Heavy flavor spectroscopy study at LHCb

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On behalf of the LHCb collaboration

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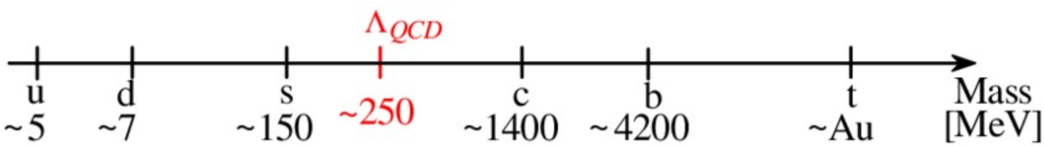
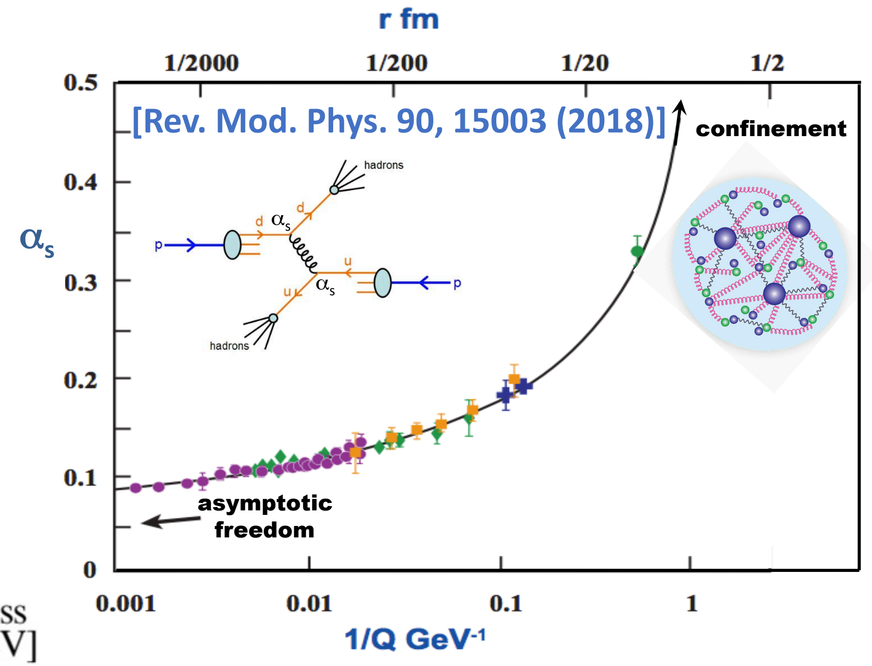
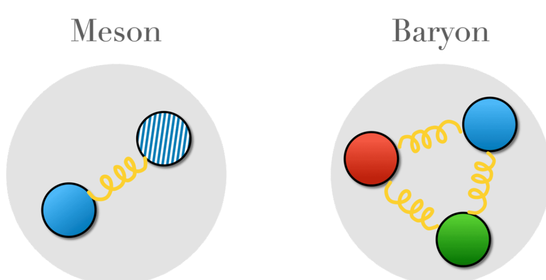
第七届强子谱和强子结构研讨会 @ 电子科技大学, 2024.04.26

Introduction

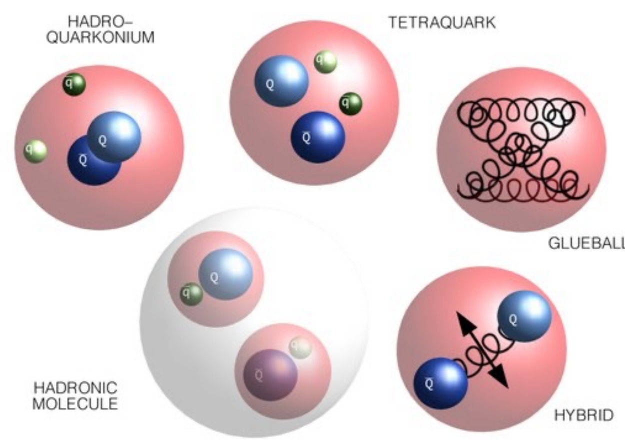
- ➢ ***QCD dilemma***: understanding the non-perturbative property of QCD at low-energy scale
- ➢ ***Hadron spectroscopy***: a main tool to probe QCD at low-energy regime
  - ✓ ***heavy quarks*** bring advances both experimentally and theoretically







conventional hadrons

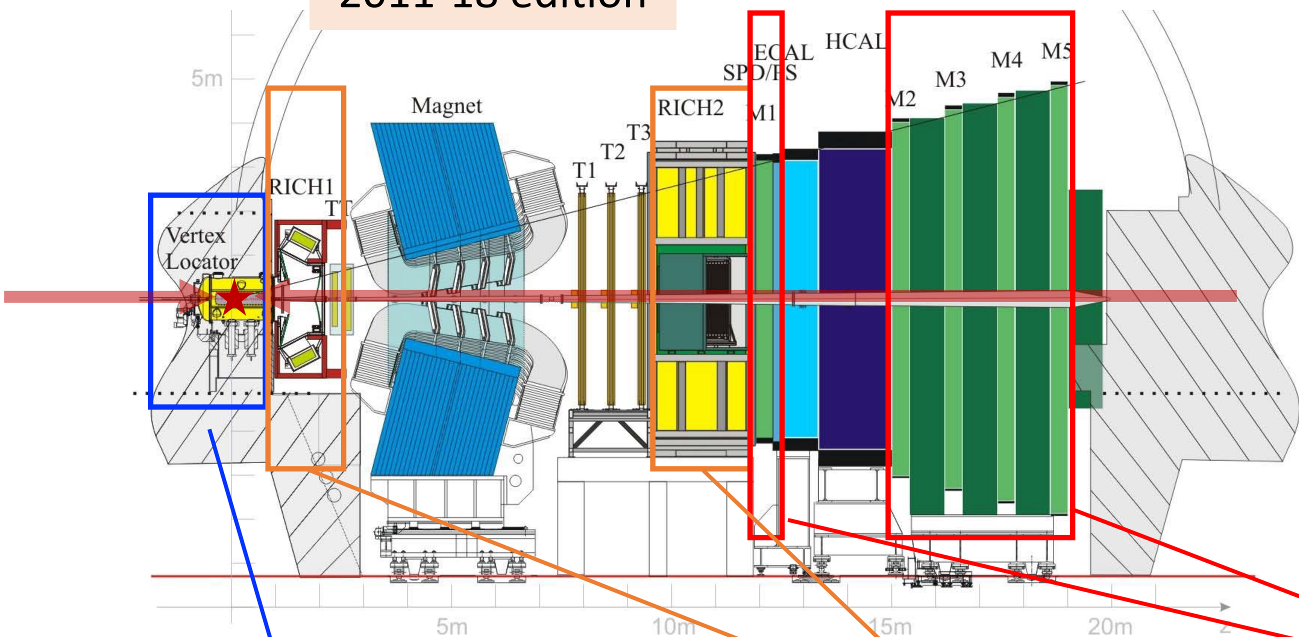


exotic hadrons

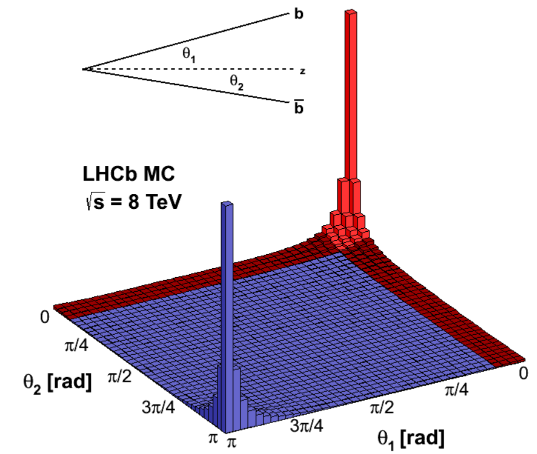
The LHCb detector

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, dedicated to heavy flavor physics at the Large Hadron Collider

2011-18 edition



2.4% 4π angle
$\Rightarrow$ 25% $b\bar{b}$



Vertex Locator: high precision; capable of separating b/c hadron production and decay vertices

$\sigma_{\text{PV},x/y}$~10 μm, $\sigma_{\text{PV},z}$~60 μm

RICHs: efficient identification of pions, kaons and protons

$\varepsilon(K \to K)$~95%
@ misID rate $(\pi \to K)$~5%

Muon system (M1-M5): efficient muon identification and trigger

$\varepsilon(\mu \to \mu)$~97%
@ misID rate $(\pi \to \mu)$~$1-3\%$

[JINST 3 (2008) S08005]

LHCb Physics today

CERN LHCC 98-4
LHCC/P4
20 February 1998

LHCb

Technical Proposal

A Large Hadron Collider Beauty Experiment for
Precision Measurements of
CP Violation and Rare Decays

Decay Modes	Visible Br. fraction	Offline Reconstr.
$B_d^0 \to \pi^+\pi^- + \text{tag}$	0.7×10^{-5}	6.9 k
$B_d^0 \to K^+\pi^-$	1.5×10^{-5}	33 k
$B_d^0 \to \rho^+\pi^- + \text{tag}$	1.8×10^{-5}	551
$B_d^0 \to J/\psi K_S + \text{tag}$	3.6×10^{-5}	56 k
$B_d^0 \to \overline{D}^0 K^{*0}$	3.3×10^{-7}	337
$B_d^0 \to K^{*0}\gamma$	3.2×10^{-5}	26 k
$B_s^0 \to D_s^-\pi^+ + \text{tag}$	1.2×10^{-4}	35 k
$B_s^0 \to D_s^- K^+ + \text{tag}$	8.1×10^{-6}	2.1 k
$B_s^0 \to J/\psi\phi + \text{tag}$	5.4×10^{-5}	44 k

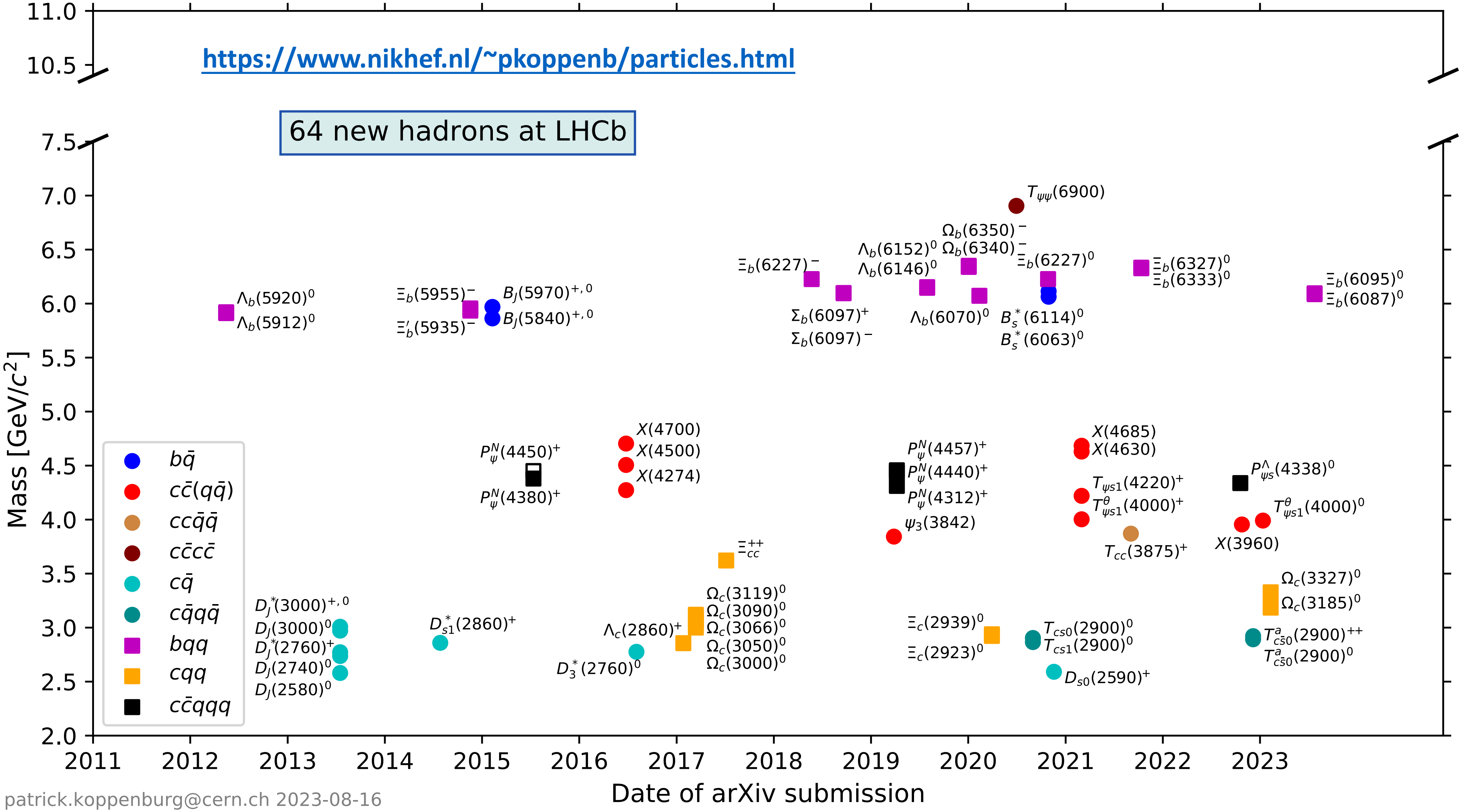
Most cited LHCb physics results today:

1. **Pentaquark** in $J/\psi p$
2. Test of lepton universality in $B \to K\ell^+\ell^-$ (R_K)
3. Test of lepton universality in $B \to D\ell$ (R_D)
4. Angular analysis in $B \to K\pi\pi$
5. $B_s^0 \to \mu\mu$
6. Ξ_{cc} baryon
7. resonant character of $Z(4430)$ tetraquark
8. $X(3872)$ quantum numbers
9. charm production cross-section
10. **CP violation in charm**
11. beauty production cross-section
12. **fully charmed tetraquark** in double J/ψ
13. doubly charmed tetraquark
14. b-hadron production fractions
15. charm hadron spectroscopy

By Giacomo Graziani

G. Graziani slide 3

Hadrons observed at LHCb



Selected new measurements

- **Conventional hadrons**

Excited states:

✓ Observation of $\Xi_b^{-/0**} \to \Xi_b^{-/0}\pi^+\pi^-$ **[PRL 131 (2023) 171901]**

✓ Observation of new $\Omega_c^0 \to \Xi_c^+ K^-$ **[PRL 131 (2023) 131902]**

Decay properties:

✓ Observation of $B_c^+ \to J/\psi\pi^+\pi^0$ **[arXiv:2402.05523]**

✓ Study of $B_c^+ \to \chi_c\pi^+$ decays **[JHEP 02 (2024) 173]**

✓ Observation of $\Lambda_b^0 \to D^+D^-\Lambda$ **[arXiv: 2403.03586]**

- **Exotic hadrons**

✓ Search for prompt production of pentaquarks in open charm final states **[arXiv: 2404.07131]**

✓ Modification of $\chi_{c1}(3872)$ production in $p\mathrm{Pb}$ collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\ \mathrm{TeV}$ **[arXiv: 2402.14975]**

✓ First measurement of $J/\psi\phi$ production in pp collisions with no additional activity **[LHCb-PAPER-2023-043] in preparation**

Conventional hadrons

-- Excited states

- ✓ Observation of $\Xi_b^{-/0**} \to \Xi_b^{-/0}\pi^+\pi^-$ [PRL 131 (2023) 171901]
- ✓ Observation of new $\Omega_c^0 \to \Xi_c^+ K^-$ [PRL 131 (2023) 131902]

Singly-heavy baryons

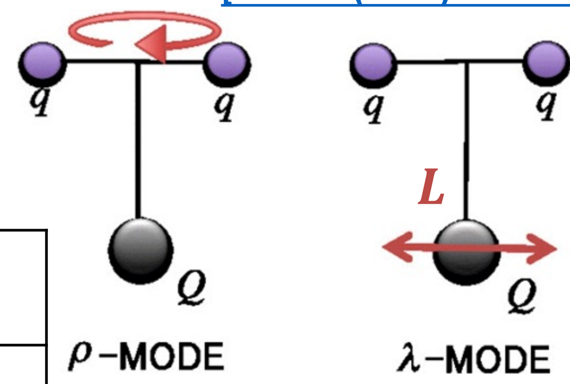
- Missing resonances problem in baryon physics

⇒ heavy quark-light diquark $Q[qq]$ model is widely used to describe Qqq systems

✓ λ-mode: low-lying states well established for most species

✓ ρ-mode: no firm assignment yet

[PRD 92 (2015) 114029]

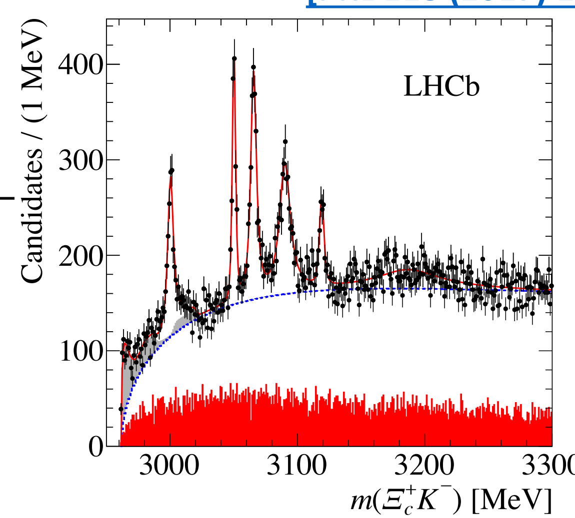


- **$\Xi_b^{-/0}$ spectrum** (based on λ-mode)

	$J^P_{[qq]} = 0^+$	$J^P_{[qq]} = 1^+$
$L = 0$	$(1/2)^+$ $\Xi_b^{0,-}$	$(1/2)^+, (3/2)^+$ $\Xi_b'(5935)^-, \Xi_b(5955)^- \to \Xi_b^0\pi^-$ $\Xi_b(5945)^0 \to \Xi_b^-\pi^+$
$L = 1$	$(1/2)^-, (3/2)^-$ $\boldsymbol{\Xi_b(6100)^- \to \Xi_b(5945)^0\pi^-}$ [PRL 126 (2021) 252003] by CMS	……

- **Ω_c^0 spectrum**:
  yet no consensus on the interpretation of observed excited states

[PRL 118 (2017) 182001]

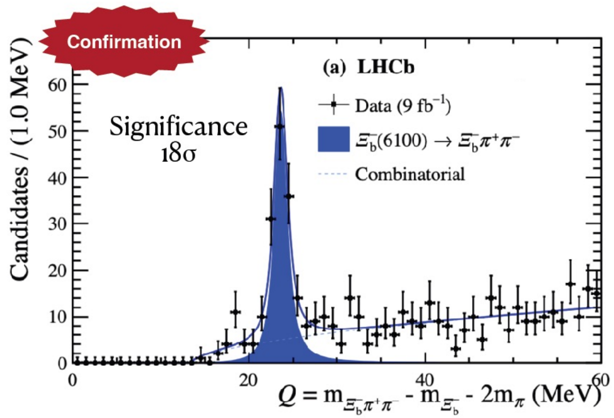


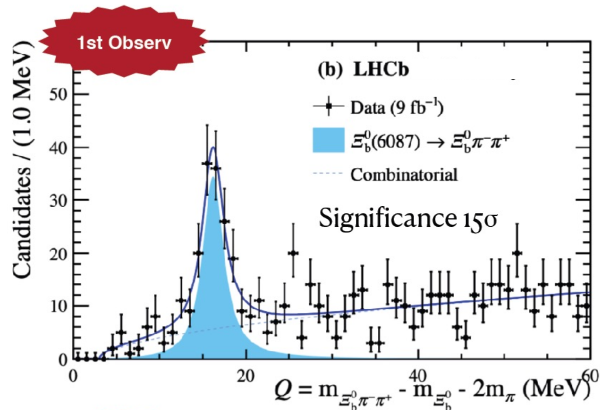
Observation of $\Xi_b^{-/0**} \to \Xi_b^{-/0}\pi^+\pi^-$

[PRL 131 (2023) 171901]

- $\Xi_b^-\pi^+\pi^-$ with $\Xi_b^- \to \Xi_c^0[pK^-K^+\pi^+]\pi^-$ and $\Xi_b^- \to \Xi_c^0[pK^-K^+\pi^+]\pi^-\pi^+\pi^-$: an LHCb record of 9 tracks!
- $\Xi_b^0\pi^+\pi^-$ with $\Xi_b^0 \to \Xi_c^+[pK^-\pi^+]\pi^-$ and $\Xi_b^0 \to \Xi_c^+[pK^-\pi^+]\pi^-\pi^+\pi^-$

[PRL 126 (2021) 252003] by CMS

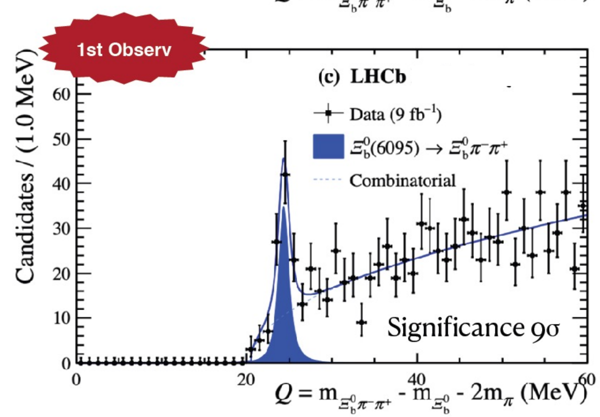




	Value [MeV]
Q_0 ($\Xi_b^-(6100)$)	$23.60 \pm 0.11 \pm 0.02$
Γ ($\Xi_b^-(6100)$)	$0.94 \pm 0.30 \pm 0.08$
m_0 ($\Xi_b^-(6100)$)	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6$ (Ξ_b^-)
Q_0 ($\Xi_b^0(6087)$)	$16.20 \pm 0.20 \pm 0.06$
Γ ($\Xi_b^0(6087)$)	$2.43 \pm 0.51 \pm 0.10$
m_0 ($\Xi_b^0(6087)$)	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5$ (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)

Confirmation

1st Observ



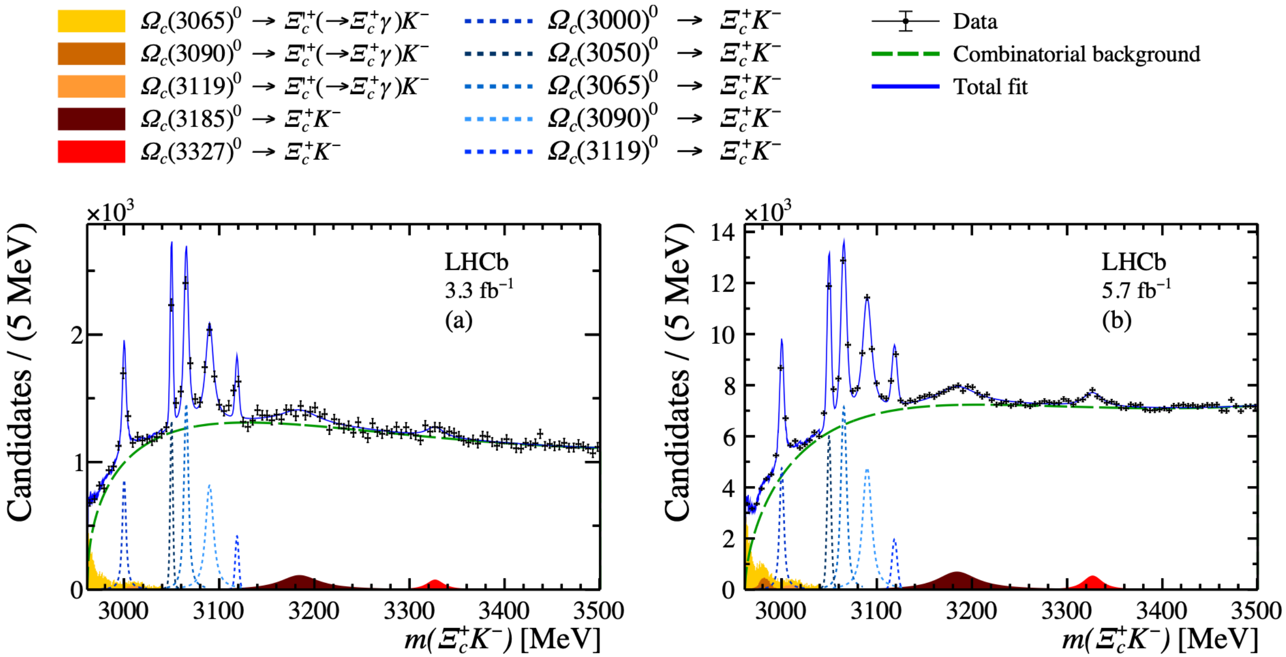
✓ Consistent with naïve expectation for 1P $J^P_{[qq]} = 0^+$ $(1/2)^-, (3/2)^-$ doublet

Observation of new $\Omega_c^0 \to \Xi_c^+ K^-$

Zhihao Xu
Jibo He

[PRL 131 (2023) 131902]

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

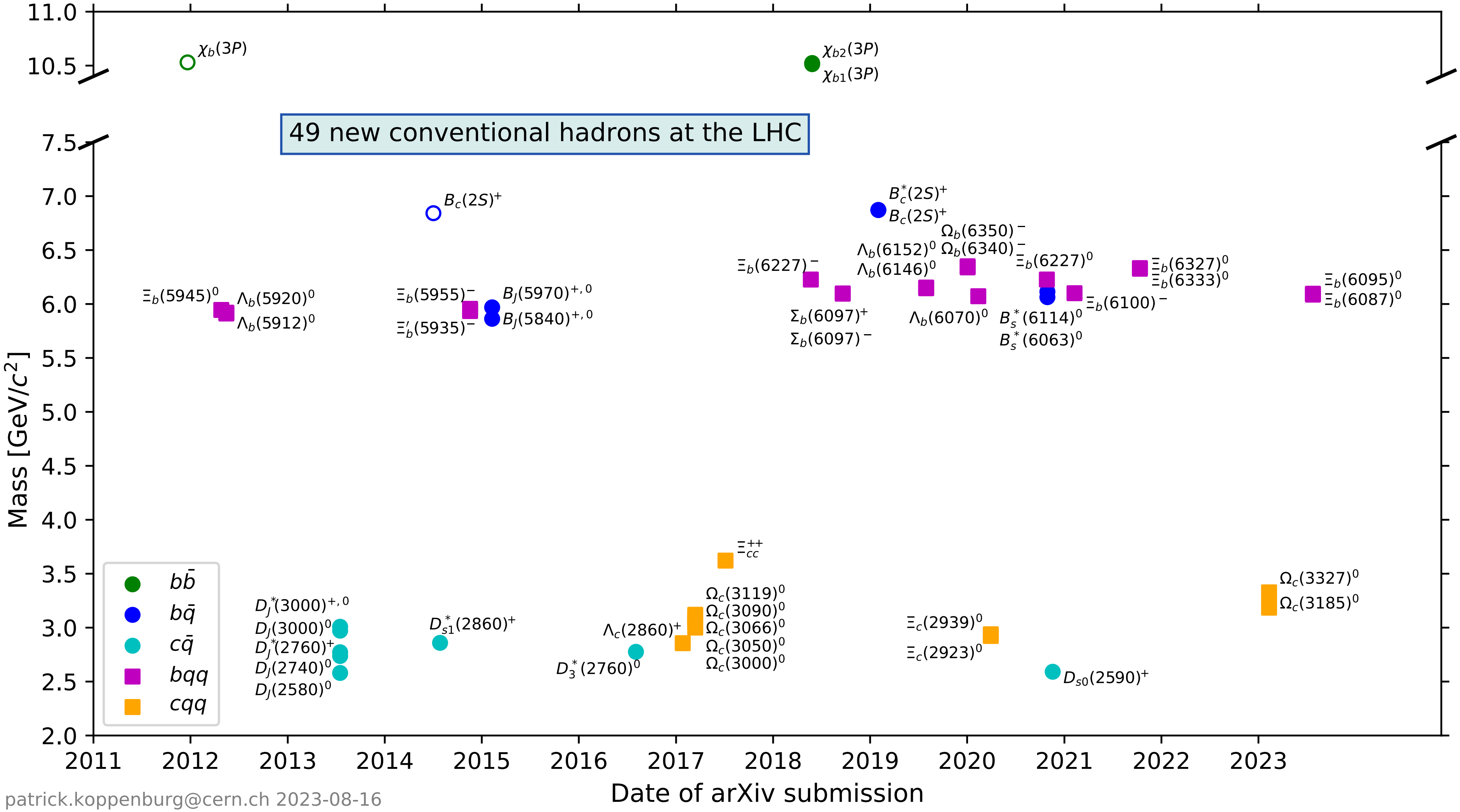


Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07 \,^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23 \,^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04 \,^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17 \,^{+0.64}_{-0.72}$
		$< 1.8\,\text{MeV}, 95\%$ C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06 \,^{+0.06}_{-0.06}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

✓ Most precise mass and width measurement

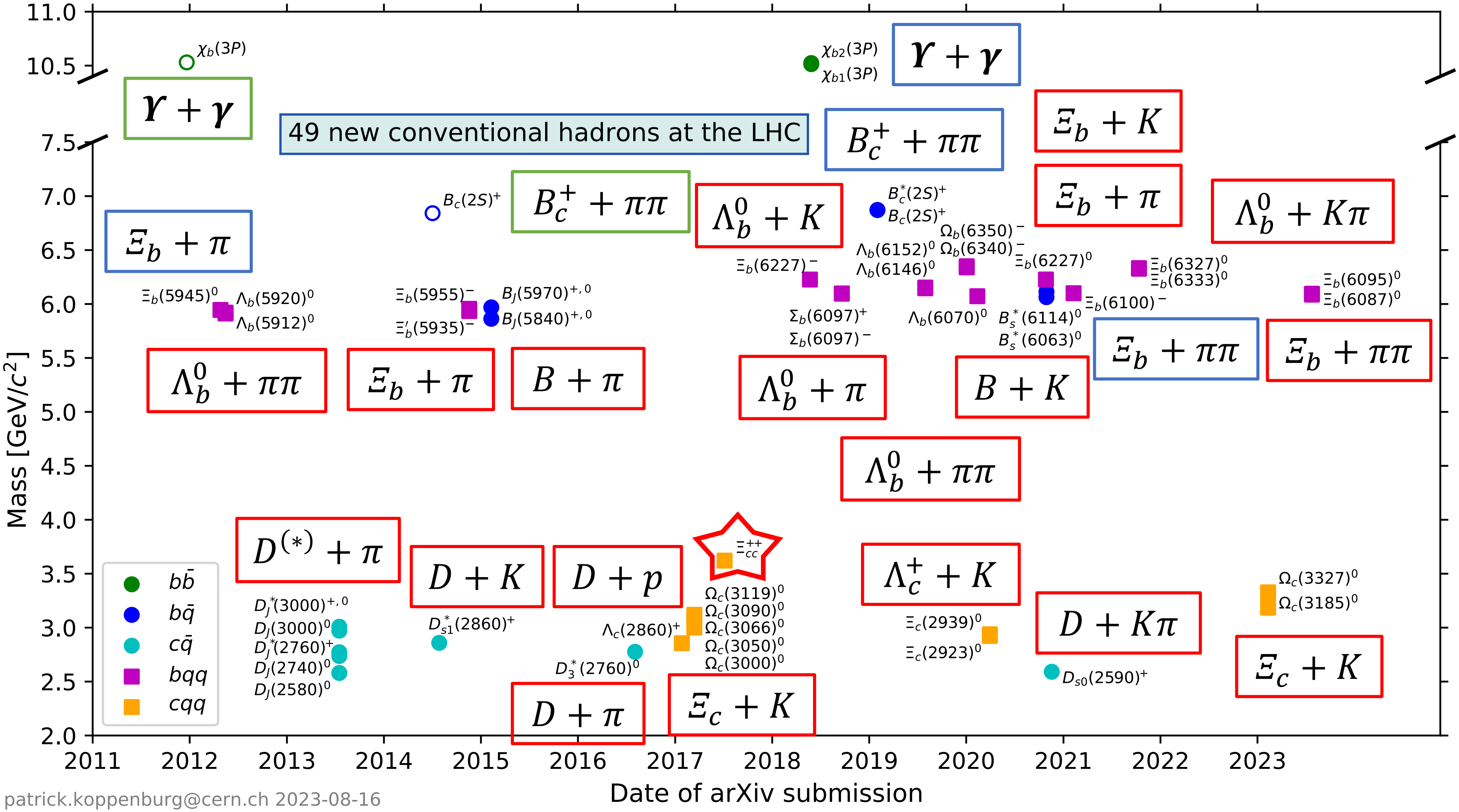
✓ Two new states:

Conventional hadrons at LHC



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

Conventional hadrons at LHC



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

LHCb **CMS** **ATLAS**

Conventional excited hadrons at LHCb

$\boldsymbol{D}$: $D^{(*)}+\pi$

$\boldsymbol{D_s^+}$: $D+K$, $D+K\pi$

$\boldsymbol{\Lambda_c^+}$ $\boldsymbol{\Sigma_c}$: $\Lambda_c^+ + \pi$, $\Lambda_c^+ + \pi\pi$, $D+p$

$\boldsymbol{\Xi_c}$: $\Xi_c + \pi$, $\Xi_c + \pi\pi$, $\Lambda_c^+ + K$

$\boldsymbol{\Omega_c^0}$: $\Xi_c + K$

$\boldsymbol{B}$: $B+\pi$

$\boldsymbol{B_s^0}$: $B+K$

$\boldsymbol{B_c^+}$: $B_c^+ + \pi\pi$

$\boldsymbol{\Lambda_b^0}$ $\boldsymbol{\Sigma_b}$: $\Lambda_b^0 + \pi$, $\Lambda_b^0 + \pi\pi$

$\boldsymbol{\Xi_b}$: $\Xi_b + \pi$, $\Xi_b + \pi\pi$, $\Lambda_b^0 + K$, $\Lambda_b^0 + K\pi$

$\boldsymbol{\Omega_b^-}$: $\Xi_b + K$

suggestions?

Conventional hadrons

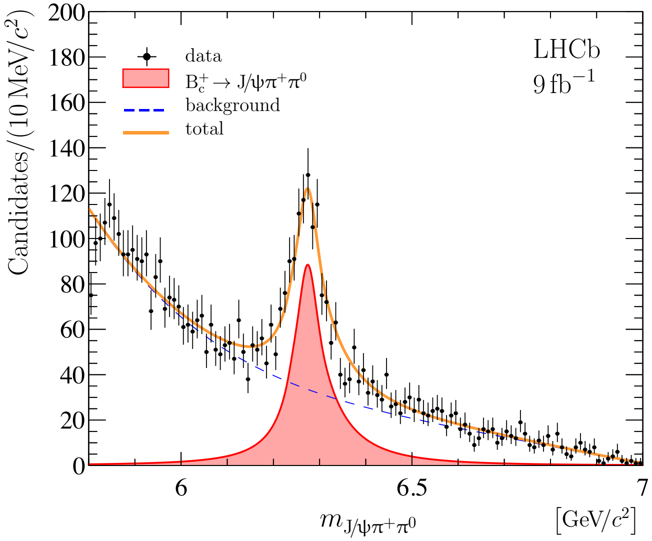
-- Decay properties

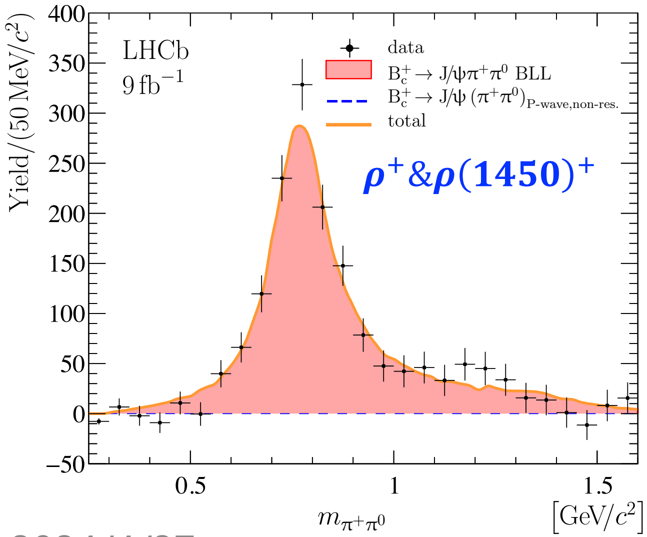
- ✓ Observation of $B_c^+ \to J/\psi\pi^+\pi^0$ [arXiv:2402.05523]
- ✓ Study of $B_c^+ \to \chi_c\pi^+$ decays [JHEP 02 (2024) 173]
- ✓ Observation of $\Lambda_b^0 \to D^+D^-\Lambda$ [arXiv: 2403.03586]

Observation of $B_c^+ \to J/\psi\pi^+\pi^0$ [arXiv:2402.05523]

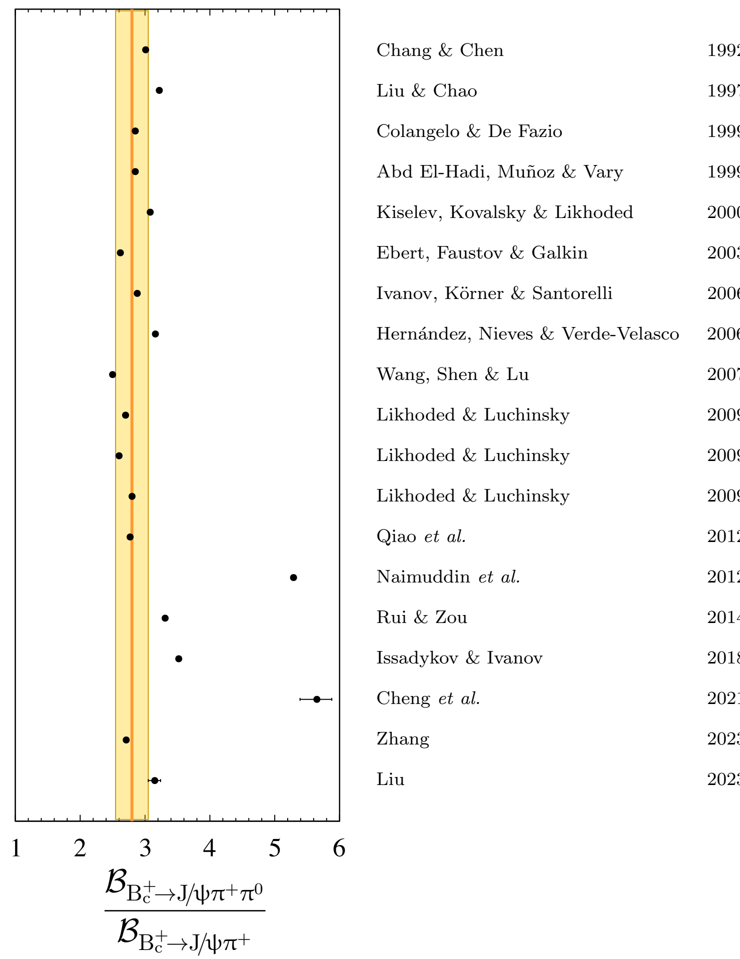
➢ First observation of $B_c^+ \to J/\psi\pi^+\pi^0$ with significance > 20 σ

$N = (1.08 \pm 0.06)\times10^3$





$$\frac{\mathcal{B}_{B_c^+\to J/\psi\pi^+\pi^0}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = 2.80 \pm 0.15 \pm 0.11 \pm 0.16$$

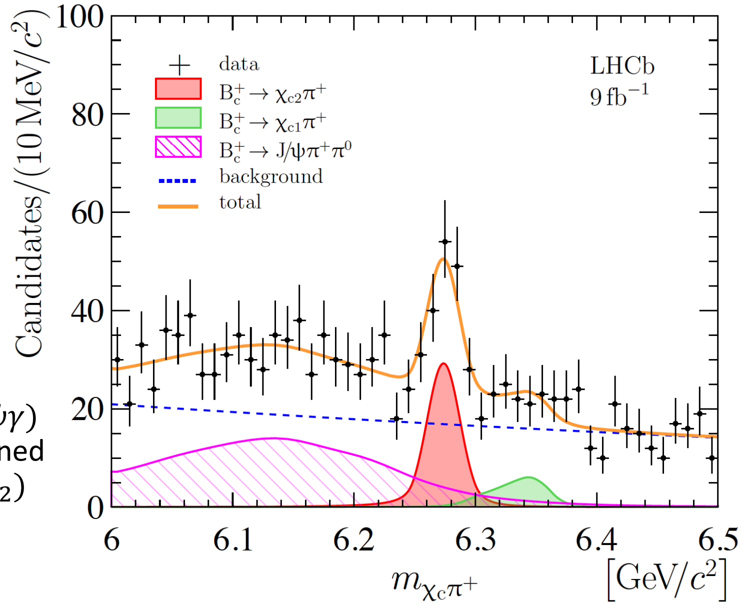


Study of $B_c^+ \to \chi_c \pi^+$

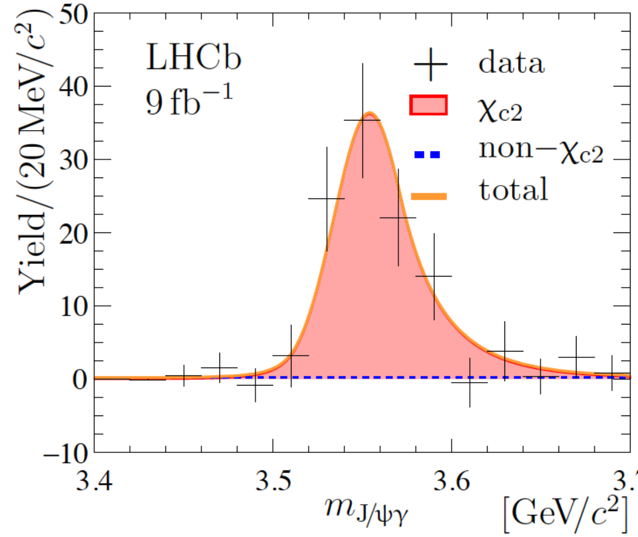
[JHEP 02 (2024) 173]

- First observation of $B_c^+ \to \chi_{c2}\pi^+$ with significance $> 7\,\sigma$
- Upper limit set on $B_c^+ \to \chi_{c1}\pi^+$

$N(\chi_{c2}) = 108 \pm 16$

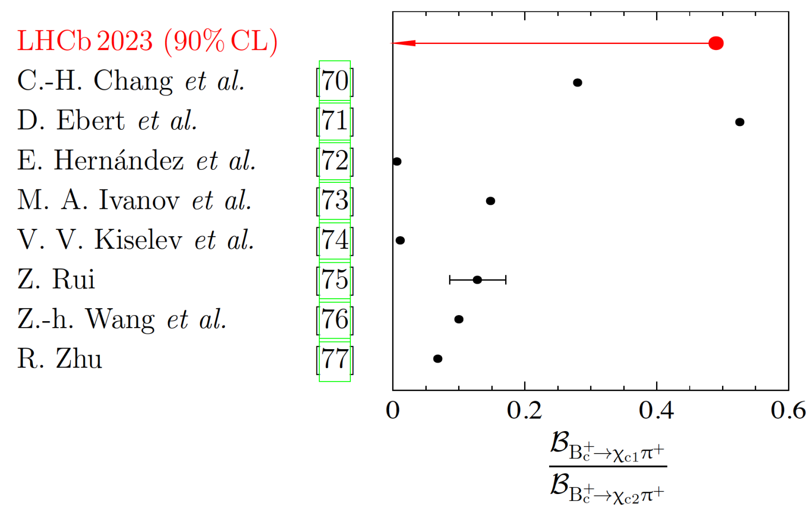


* $m(J/\psi\gamma)$ constrained to $M(\chi_{c2})$



$$\frac{\mathcal{B}_{B_c^+\to\chi_{c2}\pi^+}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = 0.37 \pm 0.06 \pm 0.02 \pm 0.01$$

$$\frac{\mathcal{B}_{B_c^+\to\chi_{c1}\pi^+}}{\mathcal{B}_{B_c^+\to\chi_{c2}\pi^+}} < 0.49 \text{ at } 90\% \text{ CL}$$



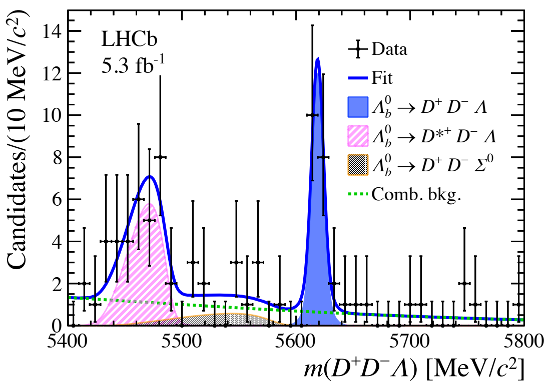
Observation of $\Lambda_b^0 \to D^+ D^- \Lambda$

[arXiv: 2403.03586]

- **First observation** of $\Lambda_b^0 \to D^+ D^- \Lambda$ with significance of 16 σ

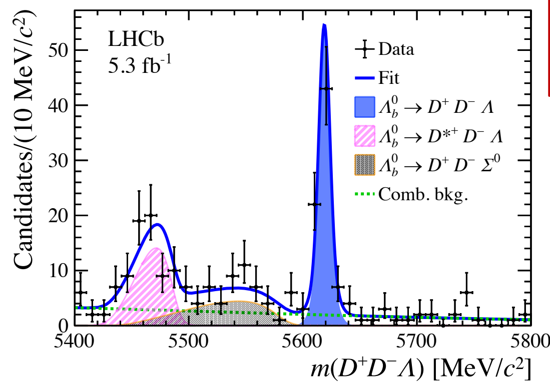
✓ Λ decay inside VELO

$N = 19 \pm 5$



✓ Λ decay outside VELO

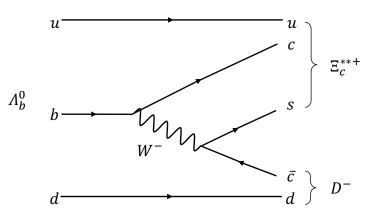
$N = 73 \pm 9$

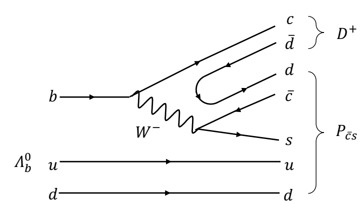


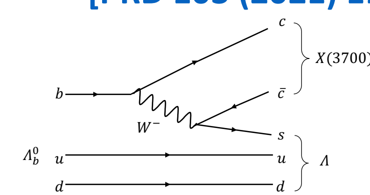
$$\frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda)}{\mathcal{B}(B^0 \to D^+ D^- K_S^0)} = 0.179 \pm 0.022 \pm 0.014$$

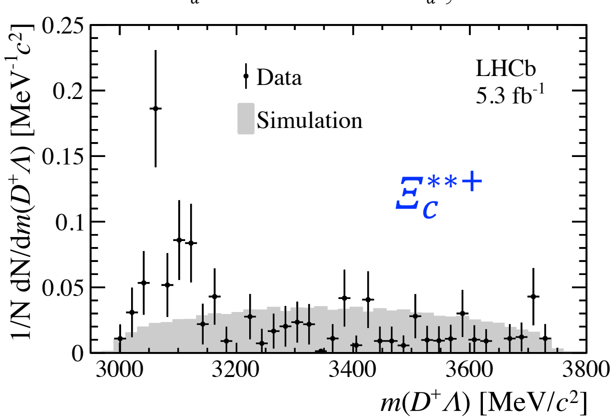
$$\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4}$$

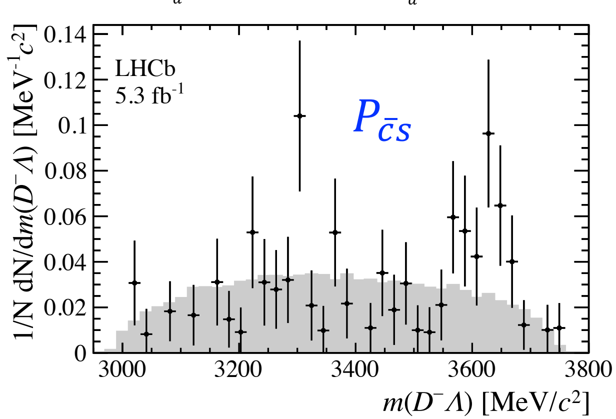
[PRD 103 (2021) 114013]

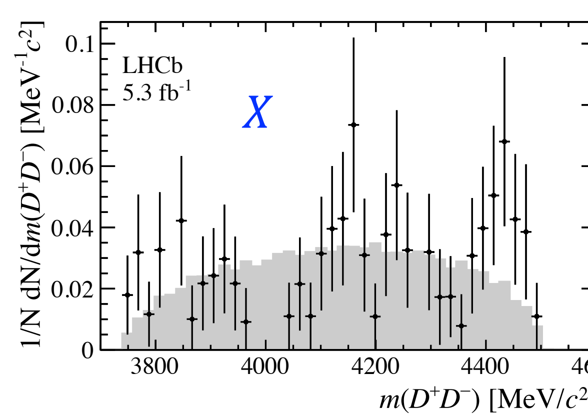




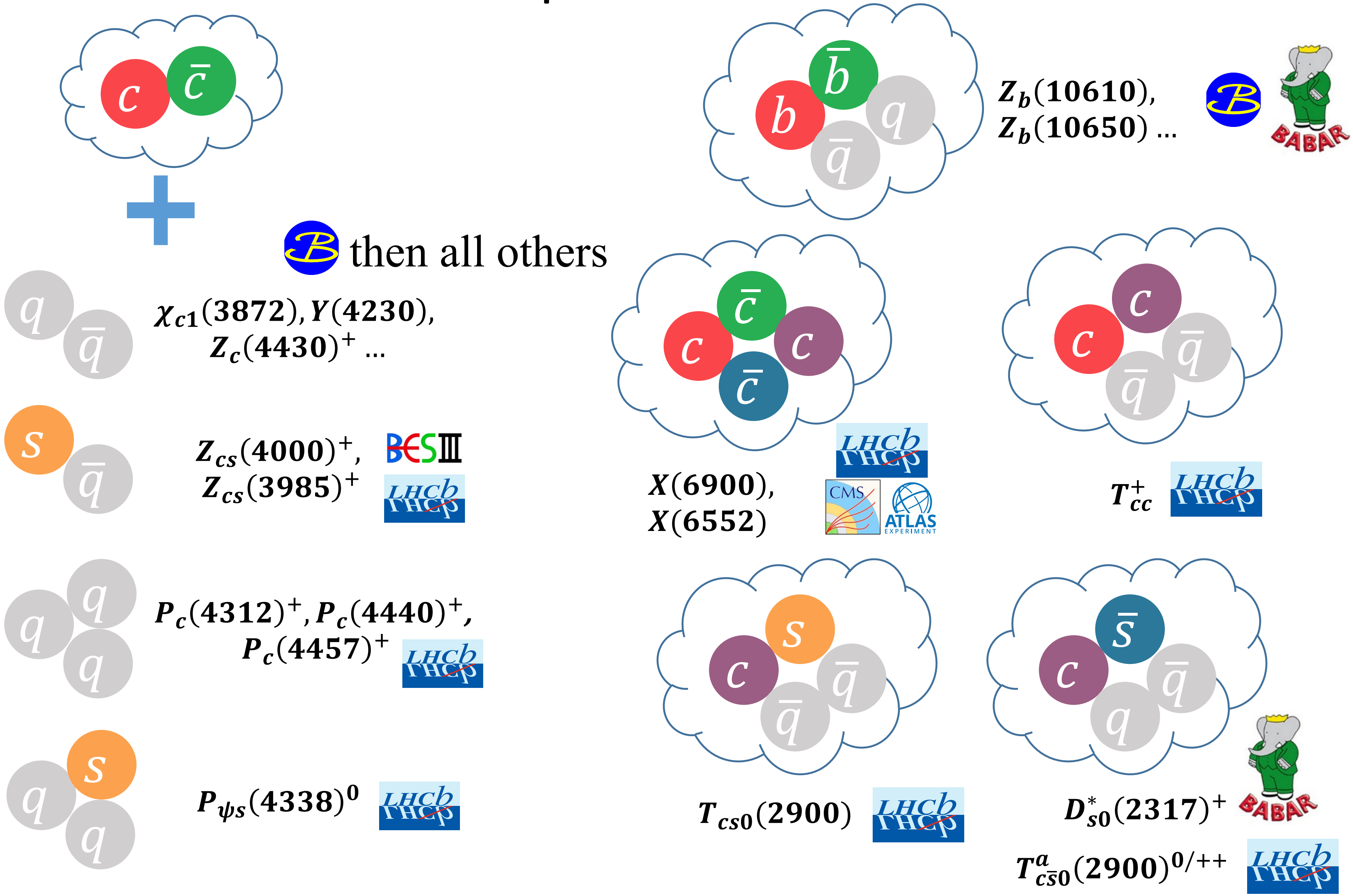








Map of exotics

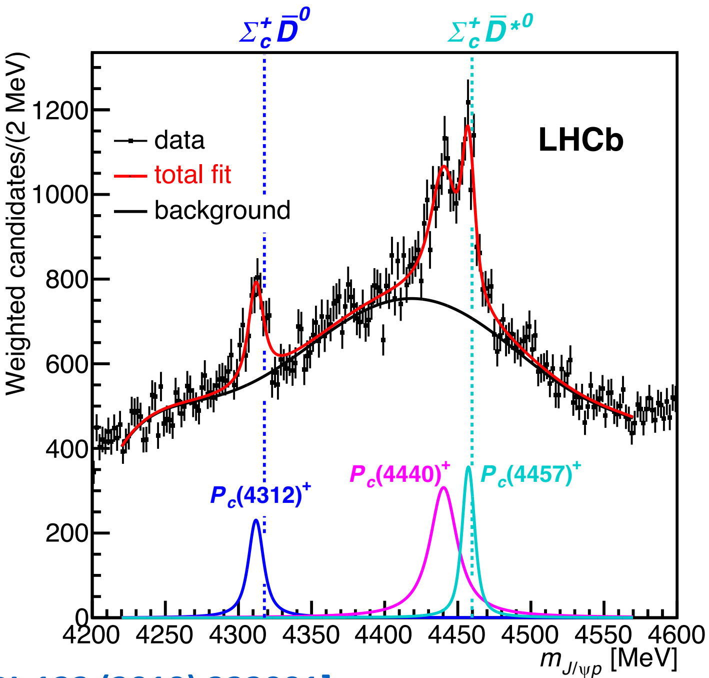


Exotic hadrons

- ✓ Search for prompt production of pentaquarks in open charm final states
  [arXiv: 2404.07131]
- ✓ Modification of $\chi_{c1}(3872)$ production in $p\mathrm{Pb}$ collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\ \mathrm{TeV}$
  [arXiv: 2402.14975]
- ✓ First measurement of $J/\psi\phi$ production in pp collisions with no additional activity **[LHCb-PAPER-2023-043] in preparation**

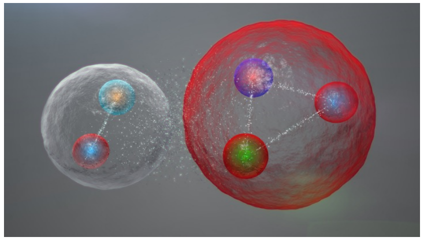
Background for pentaquark study

$\Lambda_b^0 \to [J/\psi\, p]K^-$



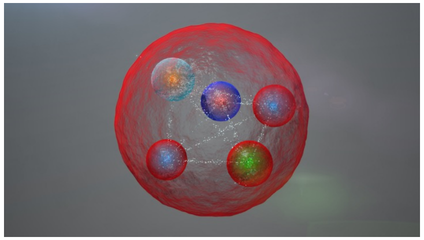
[PRL 122 (2019) 222001]

Hadron molecule



- Mass proximity to threshold **natural**
- Fall-apart decay **dominant**

Compact multiquark



- Mass proximity to threshold **accidental**
- No (strong) hierarchy of couplings

Proximity of $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

➢The observation of new decay modes can shed light on the binding scheme of the exotic hadrons ⇒ search through open charm modes

Search for pentaquarks via open charm

[arXiv: 2404.07131]

- Inclusive search performed using 5.7 fb^{-1} data from 2016-2018
- Reconstruction: $\Lambda_c^+ \to pK^-\pi^+, D^- \to K^+\pi^-\pi^-, D^0 \to K^-\pi^+$
  $\Sigma_c^{++(0)} \to \Lambda_c^+\pi^{+(-)}, D^{*-} \to \overline{D}^0\pi^-$

✓hidden-charm pentaquarks

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	$\overline{D}^0$	+1	1/2	1	0	✓
Λ_c^+	D^-	0	−1/2	1	0	✓
Λ_c^+	D^{*-}	0	−1/2	1	0	✓
Σ_c^{++}	$\overline{D}^0$	+2	3/2	1	0	✓
Σ_c^{++}	D^-	+1	1/2	1	0	✓
Σ_c^{++}	D^{*-}	+1	1/2	1	0	×
Σ_c^0	$\overline{D}^0$	0	−1/2	1	0	✓
Σ_c^0	D^-	−1	−3/2	1	0	✓
Σ_c^0	D^{*-}	−1	−3/2	1	0	×
Σ_c^{*++}	$\overline{D}^0$	+2	3/2	1	0	✓
Σ_c^{*++}	D^-	+1	1/2	1	0	✓
Σ_c^{*++}	D^{*-}	+1	1/2	1	0	✓
Σ_c^{*0}	$\overline{D}^0$	0	−1/2	1	0	✓
Σ_c^{*0}	D^-	−1	−3/2	1	0	✓
Σ_c^{*0}	D^{*-}	−1	−3/2	1	0	✓

✓doubly-charmed pentaquarks & excited Ξ_{cc}

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	D^0	+1	−1/2	3	2	✓
Λ_c^+	D^+	+2	1/2	3	2	✓
Λ_c^+	D^{*+}	+2	1/2	3	2	✓
Σ_c^{++}	D^0	+2	1/2	3	2	×
Σ_c^{++}	D^+	+3	3/2	3	2	×
Σ_c^{++}	D^{*+}	+3	3/2	3	2	×
Σ_c^0	D^0	0	−3/2	3	2	×
Σ_c^0	D^+	+1	−1/2	3	2	×
Σ_c^0	D^{*+}	+1	−1/2	3	2	×
Σ_c^{*++}	D^0	+2	1/2	3	2	✓
Σ_c^{*++}	D^+	+3	3/2	3	2	✓
Σ_c^{*++}	D^{*+}	+3	3/2	3	2	×
Σ_c^{*0}	D^0	0	−3/2	3	2	✓
Σ_c^{*0}	D^+	+1	−1/2	3	2	✓
Σ_c^{*0}	D^{*+}	+1	−1/2	3	2	×

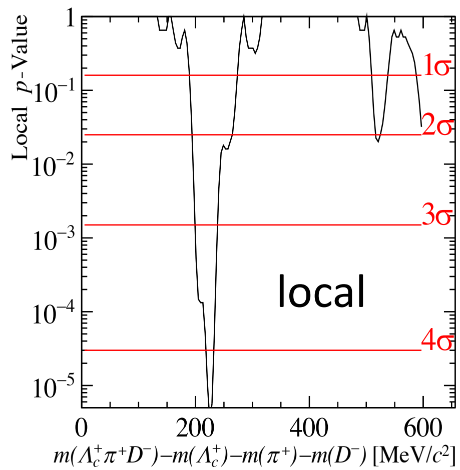
*10 modes too statistically limited to set upper limits

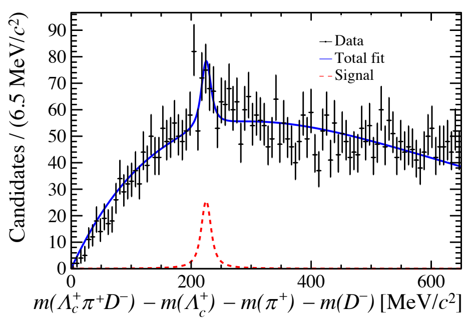
Results

- No significant signals are found

[arXiv: 2404.07131]

- Upper limits set on $R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\varepsilon_{\Lambda_c^+}}{\varepsilon_{P_c}} \to \frac{\sigma(P_c)\times\mathcal{B}\left(P_c\to\Lambda_c^+ D(\pi)\right)\times\mathcal{B}(D)}{\sigma(\Lambda_c^+)}$





$c\bar{c}uud$

$M\sim 4520.69$ MeV

*Complete list in paper

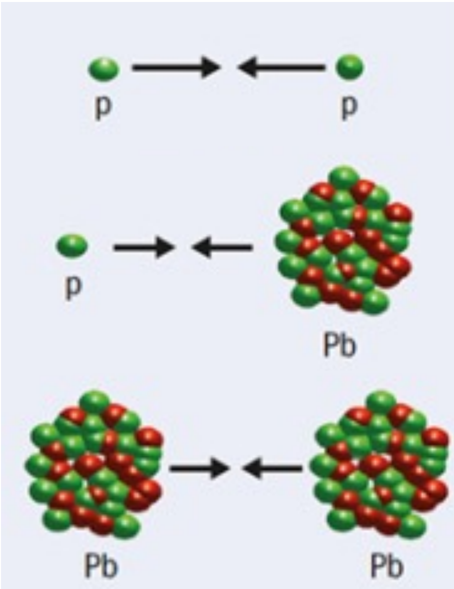
Decay Mode	Width (MeV/c^2)	Significance (σ) Local	Significance (σ) Corrected	Q-value (MeV/c^2)	Signal Yield	UL ($\times 10^{-3}$) 90% CL	UL ($\times 10^{-3}$) 95% CL
$\Lambda_c^+\pi^+D^-$	0	3.59	2.21	225	41.6 ± 12.6	3.95	4.19
	5	4.01	2.89	225	64.7 ± 17.4	4.43	4.69
	10	4.30	3.32	225	87.1 ± 21.6	4.64	4.85
	15	4.50	3.62	225	108.2 ± 25.3	4.72	4.90
$\Lambda_c^+\pi^-D^-$	0	3.36	1.90	257	38.1 ± 12.4	4.28	4.56
	5	3.86	2.71	253	62.1 ± 17.1	4.62	4.83
	10	4.18	3.20	249	83.7 ± 21.2	4.72	4.88
	15	4.44	3.56	249	103.5 ± 24.6	4.77	4.92
$\Lambda_c^+\pi^+\overline{D}^0$	0	3.18	1.58	245	41.9 ± 13.7	2.87	3.06
	5	3.73	2.53	245	67.6 ± 19.2	3.22	3.35
	10	4.06	3.06	245	91.6 ± 24.1	3.29	3.39
	15	4.30	3.42	245	115.0 ± 28.5	3.30	3.40

✓ Pseudo-experiments indicate average number of channels fluctuate above 3 σ is 7 ± 5, so we conclude the results are consistent with background-only

✓ Known P_c^+ states tested and yields all agree with 0

$P_c(4312)^+$	$M = 4311.9$ MeV, $\Gamma = 10$ MeV
$P_c(4440)^+$	$M = 4440$ MeV, $\Gamma = 21$ MeV
$P_c(4457)^+$	$M = 4457.3$ MeV, $\Gamma = 6.4$ MeV

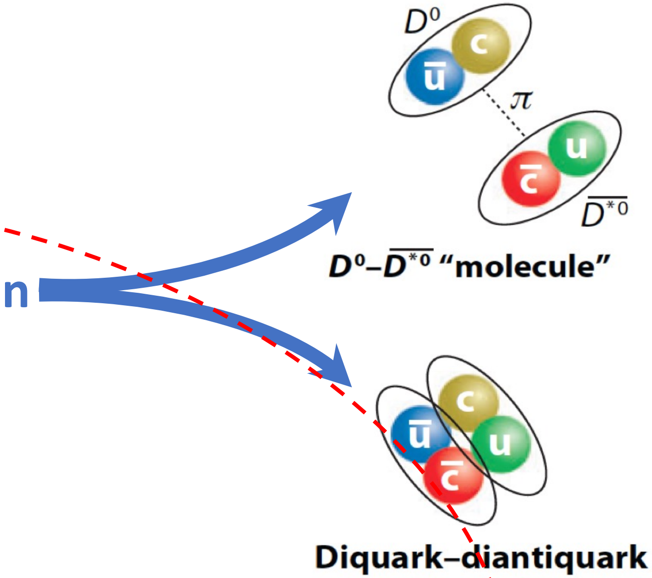
$\chi_{c1}(3872)$ in hadronic collisions



✓Enhancement:
quark coalescence…

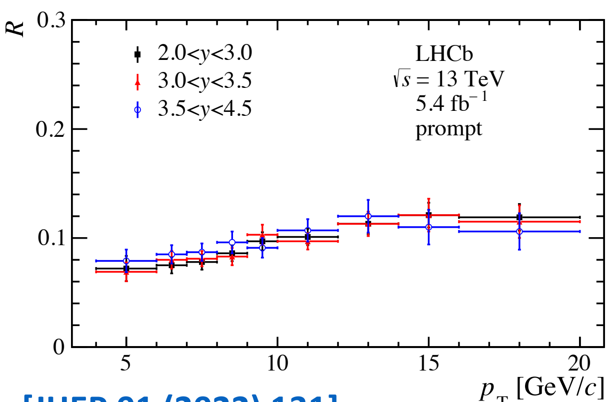
✘Suppression:
breakup due to interactions with comoving particles…

differ in



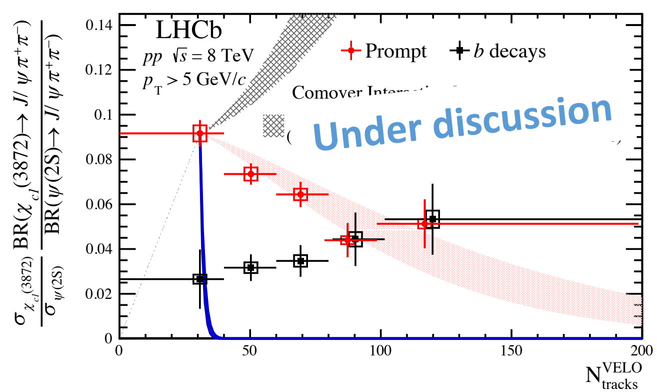
➢ Measurements of $\chi_{c1}(3872)$ production wrt $\psi(2S)$

✓In *pp* collisions



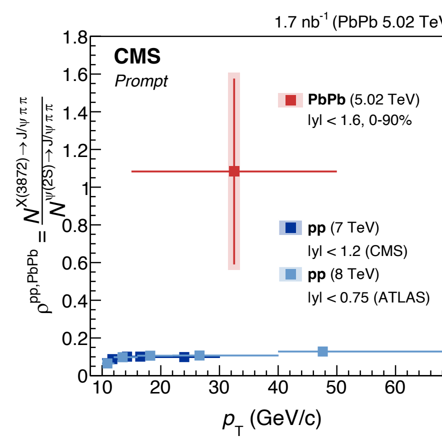
[JHEP 01 (2022) 131]

✓In *pp* collisions vs multiplicity



[PRL 126 (2021) 092001]

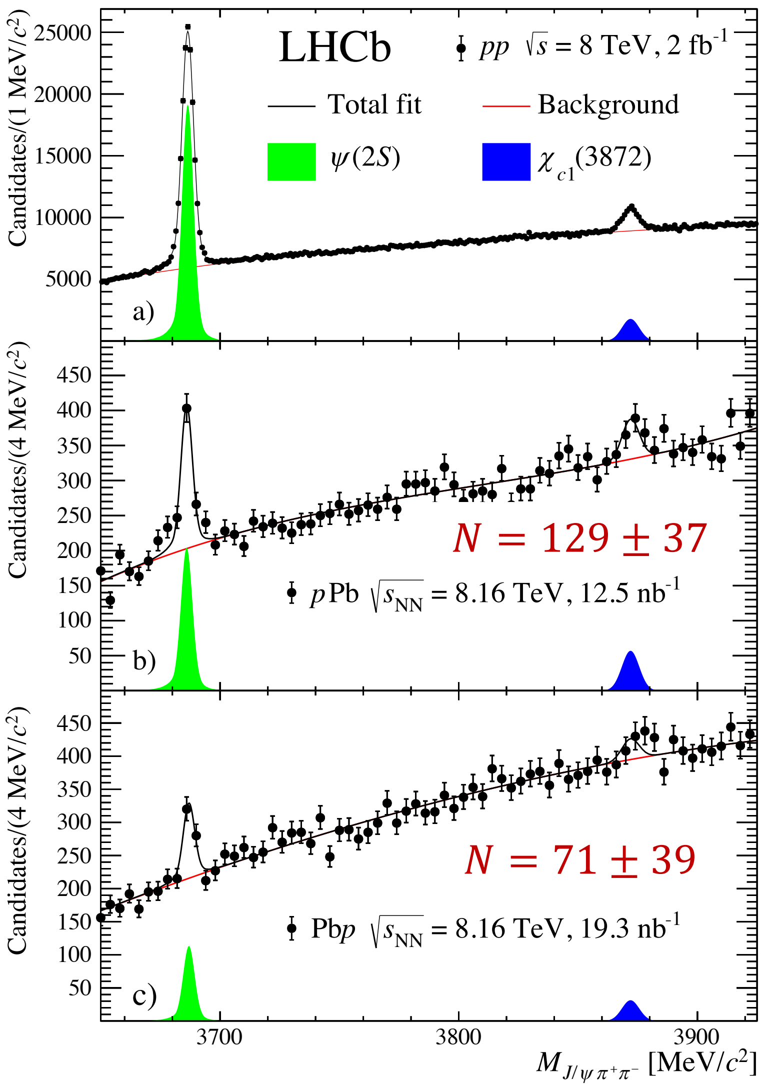
✓In PbPb collisions

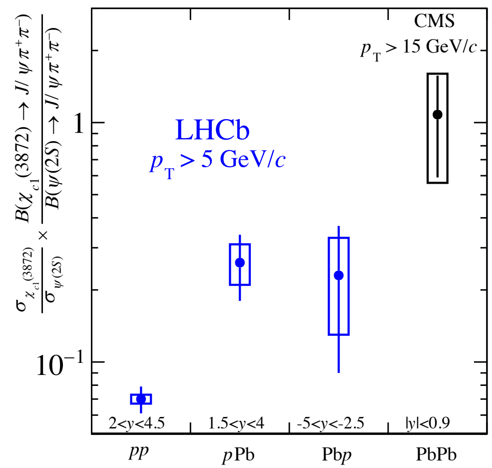


[PRL 128 (2022) 032001]

$\chi_{c1}(3872)$ in pPb

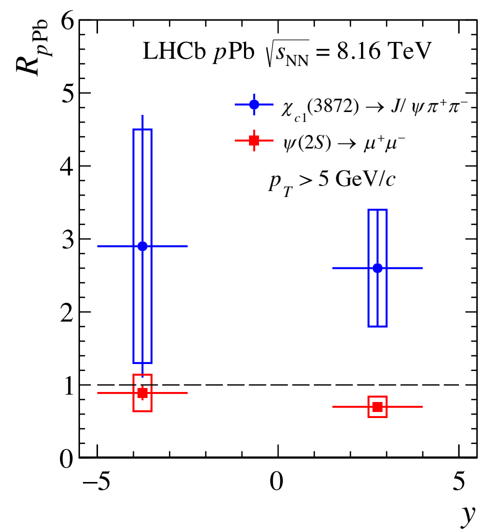
[arXiv: 2402.14975]





$$\frac{\sigma^{\chi_{c1}(3872)}}{\sigma^{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]}$$

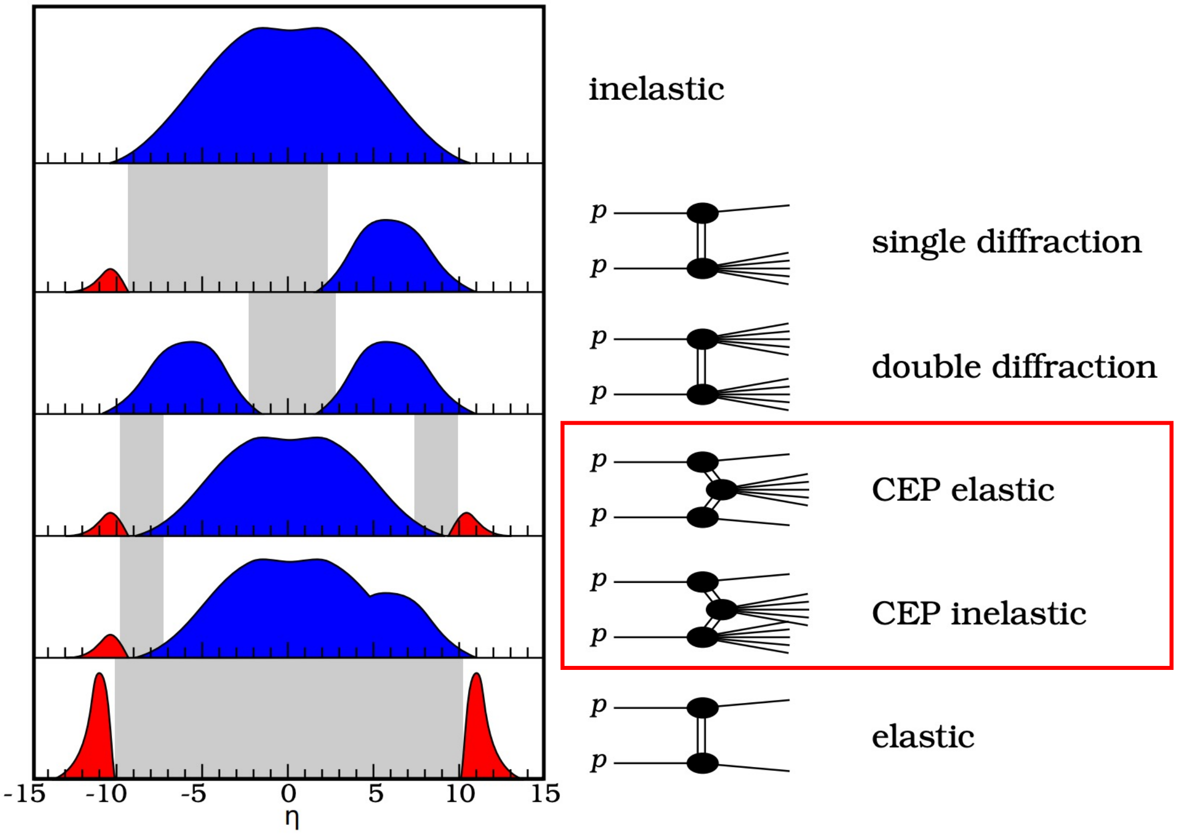
✓Increase with system size $\Rightarrow$ $\chi_{c1}(3872)$ experience different dynamics in nuclear medium than $\psi(2S)$



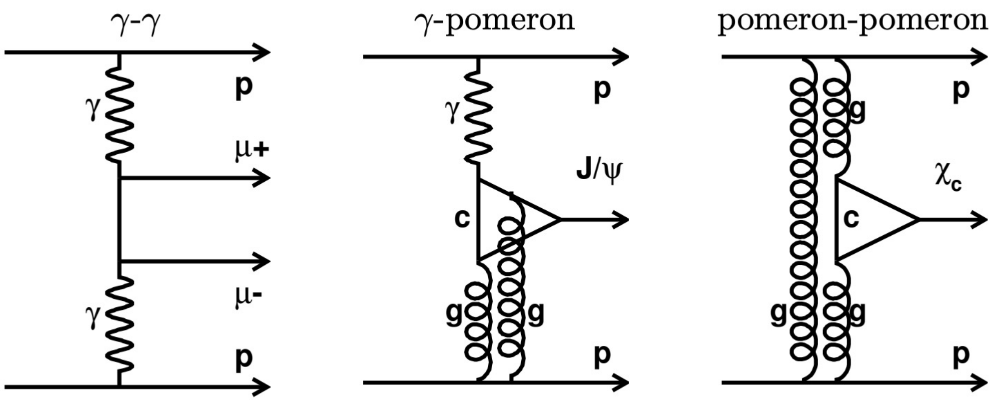
$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}}$$

✓Enhancement in pPb $\Rightarrow$ enhancement due to coalescence dominates over suppression due to breakup

Central exclusive production (CEP)



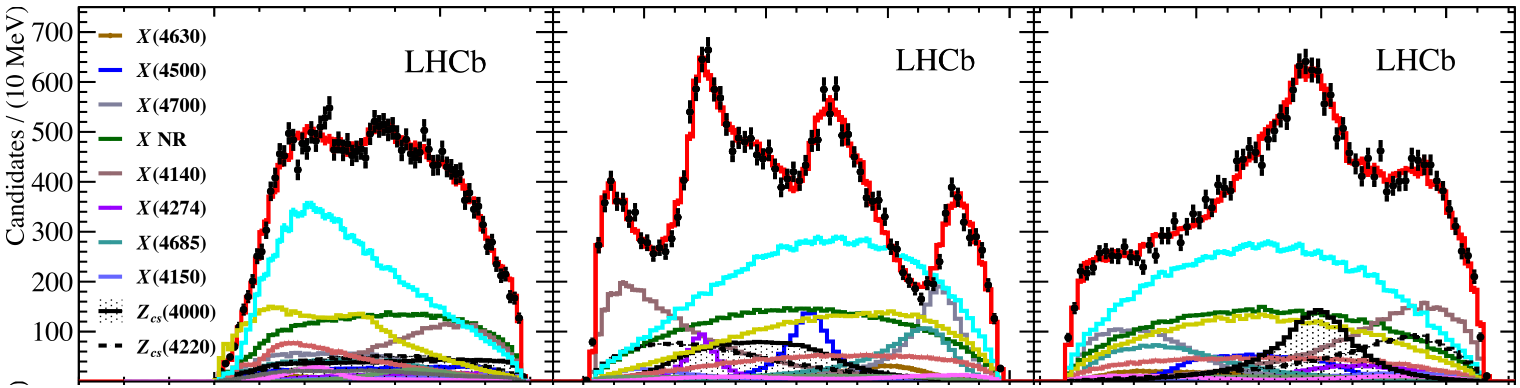
- ✓Experimentally clean even @LHC
- ✓Spin-parity option narrowed down
- ✗Much smaller rate



*glueball

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

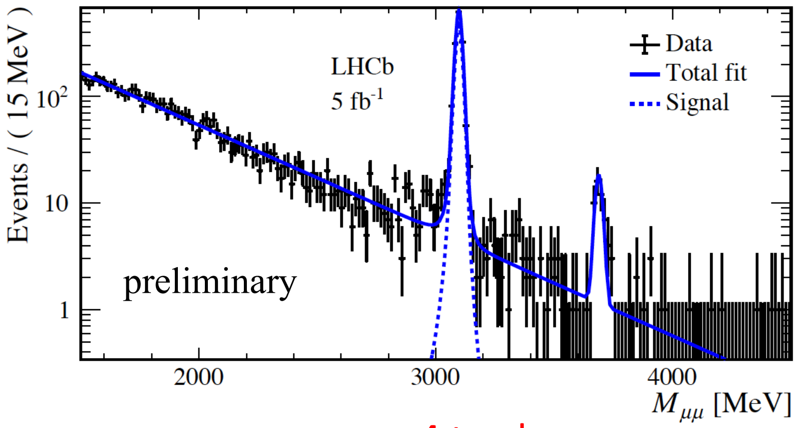
[PRL 127 (2021) 082001]

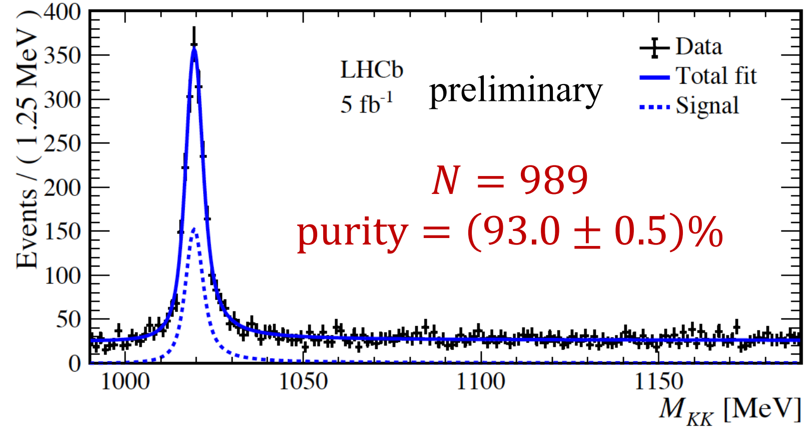


$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5\,^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3\,^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
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)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

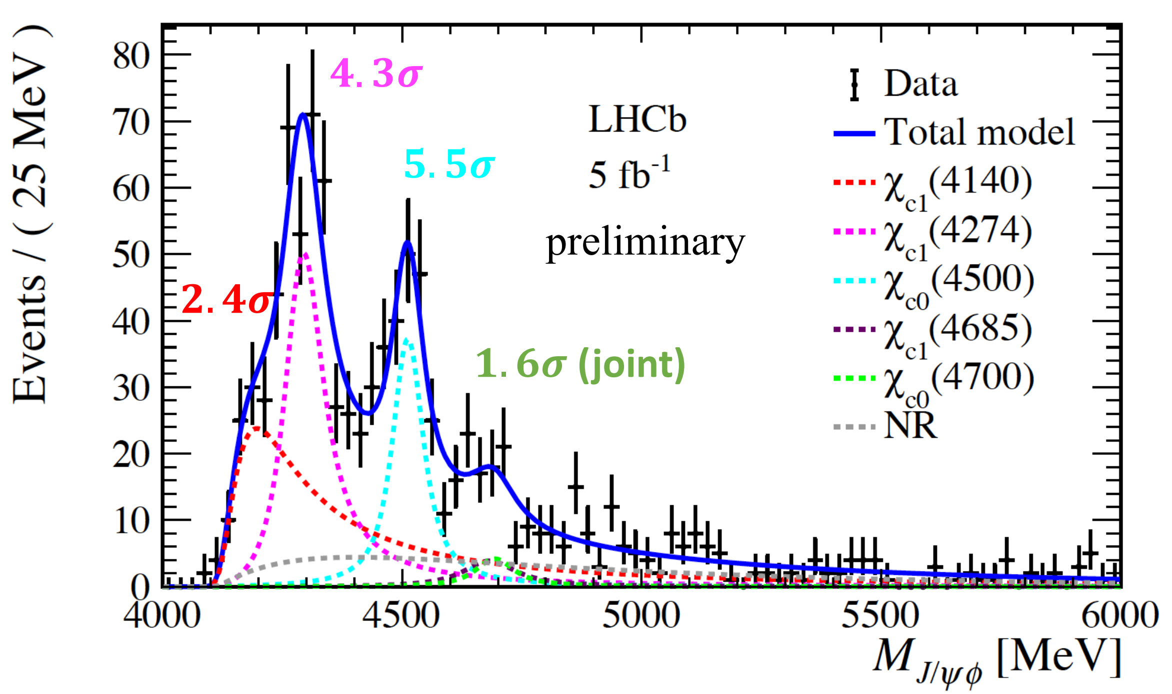
$X \to J/\psi\phi$ in CEP

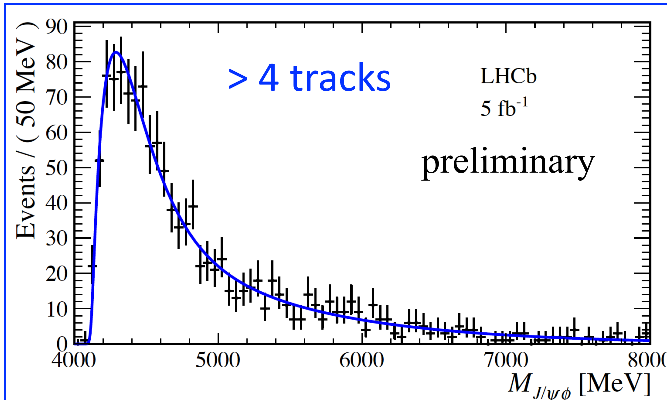
[LHCb-PAPER-2023-043]
in preparation





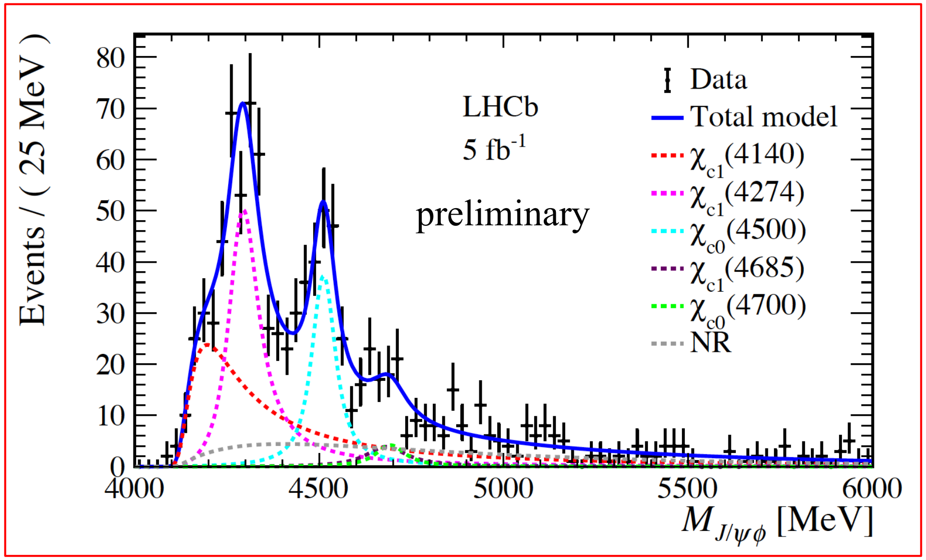
4 tracks



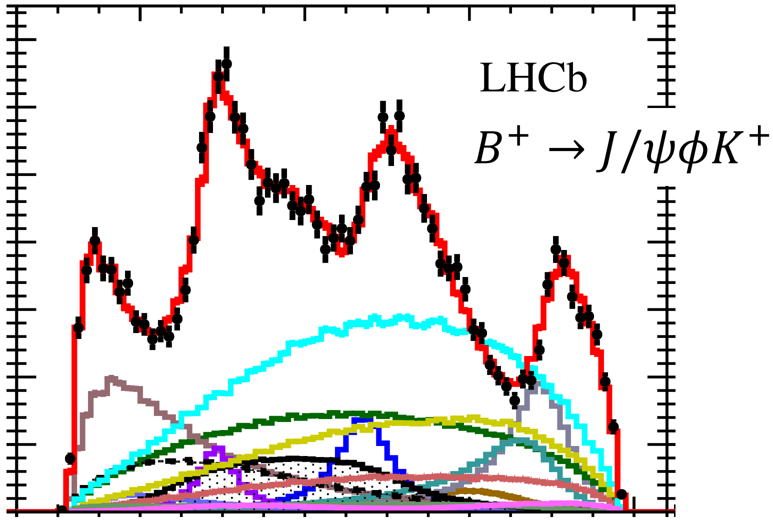


Results

[LHCb-PAPER-2023-043]
in preparation



[PRL 127 (2021) 082001]



✓Mass & width measurement: slightly higher mass of $X(4500)$

Parameter (MeV)	This Letter	Ref. [12]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

✓Cross-section measurement:

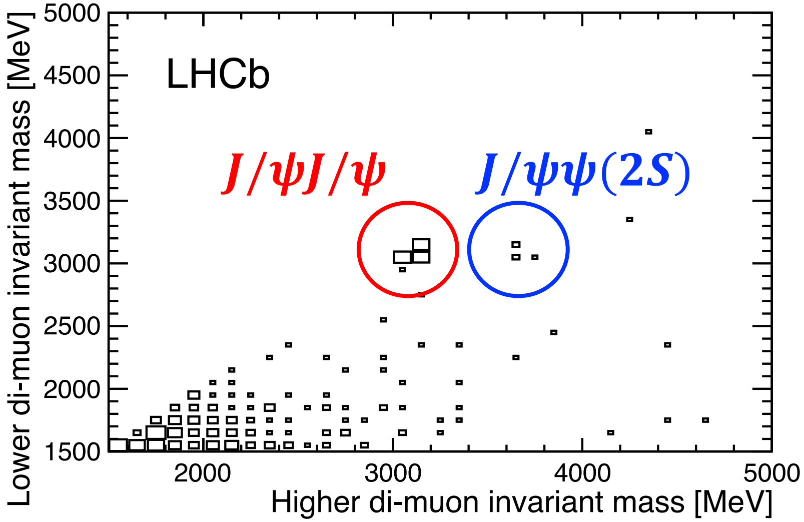
$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.85 \pm 0.16 \pm 0.30)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.77^{+0.14}_{-0.13} \pm 0.18)\,\text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.44^{+0.09}_{-0.08} \pm 0.07)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\,\text{pb},$$
$$\sigma_{NR} \times \mathcal{B}_{\rm eff}^{NR} = (0.46^{+0.25}_{-0.19}\,{}^{+0.21}_{-0.22})\,\text{pb},$$

➢First exotic hadron measurement in CEP!

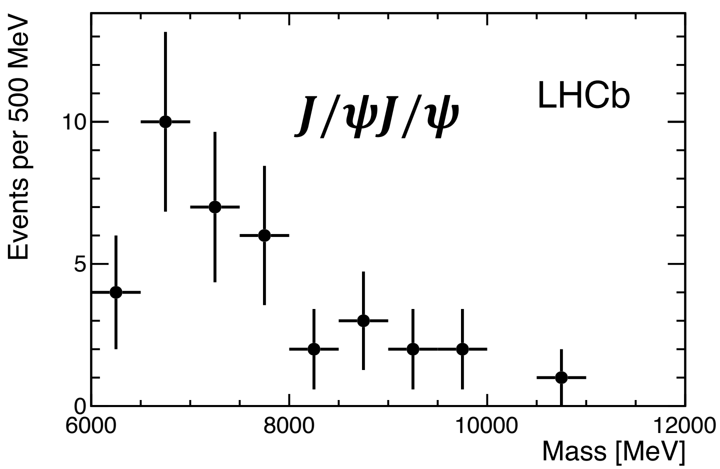
Other exotics in CEP

- $X \to J/\psi\, J/\psi$: CEP of charmonium pairs studied using 3 fb^{-1} Run1 data

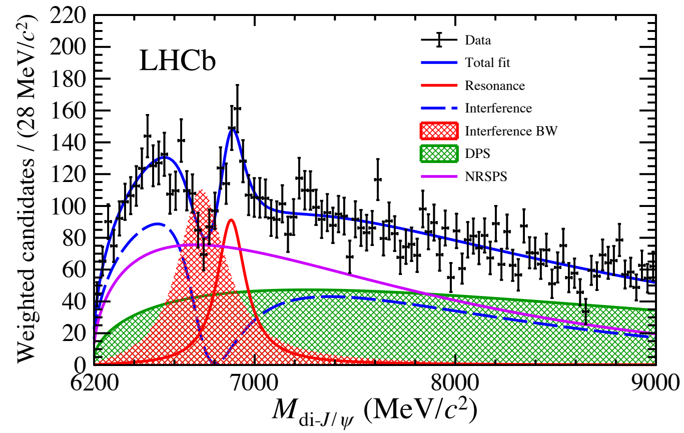
[J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002]



$$\sigma^{J/\psi\, J/\psi} = 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},$$
$$\sigma^{J/\psi\,\psi(2S)} = 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},$$
$$\sigma^{\psi(2S)\psi(2S)} < 237\,\text{pb},$$
$$\sigma^{\chi_{c0}\chi_{c0}} < 69\,\text{nb},$$
$$\sigma^{\chi_{c1}\chi_{c1}} < 45\,\text{pb},$$
$$\sigma^{\chi_{c2}\chi_{c2}} < 141\,\text{pb},$$



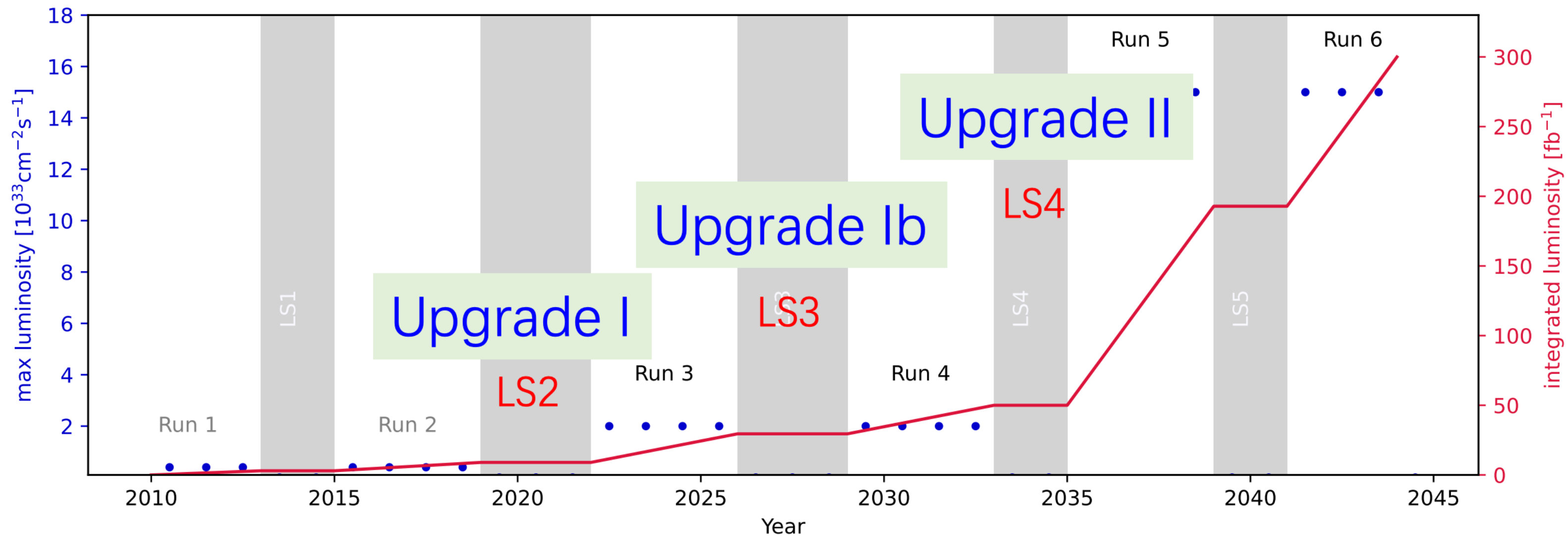
[Science Bulletin 65 (2020) 1983]



- $\chi_{c1}(3872)$? Other suggestions?

Summary and prospects

- LHCb keeps making important contributions to spectroscopy study
  - ✓ **Exotic heavy hadron:**
    search for pentaquark in open-charm modes;
    first measurement of $\chi_{c1}(3872)$ production in pPb;
    first measurement of exotic hadron in CEP …
  - ✓ **Conventional heavy hadron:** new Ξ_b^{**} and Ω_c^{**} states and more decays…
- In Run 3, the upgraded LHCb detector and an improved software-only trigger system are implemented

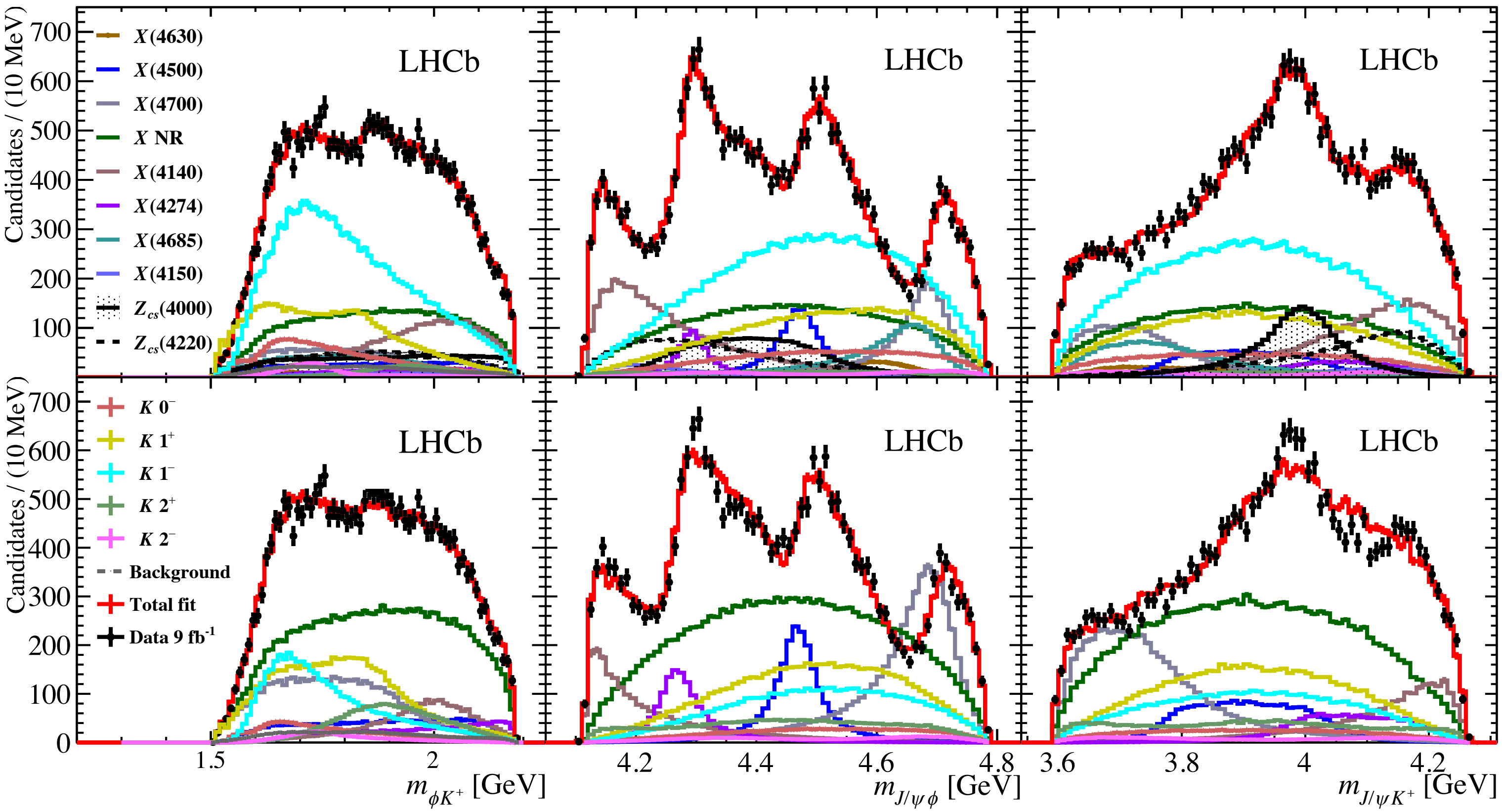


More data, more chances!

Back up

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

[PRL 127 (2021) 082001]



Updated model

Run 1 model