Heavy flavour baryons

Mat Charles (UPMC/LPNHE)

QCD spectroscopy and exotic hadrons session,
LHCb implications workshop, 9 Nov 2017

What this talk is about

- I'll cover:
  - Masses and lifetimes of singly heavy ground states (briefly)
  - Resonances with one heavy quark, including
    - Low-lying excited Ξ_b states
    - $\Omega_c \to \Xi_c K$ resonances
    - b-baryons as a lab for c-baryon spectroscopy
  - Ξ_{cc} past, present & future
  - Ξ_b^0 oscillation search
- Other LHCb talks will cover:
  - Exotic hadrons (Sebastian Neubert) including pentaquarks
  - Heavy flavour production (Michael Winn)
  - Asymmetries in charm baryon production and decay (Jolanta Brodzicka)
  - bc-hadrons at LHCb, including Ξ_{bc} (Daria Savrina)
  - Heavy baryon decays as probes for CKM physics, $b \to s l^+ l^-$ anomalies, etc (e.g. Elena Graverini, Daniel O'Hanlon, ...)

DON’T PANIC

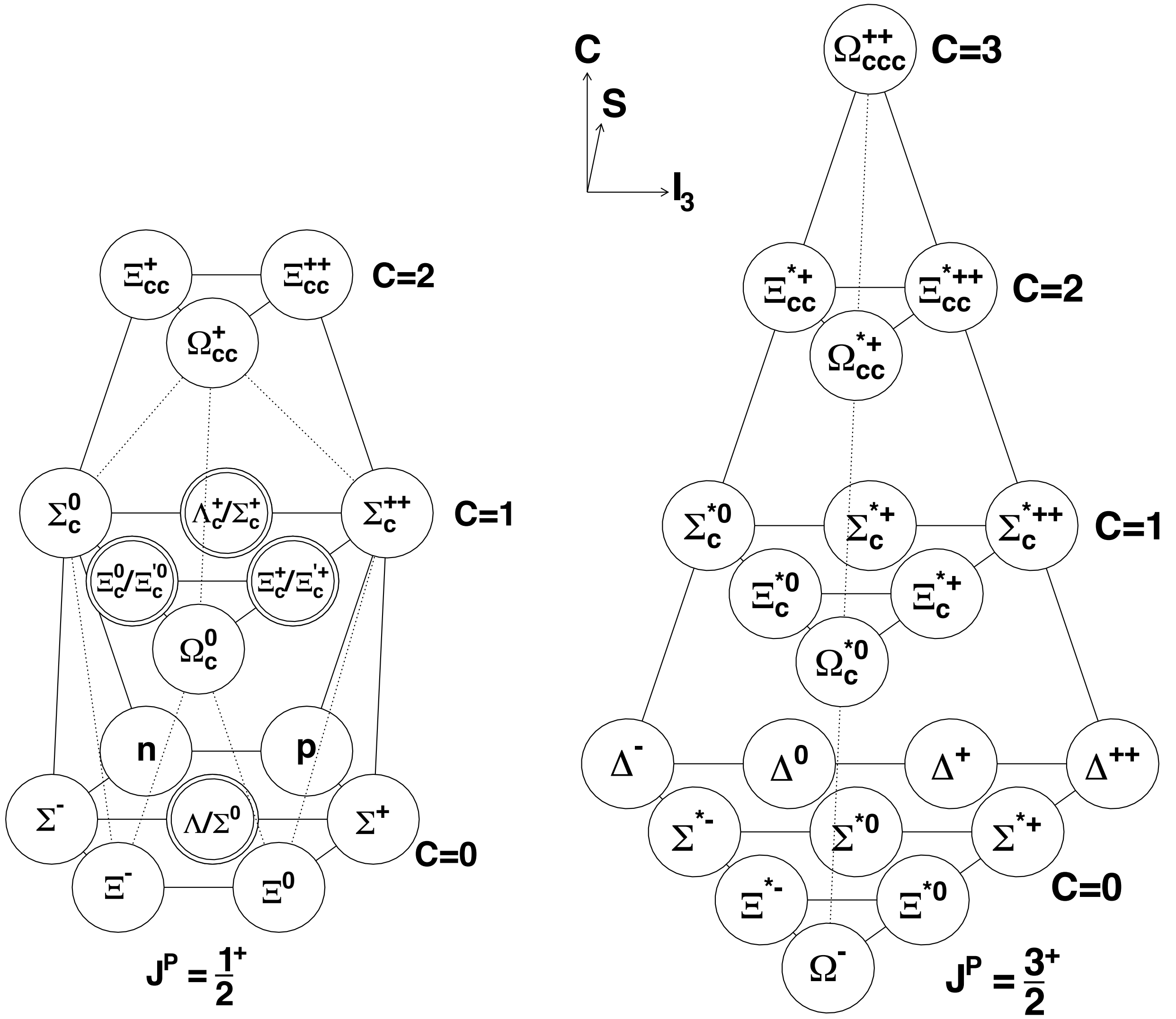
Crib sheet

- Baryon => 3 valence quarks
- If all three are u or d:
  - Isospin $^1/_2$ => n or p
  - Isospin $^3/_2$ => Δ
- If two are u or d:
  - Isospin 0 => Λ
  - Isospin 1 => ∑
- If one is u or d:
  - Isospin $^1/_2$ => Ξ
- If none are u or d:
  - Isospin 0 => Ω
- By default, non-{u/d} quarks are s. Add subscripts to replace them, e.g.
  - Ξ^0 = ssu
  - $\Xi_c{}^+$ = csu
  - $\Xi_{cc}{}^{++}$ = ccu

"Ground states" ambiguous:

1) Lowest states that decay weakly
2) All states that are neither orbitally nor radially excited

For second meaning, here are the ground states (with beauty 0):



Why do we do spectroscopy?

In roughly ascending order:

- It's good clean fun^W physics
  - ... and sometimes you actually get to see a signal
- It provides inputs to pheno calculations in the area
- Empowers searches for New Physics

  Zoltan's talk on Thursday

  - Necessary inputs, e.g. charm resonances for $B \rightarrow D^{(*)} \tau \nu$
  - Opens new paths (time until first CPV search with Ξ_{cc}?)
- Sometimes you find something unexpected
  - See: pentaquarks

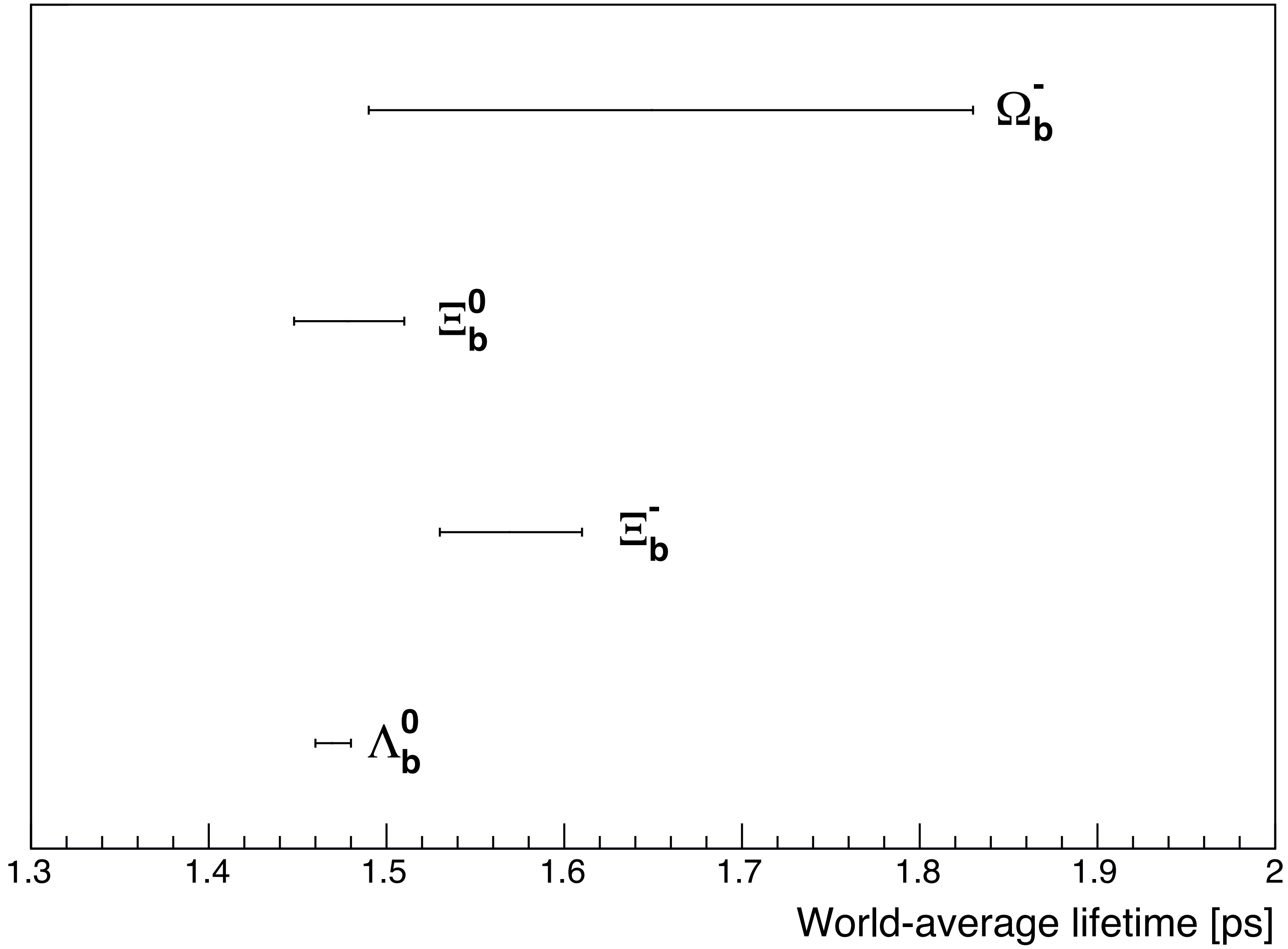
Weakly decaying b-baryons

- Skipping details, but:
- Precise measurements of masses and lifetimes, often using ratio technique.

$$M(\Lambda_b^0) = 5619.65 \pm 0.17 \pm 0.17\,\mathrm{MeV}/c^2$$

$$M(\Xi_b^0) - M(\Lambda_b^0) = 172.44 \pm 0.39 \pm 0.17 \ \ \mathrm{MeV}/c^2$$

$$M(\Xi_b^-) - M(\Lambda_b^0) = 178.36 \pm 0.46 \pm 0.16 \ \ \mathrm{MeV}/c^2$$



See backups for Ω_b^- mass info.

LHCB-PAPER-2015-060 ; arXiv:1603.06961
LHCB-PAPER-2014-048 ; arXiv:1409.8568
LHCB-PAPER-2014-021 ; arXiv:1405.7223
LHCB-PAPER-2016-008 ; arXiv:1604.01412
LHCB-PAPER-2012-048 ; arXiv:1302.1072
LHCB-PAPER-2014-003 ; arXiv:1402.6242
LHCB-PAPER-2014-048 ; arXiv:1409.8568
LHCB-PAPER-2014-021 ; arXiv:1405.7223
LHCB-PAPER-2016-008 ; arXiv:1604.01412
LHCb-PAPER-2014-010 ; arXiv:1405.1543

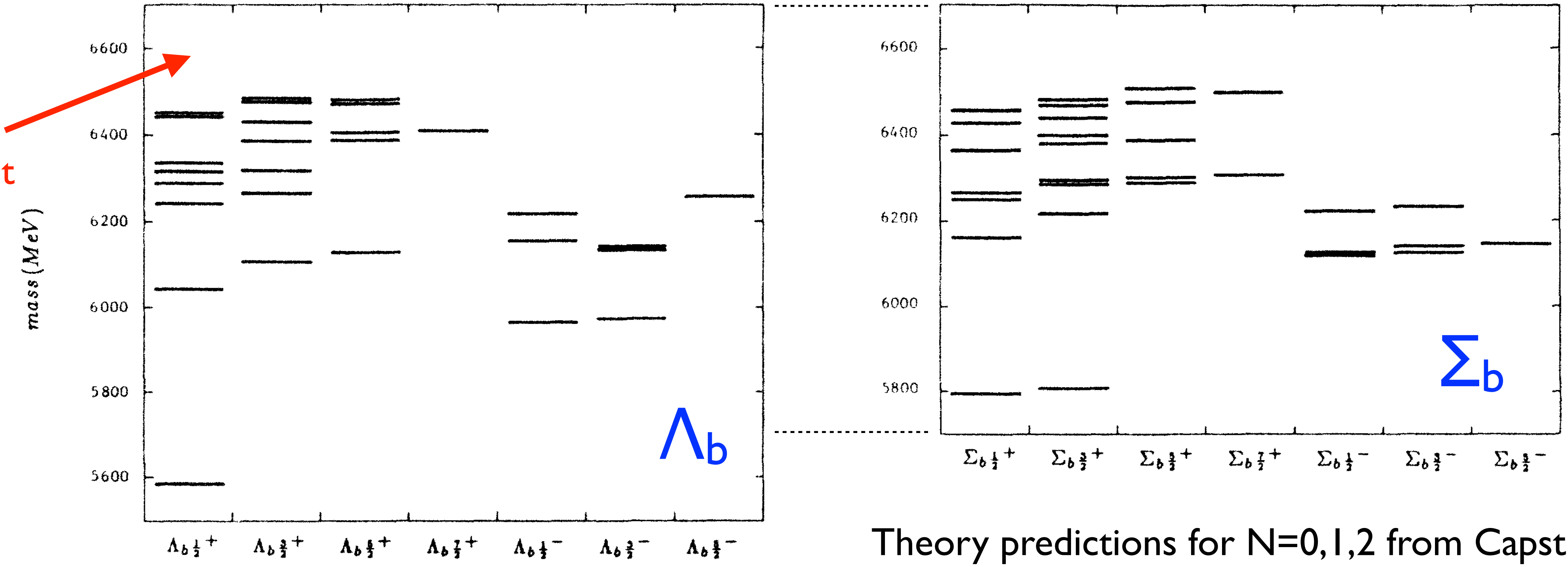
LHCb results: weakly decaying c-baryons

$M(\Xi_c^+) - M(\Lambda_c^+) = 181.51 \pm 0.14 \pm 0.10 \ \mathrm{MeV}/c^2$

- True, results from B-factories for masses already exist...
- ... but surely LHCb can add something, esp. on lifetimes.

Singly heavy resonances

- The low-lying states are pretty easy to understand.
  - ... especially the "ground states" (n=L=0). Even an experimentalist can calculate their masses!
- Higher excited states are tougher, because:
  - They are hard to see (cross-sections for inclusive production and BFs for exclusive production usually drop rapidly)
  - There are many of them -- density of states gets large rapidly
  - They mix! States with same J^P and flavour quantum numbers can mix, even if internal numbers differ... and there are a lot of states.

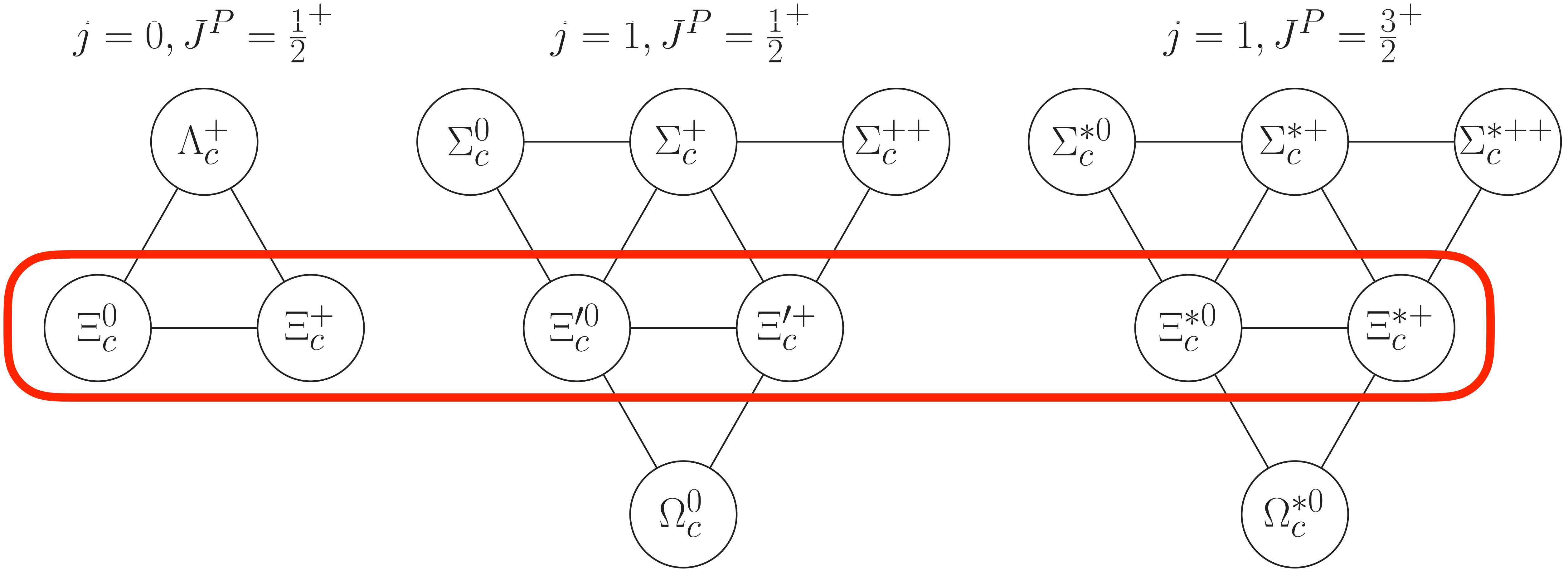


NB states continue up here for N>2, just not plotted.

Theory predictions for N=0,1,2 from Capstick & Isgur, Phys.Rev. D34 (1986) 280

Warm-up: Ξ_b ground states

Diagrams show Ξ_c, but Ξ_b works [almost] the same way



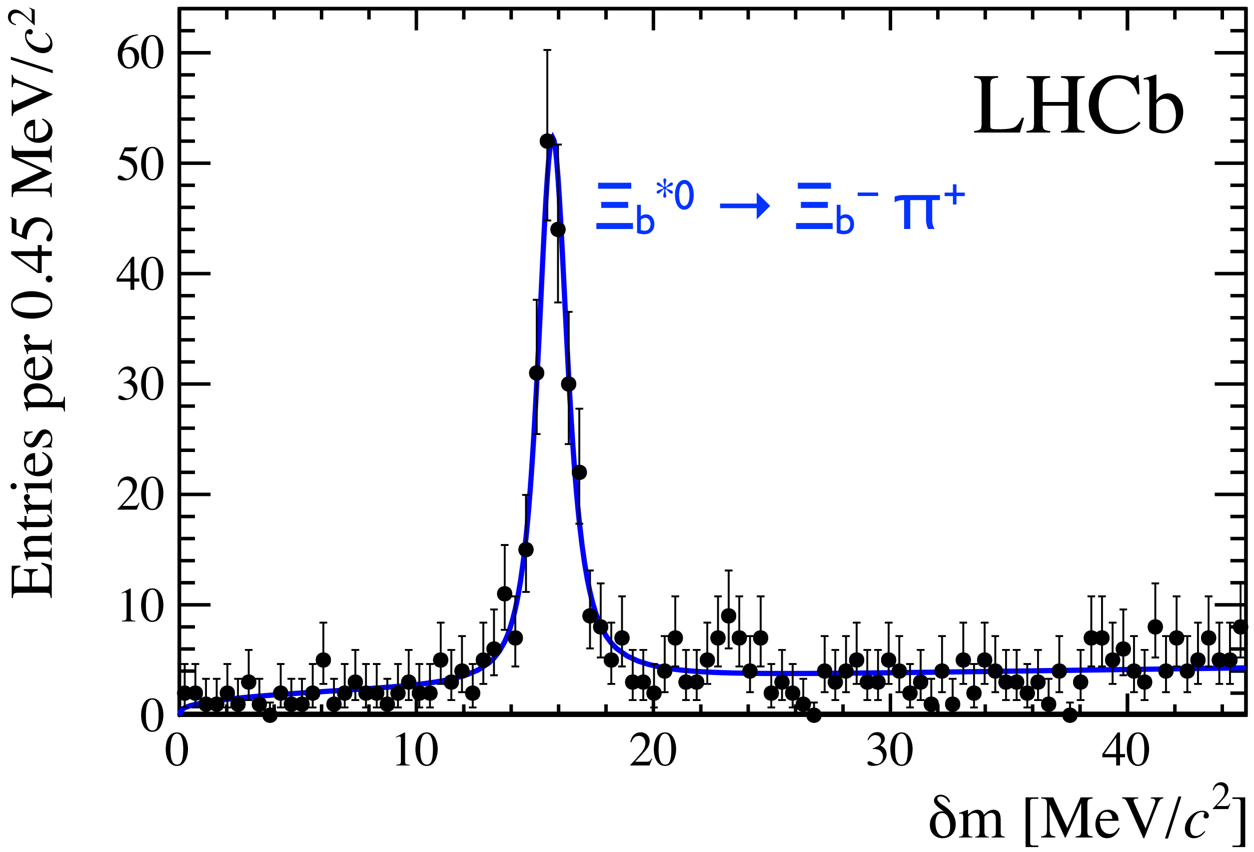
- If you put three quarks with different flavours together*, QM says there are not two but three ways to do it:
  - $J = (^1/_2 + {}^1/_2) + {}^1/_2 = 0 + {}^1/_2 = {}^1/_2$, mixed symmetry => Ξ_b
  - $J = (^1/_2 + {}^1/_2) + {}^1/_2 = 1 + {}^1/_2 = {}^1/_2$, mixed symmetry => $\Xi_b{}'$
  - $J = (^1/_2 + {}^1/_2) + {}^1/_2 = 1 + {}^1/_2 = {}^3/_2$, totally symmetric => $\Xi_b{}^*$

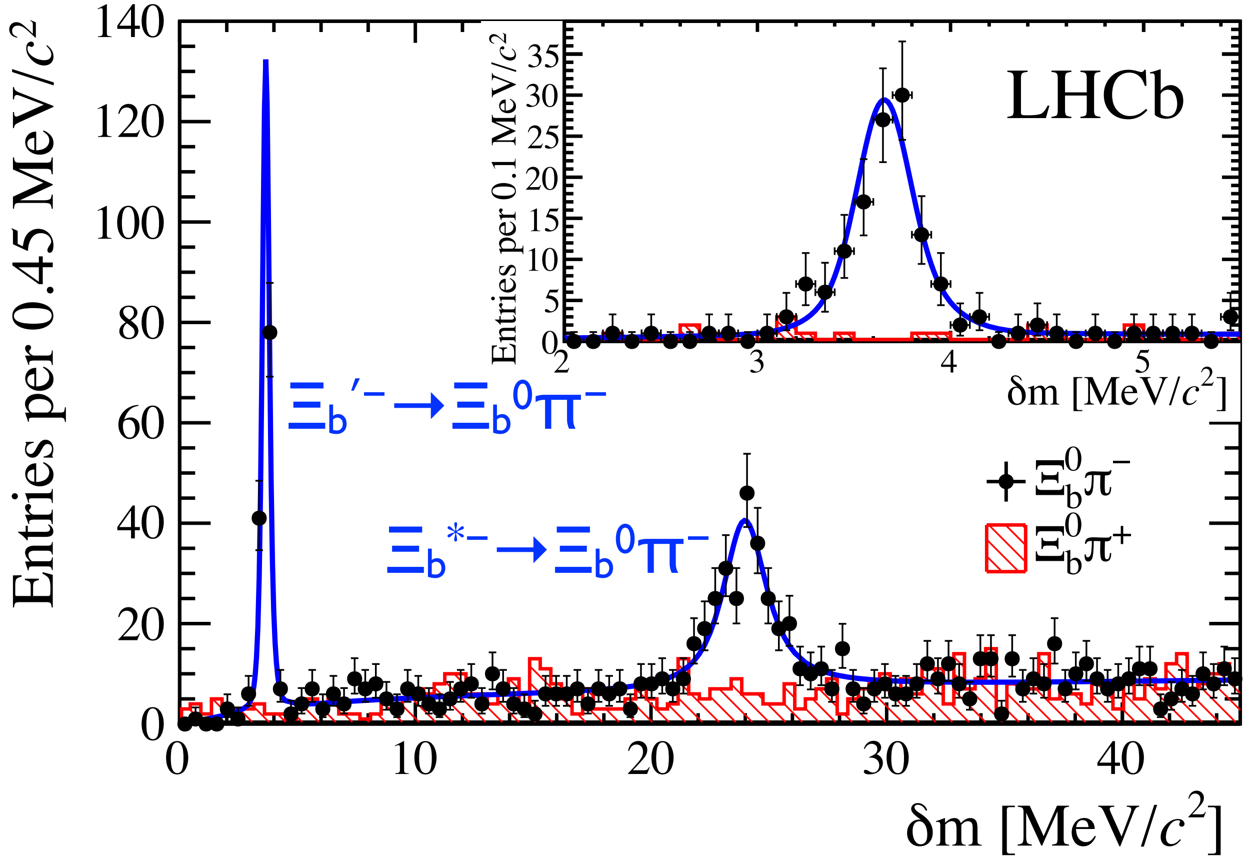
diquark

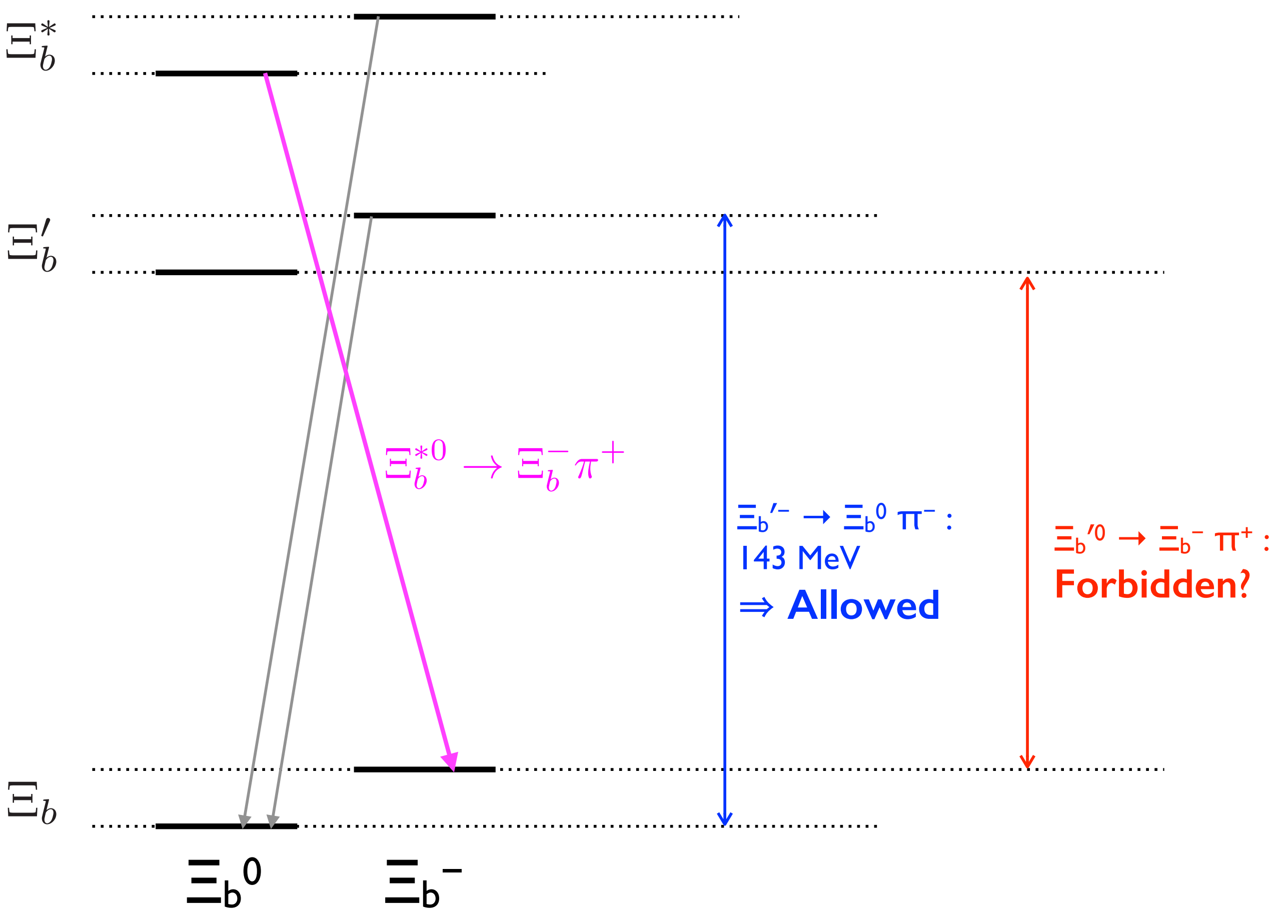
See Vinicius Rodrigues Debastiani's slides from Tuesday for more

* and wavefunction is spatially symmetric

Ξ_b measurements at LHCb







5 of the 6 ground states now seen. The last one, $\Xi_b'^0$, is (presumably!) below threshold for $\Xi_b^-\pi^+$ and so hard to see at LHCb.

Ξ_b^{*0} first observed by CMS: PRL 108, 252002 (2012)

LHCB-PAPER-2016-010 ; arXiv:1604.03896
LHCB-PAPER-2014-061 ; arXiv:1411.4849

Ξ_b measurements at LHCb

- Very precise measurements of masses and widths
- ... especially for the state closest to threshold.

$$\begin{aligned} m(\Xi_b'^{-}) - m(\Xi_b^0) - m(\pi^-) &= 3.653 \pm 0.018 \pm 0.006\,\mathrm{MeV}/c^2, \\ m(\Xi_b^{*-}) - m(\Xi_b^0) - m(\pi^-) &= 23.96 \pm 0.12 \pm 0.06\,\mathrm{MeV}/c^2, \\ \Gamma(\Xi_b^{*-}) &= 1.65 \pm 0.31 \pm 0.10\,\mathrm{MeV}, \end{aligned}$$

$$\Gamma(\Xi_b'^{-}) < 0.08\,\mathrm{MeV} \text{ at } 95\% \text{ confidence level.}$$

$$\begin{aligned} m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) &= 15.727 \pm 0.068\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst})\ \mathrm{MeV}/c^2, \\ \Gamma(\Xi_b^{*0}) &= 0.90 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})\ \mathrm{MeV}. \end{aligned}$$

J consistent with expectations (but little information)

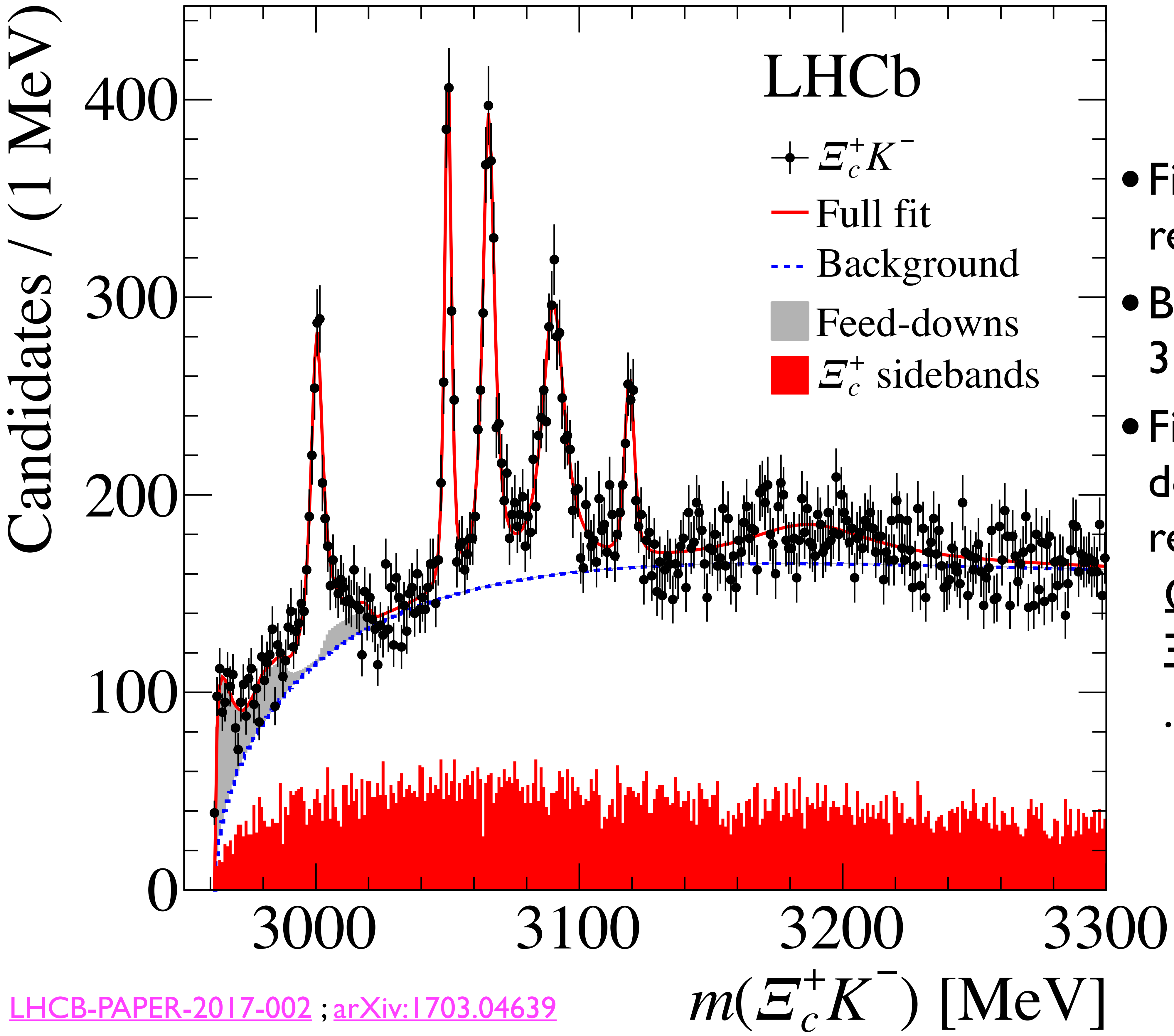
Ratios of (σ × BF) also measured.

LHCB-PAPER-2016-010 ; arXiv:1604.03896
LHCB-PAPER-2014-061 ; arXiv:1411.4849

Low-lying excited $\Omega_c^0 \rightarrow \Xi_c^+ K^-$

- Switch now from a study of Ξ_b ground states to low-lying excited Ω_c states.
- Reminder: "excited" here means:
  - orbital excitation: $L > 0$, e.g. 1P, 1D, ... with parity = $(-1)^L$
  - radial excitation, e.g. 2S, 3S, ...
  - or both (2P, 3D, etc etc etc)
- Note that more obvious mode $\Omega_c^0 \pi^0$ violates isospin.

Low-lying excited $\Omega_c^0 \to \Xi_c^+ K^-$



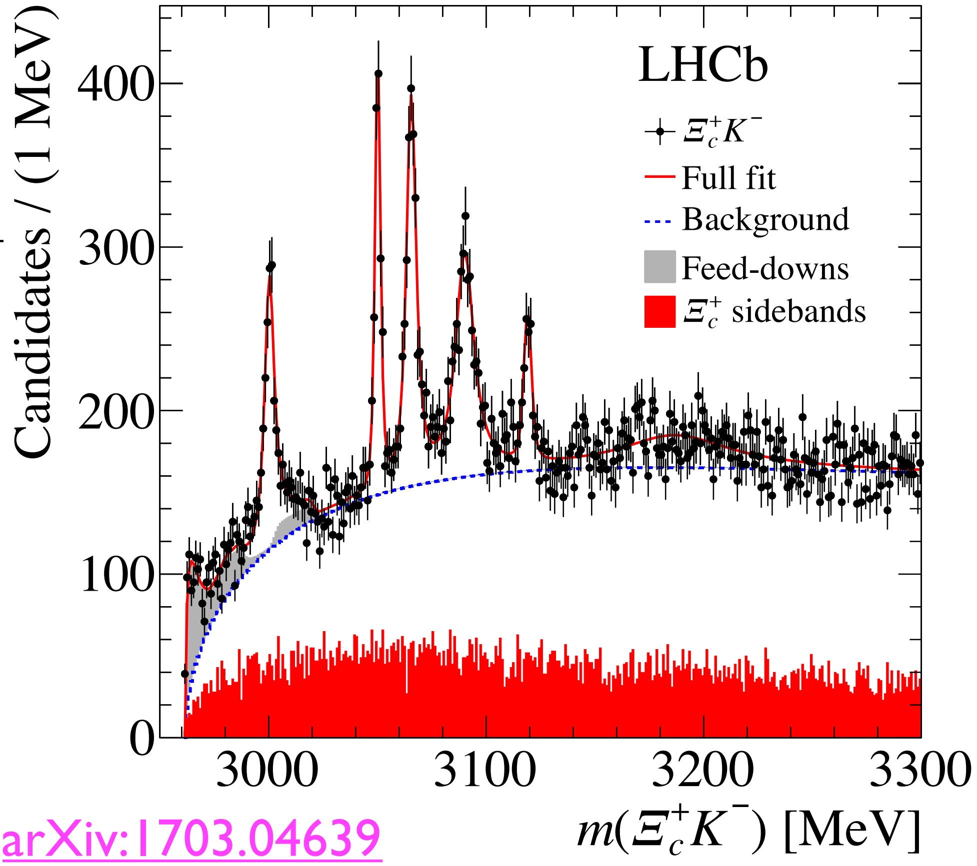
- Five clear, narrow resonances
- Broad excess around 3190 MeV
- Fit also includes feed-down from same resonances:

  $\Omega_c^0 \to \Xi_c'^+ K^-$,
  $\Xi_c'^+ \to \Xi_c^+ \gamma$
  ... and photon missed

LHCB-PAPER-2017-002 ; arXiv:1703.04639

Low-lying excited $\Omega_c^0 \rightarrow \Xi_c^+ K^-$

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
		$< 1.2\,\text{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	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
		$< 2.6\,\text{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\text{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\text{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\text{fd}}$			$190 \pm 70 \pm 20$	



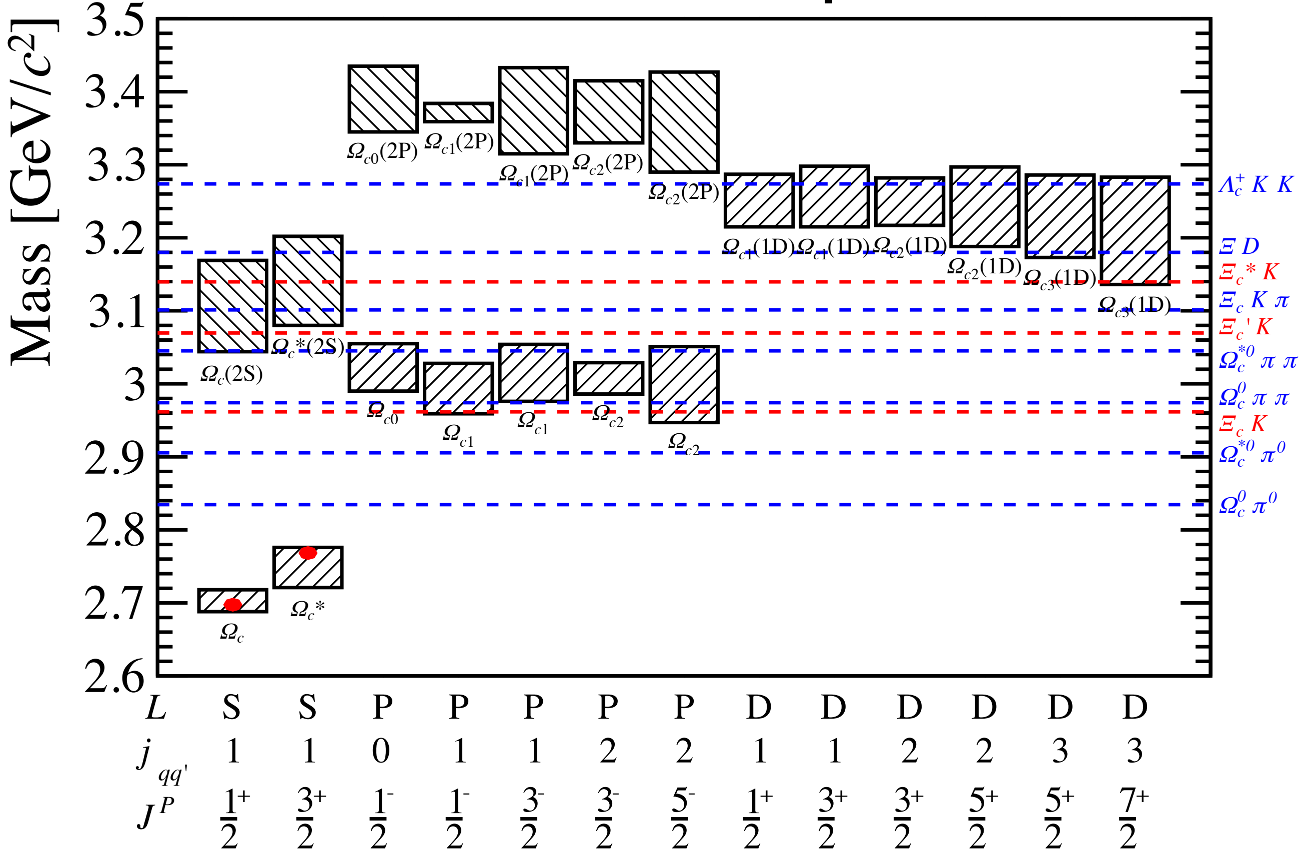
Two states are very narrow; possible exotic interpretation (see talk by Sebastian Neubert; also Tuesday's workshop).

LHCB-PAPER-2017-002 ; arXiv:1703.04639

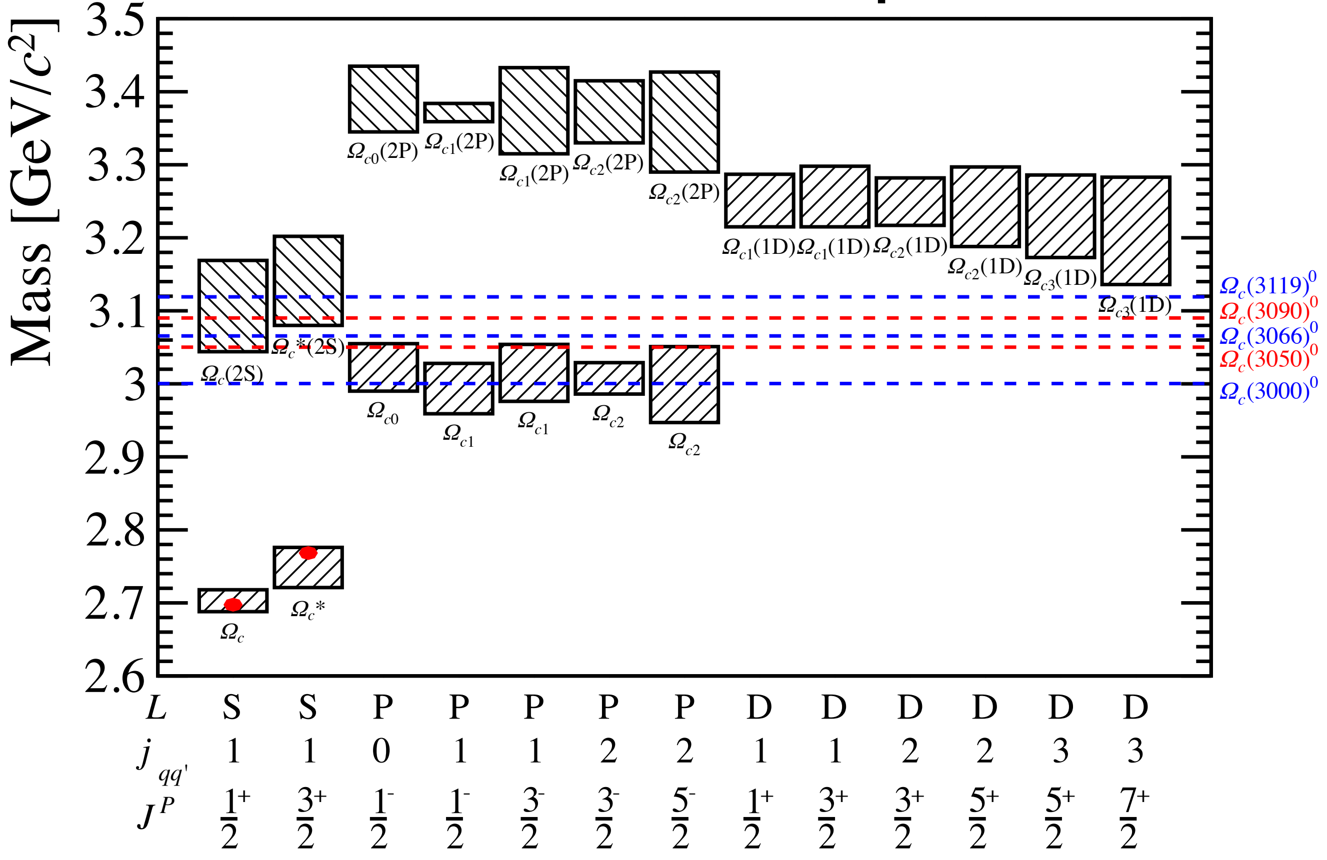
e.g. Montaña et al: arXiv:1709.08737
e.g. Debastiani et al: arXiv:1710.04231

Low-lying excited $\Omega_c^0 \rightarrow \Xi_c^+ K^-$

Thresholds vs some predictions



Observations vs some predictions



- Without measurements of quantum numbers, matching the five peaks to states is tricky
  - Obvious first guess: $^1/_2^-$, $^1/_2^-$, $^3/_2^-$, $^3/_2^-$, $^5/_2^-$
  - If first two states are below threshold, peaks could be $^3/_2^-$, $^5/_2^-$, $^5/_2^-$, $^1/_2^+$, $^3/_2^+$
  - Or exotic interpretation, or...
- Aside: $\Xi_c^{*+} K^-$ would be a nice mode for a follow-up search.

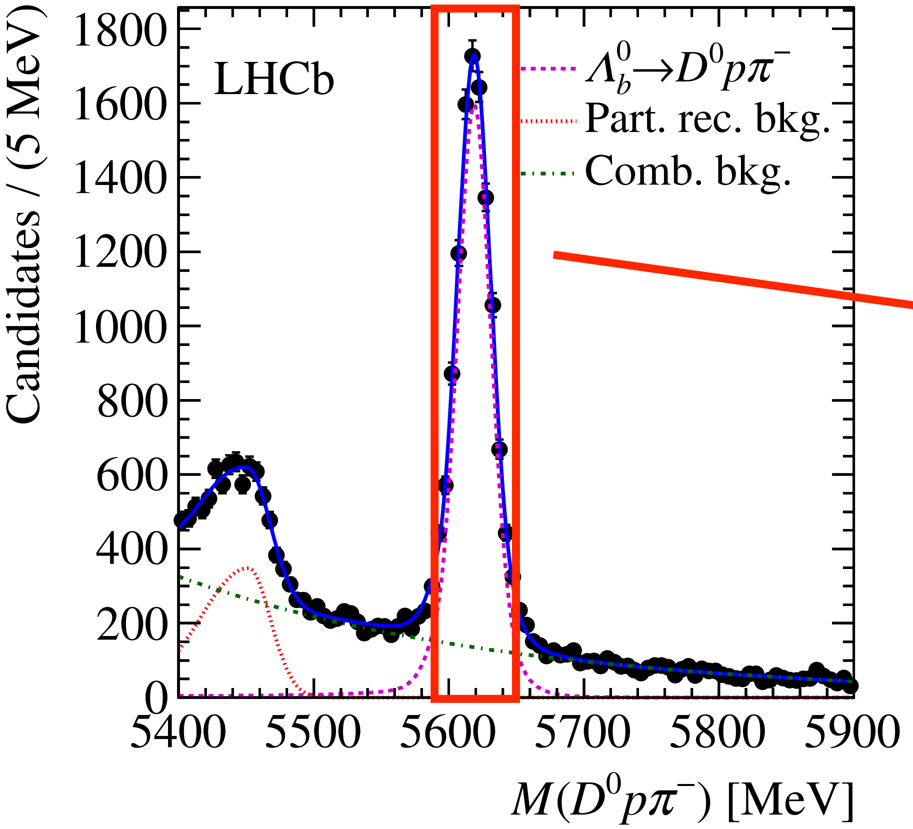
Migura, Merten, Metsch, & Petry, Eur.Phys.J.A28 (2006) 41
Ebert, Faustov, & Galkin, PRD 84 (2011) 014025
Valcarce, Garcilazo, & Vijande, Eur. Phys. J. A37 (2008) 217
Ebert, Faustov, & Galkin, PLB 659 (2008)
Roberts and Pervin, Int. J. Mod. Phys. A23 (2008) 2817
Garcilazo, Vijande, & Valcarce, J. Phys. G34 (2007) 961
Shah, Thakkar, Rai, & Vinodkumar, Chin. Phys. C40 (2016) 123102
Karliner & Rosner, Phys. Rev. D 95, 114012 (2017)

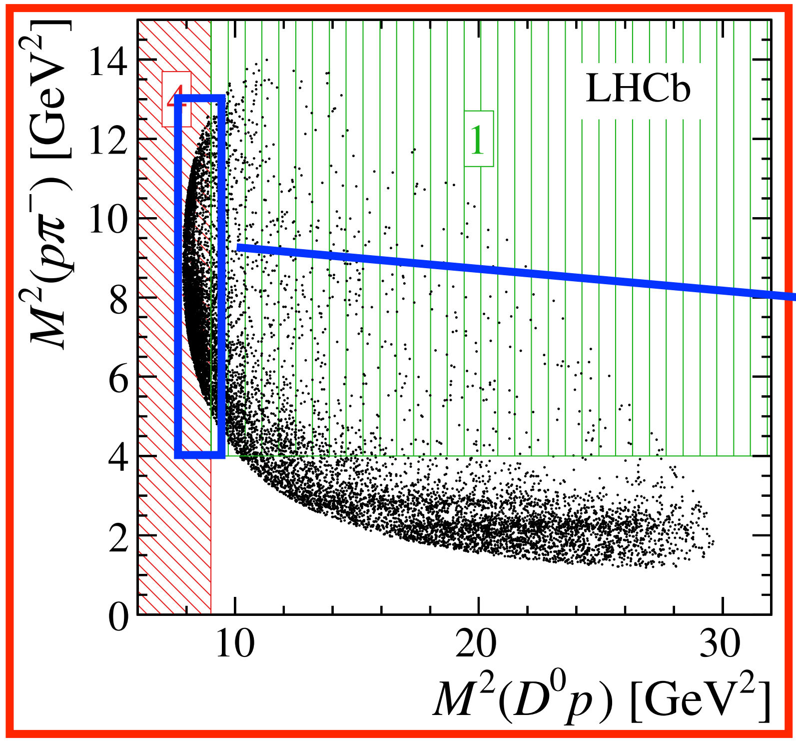
Exclusive decays

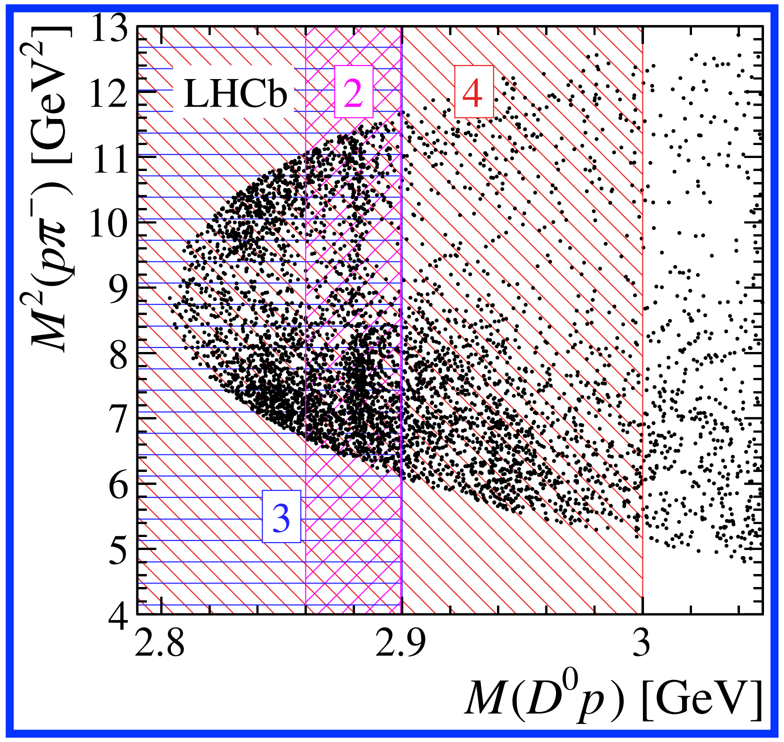
- Interpretation is difficult without knowing QNs
- So try to work in a system where we can measure them!
- Decays of charmed hadrons used to study light hadrons...
  - ... e.g. spin of Ω^- measured for first time in $\Xi_c^0 \to \Omega^- K^+$ (BABAR, Phys.Rev.Lett.97:112001,2006)
- ... and likewise we can use beauty decays to study charm.
- Recent example: (D^0p) in $\Lambda_b^0 \to D^0p\pi^-$
- I can't do justice to this detailed amplitude analysis in just a couple of slides, but let me give you a taste...

LHCB-PAPER-2016-061 ; arXiv:1701.07873

D^0p amplitude in $\Lambda_b^0 \rightarrow D^0p\pi^-$







Caution: x axis changes from M^2 to M

- Series of amplitude fits
  - ... beginning with easier bits (non-res region 1, $\Lambda_c(2880)$-dominated region 2)
  - ... then adding near-threshold resonances (region 3) and $\Lambda_c(2940)$ in region 4.
  - N*-dominated region not used in fit (simplifies life -- but lose a bit of info)
- Known $\Lambda_c(2880)$ and $\Lambda_c(2940)$ studied
  - $\Lambda_c(2880)$: $J = {}^5/_2$ strongly preferred, consistent with Belle
  - $\Lambda_c(2940)$: $J^P = {}^3/_2{}^-$ preferred, but other values not fully ruled out
- Threshold enhancement, consistent with ${}^3/_2{}^+$ resonance: $\Lambda_c(2860)$

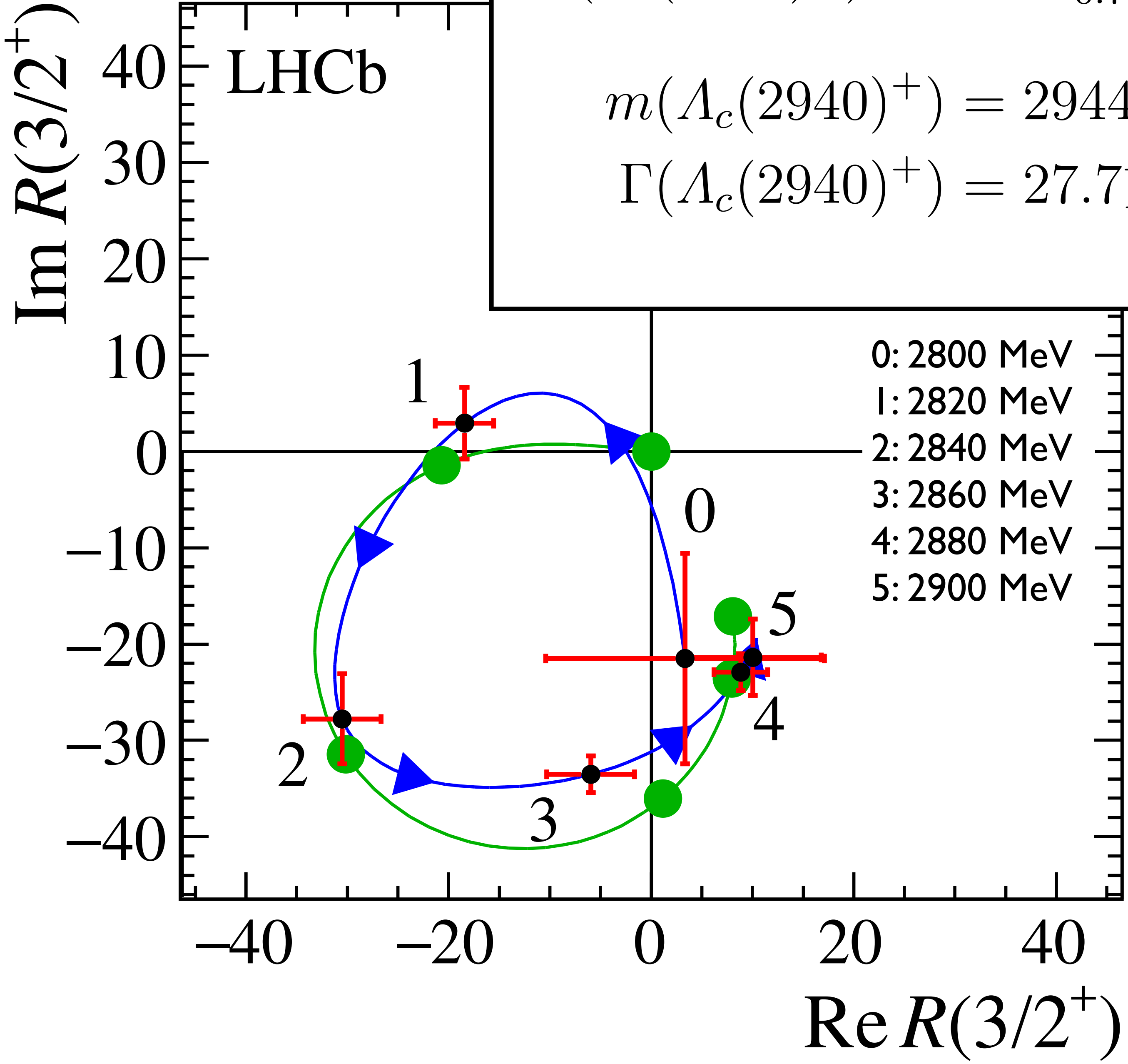
LHCB-PAPER-2016-061 ; arXiv:1701.07873

D^0p amplitude in $\Lambda_b^0 \rightarrow D^0 p \pi^-$

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

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

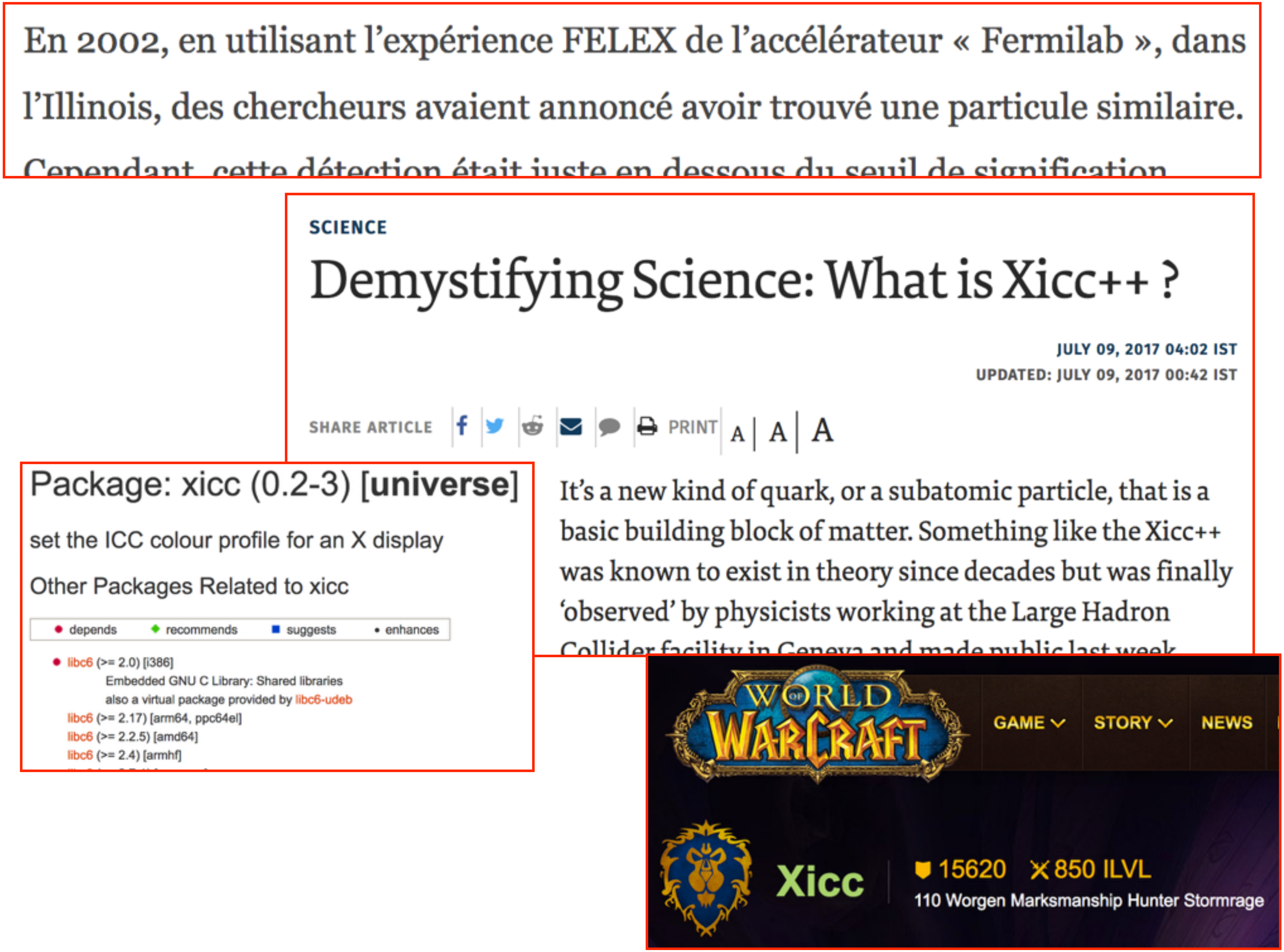
$$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\mathrm{stat}) \pm 0.4(\mathrm{syst})^{+0.1}_{-4.6}(\mathrm{model})\ \mathrm{MeV},$$
$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\mathrm{stat}) \pm 0.9(\mathrm{syst})^{+5.2}_{-10.4}(\mathrm{model})\ \mathrm{MeV}.$$



Argand diagram for $J^P={}^3/_2{}^+$ partial wave in the $\Lambda_c(2860)$ region.

- Known $\Lambda_c(2880)$ and $\Lambda_c(2940)$ studied
  - $\Lambda_c(2880)$: J = $^5/_2$ strongly preferred, consistent with Belle
  - $\Lambda_c(2940)$: $J^P = {}^3/_2{}^-$ preferred, but other values not fully ruled out
- $\Lambda_c(2860)$ consistent with $^3/_2{}^+$ resonance:

LHCB-PAPER-2016-061 ; arXiv:1701.07873



En 2002, en utilisant l'expérience FELEX de l'accélérateur « Fermilab », dans l'Illinois, des chercheurs avaient annoncé avoir trouvé une particule similaire. Cependant, cette détection était juste en dessous du seuil de signification

SCIENCE

Demystifying Science: What is Xicc++ ?

JULY 09, 2017 04:02 IST
UPDATED: JULY 09, 2017 00:42 IST

It's a new kind of quark, or a subatomic particle, that is a basic building block of matter. Something like the Xicc++ was known to exist in theory since decades but was finally 'observed' by physicists working at the Large Hadron Collider facility in Geneva and made public last week

Package: xicc (0.2-3) **[universe]**

set the ICC colour profile for an X display

Other Packages Related to xicc

● depends ◆ recommends ■ suggests • enhances

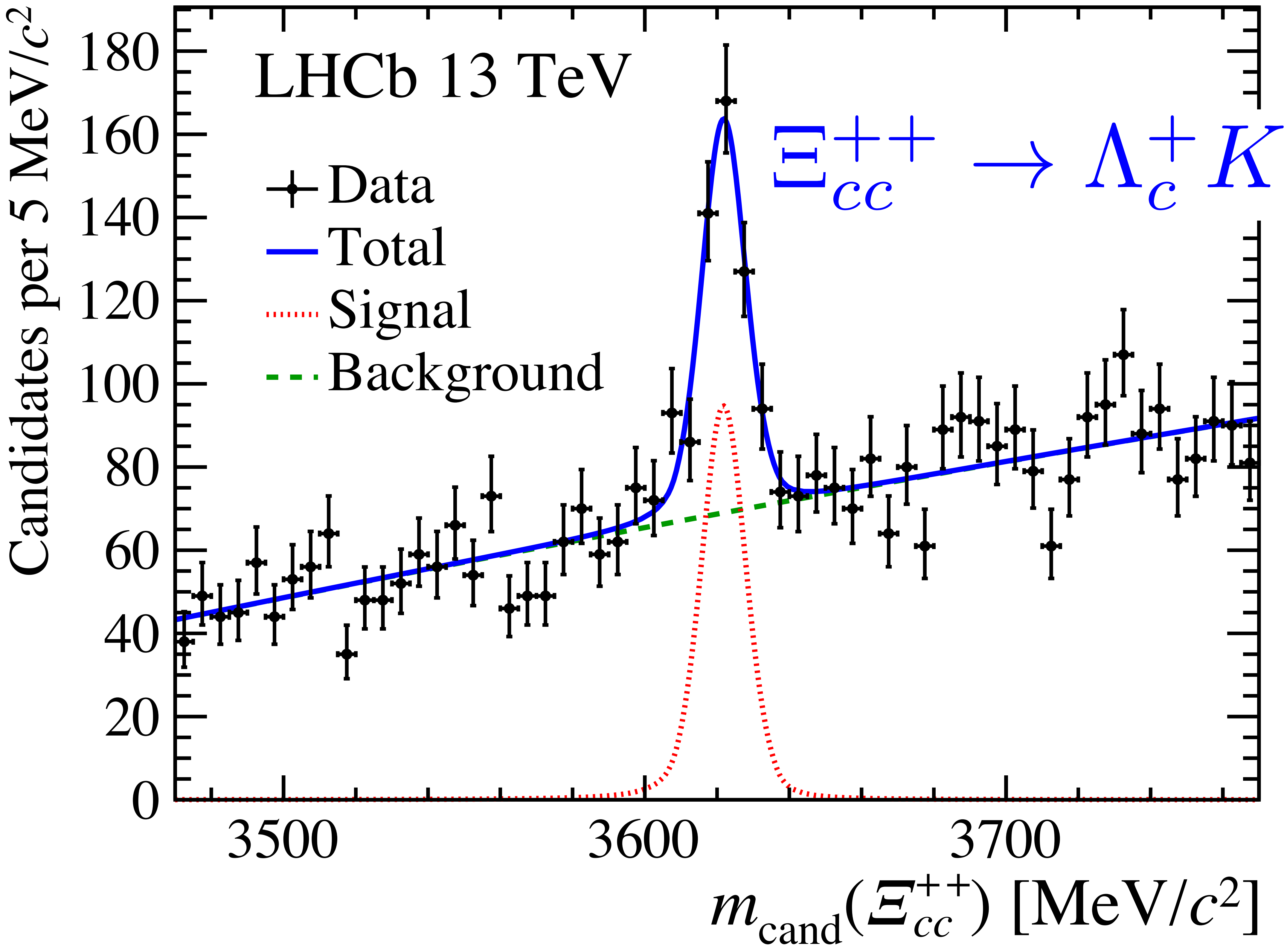
- ● libc6 (>= 2.0) [i386]
  Embedded GNU C Library: Shared libraries
  also a virtual package provided by libc6-udeb
- libc6 (>= 2.17) [arm64, ppc64el]
- libc6 (>= 2.2.5) [amd64]
- libc6 (>= 2.4) [armhf]

Xicc

15620 850 ILVL

110 Worgen Marksmanship Hunter Stormrage

Doubly charmed baryon!

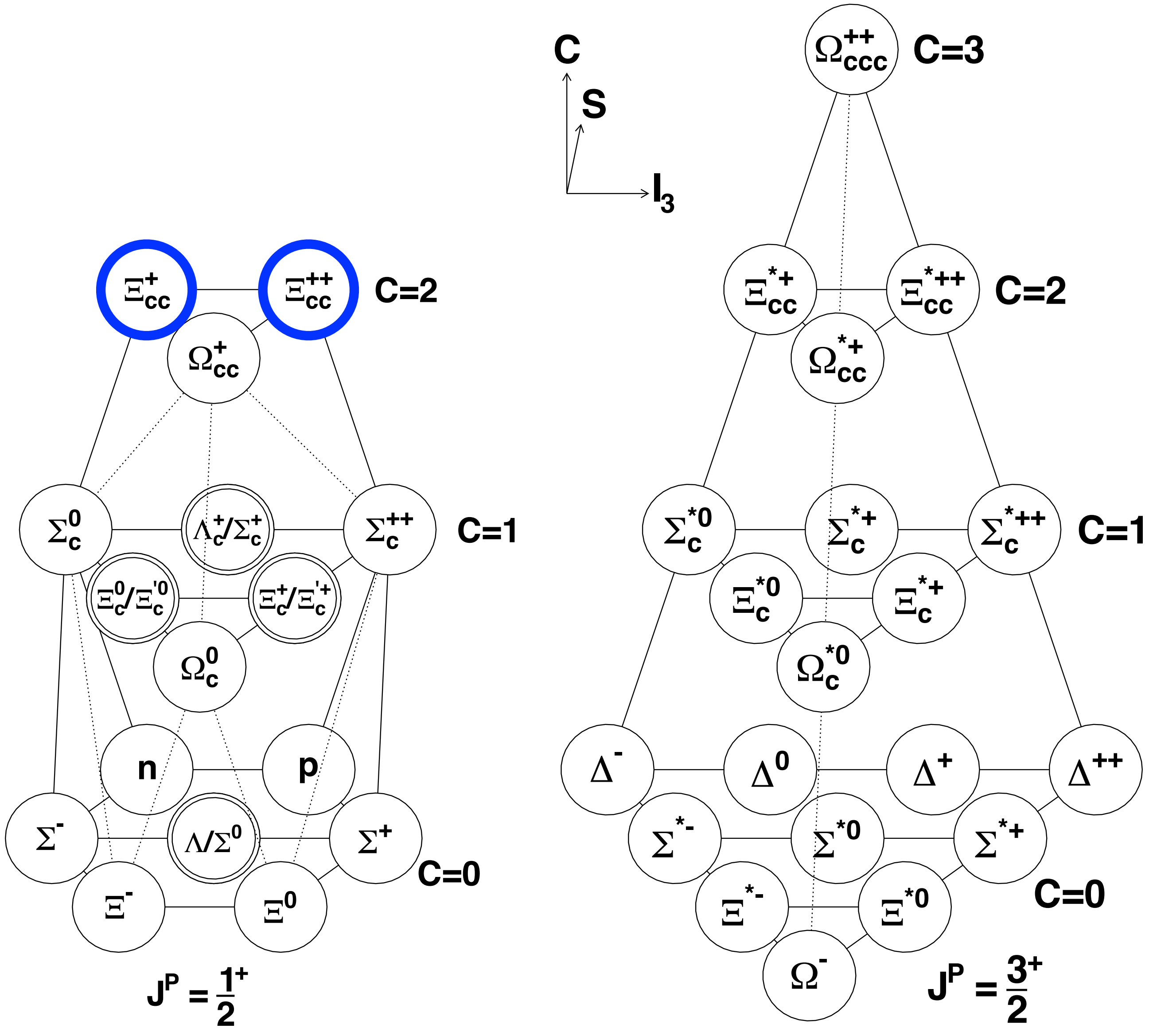


$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

LHCB-PAPER-2017-018 ; arXiv:1707.01621

One year earlier...

- Ξ_{cc} predictions:
  - Isodoublet of weakly decaying states: Ξ_{cc}^{++} (ccu) and Ξ_{cc}^{+} (ccd)
  - Mass around 3500-3700 MeV
  - Lifetimes: $\tau(\Xi_{cc}^{++})$ ~ few hundred fs; $\tau(\Xi_{cc}^{++})/\tau(\Xi_{cc}^{+})$ ~ 3 to 4
- Ξ_{cc} observation(s) claimed by SELEX, but never reproduced.
  - Various oddities with SELEX result
- Longstanding experimental puzzle!



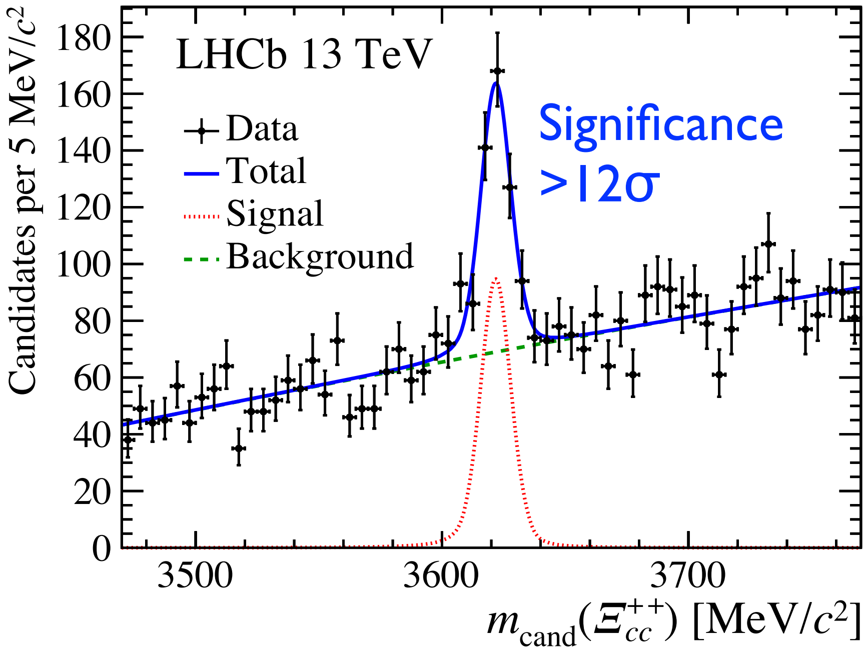
SELEX papers:
PRL 89:112001 (2002)
PLB B628:18-24 (2005)

LHCB-PAPER-2017-018 ; arXiv:1707.01621
LHCB-PAPER-2013-049 ; arXiv:1310.2538

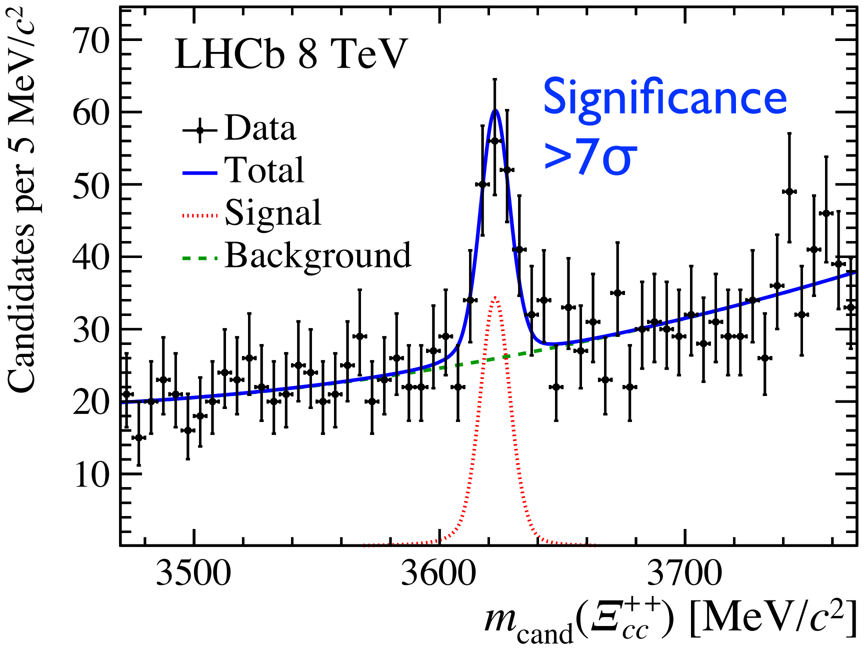
LHCb observation of Ξ_{cc}^{++}

- LHCb observed Ξ_{cc}^{++} with 2016 sample (main dataset) and measured m = $3621.40 \pm 0.72\,(\mathrm{stat}) \pm 0.27\,(\mathrm{syst}) \pm 0.14\,(\Lambda_c^+)\;\mathrm{MeV}/c^2$
- Observation confirmed with 2012 sample (crosscheck).
- Lifetime significantly different from zero: observation persists when requiring $(t / \sigma_t) > 5$
  - σ_t varies event by event, but typical resolution ~ 40-50fs

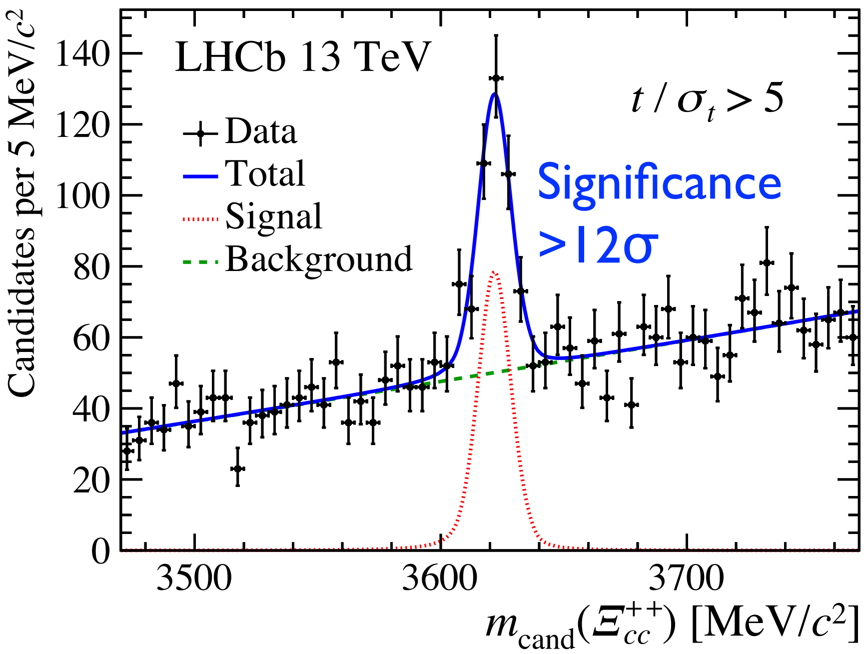
2016 data



2012 data



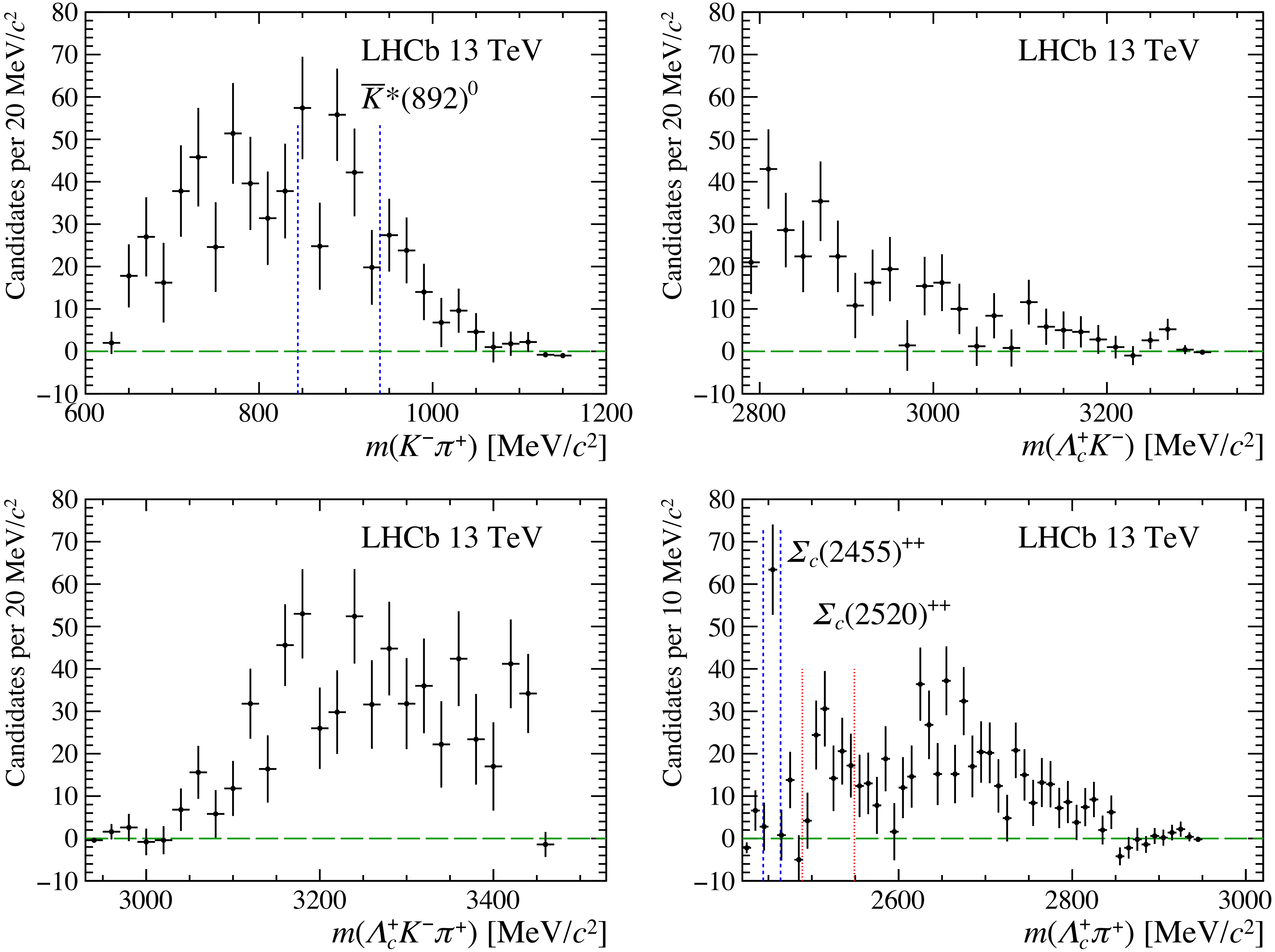
With lifetime cut



LHCB-PAPER-2017-018 ; arXiv:1707.01621

Resonant structure?

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



Picture is fuzzy. Clearly some resonant contributions, e.g. $\Sigma_c(2455)^{++}$, but no single resonance dominates.

LHCB-PAPER-2017-018 ; arXiv:1707.01621

LHCb Ξ_{cc}^{++} vs SELEX Ξ_{cc}^{+}

- Masses differ by 103±2 MeV (3621 vs 3519 MeV).
- Clearly not compatible with being an isodoublet.
- Both claims are for weakly decaying states => not compatible with one being an excitation of the other.
- Reported lifetime of SELEX Ξ_{cc}^{+} very short (< 33fs).

In a very narrow, legal sense, the results aren't mutually exclusive, but in practice either (a) one is wrong*, or (b) the constituent quark model is badly broken.

But enough history -- what about the future?

LHCB-PAPER-2017-018 ; arXiv:1707.01621

* SELEX peak could also be a narrow, strongly decaying Ξ_c resonance that they misidentified... but this interpretation doesn't explain nonobservation of $\Xi_c(2970)$, $\Xi_c(3055)$, etc.

What's next for Ξ_{cc}^{++} ?

- Ξ_{cc}^{++} lifetime measurement! Crucial to the interpretation.
  - Will also give us a clue about Ξ_{cc}^{+} lifetime.
- Ξ_{cc}^{++} production cross-section

veil of ignorance

- More Ξ_{cc}^{++} decay modes! Ratios of branching fractions.
- Constraints on spin, parity
- Ξ_{cc}^{+} search
  - Tougher, due to shorter expected lifetime.
  - We failed to find $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ with 0.65 fb^{-1} earlier... but we have better triggers, more modes, and much more data now.
- Ξ_{cc}^{+} properties, production relative to Ξ_{cc}^{++}, etc
- Ω_{cc}^{+} search (tougher still)
- Excited states
  - Lowest expected to decay electromagnetically -- tough for LHCb
  - Add pions, kaon... see what's out there!

Déjà vu: Why do we do spectroscopy?

In roughly ascending order:

- It's good clean fun^W physics
  - ... and sometimes you actually get to see a signal
- It provides inputs to pheno calculations in the area
- Empowers searches for New Physics
  - Necessary inputs, e.g. charm resonances for $B \rightarrow D^{(*)} \tau \nu$
  - Opens new paths (time until first CPV search with Ξ_{cc}?)
- Sometimes you find something unexpected
  - See: pentaquarks

Let's have a concrete example!

Search for Ξ_b^0 oscillations

- Basic idea: search for baryon-antibaryon oscillations of Ξ_b^0 (bsu), tagged by resonances: $\Xi_b^{(*/\prime)-} \to \Xi_b^0\,\pi^-$
- Baryon oscillations similar to meson mixing, but without DCS/ interference terms. [B-field effects negligible for Ξ_b^0 at LHCb]

Ξ_b^0 mixing:

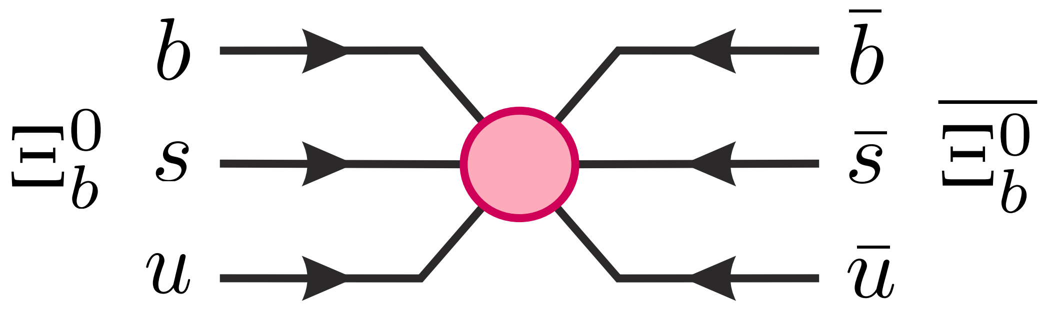
$$\boxed{\frac{\Gamma(\Xi_b^0 \to \bar{f})}{\Gamma(\Xi_b^0 \to f)} \simeq \left|\frac{q}{p}\right|^2 \left[(\Delta\Gamma/4)^2 + (\Delta m/2)^2\right] t^2 = \alpha t^2}$$

pure quadratic in t

D^0 mixing:

$$\boxed{\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} \simeq R_D + \sqrt{R_D}\, y'\,\Gamma t + (x'^2 + y'^2)\Gamma^2 t^2}$$

- Physics motivation: flavour-diagonal six-fermion BSM vertices allow such BNV without excessive proton decay.
(Ξ$_b^0$ is special: one valence quark from each generation)



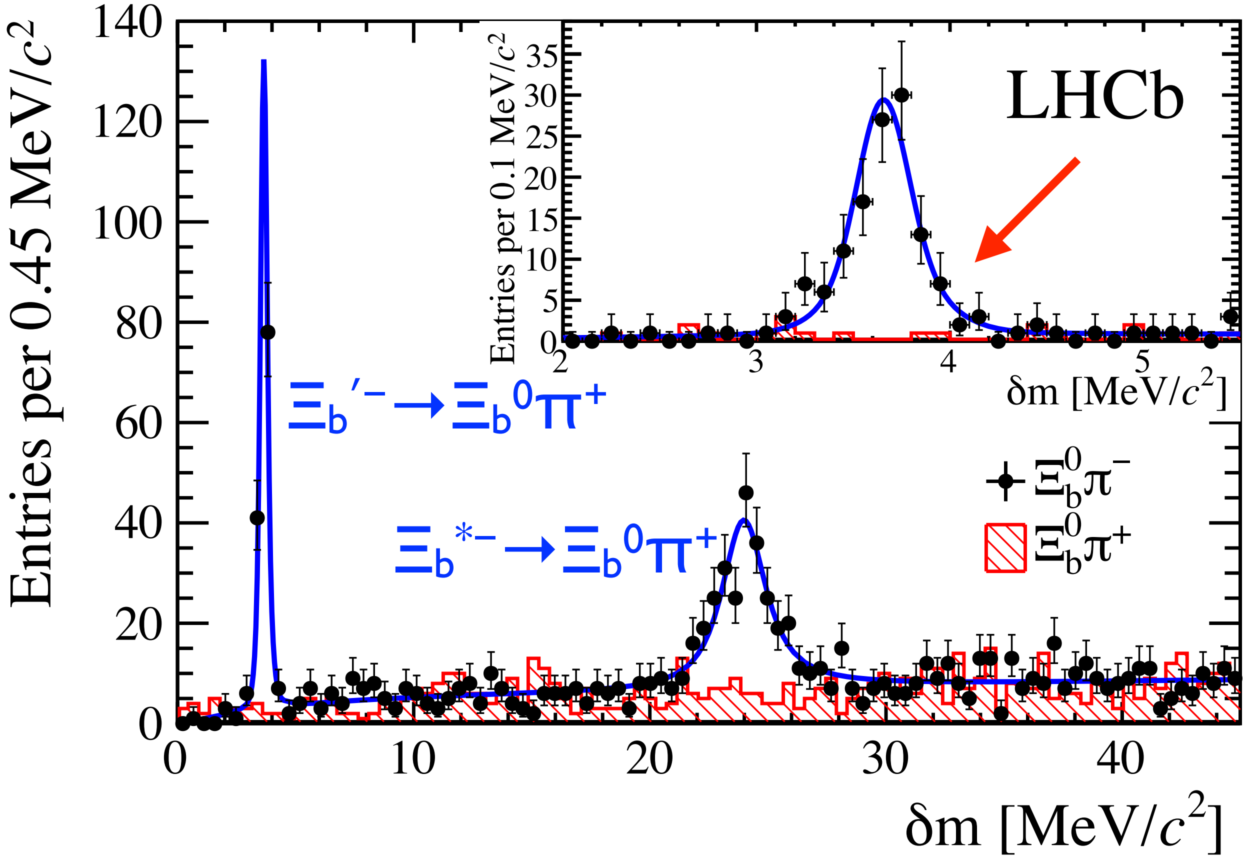
Kuzmin, hep-ph/9609253
Smith, PRD 85 (2012) 036005
Durieux, Gerard, Maltoni, & Smith, PLB 721 (2013) 82-85

McKeen & Nelson, PRD 94, 076002 (2016)
Aitken, McKeen, Nelson & Neder, PRD 96, 075009 (2017)

LHCB-PAPER-2017-023 ; arXiv:1708.05808

Search for Ξ_b^0 oscillations

- To make the analysis go, you need to do three things:
  - Measure the Ξ_b^0 decay time -- easy at LHCb
  - Identify the Ξ_b^0 baryon number at decay -- easy from final state
  - Identify (tag) the Ξ_b^0 baryon number at production -- hmm!
- LHCb has tagging tools... but tagging power is O(few %).
  - Typical mistag rate: forty-some percent. This is fine if looking at B^0/B_s oscillations with high stats, but fatal for a very rare BSM process.
- But we have a solution! Remember this?

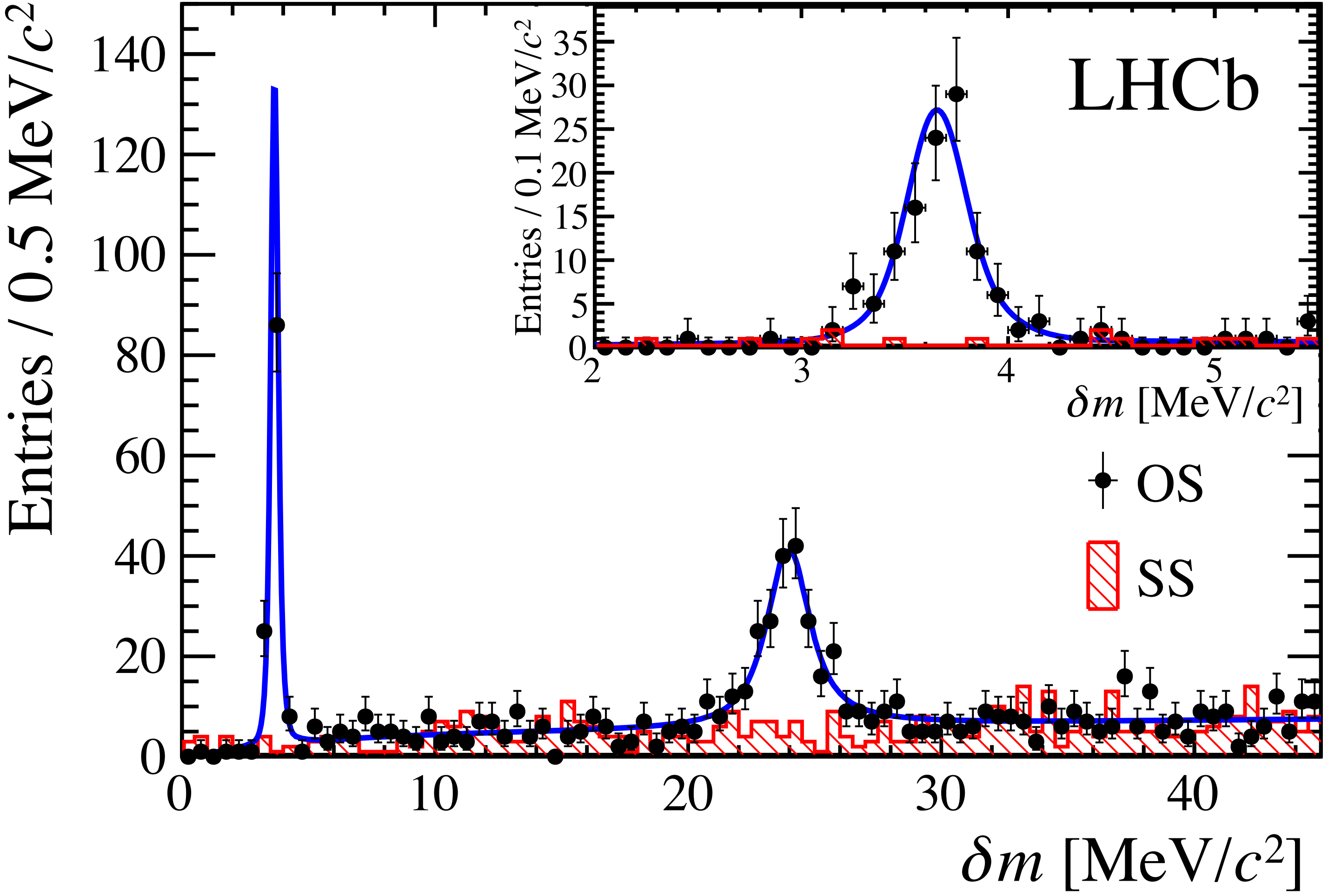


With these freshly discovered resonances, we have a small but very clean sample of Ξ_b^0 whose flavour at production is known.

LHCB-PAPER-2014-061 ; arXiv:1411.4849
LHCB-PAPER-2017-023 ; arXiv:1708.05808

Search for Ξ_b^0 oscillations

Selection slightly tighter w.r.t. previous analysis

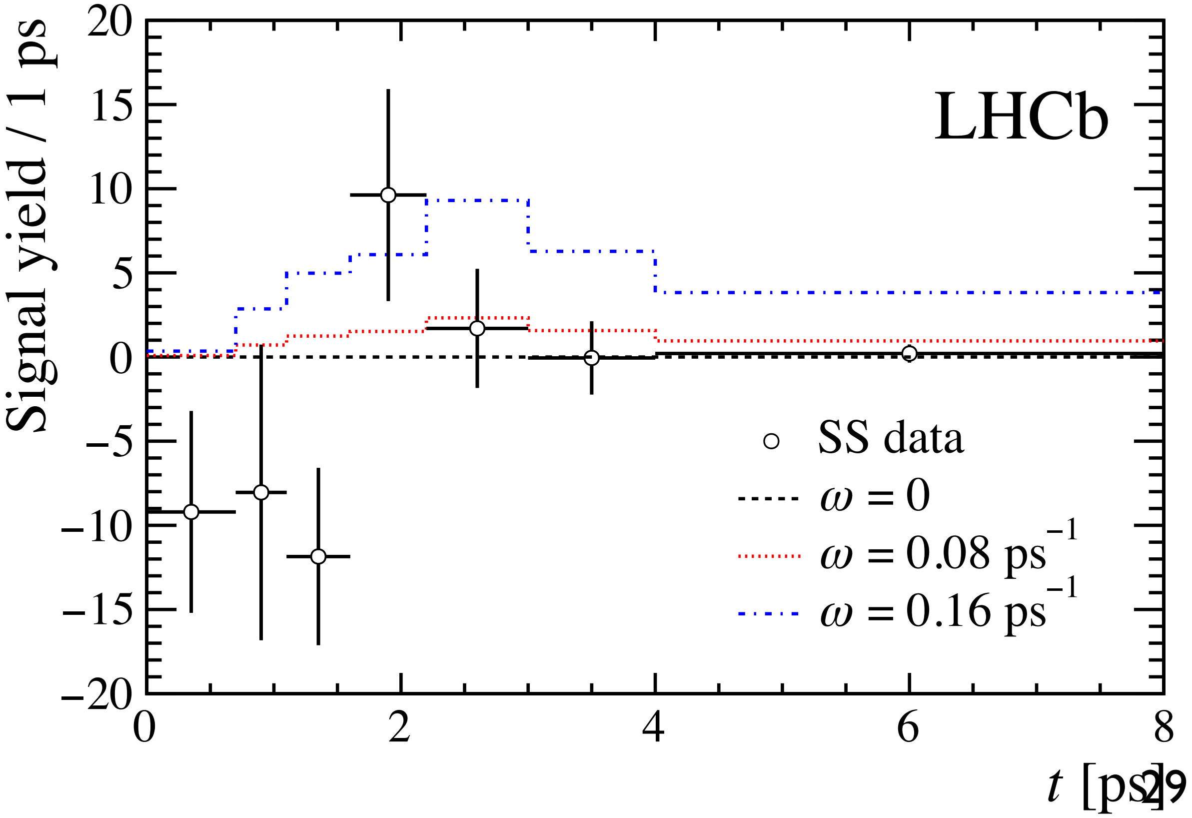


Absence of a clear signal in the same-sign (BNV) channel.

Quantitative analysis to set upper limit on oscillation rate.

$$R(t) \equiv \frac{P_{X\to\overline{X}}(t)}{P_{X\to X}(t)} = \tan^2(t/\tau_{\rm mix}) \simeq \frac{t^2}{\tau^2_{\rm mix}} \equiv (\omega t)^2$$

- Data => $\omega < 0.08\ \mathrm{ps}^{-1}$ at 95% CL
- Corresponds to oscillation period $(2\pi/\omega) > 80$ ps at 95% CL
- c.f. Ξ_b^0 lifetime ~ 1.5 ps
- Can improve with Run 2, and with semileptonic decays of Ξ_b^0

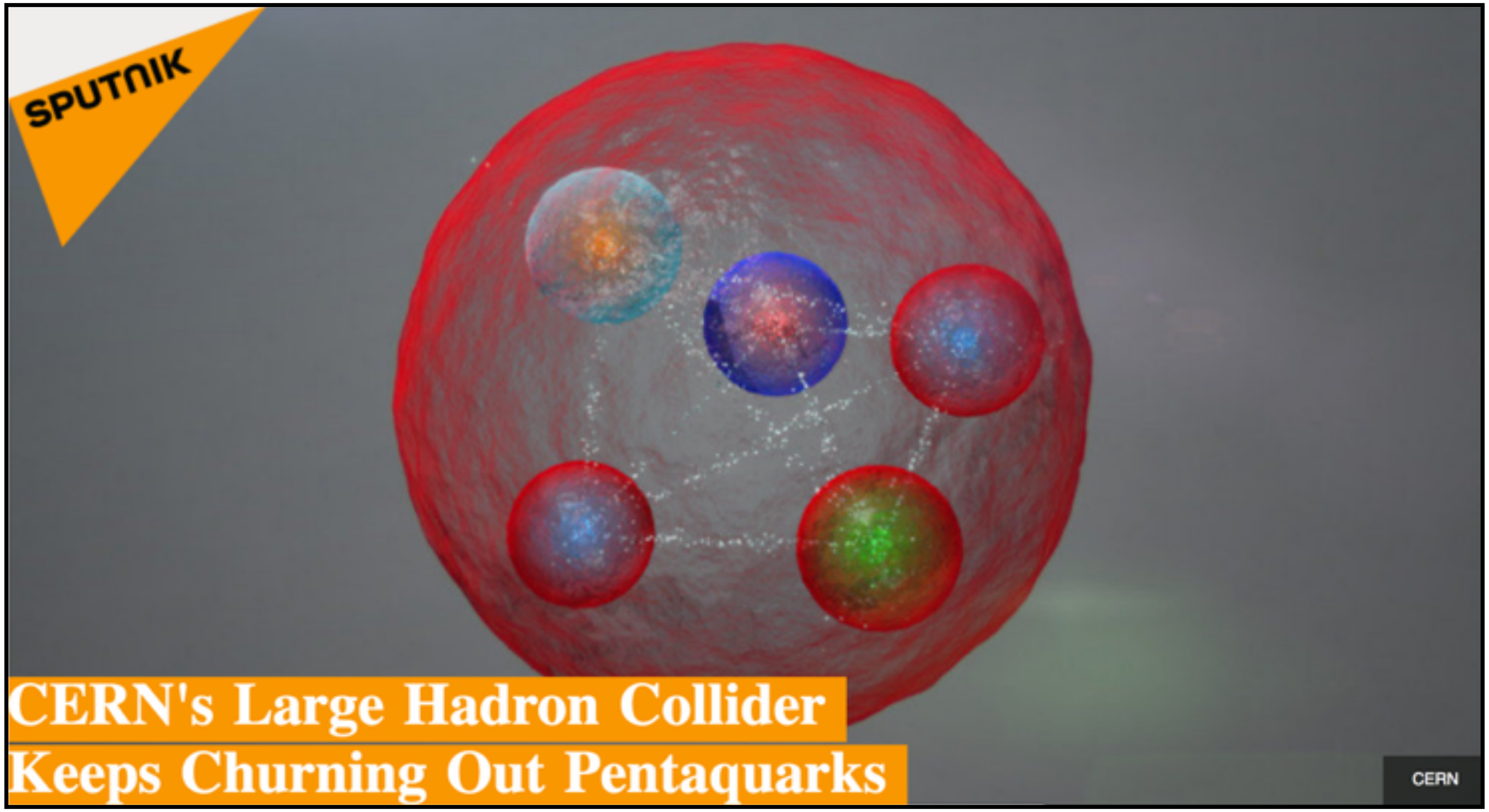


Penultimate words

- LHCb has done some really cool work in spectroscopy.
  - Hat tip especially to the folks who worked on $Z(4430)^-$ and pentaquark analyses.
- But these things don't come for free.
- As we upgrade the detector and move to a real-time trigger, we will get bigger and bigger samples of things we look for.
  - Ξ_{cc} is the poster child here -- analysis used Turbo (real-time) output. Not a coincidence that 2016 sample was more sensitive.
- ... but we will have zero sensitivity to things we don't plan for.
- Therefore: we need to plan carefully ahead of Run 3.
  - Maxim: the technical challenges charm has today, beauty will have a couple of years later.
- Also therefore: if you have a clever theory about new particles, make sure we have a trigger that can find them!

Last words

- Lots of good physics going on
  - Some makes headlines and some does not, but it all helps us understand flavour physics better.
- "Yesterday's discovery is today's calibration and tomorrow's background."
- Looking forward to many new backgrounds!



$$\tilde{t}$$

LHCb links & references

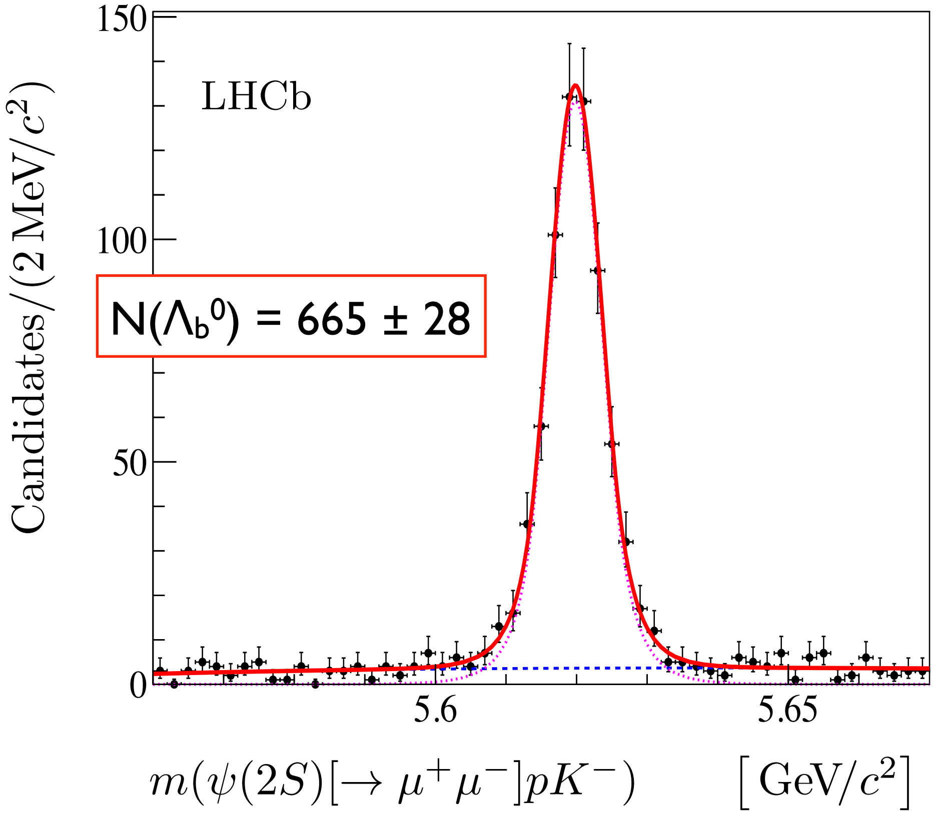
- LHCB-PAPER-2017-023 ; arXiv:1708.05808 : Search for baryon-number-violating Ξ_b^0 oscillations
- LHCB-PAPER-2017-018 ; arXiv:1707.01621 : Observation of the doubly charmed baryon Ξ_{cc}^{++}
- LHCB-PAPER-2017-002 ; arXiv:1703.04639 : Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$
- LHCB-PAPER-2016-061 ; arXiv:1701.07873 : Study of the $D^0 p$ amplitude in $\Lambda_b^0 \to D^0 p \pi^-$ decays
- LHCB-PAPER-2016-010 ; arXiv:1604.03896 : Measurement of the properties of the Ξ_b^{*0} baryon
- LHCB-PAPER-2016-008 ; arXiv:1604.01412 : Measurement of the mass and lifetime of the Ω_b^- baryon
- LHCB-PAPER-2015-060 ; arXiv:1603.06961 : Observation of $\Lambda_b^0 \to \psi(2S) p K^-$ and $\Lambda_b^0 \to J/\psi \pi^+ \pi^- p K^-$ decays and a measurement of the Λ_b^0 baryon mass
- LHCB-PAPER-2015-047 ; arXiv:1510.03829 : Evidence for the strangeness-changing weak decay $\Xi_b^- \to \Lambda_b^0 \pi^-$
- LHCB-PAPER-2014-061 ; arXiv:1411.4849 : Observation of two new Ξ_b^- baryon resonances
- LHCB-PAPER-2014-048 ; arXiv:1409.8568 : Precision measurement of the mass and lifetime of the Ξ_b^- baryon
- LHCB-PAPER-2014-021 ; arXiv:1405.7223 : Precision measurement of the mass and lifetime of the Ξ_b^0 baryon
- LHCb-PAPER-2014-010 ; arXiv:1405.1543 : Measurement of the Ξ_b^- and Ω_b^- baryon lifetimes
- LHCB-PAPER-2014-003 ; arXiv:1402.6242 : Precision measurement of the ratio of the Λ_b^0 to $\bar{B}^0$ lifetimes
- LHCB-PAPER-2014-002 ; arXiv:1403.3606 : Study of beauty hadron decays into pairs of charm hadrons
- LHCB-PAPER-2013-056 ; arXiv:1311.4823 : Studies of beauty baryon decays to $D^0 p h^-$ and $\Lambda_c^+ h^-$ final states
- LHCB-PAPER-2013-049 ; arXiv:1310.2538 : Search for the doubly charmed baryon Ξ_{cc}^+
- LHCB-PAPER-2012-048 ; arXiv:1302.1072 : Measurement of the Λ_b^0, Ξ_b^- and Ω_b^- baryon masses
- LHCB-PAPER-2012-012 ; arXiv:1205.3452 : Observation of excited Λ_b^0 baryons
- LHCB-PAPER-2011-035 ; arXiv:1112.4896 : Measurement of b-hadron masses

b-baryon ground state masses

- Masses all relative to Λ_b^0
- World average Λ_b^0 mass dominated by an LHCb study of $\Lambda_b^0 \to \mu^+ \mu^- p K^- [\pi^+ \pi^-]$

Channel	$M(\Lambda_b^0)$ [MeV/c^2]
$\Lambda_b^0 \to J/\psi\, pK^-$	$5619.62 \pm 0.04 \pm 0.34$
$\Lambda_b^0 \to \psi(2S)[\to \mu^+\mu^-]pK^-$	$5619.84 \pm 0.18 \pm 0.19$
$\Lambda_b^0 \to \psi(2S)[\to J/\psi\, \pi^+\pi^-]pK^-$	$5619.38 \pm 0.33 \pm 0.18$
$\Lambda_b^0 \to J/\psi\, \pi^+\pi^- pK^-$ excluding $\psi(2S)$	$5619.08 \pm 0.30 \pm 0.27$

$$M(\Lambda_b^0) = 5619.65 \pm 0.17 \pm 0.17\,\mathrm{MeV}/c^2$$



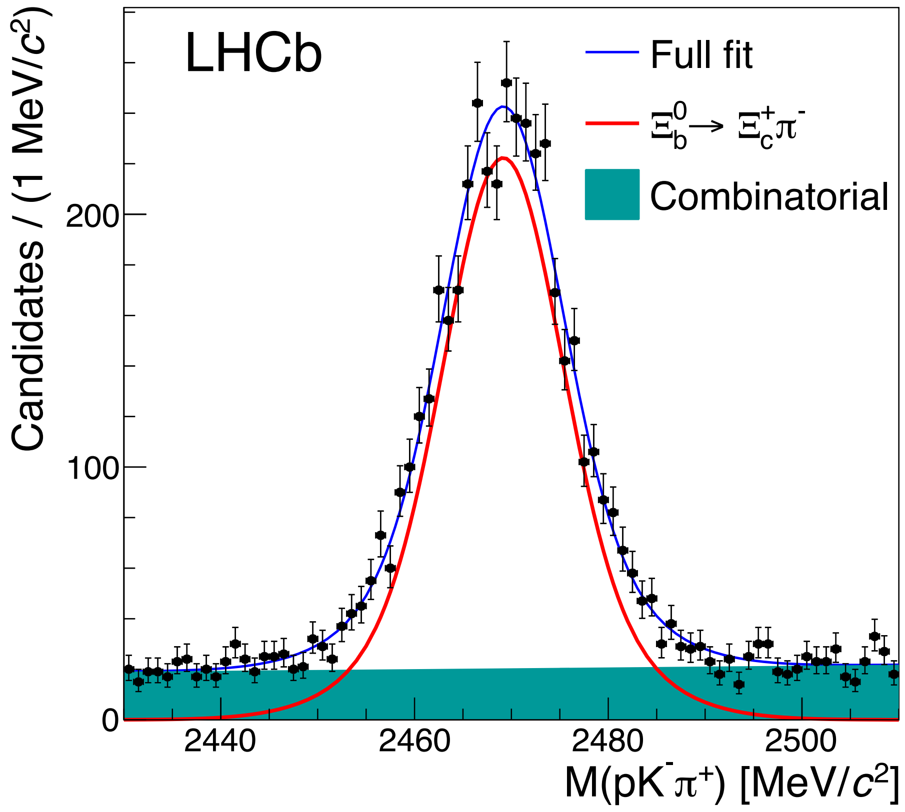
- Trade-off between stat & sys errors!
- Large q-value => large phase space => more stats
- Small q-value => closer to threshold => less to measure
- Winner is a near-threshold mode. This will be a pattern!

LHCB-PAPER-2015-060 ; arXiv:1603.06961

b-baryon ground state masses

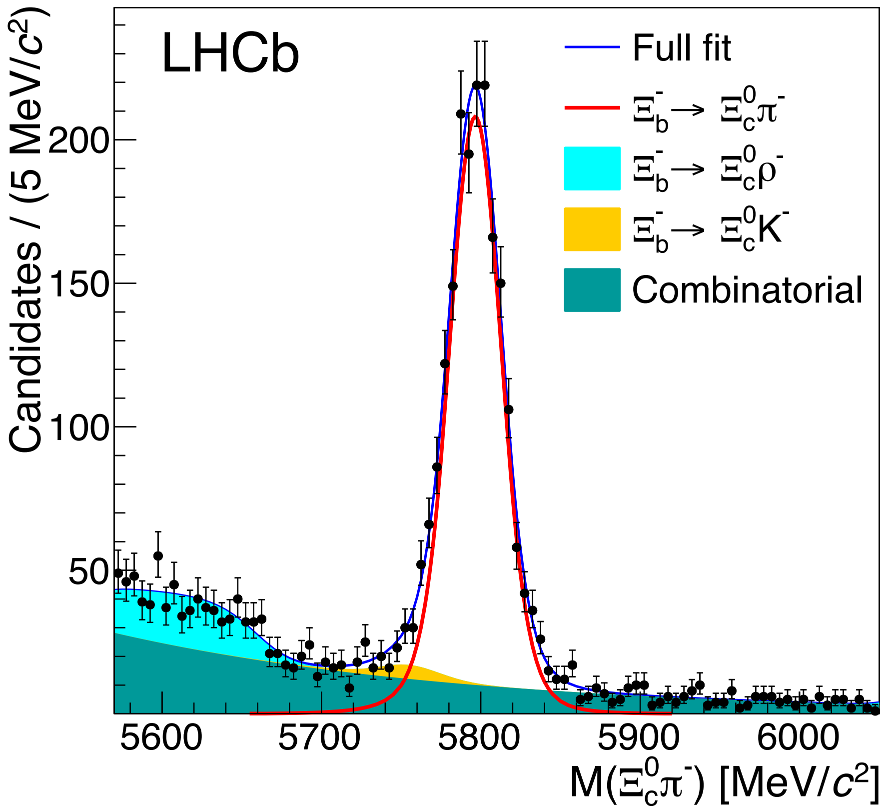
- Masses all relative to Λ_b^0
- Masses of Ξ_b^- and Ξ_b^0 dominated by a pair of papers:

$\Lambda_b^0 \to \Lambda_c^+ \pi^-$; $\Lambda_c^+ \to p K^- \pi^+$
$\Xi_b^0 \to \Xi_c^+ \pi^-$; $\Xi_c^+ \to p K^- \pi^+$



$$M(\Xi_b^0) - M(\Lambda_b^0) = 172.44 \pm 0.39 \pm 0.17 \ \mathrm{MeV}/c^2$$

$\Lambda_b^0 \to \Lambda_c^+ \pi^-$; $\Lambda_c^+ \to p K^- \pi^+$
$\Xi_b^- \to \Xi_c^0 \pi^-$; $\Xi_c^0 \to p K^- K^- \pi^+$



$$M(\Xi_b^-) - M(\Lambda_b^0) = 178.36 \pm 0.46 \pm 0.16 \ \mathrm{MeV}/c^2$$

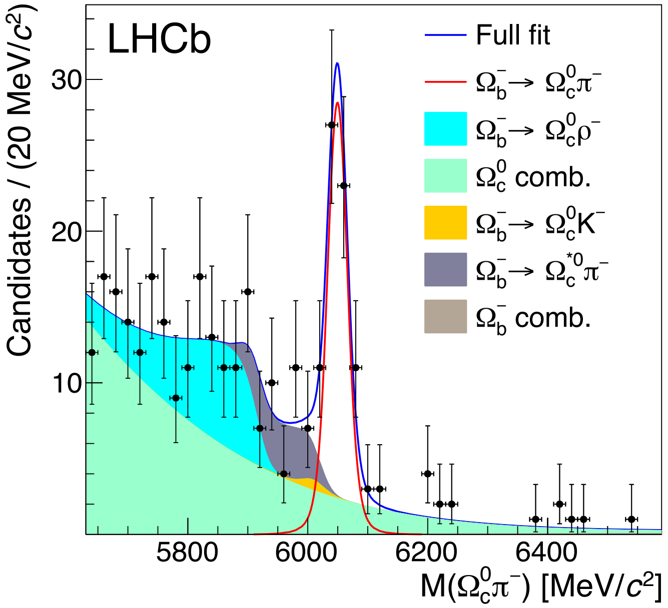
In passing, also obtain:

$$M(\Xi_c^+) - M(\Lambda_c^+) = 181.51 \pm 0.14 \pm 0.10 \ \mathrm{MeV}/c^2$$

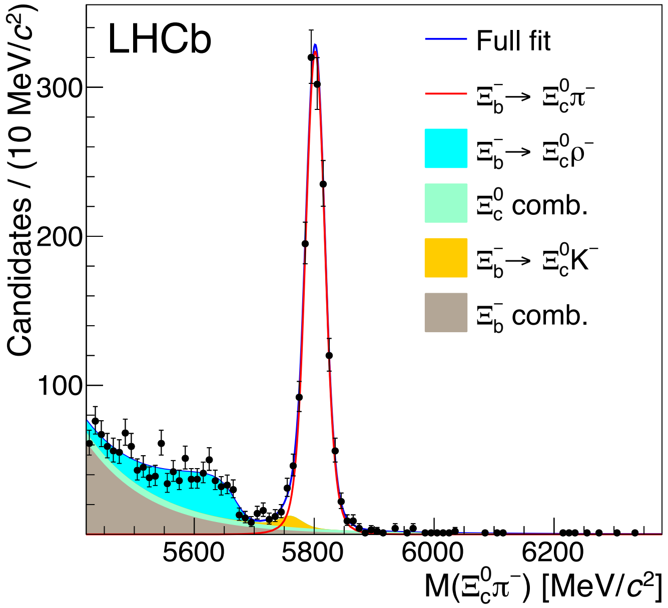
LHCB-PAPER-2014-048 ; arXiv:1409.8568
LHCB-PAPER-2014-021 ; arXiv:1405.7223

b-baryon ground state masses

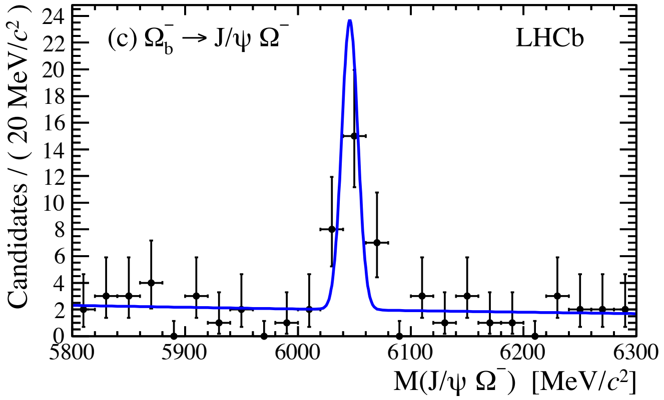
- Lastly, Ω_b^-. Here a few measurements contribute:

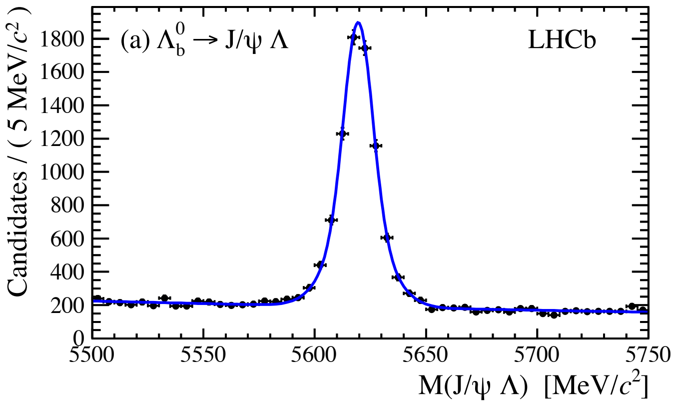


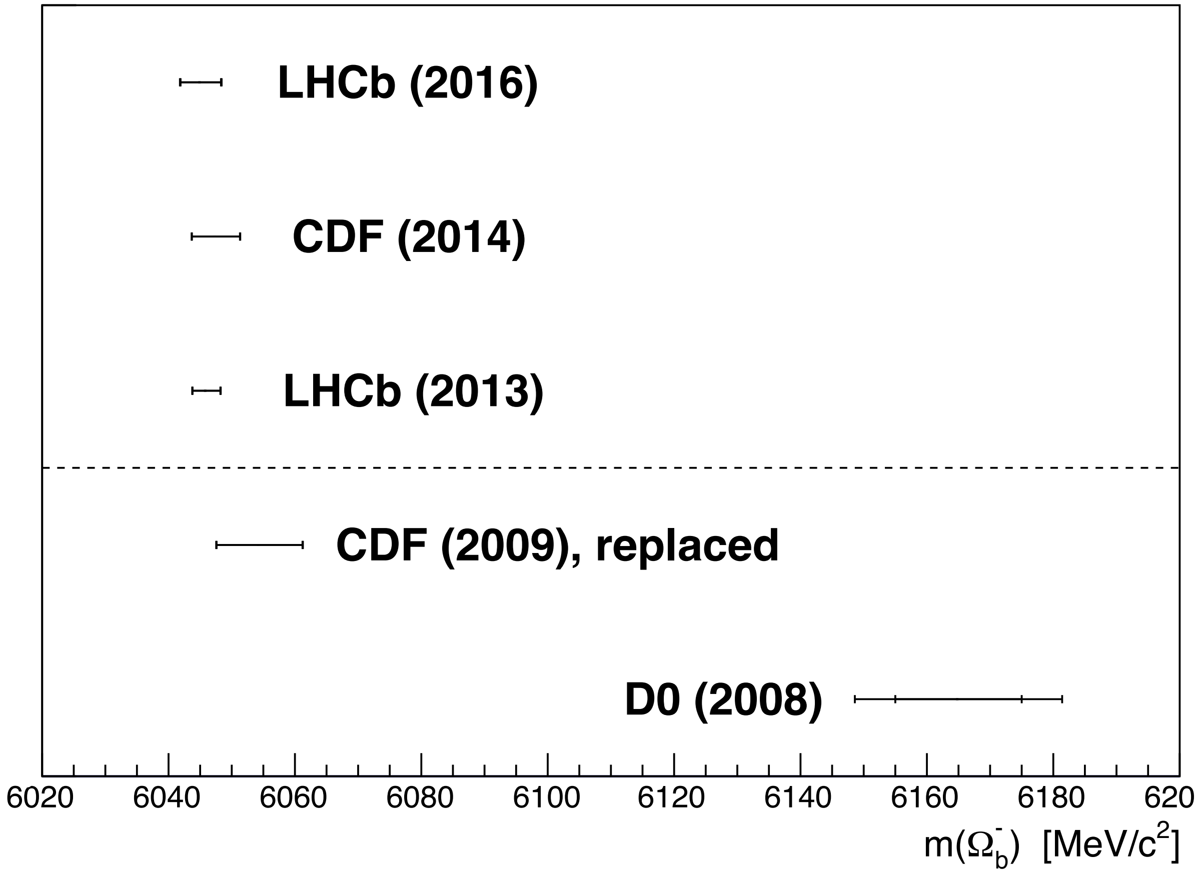
Signal mode



Control mode





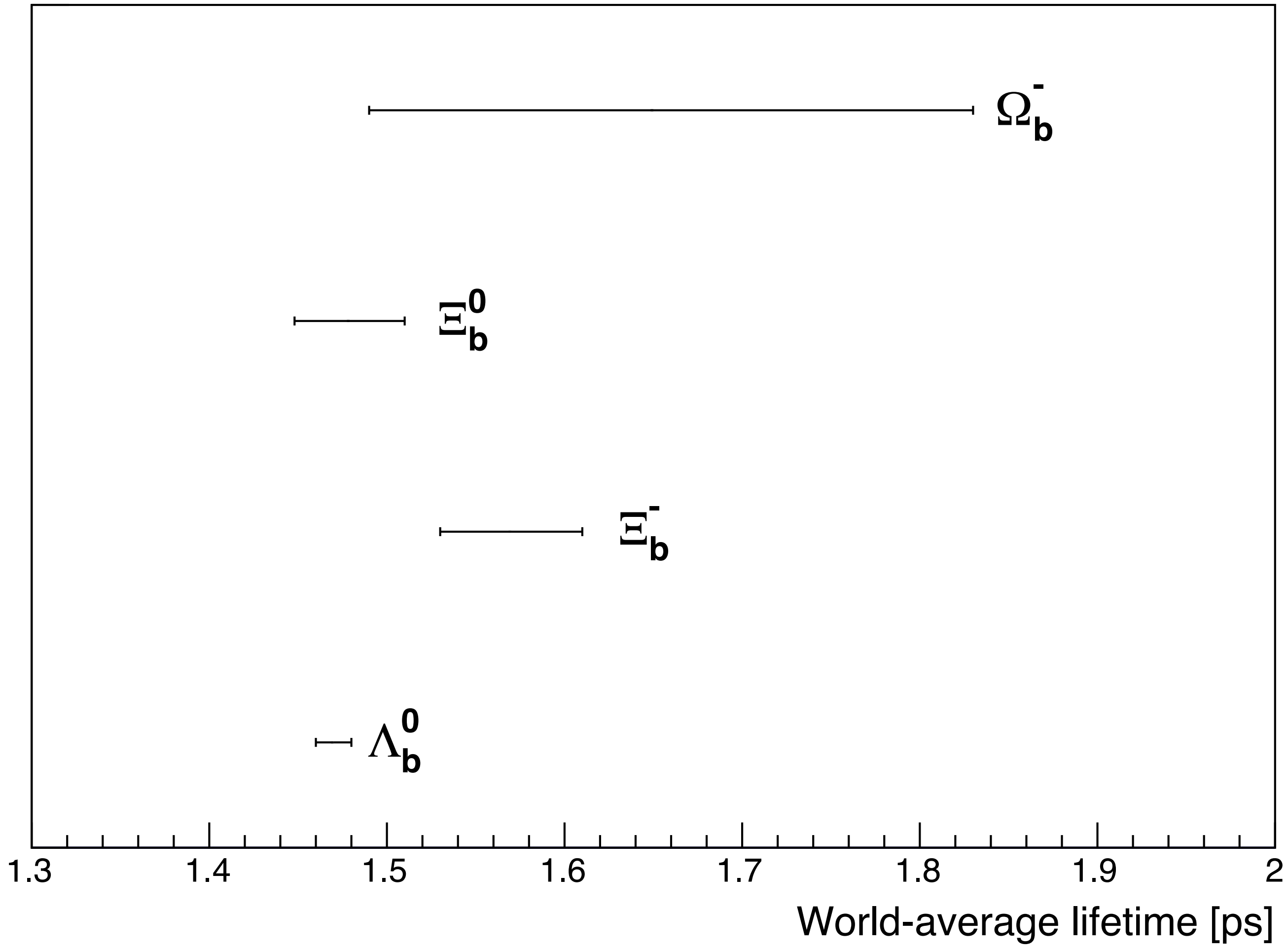


LHCB-PAPER-2016-008 ; arXiv:1604.01412
LHCB-PAPER-2012-048 ; arXiv:1302.1072

CDF: arXiv:1403.8126 ; PRD 89, 072014 (2014)
D0: arXiv:0808.4142 ; PRL 101:232002 (2008)

b-baryon ground state lifetimes

- Technique of measuring lifetime ratios relative to control mode used extensively
  - Λ_b^0 lifetime dominated by Λ_b^0/B^0 ratio ($\Lambda_b^0 \to J/\psi\, p\, K^- / \bar{B}^0 \to J/\psi\, \pi^+ K^-$)
  - Ξ_b^- and Ξ_b^0 dominated by Ξ_b/Λ_b^0 ratios (same as for masses)
  - Ω_b^- lifetime measured via ratio w.r.t. Ξ_b^-, also absolute via $\Omega_b^- \to J/\psi\, \Omega^-$
- Choose similar decay modes for numerator & denominator
- Many systematics cancel, especially if lifetimes similar



LHCB-PAPER-2014-003 ; arXiv:1402.6242
LHCB-PAPER-2014-048 ; arXiv:1409.8568
LHCB-PAPER-2014-021 ; arXiv:1405.7223
LHCB-PAPER-2016-008 ; arXiv:1604.01412
LHCb-PAPER-2014-010 ; arXiv:1405.1543