Spectroscopy of charm and bottom baryons at LHCb

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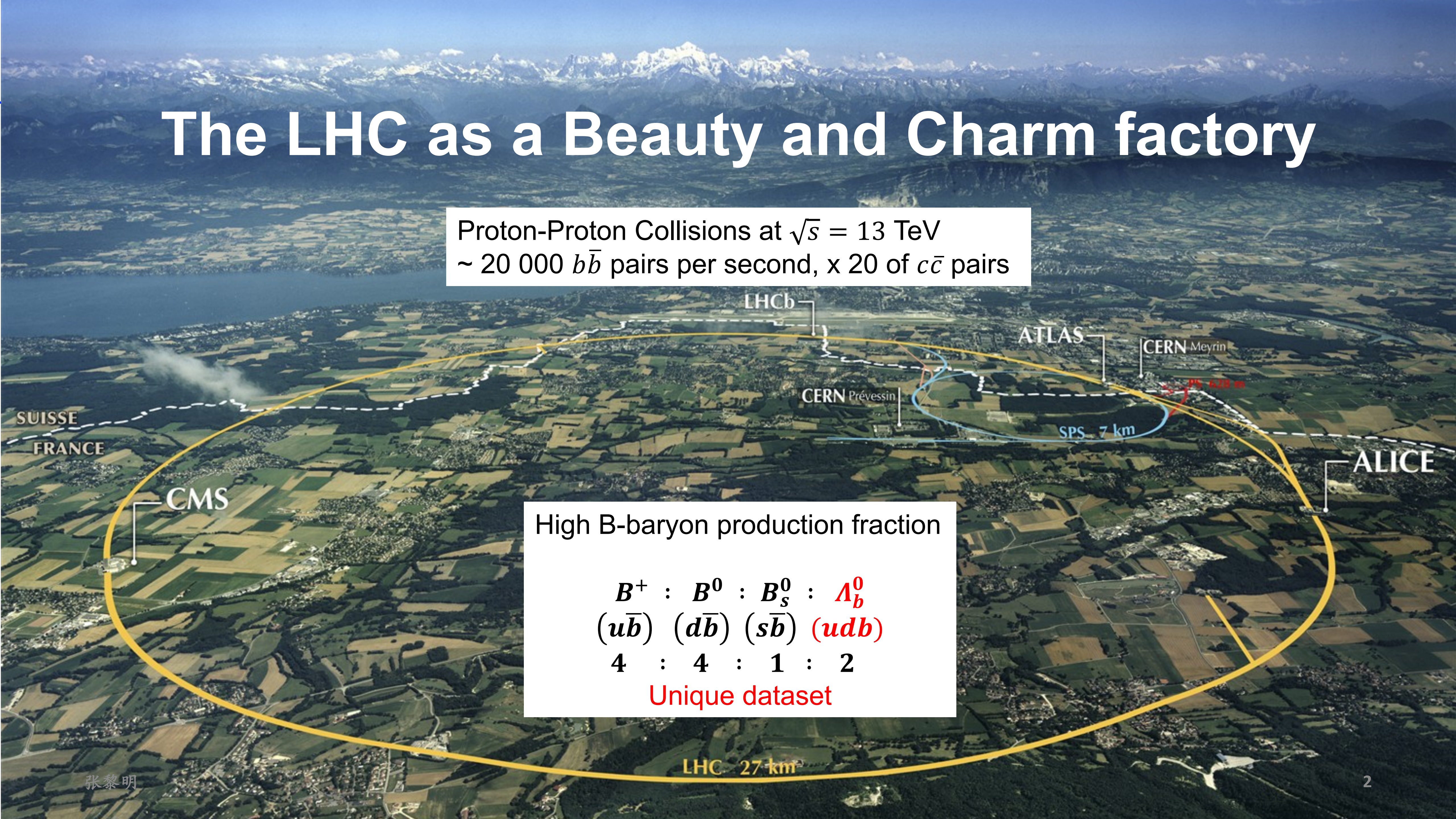
The LHC as a Beauty and Charm factory



Proton-Proton Collisions at $\sqrt{s} = 13$ TeV
~ 20 000 $b\bar{b}$ pairs per second, x 20 of $c\bar{c}$ pairs

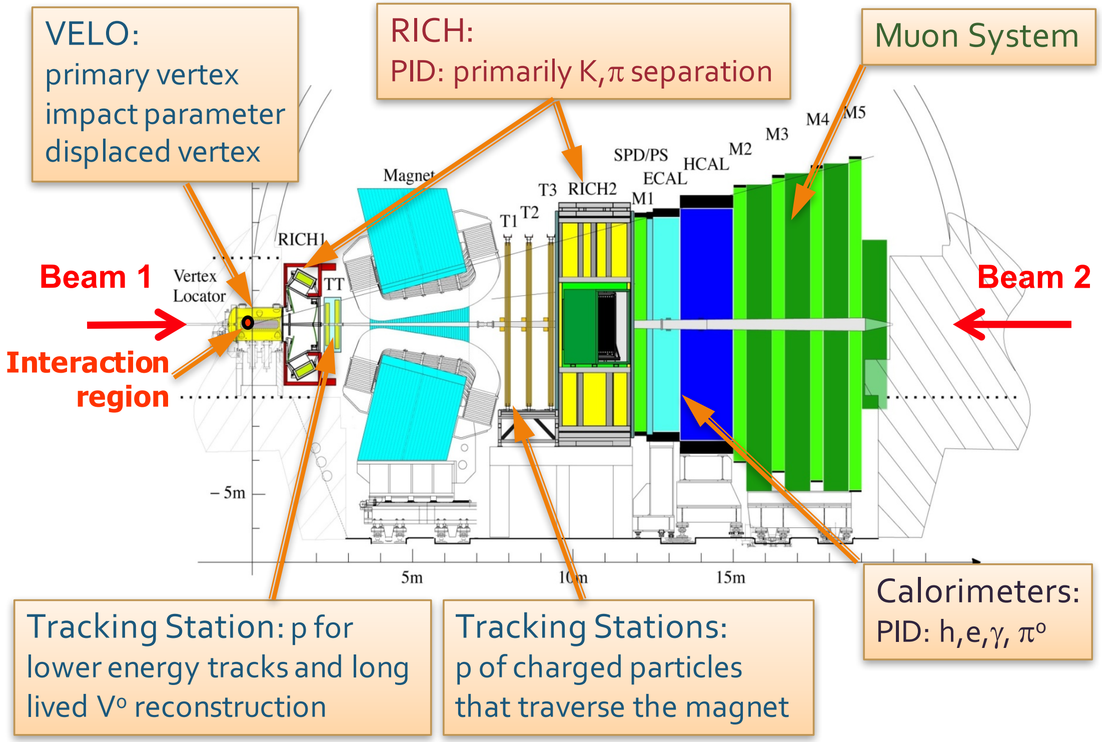
High B-baryon production fraction

$$\boldsymbol{B^+} : \boldsymbol{B^0} : \boldsymbol{B_s^0} : \boldsymbol{\Lambda_b^0}$$
$$(\boldsymbol{u\bar{b}})\ (\boldsymbol{d\bar{b}})\ (\boldsymbol{s\bar{b}})\ (\boldsymbol{udb})$$
$$\boldsymbol{4 : 4 : 1 : 2}$$

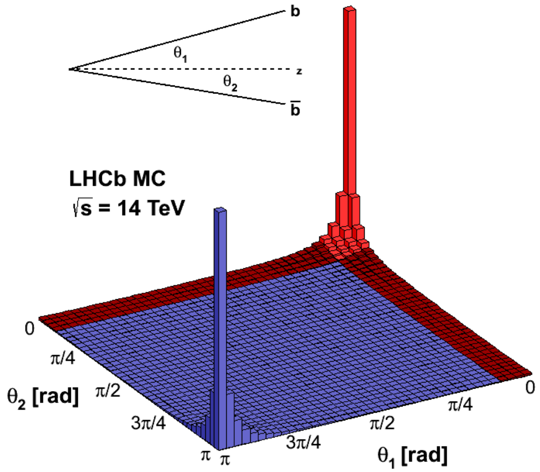
Unique dataset

LHCb detector and performance

The LHCb detector described in [JINST 3 (2008) S08005]



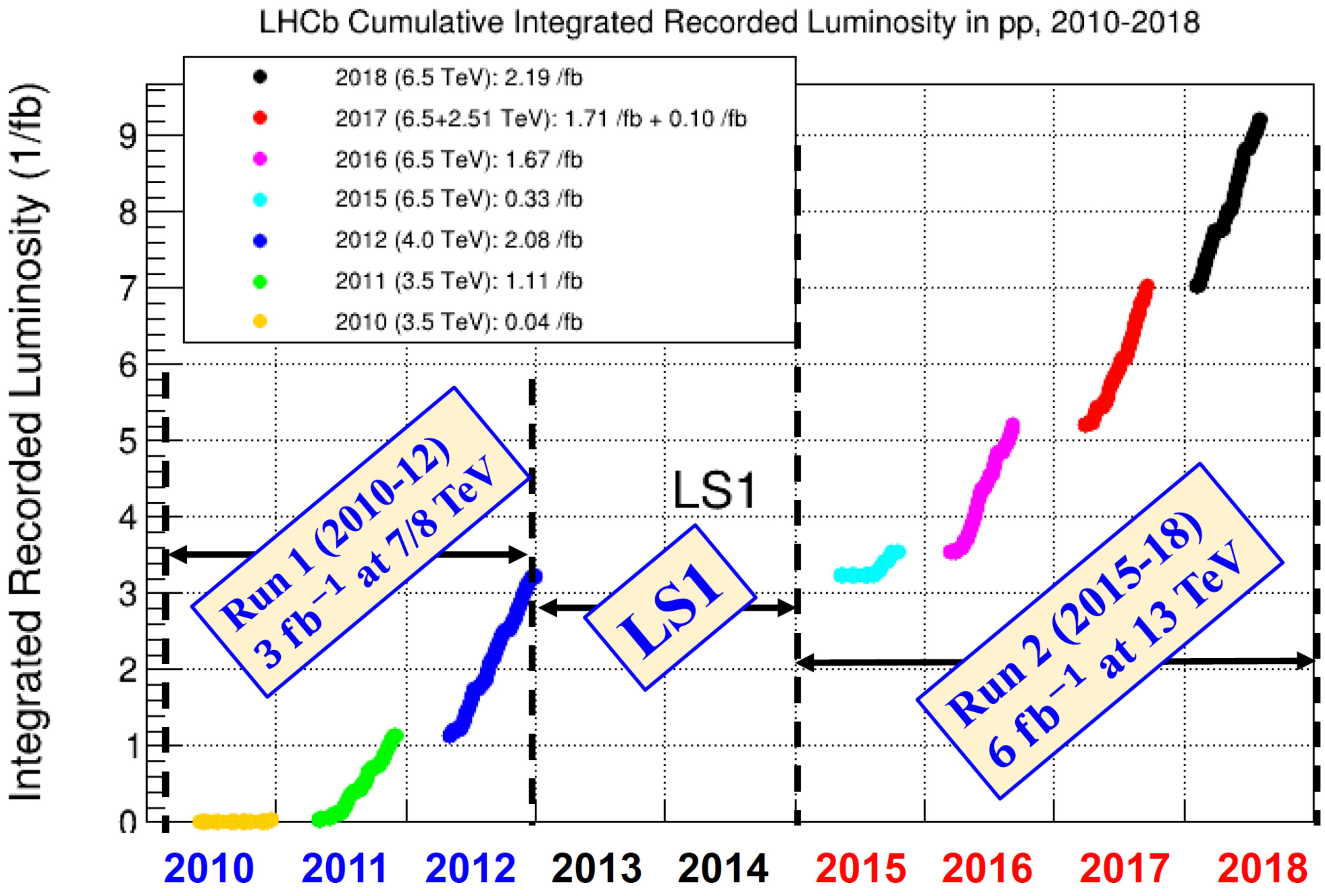
- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



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

Impact parameter:	$\sigma_{IP} = 20\ \mu\mathrm{m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass :	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

LHCb collected luminosity

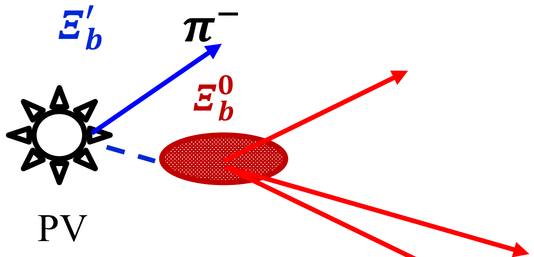


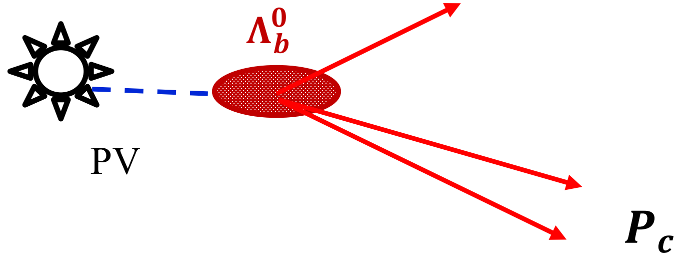
$\sigma(pp \to b\bar{b}X) \approx 300$ μb @7 TeV vs ≈ 500 μb @13 TeV

~25% can be collected in LHCb acceptance

Two methods for spectroscopy

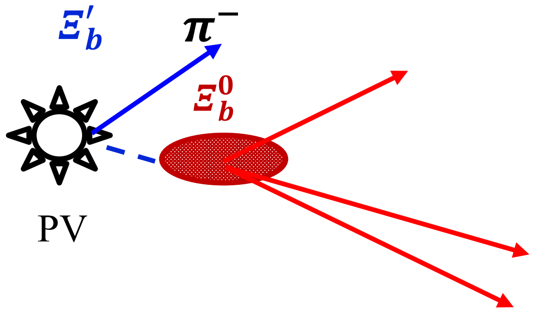
- Direct production in pp collisions
  - Combine a heavy flavour hadron with one or more light particles
  - Pros: High statistics, in principle can study all states
  - Cons: Large combinatorial background, hard to determine J^P
- Production by a heavier particle decay
  - Usually with amplitude analysis
  - Pros: Low background, Better determination of J^P
  - Cons: Low cross-section, limited states and limited J



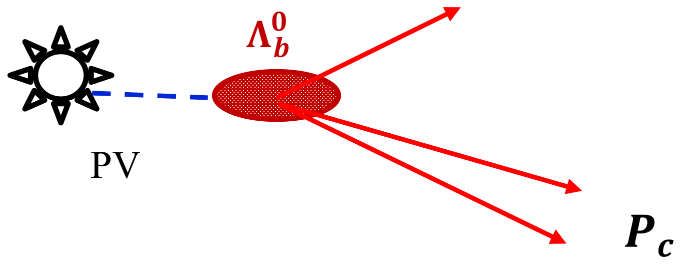


Two methods for spectroscopy

- Direct production in pp collisions
  - Ξ_{cc}^{++}, $\Omega_c^{**} \rightarrow \Xi_c K$
  - All excited B, $\Xi_b^{**} \rightarrow \Xi_b \pi$; $\Lambda_b K$

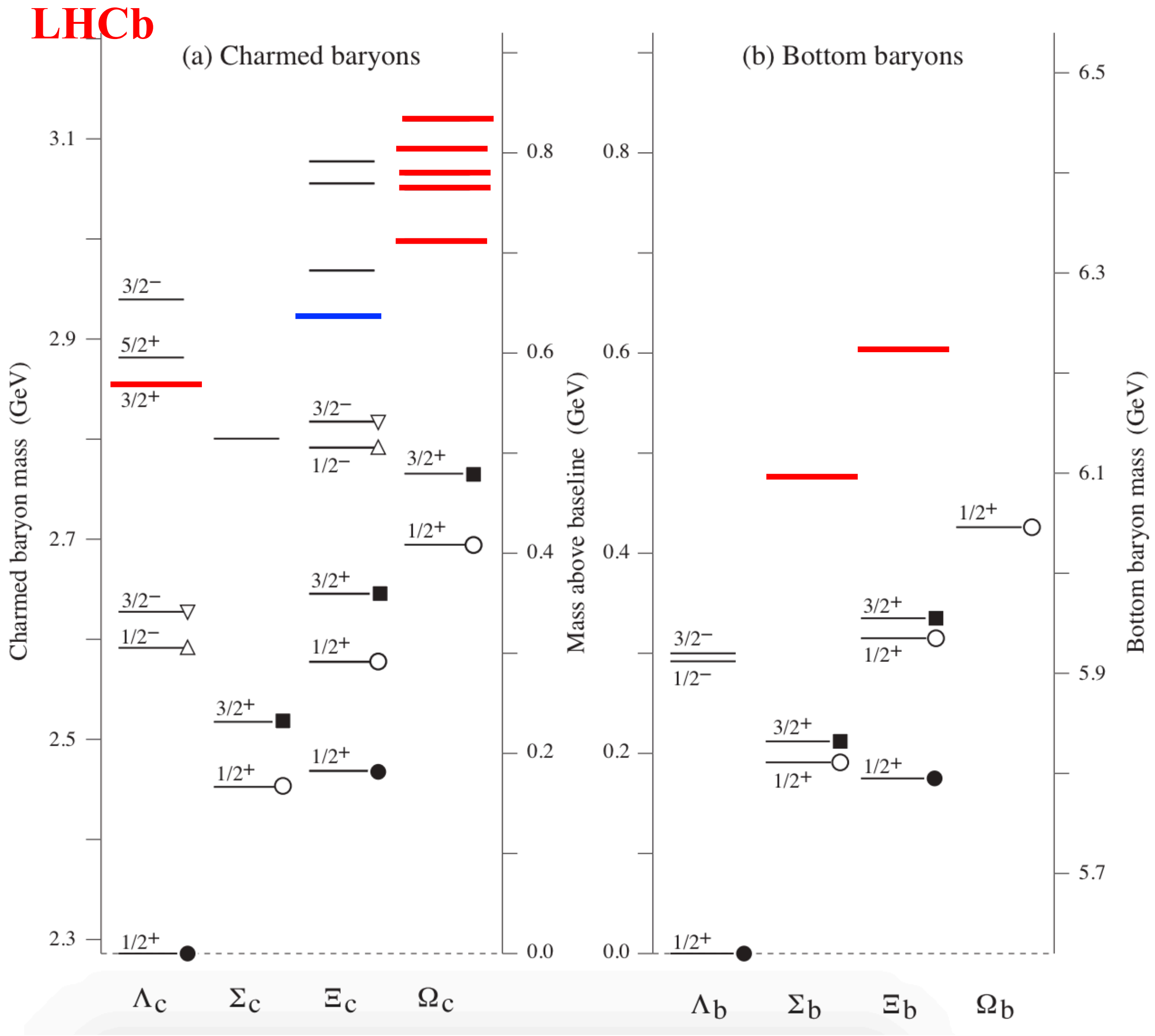


- Production by a B or D decays
  - X(3872) J^P
  - $Z_c(4430)$
  - X(4140) ….
  - $P_c(4312)$, $P_c(4440)$, $P_c(4447)$
  - $D_{(s)J}$



Charmed and bottom baryons

- 25 charmed baryons observed
  - Missing many Σ_c^*?
- 11 bottom baryons observed
- Bottom are very similar to charmed baryons



(Experimental results by end of 2018)

$\Omega_{c,b}^{**}$ baryons

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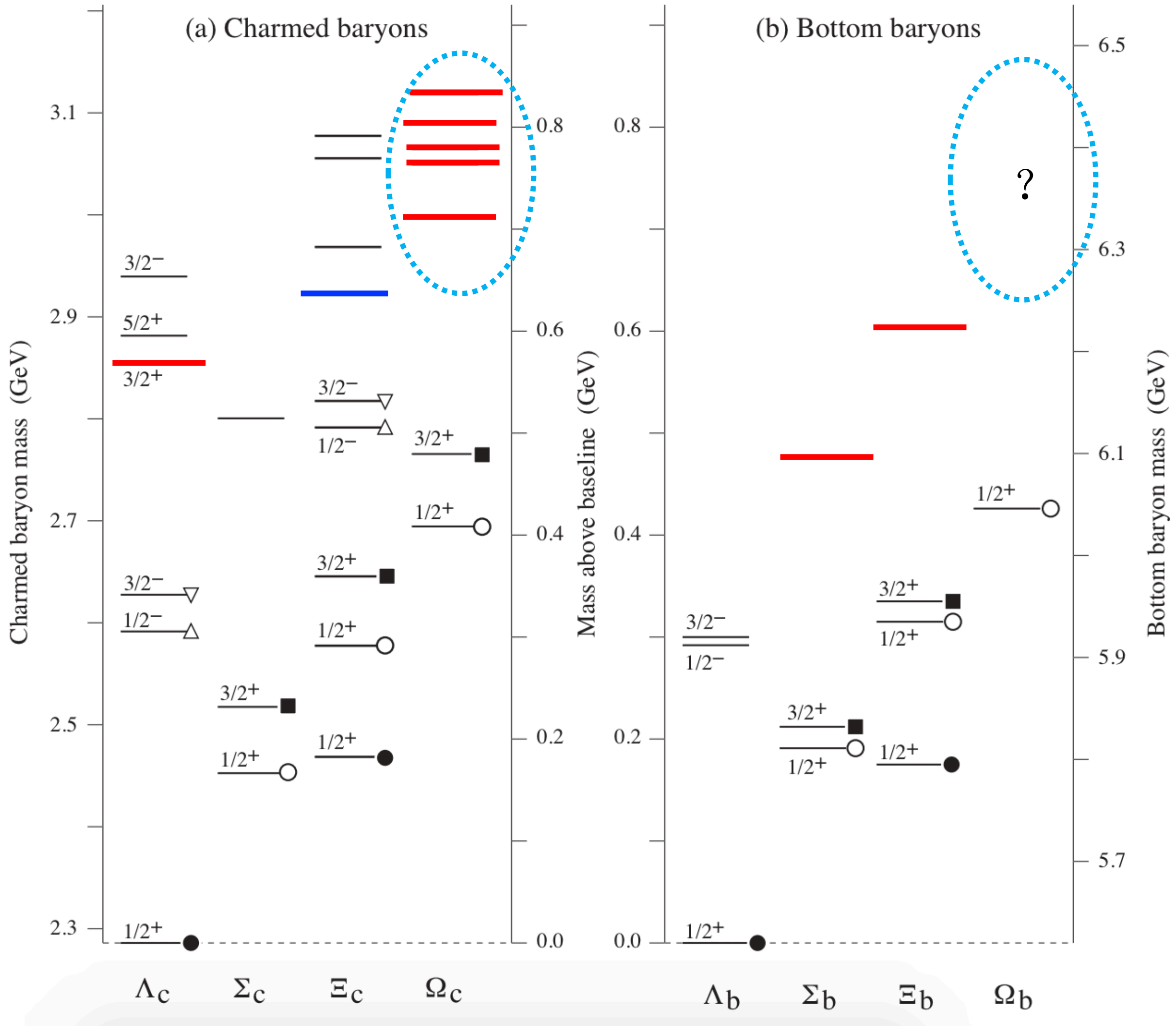
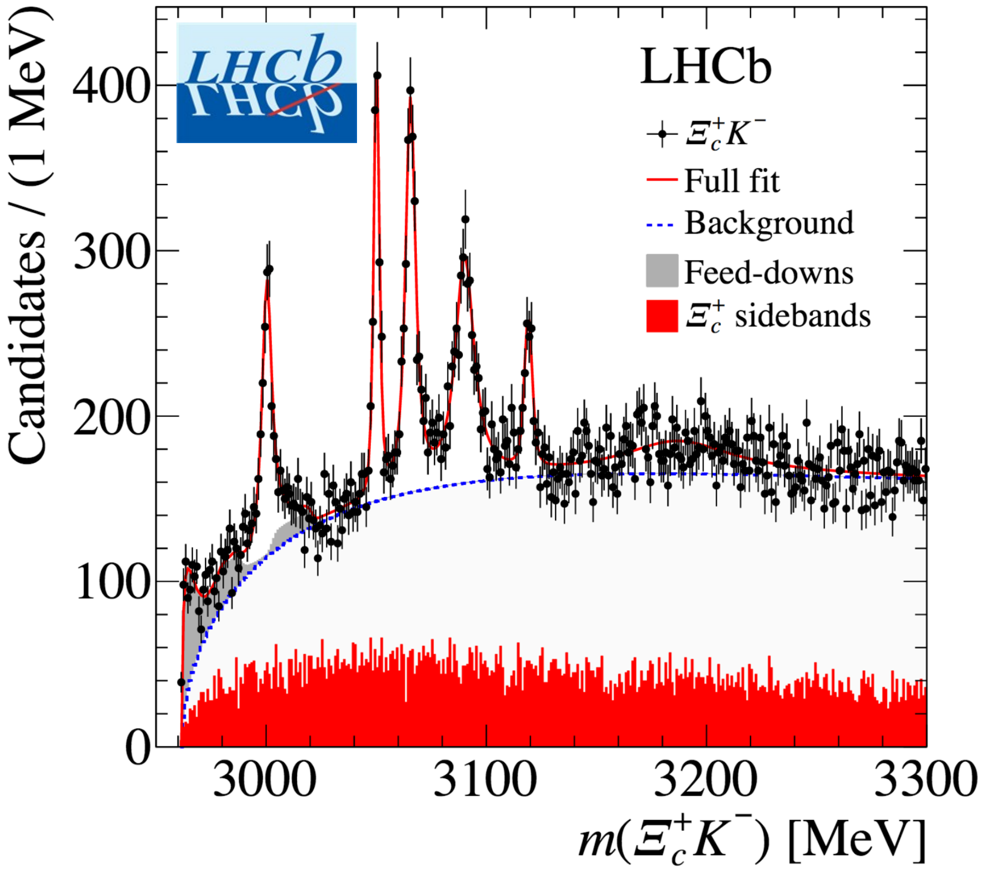


(Experimental results by end of 2018)

Excited $\Omega_c \to \Xi_c^+ K^-$ states, prospect for Ω_b

- LHCb observed 5 narrow states (+ a possible wide one) in 2017
- Belle confirmed the first four states

[PRL 118 (2017) 182001]



Mass splitting 20-50 MeV

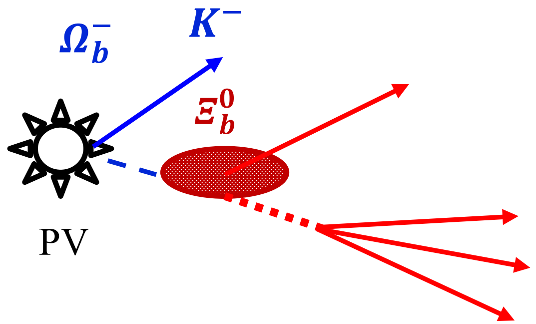
Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		<1.2 MeV, 95% C.L.		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		<2.6 MeV, 95% C.L.		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{fd}$			$190 \pm 70 \pm 20$	

Analogical search applicable to *b*-sector

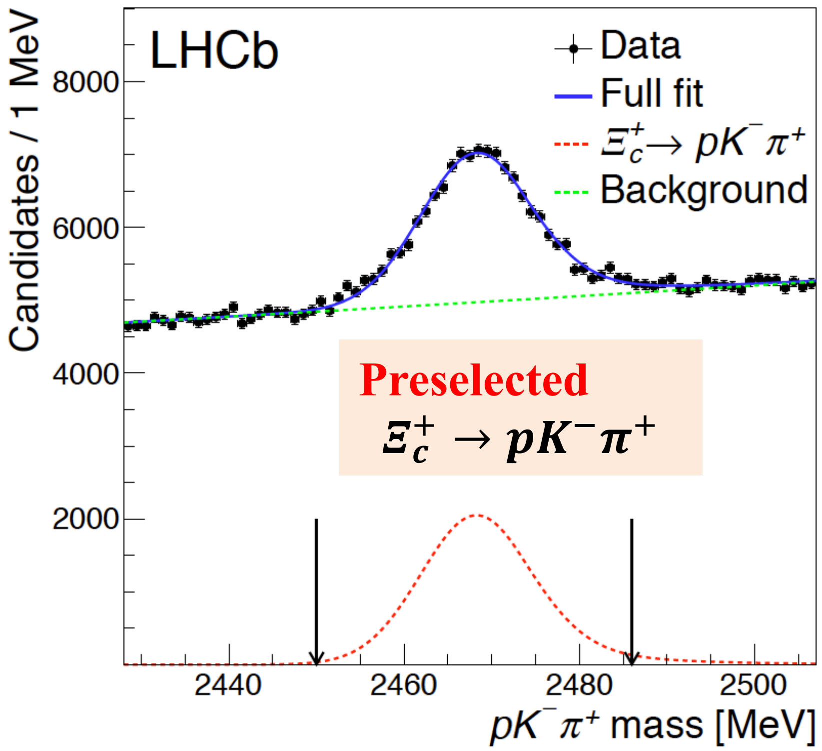
	Ξ_c^+/Ξ_b^0	Ω_c^*/Ω_b^*
$\Omega_c^* \to \Xi_c^+ K^-$	1M (3fb^{-1})	1000-2000
$\Omega_b^* \to \Xi_b^0 K^-$	0.02M (9fb^{-1}) [PRL 113 (2014) 032001 (3fb^{-1})]	20-40 (scaled from charm result)

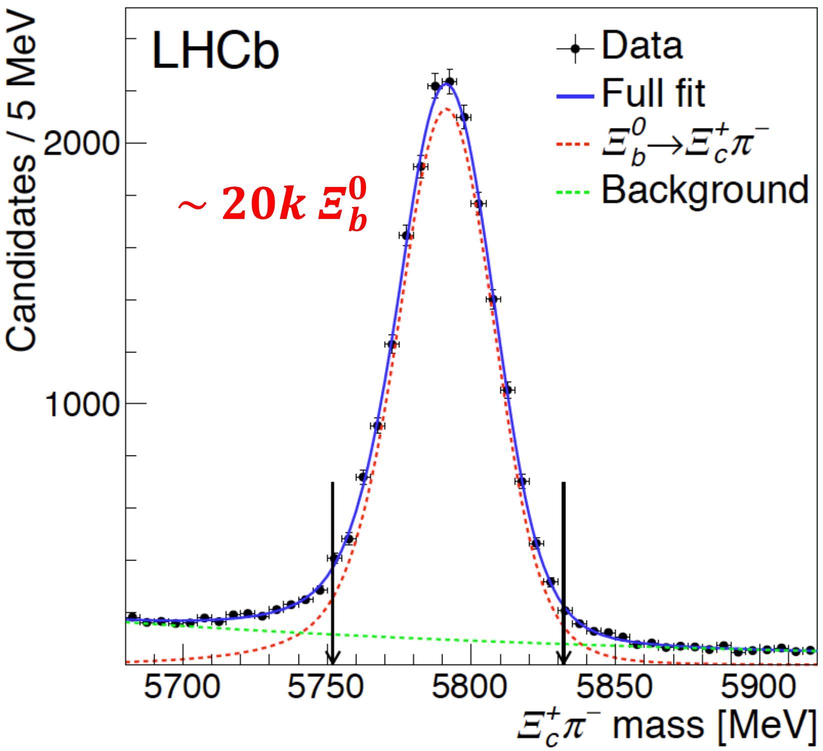
Observation of Ω_b^{**-}

[PRL 124 (2020) 082002]



- $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to pK^-\pi^+$ is reconstructed
- 20k Ξ_b^0 decays selected based on MVA discriminant
- PID of K^- is optimized by Punzi FOM





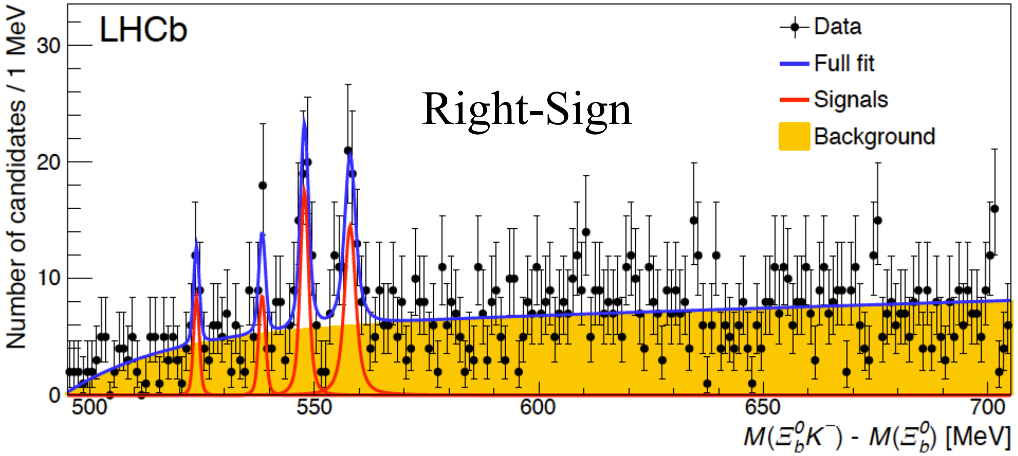
Observation of Ω_b^{**-}

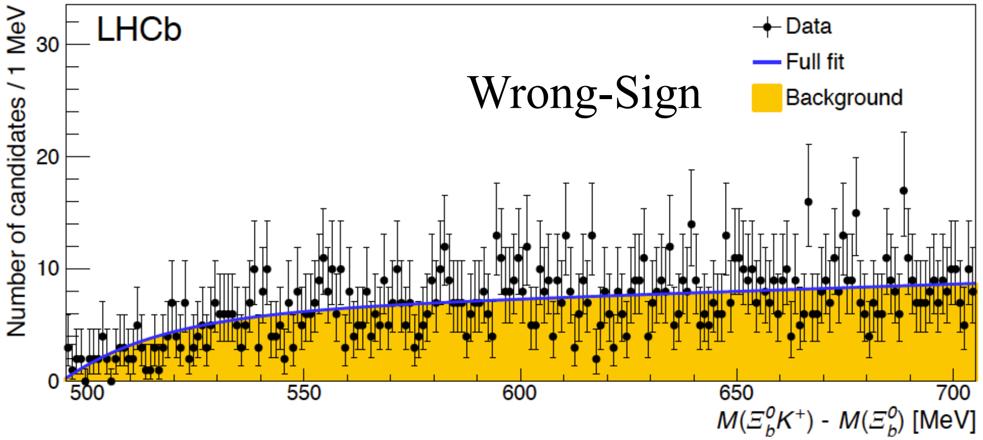
[PRL 124 (2020) 082002]

- 4 peaks are seen, the last two have global significance > 5σ

Mass splitting 10-15 MeV

State	Mass [MeV]	Width [MeV] (90% UL)	Nsig	Local significance	Global significance
$\Omega_b(6316)^-$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	<2.8	15^{+6}_{-5}	3.6	2.1
$\Omega_b(6330)^-$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	<3.1	18^{+6}_{-5}	3.7	2.6
$\Omega_b(6340)^-$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	<1.5	47^{+11}_{-10}	**7.2**	**6.7**
$\Omega_b(6350)^-$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	<2.8 $1.4^{+1.0}_{-0.8} \pm 0.1$	57^{+14}_{-13}	**7.0**	**6.2**





$\Omega_{c,b}^{**}$ baryons

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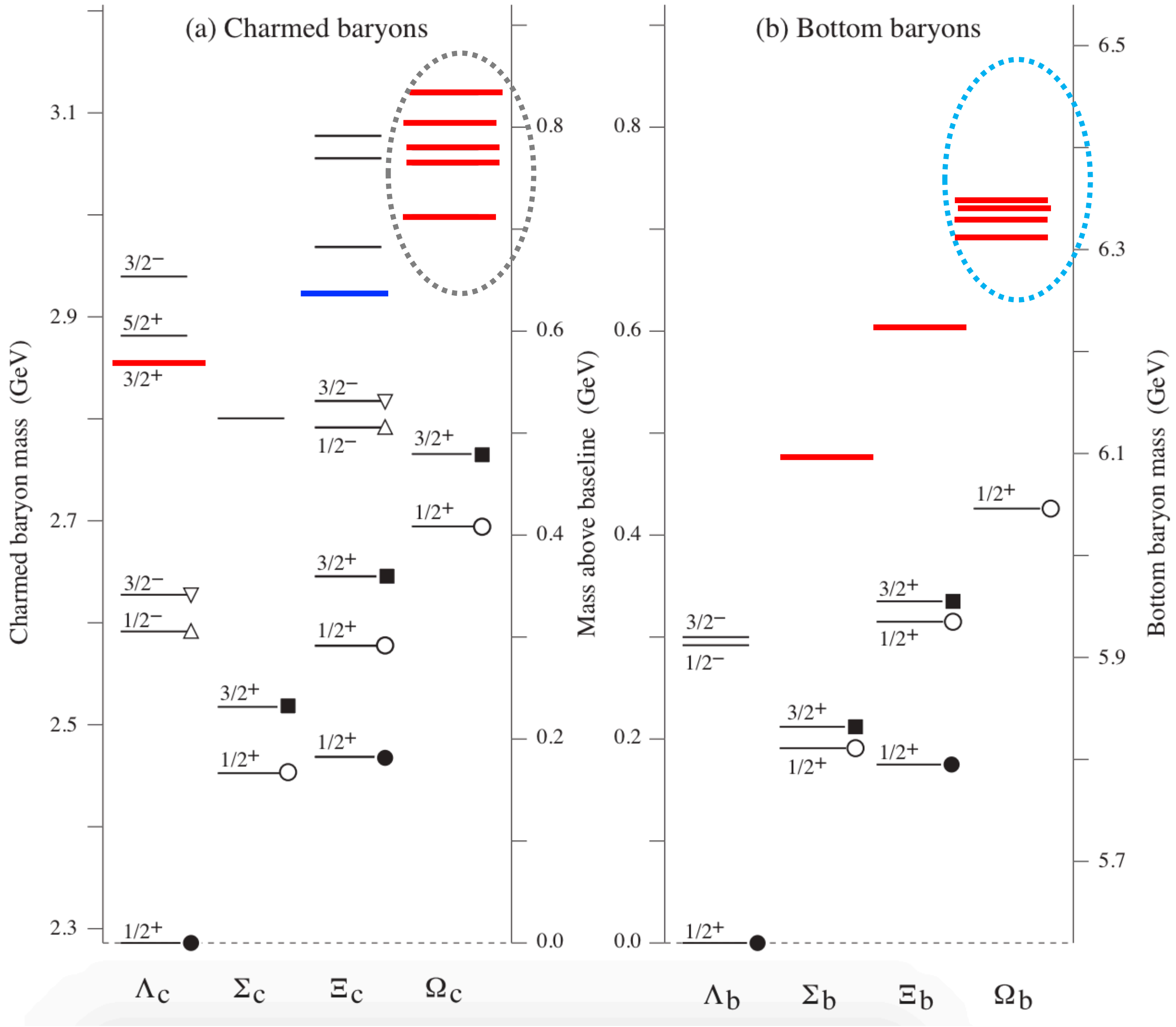

Ξ_c^{**} baryons

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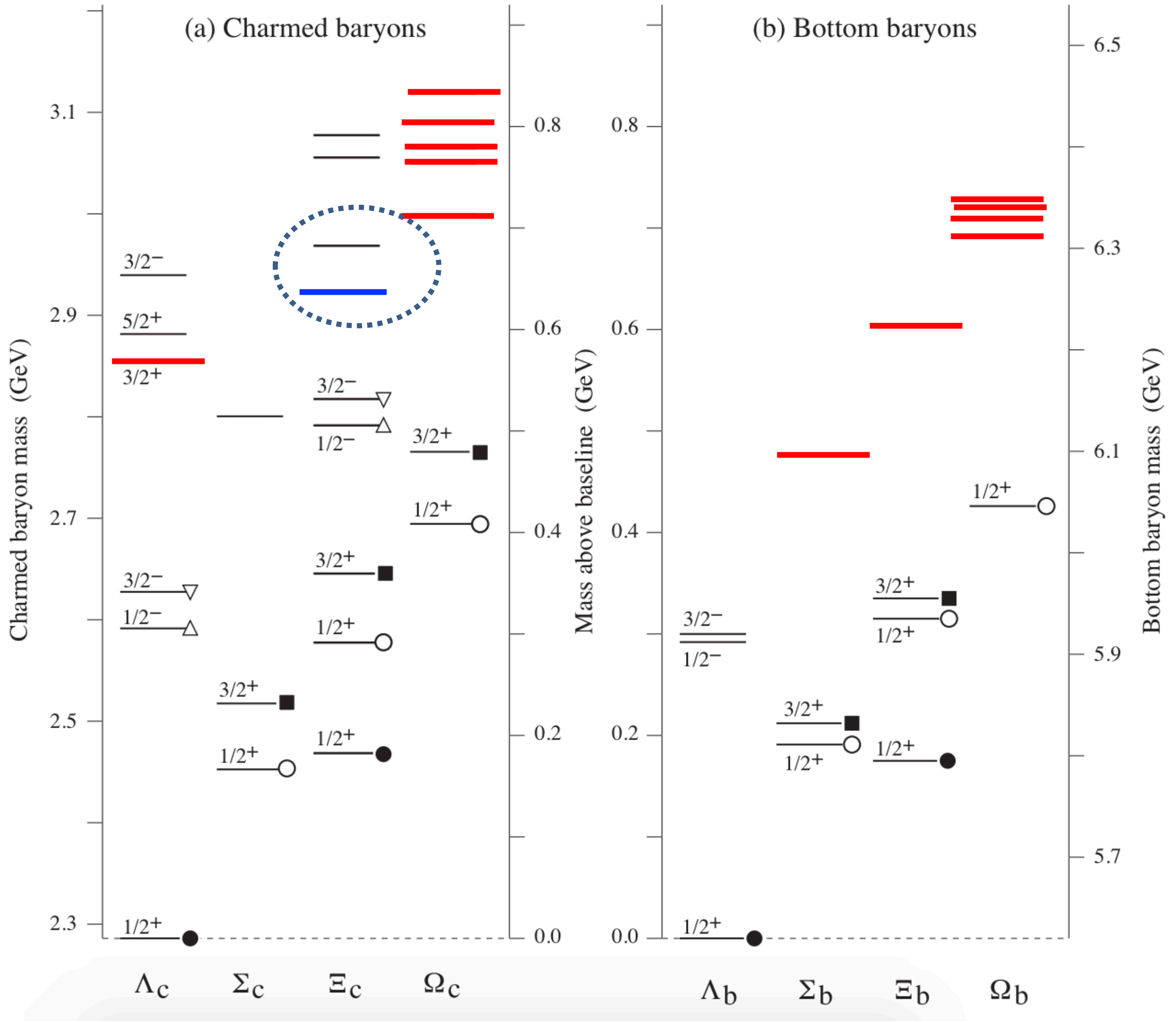


Belle's $\Xi_c(2930)$ from $B \to \Lambda_c \bar{\Lambda}_c K$

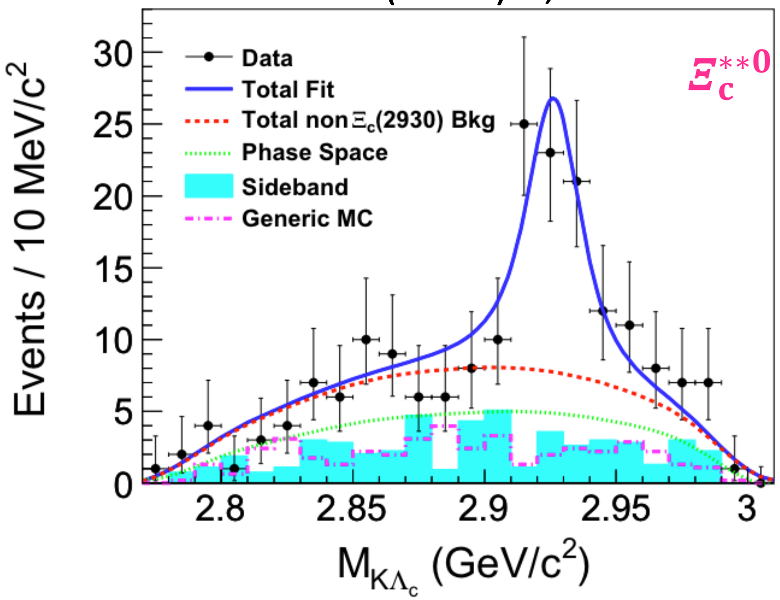
$\Xi_c(2930)$ MASSES

$\Xi_c(2930)^+$ MASS	2942 ± 5 MeV
$\Xi_c(2930)^0$ MASS	$2929.7^{+2.8}_{-5.0}$ MeV
$\Xi_c(2930)^+ - \Xi_c(2930)^0$ MASS DIFFERENCE	

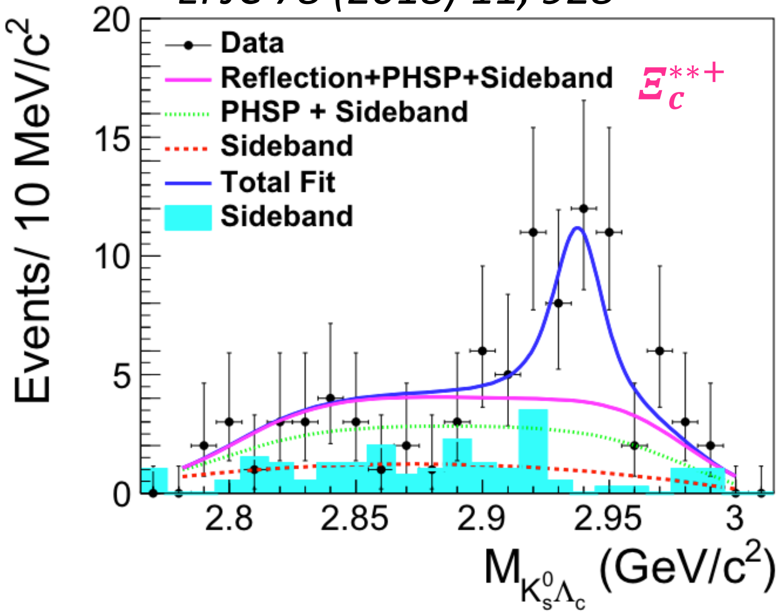
$\Xi_c(2930)$ WIDTHS

$\Xi_c(2930)^+$ WIDTH	15 ± 9 MeV
$\Xi_c(2930)^0$ WIDTH	26 ± 8 MeV

EPJC 78 (2018) 3, 252



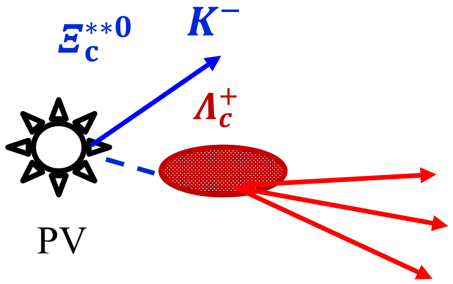
EPJC 78 (2018) 11, 928



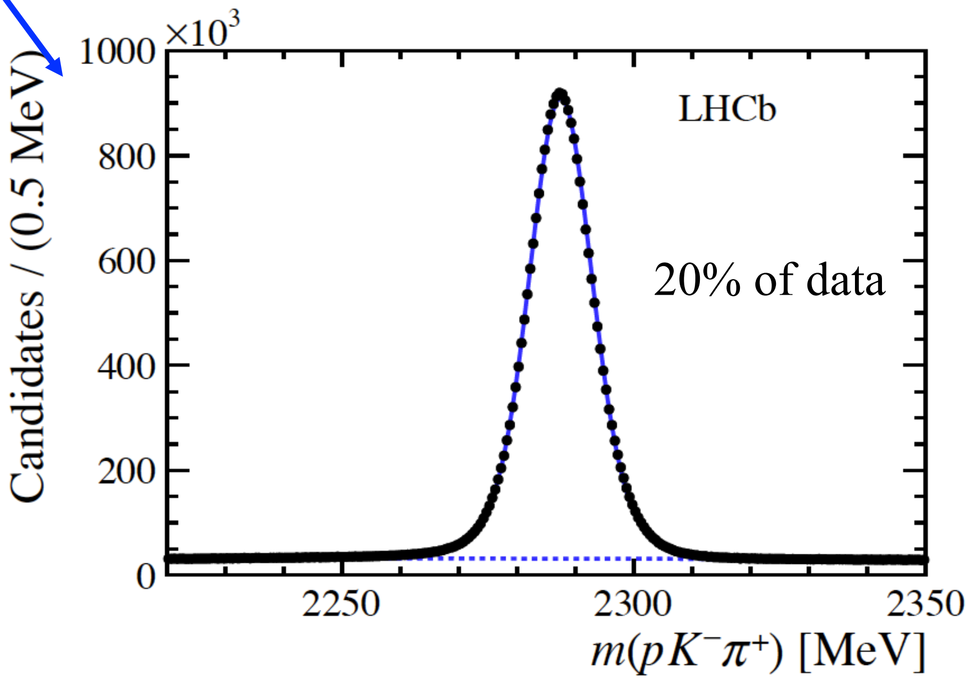
New Ξ_c^{**0} from LHCb

[arXiv:2003.13649]

- Checked prompt production of $\Xi_c^{**0} \to \Lambda_c^+ K^-$
- Large and clean Λ_c^+ candidates



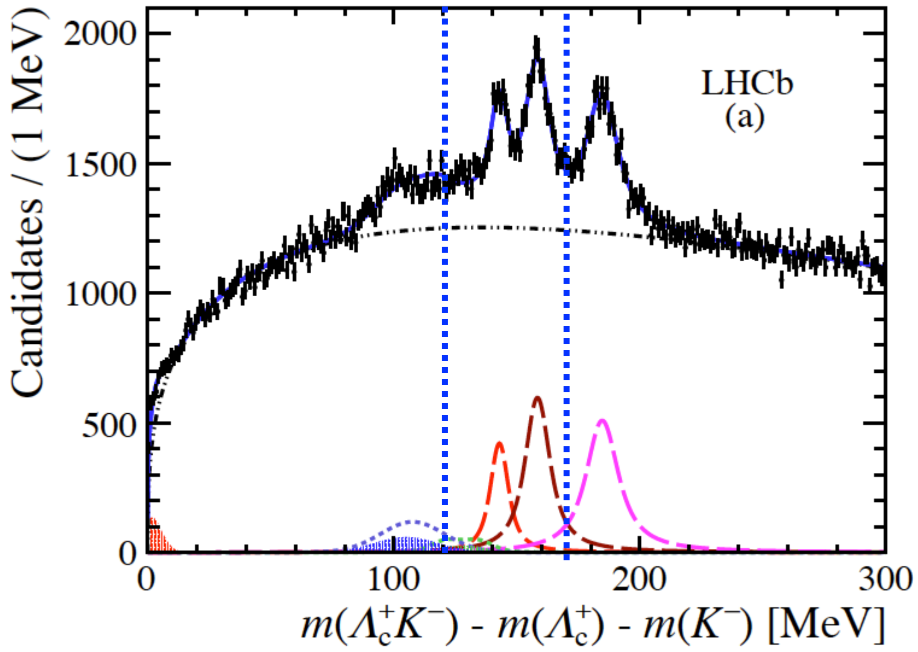
- Combine with Kaon
  - Using pT and PID to suppress combinatorial background from PV



New Ξ_c^{**0} from LHCb

[arXiv:2003.13649]

- Large statistics data shows Belle's $\Xi_c(2930)$ is a composite of two narrow Ξ_c^{**}'s
- A third peak is also seen
  - position close to kinematic limit of the B decay used by Belle



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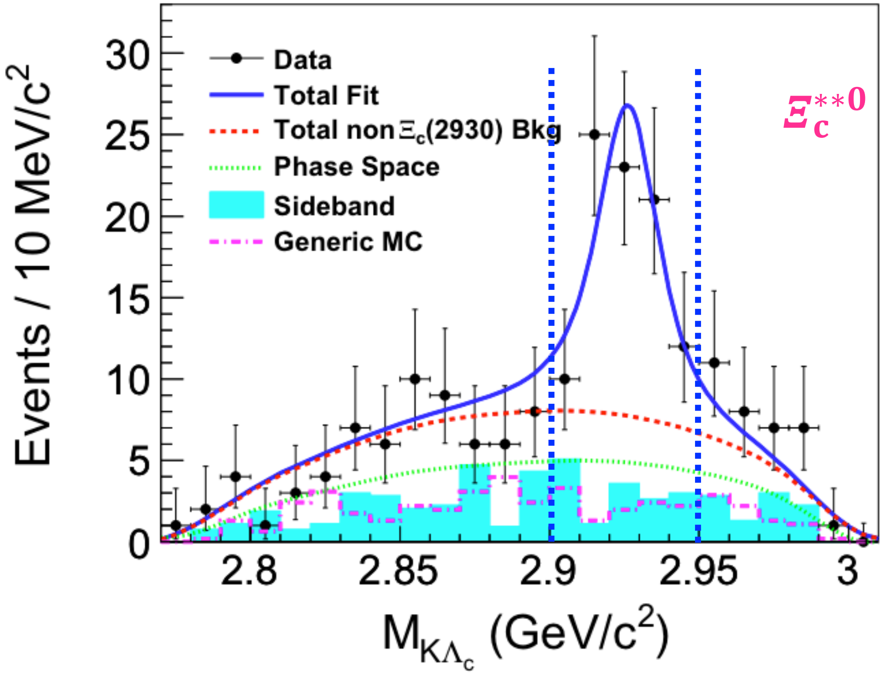
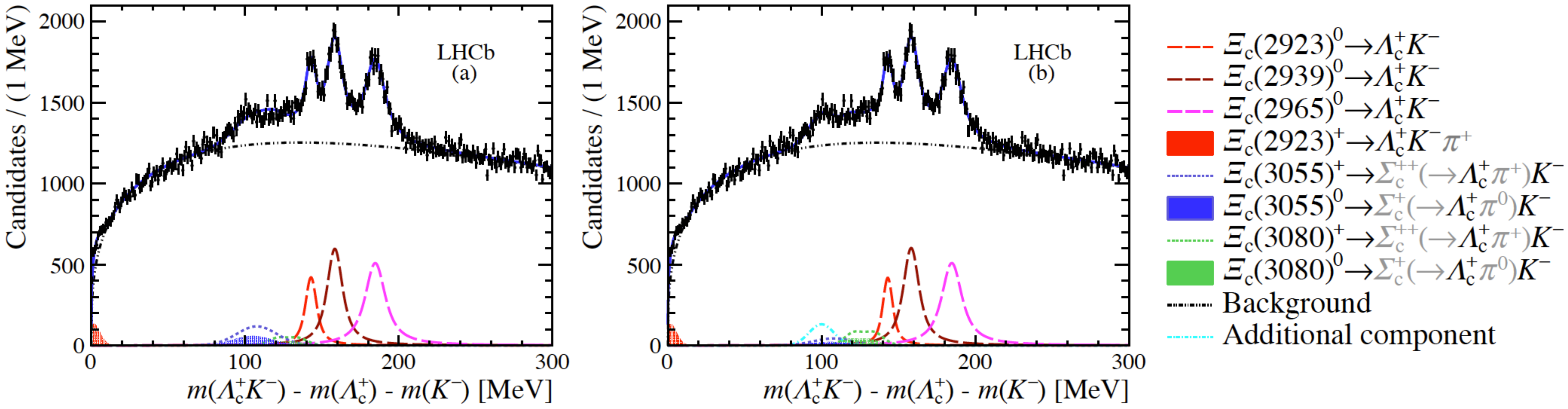


Fit results

[arXiv:2003.13649]

- S-wave relativistic BW fit signal shape
- Low mass bump is modelled by reflections of heavier Ξ_c^{**}(default)
  - possible new Ξ_c^{**} at $\delta m = 100$ MeV(syst.) to improve fit, more data needed to confirm

State	Mass [MeV]	Width [MeV]	Nsig
$\Xi_c(2923)^0$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$	5400
$\Xi_c(2939)^0$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$	10400
$\Xi_c(2965)^0$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$	11700



Further discussion

[arXiv:2003.13649]

- If $\Xi_c(2965)$ is $\Xi_c(2970)$ in PDG? More studies? Theoretical inputs?

State	Mass [MeV]	Width [MeV]
$\Xi_c(2965)^0$ [LHCb]	2964.9 ± 0.3	14.1 ± 1.6
$\Xi_c(2970)^0$ [PDG]	$2967.8^{+0.8}_{-0.9}$	$28.1^{+3.4}_{-4.0}$

$\Xi_c(2970)$

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+ \overline{K} \pi$	seen
Γ_2	$\Sigma_c(2455)\overline{K}$	seen
Γ_3	$\Lambda_c^+ \overline{K}$	not seen
Γ_4	$\Xi_c 2\pi$	seen
Γ_5	$\Xi_c' \pi$	seen
Γ_6	$\Xi_c(2645)\pi$	seen

- Equal spacing rule predicted mass of Ω [Gell-Mann, Okubo], still holds for the excited states, implies same multiplets

$$m(\Omega_c(2770)^0) - m(\Xi_c(2645)^0) \simeq m(\Xi_c(2645)^0) - m(\Sigma_c(2520)^0) \simeq 125\ \text{MeV}.$$

$$\begin{aligned} m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) &\simeq 125\ \text{MeV}, \\ m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) &\simeq 125\ \text{MeV}, \\ m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) &\simeq 125\ \text{MeV}. \end{aligned}$$

Multiplets between Ξ_c^{**} and Ω_c^{**}

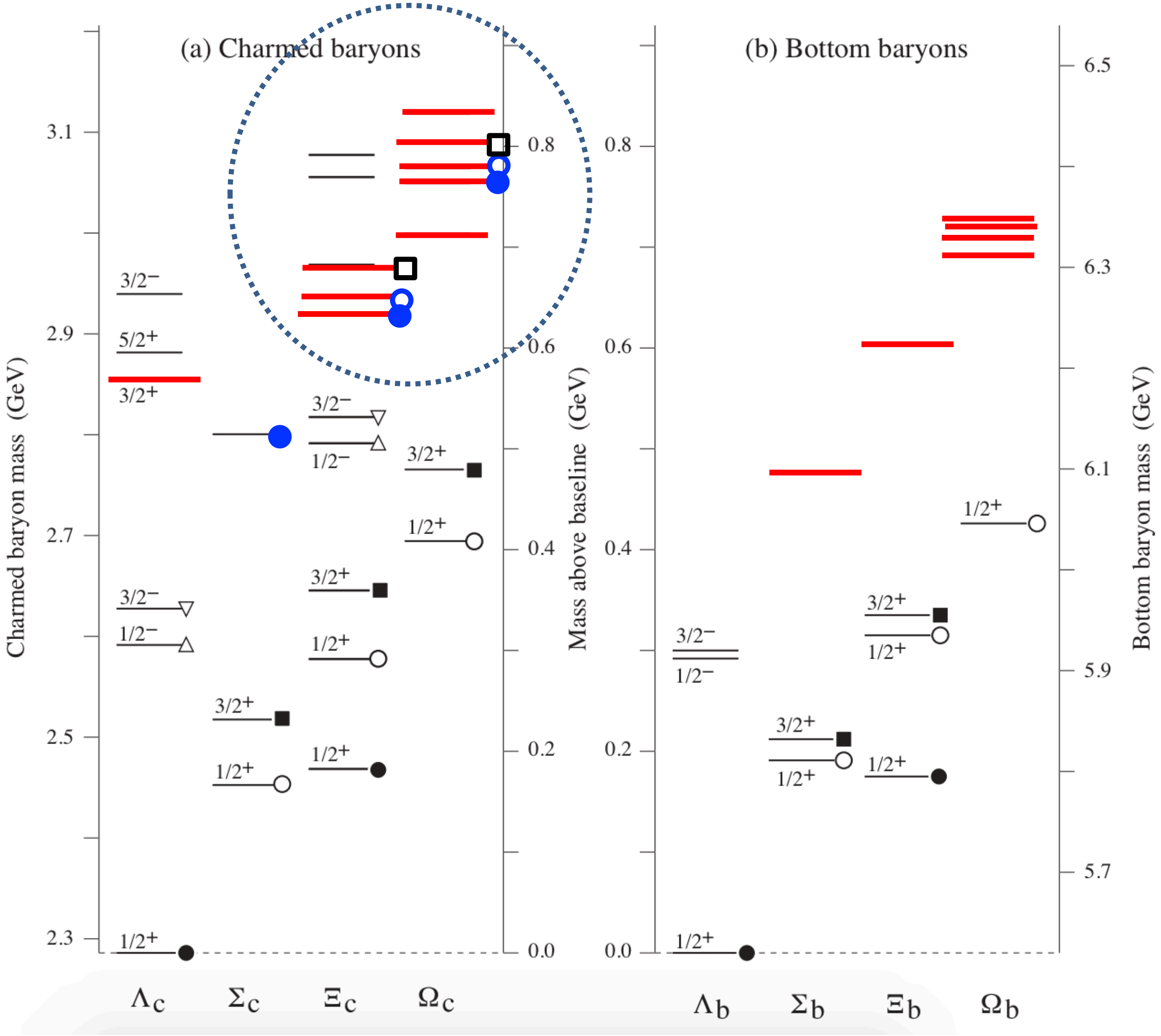
- The 3 Ξ_c^{**} and the 3 of 5 Ω_c^{**} might be the same multiplets

● $m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) \simeq 125\,\text{MeV},$

○ $m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) \simeq 125\,\text{MeV},$

□ $m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) \simeq 125\,\text{MeV}.$

■ $m(\Omega_c(2770)^0) - m(\Xi_c(2645)^0) \simeq m(\Xi_c(2645)^0) - m(\Sigma_c(2520)^0) \simeq 125\,\text{MeV}.$



- More Σ_c^{**} expected?

$\Lambda_b^{**}/\Sigma_b^{**}$ baryons

- 25 charmed baryons observed
  - Missing many Σ_c^{*}?
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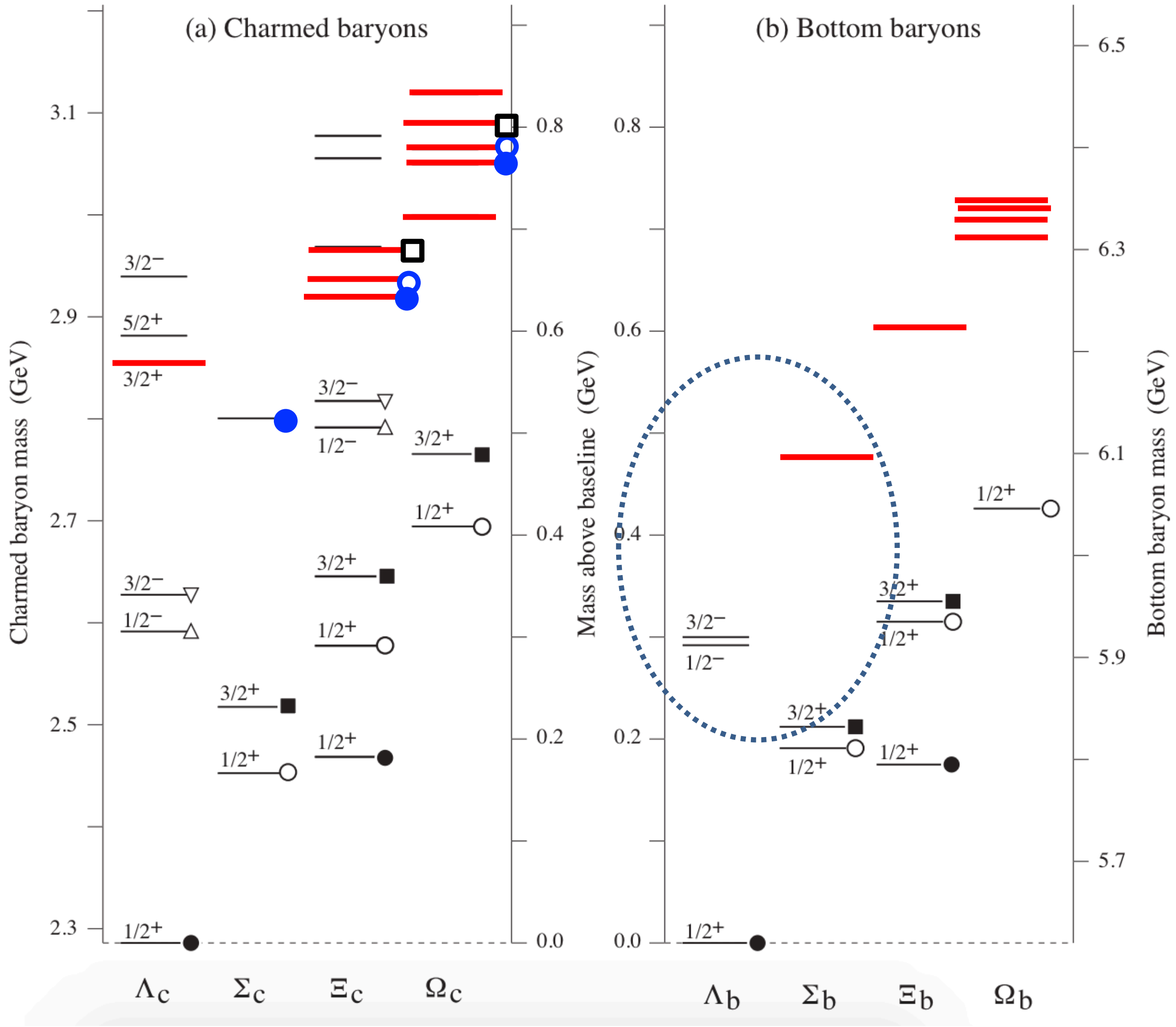
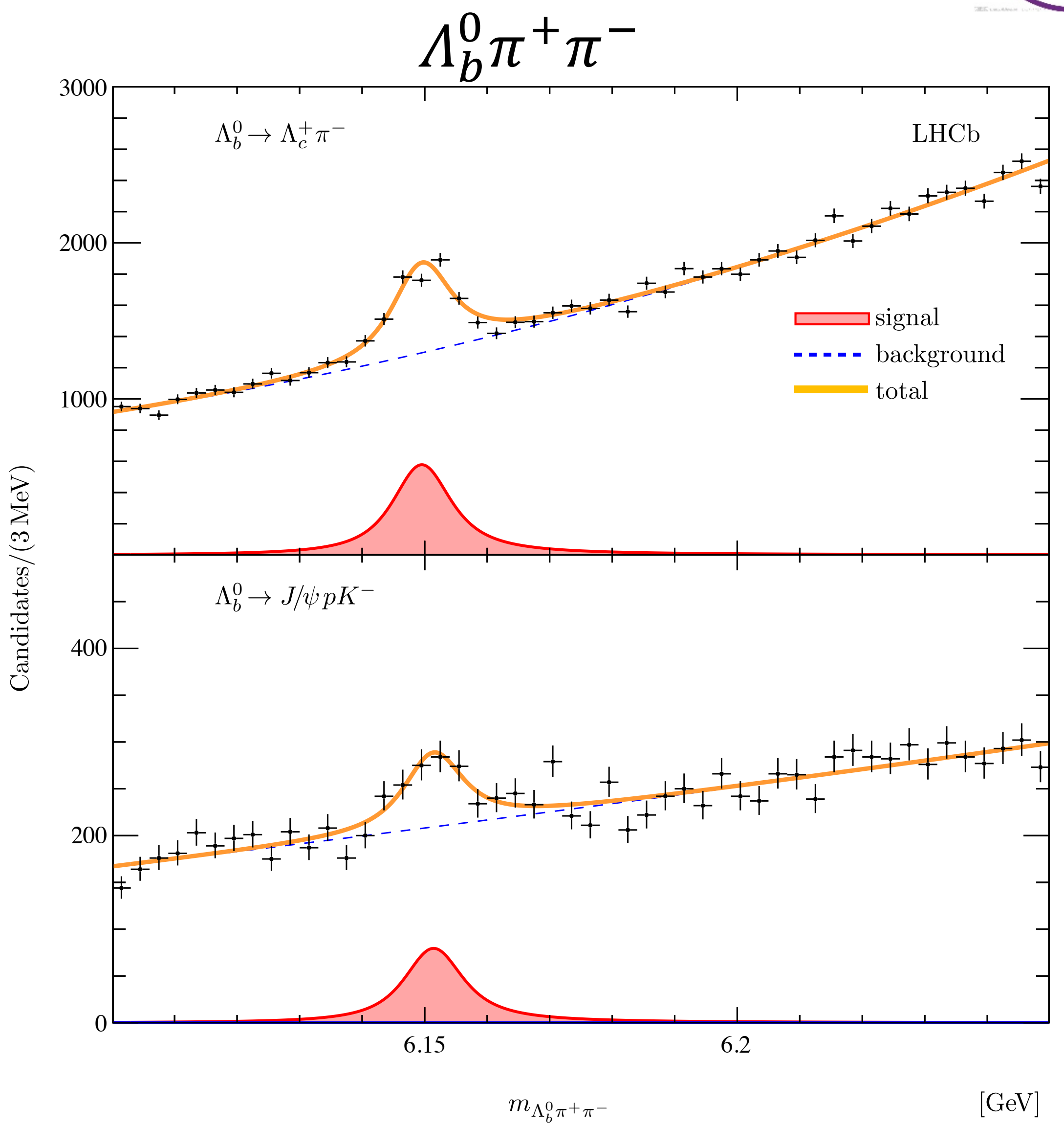


Λ_b^0/Σ_b^0 excitations in $\Lambda_b^0\pi^+\pi^-$

[PRL 123 (2019) 152001]

- Adding $\pi^+\pi^-$ to the Λ_b^0 $\Rightarrow$ probe Λ_b^0 excitations
- Λ_b^0 is reconstructed in
  - $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and
  - $\Lambda_b^0 \to J/\psi p K^-$
- Structure around 6.15GeV
- Investigate substructure of decays $(\Sigma_b^{(*)} \to \Lambda_b\pi)\pi$



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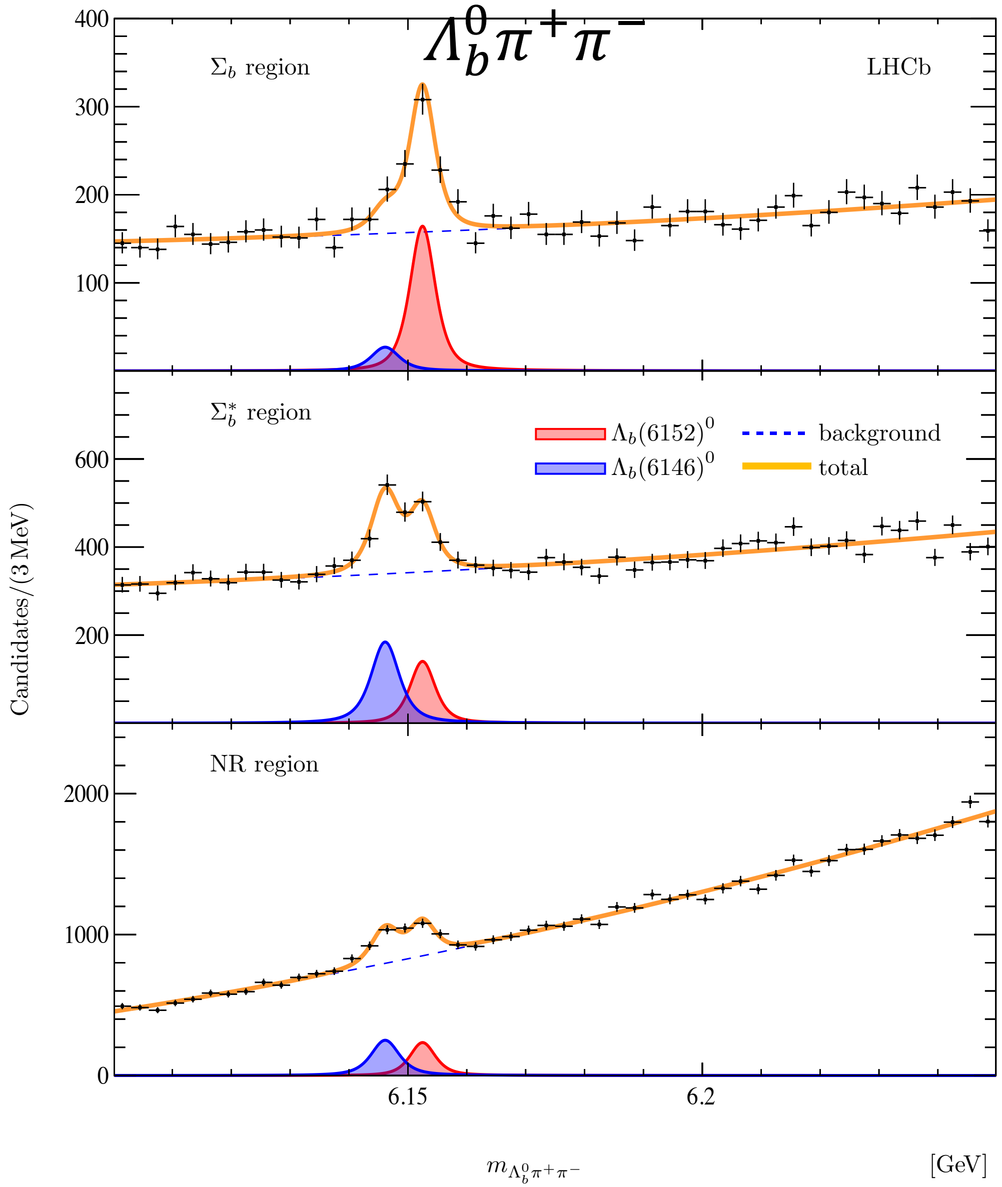
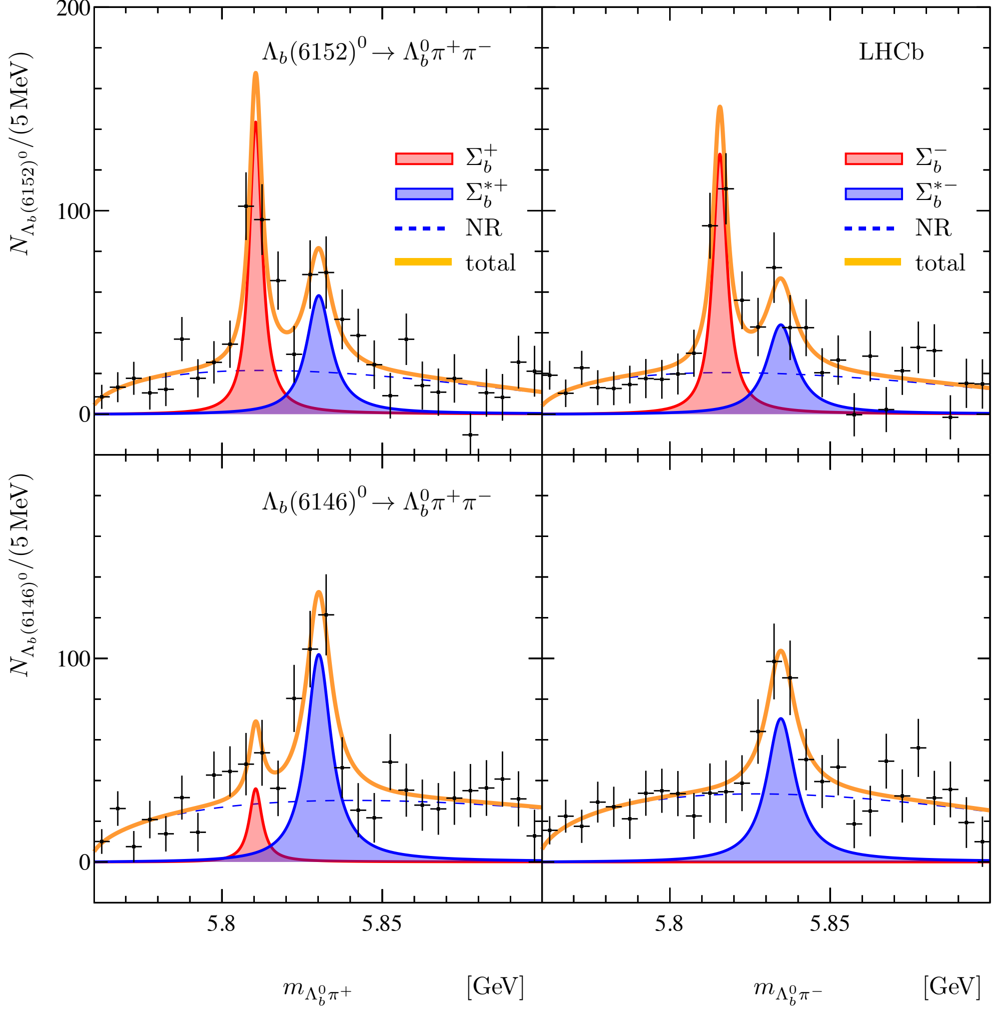


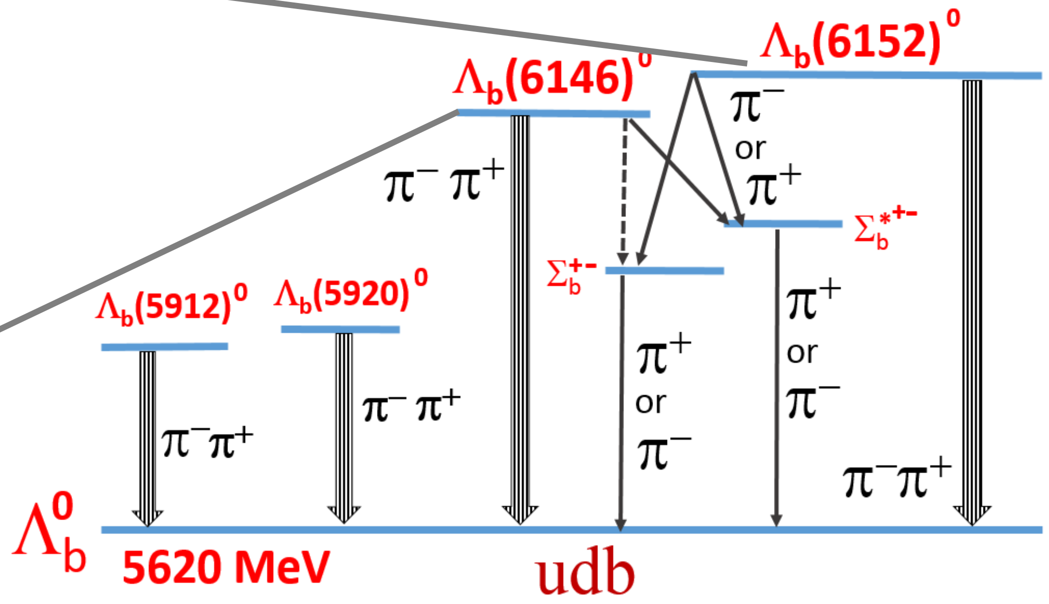
Two new Λ_b^0/Σ_b^0 excitations

[PRL 123 (2019) 152001]

$\Lambda_b^0\pi^\pm$



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



Different coupling to the Σ_b and Σ_b^*

Interpretation as neutral Σ_b^0 states cannot be excluded

Theorists prefer to 1D Λ_b^0 states

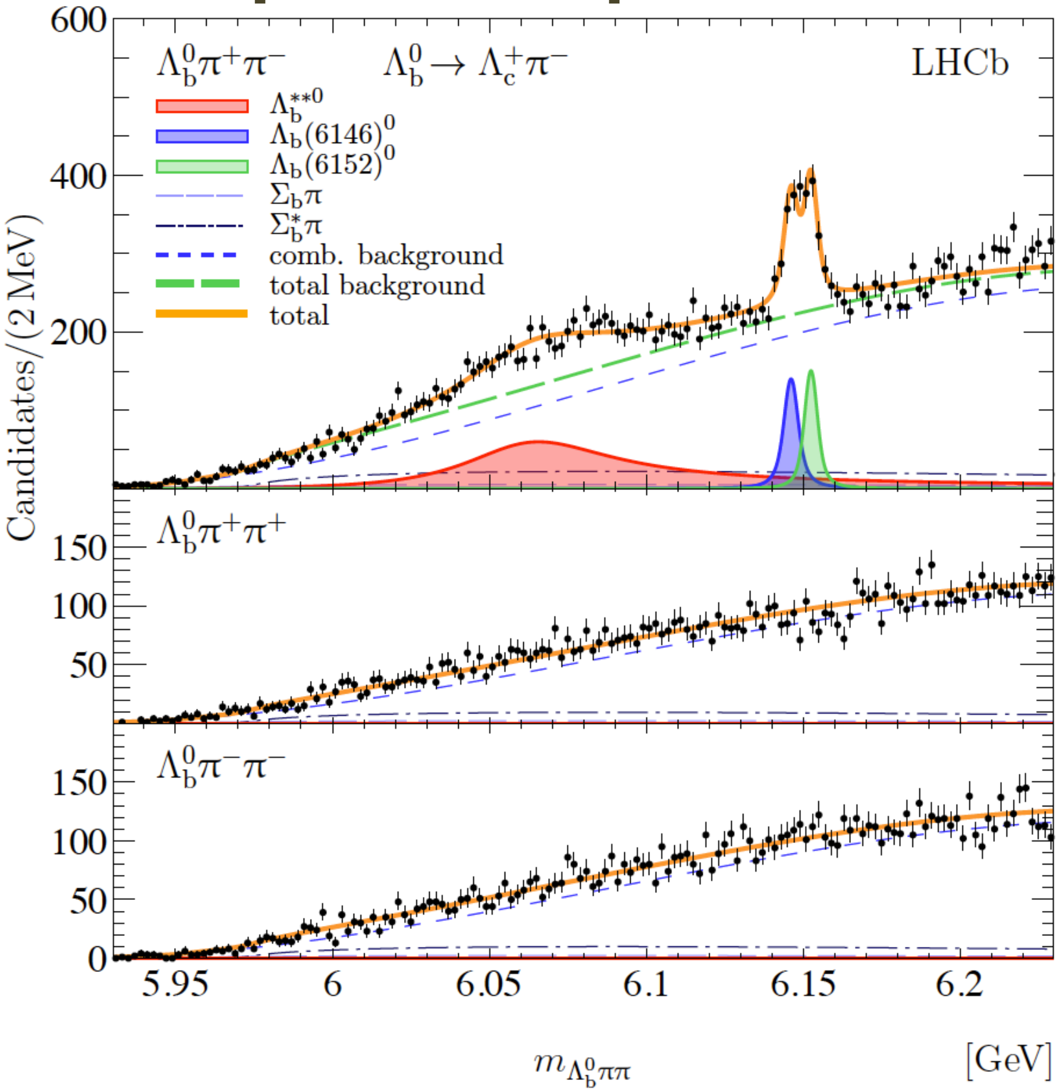
Another new baryon in $\Lambda_b^0\pi^+\pi^-$

- A broad structure is just below the two peaks

$$m = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2\,\text{MeV},$$
$$\Gamma = 72 \pm 11 \pm 2\,\text{MeV},$$

- Consistent with prediction of $\Lambda_b(2S)^0$

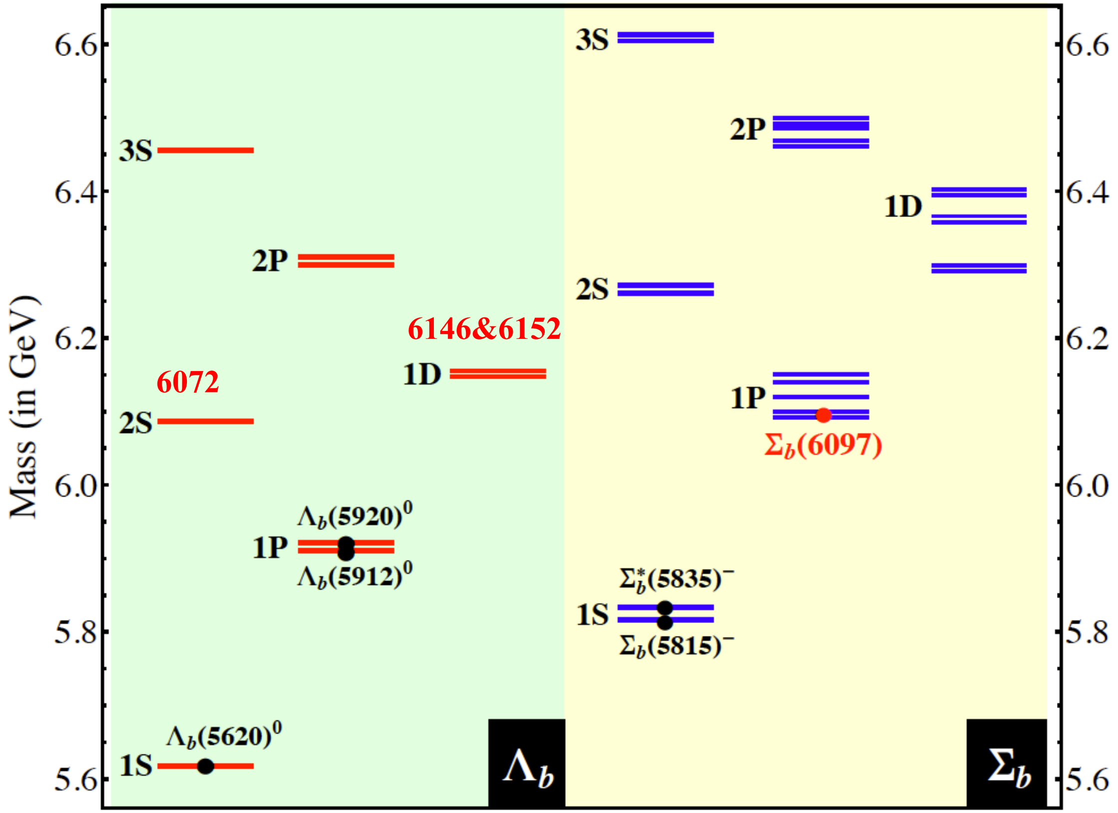
[arXiv:2002.05112]



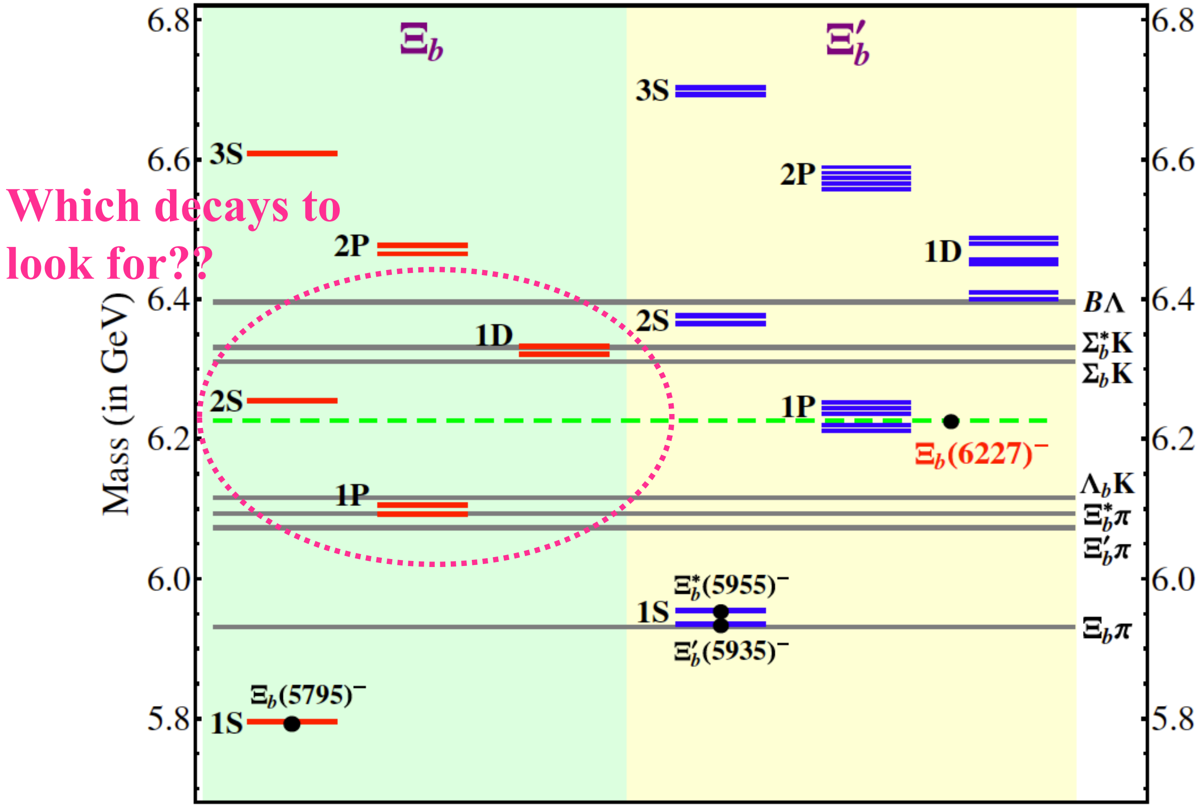
Theoretical explanations

- Interpret $\Lambda_b(6146)$, $\Lambda_b(6152)$ as 1D
  [PRD 100 (2019), 094032; 2002.11435]

Or superposition of several states?



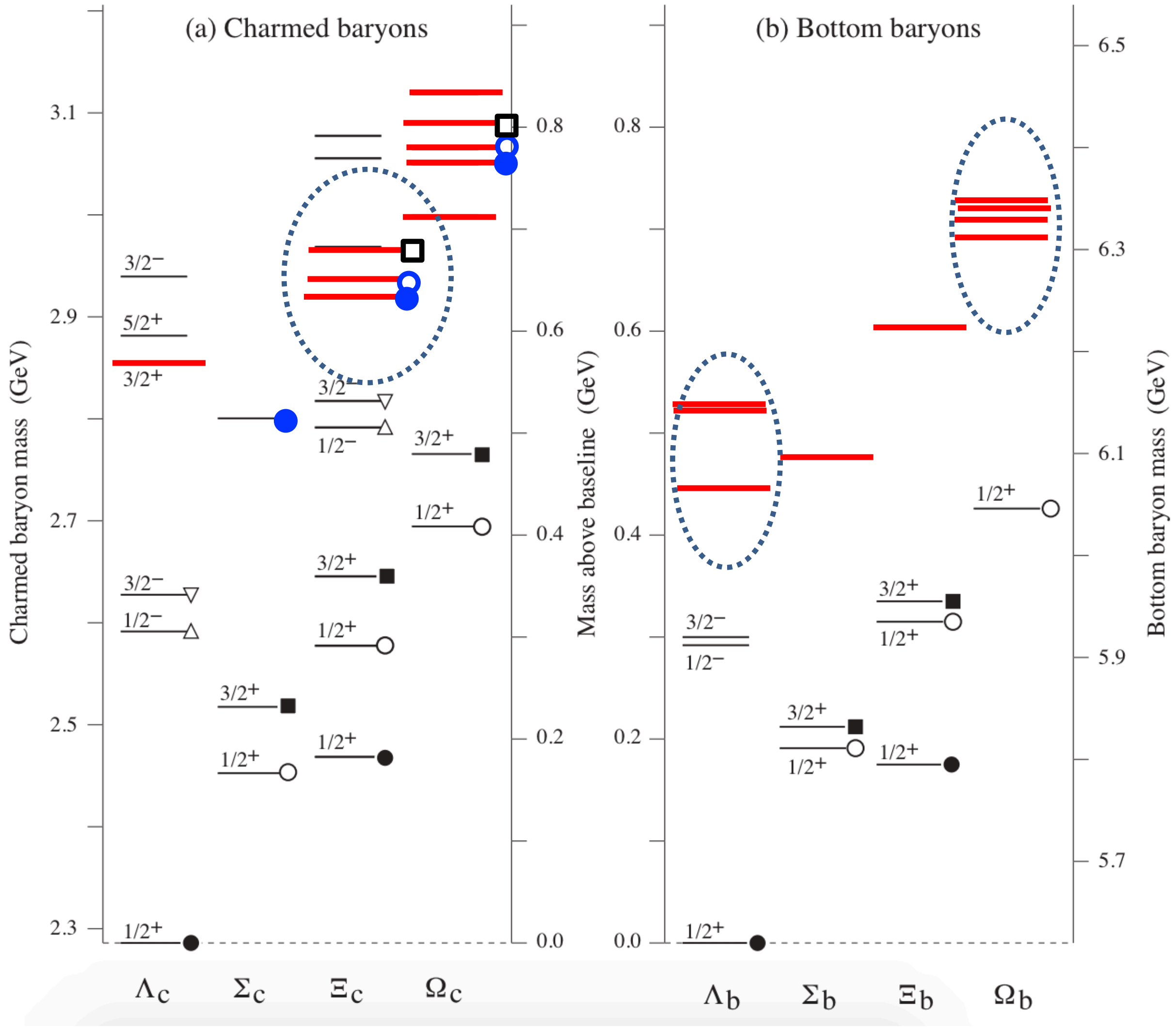
[Bing Chen, Xiang Liu PRD 98 (2018) 074032]



[Bing Chen *et. al.* PRD 98 (2018) 031502(R)]

$\Lambda_b^{**}/\Sigma_b^{**}$ baryon summary

- 26 charmed baryons observed
  - Missing many Σ_c^*?
  - See more Ξ_c^{**}
- 16 bottom baryons observed
  - See 4 narrow Ω_b^{**-}
  - See 3 more $\Lambda_b^{**0}/\Sigma_b^{**0}$
- Bottom are very similar to charmed baryons



Summary

- Baryons have rich spectra
- Exploring meson and baryon excitation spectra
- Studying exotic hadron spectroscopy
  - Not showing is the pentaquark baryon states
- Remarkable facts:
  - Lots of excited charm and bottom baryons are very narrow
  - Equal spacing rule (~125 MeV) works well for charm and bottom Σ, Ξ and Ω

- **Your suggestions may results in more discoveries**

Backup

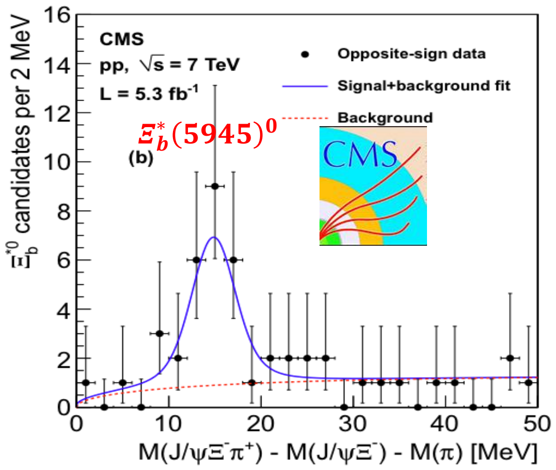
Ξ_b baryon spectroscopy

- Numbers of excited *b*-baryons have already been discovered
  - $\Xi_b^*(5945)^0 \to \Xi_b^- \pi^+$ [CMS'12]
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \to \Xi_b^0 \pi^-$ [LHCb'15]
  - $\Xi_b'^{\,0}$ not yet observed

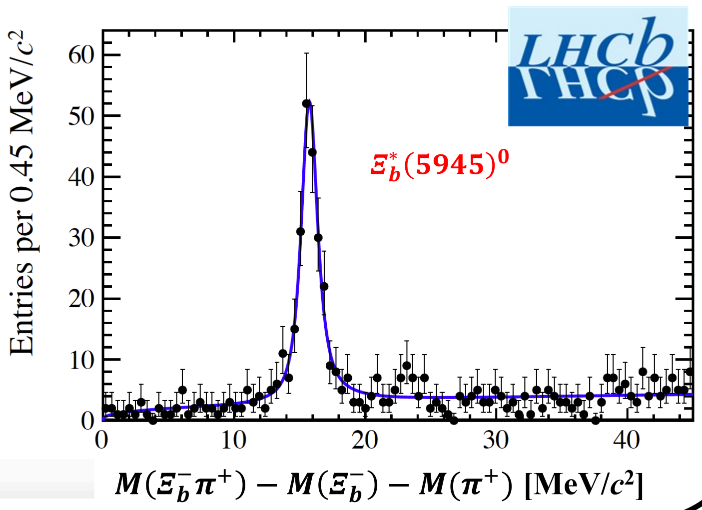
State	J^P	$b(sq)$
Ξ_b	$1/2^+$	$\uparrow (\uparrow\downarrow)$
Ξ_b'	$1/2^+$	$\downarrow (\uparrow\uparrow)$
Ξ_b^*	$3/2^+$	$\uparrow (\uparrow\uparrow)$

Neutral Ξ_b^*

PRL 108, 252002 (2012)

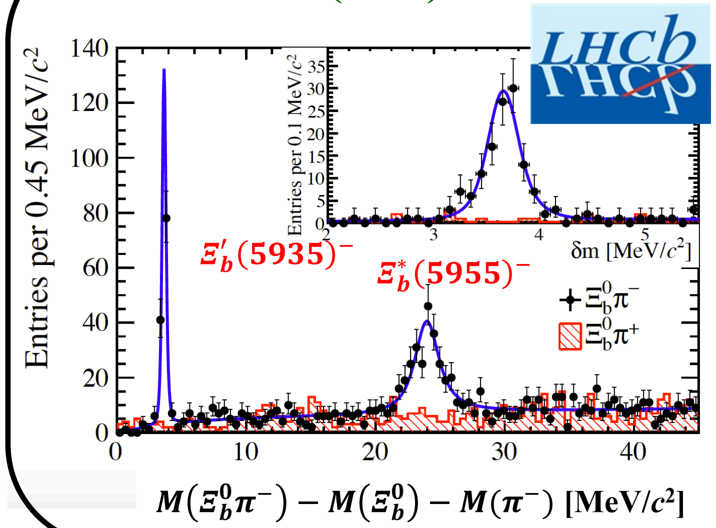


JHEP 05 (2016) 161



Charged $\Xi_b'^{(*)}$

PRL 114 (2015) 062004



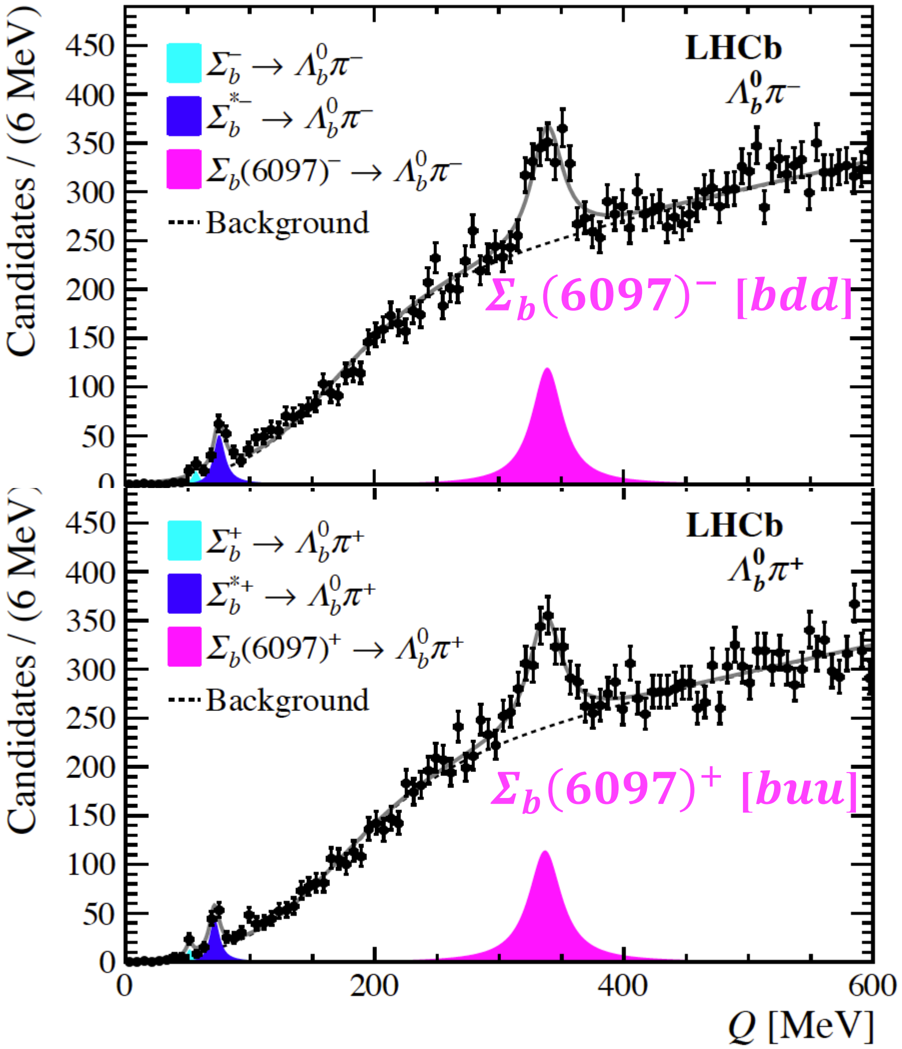
Σ_b spectroscopy: Observation of $\Sigma_b(6097)^{\pm}$

- $\Lambda_b^0 \to \Lambda_c^+\pi^-$ combined with $\pi^{\pm}$ from PV
- Fit: relativistic BW convoluted with resolutions of 1.0-2.4 MeV

Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$

$\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ parameters are measured,
5x more precise than the previous CDF values

[PRL 122 (2019) 012001]



Observation of a new $\Xi_b^{**}(6227)^-$ state

[PRL 121 (2018) 072002]

- Reconstruct $\Xi_b^- \to \Lambda_b^0 K^-$ and $\Xi_b^0 \pi^+$
  - Hadronic (HD) and Semileptonic (SL) decays for Λ_b^0
  - SL decays for $\Xi_b^0 \to \Xi_c^+ \mu^- X \bar{\nu}_\mu$

- With hadronic mode

$$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst})\ \text{MeV}/c^2,$$
$$\Gamma = 18.1 \pm 5.4\,(\text{stat}) \pm 1.8\,(\text{syst})\ \text{MeV}/c^2,$$
$$M(\Xi_b^{**-}) = 6226.9 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV}/c^2,$$

Mass peak position is consistent between the three decay channels

The most massive baryons observed so far!