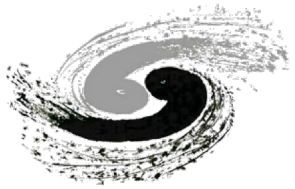
Recent LHCb results on hadron spectroscopy

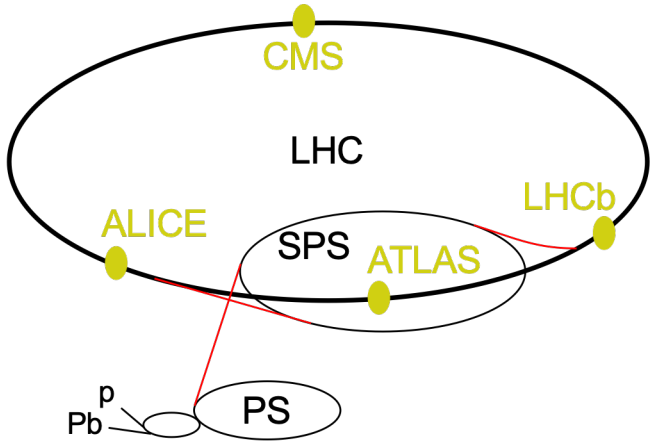


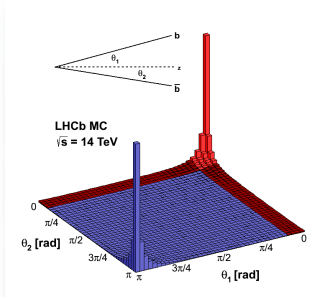
Yiming Li 李一鸣
Institute of High Energy Physics, CAS
on behalf of LHCb-China group

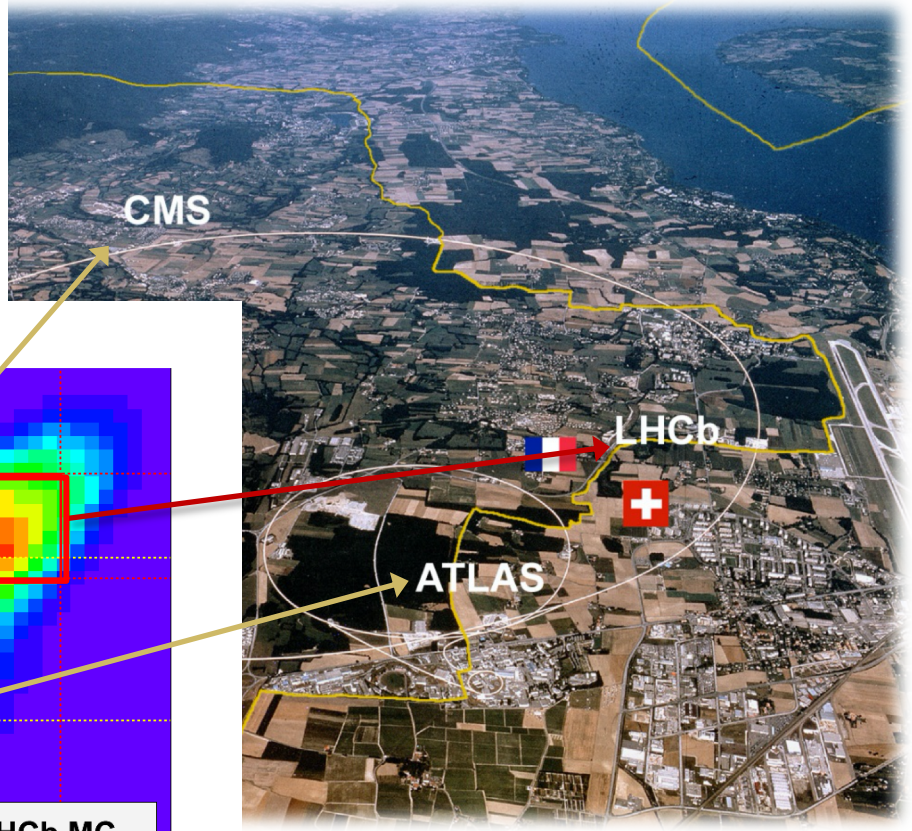
The third LHCb physics frontiers workshop, 16 Apr 2023 @ UCAS

Heavy flavour production at LHC

Zhenwei Yang, "Production results from LHCb"

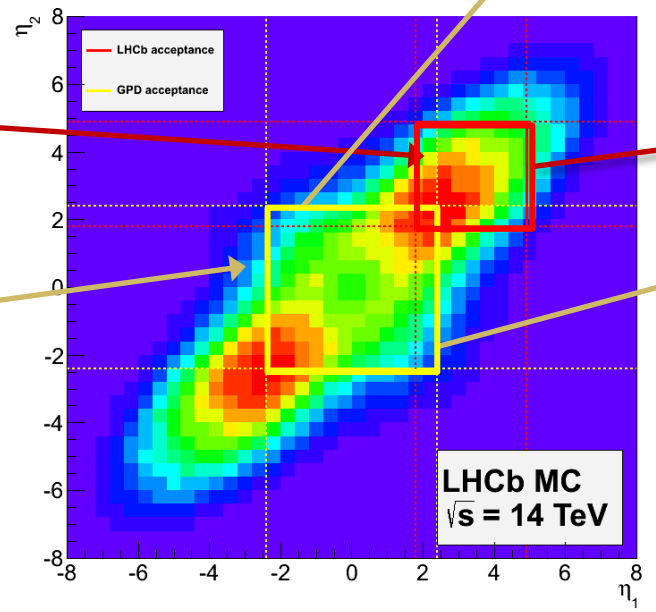






27% $b/\bar{b}$

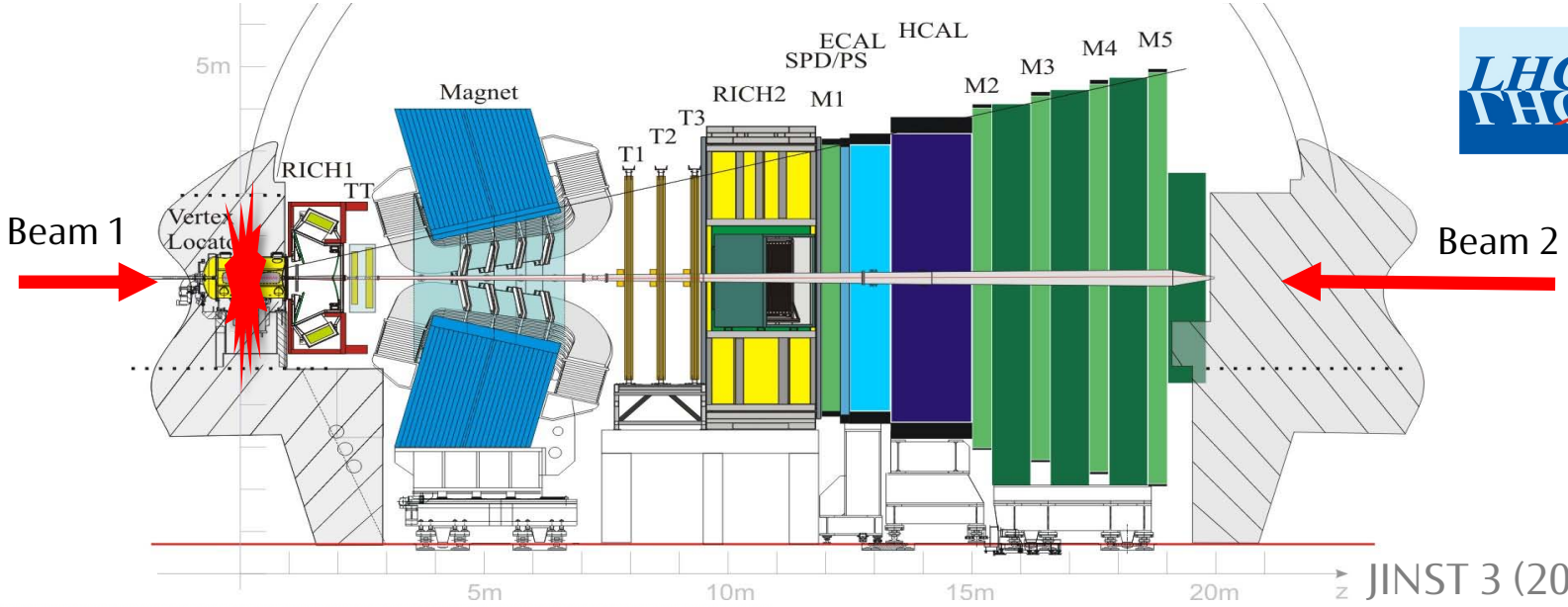
49% $b/\bar{b}$



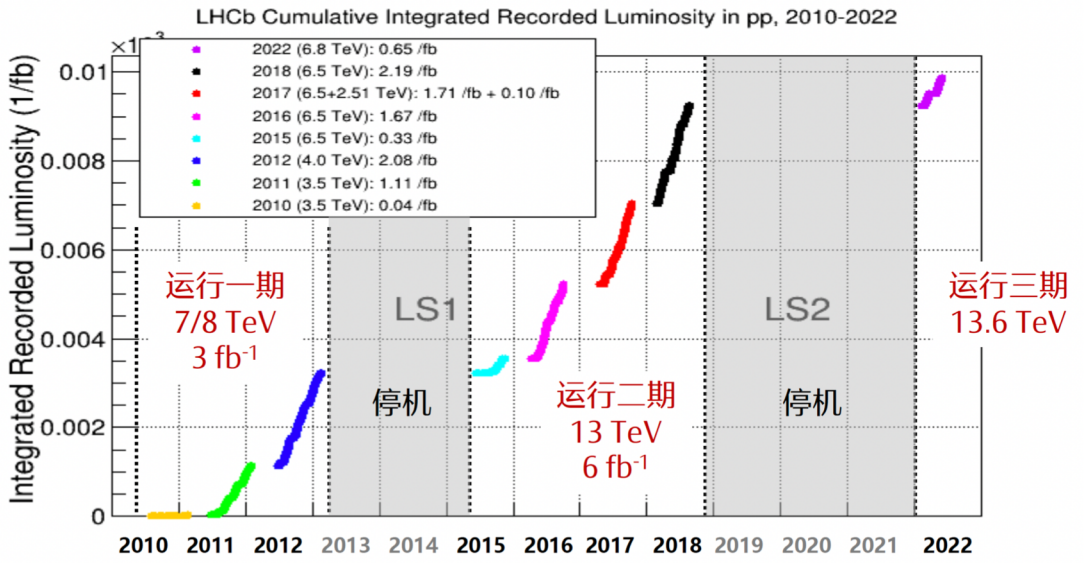
$\sigma(b\bar{b})$: 200~500 μb @ 7-14 TeV

$\sigma(c\bar{c}) \sim 20\times\sigma(b\bar{b})$

LHCb in Run 1+2



JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022



Vertex res.	$\sigma_{IP} = 20\ \mu m$
Time res.	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum res.	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass	$\sigma_m = 8$ MeV/c^2 for $B \to J/\psi X$
Hadron ID	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL res.	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$

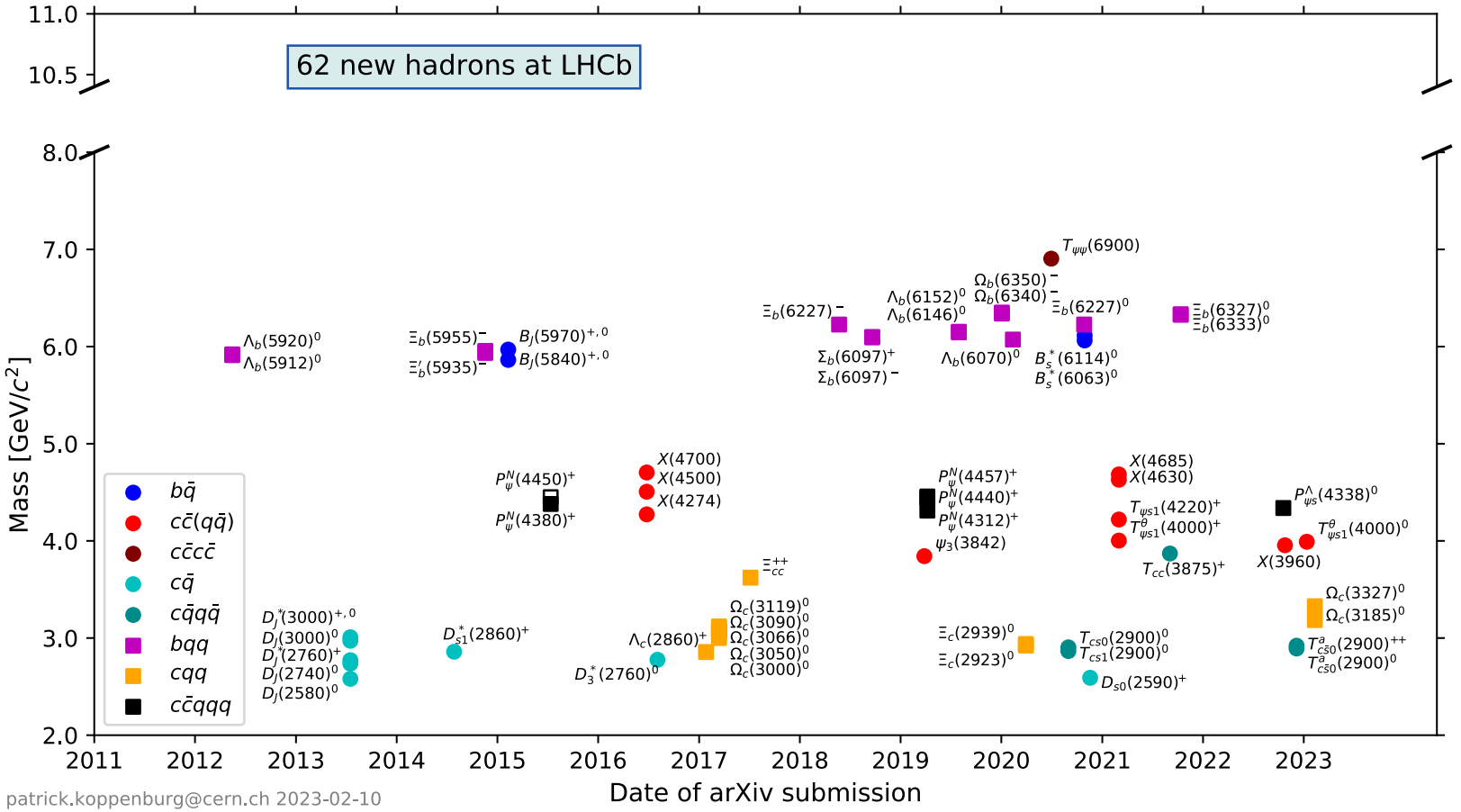
Approaches of new particle search

- Particles produced promptly in pp collision
  - Fully exploiting the large cross-section at LHC
  - Large combinatorial background
  - Only mass & width/lifetime
  - Effective for long-lived particles
    - $\tau > \sim$ ps
- Particles produced in b-decays
  - Limited by available phase space
  - Yield suppressed by b-decay BF
  - Background is generally clean due to effective b-selection
  - Mass, width and angular distribution (hence quantum numbers!)
- Common features
  - Most powerful for final states of all charged tracks:
    - Excellent momentum resolution and PID
  - Possible with K_S^0 or π^0 in the final state with reduced efficiency
  - Partial reconstruction also effective with a soft γ or π^0 missing

New particles in a glance

- 62 new hadrons discovered at LHCb!

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



Selected highlights

- Conventional states
  - Charm baryons: Ξ_c^{**}, Ω_c^{**}
  - Beauty baryons: Ξ_b^{**}
  - Doubly heavy hadrons: Ξ_{cc}^{++}, Ξ_{bc}^{0}, B_c^+
- 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

Exotic hadron naming convention: arXiv:2206.15233

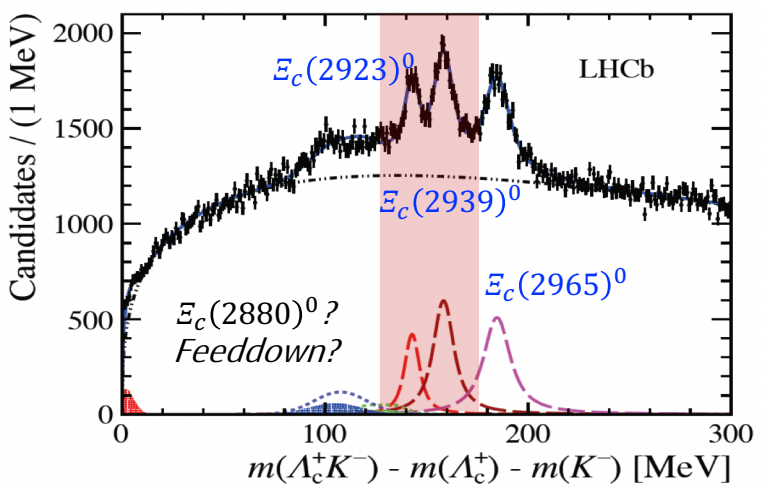
Ξ_c baryon in B decay

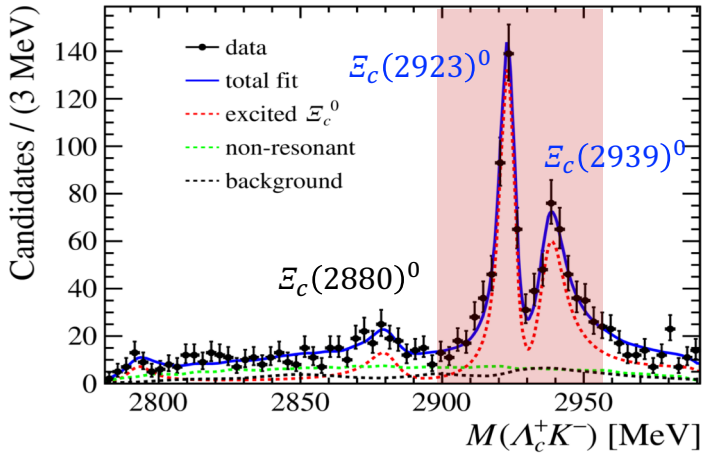
arXiv:2211.00812 (Accepted by PRD)

- $\Xi_c(2930)^0$ (csd) 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 PHYS. REV. LETT. 124 (2020) 222001
- Confirmed by recent $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ study at LHCb
  - No significant structure in $\bar{\Lambda}_c^- \Lambda_c^+$ or $\bar{\Lambda}_c^- K^-$

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

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





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

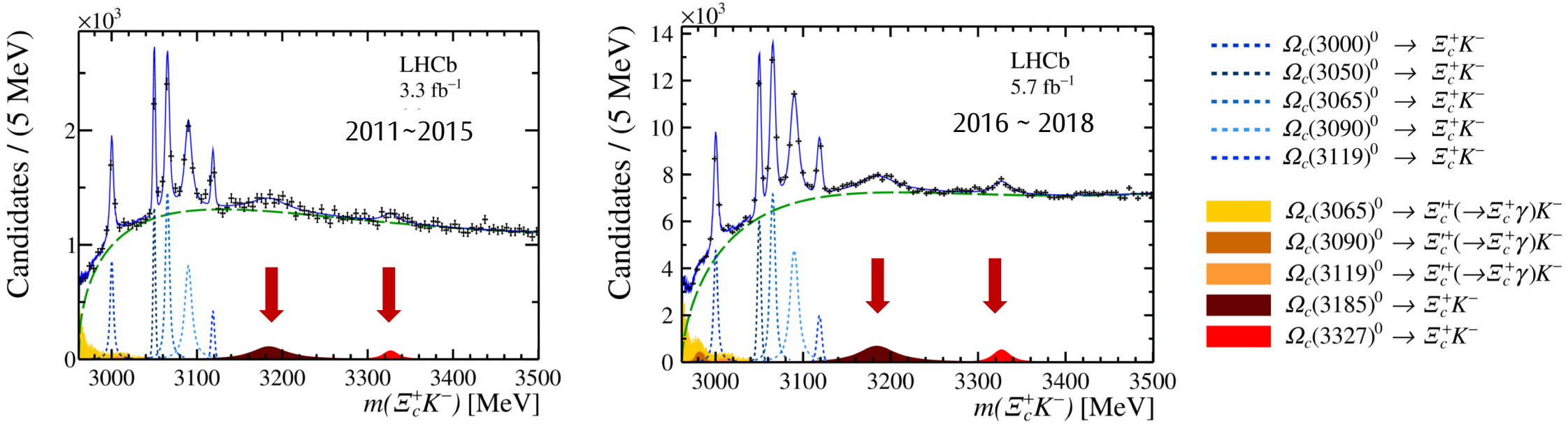
arXiv:2302.04733 (Submitted to PRL)

- Five new Ω_c states (css) found in $\Xi_c^+ K^-$ at LHCb
  - Four confirmed in e^+e^- at Belle and in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay at LHCb

PRL 118 (2017) 182001
PRD 97 (2018) 051102
PRD104 (2021) L091102

- 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 ± 0.07	3.83 ± 0.23
$\Omega_c(3050)^0$	3050.18 ± 0.04	0.67 ± 0.17
$\Omega_c(3065)^0$	3065.63 ± 0.06	3.79 ± 0.20
$\Omega_c(3090)^0$	3090.16 ± 0.11	8.48 ± 0.44
$\Omega_c(3119)^0$	3118.98 ± 0.12	0.60 ± 0.63
new $\Omega_c(3185)^0$	3185.1 ± 1.7	50 ± 7
new $\Omega_c(3327)^0$	3327.1 ± 1.2	20 ± 5

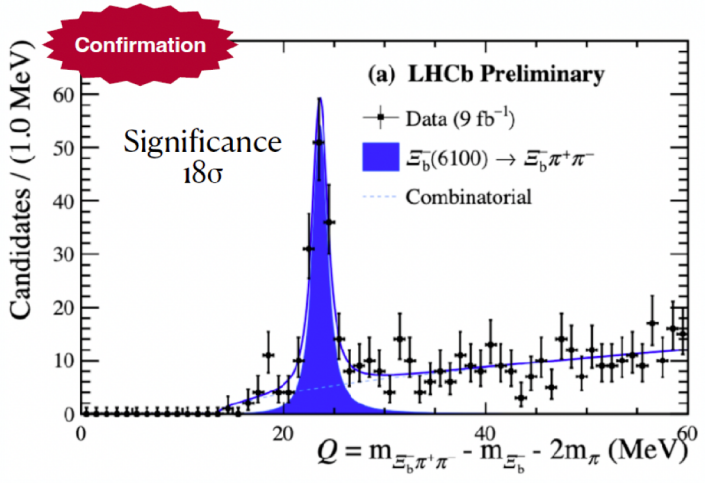


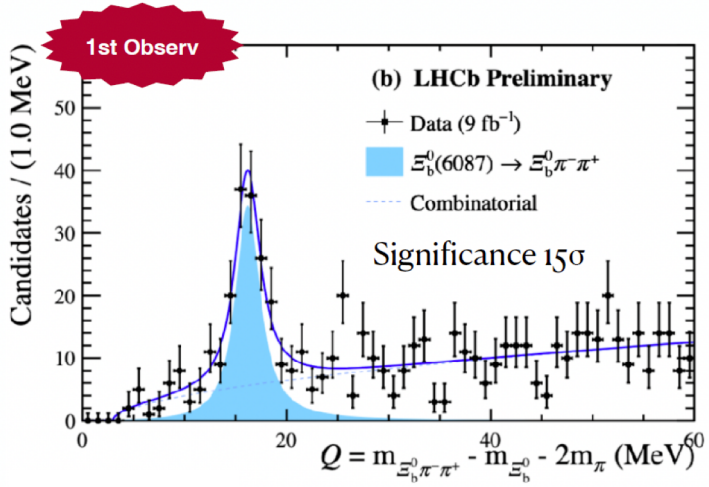
New Ξ_b^{**} baryons

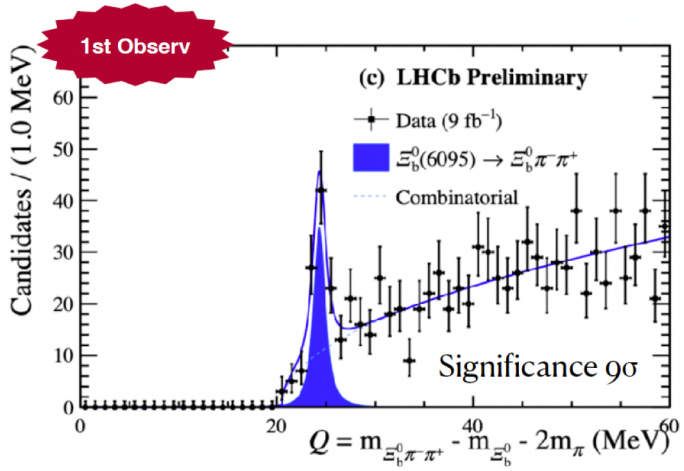
LHCb-PAPER-2023-008 (In preparation)

- 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:
  - $\Xi_b(6100)^- \to \Xi_b^{*0}\pi^- \to [\Xi_b^-\pi^+]\pi^-$

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





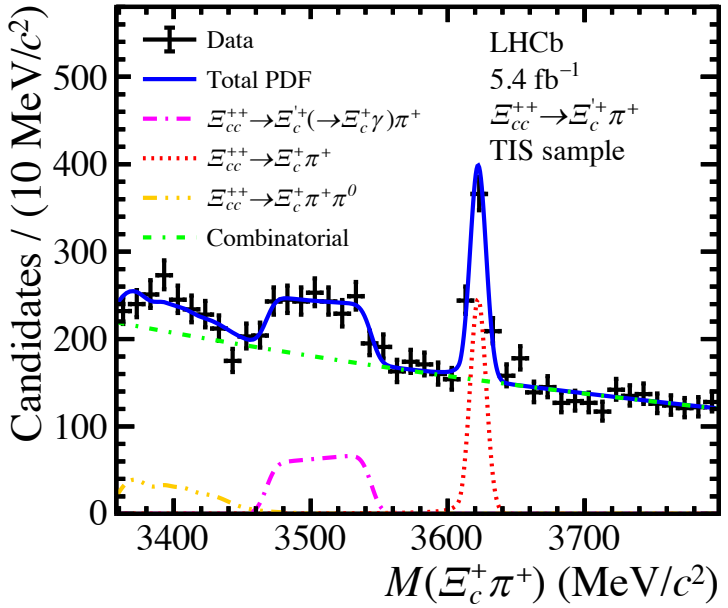


New decay mode of Ξ_{cc}^{++}

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

JHEP 05 (2022) 038

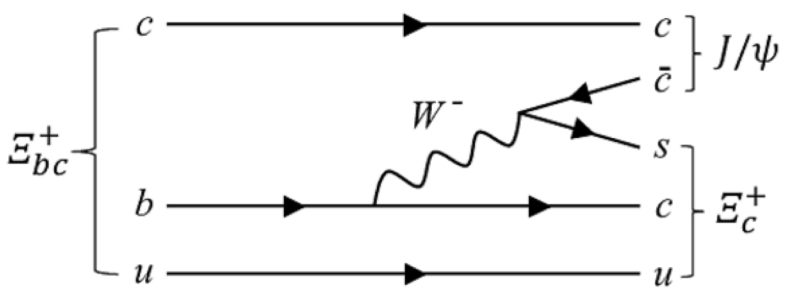


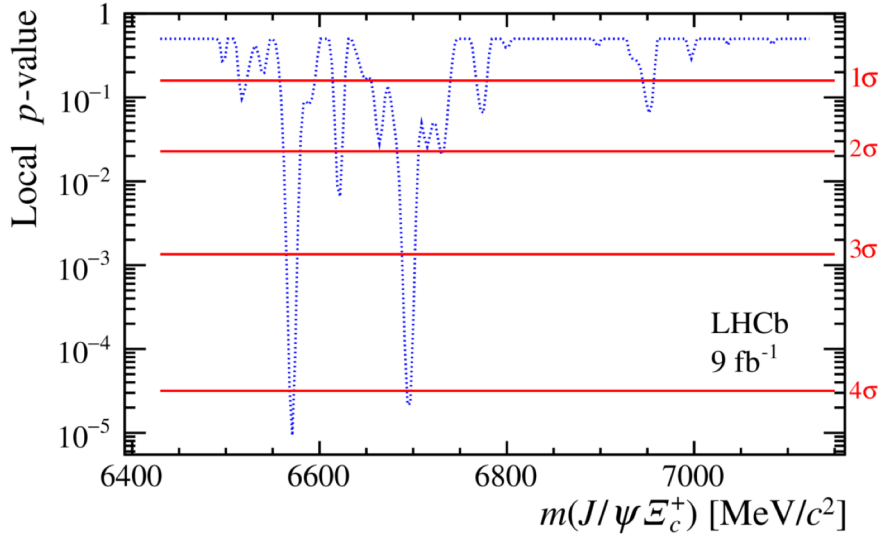
Search of Ξ_{bc}

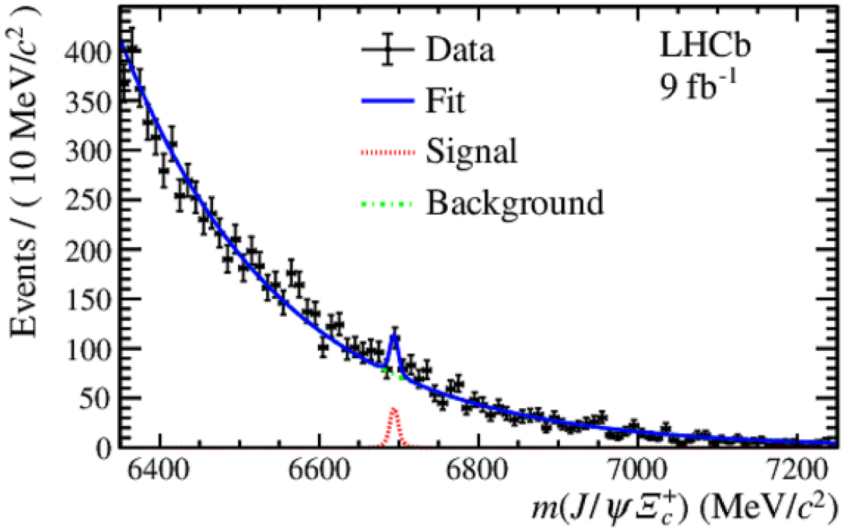
arXiv: 2204.09541 (Accepted by CPC)

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

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



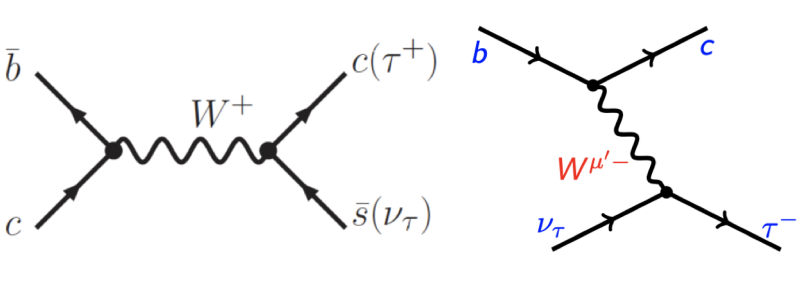


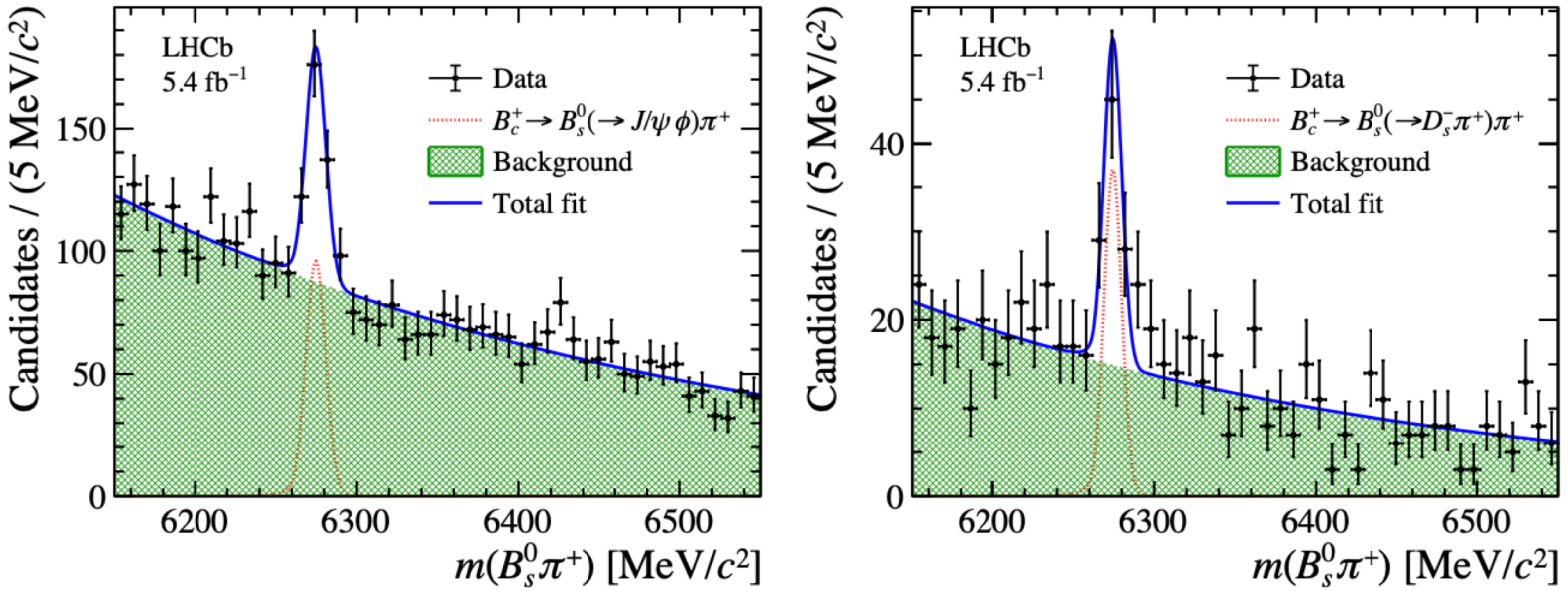


B_c^+ decay BF measurement

arXiv:2210.12000 (submitted to JHEP)

- $B_c^+ \to B_s^0 \pi^+$
  - First B weak decay to another beauty PRL 111 (2013) 181801
  - Branching fraction expected to be large, and contributes to more stringent limit on $B_c^+ \to \tau^+ \nu$ decay BF
  - $\frac{\mathcal{B}(B_c^+ \to B_s^0 \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 91 \pm 10 \pm 8 \pm 3$





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  - Beauty baryons: Ξ_b^{**}
  - Doubly heavy hadrons: Ξ_{cc}^{++}, Ξ_{bc}^{0}, B_c^{+}

- 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

Exotic hadron naming convention: arXiv:2206.15233

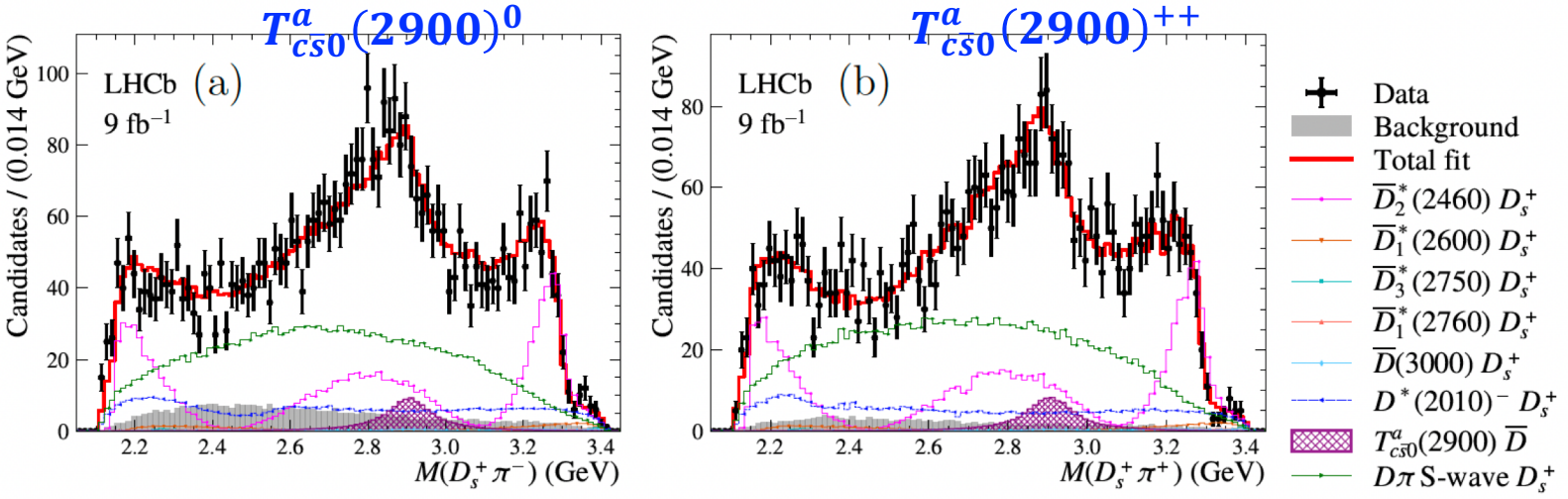
Tetraquark with open charm: $T^a_{c\bar{s}0}(2900)$

arXiv: 2212.02716 (Accepted by PRL)
arXiv: 2212.02717 (Accepted by PRD)

- First observation of doubly charged $T^a_{c\bar{s}0}(2900)^{++}(cu\bar{s}\bar{d})$ and its isospin partner $T^a_{c\bar{s}0}(2900)^0(cu\bar{s}\bar{u})$
  - $B^{+/0} \to \bar{D}^{-/0} D_s^+ \pi^{+/-}$
  - Both states have $J^P = 0^+$
  - Amplitude analysis using the package TF-PWA

- Reminder: $T_{cs0}(2900)^0$ and $T_{cs1}(2900)^0$ with quark content $(cs\bar{u}\bar{d})$ with $J^P = 0^+$ and 1^- found in Dalitz analysis of the $B^+ \to D^+ D^- K^+$ decay
  - $T^a_{c\bar{s}0}(2900)^0$ mass is consistent with $T_{cs0}(2900)^0$, but width and flavour differ

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



Assuming isospin symmetry:
$m = 2908 \pm 11 \pm 20$ MeV
$\Gamma = 136 \pm 23 \pm 11$ MeV

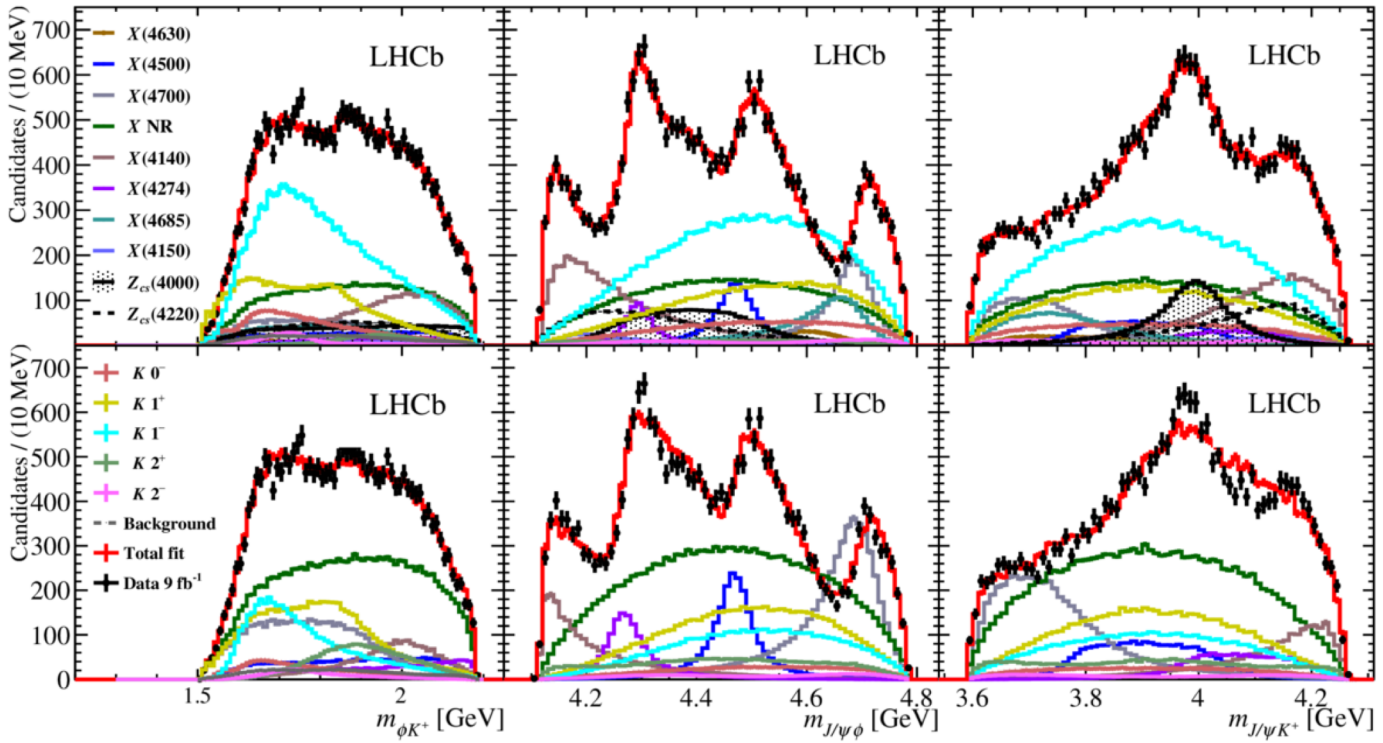
$m = 2866 \pm 7 \pm 2$ MeV
$\Gamma = 57 \pm 12 \pm 4$ MeV

Tetraquark with hidden charm: $Z_{cs}(4000)^+$

- $B^+ \to J/\psi\phi K^+$: a zoo of exotic states
  - Multiple exotic states found in $J/\psi\phi$ system
  - Two Z_{cs} states in $J/\psi K$ system

PRL 127 (2021) 082001

J^P	Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]
2^-	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$
1^-	$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$
0^+	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$
	$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$
	$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)		
1^+	$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$
	$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$
	$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$
1^+	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

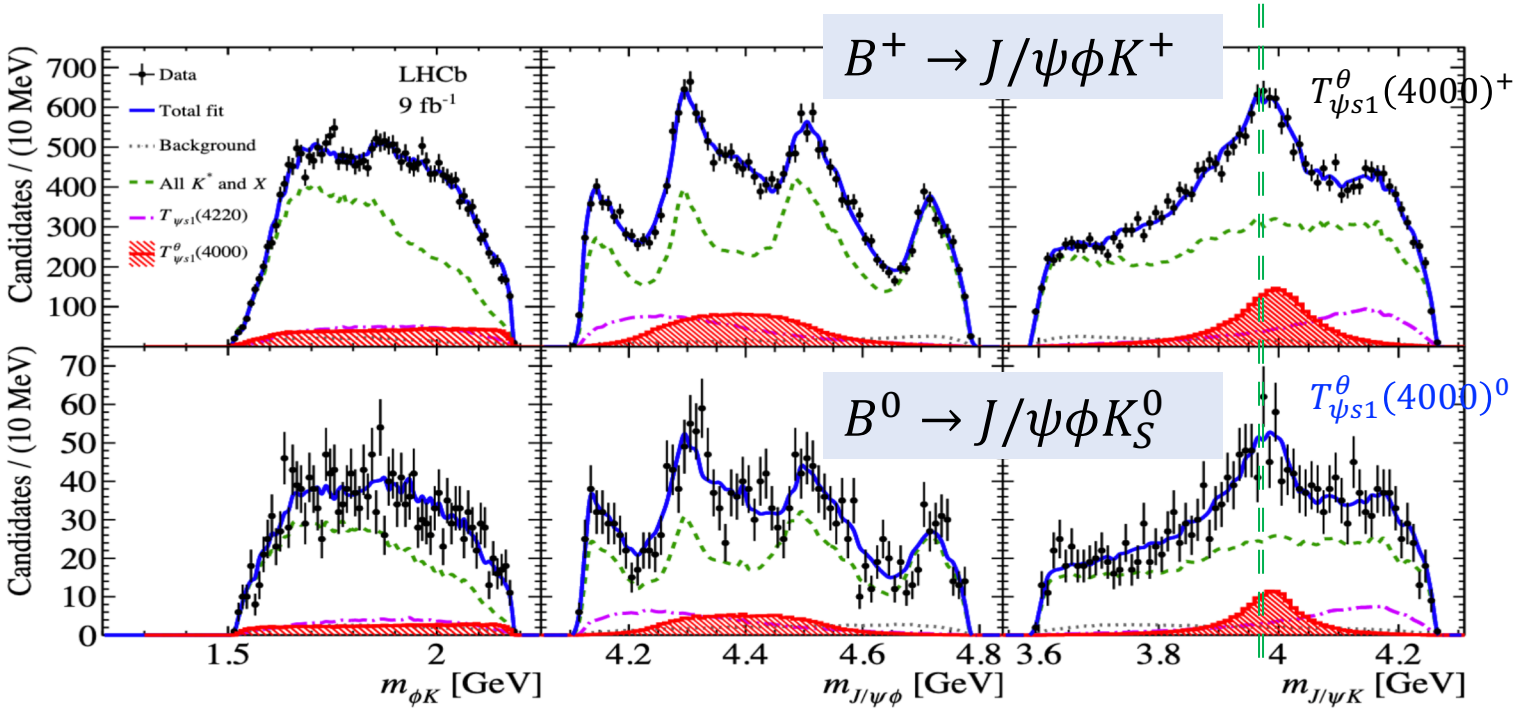


Tetraquark with hidden charm: $Z_{cs}(4000)^0$

arXiv:2301.04899 (Accepted by PRL)

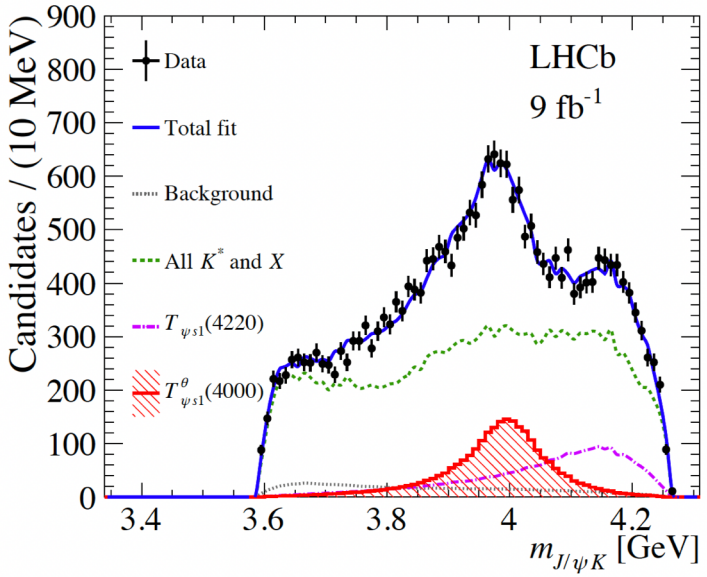
- Combined fit to $B^+ \to J/\psi\phi K^+$ and $B^0 \to J/\psi\phi K_S^0$ find evidence (4.0 σ) of $Z_{cs}(4000)^0$ or $T^{\theta}_{\psi s1}(4000)^0$, with quark content $c\bar{c}s\bar{d}$
  - Assuming isospin asymmetry the significance is 5.4 sigma
  - $J^P = 1^+$

State	Mass (MeV)	Width (MeV)
$T^{\theta}_{\psi s1}(4000)^0$	$3991\ ^{+12}_{-10}\ ^{+9}_{-17}$	$105\ ^{+29}_{-25}\ ^{+17}_{-23}$



Z_{cs} at LHCb and BESIII

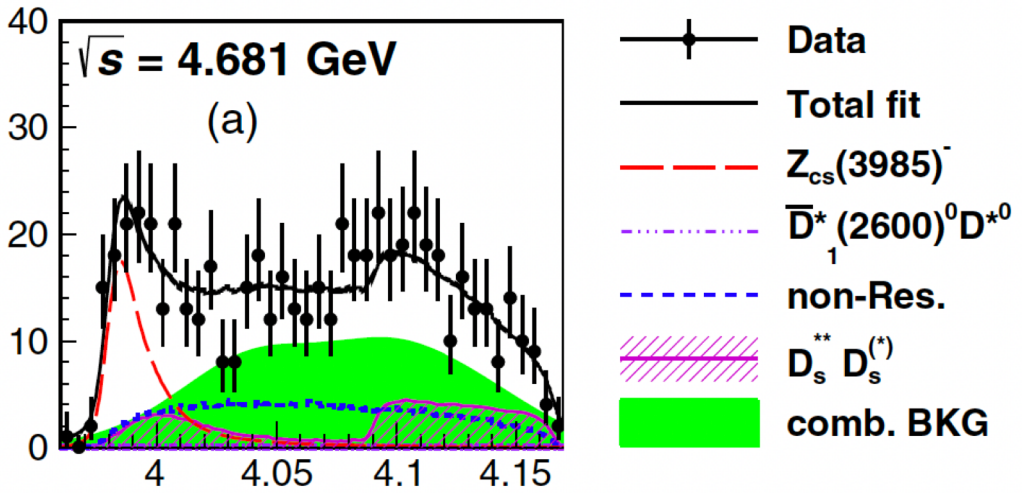
LHCb: $Z_{cs}(4000)^+$ in $B^+ \to J/\psi\phi K^+$



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

BESIII: $Z_{cs}(3985)^+$ in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

PRL 126 (2021) 102001



$m = 3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV
$\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV

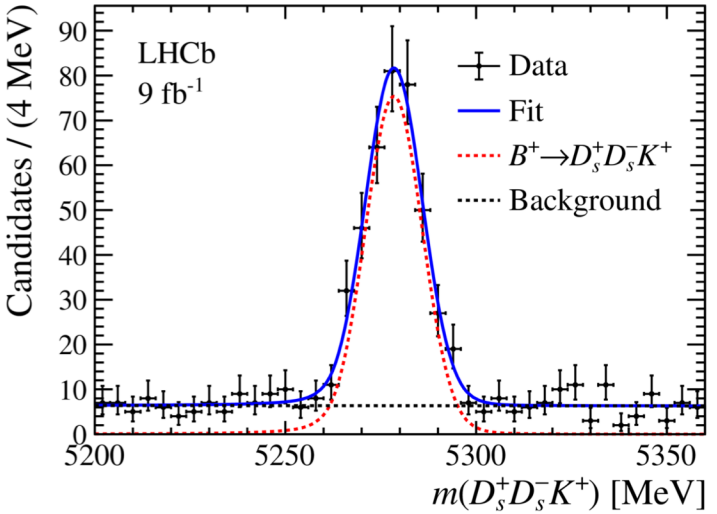
- Significantly different in width
- No evidence that $Z_{cs}(4000)^+$ and $Z_{cs}(3985)^+$ are the same state

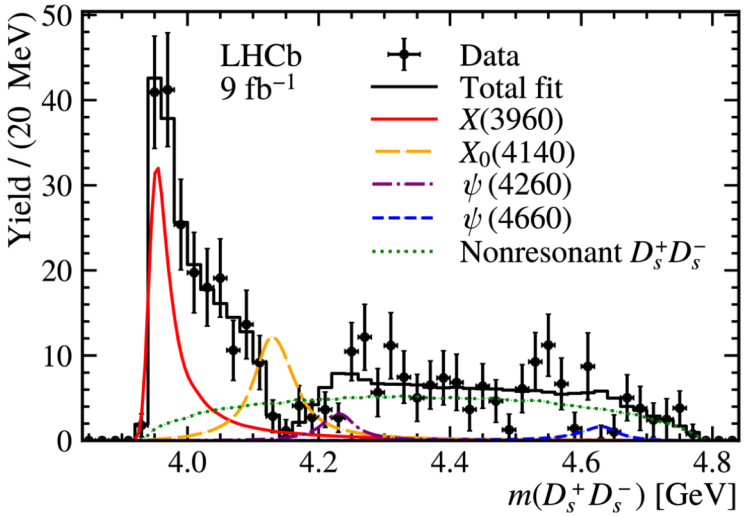
Tetraquark with hidden charm $X(3960)$

arXiv: 2210.15153 (Accepted by PRL)
arXiv: 2211.05034 (Accepted by PRD)

- First observation of $B^+ \to D_s^+ D_s^- K^+$
  - $\frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033 \pm 0.027 \pm 0.034$

- Near-threshold structure $X(3960)$ ($c\bar{c}s\bar{s}$) observed in the $D_s^+ D_s^-$ system (>12σ)
  - $m = 3956 \pm 5 \pm 10$ MeV
  - $\Gamma = 43 \pm 13 \pm 8$ MeV
  - $J^{PC} = 0^{++}$
  - 3.9σ evidence of $X_0(4140)$: tetraquark? Cross-channel effect?
  - $J^{PC} = 1^{--}$: Evidence of $\psi(4260)$ and $\psi(4660)$

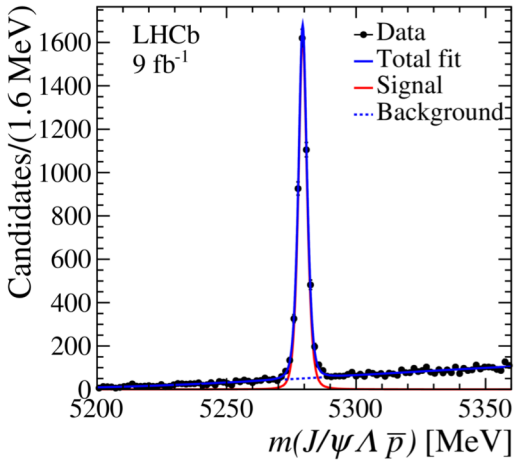


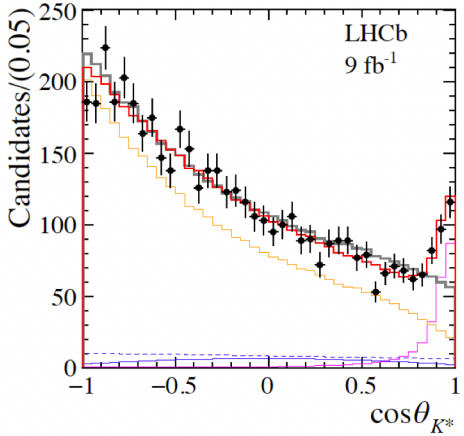


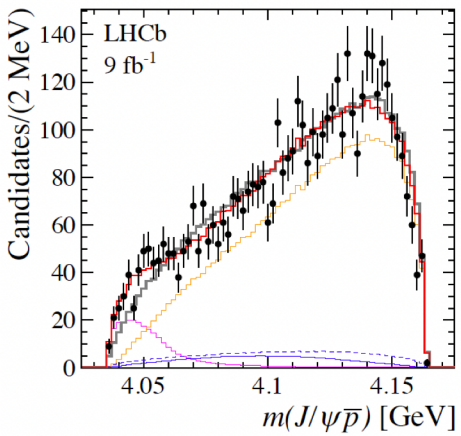
Pentaquark

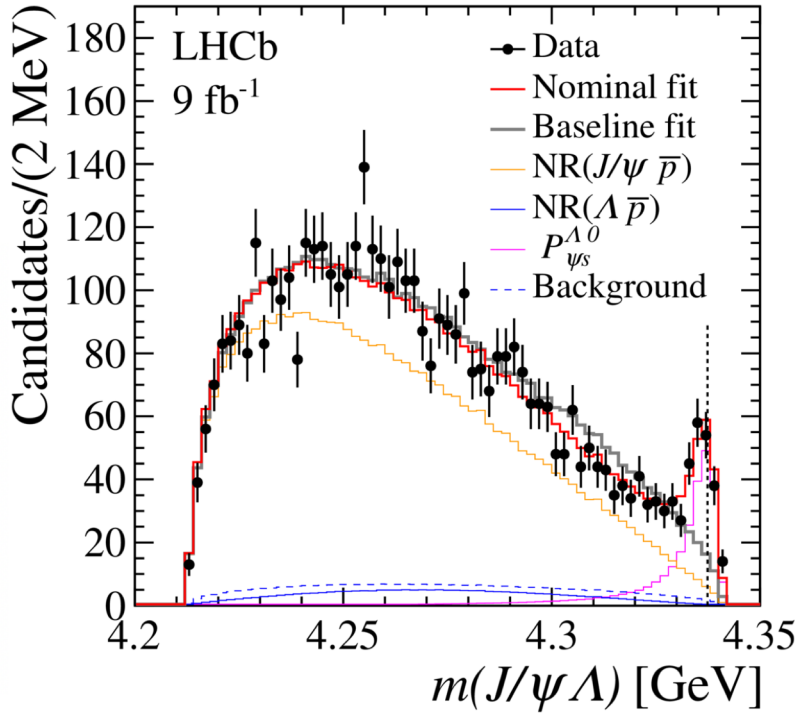
arXiv: 2210.10346 (Accepted by PRL)

- 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
  - $m = 4338.2 \pm 0.7 \pm 0.4$ MeV
  - $\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV
  - $J^P = (1/2)^-$
- Most precise single measurement of B^- mass:
  - $5279.44 \pm 0.05 \pm 0.07$ MeV





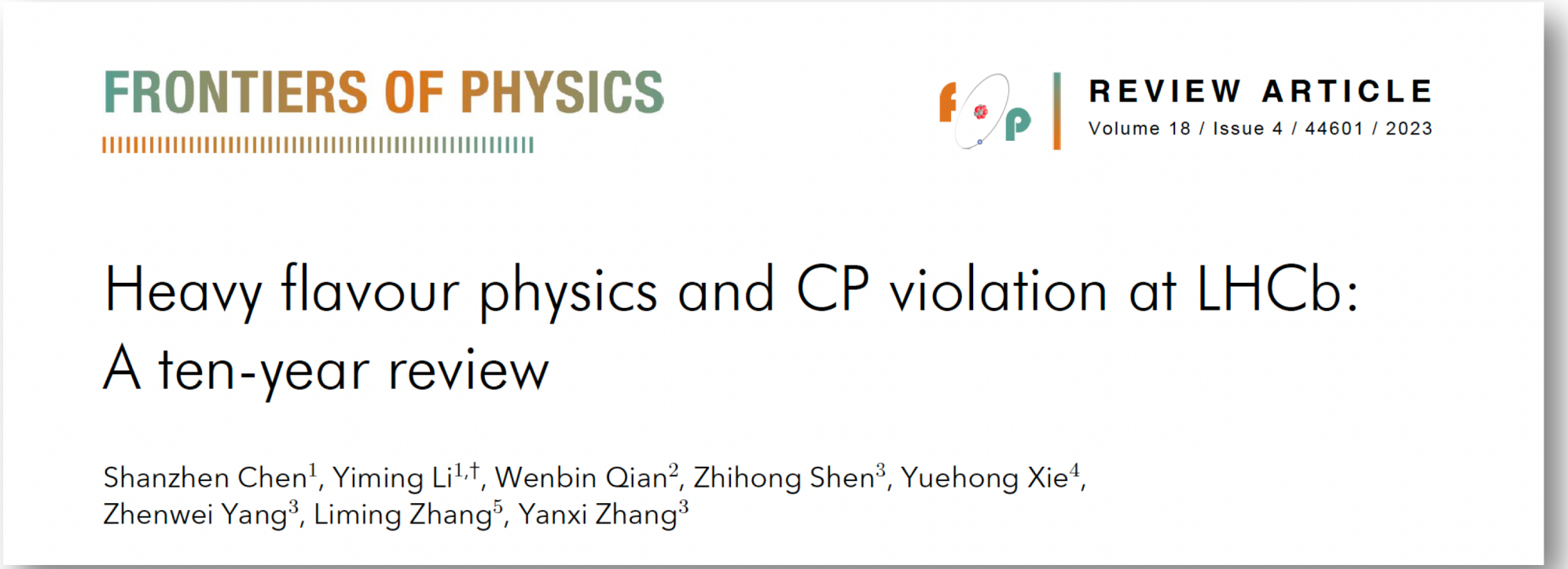




Summary & Prospects

- Thanks to the huge production rate at LHC and excellent detector performance, LHCb has greatly extended our knowledge on heavy hadron spectroscopy, both for conventional or exotic hadrons
- Chinese groups have been playing a crucial role, largely benefiting from active interaction with theoretical community

S. Chen et al., Front. Phys. 18(4), 44601 (2023)



Summary & Prospects

https://lhcb-outreach.web.cern.ch

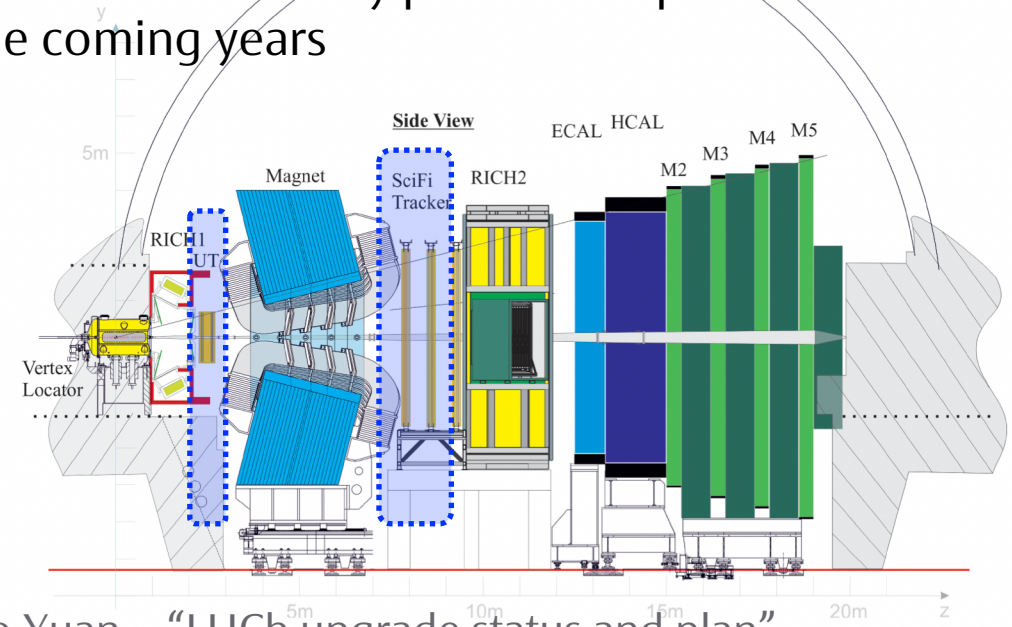
- Upgrade I installation completed!
  - $\mathcal{L}$: $4\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow 2\times10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Removal of hardware trigger
  - New tracking system
  - Chinese groups played key roles in Upstream Tracker and Scintillator Fibre Tracker
- More data & discovery potential expected in the coming years

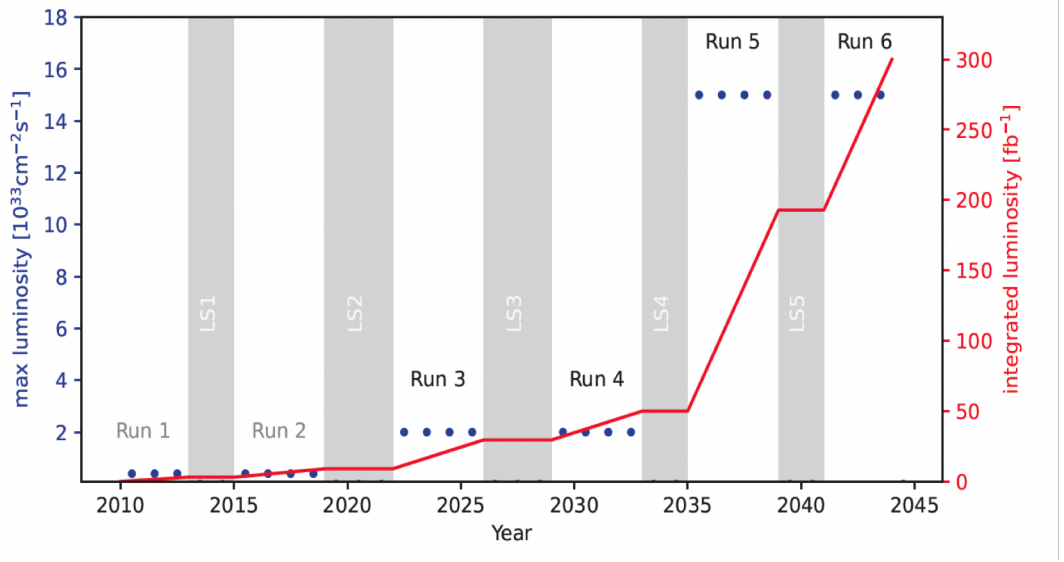
DETECTOR LATEST POSTS

Upstream Tracker closing completes installation of the LHCb Upgrade 1 detector

APR 14, 2023 PIETRZYK

Start of 2023 data taking. Recently the Upstream Tracker (UT), a sub-detector of the LHCb experiment, was closed around the LHC beam pipe. This event...





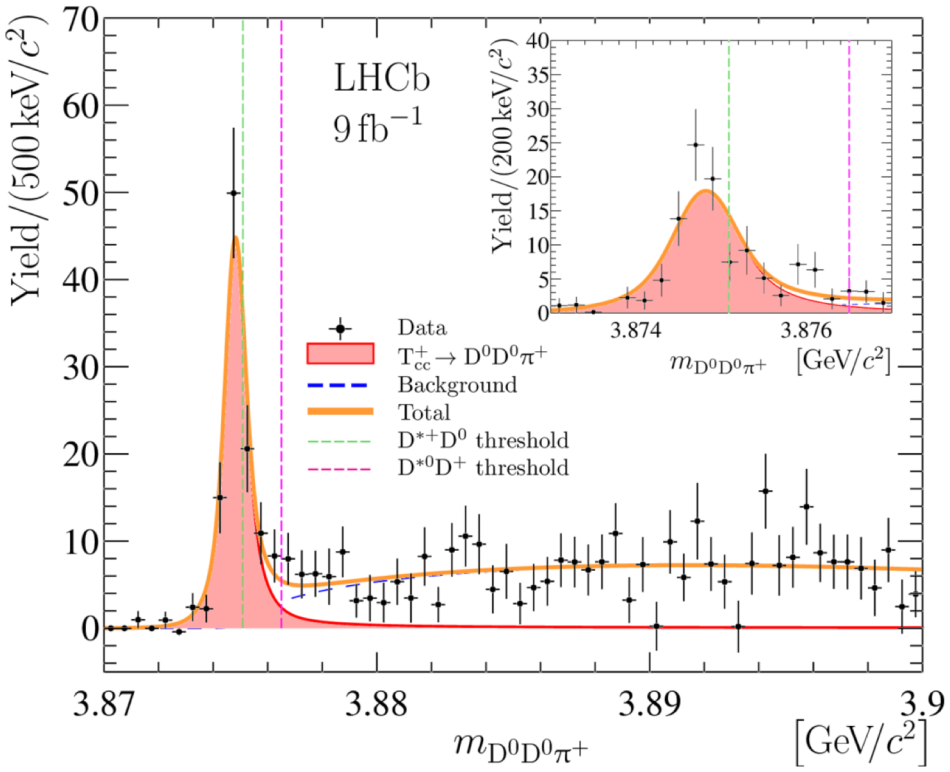
Xuhao Yuan, "LHCb upgrade status and plan"

BACKUP

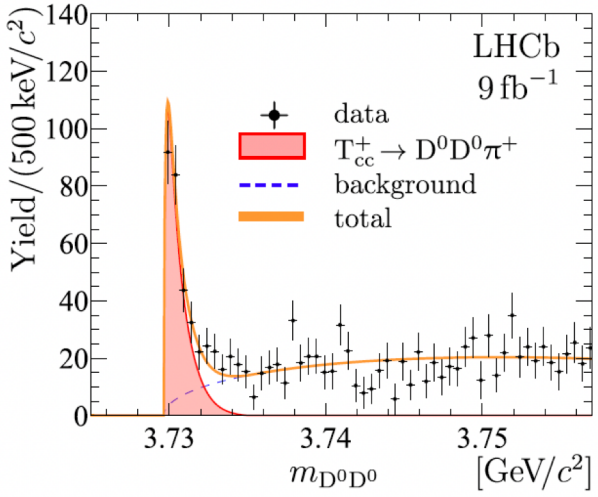
Doubly charmed tetraquark

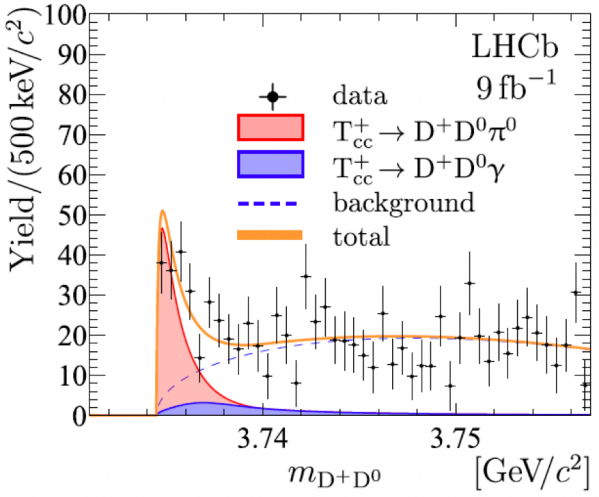
Nature Physics 18 (2022) 751
Nature Comm. 13 (2022) 3351

- 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



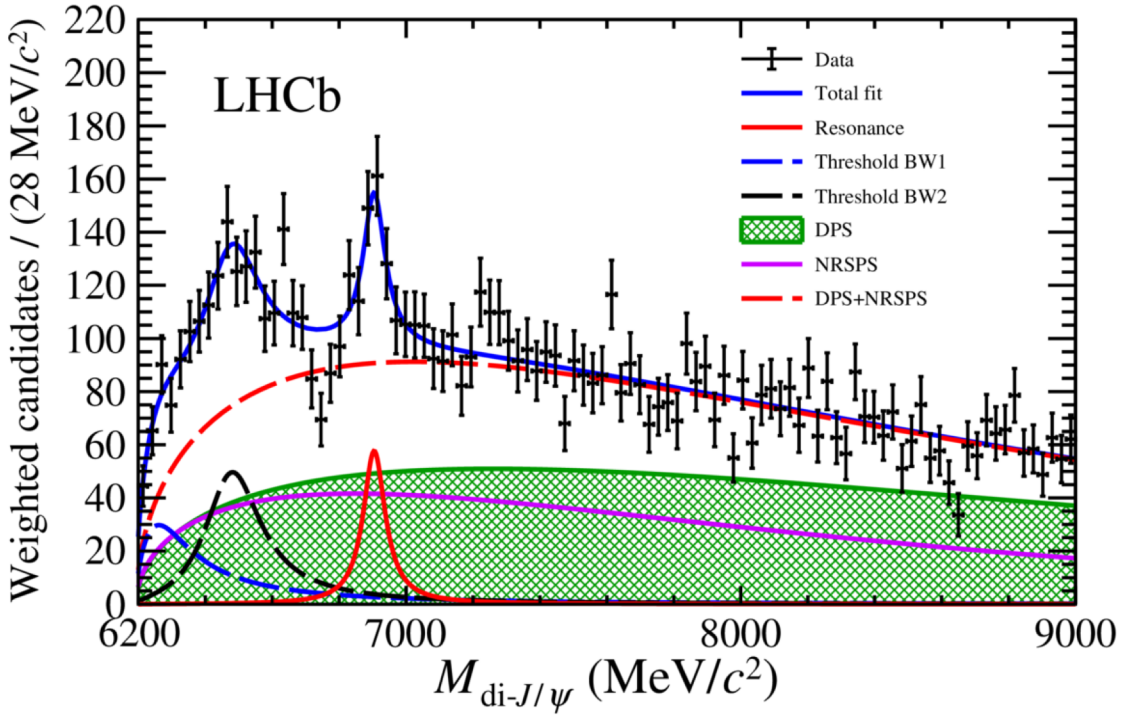
	$\delta\mathfrak{m}$ [keV/c^2]	$\mathfrak{w}$ [keV/c^2]
$\mathfrak{F}^{\mathrm{BW}}$	-279 ± 59	409 ± 163
$\mathfrak{F}^{\mathrm{U}}$	-361 ± 40	47.8 ± 1.9





Fully charmed tetraquark

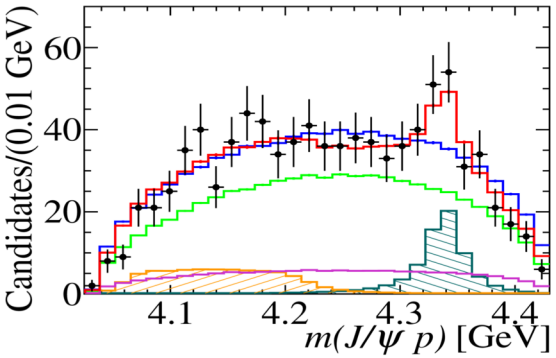
- Narrow resonance of $X(6900)$ or $T_{\psi\psi}(6900)$ discovered with full LHCb Run 1+2 data in prompt $J/\psi J/\psi$ pair spectrum
  - First tetraquark with all-charm quark
  - Recently confirmed by CMS and ATLAS

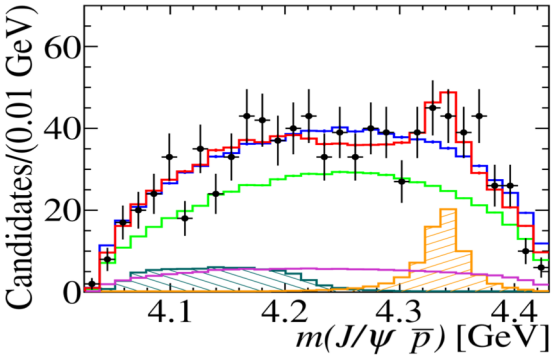


Science Bulletin 65 (2020) 1983

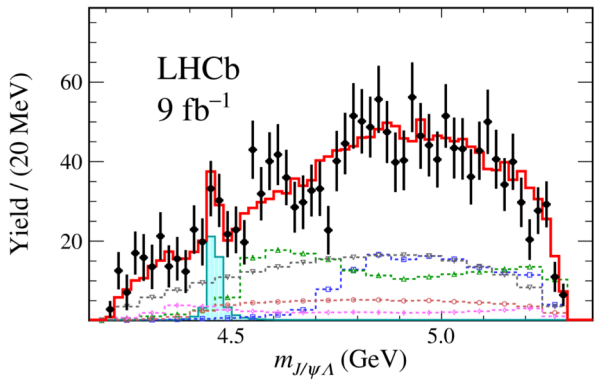
Pentaquark

- Evidence of $P_\psi^N(4337)^+$ in the $B_s^0 \to J/\psi p\bar{p}$ decay





PRL 128 (2022) 062001



- First evidence of pentaquark with strangeness $P_{\psi s}^{\Lambda}(4459)^0$ ($c\bar{c}uds$) discovered in $\Xi_b^- \to J/\psi\Lambda K^-$

PRL 128 (2022) 062001