Credit: Ivan Polyakov [arXiv: 2410.06923]

LHCb上XYZ粒子实验进展

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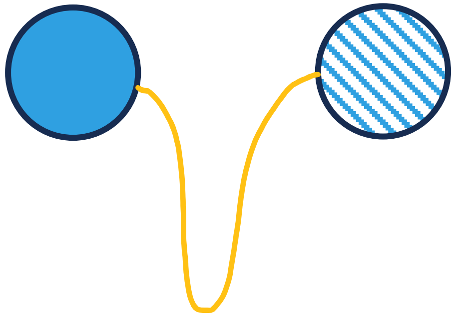
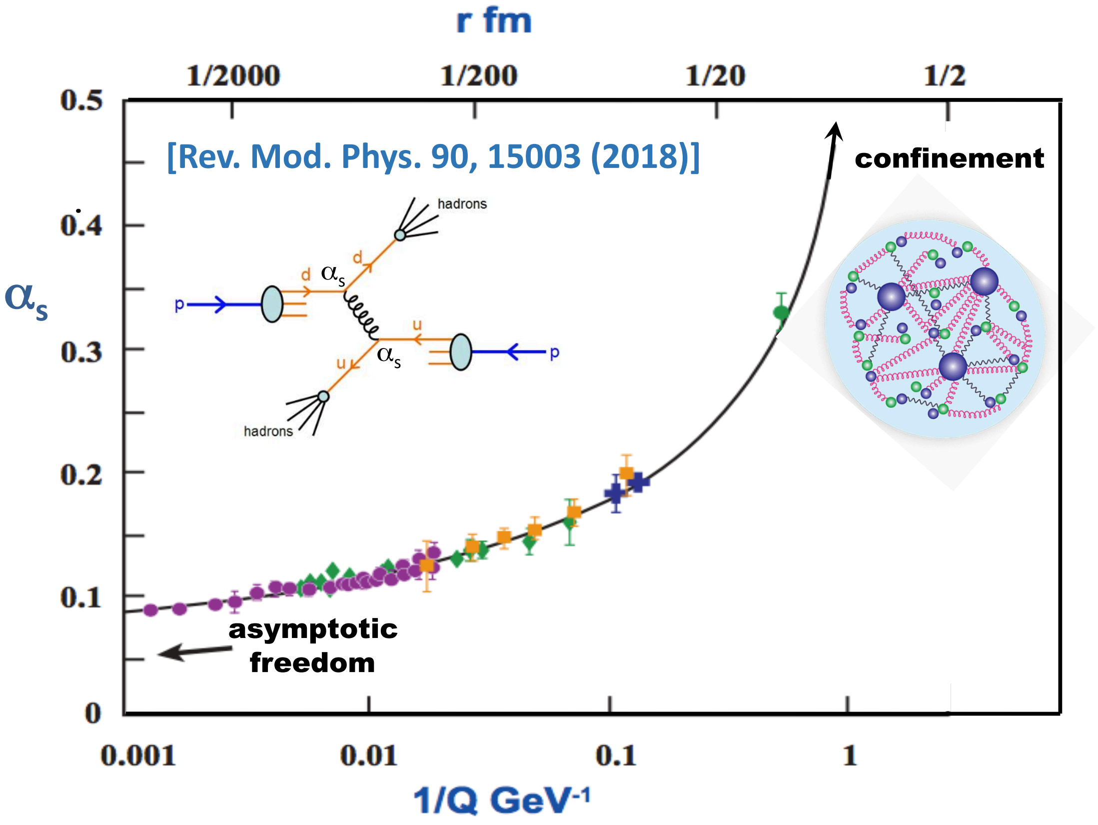
On behalf of the LHCb collaboration

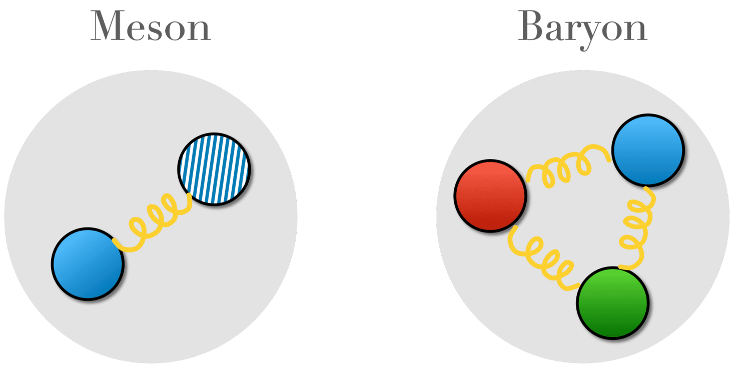
北京大学

第十届XYZ研讨会 @ 湖南师范大学，2025.04.11-15

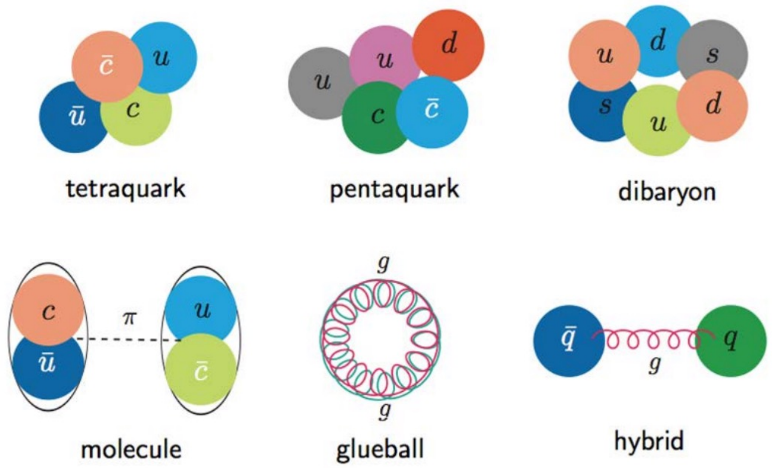
XYZ for QCD







conventional hadrons

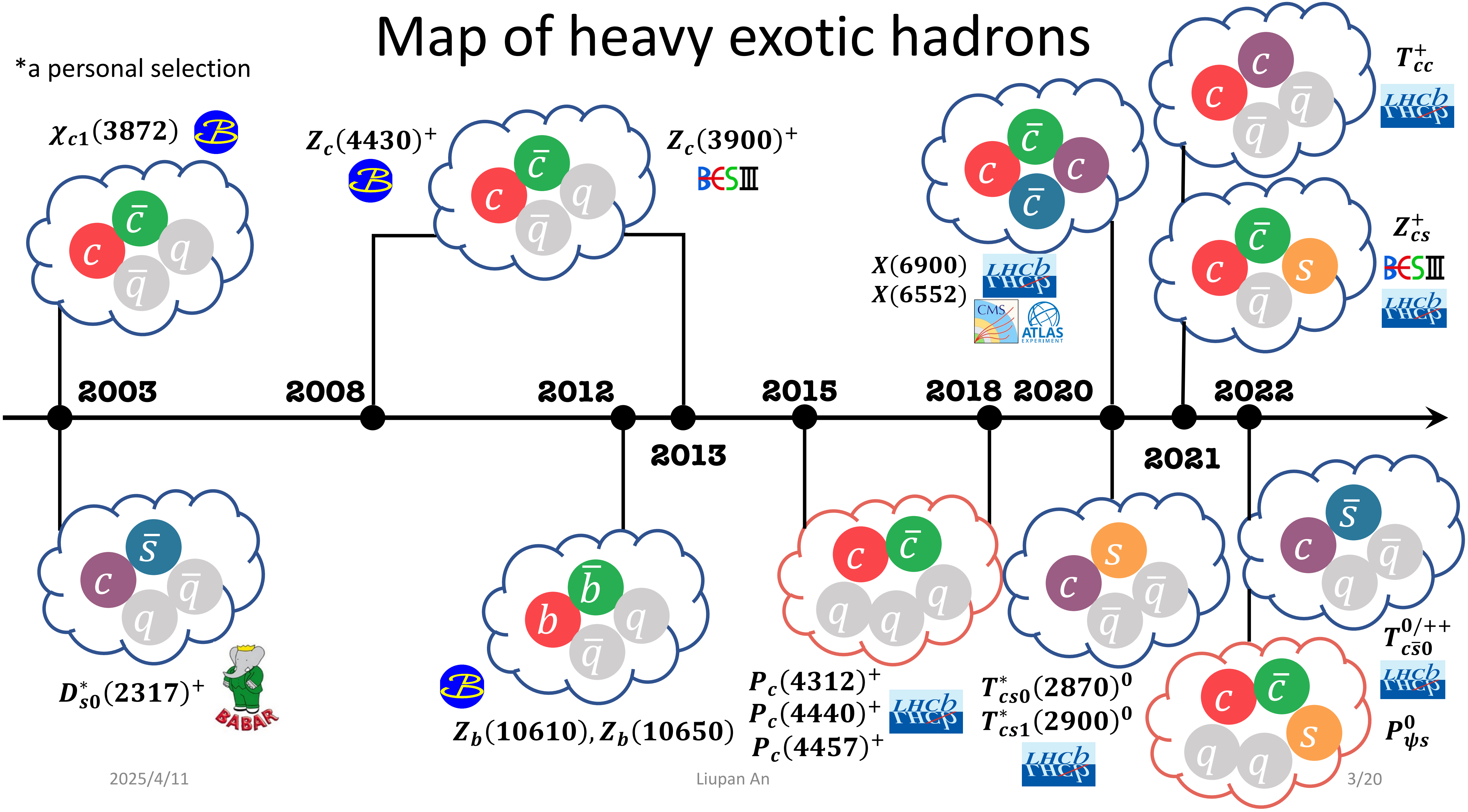


exotic hadrons

- ***Color confinement***:
  - ✓clear indication from both experiments and Lattice QCD
  - ✓believed to be related to increase of α_s at low energy, but **never demonstrated analytically**

Map of heavy exotic hadrons

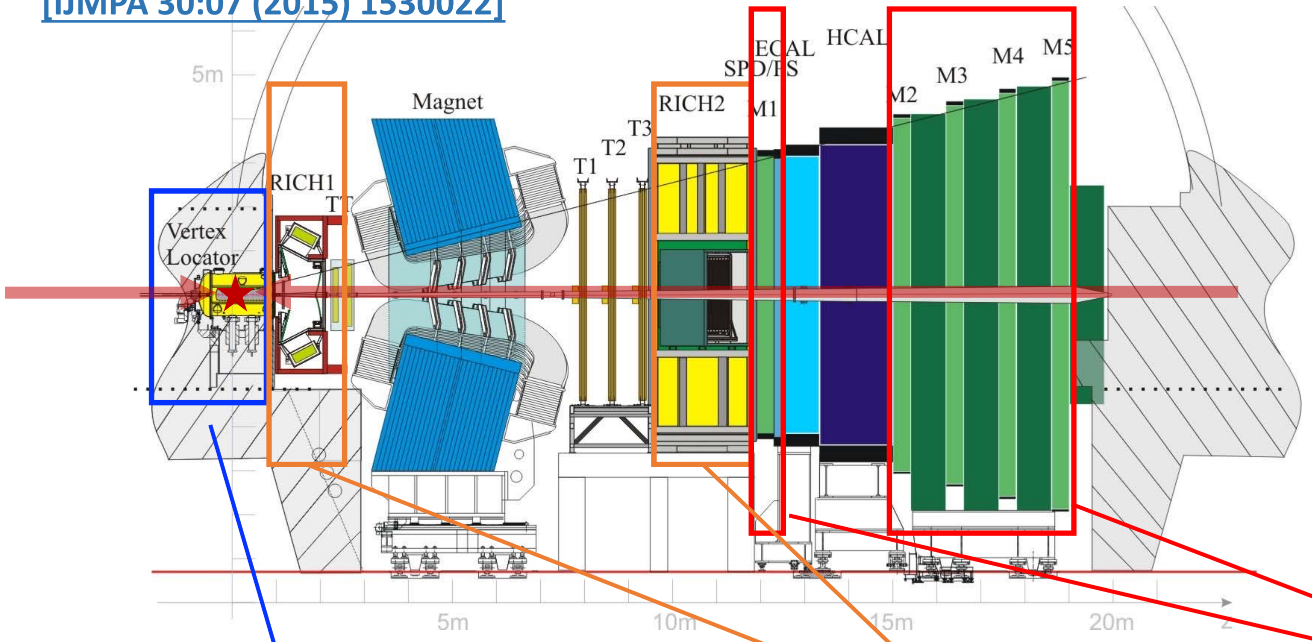
*a personal selection

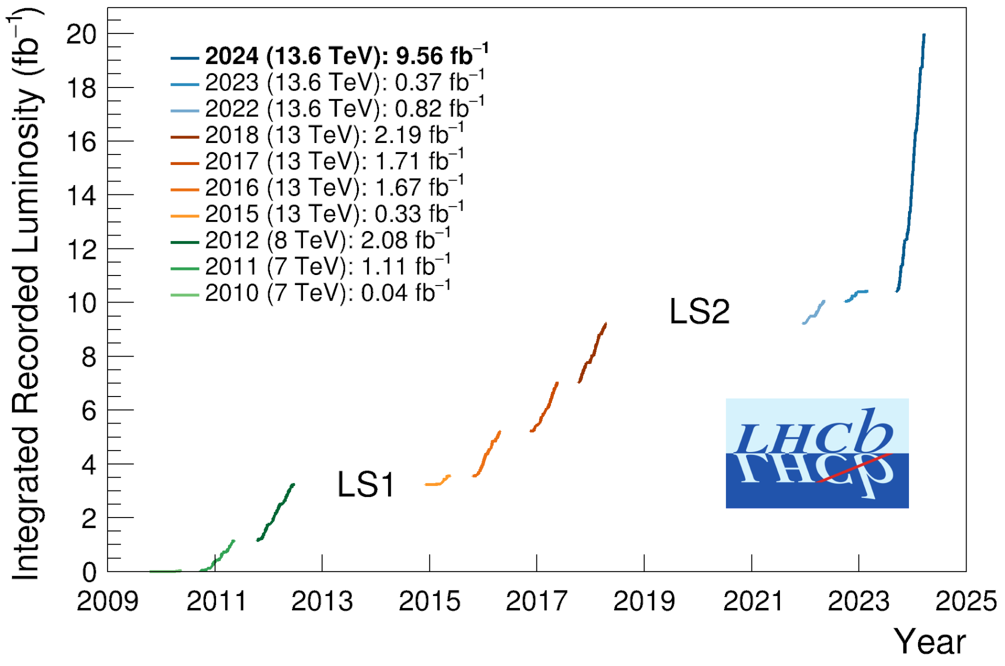


LHCb detector in Run 1 & 2

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, with excellent ***vertexing***, ***tracking*** and ***particle identification (PID)*** performance

[JINST 3 (2008) S08005]
[IJMPA 30:07 (2015) 1530022]





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

$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$

RICHs: efficient identification of pions, kaons and protons

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

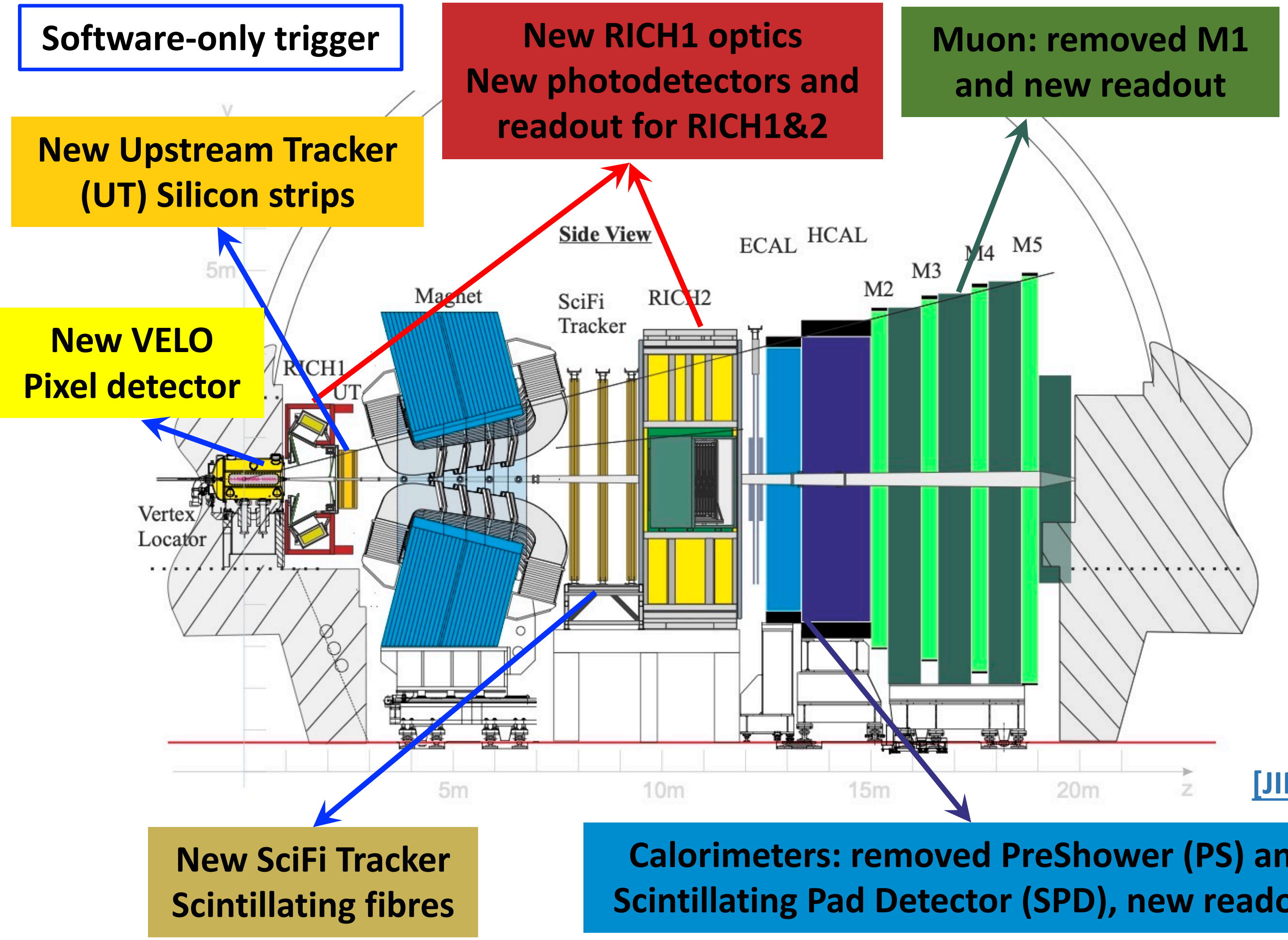
Muon system (M1-M5): efficient muon identification and trigger

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

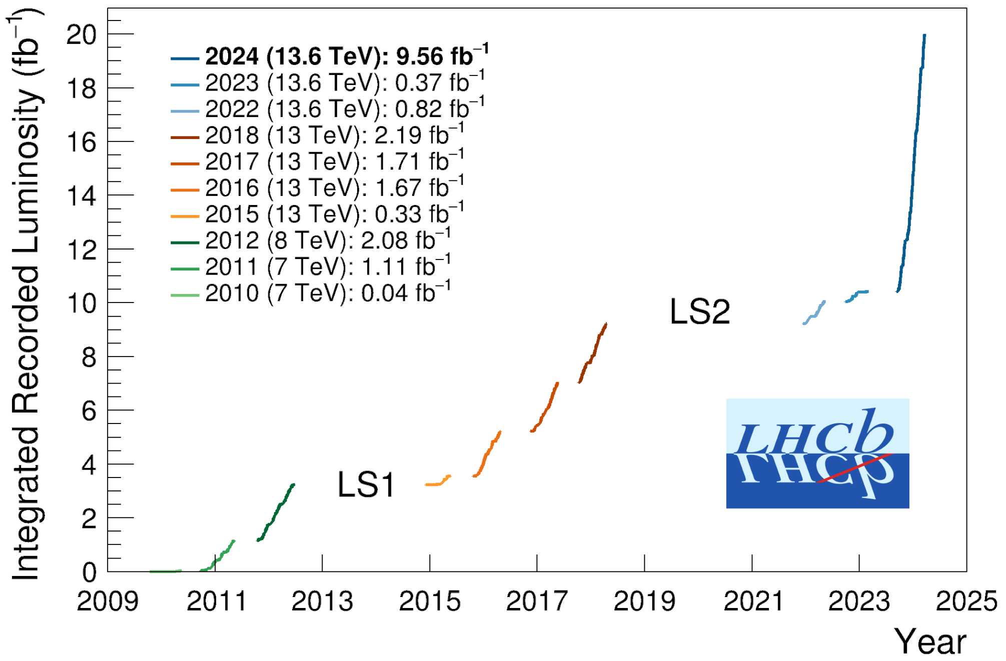
- Run 1 (2011-2012): $1\ \mathrm{fb}^{-1}$ @ 7 TeV & $2\ \mathrm{fb}^{-1}$ @ 8 TeV
- Run 2 (2015-2018): $6\ \mathrm{fb}^{-1}$ @ 13 TeV

LHCb detector in Run 3

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, with excellent ***vertexing***, ***tracking*** and ***particle identification (PID)*** performance

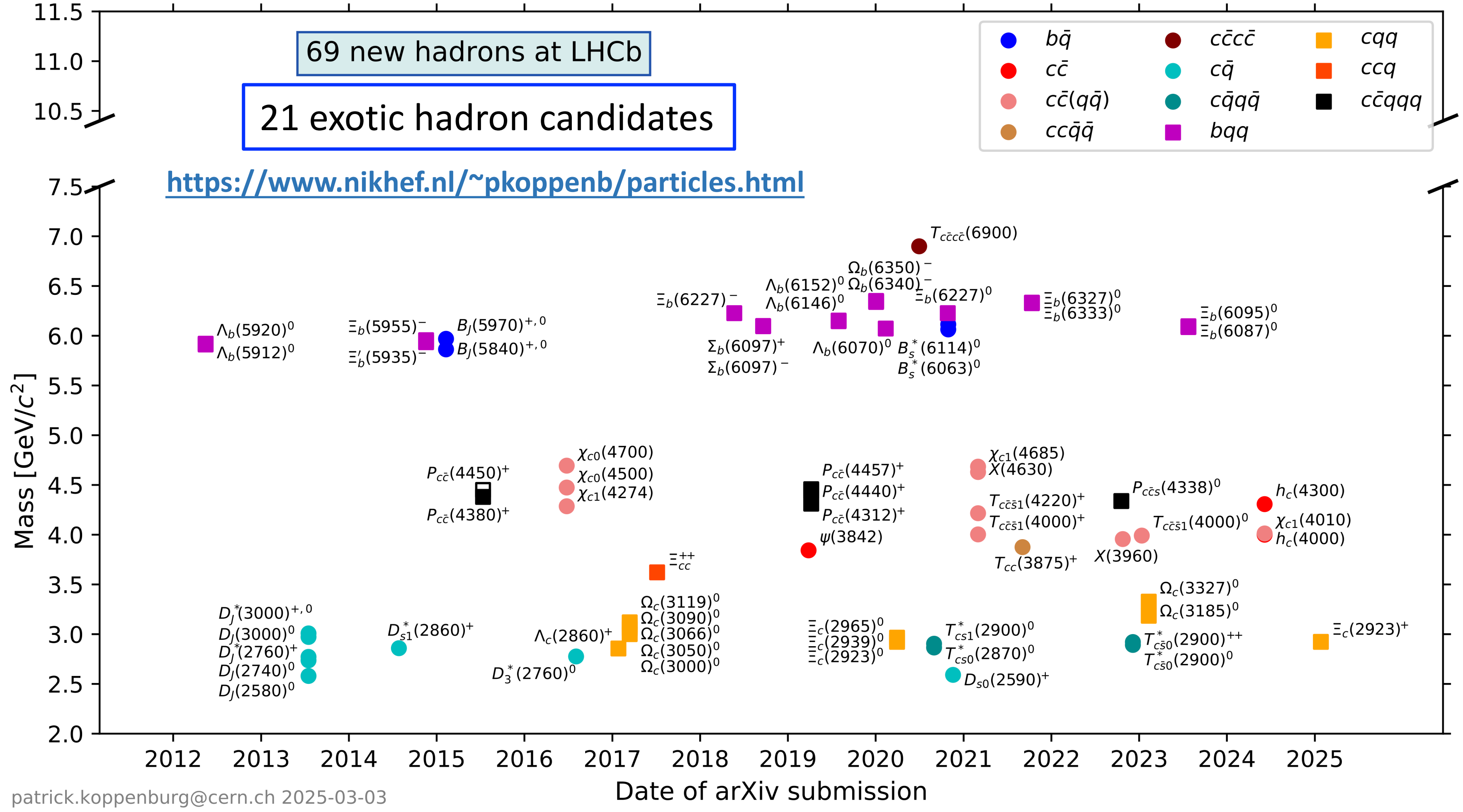


- Run 3: $10\ \text{fb}^{-1}$+rapidly growing @ 13.6 TeV



[JINST 19 (2024) P05065]

Exotic hadrons at LHCb



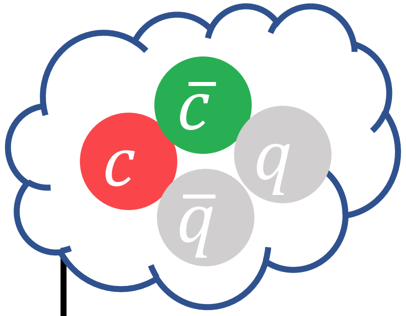
*Only most recent results covered in this talk

04.13:
◎ 任赞：LHCb上隐粲四夸克态的研究进展
◎ 童星显：LHCb上粲重子的研究

04.14:
◎ 宋宇翔：LHCb上五夸克态的研究进展
◎ 朱琳萱：LHCb上$B \to DDh$的分析

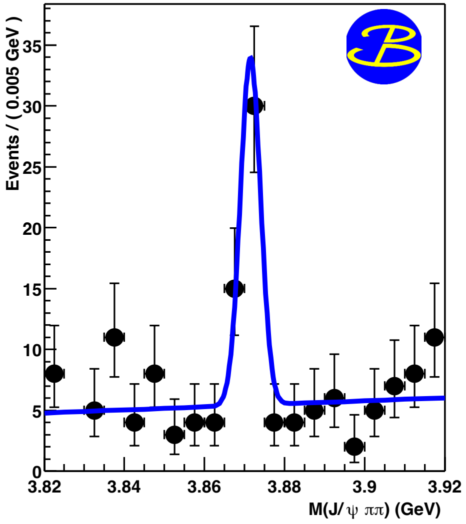
$\chi_{c1}(3872)$

$\chi_{c1}(3872)$

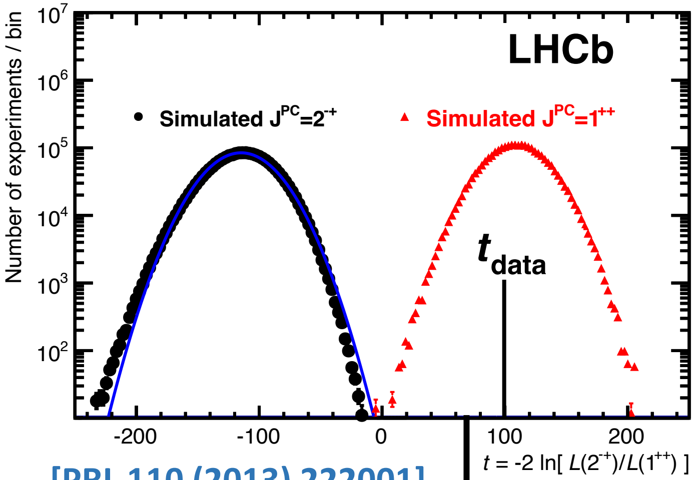


2003

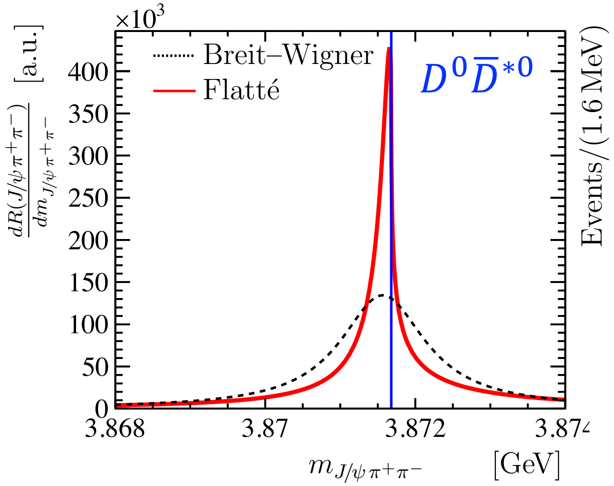
[PRL 91 (2003) 262001]



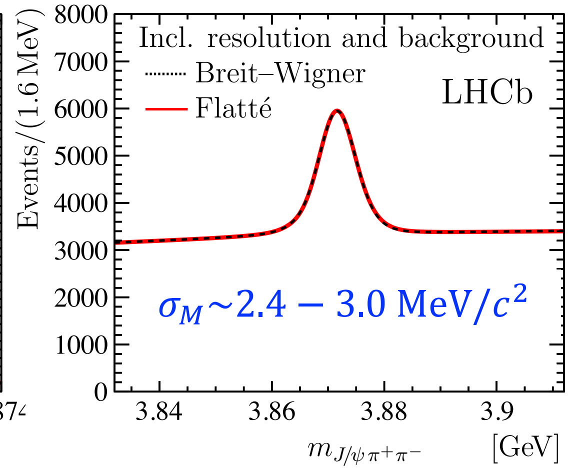
[PRL 110 (2013) 222001]



2013



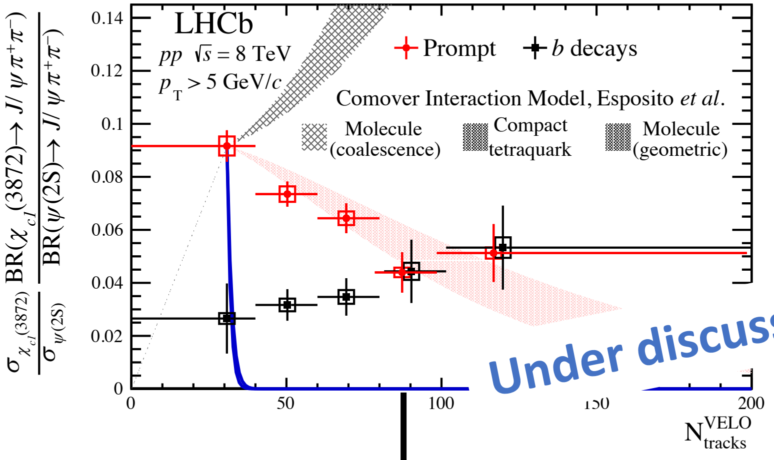
[PRD 102 (2020) 092005]



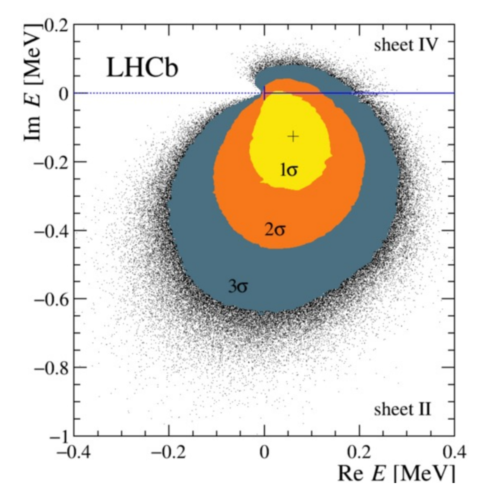
2020

2021

[PRL 126 (2021) 092001]



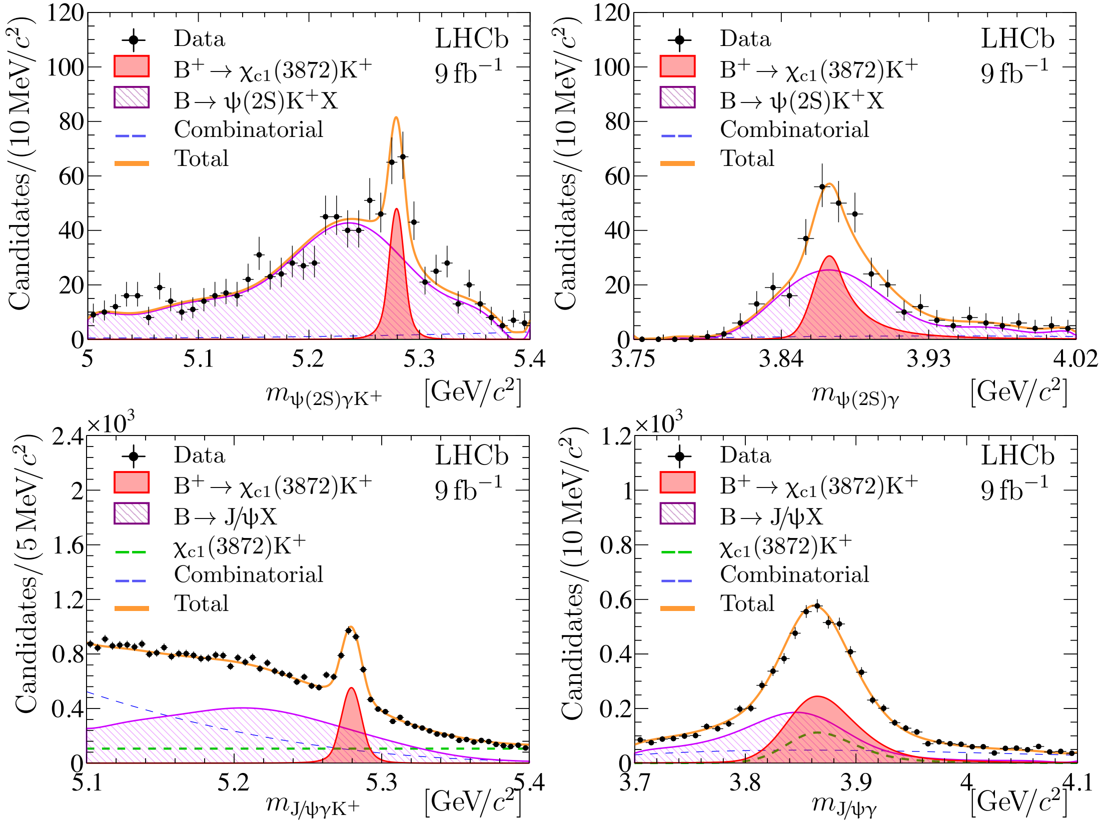
Under discussion



Radiative decays of $\chi_{c1}(3872)$

[JHEP 11 (2024) 121]

- Nature of $\chi_{c1}(3872)$ still under debate, while study of radiative decays provides a way to probe it
  - $\chi_{c1}(3872) \to \psi(2S)\gamma$ observed for the first time using $B^+ \to \chi_{c1}(3872)K^+$ decay with 9 fb^{-1} data

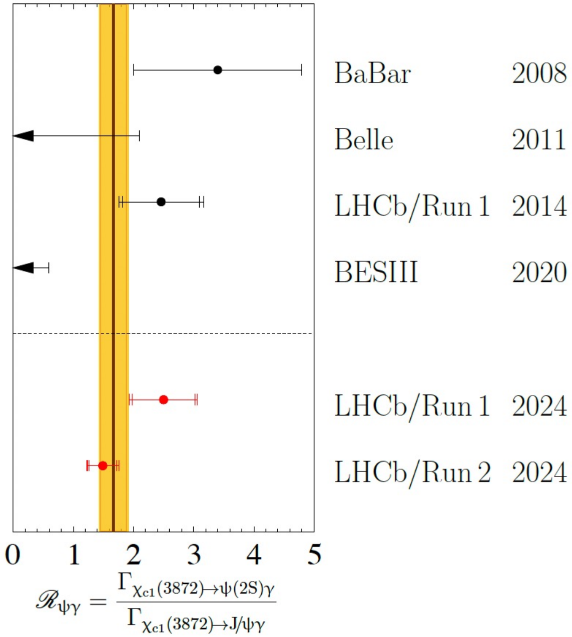


Run1: $N = 40 \pm 8; 5.3\sigma$

Run2: $N = 63 \pm 10; 6.7\sigma$

$$\mathcal{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$



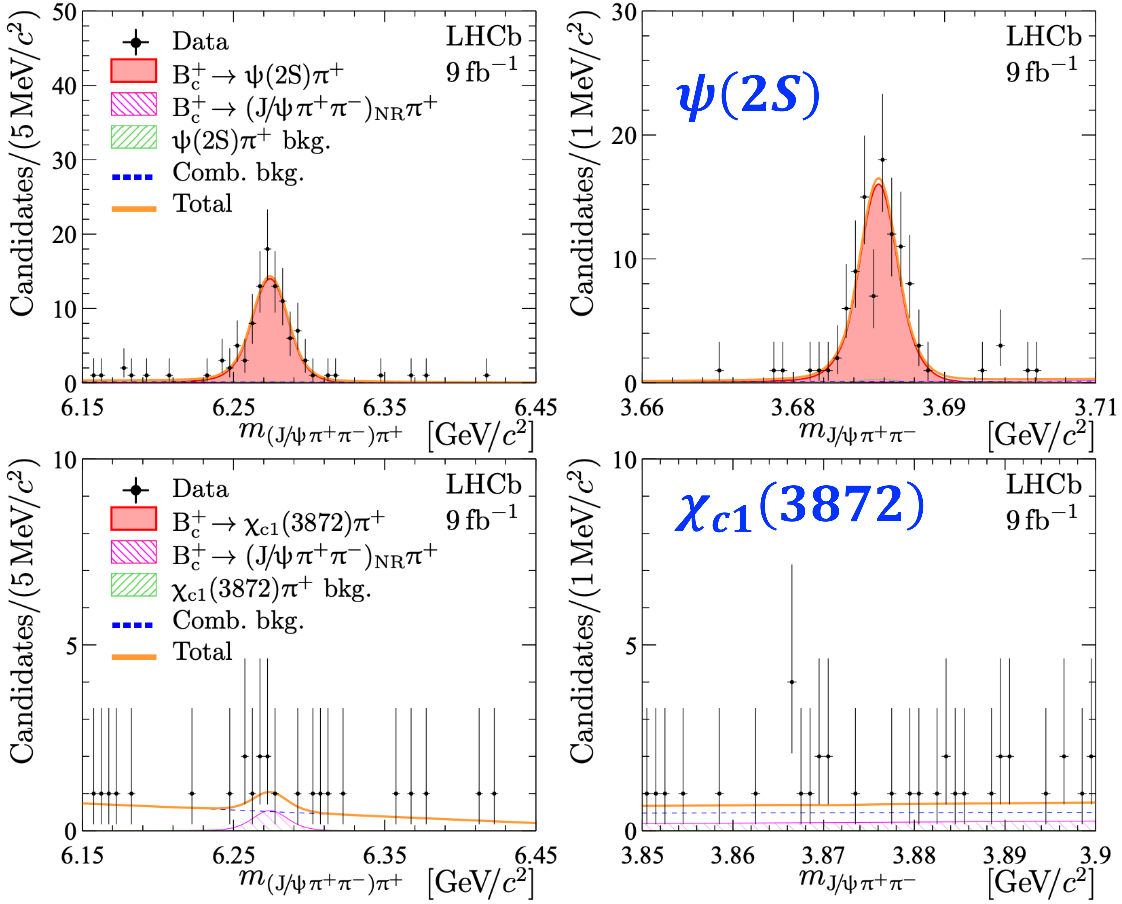
✓ Possible explanation: different contributions from W_{c1}, isovector partner of $\chi_{c1}(3872)$, in B^+ decays and e^+e^- annihilations?

[arXiv: 2502.04458]

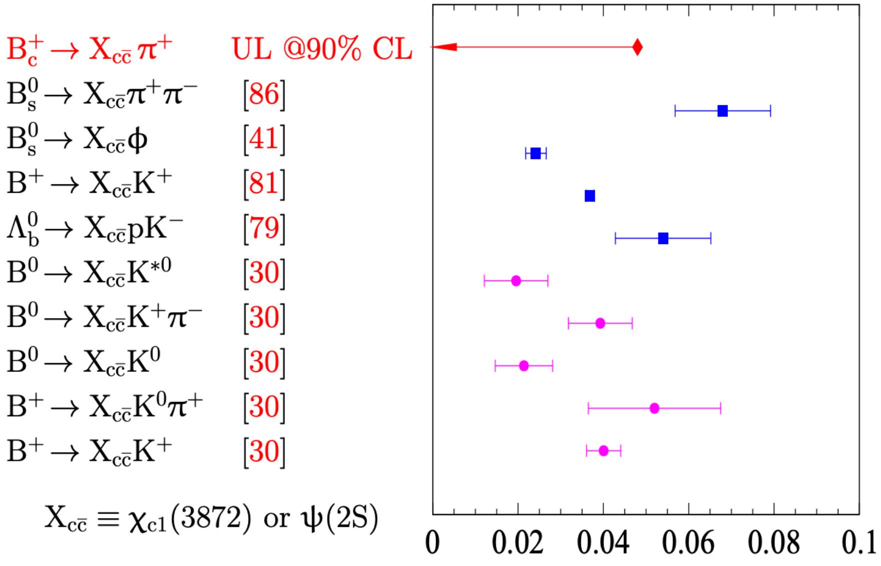
Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$

[arXiv: 2503.20039]

- The compact-tetraquark interpretation of $\chi_{c1}(3872)$ predicts enhancement of $\mathcal{B}(B_c^+ \to \chi_{c1}(3872)\pi^+)$ [PR D71 (2005) 014028]
- ATLAS reported significant enhancement of $\chi_{c1}(3872)$ production from B_c^+, assuming short-lived contribution of non-prompt $\chi_{c1}(3872)$ to arise from B_c^+ decays [JHEP 01 (2017) 117]



- No signal observed from 9 fb^{-1} LHCb Run1+2 data

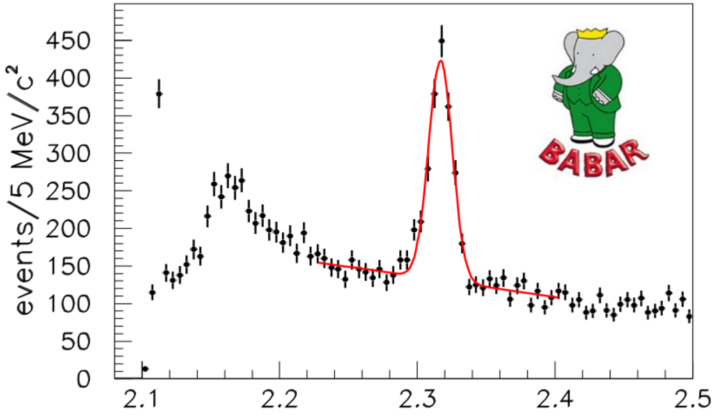


$$\frac{\mathcal{B}_{H_b\to\chi_{c1}(3872)X}}{\mathcal{B}_{H_b\to\psi(2S)X}} \times \frac{\mathcal{B}_{\chi_{c1}(3872)\to J/\psi\pi^+\pi^-}}{\mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}}$$

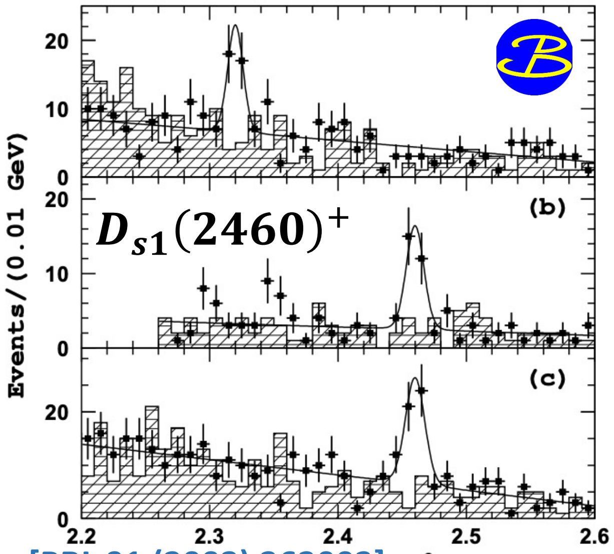
$$\mathcal{R}^{\chi_{c1}(3872)}_{\psi(2S)} = \frac{\mathcal{B}_{B_c^+\to\chi_{c1}(3872)\pi^+}}{\mathcal{B}_{B_c^+\to\psi(2S)\pi^+}} \times \frac{\mathcal{B}_{\chi_{c1}(3872)\to J/\psi\pi^+\pi^-}}{\mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}} < 0.05\,(0.06) \text{ at } 90\,(95)\% \text{ CL}$$

Puzzle in $D_s^{\pm}$ spectroscopy

$D_{s0}^*(2317)^+$



[PRL 90 (2003) 242001]

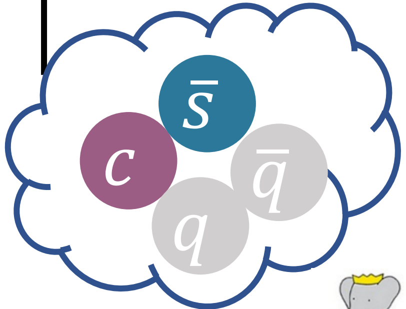


$D_{s1}(2460)^+$

[PRL 91 (2003) 262002]

L	j_q	J^P	$m(D^{\pm})$ (MeV)	$m(D_s^{\pm})$ (MeV)
0	1/2	0^-	1869.66 ± 0.05	1968.35 ± 0.07
		1^-	2010.26 ± 0.05	2112.2 ± 0.4
1	1/2	0^+	2343 ± 10	2317.8 ± 0.5
		1^+	2412 ± 9	2459.5 ± 0.6
	3/2	1^+	2422.1 ± 0.6	2535.11 ± 0.06
		2^+	$2461.1^{+0.7}_{-0.8}$	2569.1 ± 0.8

2003



$D_{s0}^*(2317)^+$

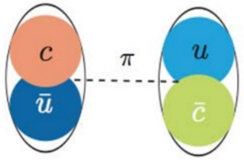
- **$D_{s0}^*(2317)^{\pm}$** and **$D_{s1}(2460)^{\pm}$** are considered candidates of (DK, D^*K) molecules
  - ✓ Their masses much below theoretical prediction
  - ✓ $m(D_{s0}^*(2317)^{\pm}) < m\big(D_0^*(2300)\big)$ i.e. $c\bar{u}/c\bar{d}$ heavier than $c\bar{s}$
  - ✓ $m(D_{s1}(2460)^{\pm}) - m(D_{s0}^*(2317)^{\pm}) \simeq m(D^*) - m(D)$
  - ✓ $D_{s0}^*(2317)^{\pm}$ decay ~100% through the isospin breaking mode $D_s^+\pi^0$

⇒ As D^*K molecule, a double-bump lineshape is expected in $\pi^+\pi^-$ spectrum from the $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ decay

[Commun. Theor. Phys. 75 (2023) 055203]

$T_{c\bar{s}}$ states at LHCb

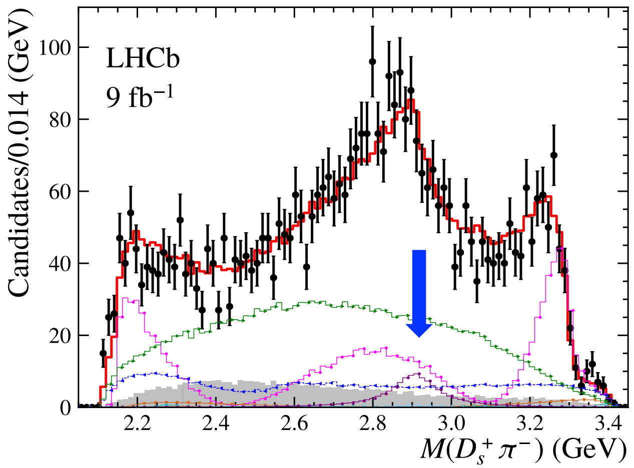
Hadron molecule



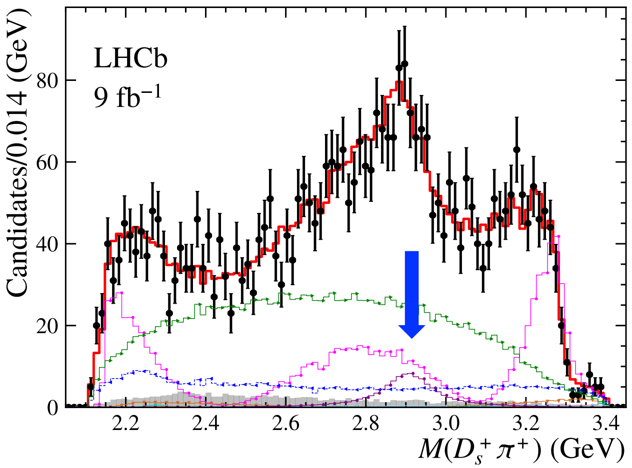
$D_{s0}^*(2317)^+ \to DK$
$D_{s1}(2460)^+ \to D^*K$
$T_{c\bar{s}0}^*(2900)^{0/++} \to D^*K^*$

$\Rightarrow$ partners expected, may couple to $D_s^+\pi^\pm$

$T_{c\bar{s}0}^*(2900)^0$

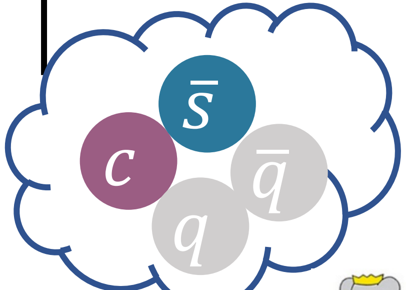


$T_{c\bar{s}0}^*(2900)^{++}$



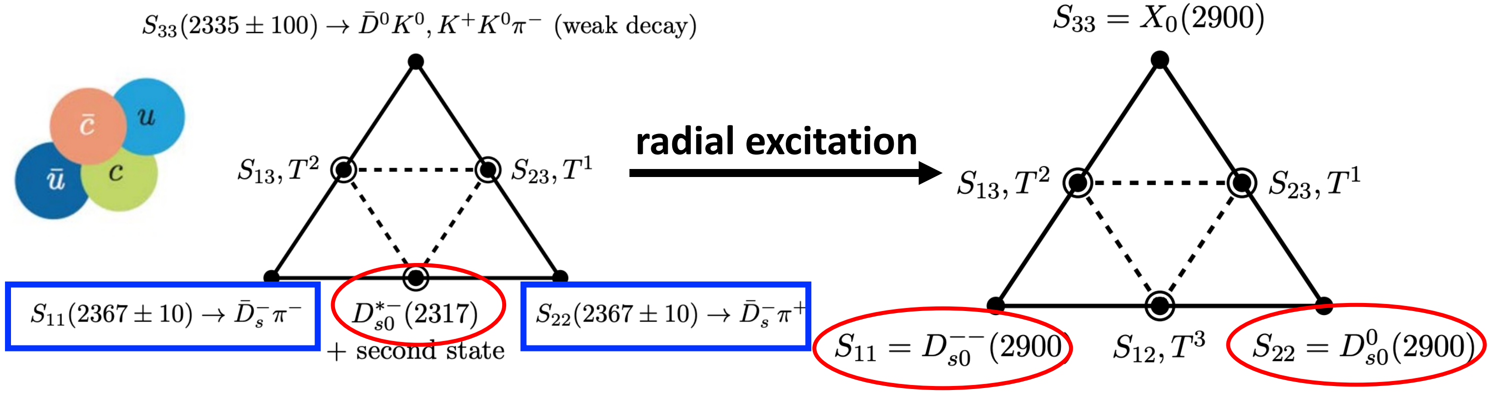
[PRL 131 (2023) 041902]

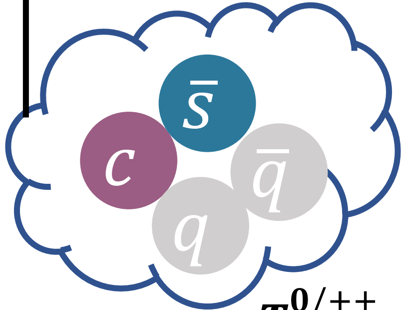
2003 — **2022**



$D_{s0}^*(2317)^+$

Compact multiquark [PRD 110 (2024) 034014]





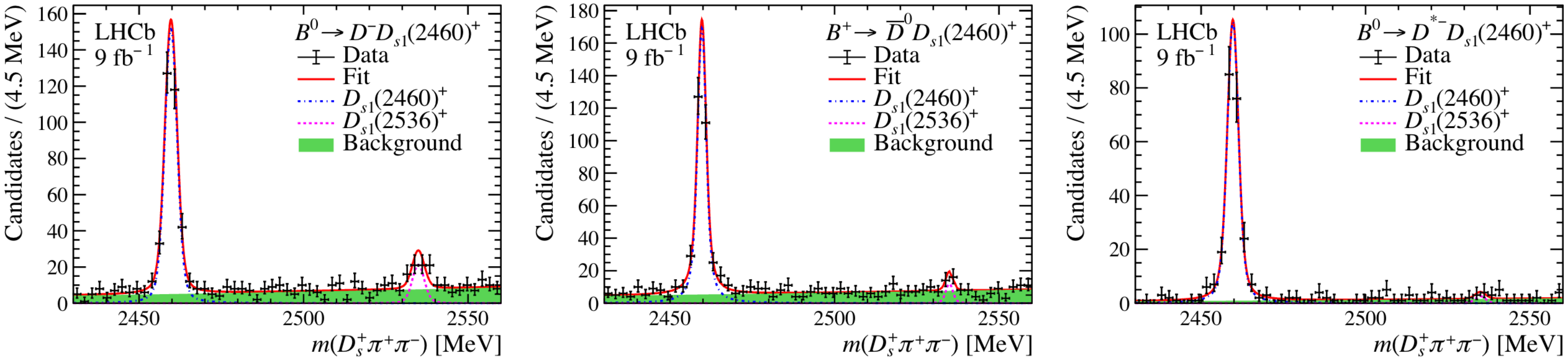
$T_{c\bar{s}0}^{0/++}$

➢ Theories motivate search for potential existence of $D_s^+\pi^\pm$ structure

Study of $D_{s1}(2460) \to D_s^+\pi^+\pi^-$

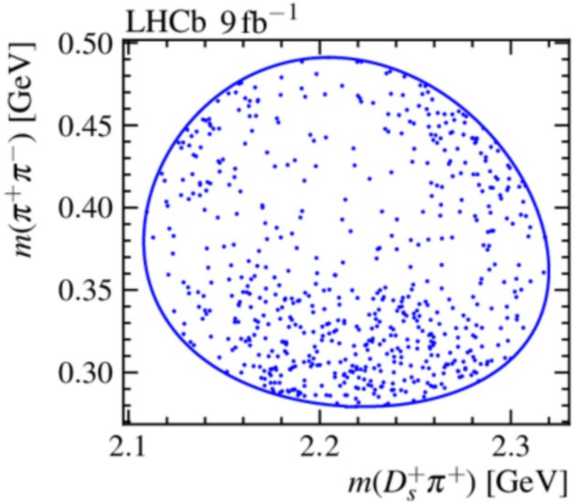
[arXiv:2411.03399]

- A combined amplitude analysis of $D_{s1}(2460) \to D_s^+\pi^+\pi^-$ in $B^0 \to D^- D_s^+\pi^+\pi^-$, $B^+ \to \overline{D}^0 D_s^+\pi^+\pi^-$ and $B^0 \to D^{*-} D_s^+\pi^+\pi^-$ is performed using 9 fb^{-1} data



Channel	Signal yield	Background yield	Signal fraction (%)
$B^0 \to D^- D_s^+\pi^+\pi^-$	305 ± 20	22 ± 1	93.2 ± 0.4
$B^+ \to \overline{D}^0 D_s^+\pi^+\pi^-$	279 ± 18	24 ± 1	92.2 ± 0.5
$B^0 \to D^{*-} D_s^+\pi^+\pi^-$	205 ± 14	4 ± 1	98.0 ± 0.2

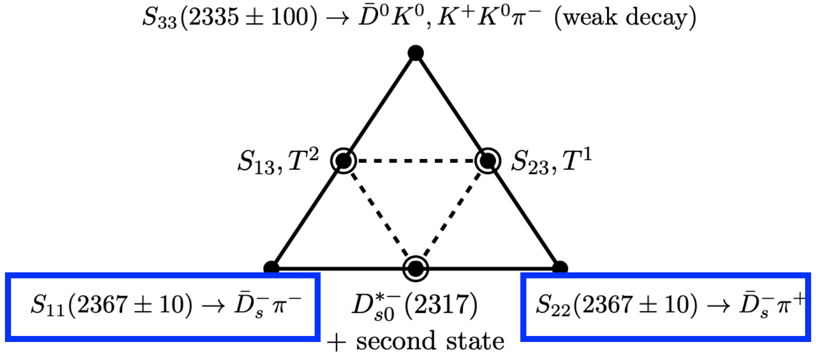
~ 800 signal candidates in total



Amplitude fits of $D_{s1}(2460) \to D_s^+\pi^+\pi^-$

[arXiv:2411.03399]

Model	ΔNLL
Chiral dynamics	252.4
K-matrix $\pi\pi$ S-wave	249.0
$f_0(500) + f_0(980)$	245.2
$f_0(500) + f_0(980) + \rho(770)^0$	148.0
$f_0(500) + f_0(980) + f_2(1270)$	3.7
$f_0(500) + f_0(980) + f_2(1270) + \rho(770)^0$	−2.8
K-matrix $\pi\pi$ S-wave $+ f_2(1270)$	5.9
$f_0(500) +$ RBW $T_{c\bar{s}}(0^+)$	3.5
$f_0(500) +$ K-matrix $T_{c\bar{s}}(0^+)$	0.0
$f_0(500) + f_0(980) +$ RBW $T_{c\bar{s}}(0^+)$	−3.0
$f_0(500) + \rho(770)^0 +$ RBW $T_{c\bar{s}}(0^+)$	−1.1
$f_0(500) + f_2(1270) +$ RBW $T_{c\bar{s}}(0^+)$	−4.3
$f_0(500) +$ RBW $T_{c\bar{s}}(1^-)$	62.9



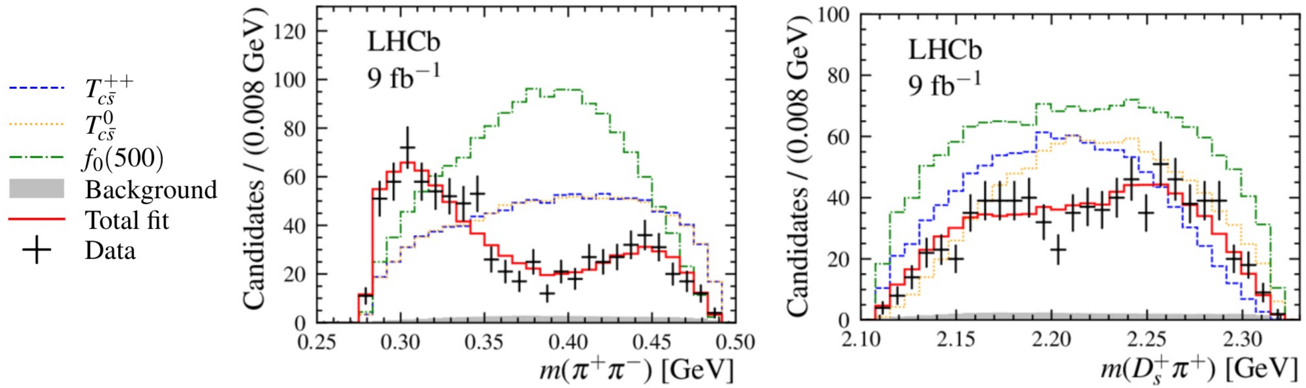
[PRD 110 (2024) 034014]

The physical credibility with only $\pi\pi$ res. is doubted:

- ✗ A large contribution from the tail of $f_2(1270)$
- ✗ Large destructive interference between $f_0(500)$ and $f_0(980)$
- ✗ $f_0(500)$ mass and width different from before

By adding exotic $T_{c\bar{s}}^{++/0} \to D_s^+\pi^\pm$ contributions under isospin symmetry

- ✓ $f_0(980)$ and $f_2(1270)$ not significant
- ✓ $f_0(500)$ mass and width agree with before



➢ Results on $T_{c\bar{s}}^{++/0}$

- ✓ $> 10\,\sigma$ significance vs. $f_0(500) + f_0(980)$ model
- ✓ $M = 2327 \pm 13 \pm 13\ \mathrm{MeV}/c^2, \Gamma = 96 \pm 16^{+170}_{-23}$ MeV
- ✓ $J^P = 0^+$ favored with 10 σ significance

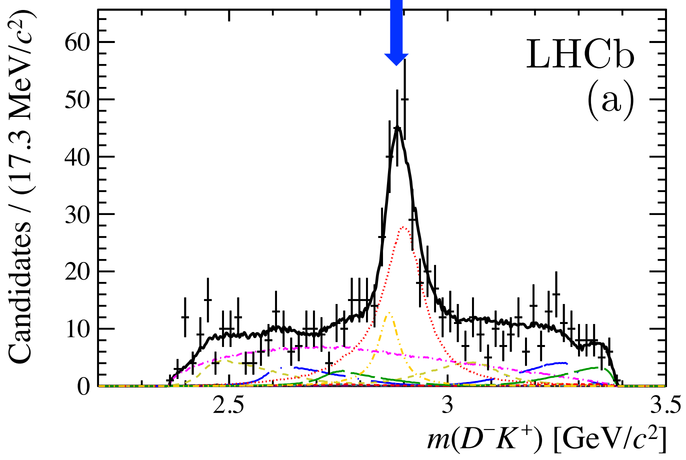
T_{cs} states at LHCb

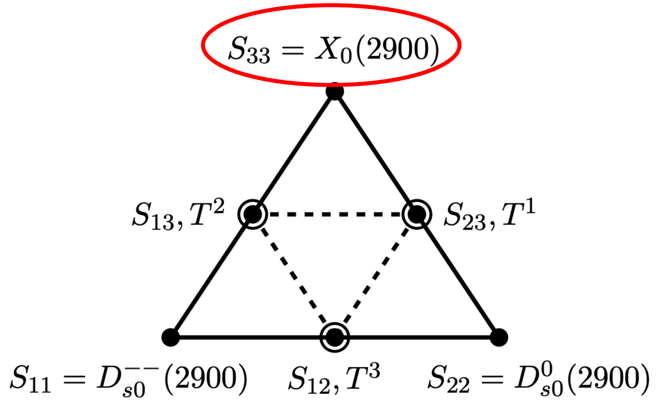
$B^+ \to D^+ D^- K^+$

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

[PRL 125 (2020) 242001]
[PR D102 (2020) 112003]

$T^*_{cs0}(2870)^0, T^*_{cs1}(2900)^0$

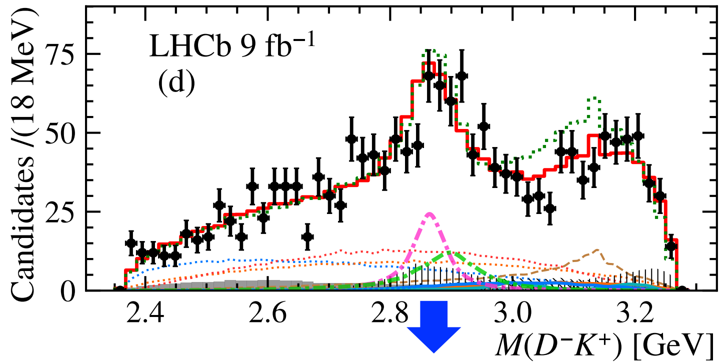




[PRD 110 (2024) 034014]

2020

$B^+ \to D^{*+} D^- K^+$



$T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^-K^+$

$T^*_{\bar{c}\bar{s}0}(2900)^0 \to D^-K^+$

Property	$B^+ \to D^+D^-K^+$	$B^+ \to D^{*+}D^-K^+$
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

2σ

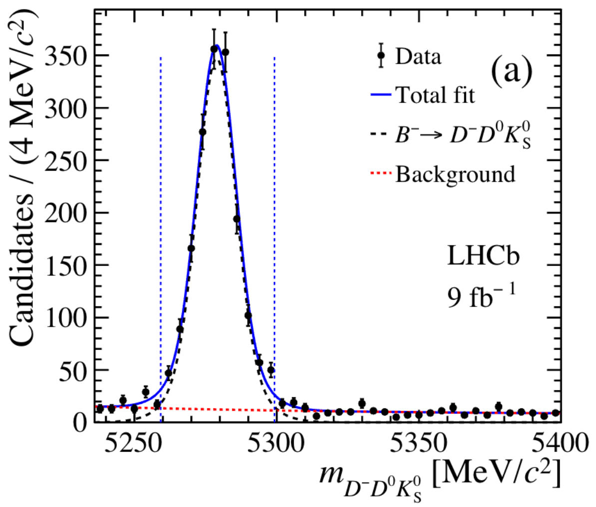
[PRL 133 (2024) 131902]

$T^*_{cs0}(2870)^0$
$T^*_{cs1}(2900)^0$

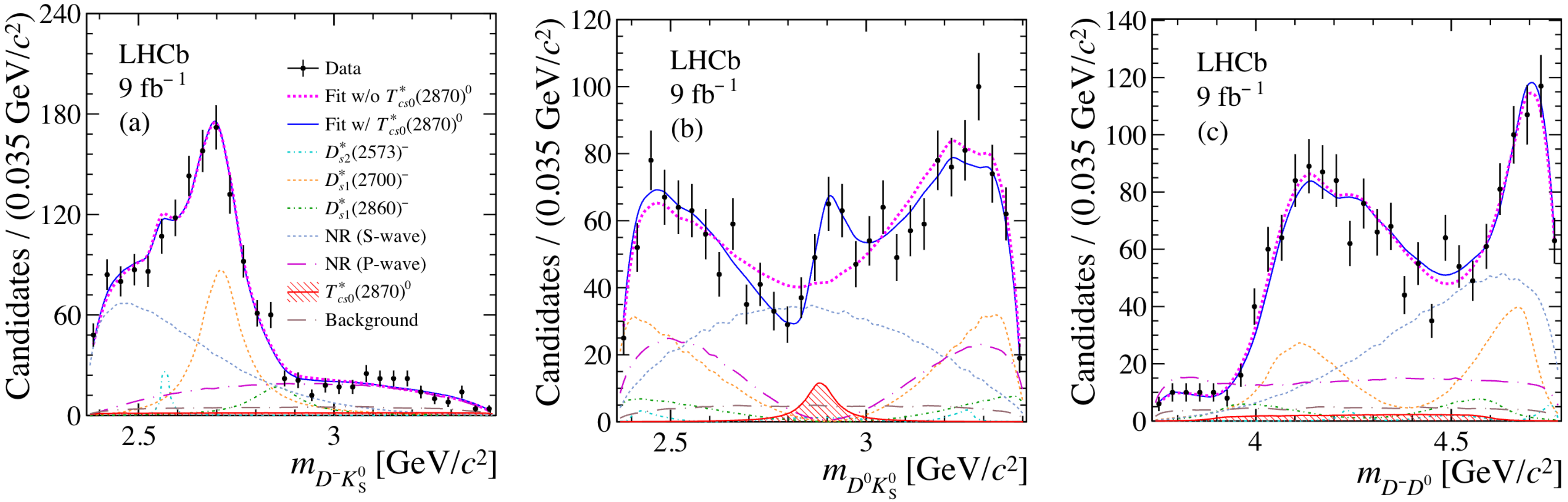
Observation of $T_{cs0}^{*}(2870)^{0} \to D^{0}K_{S}^{0}$

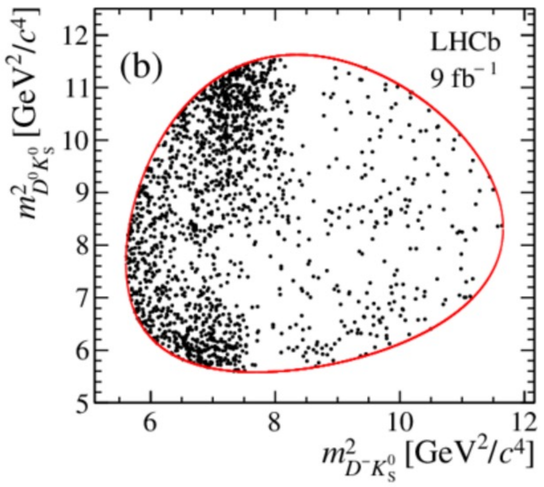
[PRL 134 (2025) 101901]

- An amplitude analysis of $B^{-} \to D^{-}D^{0}K_{S}^{0}$ is performed using 9 fb^{-1} data



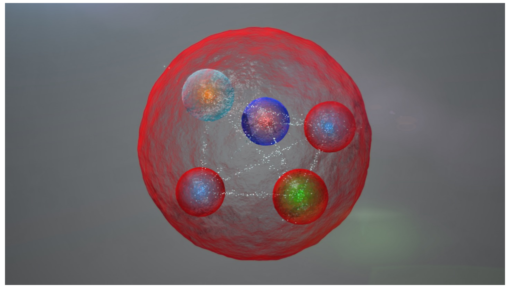
$N = 1540 \pm 40$



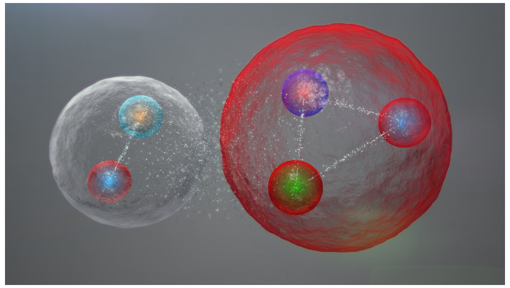


- Fit with only $B^{-} \to D_{sJ}^{*-}(\to D^{-}K_{S}^{0})D^{0}$ cannot describe $D^{0}K_{S}^{0}$ distribution
- $T_{c\bar{c}}^{-} \to D^{-}D^{0}$ considered but no significant signal found
- $T_{cs0}^{*}(2870)^{0} \to D^{0}K_{S}^{0}$ observed with 5.3 σ significance
  - ✓ **$M = 2883 \pm 11 \pm 8\ \text{MeV}/c^{2}, \Gamma = 87^{+22}_{-47} \pm 17\ \text{MeV}$**
  - ✓ **$J^{P} = 0^{+}$** preferred
- No evidence for $T_{cs1}^{*}(2900)^{0}$ → isospin violation between $D^{0}K_{S}^{0}$ and $D^{+}K^{-}$

Pentaquark studies at LHCb

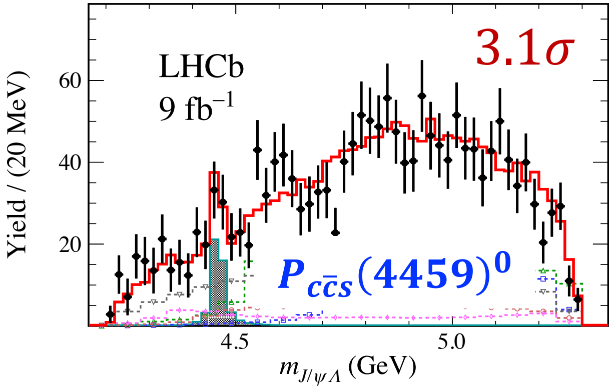


vs.



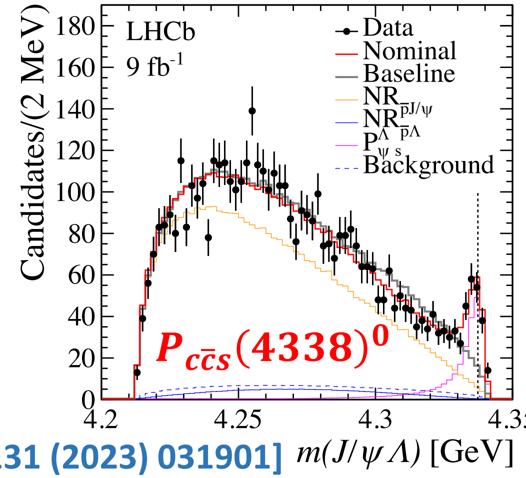
binding scheme → decay modes

$\Xi_b^- \to [J/\psi\Lambda]K^-$



[Science Bulletin 66 (2021) 1278]

$B^- \to [J/\psi\Lambda]\bar{p}$



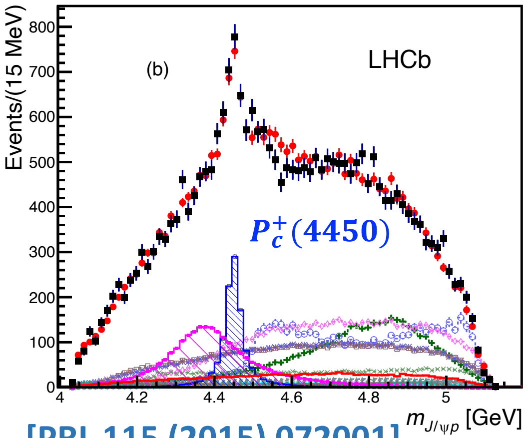
[PRL 131 (2023) 031901]

2015

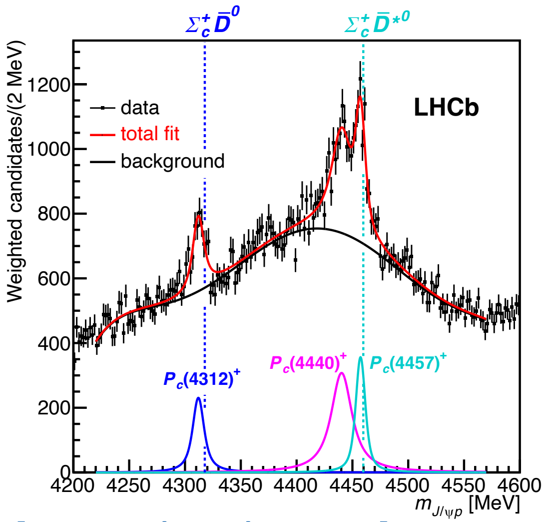
2018

2022

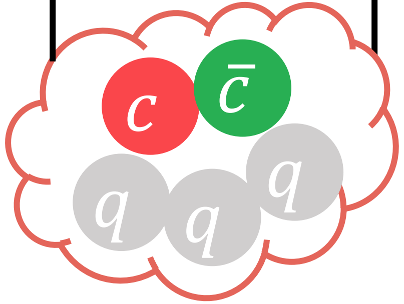
$\Lambda_b^0 \to [J/\psi\, p]K^-$



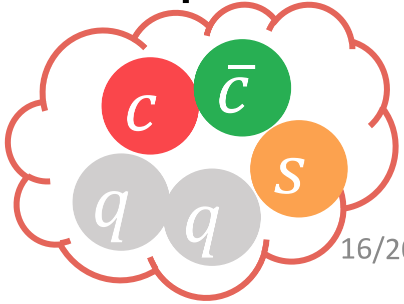
[PRL 115 (2015) 072001]



[PRL 122 (2019) 222001]



$P_c(4312)^+$
$P_c(4440)^+$
$P_c(4457)^+$



$P_{\psi s}^0$

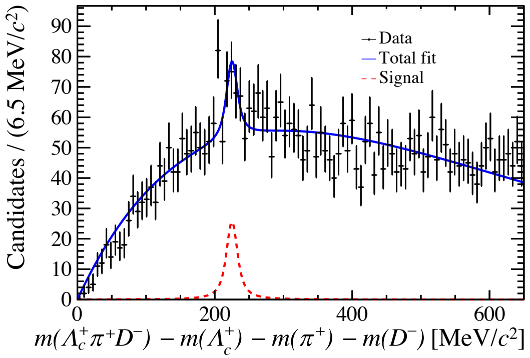
Pentaquark studies via open charm modes

prompt production

[PR D110 (2024) 032001]

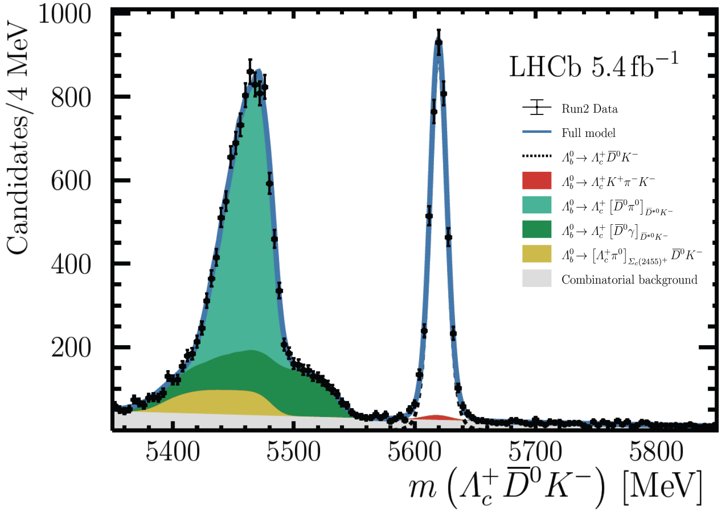
Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	$\overline{D}^0$	+1	$1/2$	1	0	✓
Λ_c^+	D^-	0	$-1/2$	1	0	✓
Λ_c^+	D^{*-}	0	$-1/2$	1	0	✓
Σ_c^{++}	$\overline{D}^0$	+2	$3/2$	1	0	✓
Σ_c^{++}	D^-	+1	$1/2$	1	0	✓
Σ_c^{++}	D^{*-}	+1	$1/2$	1	0	×
Σ_c^0	$\overline{D}^0$	0	$-1/2$	1	0	✓
Σ_c^0	D^-	−1	$-3/2$	1	0	✓
Σ_c^0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

- No significant signals
- Largest deviation from bkg. shown in $\Lambda_c^+\pi^+D^-(c\bar{c}uud)$ @ $M\sim4520.69$ MeV



$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$

[EPJC 84 (2024) 575]



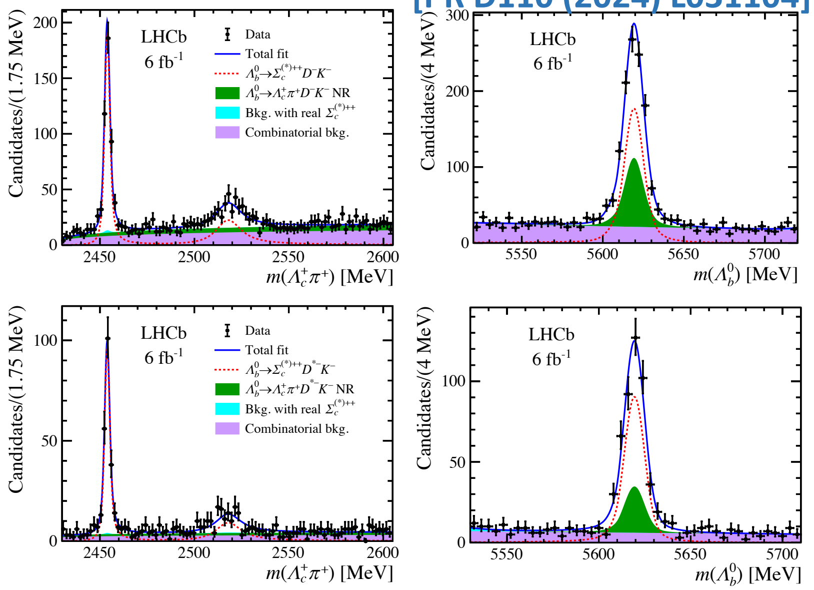
$$\frac{\mathcal{B}(\Lambda_b^0\to J/\psi pK^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\overline{D}^0K^-)} = 0.152^{+0.032}_{-0.028},$$

$$\frac{\mathcal{B}(\Lambda_b^0\to J/\psi pK^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\overline{D}^{*0}K^-)} = 0.049^{+0.011}_{-0.009},$$

- Essential input for extraction of $\mathcal{B}(P_c^+\to\Lambda_c^+\overline{D}^{(*)0})/\mathcal{B}(P_c^+\to J/\psi p)$ in the future

$\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$

[PR D110 (2024) L031104]



$$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\overline{D}^0K^-)} = 0.282\pm0.016\pm0.016\pm0.005,$$

$$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{*++}D^-K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)} = 0.460\pm0.052\pm0.028,$$

$$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^{*-}K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)} = 2.261\pm0.202\pm0.129\pm0.046,$$

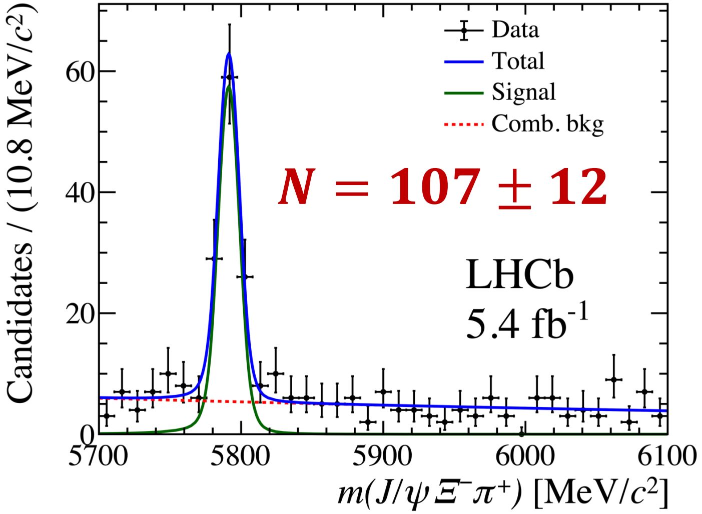
$$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{*++}D^{*-}K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)} = 0.896\pm0.137\pm0.066\pm0.018,$$

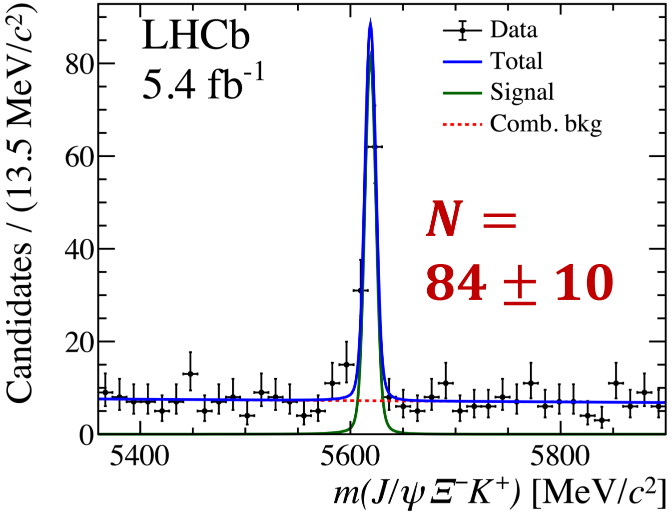
- Study of resonant structures calls for larger dataset

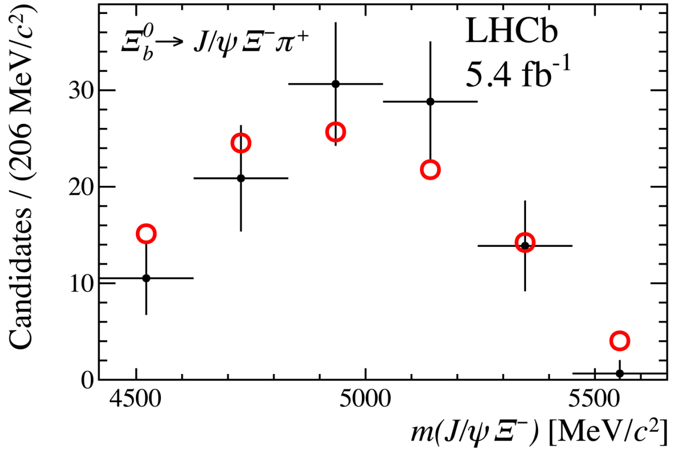
$\Xi_b^0 \to J/\psi \Xi^- \pi^+$ and $\Lambda_b^0 \to J/\psi \Xi^- K^+$

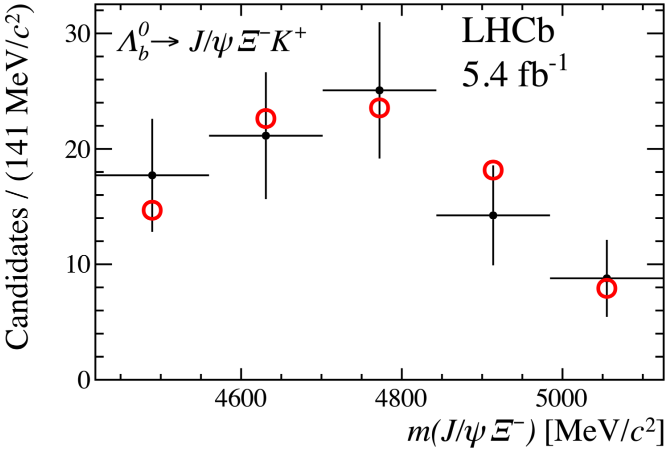
[arXiv: 2501.12779]

$J/\psi p \to c\bar{c}uud$ → $J/\psi \Lambda \to c\bar{c}sud$ → ? → $J/\psi \Xi \to c\bar{c}ssu/d$









- **First observation** of $\Xi_b^0 \to J/\psi \Xi^- \pi^+$

$$\frac{\mathcal{B}(\Xi_b^0 \to J/\psi \Xi^- \pi^+)}{\mathcal{B}(\Xi_b^- \to J/\psi \Xi^-)} = (11.9 \pm 1.4 \pm 0.6) \times 10^{-2}$$

- **Most precise** measurement of $\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)$

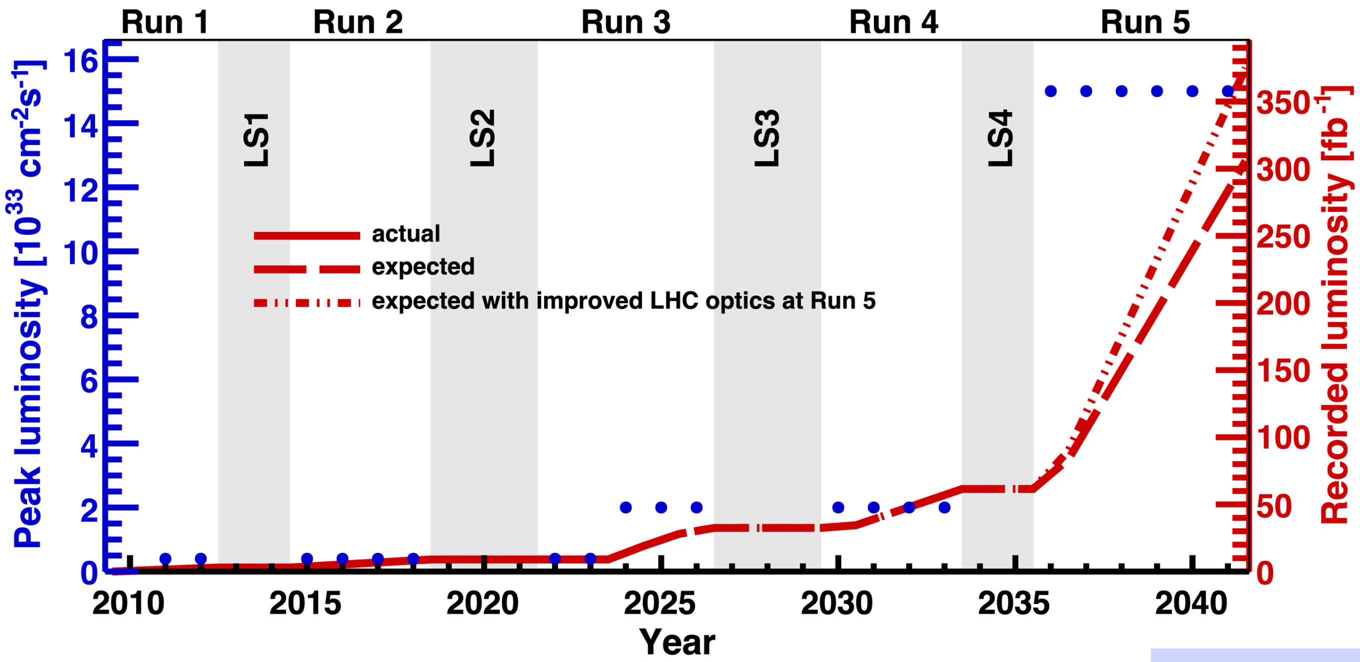
$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (1.17 \pm 0.14 \pm 0.08) \times 10^{-2}$$

$$\left.\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S) \Lambda)}\right|_{\text{CMS}} = (3.4 \pm 1.2) \times 10^{-2}$$

$$\left.\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S) \Lambda)}\right|_{\text{LHCb}} = (2.3 \pm 0.3) \times 10^{-2}$$

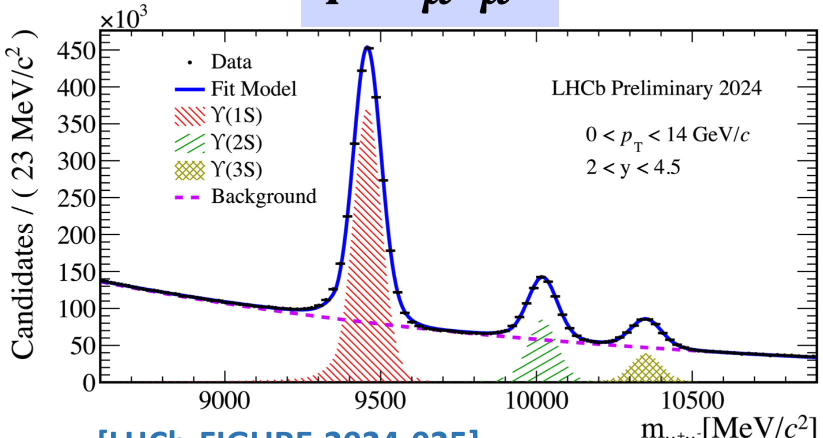
- Larger statistics needed for amp. study

Prospects for Run3



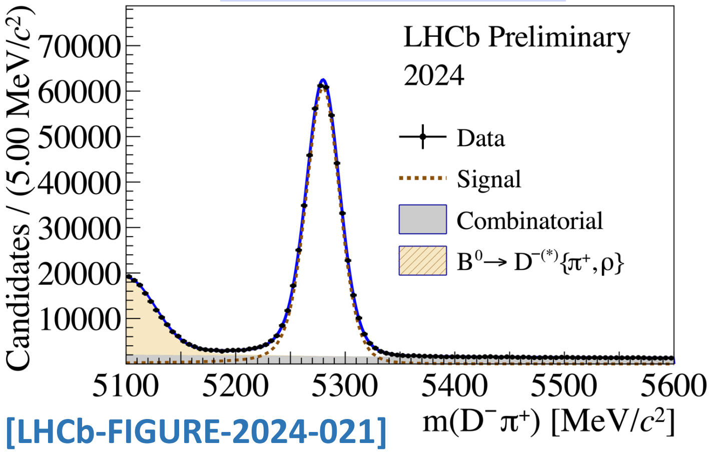
- ✓ 9 fb^{-1} @ Run 1-2 → ~30 fb^{-1} by Run 3
- ✓ Upgraded sub-detectors
- ✓ Software-only trigger system
  → trigger efficiency for fully hadronic modes largely improved

$\Upsilon \rightarrow \mu^+\mu^-$



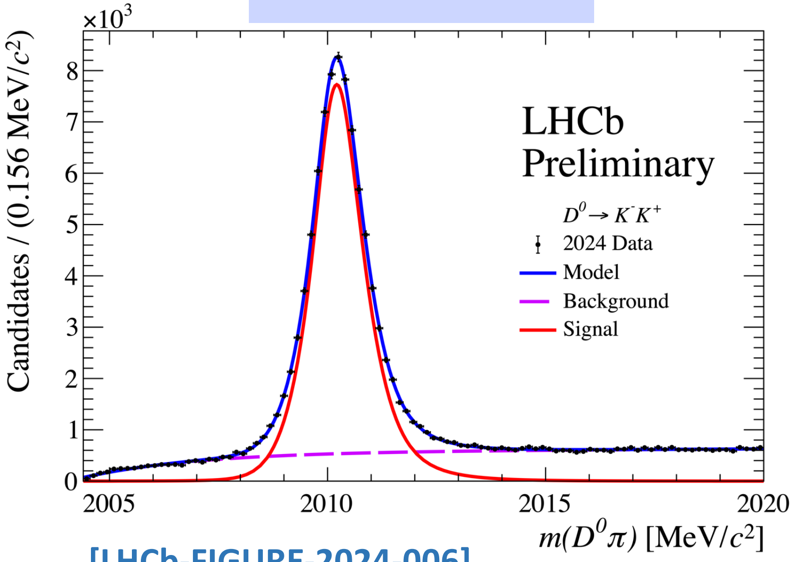
[LHCb-FIGURE-2024-025]

$B^0 \rightarrow D^-\pi^+$



[LHCb-FIGURE-2024-021]

$D^{*+} \rightarrow D^0\pi^+$



[LHCb-FIGURE-2024-006]

Summary

➢The LHCb experiment maintains a strong momentum in exotic hadron – XYZ research

Charmonium-like states

- ✓Radiative decays of $\chi_{c1}(3872)$
- ✓Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$

Open-charm tetraquark states

- ✓Amplitude analysis of $D_{s1}(2460) \to D_s^+\pi^+\pi^-$
- ✓Observation of $B^- \to T_{cs0}^*(2870)^0\left(\to D^0K_S^0\right)D^-$

Pentaquark states

- ✓Pentaquark studies via open charm modes:
  prompt production, $\Lambda_b^0 \to \Lambda_c^+\overline{D}^{(*)0}K^-$, $\Lambda_b^0 \to \Sigma_c^{(*)++}D^{(*)-}K^-$
- ✓Measurement of $\Xi_b^0 \to J/\psi\Xi^-\pi^+$ and $\Lambda_b^0 \to J/\psi\Xi^-K^+$

Stay tuned!

Credit: Ivan Polyakov [arXiv: 2410.06923]
A brief guide to exotic hadrons

谢谢！