Conventional Heavy Baryon Spectroscopy at LHCb

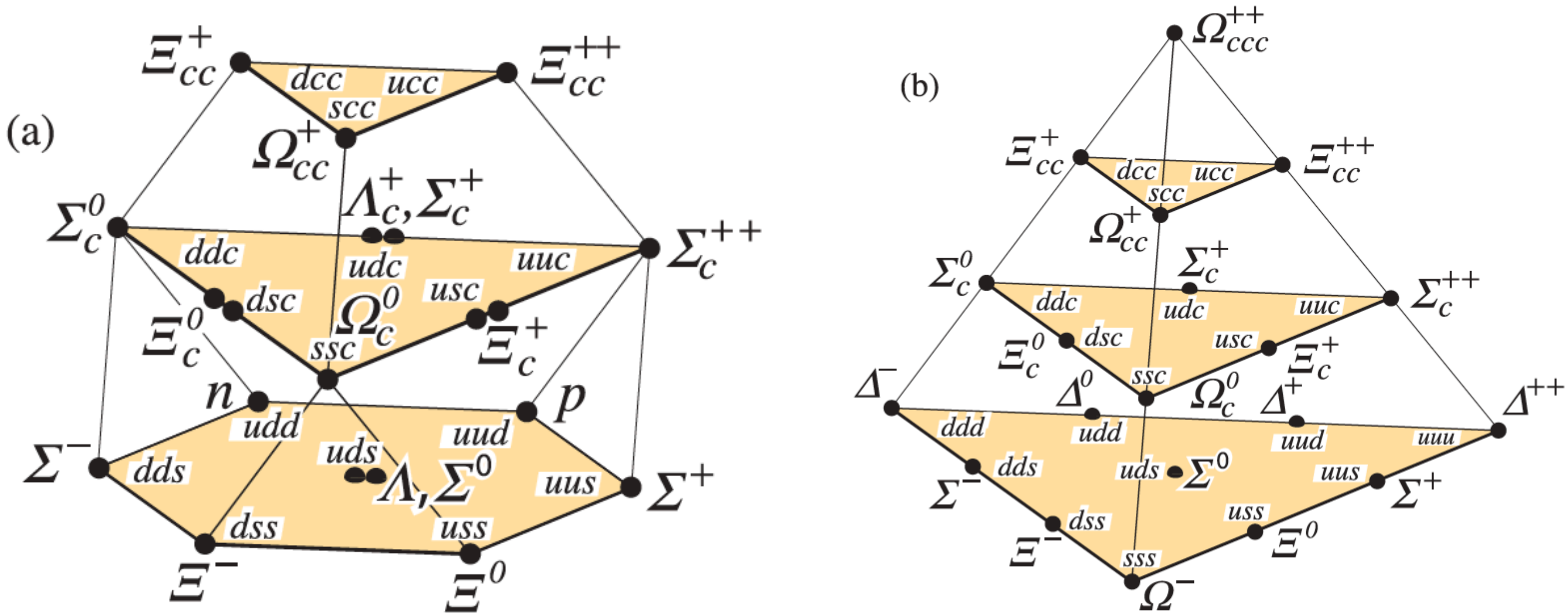
Beauty May, 2018

Introduction

- Conventional baryons we believe are formed of three quarks of different colors
- Whether two of these form a diquark is an arguable question
  - If they do, then which two out of the three?
  - Or can there be a superposition of such states so there is a probability that there are three such diquark states, and maybe even three independent quarks?
  - Can some have diquark structure & others not?

- It is also of great interest to establish normal states so others can be classified as "exotic"

c-baryons SU(4) multiplets

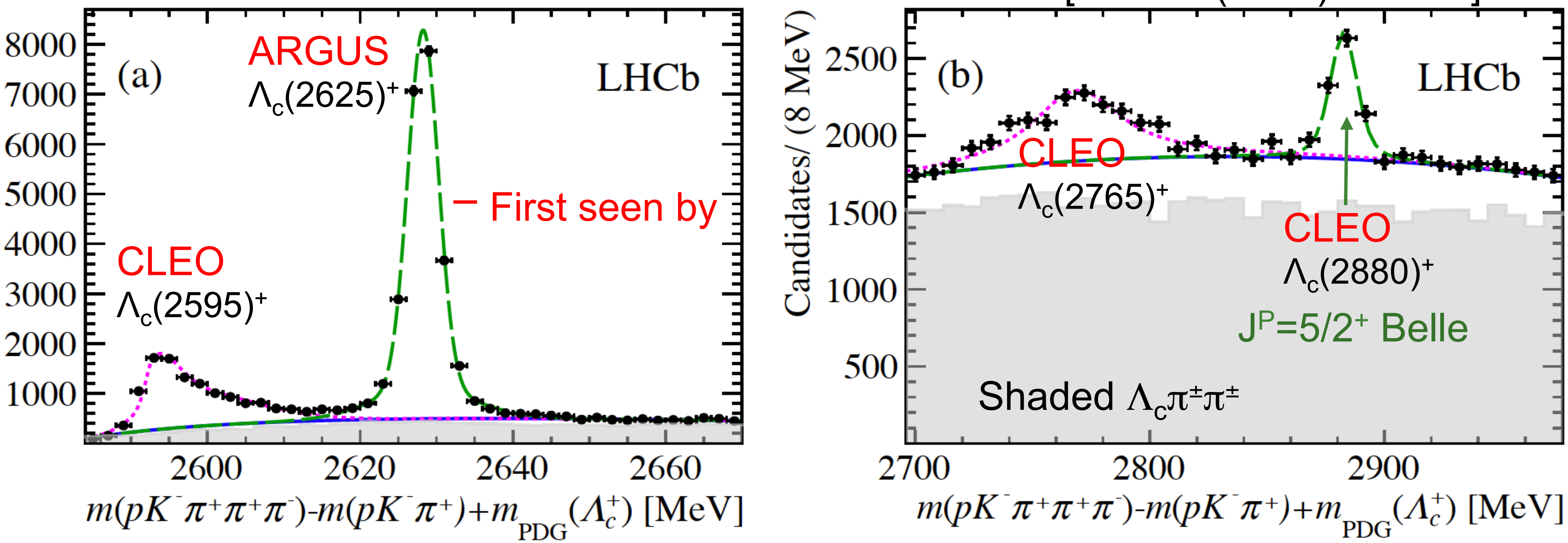


- Many states not yet seen, many excited states with higher radial or ℓ quantum #'s
- Similar plot for b-baryon states

Λ_c* states I

- Semileptonic decay $\Lambda_b \rightarrow \Lambda_c\pi^+\pi^- \mu^-\nu(X)$
- New sightings from LHCb (Mass of $\Lambda_c\pi^+\pi^-$)

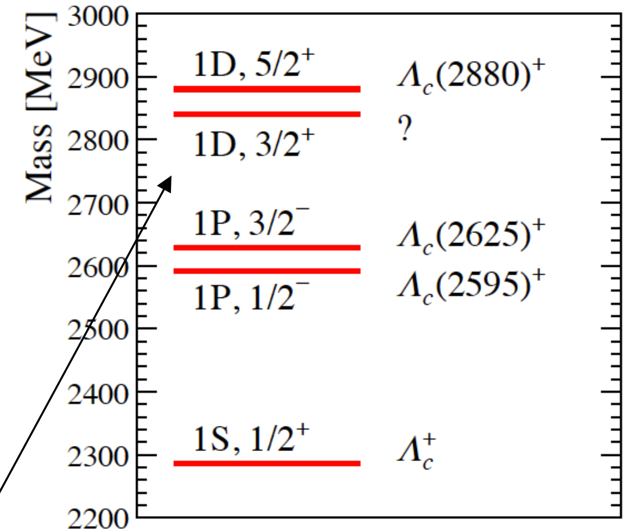
[PRD96 (2017) 112005]

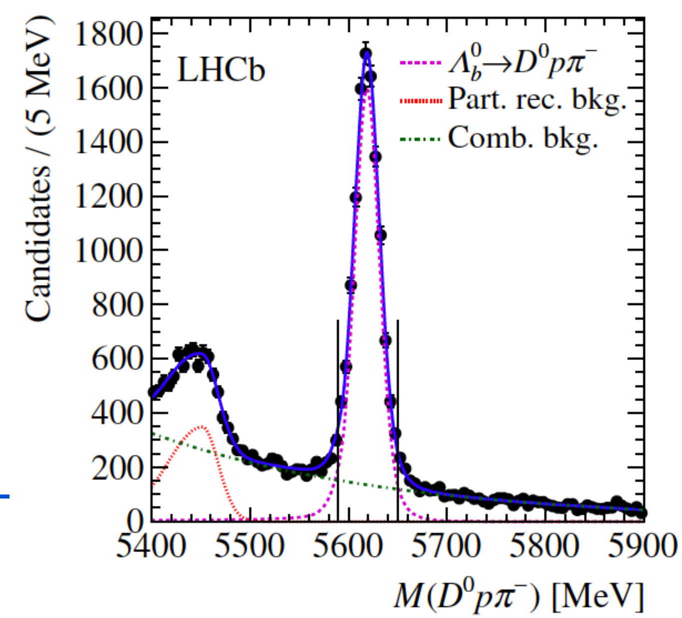


- Λ_b decays, good place to measure for M, Γ & J^P

Λ_c* states II

- Non-relativistic heavy quark – light quark diquark model expectations (B. Chen et. al Eur. Phys. J. A (2015) 51)
- The excited states are 1P & 1D doublets, small mass splittings, but one missing state & no place for the $\Lambda_c(2765)^+$
- Look for $\Lambda_b \rightarrow D^0 p\pi^-$, $\Lambda_c^* \rightarrow D^0 p$



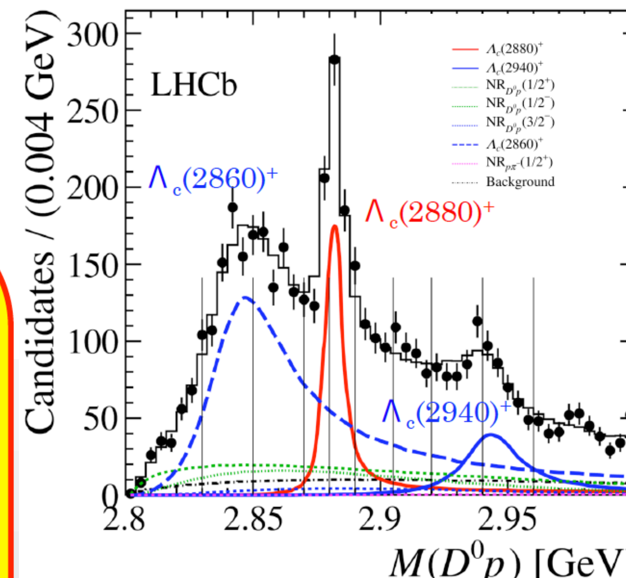


Λ_c* states III

- Amplitude analysis of $\Lambda_b \to D^0 p \pi^-$. Do a 5-dimension amplitude fit of the angular distributions
- Fit results: See new state at 2860 MeV

could be part of the J^P 3/2$^-$ (doublet)

[JHEP 05 (2017) 030]



$\Lambda_c(2860)^+$ with $J^P = 3/2^+$ (preferred)

$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\,\text{MeV}$$
$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\,\text{MeV}$$

$\Lambda_c(2880)^+$ with $J^P =$ 5/2$^+$ (preferred)

$$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})\,\text{MeV}$$
$$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})\,\text{MeV}$$

$\Lambda_c(2940)^+$ with $J^P = 3/2^-$ (preferred)

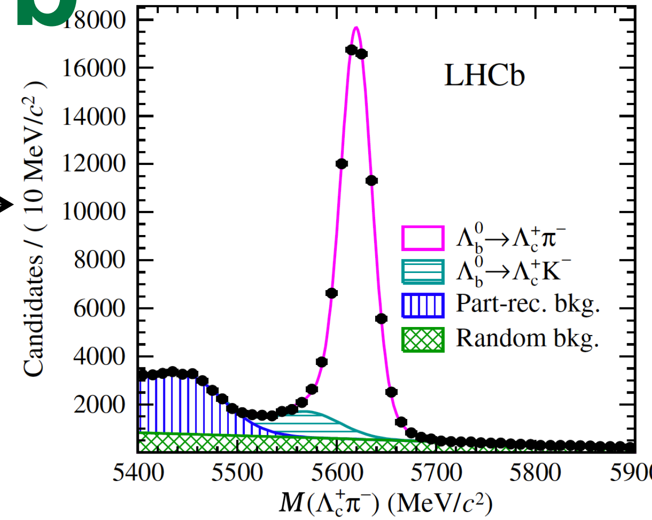
$$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\,\text{MeV}$$
$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})\,\text{MeV}$$

Consistent with Belle

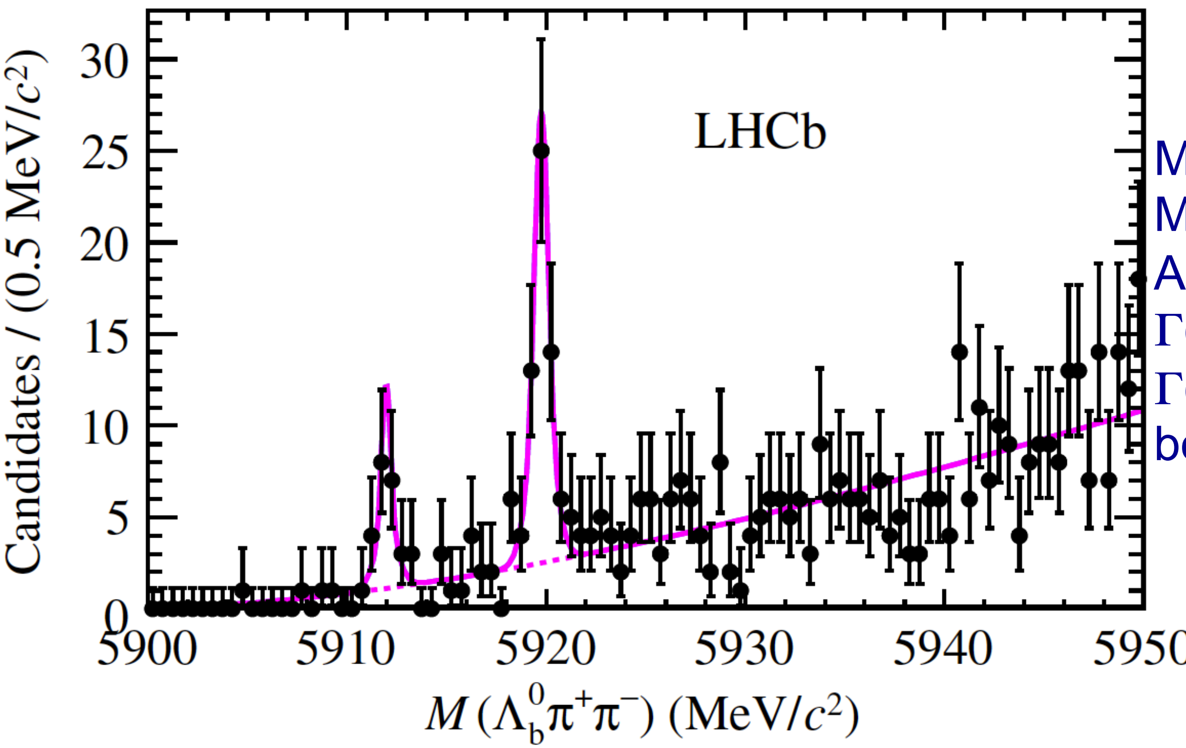
1st seen by Belle

Excited Λ_b states

- Using $\Lambda_c \to pK^-\pi^+$, reconstruct $\Lambda_b \to \Lambda_c^+\pi^-$,
- Next look at $\Lambda_b\pi^+\pi^-$



PRL 109, 172003 (2012)

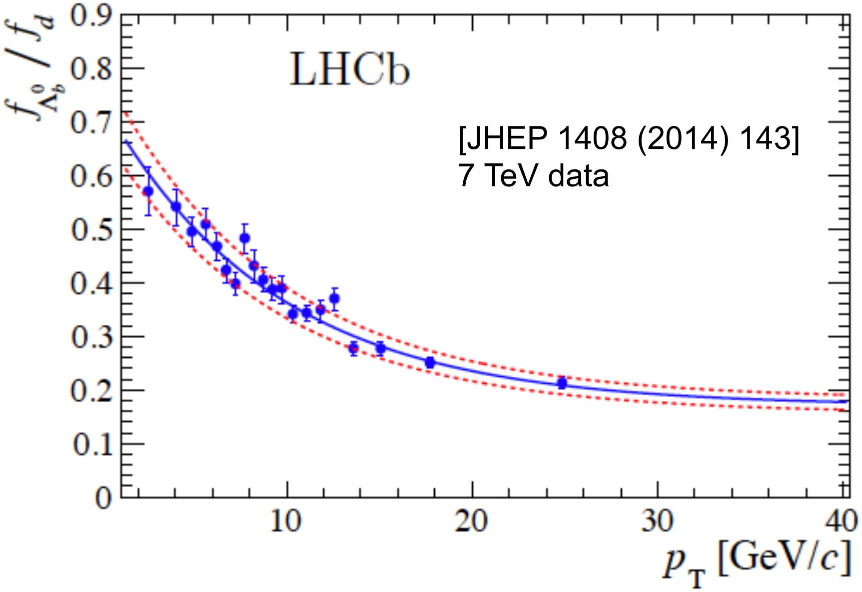


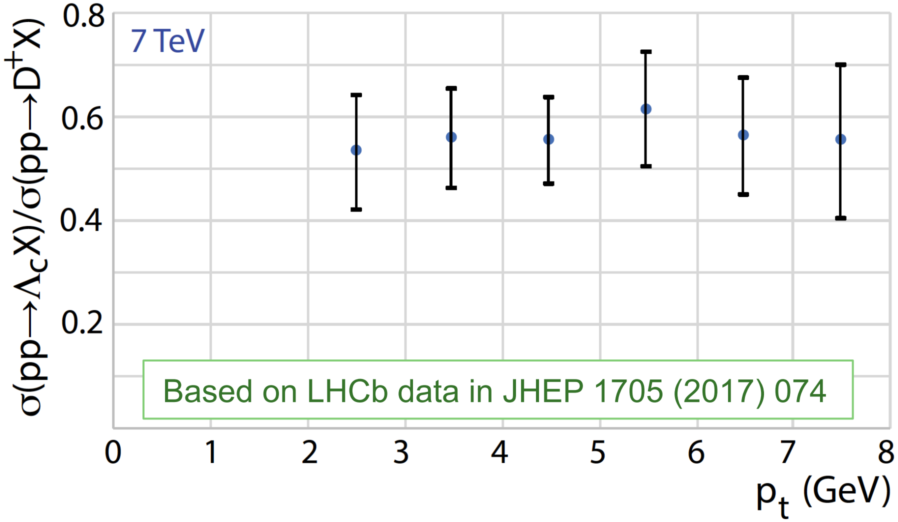
M(5912)=5911.97±0.12±0.02 MeV
M(5920)=5920.77±0.08±0.02 MeV
Add error on Λ_b mass ±0.66 MeV
Γ(5912)<0.66 MeV
Γ(5912)<0.63 MeV,
both at 90% c.l.

Can we see any more such states?

Heavy baryon p_t spectra

- Can we learn anything about internal structure of heavy baryons from the ratio of their p_t spectra to b mesons?
- Λ_b^0/B^0 Λ_c^+/D^+

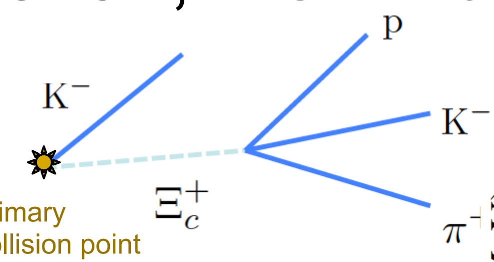


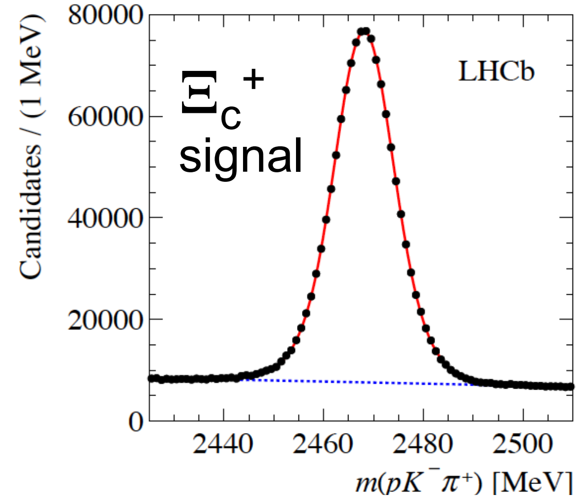


- Why are they so different?

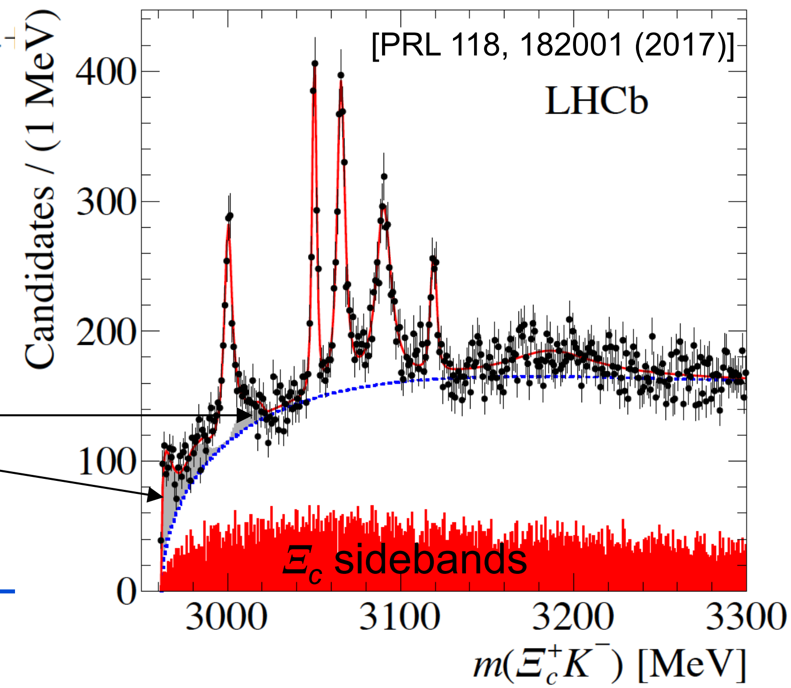
Discovery of 5 Ω_c^* states

- $\Omega_c^* \rightarrow \Omega_c\gamma$ at 2700 MeV seen by Babar (& Belle). Ω_c is css
- $\Omega_c^* \rightarrow \Xi_c^+ K^-$ search, first find $\Xi_c^+ \rightarrow p K^- \pi^+$, then add a K^-





- Observe 5 narrow peaks + one wide one at ~3188 MeV
- Some feed-down from $\Omega_c^* \rightarrow \Xi_c^{+\prime} K^-$, $\Xi_c^{+\prime} \rightarrow \Xi_c^+ \gamma$.



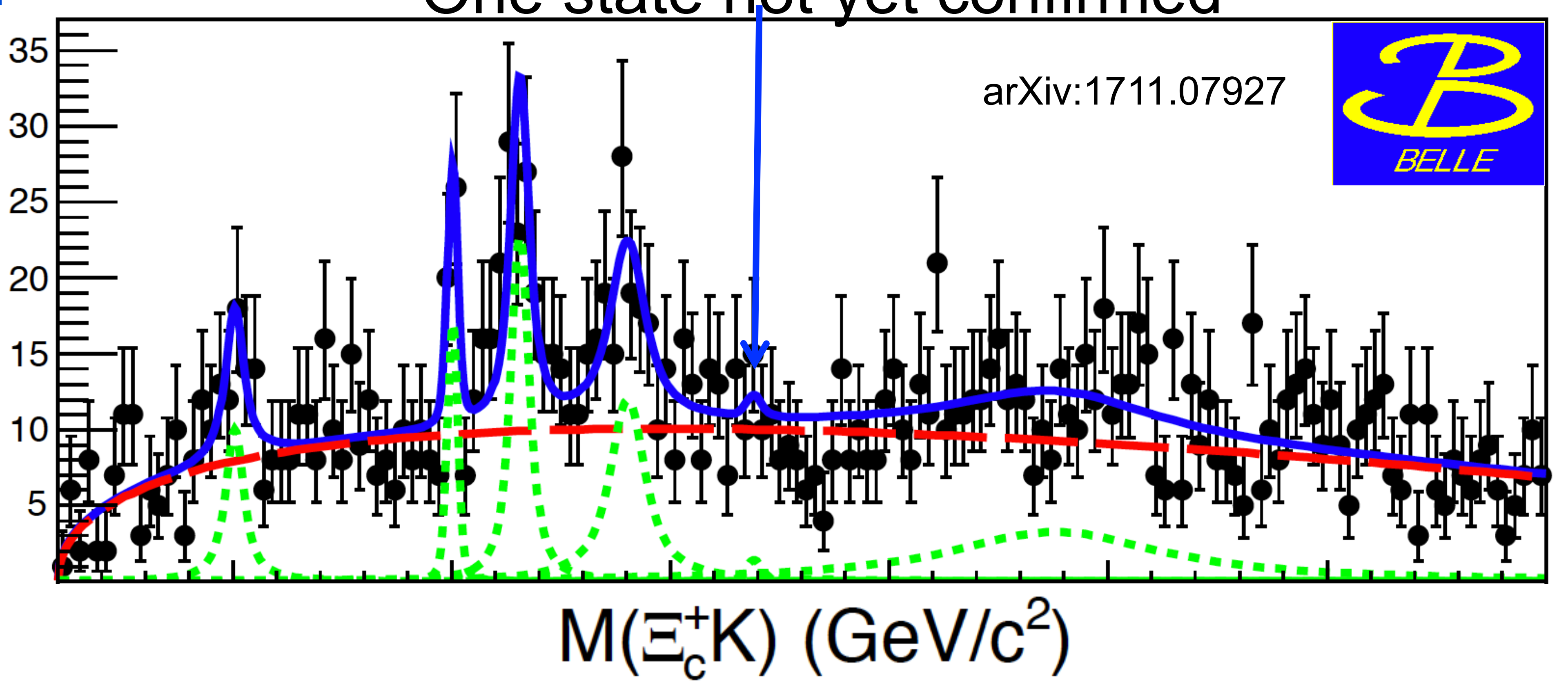
Masses & Γ's

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		<2.6 MeV, 95% C.L.
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

Narrow widths, order a few MeV, may be explained by the internal structure being c+ss diquark (hard to tear the diquark apart), needed to form csu (Ξ_c^+) + su(K^-)

Confirmation of most states

One state not yet confirmed



Models

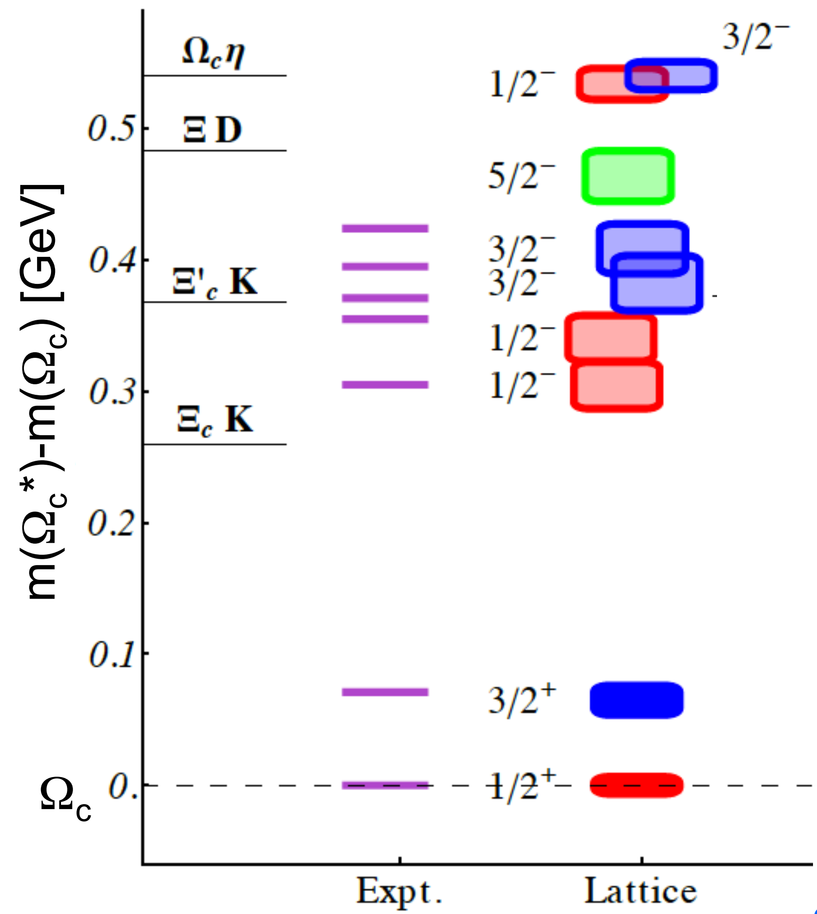
- Many models that predict mass & J^P, but not widths Karliner & Rosner arXiv:1703.07774

State	Mass (MeV)[a]	Proposed J^P
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1$	$1/2^-$ $(3/2^-)$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1$	$1/2^-$ $(3/2^-)$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3$	$3/2^-$ $(5/2^-)$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5$	$3/2^-$ $(1/2^+)$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9$	$5/2^-$ $(3/2^+)$

[a] Additional common error of +0.3,–0.5 MeV from $M(\Xi_c^+)$ uncertainty

- There are other studies using QCD sum rules, chiral soliton models, constituent quark models & pentaquarks
- Need to measure J^P

Lattice arXiv:1704.00259

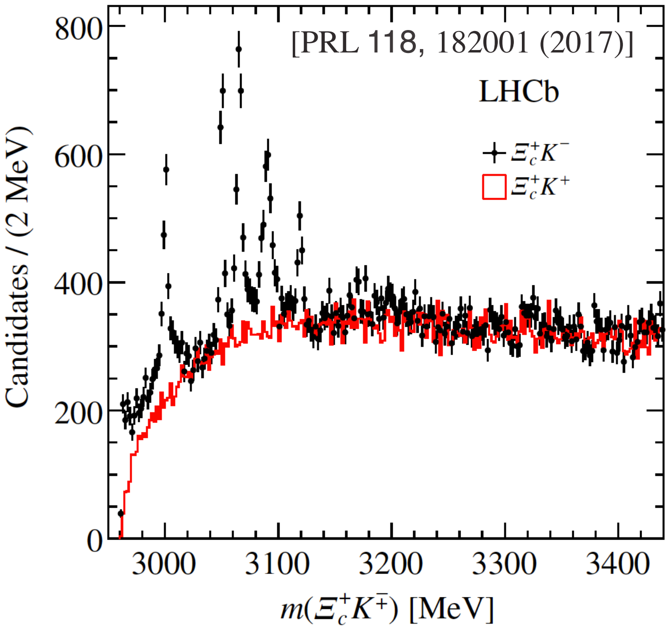


Some more models

- From K-L Wang et. al, arXiv:1703.09130

State	[19]	[20]	[21]	[23]	[29]	[25]	[27]	[28]	[32]	[26]	Quark model This work
$\Omega_c(3000)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^+$ or $3/2^+$	$1/2^-$		$1/2^-$
$\Omega_c(3050)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$5/2^-$	$3/2^-$	$1/2^-$	$5/2^+$ or $7/2^+$	$3/2^-$		$3/2^-$
$\Omega_c(3066)$	$1/2^+$	$1/2^+$ or $1/2^-$	$3/2^-(5/2^-)$	$3/2^-$	$3/2^-$	$5/2^-$	$3/2^-$	$3/2^-$	$1/2^+$		$3/2^-$
$\Omega_c(3090)$			$3/2^-$ $(1/2^+)$	$3/2^-$	$1/2^-$	$1/2^+$	$3/2^-$	$5/2^-$	$1/2^+$		$5/2^-$
$\Omega_c(3119)$	$3/2^+$	$3/2^+$	$5/2^-$ $(3/2^+)$	$5/2^-$	$3/2^-$	$3/2^+$	$5/2^-$	$5/2^+$ or $7/2^+$	$3/2^+$	$1/2^-$	$1/2^+$ or $3/2^+$

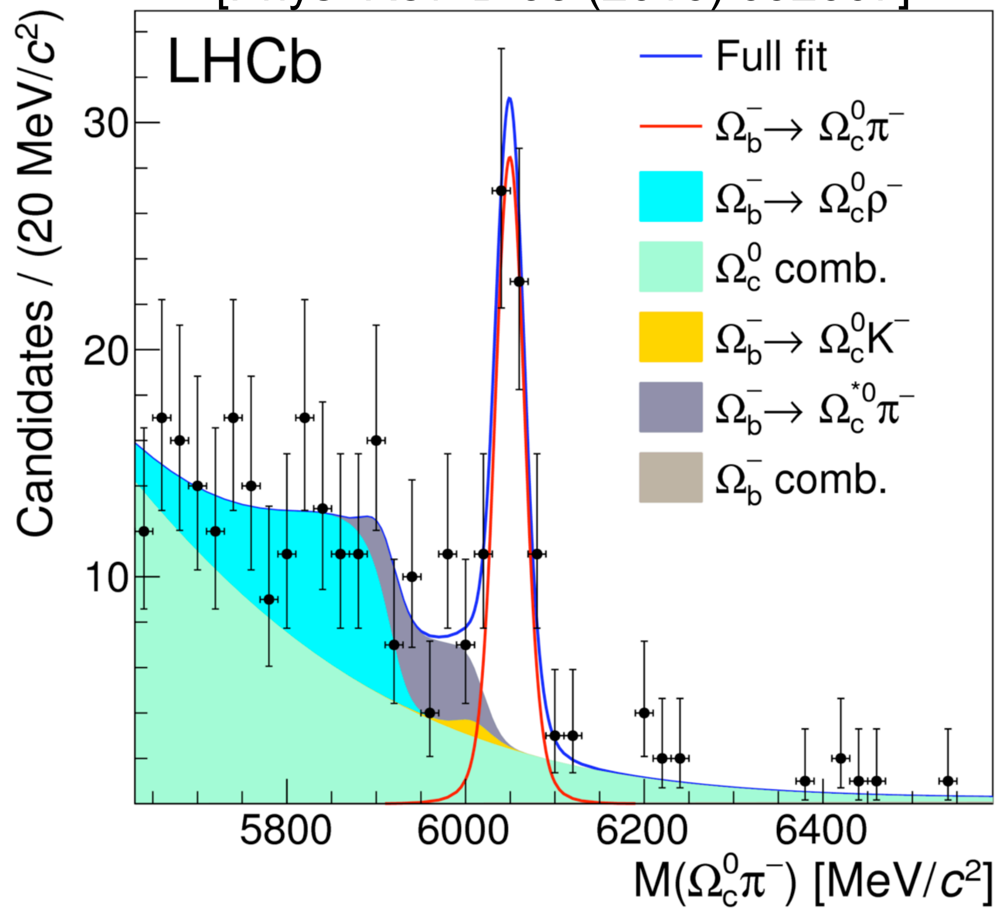
- Pentaquark models predict signals in like-sign $\Xi_c^+K^+$, but not seen



How to measure J^P?

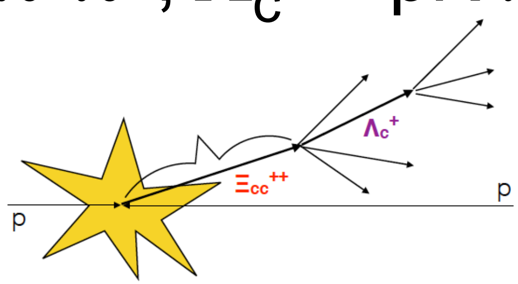
- Not easy in direct production due to unknown polarization
- Try an Ω_b decay, say $\Omega_b \to \Omega_c^{*}\pi^-$
- Already see $\Omega_b \to \Omega_c \pi^-$, $\Omega_c \to pK^+K^-\pi^-$

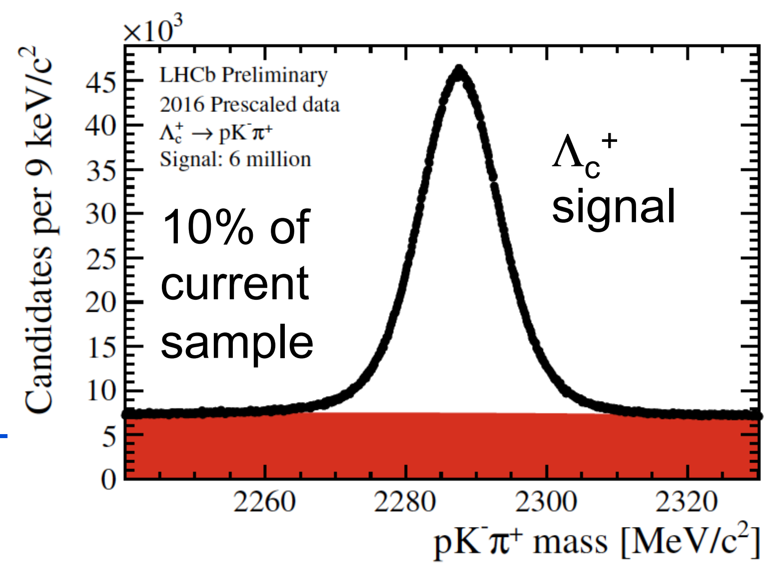
[Phys. Rev. D 93 (2016) 092007]



A doubly charmed baryon

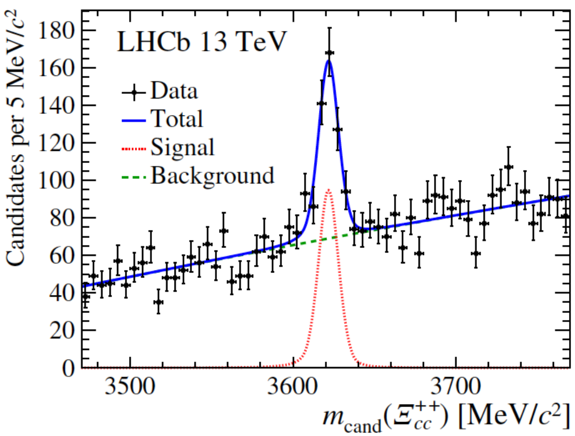
- Here we look for a baryon with quark content: ccu, called the Ξ_{cc}^{++}
- Selex measured the isospin partner (ccd) at a mass of 3518.87±1.7 MeV using a Σ^- beam in the $\Lambda_c^+K^-\pi^+$ decay mode (hep-ex/0208014, hep-ex/0406033)
- Not confirmed by Focus, BaBar, Belle
- LHCb looks for $\Xi_{cc}^{++}\rightarrow \Lambda_c^+K^-\pi^+\pi^+$, $\Lambda_c^+\rightarrow pK^-\pi^+$

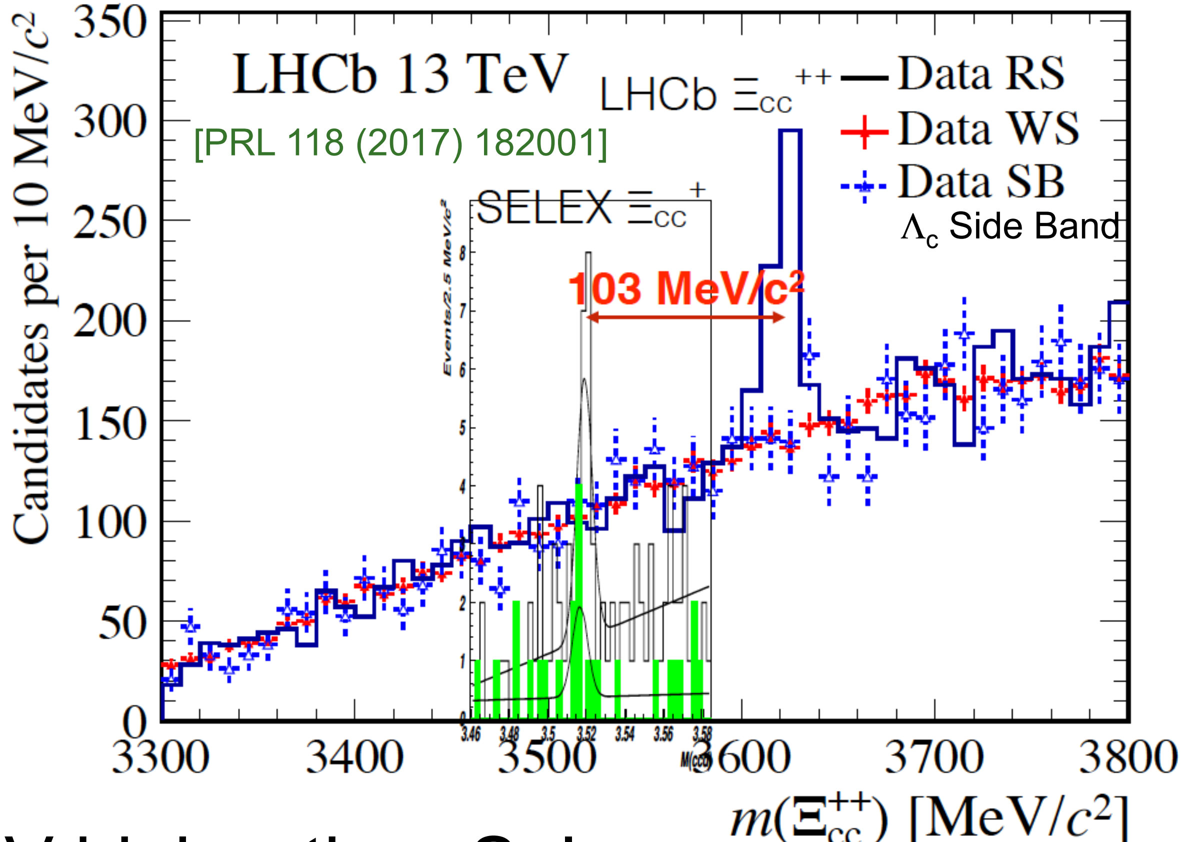




LHCb results

- LHCb signal





- Mass of Ξ_{cc}^{++} is 3621.40±0.72±0.30 MeV, about 103 MeV higher than Selex & consistent with theoretical expectations*
- Can be explained with cc diquark orbited by u quark

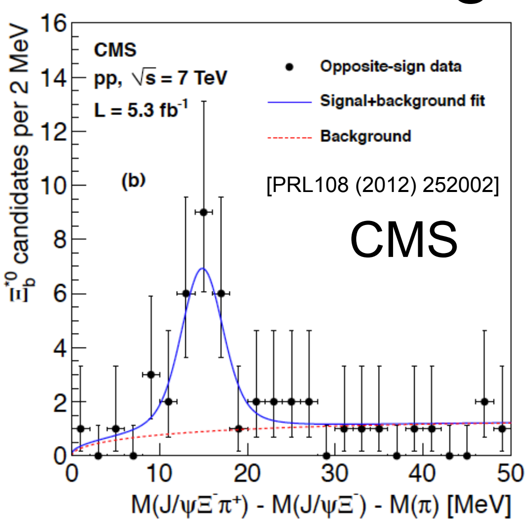
*Z. S. Brown et. al, PRD **90**, 094507 (2014).

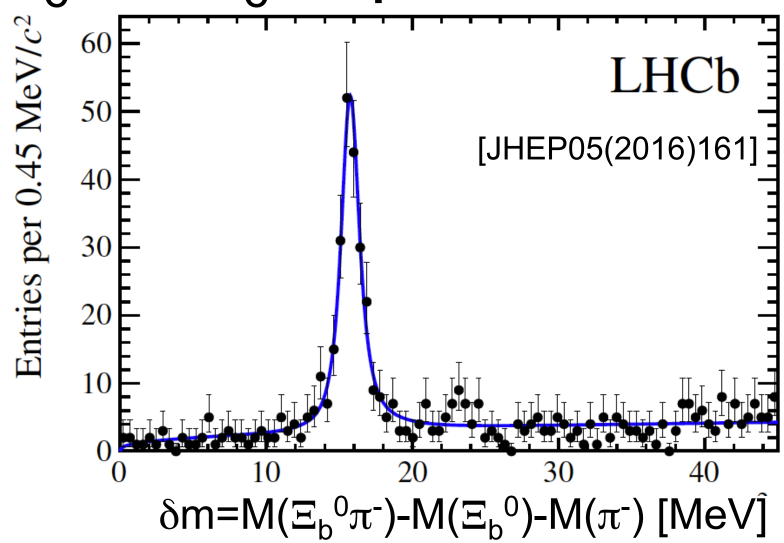
Implications

- Weakly decaying $bb\bar{u}\bar{d}$ tetraquark, Karliner & Rosner arXiv:1707.07666, Eichten & Quigg arXiv:1707.09575,
- “Quark level nuclear fusion” Ξ_c^{++} (ccu) is formed from a cc diquark, which implies a binding energy of 130 MeV leading to $\Lambda_c^+\Lambda^+_c \rightarrow \Xi_c^{++}n$, the analogue of DT→4He n (Also for b quarks) (Karliner & Rosner, Nature 551 (2017) 89)
- Prediction of triple-charm molecular pentaquark states: $\Xi_c D$ (R. Chen et al. arXiv: 1711.09579)
- ……

Excited Ξ_b^0 states

- $\Xi_b^{0*} \to \Xi_b^- \pi^+$, $\Xi_b^- \to \Xi_c^0 \pi^-$
- 1st seen by CMS using $\Xi_b^0 \to J/\psi \Xi^-$, confirmed by LHCb using $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to p K^- K^- \pi^-$





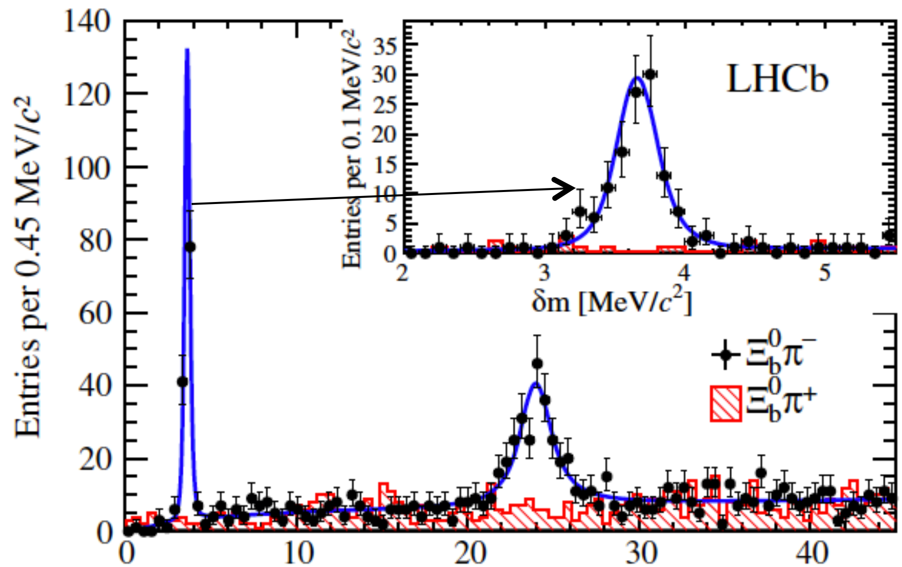
- LHCb precisely measures:

$\delta m = 15.727 \pm 0.068 \pm 0.023$ MeV

$\Gamma = 0.90 \pm 0.16 \pm 0.08$ MeV

Excited Ξ_b^- states

- $\Xi_b^{*-} \rightarrow \Xi_b^0\,\pi^-$, $\Xi_b^0 \rightarrow \Xi_c^+\,\pi^-$, $\Xi_c^+ \rightarrow pK^-\pi^+$
- J^P of states, consistent with $\frac{1}{2}^+(')$ & $^3/_2{}^+(^*)$
- Can identify using quark model



δm=M($\Xi_b^+\pi^-$)-M(Ξ_b^+)-M(π^-) [MeV]

[PRL 114, 062004 (2015)]

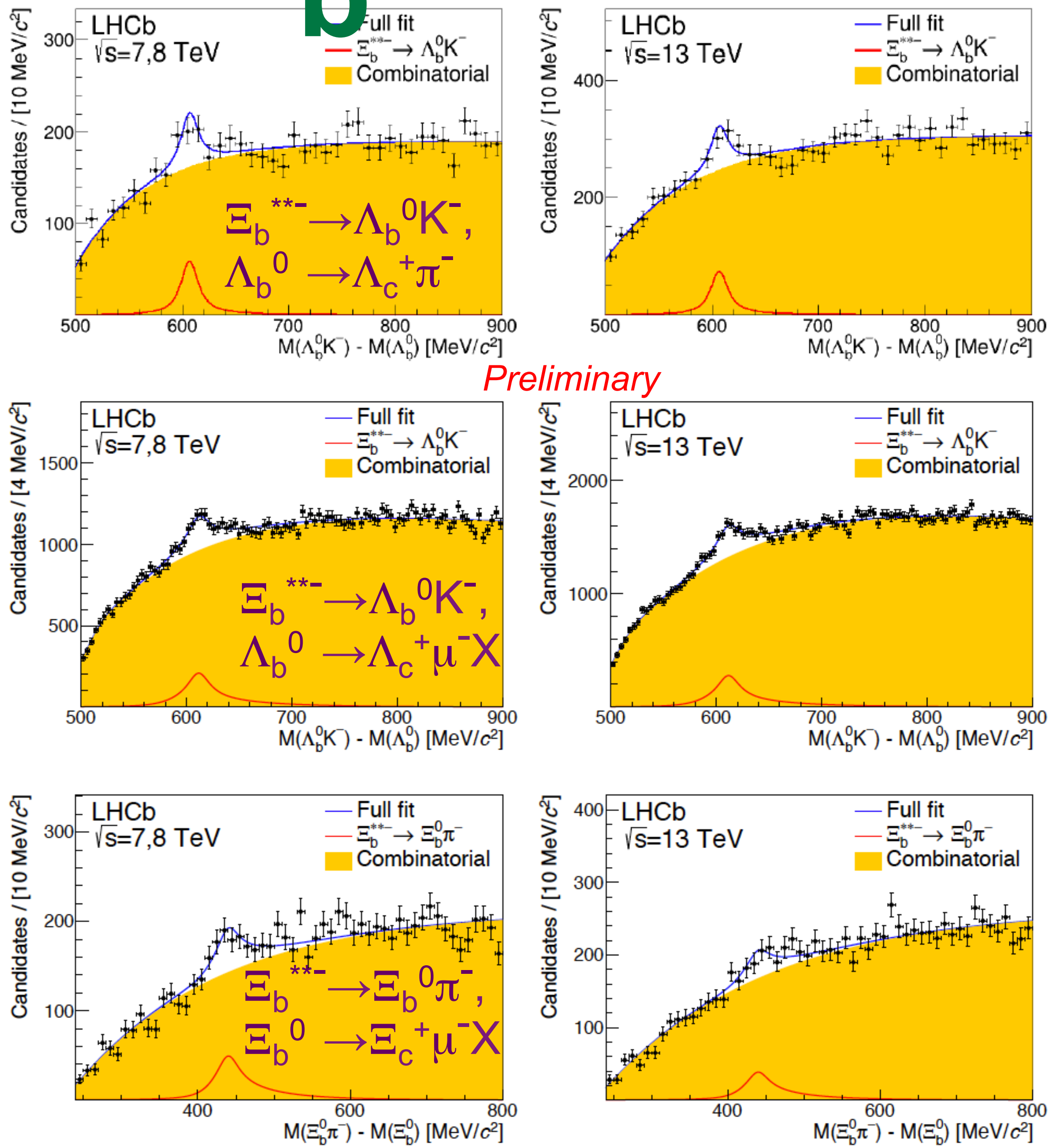
$$\delta m(\Xi_b'^-) = 3.653 \pm 0.018 \pm 0.006\ \mathrm{MeV}/c^2,$$
$$\delta m(\Xi_b^{*-}) = 23.96 \pm 0.12 \pm 0.06\ \mathrm{MeV}/c^2,$$
$$\Gamma(\Xi_b^{*-}) = 1.65 \pm 0.31 \pm 0.10\ \mathrm{MeV},$$
$$\Gamma(\Xi_b'^-) < 0.08\ \mathrm{MeV\,at\,95\%\ C.L.}$$

Isospin splitting

- $M(\Xi_b^+)$=5797.3±0.5 MeV (LHCb avg)
- $M(\Xi_b^0)$=5791.9±0.5 MeV (PDG avg)
- For Ξ_b δI_g=5.4±0.8 MeV
- Assuming these states are assigned properly
- $M(\Xi_b^{+*})$=5815.9±0.5 MeV
- $M(\Xi_b^{0*})$=5813.0±0.5 MeV
- For Ξ_b^* δI_*=2.8±0.8 MeV
- Splitting decreasing

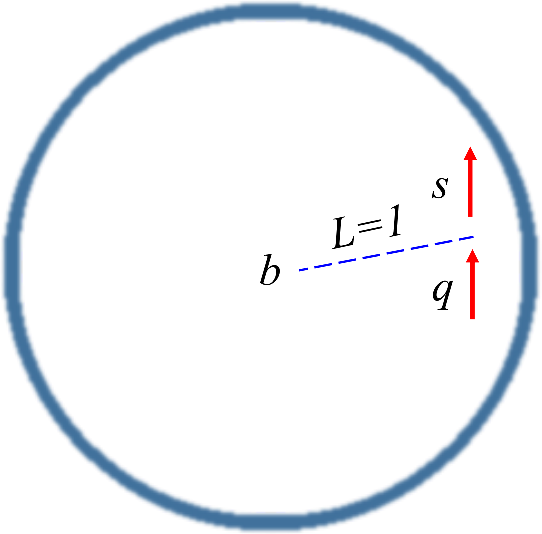
A new Ξ_b^{**-} state

- Seen in both fully hadronic decays & semileptonic decays
- Mass (MeV) =6226.9±2.0±0.3±0.2
- Γ=18.1±5.4±1.8 MeV
- J^P not yet measured



Quark model

Ξ_b' states



$$j_{sq} = L + s_{qs} = \{0,1,2\}$$

$$J = j_{sq} + s_b = \left\{\frac{1}{2},\frac{3}{2},\frac{5}{2}\right\}$$

Wang, et al,
PRD96, 116016 (2017)

$\vert {}^{2S+1}L_\lambda\, J^P\rangle$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$
$\vert {}^2P_\lambda \frac{1}{2}^-\rangle$	$\Xi_b'(6233)$	$\Lambda_b K$	12.11	44.77%
		$\Xi_b \pi$	4.77	17.63%
		$\Xi_b' \pi$	9.23	34.12%
		$\Xi_b^*(5945)\pi$	0.94	3.48%
		total	27.05	
$\vert {}^2P_\lambda \frac{3}{2}^-\rangle$	$\Xi_b'(6234)$	$\Lambda_b K$	4.14	17.14%
		$\Xi_b \pi$	14.91	61.74%
		$\Xi_b' \pi$	2.37	9.81%
		$\Xi_b^*(5945)\pi$	2.73	11.30%
		total	24.15	
$\vert {}^4P_\lambda \frac{1}{2}^-\rangle$	$\Xi_b'(6227)$	$\Lambda_b K$	17.28	53.60%
		$\Xi_b \pi$	10.01	31.05%
		$\Xi_b' \pi$	4.54	14.08%
		$\Xi_b^*(5945)\pi$	0.41	1.27%
		total	32.24	
$\vert {}^4P_\lambda \frac{3}{2}^-\rangle$	$\Xi_b'(6224)$	$\Lambda_b K$	0.98	6.19%
		$\Xi_b \pi$	2.67	16.87%
		$\Xi_b' \pi$	0.10	0.63%
		$\Xi_b^*(5945)\pi$	12.08	76.31%
		total	15.83	
$\vert {}^4P_\lambda \frac{5}{2}^-\rangle$	$\Xi_b'(6226)$	$\Lambda_b K$	4.20	17.22%
		$\Xi_b \pi$	16.37	67.12%
		$\Xi_b' \pi$	0.60	2.46%
		$\Xi_b^*(5945)\pi$	3.22	13.20%
		total	24.39	

Closest to observed state
in mass but not width

- What would diquark model predict?

Conclusions

- LHCb has produced striking new results
  - Double charmed baryons
  - Very narrow excited Ω_c states
  - P_t dependence of Λ_b and Λ_c fractions
  - Excited Ξ_b states and isospin mass splittings
- There will be many new results: new states, J^P determinations, etc…
- This data should allow the structure of baryons to be better understood