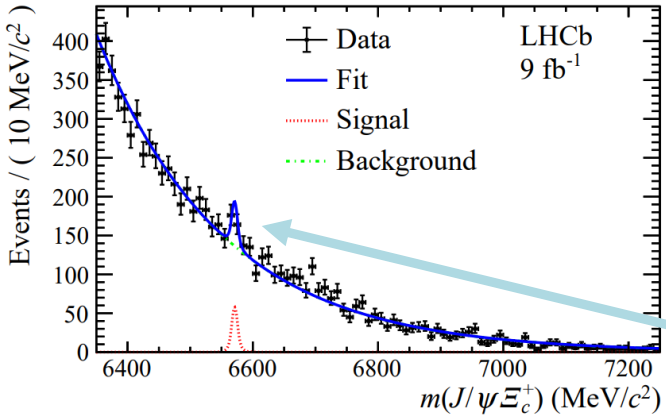


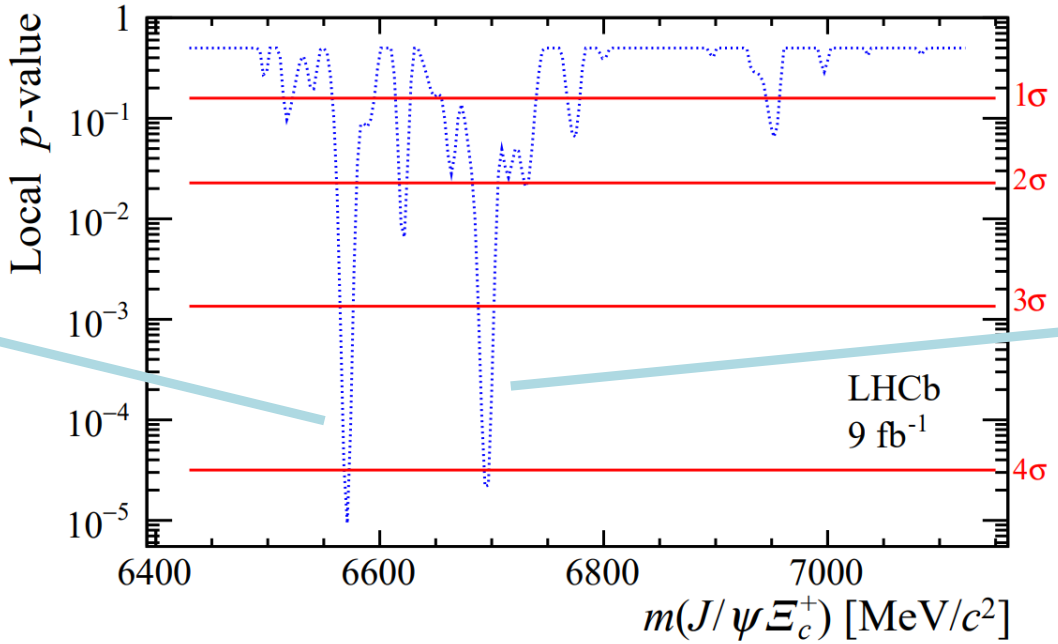
$\Xi_{bc}^{+} \to J/\psi\, \Xi_c^{+}$

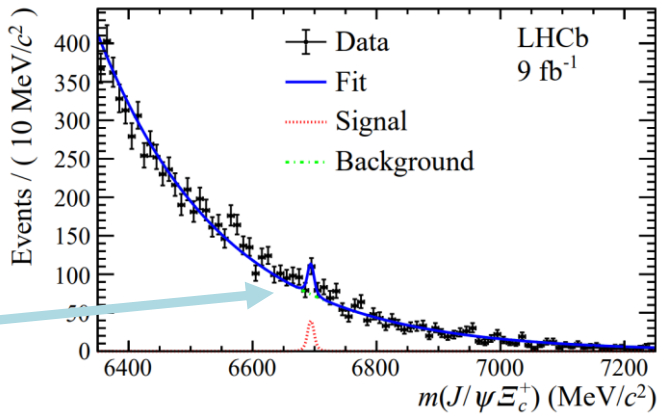


ARXIV:2204.09541

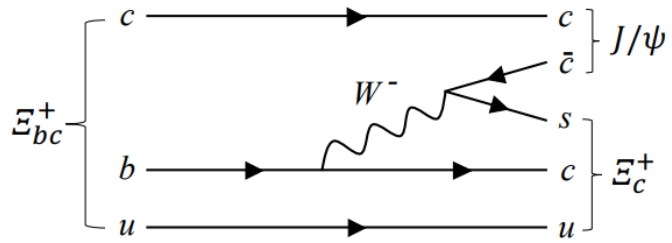
- First search for $\Xi_{bc}^{+} \to J/\psi\, \Xi_c^{+}$, with 9 fb^{-1}.
- Two peaking structures seen
  - Mass: 6571 MeV. Local (global) significance: 4.3(2.8) σ
  - Mass: 6694 MeV. Local (global) significance: 4.1(2.4) σ





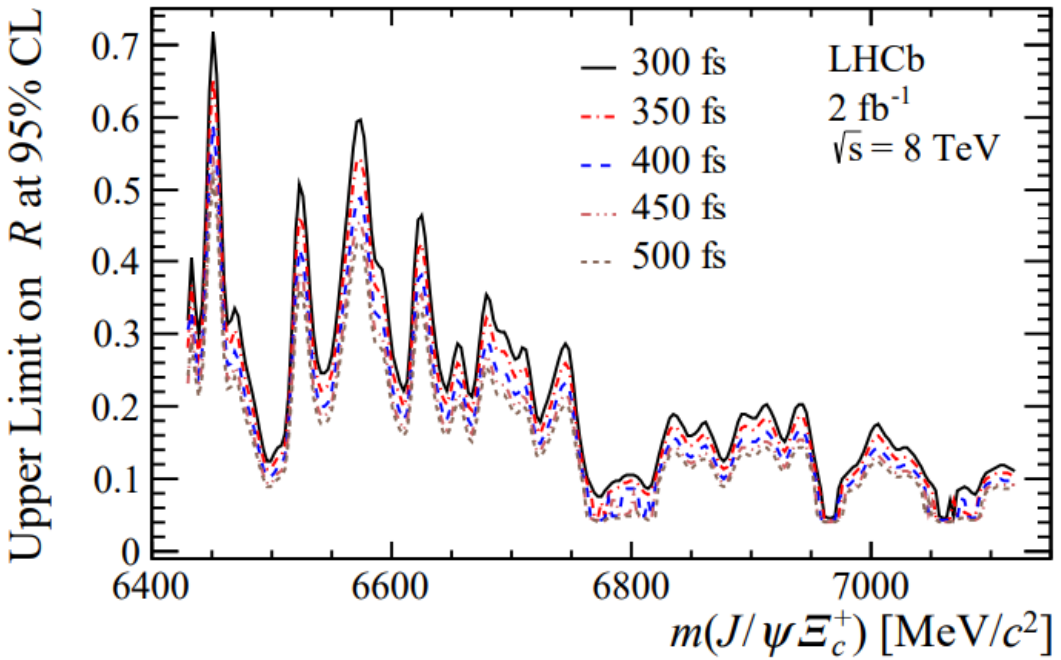


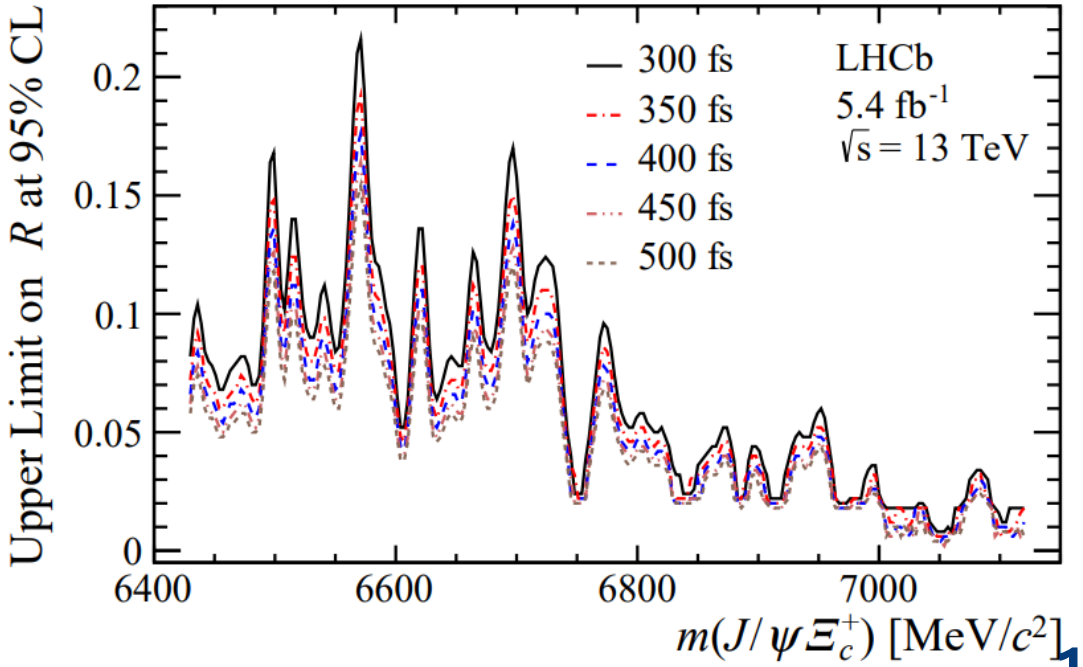
$\Xi_{bc}^{+} \to J/\psi\, \Xi_c^{+}$



ARXIV:2204.09541

$$\mathcal{R} = \frac{\sigma(\Xi_{bc}^{+}) \times \mathcal{B}(\Xi_{bc}^{+} \to J/\psi\, \Xi_c^{+}) \times \mathcal{B}(\Xi_c^{+} \to pK^{-}\pi^{+})}{\sigma(B_c^{+}) \times \mathcal{B}(B_c^{+} \to J/\psi\, D_s^{+}) \times \mathcal{B}(D_s^{+} \to K^{+}K^{-}\pi^{+})}$$





Summary

- Heavy baryons
  - Observation of excited Ξ_c^0 baryons
  - Observation of excited Ξ_b^- baryons
  - **Observation of excited Ω_c^0 baryons (recent)**
  - **Observation of excited Ξ_b^0 baryons (recent)**

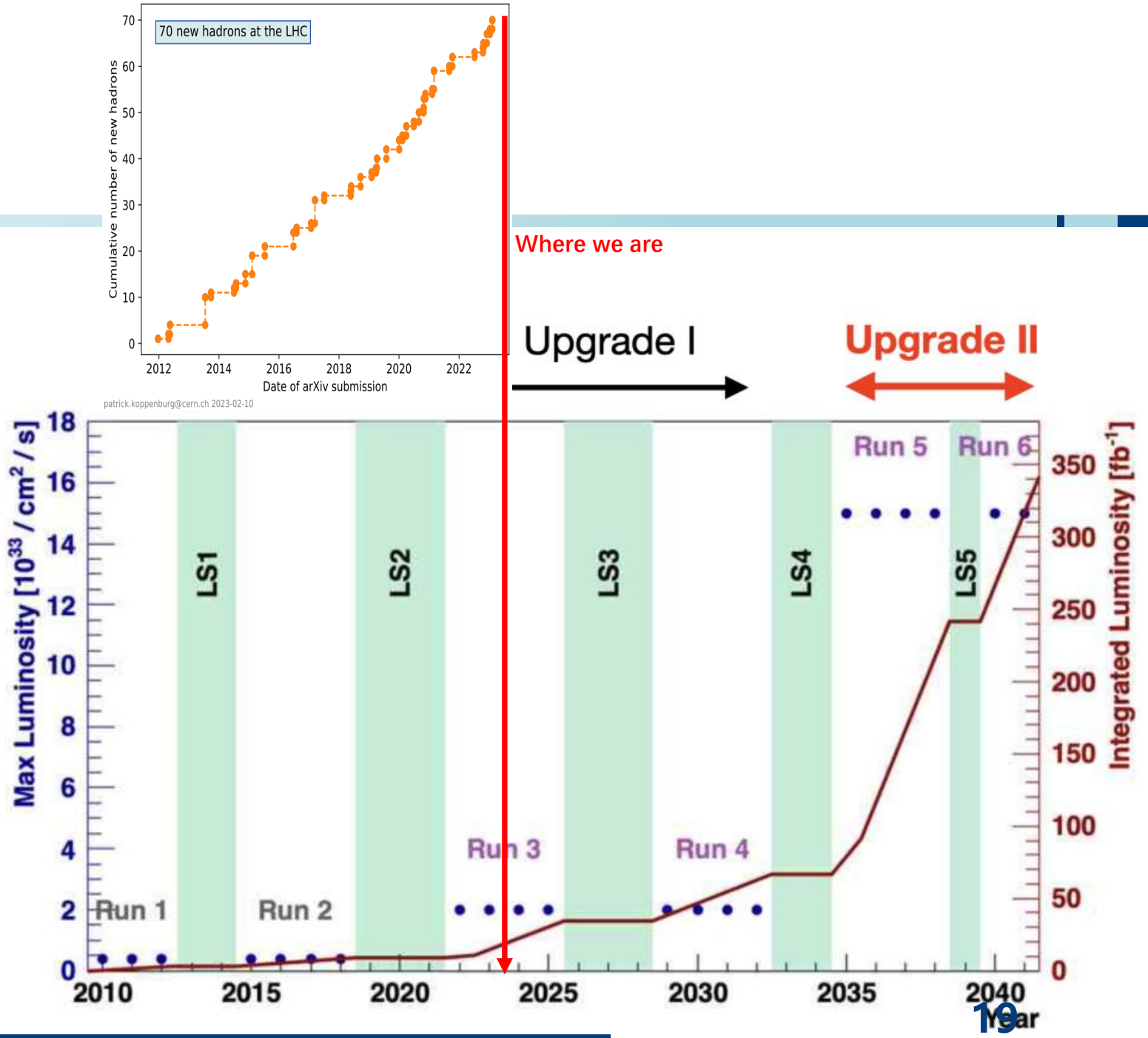
- Double Heavy baryons
  - Measurement of $\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)}$
  - First search for $\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$

Future

- Higher luminosity
- Better detector
- Improved techniques
- ……

- More particles…
- More decays…
- Higher precision…

- Fulfill hadron picture



Thanks!