Recent results on heavy baryon spectroscopy at the LHCb detector

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on behalf of the LHCb collaboration

LHC seminar
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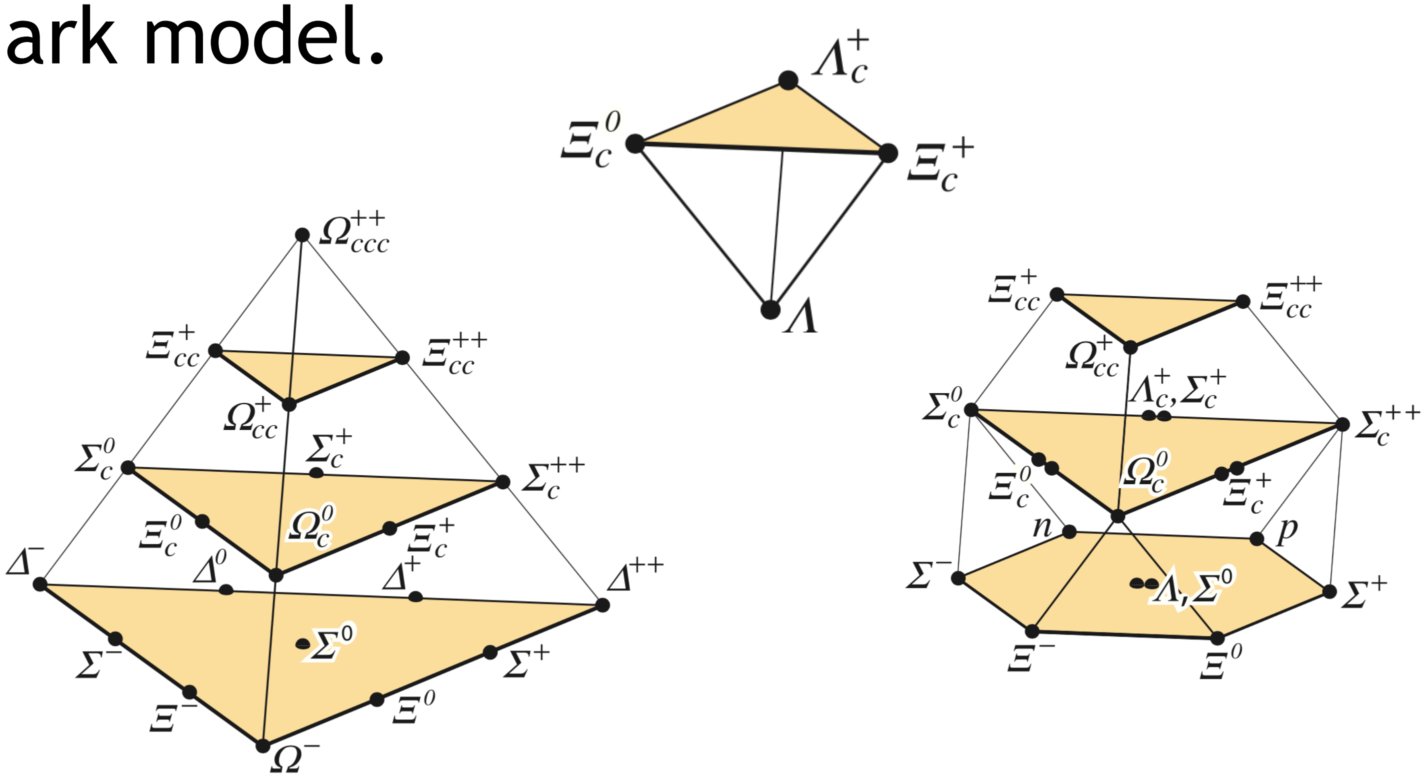
Motivation

- Hadron spectroscopy studies the masses and decays of hadrons
- The properties of these hadrons are a result of quantum chromodynamics (QCD)
- QCD describes the theory of strong interactions between quarks and gluons, binding quarks and antiquarks into hadrons

Expected spectrum of ground state hadrons known to be well explained by the constituent quark model.

SU(4) flavour multiplets of ground state baryons containing the four lightest quarks (u, d, s & c):
(can be expanded to SU(5) including bottom quark)



Motivation

However, understanding the structure and properties of hadrons from QCD remains a challenge.
$\longrightarrow$ non-perturbative long distance effects involved.

Why study hadron spectroscopy?

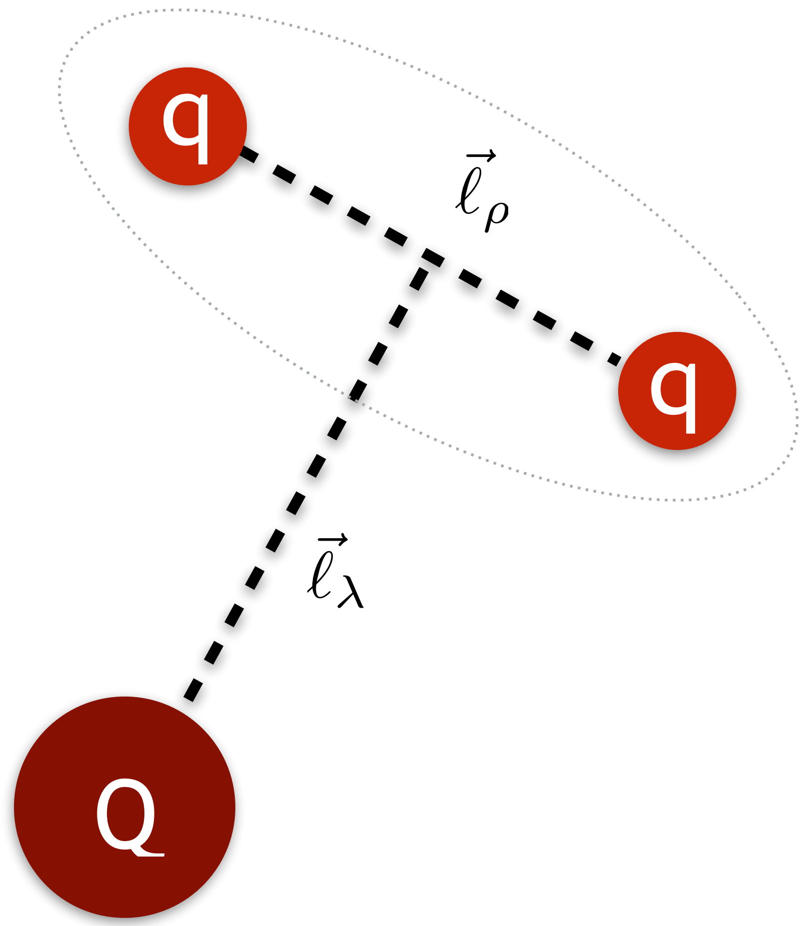
- provides great experimental place to test theoretical models probing QCD
- increase understanding of the nature of exotic hadrons
- excited states as input to other analyses
- measure the masses and widths of excited baryons

Plethora of new spectroscopy results from the LHC in the past years!

Motivation

These results have lead to a big effort from the theory community to understand the structure of the many newly discovered hadrons.

- Constituent quark model
- Quarks and diquarks
- Tightly bound vs. molecular
- Combination of the above?



***HQET** = heavy quark effective theories.*
Can be used to predict the masses of heavy mesons/baryons.

We can validate HQET by measuring excited heavy meson properties.

Heavy baryon model:
Diquark system (q,q)
Static heavy quark (Q)

Outline

Many interesting recent results…
… this talk will focus on a selection of recent results from LHCb.

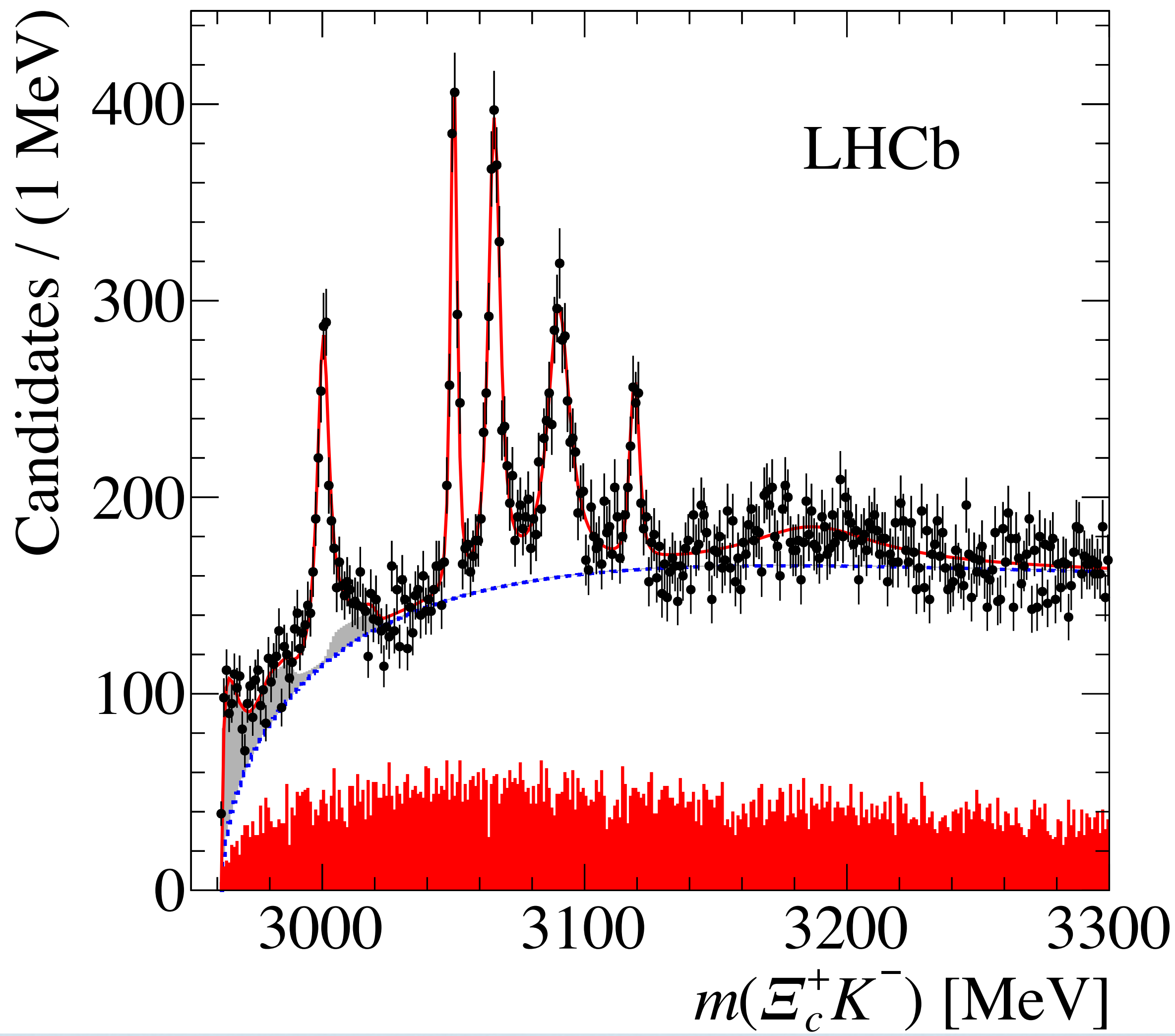
- Charmed baryons
  - Excited Ξ_c^0 states NEW!
    arXiv:2003.13649
- Beauty baryons
  - Precise measurement of $\Sigma_b^\pm$ / $\Sigma_b^{*\pm}$ properties PRL 122 (2019) 012001
  - Excited Ω_b^- resonances PRL 124 (2020) 082002
  - The $\Lambda_b^0\pi^+\pi^-$ mass spectrum
    PRL 123 (2019) 152001 arXiv:2002.05112
- Doubly charmed baryons JHEP 10 (2019) 124
  - New Ξ_{cc}^{++} decay modes PRL 121 (2018) 062002
  - Measurements of Ξ_{cc}^{++} properties: → lifetime measurement PRL 121 (2019) 052002; production at 13 TeV Chin.Phys. C44 (2020) 022001; precision mass measurement JHEP 02 (2020) 049
  - Search for the Ξ_{cc}^+ baryon
    Sci.China Phys.Mech.Astron. (2020) 63 221062

The beginning of the story…

5 charming baryons

Discovery of five narrow excited Ω_c^0 states in the $\Xi_c^+ K^-$ spectrum.

$\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, $\Omega_c(3119)^0$



PRL 118 (2017) 182001

Beautiful Ω_b^- baryons decaying to $\Xi_b^0 K^-$

Beautiful Ω_b^- baryons

The discovery of five narrow excited Ω_c^0 states lead to a surge in theoretical interpretations.

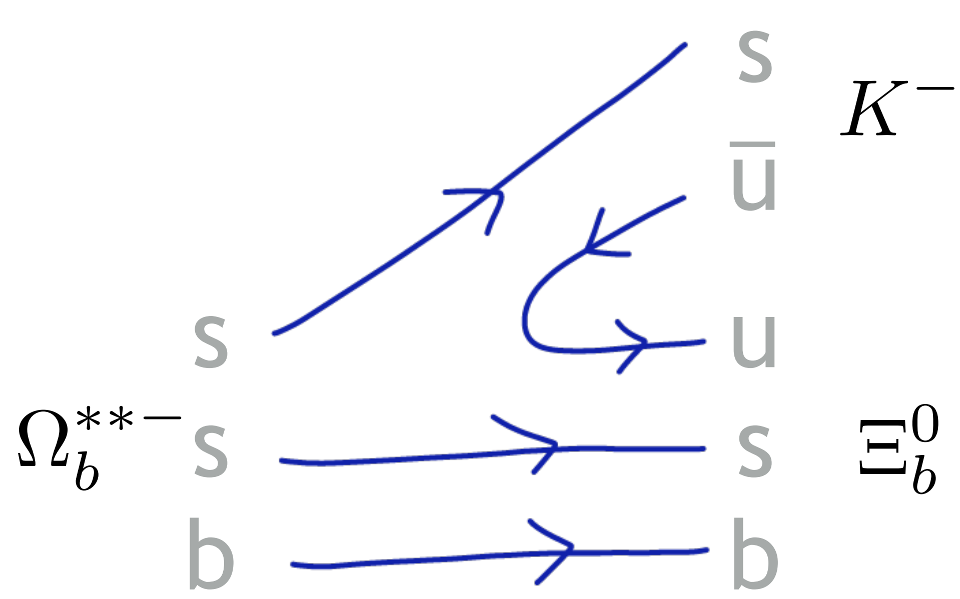
⟶ New predictions for $\Xi_b^0 K^-$ resonances.

Search for analogous Ω_b^{**-} resonances in the $\Xi_b^0 K^-$ spectrum using full Run I + II data set [9 fb^{-1}]. PRL 124 (2020) 082002

Decay chain:

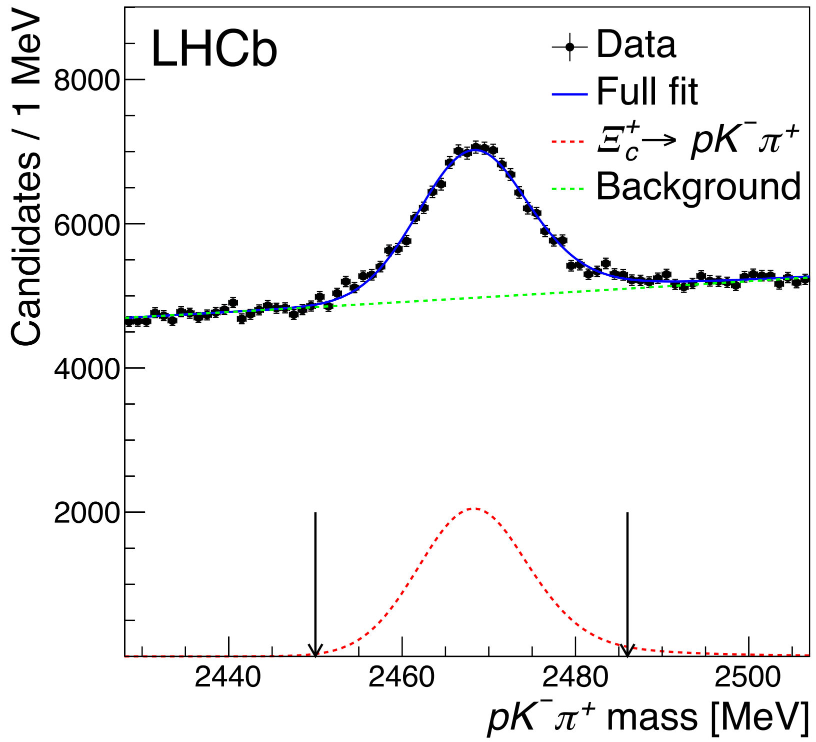
$$\Omega_b^- \to \Xi_b^0 \; K^-$$
$$\hookrightarrow \Xi_c^+ \; \pi^-$$
$$\hookrightarrow pK^-\pi^+$$

Feynman diagram:



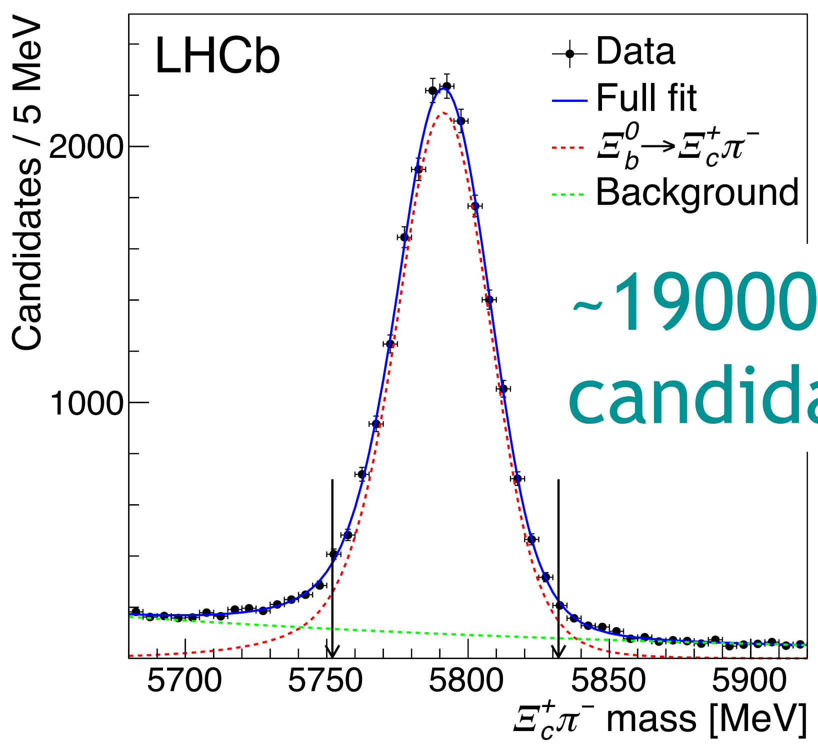
Beautiful Ω_b^- baryons

$\Omega_b^- \to \Xi_b^0 K^-$
$\quad \hookrightarrow \Xi_c^+ \pi^-$
$\quad\quad \hookrightarrow pK^-\pi^+$



$\Xi_c^+ \to pK^-\pi^+$ are selected using :

- Particle identification requirements on final state hadrons
- Requirements on the topology of the decay



~19000 Ξ_b^0 candidates

$\Xi_b^0 \to \Xi_c^+\pi^-$ events are selected using a boosted decision tree

Further background reduction is achieved through a particle identification requirement on the bachelor kaon

PRL 124 (2020) 082002

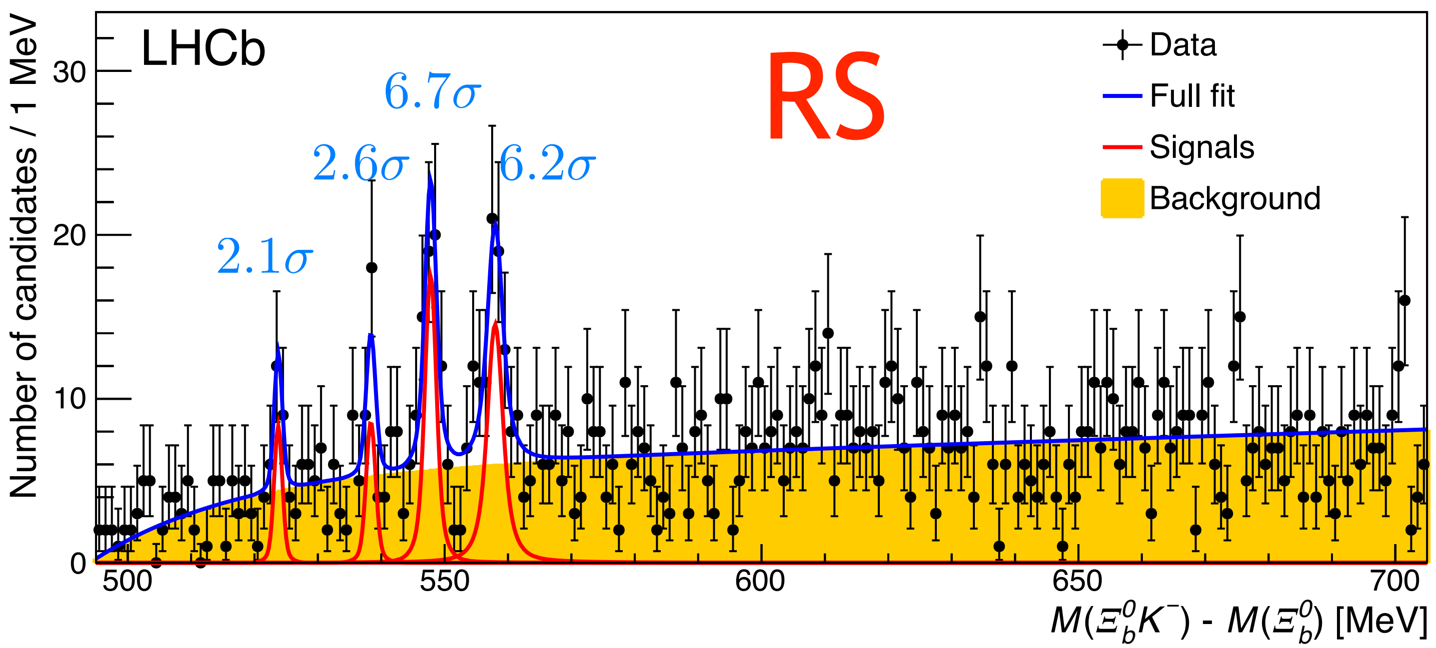
$$\Omega_b^- \to \Xi_b^0 K^-$$
$$\hookrightarrow \Xi_c^+ \pi^-$$
$$\hookrightarrow pK^-\pi^+$$

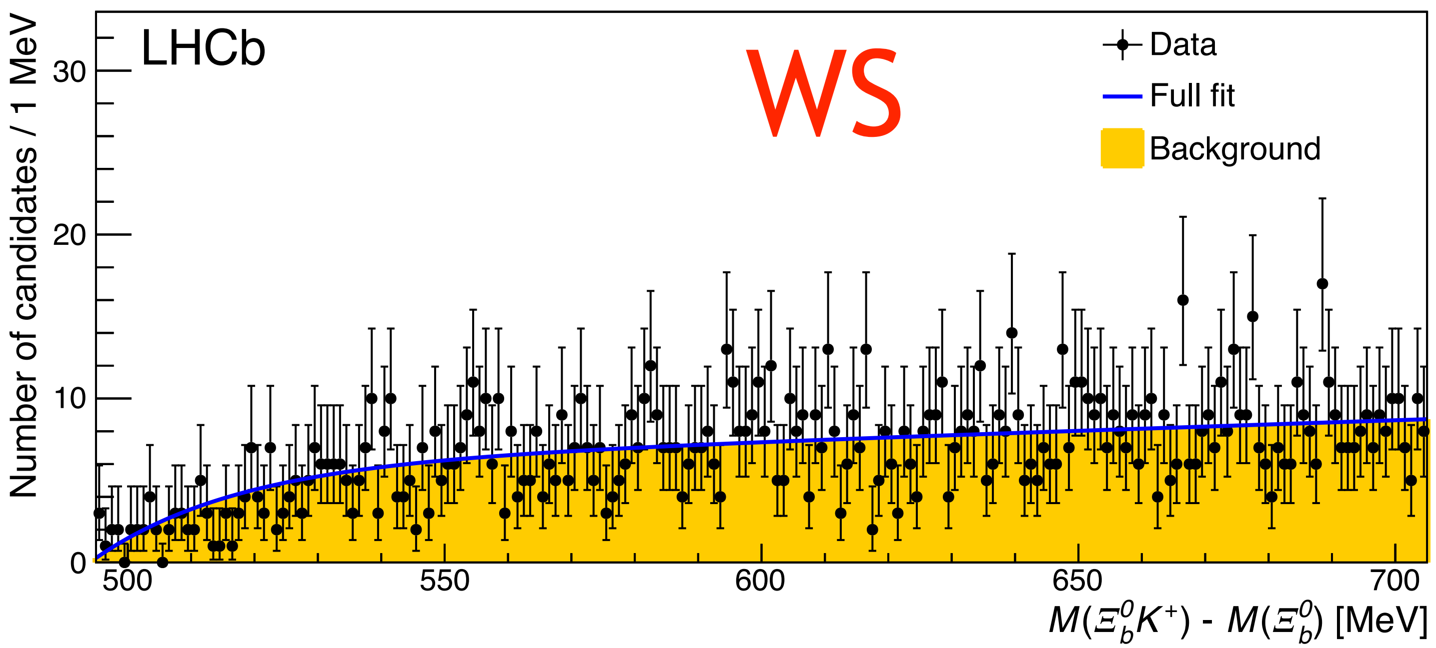
Beautiful Ω_b^- baryons

Simultaneous unbinned extended maximum likelihood fit to wrong-sign (WS) and right-sign (RS) spectra

Four signal peaks seen
Modeled using S-wave relativistic Breit-Wigner convoluted with Gaussian resolution function

Global significances account for look-elsewhere effect





$$\Omega_b^- \to \Xi_b^0 K^-$$
$$\hookrightarrow \Xi_c^+ \pi^-$$
$$\hookrightarrow pK^-\pi^+$$

Beautiful Ω_b^- baryons

Results:

	$\delta M_{\rm peak}$ [MeV]	Mass [MeV]	Width [MeV]	
$\Omega_b(6316)^-$	$523.74 \pm 0.31 \pm 0.07$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	$< 2.8\ (4.2)$	2.1σ
$\Omega_b(6330)^-$	$538.40 \pm 0.28 \pm 0.07$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	$< 3.1\ (4.7)$	2.6σ
$\Omega_b(6340)^-$	$547.81 \pm 0.26 \pm 0.05$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	$< 1.5\ (1.8)$	6.7σ
$\Omega_b(6350)^-$	$557.98 \pm 0.35 \pm 0.05$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	$< 2.8\ (3.2)$ $1.4\,^{+1.0}_{-0.8} \pm 0.1$	6.2σ

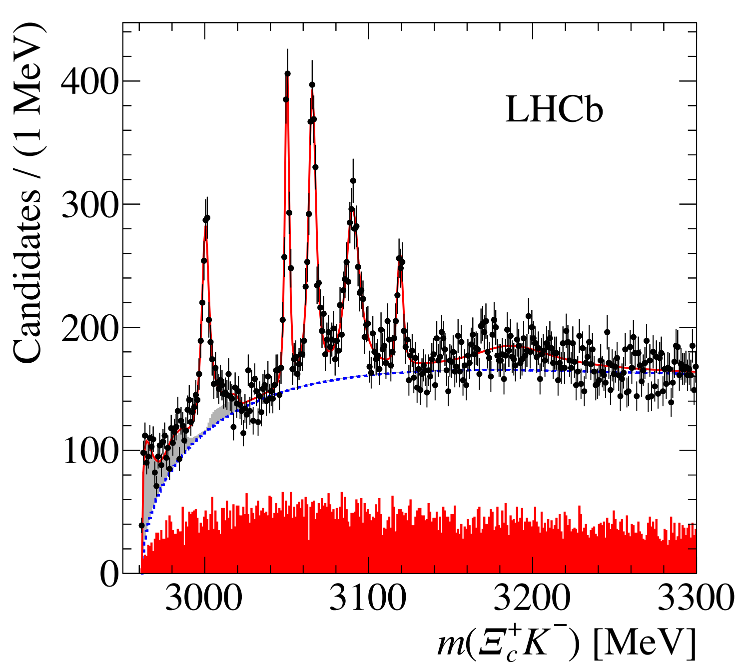
Possible interpretations:

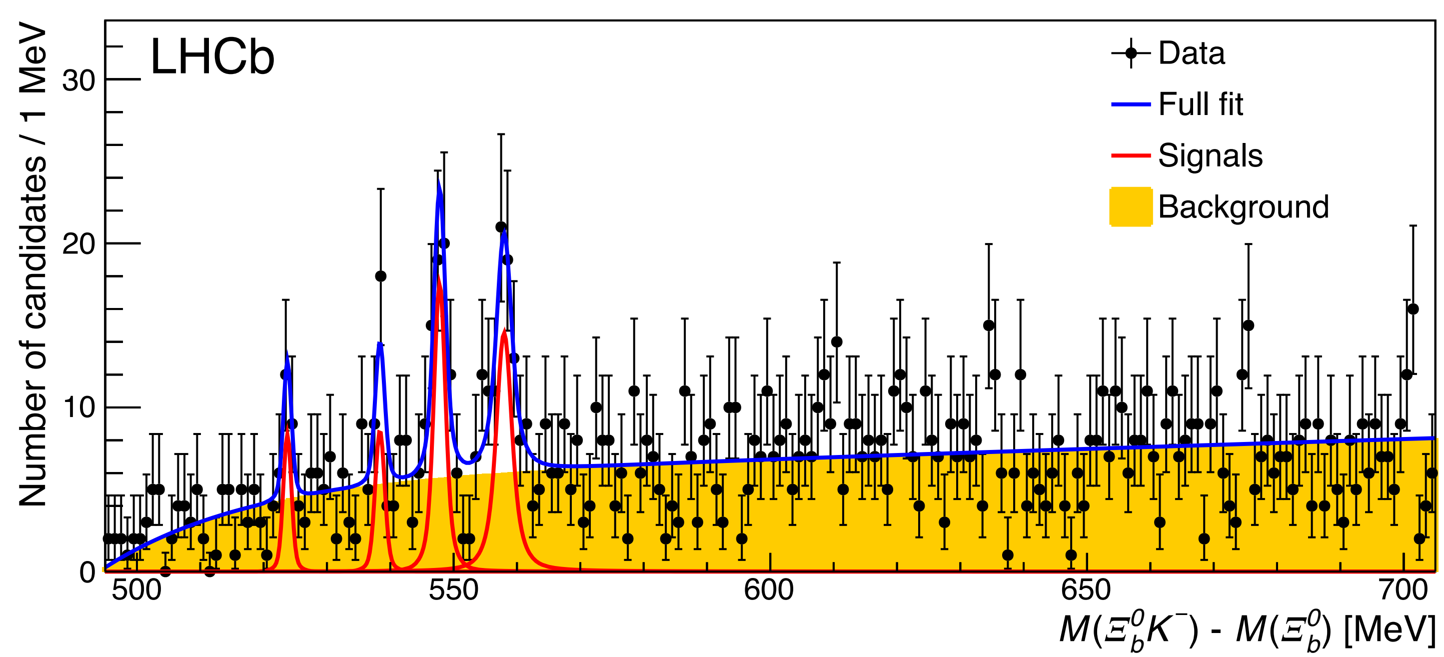
- Excited Ω_b^- states
  -L=1 angular momentum excitations of the ground state
  -n=2 radial excitations
- Decay of higher mass excited Ω_b^- state:
  $\Omega_b^{**-} \to \Xi_b^{\prime 0}(\to \Xi_b^0 \pi^0) K^-$, where π^0 is undetected
  and assuming $m(\Xi_b^{\prime 0}) > m(\Xi_b^0) + m(\pi^0)$

Beautiful Ω_b^- baryons

Similar spectra are observed in $\Xi_b^0 K^-$ & $\Xi_c^+ K^-$
as expected from heavy quark symmetry.

Ω_b^- are higher mass partners of the Ω^- baryon
→ Ω^- famously predicted by the 'Eightfold Way'
→ would also expect Ξ_c^0 higher mass partners





PRL 124 (2020) 082002

Search for Ξ_c^0 baryons decaying to $\Lambda_c^+ K^-$

arXiv:2003.13649

More charmed baryons?

Look at a different charmed mass spectrum to better understand the discovery of five narrow excited Ω_c^0 states.

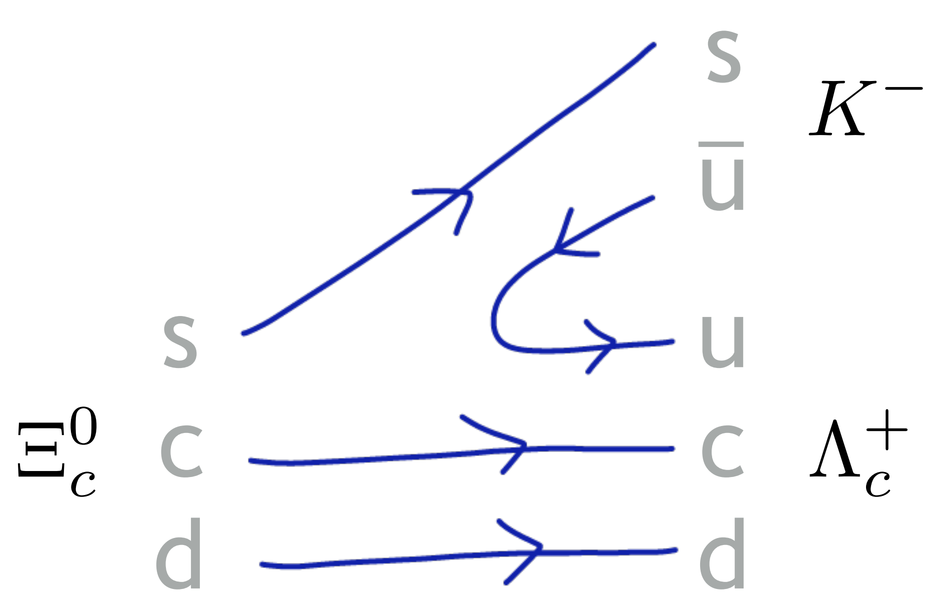
Search for analogous Ξ_c^0 resonances in the $\Lambda_c^+ K^-$ spectrum using 2016-2018 data [5.6 fb^{-1}].

Decay chain:

$\Xi_c^0 \to \Lambda_c^+ K^-$
$\quad\quad \hookrightarrow pK^-\pi^+$

Mass spectrum has previously been studied by Belle (1, 2) and Babar (3, 4), where a peak was observed at similar mass and width: the $\Xi_c(2930)^0$ baryon.

Feynman diagram:

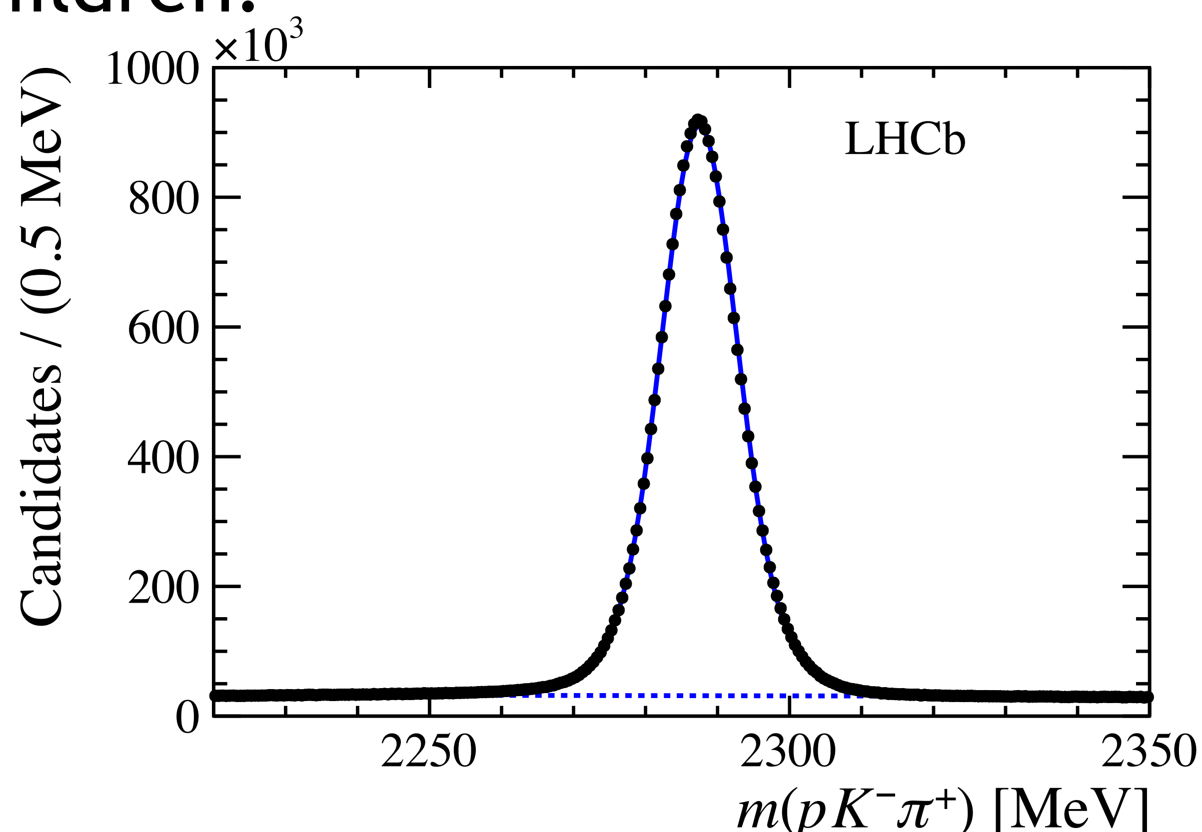


$$\Xi_c^0 \rightarrow \Lambda_c^+ K^-$$
$$\quad \hookrightarrow pK^-\pi^+$$

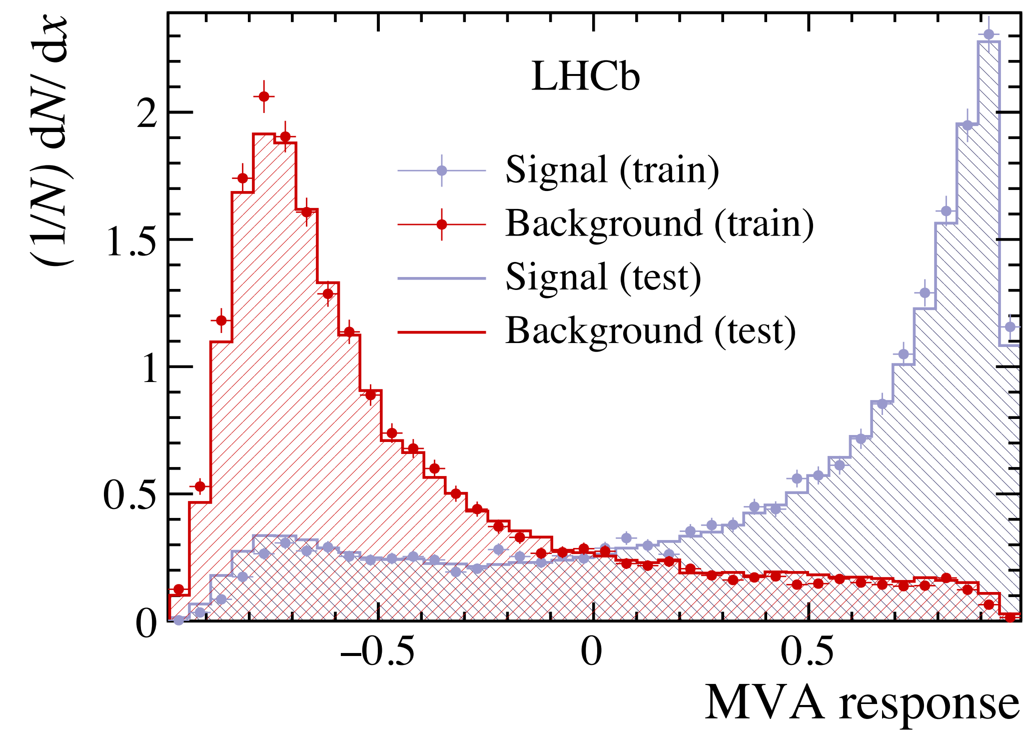
Charmed Ξ_c^0 baryons

Select $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays using multivariate boosted decision tree.

Input variables based on decay topology and p_T and particle identification information of the children.



BDTG overtraining test



About 125 million Λ_c^+ signal decays with a purity of 93% are selected for further analyses.

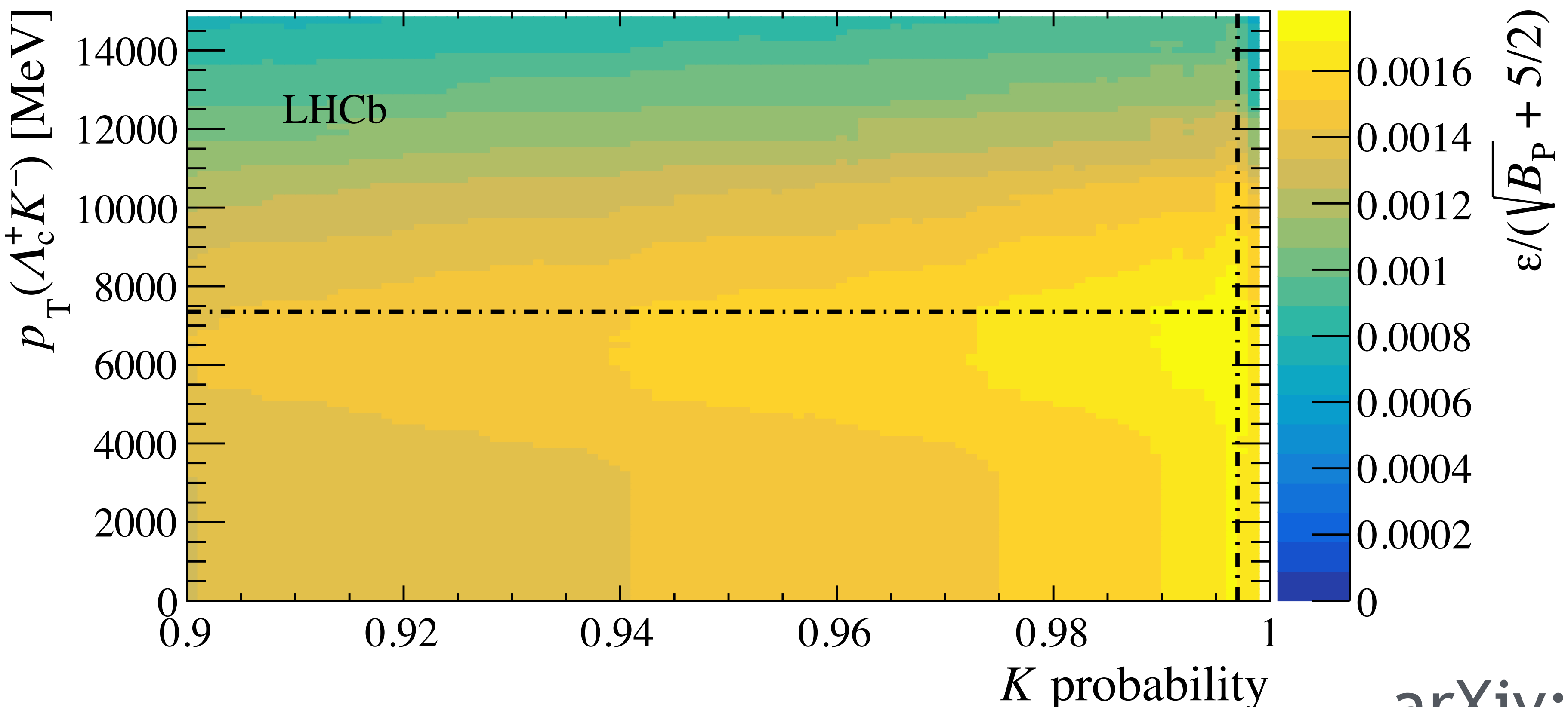
arXiv:2003.13649

Charmed Ξ_c^0 baryons

$\Xi_c^0 \to \Lambda_c^+ K^-$
$\quad \hookrightarrow pK^-\pi^+$

Large amount of combinatorial background due to the large number of kaon candidates from the primary vertex.

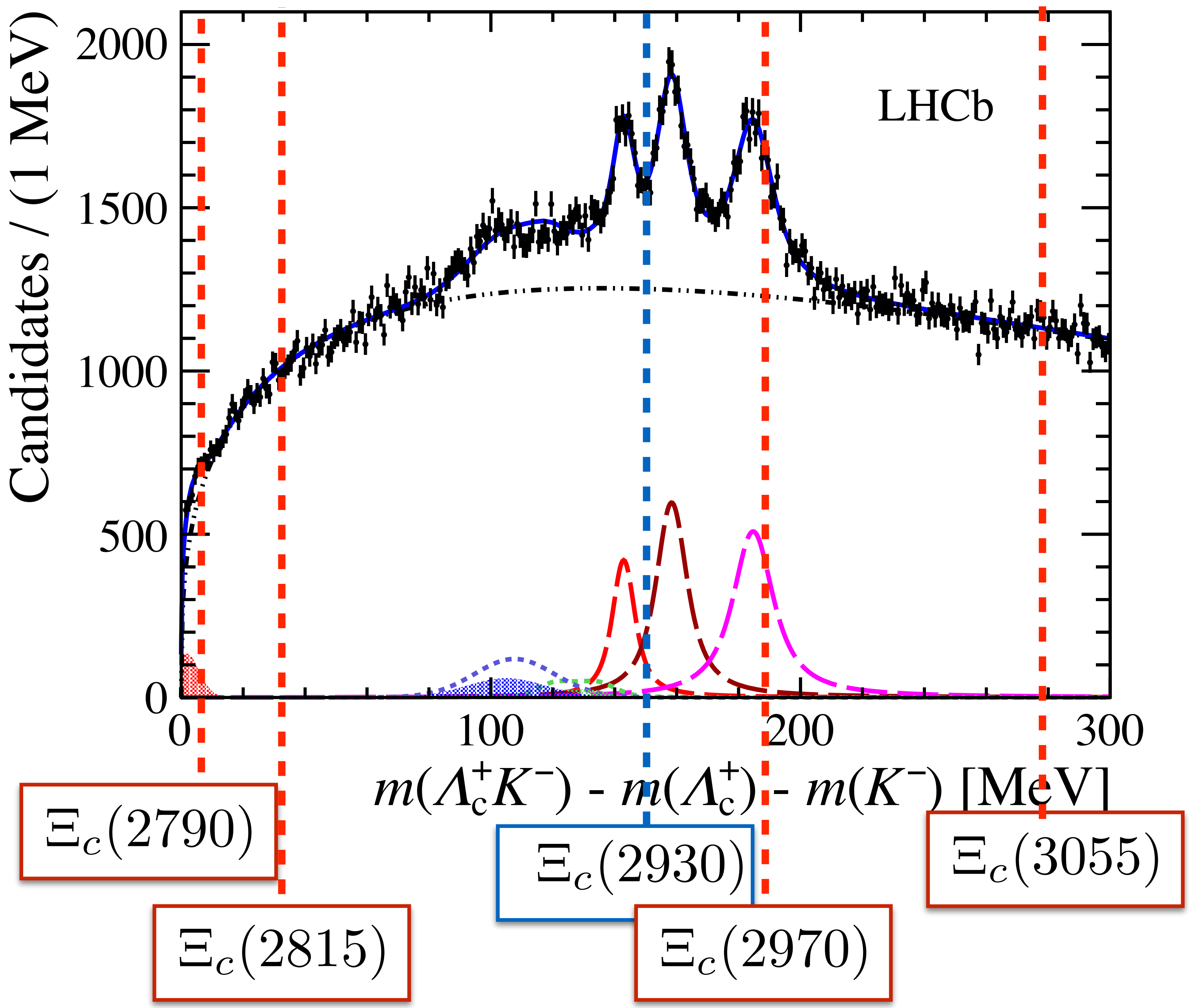
Background suppressed by simultaneously optimising selection requirements on the particle identification response of the bachelor kaon and the p_T of the bachelor kaon.



arXiv:2003.13649

$\Xi_c^0 \to \Lambda_c^+ K^-$
$\hookrightarrow pK^-\pi^+$

The $\Lambda_c^+ K^-$ mass spectrum



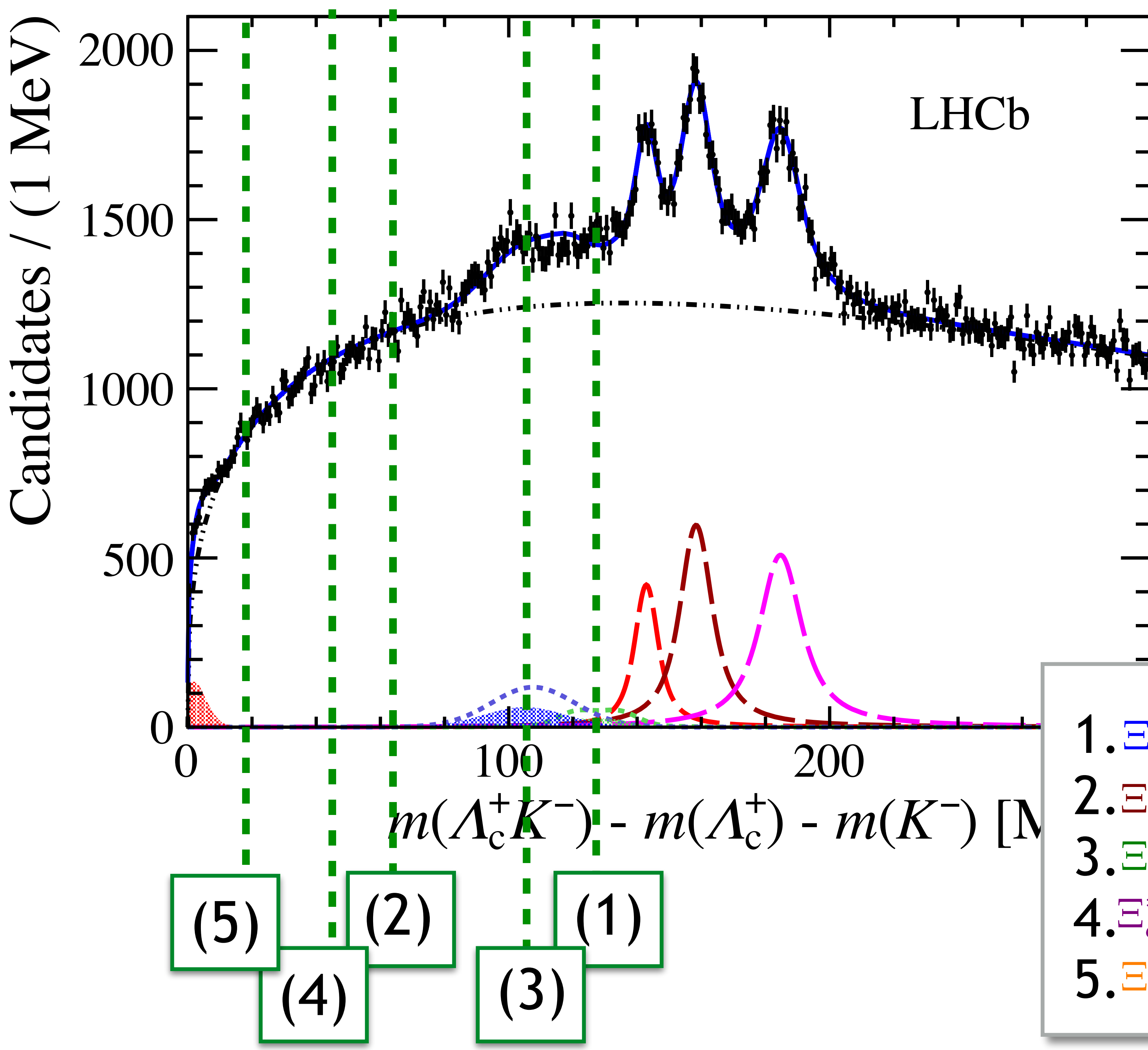
Marked are the current known Ξ_c^0 states with $m > m(\Lambda_c^+) + m(K^-)$.

red - not yet observed in this decay mode
blue - observed in this decay mode

arXiv:2003.13649

$\Xi_c^0 \to \Lambda_c^+ K^-$
$\hookrightarrow pK^-\pi^+$

The $\Lambda_c^+ K^-$ mass spectrum



Several feed-down decays are considered:

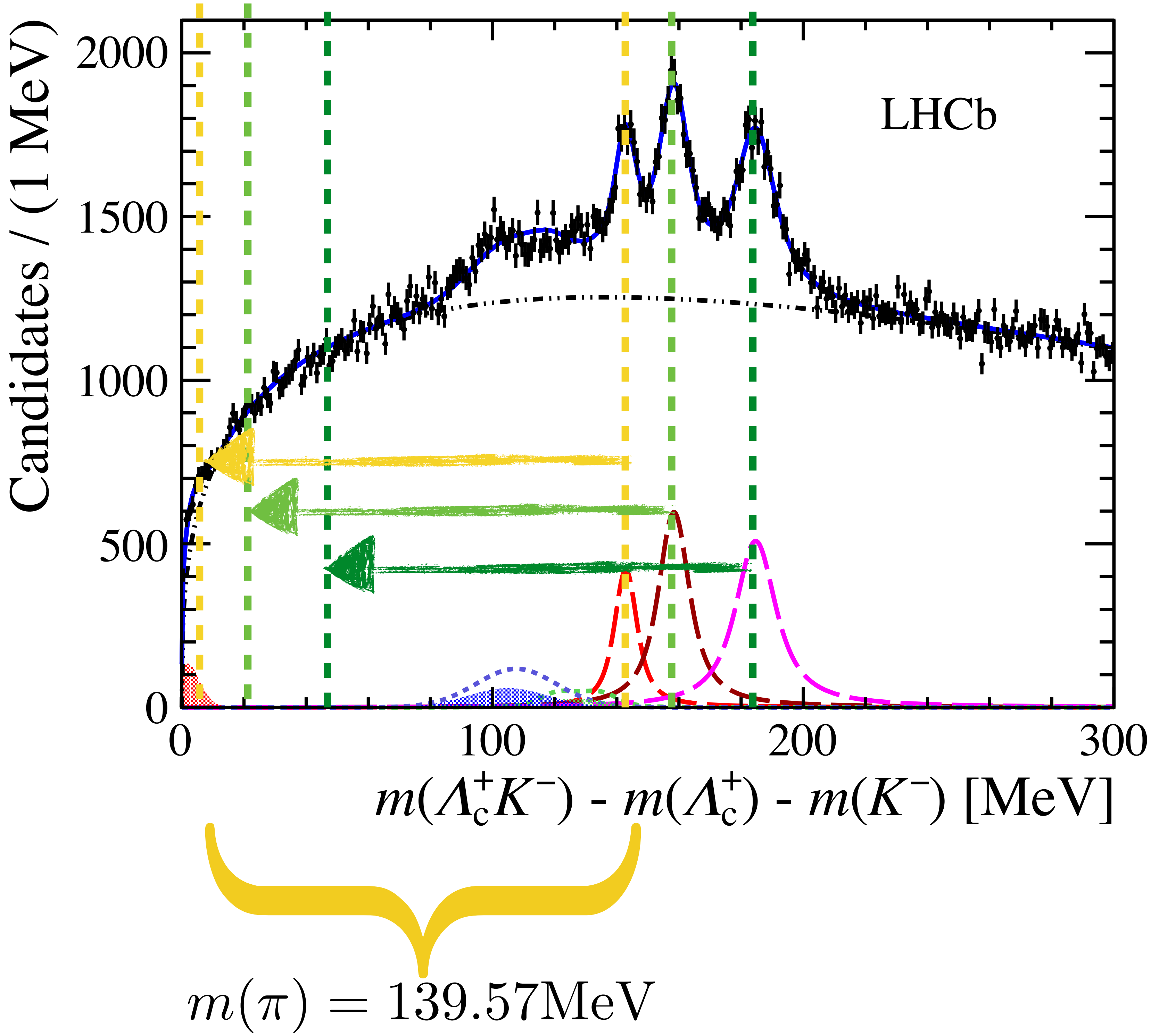
- Both charged and neutral decays are looked at
- The pion is missing in the reconstruction

No excess of events seen for decays (2), (4) and (5)

1. $\Xi_c^{**+}(3080) \to (\Sigma_c^{++}(2455) \to \Lambda_c^+\pi^+)K^-$
2. $\Xi_c^{**+}(3080) \to (\Sigma_c^{++*}(2520) \to \Lambda_c^+\pi^+)K^-$
3. $\Xi_c^{**+}(3055) \to (\Sigma_c^{++}(2455) \to \Lambda_c^+\pi^+)K^-$
4. $\Xi_c^{**+}(3055) \to (\Sigma_c^{++*}(2520) \to \Lambda_c^+\pi^+)K^-$
5. $\Xi_c^{**+}(2970) \to (\Sigma_c^{++}(2455) \to \Lambda_c^+\pi^+)K^-$

The $\Lambda_c^+ K^-$ mass spectrum

$\Xi_c^0 \to \Lambda_c^+ K^-$
$\hookrightarrow pK^-\pi^+$



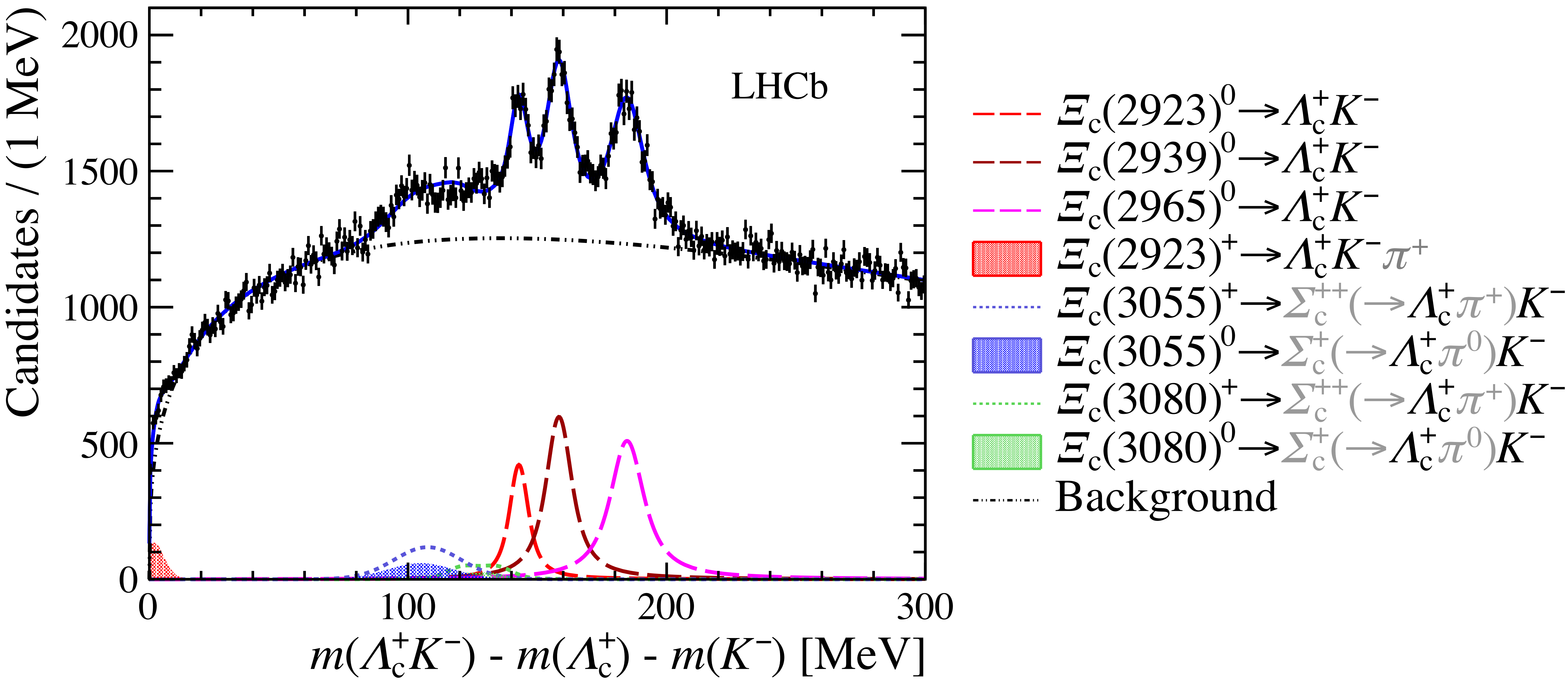
Furthermore, contributions where excited states decay to $\Lambda_c^+ K^- \pi$ are considered

- Both charged and neutral decays are looked at
- The pion is missing in the reconstruction

arXiv:2003.13649

The $\Lambda_c^+ K^-$ mass spectrum

$\Xi_c^0 \to \Lambda_c^+ K^-$
$\hookrightarrow pK^-\pi^+$



arXiv:2003.13649

$\Xi_c^0 \to \Lambda_c^+ K^-$
$\hookrightarrow pK^-\pi^+$

Charmed Ξ_c^0 baryons

Three signal peaks are observed with high significance.

Results:

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

Two structures seen in vicinity of previously observed $\Xi_c(2930)^0$
- limited statistics may have prevented distinction between two separate states previously
- different production mechanisms

The $\Xi_c(2965)^0$ is close to the $\Xi_c(2970)^0$
- $\Xi_c(2965)^0$ is lower in both mass and width
- B-factories have not observed the $\Xi_c(2970)^0$ in its decay to $\Lambda_c^+ K^-$
- More studies required…

arXiv:2003.13649

Charmed Ξ_c^0 baryons

Equal spacing rule

- Gell-Mann-Okubo formula for baryons:

$$m(\Omega_c^{**}) - m(\Xi_c^{**}) = m(\Xi_c^{**}) - m(\Sigma_c^{**})$$

- E.g. for the states in the 3/2+ multiplet:

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

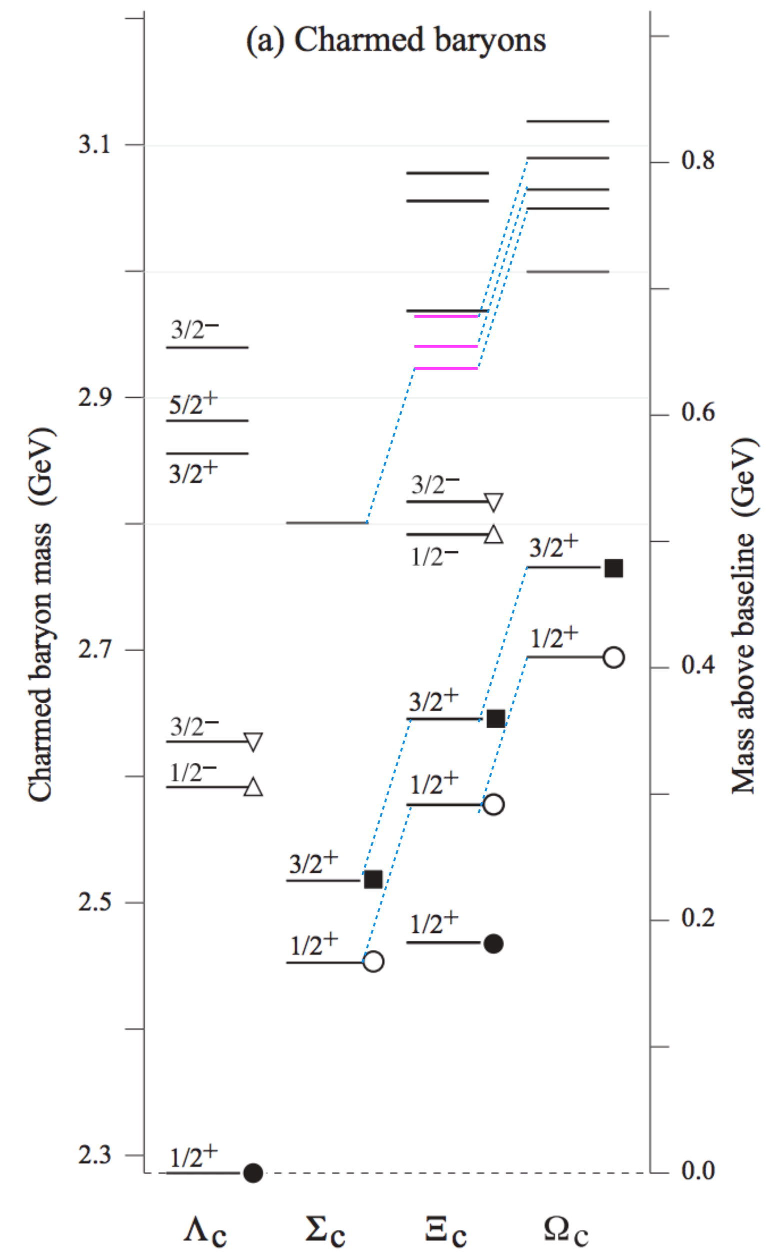
- And...

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

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

$$m\left(\Omega_c(3090)^0\right) - m\left(\Xi_c(2965)^0\right) \simeq 125\text{MeV}$$

adapted from [PDG]



Equal spacing

'New' states

Excerpt taken from arXiv:2004.02374 :

The LHCb Collaboration also pointed out several equalities of mass gaps,

$$m[\Omega_c(3050)^0] - m[\Xi_c(2923)^0] \simeq 125 \text{ MeV}, \quad (7)$$

$$m[\Omega_c(3065)^0] - m[\Xi_c(2939)^0] \simeq 125 \text{ MeV}, \quad (8)$$

$$m[\Omega_c(3090)^0] - m[\Xi_c(2965)^0] \simeq 125 \text{ MeV}, \quad (9)$$

$$m[\Xi_c(2923)^0] - m[\Sigma_c(2800)^0] \simeq 125 \text{ MeV}, \quad (10)$$

which strongly suggests that the $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ and $\Xi_c(2965)^0$ should be the corresponding charmed strange partners of the $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, and $\Omega_c(3090)^0$, respectively. Also, the $\Sigma_c(2800)^0$ may be the non-strange partner

Studies of the $\Lambda_b^0\pi^+\pi^-$ system

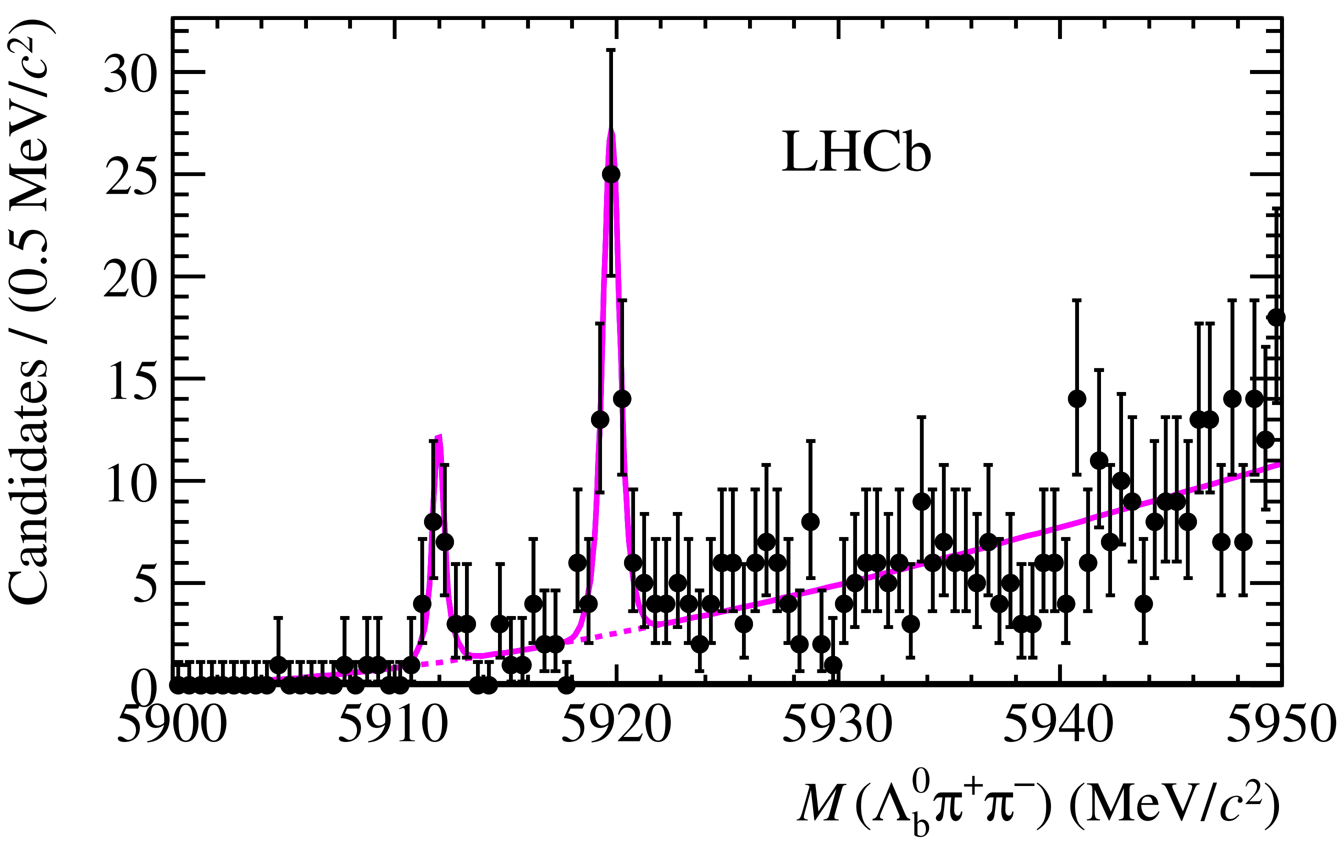
$\Lambda_b^0\pi^+\pi^-$ system

The mass spectrum has been extensively studied at LHCb:

- Initially studied low mass (near threshold) region with 1 fb^{-1}
  $\longrightarrow$ two narrow $\Lambda_b(1P)^0$ resonances
  [PRL 109 (2012) 172003]

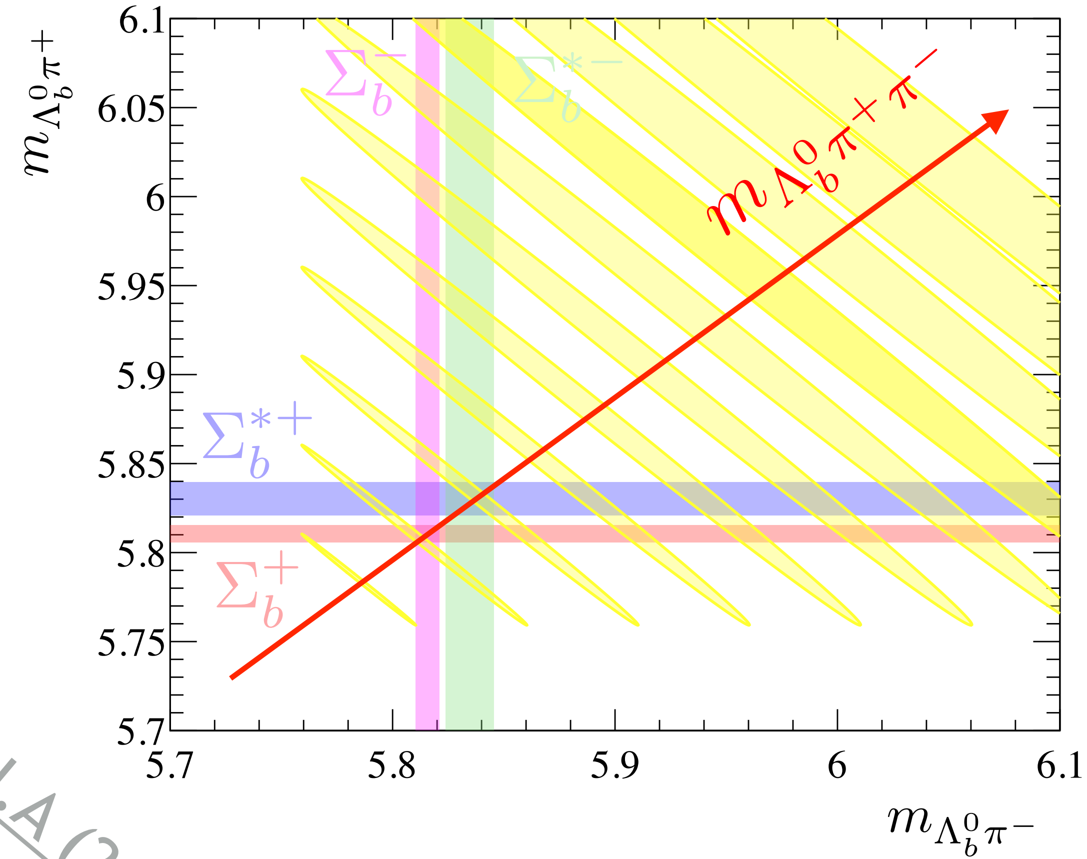
Two new recent updates which I will cover in detail today:

- High mass region with 9 fb^{-1}
  [PRL 123 (2019) 152001]
- Intermediate mass region with 9 fb^{-1}
  [arXiv:2002.05112]



$\Lambda_b^0\pi^+\pi^-$ system

Theoretical predictions of the lightest excited Λ_b^0 states:



Baryon	State	J^P	[PRD 34 (1986) 2809]	[Int.J.Mod.Phys.A23:2817]	[PRD 84 (2011) 014025]	[Eur.Phys.J.A (2015) 51:82]
Λ_b^0	1S	$\frac{1}{2}^+$	5585	5612	5620	5619
	1P	$\frac{1}{2}^-$	5912	5939	5930	5911
		$\frac{3}{2}^-$	5920	5941	5942	5920
	2S	$\frac{1}{2}^+$	6045	6107	6089	
	1D	$\frac{3}{2}^+$	6145	6181	6190	6147
		$\frac{5}{2}^+$	6165	6183	6196	6153

$\Lambda_b^0\pi^+\pi^-$ mass region

low mass

intermediate mass

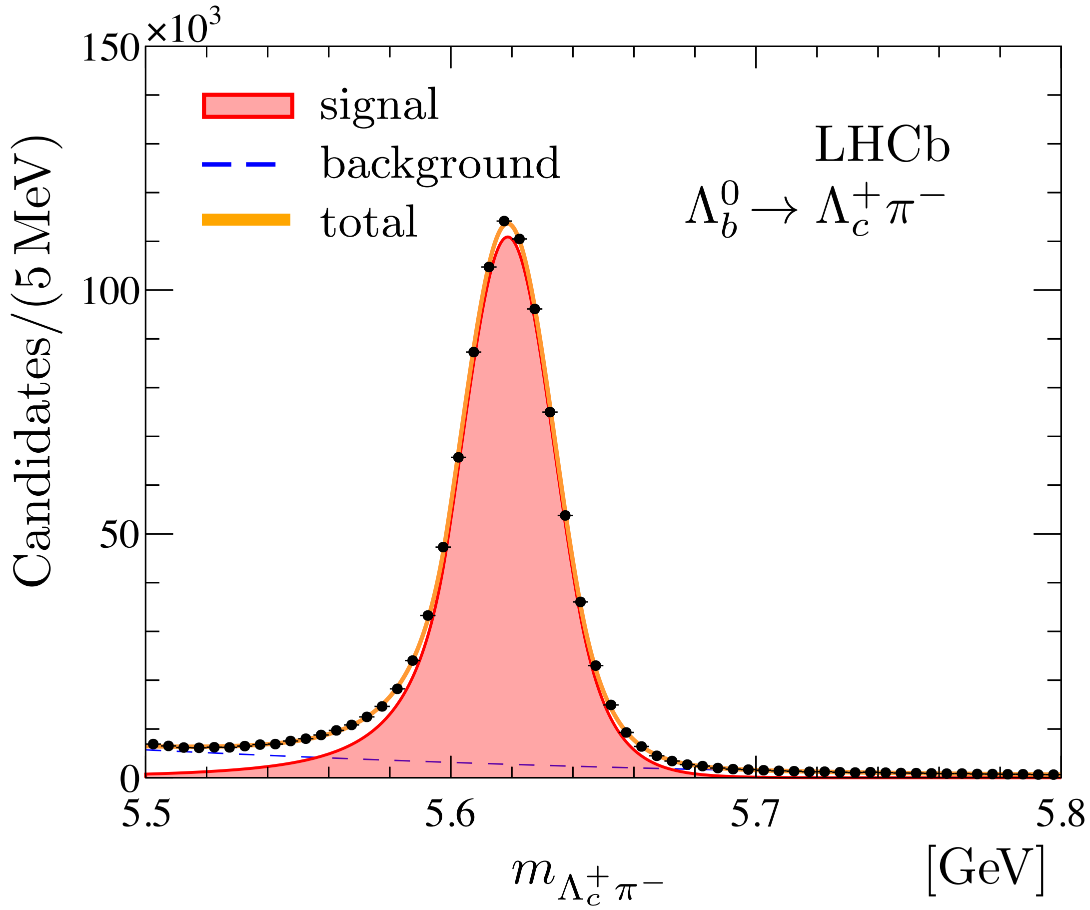
high mass

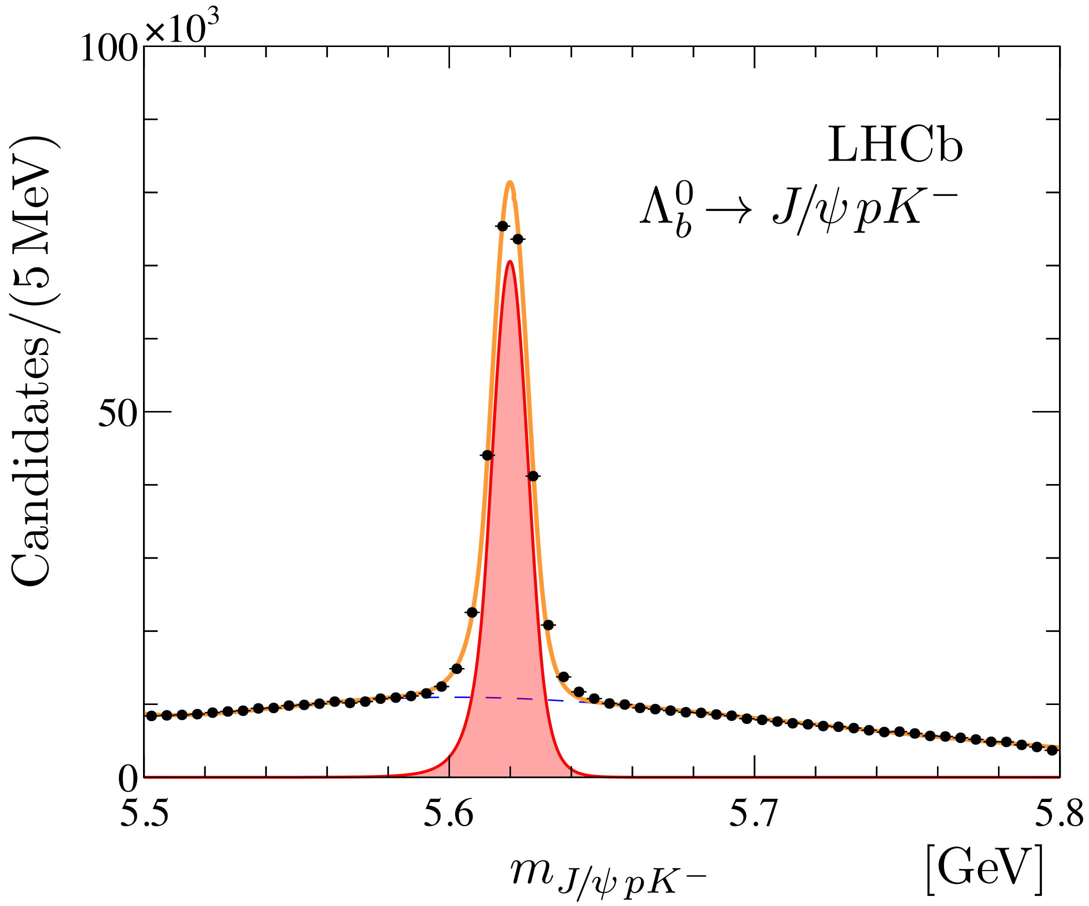
Excited Λ_b^0 baryons

arXiv:2002.05112
PRL 123 (2019) 152001

Two recent studies follow very similar analysis strategies and selection requirements:

- Select $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ & $\Lambda_b^0 \to J/\psi p K^-$ samples using BDTs.



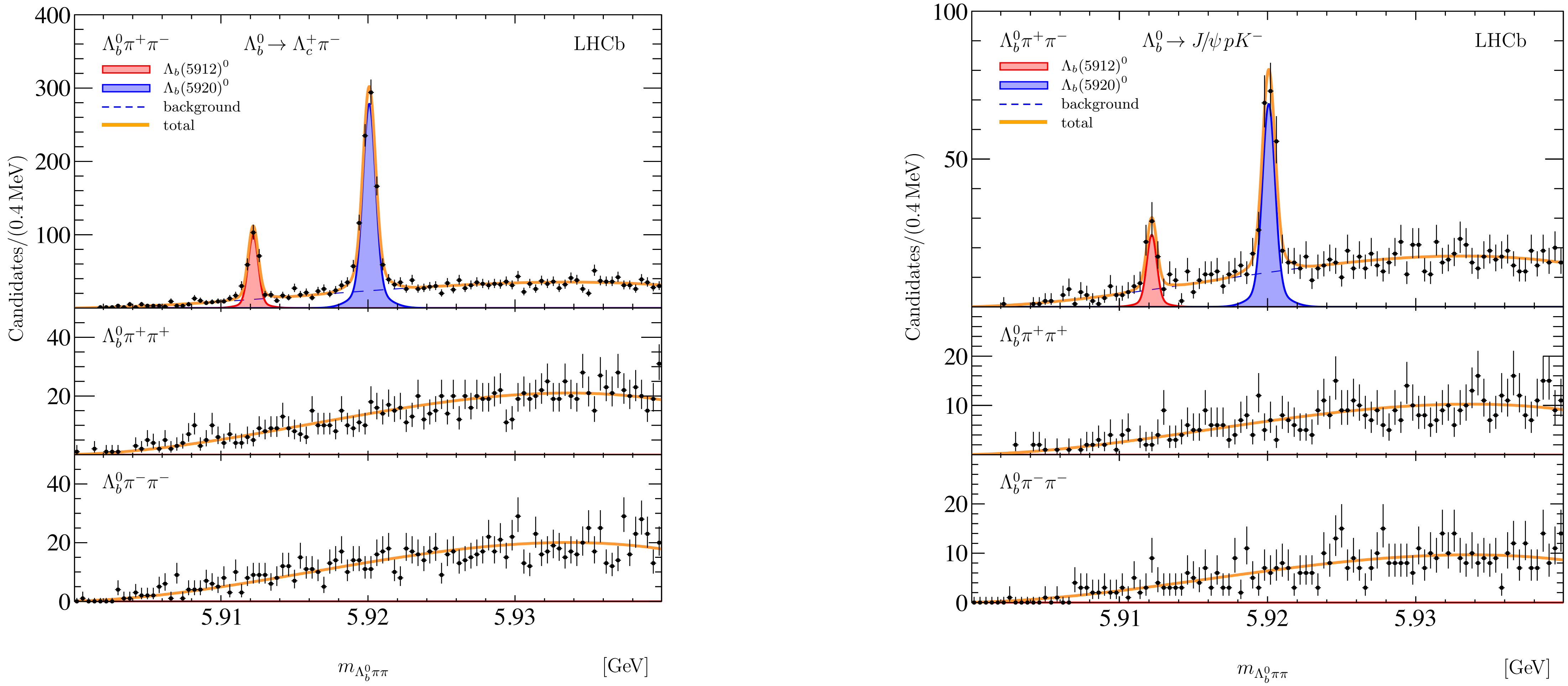


- Add two prompt pions.

arXiv:2002.05112

Excited Λ_b^0 baryons - intermediate mass

Also: more precise measurement of low mass states using both $\Lambda_b^0 \to \Lambda_c^+\pi^-$ & $\Lambda_b^0 \to J/\psi p K^-$

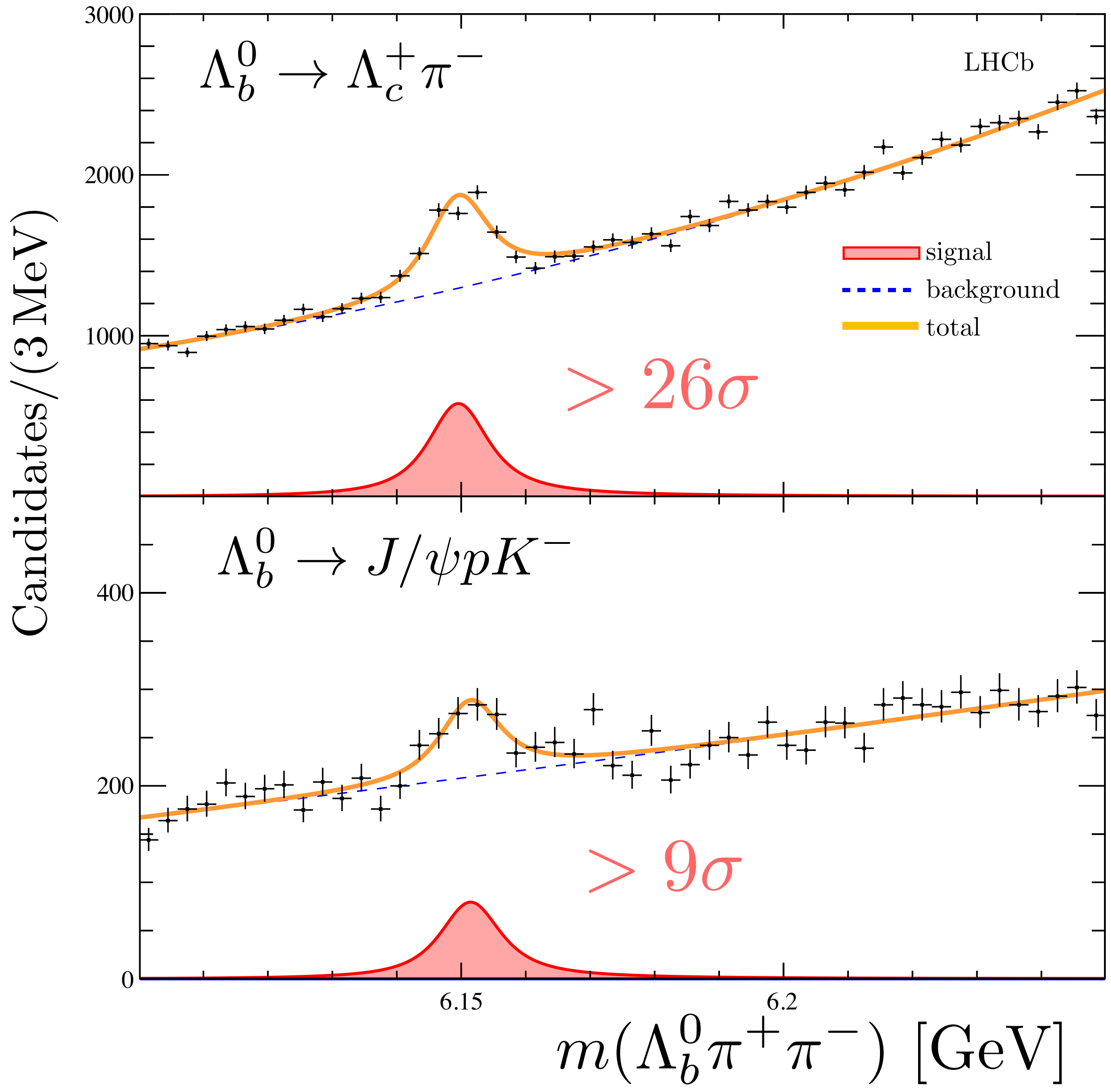


$$m(\Lambda_b(5912)^0) = 5912.21 \pm 0.03 \pm 0.01 \pm 0.21 \text{ MeV} \qquad \Gamma(\Lambda_b(5912)^0) < 0.28 \text{ MeV}$$

$$m(\Lambda_b(5920)^0) = 5920.11 \pm 0.02 \pm 0.01 \pm 0.21 \text{ MeV} \qquad \Gamma(\Lambda_b(5920)^0) < 0.20 \text{ MeV}$$

Excited Λ_b^0 baryons - high mass

PRL 123 (2019) 152001



- Mass region:
  $6.1 \text{ GeV} < \Lambda_b^0 \pi^+ \pi^- < 6.25 \text{ GeV}$
- New structure observed around 6.15 GeV in $m(\Lambda_b^0 \pi^+ \pi^-)$.
- Structure is above $\Sigma_b^{(*)\mp} \pi^\pm$ threshold.
- More statistics in sample where Λ_b^0 is reconstructed in $\Lambda_c^+ \pi^-$ final state.

Excited Λ_b^0 baryons - high mass

PRL 123 (2019) 152001

Split data in three regions in $m(\Lambda_b^0\pi^{\mp})$:

- $\Sigma_b^{\pm}\pi^{\mp}$
- $\Sigma_b^{*\pm}\pi^{\mp}$
- Non-resonant

Perform simultaneous fit in the three regions.

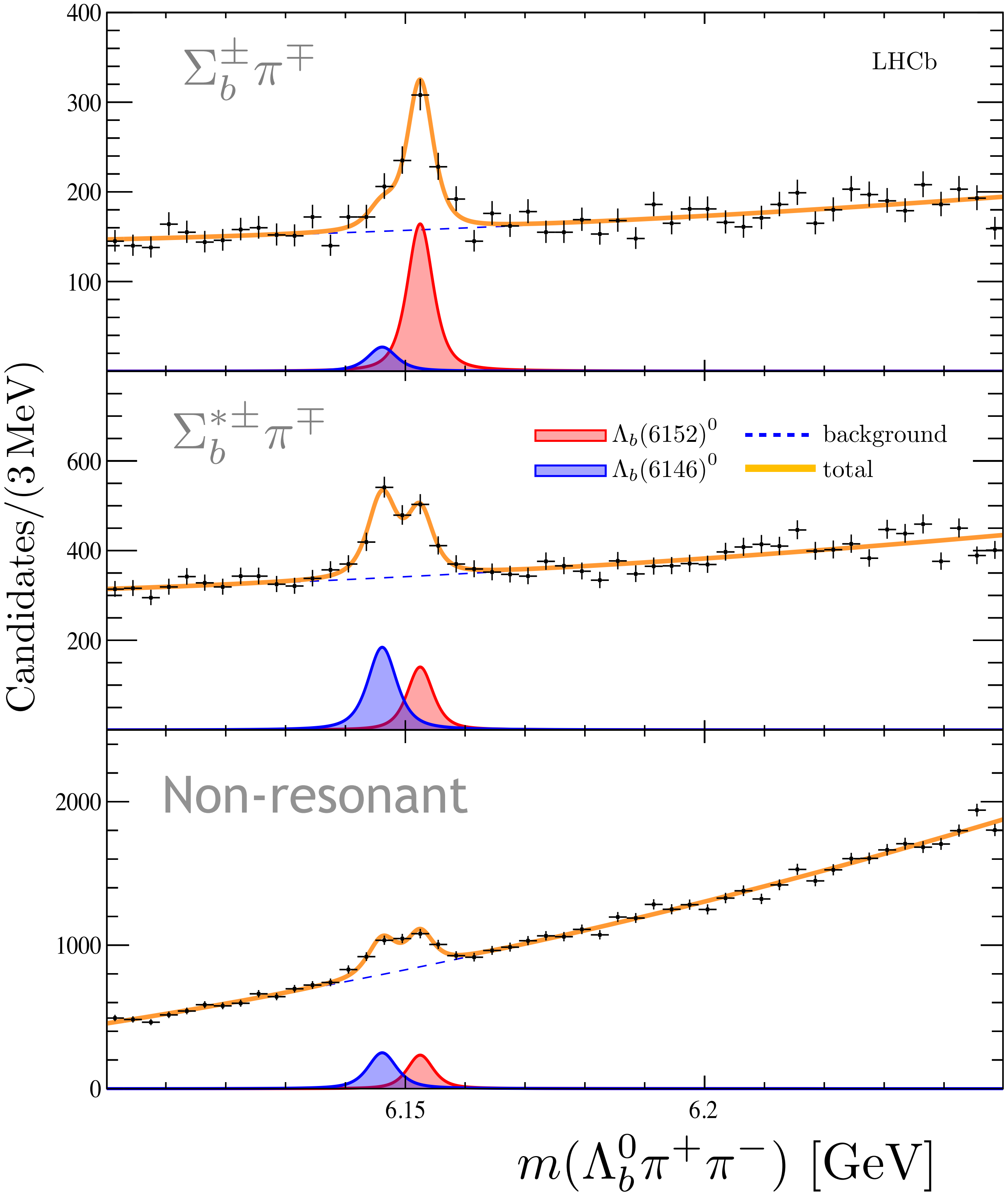
Two peak hypothesis favoured at 7σ significance.

$m(\Lambda_b(6146)^0) = 6146.16 \pm 0.33 \pm 0.22 \pm 0.16$ MeV

$m(\Lambda_b(6152)^0) = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16$ MeV

$\Gamma(\Lambda_b(6146)^0) = 2.9 \pm 1.3 \pm 0.3$ MeV

$\Gamma(\Lambda_b(6152)^0) = 2.1 \pm 0.8 \pm 0.3$ MeV



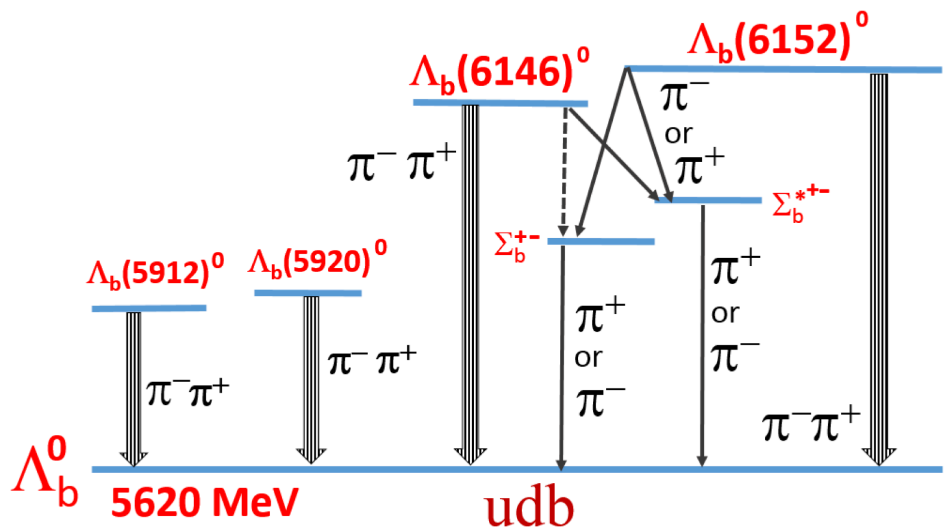
Excited Λ_b^0 baryons - high mass

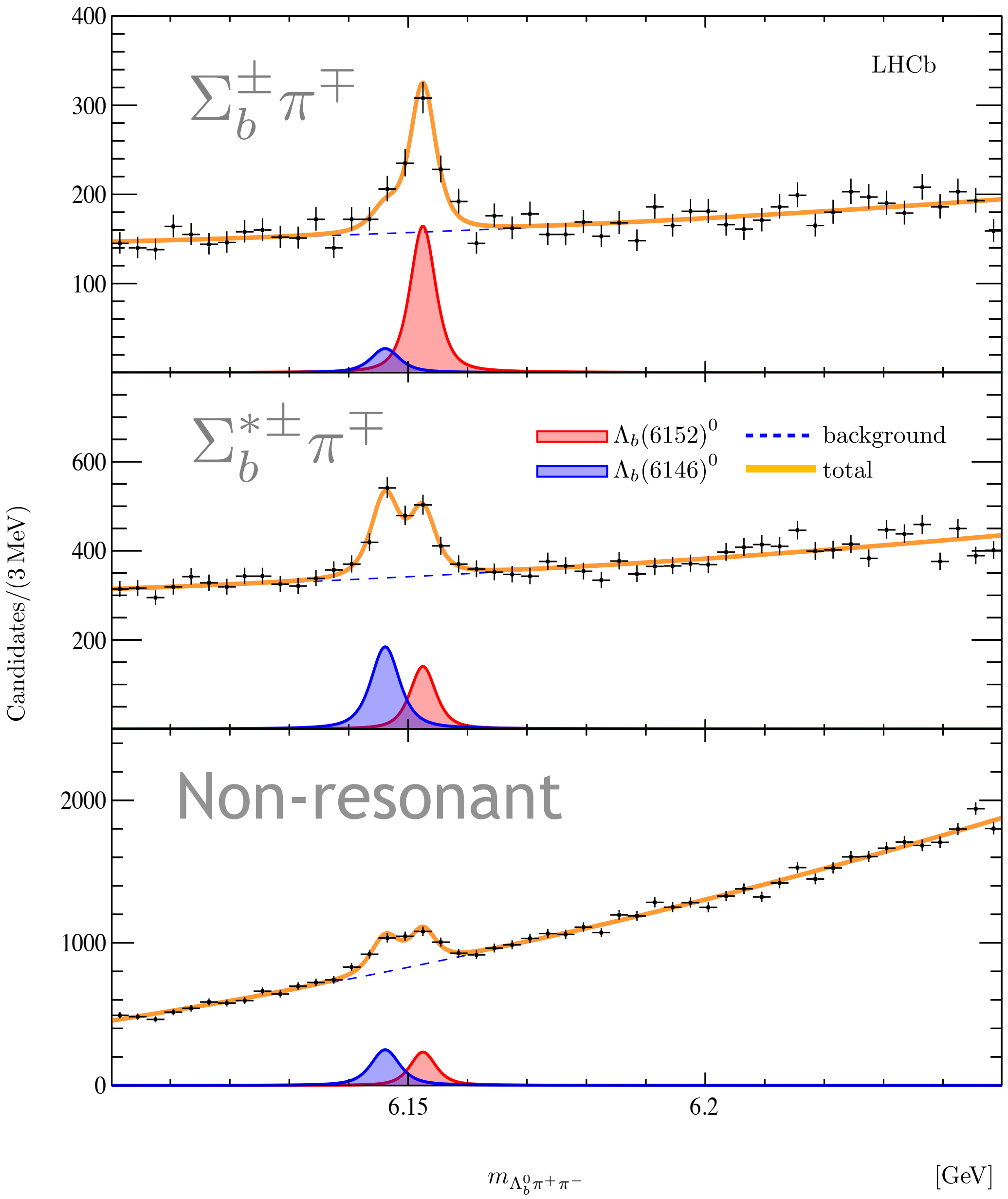
PRL 123 (2019) 152001

Possible interpretation of the newly observed Λ_b^{*0} states :

$\Lambda_b(6152)^0$ couples to $\Sigma_b^{\pm}$ & $\Sigma_b^{*\pm}$.
$\Lambda_b(6146)^0$ couples primarily to $\Sigma_b^{*\pm}$.

Consistent with a $\Lambda_b(1D)^0$ doublet with $J^P = 3/2^+$ and $5/2^+$. [arXiv:1910.03318] [PRD 100 (2019) 054013]



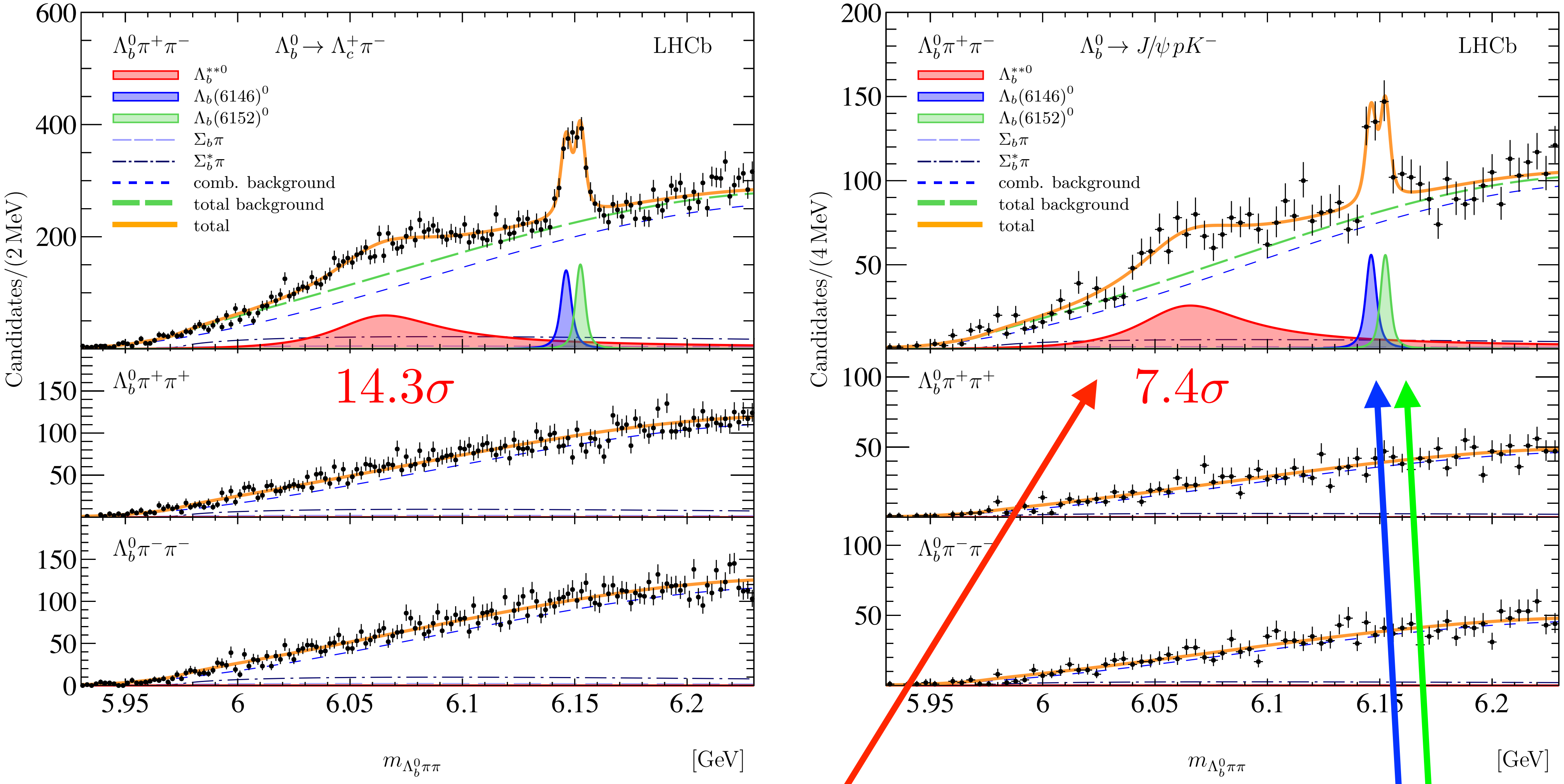


Other interpretations such as excited Σ_b possible but less likely.

arXiv:2002.05112

Excited Λ_b^0 baryons - intermediate mass

- Simultaneous binned fit in six distributions, where background parameters are shared *(200 keV bins)*

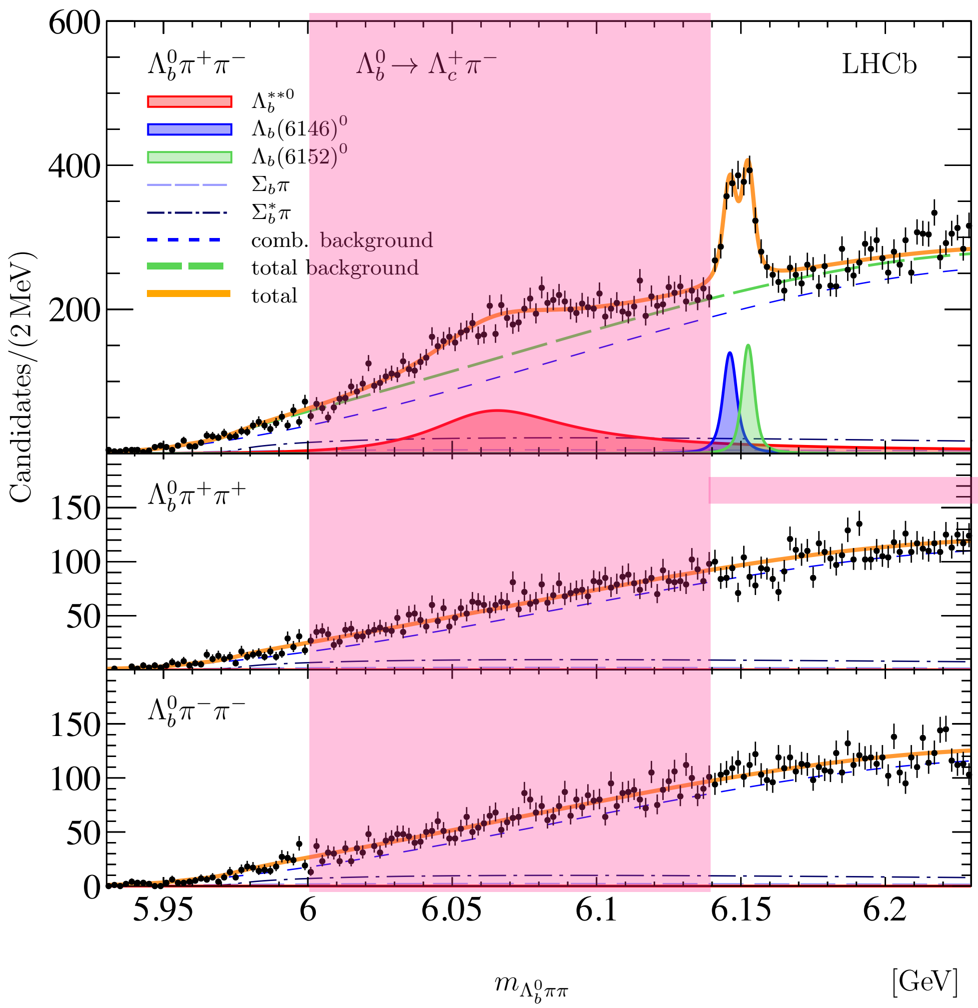


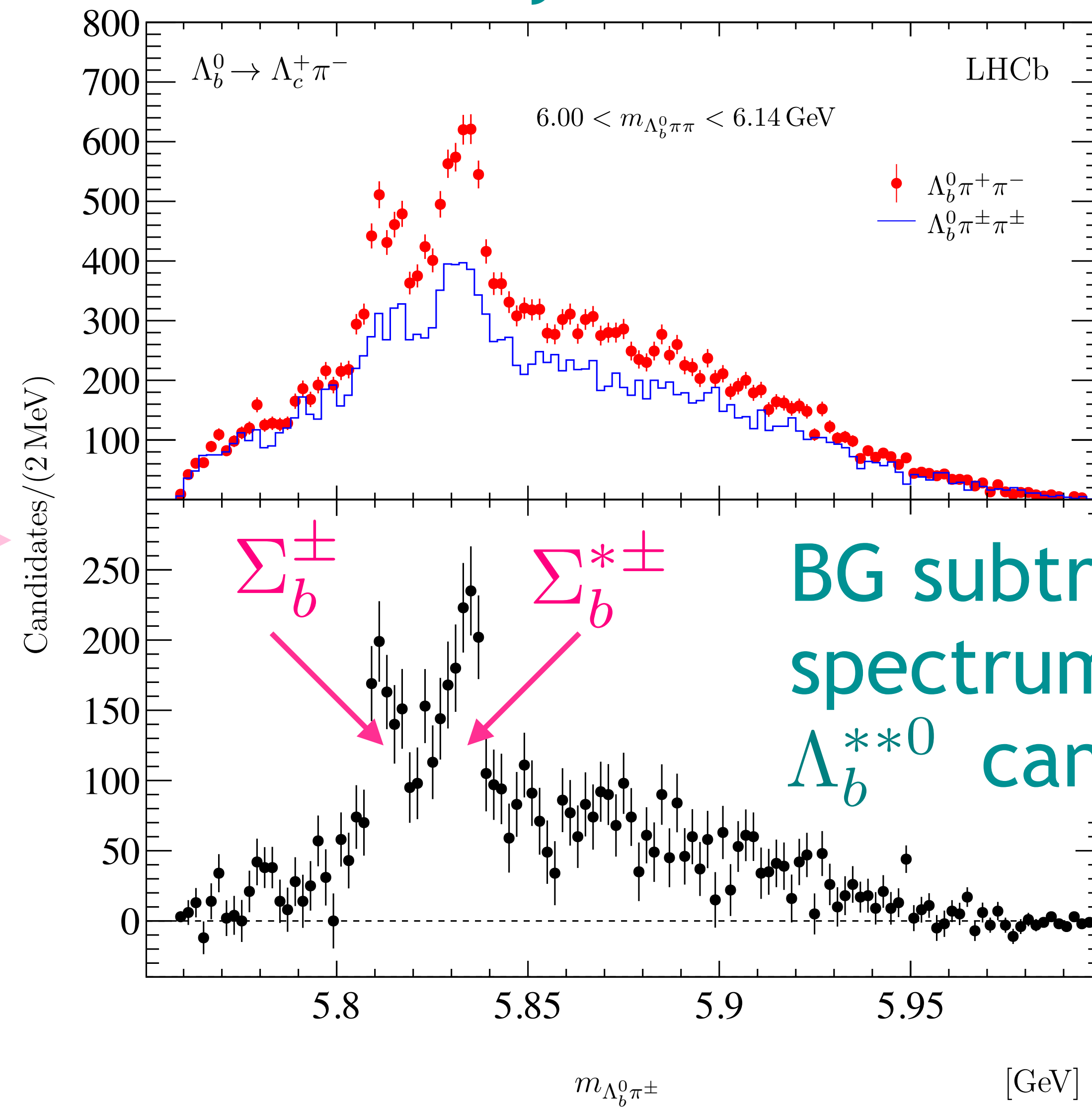
Excited Λ_b^0 baryons - intermediate mass

arXiv:2002.05112

- Cannot use trick from PRL 123 (2019) 152001 to split data in three regions, as kinematic regions overlap in the region of the Λ_b^{**0} .
- Select signal region and use WS samples as background proxy.

⟶ Largest fraction from non-resonant decays





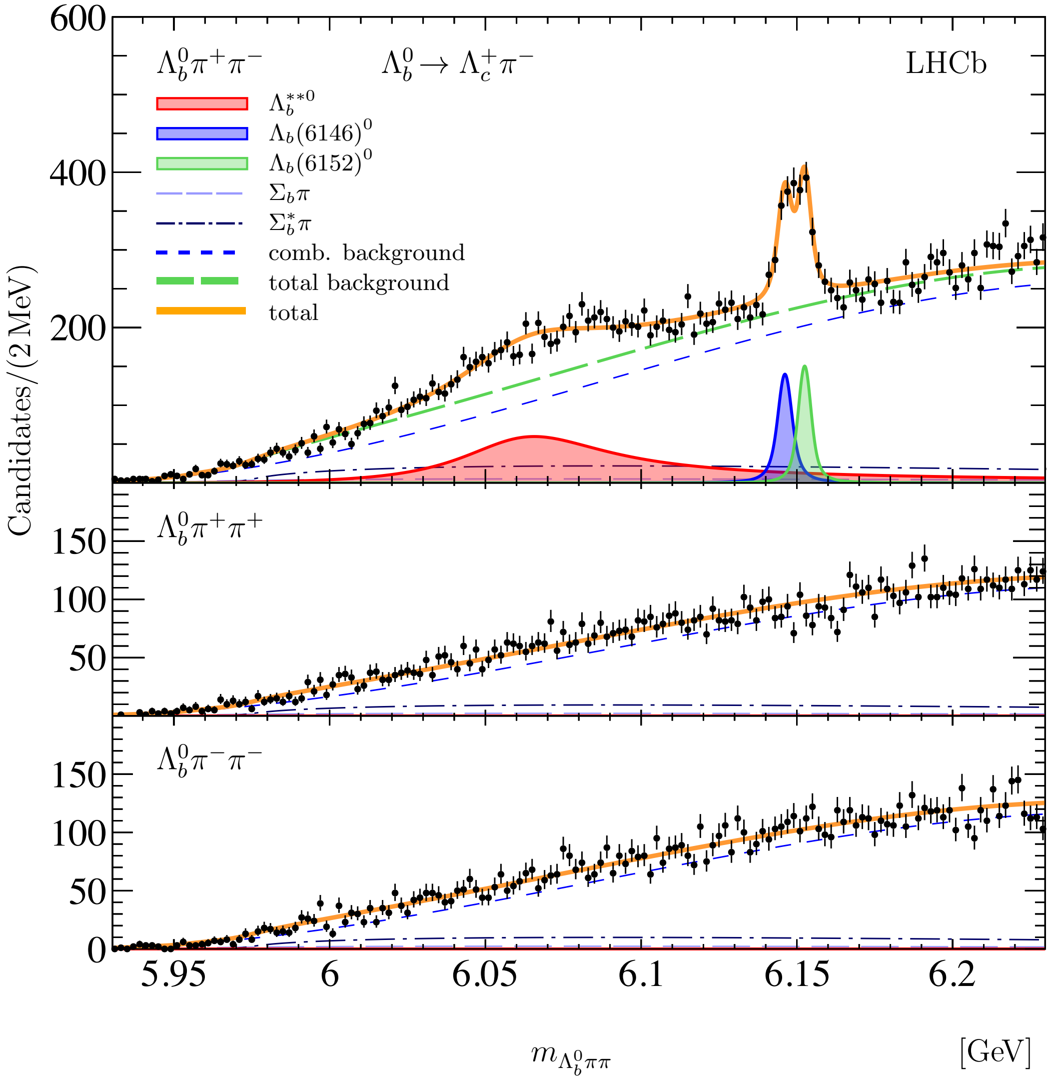
BG subtracted spectrum of the Λ_b^{**0} candidates

Excited Λ_b^0 baryons -results

arXiv:2002.05112

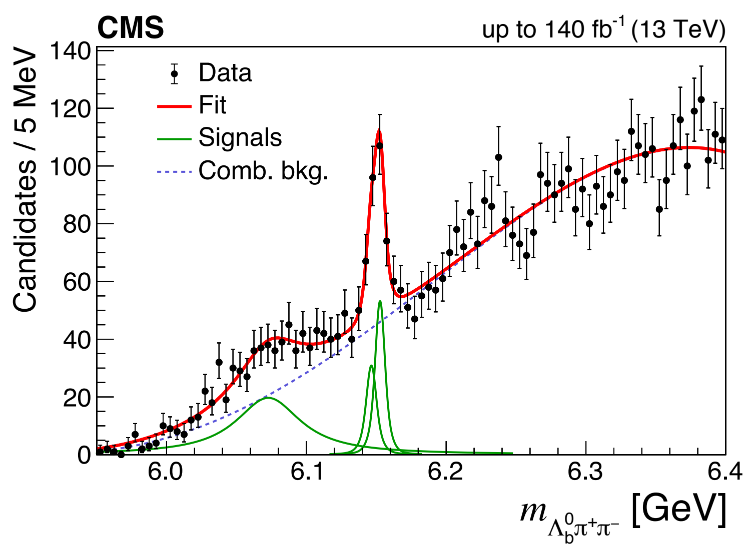
Λ_b^{**0} state consistent with recent CMS search [Phys.Let.B 803 (2020) 135345]

LHCb result



$$m(\Lambda_b^{**0}) = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 \text{ MeV}$$
$$\Gamma(\Lambda_b^{**0}) = 72 \pm 11 \pm 2 \text{ MeV}$$

CMS result



- 4σ significance
- $m(\Lambda_b^{**0}) = 6073 \pm 5$ MeV
- $\Gamma(\Lambda_b^{**0}) = 55 \pm 11$ MeV

Excited Λ_b^0 baryons -results

arXiv:2002.05112
PRL 123 (2019) 152001

Five excited Λ_b^0 have now been found!

State		Mass [MeV]	Width [MeV]
$\Lambda_b(5912)^0$	(1P)	5912.21$\pm$0.03$\pm$0.01$\pm$0.21	< 0.28
$\Lambda_b(5920)^0$	(1P)	5920.11$\pm$0.02$\pm$0.01$\pm$0.21	< 0.20
Λ_b^{**0}	(2S)	6072.3$\pm$2.9$\pm$0.6$\pm$0.2	72$\pm$11$\pm$2
$\Lambda_b(6146)^0$	(1D)	6146.16$\pm$0.33$\pm$0.22$\pm$0.16	2.9$\pm$1.3$\pm$0.3
$\Lambda_b(6152)^0$	(1D)	6152.51$\pm$0.26$\pm$0.22$\pm$0.16	2.1$\pm$0.8$\pm$0.3

Interpretation:
- $\Lambda_b(2S)^0$ state
- could be a superposition of several narrow states
- excited Σ_b interpretation disfavoured

Conclusion

Many interesting experimental baryon spectroscopy measurements from LHCb at the moment.

Unique experimental possibilities at LHCb, e.g. *heavy b-hadrons*.

Many more interesting avenues to explore than what has been shown today, e.g. doubly heavy baryons and strange baryons.

Much more to come out of the full Run 1 + Run 2 dataset…

(spin & parity measurements of new states
search for other decay modes
branching ratio measurements)

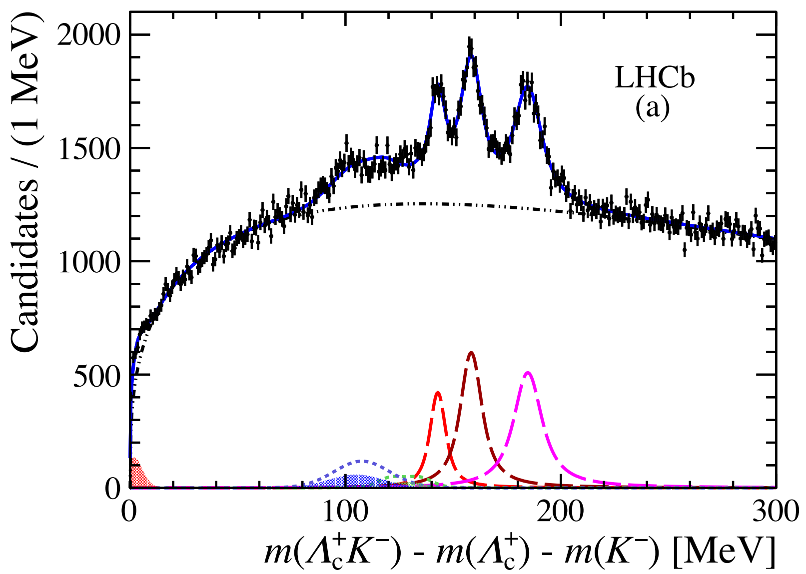
… and more data to be taken after the Upgrade!

Stay tuned!

BACKUP

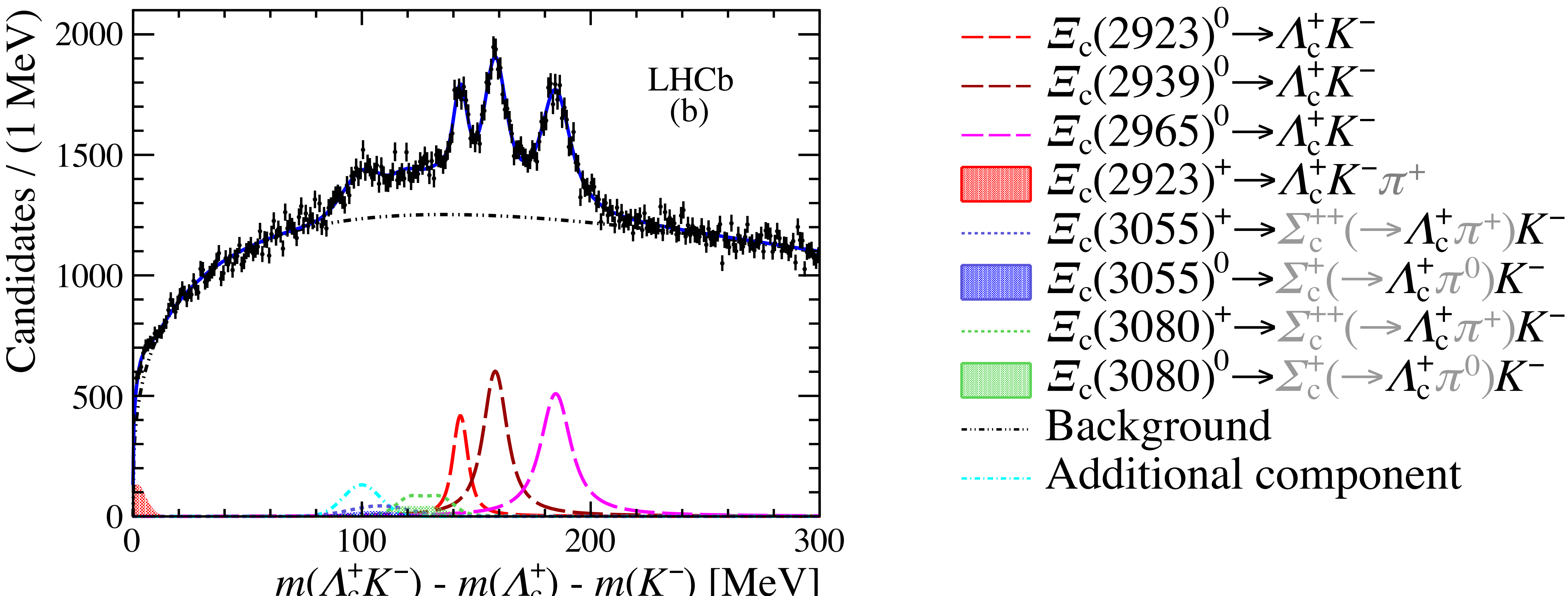
The $\Lambda_c^+ K^-$ mass spectrum

arXiv:2003.13649



Could be due to:

- statistical fluctuation
- mis-modelling of feed-down decays
- partially reconstructed new baryon
- another new baryons
- combination of the above…



3-body Breit-Wigner

arXiv:2002.05112

$$\mathfrak{S}(m|m_0,\Gamma) \propto \frac{\Gamma \rho_3(m)}{(m_0^2 - m^2)^2 + m_0^2\Gamma^2 \left(\frac{\rho_3(m)}{\rho_3(m_0)}\right)^2},$$

Kaellen function

$$\rho_3(m) \equiv \frac{\pi^2}{4m^2} \int_{4m_\pi^2}^{(m-m_{\Lambda_b^0})^2} \frac{dm_{\pi\pi}^2}{m_{\pi\pi}^2} \lambda^{1/2}\left(m_{\pi\pi}^2, m^2, m_{\Lambda_b^0}^2\right) \lambda^{1/2}\left(m_{\pi\pi}^2, m_\pi^2, m_\pi^2\right),$$

3-body phase space

- Normal Breit-Wigner lead to very large systematic due to choice of $m_{\pi\pi}$
- 3-body Breit-Wigner well-motivated for broad non-resonant decays, such as $\Lambda_b(2S)^0 \to \Lambda_b^0 f_0(500)$

The $\Lambda_c^+ K^-$ systematic errors

arXiv:2003.13649

Source	$\Xi_c(2923)^0$		$\Xi_c(2939)^0$		$\Xi_c(2965)^0$	
	m [MeV]	Γ [MeV]	m [MeV]	Γ [MeV]	m [MeV]	Γ [MeV]
Alternative fit model	0.15	1.6	0.14	0.4	0.04	1.1
Resonance interferences	0.08	0.7	0.06	1.0	0.11	0.7
Momentum-scale	0.04	–	0.05	–	0.06	–
Energy losses	0.04	–	0.04	–	0.04	–
Resolution calibration	–	0.6	–	0.2	–	0.3
Total	0.20	1.8	0.17	1.1	0.14	1.3

Beautiful Ω_b^- baryons systematic errors

PRL 124 (2020) 082002

Source	Peak 1 [MeV]	Peak 2 [MeV]	Peak 3 [MeV]	Peak 4 [MeV]
Momentum scale	0.01	0.02	0.02	0.03
Energy loss	0.04	0.04	0.04	0.04
Signal shape	0.02	0.02	0.02	0.02
Background	0.05	0.05	0.01	0.01
Total	0.07	0.07	0.05	0.05

Excited Λ_b^0 baryons systematic errors

high mass PRL 123 (2019) 152001

Source	$\Lambda_b(6146)^0$		$\Lambda_b(6152)^0$	
	m	Γ	m	Γ
Momentum scale	80	—	80	—
Signal model	50	50	50	50
Resolution model	15	270	< 10	310
Background model	30	30	30	20
Total	100	280	100	320
Including Λ_b^0 mass systematic	220	280	220	320

Excited Λ_b^0 baryons systematic errors

intermediate & low mass arXiv:2002.05112

Source	$\Delta m_{\Lambda_b^{**0}}$ [MeV]	$\Gamma_{\Lambda_b^{**0}}$ [MeV]	$\Delta m_{\Lambda_b(}$ [Me
Fit model			
Signal parameterisation	0.50	1.50	
Background parameterisation	0.03	0.25	
Fit range	0.10	0.30	
$\Lambda_b(1D)^0$ parameters			
Momentum scale uncertainty	0.08	–	0.01
Sum in quadrature	0.52	1.55	0.01

Comparison

- $\Xi_c(2970)^0$ has been seen before, but not in this decay mode.

Collaboration	Decay Mode	Mass [MeV]	Width [MeV]	Significance
Belle	$\Lambda_c^+\pi^-K_S^0$	$2977.1 \pm 8.8 \pm 3.5$	-	1.5σ
Babar	$\Lambda_c^+\pi^-K_S^0$	$2972.9 \pm 4.4 \pm 1.6$	$31 \pm 7 \pm 8$	1.7σ
Belle	$\Xi_c(2645)^+\pi^-$	$2965.7 \pm 2.4^{+1.1}_{-1.2}$	$15 \pm 6 \pm 3$	6.1σ
Belle	$\Xi_c(2645)^+\pi^-$ $\Xi_c'\pi^-$	$2970.8 \pm 0.7 \pm 0.2^{+0.3}_{-0.4}$	$30.3 \pm 2.3^{+1.0}_{-1.8}$	$> 5\sigma$
PDG			$28.1^{+3.4}_{-4.0}$	

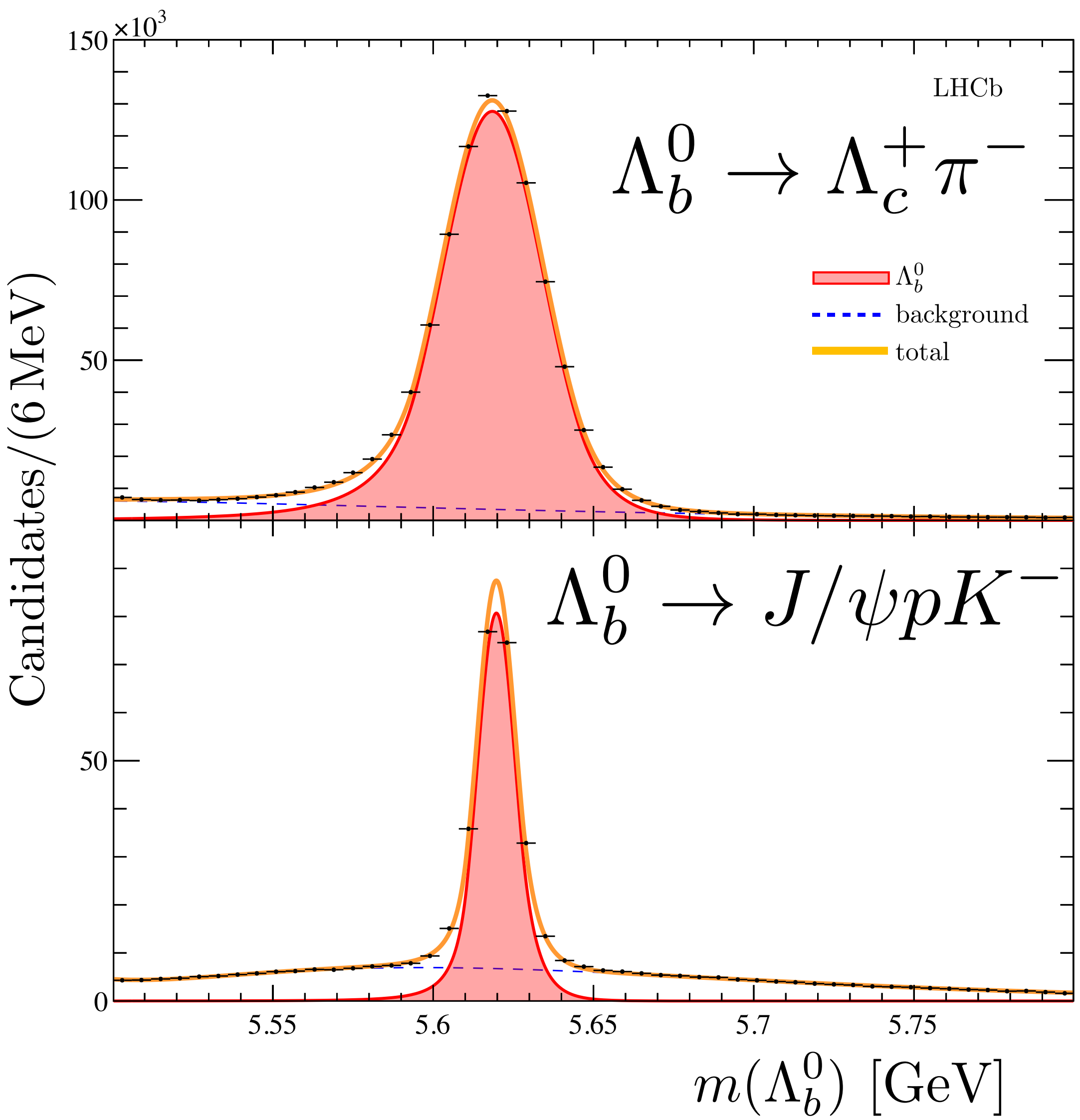
- How come the width and mass measured in this analysis are smaller than previous measurements?
  Our measurement:

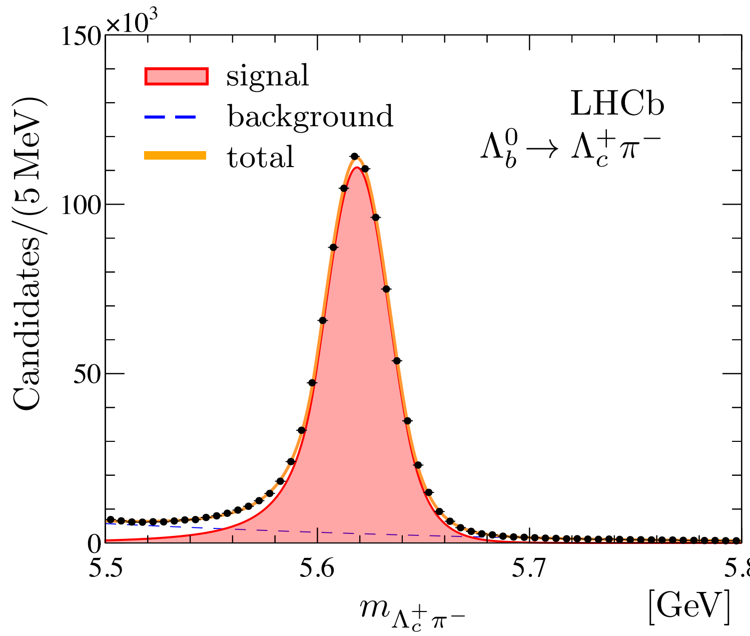
$$m\left(\Xi_c(2965)^0\right) = 2964.88 \pm 0.26(\text{ stat }) \pm 0.14(\text{ syst }) \pm 0.14(\text{ PDG }) \text{ MeV}$$
$$\Gamma\left(\Xi_c(2965)^0\right) = 14.07 \pm 0.91(\text{ stat }) \pm 1.34(\text{ syst}) \text{ MeV},$$

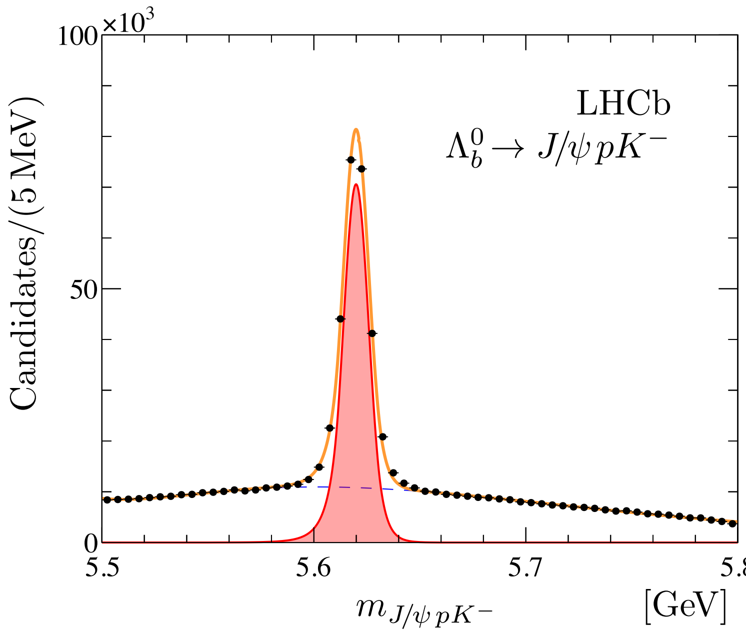
Excited Λ_b^0 baryons

Two recent studies follow very similar analysis strategies and selection requirements:

- Select $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ & $\Lambda_b^0 \to J/\psi p K^-$ samples using BDTs.
- Add two prompt pions.

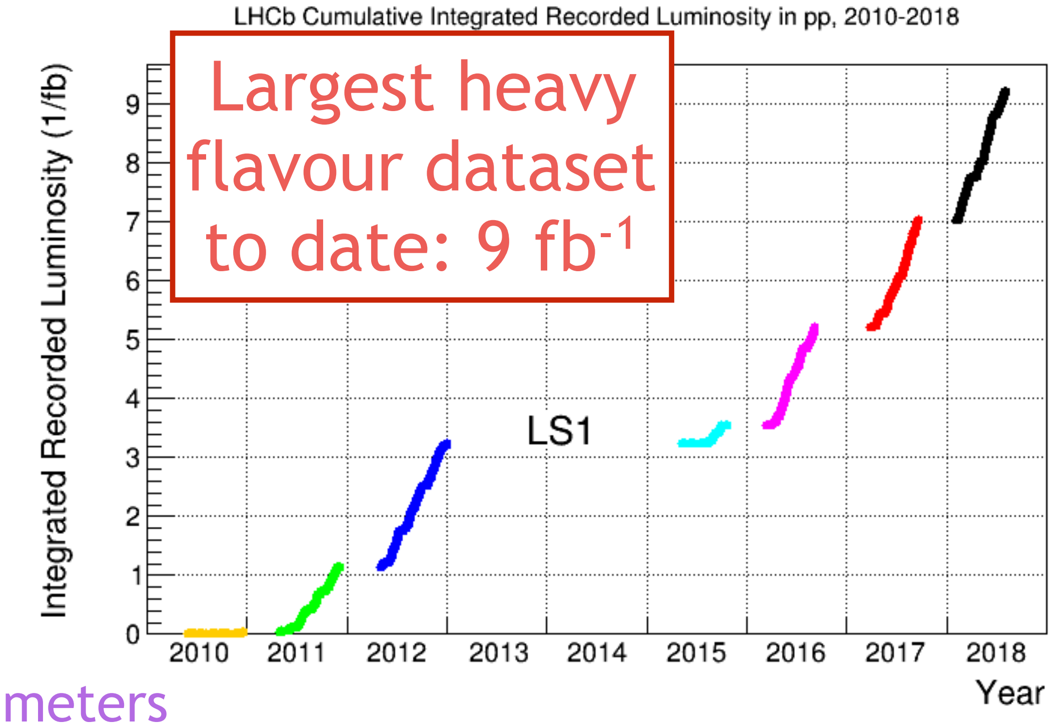


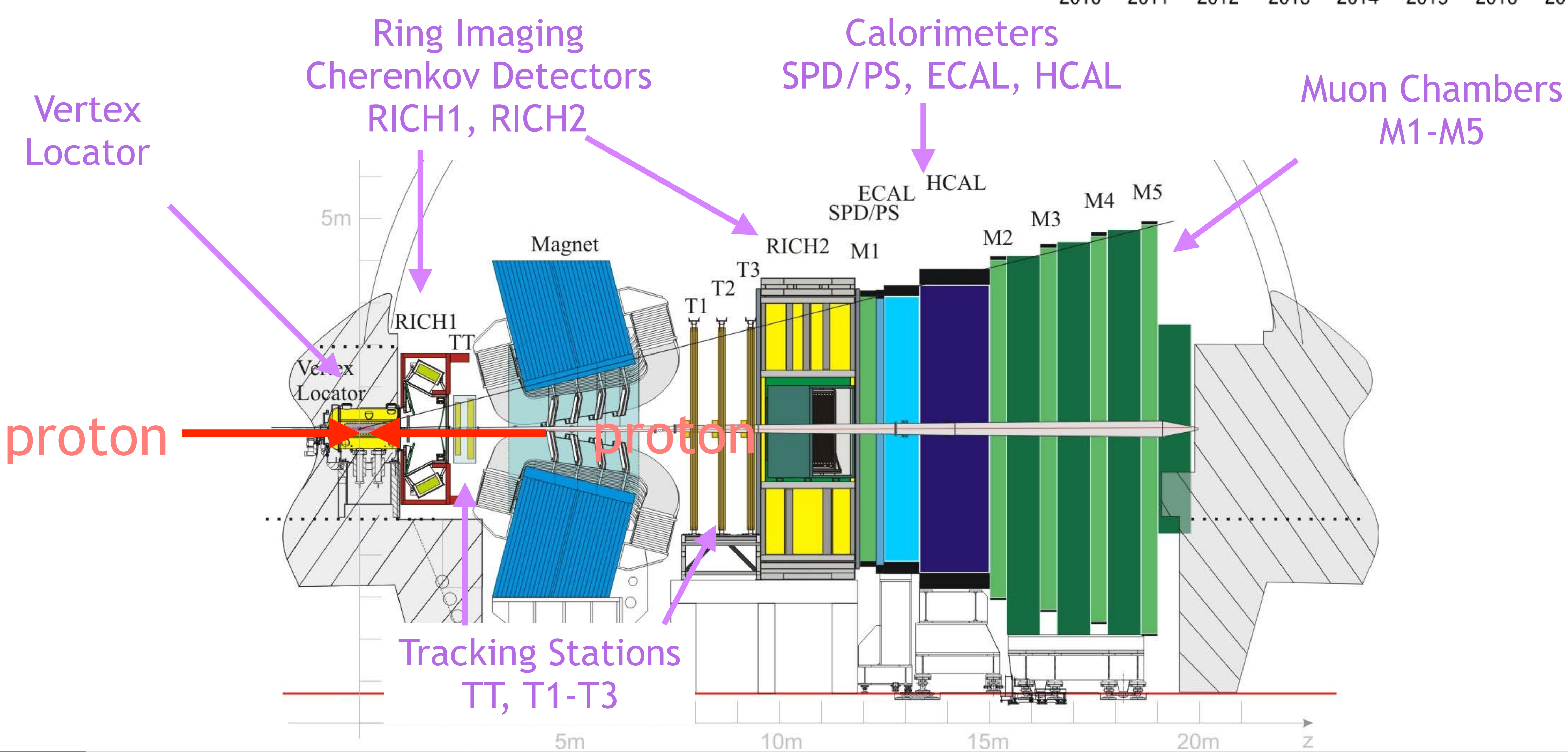




The LHCb detector

- Forward spectrometer
- Precision tracking
- Excellent particle identification
- High trigger efficiency





Future prospects

[arXiv:1808.08865]

Summary of expected signal yields in several important spectroscopy modes at LHCb:

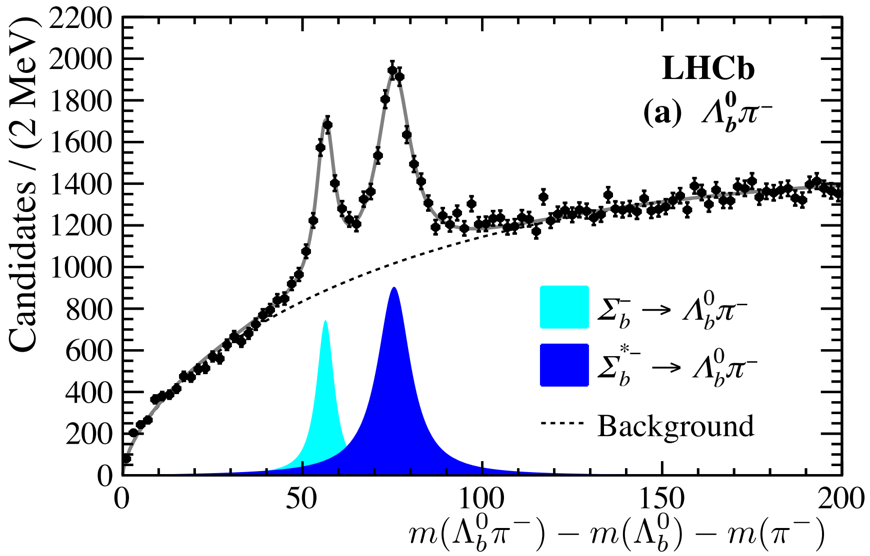
Decay mode	LHCb 23 fb^{-1}	50 fb^{-1}	300 fb^{-1}	Belle II 50 ab^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi pK^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	< 6k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600	—

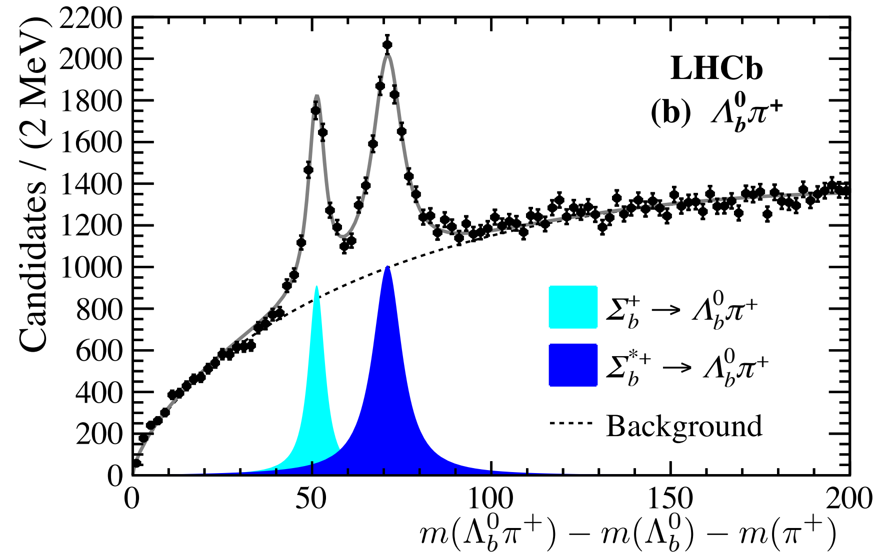
Expected yields competitive with Belle II projections!

Study of $\Sigma_b^{(*)\pm}$ states

Two ground state I=1 triplets expected: $J^P = 1/2^+$ (Σ_b)
$J^P = 3/2^+$ (Σ_b^*)

Precise measurement of the $\Sigma_b^{(*)\pm}$ states (discovered by CDF [PRL 99 (2007) 202001])
LHCb measurement near $\Lambda_b^0\pi^\pm$ threshold [PRL 122 (2019) 012001]
Mass and width measurement 5 times more precise compared to CDF result ($3fb^{-1}$)

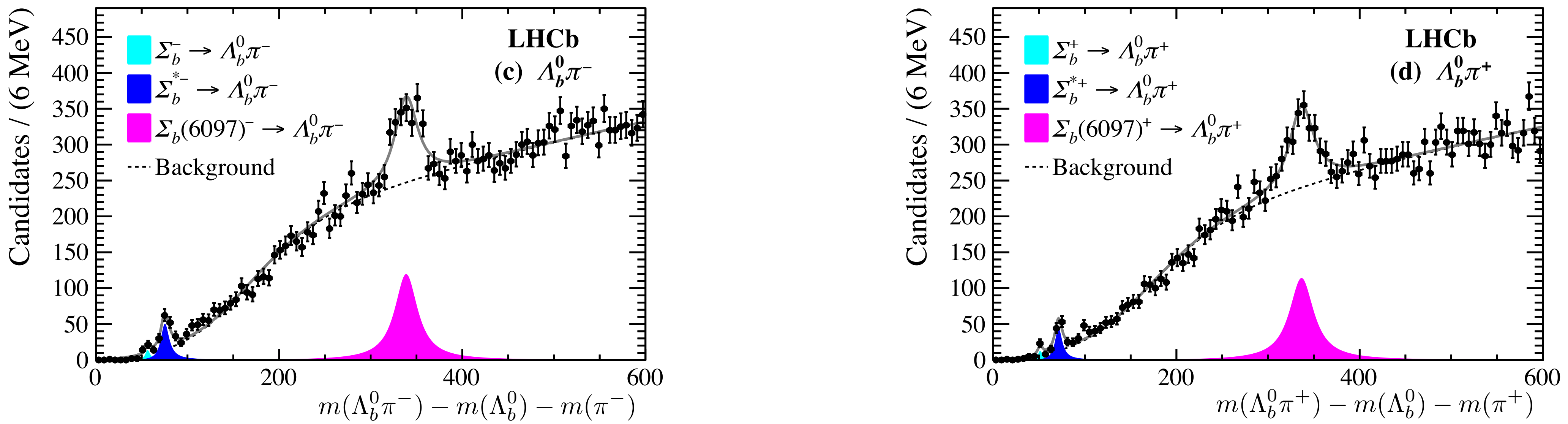




$$m(\Sigma_b^-) = 5815.64 \pm 0.14 \pm 0.24 \text{ MeV} , \; \Gamma(\Sigma_b^-) = 5.33 \pm 0.42 \pm 0.37 \text{ MeV}$$
$$m(\Sigma_b^{*-}) = 5834.73 \pm 0.17 \pm 0.25 \text{ MeV} , \; \Gamma(\Sigma_b^{*-}) = 10.64 \pm 0.60 \pm 0.33 \text{ MeV}$$
$$m(\Sigma_b^+) = 5810.55 \pm 0.11 \pm 0.23 \text{ MeV} , \; \Gamma(\Sigma_b^+) = 4.83 \pm 0.31 \pm 0.37 \text{ MeV}$$
$$m(\Sigma_b^{*+}) = 5830.28 \pm 0.14 \pm 0.24 \text{ MeV} , \; \Gamma(\Sigma_b^{*+}) = 9.34 \pm 0.47 \pm 0.26 \text{ MeV}$$

Study of $\Sigma_b^{(*)\pm}$ states

Expanding the $m(\Lambda_b^0\pi^\pm)$ region: observation of new states, $\Sigma_b(6097)^\pm$



$$m(\Sigma_b(6097)^-) = 6098.0 \pm 1.7 \pm 0.5 \text{ MeV} \;,\; \Gamma(\Sigma_b(6097)^-) = 28.9 \pm 4.2 \pm 0.9 \text{ MeV}$$
$$m(\Sigma_b(6097)^+) = 6095.8 \pm 1.7 \pm 0.4 \text{ MeV} \;,\; \Gamma(\Sigma_b(6097)^+) = 31.0 \pm 5.5 \pm 0.7 \text{ MeV}$$

Heavy quark limit predicts five $\Sigma_b(1P)$ states, several in mass region around 6100 MeV.
$\Sigma_b(6097)^\pm$ could be one of these states, or a superposition.
Other interpretations, such as molecular states may also be possible.