Spectroscopy of Singly-Heavy* Hadrons

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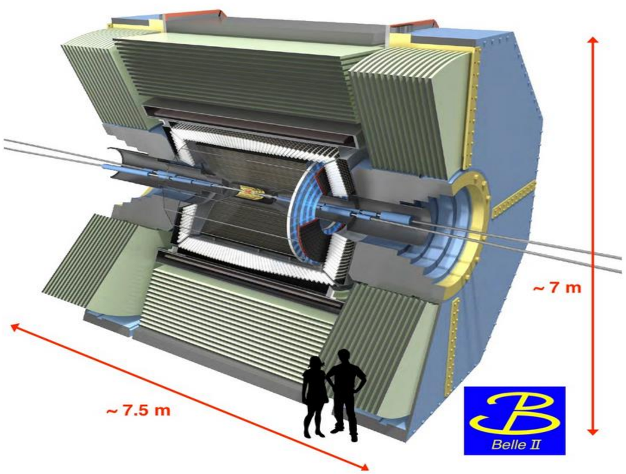
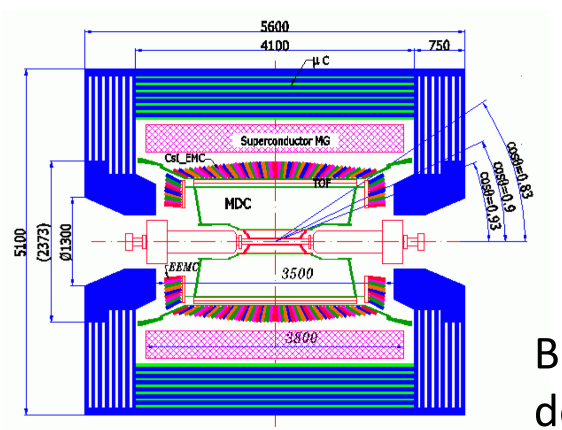
*Charm and bottom are heavy, strange is strange – sometimes it is heavy and sometimes it is light

I will comment on the general patterns we see in the experimental results for heavy hadrons, and highlight some interesting recent results.

e$^+$e$^-$ machines
Clean signals
Comparatively low yields



Belle II now taking data
(Belle still analyzing, previously BaBar and CLEO)

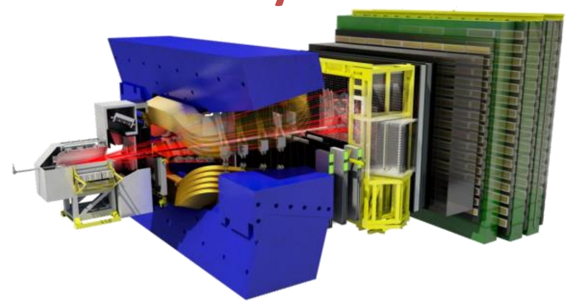


BES III – many results on charm decays, but fewer on spectroscopy

Hadron machines

HUGE yields

LHCb is the only experiment dedicated to heavy flavors at LHC:



CMS and ATLAS take even more data…

(previous experiments D0 and CDF)

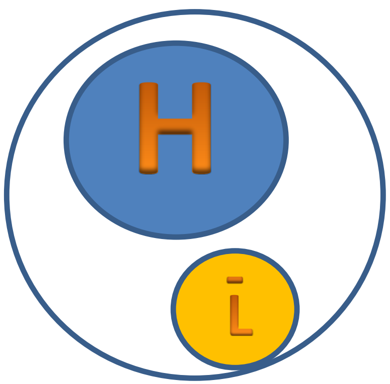
The Quark Model dates from 1960

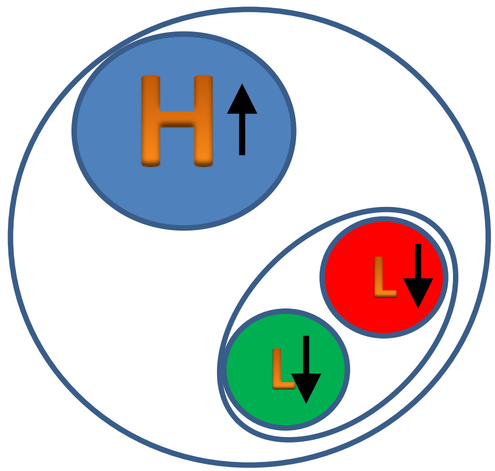
Gell-Mann taught us how to construct baryons and mesons, and predicted the Ω^- particle

He also showed the difference between the Λ and a Σ

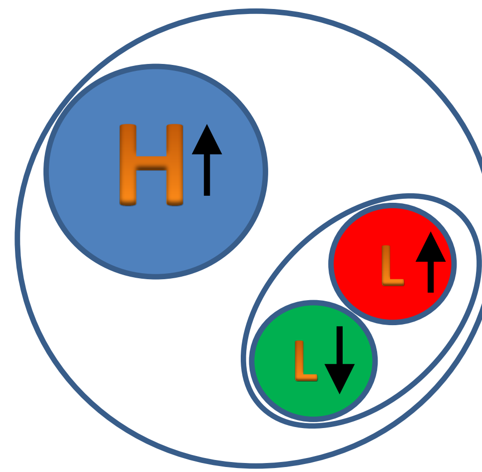
In his day H is strange
L is up/down

Murray Gell-Mann, Sept 1929-May 2019





Σ



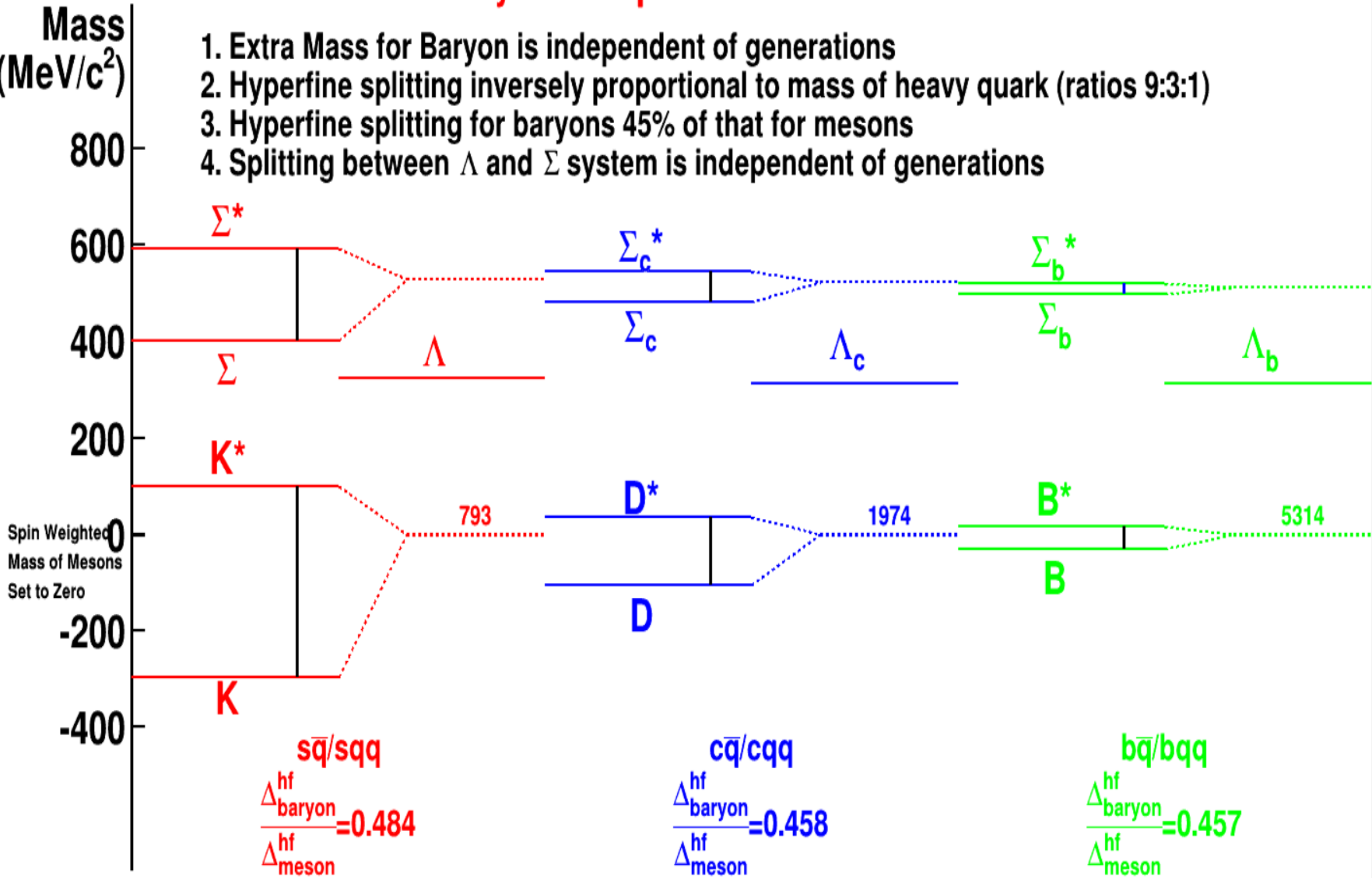
Λ

Heavy Meson

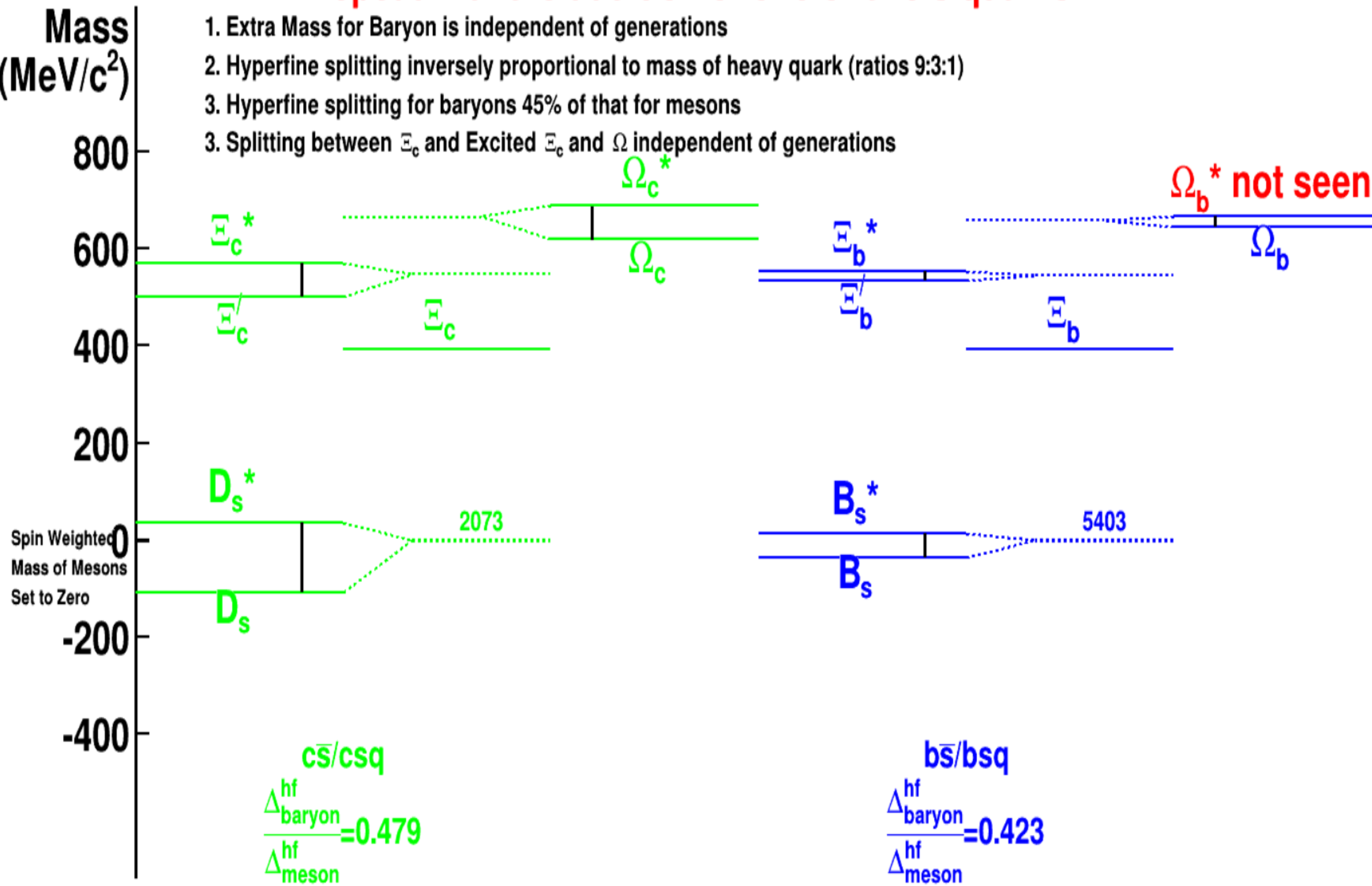
Heavy Baryon

Meson/Baryon Comparison for 3 Generations

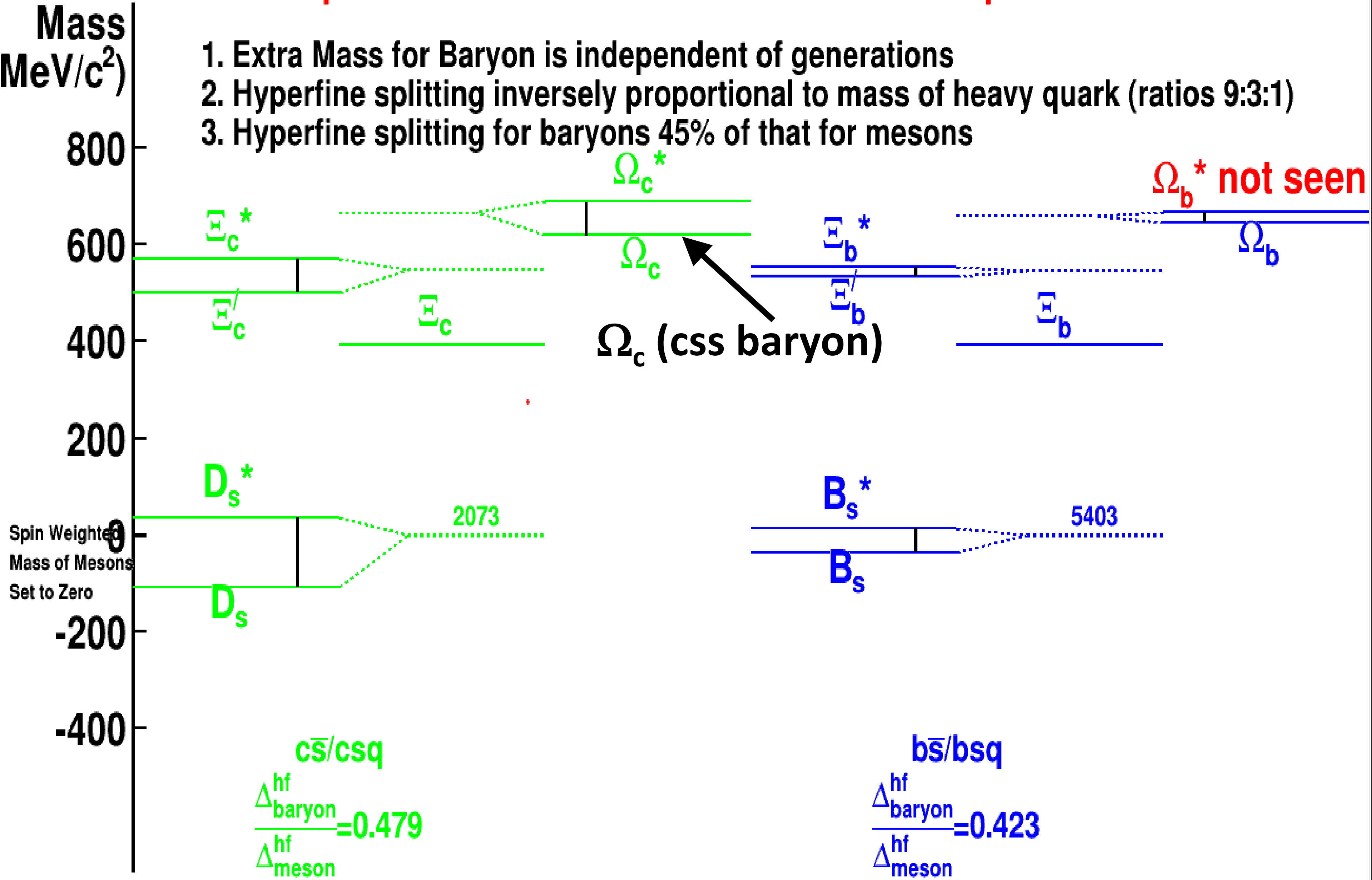
1. Extra Mass for Baryon is independent of generations
2. Hyperfine splitting inversely proportional to mass of heavy quark (ratios 9:3:1)
3. Hyperfine splitting for baryons 45% of that for mesons
4. Splitting between Λ and Σ system is independent of generations



Repeat with the addition of one or two s quarks



Repeat with the addition of one or two s quarks



The history of measurements of the mass and lifetime of the Ω_c (css)

Experiment	Mass (MeV)	Lifetime (10^{-13} s)	Comment
WA 62 (1985)	2748 ± 10		3 events and wrong mass. Ignore
ARGUS (1992)	$2719 \pm 7 \pm 2.5$		Wrong cross-section (by a factor of 50) Ignore
E-687 (1993)	$2705.9 \pm 3.3 \pm 2.0$		10 events
E-687 (1994)	$2699 \pm 1.5 \pm 2.5$	$0.86 \pm 0.24 \pm 0.28$	The decay mode ($\Sigma^+ K^- K^- \pi^+$) has not been seen by others! Ignore
CLEO II	$2694.6 \pm 2.6 \pm 1.9$		Sum of 5 channels
WA-89 (1995)	2707.5 ± 3.9 2720.0 ± 3.4 2719.8 ± 4.7	$0.55 \pm 0.12 \pm 0.21$	Masses in different modes did not agree and are wrong! Ignore
FOCUS (2003)	2697.5 ± 2.2	$0.72 \pm 0.11 \pm 0.11$	59 ± 12 events
BELLE (2009)	$2693.6 \pm 0.3 \pm 1.6$		725 events
LHCb		**$2.68 \pm 0.24 \pm 0.10$**	978 ± 60 events (mode pKKπ)

The moral is: if you want to measure a particle's lifetime, first make sure you are seeing the particle.

	Ξ_c^0	Ξ_c^+	Λ_c^+
LHCb	$1.545 \pm 0.017 \pm 0.016 \pm 0.010$	$4.568 \pm 0.035 \pm 0.029 \pm 0.031$	$2.035 \pm 0.010 \pm 0.013 \pm 0.014$
PDG	1.12 ± 0.12	4.42 ± 0.26	2.00 ± 0.06

Repeat with the addition of one or two s quarks

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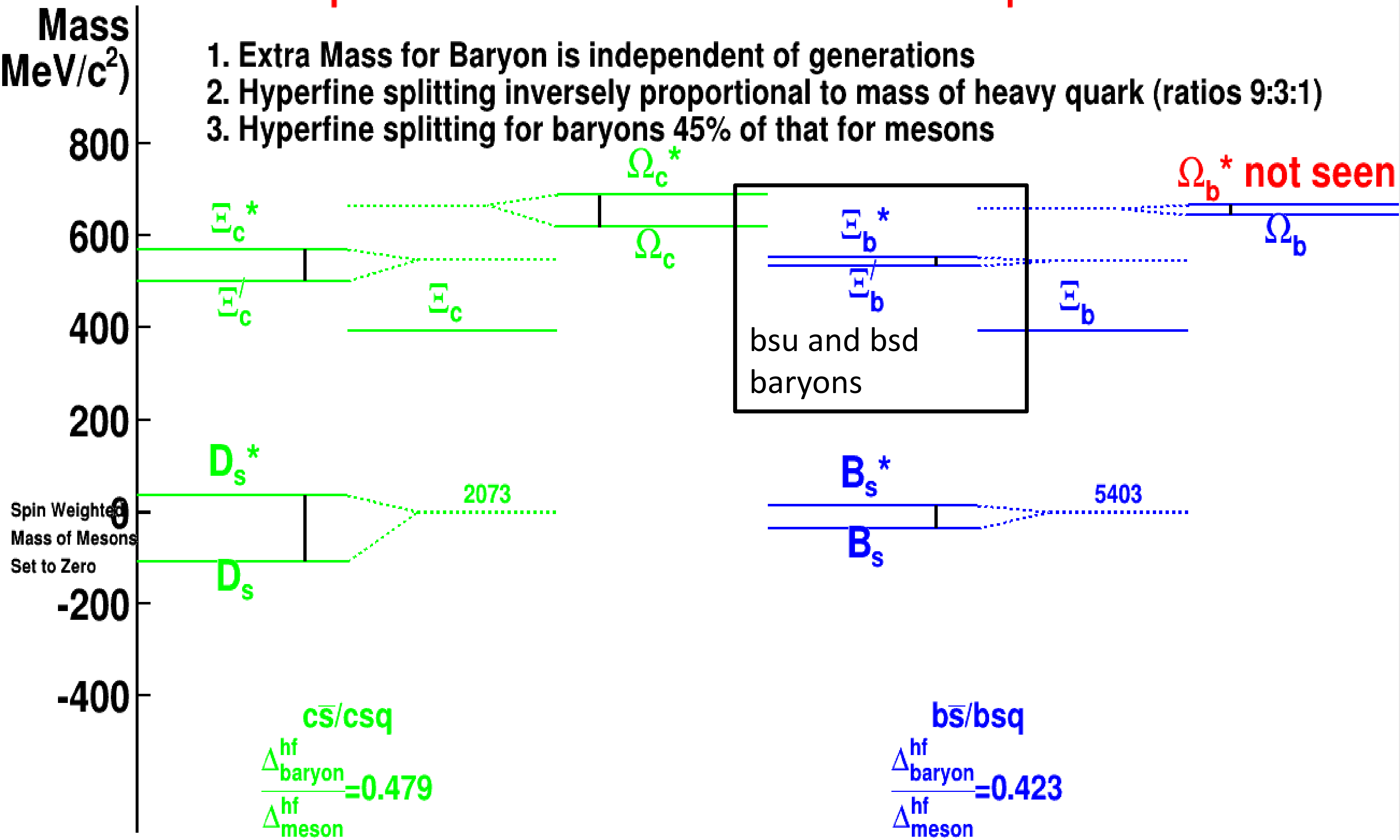
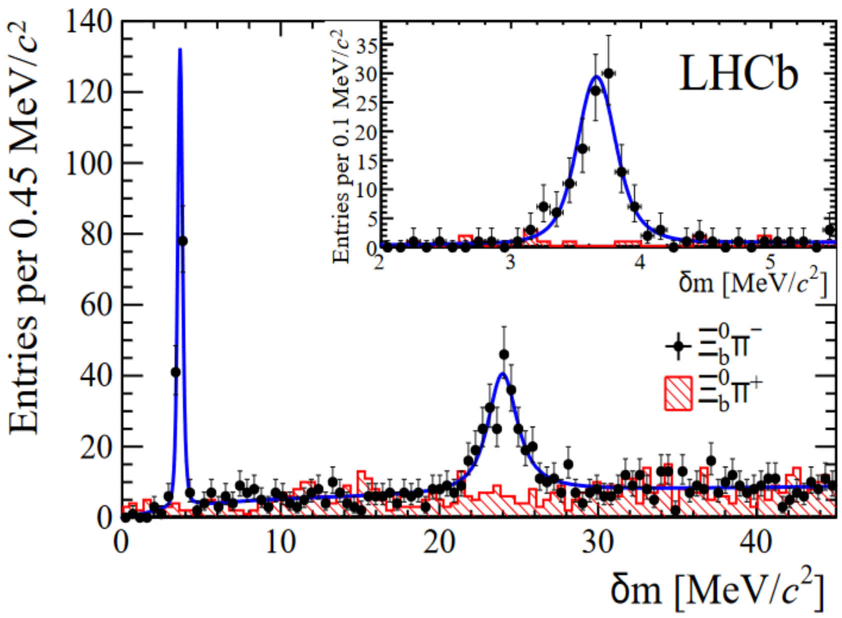
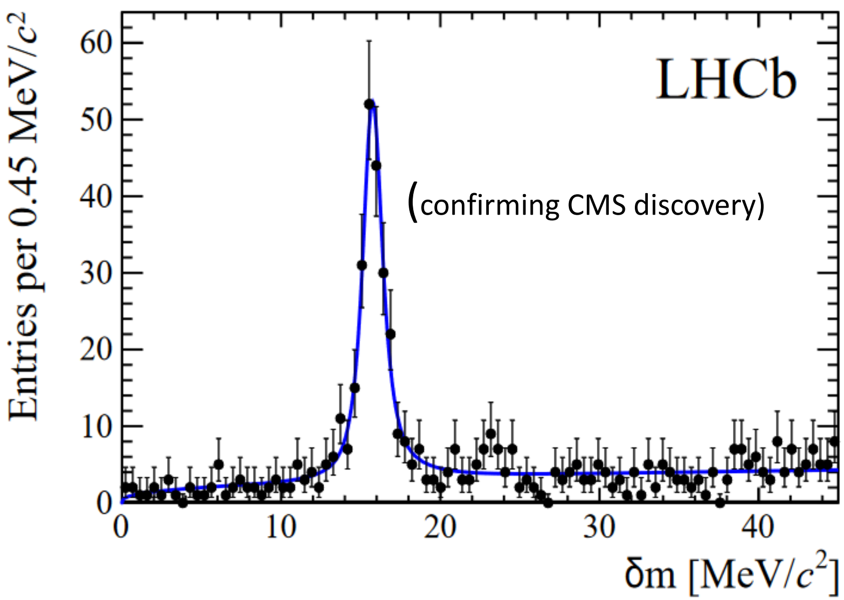
3. Hyperfine splitting for baryons 45% of that for mesons





$\Xi_b^0\,\pi^-$ shows 2 peaks, corresponding to $J^p=1/2^+$ and $J^P=3/2^+$



$\Xi_b^-\,\pi^+$ shows only one peak, presumably the other is below strong-decay threshold, and remains to be discovered

Repeat with the addition of one or two s quarks

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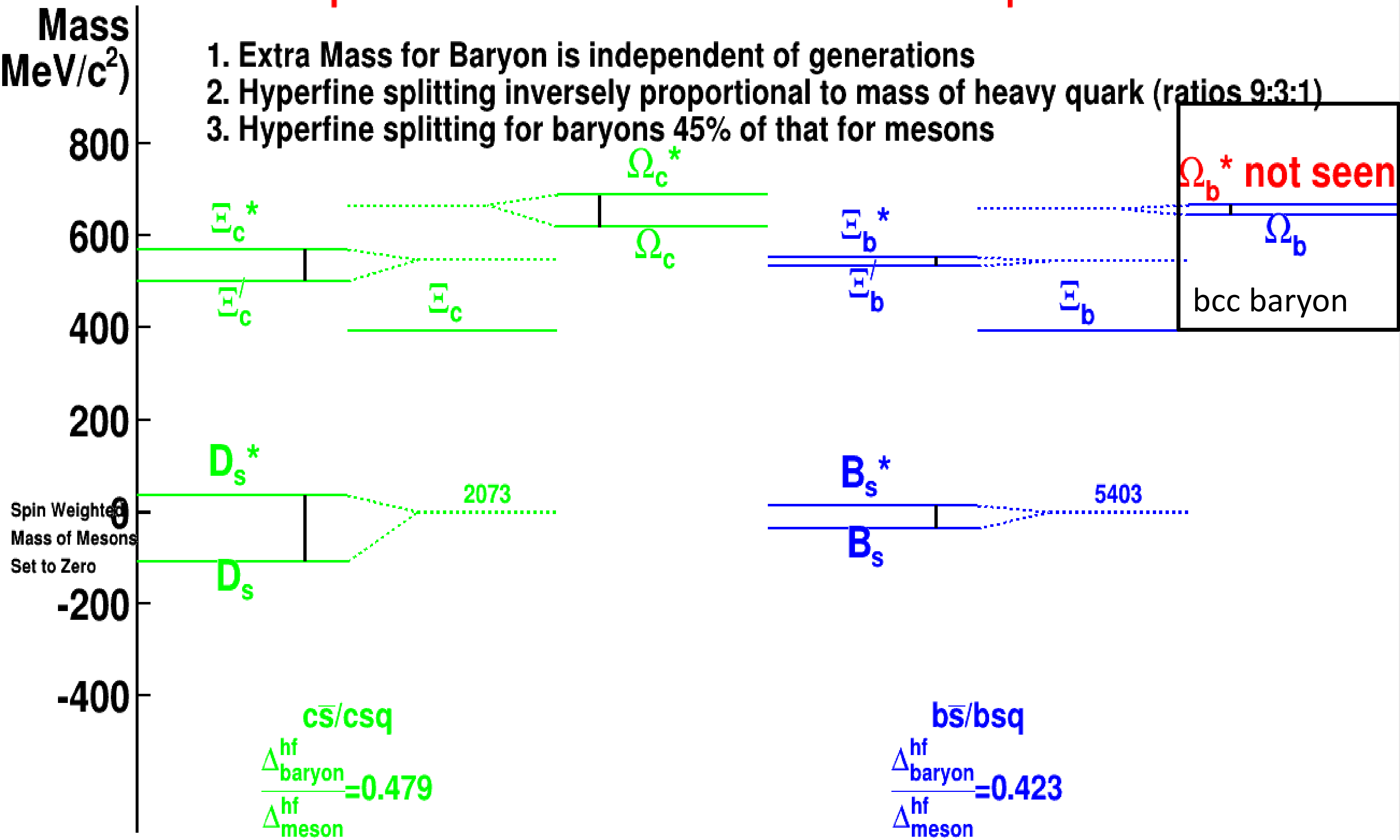


Using masses of D_s, D_s^*, B_s, B_s^*, Ω_c, Ω_c^* , we can predict the mass of the Ω_b to be 6050 MeV

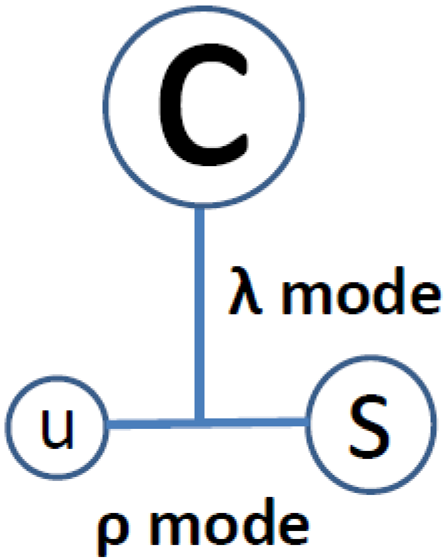
Experiment	Mass (MeV)	
D0 (2008)	$6165 \pm 10 \pm 13$	Claimed to be > 5σ
CDF (2009)	$6054.4 \pm 6.9 \pm 0.9$	
LHCb (2013)	$6046.0 \pm 2.2 \pm 0.5$	
CDF (2014)	$6047.5 \pm 3.8 \pm 0.6$	(replaces earlier analysis)
LHCb (2016)	$6045.1 \pm 3.2 \pm 0.8$	

Ω_b^* not yet seen (low energy photon transition), predicted mass 6070 MeV

In p-wave heavy baryons (i.e. 1 unit of orbital angular momentum), the orbital angular momentum can be in two different places - either between the heavy quark and light di-quark (λ-modes, low mass excitation) or between the two lighter quarks (ρ-mode, higher mass excitation).

The di-quark itself can be spin-0, or spin-1 (the latter being the only one possible when both quarks are the same flavor). This leads to many different states.

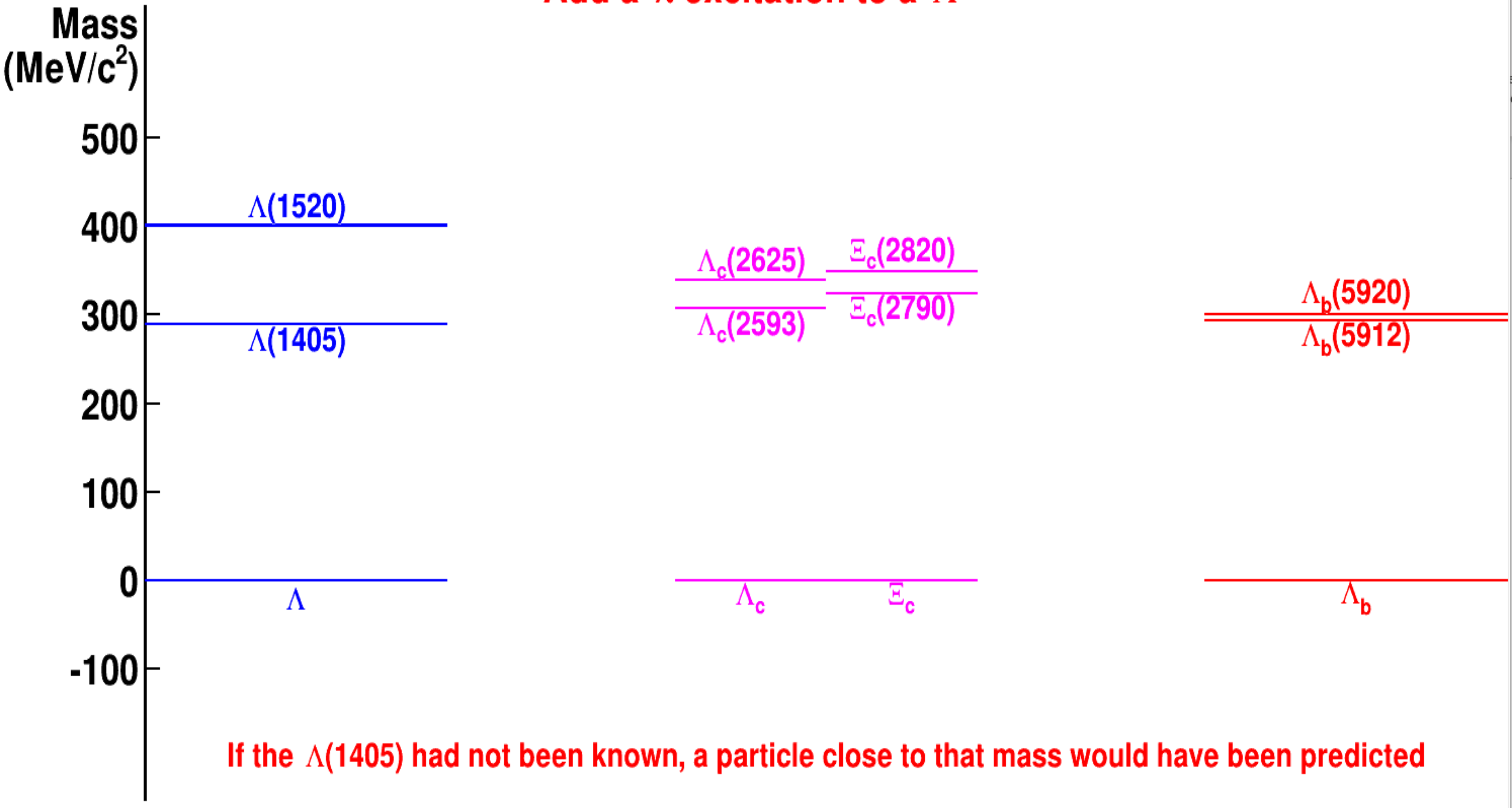
For the $\Lambda_{c/b}$(hud) and $\Xi_{c/b}$ (hsd and hsu) this leads to two "low" mass orbital excitations ($J^P=1/2^-$ and $3/2^-$).



Ξ_c^+ is an example

HQET tells us that in decays, the rule of transitions between different J^P states, must be obeyed both for the entire state, and separately for the "light" degrees of freedom. The heavy quark just sits there and cannot move. This makes many narrow states

Add a λ excitation to a Λ

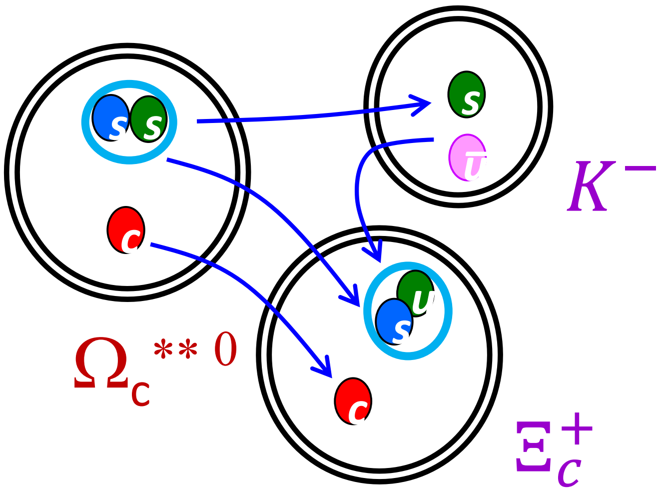


If the $\Lambda(1405)$ had not been known, a particle close to that mass would have been predicted

For the Ω_c(css) the model leads to five ($J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$)

$J^P_{LIGHT} = 0^-$ $\quad 1^-$ $\quad 2^-$

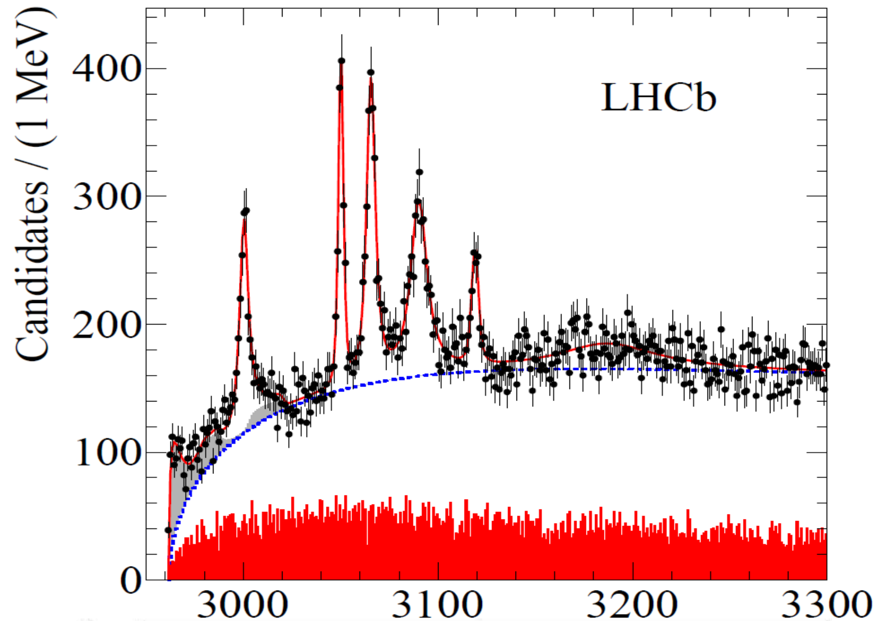
5 narrow states are expected, with masses around 3000 MeV and mass splittings of around 30 MeV

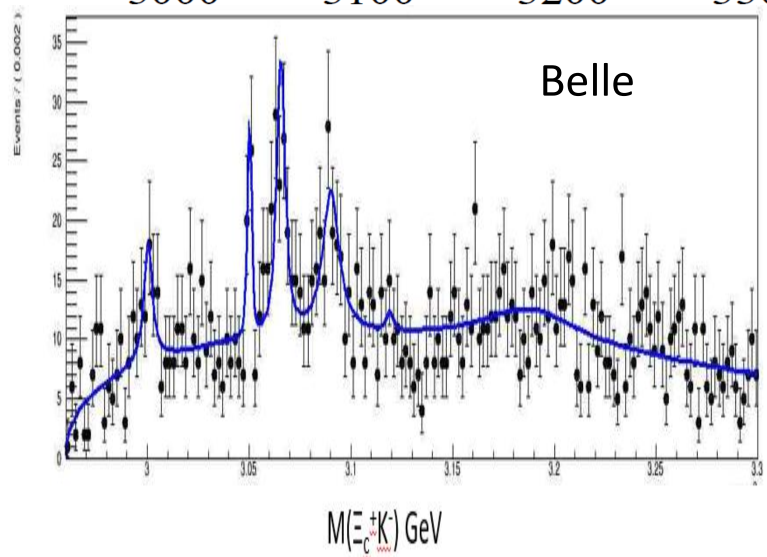


Rips the ss diquark apart – makes it narrow?

No consensus as to which state is which, or if they are all orbital excitations.

When identifying the states, we should remember that not just the mass and width, but the relative yields might be important. (e.g. the 3119 could be ½$^-$)

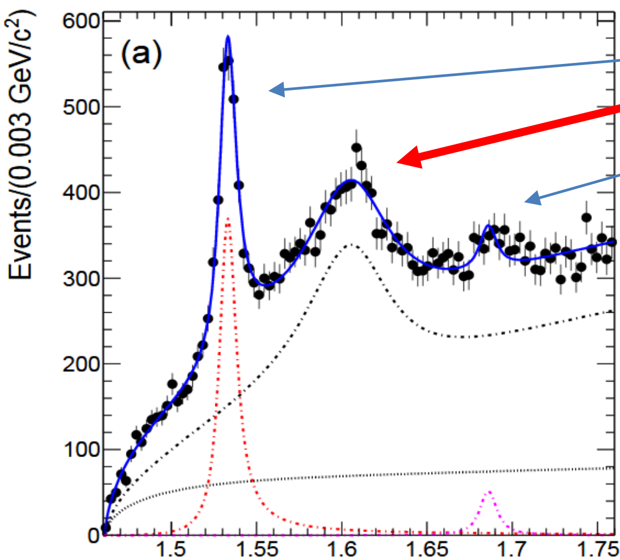




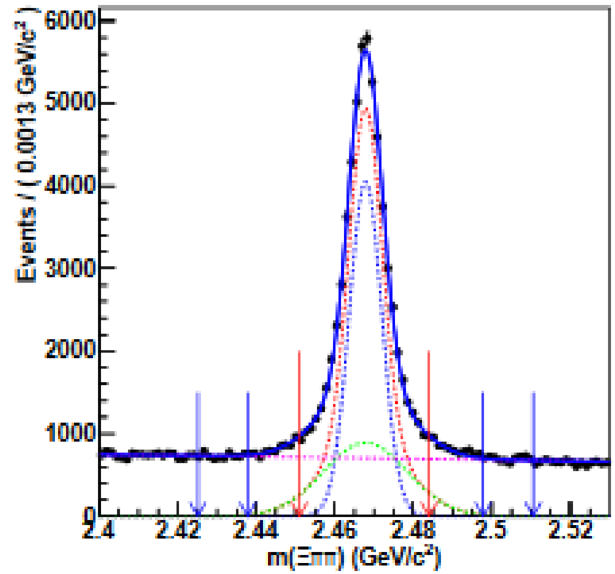
R. Aaij et al PRL 118, 182001 (2017) LHCb
J. Yelton et al, Phys. Rev. D97, 051102 (2018) Belle

An aside – there is another particle with as ss diquark, the Ξ

Looking at the substructure of the $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$ we can look for excited Ξ^0 resonances



Fit includes:
$\Xi^0(1530)$
$\Xi^0(1620)$
$\Xi^0(1690)$



(Belle data 50,000 signal plus 11,500 background within signal band)

Ξ States mass	Main Decay	Width
1620	Ξπ	60 MeV
1690	Λ/Σ	narrow
1820	Λ/Σ	24 MeV
1950	Λ/Σ	60 MeV
2030	Λ/Σ	20 MeV

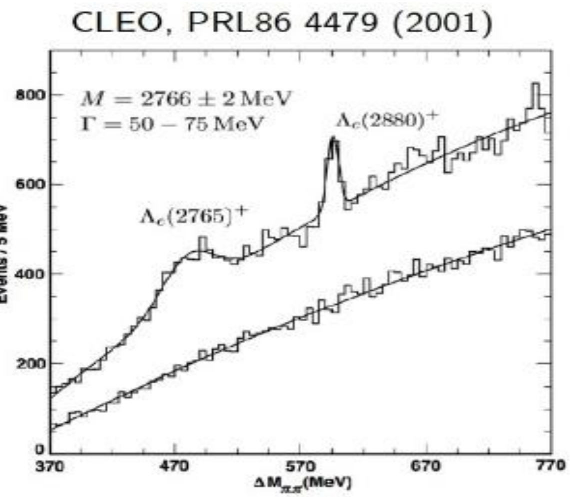
M. Sumihama et al, PRL 122, 072501 (2019)

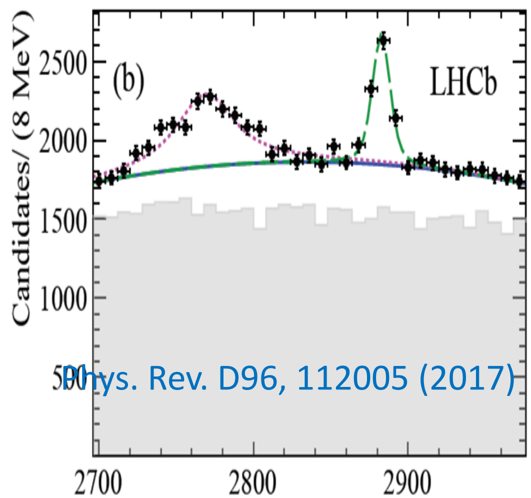
Note that the quark-diquark model predicts 5 L=1 states, 2 of which have $J^P=1/2^-$, only one of which decays easily to Ξπ

Will now review latest news for the excited states of the following systems:

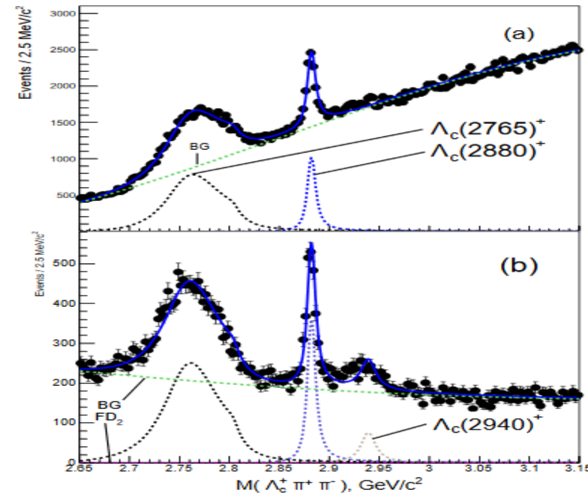
Λ_c^+ (cud) $\Xi_c^{+/-}$ (csu, csd) Λ_b(cud)/Σ_b(bud, buu, bdd) $\Xi_b^{+/-}$(bsu, bsd) Ω_b (bss)

News about the excited Λ_c system :





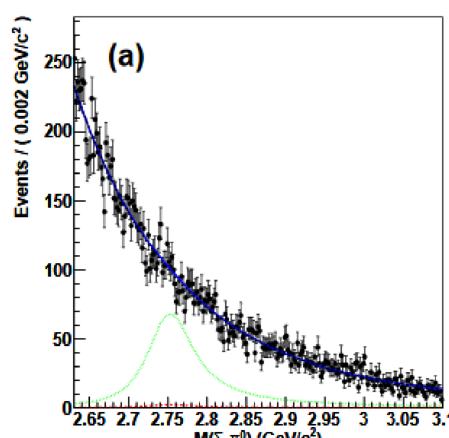
Phys. Rev. D96, 112005 (2017)

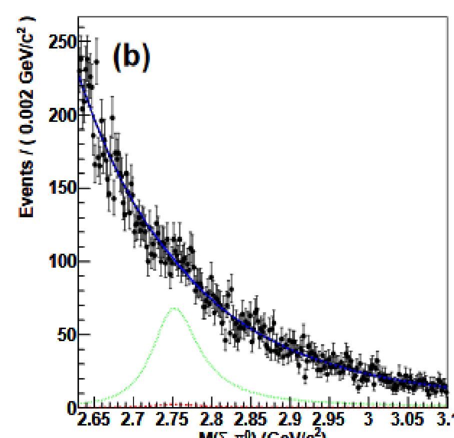


BELLE preliminary

2765 state clearly exists.

Not seen in $\Sigma_c^{++/0}\pi^0$



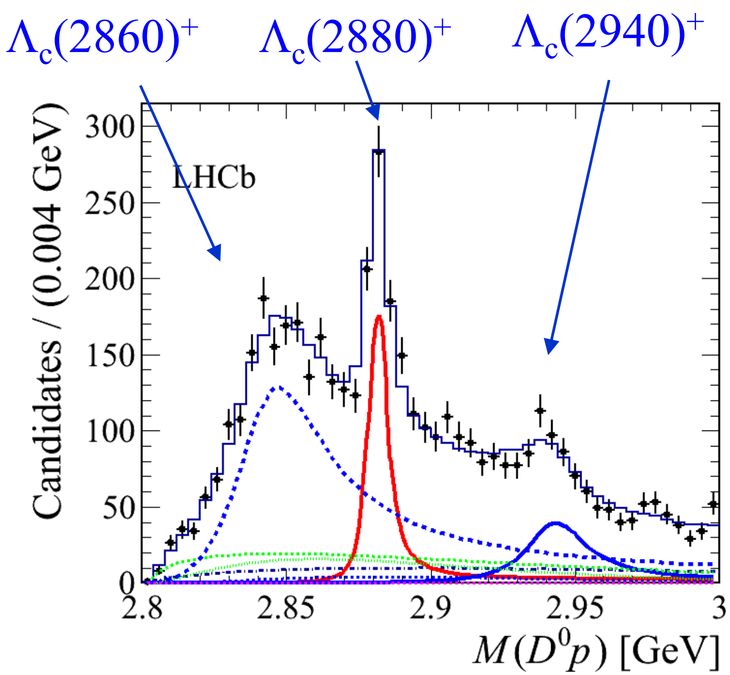


It is a Λ_c

Copious production!

Potential models suggest 2S state ??

In similar mass range, LHCb look use an amplitude analysis of $\Lambda_b \to D^0 p \pi^-$



- New resonance: $\Lambda_c(2860)^+$, $J^P = 3/2^+$

$$M(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7} \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV}$$

$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1} \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}$$

Confirms $\Lambda_c(2880)^+$ has $J^P = 5/2^+$
Implies $\Lambda_c(2940)^+$ has $J^P = 3/2^-$

(mass is very close to pD* threshold, seems a little low for a 2P state)

JHEP, 1705 030 (2017), LHCb

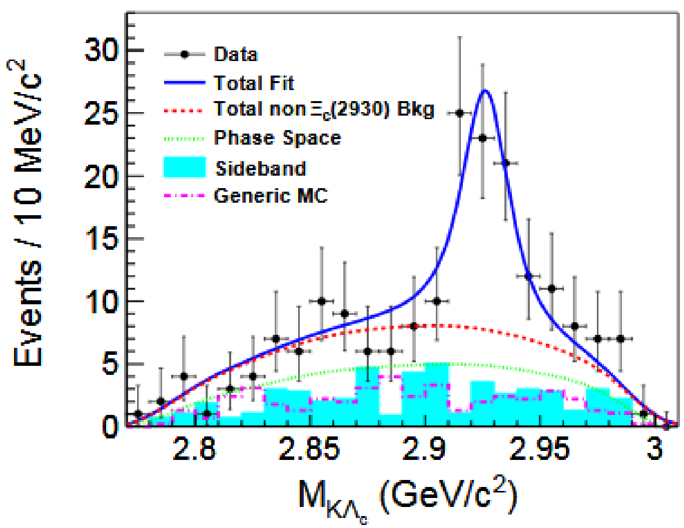
Question:
Why is the $\Lambda_c(2880)$ so narrow? Why doesn't $\Sigma^*\pi$ via p-wave dominate?

News on the excited Ξ_c system : Observation of the $\Xi_c(2930)^0$ and Evidence of the $\Xi_c(2930)^+$

Most charmed baryons analyses performed by Belle have been using continuum production, e.g. Belle have made measurements of the masses and widths of the: $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2970)$, $\Xi_c(3055)$ and $\Xi_c(3080)$ iso-doublets.

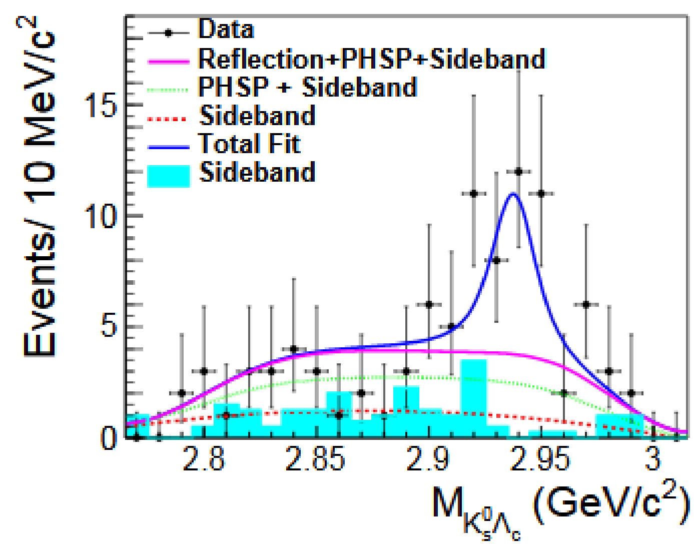
In 2008, BaBar reported a peak in the $\Lambda_c^+K^-$ mass projection of $\Lambda_c^-\Lambda_c^+K^-$ from B decays, but this remained only a "one-star" resonance PDG with no new analyses until now.

Recently Belle has performed searches for both the $\Xi_c(2930)^0$ and $\Xi_c(2930)^+$ in the resonant substructure of B decays using largest sample of BB pairs in the world: $(772\pm11) \times 10^6$



$M(\Xi_c(2930)^0) = 2928.9 \pm 3.0\ ^{+0.9}_{-12.0}$ MeV/c^2 5.1 σ

$\Gamma = 19.5 \pm 8.4\ ^{+5.9}_{-7.9}$ MeV Y.B. Li et al, EPJ C78, 252 (2018)



$M(\Xi_c(2930)^+) = 2942.3 \pm 4.4 \pm 1.6$ MeV/c^2 3.9 σ

$\Gamma = 14.8 \pm 8.8 \pm 2.5$ MeV Y.B. Li et al, EPJ C78, 928 (2018)

Particle	Mass/Width (positive state)	Mass/Width (neutral state)		comments
$\Xi_c^{/}$	2578.57 ± 0.5 -	2679.2 ± 0.5 -	$1/2^+$	
$\Xi_c(2645)$	2645.57 ± 0.26 2.14 ± 0.19	2645.57 ± 0.21 2.35 ± 0.22	$3/2^+$	
$\Xi_c(2790)$	2792.4 ± 0.5 $8.9 \pm 0.6 \pm 0.8$	2794.1 ± 0.5 $10.0 \pm 0.7 \pm 0.8$	$1/2^-$	
$\Xi_c(2815)$	2816.73 ± 0.21 $2.43 \pm 0.20 \pm 0.17$	2820.36 ± 0.27 $2.54 \pm 0.18 \pm 0.17$	$3/2^-$	
$\Xi_c(2930)$	$2942.3 \pm 4.4 \pm 1.5$ $14.8 \pm 8.8 \pm 2.5$	$2929.7^{+2.8}_{-5.0}$ 26 ± 8	??	Only observed in B decays
$\Xi_c(2970)$	$2967.8^{+0.9}_{-0.7}$ $20.9^{+2.5}_{-3.5}$	2969.4 ± 0.8 $28.1^{+3.4}_{-4.0}$	$1/2^+$???	Radial excitation?
$\Xi_c(3055)$	3055.9 ± 0.4 $7.8 \pm 1.2 \pm 1.5$	$3059.0 \pm 0.5 \pm 0.6$ $6.4 \pm 2.1 \pm 1.1$	$3/2^+$???	$\Lambda D^+/\Sigma_c^{++}K^- \sim 5$
$\Xi_c(3080)$	3077.2 ± 0.4 3.6 ± 1.1	3079.9 ± 1.4 5.6 ± 2.2	$5/2^+$???	$\Lambda D^+/\Sigma_c^{++}K^- \sim 1.3$
$\Xi_c(3123)$				Low significance and not confirmed by Belle

B. Aubert et al, Phys. Rev. D(2008), 031101 (BaBar)
B. Aubert et al, Phys. Rev. D77 012002 (BaBar)
Y. Kato et al, Phys. Rev. D89 (2014), 052003 (Belle)
J. Yelton et al, Phys. Rev. D94, (2016), 052011 (Belle)
Y. Kato et al, Phys. Rev. D94 (2016), 032002 (Belle)

Also absolute b.f. now measured:

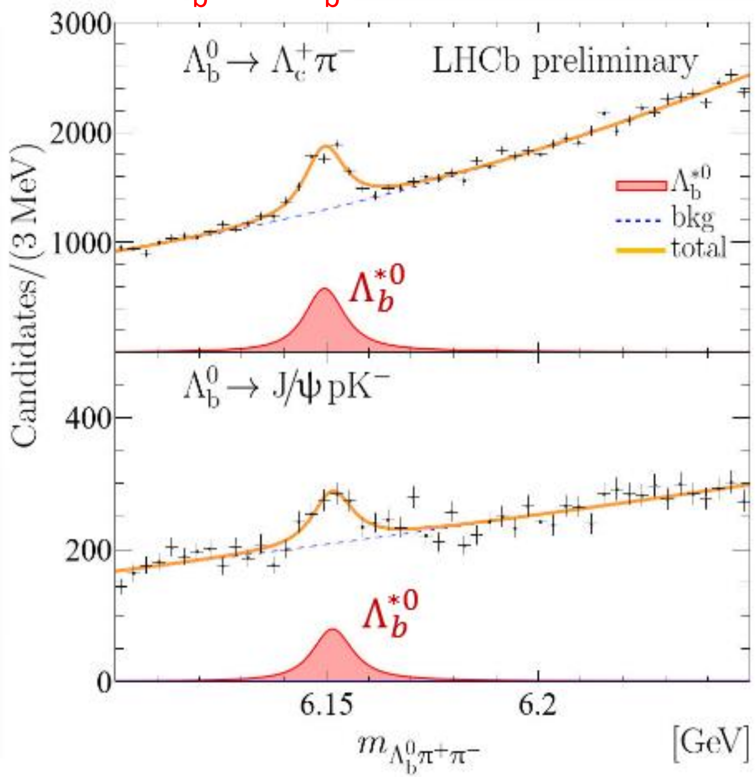
$B(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = (2.86 \pm 1.2)\%$

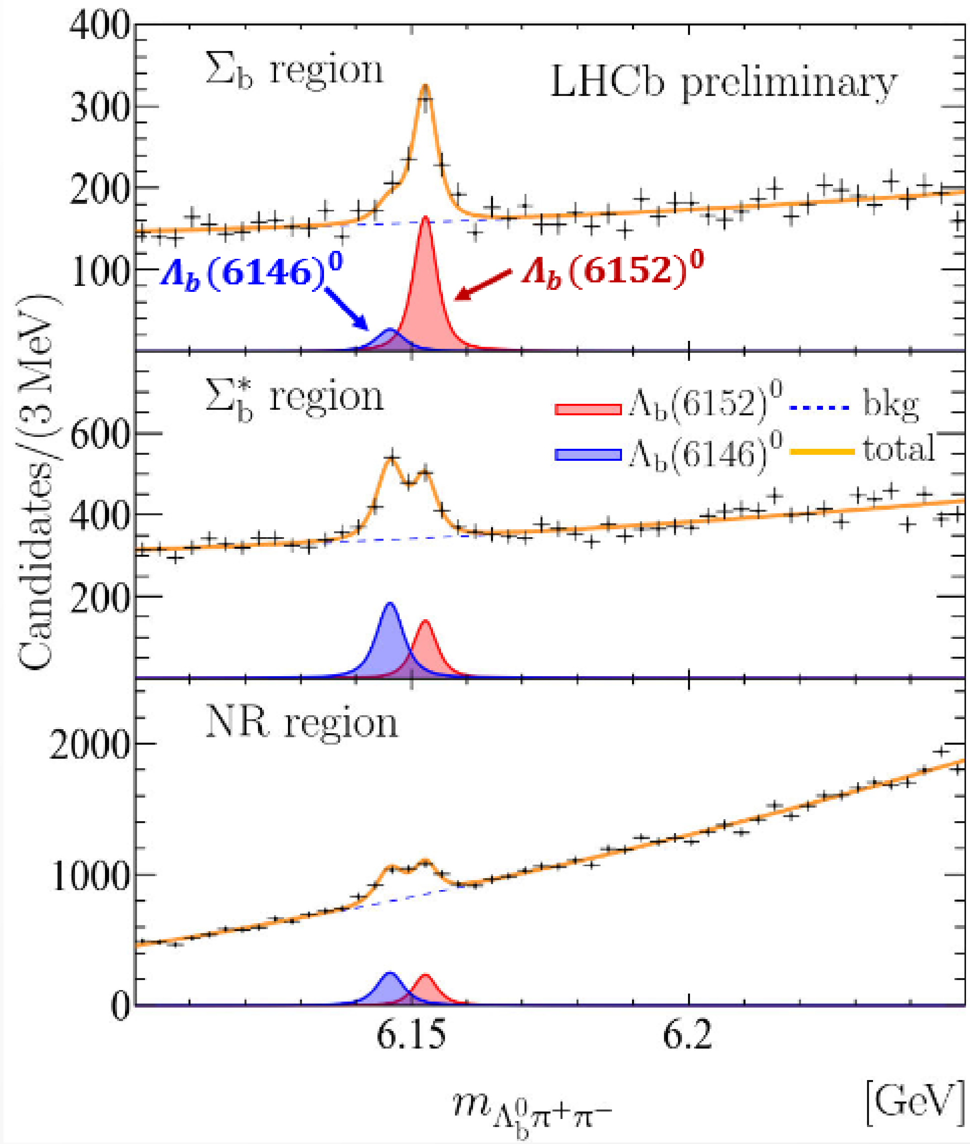
$B(\Xi_c^0 \to \Xi^- \pi^+) = (1.80 \pm 0.5)\%$

Y. Li et al, PRL 122, 082001(2019) and arXiv:1904.12093 (Belle)

LHCb look at dipion decays into Λ_b to look for excited Λ_b

$\Lambda_b^* \to \Lambda_b \pi^+ \pi^-$





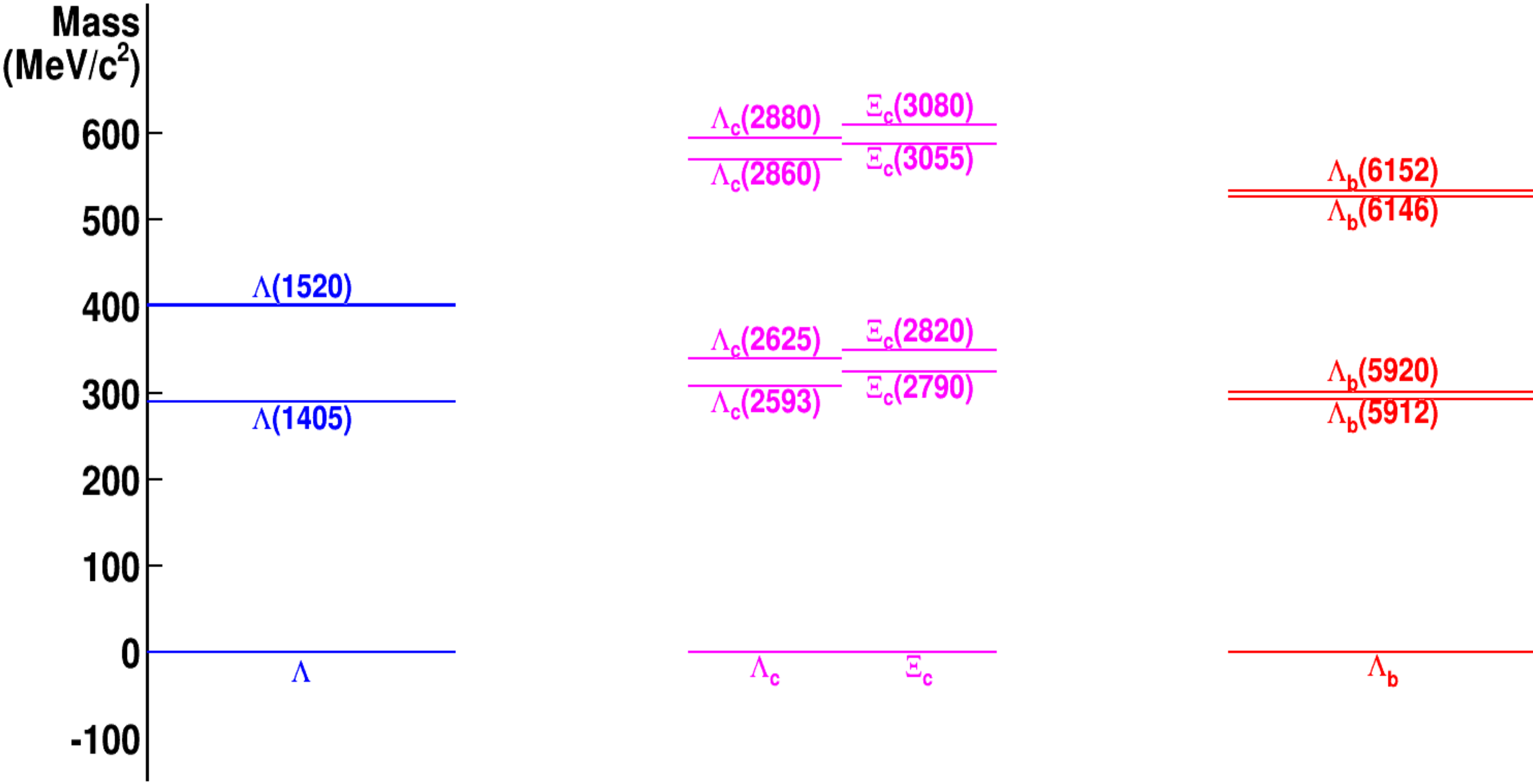
$M(\Lambda_b(6152)^0) = 6152.51 \pm 0.26\ \mathrm{MeV}/c^2$

$M(\Lambda_b(6146)^0) = 6146.17 \pm 0.33\ \mathrm{MeV}/c^2$

$\Gamma(\Lambda_b(6152)^0) = 2.11 \pm 0.81\ \mathrm{MeV}/c^2$

$\Gamma(\Lambda_b(6146)^0) = 2.90 \pm 1.28\ \mathrm{MeV}/c^2$

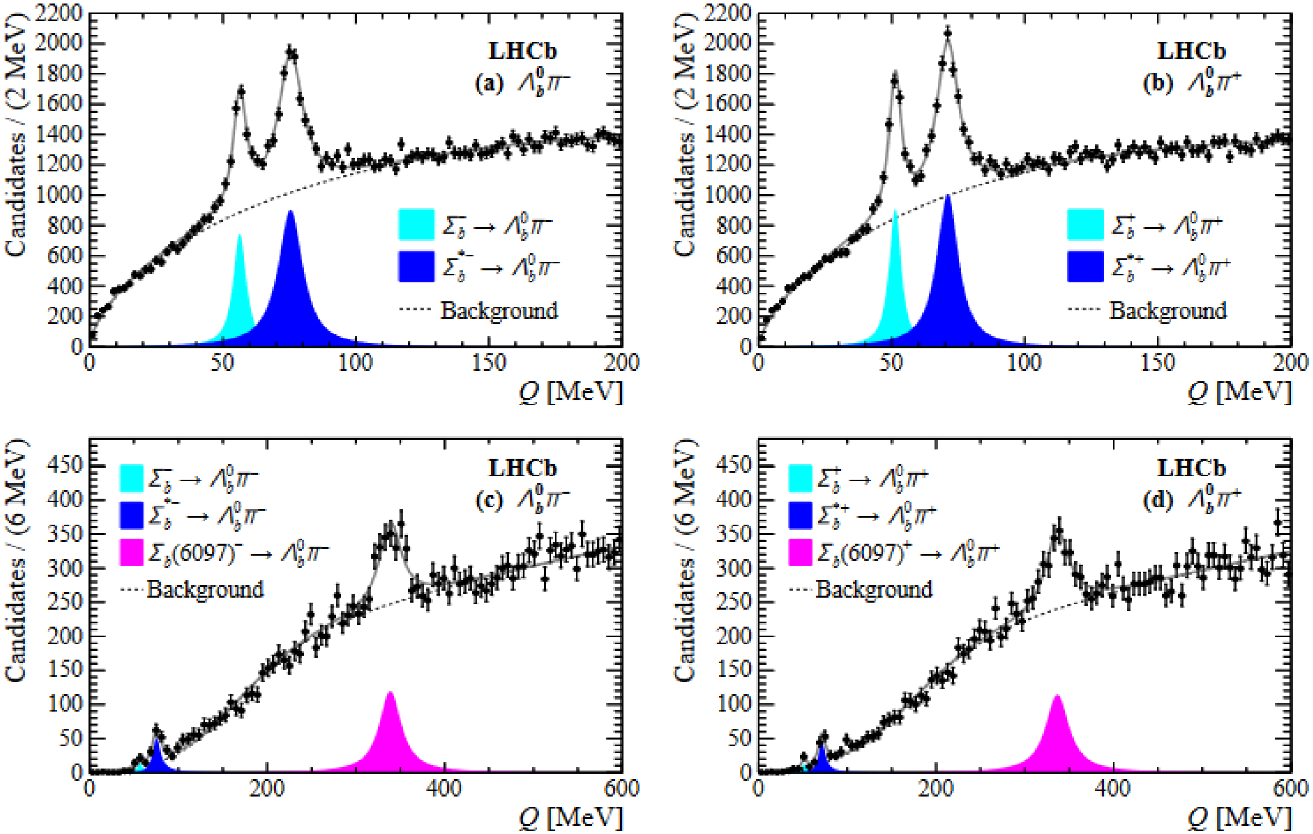
Submitted to PRL, arXiv:1907.13598



Note that the new states cannot decay into pB so are narrower than the analogous charm states

News on excited Σ_b (bud/buu/bdd)

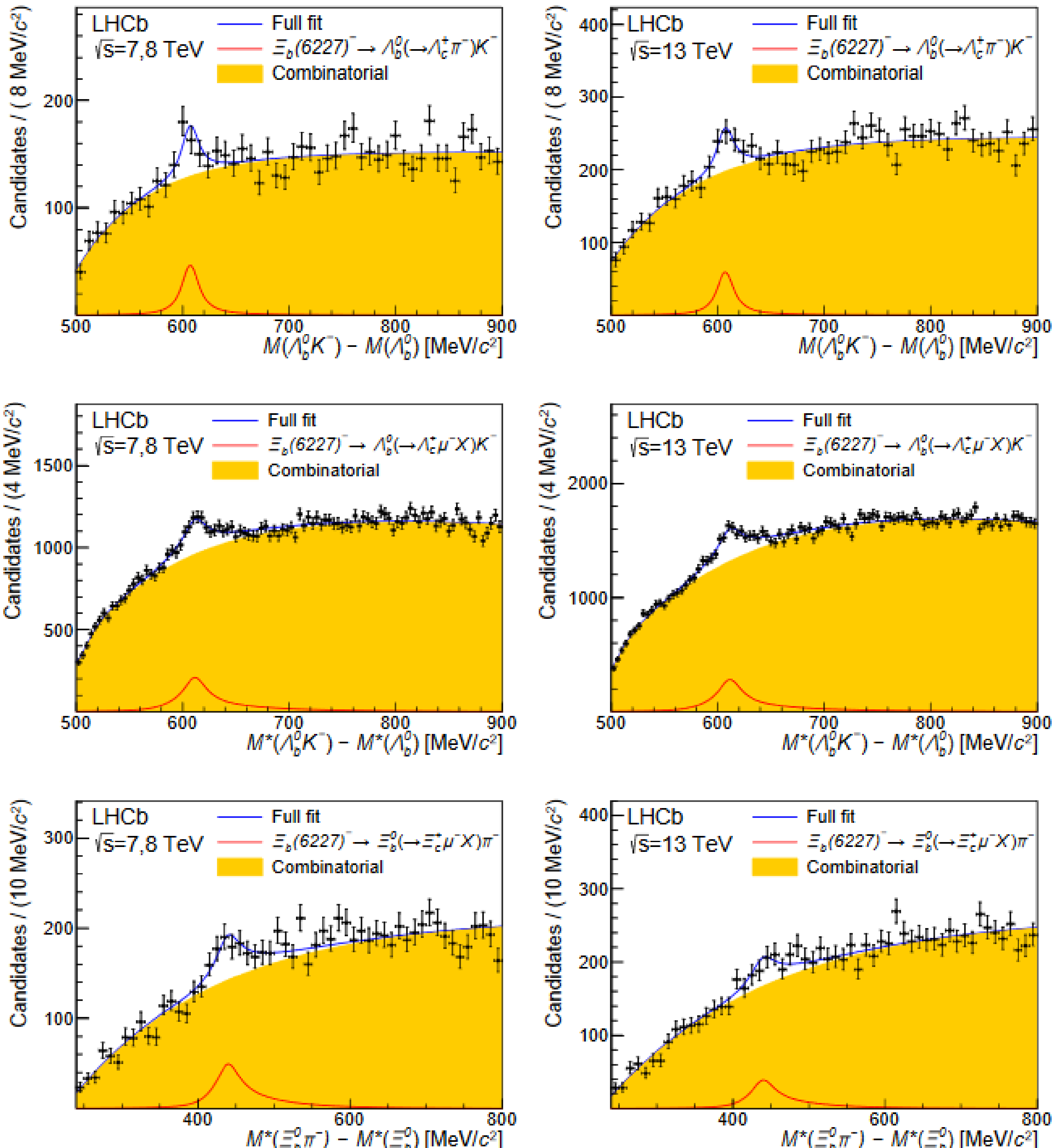
In addition to the $\Sigma_b^{+/-}$ and $\Sigma_b^{*+/-}$ (confirming CDF result) and there is another state at a higher mass



Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$
$m(\Sigma_b^-)$	$5815.64 \pm 0.14 \pm 0.24$
$m(\Sigma_b^{*-})$	$5834.73 \pm 0.17 \pm 0.25$
$m(\Sigma_b^+)$	$5810.55 \pm 0.11 \pm 0.23$
$m(\Sigma_b^{*+})$	$5830.28 \pm 0.14 \pm 0.24$
$\Gamma(\Sigma_b^-)$	$5.33 \pm 0.42 \pm 0.37$
$\Gamma(\Sigma_b^{*-})$	$10.68 \pm 0.60 \pm 0.33$
$\Gamma(\Sigma_b^+)$	$4.83 \pm 0.31 \pm 0.37$
$\Gamma(\Sigma_b^{*+})$	$9.34 \pm 0.47 \pm 0.26$

PRL 122 012001 (2019) LHCb

In addition, one clear higher mass, wider peak. This is in the region where we expect orbital excitations. Maybe more than one particle? Maybe others are too wide? It feels similar to the $\Sigma_c(2800)$



LHCb

A new excited Ξ_b

$M = 6226.9 \pm 2.1$ MeV/c^2

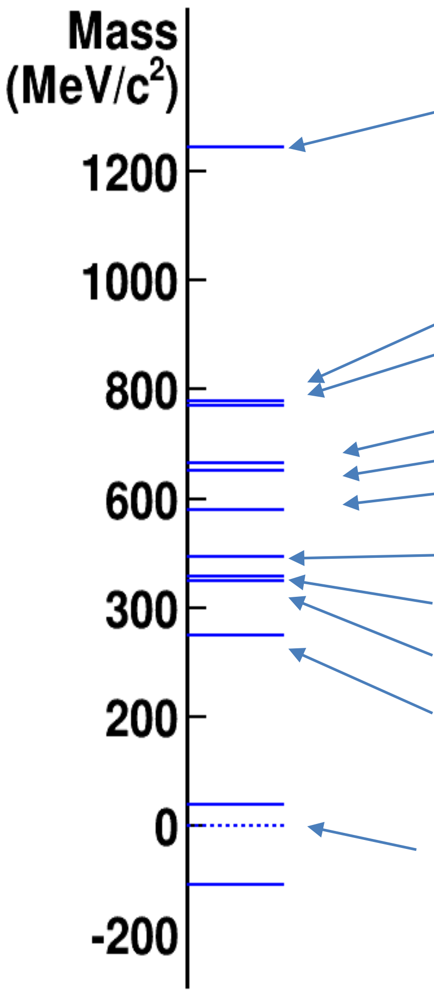
PRL 121 072002 (2018) LHCb

What is is? Maybe a radial excitation?

Heavy (charm and bottom) Mesons

HQET expects 4 L=1 states. D_0, $D_1(j_{light}=1/2)$, $D_1(j_{light}=3/2)$, D_2

Two of these are expected to be very wide, because they can decay s-wave with



D(3000) now measured to have M = 3214 ± 29 ± 49 with a comprehensive analysis by LHCb, Phys. Rev. D94, 072001

Seen in two modes and 2 experiments, thought to be spin 3

70 MeV wide. Unknown spin-parity LHCb 2013

Narrow state reported only by Delphi. Wrong!

Wide state with contradictory masses

Wide state at 2550, radial excitation?

Well-defined D_2

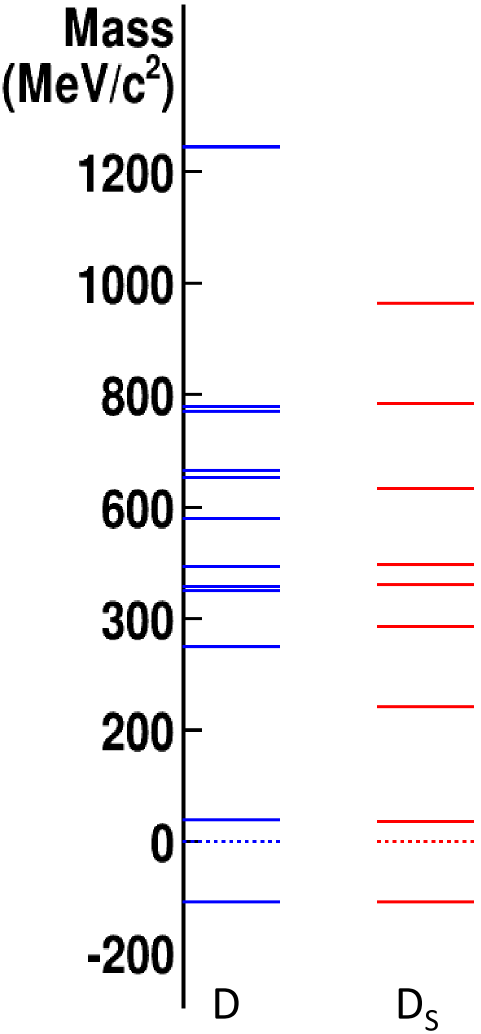
Very wide D_1 (*charged state not yet found*)

Well-defined D_1, $j_{light}=1/2^+$

Very wide D_0 (used to be the $D^*_0(2400)$, now the $D^*_0(2300)$)

Spin weighted average of ground state set to zero

D_s produced a major surprise in 2003



Seen by BaBar – needs confirmation.

2 states on top of each other, one is $J^P = 1^-$, one is $J^P = 3^-$

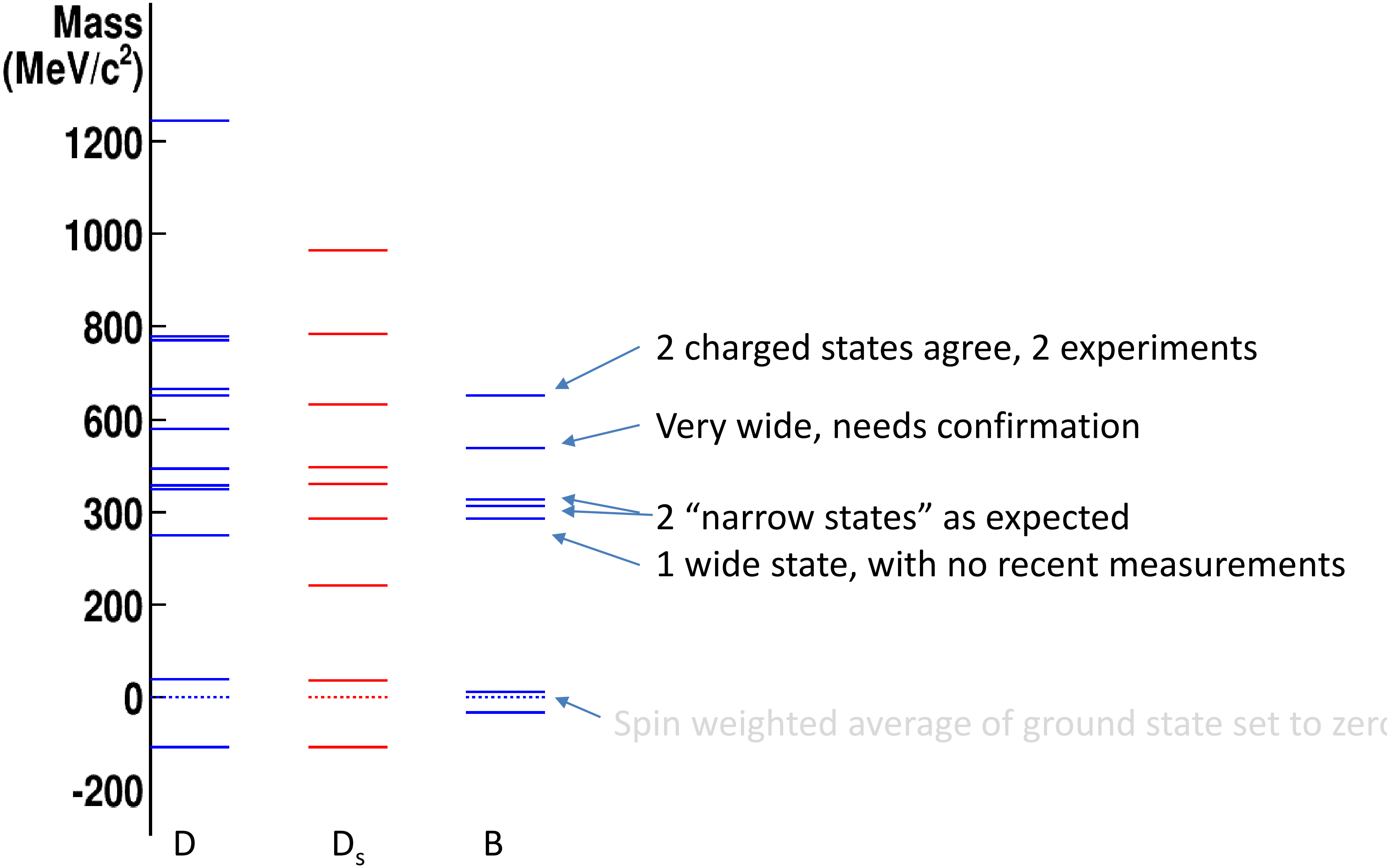
Seen by 3 experiments, $J^P = 1^-$ radial excitation?

Well-understood L=1 orbital excitations.

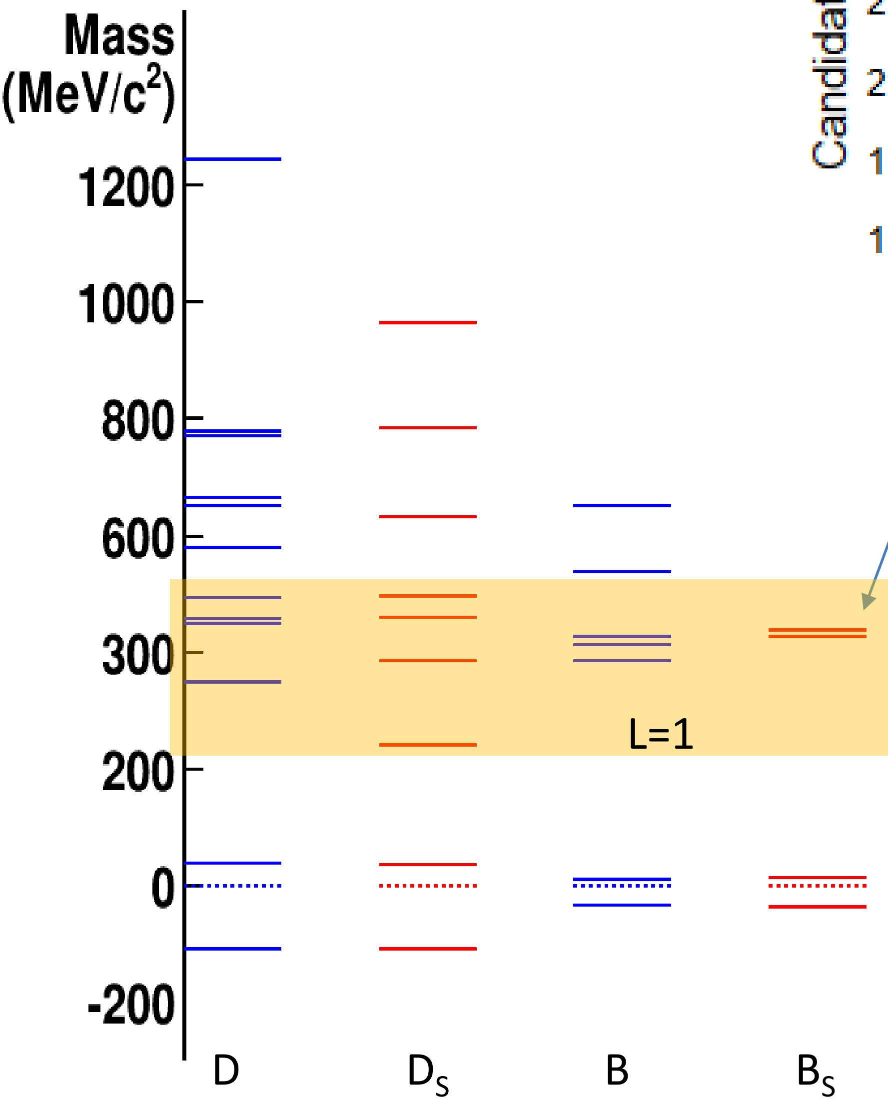
Two low mass (and thus narrow) states. Their masses and mass difference might indicate DK and D*K molecular states rather than conventional D^*_{s0} and D_{s1}

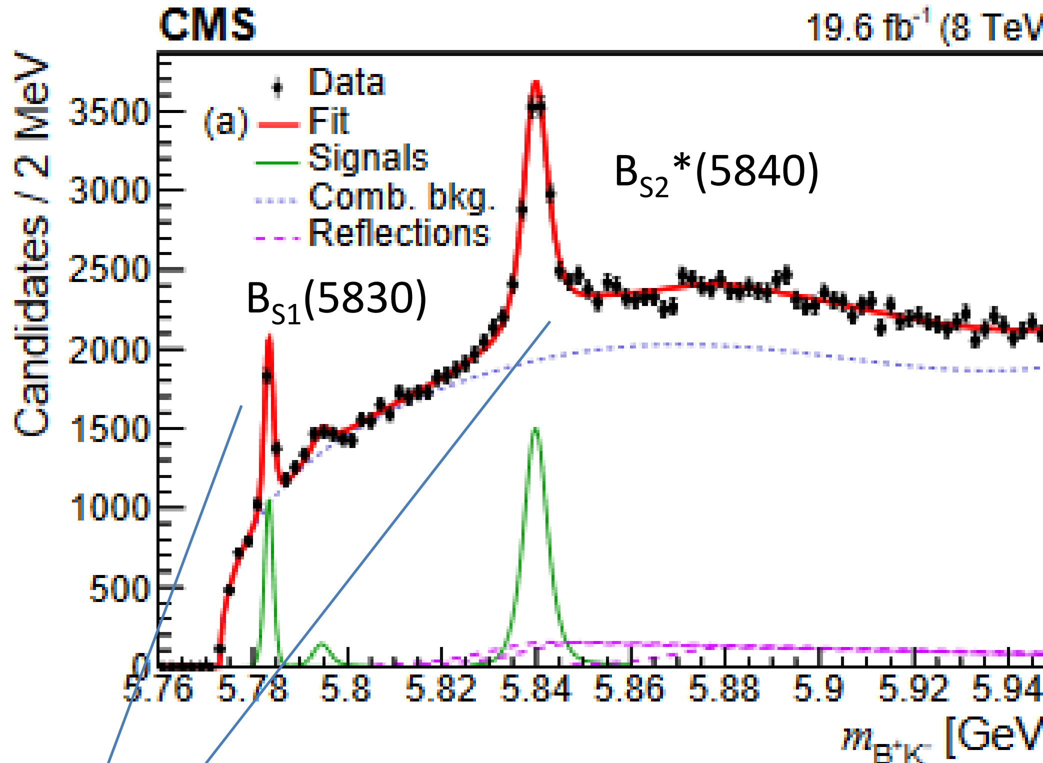
Spin weighted average of ground state set to zero

B^+/B^0 Spectrum



B_s Spectrum





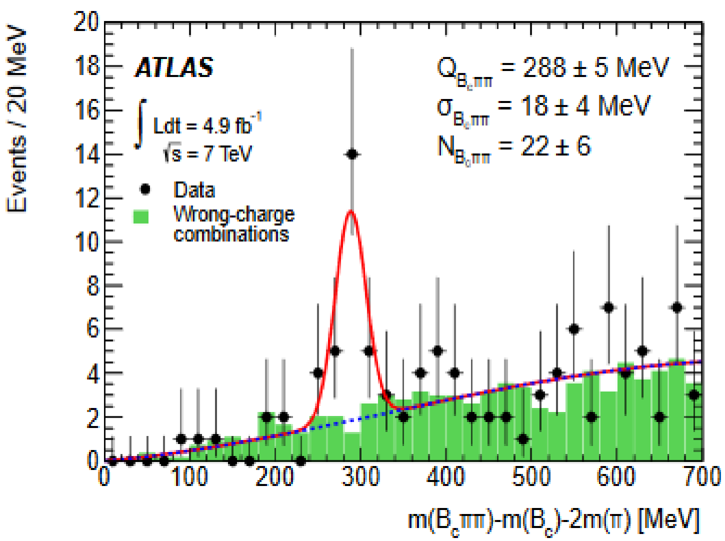
A. Sirunyam, EPJ C78 939 (2018) CMS

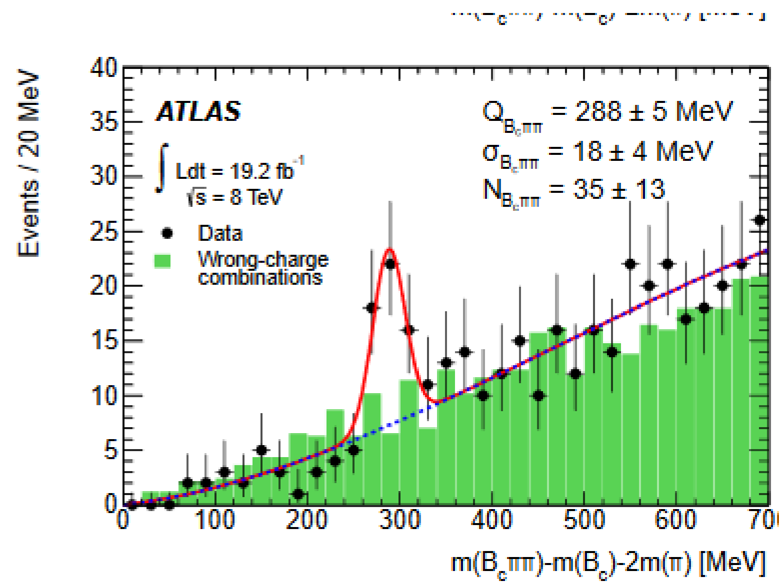
Also seen by CDF, D0 and LHCb

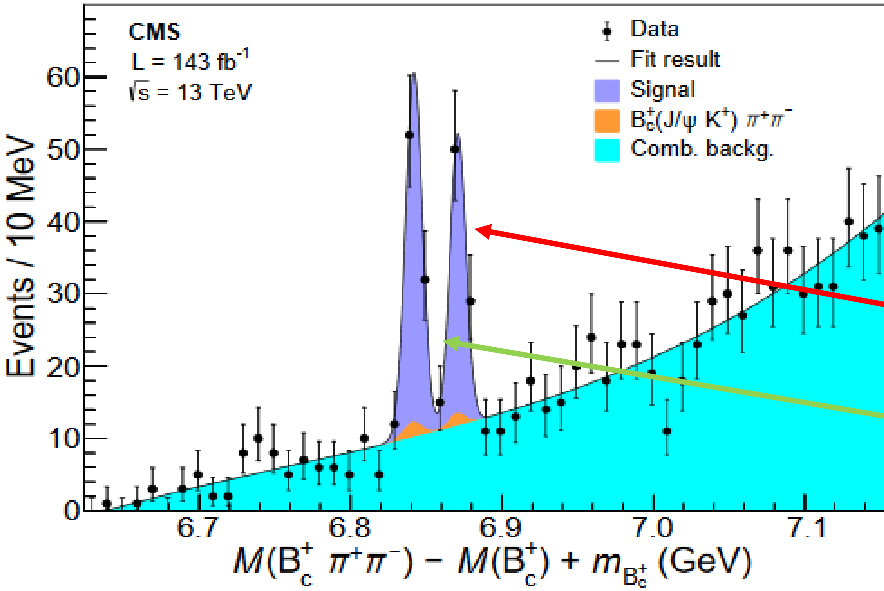
B_c Spectroscopy "The Last Meson"

Mass = 6274.9 $\pm$ 0.8 MeV 4 separate LHCb measurements as well as CDF and D0
Lifetime = (5.10 $\pm$ 0.09) x 10^{-13} s (LHCb and CMS)

What about excited states? The $B_c(2S) \to B_c\pi\pi$ would be expected to be narrow.
Claim by ATLAS at 6842 $\pm$ 4 $\pm$ 5 MeV







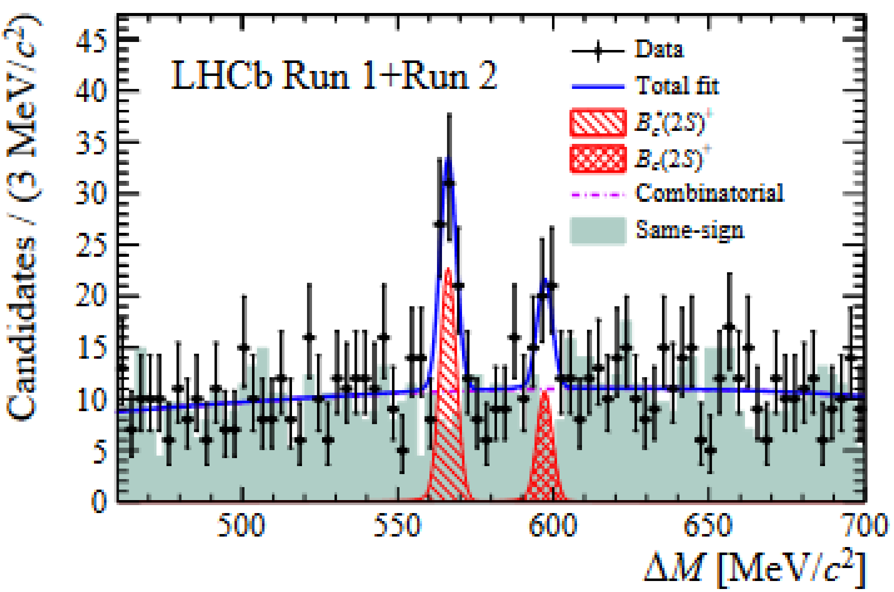
CMS Experiment

PRL 122, 132001 (2019)

Thought to be $B_c(2S)\to B_c\pi^+\pi^-$

Thought to be

$B_c^*(2S)\to B_c^*\pi^+\pi^- \to B_c\Upsilon\pi^+\pi^-$



LHCb Experiment

PRL 122, 232001 (2019)

$M(B_s(2S)) = 6871.0 \pm 1.2 \pm 0.8 \pm 0.8$ MeV/c^2

$29 \pm 1.5 \pm 0.7$ MeV/c^2 CMS

$M(B_s(2S)) = 6871.1 \pm 1.3 \pm 0.1 \pm 0.8$ MeV/c^2

$31.0 \pm 1.4 \pm 0.0$ MeV/c^2 LHCb

LHCb second signal is weak (3.9σ)

CONCLUSIONS

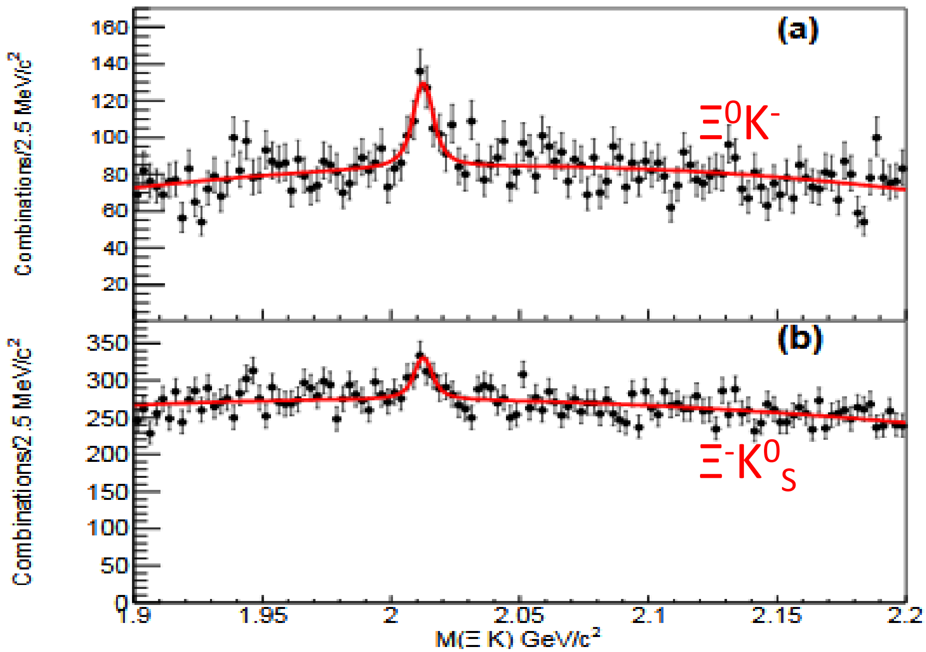
1. Many new results in the Heavy Hadron systems, particularly in baryons

2. Many more results will appear soon.

3. The heavy hadrons tend to be narrower, better defined and easier to interpret than lighter hadrons. However, there are many mysteries to be investigated.

4. If we want to understand hadrons, we need to look at them all – heavy and light – and look at all their properties (mass, width, decay channels, production mechanism).

EXTRA SLIDES



BELLE 2018 Excited Ω

Narrow-resonance data only!

A simultaneous fit yields a peak of 8.3 σ statistical significance

Final result:

M = 2012.4 $\pm$ 0.7 $\pm$ 0.6 MeV/c^2

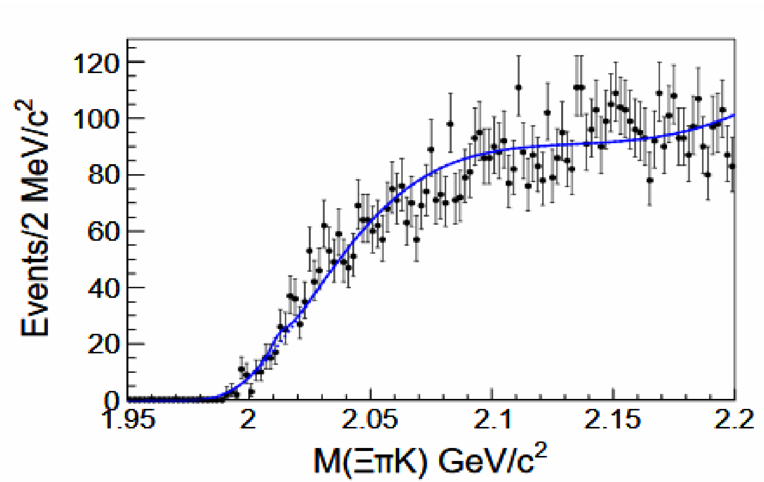
Γ = 6.4$^{+2.5}_{-2.0}$ $\pm$ 1.6 MeV

Significance of signal, including systematics > 7 σ

J. Yelton et al, PRL 121, 052003 (2018)

First guess is that this is a 3/2$^-$ orbital excitation, however there are models that propose a Ξ(1530)K "molecular" state description.

Such a state would likely also decay to Ξ(1530)K (despite the lack of phase space)



$$\mathcal{R}^{\Xi\pi K}_{\Xi K} = \frac{\mathcal{B}(\Omega(2012) \to \Xi(1530)(\to \Xi\pi)K)}{\mathcal{B}(\Omega(2012) \to \Xi K)} < 11.9\%$$

No sign of it decaying to Ξ(1530)π

S.Jia et al, arXiv:1906:00194 (Belle)