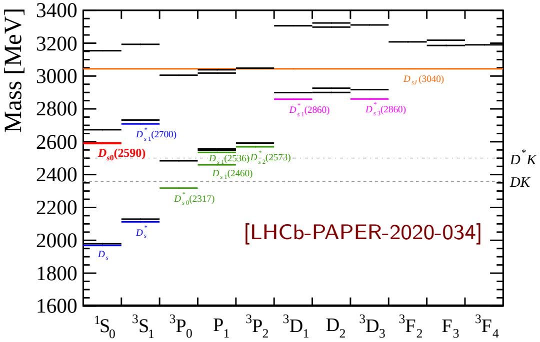
Charm hadron spectroscopy

Mikhail Mikhasenko on behalf of LHCb,
CERN, Switzerland

June 1st, 2021
CHARM2020/2021

Why studying charm hadrons?

- Two types of exotics:
  - Genuine exotics – no convent. expected
  - **Mixture** – the conventional states are influenced particle interaction.
    Mass shift towards the strongly-coupled threshold.
- b/c hadrons are narrow
- Level-splitting hierarchy due to $1/m_Q$



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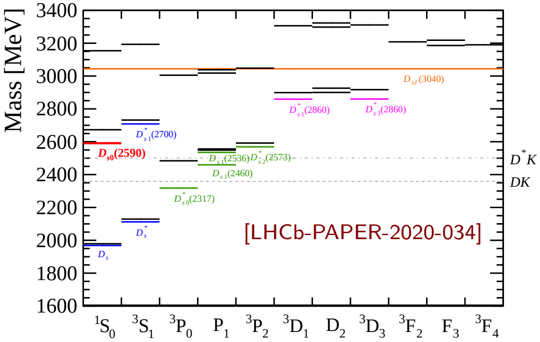
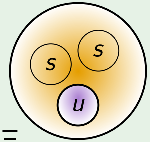
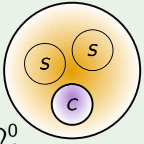


Baryons

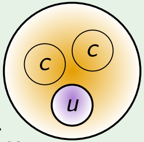
- Quark-diquark picture
- Many deeply connected sectors, e.g.



Ξ



Ω_c^0



Ξ_{cc}

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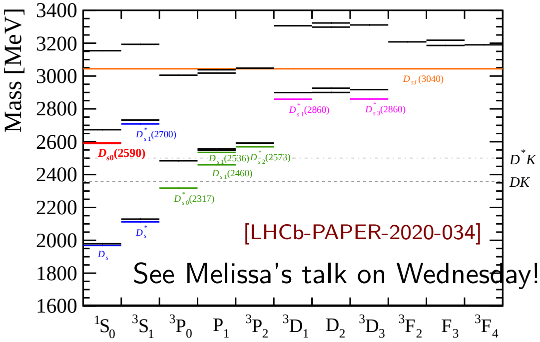

See Melissa's talk on Wednesday!

Baryons

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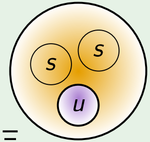

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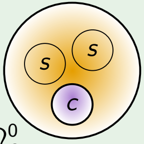

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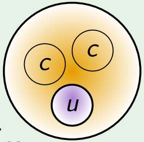
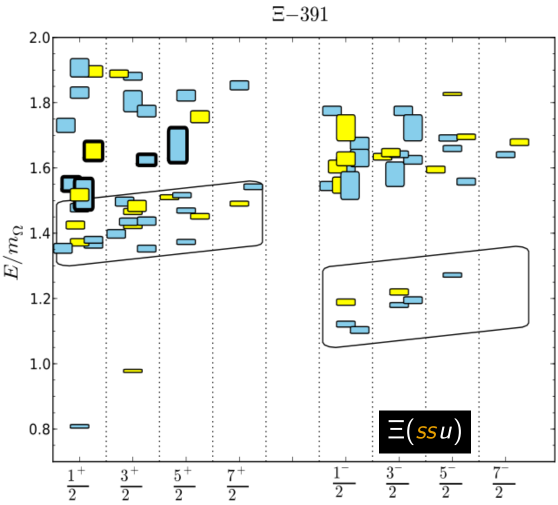
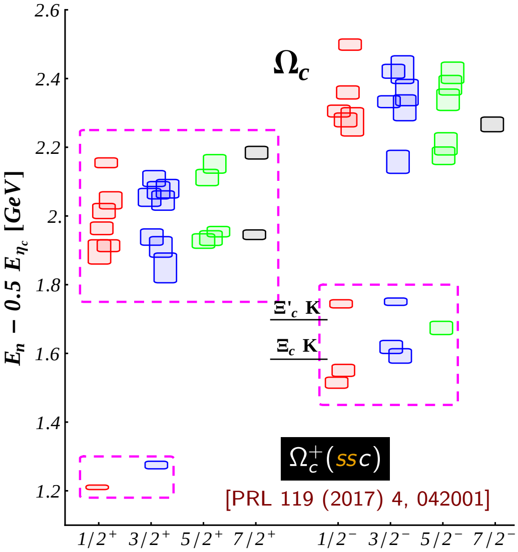


Ξ_{cc}

Lattice QCD: 5 λ modes and 2 ρ modes



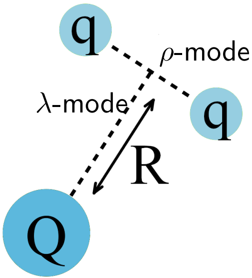
[PRD87 (2013) 054506]



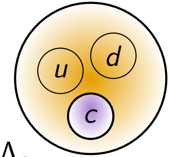
[PRL 119 (2017) 4, 042001]

Heavy-quark-diquark system

Charm-baryon sectors

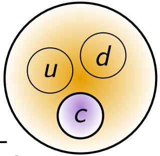


- Heavy quark is **static** and **spinless** in the limit $m_Q \to \infty$.
- Excitations of Qqq are governed by the light diquark
- $q\uparrow^{(J^P=\frac{1}{2}^+)} \otimes q\uparrow^{(J^P=\frac{1}{2}^+)} \quad \Rightarrow \quad \underbrace{\uparrow\downarrow^{(J^P=0^+)}}_{\text{“good”}}$ and $\underbrace{\uparrow\uparrow^{(J^P=1^+)}}_{\text{“bad”}}$
- Excitation pattern is different for “good” and “bad” diquarks



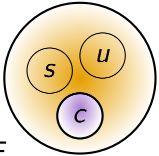
Λ_c

“good”



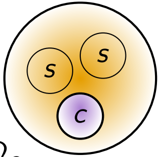
Σ_c

“bad” (isospin)



Ξ_c

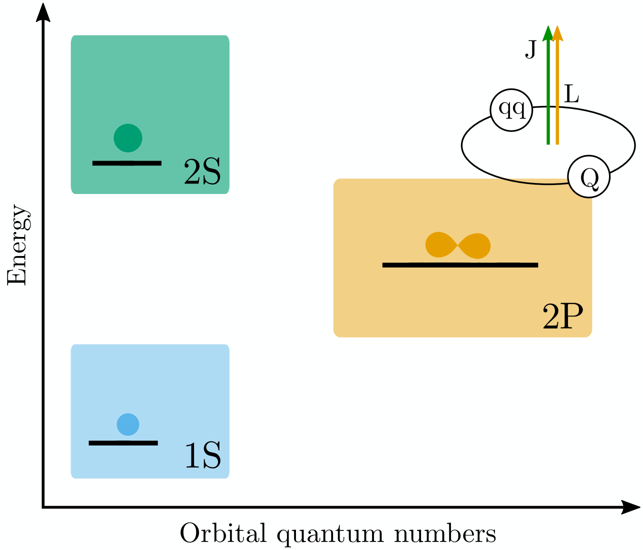
“good” + “bad”



Ω_c

“bad” (identity)

Excitation spectrum of baryons with “bad” diquark



Structure:

- Radial and orbital excitations

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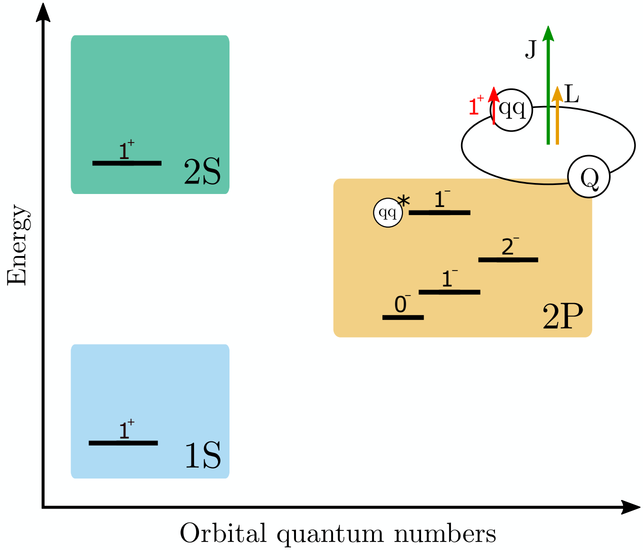

Structure:

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- Light d.o.f.: Spin-Orbit splitting

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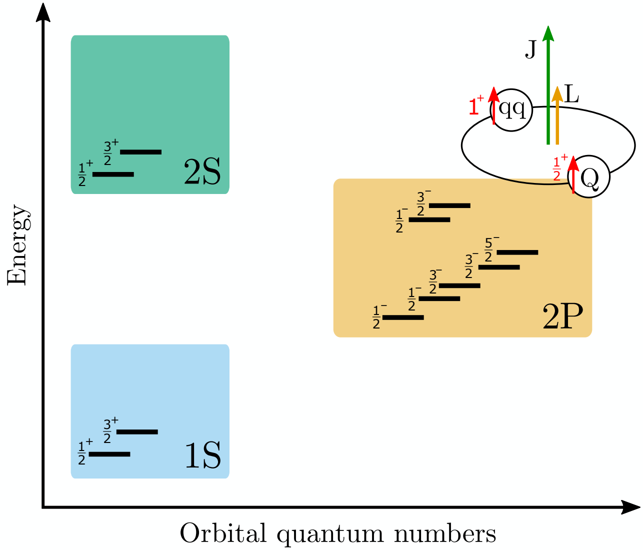

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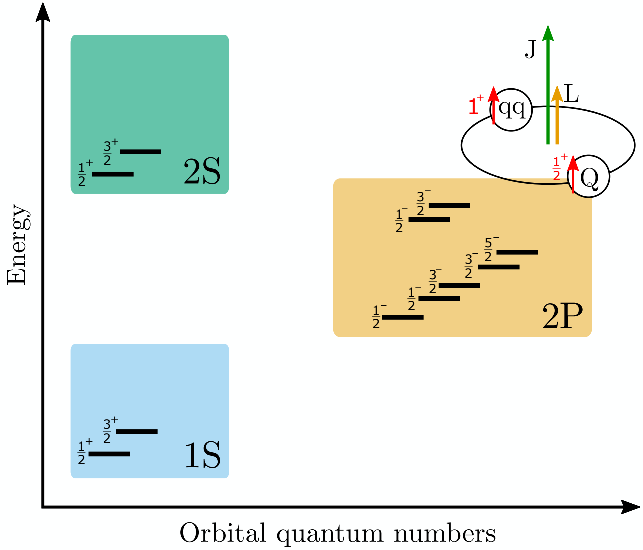

Structure:

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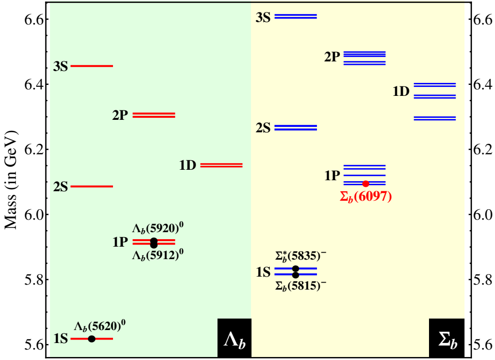
- Light d.o.f.: Spin-Orbit splitting
- “Hyperfine” doublets: heavy-quark spin

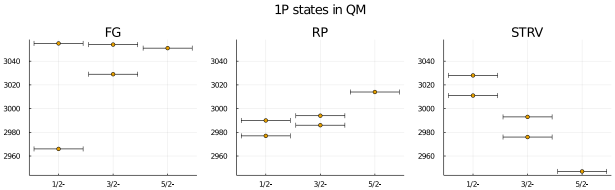
Counting of states
– model independent
Size of splitting, the order
– differs from model to model

Phenomenological models

- Agree on the general pattern
- Agree on relation between the sectors



[Bing Chen et al., PRD98 (2018) 074032]



[Faustov-Galkin, EPJ Web Conf. 204 (2019) 08001]
[Roberts-Pervin, Int.J.Mod.Phys.A 23 (2008) 2817-2860]
[Shah-Thakkar-Rai-Vinodkumar, EPJA 52 (2016) 10, 313]

- Often neglect the diquark excitation
- Disagree on the splitting and the order

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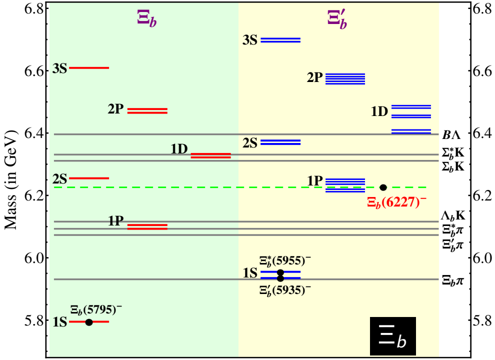
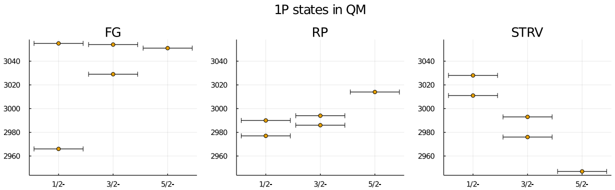


[Bing Chen et al., PRD98 (2018) 031502]



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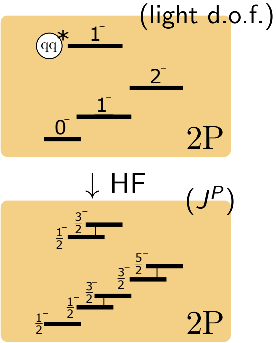
- Often neglect the diquark excitation
- Disagree on the splitting and the order

Strong transitions to a baryon and a pseudoscalar

$$\Omega_c^{**0} \to \Xi_c^+ K^- \qquad \Xi_c^{**0} \to \Lambda_c^+ K^- \qquad \Sigma_c^{**0} \to \Lambda_c^+ \pi^-$$

$$\Omega_b^{**-} \to \Xi_b^0 K^- \qquad \Xi_b^{**-} \to \Lambda_b^0 K^- \qquad \Sigma_b^{**-} \to \Lambda_b^0 \pi^-$$

HQSS ($m_Q \to \infty$) gives the selection rule based on the light d.o.f. [Chiladze, Falk, PRD 56 (1997)]
Can be applied to the decay to ground-state baryon and pseudoscalar ($B + P$):



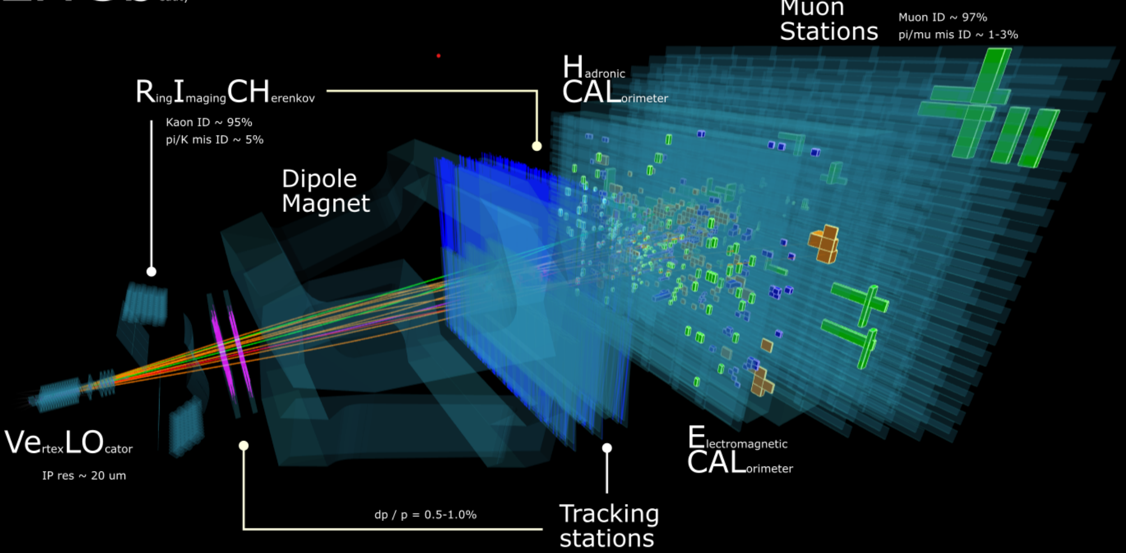
J^P (light d.o.f.)	J^P	$B+P$ (light d.o.f.)	$B+P$
0^-	$1/2^-$	S-wave	S-wave
1^-	$1/2^-$	forbidden	S-wave
	$3/2^-$	forbidden	D-wave
2^-	$3/2^-$	D-wave	D-wave
	$5/2^-$	D-wave	D-wave
1^-	$1/2^-$	forbidden	S-wave
	$3/2^-$	forbidden	S-wave

Four of seven are expected to be suppressed

Experimental observations

[Image: Maximilien Brice/CERN] [map]

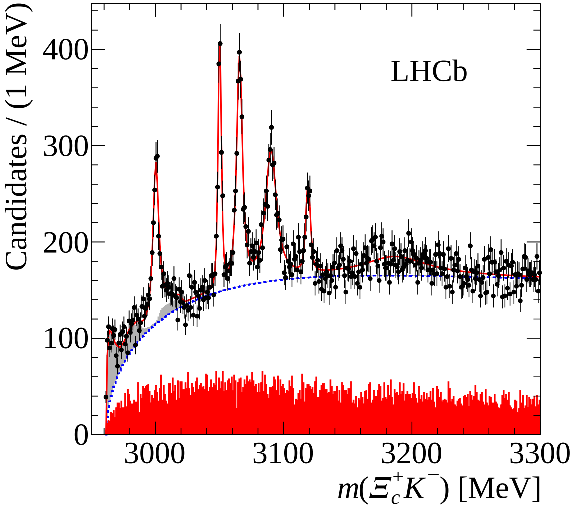
LHCb$_{\mathrm{eauty}}$ [display]

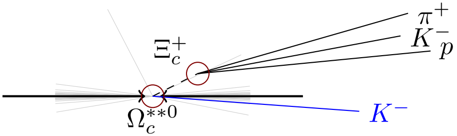


pp collider (7+7 TeV)

Ω_c^{**0} states in prompt production

[LHCb, PRL 118, 182001 (2017)]





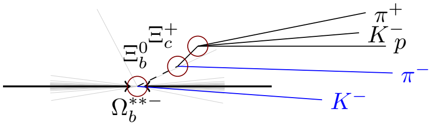
- 5 super-narrow structures
- 1 broad structure
- 3 gray components partially reconstructed $\Omega_c^{**0} \to \Xi_c'^+(\to \Xi_c^+\gamma)K$

A popular J^P assignment:
the narrow states are λ modes
in the natural order $\frac{1}{2}^-, \frac{1}{2}^-, \frac{3}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$.

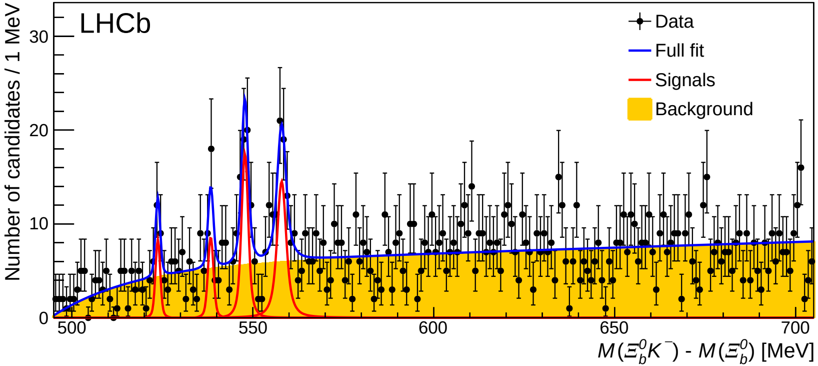
[Karliner:2017kfm, Padmanath:2017lng, Wang:2017zjw]

Ω_b^{**-} states in prompt production

[LHCb, PRL 124, 082002 (2020)]



- $\sim$ 100x smaller statistics
- Four peaks are seen with significance $> 3\sigma$
- No fifth narrow state
- Do we see HQSS suppression for the first two?



The new states are

$\Omega_b(6315)^-$

$\Omega_b(6330)^-$

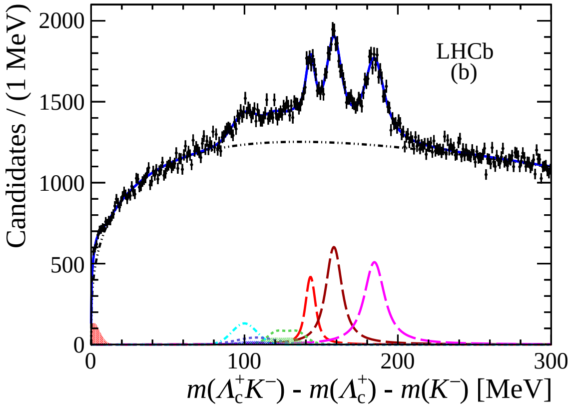
$\Omega_b(6340)^-$

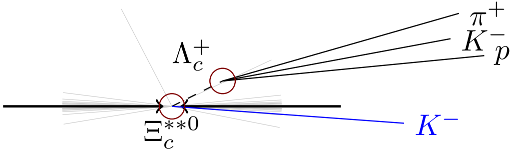
$\Omega_b(6350)^-$

Ξ_c^{**0} states in prompt production

[LHCb, PRL 124, 222001 (2020)]

$$\Xi_c^{**0} \begin{pmatrix} c \\ s \\ d \end{pmatrix} \to \Lambda_c^+ \begin{pmatrix} c \\ u \\ d \end{pmatrix} + K^- \begin{pmatrix} s \\ \bar{u} \end{pmatrix}$$





- Four structures are clearly visible
- More combersome partially-reconstructed decays
- No fifth narrow state
- The peaks are wider(!)

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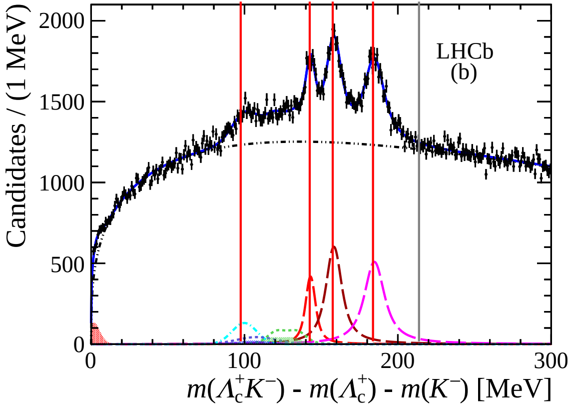

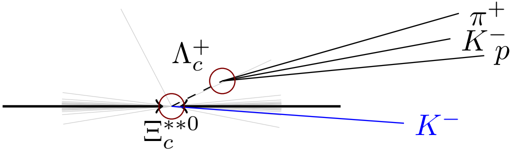

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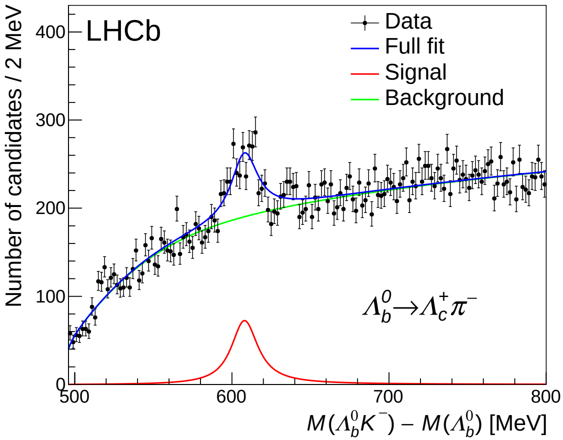
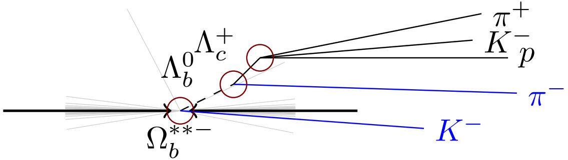
- More combersome partially-reconstructed decays
- No fifth narrow state
- The peaks are wider(!)
- Same peak spacing as for Ω_c^{**0}

Ξ_b^{**-} states in prompt production

[LHCb, PRD 103, 012004 (2021)]

Λ_b is reconstructed in two final states: $\Lambda_c^+\pi^-$ and $\Lambda_c^+\pi^+\pi^-\pi^-$





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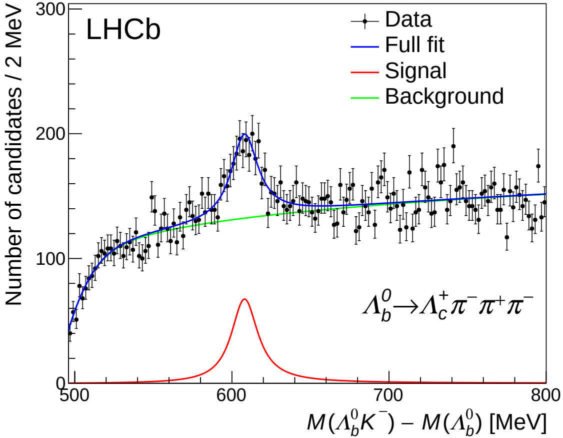

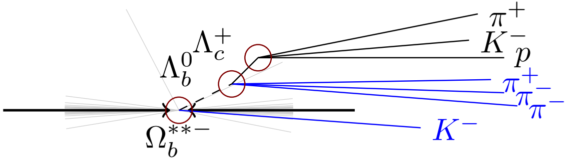

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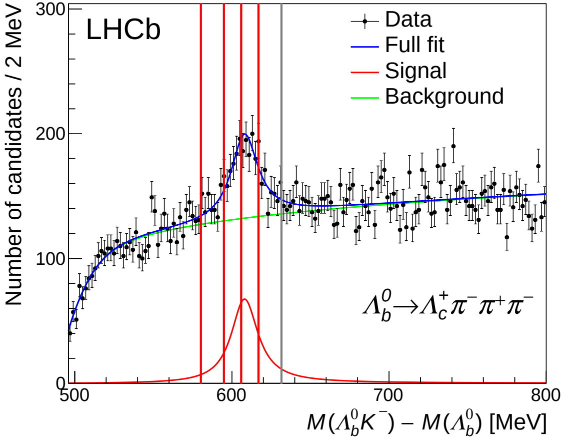
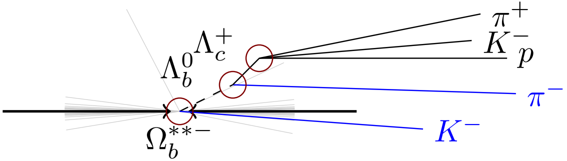


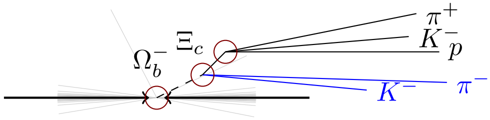


- One clear structure but anomalously broad
- Splitting from Ω_b^{**-} indicates that it will be hard to resolve.

The first exclusive observation of Ω_c^{**0}

[LHCb-PAPER-2021-012, in preparation]

In $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay



- Strict exclusivity cut $\Rightarrow$ No feed down!
- Same four peaks (no clear fifth)
- $+$ **the threshold structure** (5.3σ)

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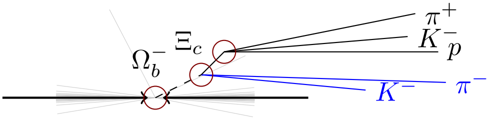

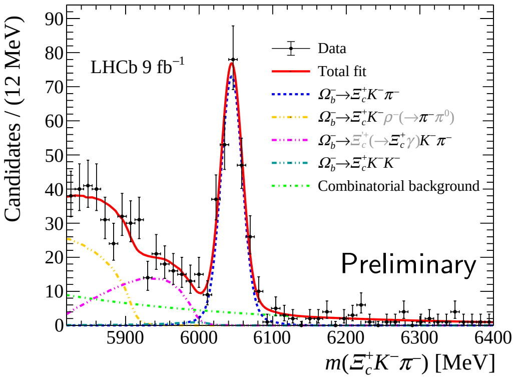

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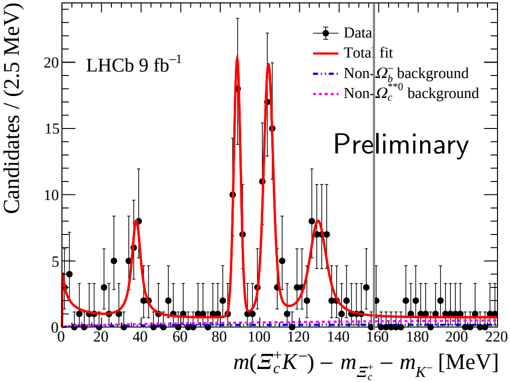
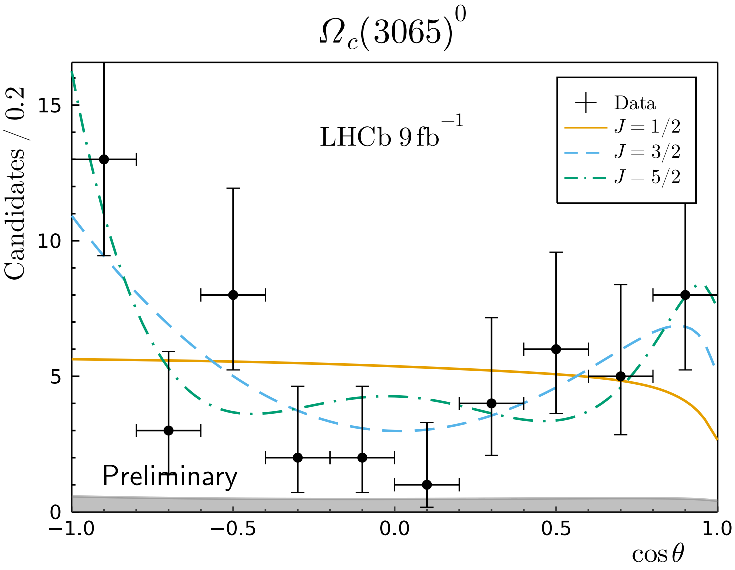


Angular analysis of $\Omega_b^- \to \Omega_c^{**0}(\to \Xi_c^+ K^-)\pi^-$

[LHCb-PAPER-2021-012, in preparation]

- Spin of Ω_b^- is $1/2$
- Ω_c^{**0} cannot have spin projection $> 1/2$
- $\Rightarrow$ non-trivial angular dependence for $J = 3/2$, $J = 5/2$.
- Noticible inefficiency at $\cos\theta = 1$ (soft K^-).

3.6σ: $J(\Omega_c(3065)^0)! = 1/2$
2.2σ: $J(\Omega_c(3050)^0)! = 1/2$



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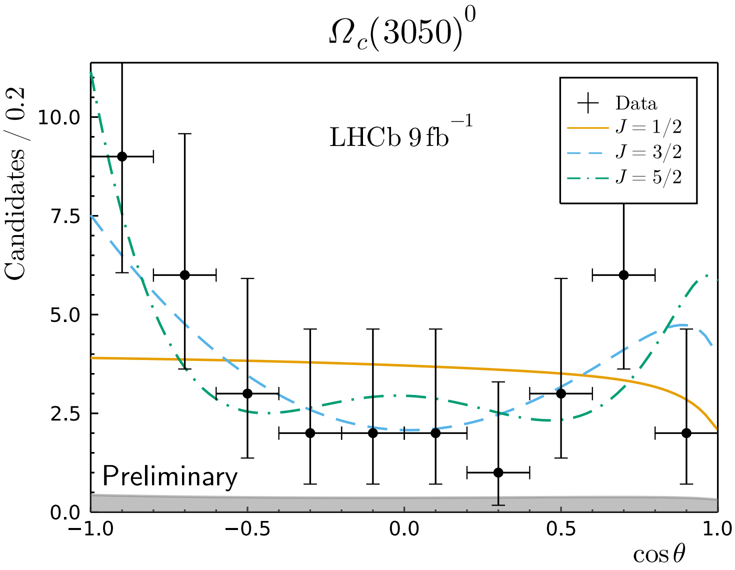
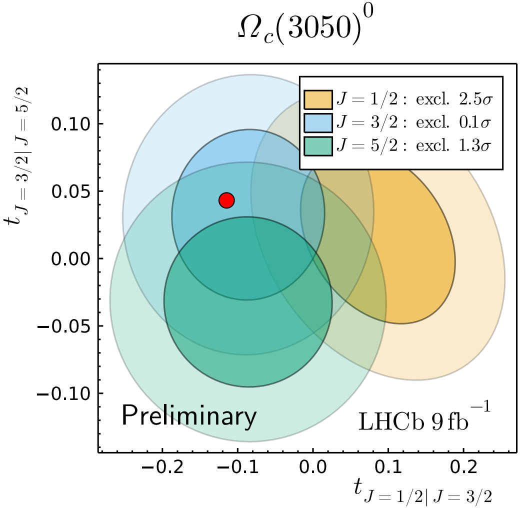
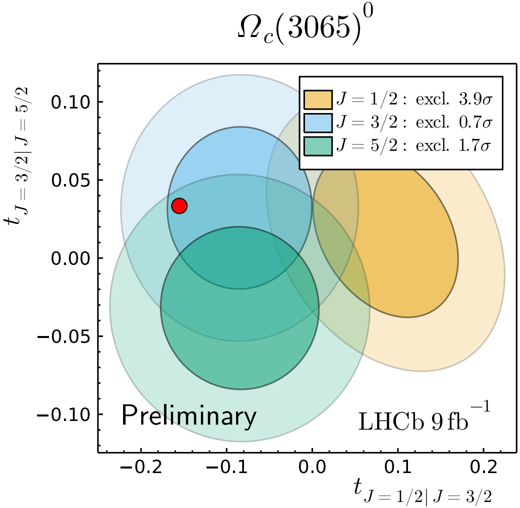


Spin hypotheses testing

[LHCb-PAPER-2021-012, in preparation]

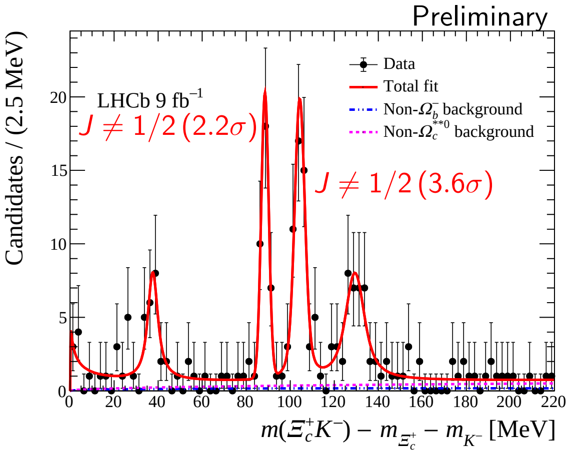
- 2d Log Likelihood ratio as a test statistics $t_{J|J'} = \frac{1}{N}\sum_{i=1}^{N} \log\left(I_J(\cos\theta_i)/I'_J(\cos\theta_i)\right)$





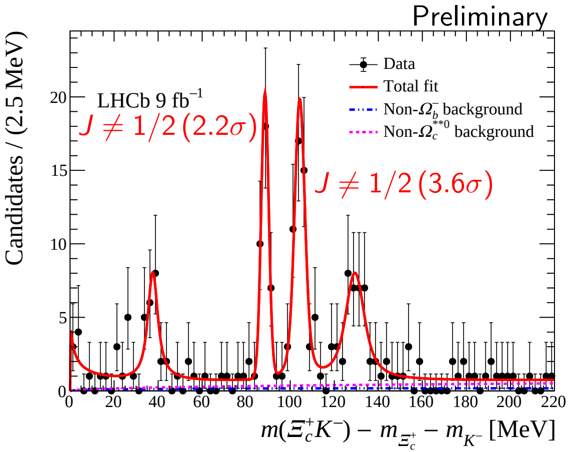
Combined spin test

[LHCb-PAPER-2021-012, in preparation]

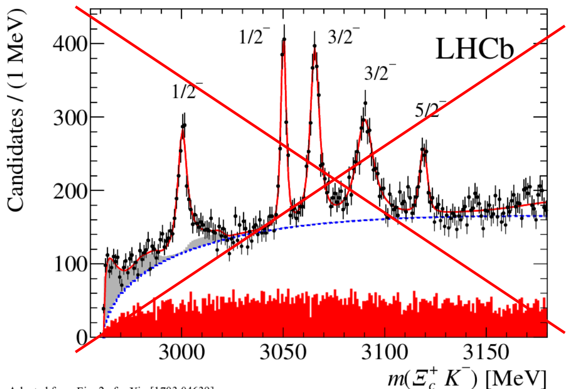


Combined spin test

[LHCb-PAPER-2021-012, in preparation]



Excluded by 3.6σ

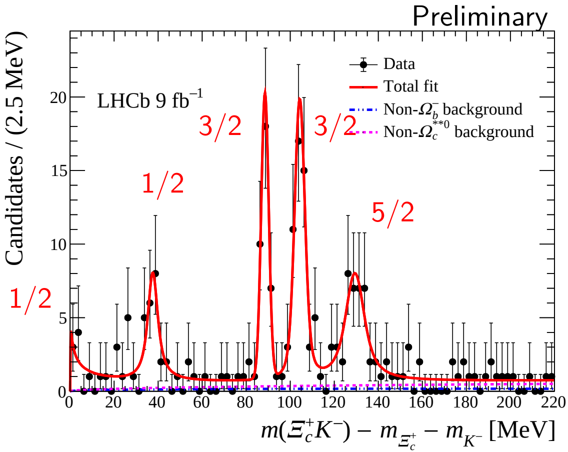


Adapted from Fig. 2 of arXiv:[1703.04639]

to be revisited!

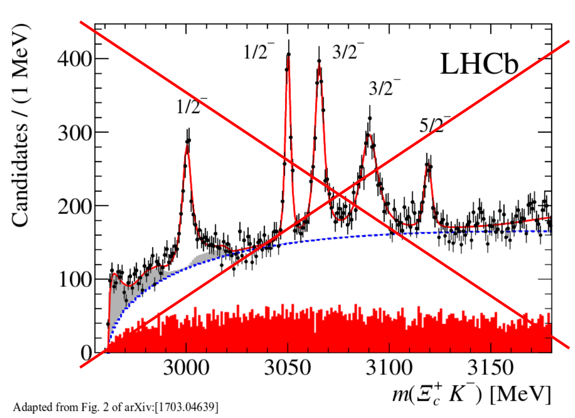
Combined spin test

[LHCb-PAPER-2021-012, in preparation]



One plausible assignments

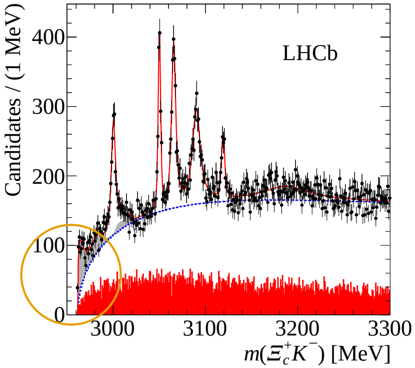
Excluded by 3.6σ

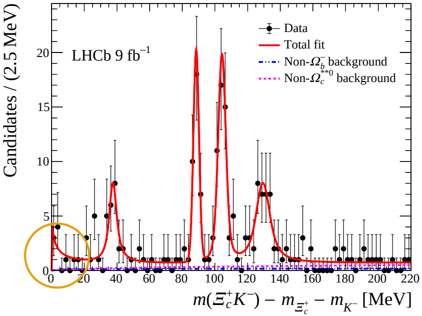


to be revisited!

The threshold structure

[LHCb-PAPER-2021-012, in preparation]





- Explained in the prompt analysis by the partially reconstructed $\Omega_c(3065)^+ \to \Xi_c'^+ K^-$ with anomalously large coupling.

- Exclusive analysis: no feed down is possible
- Other non-physical sources are excluded
- Singinifance in the nominal fit is 5.3σ, 4.3σ including systematics
- No model sensitivity due to the low statistics

Further investigation in needed!

Summary

$1P$ mupltiplet of "bad" diquark – a fundamental piece of the baryon spectroscopy puzzle

- 7 states: five λ-modes and two ρ-modes
- In common for Ξ, $\Sigma_{b/c}$, $\Omega_{b/c}$, $\Xi_{b/c}$, Ξ_{cc}
- State splittings indicate spin-orbit and "hyperfine" interaction
- Charm (beaty) baryons are narrow – good chance to resolve it:
  - Assign quantum numbers, reveal the light quark dynamics
  - Identify diquark excitation for the first time

The threshold structure

- Is a state?
  Compact / Molecular component?
- Present at other sectors?

The fifth narrow state

- Why only seen in inclusive $\Xi_c^+ K^-$
- The first manifestation of the diquark excitation? $2S$ states?