HEAVY FLAVOUR SPECTROSCOPY AT LHCb

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WIFAI
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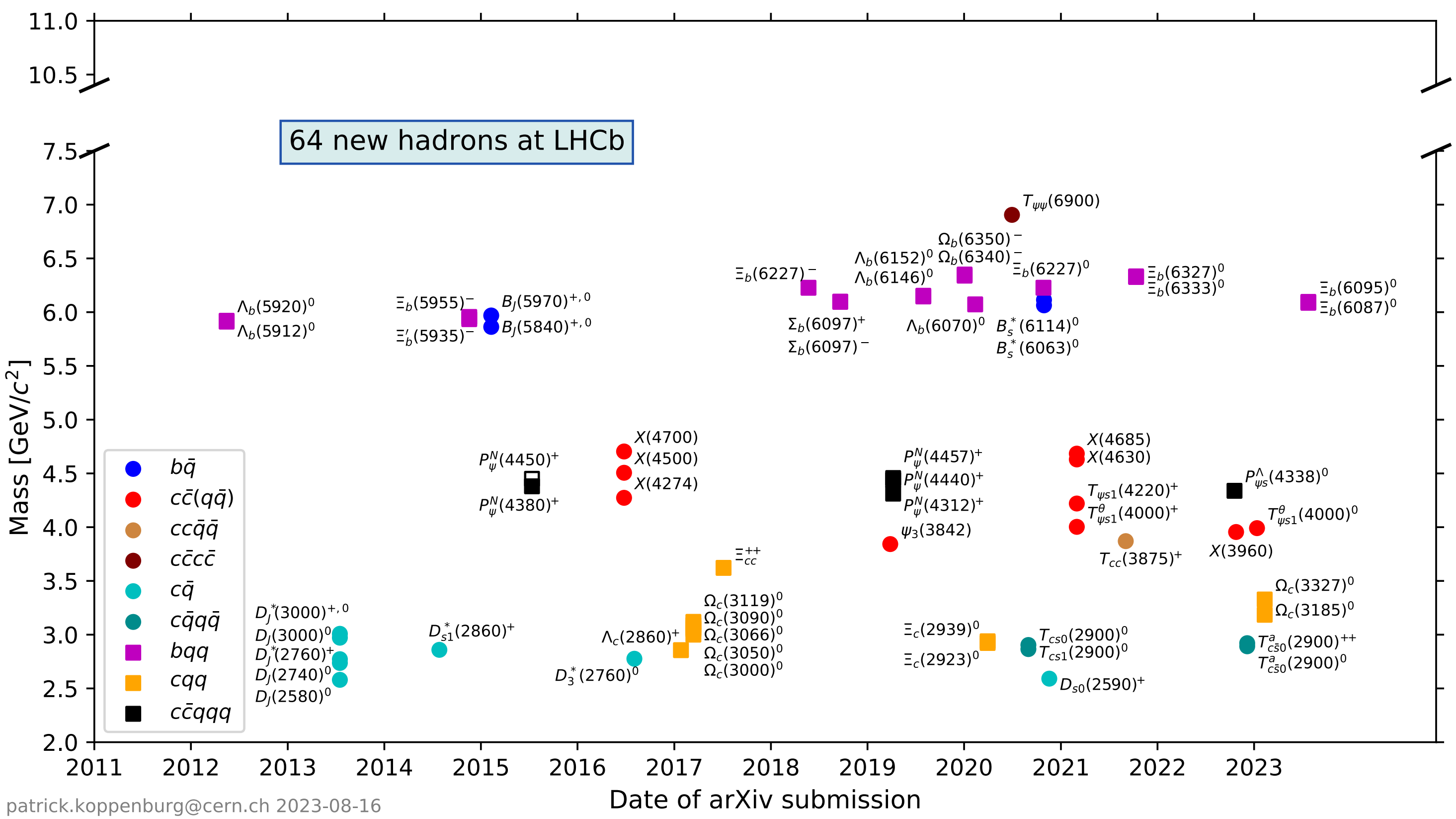
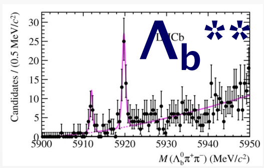
50+ New Hadrons at LHCb!

- ➢ Over the past 10 years LHCb has discovered 64 new hadrons
- ➢ Observations of new states challenge our current understanding of QCD and the validity of the HQET assumptions

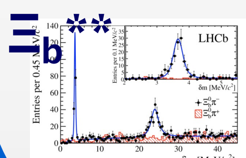


Hadron Spectroscopy

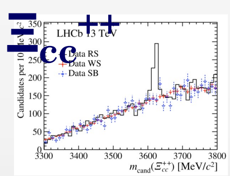
Exotic candidates have been already observed? Many other?
Are they really exotic states? Which kind?



PRL 109 (2012) 172003

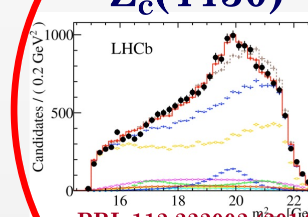


PRL 114 (2015) 062004



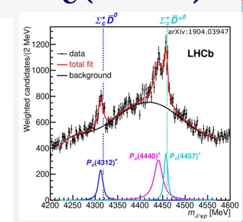
PRL 119 (2017) 112001

$Z_c(4430)^+$



PRL 112 222002 (2014)
PRD 92 112009 (2015)

$P_c(4312)^+$



PRL 122 (2019) 222001

HADRON SPECTROSCOPY

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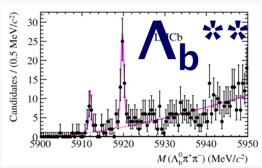

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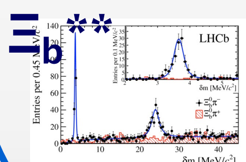

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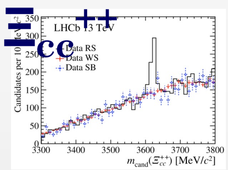
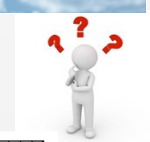
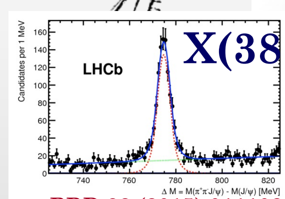
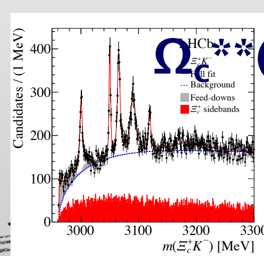


PRL 119 (2017) 112001

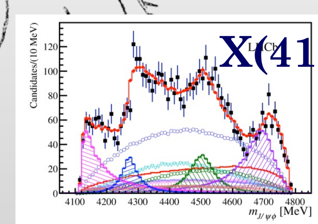




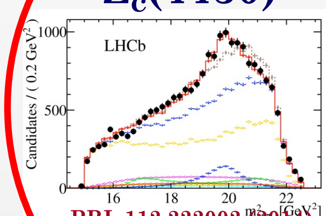
PRD 92 (2015) 011102
PRL 110 (2013) 222001



PRL 118 (2017) 182001



PRL 118 (2017) 022003
PRD 95 (2017) 012002



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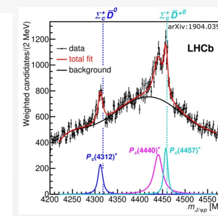
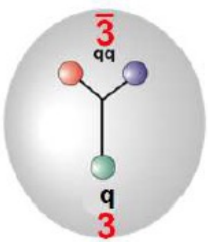


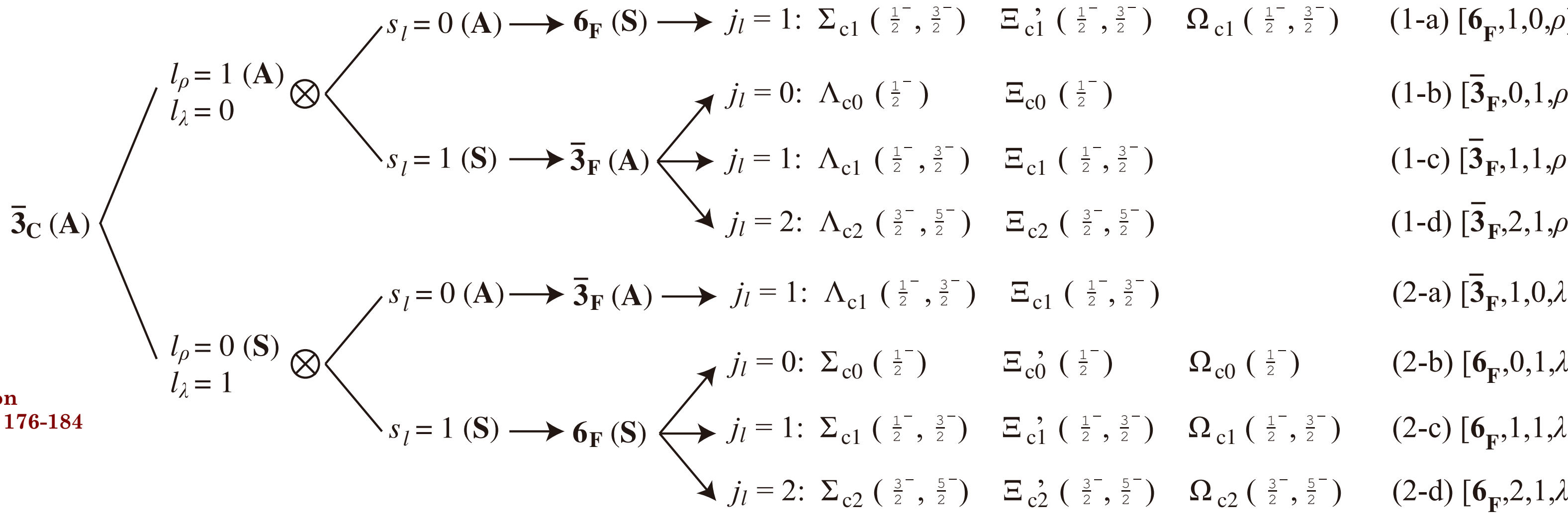
PRL 122 (2019) 222001

Conventional Spectroscopy

P-WAVE CHARM BARYONS



Credit: M. Pennington
AIP Conf.Proc. 1432 (2012) 176-184



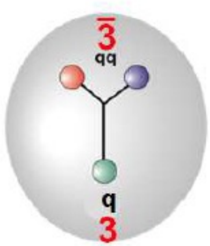
[Phys. Rev. D91 (2015) 054034]

For each $j_{qq}>0$ → doublet $J^P = j_{qq} \pm 1/2$

7 excited L = 1 Ω_c → 5λ-mode excited states

D- wave: 14 excited L = 2 Ω_c → 6λ-mode excited states

P-wave Charm Baryons



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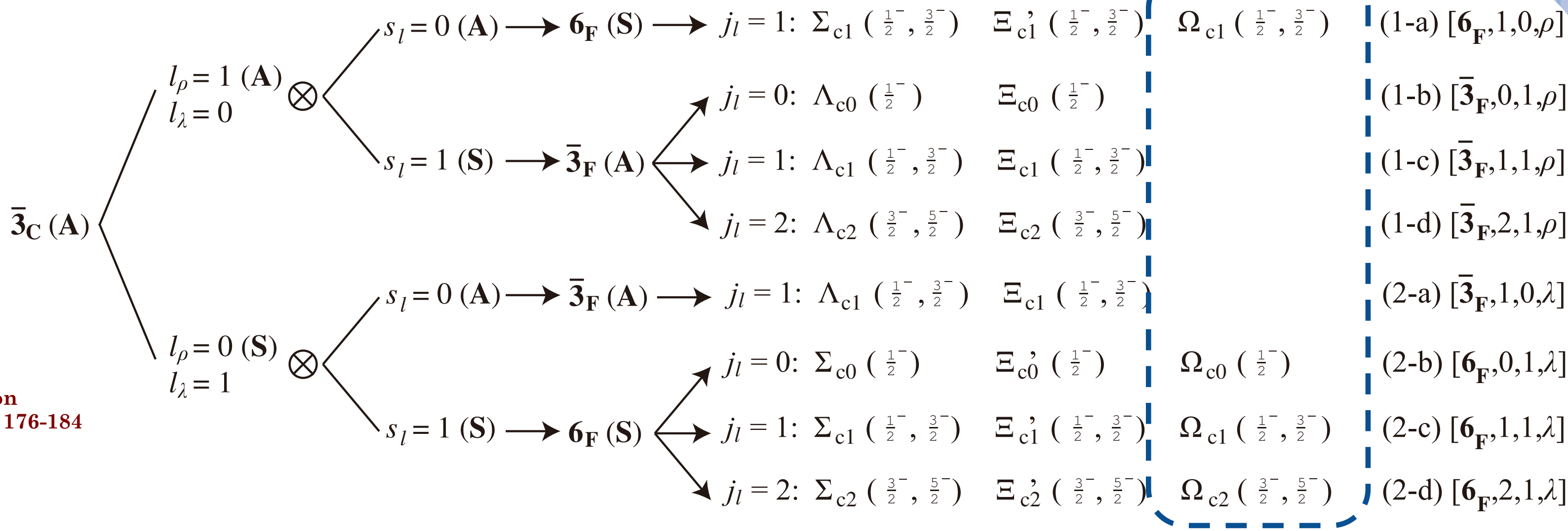

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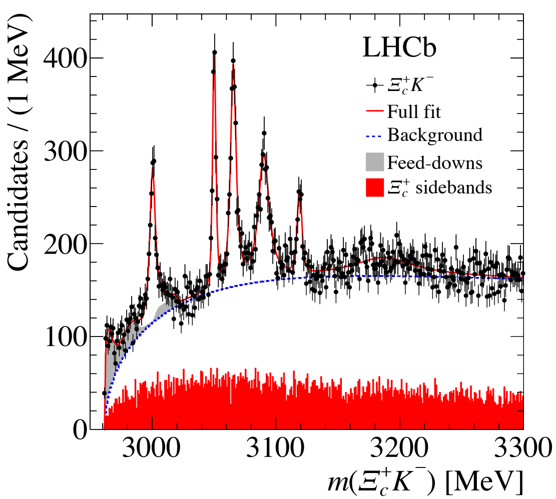
FIVE NEW EXCITED Ω^0_c STATES!

- Five excited Ω^0_c states observed in prompt pp collisions in 2017
- Comprehensive explanation of all peaks is still missing
- Large production cross sections of beauty baryons at LHC: Λ^0_b, Ξ_b, Ω^-_b , …
- Opportunity to measure quantum numbers of charmed baryon in b-hadron decays.



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First Exclusive Observation of Ω_c^{**0} in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ Decays

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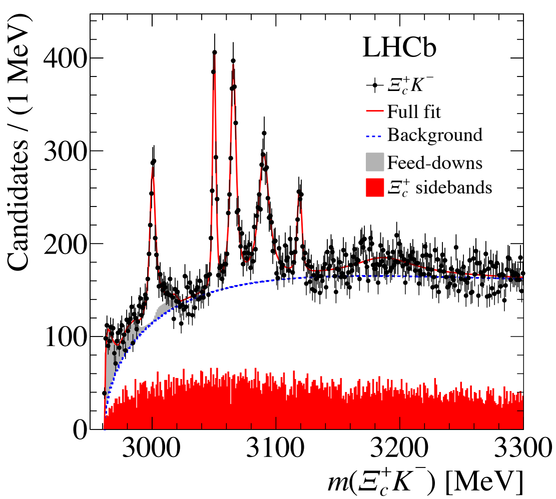
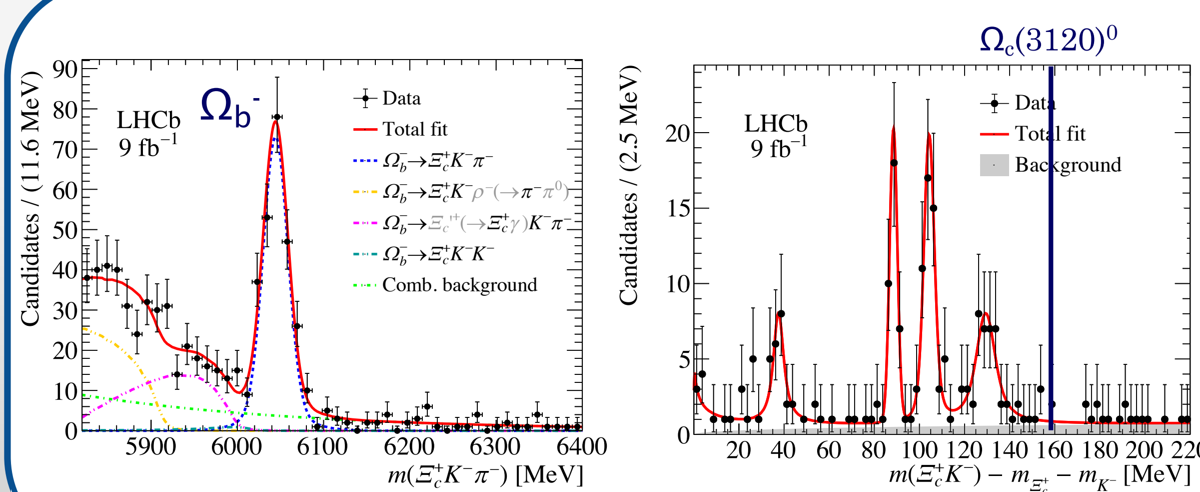
- Four Ω^0_c states observed also in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays
- $\Omega_c(3120)^0$ not present (as in e^+e^- collisions at Belle [PRD 97 (2018) 051102])



[PRL 118 (2017) 182001]



[PRD 104 (2021) L091102]

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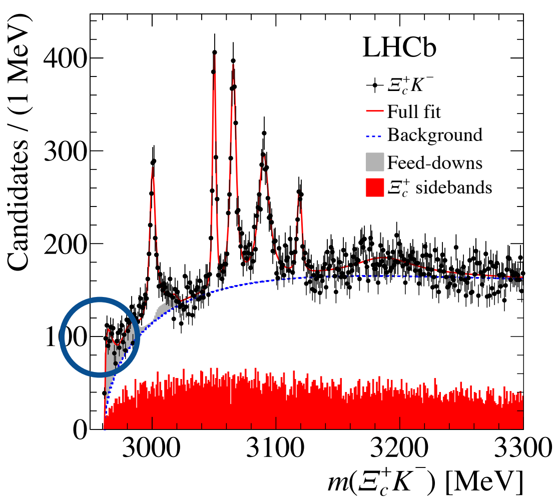
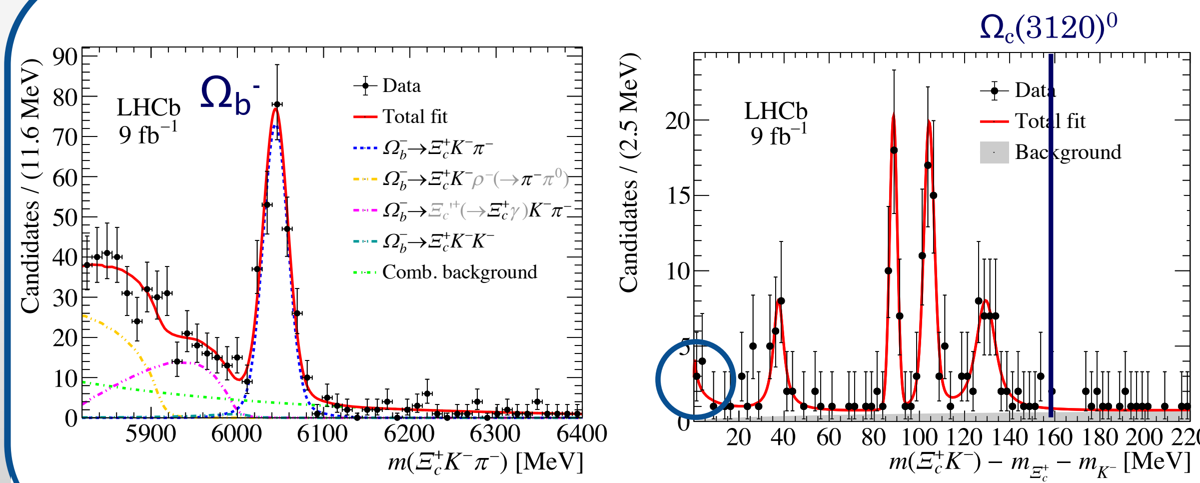
- $\Omega_c(3120)^0$ not present (as in e^+e^- collisions at Belle [PRD 97 (2018) 051102])
- Intriguing enhancement at threshold. A new Ω^0_c ?



[PRL 118 (2017) 182001]

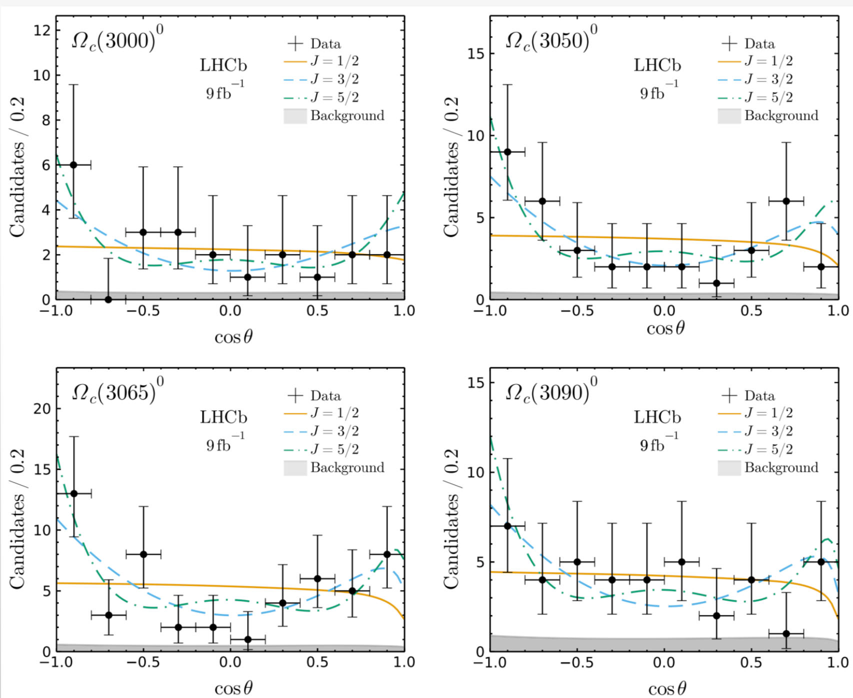


[PRD 104 (2021) L091102]

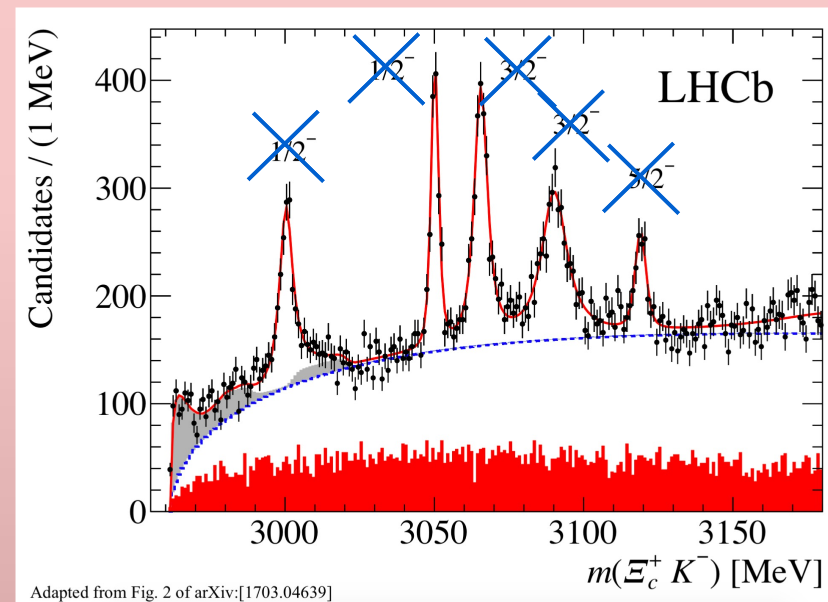
Angular Analysis of $\Omega_b^- \to \Omega_c^{**0}(\to \Xi_c^+ K^-)\pi^-$

[PRD 104 (2021) L091102]

- Analysis of angular distributions to assess J^P of the Ω_c^{**0}
- A popular J^P assignment (i.e. λ-modes in the natural order $1/2^-$, $1/2^-$, $3/2^-$, $3/2^-$, $5/2^-$) is disfavoured



Excluded by 3.6σ

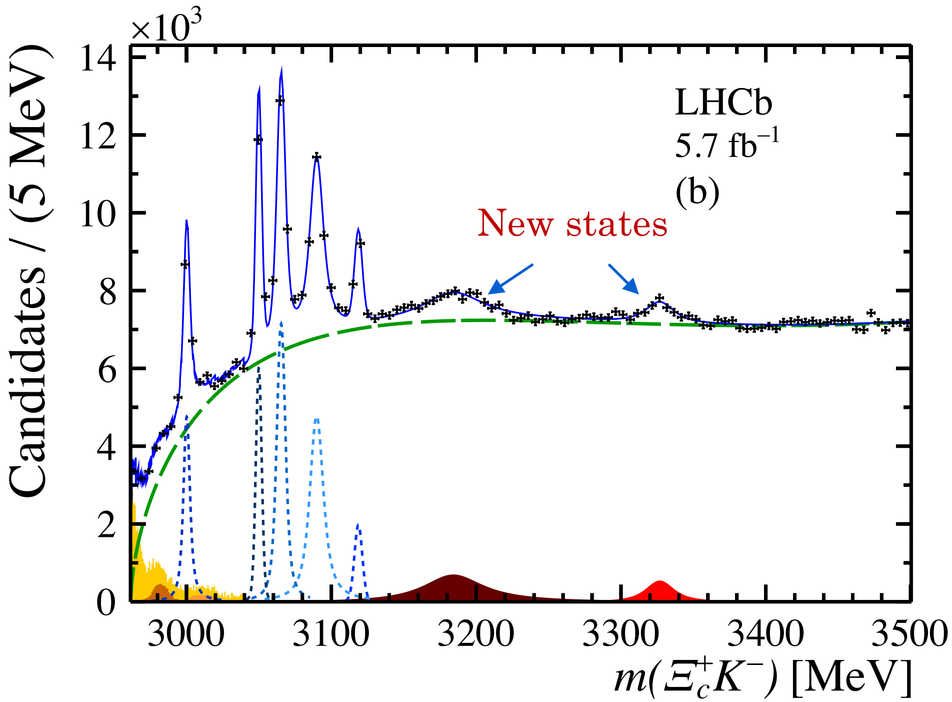


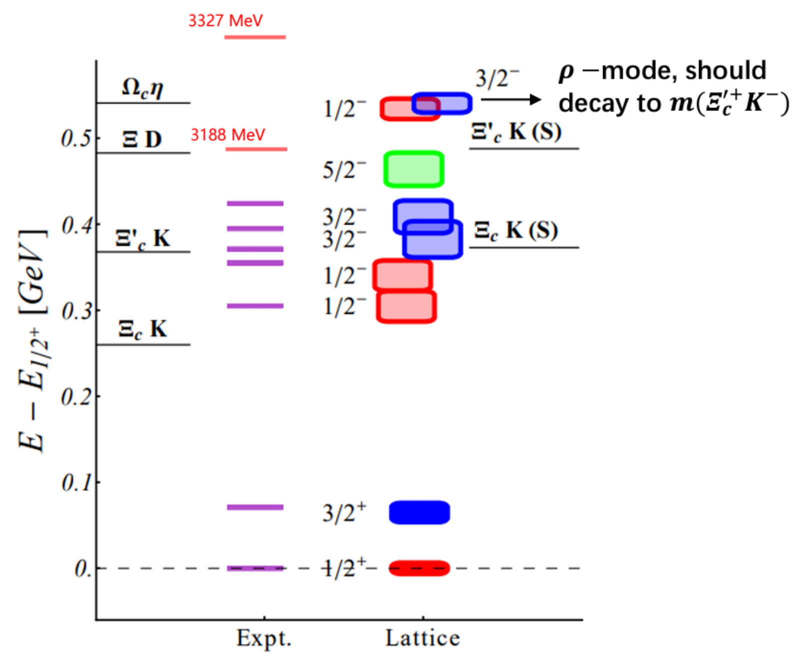
[Karliner & Rosner PRD 95 (2017) 114012]

Updated Search (Run I-II)

[PRL 131 (2023) 131902]

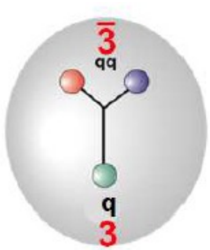
- Larger integrated luminosity → Larger sensitivity to broad states
- Observation of two new states: $\Omega_c(3185)$ and $\Omega_c(3327)$
- A comprehensive explanation becomes even more difficult





[arXiv:1704.00259]

P-WAVE CHARM BARYONS



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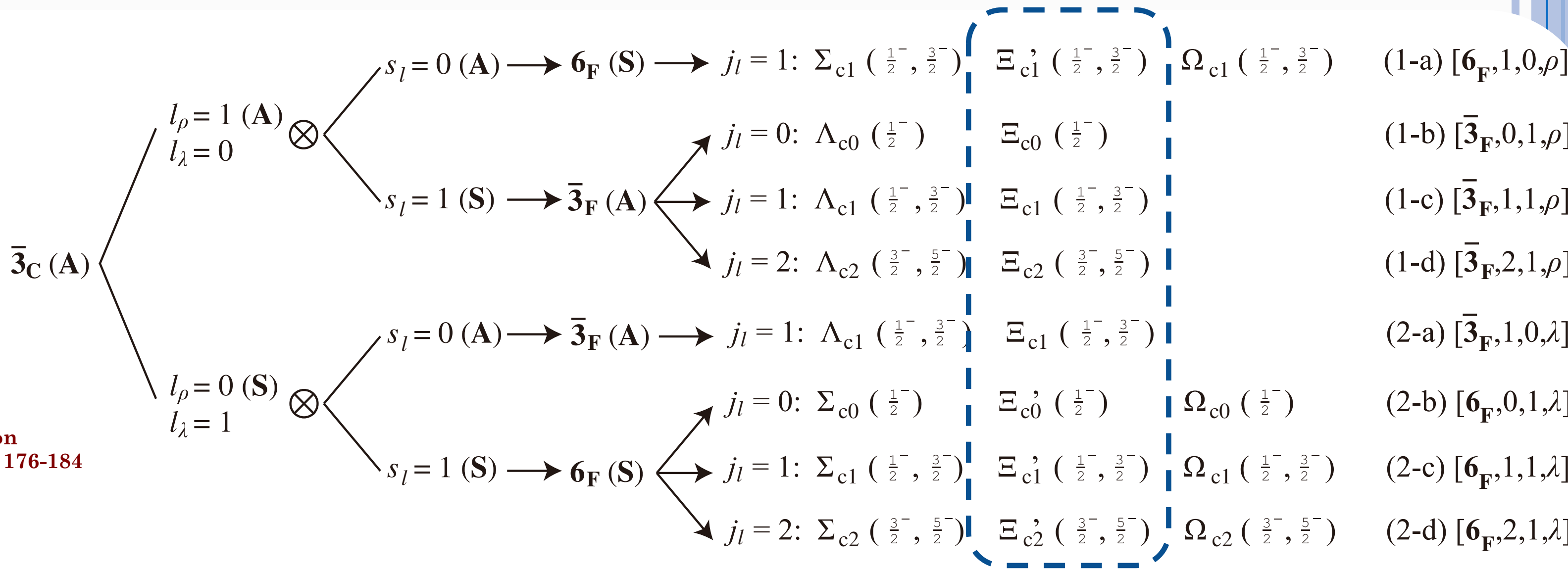

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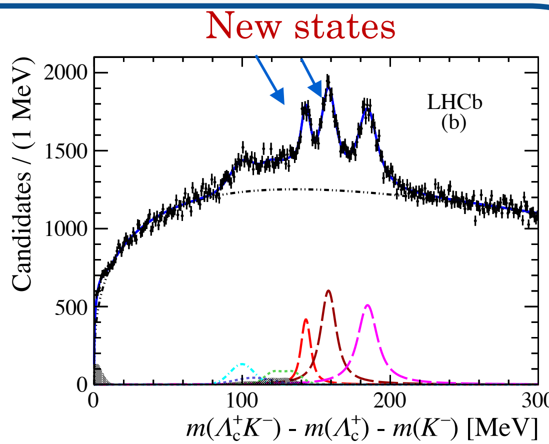
Excited Ξ_c^0 States

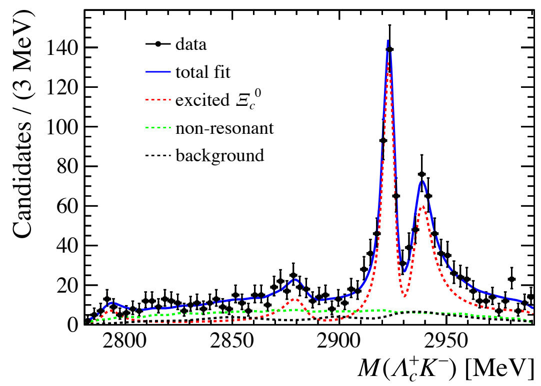
[PRL 124 (2020) 222001, PRD 108 (2023) 012020]

- Two excited Ξ^0_c states observed in the $\Lambda^+_c K^-$ spectrum in prompt pp collisions
- Confirmation in exclusive B decays, $B^- \rightarrow \Lambda^+_c \Lambda^-_c K^-$ decays, plus evidence of 2 more states
- The mass of $\Xi_c(2965)$ consistent to the $\Xi_c(2970)$ one but their widths differ

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



Resonance	m (MeV)	Γ (MeV)
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$
$\Xi_c(2880)^0$ (3.8σ)	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.3 \pm 5.8$
$\Xi_c(2790)^0$ (3.7σ)	–	–



EXCITED Ω_c^0 VS Ξ_c^0 STATES

Universal mass difference?

$$m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq 125\,\text{MeV},$$
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$$\Omega_c^{**0} \to \Xi_c^+ K^-$$

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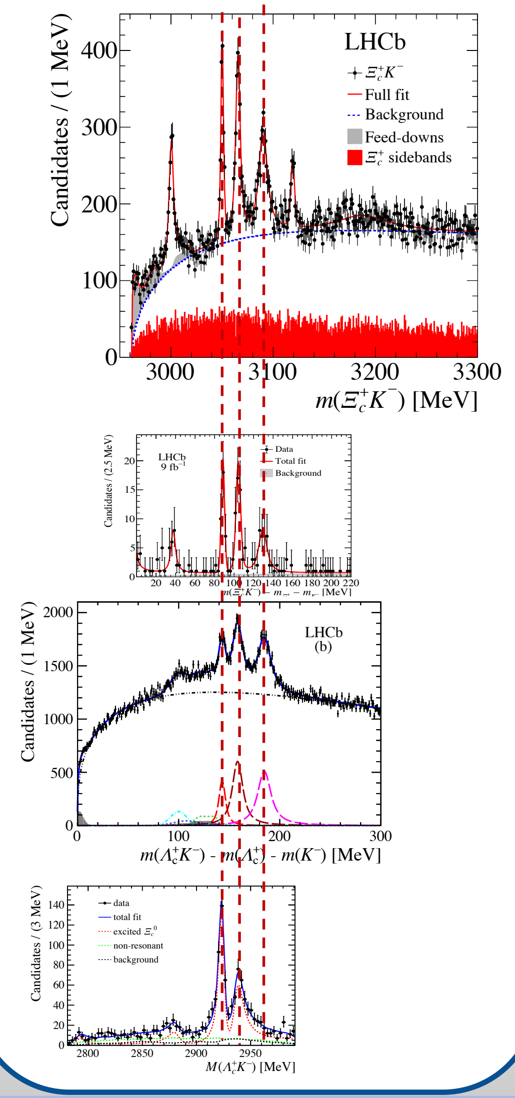
$$\Xi_c^{**0} \to \Lambda_c^+ K^-$$

$$B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$$



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Is Ξ_c(2880) the partner of the Ω_c(3000)?

$$\Omega_c^{**0} \to \Xi_c^+ K^-$$

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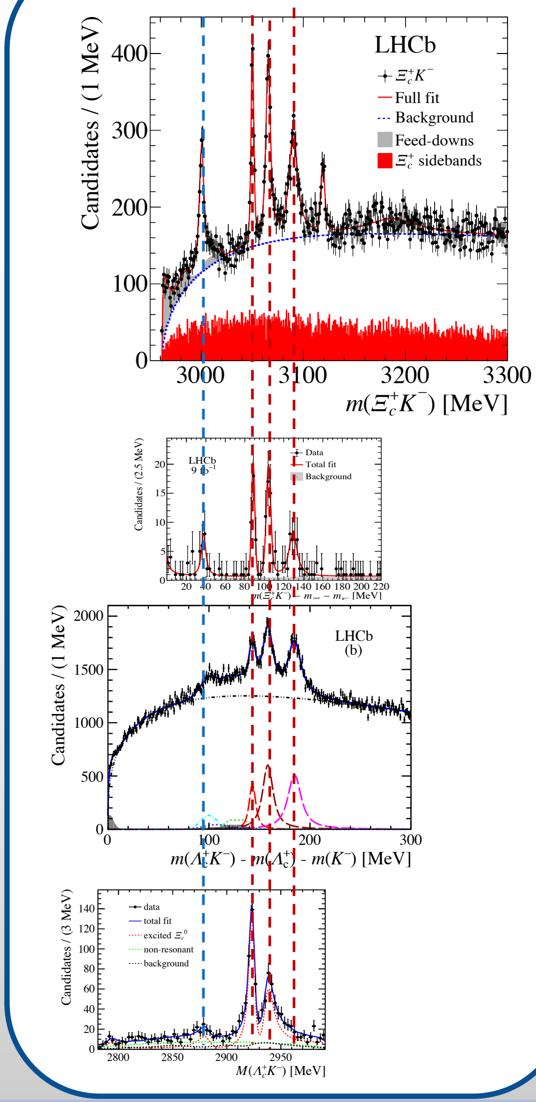

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Is $\Xi_c(2880)$ the partner of the $\Omega_c(3000)$?

Where is the partner of $\Omega_c(3120)$? Does it decay in different decay modes (N.B. Single pion decays are suppressed in Ω_c sector)

The $\Omega_c(3120)$ not seen neither in exclusive decays nor in e^+e^- collisions. Is it a standard baryon?

$$\Omega_c^{**0} \to \Xi_c^+ K^-$$

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

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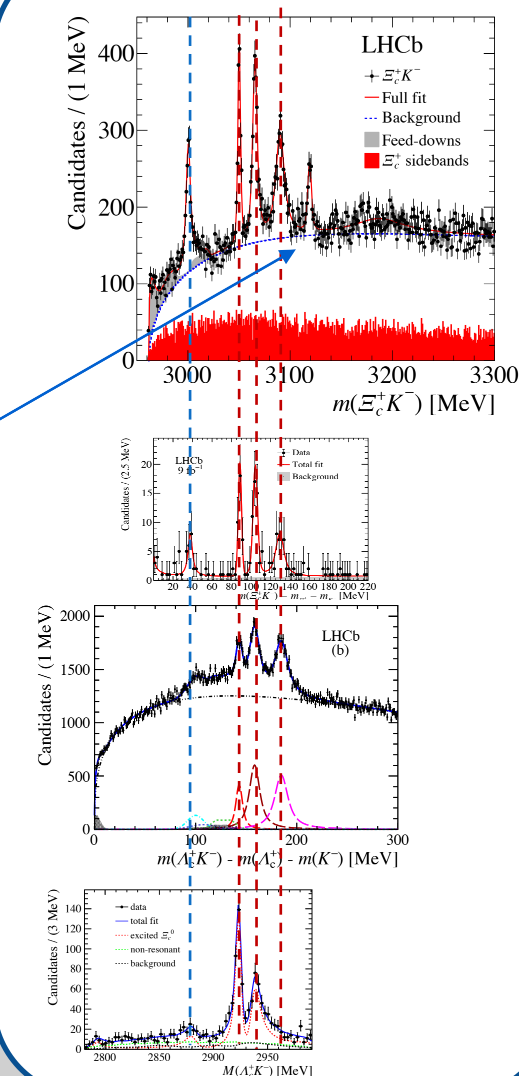
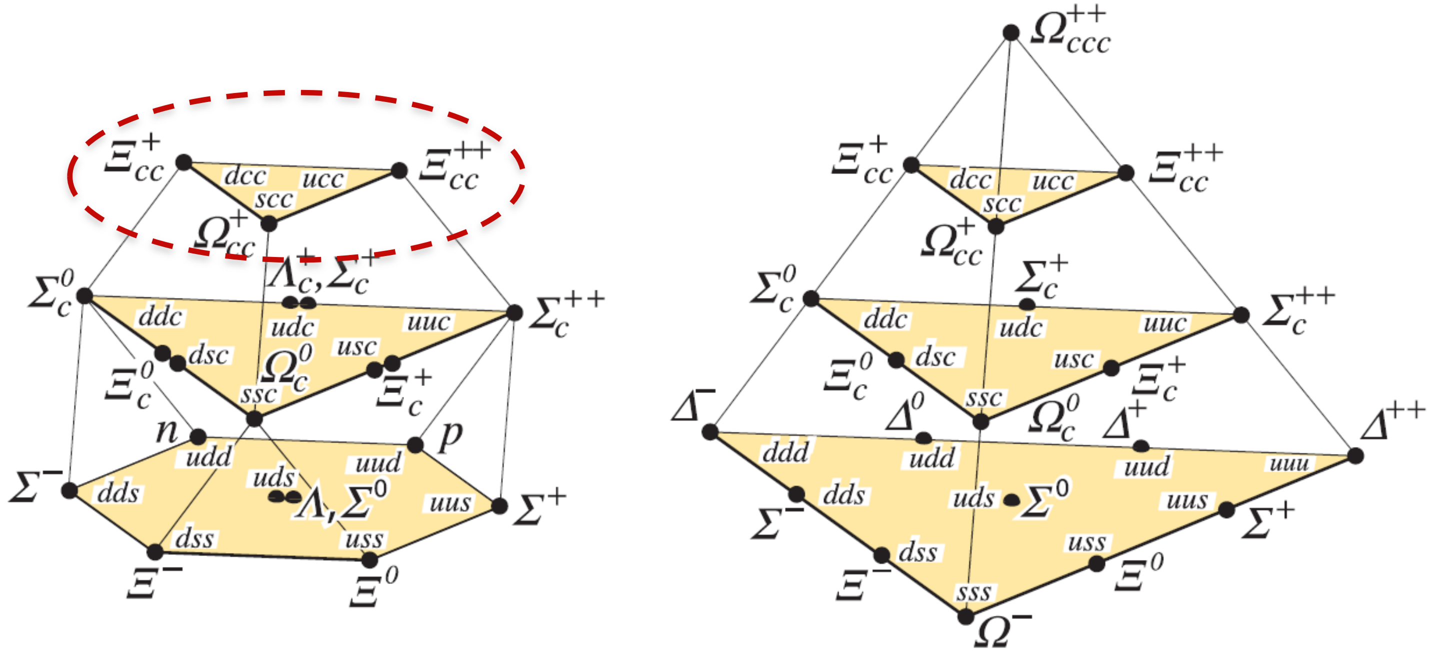


Doubly Heavy Baryons

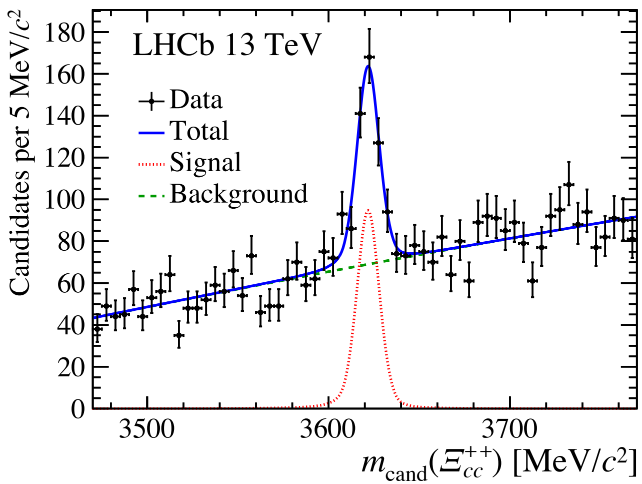
- Three weakly decaying C = 2 states are expected:
- Ξ_{cc} isodoublet (ccu; ccd) and an Ω_{cc} isosinglet (ccs), each with $J^P = 1/2^+$



Doubly Heavy Baryons: Ξ_{cc}^{++}

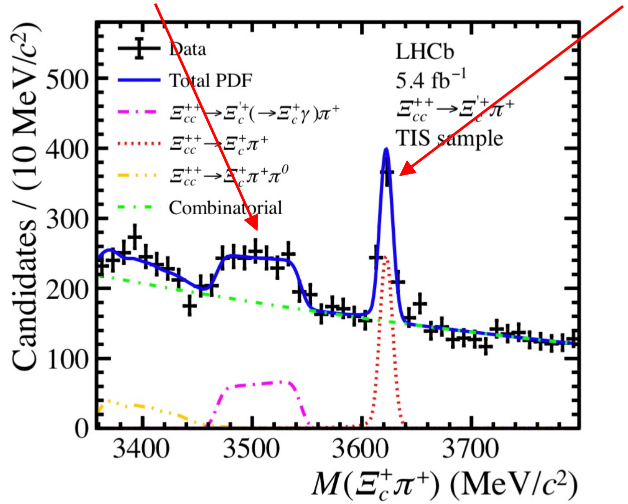
- Ξ_{cc}^{++} observed in three different decay modes!
- Mass and lifetime consistent with a weakly decaying state

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



[PRL 119 (2017) 112001]

$\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+$ $\Xi_{cc}^{++} \to \Xi_c^{+} \pi^+$



[PRL 121 (2018) 052002, JHEP 05 (2022) 038]

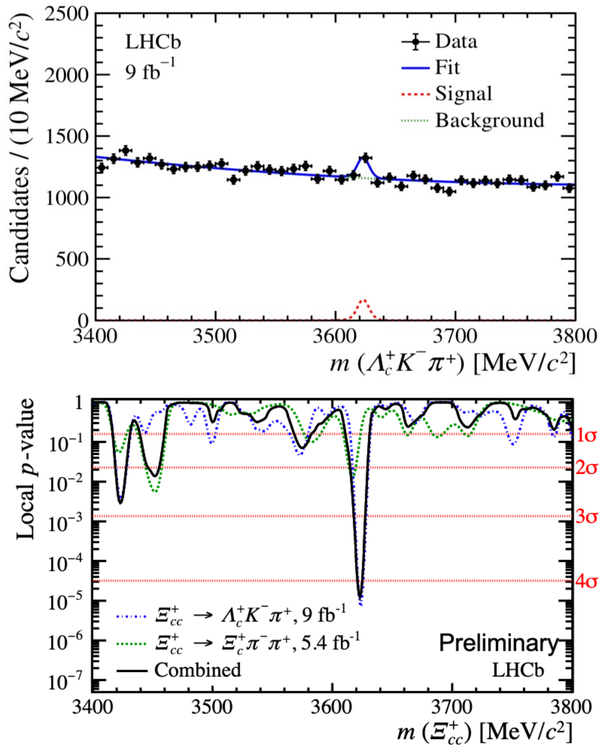
$$m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65(\text{stat}) \pm 0.31(\text{syst})\ \text{MeV}$$
$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014(\text{syst})\ \text{ps}$$

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17_{\text{stat}} \pm 0.10_{\text{syst}}$$

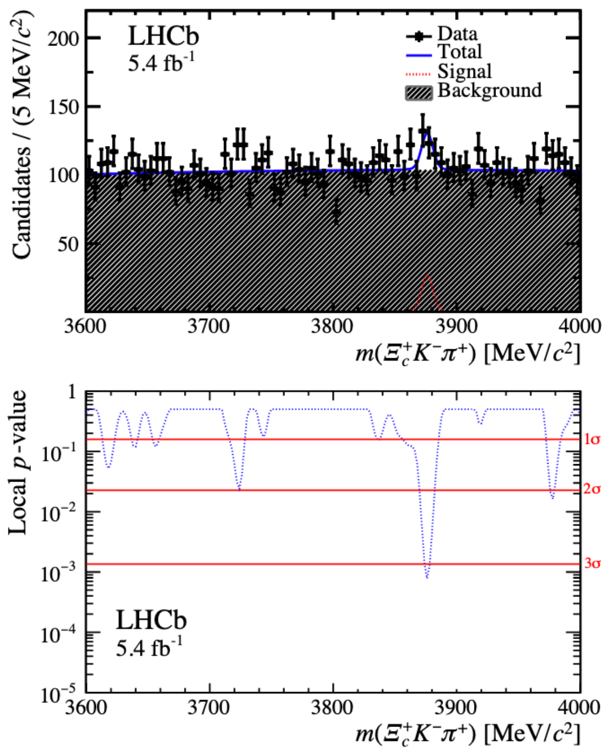
SEARCH FOR Ξ_{cc}^{+} & Ω_{cc}^{+}

- No significant signals
- $\Xi_{cc}^{+} \rightarrow \Xi_{c}^{+}\pi^{-}\pi^{+}$ when combined with $\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+}K^{-}\pi^{+}$
  - ✓ Local (global) significance 4σ (2.9σ) @ $m = 3623.0 \pm 1.4_{stat}$ MeV
- $\Omega_{cc}^{+} \rightarrow \Xi_{c}^{+}K^{-}\pi^{+}$ bump at 3876 MeV, with local (global) significance 3.2σ (1.8σ)

$\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+}K^{-}\pi^{+}$ & $\Xi_{cc}^{+} \rightarrow \Xi_{c}^{+}\pi^{-}\pi^{+}$



$\Omega_{cc}^{+} \rightarrow \Xi_{c}^{+}K^{-}\pi^{+}$



[Sci.China-Phys.Mech.Astron. 64 (2021) 101062, Sci.China Phys.Mech.Astron. 63 (2020) 221062, JHEP 12 (2021) 107]

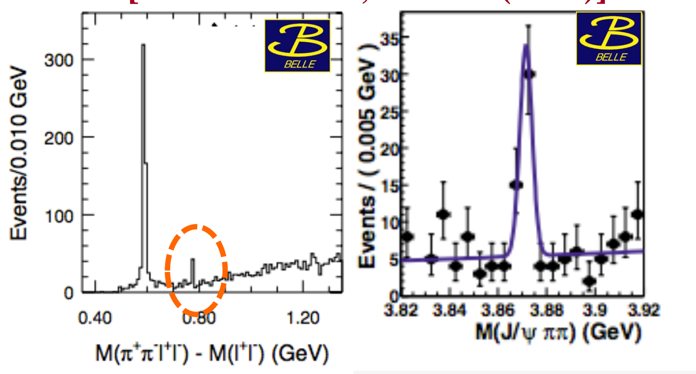
Exotic Spectroscopy

The X(3872) State (aka $\chi_{c1}(3872)$)

Discovered in 2003 by the Belle collaboration in the $B \to K X(3872)$ decay where $X(3872) \to J/\psi \pi^+ \pi^-$

- Mass is roughly equal to $m(D^0) + m(D^{*0})$
- Width is surprisingly narrow (< 1.2 MeV)
- Large production rate in $p\bar{p}$ collisions

[Belle: PRL 91, 262001 (2003)]



LHC experiments are largely contributing to shed light on the nature of the X(3872) state

- Determination of the quantum numbers $J^{PC} = 1^{++}$ **[PRL110 222001 (2013), PRD92 011102 (2015)]**
- Precise mass measurement **[EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]**

$$E_B = m(D^0) + m(D^{*0}) - m(X(3872)) = 104 \pm 138\,\mathrm{keV/c^2}$$

➡ *Loosely bound in the molecule scenario*

- Measurement of natural width: **[JHEP 08 (2020) 123, PRD 102 (2020) 092005]**

$$\Gamma^{\mathrm{BW}}_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21\ \mathrm{MeV}$$

- Production cross-section in *pp* collisions at $\sqrt{s} = 7$ TeV **[EPJC 72 (2012) 1972,]**
- Measurement of branching ratios **[Nucl.Phys.B886 (2014) 665]**

$$\frac{BR(X(3872) \to \psi(2S)\gamma)}{BR(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

➡ *Pure molecule scenario disfavored*

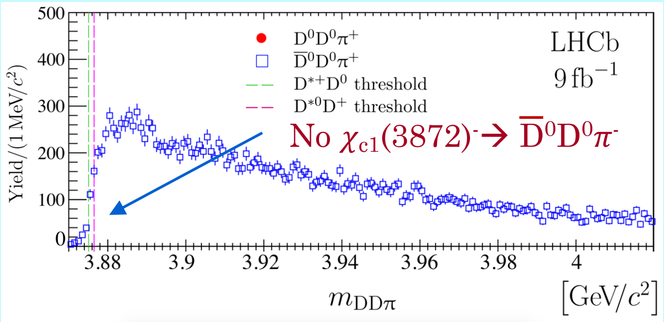
LOOKING FOR $\chi_{c1}(3872)$ PARTNERS

[JHEP 2022 (2022) 46, Nat. Comm. 13 (2022) 3351]

$\chi_{c1}(3872)$ ($J^{PC} = 1^{++}$)

Isospin partner

$\chi_{c1}(3872)^{\pm} \rightarrow D^0 D^{*-}$

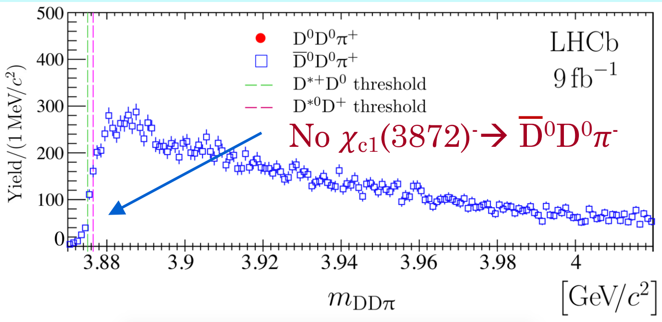


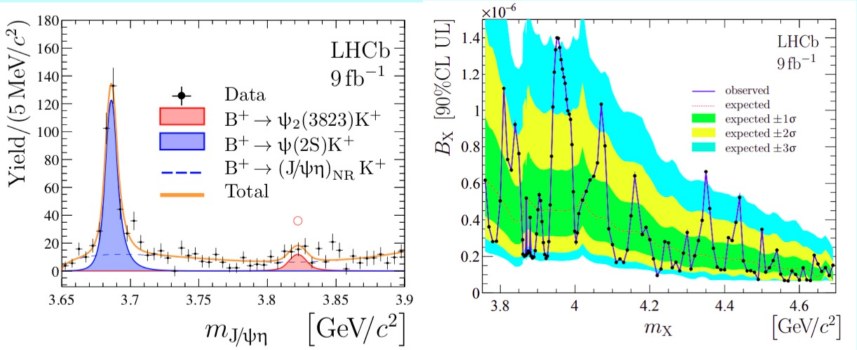
LOOKING FOR $\chi_{c1}(3872)$ PARTNERS

[JHEP 2022 (2022) 46, Nat. Comm. 13 (2022) 3351]

$\chi_{c1}(3872)$ ($J^{PC} = 1^{++}$) → C-odd partner → $\tilde{\chi}_{c1}(3872)$ ($J^{PC} = 1^{+-}$) → J/ψ η

$\chi_{c1}(3872)$ → Isospin partner → $\chi_{c1}(3872)^{\pm}$ → $D^0\, D^{*-}$





Search for charmonium states decaying to J/ψ η in $B^+ \to J/\psi\, \eta\, K^+$

- Observation of ψ(2S), ψ(3823), ψ(4040)
- UL on the production of the C-odd partner of $\chi_{c1}(3872)$ (< 1.9%)

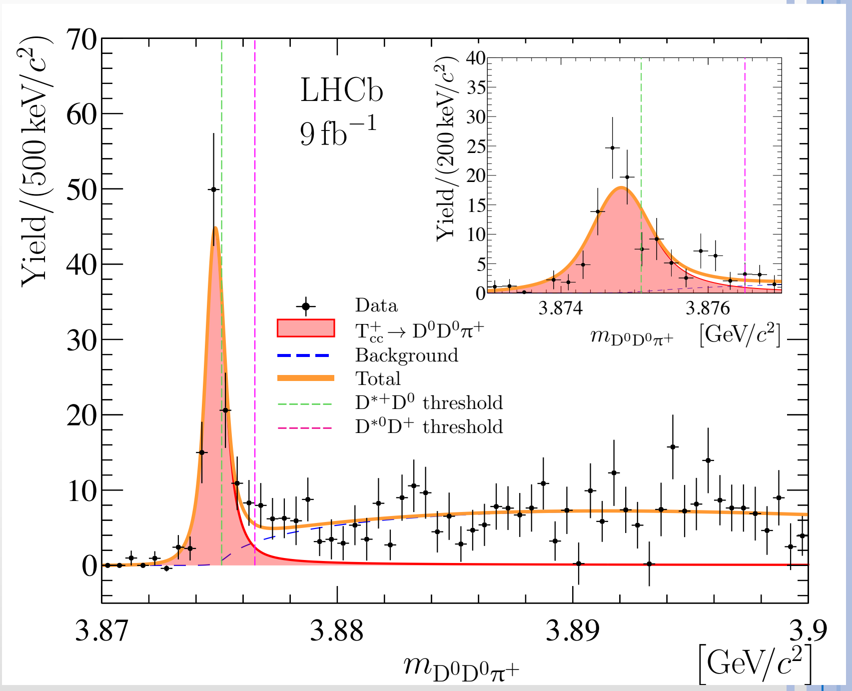
Observation of Exotic Tetraquark T_{cc}^{+} in $D^0D^0\pi^+$

[Nat. Comm. 13 (2022) 3351, Nature Phys. 18 (2022) 751]

- First observation of same-sign doubly charmed tetraquark T_{cc}^{+}
- Very narrow state in $D^0D^0\pi^+$ mass spectrum
- Manifestly exotic with quark content $cc\bar{u}\bar{d}$
- Mass ~ 3875 MeV, very close to the $D^{*+}D^0$ threshold

$$\delta m_{\mathrm{BW}} = -273 \pm 61(\mathrm{stat}) \pm 5(\mathrm{syst})^{+11}_{-14}(\mathrm{model})\ \mathrm{keV}$$
$$\Gamma = 410 \pm 65(\mathrm{stat}) \pm 43(\mathrm{syst})^{+18}_{-38}(\mathrm{model})\ \mathrm{keV}$$

- Consistent with isoscalar $J^P = 1^+$ ground state

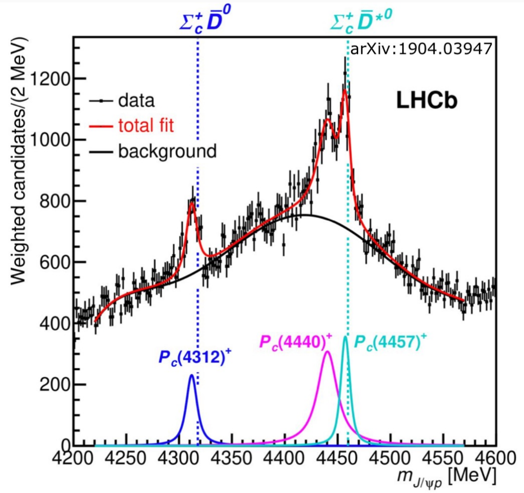


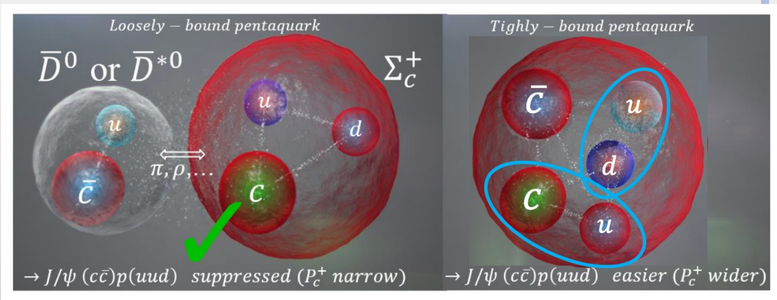
Observation of Pentaquarks in J/ψ p
(i.e. The Return of the Living Dead)

[PRL115 (2015)072001, PRL122 (2019) 222001]

- In 2003 "Observation" of a pentaquark
  $\Theta^+ \rightarrow nK^+/pK^0_S$
- Soon after the claim started fading

- Few years later LHCb claimed the observation three pentaquarks with hidden charm content
- Observed pentaquarks are close to mass threshold of some charm baryon-meson combinations.
- Structure is not clear. Could they be molecules [PRD 101 (2020) 054037)] or are they compact [EPJA 56 (2020) 142] states?

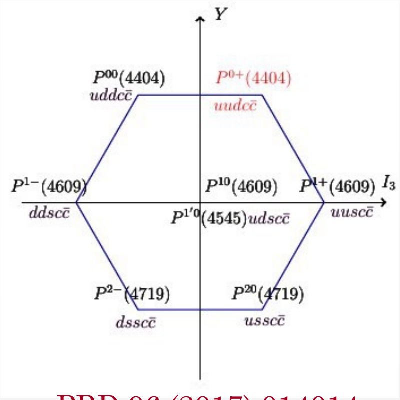




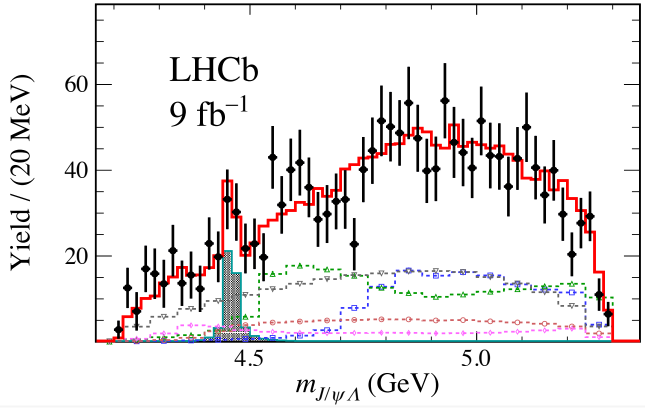
Observation of Pentaquarks with Strangeness

[PRL 131 (2023) 031901, Sci.Bull. 66 (2021) 1278]

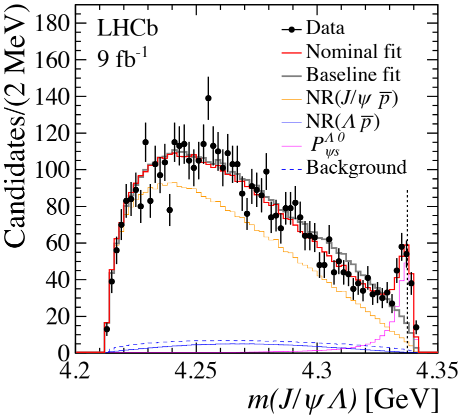
Exotic hadrons should be classified in flavour multiplets, as for the conventional hadrons



PRD 96 (2017) 014014



State	M_0 (MeV)	Γ_0 (MeV)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$



State	M_0 (MeV)	Γ_0 (MeV)
$P^{\Lambda}_{\psi s}(4338)^0$	$4338.2 \pm 0.7 \pm 0.4$ MeV	$7.0 \pm 1.2 \pm 1.3$ MeV

Search for Prompt Production of Pentaquarks in Open-Charm Hadrons

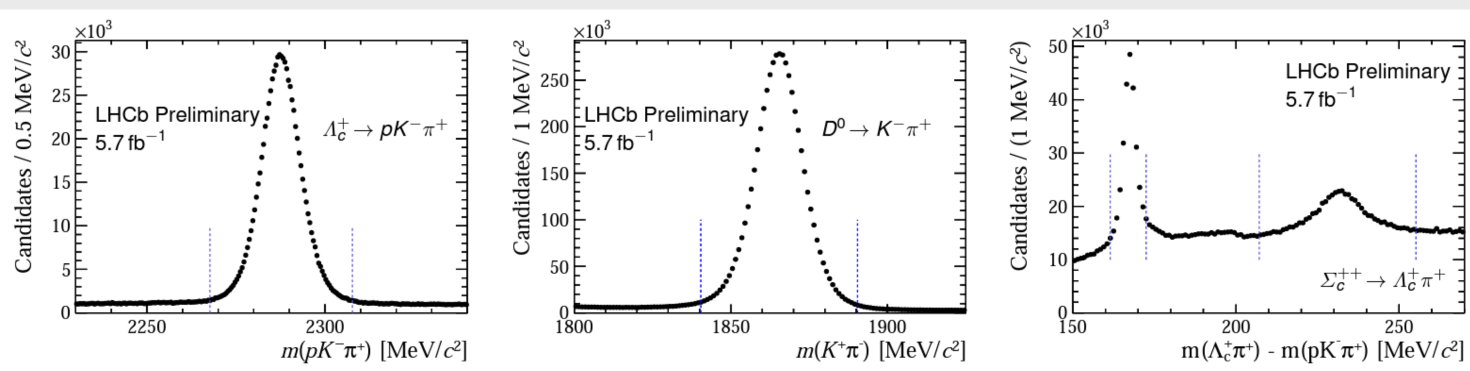
[LHCb-PAPER-2023-018 in preparation]

NEW

Search for pentaquark decays into a range of combinations of open-charm Σ_c o Λ_c^+ baryons with D mesons

$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^0\bar{D}^0$	~~$\Sigma_c^0 D^0$~~	$\Sigma_c^0 D^-$	~~$\Sigma_c^0 D^+$~~	~~$\Sigma_c^0 D^{*-}$~~	~~$\Sigma_c^0 D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$	$\Sigma_c^{*++}D^0$	$\Sigma_c^{*++}D^-$	$\Sigma_c^{*++}D^+$	$\Sigma_c^{*++}D^{*-}$	~~$\Sigma_c^{*++}D^{*+}$~~
$\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*0}D^0$	$\Sigma_c^{*0}D^-$	$\Sigma_c^{*0}D^+$	$\Sigma_c^{*0}D^{*-}$	~~$\Sigma_c^{*0}D^{*+}$~~
$\Lambda_c^+\bar{D}^0$	$\Lambda_c^+D^0$	$\Lambda_c^+D^-$	$\Lambda_c^+D^+$	$\Lambda_c^+D^{*-}$	$\Lambda_c^+D^{*+}$
$\Lambda_c^+\bar{D}^0\pi^+$	$\Lambda_c^+D^0\pi^+$	$\Lambda_c^+D^-\pi^+$	$\Lambda_c^+D^+\pi^+$	$\Lambda_c^+D^{*-}\pi^+$	$\Lambda_c^+D^{*+}\pi^+$
$\Lambda_c^+\bar{D}^0\pi^-$	$\Lambda_c^+D^0\pi^-$	$\Lambda_c^+D^-\pi^-$	$\Lambda_c^+D^+\pi^-$	$\Lambda_c^+D^{*-}\pi^-$	$\Lambda_c^+D^{*+}\pi^-$

- Baryons/mesons are built in trigger, and optimised individually. Optimisation then applied in signal combination
- Range of $c\bar{c}$ ($\Lambda_c^+D^-$, $\Sigma_c\,\bar{D}^0$) and cc ($\Lambda_c^+ D^0$, $\Sigma_c D^+$…) modes (N.B. Excited doubly charmed baryons could also appear in some of the latter spectra)

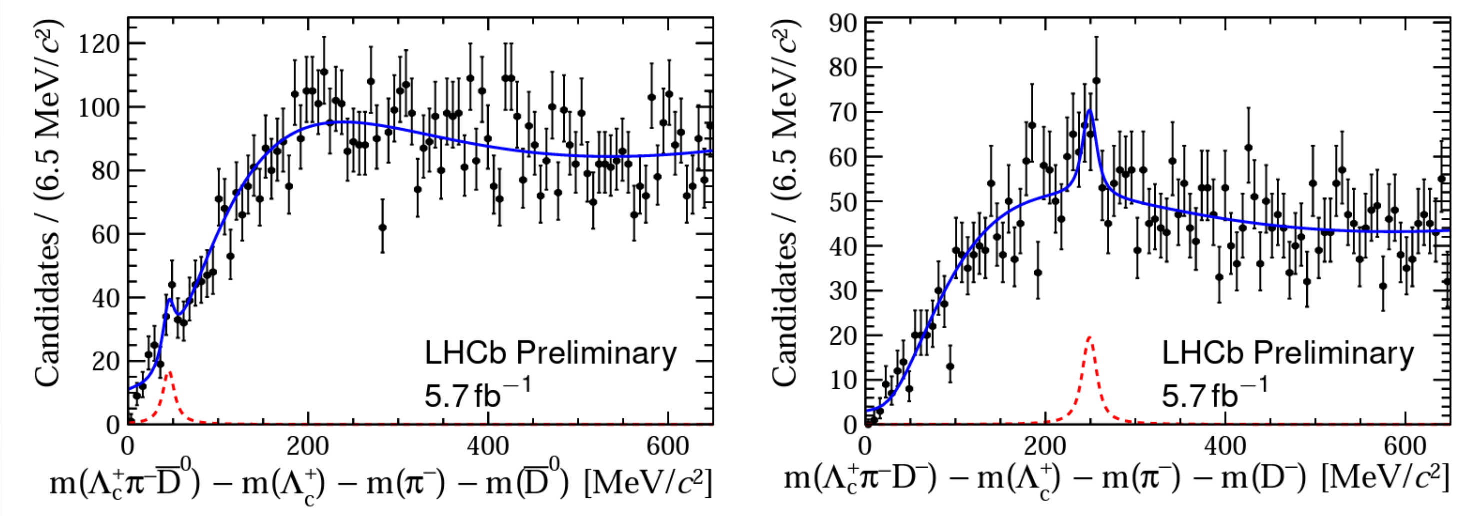


Search for Prompt Production of Pentaquarks in Open-Charm Hadrons

[LHCb-PAPER-2023-018 in preparation]

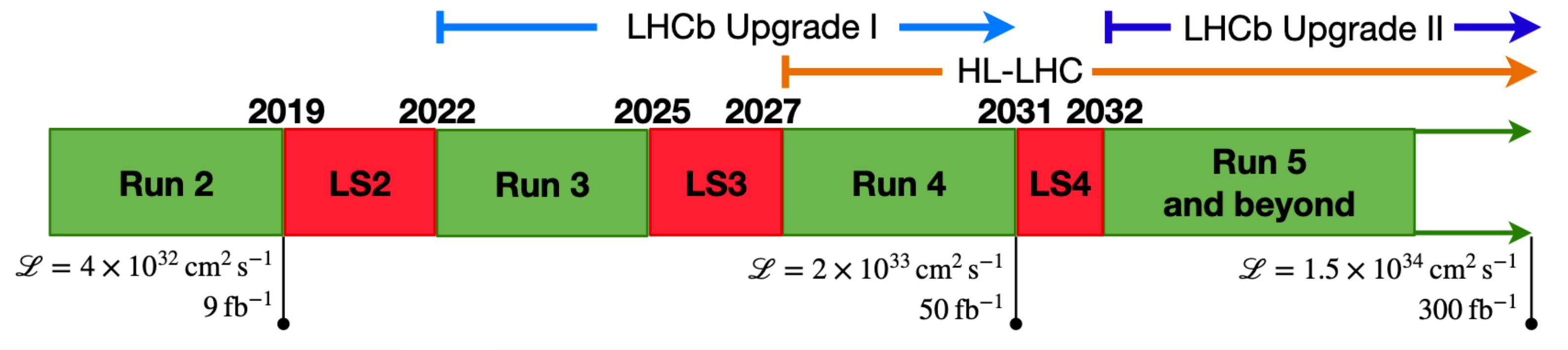
NEW

- Since no signal was seen (even for the known pentaquarks), upper limits (ULs) are set in each mode
- Highest global significances are in $\Lambda_c^+ D^0 \pi^-$ and $\Lambda_c^+ D^- \pi^-$ modes.



Paper in preparation

Summary



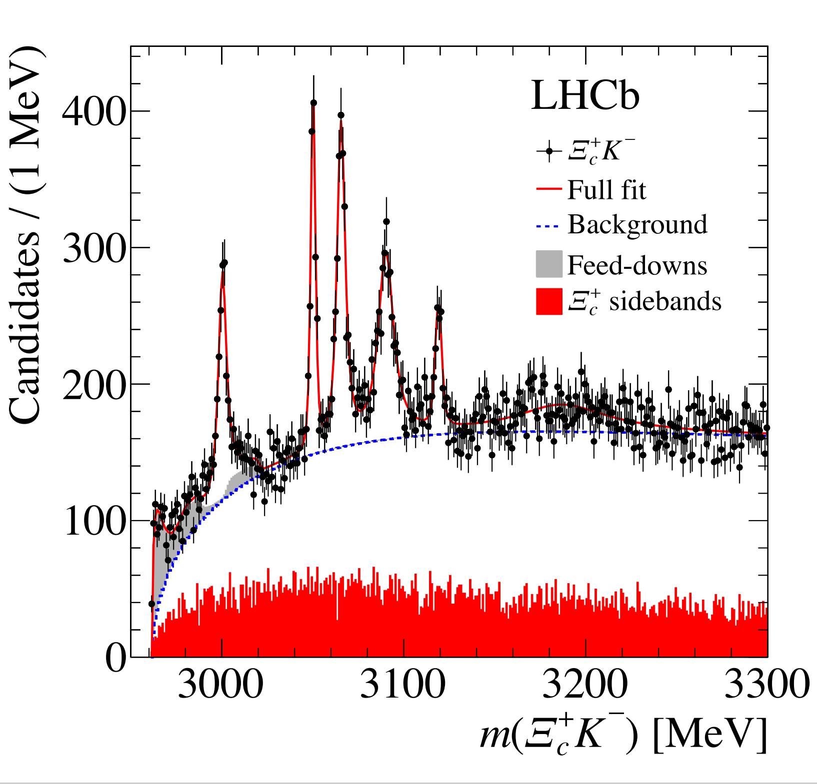
- Unprecedented samples of $D_{(s)}$, Λ_c, $\Xi_c \rightarrow$ hhh , where h = p, K, π. Spectroscopy of light hadrons by amplitude analyses with high precision. Which extend is the isobar model valid at?
- Measurement of quantum number of charmed hadrons from b-hadron decays→ Probe of internal degree of freedom. Is the diquark a building block of hadrons?
- Observation of Ξ_{cc}^+ and Ω_{cc}^+ with Run 3 data? What about T_{bc}?
- Nature of $\chi_{c1}(3872)$ still uncertain after 20 years! What is missing?
- Search for patterns in spectroscopy: e.g. exotic flavour multiplets

Back-up slides

Five New Excited Ω^0_c States!

[LHCb: PRL 118 (2017) 182001]

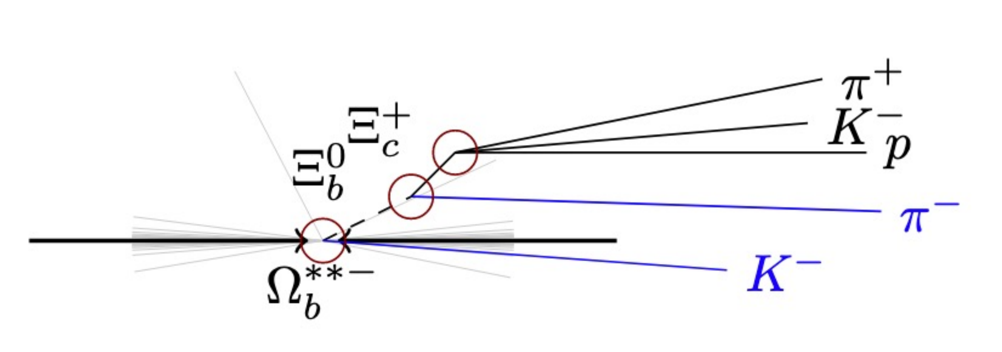
- Observation of **5** new excited Ω_c states! Two of them extremely narrow
- Comprehensive explanation of all peaks challenges our current knowledge. Are they orbitally excited (L=1) states? Or radially excitations? Or pentaquarks?



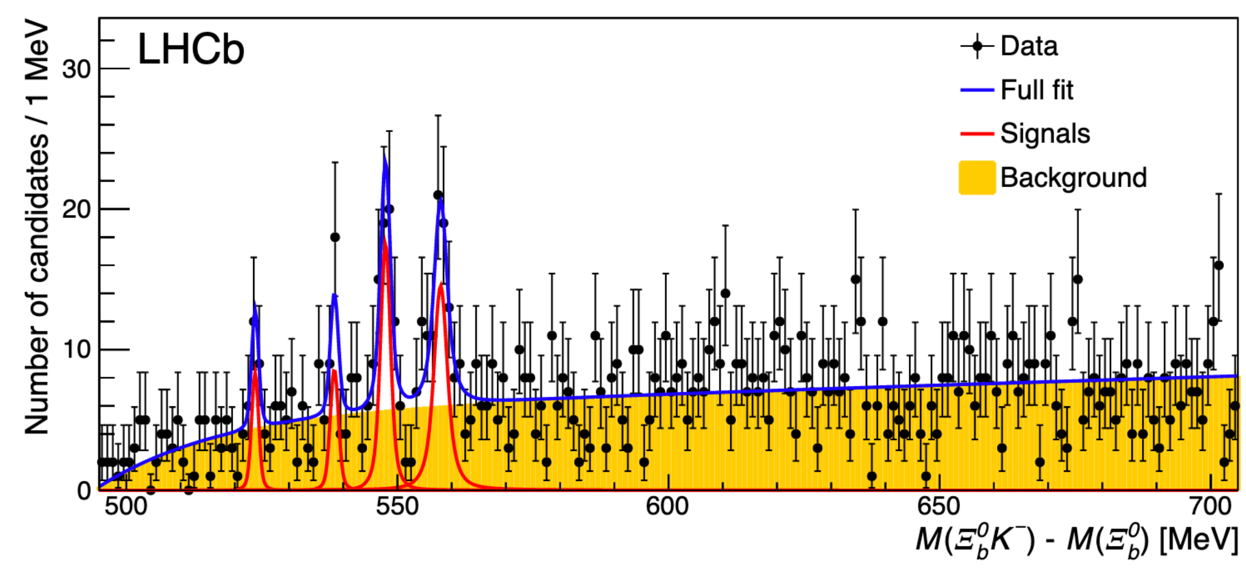
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		$< 1.2\,\mathrm{MeV}, 95\%$ CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$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

Observation of $\Omega_b^{**-} \rightarrow \Xi_b^0 K^-$

[PRL 124 (2020) 082002]



Observation of 4 narrow Ω_b^{**-} with significance > 3σ



The new states are

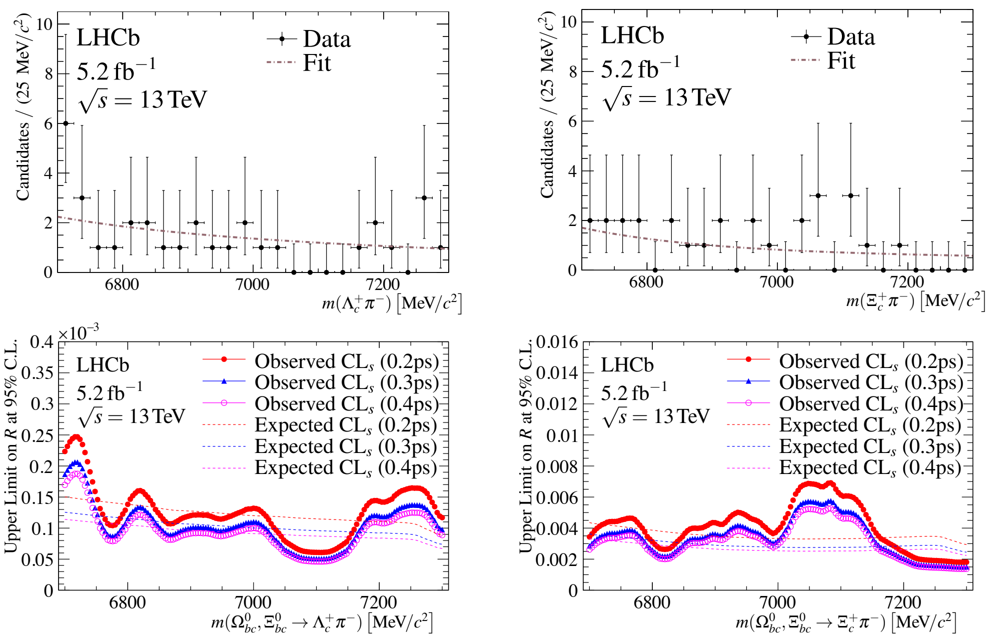
$\Omega_b(6315)^-$
$\Omega_b(6330)^-$
$\Omega_b(6340)^-$
$\Omega_b(6350)^-$

Search for Ξ_{bc}^0, Ξ_{bc}^+, Ω_{bc}^0

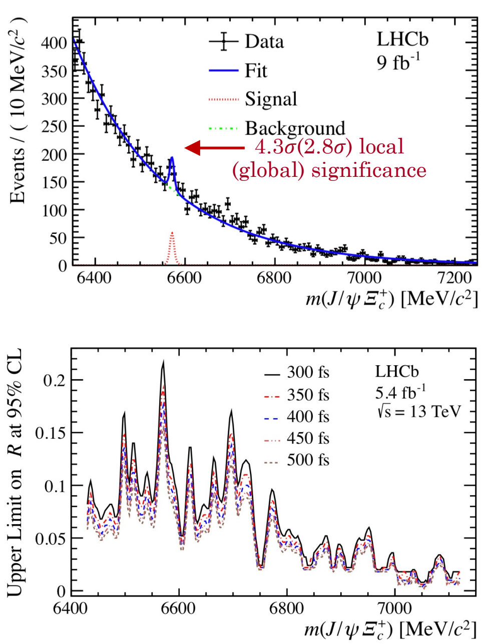
[Chin. Phys. C 45 (2021) 093002, LHCb-PAPER-2022-005 (in preparation)]

- No obvious signals
- Search for (1) Ω_{bc}^0/ $\Xi_{bc}^0 \rightarrow \Lambda_c^+(\Xi_c^+)\pi^-$ & (2) $\Xi_{bc}^+ \rightarrow J/\psi\ \Xi_c^+$
- UL as function of m and τ on the production relative to (1) Λ_b^0/ $\Xi_b^0 \rightarrow \Lambda_c^+(\Xi_c^+)\pi^-$ & (2) $B_c^+ \rightarrow J/\psi\ D_s^+$

$\Omega_{bc}^0/\Xi_{bc}^0 \rightarrow \Lambda_c^+(\Xi_c^+)\pi^-$

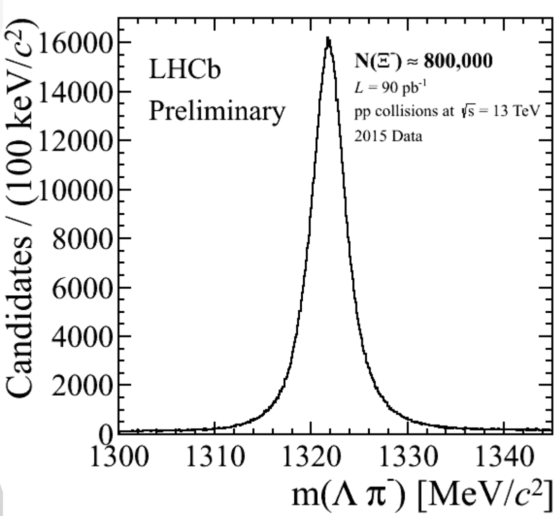


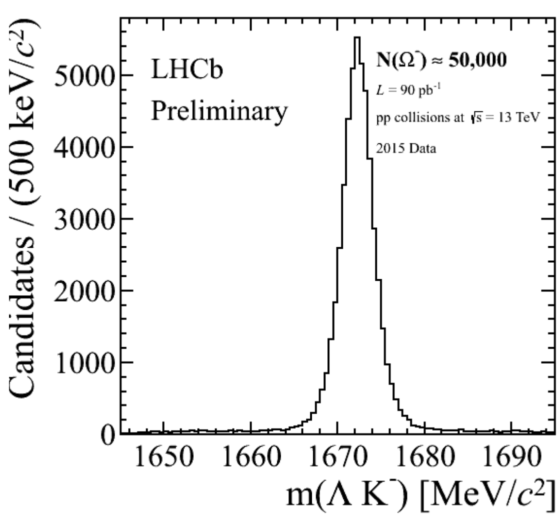
$\Xi_{bc}^+ \rightarrow J/\psi\Xi_c^+$



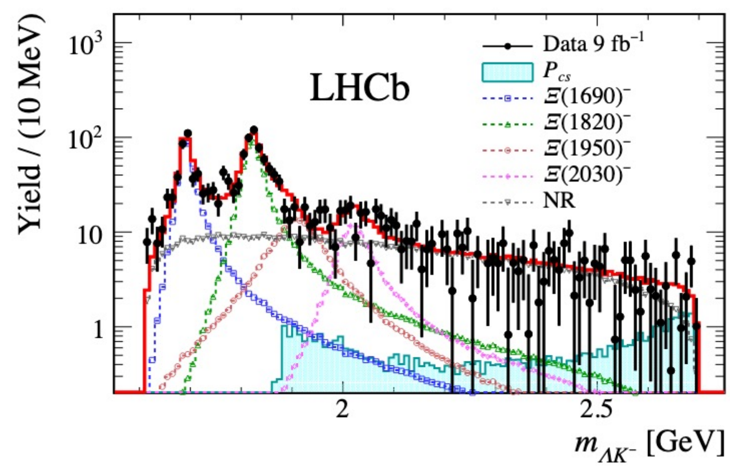
LIGHT SPECTROSCOPY

- LHCb can contribute to study the spectroscopy of the light sector in prompt production and from b-hadron decays
- Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi \Lambda K^-$ decay





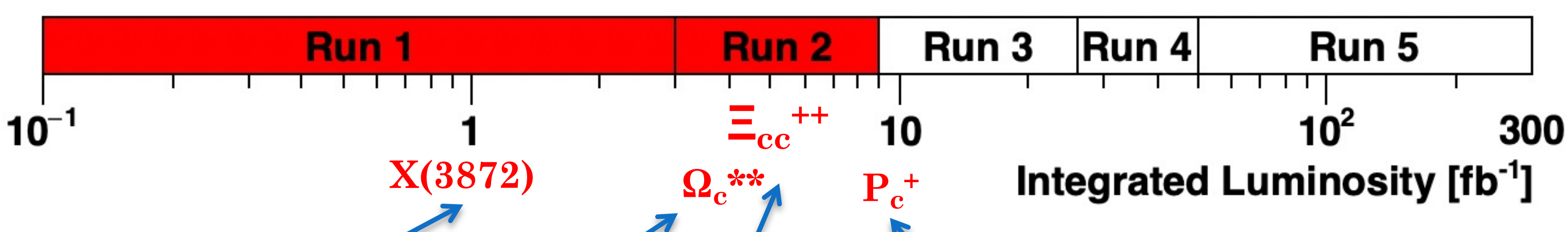
[LHCb: arXiv:2012.10380]

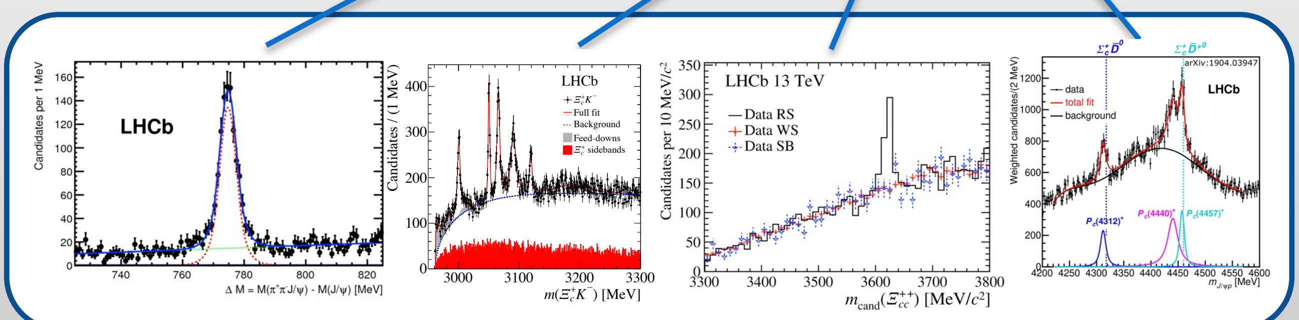


SUMMARY II

The large data set collected in the HL-LHC era, together with an upgraded detector, will boost sensitivity in searches for heavy states with small production cross sections and/or small decay rates

Predictions are always complicated…even more when concerning unknown states!





…to be continued