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Hadron Physics in LHCb

https://indico.mitp.uni-mainz.de/event/191/contributions/3200/

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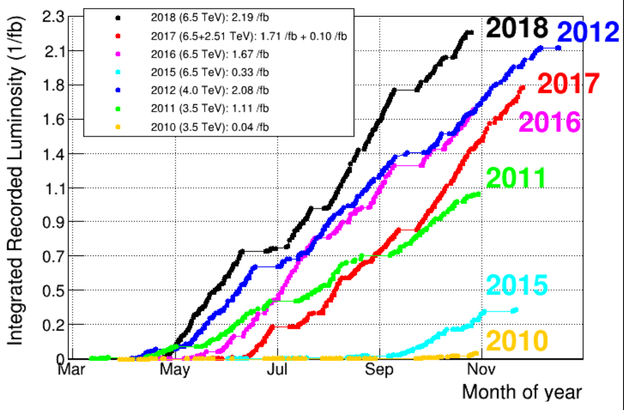
On behalf of the LHCb Collaboration

Istituto Nazionale di Fisica Nucleare

International Winter Meeting on Nuclear Physics
20-24 January 2020
Bormio, Italy

Outline

- LHCb is an extraordinary lab for hadron spectroscopy
- High cross section and excellent Trigger/DAQ allows high yields of heavy hadrons
  - 10^{11} bb/year
  - 20x for cc/year



- New results now include the full Run1+Run2 dataset
- I will cover only a selection of very recent results by LHCb
- More results in talks by **Vincent Tisserand** (Flavour) and **Valery Pugatch** (Ions)

Shopping list

New

- **First observation of excited Ω_b^- states**
  PAPER-2019-042 arXiv2001.00851, submitted by PRL

Super New

- **Observation of a new baryon state inthe $\Lambda_b\,\pi^+ + \pi^-$ mass spectrum**
  PAPER-2019-045, paper appearing soon on arXiv

New

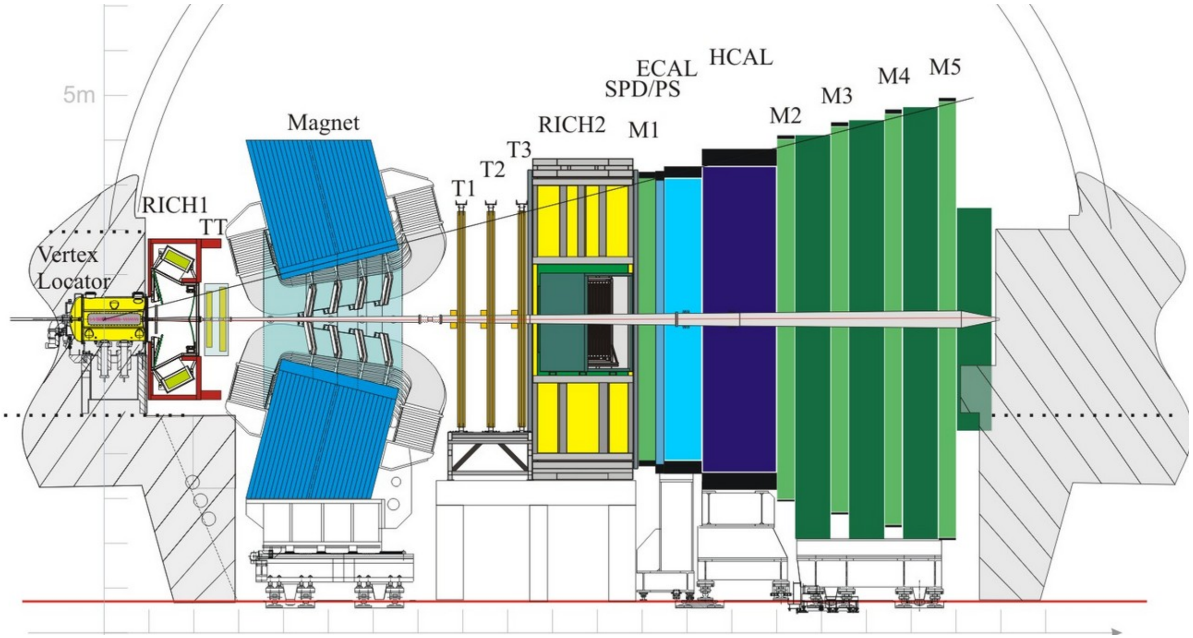
- **Precision measurement of the Ξ^{++}_{cc} mass**
  PAPER-2019-037 arXiv:1911.08594, sumitted to JHEP

- **Isospin amplitudes in $\Lambda_b \to J/\psi\Lambda(\Sigma^0)$ and $\Xi_b \to J/\psi\Xi^0(\Lambda)$ decays**
  PAPER-2019-039 arXiv:1912.02110, submitted to PRL

The LHCb detector

2008 JINST 3 S08005

- The LHCb experiment has proven very successful in finding new hadronic states
- Excellent resolution + PID allows detailed states with Kaons and Protons (gold for baryons)
- Main issues are related to high multiplicity and prompt background



Fully instrumented: $2 < \eta < 5$

Some sensitivity: $-3.5 < \eta < -1.5$

- Good Vertex measurements (20um and decay time resolution ~45 fs)
- Precise Tracking resolution ~0.5%
- Excellent PID up to 100GeV
- Versatile Trigger (L0+Hlt)

New

New Baryons !

Hadrons

- The LHCb experiment has discovered many new states lately
- The study of hadrons containing heavy quarks has undergone a renaissance
- Very big datasets of charmed and bottomed baryons → look for unknown resonances
- No limit on energy due to beam energies (e.g. in b-factories)

CERN-EP-2019-153
LHCb-PAPER-2019-025
January 16, 2020

Observation of new resonances in the $\Lambda_b^0\pi^+\pi^-$ system

CERN-EP-2018-243
LHCb-PAPER-2018-032
October 12, 2018

Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems and precise measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ properties

CERN-EP-2019-047
LHCb-PAPER-2019-005
March 28, 2019

Near-threshold $D\overline{D}$ spectroscopy and observation of a new charmonium state

CERN-EP-2019-050
LHCb-PAPER-2019-007
June 12, 2019

Observation of an excited B_c^+ state

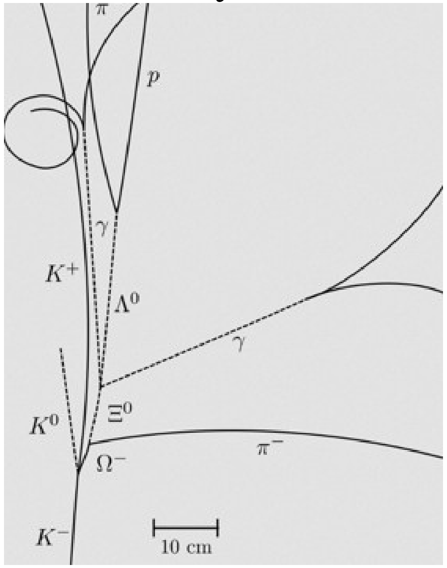
- Not to mention very important achievements as
  Pentaquarks
  Doubly-Charmed baryons

First observation of excited Ω_b^- states

arXiv2001.00851

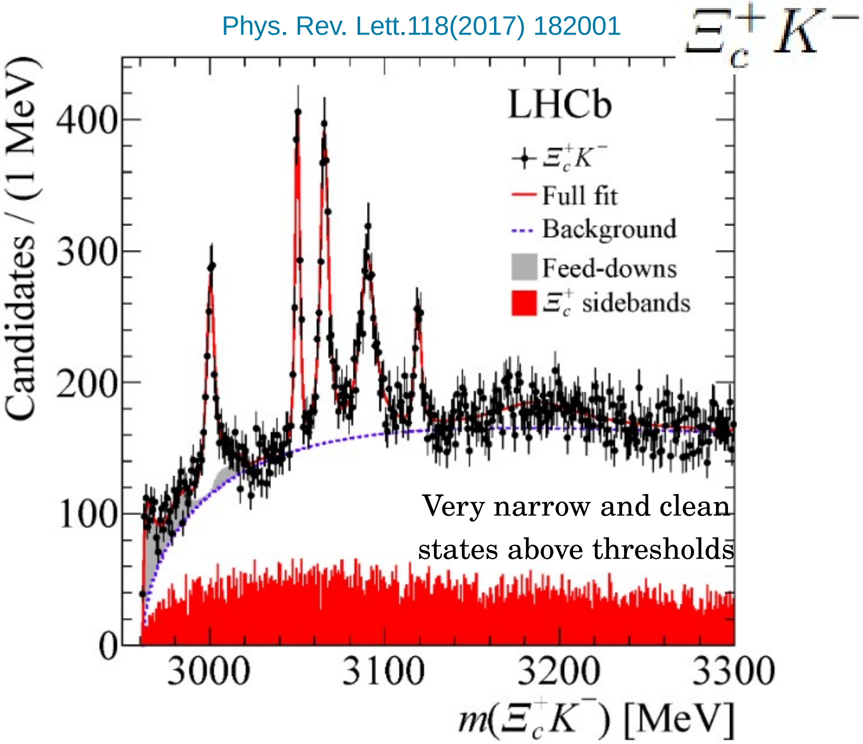
- 6th January 2020: Observation of new Ω_b baryon states (first time presented)
- A new system of four particles interpreted as four narrow excited Ω_b^- states
- These states are named the **$\Omega_b(6316)^-$, $\Omega_b(6330)^-$, $\Omega_b(6340)^-$ and $\Omega b(6350)^-$**
- History repeating as in 2017 five excited states of the Ω_c^0 baryon in the $\Xi_c^+K^-$ mass spectrum
- Analysis uses the same idea, but with bottom particles, where yields are lower (+more stat)

New Ω baryon in 1964



Excited Ωc in2017

Phys. Rev. Lett.118(2017) 182001

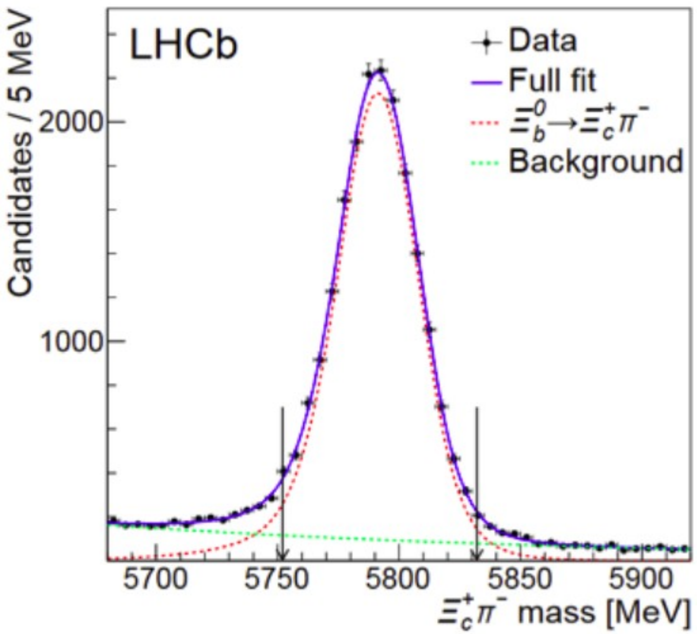


First observation of excited Ω_b^- states

arXiv2001.00851

- Use pp collisions corresponding to a total integrated lumi of 9fb^{-1}
- Idea: search for narrow resonances in the $\Xi^0_b K^-$ mass close to the kinematic threshold
- Similar idea to the charmed case (but no feed-down from $b \to c$ transitions)

- Samples of Ξ_b^0 candidates formed by pairing $\Xi_c^+ \pi^-$, $\Xi_c^+ \to pK^-\pi^+$
- All particles have PID requirements
- Use topology of the decay
- Signal selected with Multivariate analysis (BDT)
- **The fitted Ξ_b^0 signal yield is 19200 ± 200**



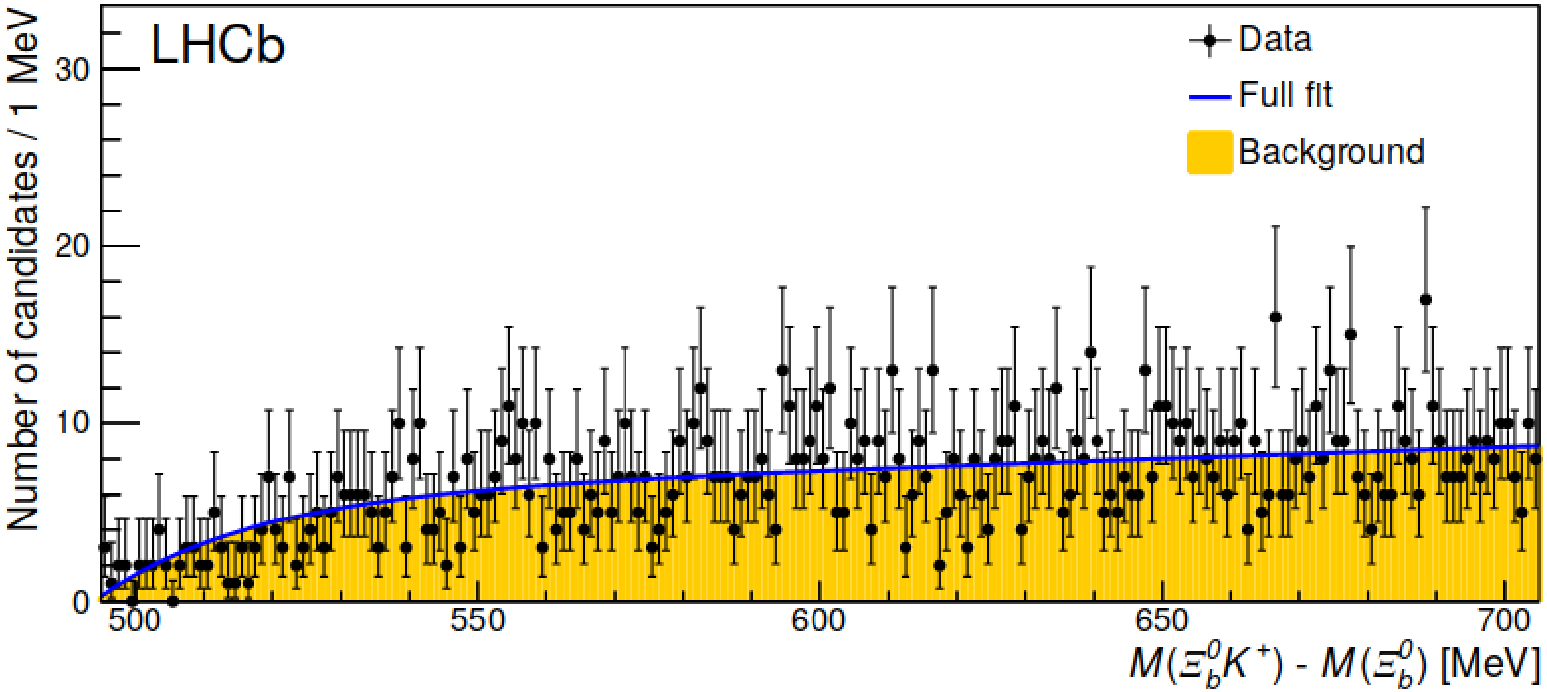
- Then combine with a charged K coming from same PV
- Apply tight PID to exclude prompt pions
- Look for mass difference: resonances as bumps in

$$\delta M \equiv M(\Xi_b^0 K^-) - M(\Xi_b^0)$$

First observation of excited Ω_b^- states

arXiv2001.00851

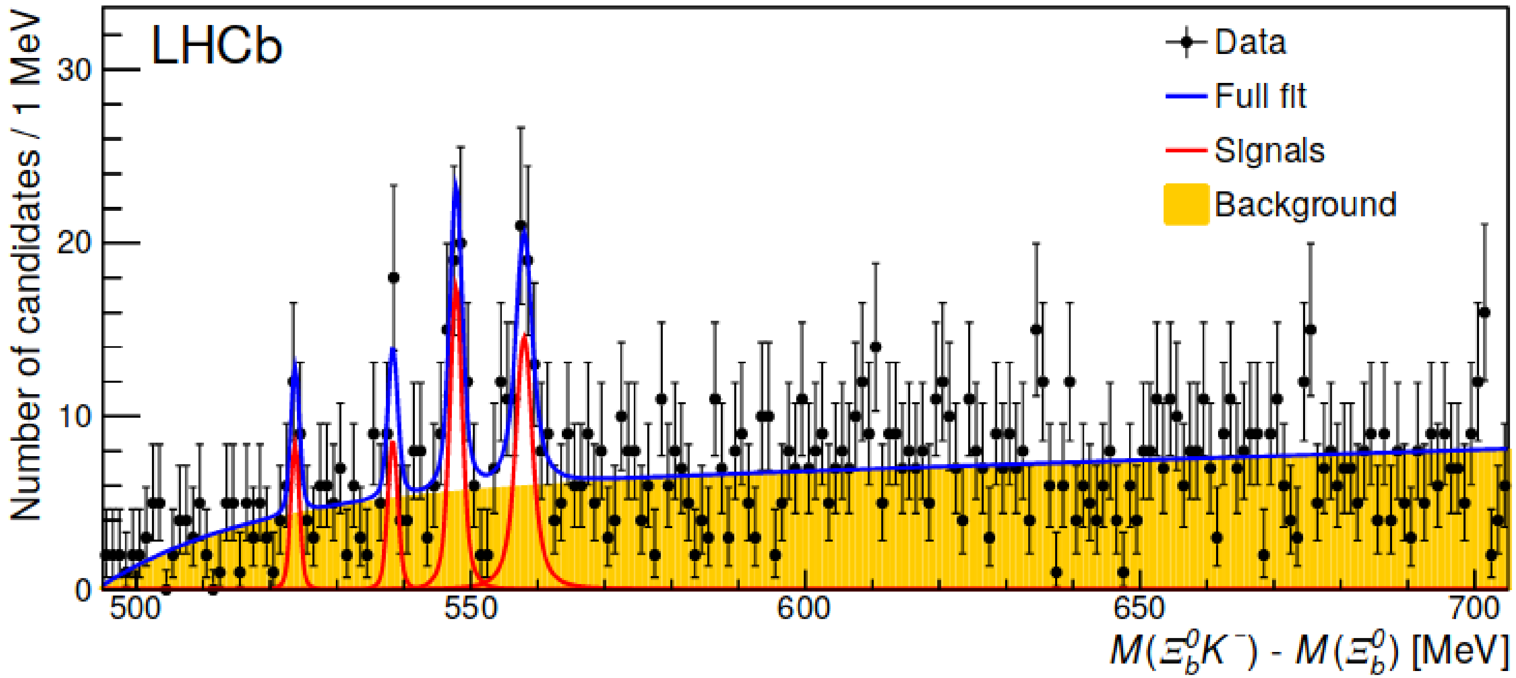
- The experimental δM resolution is obtained from simulated events
- Resolution variation vs δM mass is taken into account
- In the δM interval of interest σ is in the range of 0.7 - 0.8 MeV
- Study the right-sign (RS) and wrong-sign (WS) candidates



First observation of excited Ω_b^- states

arXiv2001.00851

- **Four peaks are seen in the RS spectrum**
- Perform a simultaneous unbinned extended maximum-likelihood fit to RS and WS
- A common background shape is used to describe both the RS and WS spectra



First observation of excited Ω_b^- states

arXiv2001.00851

- Measured masses

$$m(\Omega_b(6316)^-) = 6315.64 \pm 0.31 \pm 0.07 \pm 0.50\,\text{MeV},$$
$$m(\Omega_b(6330)^-) = 6330.30 \pm 0.28 \pm 0.07 \pm 0.50\,\text{MeV},$$
$$m(\Omega_b(6340)^-) = 6339.71 \pm 0.26 \pm 0.05 \pm 0.50\,\text{MeV},$$
$$m(\Omega_b(6350)^-) = 6349.88 \pm 0.35 \pm 0.05 \pm 0.50\,\text{MeV},$$

uncertainties are statistical, systematic and the last is due to the knowledge of the Ξ^0_bmass

- The natural widths of the three lower mass states are consistent with zero
    - UL $\Gamma(\Omega b(6316)) < 2.8$ MeV
    - UL $\Gamma(\Omega b(6330)) < 3.1$ MeV
    - UL $\Gamma(\Omega b(6340)) < 1.5$ MeV
- The natural width of the Ωb(6350) peak is $1.4^{+1.0}_{-0.8} \pm 0.1$MeV

- Local significances ranging from 3.6σ to 7.2σ
- Still significant after look-else where effect

First observation of excited Ω_b^- states

arXiv2001.00851

Significances

Peak of δM [MeV]	Width [MeV]	Signal yield	Significances [σ] Local	Global
523.74 ± 0.31	$0.00^{+0.7}_{-0.0}$	15^{+6}_{-5}	3.6	2.1
538.40 ± 0.28	$0.00^{+0.4}_{-0.0}$	18^{+6}_{-5}	3.7	2.6
547.81 ± 0.26	$0.47^{+0.6}_{-0.5}$	47^{+11}_{-10}	7.2	6.7
557.98 ± 0.35	$1.4^{+1.0}_{-0.8}$	57^{+14}_{-13}	7.0	6.2

Systematics

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

In summary

	δM_{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)
$\Omega_b(6330)^-$	$538.40 \pm 0.28 \pm 0.07$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	< 3.1 (4.7)
$\Omega_b(6340)^-$	$547.81 \pm 0.26 \pm 0.05$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	< 1.5 (1.8)
$\Omega_b(6350)^-$	$557.98 \pm 0.35 \pm 0.05$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	< 2.8 (3.2) $1.4^{+1.0}_{-0.8} \pm 0.1$

First observation of excited Ω_b^- states

arXiv2001.00851

Possible interpretation of the states

- They are qualitatively similar to those observed in the $\Xi_c^+ K^-$ mass spectrum
- The simplest interpretation of these peaks is that they correspond to excited Ω_b states
- Possibly the L = 1 excitations of the ground state (or possible n = 2 radial excitations)
- Different models predict five states most of which should be narrow (<1MeV)

- Quark-diquark models have also predicted several excited Ω_b states
- However,there are no predictions for the decay widths
- Molecular models have also been employed,where two narrow states are predicted at 6405 and 6465MeV: no such peaks at those masses are seen in our data
-
- An alternate interpretation for one or more of the observed peaks is that they arise from the decay of a higher-mass excited Ω_b state, $\Omega_b^{**-} \to \Xi_b^{\prime 0}(\to \Xi_b^0 \pi^0) K^-$, where π^0 meson is undetected
- While the $\Xi_b^{\prime -}$, Ξ_b^{*-} and Ξ_b^{*0} baryons have been observed, the $\Xi_b^{\prime 0}$ is yet to be seen

K. Thakkar, Z. Shah, A. K. Rai, and P. C. Vinodkumar, *Excited state mass spectra and Regge trajectories of bottom baryons*, Nucl. Phys. **A965** (2017) 57, arXiv:1610.00411.

S. S. Agaev, K. Azizi, and H. Sundu, *On the nature of the newly discovered Ω states*, EPL **118** (2017) 61001, arXiv:1703.07091.

S. S. Agaev, K. Azizi, and H. Sundu, *Decay widths of the excited Ω_b^- baryons*, Phys. Rev. **D96** (2017) 094011, arXiv:1708.07348.

Q. Mao *et al.*, *D-wave heavy baryons of the $SU(3)$ flavor $\mathbf{6}_F$ representation*, Phys. Rev. **D96** (2017) 074021, arXiv:1707.03712.

E. Santopinto *et al.*, *The Ω_c^0-puzzle solved by means of spectrum and strong decay amplitude predictions*, Eur. Phys. J. **C79** (2019) 1012, arXiv:1811.01799.

G. Yang, J. Ping, and J. Segovia, *The S- and P-wave low-lying baryons in the chiral quark model*, Few Body Syst. **59** (2018) 113, arXiv:1709.09315.

W. Roberts and M. Pervin, *Heavy baryons in a quark model*, Int. J. Mod. Phys. **A23** (2008) 2817, arXiv:0711.2492.

Y.-X. Yao, K.-L. Wang, and X.-H. Zhong, *Strong and radiative decays of the low-lying d-wave singly heavy baryons*, Phys. Rev. D **98** (2018) 076015.

E.-L. Cui, H.-M. Yang, H.-X. Chen, and A. Hosaka, *Identifying the $\Xi_b(6227)$ and $\Sigma_b(6097)$ as P-wave bottom baryons of $J^P = 3/2^-$*, Phys. Rev. D **99** (2019) 094021.

Observation of a new baryon in $\Lambda_b \pi^+ + \pi^-$

PAPER-2019-045
soon on arXiv

- Excited beauty baryons have been studied by CDF and LHCb
- The family of these baryons consists of Λ_b isosinglet and the Σ_b isotriplet states

$\Lambda_b\pi^\pm$ spectrum Phys. Rev. Lett.99(2007) 202001

The lightest charged $\Sigma^{(*)\pm}_b$ baryons have been observed by the CDF

Later states confirmed by LHCb + heavier $\Sigma_b(6097)^\pm$ states were discovered (LHCb)

Phys. Rev. Lett. 122, 012001 (2019)

$\Lambda_b\pi^+\pi^-$ final state

Near threshold has been studied by LHCb Phys. Rev.Lett.109(2012) 172003

- In 2011, discovery of two narrow states, $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ Phys. Rev. Lett. 123 (2019) 152001
- In 2019, doublet of narrow states $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ discovered
- Interpretations of those states as 1P and 2D, but states are missing
- Notably predicted in the region between the established narrow doublet states

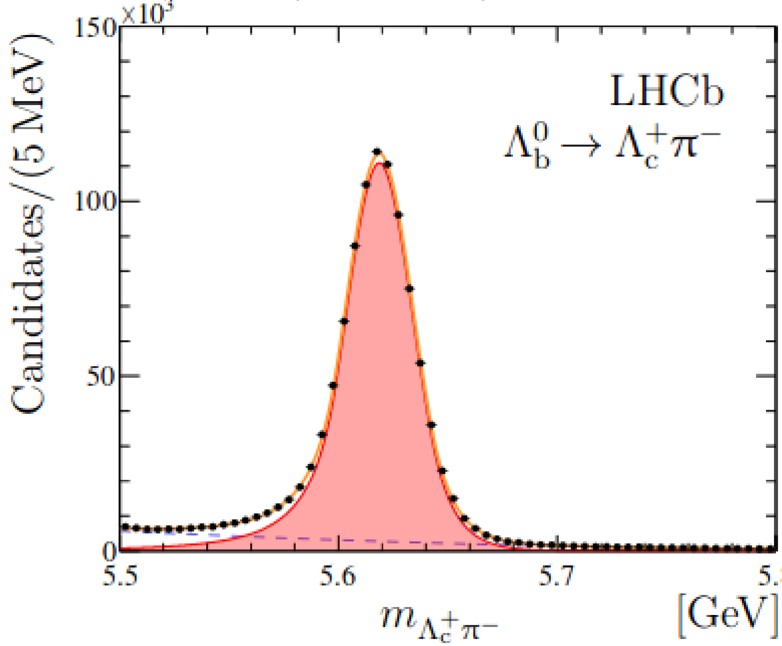
Observation of a new baryon in $\Lambda_b \pi^+ + \pi^-$

PAPER-2019-045
soon on arXiv

- The analysis uses pp collision data recorded by LHCb in 2011–2018
- The Λ_b reconstructed via $\Lambda b \to \Lambda c+\pi-$ and $\Lambda b \to J/\psi\ p\ K-$ decay chains
- BDT selection similar to previous analyses to maintain consistency

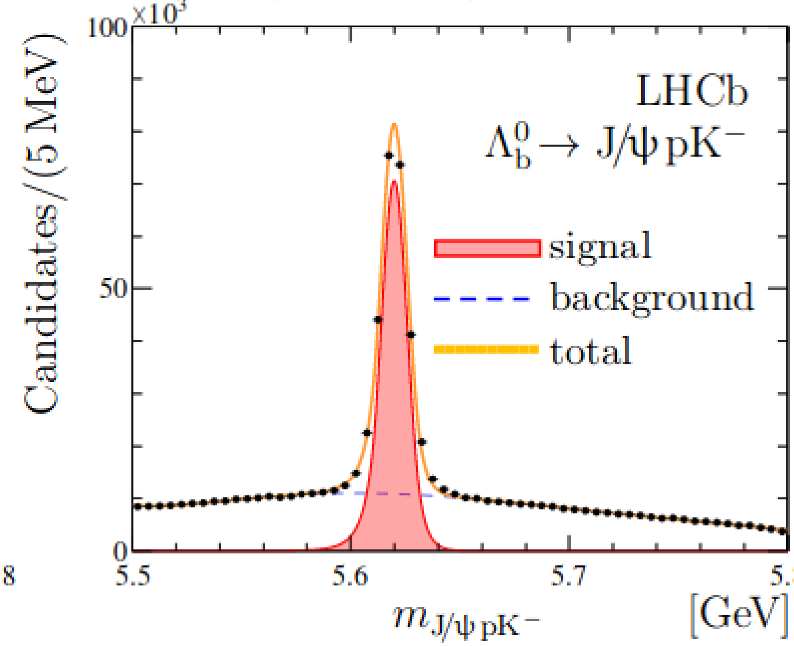
Large yields!

$(937.9 \pm 1.6) \times 10^3$



Large yields!

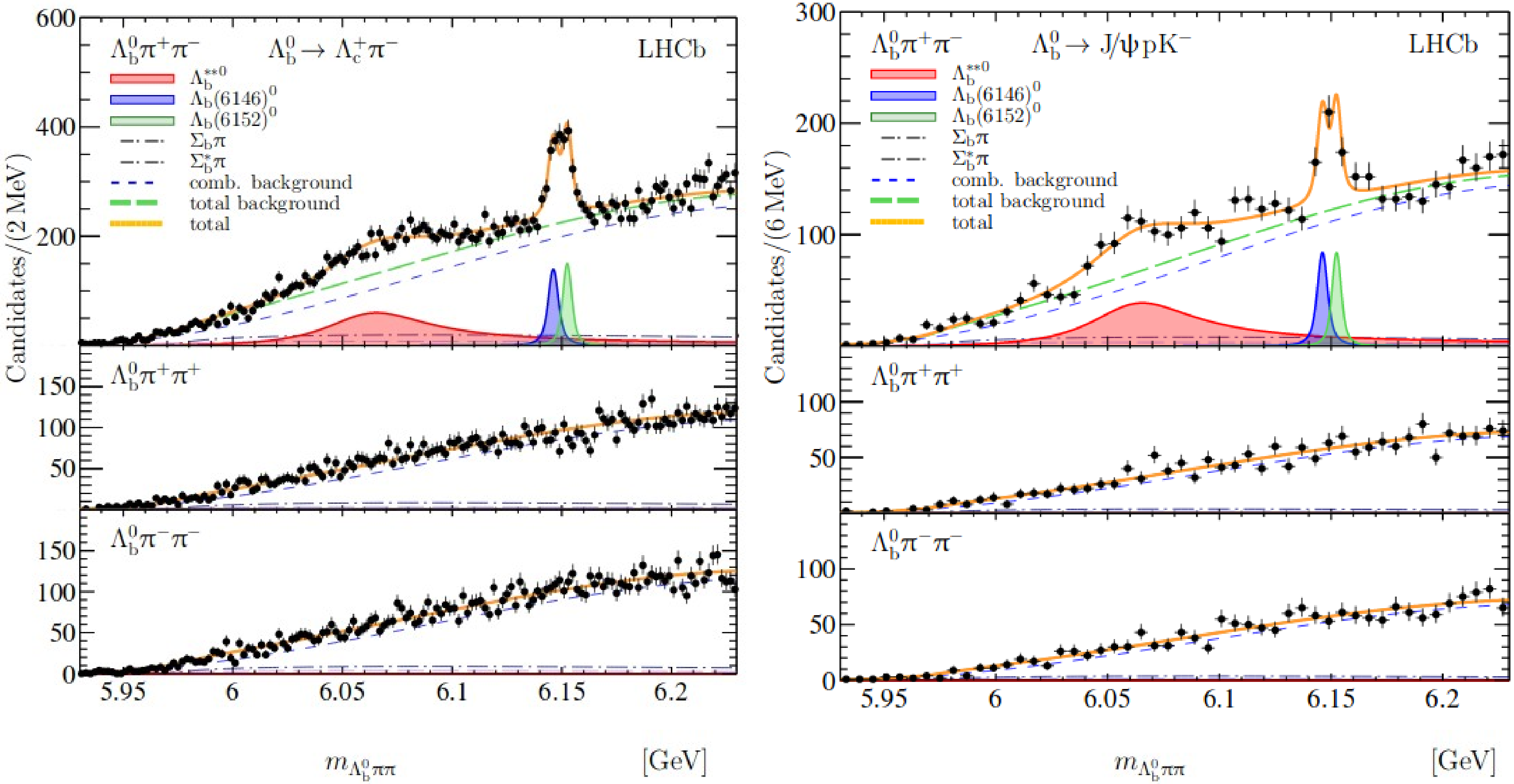
$(223.0 \pm 0.6) \times 10^3$



Observation of a new baryon in $\Lambda_b \pi^+ + \pi^-$

PAPER-2019-045
soon on arXiv

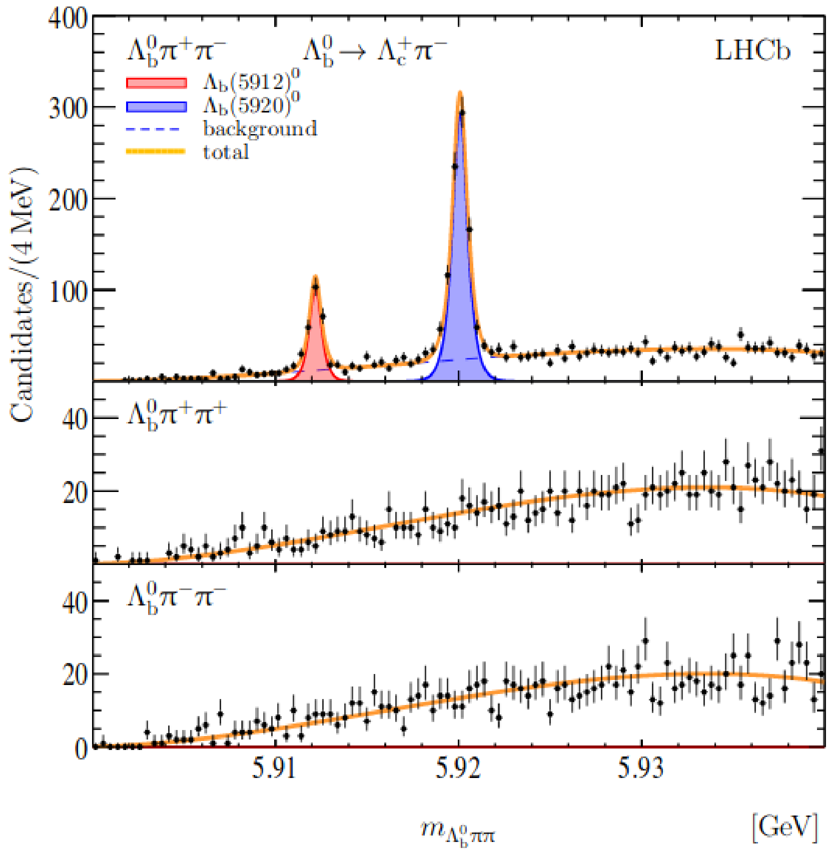
- Simultaneous binned maximum-likelihood fit is performed
- Excess of events clearly appearing (confirmed in both independent samples)



Observation of a new baryon in $\Lambda_b\,\pi^+ + \pi^-$

PAPER-2019-045
soon on arXiv

- Fit to the lower mass window (where the 1P are)
- Widths still too narrow to be distinguished from exp resolution
- **Now probing the 200keV range of widths**



$$\Delta m_{\Lambda_b(5912)^0} = 292.589 \pm 0.029 \pm 0.010 \text{ MeV},$$
$$\Delta m_{\Lambda_b(5920)^0} = 300.492 \pm 0.019 \pm 0.010 \text{ MeV},$$

$$\Gamma_{\Lambda_b(5912)^0} < 0.25\,(0.28) \text{ MeV},$$
$$\Gamma_{\Lambda_b(5920)^0} < 0.19\,(0.20) \text{ MeV},$$

Observation of a new baryon in $\Lambda_b \pi^+ + \pi^-$

PAPER-2019-045
soon on arXiv

- **A broad structure in the $\Lambda b \pi^+ \pi^-$ mass spectrum is observed**
- The significance of the new structure exceeds 14 standard deviations
- Mass and natural width of the new state

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

- The structure is consistent with the first radial excitation of the Λb baryon [$\Lambda b(2S)^0$]
- Updated measurements of previously observed $\Lambda b(5912)^0$ and $\Lambda b(5920)^0$ states

- Several exited Σb(1P) states are expected with the mass close to the measured value
  But the partial decay widths for Σb(1P) states into Λbππ predicted to be very small

- If the observed broad peak corresponds to the $\Sigma b(1P)^{(*)0}$ state → two peaks with similar masses and widths and significantly larger yields should be visible in the $\Lambda b\pi\pm$ spectra due to decays of the charged isospin partners $\Sigma b(1P)^{(*)\pm} \to \Lambda b \pi^\pm$
- However, no signs of states with such mass and width and large production yields are observed in the analysis of the $\Lambda b \pi^\pm$ mass spectra and the observed $\Sigma b(6097)^\pm$ states have significantly smaller natural width and relatively small yields

Observation of a new baryon in $\Lambda_b\,\pi^{+}+\pi^{-}$

PAPER-2019-045
soon on arXiv

- If interested, supplementary material that will posted on the public CDS
- With detailed discussion on interpretation
- Is it a neutral component of the $\Sigma b(6097)$ triplet?

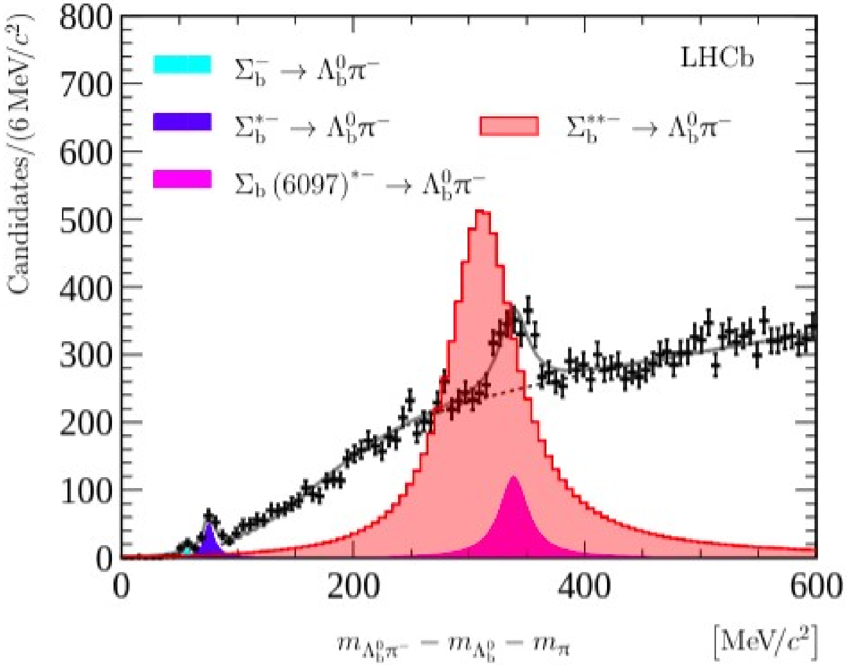


Figure 7: The $\Lambda_b^0\pi^-$ mass spectrum from Ref. [3] with superimposed expected signal from the $\Sigma_b^{**-} \to \Lambda_b^0\pi^-$ decays.

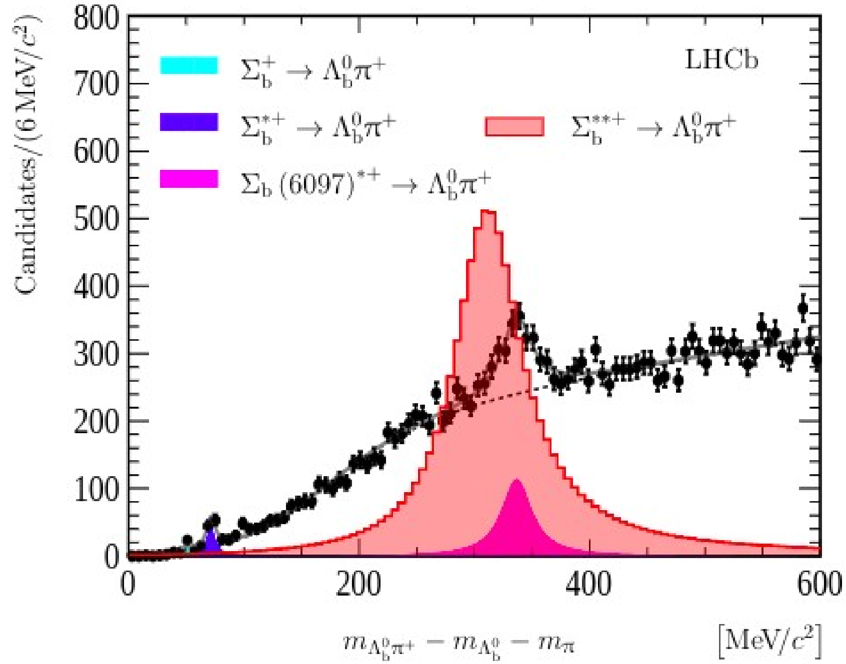


Figure 8: The $\Lambda_b^0\pi^+$ mass spectrum from Ref. [3] with superimposed expected signal from the $\Sigma_b^{**+} \to \Lambda_b^0\pi^+$ decays.

Other topics on Flavour

Precision measurement of the Ξ^{++}_{cc} mass

arXiv:1911.08594

- Most precise measurement of the Ξ^{++}cc mass to date
- Data collected between 2016 and 2018 in pp collisions
- Luminosity corresponds to 5.6 fb^{-1}
- **Use both known decays (and observed by LHCb**
- Extremely important to understand the cc system (in a baryon)

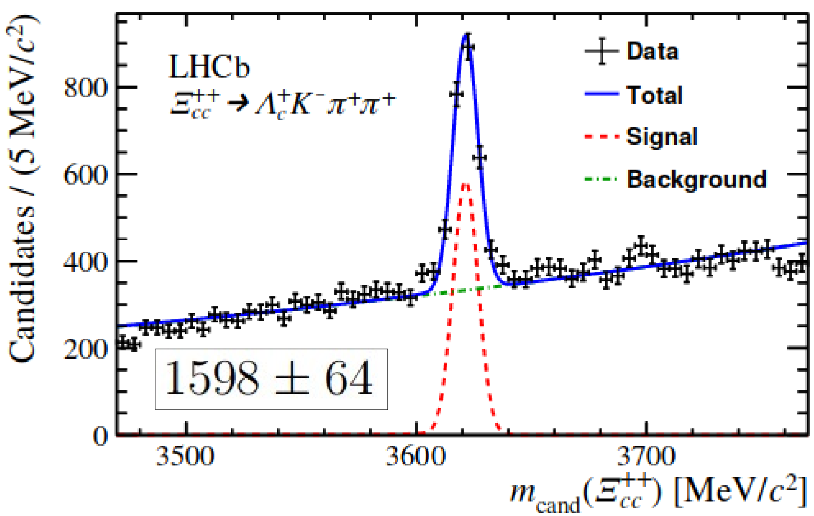
$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$
$$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$

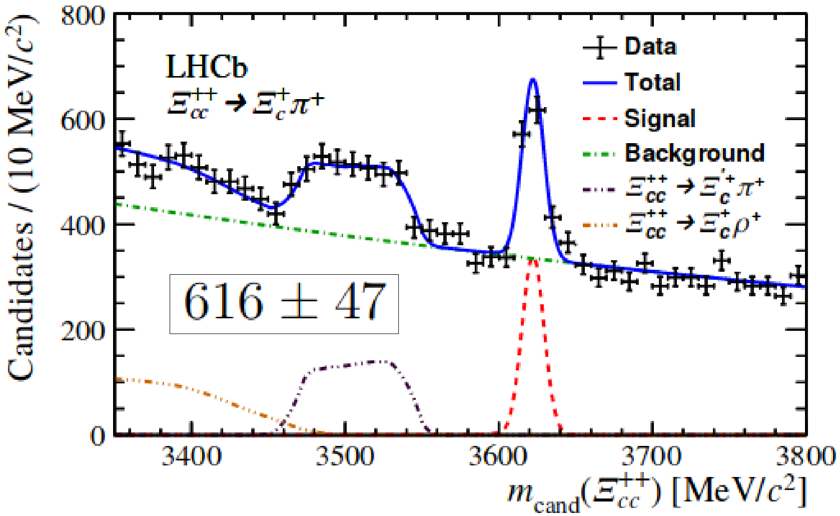
LHCb collaboration, R. Aaij *et al.*, *Observation of the doubly charmed baryon Ξ_{cc}^{++}*, Phys. Rev. Lett. **119** (2017) 112001, arXiv:1707.01621.

LHCb collaboration, R. Aaij *et al.*, *First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$*, Phys. Rev. Lett. **121** (2018) 162002, arXiv:1807.01919.

- Selection is based on optimised MVA
- To improve mass resolution we mass differences

$$m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+ \pi^+) - m(\Lambda_c^+) + M_{\text{PDG}}(\Lambda_c^+),$$
$$m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Xi_c^+ \pi^+) - m(\Xi_c^+) + M_{\text{LHCb}}(\Xi_c^+),$$





Precision measurement of the Ξ^{++}_{cc} mass

arXiv:1911.08594

- Multiple scattering can increase/decrease the opening angle between the $\Xi^{++}cc$ products
- Since selection is more efficient for candidates with larger reco decay lengths we could have a bias on the mass
- Effect was studied with charmed hadrons, D^+, D^0, D^+s, Λ^+c $\rightarrow$ well reproduced by simulation

	Uncertainty [MeV/c^2]	
Source	$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
Momentum-scale calibration	0.21	0.34
Energy-loss correction	0.05	0.03
Simulation/data agreement	0.09	0.05
Selection-induced bias on the Ξ_{cc}^{++} mass	0.09	0.09
Final-state radiation	0.05	0.16
Background model	0.01	0.04
Λ_c^+, Ξ_c^+ mass	0.14	0.22
Total	0.29	0.49

- The combined $\Xi^{++}cc$ mass is determined to be

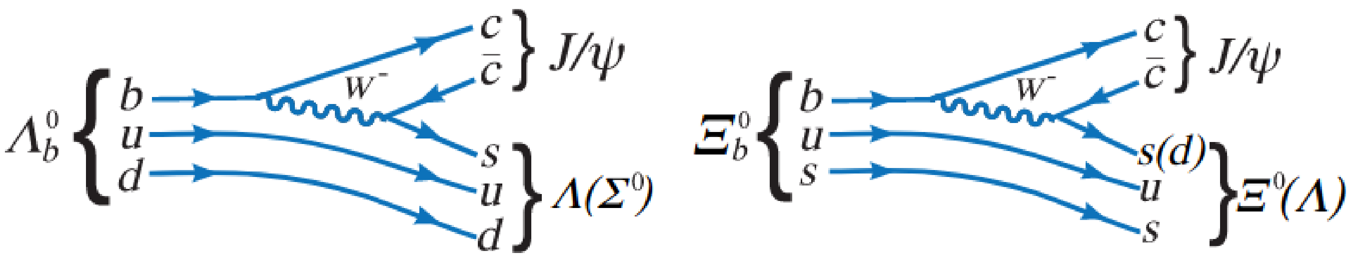
$$3621.55 \pm 0.23\,(\text{stat}) \pm 0.30\,(\text{syst})\ \text{MeV}/c^2$$

Isospin amplitudes in Λb and decays

[arXiv:1912.02110](https://arxiv.org/abs/1912.02110)

- Ratios of isospin amplitudes in hadron decays are a useful probe of the interplay between weak and strong interactions (useful for searches on NP)
- We measure the isospin ratio

$$|A_1(\Lambda_b^0 \to J/\psi \Sigma^0)/A_0(\Lambda_b^0 \to J/\psi \Lambda)|$$



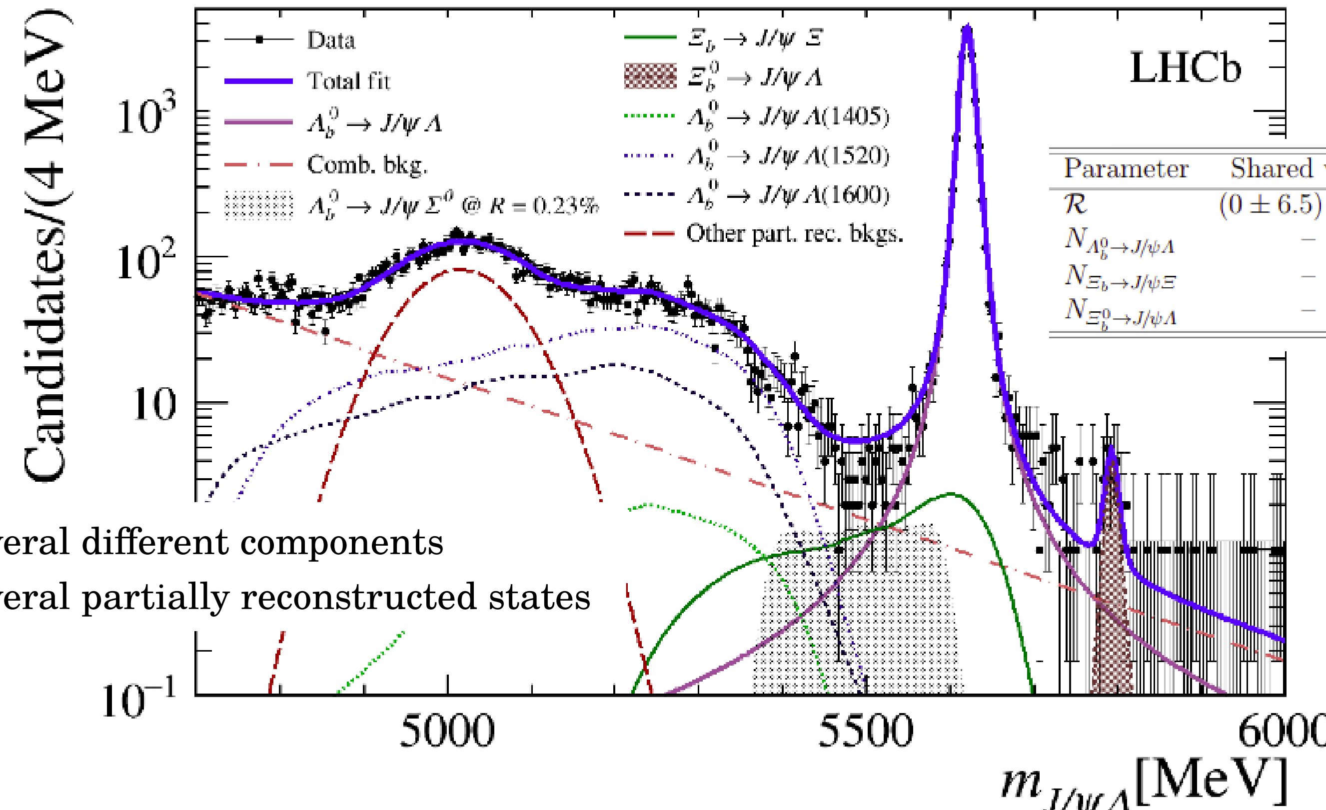
- **First, the Cabibbo suppressed $\Xi b^0 \to J/\psi\ \Lambda$ decay is observed for the first time**
- Isospins of the J/ψ Λ Λb and are zero, that of the Σ^0 baryon is one
- Since the b→ccs weak operator involves no isospin change
- We expect a dominant $A_{I=0}$ amplitude and a preference for the J/ψ Λ final-state
- Isospin breaking effects are possible due to the difference in mass and charge of the u and d quarks but can also be induced by electroweak-penguin or NP processes

Isospin amplitudes in Λ_b and decays

- Strategy
  - fully reconstruct the $J/\psi\ \Lambda$ final state
  - partially reconstruct the $J/\psi\Sigma^0$ mode (ignoring the photon from the $\Sigma^0 \to \gamma\Lambda$ decay)
  - Reason: low efficiency of the calorimeter at small photon energies

arXiv:1912.02110

- Mass distributions show very complicate components



Parameter	Shared value	Run 1 value	Run 2 value
$\mathcal{R}$	$(0 \pm 6.5)\cdot 10^{-4}$	–	–
$N_{\Lambda_b^0\to J/\psi\Lambda}$	–	4417 ± 66	$16\,970 \pm 130$
$N_{\Xi_b\to J/\psi\Xi}$	–	19.9 ± 4.7	127 ± 18
$N_{\Xi_b^0\to J/\psi\Lambda}$	–	6.2 ± 3.0	17.8 ± 5.1

Several different components

Several partially reconstructed states

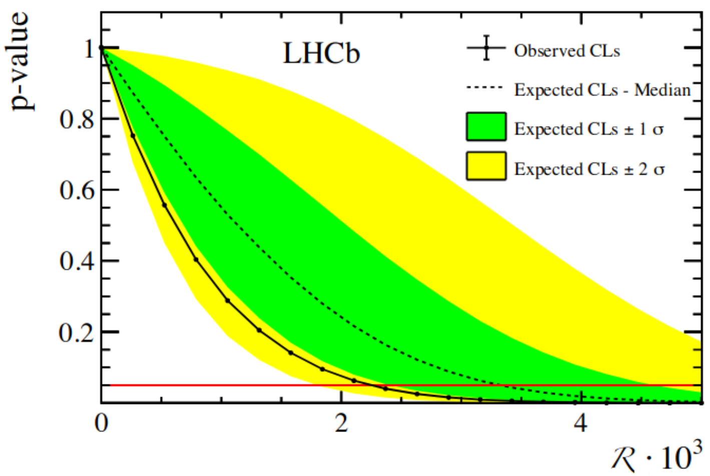
Isospin amplitudes in Λb and decays

arXiv:1912.02110

- We jointly fit all components to extract the yields
- The parameter of interest is

$$\mathcal{R} = \frac{|A_1|^2}{|A_0|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Sigma^0)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} \cdot \Phi_{\Lambda_b^0} = \frac{N_{\Lambda_b^0 \to J/\psi \Sigma}}{N_{\Lambda_b^0 \to J/\psi \Lambda}} \cdot \frac{\epsilon_{\Lambda_b^0 \to J/\psi \Lambda}}{\epsilon_{\Lambda_b^0 \to J/\psi \Sigma}} \cdot \Phi_{\Lambda_b^0}$$

- Need to consider respective efficiencies (estimated from simulation);
- $\Phi_{\lambda b}$ is a phase space correction factor
- R is consistent with zero as no signal is observed



$$|A_1/A_0| = \sqrt{\mathcal{R}} < 1/20.9 \text{ at } 95\% \text{ CL}$$

- This limit is stringent and rules out isospin violation at a~1% rate.
- Isospin violation has been seen at this level, e.g. in ρ–ω mixing ($B^0 \to J/\psi \pi^+\pi^-$ decays)
- Our limit implies that the Λb might be formed of a b-quark and a ud-diquark

Summary

- Presented only a short list of the latest results from LHCb
- Expect many new final states investigated and maybe new surprises

- **Upgrade phase in full process → expect to collect more luminosity**
- **More luminosity == more statistics == many new final states available**
- **You can follow our progress on our page (weekly updates and videos)**

Stay Tuned!