Recent results on spectroscopy with LHCb

(On behalf of the LHCb experiment)

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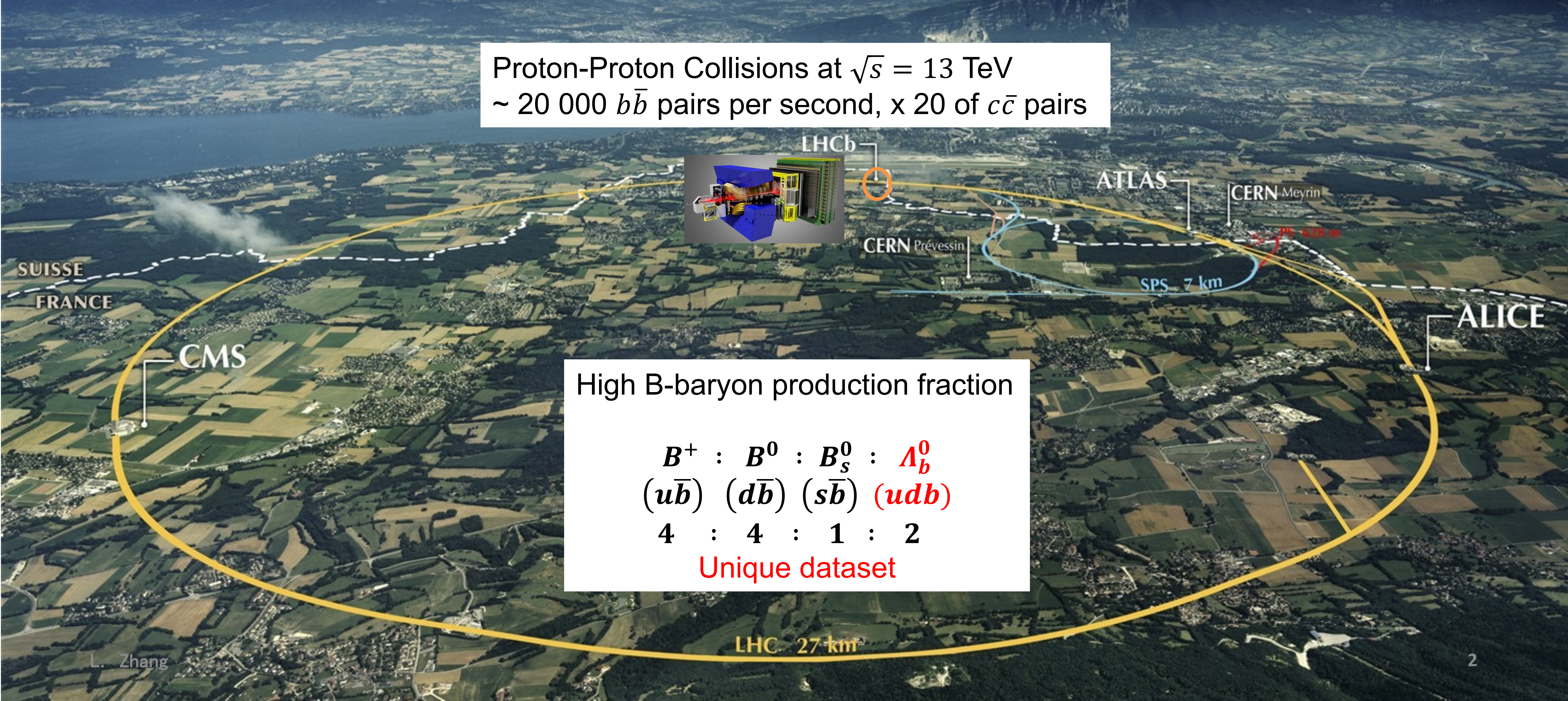
BEAUTY 2023

Clermont-Ferrand, 3-7 July 2023

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

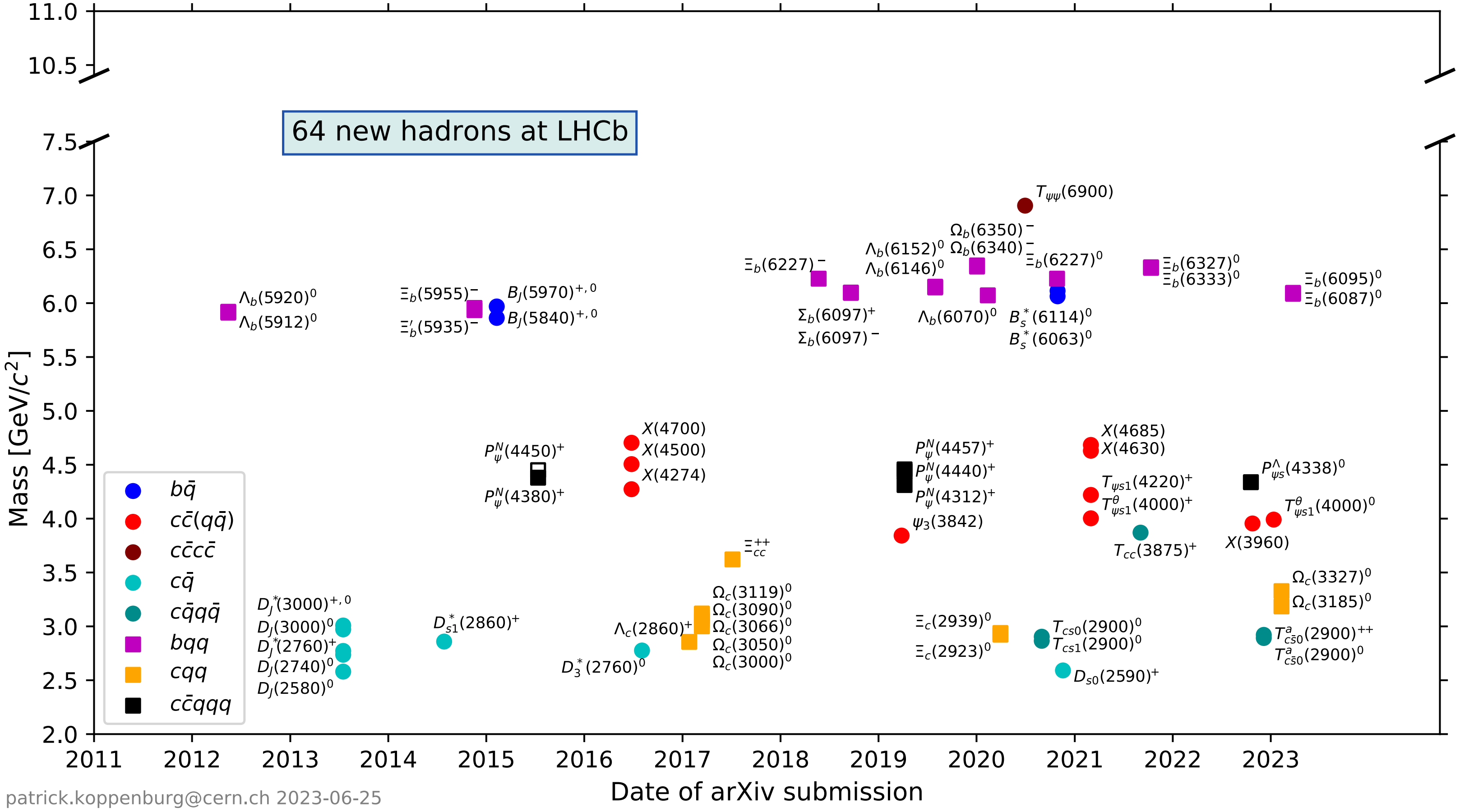
$$\boldsymbol{B^+ : B^0 : B_s^0 : \Lambda_b^0}$$
$$\boldsymbol{(u\bar{b})\ (d\bar{b})\ (s\bar{b})\ (udb)}$$
$$\boldsymbol{4 : 4 : 1 : 2}$$

Unique dataset

New particles in a glance

- 72 new hadrons discovered by LHC, 64 from LHCb!

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



Exotic hadron naming convention: arXiv:2206.15233

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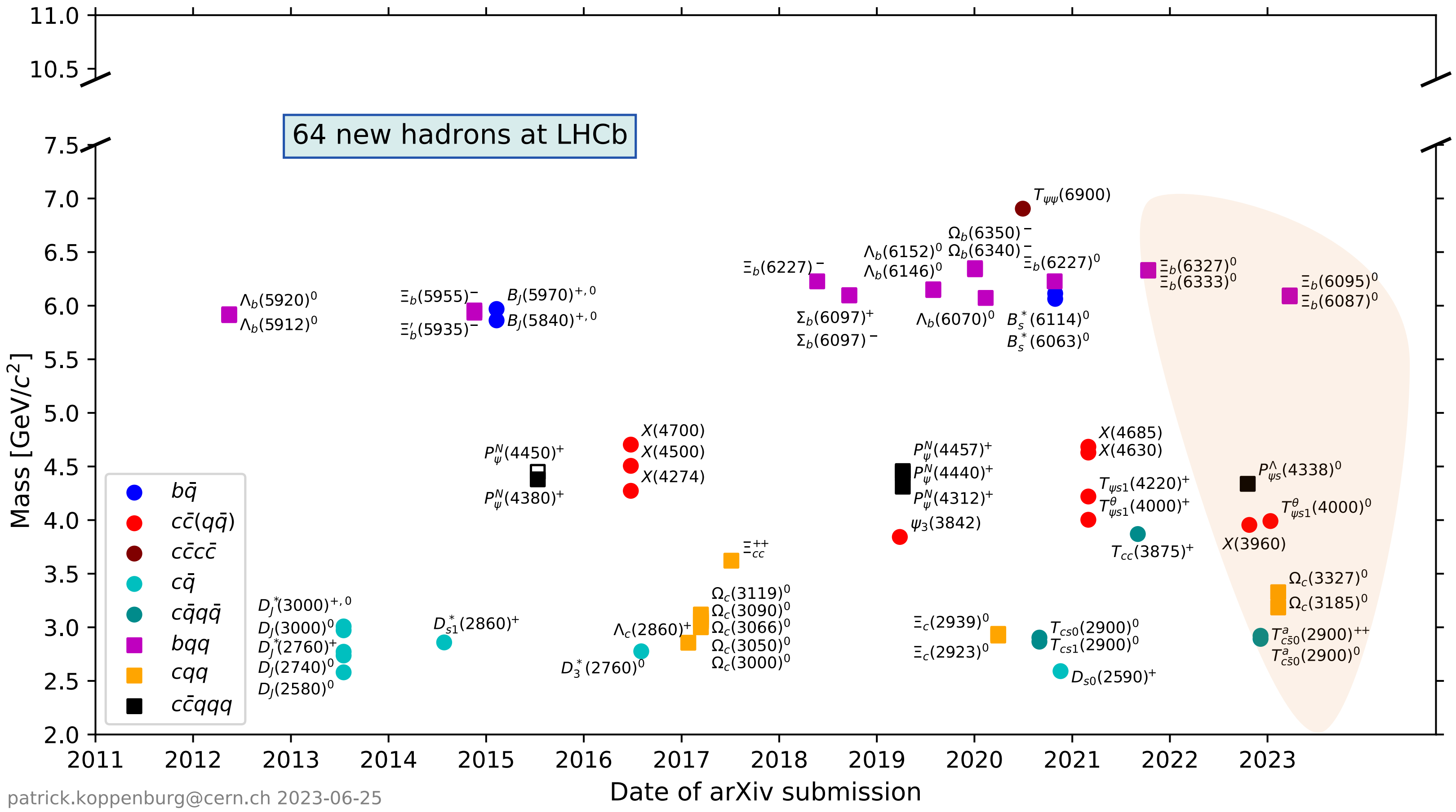


Exotic hadron naming convention: arXiv:2206.15233

Contents

- Conventional states
  - Charm baryons: Ω_c^{**}
  - Beauty baryons: Ξ_b^{**}

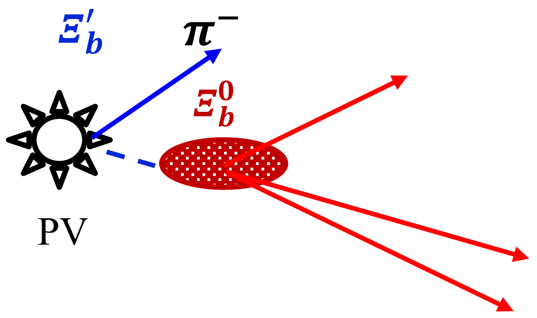
- Exotic hadrons
  - Tetraquark states:

    $T_{c\bar{s}0}^{a}(2900)^{++/0}, T_{\psi s1}^{\theta}(4000)^{0}, X(3960),$
  - Pentaquark states: $P_{\psi s}^{\Lambda}(4338)^{0}$

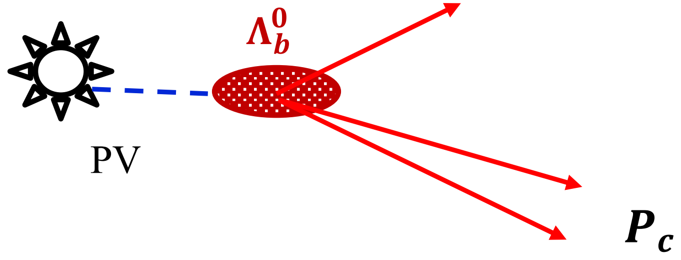
Full list: https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html

Two methods for spectroscopy

- Direct production in pp collisions
  - Usually 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



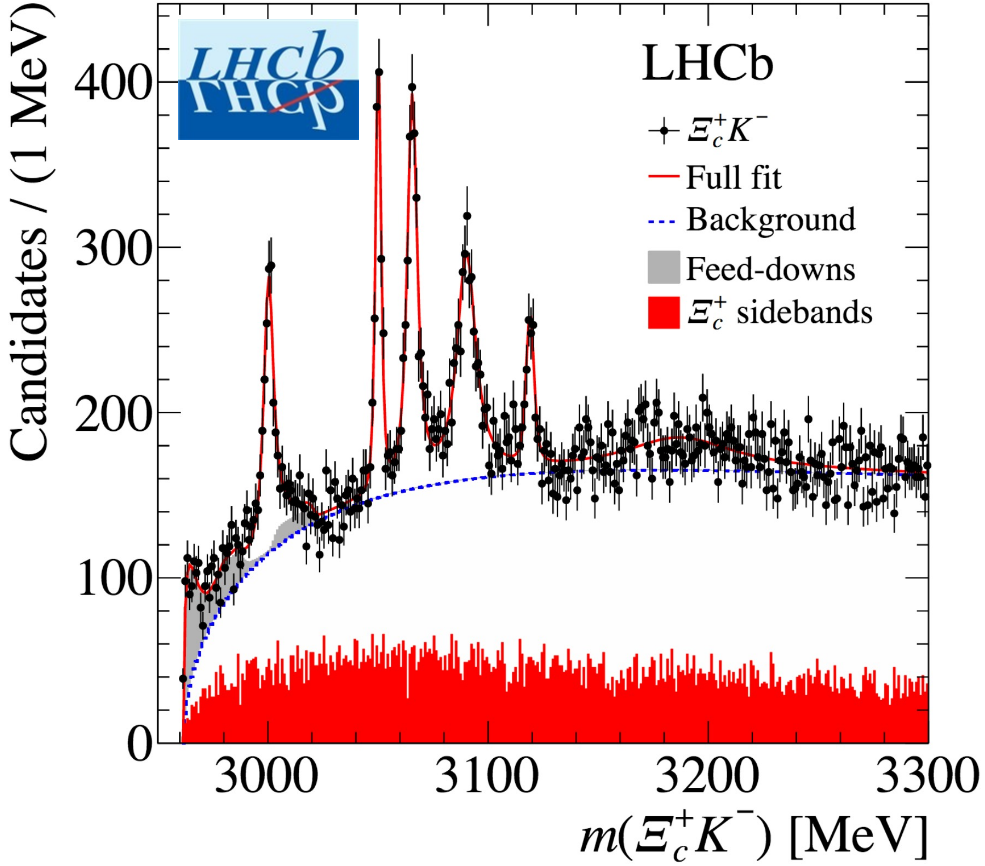
- Production by a heavier particle decay
  - Usually with amplitude analysis
  - Pros: Low background, Better determination of J^P
  - Cons: Low cross-section, limited mass range



Excited $\Omega_c \to \Xi_c^+ K^-$ states

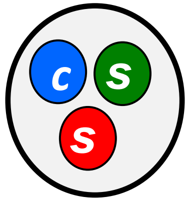
- LHCb observed 5 narrow states (+ a possible wide one) in 2017
- Belle confirmed the first four states [PRD 97 (2018) 051102]

[PRL 118 (2017) 182001]



Mass splitting 20-50 MeV

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ <1.2 MeV, 95% C.L.	$970 \pm 60 \pm 20$	20.4
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$ <2.6 MeV, 95% C.L.	$480 \pm 70 \pm 30$	10.4
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{fd}$			$190 \pm 70 \pm 20$	

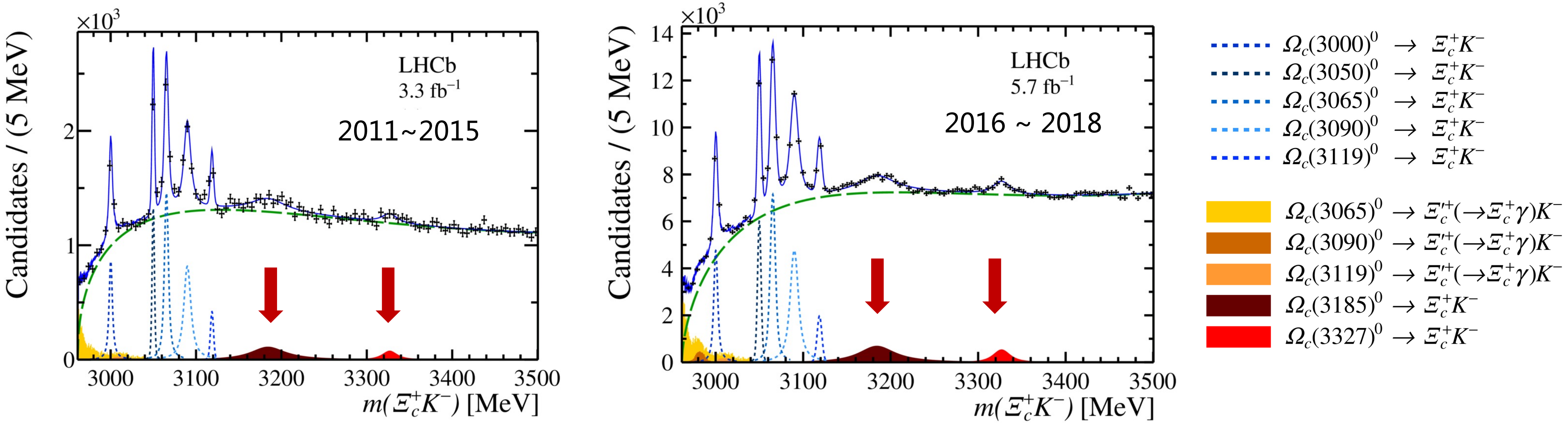


New Ω_c states in $\Xi_c^+ K^-$ final state

arXiv:2302.04733

- Search updated with full Run 1+2 data
  - Five states confirmed
  - Two new states observed near ΞD, ΞD^* thresholds

	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 MeV, 95% C.L.
	$\Omega_c(3065)^0$	$3065.63 \pm 0.06\,^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\,^{+0.38}_{-0.47}$
	$\Omega_c(3090)^0$	$3090.16 \pm 0.11\,^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\,^{+0.61}_{-1.62}$
	$\Omega_c(3119)^0$	$3118.98 \pm 0.12\,^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\,^{+0.90}_{-1.05}$
new			< 2.5 MeV, 95% C.L.
→	$\Omega_c(3185)^0$	$3185.1 \pm 1.7\,^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\,^{+10}_{-20}$
→	$\Omega_c(3327)^0$	$3327.1 \pm 1.2\,^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\,^{+13}_{-1}$



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

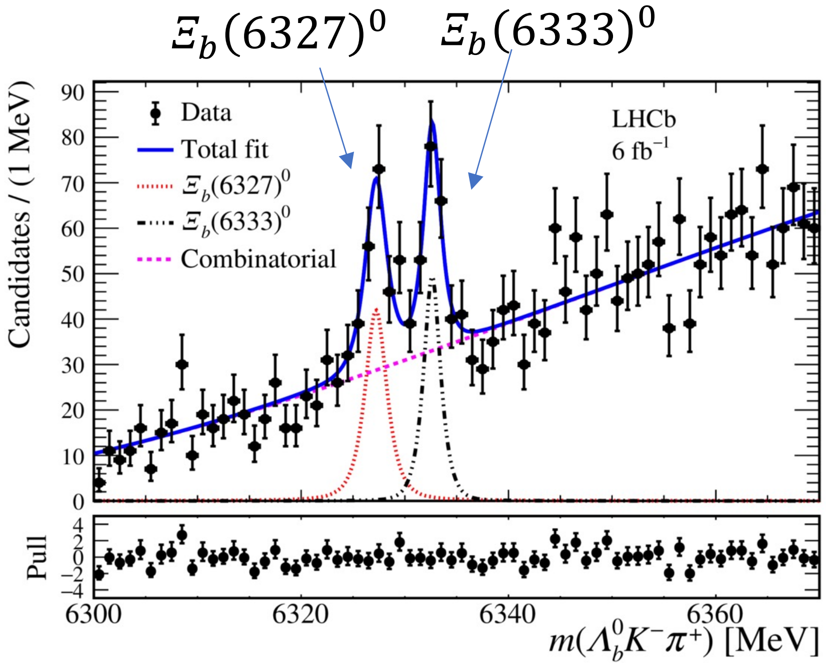
$$m_{\Xi_b(6327)^0} = 6327.28\,^{+0.23}_{-0.21}(\text{stat}) \pm 0.12(\text{syst}) \pm 0.24(m_{\Lambda_b^0})\ \text{MeV}$$

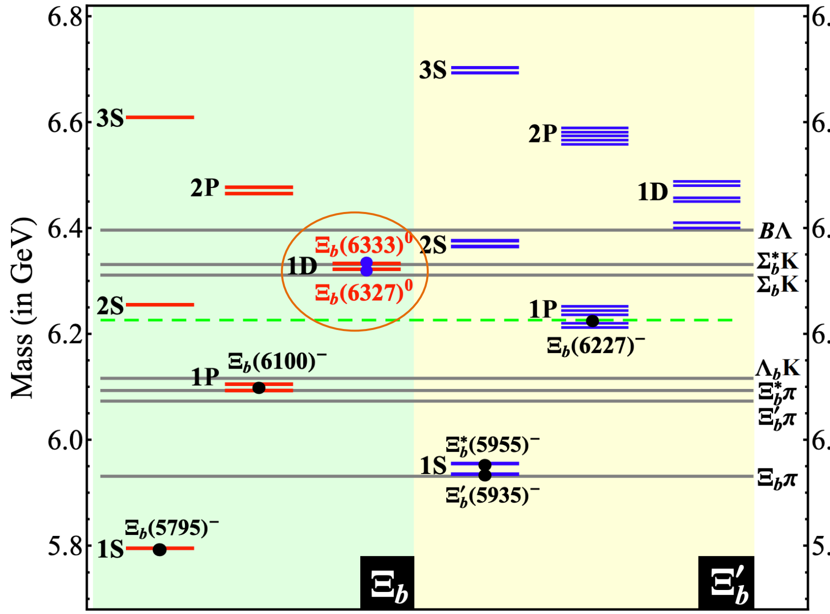
$$m_{\Xi_b(6333)^0} = 6332.69\,^{+0.17}_{-0.18}(\text{stat}) \pm 0.03(\text{syst}) \pm 0.22(m_{\Lambda_b^0})\ \text{MeV}$$

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

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

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





Bing Chen et. al. PRD 98 (2018) 031502(R)

New Ξ_b^{**} baryons

LHCb-PAPER-2023-008 (In preparation)

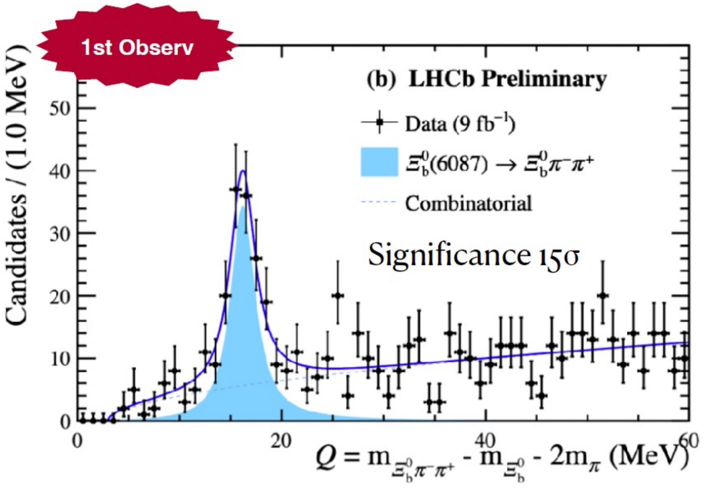
- Search for new $\Xi_b^{**-/0}(bsq)$ states in $\Xi_b^{-/0}\pi^+\pi^-$ final states
  - $\Xi_b^{-/0} \to \Xi_c^{0/+}\pi^-$ and $\Xi_c^{0/+}\pi^-\pi^+\pi^-$ (max. 9 tracks!)
- Observation of two new states:
  - $\Xi_b(6087)^0 \to \Xi_b'^-\pi^+ \to [\Xi_b^0\pi^-]\pi^+$
  - $\Xi_b(6095)^0 \to \Xi_b^{*-}\pi^+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

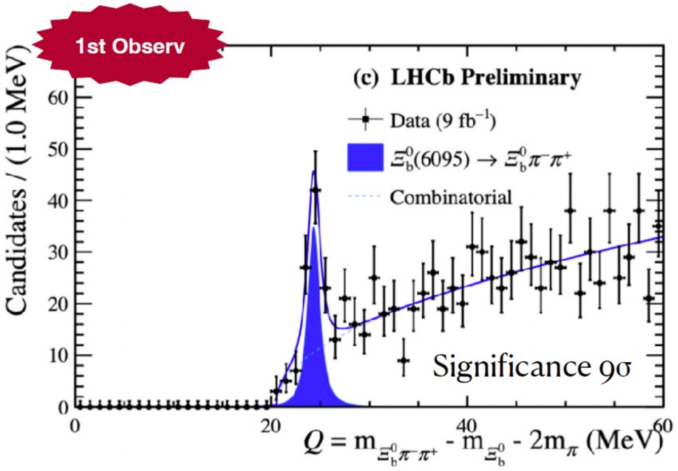
	Value [MeV]
Q_0 ($\Xi_b^-(6100)$)	$23.60 \pm 0.11 \pm 0.02$
Γ ($\Xi_b^-(6100)$)	$0.94 \pm 0.30 \pm 0.08$
m_0 ($\Xi_b^-(6100)$)	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6$ (Ξ_b^-)
Q_0 ($\Xi_b^0(6087)$)	$16.20 \pm 0.20 \pm 0.06$
Γ ($\Xi_b^0(6087)$)	$2.43 \pm 0.51 \pm 0.10$
m_0 ($\Xi_b^0(6087)$)	$6087.24 \pm 0.20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

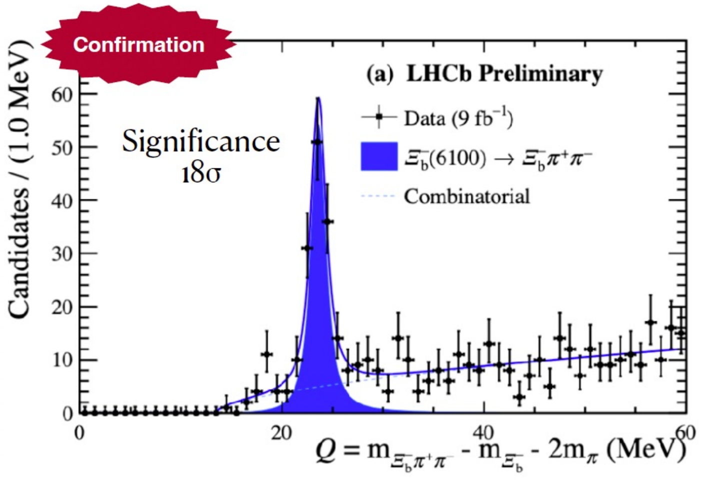
Confirmation

1st Observ

Improvements







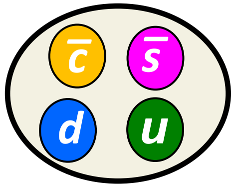
Open flavor tetraquark

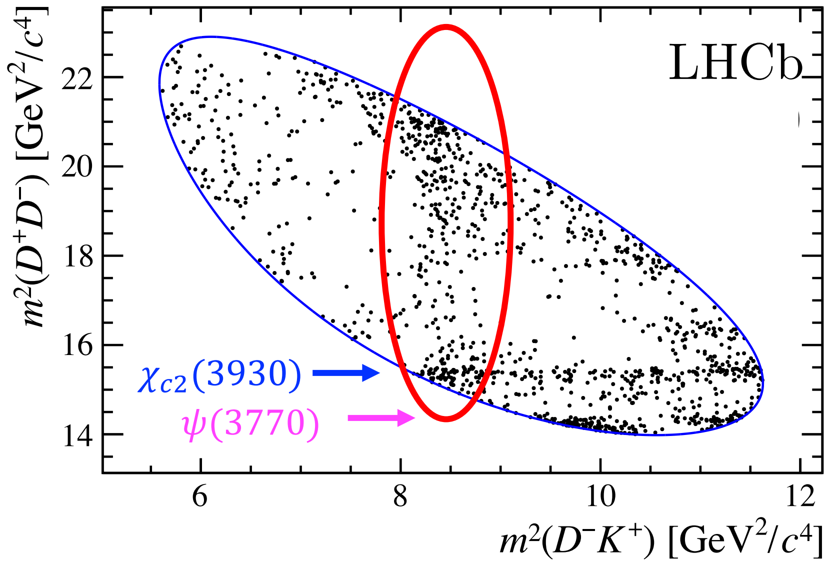
First discovery of open-charm tetraquark candidates with four different flavors $[cs\bar{u}\bar{d}]$

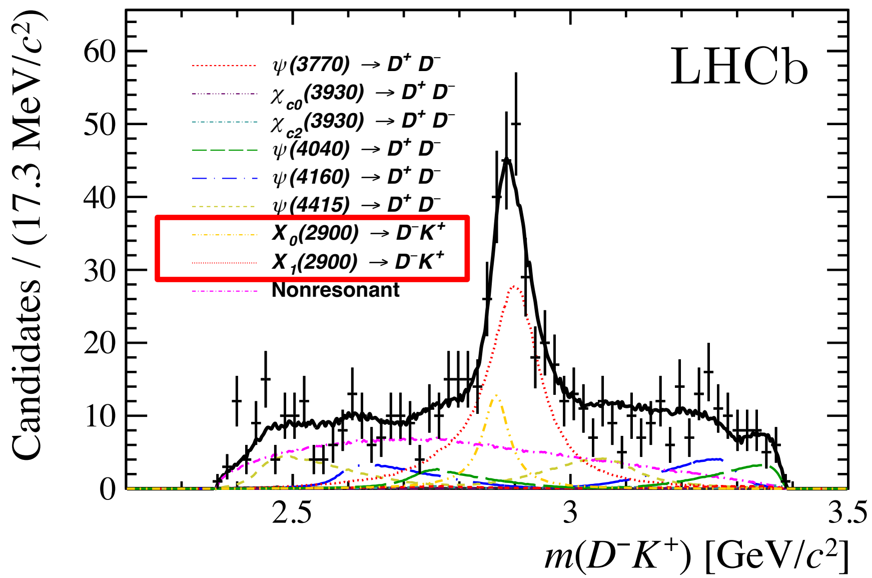
- Resonant structures observed in the D^-K^+ system from an amplitude analysis of the $B^+ \to D^+D^-K^+$ decay

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

$m(D^+D^-) > 4\ \mathrm{GeV}/c^2$







$$X_0(2900): \quad M = 2.866 \pm 0.007 \pm 0.002\,\mathrm{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\,\mathrm{MeV}$$
$$X_1(2900): \quad M = 2.904 \pm 0.005 \pm 0.001\,\mathrm{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\,\mathrm{MeV}$$

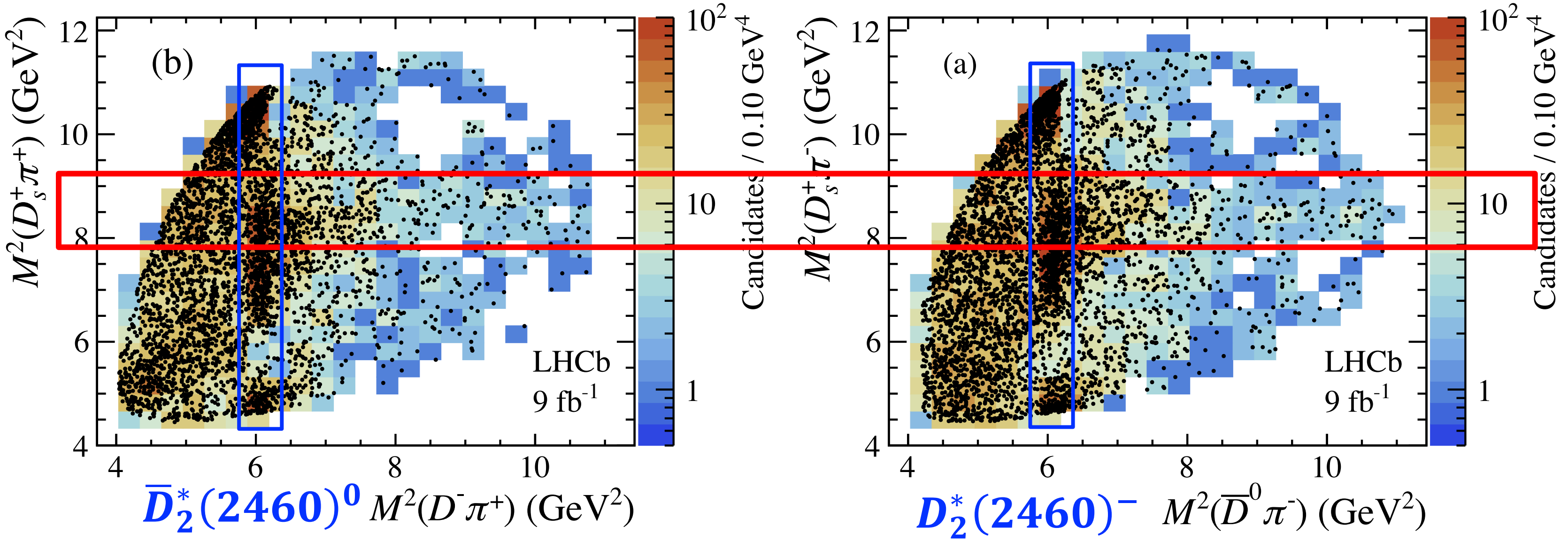
Study of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

[arXiv: 2212.02716]

- Full 9 fb^{-1} Run1+Run2 LHCb data

  ⇒ 4420 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ candidates with signal purity of 90.7%

  3940 $B^+ \to D^- D_s^+ \pi^+$ candidates with signal purity of 95.2%



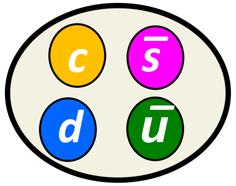
✓Faint horizontal band at $M^2(D_s^+\pi) \approx 8.5\ \mathrm{GeV}^2$ indicating $T_{c\bar{s}}$ candidates

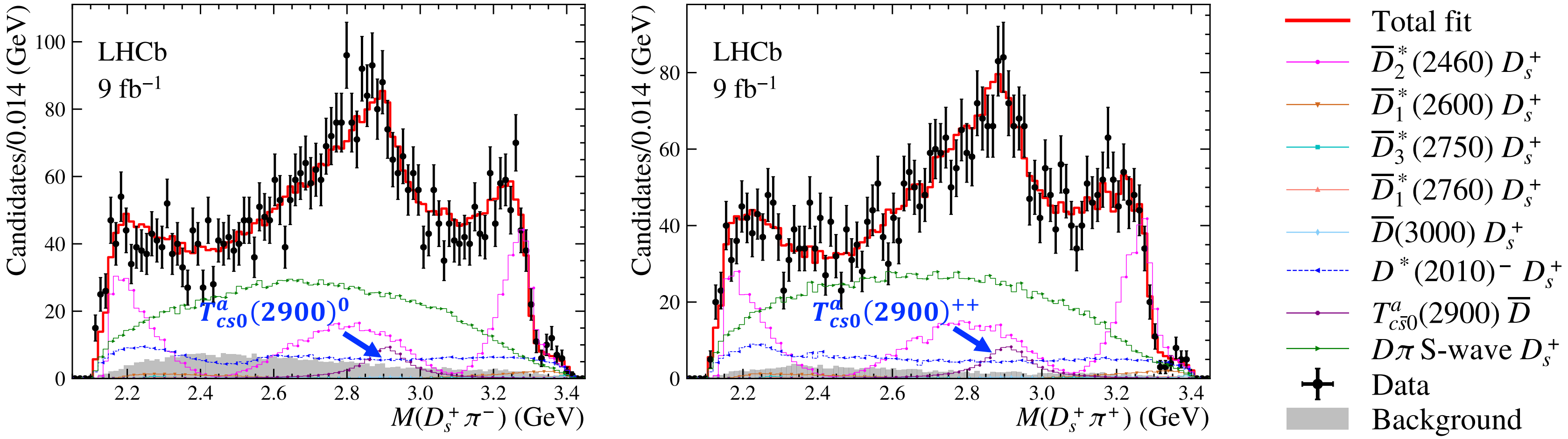
⇒ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

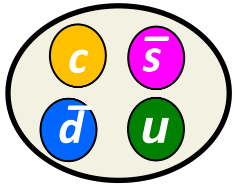
Observation of $T^{a}_{c\bar{s}0}(2900)^{0/++}$

[arXiv: 2212.02716]

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







➢ $T^{a}_{c\bar{s}0}(2900)^{0} \rightarrow D_s^+\pi^-$ & $T^{a}_{c\bar{s}0}(2900)^{++} \rightarrow D_s^+\pi^+$ significance $> 9\sigma$

First discovery of doubly-charged tetraquark candidate

➢ $J^P = 0^+$ favored over other spin-parity by more than 7.5σ

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

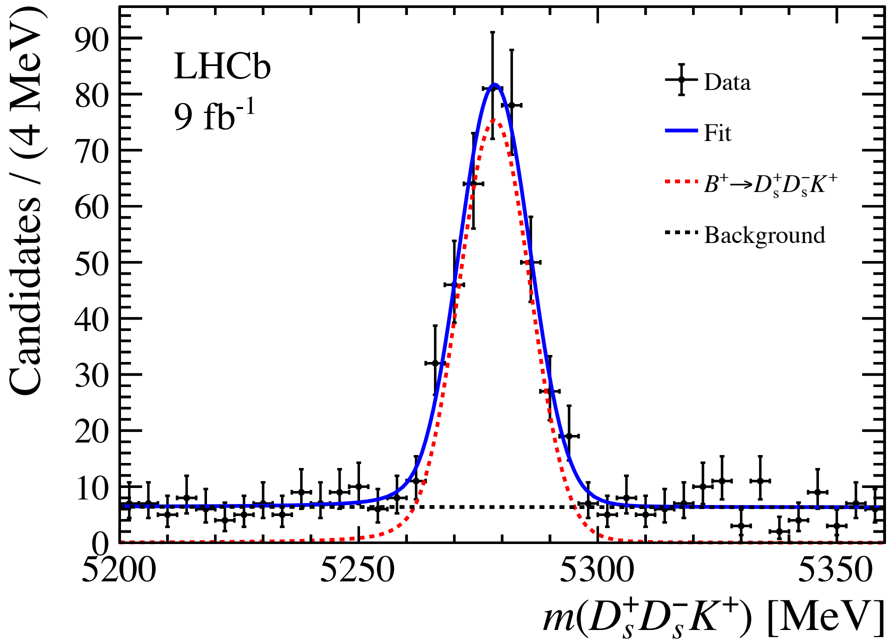
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\ \text{GeV}$$

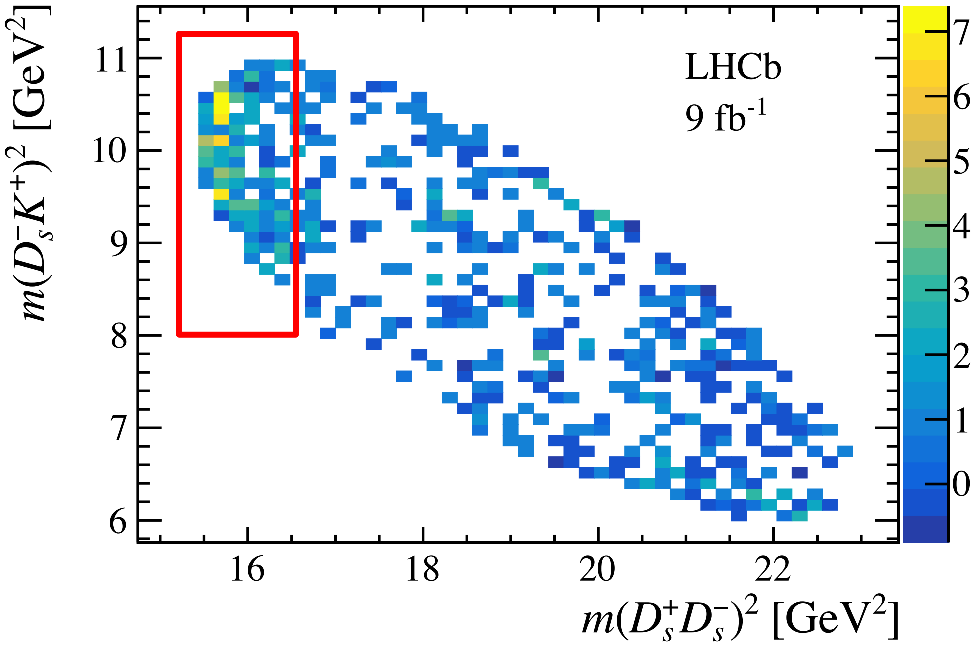
vs $X_0(2900)$: Similar mass, but different width and flavor contents

Observation of $B^+ \to D_s^+ D_s^- K^+$

[arXiv: 2211.05034]

- Full 9 fb^{-1} Run1+Run2 LHCb data





$N_{\text{sig}} = 360 \pm 22$

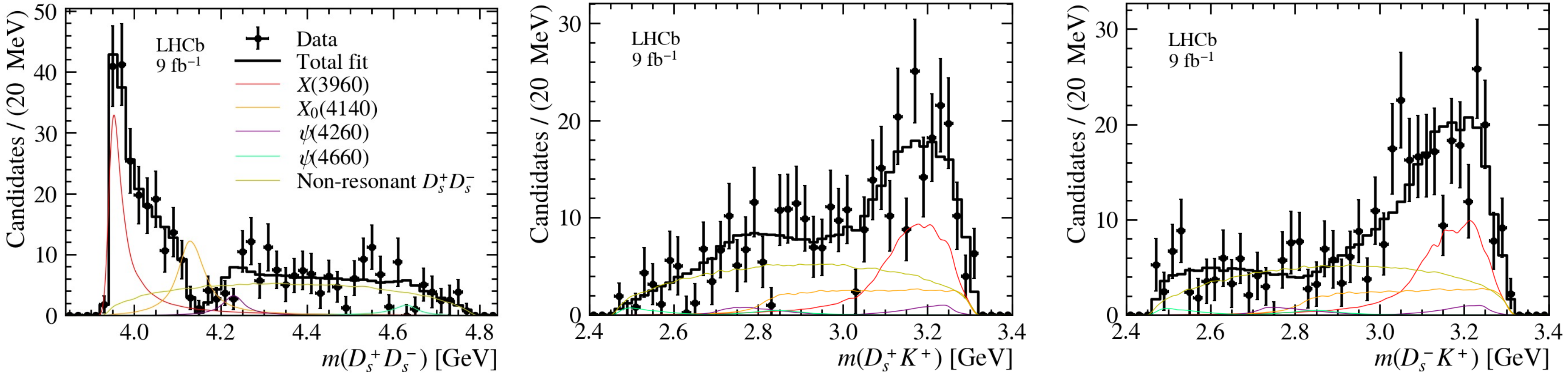
Purity: 84%

✓Near-threshold enhancement in $m(D_s^+ D_s^-)$

⇒ amplitude analysis

Observation of $X(3960) \to D_s^+ D_s^-$ [arXiv: 2210.15153]

- Baseline model well describes data
  - 0^{++}: $X(3960)$ (14.3σ), $X_0(4140)$ (3.9σ), Non-resonant
  - 1^{--}: $\psi(4260)$, $\psi(4660)$



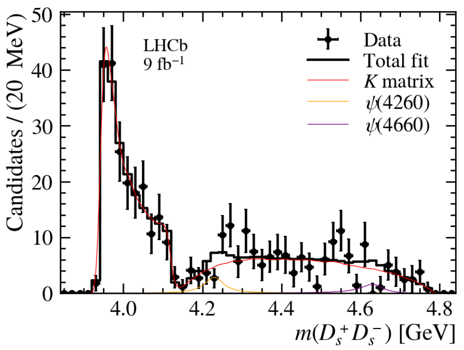
➢ $X(3960)$: threshold enhancement

✓ $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ

➢ $X_0(4140)$: dip at ~ 4.14 GeV via interference

✓ $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 3.5σ and 4.2σ

✓ the dip can also be described by $J/\psi\phi \leftrightarrow D_s^+ D_s^-$ scattering



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

[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 $c\bar{c}s\bar{s}$

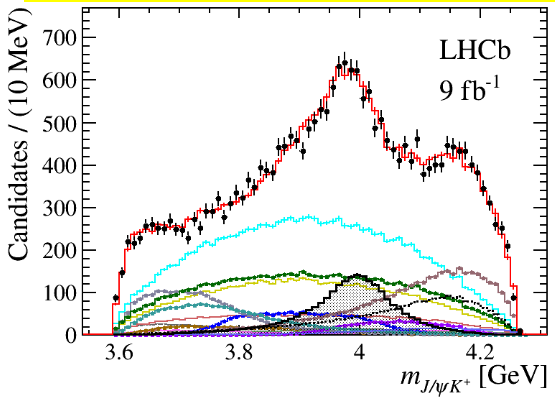
- Different particles?
  - No obvious candidate within conventional charmonium multiplets for them; likely to be exotic

Z_{cs} $[c\bar{c}u\bar{s}]$ states

- Charged Z_{cs} states observed at BESIII and LHCb: $Z_{cs}(3985)^{\pm}$, $Z_{cs}(4000)^{\pm}$, $Z_{cs}(4220)^{\pm}$
- $Z_{cs}(3985)^{\pm}$, $Z_{cs}(4000)^{\pm}$ have similar mass but very different widths
- BESIII also find an evidence for the neutral isospin partner

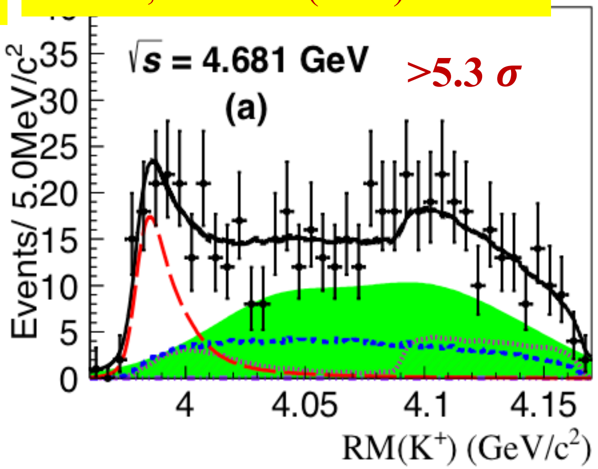
$B^+ \to J/\psi K^+ \phi$

LHCb, PRL127 (2021) 082001



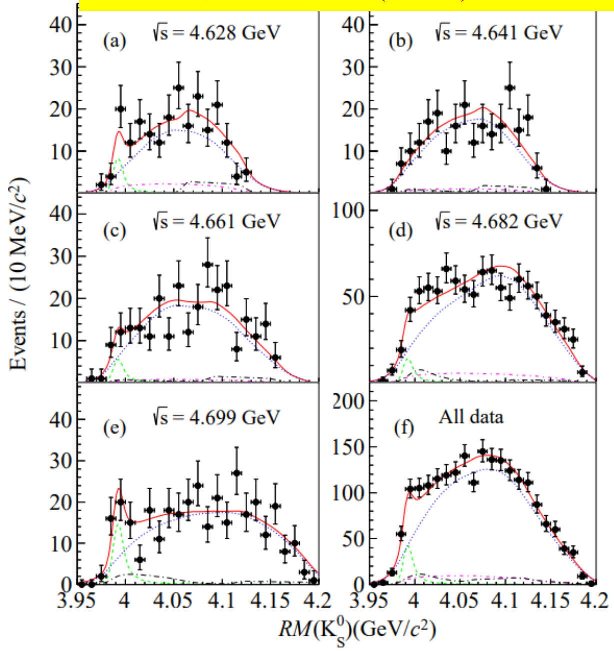
$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

BESIII, PRL 126 (2021) 102001



$e^+e^- \to K_S^0(D_s^- D^{*+} + D_s^{*-} D^+)$

BESIII, PRL 129 (2022) 112003



LHCb

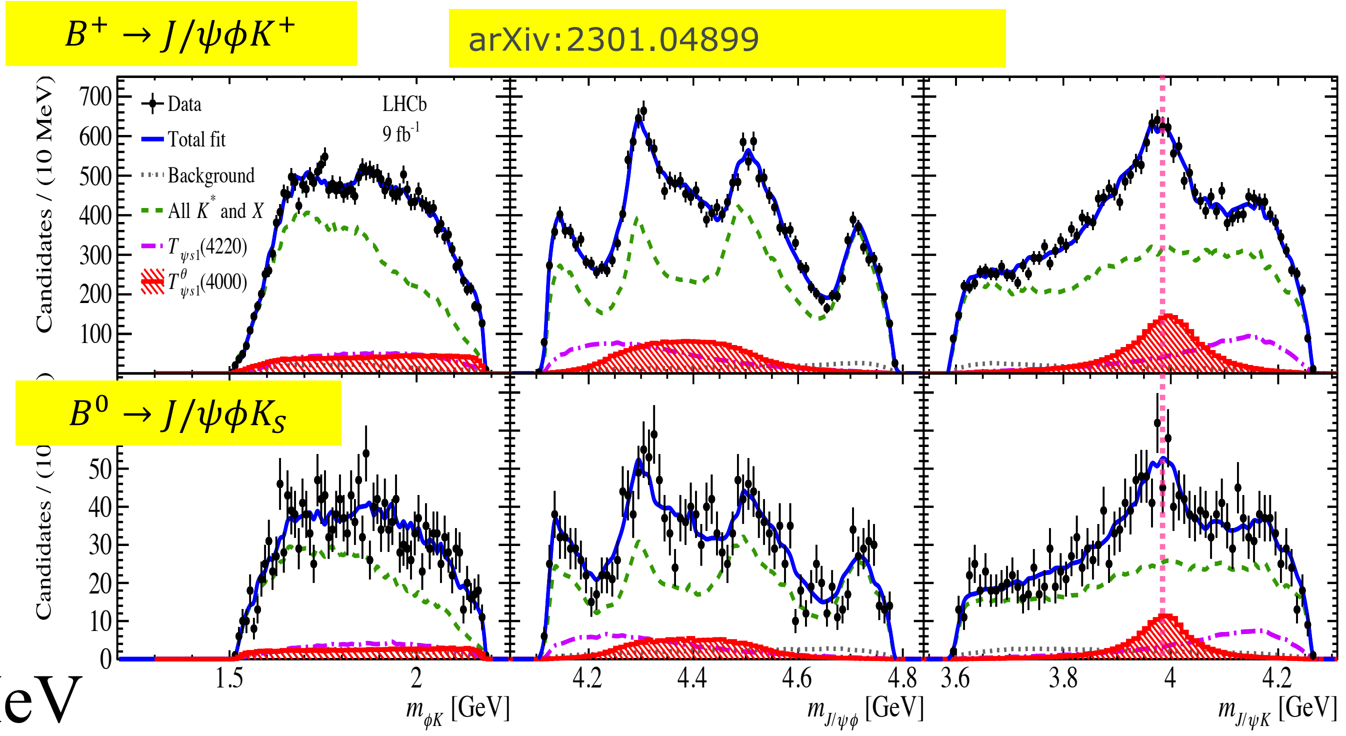
		Mass [MeV]	width [MeV]	
All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

BESIII

	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

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

- Simultaneous fit to $B^0 \to J/\psi\phi K_S$ and $B^+ \to J/\psi\phi K^+$, assuming isospin symmetry for all the intermediate states, except for the charged and neutral $T_{\psi s1}^{\theta}(4000)$ states
- Consistent with being isospin partners: $\Delta m = -12.1^{+11.1+6.0}_{-10.2-4.2}$ MeV



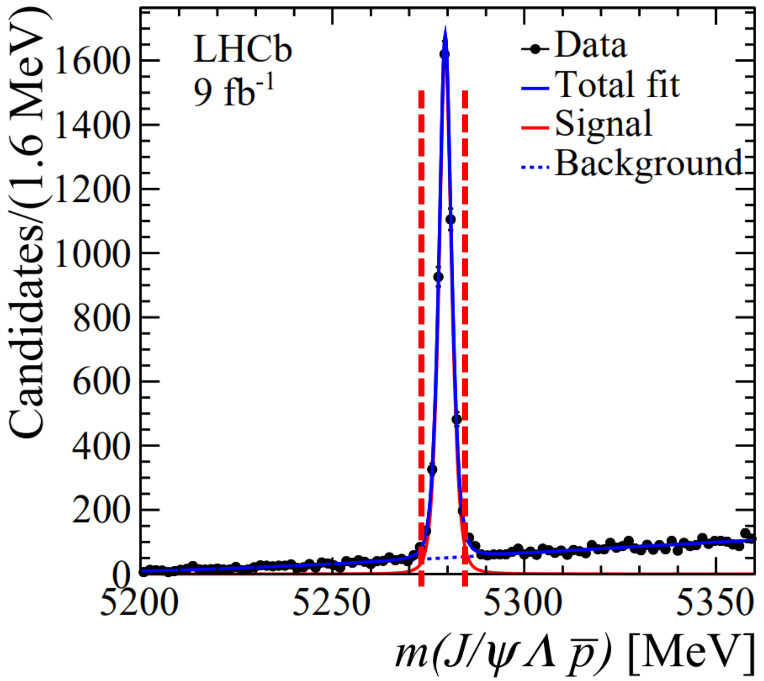
- Significance is 4.0σ without isospin symmetry for $T_{\psi s1}^{\theta}(4000)$, while 5.4$\sigma$ with isospin symmetry constrain

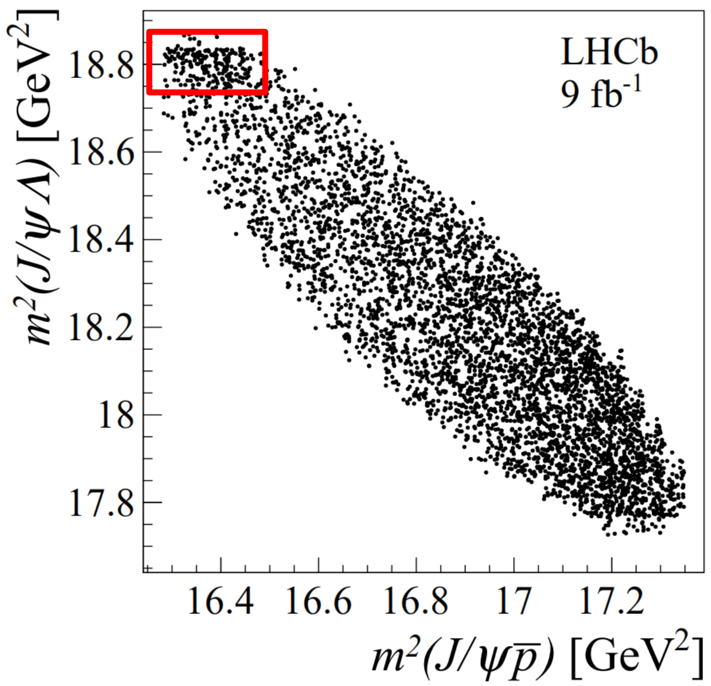
	J^P	Mass (MeV/c^2)	Width (MeV)	Fit fraction
$T_{\psi s1}^{\theta}(4000)^0 \to J/\psi K_S^0$	1^+	$3991.3^{+11.7+8.5}_{-10.4-16.7}$	$104.8^{+29.3+17.1}_{-25.3-23.3}$	$7.9 \pm 2.5^{+3.0}_{-2.8}$
$Z_{cs}^+ / T_{\psi s1}^{\theta}(4000)^+ \to J/\psi K^+$	1^+	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$

$Z_{cs}(4000)^+ = T_{\psi s1}^{\theta}(4000)^+$ in the new naming convention

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, $\mathcal{L} = 9\ \text{fb}^{-1}$
- Most precise single measurement of B^- mass:
  - $\mathbf{5279.44 \pm 0.05 \pm 0.07}$ **MeV**





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

Purity in signal region : 93%

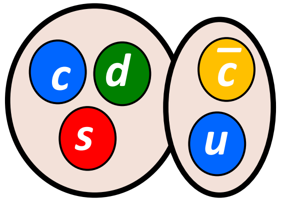
Horizontal band at $m^2(J/\psi\Lambda) \sim 18.8\text{GeV}^2$

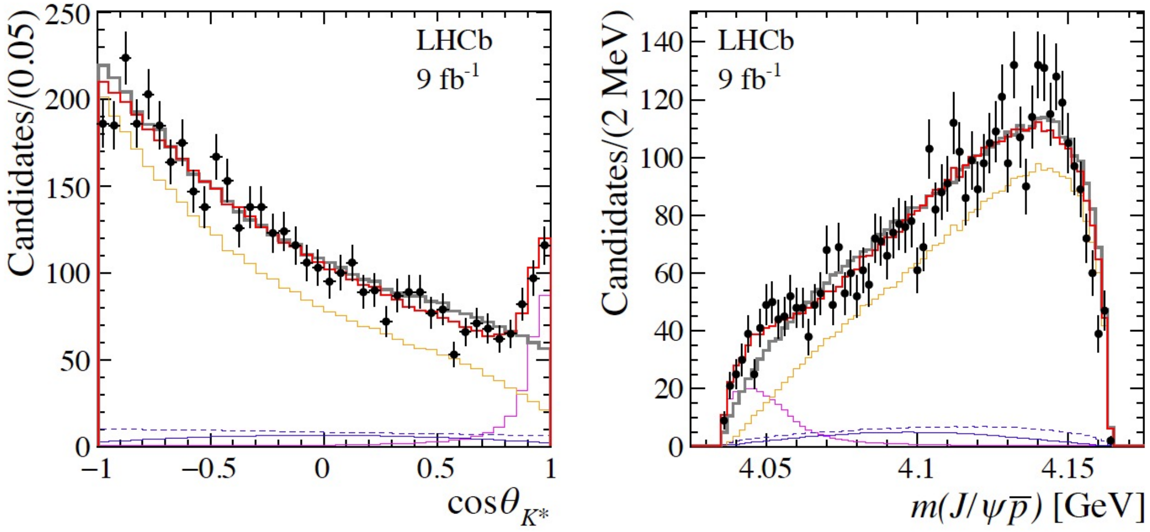
Further confirmed by amplitude analysis

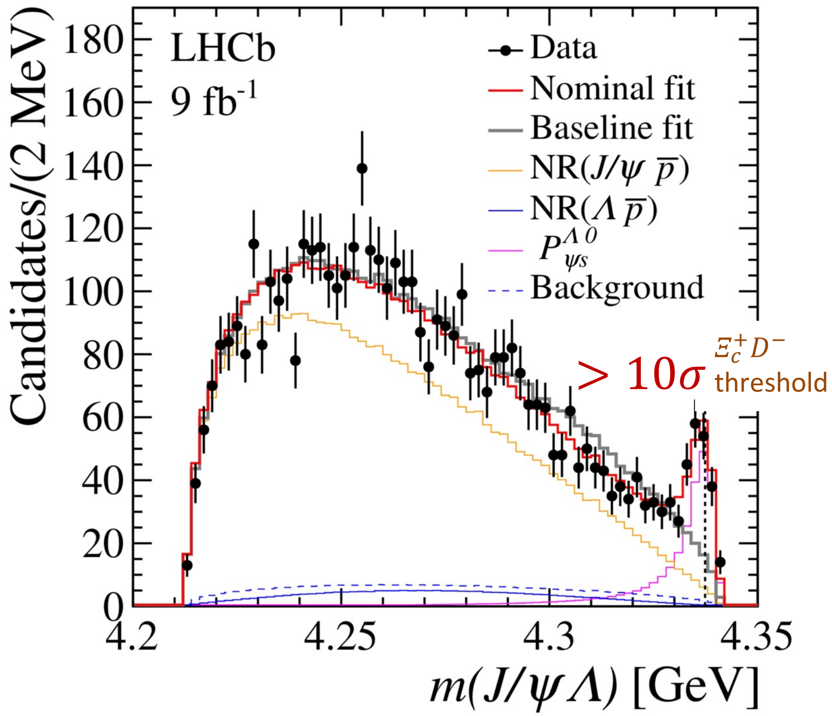
Pentaquark with strangeness

arXiv: 2210.10346

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

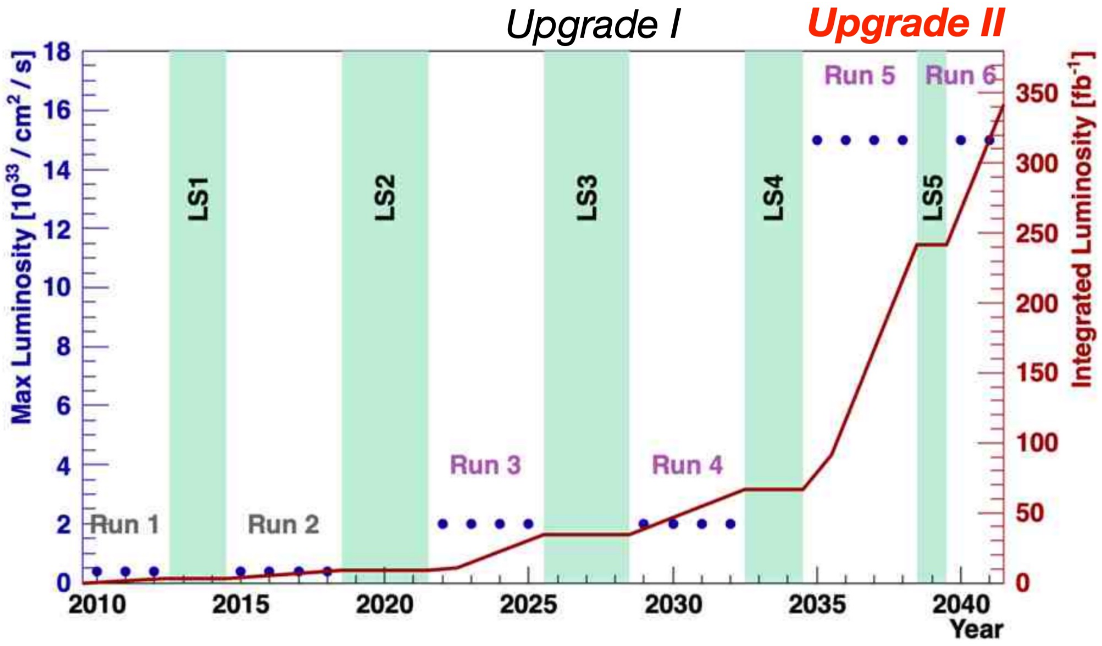






Summary and prospects

- LHCb keeps making important contributions to heavy hadron spectroscopy, both for conventional and exotic hadrons
- With the upgraded LHCb detector and an improved software-only trigger system in Run 3, **more exciting results are to come!**



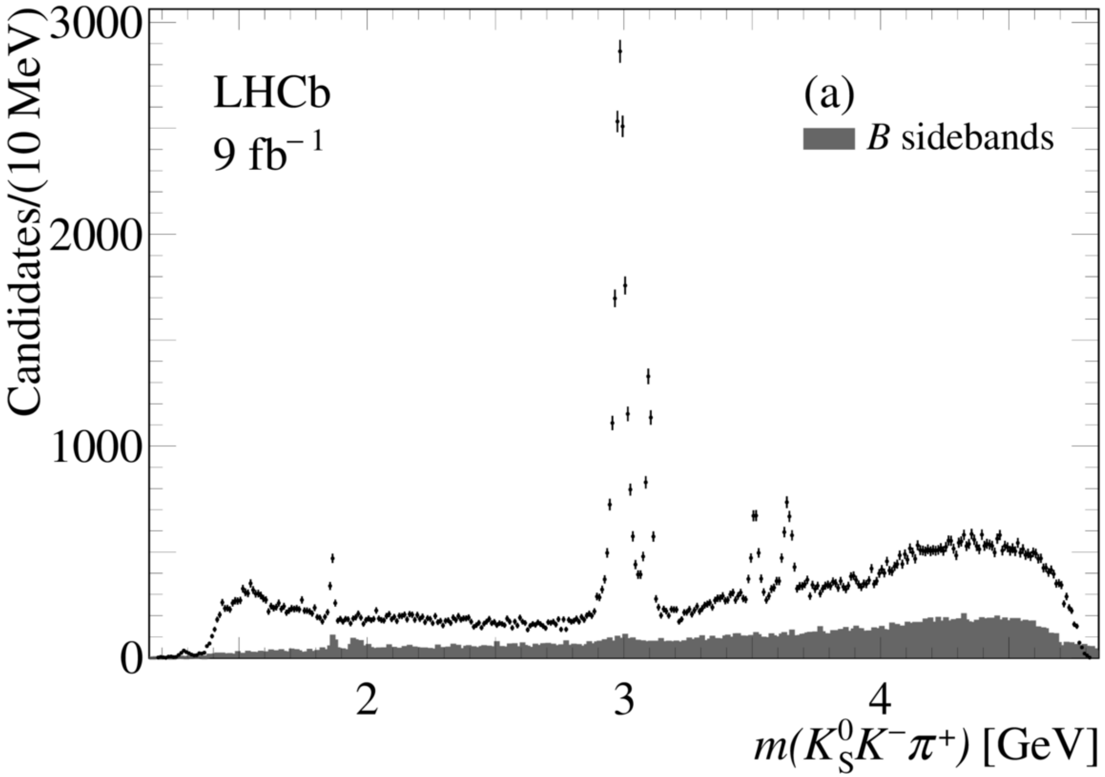
BACKUP

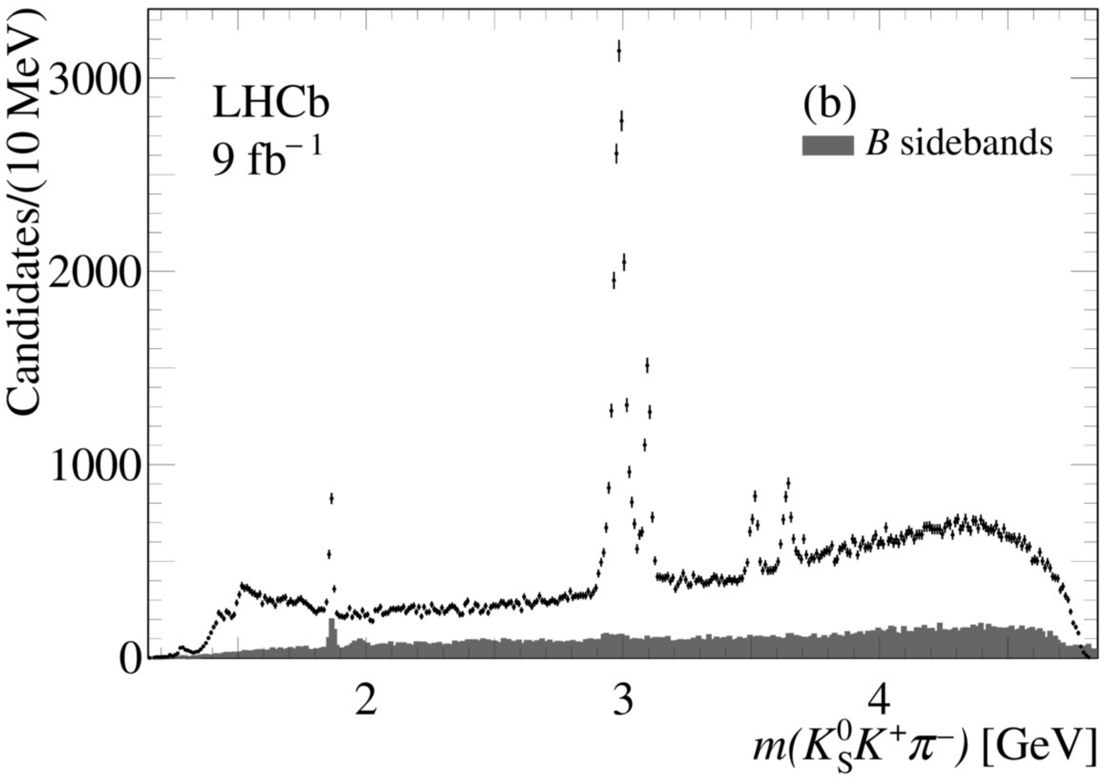
Study of charmonium→$K_S^0 K\pi$ via B decays

- $B^+ \to (K_S^0 K^{\mp}\pi^{\pm})K^+$ decays are studied

arXiv:2304.14891

- $K_S^0 K\pi$ invariant mass shows charmonium from η_c, J/ψ, χ_{c1} and $\eta_c(2S)$
- Dalitz plot analyses of η_c and $\eta_c(2S)$ decays are performed

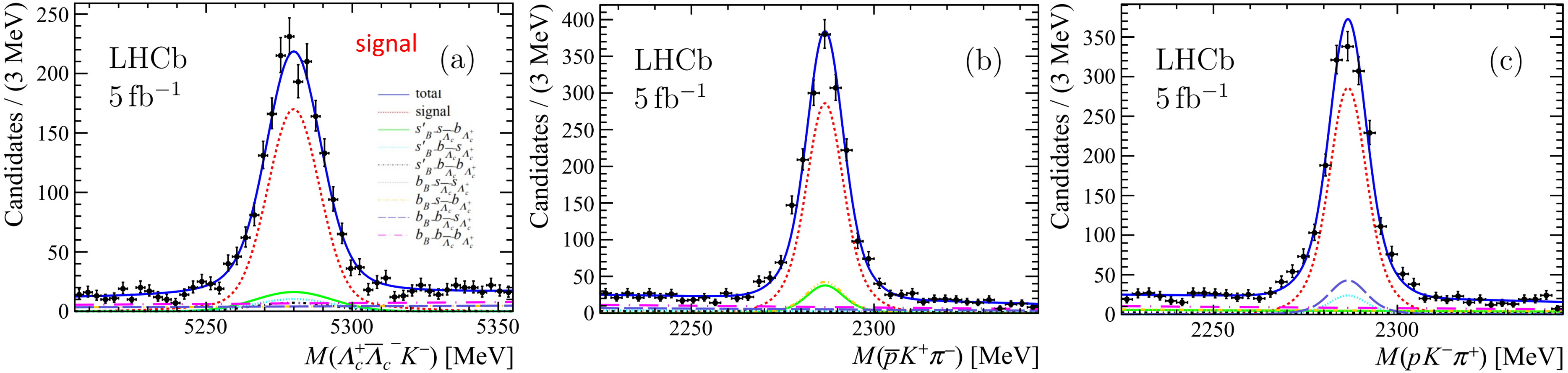




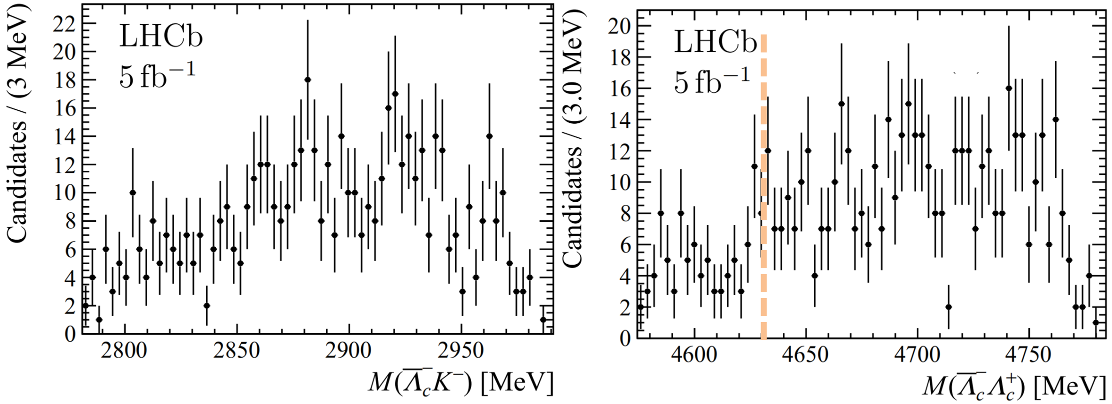
The $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay

arXiv:2211.00812

- 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 $N_{\rm sig} = 1365 \pm 42$

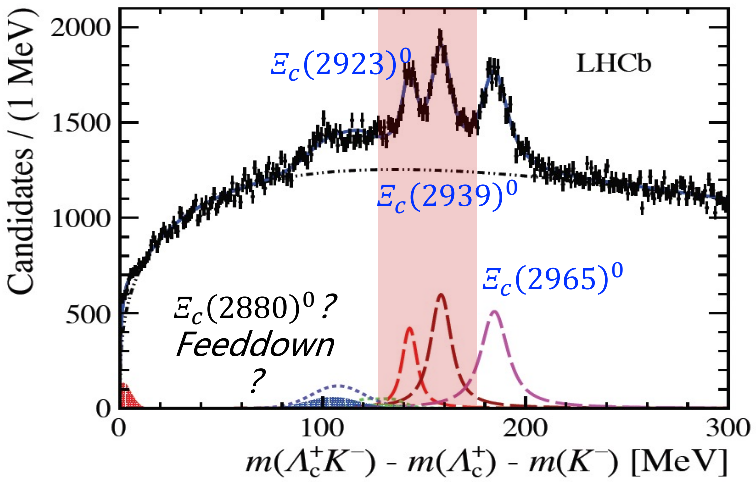


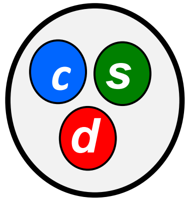
- No significant hint for exotic hadrons in $\Lambda_c^+ \overline{\Lambda}_c^-$ or $\overline{\Lambda}_c^- K^-$ mass spectra



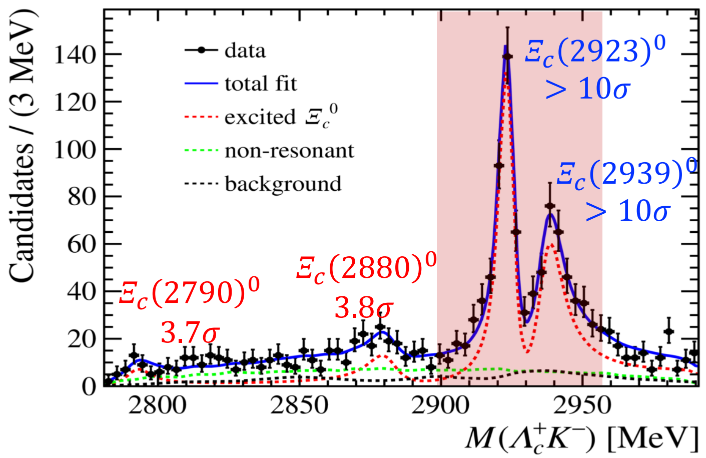
Ξ_c baryon in B decay

- $\Xi_c(2930)^0$ found in $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ at BaBar, confirmed by Belle EPJC 78 (2018) 3, 252
- 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)
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$

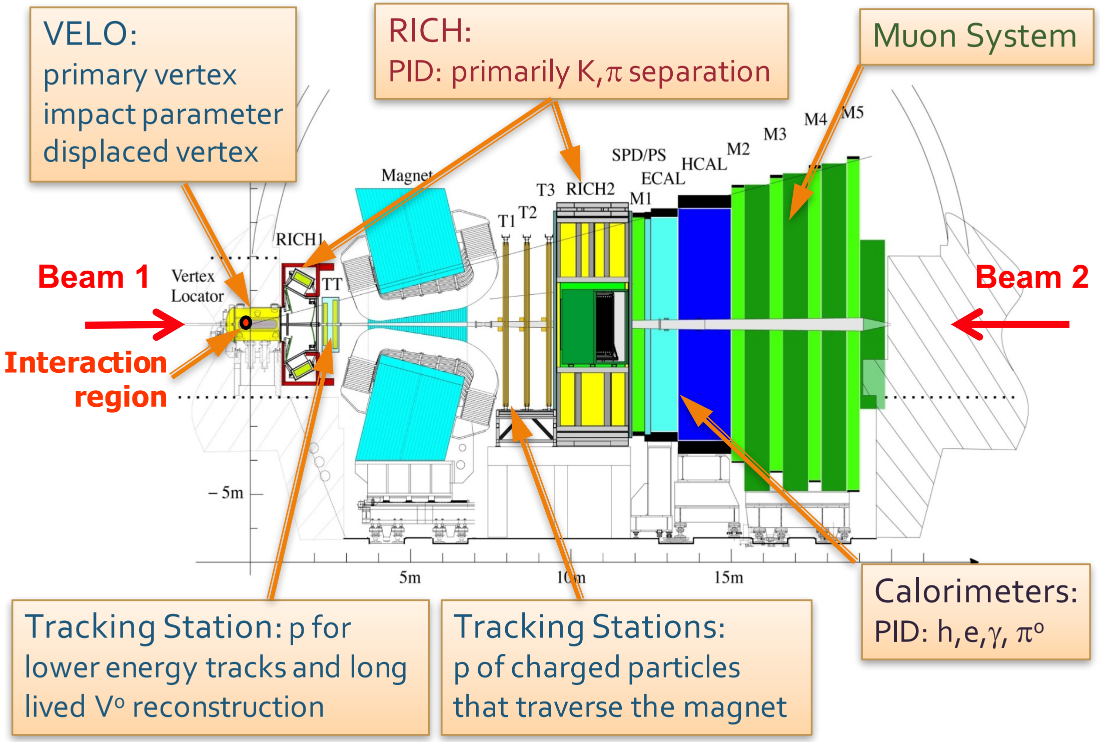


$$R_{\mathcal{B}} = \frac{\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-)}{\mathcal{B}(B^- \to D^- D^+ K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25$$

arXiv:2211.00812

LHCb detector and performance

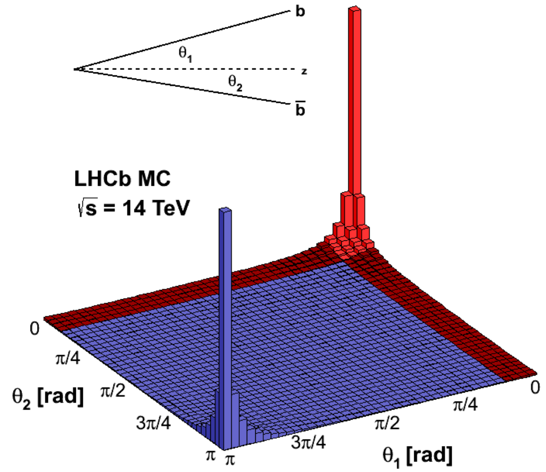
The LHCb detector described in [JINST 3 (2008) S08005]



LHCb coverage $2 < \eta < 5$

2.4% 4π angle

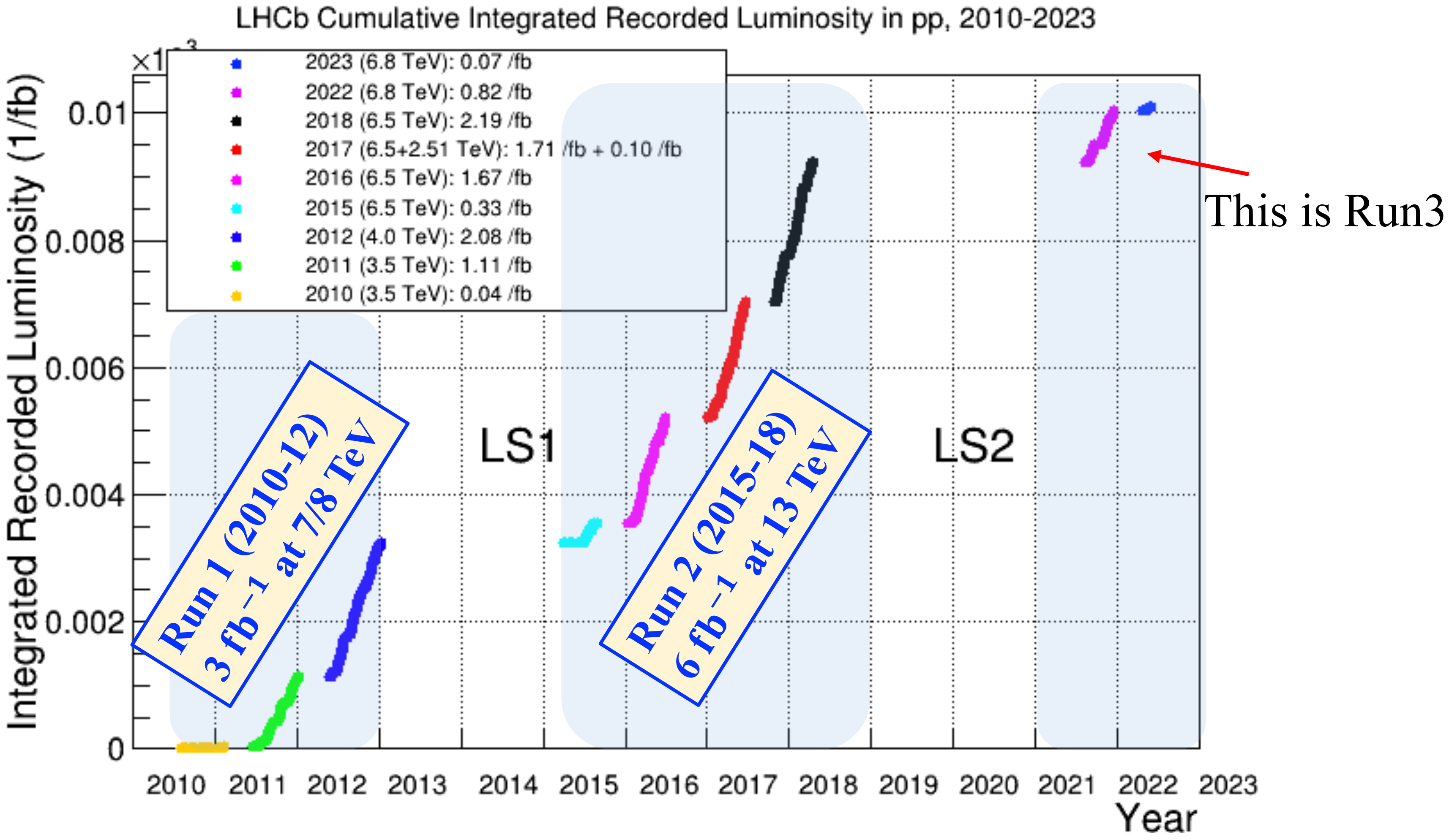
$\Rightarrow$ 25% $b\bar{b}$



[Int. J. Mod. Phys. A 30 (2015) 1530022]

Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\boldsymbol{m_{J/\psi}}$**)**
RICH $K - \pi$ separation:	$\boldsymbol{\epsilon(K \to K) \sim 95\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to K) \sim 5\%}$
Muon ID:	$\boldsymbol{\epsilon(\mu \to \mu) \sim 97\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to \mu) \sim 1 - 3\%}$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

LHCb collected luminosity



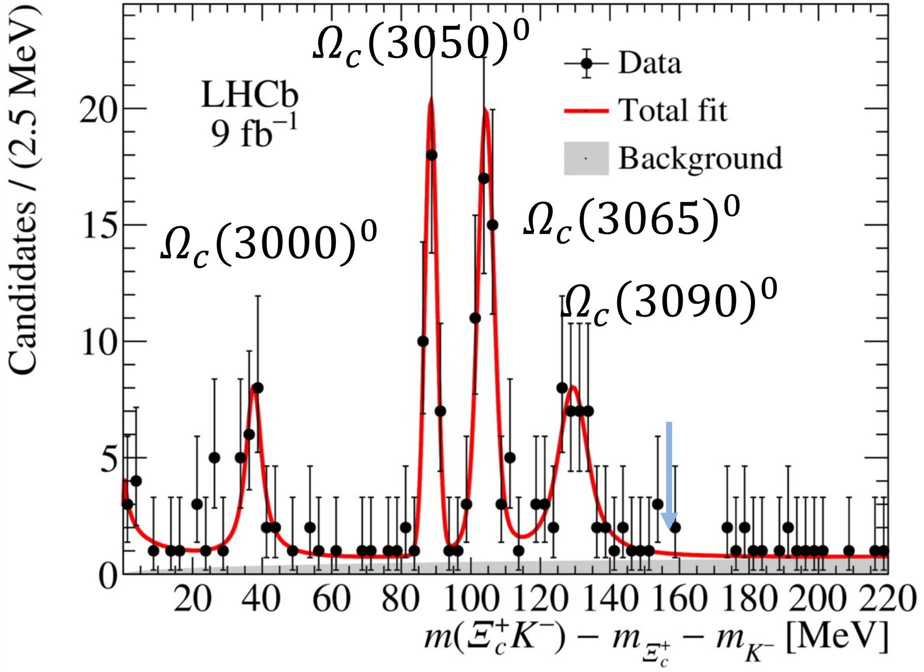
$\sigma(pp \to b\bar{b}X) \approx 300$ μb @7 TeV vs ≈ 500 μb @13 TeV

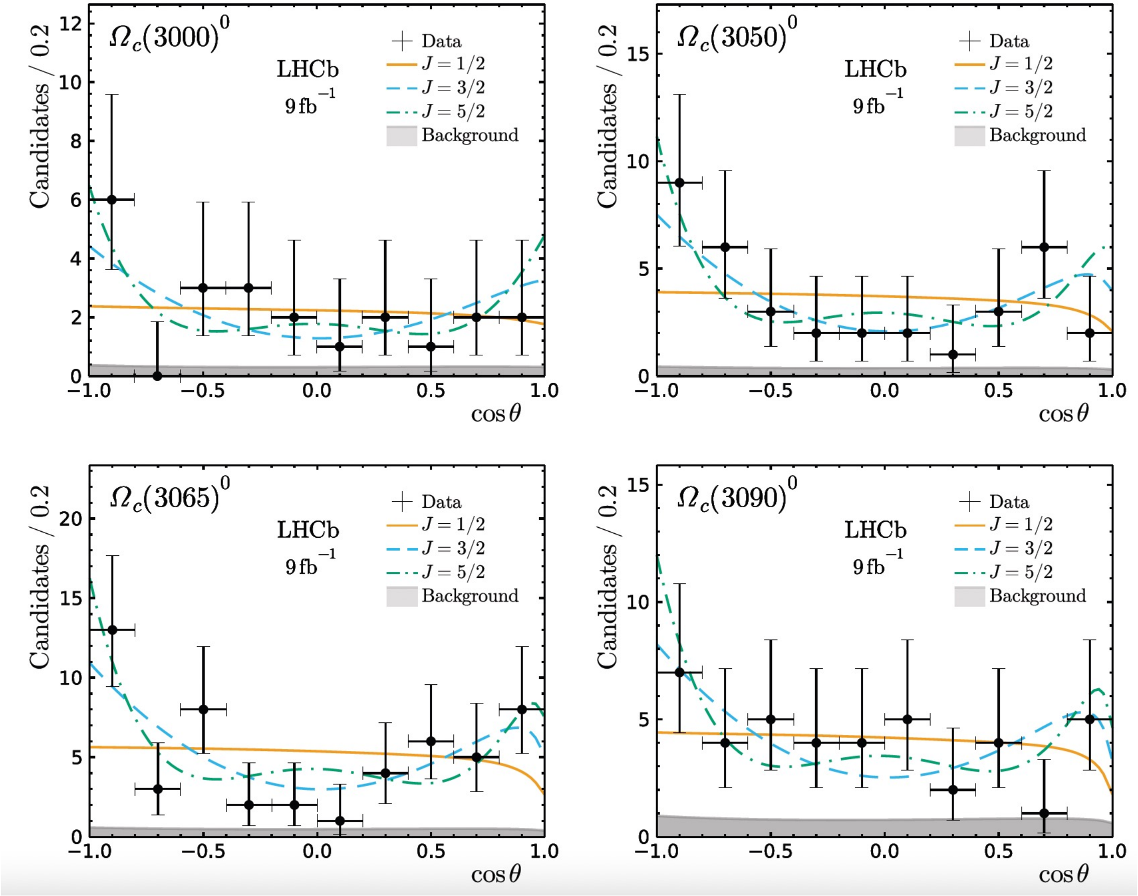
~25% can be collected in LHCb acceptance

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





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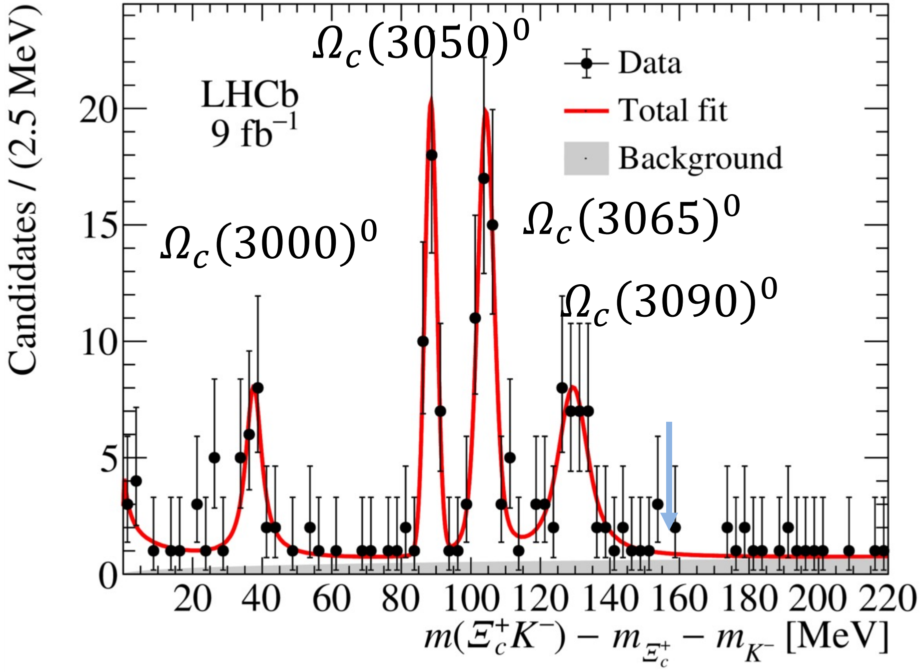


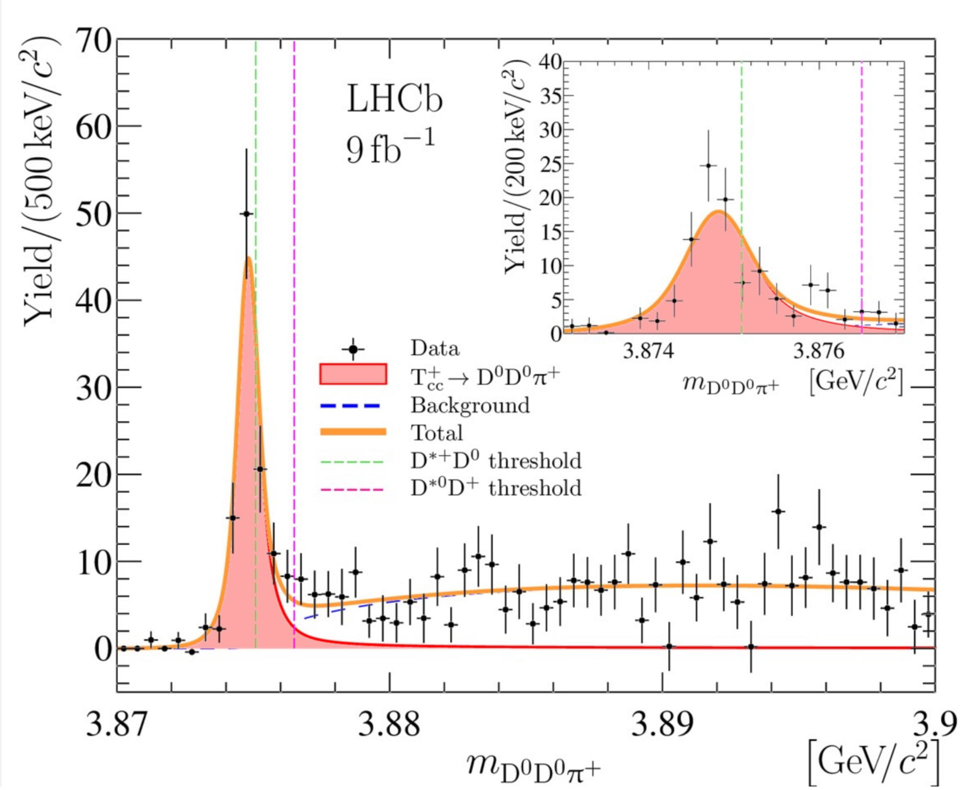
The order of J=1/2 1/2 3/2 3/2 are rejected at 3.5σ

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

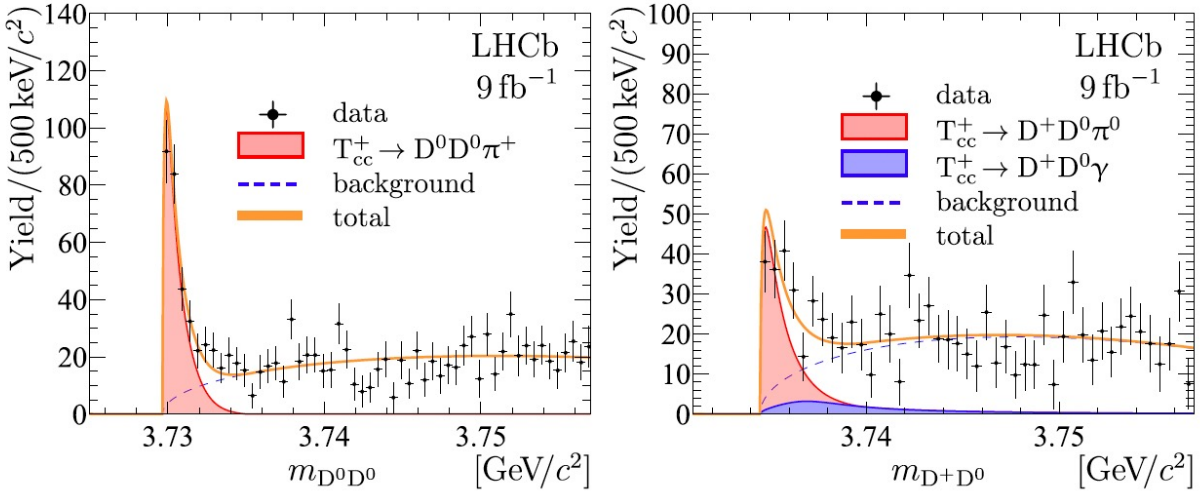
Doubly charmed tetraquark

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

- A narrow resonance $T_{cc}^{+}\ (cc\bar{u}\bar{d})$ discovered in prompt $D^0D^0\pi^+$ spectrum, just below the $D^{*+}D^0$ mass



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



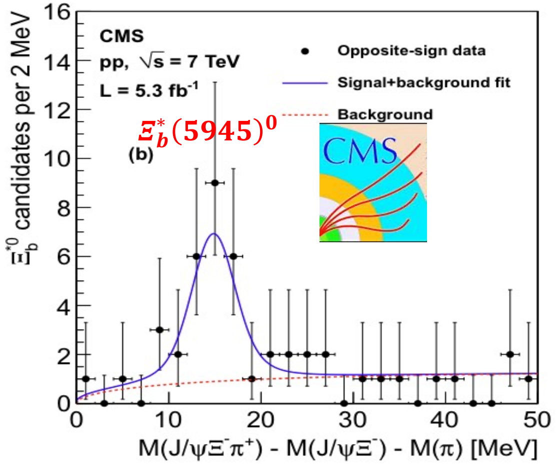
Ξ_b baryon spectroscopy

- 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

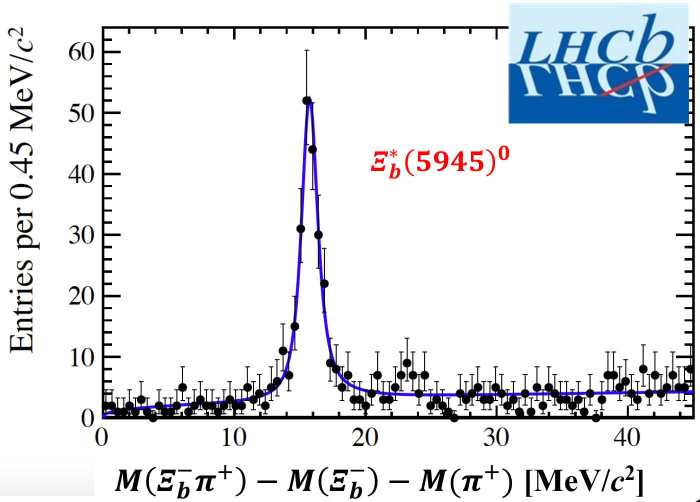
State	J^P	$b(sq)$
Ξ_b	$1/2^+$	↑ (↑↓)
Ξ_b'	$1/2^+$	↓ (↑↑)
Ξ_b^*	$3/2^+$	↑ (↑↑)

Neutral Ξ_b^*

PRL 108, 252002 (2012)

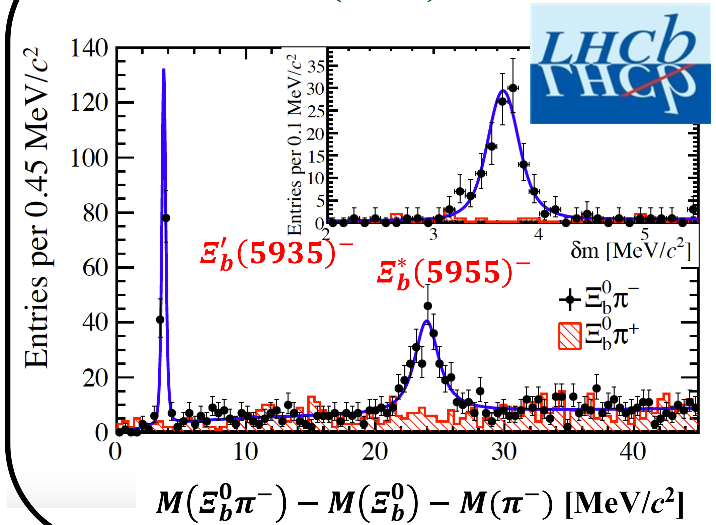


JHEP 05 (2016) 161



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

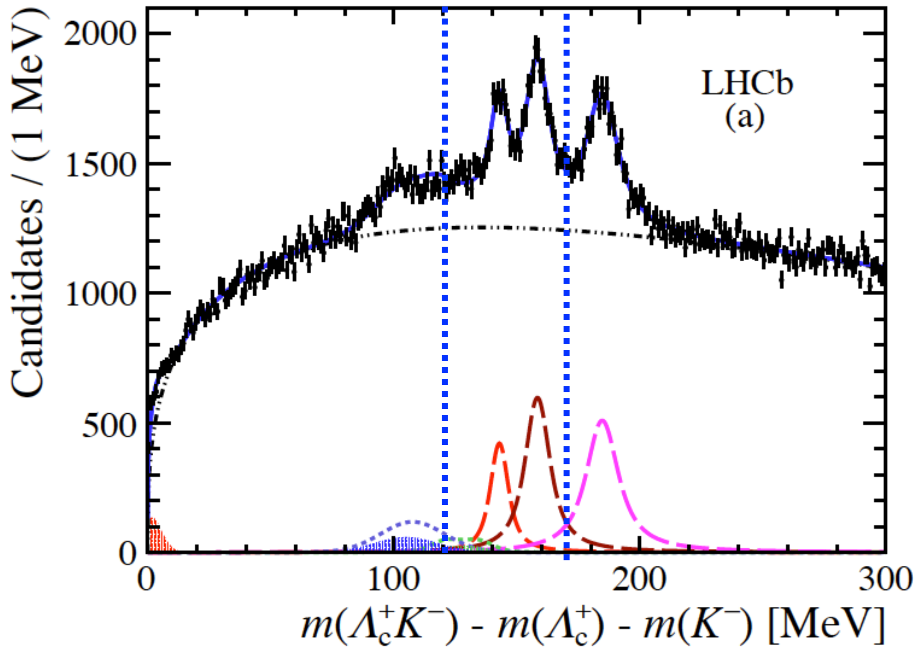
PRL 114 (2015) 062004



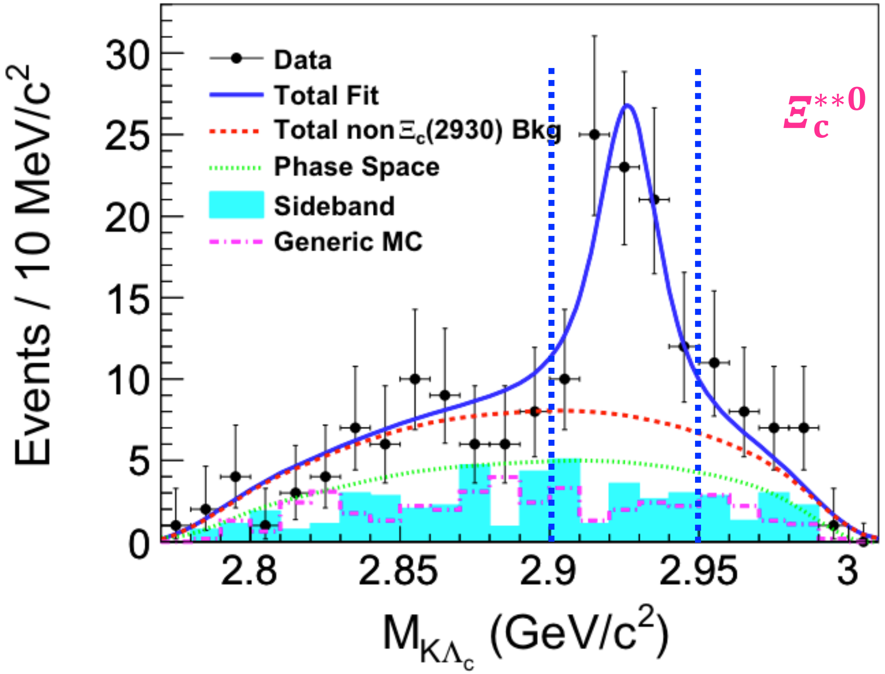
New Ξ_c^{**0} from LHCb

[arXiv:2003.13649]

- Large statistics data shows Belle's $\Xi_c(2930)$ is a composite of two narrow Ξ_c^{**}'s
- A third peak is also seen
  - position close to kinematic limit of the B decay used by Belle

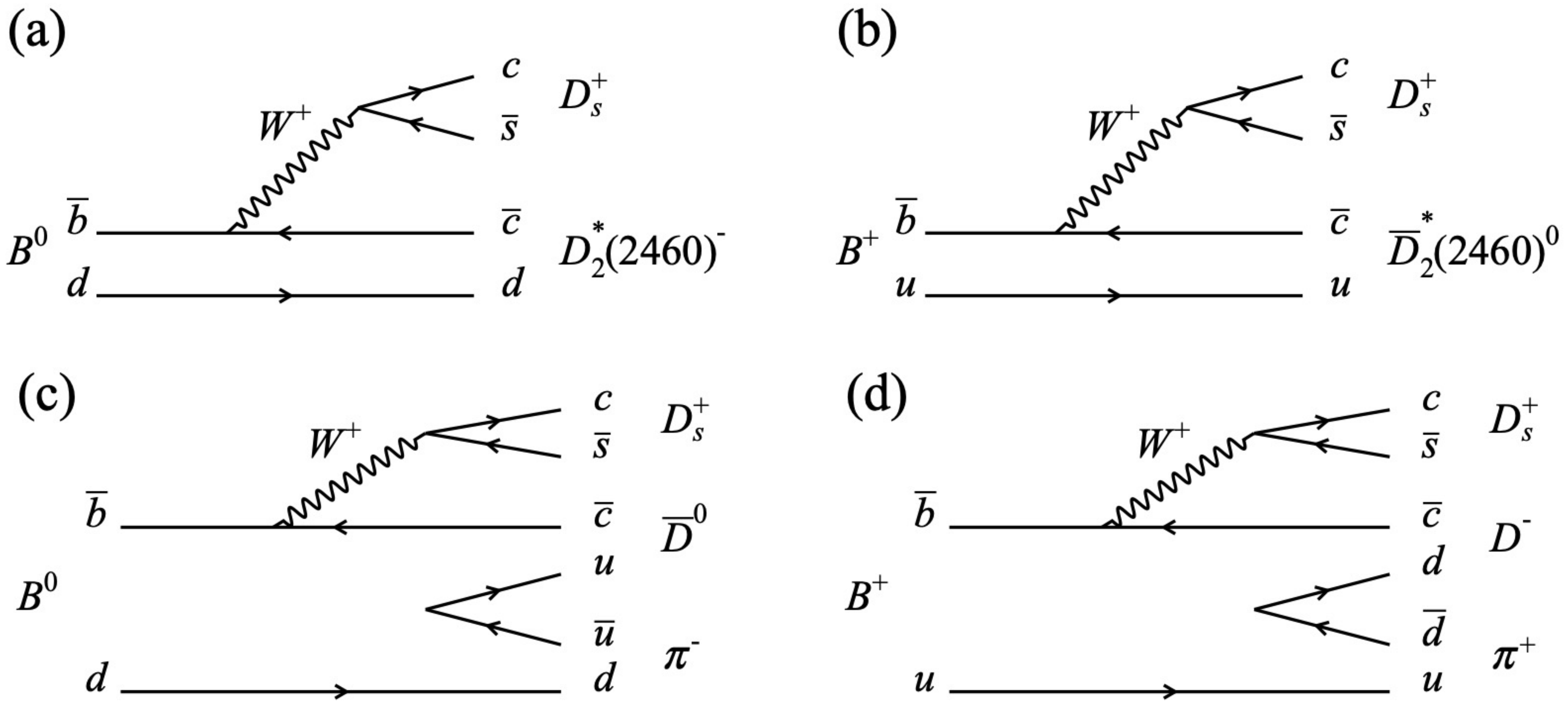


EPJC 78 (2018) 3, 252



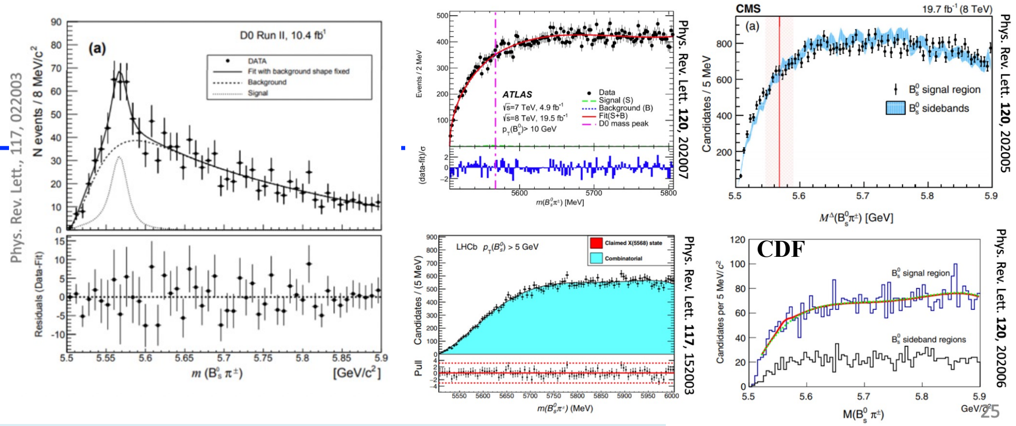
Feynman diagrams

- Two decays considered: $B^0 \to \bar{D}^0 D_s^+ \pi^-$, $B^+ \to D^- D_s^+ \pi^+$ related by isospin symmetry



Open flavor tetraquark

- D0 (16') claimed evidence for the $X(5568)$ in decaying to $B_s\pi^+$, interpreted as tetraquark state $[b\bar{s}u\bar{d}]$
- But not seen in other experiments

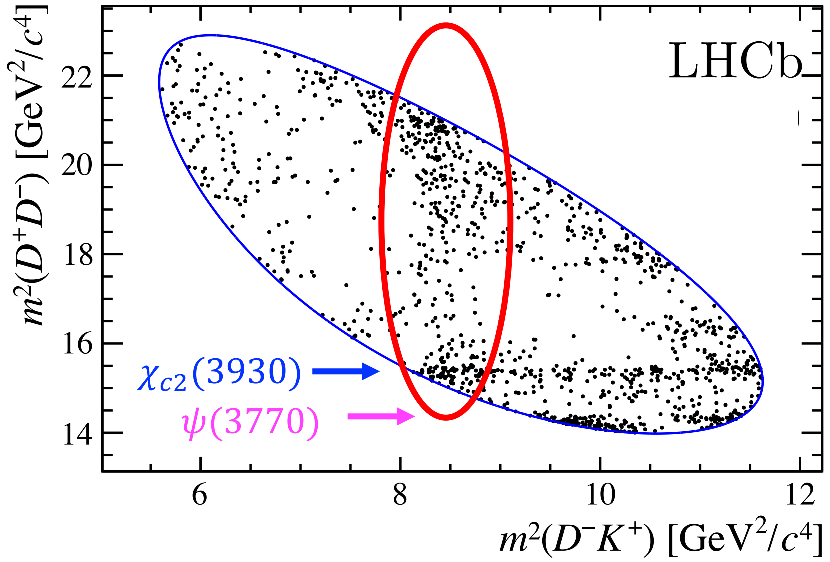


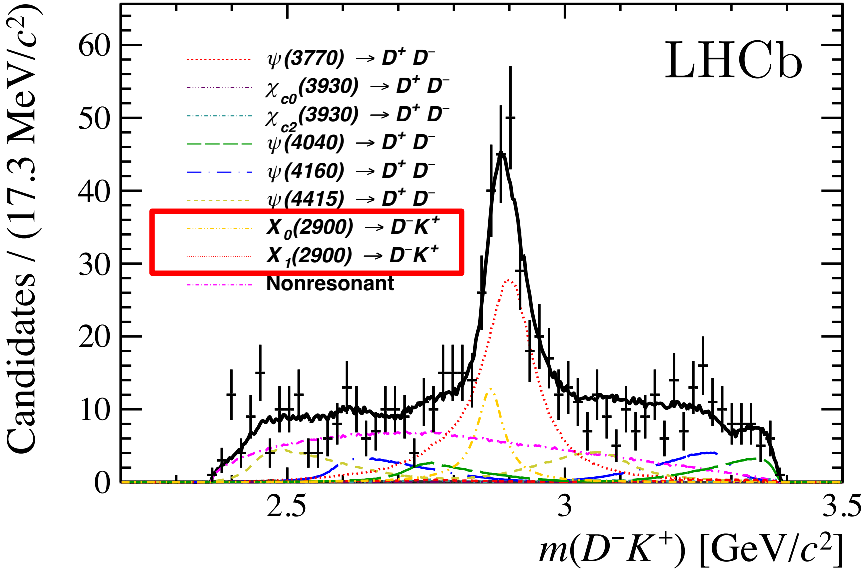
First discovery of open-charm tetraquark candidates with four different flavors $[cs\bar{u}\bar{d}]$

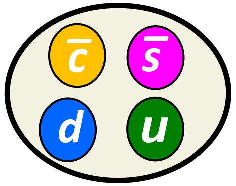
- Resonant structures observed in the D^-K^+ system from an amplitude analysis of the $B^+ \to D^+D^-K^+$ decay

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

$m(D^+D^-) > 4\ \mathrm{GeV}/c^2$







$$X_0(2900):\quad M = 2.866 \pm 0.007 \pm 0.002\,\mathrm{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\,\mathrm{MeV}$$
$$X_1(2900):\quad M = 2.904 \pm 0.005 \pm 0.001\,\mathrm{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\,\mathrm{MeV}$$