Review of hadron spectroscopy @ LHCb

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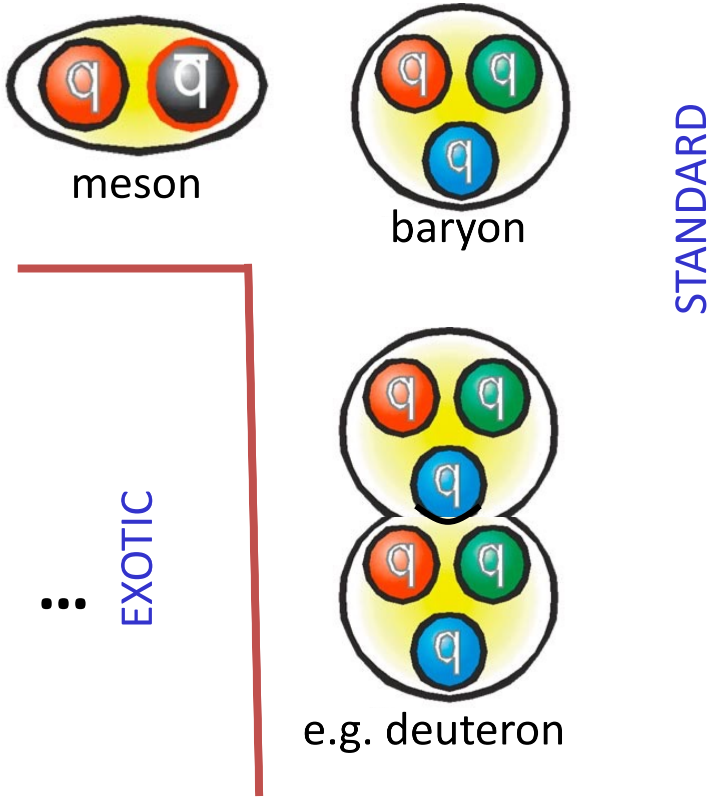
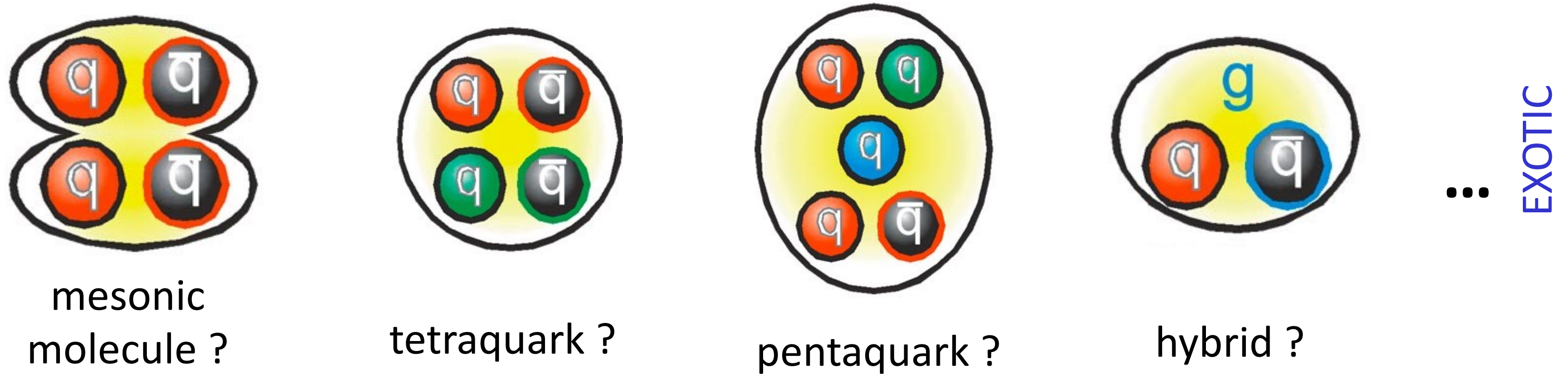
Introduction

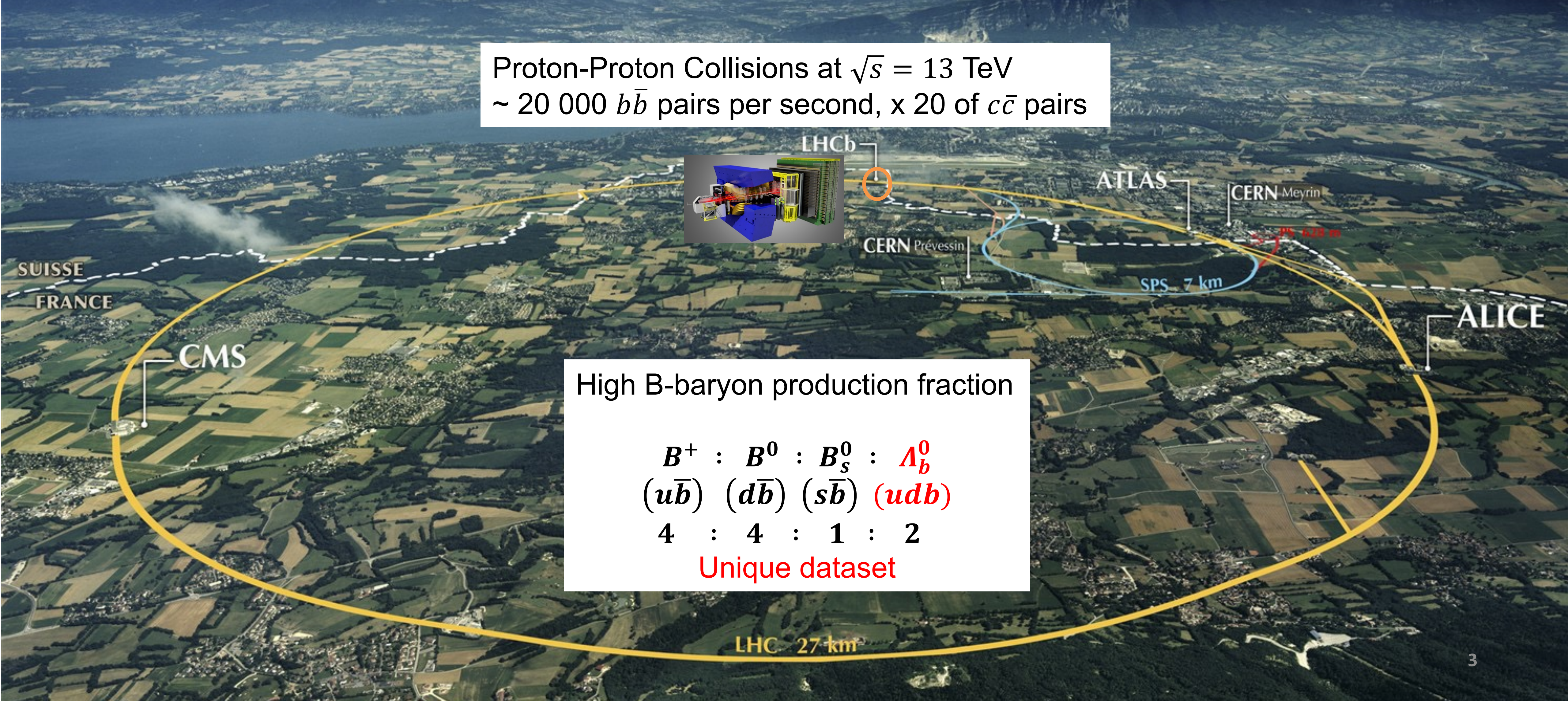
- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
  - e.g. lattice QCD, diquark model, potential model …
- Exotic hadrons provide unique probe to QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence





The LHC as a Beauty and Charm factory

Proton-Proton Collisions at $\sqrt{s} = 13$ TeV
~ 20 000 $b\bar{b}$ pairs per second, x 20 of $c\bar{c}$ pairs



High B-baryon production fraction

$$\begin{array}{ccccccc} B^+ & : & B^0 & : & B_s^0 & : & \Lambda_b^0 \\ (u\bar{b}) & & (d\bar{b}) & & (s\bar{b}) & & (udb) \\ 4 & : & 4 & : & 1 & : & 2 \end{array}$$

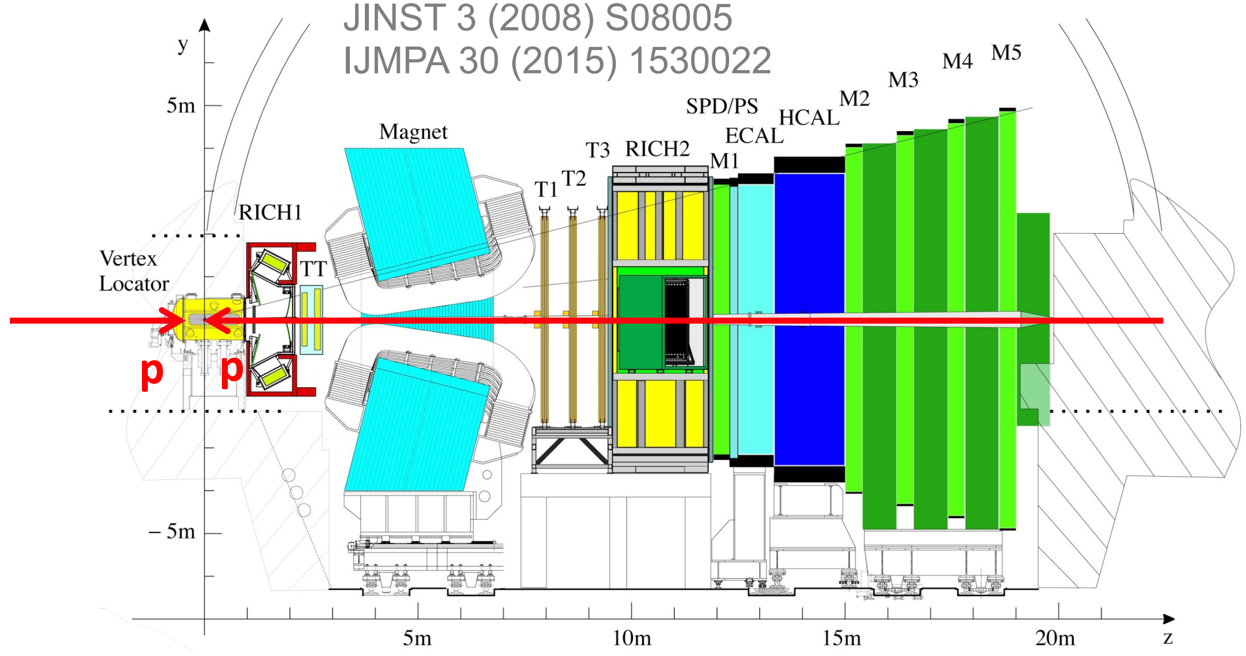
Unique dataset

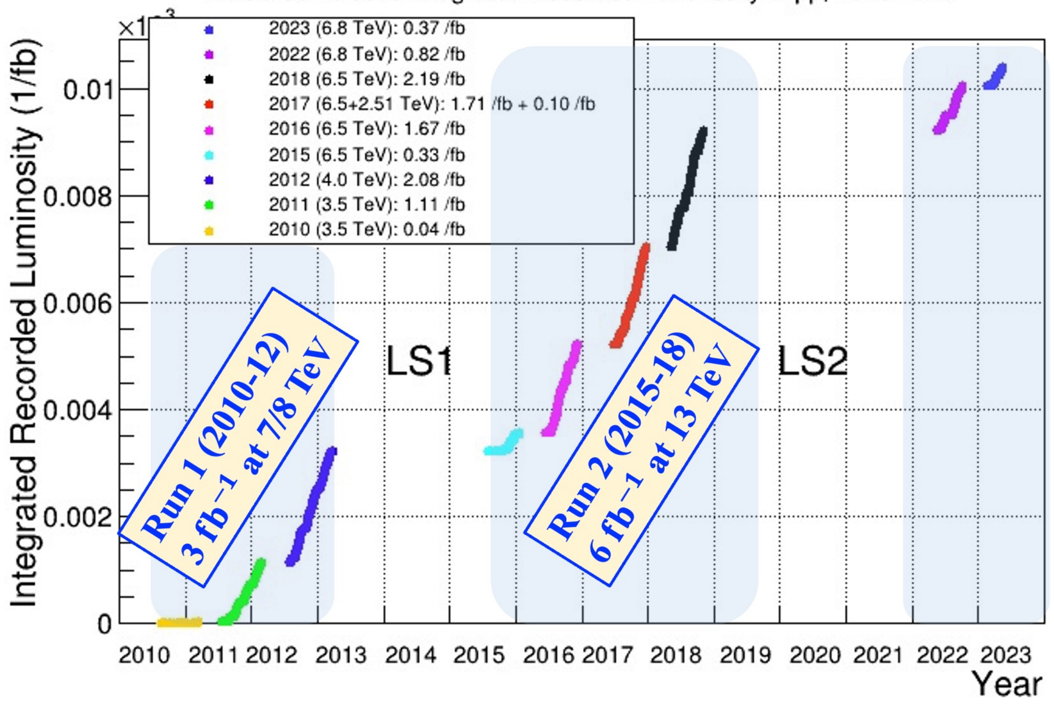
The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - >10^4 $\times$ larger b production rate than the B factories @ Υ(4S)
  - Access to all b-hadrons: B^+, B^0, B_s^0, B_c^+, b-baryons
- Can also study hadron spectroscopy and exotic states
- Acceptance optimised for forward $b\bar{b}$ production

➢ All results based on full or part of run-1 and run-2 datasets

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

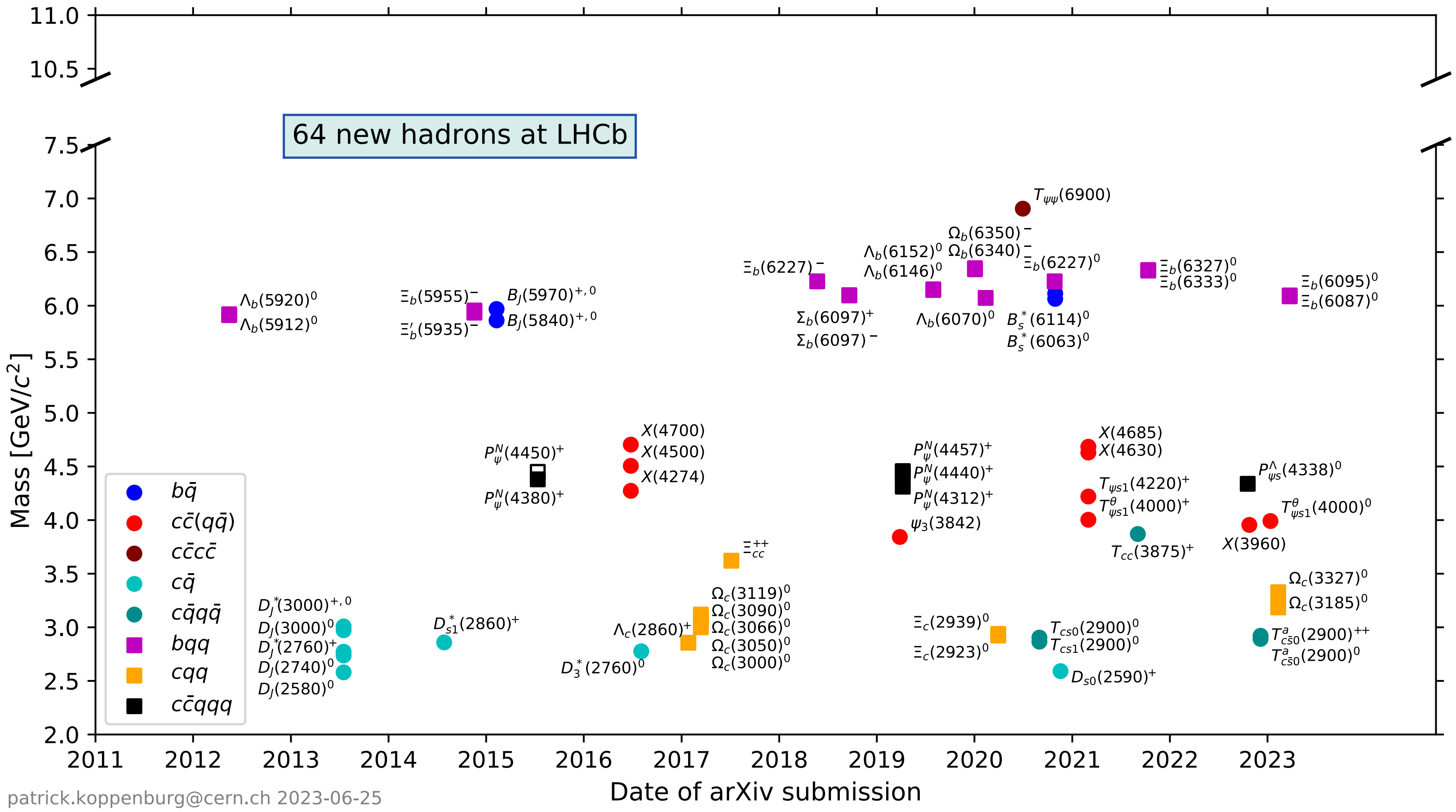




New particles in a glance

- 64 new hadrons discovered by LHCb!

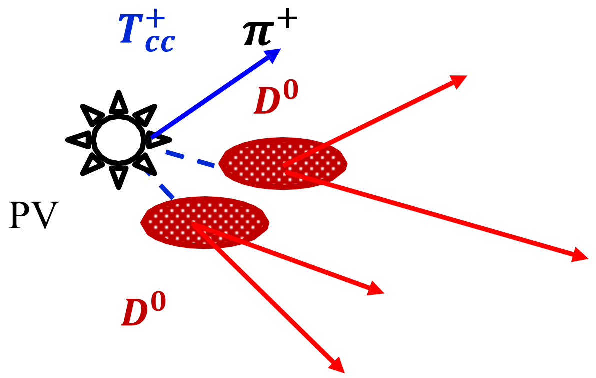
https://www.nikhef.nl/~pkoppenb/particles.html



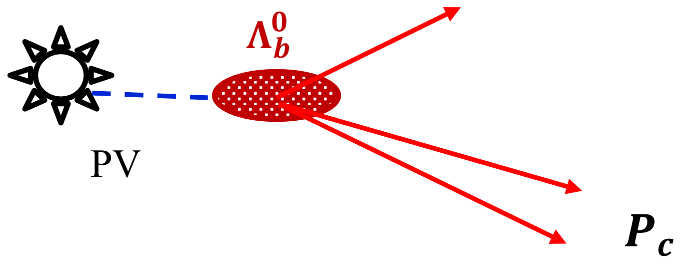
Exotic hadron naming convention: arXiv:2206.15233

Two methods for spectroscopy

- Direct production in pp collisions
  - Combine a heavy flavour hadron with one or more light particles
  - Pros: High statistics, in principle can study all states
  - Cons: Large combinatorial background, hard to determine J^P



- Production by a heavier particle decay
  - Usually with amplitude analysis
  - Pros: Low background, Better determination of J^P
  - Cons: Low cross-section, limited mass range



Selected topics

Conventional hadrons

- Singly-heavy baryons
- Doubly-charmed baryons

Exotic hadrons

- Hidden-charm tetraquarks
- Open (doubly)-charmed tetraquarks
- Hidden-charm pentaquarks

Singly-heavy baryons

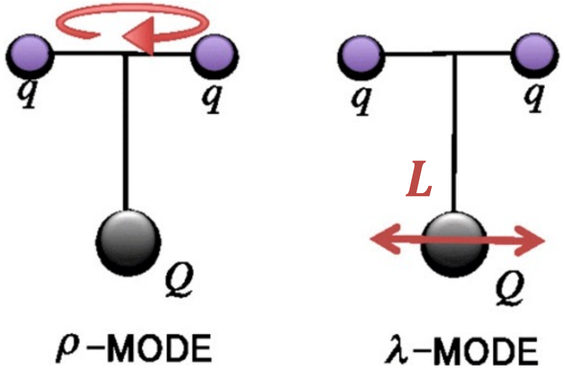
Singly-heavy baryons

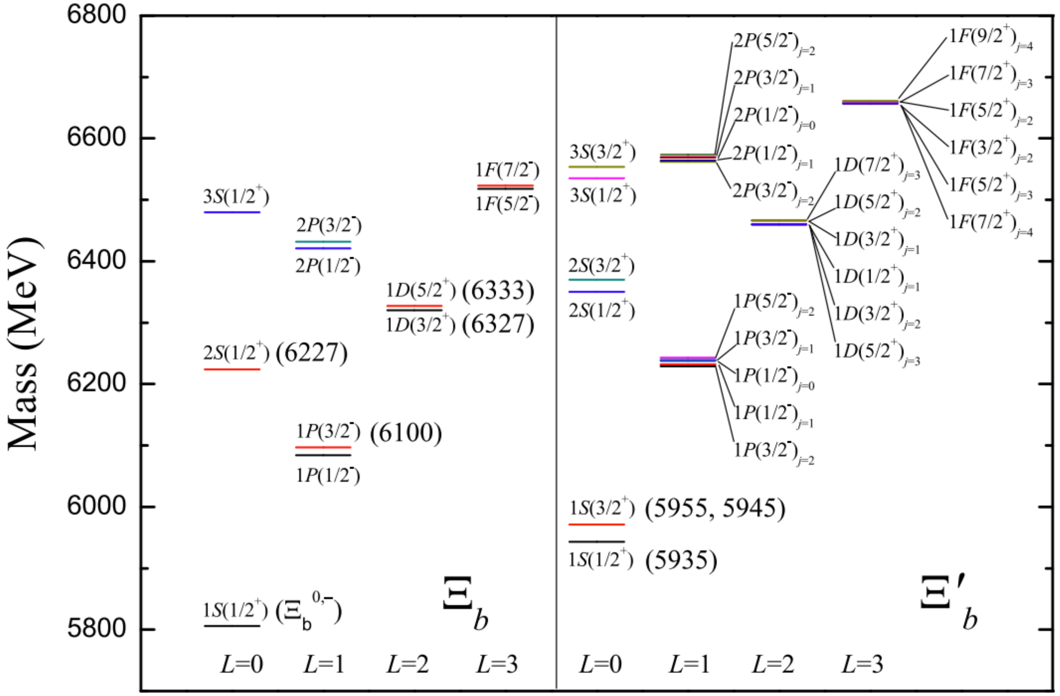
- Qqq baryons is well described by heavy quark-light diquark $Q[qq]$ model
  - ✓ λ-mode: can describe almost all observed states

Configuration	$J^P_{[qq]} = 0^+$	$J^P_{[qq]} = 1^+$
Naming	Λ_Q, Ξ_Q	$\Sigma_Q, \Xi'_Q, \Omega_Q$

  - ✓ ρ-mode: no firm assignment yet

[PRD 92 (2015) 114029]





Chinese Phys. C **47** (2023) 073105

Charmed and bottom baryons

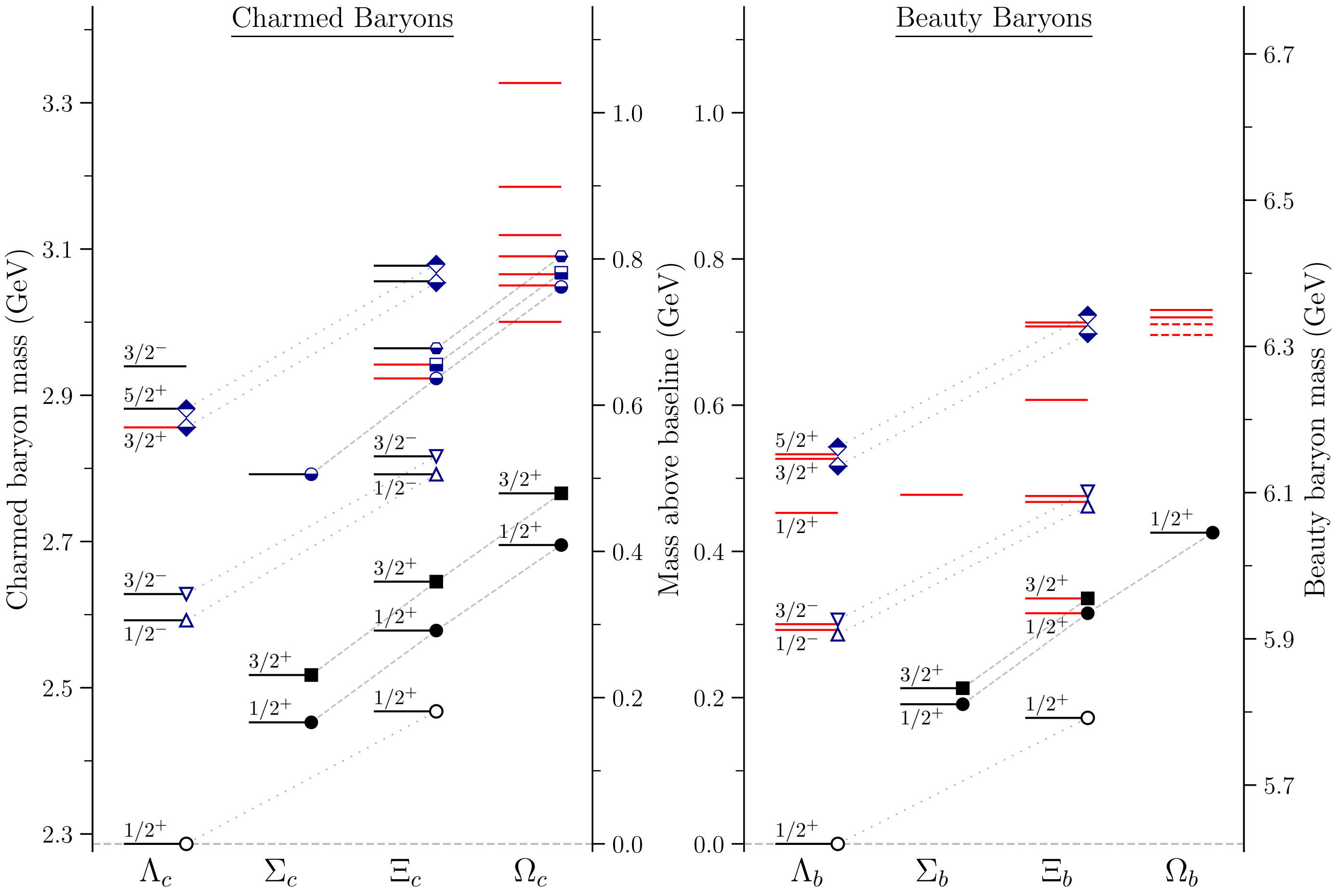
- LHCb has made great contributions to heavy baryon spectroscopy
  - Bottom are very similar to charmed baryons
  - Equal spacing rule predicted mass of Ω [Gell-Mann, Okubo], still holds for the excited states, implies same multiplets

$$m(\Omega_c(2770)^0) - m(\Xi_c(2645)^0) \simeq m(\Xi_c(2645)^0) - m(\Sigma_c(2520)^0) \simeq 125\,\text{MeV}.$$

$$m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) \simeq 125\,\text{MeV},$$
$$m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) \simeq 125\,\text{MeV},$$
$$m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) \simeq 125\,\text{MeV}.$$

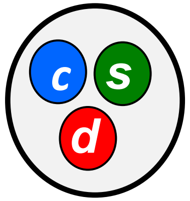
LHCb

Figure modified from PDG'20



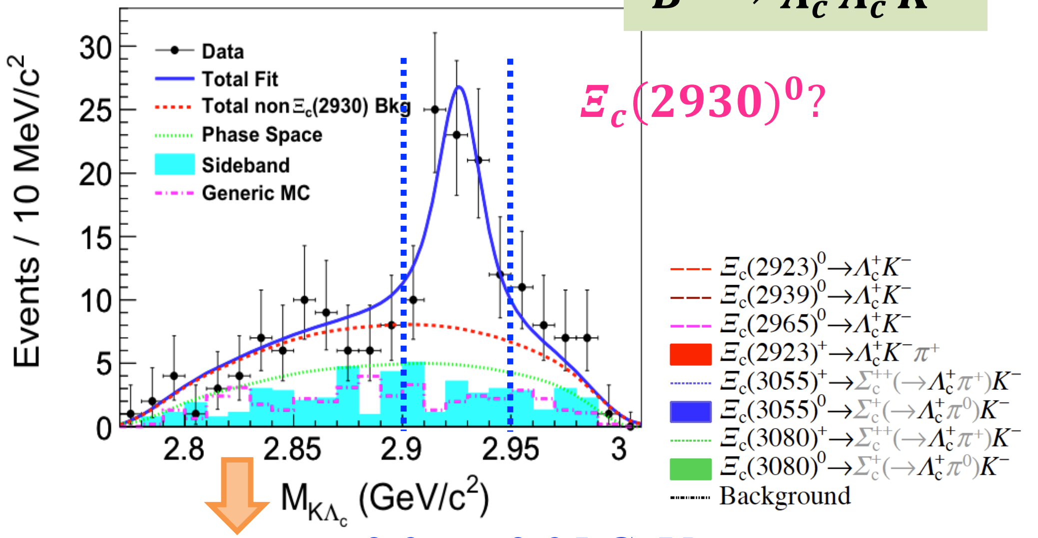
Ξ_c^{**0} states at 2.9 GeV

- Large statistics data shows Belle's $\Xi_c(2930)$ is a composite of two narrow Ξ_c^{**}'s
  - $\Xi_c(2923)^0$
  - $\Xi_c(2939)^0$
  - confirmed by LHCb's *B* decay sample
- A third peak $\Xi_c(2965)^0$ is also seen

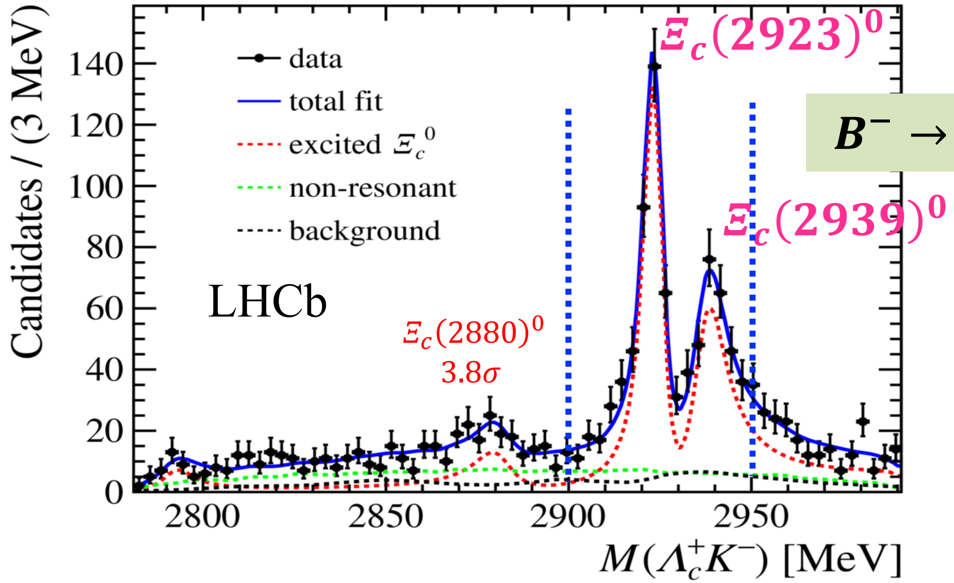


[Belle, EPJC 78 (2018) 3, 252]

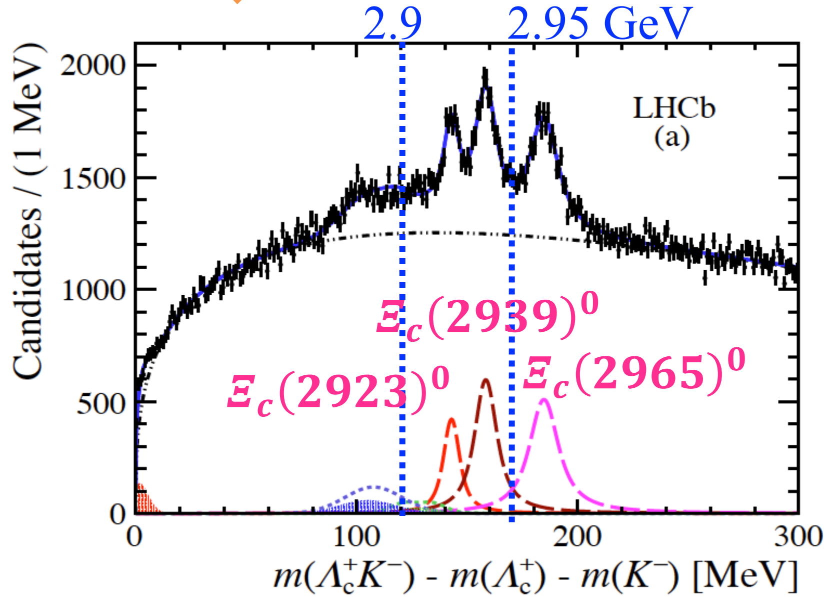
$B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$



[PRD 108 (2023) 012020]



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



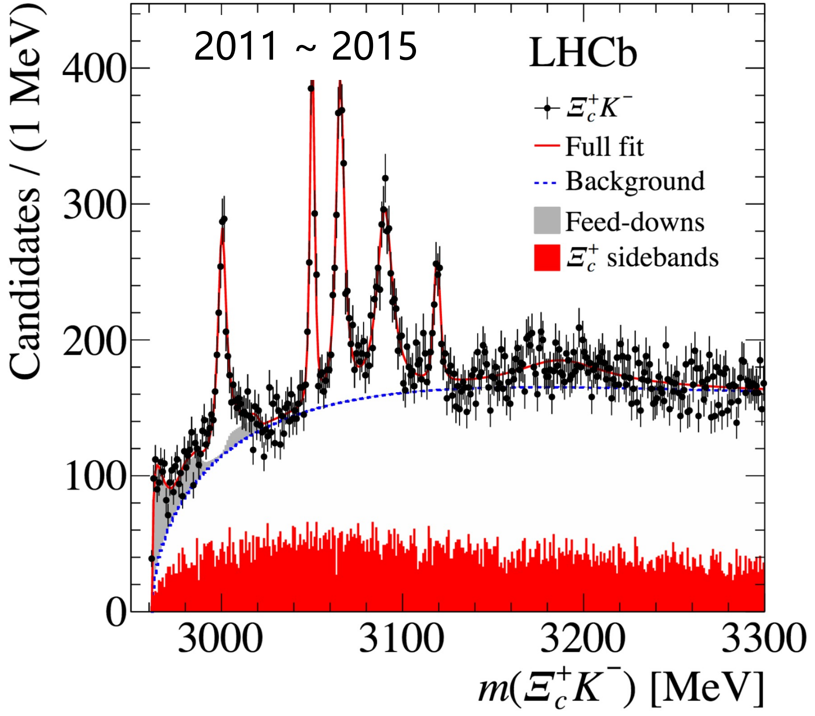
[PRL 124 (2020) 222001]

New Ω_c states in $\Xi_c^+ K^-$ final state

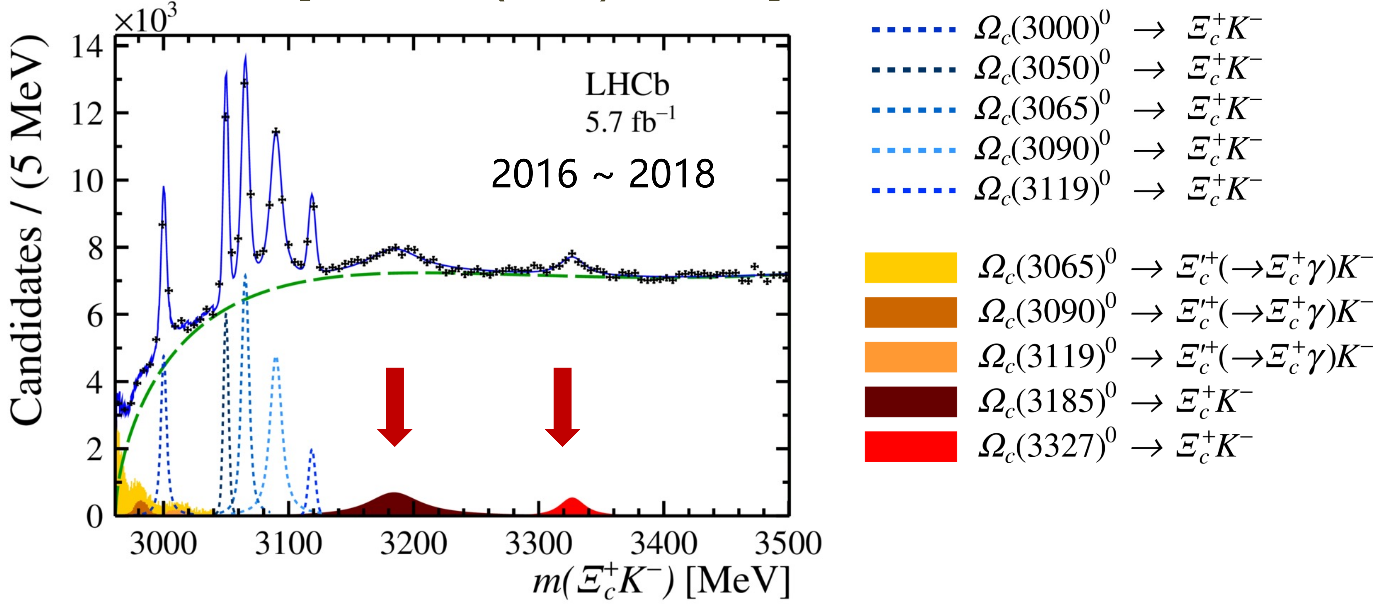
- LHCb observed 5 narrow states in 2017
- Belle confirmed the first four states
- Two new states observed with full Run 1+2 data

Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07 \,^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23 \,^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04 \,^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17 \,^{+0.64}_{-0.72}$
		$< 1.8\,\text{MeV}, 95\%$ C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06 \,^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20 \,^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11 \,^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44 \,^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12 \,^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63 \,^{+0.90}_{-1.05}$
		$< 2.5\,\text{MeV}, 95\%$ C.L.
new → $\Omega_c(3185)^0$	$3185.1 \pm 1.7 \,^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7 \,^{+10}_{-20}$
new → $\Omega_c(3327)^0$	$3327.1 \pm 1.2 \,^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5 \,^{+13}_{-1}$

[PRL 118 (2017) 182001]



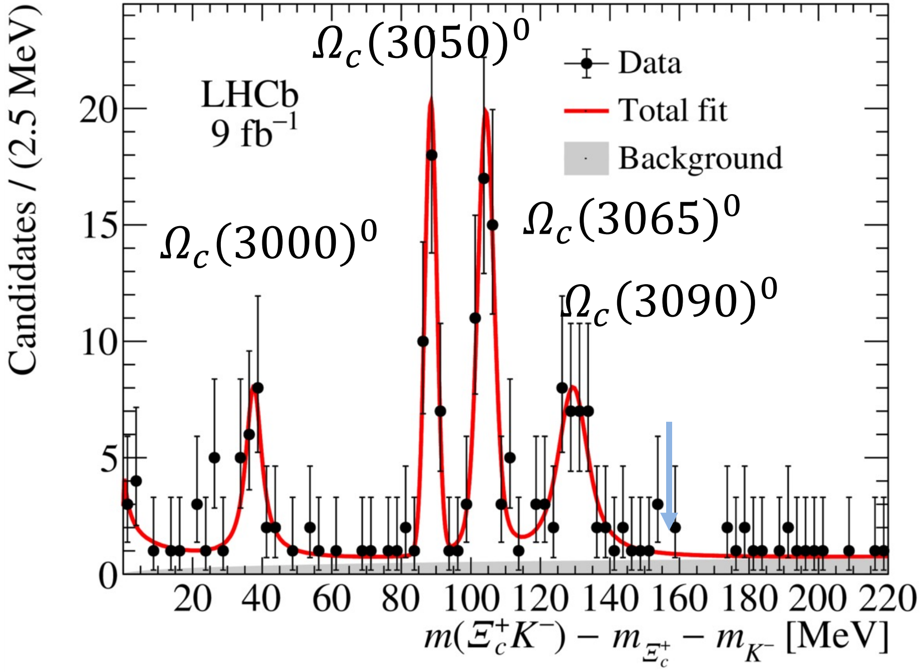
[PRL 131 (2023) 131902]



Ω_c states from $\Omega_b^- \to \Xi_c^+ K^- \pi^-$

PRD 104 (2021) L091102

- J^P is important to interpret these states
- $\sim 240\ \Omega_b^-$ signals obtained
- First four Ω_c states are observed
- Spin hypothesis are tested



The order of J=1/2 1/2 3/2 3/2 are rejected at 3.5σ

State	Observable	Measurement
Ω_b^-	m	$6044.3 \pm 1.2 \pm 1.1\,^{+0.19}_{-0.22}$ MeV
	$\mathcal{R}$	$1.35 \pm 0.11 \pm 0.05$
Threshold structure	Significance	$4.3\,\sigma$
$\Omega_c(3000)^0$	Significance	$6.2\,\sigma$
	ΔM	$37.6 \pm 0.9 \pm 0.9$ MeV
	m	$2999.2 \pm 0.9 \pm 0.9\,^{+0.19}_{-0.22}$ MeV
	Γ	$4.8 \pm 2.1 \pm 2.5$ MeV
	$\mathcal{P}$	$0.11 \pm 0.02 \pm 0.04$
	J rejection	$0.5\,\sigma\,(J=1/2), 0.8\,\sigma\,(J=3/2), 0.4\,\sigma\,(J=5/2)$
$\Omega_c(3050)^0$	Significance	$9.9\,\sigma$
	ΔM	$88.5 \pm 0.3 \pm 0.2$ MeV
	m	$3050.1 \pm 0.3 \pm 0.2\,^{+0.19}_{-0.22}$ MeV
	Γ	< 1.6 MeV, 95% CL
	$\mathcal{P}$	$0.15 \pm 0.02 \pm 0.02$
	J rejection	$2.2\,\sigma\,(J=1/2), 0.1\,\sigma\,(J=3/2), 1.2\,\sigma\,(J=5/2)$
$\Omega_c(3065)^0$	Significance	$11.9\,\sigma$
	ΔM	$104.3 \pm 0.4 \pm 0.4$ MeV
	m	$3065.9 \pm 0.4 \pm 0.4\,^{+0.19}_{-0.22}$ MeV
	Γ	$1.7 \pm 1.0 \pm 0.5$ MeV
	$\mathcal{P}$	$0.23 \pm 0.02 \pm 0.02$
	J rejection	$3.6\,\sigma\,(J=1/2), 0.6\,\sigma\,(J=3/2), 1.2\,\sigma\,(J=5/2)$
$\Omega_c(3090)^0$	Significance	$7.8\,\sigma$
	ΔM	$129.4 \pm 1.1 \pm 1.0$ MeV
	m	$3091.0 \pm 1.1 \pm 1.0\,^{+0.19}_{-0.22}$ MeV
	Γ	$7.4 \pm 3.1 \pm 2.8$ MeV
	$\mathcal{P}$	$0.19 \pm 0.02 \pm 0.04$
	J rejection	$0.3\,\sigma\,(J=1/2), 0.8\,\sigma\,(J=3/2), 0.5\,\sigma\,(J=5/2)$
$\Omega_c(3120)^0$	$\mathcal{P}$	< 0.03, 95% CL

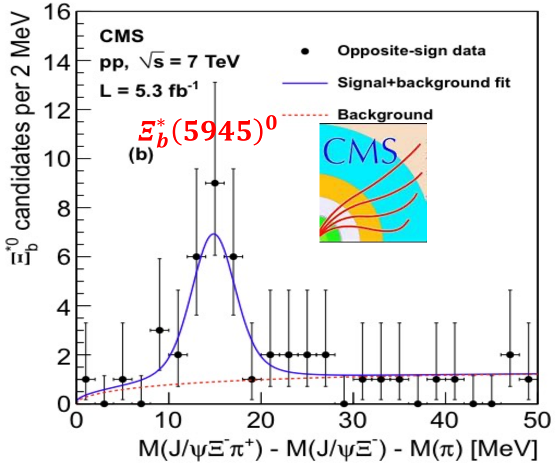
Ξ_b baryon spectroscopy

- Numbers of excited *b*-baryons have already been discovered
  - $\Xi_b^*(5945)^0 \to \Xi_b^- \pi^+$ [CMS'12]
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \to \Xi_b^0 \pi^-$ [LHCb'15]
  - $\Xi_b'^{\,0}$ not yet observed

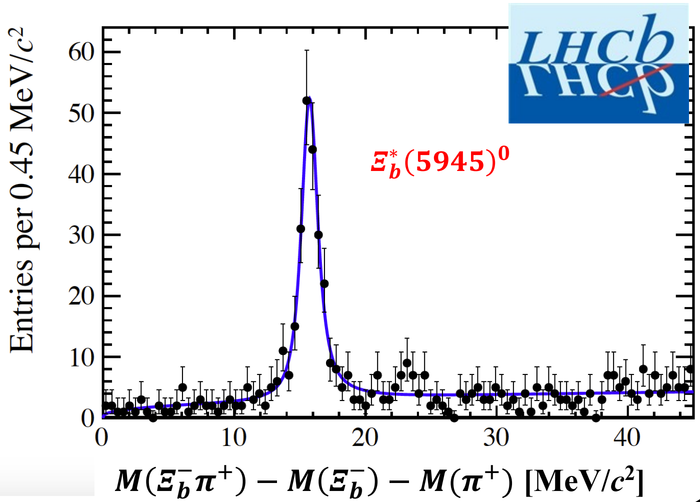
State	J^P	$b(sq)$
Ξ_b	$1/2^+$	$\uparrow(\uparrow\downarrow)$
Ξ_b'	$1/2^+$	$\downarrow(\uparrow\uparrow)$
Ξ_b^*	$3/2^+$	$\uparrow(\uparrow\uparrow)$

Neutral Ξ_b^*

PRL 108, 252002 (2012)

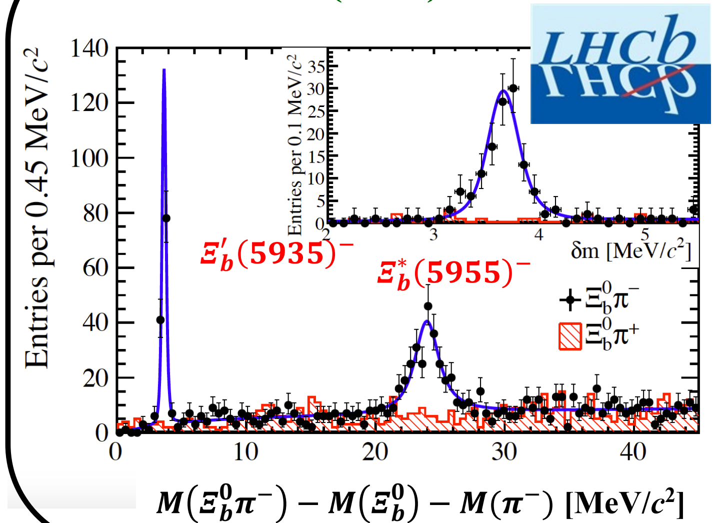


JHEP 05 (2016) 161



Charged $\Xi_b'^{(*)}$

PRL 114 (2015) 062004



New Ξ_b^{**} baryons

[PRL 128 (2022) 162001]

- Two new states observed in the combination of $\Lambda_b^0 K^- \pi^+$
- Consistent with 1D Ξ_b doublets

$$m_{\Xi_b(6327)^0} = 6327.28\,^{+0.23}_{-0.21}(\text{stat}) \pm 0.12(\text{syst}) \pm 0.24(m_{\Lambda_b^0})\ \text{MeV}$$

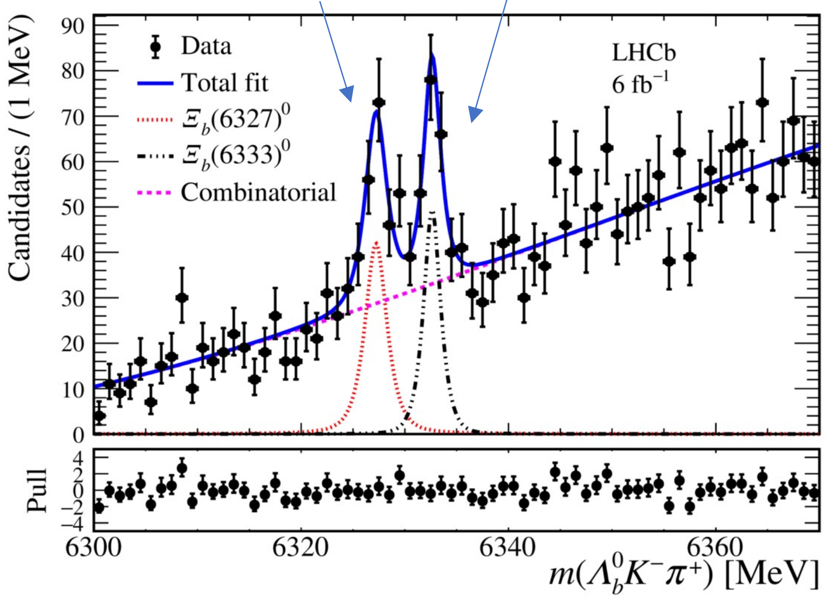
$$m_{\Xi_b(6333)^0} = 6332.69\,^{+0.17}_{-0.18}(\text{stat}) \pm 0.03(\text{syst}) \pm 0.22(m_{\Lambda_b^0})\ \text{MeV}$$

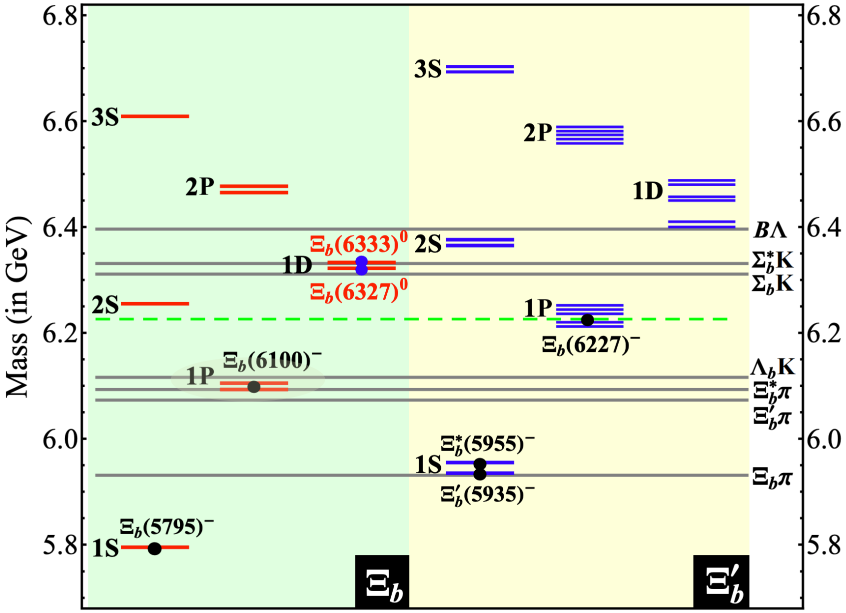
$$\Delta m \equiv m_{\Xi_b(6333)^0} - m_{\Xi_b(6327)^0} = 5.41\,^{+0.26}_{-0.27}(\text{stat}) \pm 0.12(\text{syst})\ \text{MeV}$$

$$\Gamma_{\Xi_b(6327)^0} < 2.20\ (2.56)\ \text{MeV at 90\% (95\%) CL}$$

$$\Gamma_{\Xi_b(6333)^0} < 1.60\ (1.92)\ \text{MeV at 90\% (95\%) CL}$$

$\Xi_b(6327)^0$ $\Xi_b(6333)^0$

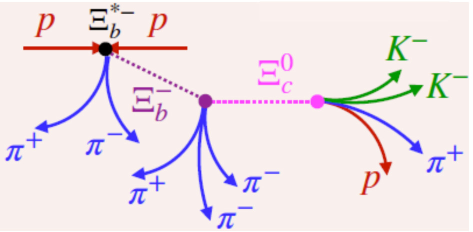




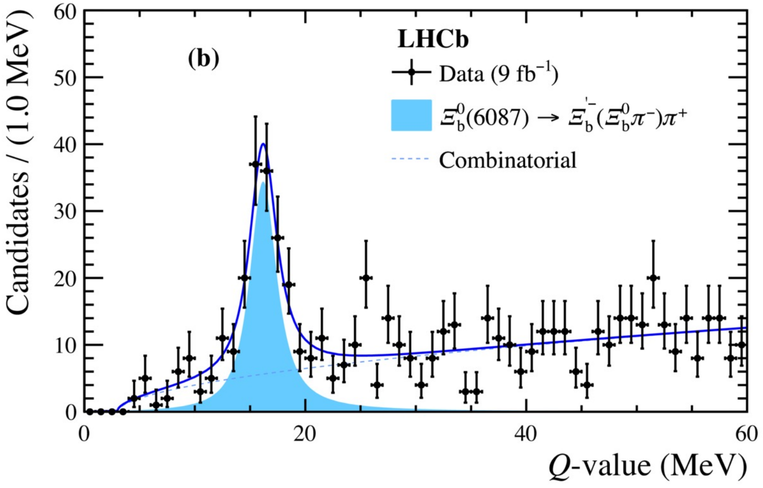
New Ξ_b^{**} baryons

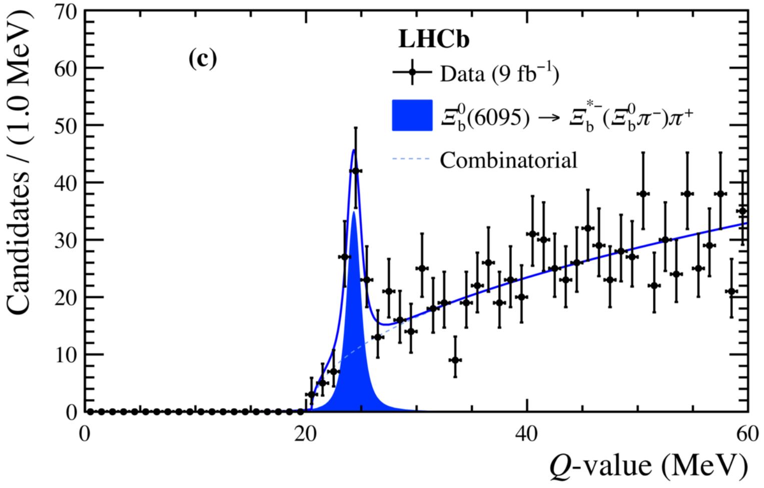
[PRL 131 (2023) 171901]

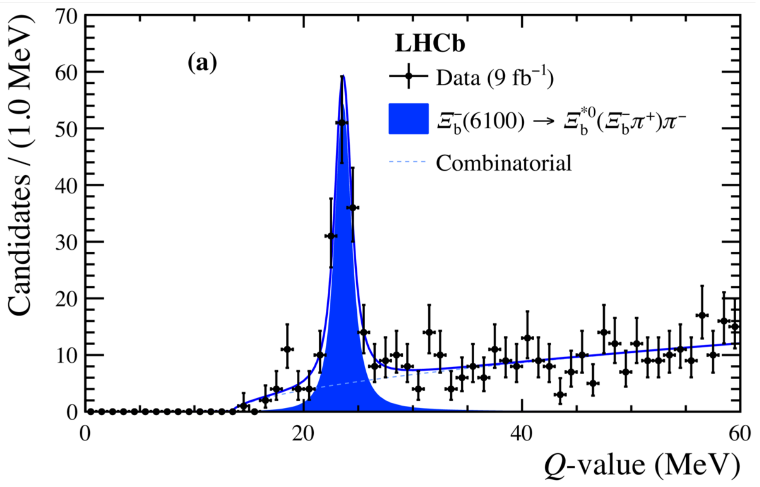
- Search for $\Xi_b^{**-/0}(bsq)$ in $\Xi_b^{-/0}\pi^+\pi^-$ final states
  - $\Xi_b^{-/0} \rightarrow \Xi_c^{0/+}\pi^-$ and $\Xi_c^{0/+}\pi^-\pi^+\pi^-$ (max. 9 tracks!)
- Observation of two new states:
  - $\Xi_b(6087)^0 \rightarrow \Xi_b'^-\pi^+ \rightarrow [\Xi_b^0\pi^-]\pi^+$
  - $\Xi_b(6095)^0 \rightarrow \Xi_b^{*-}\pi^+ \rightarrow [\Xi_b^0\pi^-]\pi^+$
- Confirmation of one state observed by CMS:
  - $\Xi_b(6100)^- \rightarrow \Xi_b^{*0}\pi^- \rightarrow [\Xi_b^-\pi^+]\pi^-$ [PRL 126 (2021) 252003]



	Value [MeV]	
$Q_0\ (\Xi_b^-(6100))$	$23.60 \pm 0.11 \pm 0.02$	Confirmation
$\Gamma\ (\Xi_b^-(6100))$	$0.94 \pm 0.30 \pm 0.08$	
$m_0\ (\Xi_b^-(6100))$	$6099.74 \pm 0.11 \pm 0.02\ \pm 0.6\ (\Xi_b^-)$	
$Q_0\ (\Xi_b^0(6087))$	$16.20 \pm 0.20 \pm 0.06$	
$\Gamma\ (\Xi_b^0(6087))$	$2.43 \pm 0.51 \pm 0.10$	
$m_0\ (\Xi_b^0(6087))$	$6087.24 \pm 0.20 \pm 0.06\ \pm 0.5\ (\Xi_b^0)$	
$Q_0\ (\Xi_b^0(6095))$	$24.32 \pm 0.15 \pm 0.03$	1st Observ
$\Gamma\ (\Xi_b^0(6095))$	$0.50 \pm 0.33 \pm 0.11$	
$m_0\ (\Xi_b^0(6095))$	$6095.36 \pm 0.15 \pm 0.03\ \pm 0.5\ (\Xi_b^0)$	
$Q_0\ (\Xi_b^{*0})$	$15.80 \pm 0.02 \pm 0.01$	
$\Gamma\ (\Xi_b^{*0})$	$0.87 \pm 0.06 \pm 0.05$	
$m_0\ (\Xi_b^{*0})$	$5952.37 \pm 0.02 \pm 0.01\ \pm 0.6\ (\Xi_b^-)$	
$Q_0\ (\Xi_b'^-)$	$3.66 \pm 0.01 \pm 0.00$	
$\Gamma\ (\Xi_b'^-)$	$0.03 \pm 0.01 \pm 0.03$	Improvements
$m_0\ (\Xi_b'^-)$	$5935.13 \pm 0.01 \pm 0.00\ \pm 0.5\ (\Xi_b^0)$	
$Q_0\ (\Xi_b^{*-})$	$24.27 \pm 0.03 \pm 0.01$	
$\Gamma\ (\Xi_b^{*-})$	$1.43 \pm 0.08 \pm 0.08$	
$m_0\ (\Xi_b^{*-})$	$5955.74 \pm 0.03 \pm 0.01\ \pm 0.5\ (\Xi_b^0)$	







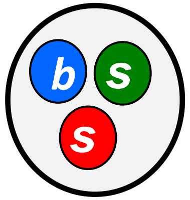
Observation of Ω_b^{**-}

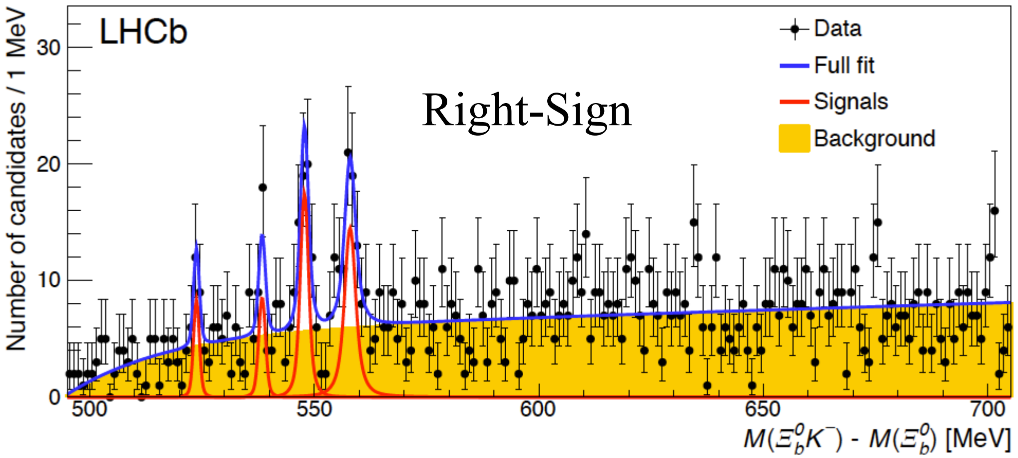
[PRL 124 (2020) 082002]

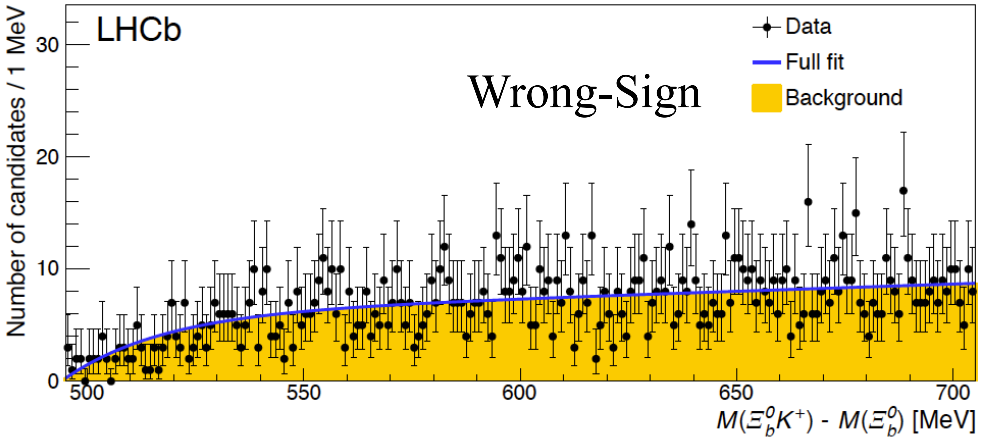
- $\Omega_b^{**-} \to \Xi_b^0 K^-$; $\Xi_b^0 \to \Xi_c^+ \pi^-$; $\Xi_c^+ \to pK^-\pi^+$ is reconstructed
- 4 peaks are seen, the last two have global significance > 5σ

Mass splitting 10-15 MeV

State	Mass [MeV]	Width [MeV] (90% UL)	N_{sig}	Local significance	Global significance
$\Omega_b(6316)^-$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	<2.8	15^{+6}_{-5}	3.6	2.1
$\Omega_b(6330)^-$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	<3.1	18^{+6}_{-5}	3.7	2.6
$\Omega_b(6340)^-$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	<1.5	47^{+11}_{-10}	**7.2**	**6.7**
$\Omega_b(6350)^-$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	<2.8 $1.4^{+1.0}_{-0.8} \pm 0.1$	57^{+14}_{-13}	**7.0**	**6.2**







Doubly-charmed baryons

Ξ_{cc}^{++} discovery

[PRL 119 (2017) 112001]

Selected for a Viewpoint in *Physics*
PRL **119,** 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

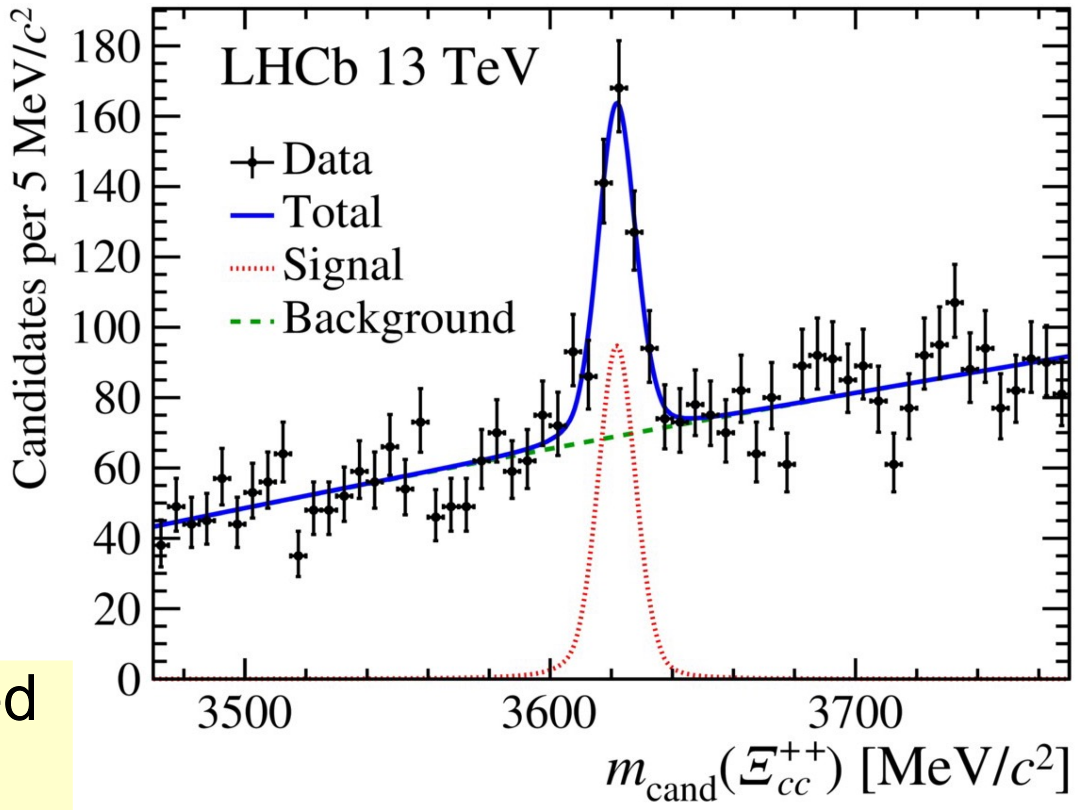
Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.**
(LHCb Collaboration)

(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})\ \text{MeV}/c^2$, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $1.7\ \text{fb}^{-1}$, and confirmed in an additional sample of data collected at 8 TeV.

DOI: 10.1103/PhysRevLett.119.112001



First doubly heavy hadron (unarguably) observed

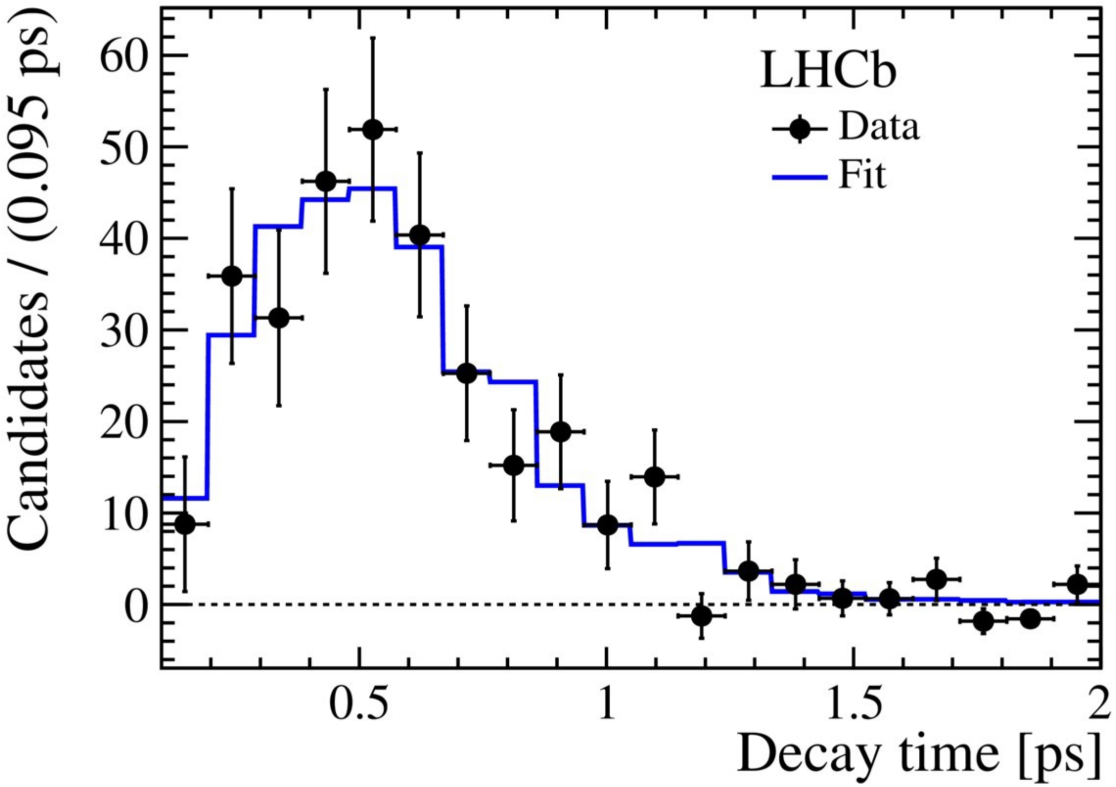
Discovery channel: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$

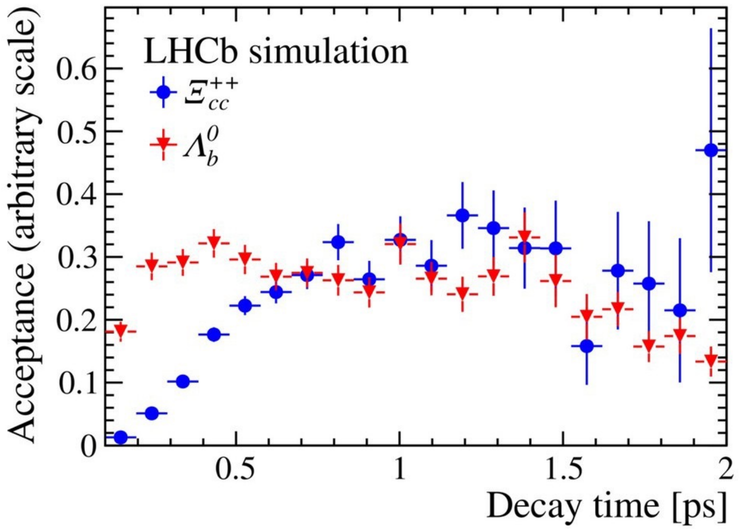
Subsequently seen also in $\Xi_c^{(\prime)+}\pi^+$ decays

First (so far only) weakly decaying hadron discovered at LHC

Lifetime measurment

PRL 121 (2018) 052002





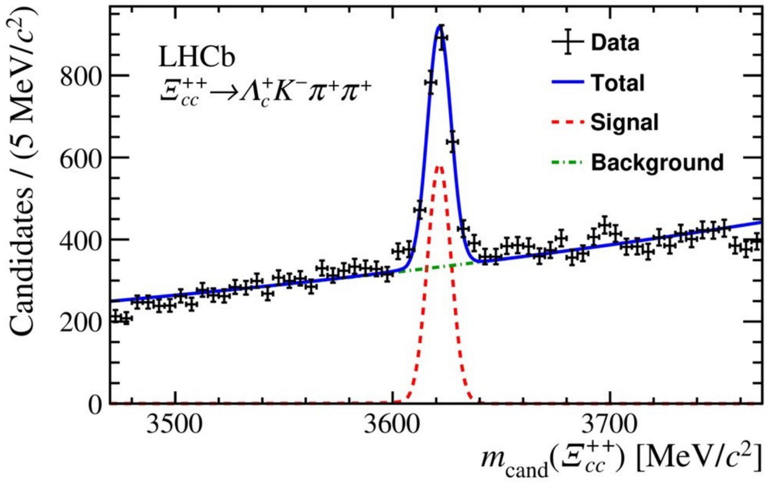
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ channel

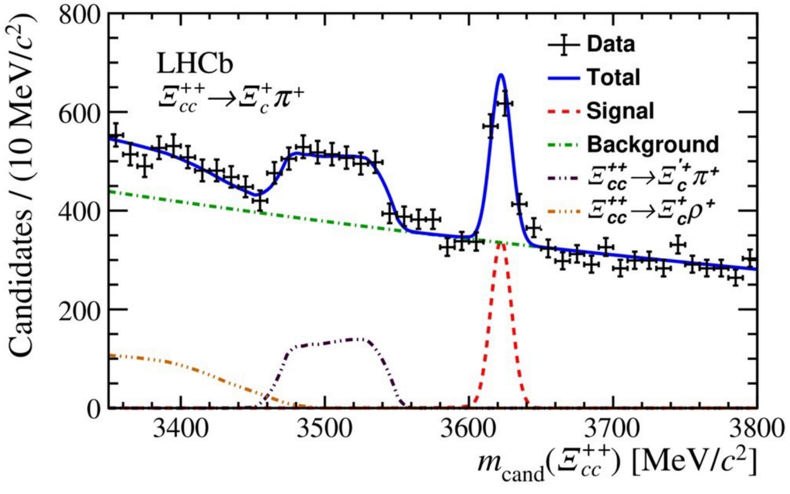
Non-trivial decay-time acceptance

- use $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ as control channel

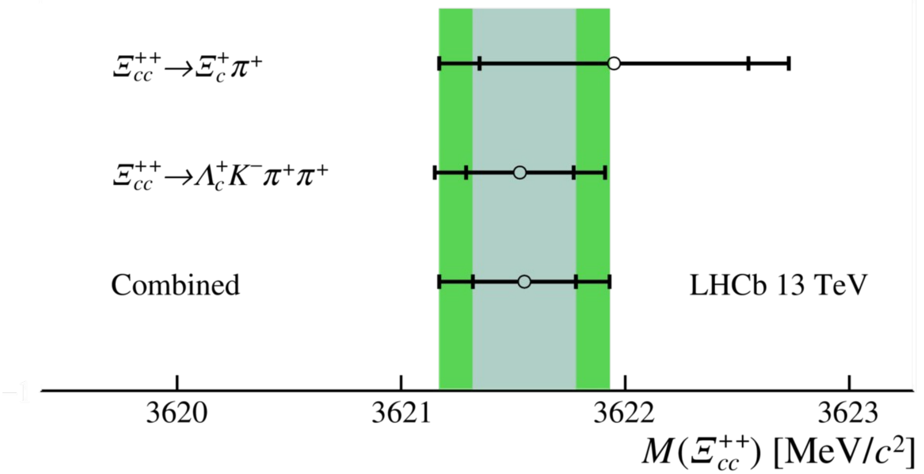
$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}\,(\text{stat}) \pm 0.014\,(\text{syst})\text{ ps}$$

Mass measurement & production rate





JHEP 02 (2020) 049
[CP C44 (2020) 022001](CP C44 (2020) 022001)



$$\frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

- in LHCb acceptance:
  $4 < p_T < 15$ GeV/c & $2.0 < y < 4.5$
- for pp collisions at $\sqrt{s} = 13$ TeV
- assuming central value of $\tau(\Xi_{cc}^{++})$

Both $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^-$ and $\Xi_c^+ \pi^+$ channels

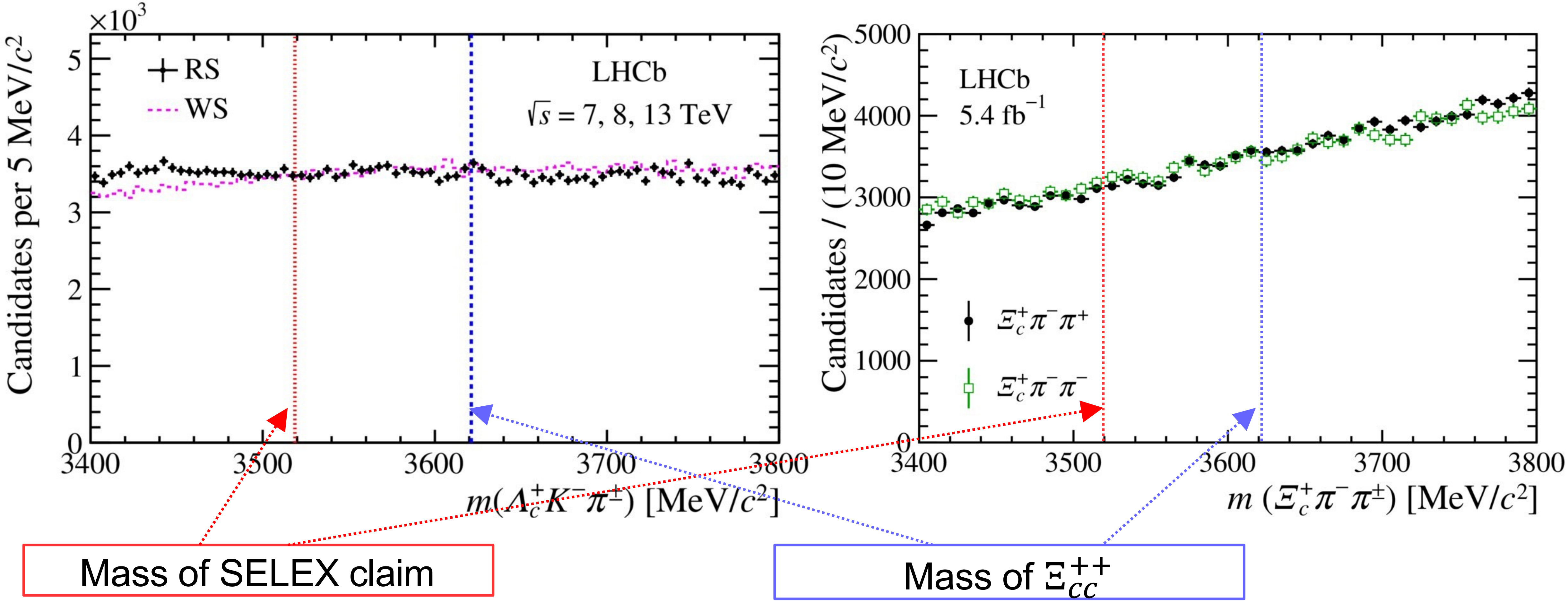
$\boldsymbol{m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65(\mathrm{stat}) \pm 0.31(\mathrm{syst})\ \mathrm{MeV}/c^2}$

Largest systematic uncertainties from

- momentum scale
- Λ_c^+ and Ξ_c^+ masses

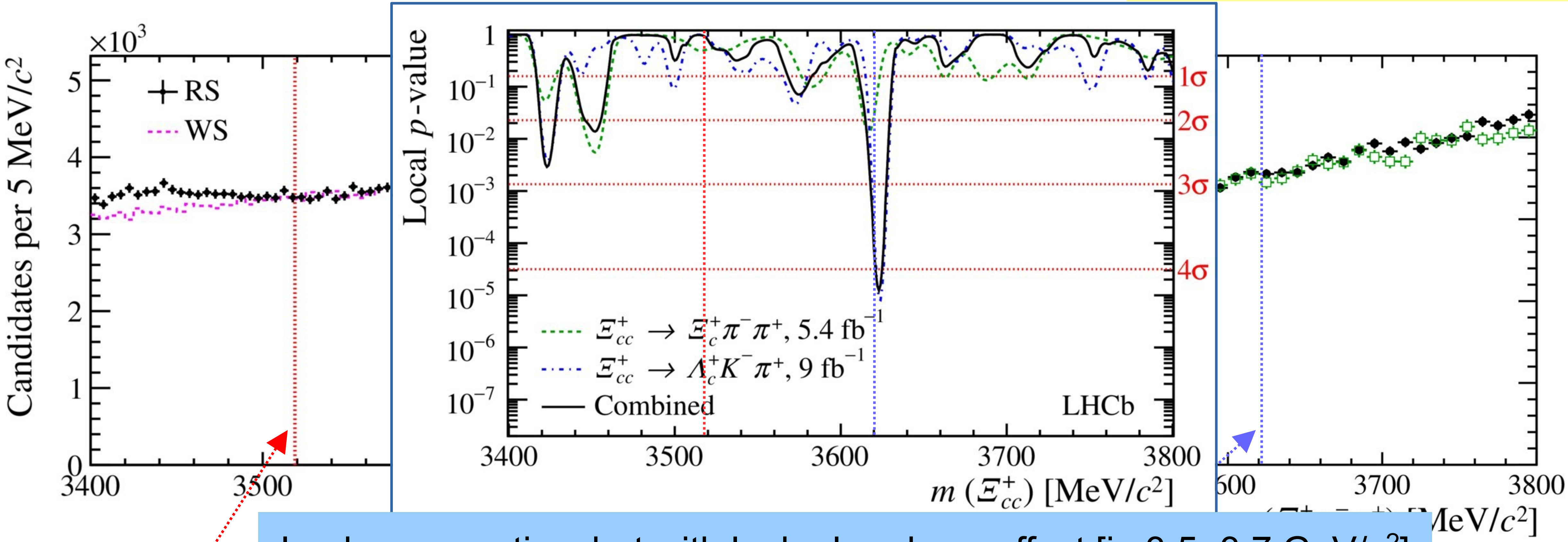
Searches for Ξ_{cc}^{+}

SCPMA 63 (2020) 221062
JHEP 12 (2021) 107



Searches for Ξ_{cc}^{+}

SCPMA 63 (2020) 221062
JHEP 12 (2021) 107



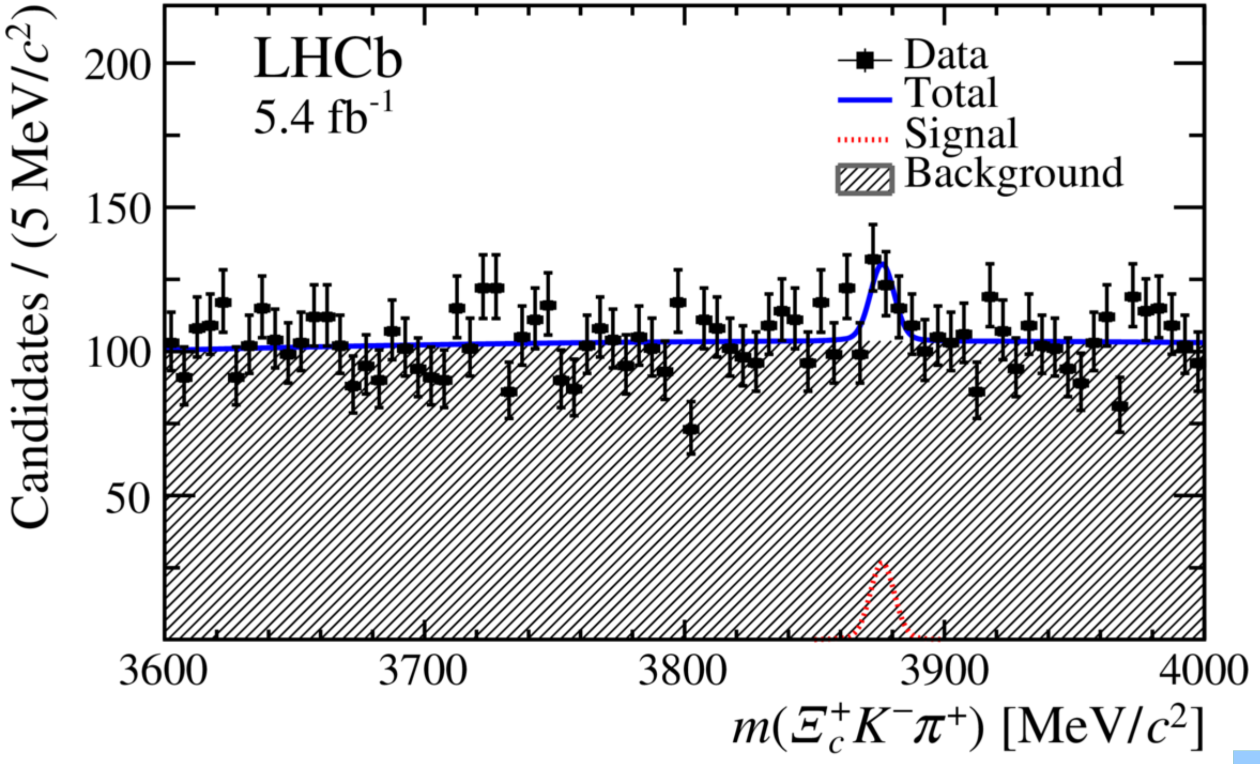
Mass of SE

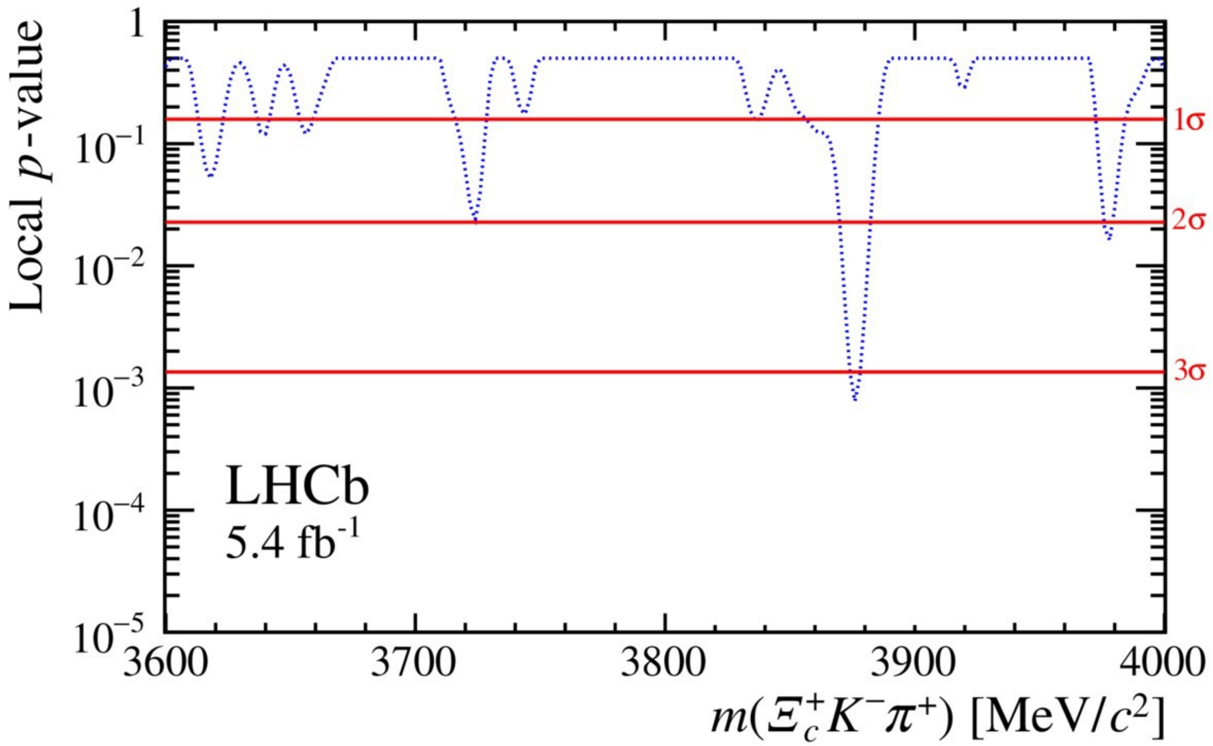
Looks suggestive, but with look-elsewhere-effect [in 3.5−3.7 GeV/c²]

global significance is 2.9σ

Search for Ω_{cc}^{+}

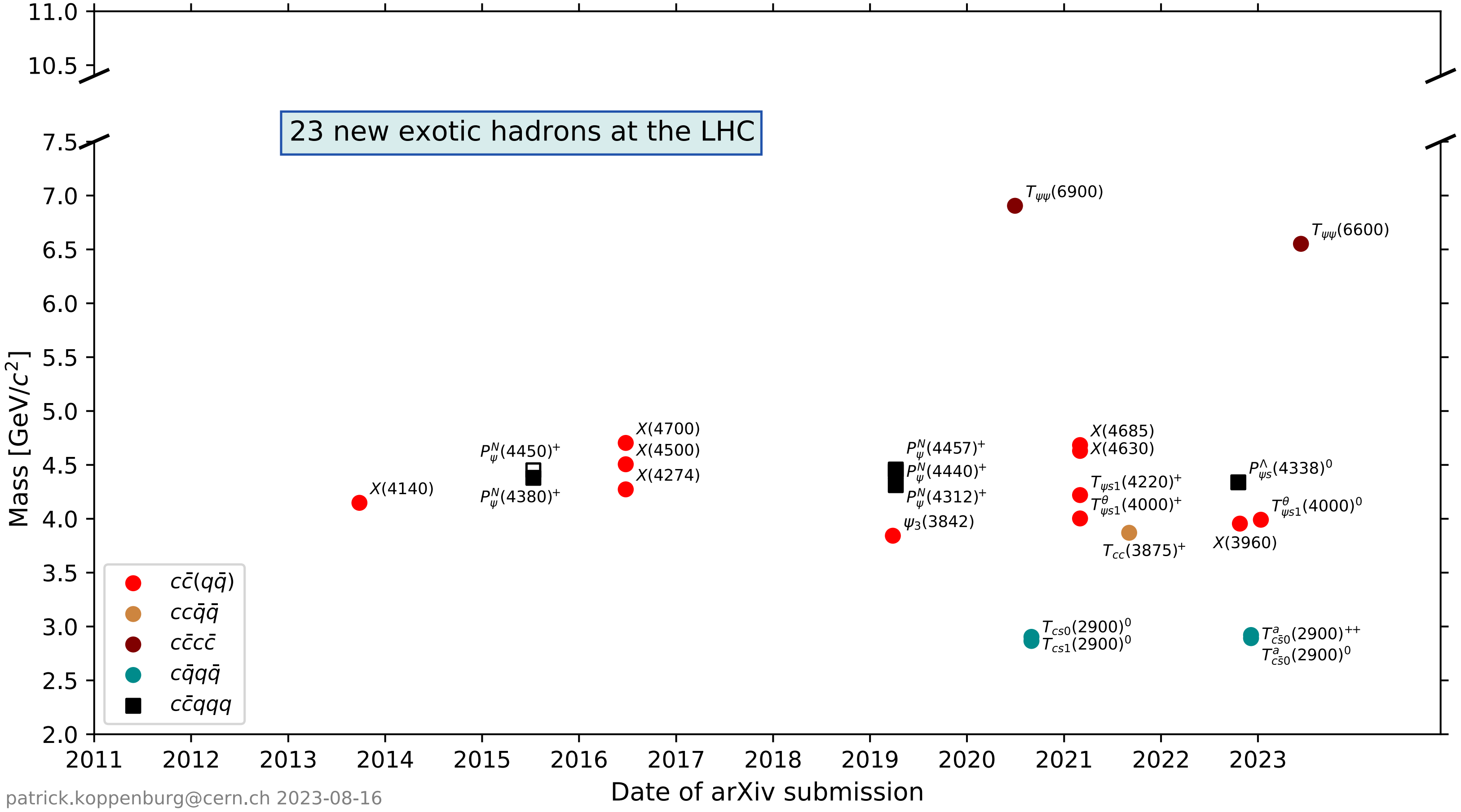
SCPMA 64 (2021) 101062



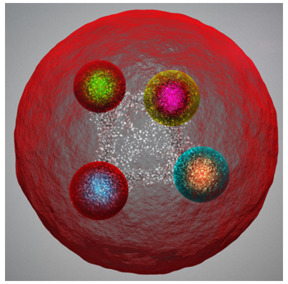


With look-elsewhere-effect [in 3.6−4.0 GeV/c²] global significance is 1.8 σ

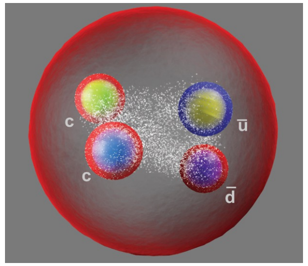
Exotic hadrons @ LHCb



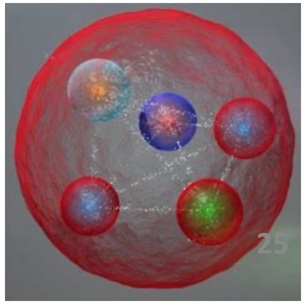
- Hidden-charm tetraquark



- Open (doubly)-charmed tetraquark



- Hidden-charm pentaquark

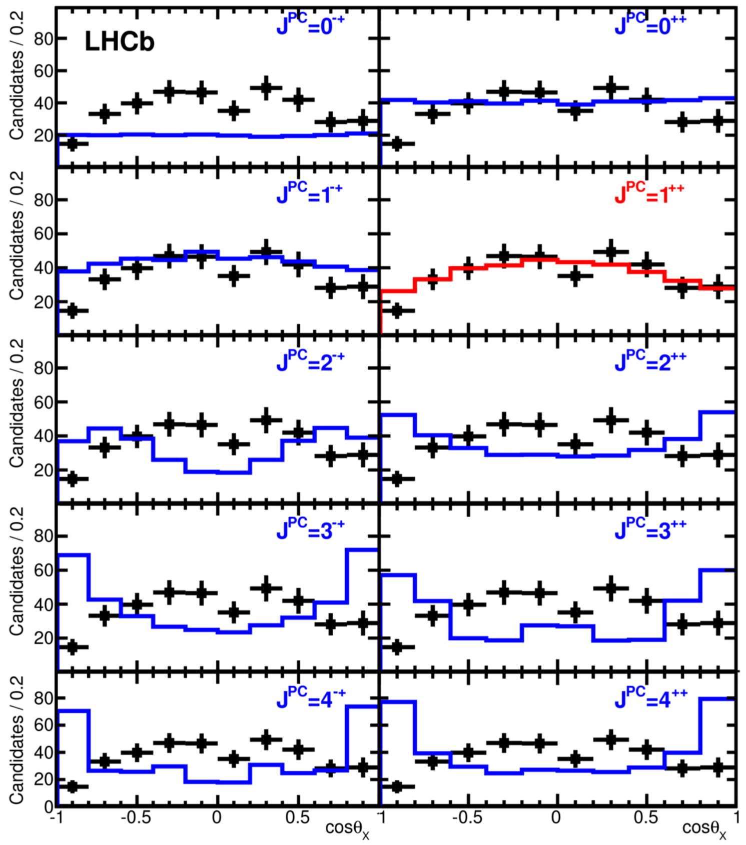


Hidden-charm tetraquark

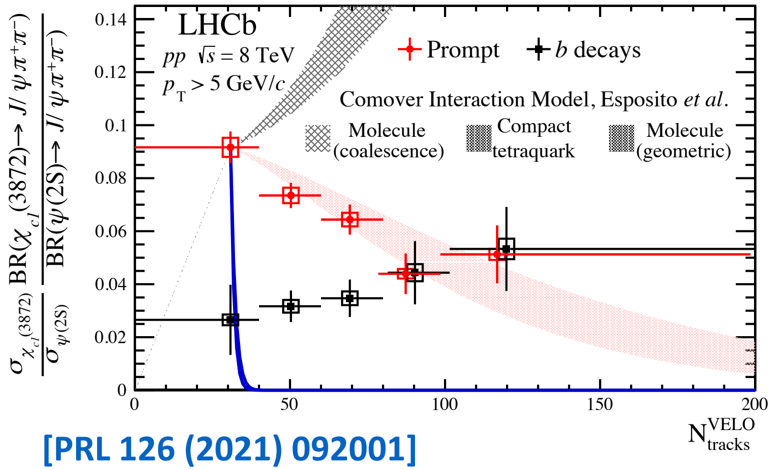
Study of $\chi_{c1}(3872)/X(3872)$

✓ $J^{PC}=1^{++}$

[PRD 92 (2015) 011102 (R)]

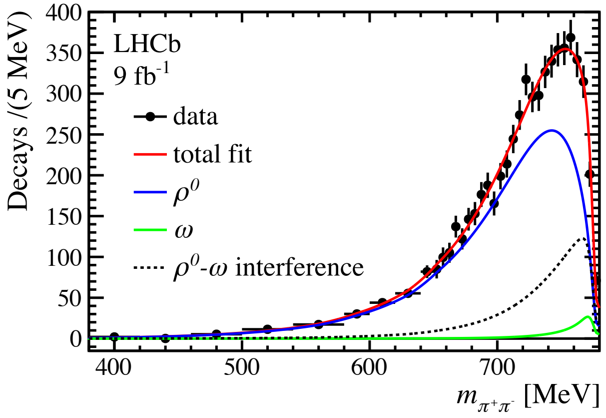


✓ production



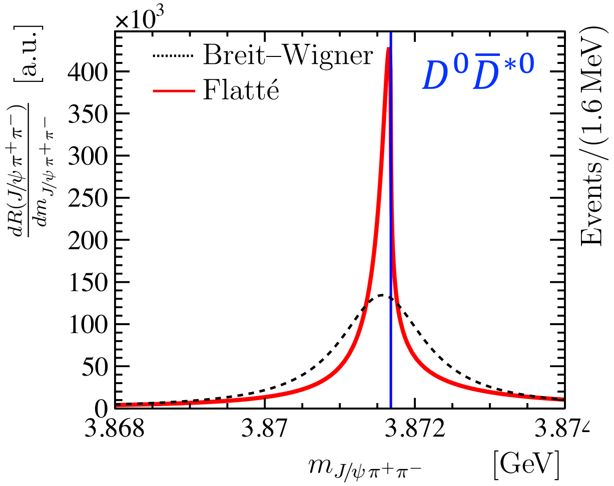
[PRL 126 (2021) 092001]

✓ decay

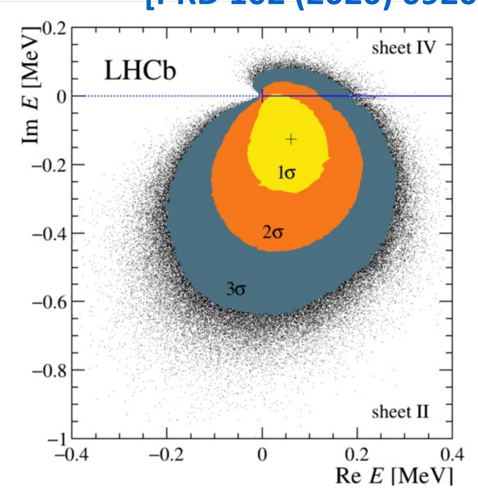


[PRD 131 (2023) L011103]

✓ lineshape



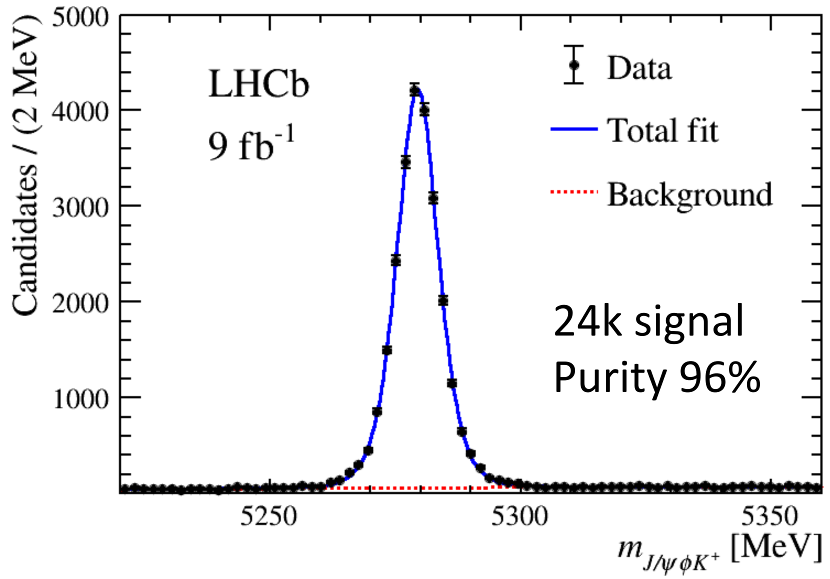
[PRD 102 (2020) 092005]

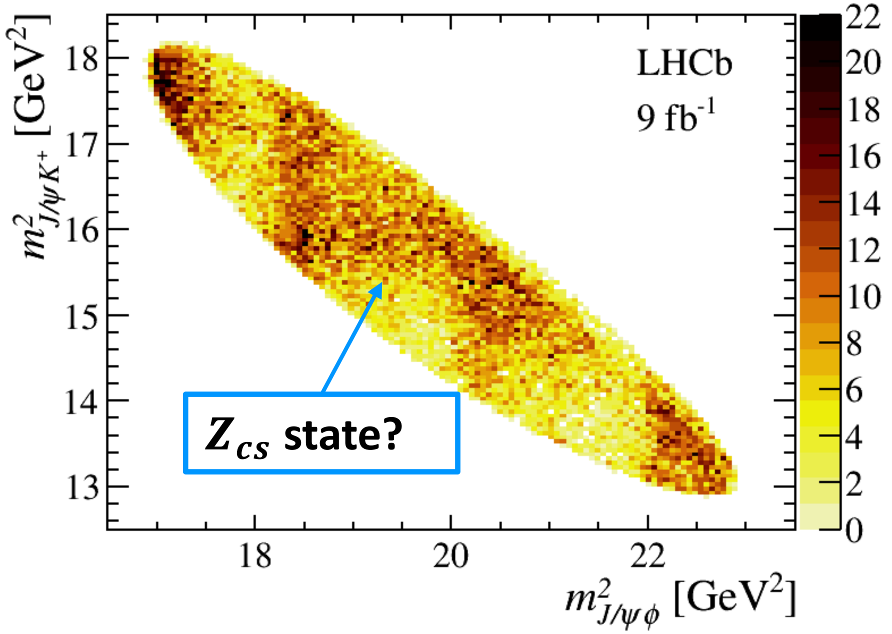


Exotic states in $B^+ \to J/\psi\phi K^+$ decays

- $B^+ \to J/\psi\phi K^+$ decays initially used for study of $J/\psi\phi$ structures
  - $X(4140)$ first observed by CDF and confirmed by CMS

    [arXiv:1101.6058] [PLB 734 (2014) 261]
  - With run-1 data, LHCb observed $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ [PRL 118 (2017) 022003]
- With run-1 and 2 data, 6 x signal decays obtained
  - Clearly visible: 4 structures in $J/\psi\phi$ mass and an obvious $J/\psi K^+$ band [PRL 127 (2021) 082001]

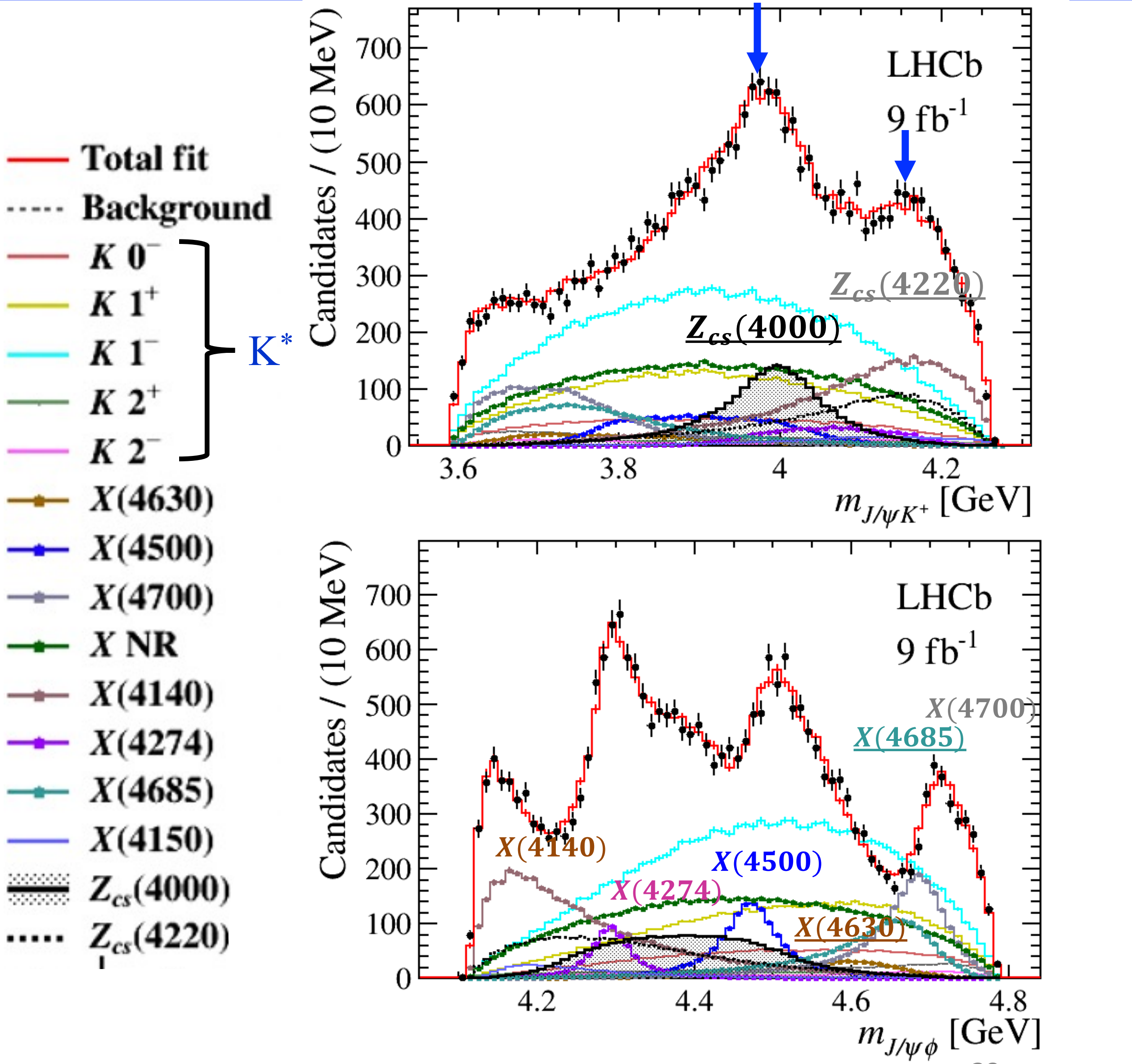




Observation of new resonances $\rightarrow J/\psi K^+$ and $J/\psi\phi$

[PRL 127 (2021) 082001]

- Run-1 fit model doesn't work well
- Fit needs more states, in which
  4 new exotic-like states are observed



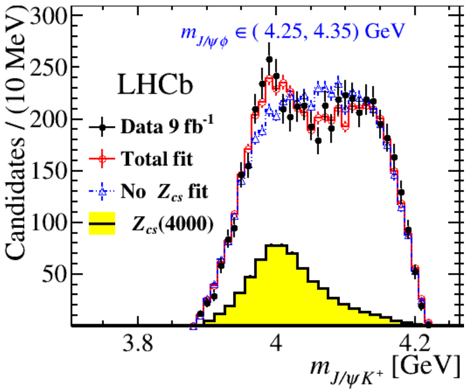
- New states:
  $Z_{cs}(4000)^+$ $J^P = 1^+$
  $Z_{cs}(4220)^+$, $J^P = 1^{+/-}$
  $X(4685)$, $X(4630)$

- Confirmed previous observed states:
  $X(4140)$, $X(4274)$,
  $X(4500)$, $X(4700)$

Comparison with BESIII

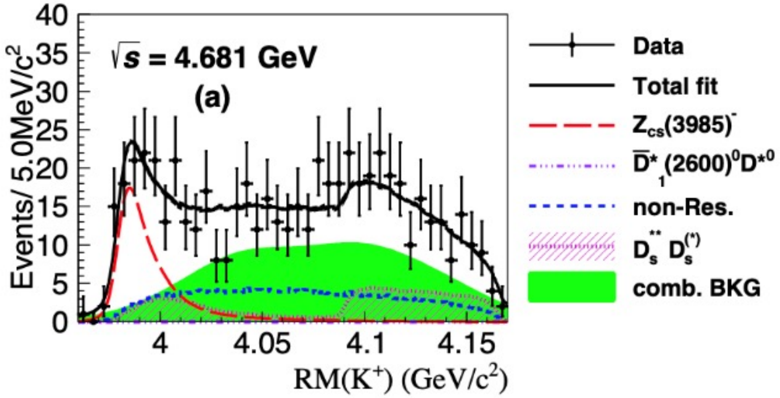
- BESIII observed a narrow $Z_{cs}(3985)^{+}$ with different final states $D_s^{+}\bar{D}^{*} + \bar{D}D_s^{*+}$
- Two states have similar masses, but different widths
- No evidence $Z_{cs}(4000)^{+}$ is the same as $Z_{cs}(3985)^{+}$ seen by BESIII
  - Fix $Z_{cs}(4000)^{+}$ to BESIII's result; $2\ln L$ is worse by 160
  - Adding on top of the default model almost doesn't improve the fit likelihood

[PRL 127 (2021) 082001]



$m(Z_{cs}(4000)^{+}) = (4003 \pm 6^{+4}_{-14})$ MeV
$\Gamma(Z_{cs}(4000)^{+}) = (131 \pm 15 \pm 26)$ MeV

[PRL 126 (2021) 102001]

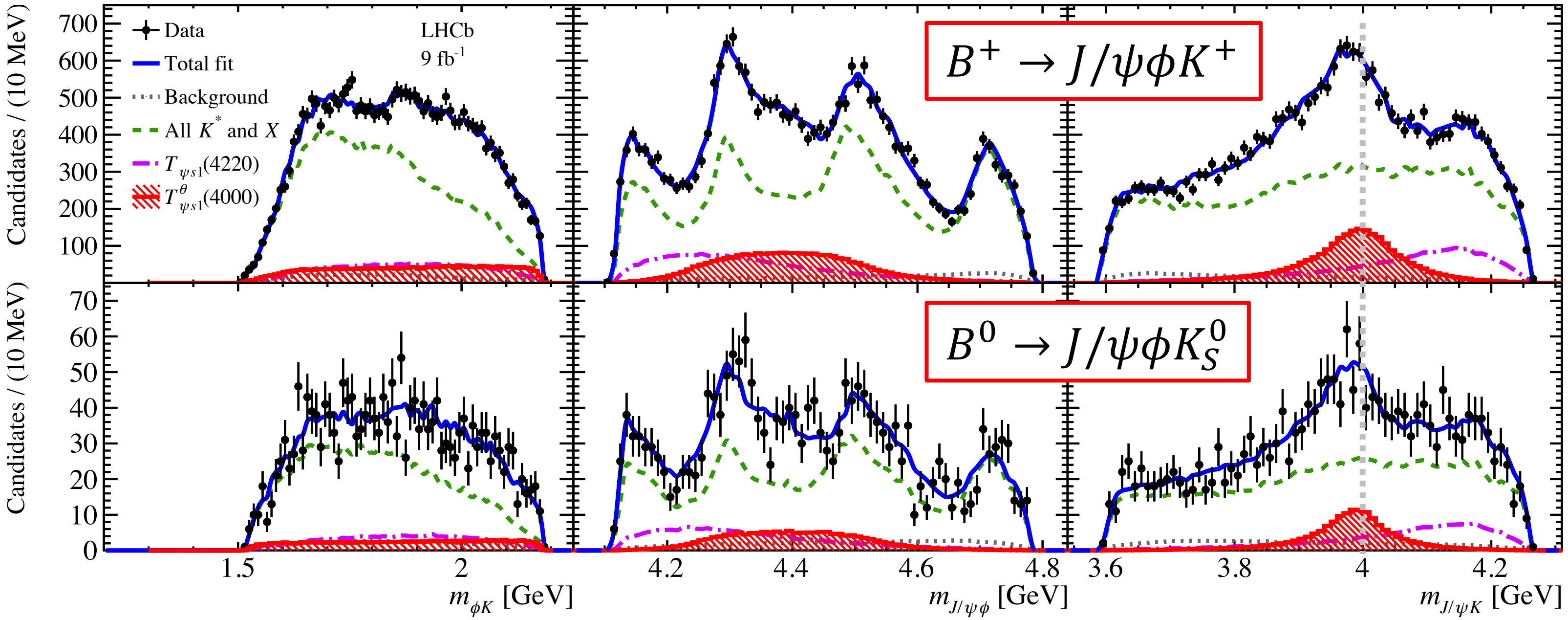


$m_{\rm pole}(Z_{cs}(3985)^{-}) = (3982.5^{+1.8}_{-2.6} \pm 2.1)\,\mathrm{MeV}/c^2,$
$\Gamma_{\rm pole}(Z_{cs}(3985)^{-}) = (12.8^{+5.3}_{-4.4} \pm 3.0)\,\mathrm{MeV}.$

Evidence of $T_{\psi s1}^{\theta}(4000)^0$ in $B^0 \to J/\psi \phi K_S^0$

[PRL 131 (2023) 131901]

- $B^0 \to J/\psi \phi K_S^0$ and $B^+ \to J/\psi \phi K^+$ are related by isospin symmetry
- Joint amplitude fit assumes isospin symmetry except for $T_{\psi s1}^{\theta}(4000)^0$
- Its significance is 4σ (5.4σ under isospin assumption)
- $T_{\psi s1}^{\theta}(4000)^0$ and $T_{\psi s1}^{\theta}(4000)^+ \equiv Z_{cs}(4000)^+$ are likely to be isospin partners



$$M(T_{\psi s1}^{\theta}(4000)^0) = 3991\,^{+12}_{-10}\,^{+9}_{-17}\ \text{MeV}$$

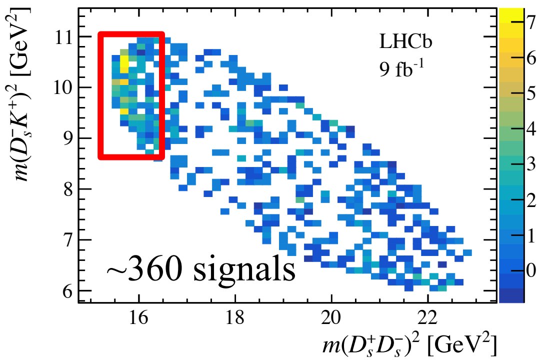
$$\Gamma(T_{\psi s1}^{\theta}(4000)^0) = 105\,^{+29}_{-25}\,^{+17}_{-23}\ \text{MeV}$$

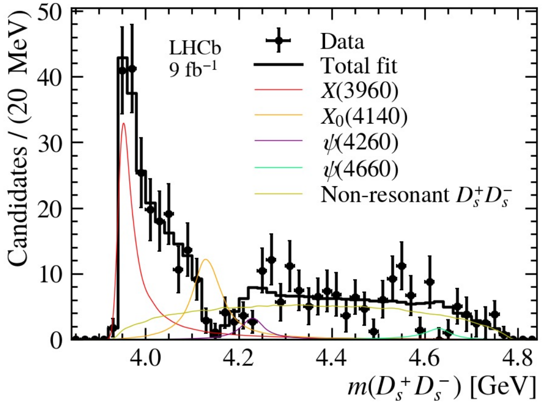
$$\Delta M\left(T_{\psi s1}^{\theta 0} - T_{\psi s1}^{\theta +}\right) = -12^{+11}_{-10}\,^{+6}_{-4}\ \text{MeV}$$

$X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$ decays

[PRL 131 (2023) 071901]

- Strong threshold enhancement found in $D_s^+ D_s^-$ system
- Amplitude analysis is performed
- $X(3960)$: threshold enhancement
  - $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ
  - Could be a $c\bar{c}s\bar{s}$ tetraquark predicted by Lattice QCD [JHEP 06 (2021) 035]
  - Resonance parameters are consistent with $\chi_{c0}(3930)$ within 3σ
- More data need to study the lineshape for $X(3960)$

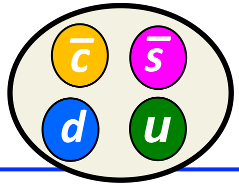




Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 [62]	55 [62]	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 [32]	64 [32]	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

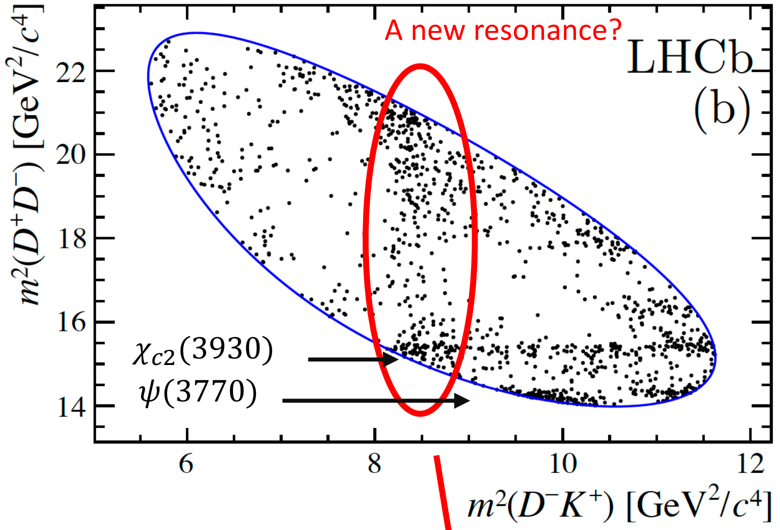
Open (doubly)-charmed tetraquark

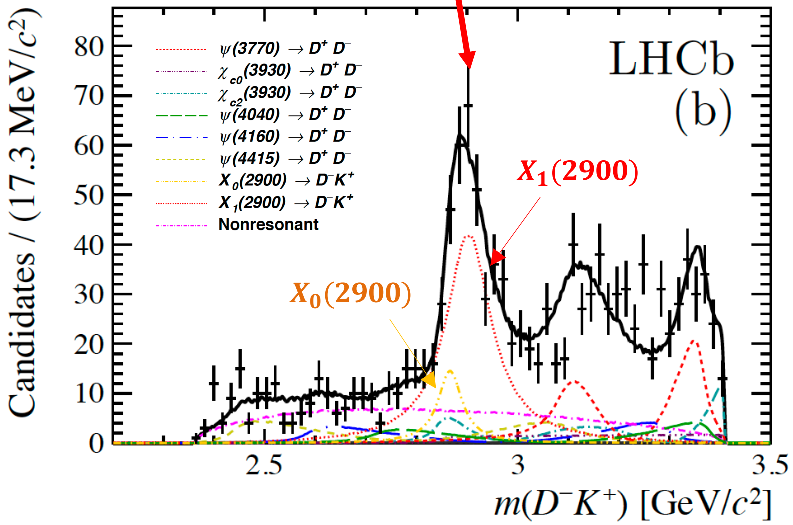
Observation of $T_{cs} \to D^- K^+$



[PRL 125 (2020) 242001]
[PRD 102 (2020) 112003]

- Amplitude analysis of $B^+ \to D^+ D^- K^+$ decays
  - ~1300 signals with purity 99.5% (9fb^{-1})
- Enhancement in $m^2(D^- K^+)$~8.5GeV^{-2}
- Described by $X_1(2900)$ and $X_0(2900)$
- **First discovery of open-charm tetraquarks with four different flavors $[cs\bar{u}\bar{d}]$!**





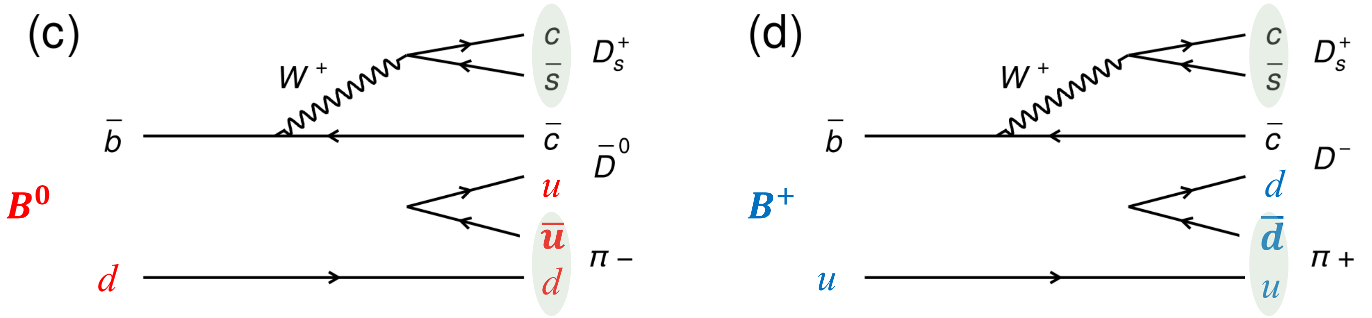
- The observation motivates study of $B \to \bar{D} D_s \pi$

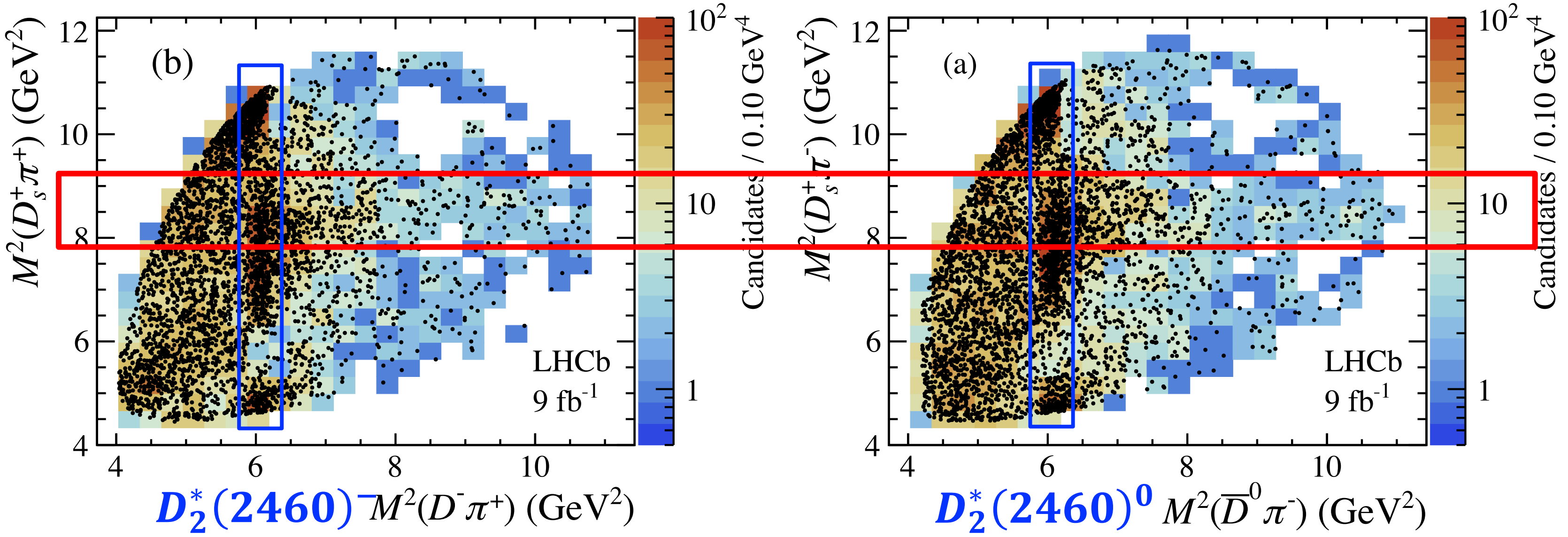
	Resonance	Mass (GeV/c^2)	Width (MeV)
new	$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
	$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
new	$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
new	$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$

Study of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

[PRL 131 (2023) 041902]

- Full 9 fb^{-1} Run1+Run2 LHCb data
  ⇒ 4420 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and
  3940 $B^+ \to D^- D_s^+ \pi^+$ candidates



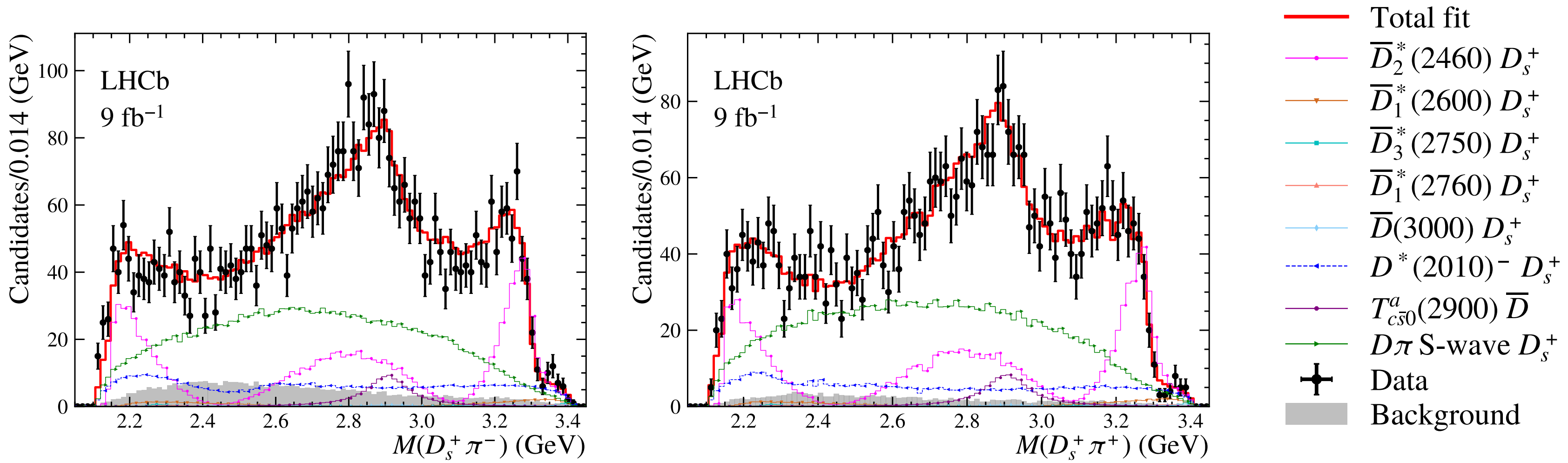


⇒ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

Observation of $T^a_{c\bar{s}0}(2900)^{0/++}$

- Fit with two $D_s^+\pi$ states sharing resonance parameters

[PRL 131 (2023) 041902]



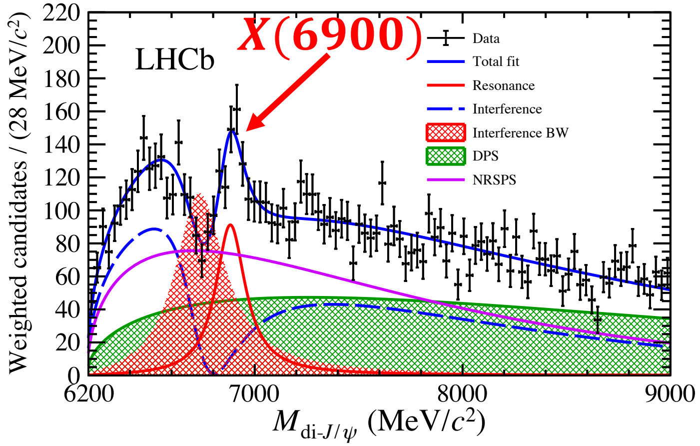
- ➢ $T^a_{c\bar{s}0}(2900)^0 \to D_s^+\pi^-$ & $T^a_{c\bar{s}0}(2900)^{++} \to D_s^+\pi^+$ significance $> 9\sigma$
  - ✓A second 1^- $D_s^+\pi$ state yields significance of only 1.3σ
  - ✓Additional $D\pi, D_s^+\pi, DD_s^+$ resonances disfavored
- ➢ $J^P = 0^+$ favored over other spin-parity by more than 7.5σ

$$M = 2.908 \pm 0.011 \pm 0.020\ \text{GeV}$$

$$\Gamma = 0.136 \pm 0.023 \pm 0.011\ \text{GeV}$$

Exotic hadron with full charm or double-charm

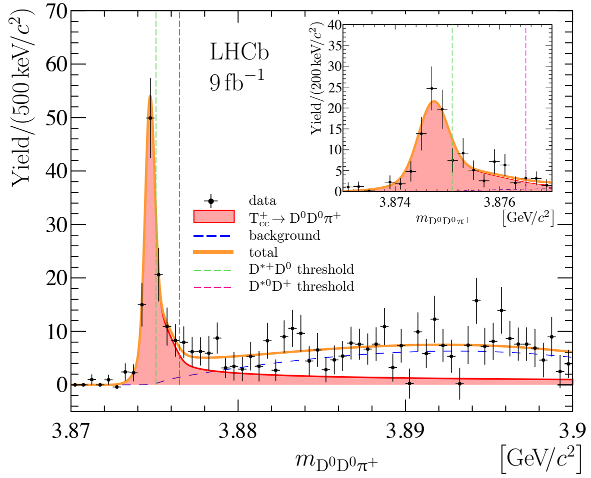
[Science Bulletin 65 (2020) 1983]



$$M\big(X(6900)\big) = 6886 \pm 11 \pm 11\ \mathrm{MeV}/c^2$$

$$\Gamma\big(X(6900)\big) = 168 \pm 33 \pm 69\ \mathrm{MeV}/c^2$$

- confirmed by ATLAS and CMS



	$\delta\mathfrak{m}$ $[\mathrm{keV}/c^2]$	$\mathfrak{w}$ $[\mathrm{keV}/c^2]$
$\mathfrak{F}^{\mathrm{BW}}$	-279 ± 59	409 ± 163
$\mathfrak{F}^{\mathrm{U}}$	-361 ± 40	47.8 ± 1.9

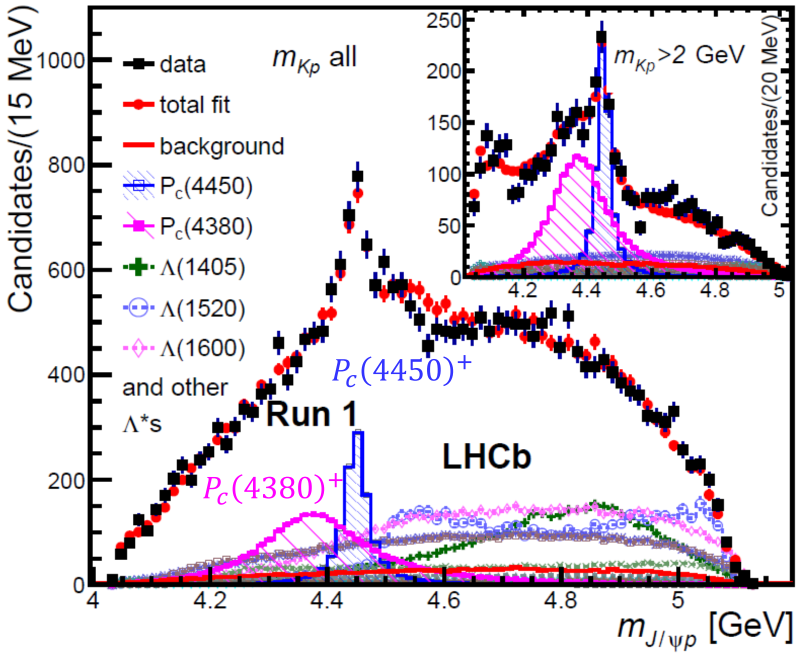
[Nature Physics 18 (2022) 751]
[Nature Comm. 13 (2022) 3351]

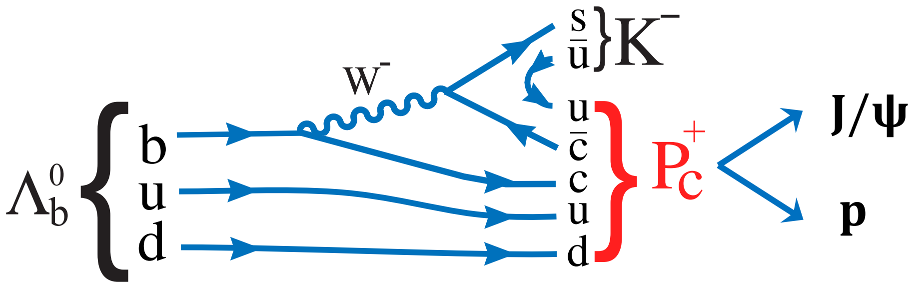
Hidden-charm pentaquarks

LHCb observation in 2015

- **Two $J/\psi p$ resonant structures** are revealed by a full 6D amplitude analysis
  - $P_c(4450)^+$ ← the prominent peak
  - $P_c(4380)^+$ ← required to obtain a good fit to the data
  - Consistent with **pentaquarks** with minimal quark content of $uudc\bar{c}$

PRL 115 (2015) 072001





$P_c(4450)^+$ $M =$ $4450 \pm 2 \pm 3$ MeV
$\Gamma =$ $39 \pm 5 \pm 19$ MeV
$F.F. =$ $4.1 \pm 0.5 \pm 1.1$ %

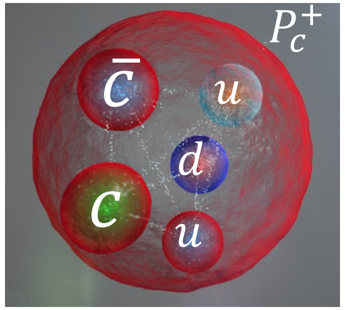
$P_c(4380)^+$ $M =$ $4380 \pm 8 \pm 29$ MeV
$\Gamma =$ $205 \pm 18 \pm 86$ MeV
$F.F. =$ $8.4 \pm 0.7 \pm 4.2$ %

Limited knowledge of P_c

- Observation of LHCb opens a gate to study pentaquarks
- To interpret the nature of P_c, more studies are needed
  - J^P, spectroscopy, decay modes and production mechanism?

$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$

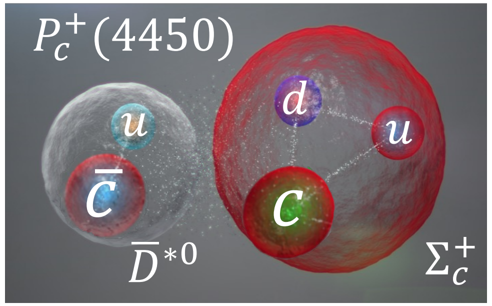
Tightly-bound pentaquark?



Maiani,Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich,Matveev,Nyiri, Sarantsev PLB 749 (2015) 454
and others

$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$

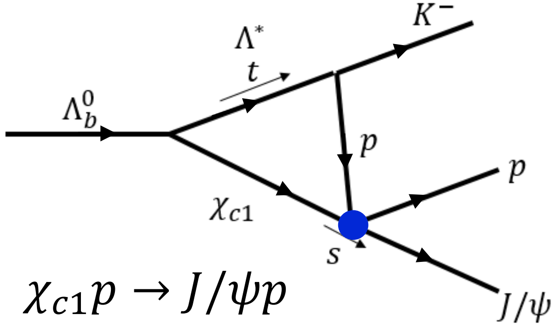
Loosely-bound pentaquark?



Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PRC84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others

$P_c(4450)^+$ = $\chi_{c1}p$ threshold?

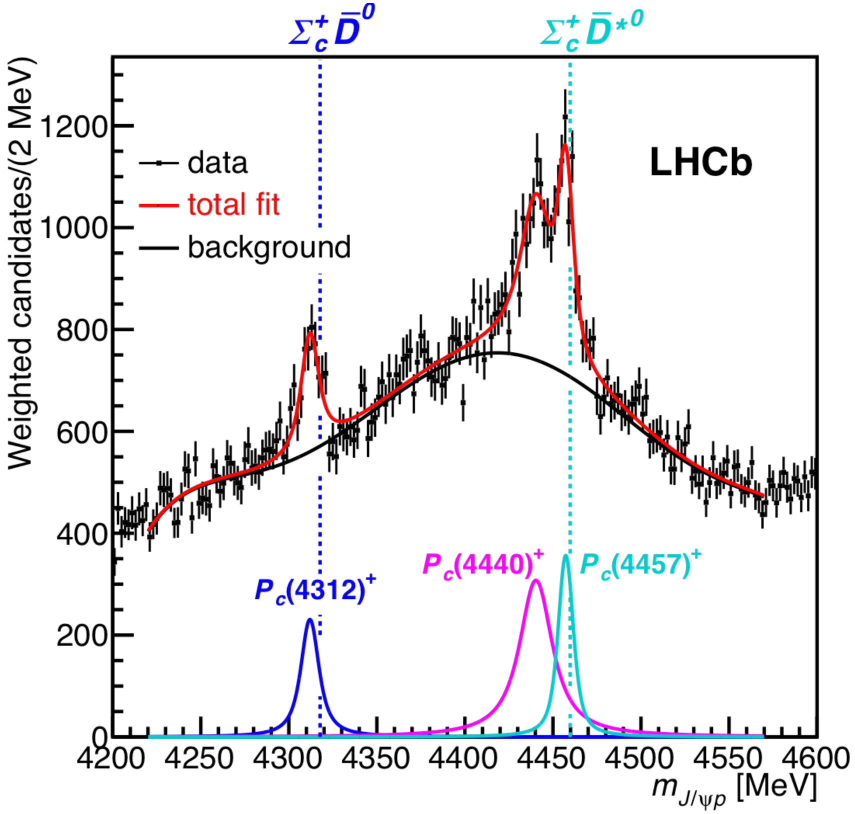
Kinematical effect: triangle diagram?



Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others

Update $\Lambda_b^0 \to J/\psi p K^-$ (3+6 fb^{-1})

- **New pentaquark and fine structure was discovered with x10 signals**
- The masses of $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$ **just below mass thresholds of $\Sigma_c^+ \bar{D}^{(*)0}$**
- J^P measures and information of $P_c(4380)^+$ require detailed amplitude analysis



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

[PRL 122 (2019) 222001]

Largest systematic uncertainty: unknown interference terms

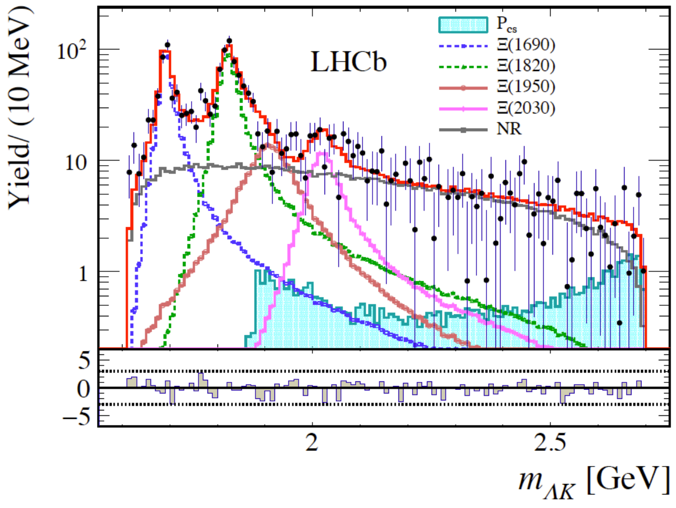
Evidence of a strange hidden-charm pentaquark

- SU(3) partner P_{cs} was predicted to exist, that decays to $J/\psi\Lambda$
  [PRL 105 (2010) 232001; PRC 93(2016) 064203 and others]

- First amplitude analysis performed to ~1750 $\Xi_b^- \to J/\psi\Lambda K^-$ decays

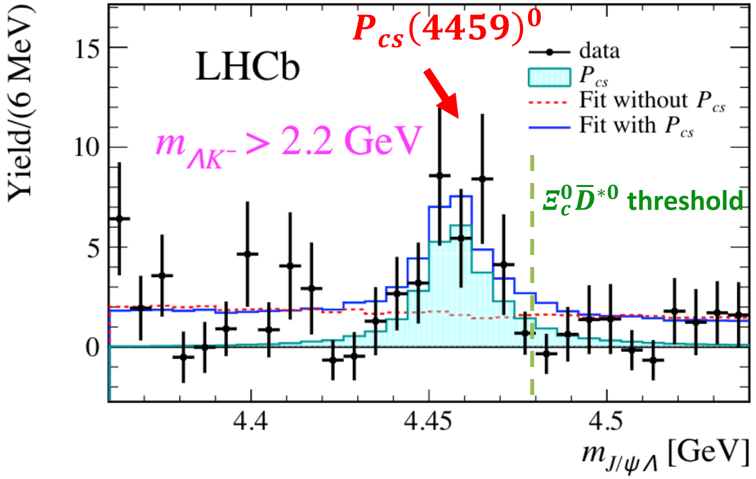
- Evidence for $P_{cs}(4459)^0$ with 3.1σ signficance

[Science Bulletin 66 (2021) 1278]



Mass is about 19 MeV below $\Xi_c^0\overline{D}^{*0}$ threshold

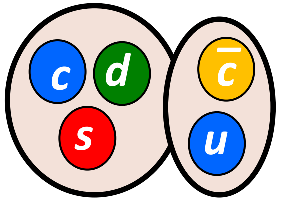
State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$

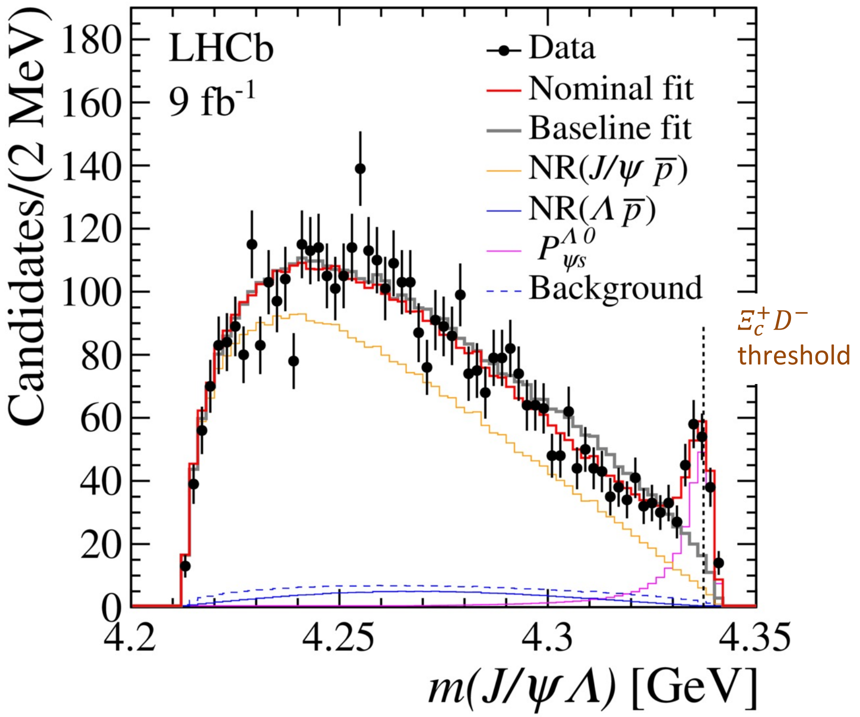


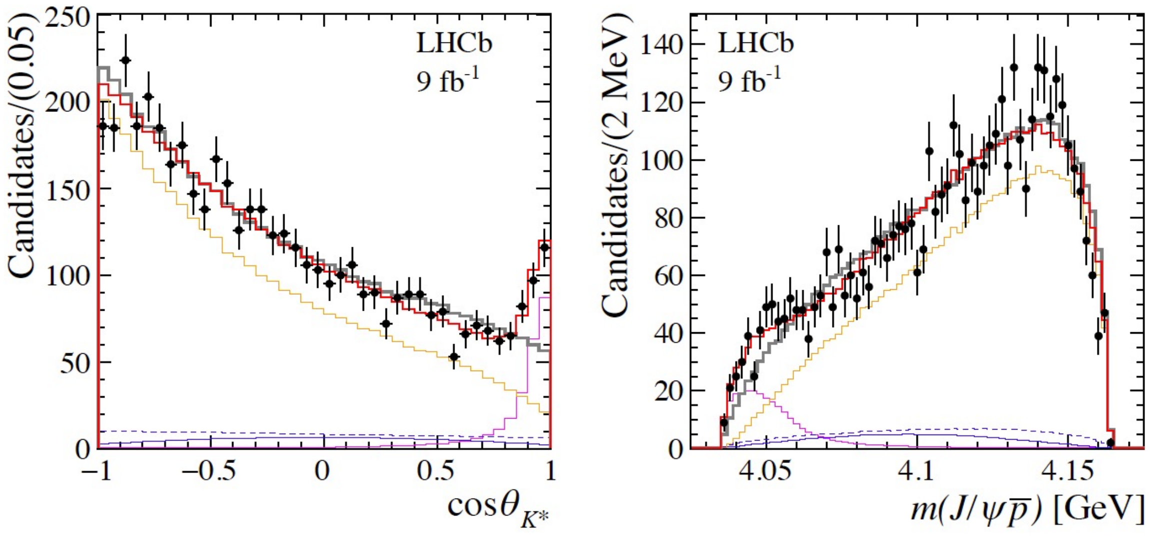
Observation of $P_{\psi s}^{\Lambda}(4338)^0$

[PRL 131 (2023) 031901]

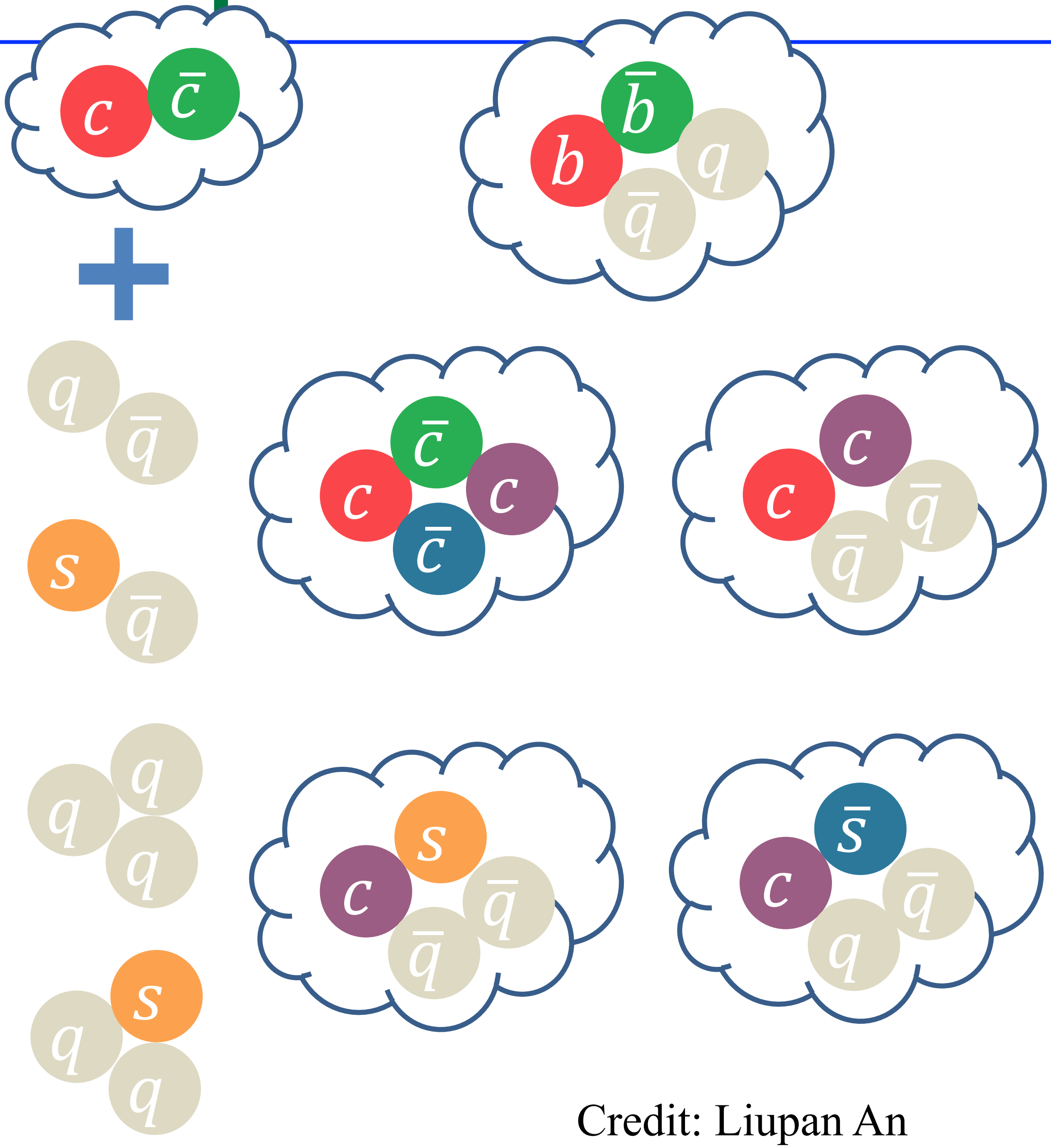
- A new pentaquark with strangeness $P_{\psi s}^{\Lambda}(4338)^0$ ($c\bar{c}sud$) observed from **4617** $B^- \to J/\psi\Lambda\bar{p}$ decays
  - **At $\Xi_c^+ D^-$ threshold**
  - $m = 4338.2 \pm 0.7 \pm 0.4$ **MeV**
  - $\Gamma = 7.0 \pm 1.2 \pm 1.3$ **MeV**
  - $J^P = (1/2)^-$ **preferred**, $J^P = \frac{1}{2}^+$ **rejected under** $90\%\ CL_s$





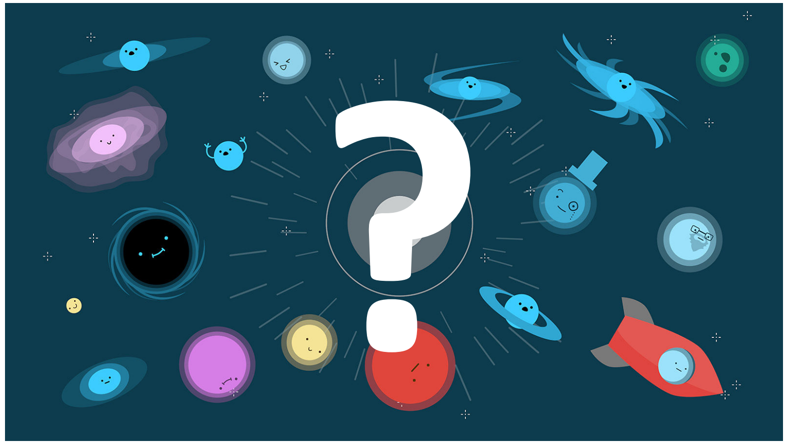


A new “particle zoo” is forming up



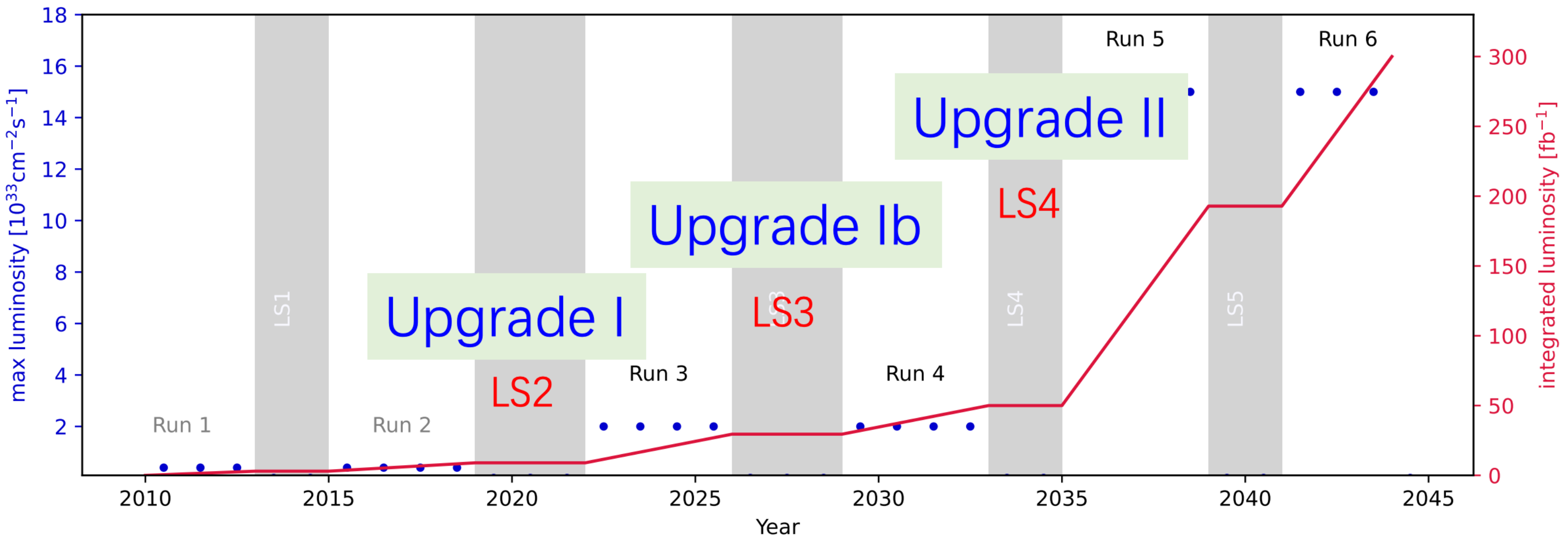
Credit: Liupan An

- We expect them to reveal deeper fundamental laws of QCD for us



Summary and prospects

- LHCb keeps making important contributions to heavy hadron spectroscopy, both for conventional or exotic hadrons
- In Run 3, the upgraded LHCb detector and an improved software-only trigger system will be implemented



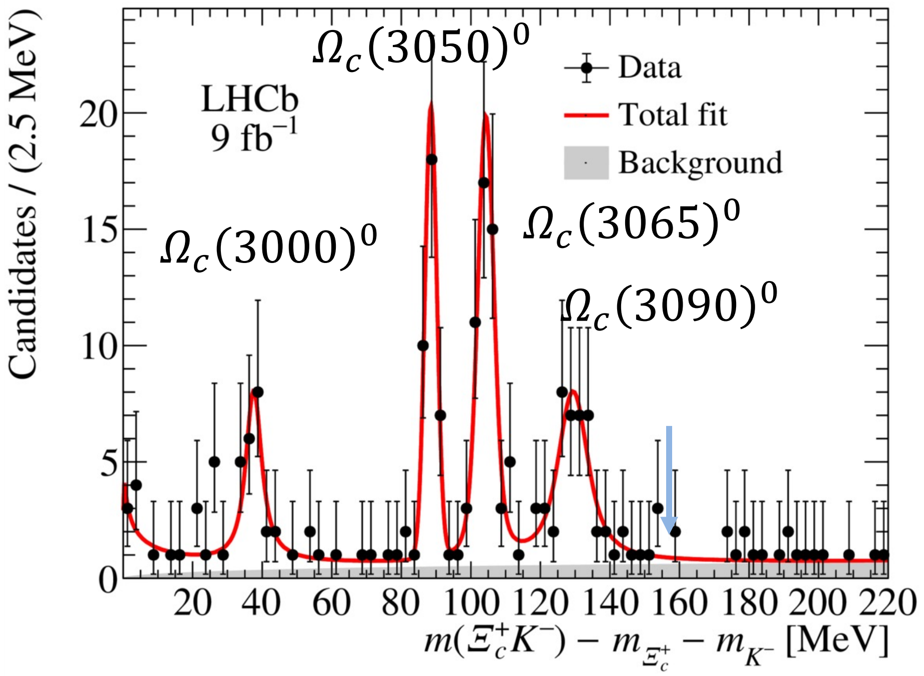
More exciting results are to come!
More data, more chances & challenges!

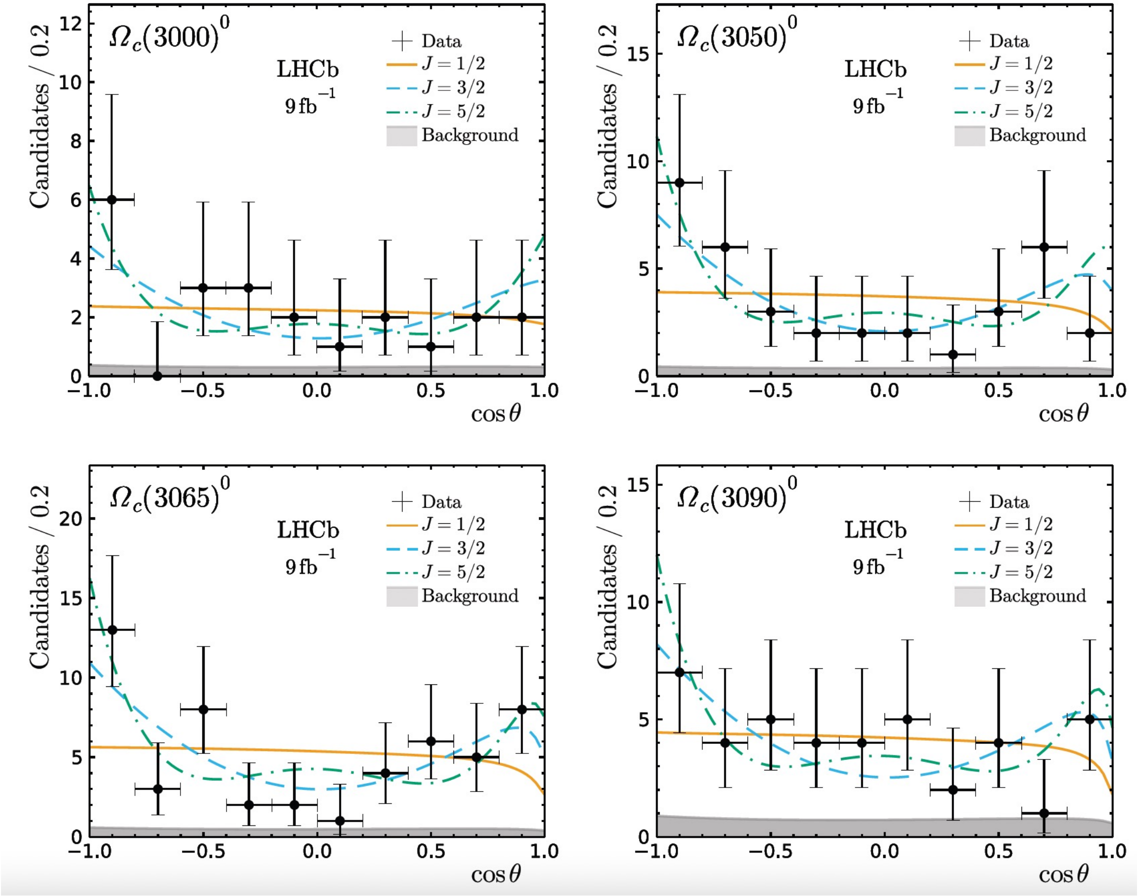
BACKUP

Ω_c states from $\Omega_b^- \to \Xi_c^+ K^- \pi^-$

PRD 104 (2021) L091102

- J^P is important to interpret these states
- $\sim 240\ \Omega_b^-$ signals obtained
- First four Ω_c states are observed
- Spin hypothesis are tested

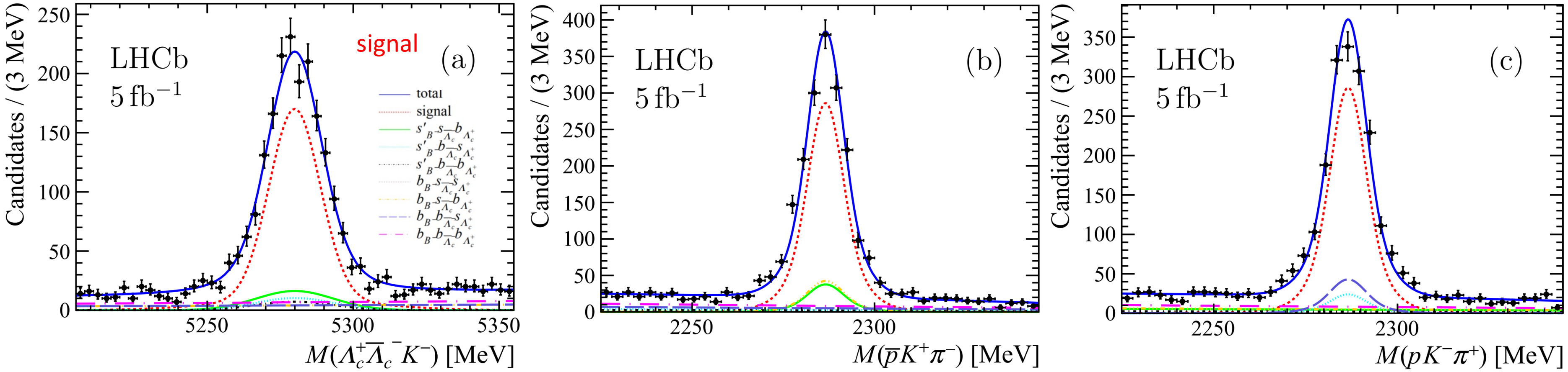




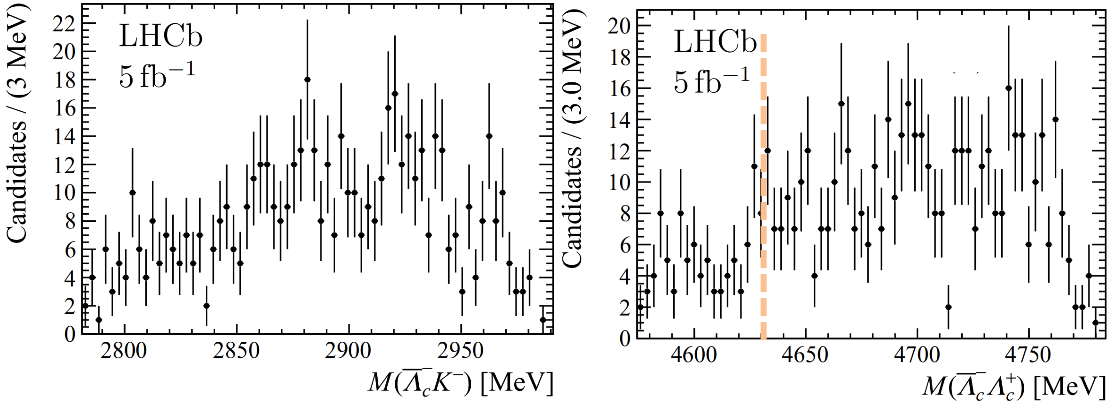
The $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay

PRD 108 (2023) 012020

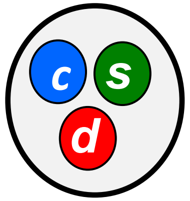
- Interesting for conventional & exotic studies
  - $\Xi_c^{0**} \to \Lambda_c^+ K^-$; exotic hadrons in $\Lambda_c^+ \overline{\Lambda}_c^-$ and $\overline{\Lambda}_c^- K^-$?
- High-purity sample, with $N_{\rm sig} = 1365 \pm 42$



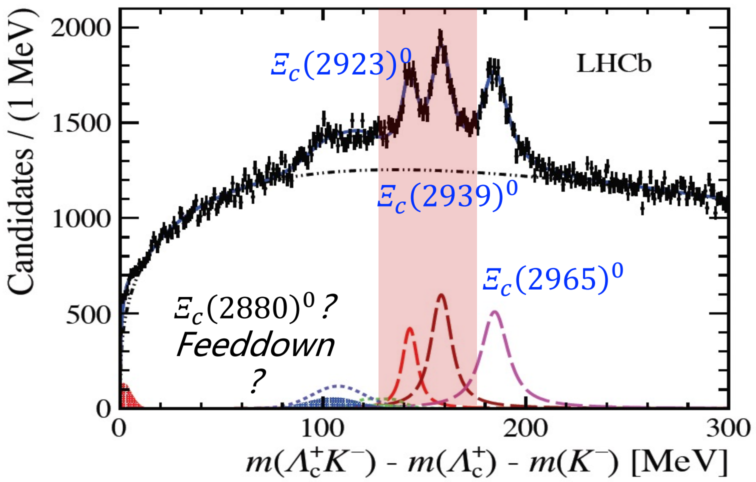
- No significant hint for exotic hadrons in $\Lambda_c^+ \overline{\Lambda}_c^-$ or $\overline{\Lambda}_c^- K^-$ mass spectra



Ξ_c baryon in B decay

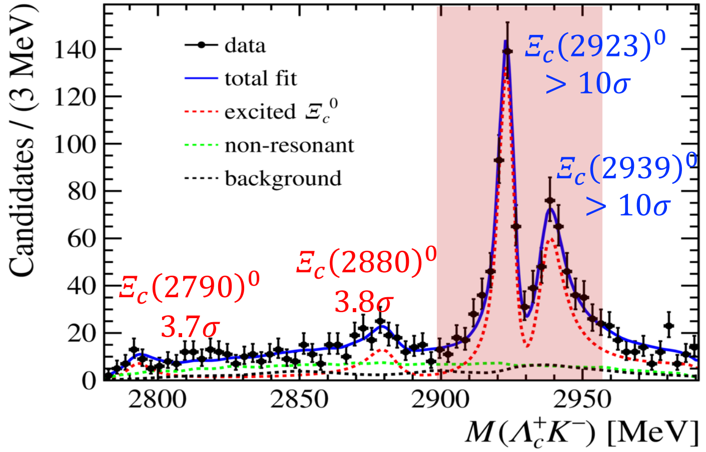


- $\Xi_c(2930)^0$ found in $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ at BaBar, confirmed by Belle
- Resolved into $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ in prompt $\Lambda_c^+ K^-$ search at LHCb PRL 124 (2020) 222001
- Confirmed by recent $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ study at LHCb
  - Evidence of a new $\Xi_c(2880)^0$



State	Mass (MeV)	Width (MeV)
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$

$$R_{\mathcal{B}} = \frac{\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-)}{\mathcal{B}(B^- \to D^- D^+ K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25$$

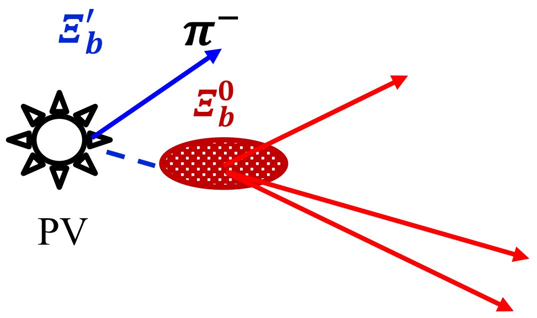


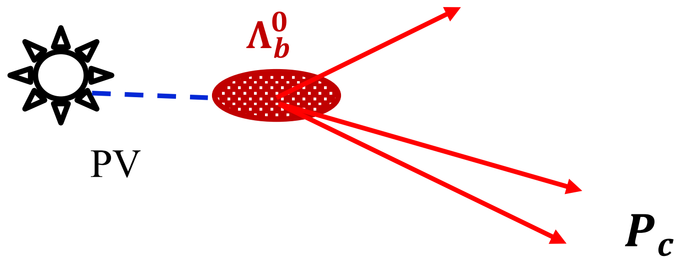
arXiv:2211.00812

Two methods for spectroscopy

- Direct production in pp collisions
  - Combine a heavy flavour hadron with one or more light particles
  - Pros: High statistics, in principle can study all states
  - Cons: Large combinatorial background, hard to determine J^P

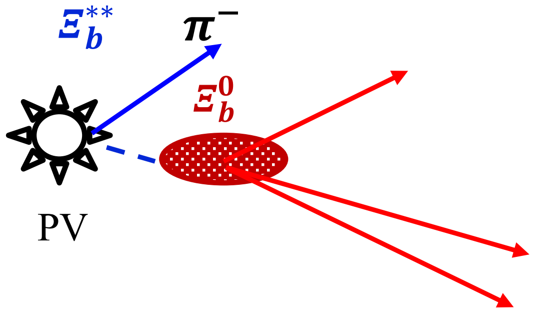
- Production by a heavier particle decay
  - Usually with amplitude analysis
  - Pros: Low background, Better determination of J^P
  - Cons: Low cross-section, limited mass range

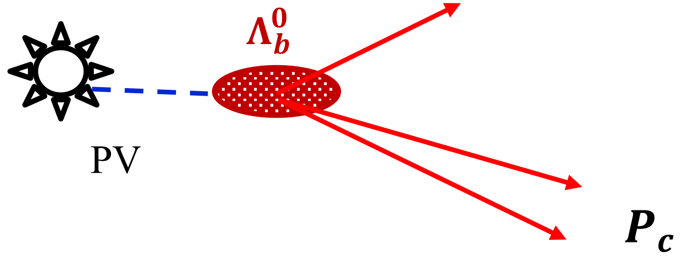




Two methods for spectroscopy

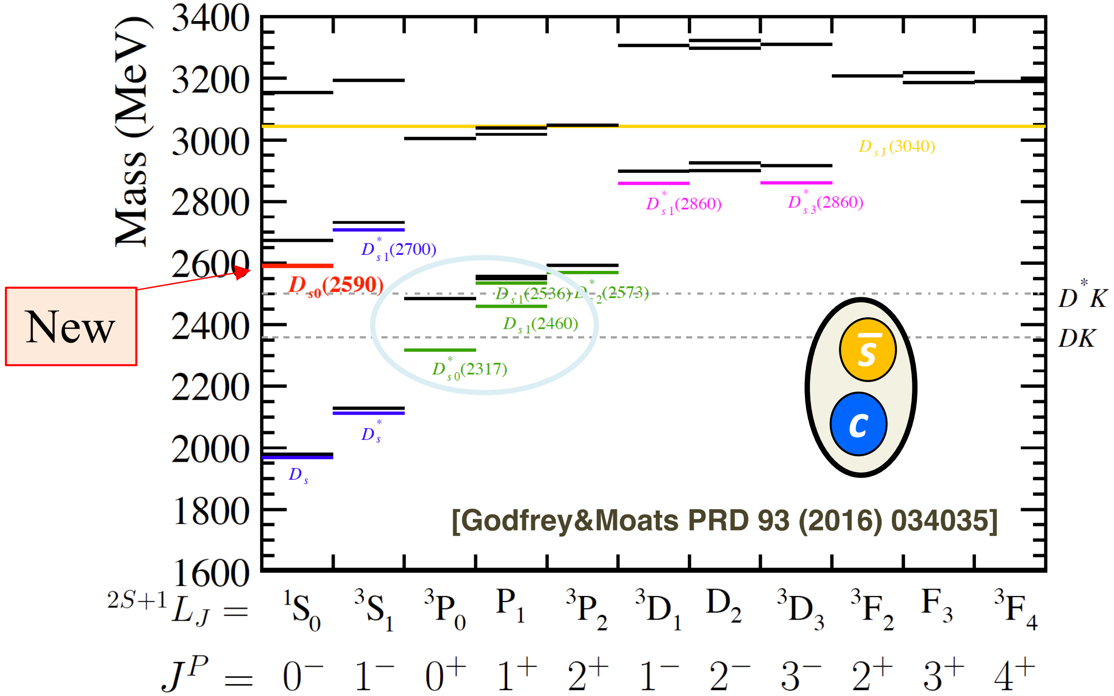
- Direct production in pp collisions
  - Ξ_{cc}^{++}, $\Omega_c^{**} \rightarrow \Xi_c K$
  - All excited B, $\Xi_b^{**} \rightarrow \Xi_b \pi; \Lambda_b K$
- Production by a B or D decays
  - X(3872) J^P
  - $Z_c(4430)$
  - X(4140) ….
  - $P_c(4312)$, $P_c(4440)$, $P_c(4447)$
  - $D_{(s)J}$

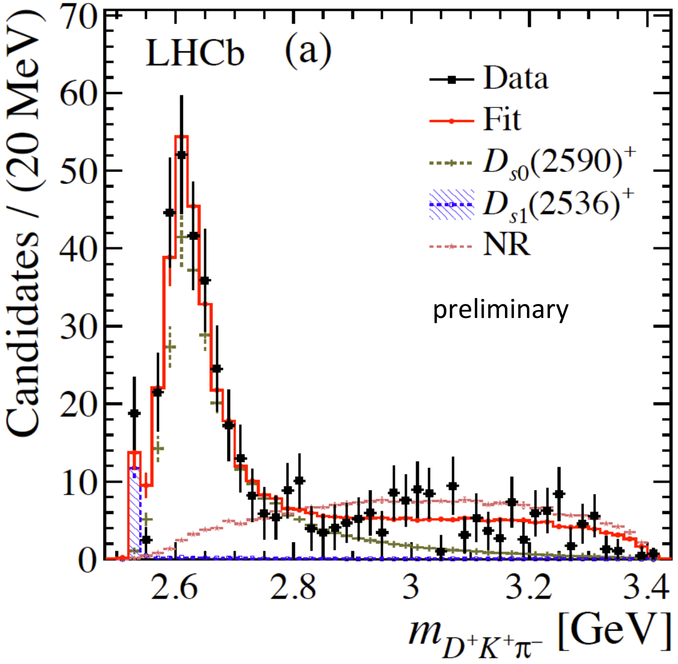




Observation of a new excited D_s^+ state

- Big puzzle: $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ have much smaller masses than the predictions
- Additional experimental input is helpful
- Use $B^0 \to D^+D^-K^+\pi^-$ decay
  - $m(K^+\pi^-) < 0.75$ GeV consistent with S-wave $K^+\pi^-$
- $D^+K^+\pi^-$ invariance mass shows a strong peak





- Amplitude fit is performed

[LHCb-PAPER-2020-034]

State	Pole Mass [MeV]	Pole Width [MeV]	J^P
$D_{s0}(2590)^+$	$2591 \pm 6 \pm 7$	$89 \pm 16 \pm 12$	0^-

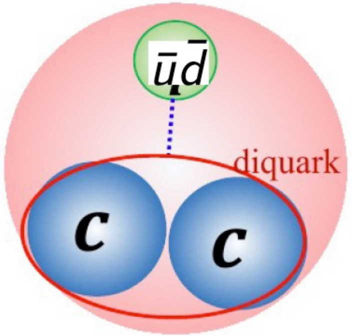
$T_{cc}^{+}\ (cc\bar{u}\bar{d})$ Nature Comm. 13 (2022) 3351

❑ Consist with $J^P = 1^+$ isoscalar

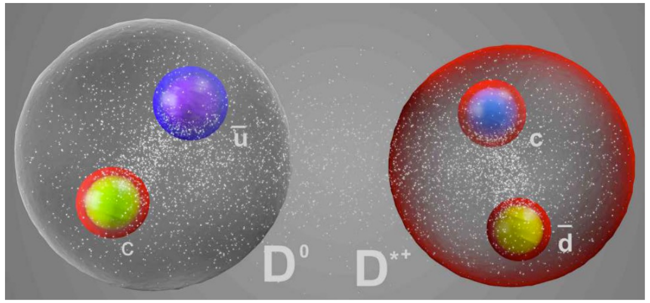
- ❑ Contribute to D^0D^0 and D^0D^+ (π/γ is missing)

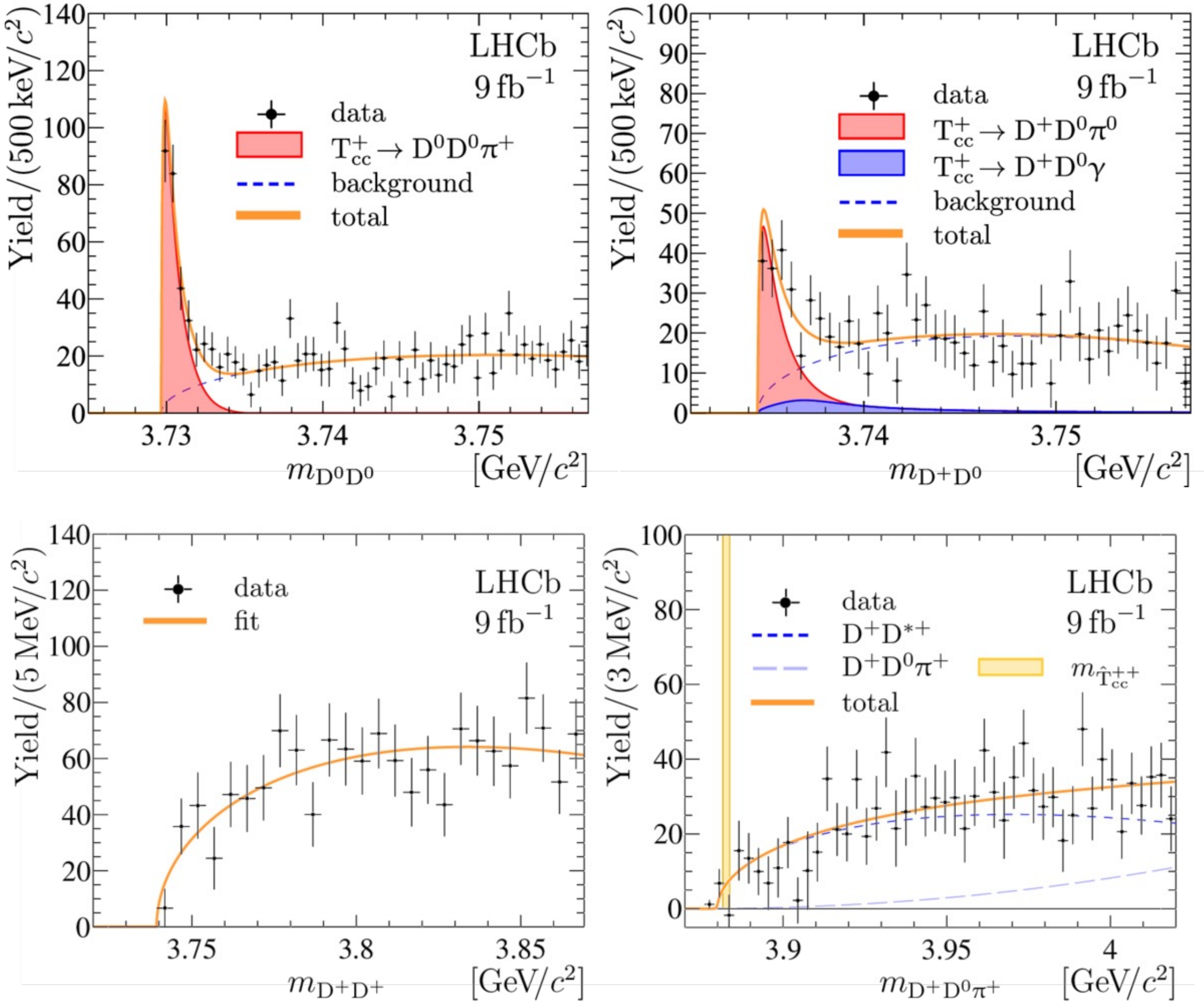
- ❑ No peaks in $D^+D^0\pi^+$ and D^+D^+
  => T_{cc}^{++} not found
  => Support that T_{cc}^{+} is an isoscalar

?



?

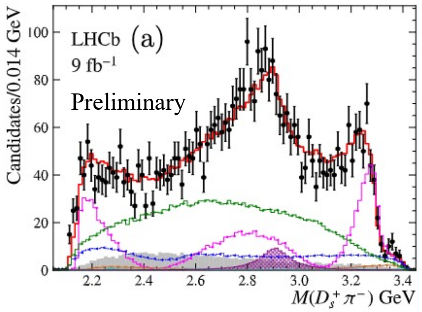




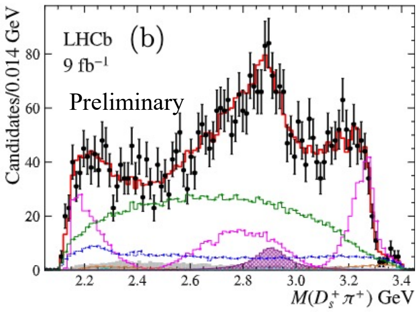
Answer: To find the predicted deep-bounded $bb\bar{u}\bar{d}$?

$T^a_{c\bar{s}0}(2900)$ and $X_{0,1}(2900)$

LHCb-PAPER-2022-026 ; LHCb-PAPER-2022-027



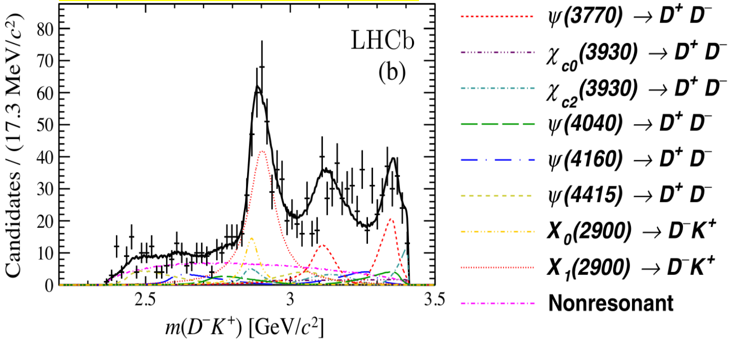
$T^a_{c\bar{s}0}(2900)^0[c\bar{s}\bar{u}d]$



$T^a_{c\bar{s}0}(2900)^{++}[c\bar{s}u\bar{d}]$

PRD 102, 112003 (2020)

$B^+ \to D^+ D^- K^+$



$X_0(2900), X_1(2900)[cs\bar{u}\bar{d}]$

	Mass (GeV)	Width (GeV)	J^P
$T^a_{c\bar{s}0}(2900)^0$ & $T^a_{c\bar{s}0}(2900)^{++}$	$2.908 \pm 0.011 \pm 0.020$	$0.136 \pm 0.023 \pm 0.020$	0^+
$X_0(2900)/T_{cs0}(2900)$	$2.866 \pm 0.007 \pm 0.002$	$0.057 \pm 0.012 \pm 0.004$	0^+
$X_1(2900)/T_{cs1}(2900)$	$2.904 \pm 0.005 \pm 0.001$	$0.110 \pm 0.011 \pm 0.004$	1^-

- **$T^a_{c\bar{s}0}(2900)$ v.s. $X_0(2900)$**
  - ✓ Similar mass, but width and flavor contents are different.
  - ✓ $T^a_{c\bar{s}1}(2900)$?
  - ✓ $T^a_{c\bar{s}0}(2900)^{++} \to D^+K^+$?
  - ✓ $T^a_{c\bar{s}0}(2900)^{+} \to D_s^+\pi^0, D_s^+\pi^+\pi^-$?

- **no isospin relation:** $[c\bar{s}u\bar{d}]$ **v.s.** $[cs\bar{u}\bar{d}]$
- **U-spin relation:** $[c\bar{s}\bar{u}d]$ **v.s.** $[c\bar{d}\bar{u}s]$
- $T^a_{c\bar{s}0}(2900)$ mass and width larger than $T_{cs0}(2900)$

$X(3960)$ and $\chi_{c0}(3930)$

[arXiv: 2211.05034]
[arXiv: 2210.15153]

	M [MeV]	Γ [MeV]	J^{PC}
$X(3960)$	$3955 \pm 6 \pm 12$	$48 \pm 17 \pm 10$	0^{++}
$\chi_{c0}(3930)$	3924 ± 2	17 ± 5	

- Same particle?

$\mathcal{FF}$: Fit fraction

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+)\times\mathcal{FF}^X_{B^+\to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+)\times\mathcal{FF}^X_{B^+\to D_s^+D_s^-K^+}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

  - Creation of $s\bar{s}$ from vacuum is suppressed wrt $u\bar{u}$ or $d\bar{d}$
  - $X \to D_s^+D_s^-$ has smaller phase-space factor than $X \to D^+D^-$

  $\Rightarrow$ X has an exotic nature! Candidate for $c\bar{c}s\bar{s}$
- Different particles?
  - No obvious candidate within conventional charmonium multiplets for them; likely to be exotic

Open flavor tetraquark

- **The $D_{s0}^{*}(2317)^{+}$ ($D_s^+\pi^0$) state was observed in 2003.**
- It is argued to contain some **tetraquark component** in several theoretical descriptions, whose $I = 1$ partners can exist in the **$D_s^{\pm}\pi^{\pm}$ final states.**
- *Cheng & Hou:* It would be astonishing if a doubly charged resonance is found. [PLB 566 (2003) 193]

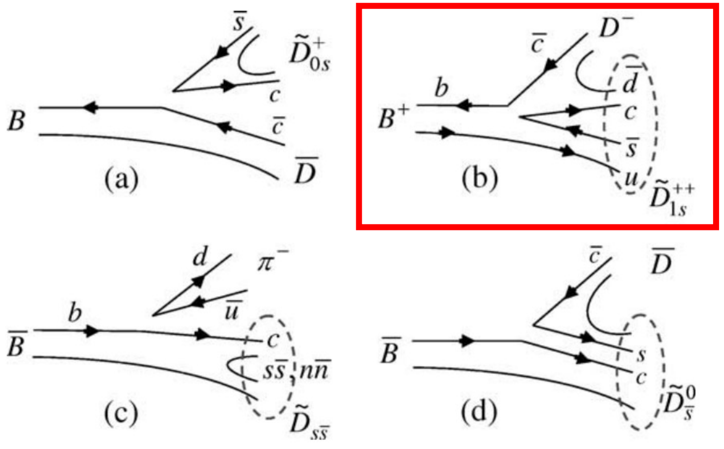
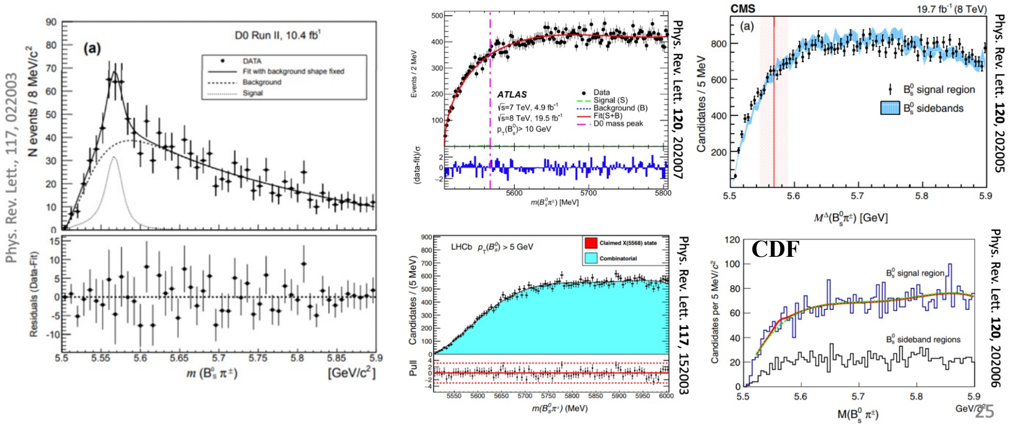


Fig. 2. Diagrams for (a) $B \to \bar{D}\tilde{D}_{0s}^{+}$, (b) $B^+ \to D^-\tilde{D}_{1s}^{++}$ ($B \to \bar{D}\tilde{D}_{Is}$), (c) $\bar{B} \to \pi^-\tilde{D}_{s\bar{s}}$, $\pi^-\tilde{D}$, (d) $\bar{B} \to D\bar{D}_{\bar{s}}^{0}$.

- D0 claimed evidence for the X(5568) in decaying to $\boldsymbol{B_s\pi^+}$, interpreted as tetraquark state $[\boldsymbol{b\bar{s}u\bar{d}}]$
- But not seen in other experiments

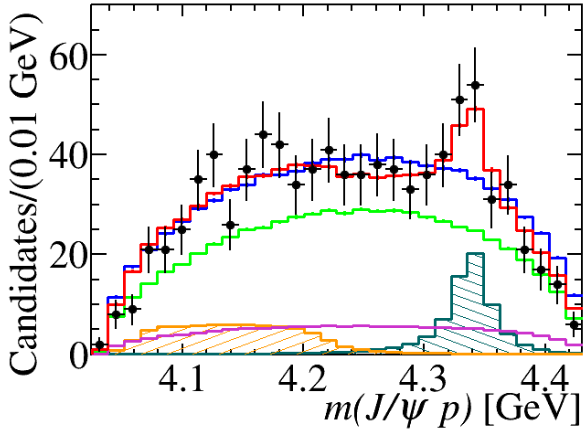


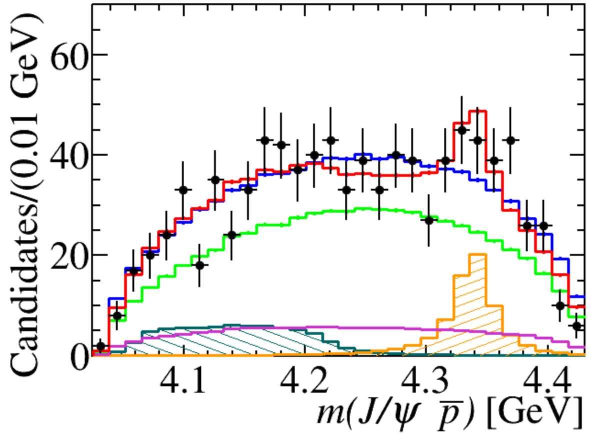
Evidence of a new $J/\psi p$ structure [arXiv:2108.04720]

The measured mass and width:

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\,\text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\,\text{MeV},$$

Can't distinguish J^P due to limited sample size





Other contributions are tested, no evidence is seen:

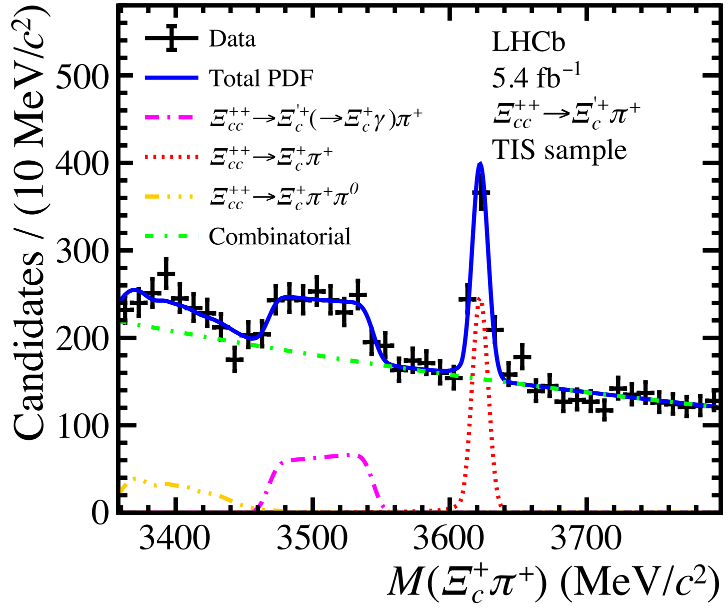
- $P_c(4312)^+$ seen in $\Lambda_b^0 \to J/\psi p K^-$[PRL 122 (2019) 222001]
- Predicted glueball state $f_J(2220)(\to p\overline{p})$[EPJC 75, 101 (2015)]

New decay mode of Ξ_{cc}^{++}

JHEP 05 (2022) 038

- LHCb opens a new era in doubly heavy baryon search
  - Starting with observation of Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$ PRL 119 (2017) 112001
  - Confirmed in $\Xi_c^+ \pi^+$ decay PRL 121 (2018) 162002

JHEP 05 (2022) 038



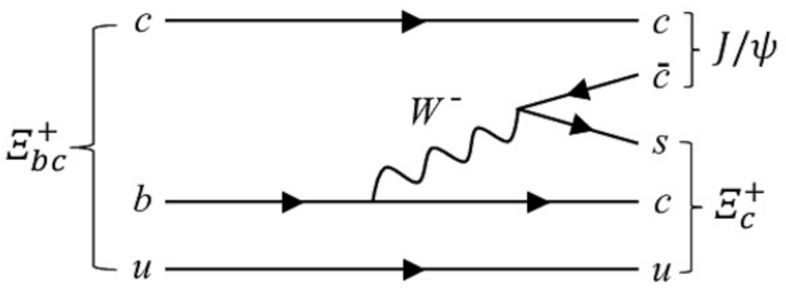
- Recently a new decay $\Xi_c^{\prime +} \pi^+$ found
  - $\Xi_{cc}^{++} \to \Xi_c^{\prime +} (\to \Xi_c^+ \gamma) \pi^+$
  - $\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{\prime +} \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)} = 1.41 \pm 0.17 \pm 0.10$ tension with prediction

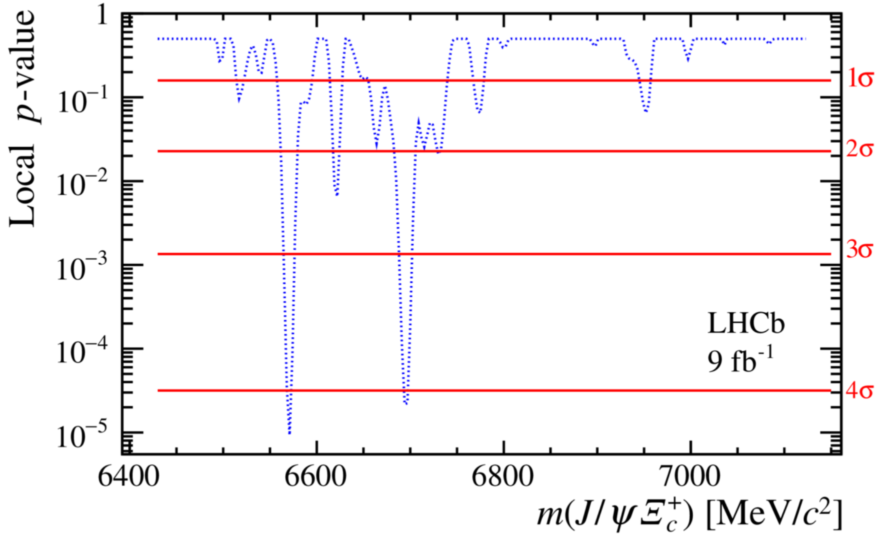
Search of Ξ_{bc}

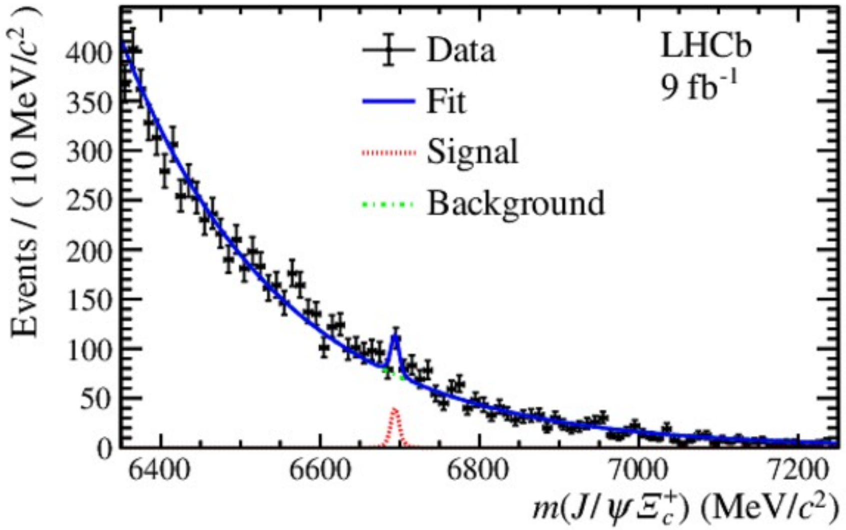
arXiv: 2204.09541 (Accepted by CPC)

- First search for Ξ_{bc}^0 performed
  - $\Xi_{bc}^+ \to J/\psi \Xi_c^+$

	6571 MeV	6694 MeV
Local significance	4.3 σ	4.1 σ
Global significance	2.8 σ	2.4 σ





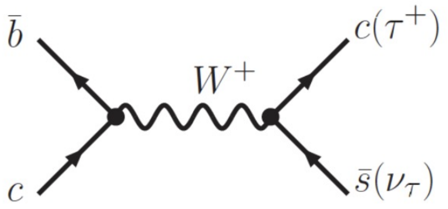


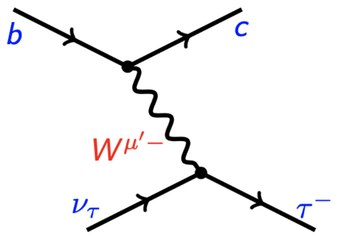
B_c^+ decay BF measurement

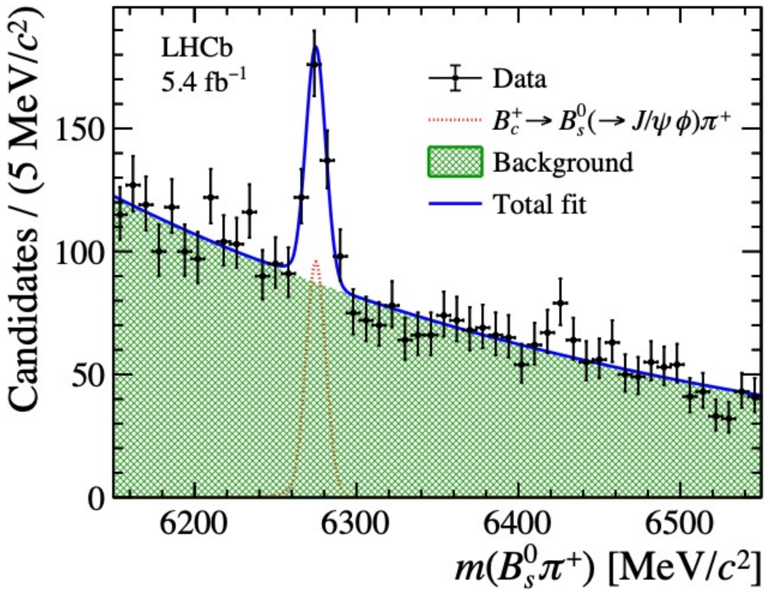
arXiv:2210.12000 (submitted to JHEP)

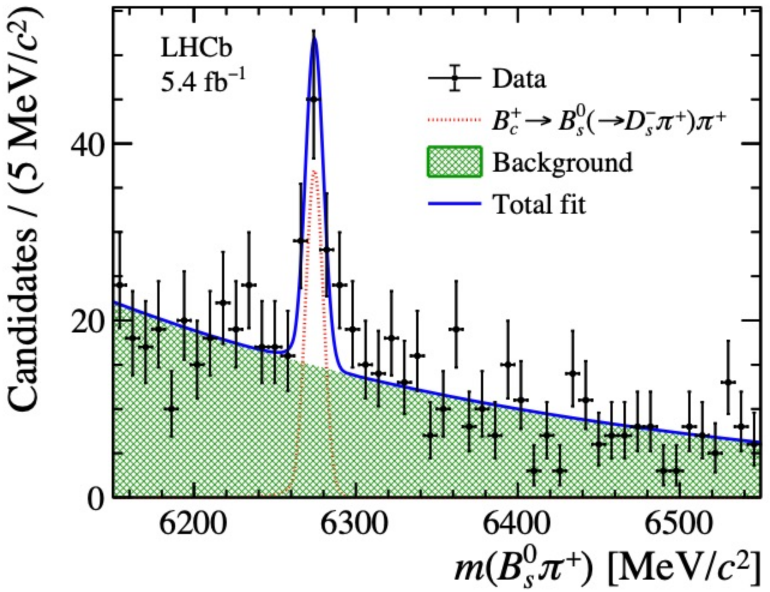
- $B_c^+ \to B_s^0 \pi^+$
  - First B weak decay to another beauty
  - Branching fraction expected to be large, and contributes to more stringent limit on $B_c^+ \to \tau^+ \nu$ decay BF
  - $\frac{\mathcal{B}(B_c^+ \to B_s^0 \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 91 \pm 10 \pm 8 \pm 3$

PRL 111 (2013) 181801





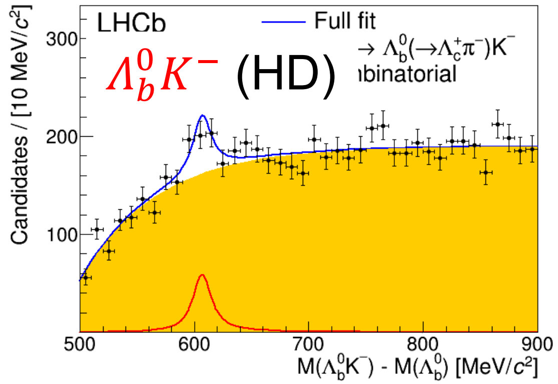


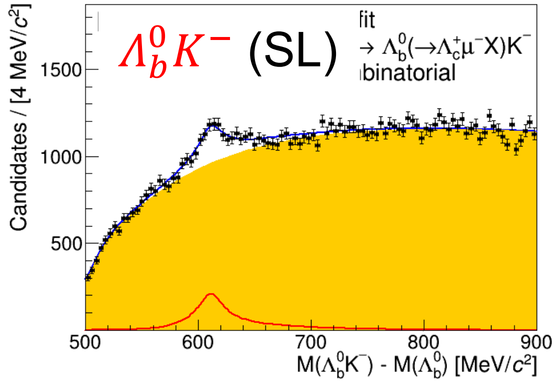


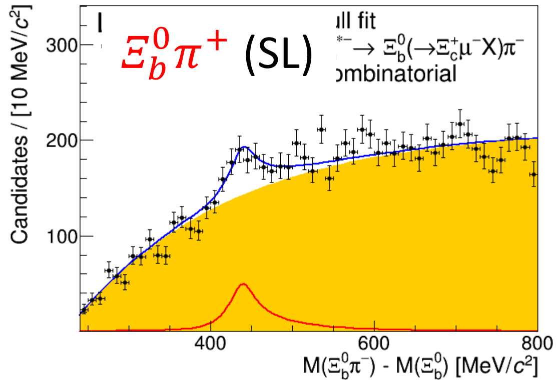
Observation of a new $\Xi_b^{**}(6227)^-$ state

[PRL 121 (2018) 072002]

- Reconstruct $\Xi_b^- \to \Lambda_b^0 K^-$ and $\Xi_b^0 \pi^+$
  - Hadronic (HD) and Semileptonic (SL) decays for Λ_b^0
  - SL decays for $\Xi_b^0 \to \Xi_c^+ \mu^- X \bar{\nu}_\mu$







- With hadronic mode

$$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst})\ \text{MeV}/c^2,$$
$$\Gamma = 18.1 \pm 5.4\,(\text{stat}) \pm 1.8\,(\text{syst})\ \text{MeV}/c^2,$$
$$M(\Xi_b^{**-}) = 6226.9 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV}/c^2,$$

Mass peak position is consistent between the three decay channels

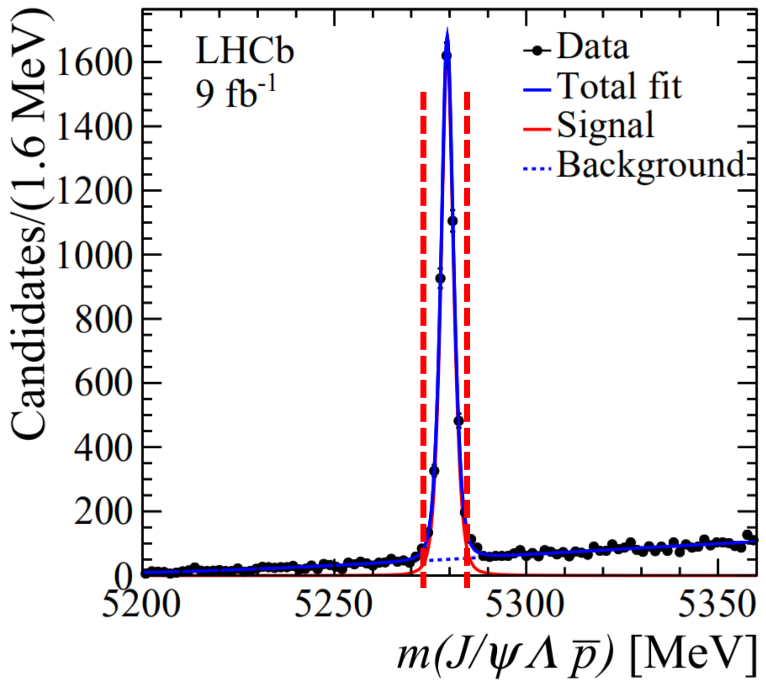
The most massive baryons observed so far!

Pentaquark study in $B^- \to J/\psi\Lambda\bar{p}$

- Search for pentaquark in $J/\psi p$ & $J/\psi\Lambda$

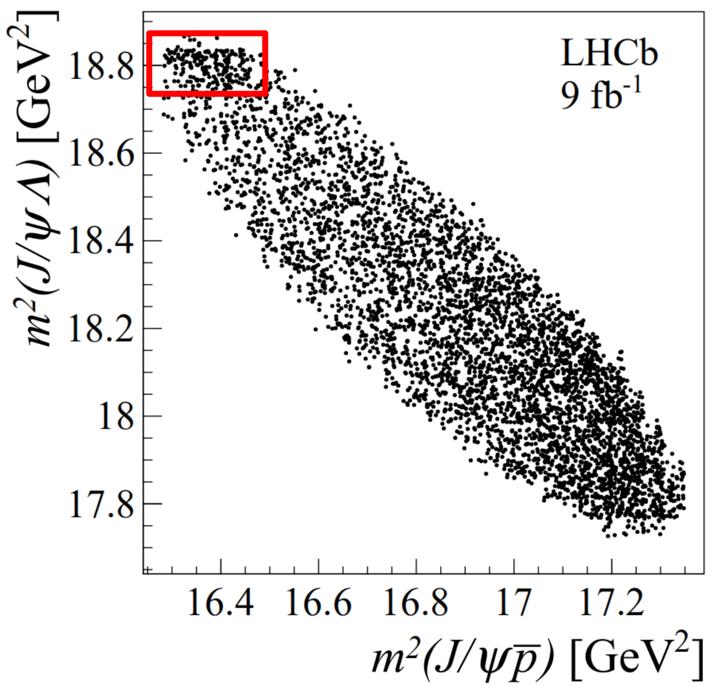
arXiv: 2210.10346

- Run1+Run2 LHCb data, $\mathcal{L} = 9\ \mathrm{fb}^{-1}$



$N_{sig} = \mathbf{4617 \pm 73}$

Purity in signal region : 93%



Horizontal band at $m^2(J/\psi\Lambda) \sim 18.8\mathrm{GeV}^2$

Further confirmed by amplitude analysis