Conventional Spectroscopy @ LHCb

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On behalf of the LHCb collaboration
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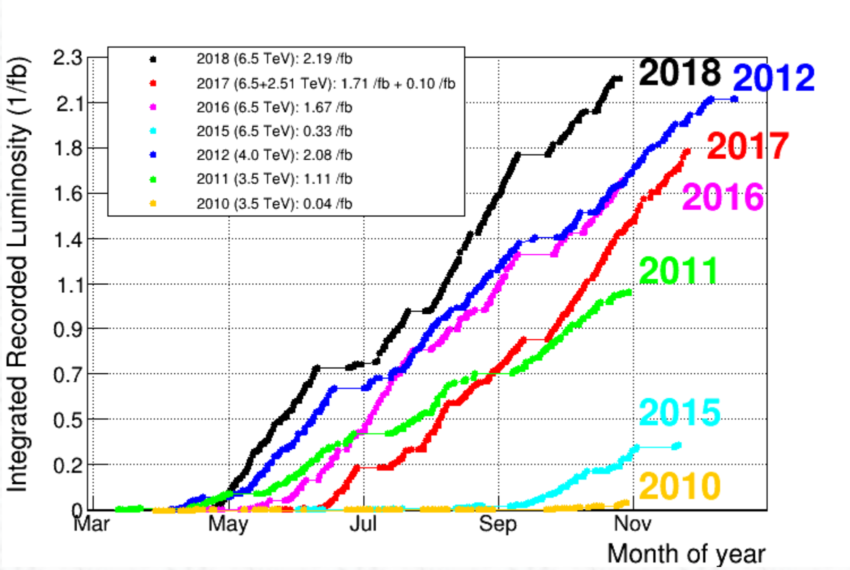
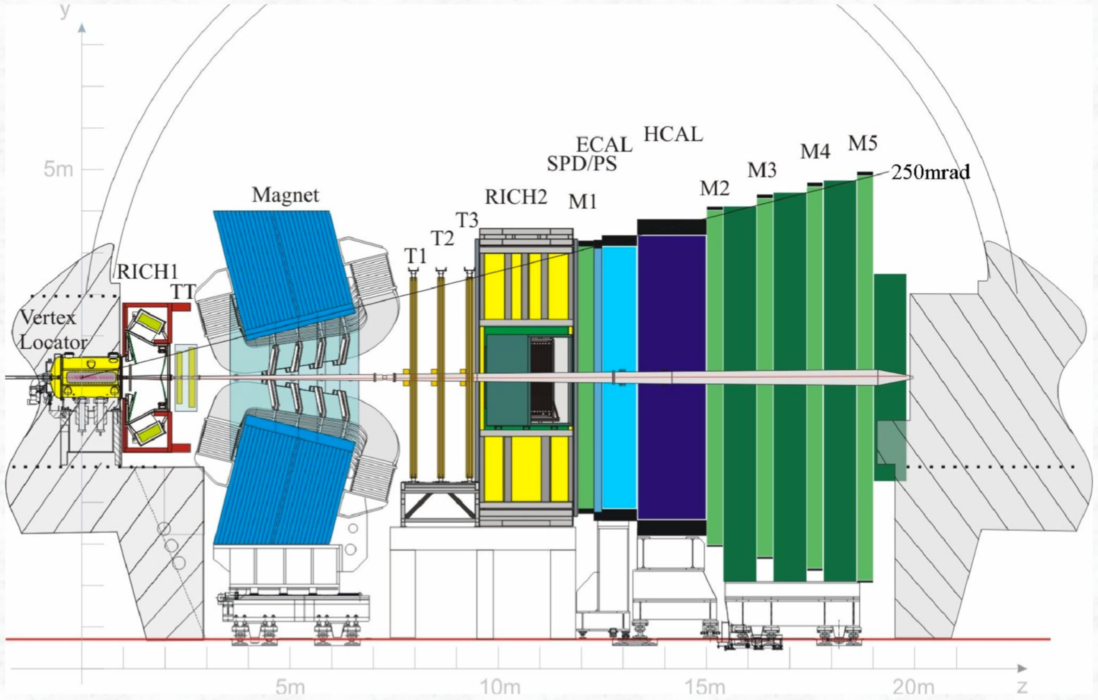
The LHCb experiment at CERN

- Single arm spectrometer designed for study of b & c quarks, working in $\eta \in [2,5]$
- VELO provides very good IP resolution
  - $20\ \mu\mathrm{m}$ for high p_T tracks
  - Excellent primary and secondary vertex resolution
- RICH detectors allow highly efficient particle identification
  - Kaon ID ~ 95% for 5% $\pi \rightarrow K$ misID
- Tracking efficiency is 96%, $\delta p/p = 0.4\%$ @ 5 GeV





- Trigger efficiency:
  - ~ 90% for dimuon channels
  - ~ 30% for multi-body hadronic final states

- Total recorded luminosity:
  - Run 1: $1\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV, $2\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV
  - Run 2: $6\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV

Outline

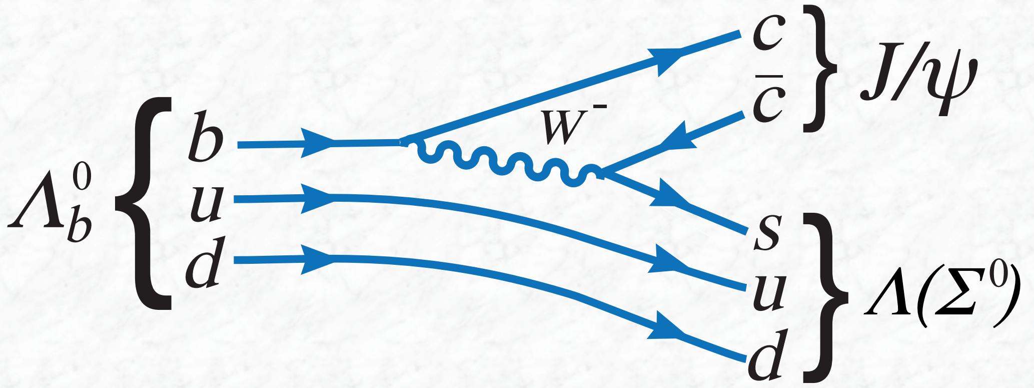
- Isospin amplitudes in Λ_b^0 and Ξ_b^0 decays
- First branching fraction measurement of $\Xi_c^0 \to \Lambda_c^+ \pi^-$
- First observation of excited Ω_b^- states in $\Xi_b^0 K^-$
- Other recent results

Isospin amplitudes in Λ_b^0 and Ξ_b^0 decays

PRL 124, 111802

Motivation

- $\Delta I = 1/2$ rule: $\mathrm{Re}(A_0)/\mathrm{Re}(A_2) \sim 22$ in $K \to \pi\pi$
  - Lattice ratio = $19.9 \pm 2.3 \pm 4.4$ RBC-UKQCD - Abbott. et. al.
  - Analytical calculation = 16.0 ± 1.5 Buras et. al.
  - Long distance QCD dynamics largely responsible, but NP can't be excluded
- Consider $\Lambda_b \to J/\psi\, \Lambda$, $\Lambda_b \to J/\psi\, \Sigma^0$
  - Quark model assigns $I = 0$ to Λ_b, not expt. confirmed
  - $\Lambda_b \to J/\psi\, \Lambda$ is $\Delta I = 0$, $\Lambda_b \to J/\psi\, \Sigma^0$ is $\Delta I = 1$



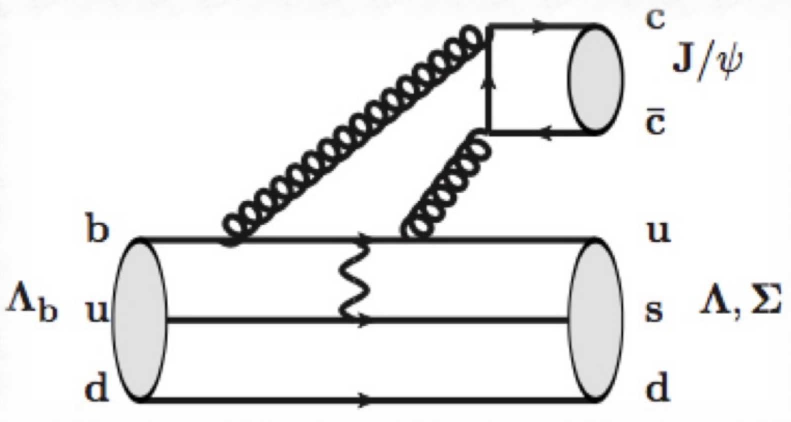
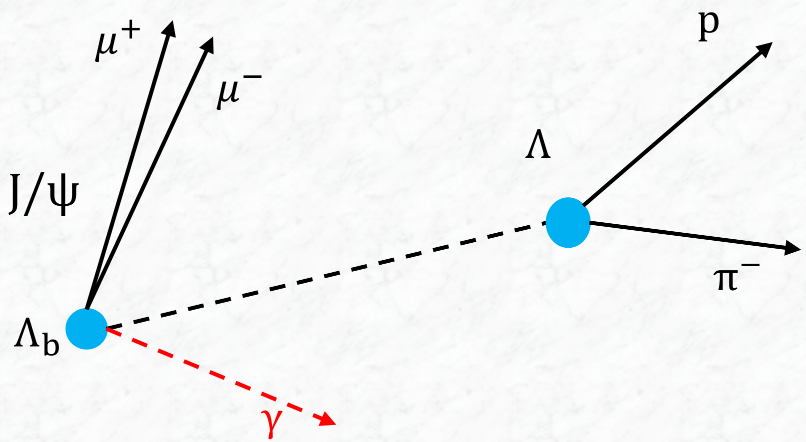


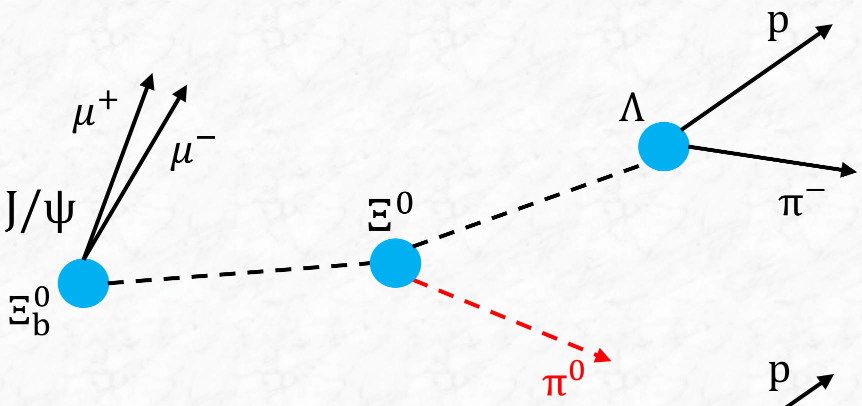
Figure from Dery et. al

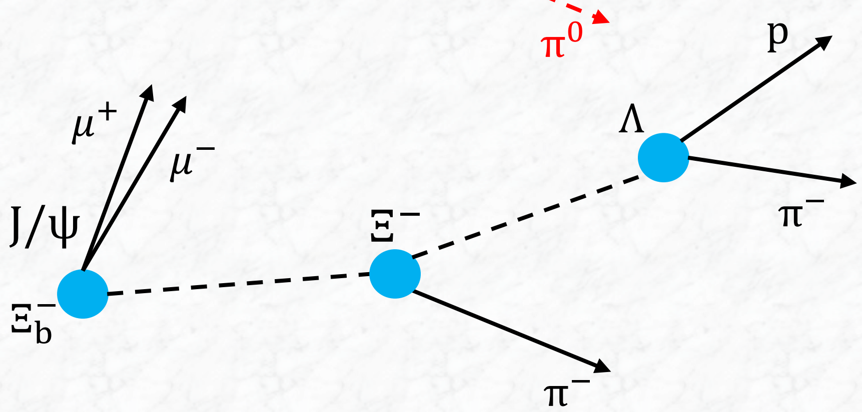
- If Λ_b consists of a isoscalar (ud) diquark, generic 1% isospin breaking will be suppressed
  - Test of diquark model
- $\Lambda - \Sigma^0$ mixing is predicted to be ~1% in amplitude Kordov et. al Dery et. al
- Isospin suppression commonly assumed in analyses
  - Pentaquark search in $\Lambda_b \to J/\psi\, p\, K^-$ assumed backgrounds from $\Lambda_b \to J/\psi\, \Sigma^*$ were suppressed compared to $\Lambda_b \to J/\psi\, \Lambda^*$. LHCb - Aaij et. al

Reconstruction

- All Run 1 and Run 2 data is used
- $\Lambda_b \to J/\psi\ (\Sigma^0 \to \Lambda\gamma)$ reconstructed without photon
  - $J/\psi \to \mu^+\mu^-, \Lambda \to p\pi^-$ form a detached vertex



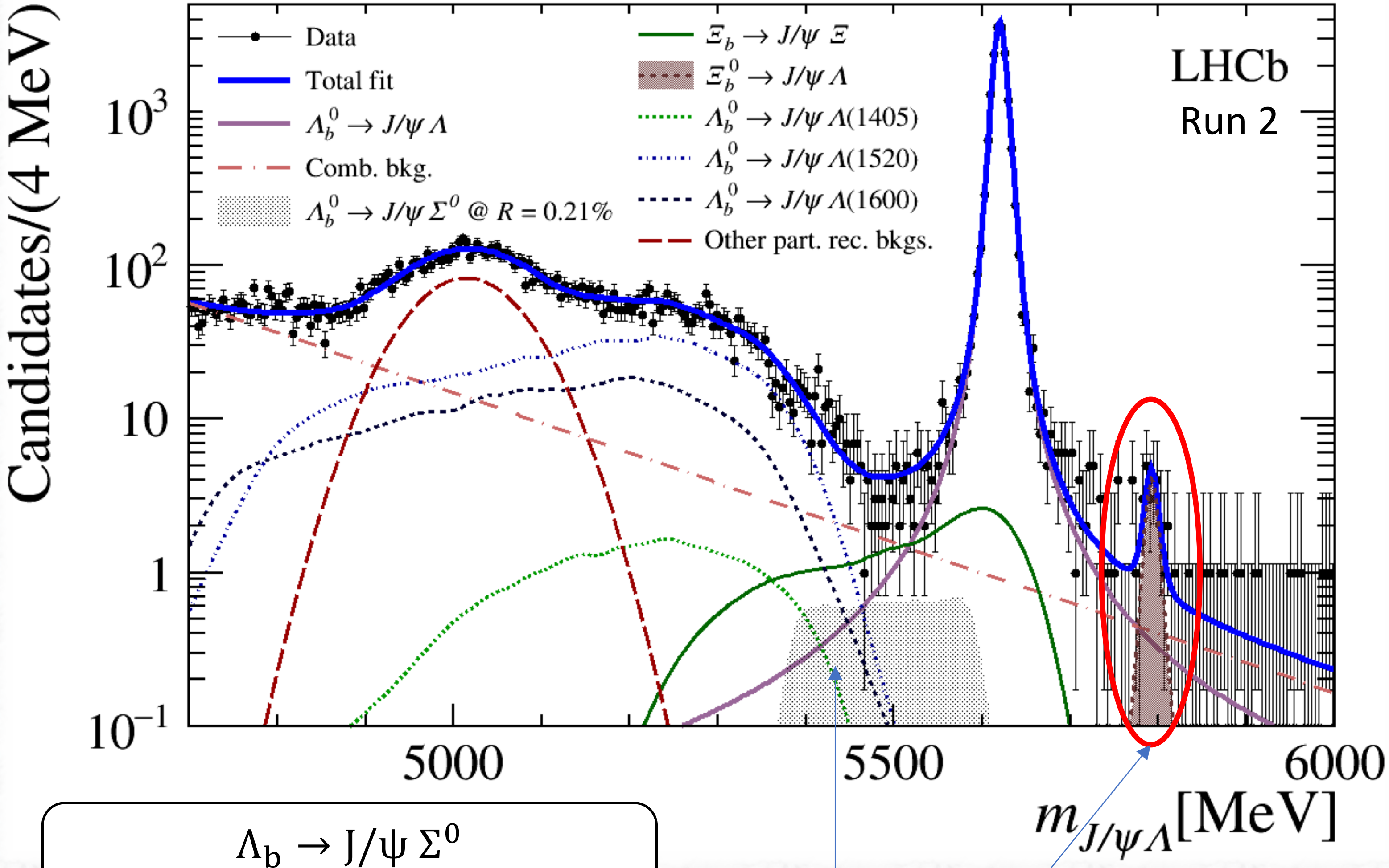




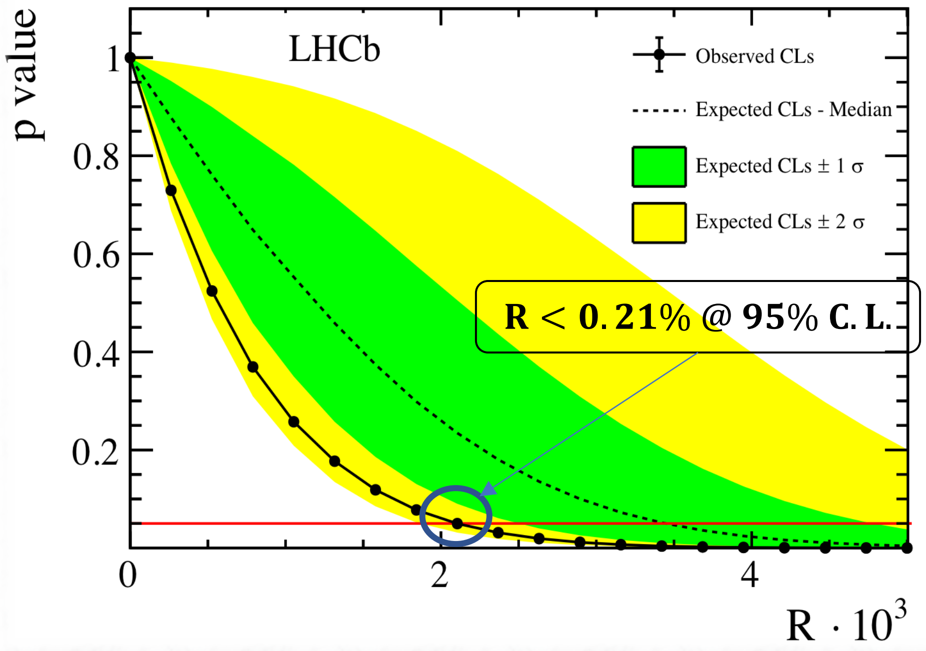
- $R \equiv \frac{|A_1|^2}{|A_0|^2} = \frac{B(\Lambda_b \to J/\psi\ \Sigma^0)}{B(\Lambda_b \to J/\psi\ \Lambda)} \cdot \Phi_{\Lambda_b} = \frac{N(\Lambda_b \to J/\psi\ \Sigma^0)}{N(\Lambda_b \to J/\psi\ \Lambda)}$

- Key backgrounds:
  - $\Lambda_b \to J/\psi\ \Lambda^*, \Lambda^* \to \pi^0\ \Sigma^0$
  - $B \to J/\psi +$ charged tracks
  - $\Xi_b \to J/\psi\ \Xi,\ \ \Xi \to \Lambda\pi$
    - Ξ_b^- decay reconstructed fully to normalize
  - Combinatorial background

Fit & Upper Limit

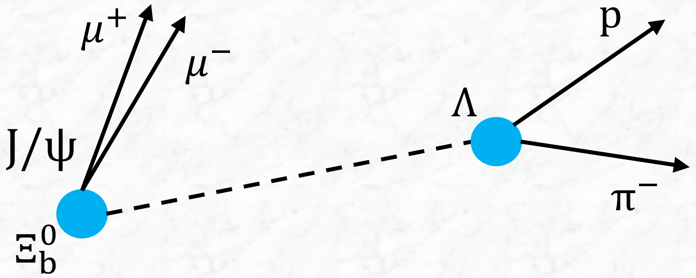


Upper limit on R obtained using CLs method, fitting jointly to Run 1 and Run 2 data.



$\Lambda_b \to J/\psi\, \Sigma^0$
(artificially scaled to upper limit)

First observation of $\Xi_b^0 \to J/\psi\, \Lambda$ with 5.6 σ significance!

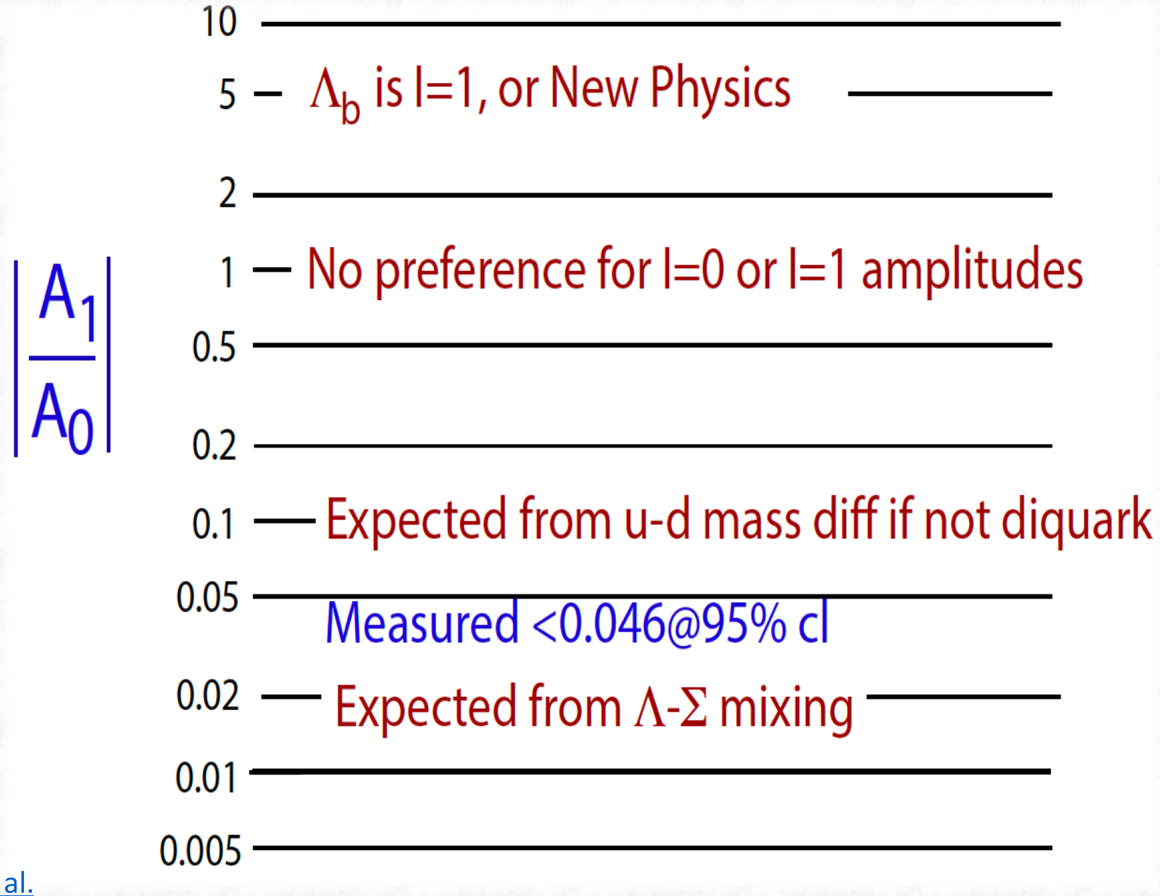


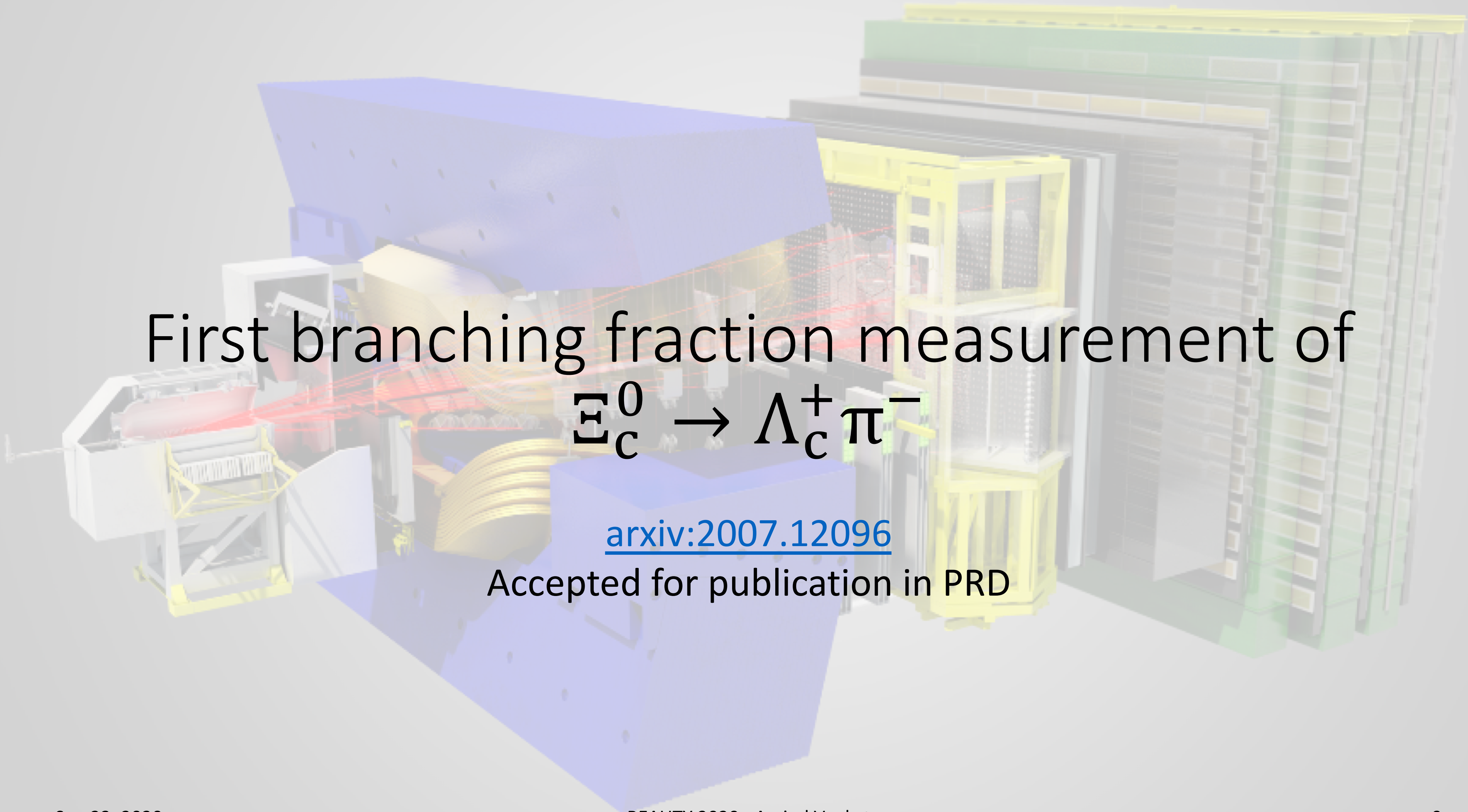
Physics Implications

- Λ_b isospin amplitude ratio $|A_1/A_0| < 4.6\%$ @ 95% C. L.
- Non sighting of $\Lambda_b \to J/\psi\ \Sigma^0$ strengthens
  - Iso-scalar assignment of Λ_b in quark model
  - $b(ud)$ diquark structure of Λ_b
  - Assumption of isospin suppression in past analyses
  - Exclusion of I=1 NP amplitudes

- $\Xi_b^0 \to J/\psi\ \Lambda$ ($\Delta I = 1/2$) vs. $\Xi_b^0 \to J/\psi\ \Xi^0$ ($\Delta I = 0$)
  - **First measurement** $\frac{B(\Xi_b^0 \to J/\psi\ \Lambda)}{B(\Xi_b^0 \to J/\psi\ \Xi^0)} = (8.2 \pm 2.1 \pm 0.9) \cdot 10^{-3}$
  - Extract $|A_0/A_{1/2}| = 0.37 \pm 0.06 \pm 0.02$
  - SU(3)$_F$ prediction : $|A_0/A_{1/2}| = 0.41 \pm 0.08$ Dery et. al

- Similar to isospin amplitudes for heavy flavour mesons (obtained from fits to data):
  - $D \to \pi\pi$: $|A_0/A_2| \approx 2.5$ (O(1) enhancement) Franco et. al.
  - $B \to \pi\pi$: $|A_0/A_2| \approx 1.5$ (Close to "no QCD" limit) Grinstein et. al.





First branching fraction measurement of $\Xi_c^0 \to \Lambda_c^+ \pi^-$

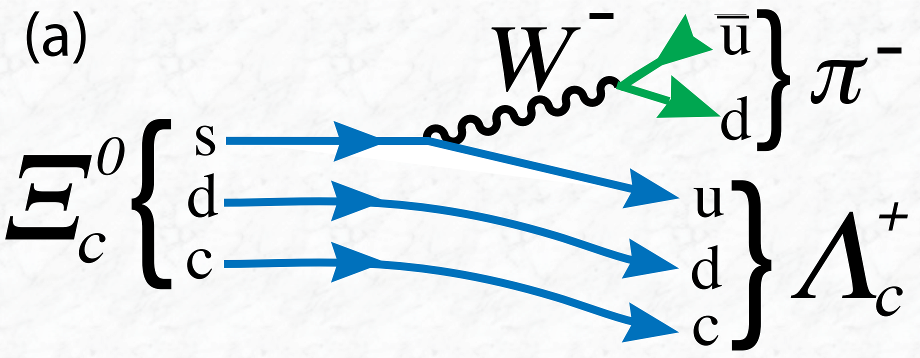
arxiv:2007.12096

Accepted for publication in PRD

Motivation

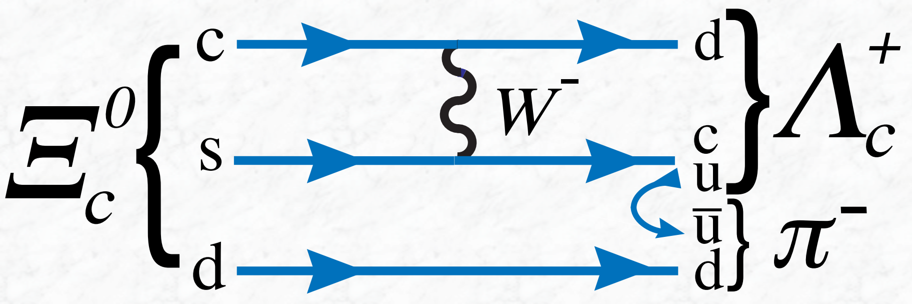
- Ξ_c^0 usually decays via c quark to charmless final states
- Can also decay via s quark
  - $s \rightarrow u\bar{u}d$ (SUUD)
  - $cs \rightarrow dc$ (Weak Scattering - WS)
- $B(\Xi_c^0 \rightarrow \pi^- \Lambda_c^+)$ depends on interference between these amplitudes
- Predictions with negative interference:
  - $B(\Xi_c^0 \rightarrow \pi^- \Lambda_c^+) > (0.025 \pm 0.015)\%$ - Voloshin
  - $B(\Xi_c^0 \rightarrow \pi^- \Lambda_c^+) < 0.03\%$ - Gronau & Rosner
  - $B(\Xi_c^0 \rightarrow \pi^- \Lambda_c^+) \sim 0.0087\%$ - Cheng et. al.
- Predictions with positive interference:
  - $B(\Xi_c^0 \rightarrow \pi^- \Lambda_c^+) = (0.14 \pm 0.07)\%$ - Gronau & Rosner
  - $B(\Xi_c^0 \rightarrow \pi^- \Lambda_c^+) < 0.3\%$ - Faller & Mannel

(a)



SUUD amplitude for Ξ_c^0 decay

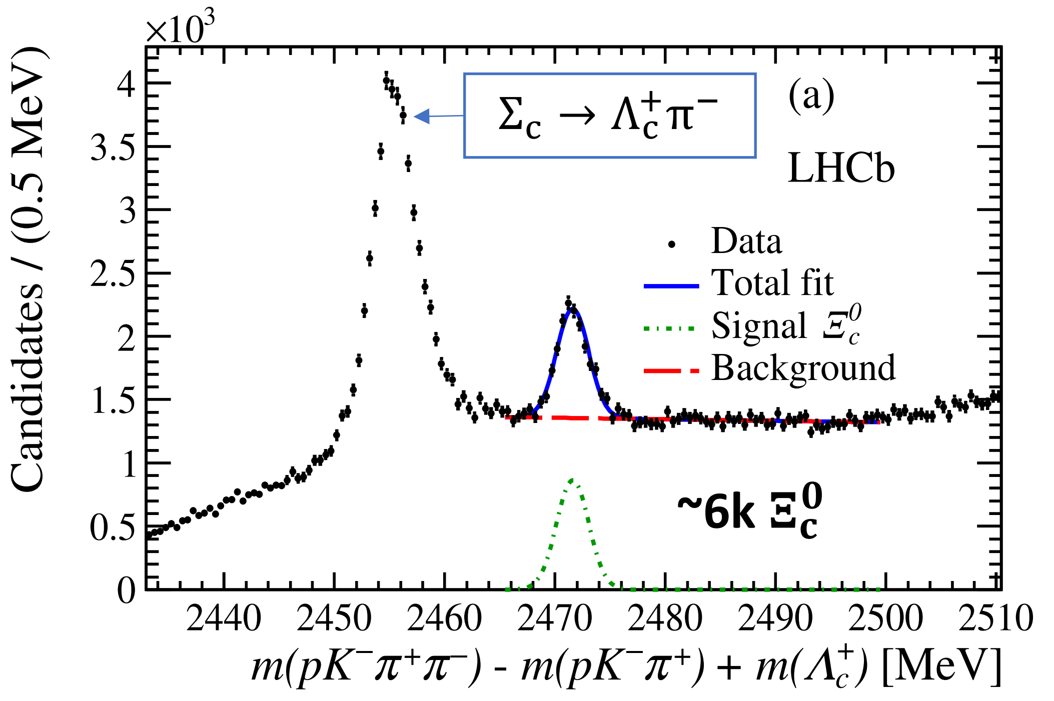
(b)

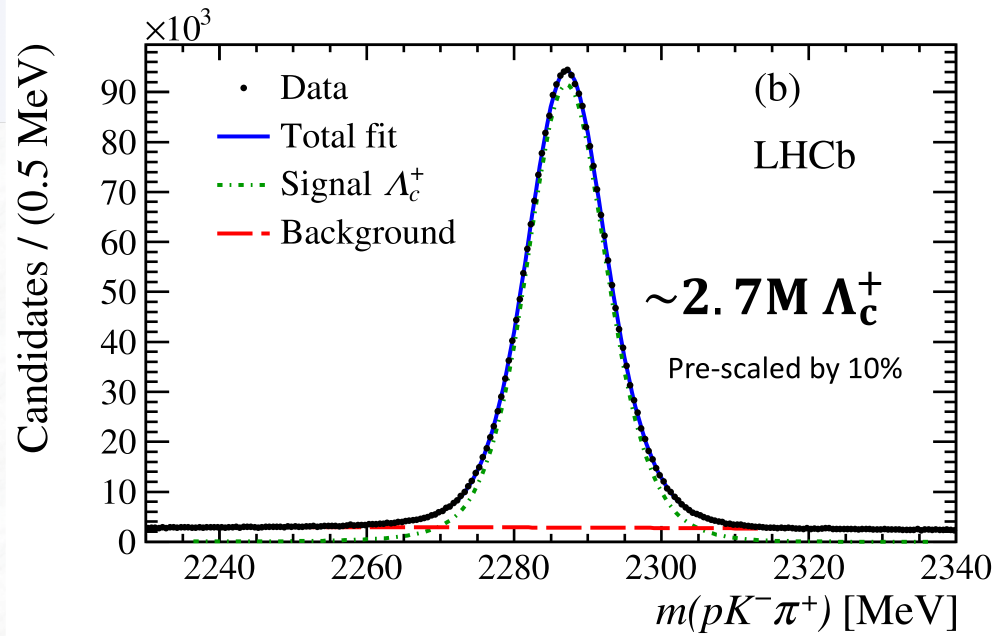


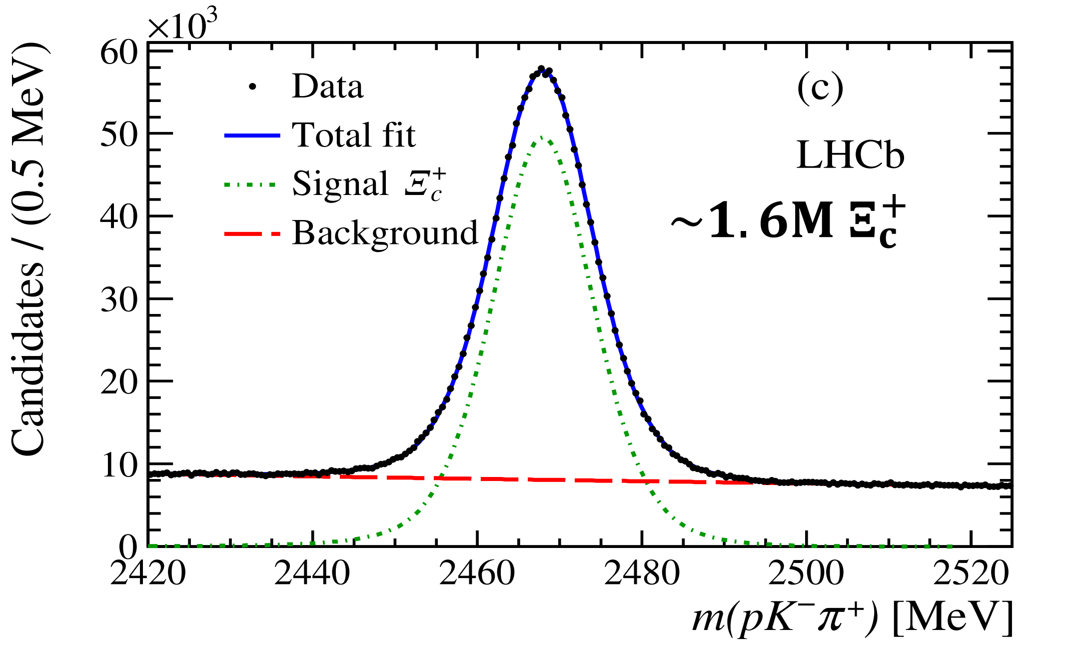
WS amplitude for Ξ_c^0 decay

Reconstruction

- 3.8 fb^{-1} of 13 TeV data – 2017, 2018
- Problem: Lack of accurately measured Ξ_c^0 modes for normalization. Two methods used. Require
  - Prompt $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - Prompt $\Xi_c^+ \rightarrow pK^-\pi^+$
- Prompt Λ_c^+ combined with additional pion to form Ξ_c^0





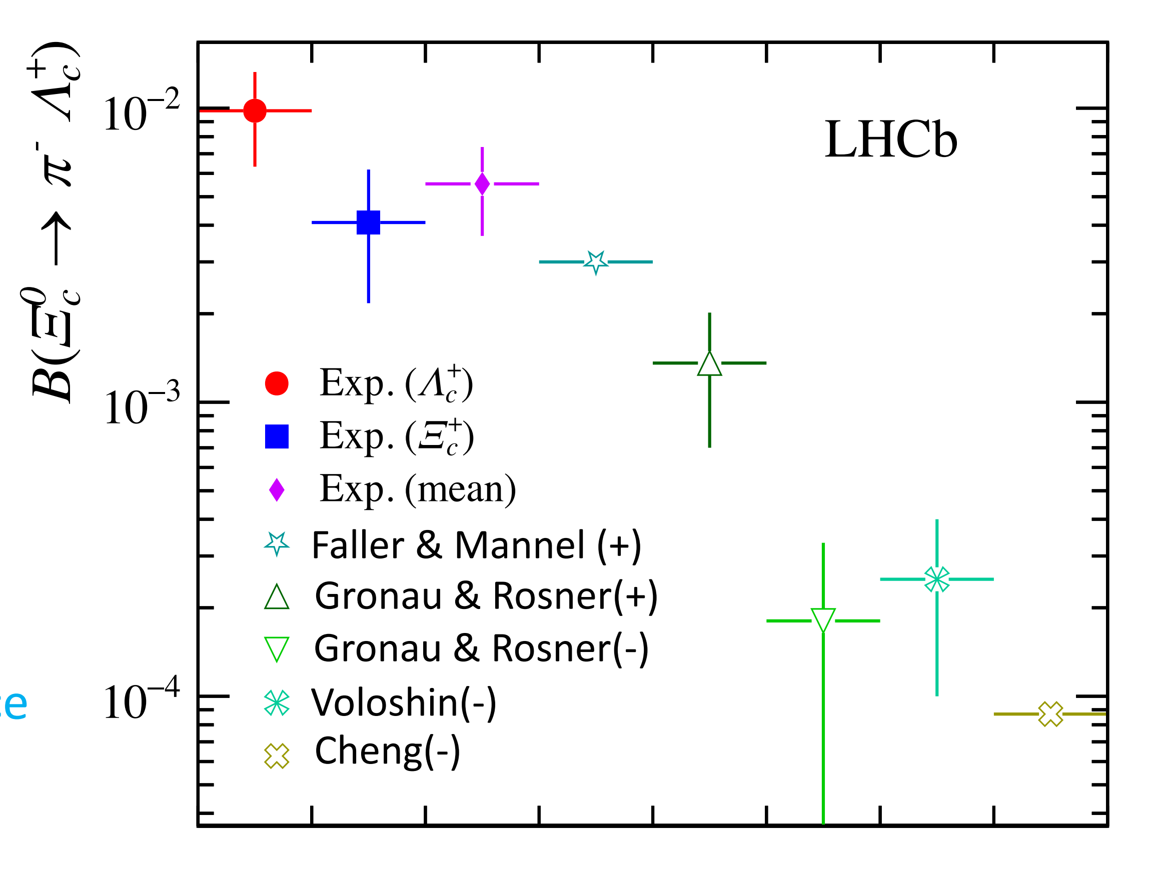


Framework

- $\frac{N(\Xi_c^0 \to \Lambda_c^+ \pi^-)}{N(\Lambda_c^+ \to pK^-\pi^+)} = \frac{f_{\Xi_c^0}}{f_{\Lambda_c^+}} \cdot B(\Xi_c^0 \to \Lambda_c^+ \pi^-)$
  - $\frac{f_{\Xi_c^0}}{f_{\Lambda_c^+}} = C \cdot \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}$ (assuming HQS, correcting for excited Ξ_b feed-down)
  - $\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 2.6)\%$ - LHCb - Aaij et. al.
- $\frac{N(\Xi_c^0 \to \Lambda_c^+ \pi^-)}{N(\Xi_c^+ \to pK^-\pi^+)} = \frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} \cdot \frac{B(\Lambda_c^+ \to pK^-\pi^+)}{B(\Xi_c^+ \to pK^-\pi^+)} \cdot B(\Xi_c^0 \to \Lambda_c^+ \pi^-)$
  - $\frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} = 1.00 \pm 0.01$ (assuming isospin symmetry)
  - $B(\Xi_c^+ \to pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$ - BELLE - Li et. al.
- $\frac{N(\Xi_c^+ \to pK^-\pi^+)}{N(\Lambda_c^+ \to pK^-\pi^+)} = \frac{f_{\Xi_c^+}}{f_{\Lambda_c^+}} \cdot \frac{B(\Xi_c^+ \to pK^-\pi^+)}{B(\Lambda_c^+ \to pK^-\pi^+)}$
  - World average $B(\Lambda_c^+ \to pK^-\pi^+) = (6.23 \pm 0.33)\%$

Results

- $B_{\Lambda_c}(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.98 \pm 0.04 \pm 0.35)\%$
- $B_{\Xi_c}(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.41 \pm 0.01 \pm 0.21)\%$
- Weighted average of B_{Λ_c} and B_{Ξ_c} yields first measurement
    - $B(\Xi_c^0 \to \pi^-\Lambda_c^+) = (0.55 \pm 0.02 \pm 0.18)\%$
- $B(\Xi_c^+ \to pK^-\pi^+) = (1.135 \pm 0.002 \pm 0.387)\%$
    - Compare w/ Belle measurement $(0.45 \pm 0.21 \pm 0.07)\%$
- We favor predictions made assuming constructive interference between $s \to u\bar{u}d$ and weak scattering amplitudes

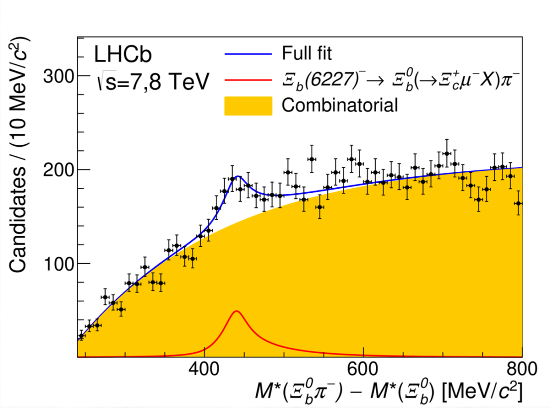


First observation of excited Ω_b^- states

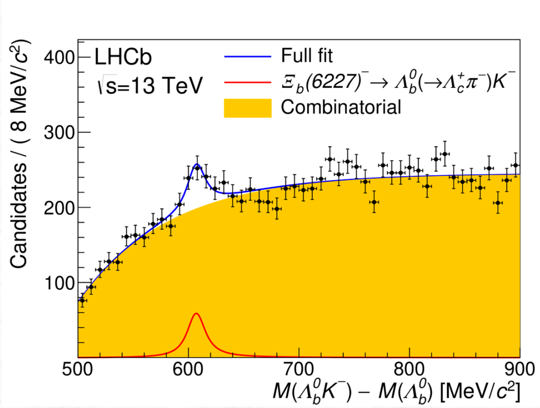
PRL:124.082002

Motivation

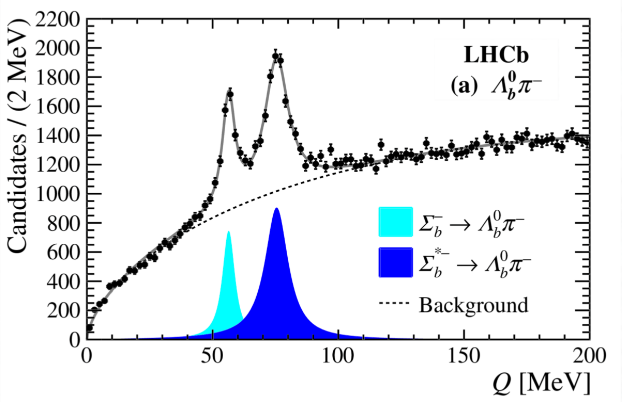
- Numerous peaking structures observed



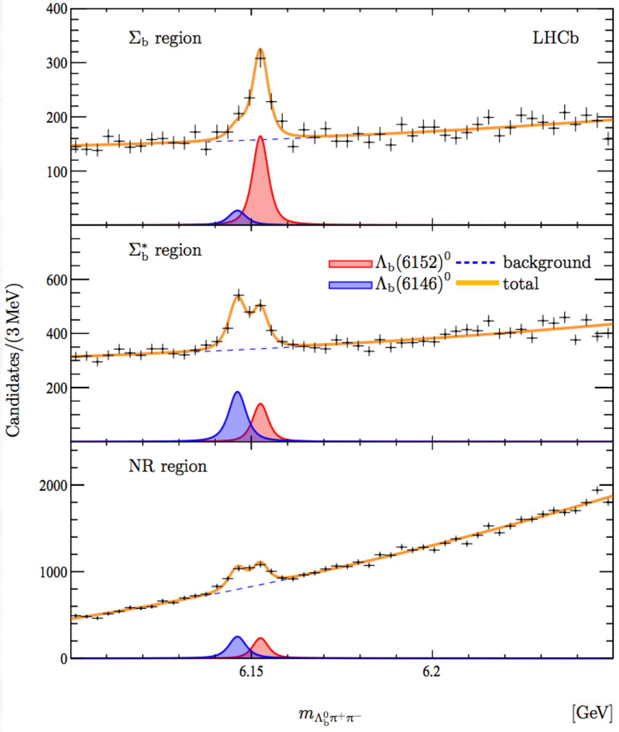
$\Xi_b(6227)^-$ in $\Xi_b^0\pi^-$



$\Xi_b(6227)^-$ in $\Lambda_b K^-$



$\Sigma_b^{(*)\pm}$ in $\Lambda_b\pi^-$



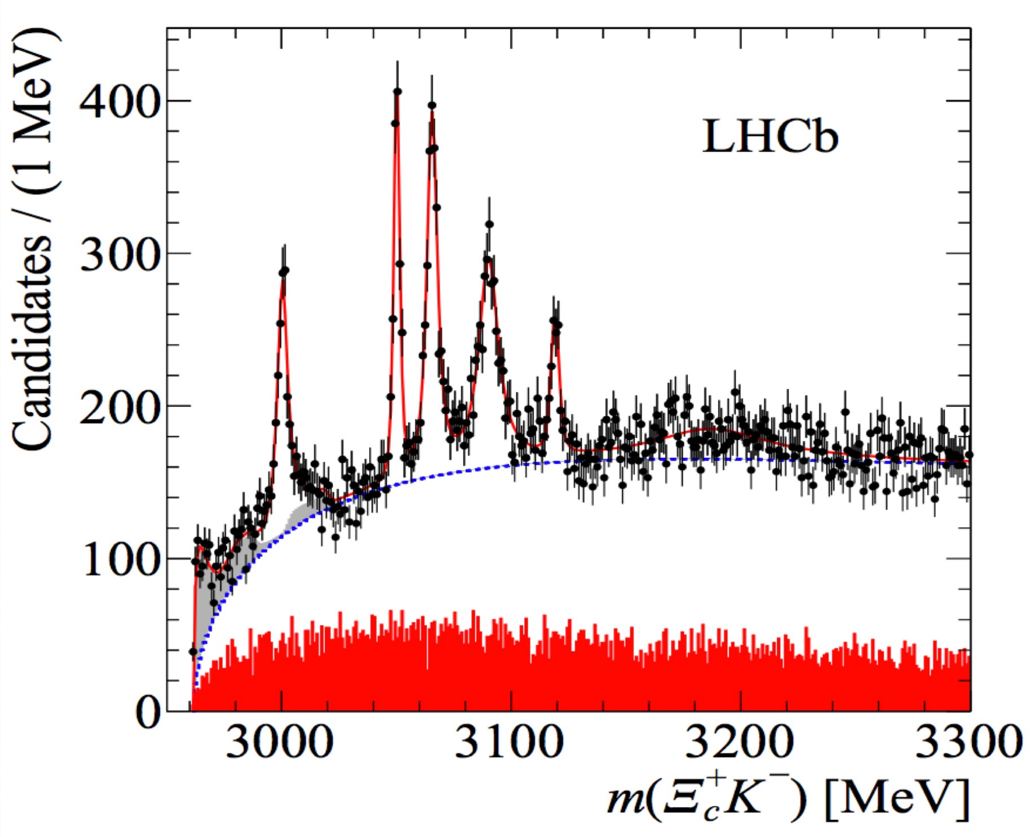
$\Lambda_b(6146, 6152)^0$ in $\Lambda_b\pi^+\pi^-$

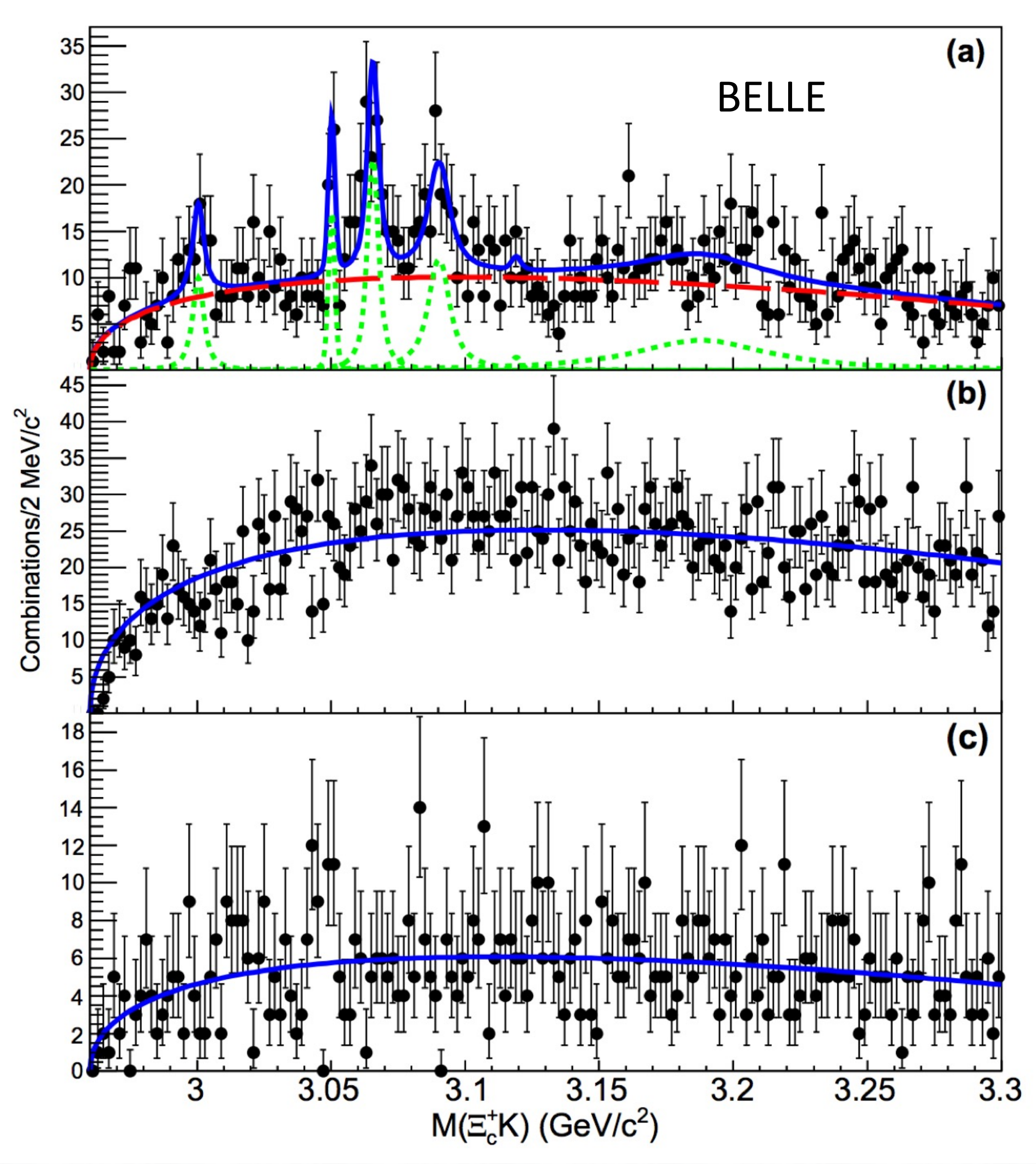
Confirmed by CMS!

- Provide valuable information to improve our understanding of QCD
- Renewed interest in hadronic structure

Motivation

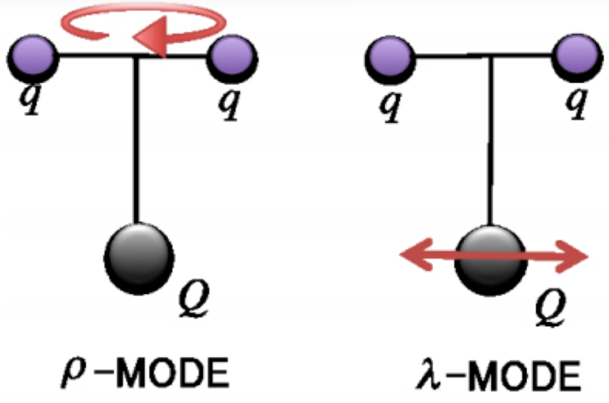
- 5 narrow states observed by LHCb in $\Xi_c^+ K^-$ in 2017 LHCb - Aaij et. al.
  - Interpreted as excited Ω_c^0 baryons
  - Mostly confirmed by Belle in 2018 BELLE-Yelton et. al.





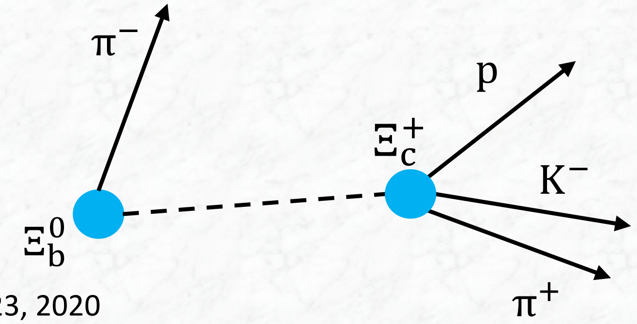
Reconstruction

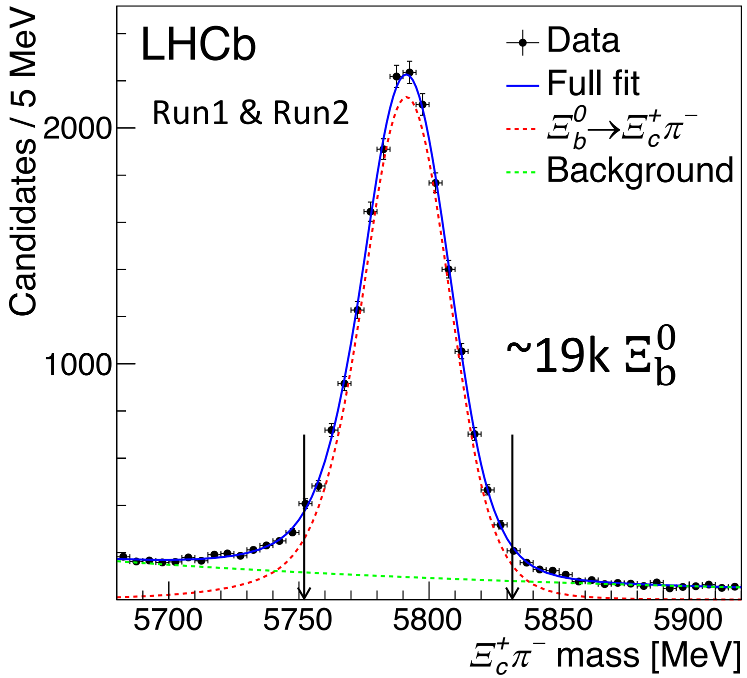
- Yoshida et. al. use constituent quark model to predict $\frac{1}{2}^{+,-}, \frac{3}{2}^{+,-}, \frac{5}{2}^{+,-}$ Ω_b states and their masses
- Karliner & Rosner interpret Ω_c states using quark-diquark model, propose 5 similar $b(ss)$ states
- Huang et. al. analyze the $\Omega_c(3119)^0$ state as a molecular ΞD pentaquark, predict $J^P = \frac{1}{2}^-$ ΞB resonance in $\Xi_b K$ channel with mass 6560 MeV and width 0.2 MeV



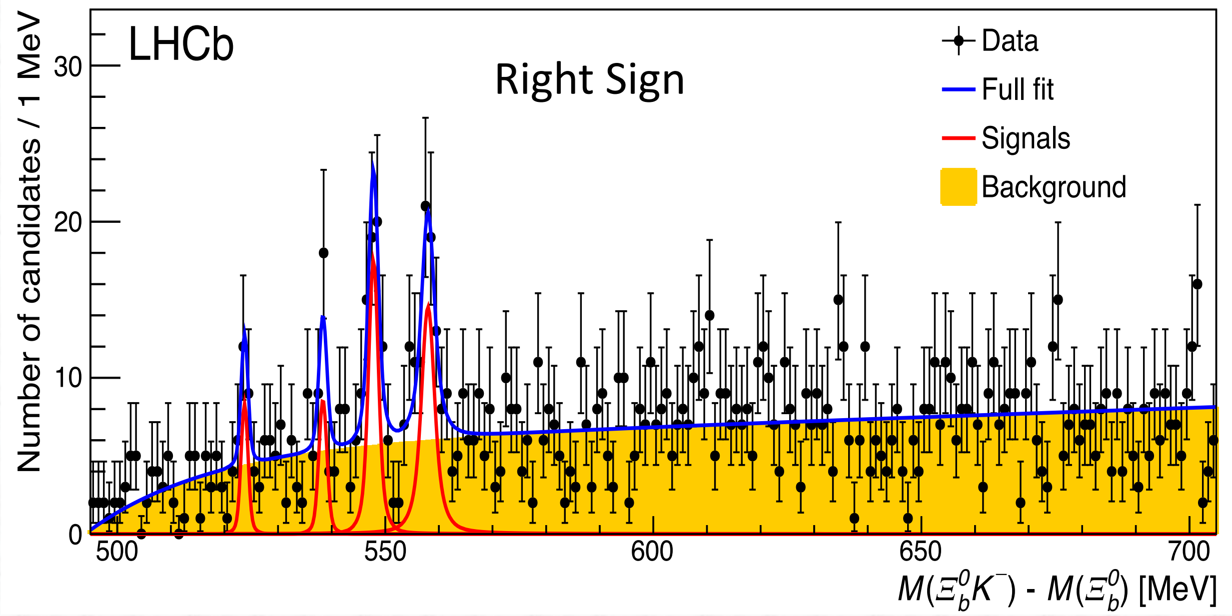
The ρ and λ excitations of a single heavy baryon
Fig. from Yoshida et. al

- We reconstruct $\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$ using all Run 1 and Run 2 data
  - Ξ_b^0 decay vertex required to be displaced from primary vertex

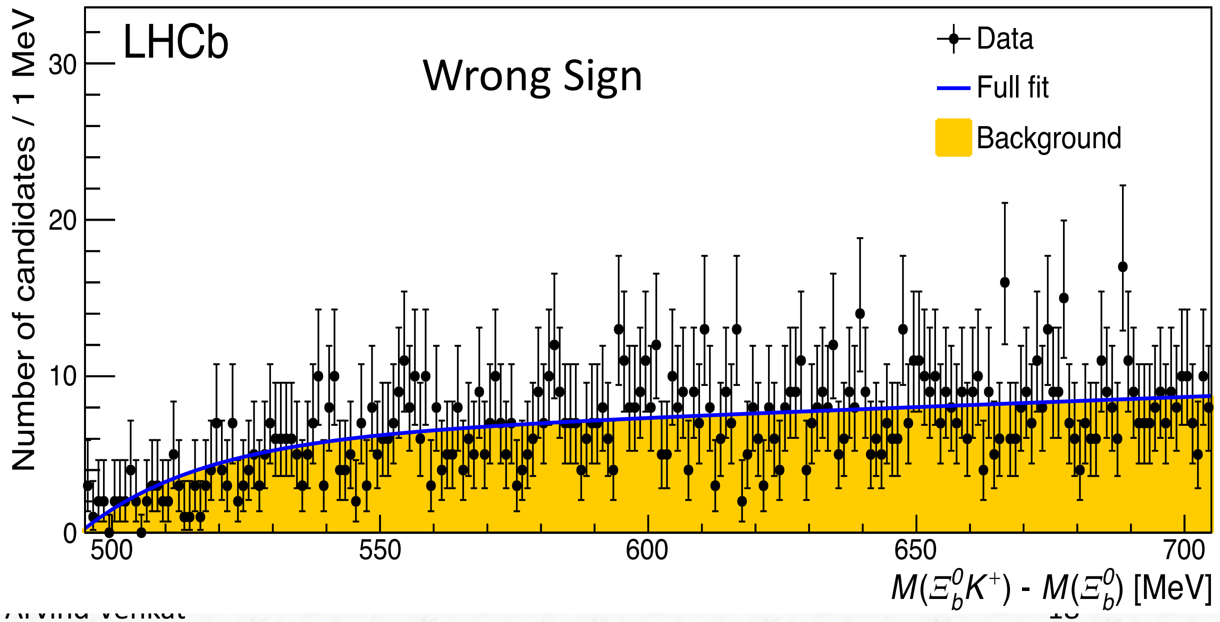




Fits

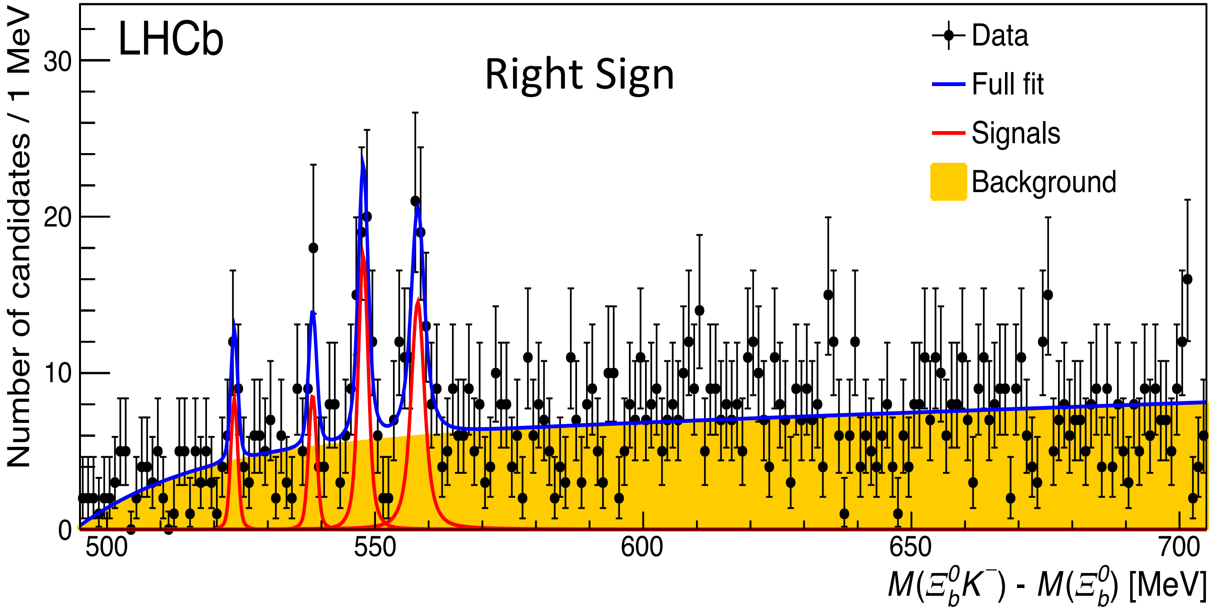


- Ξ_b^0 combined with K^- originating from PV
  - Cut on K^- PID to suppress random combinations
  - Common vertex constrained to coincide with PV
  - Improves resolution on $\delta M \equiv M(\Xi_b^0 K^-) - M(\Xi_b^0)$ by 2x
- δM resolution obtained from simulation samples generated at several masses
  - Described by sum of two Gaussians
  - Smooth monotonic function used to parametrize resolution as function of mass



- RS ($\Xi_b^0 K^-$) and WS ($\Xi_b^0 K^+$) spectra fit simultaneously
- Signal peaks described by S-wave rel. BW function with a Blatt-Weisskopf barrier factor, convoluted with the resolution function

Fits



- All peaks have natural width consistent with zero
- Global significances calculated using pseudo-experiments, account for look-elsewhere effect

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

Interpretation

- Simplest interpretation of peaks is as excited Ω_b^- states
  - L = 1 angular momentum excitations or n = 2 radial excitations

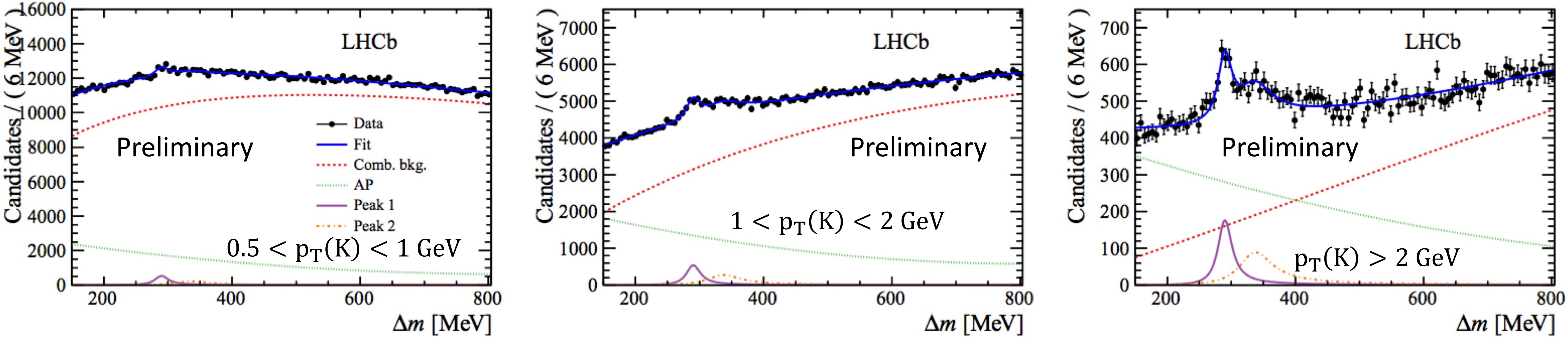
- Quark model calculations predict L = 1 states in this mass range [Yoshida et. al.]
  - $3P_0$ model predicts 5 states: [Santopinto et. al.]
    - ~8 MeV mass splitting
    - 4 lightest have $\Gamma(\Xi_b^0 K^-) < 1\ \mathrm{MeV}$, heaviest has $\Gamma(\Xi_b^0 K^-) = 1.49\ \mathrm{MeV}$
  - Chiral quark-diquark model says $\frac{3}{2}^-$ and $\frac{5}{2}^-$ are narrow, $\frac{1}{2}^-$ is $50 - 100\ \mathrm{MeV}$ wide [Wang et. al.]

- Alternate interpretation: Peaks arise from $\Omega_b^{**-} \rightarrow \Xi_b'^0(\rightarrow \Xi_b^0\pi^0)K^-$, missing π^0
  - $\Xi_b'^0$ yet to be observed.
  - Works if Ω_b^{**-} states are narrow, $m_{\Omega_b^{**-}} = m_{\Xi_b'^0} + \delta M_{peak}$ and
  - $m_{\Xi_b^0} + m_{\pi^0} < m_{\Xi_b'^0} < m_{\Xi_b'^-}$
  - Doesn't work if $\Xi_b'^0$ can only decay via $\Xi_b^0\gamma$

Other recent results!!

Observation of new excited B_s^0 states PRELIMINARY

- Excess observed in B^+K^- spectrum, ~300 MeV above threshold
- Interpreted as two overlapping B_s^{**0} states
  - Likely $L = 2$ orbitally excited mesons
  - Significance of two peak structure w.r.t. single peak = 7σ
- Structure resulting from $B^{*+} \to (B^+\gamma)\,K^-$ disfavoured, but not impossible



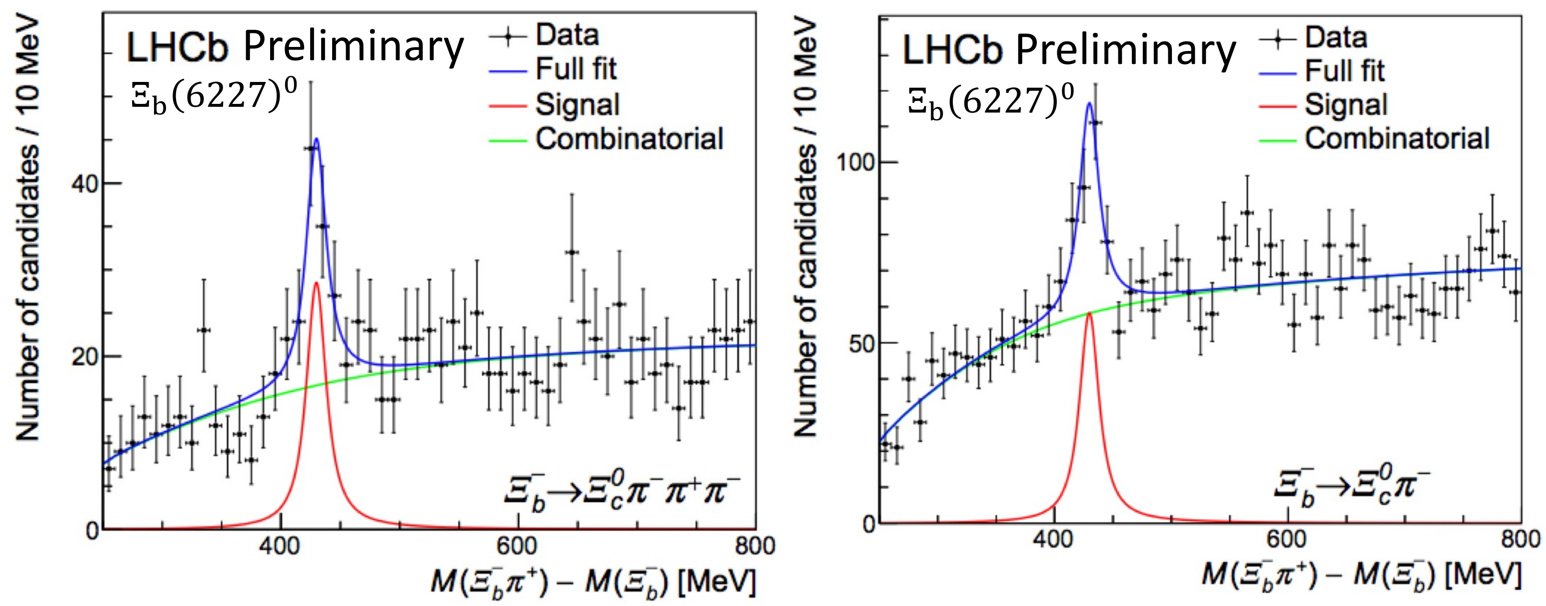
- Masses and widths determined
  - $m_1 = 6063.5 \pm 1.2 \pm 0.8$ MeV, $\Gamma_1 = 26 \pm 4 \pm 4$ MeV
  - $m_2 = 6114 \pm 3 \pm 5$ MeV, $\Gamma_2 = 66 \pm 18 \pm 21$ MeV
- Total 18900 ± 2200 cands. across both peaks and all p_T bins
- $R \equiv \frac{\sum\sigma(B_s^{**0})\times\mathcal{B}(B_s^{**0}\to B^{(*)+}K^-)}{\sigma(B_{s2}^{*0})\times\mathcal{B}(B_{s2}^{*0}\to B^+K^-)} = 0.87 \pm 0.15 \pm 0.19$

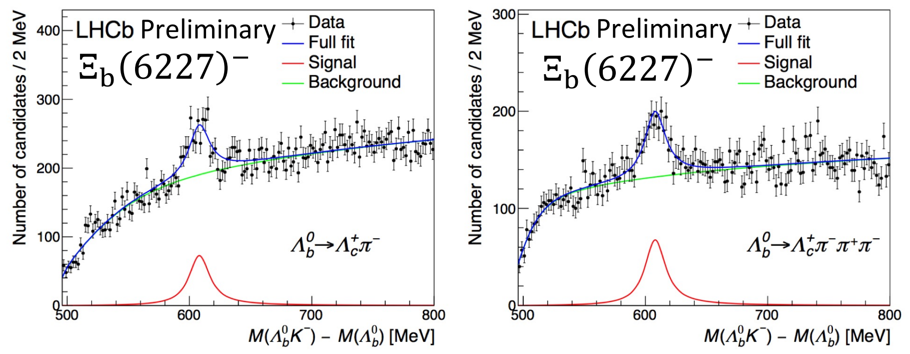
Observation of new Ξ_b state

PRELIMINARY

- New state, $\Xi_b(6227)^0$, observed in $\Xi_b^-\pi^+$ with 10σ significance
  - $\Xi_b^- \rightarrow \Xi_c^0\pi^-\pi^+\pi^-$
  - $\Xi_b^- \rightarrow \Xi_c^0\pi^-$
- $m = 6227.1^{+1.4}_{-1.5} \pm 0.5$ MeV, $\Gamma = 18.6^{+5.0}_{-4.1} \pm 1.4$ MeV

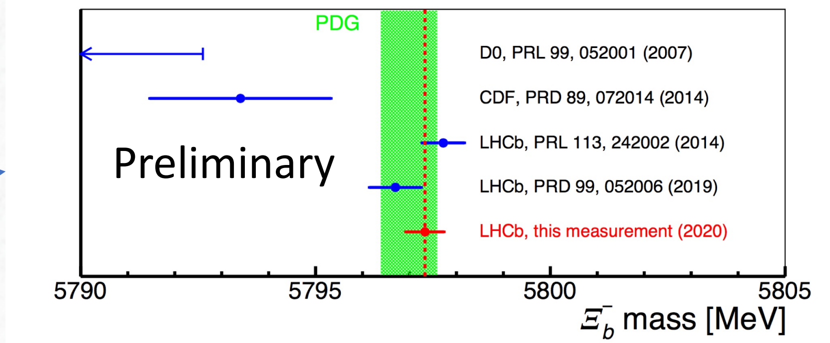
- $\frac{f_{\Xi_b(6227)^0}}{f_{\Xi_b^-}} B(\Xi_b(6227)^0 \rightarrow \Xi_b^-\pi^+) = 0.045 \pm 0.008 \pm 0.004$
  - Consistent with value for $\Xi_b(6227)^-$





$\Xi_b(6227)^0$ consistent with being isospin partner of previously observed $\Xi_b(6227)^- \rightarrow \Xi_b^0\pi^-, \Lambda_b K^-$

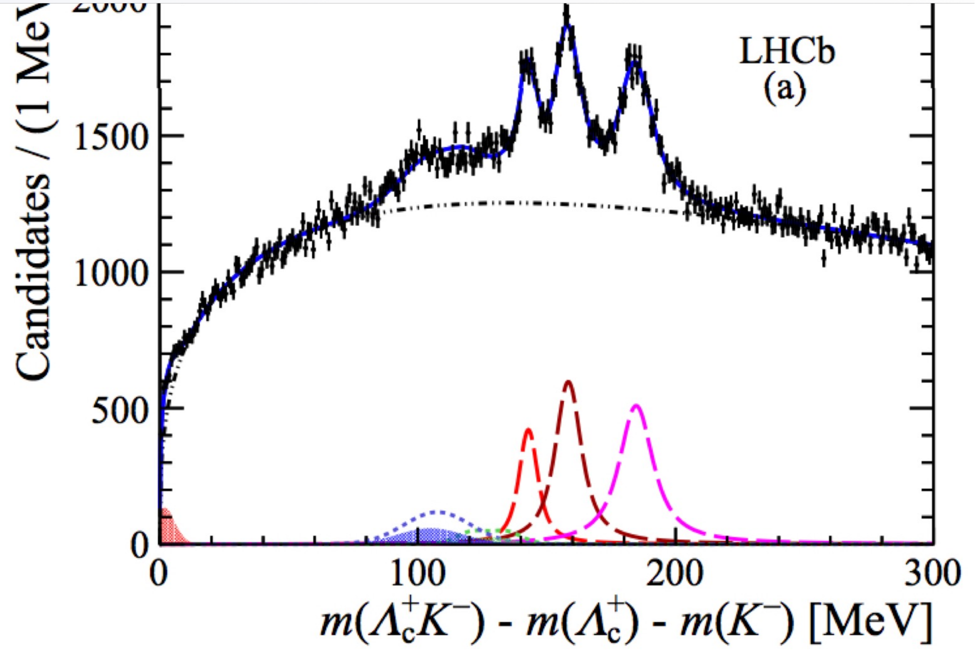
- BONUS: New precision measurement of
  - $m(\Xi_b^-) = 5797.33 \pm 0.27 \pm 0.29$ MeV
  - $m(\Xi_b(6227)^-) = 6227.9 \pm 0.8 \pm 0.5$ MeV



Other recent results

- **Observation of 3 new Ξ_c^0 states in $\Lambda_c^+ K^-$**
  PRL:124.222001

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



- **Precision measurement of B_c^+ meson mass**
  - $6274.47 \pm 0.27 \pm 0.17$ MeV JHEP07(2020)123
  - 2x improvement in precision compared to world avg.
- **Search for doubly heavy $\Xi_{bc}^0 \rightarrow D^0 p K^-$** arxiv:2009.02481, Submitted to JHEP
  - No significant excess observed
  - Upper limits set w.r.t. $\Lambda_b \rightarrow D^0 p K^-$

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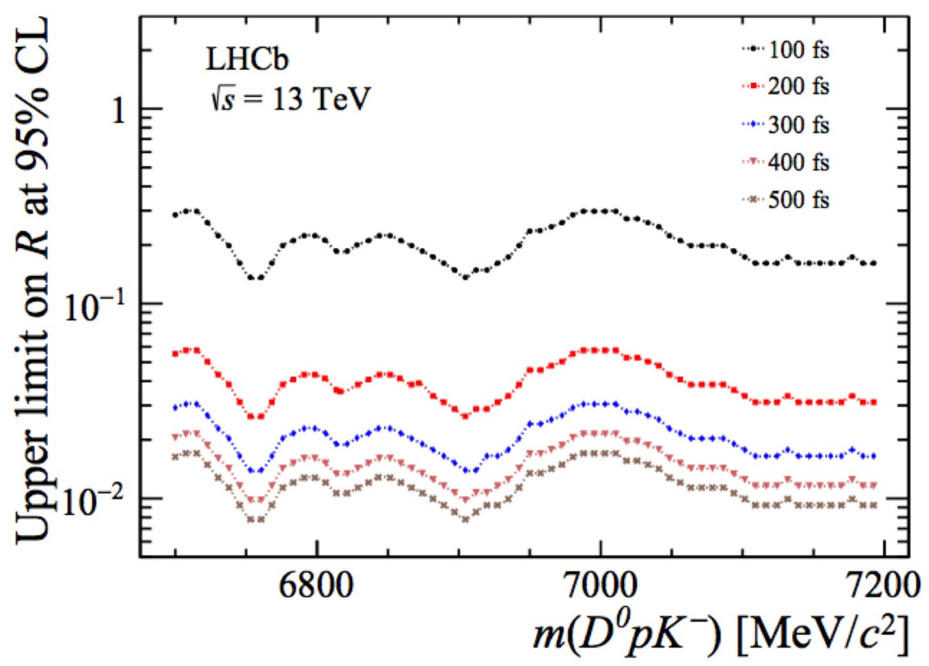


Conclusions

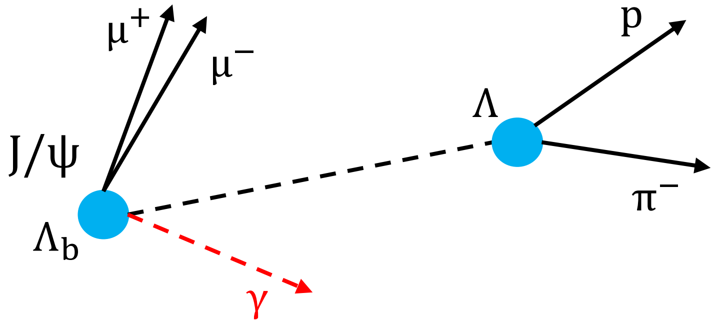
- New results in spectroscopy ***continue*** to come from LHCb
- Insight into baryon physics provided by studying isospin amplitudes in Λ_b and Ξ_b decays
    - Structure and isospin of Λ_b understood
- Suppressed $\Xi_c^0 \rightarrow \Lambda_c^+ \pi^-$ decay observed for the first time
    - Constructive interference between SUUD and WS amplitudes favoured
- Excited Ω_b^- states observed in $\Xi_b^0 K^-$
- More to follow from Run 3 datasets after upgrade -> 23 fb^{-1} by 2025/6
    - 5x instantaneous luminosity   LHCb Upgrade:1709.04709

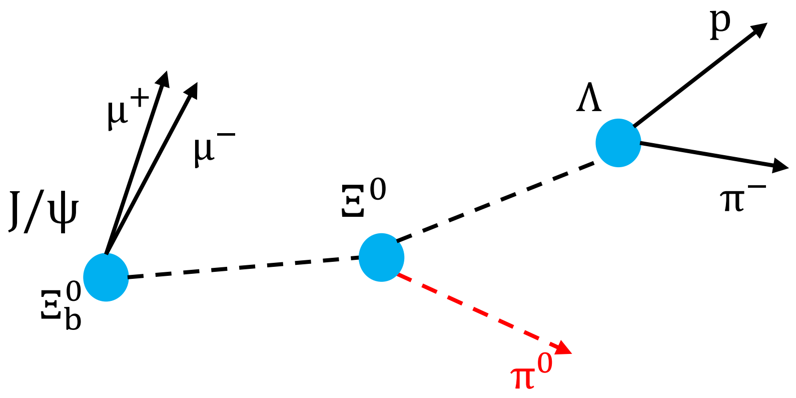
Lorenzo's talk on exotic spectroscopy@LHCb

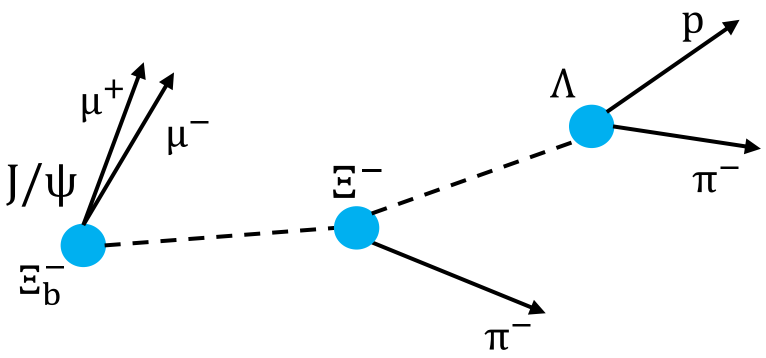
THANK YOU!

BACKUP SLIDES

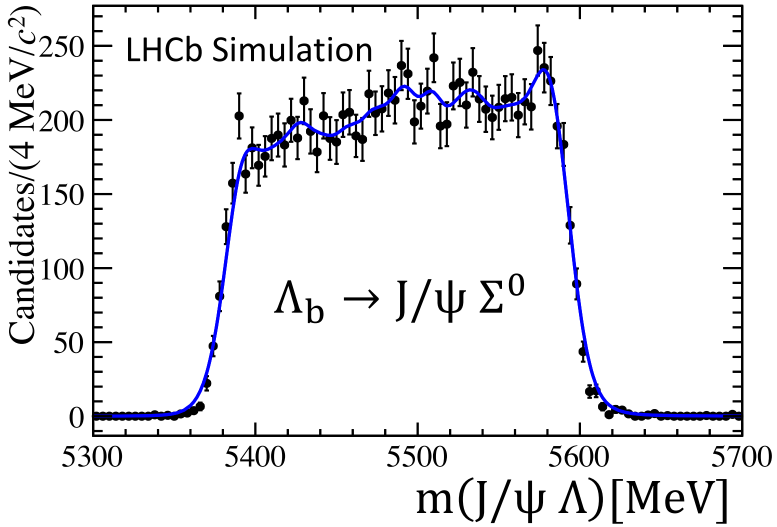
Isospin amplitudes in Λ_b^0 and Ξ_b^0 decays

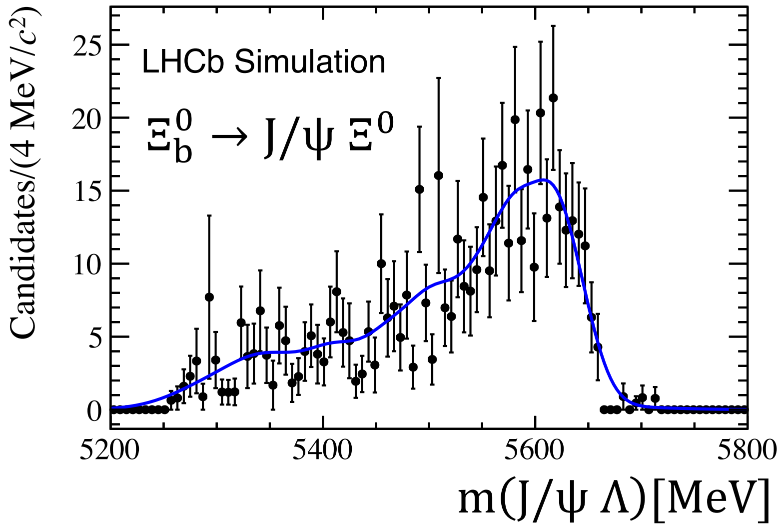


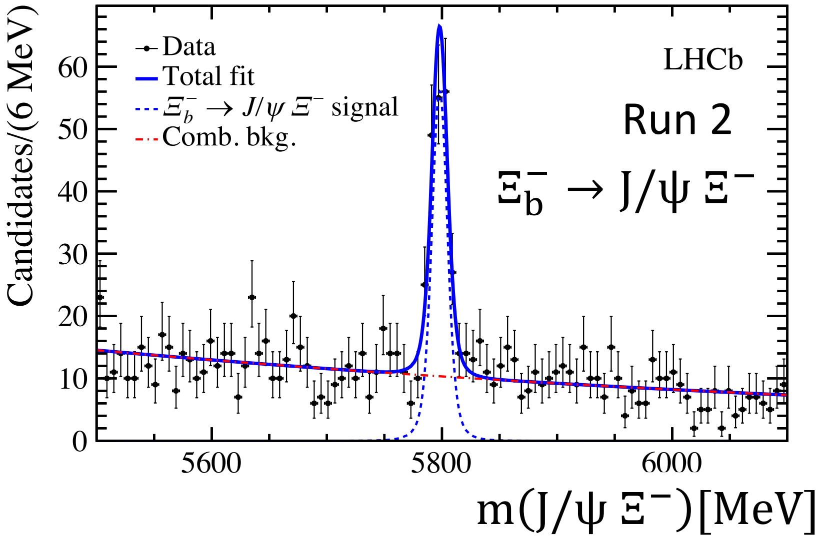




Neutral particles not reconstructed







$\Xi_c^0 \to \pi^- \Lambda_c^+$ Systematics

Source	Estimate (%)		
	$\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+)$		$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$
	$\mathcal{B}_1$	$\mathcal{B}_2$	$\mathcal{B}_3$
$f_{\Xi_b^-}/f_{\Lambda_b^0}$	32	–	32
$f_{\Xi_c^0}/f_{\Lambda_c^+} = \mathcal{C} \cdot f_{\Xi_b^-}/f_{\Lambda_b^0}$	6	–	6
$f_{\Xi_c^0}/f_{\Xi_c^+} = 1$	–	1	1
$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$	–	49	–
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$	–	5	5
Simulation statistics	4	3	2
Trigger efficiency	7	8	2
Ghost tracks	2	2	0
PID	1	1	1
Tracking efficiencies	2	2	0
Fit yields	6	6	3
Intermediate decays	2	2	2
b-decay sources	2	0	2
Lifetimes	3	3	2
Relative $\int \mathcal{L}$	–	1	1
Sum of external	33	49	33
Sum of intrinsic	12	13	6
Sum of all	35	51	34

External - LHCb

Uncertainty from feed-downs

External - BELLE

Feed-downs of excited Ξ_b baryons are not symmetric b/w Ξ_b^- and Ξ_b^0, primarily because $\Xi_b'(5935)^0$ always decays to π^0(or γ)Ξ_b^0, since the $\Xi_b^-\pi^+$ decay is kinematically forbidden to it.

Both $\Xi_b'^-$ and Ξ_b^{*-} states are seen to decay to both $\pi^-\Xi_b^0$ and $\pi^0\Xi_b^-$.

Any as yet unobserved higher mass would be isospin symmetric in their decays.

$$C = 1.18 \pm 0.04$$

Uncertainty arises from errors on rel. BF measurements.

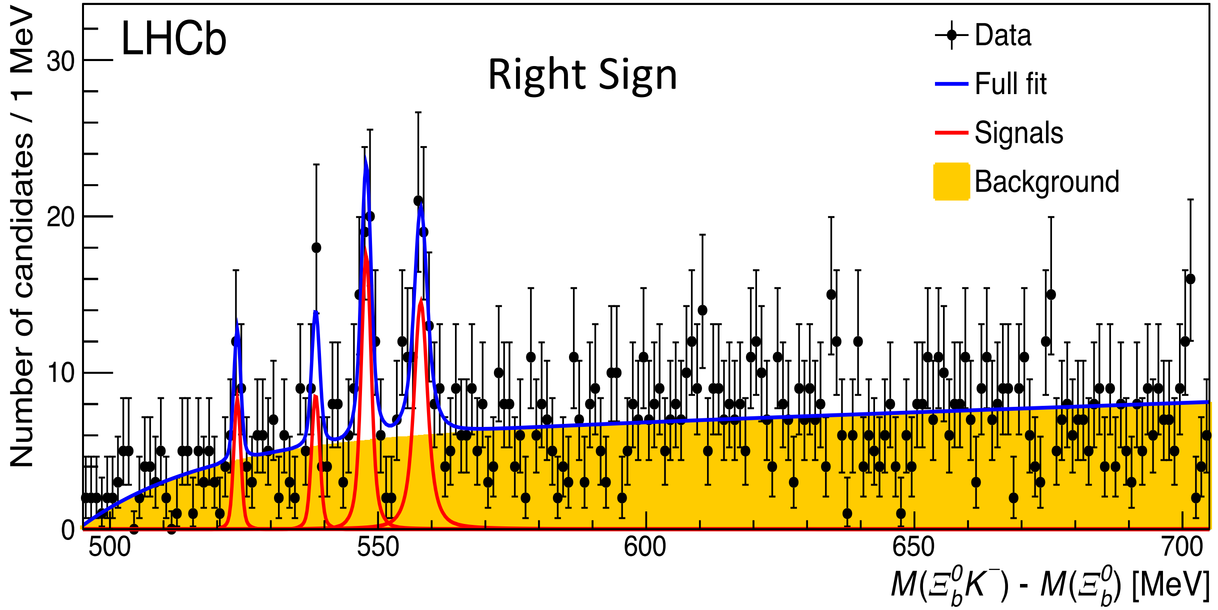
$$\begin{pmatrix} & \mathcal{B}_1 & \mathcal{B}_2 & \mathcal{B}_3 \\ \mathcal{B}_1 & 1 & 0.07 & 0.92 \\ \mathcal{B}_2 & \dots & 1 & -0.02 \\ \mathcal{B}_3 & \dots & \dots & 1 \end{pmatrix}$$

Correlation matrix for measured branching fractions

Excited Ω_b^- states - Systematics

Systematic uncertainties on measured peak positions in δM. The peaks are numbered in order of mass.

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



The primary source of systematic uncertainty on the widths is from an imperfect knowledge of the resolution on δM. Based on previous studies of $D^{*+} \to D^0\pi^+$, the resolution in simulation is found to agree with that in data within $\pm 10\%$

Deviations of ± 0.1 MeV relative to the true value are found from pseudo-experiments.

This is taken into account while calculating upper limits on the widths.