



Hadron spectroscopy at LHCb

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Outline

Conventional hadrons

- Observation of orbitally excited B_c^+ states [arXiv:2507.02149]
- Observation of a new charmed baryon decaying to $\Xi_c^+ \pi^+ \pi^-$ [PRL 135 (2025) 161901]
- Study of light-meson resonances decaying to $K_S^0 K \pi$ in the $B \rightarrow (K_S^0 K \pi) K$ channels [PRD 111 (2025) 092009]

Exotic hadrons

- Observation of the open-charm tetraquark candidate $T_{cs}^*(2870)^0$ in the $B^- \rightarrow D^- D^0 K_S^0$ decay [PRL 134 (2025) 101901]
- Study $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ in $B \rightarrow \bar{D}^{(*)} D_s^+ \pi^+ \pi^-$ decays [Sci. Bull. 70 (2025) 1432]
- Amplitude analysis of $B^0 \rightarrow \eta_c(1S) K^+ \pi^-$ decays [arXiv:2509.03133]
- First observation of the $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-$ decay and search for pentaquarks in the $\Lambda_c^+ D_s^-$ system [arXiv:2507.10713]

Introduction

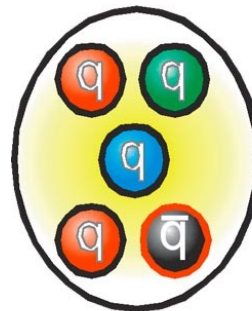
- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
 - e.g. lattice QCD, diquark model, potential model ...
- Exotic hadrons provide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



mesonic molecule



tetraquark



pentaquark



hybrid

...

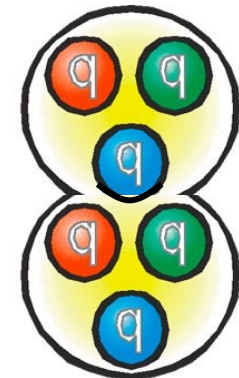
EXOTIC



meson



baryon

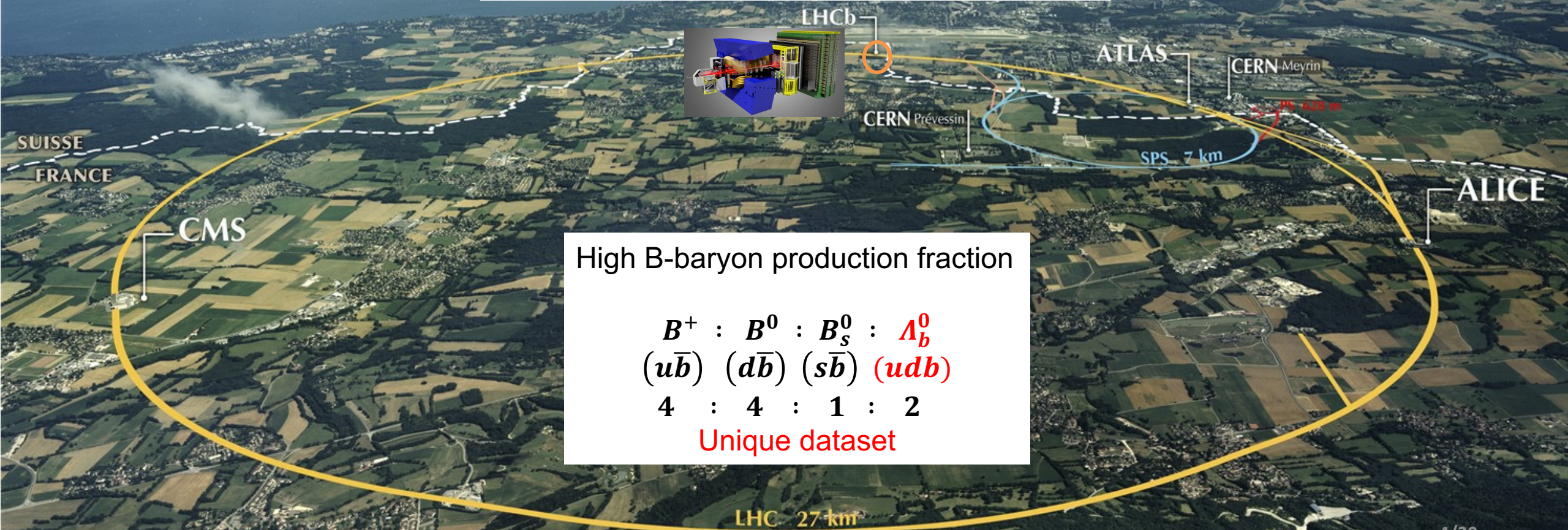


e.g. deuteron

STANDARD

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

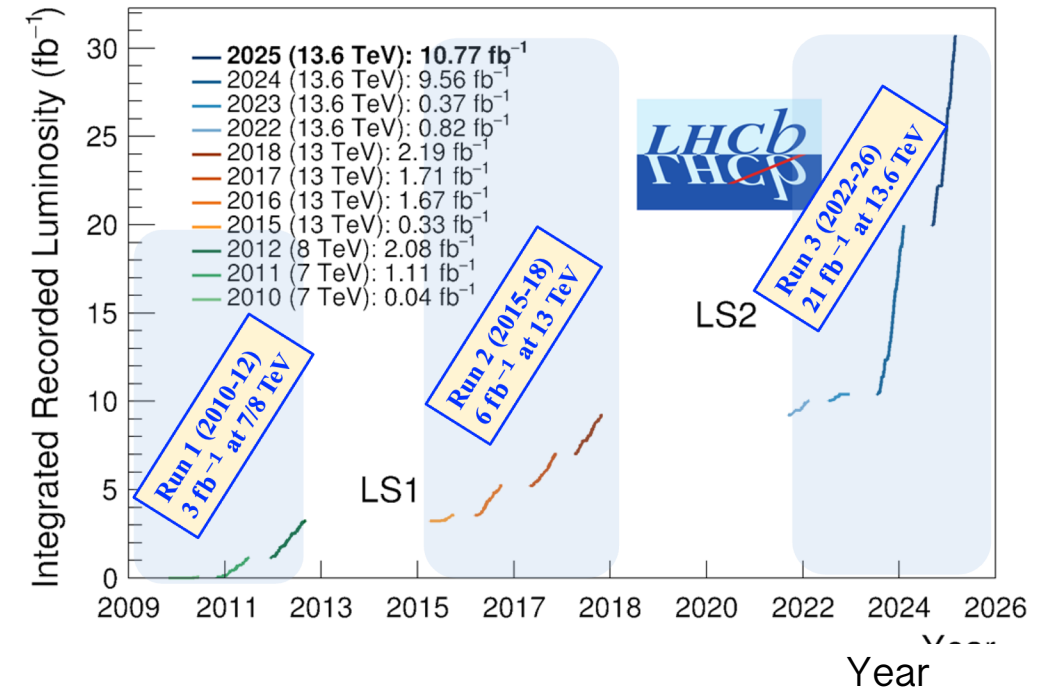
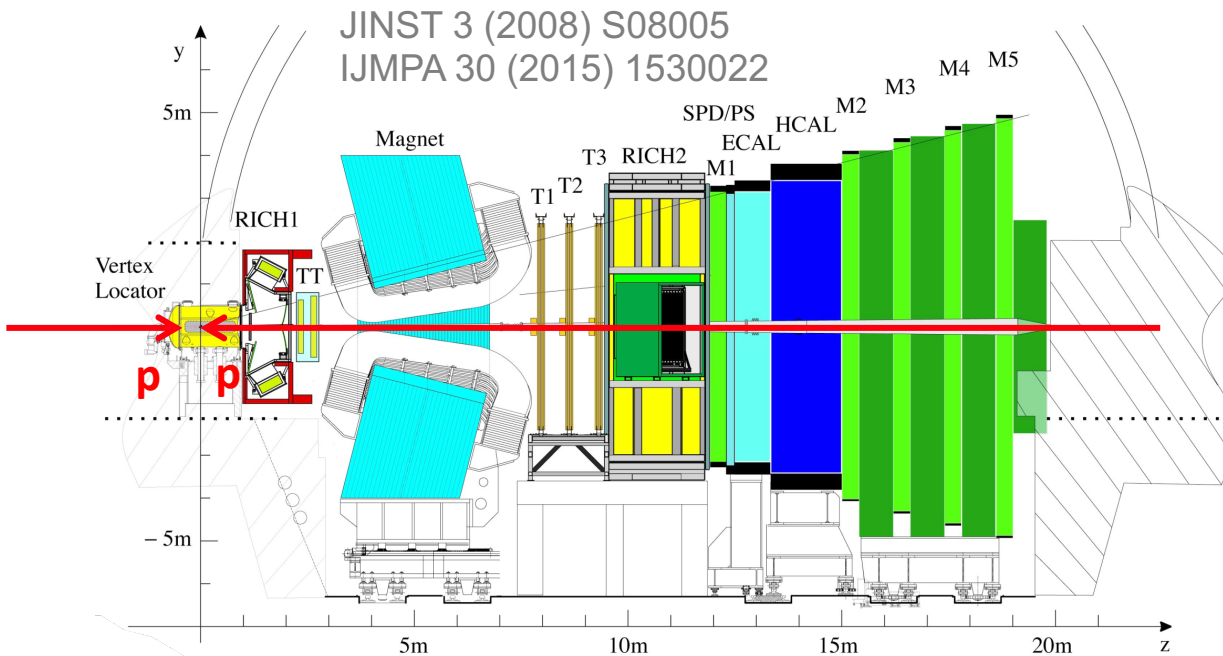
B^+	B^0	B_s^0	Λ_b^0
$(u\bar{b})$	$(d\bar{b})$	$(s\bar{b})$	$(ud\bar{b})$
4	4	1	2

Unique dataset

The LHCb Experiment

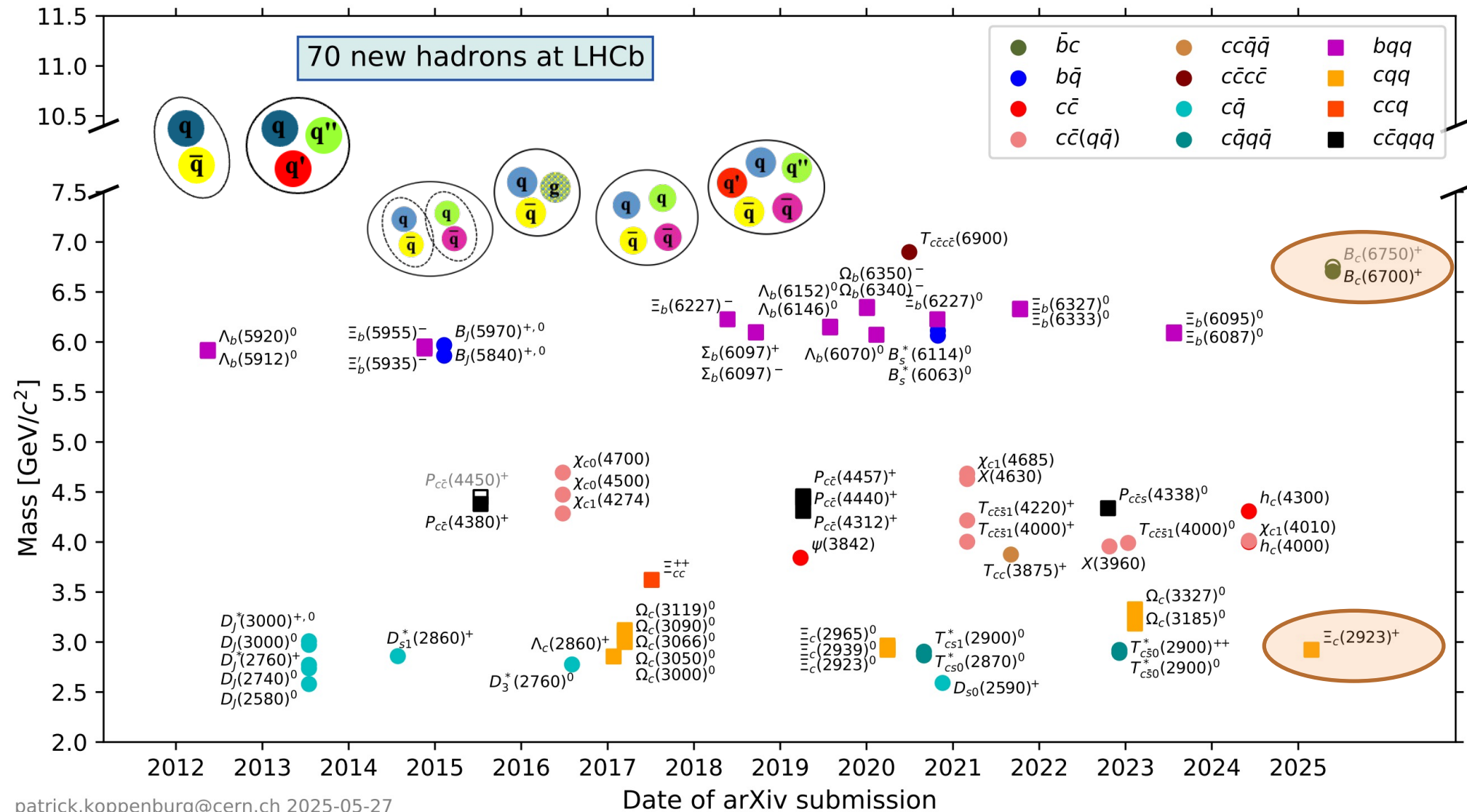
- LHCb is a dedicated flavour physics experiment at the LHC
 - $>10^4 \times$ larger b production rate than the B factories @ Y(4S)
 - Access to all b -hadrons: B^+ , B^0 , B_s^0 , B_c^+ , b -baryons
- Can also study hadron spectroscopy and exotic states
- Acceptance optimised for forward $b\bar{b}$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

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



New hadrons at LHCb

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



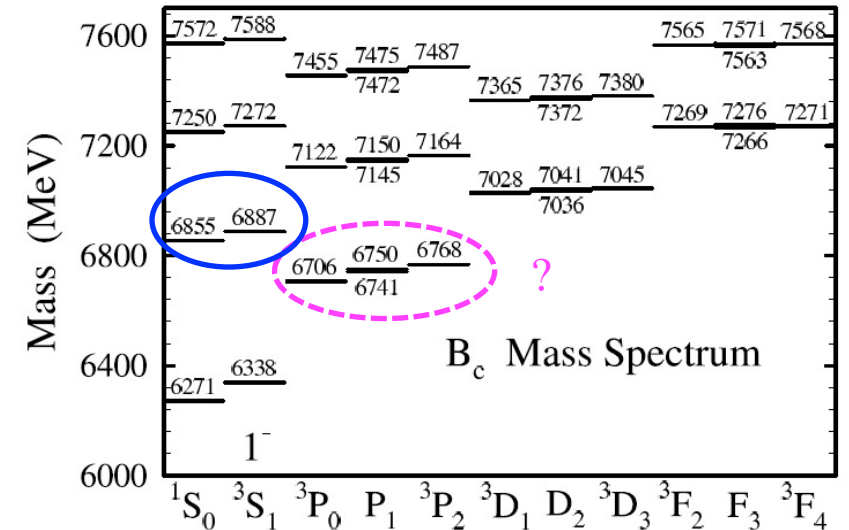
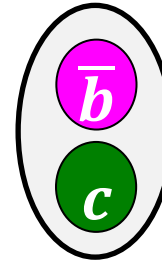
patrick.koppenburg@cern.ch 2025-05-27

Orbitally excited B_c^+ states

- B^+ spectroscopy a useful tool to tune QCD models
- So far, only two radial excitations have been discovered (Atlas, CMS & LHCb)

Expect four $L=1$ (P) states ($2S+1L_J$):

- Spin singlet $1P_1 \rightarrow B_c \gamma$
- Spin triplet $3P_0, 3P_1, 3P_2 \rightarrow B_c^*(^3S_1) \gamma$ with $B_c^* \rightarrow B_c \gamma_{\text{soft}}$



BUT: Two axial-vector states $1P_1$ & $3P_1$ can mix
& both decay to B_c and B_c^*

⇒ Expect up to 6 peaks, with some shifted by missing mass
 δM from γ_{soft}

Lots of unknowns, lots of predictions under different QCD approaches

⇒ Experimental input needed!

	δM	$M(1^3P_0)$	$M(1P_1)$	$M(1P_1')$	$M(1^3P_2)$	θ [°]
Lattice QCD [1]	41	6727	6743	6765	6783	33.4
GKLT [5]	64	6683	6717	6729	6743	17.1
GJ [6]	61	6689	6738	6757	6773	25.6
FUII [7]	55	6701	6737	6760	6772	28.5
EFG [8]	62	6699	6734	6749	6762	20.4
GI [9]	67	6706	6741	6750	6768	22.4
EQ [10]	54	6693	6731	6739	6759	18.7
LLLLGZ [11]	55	6714	6757	6776	6787	35.5
WWLC [12]	55	6705	6739	6748	6762	32.2
LTFWP [13]	53	6712	6770	6761	6783	-24.3
LLWL [14]	67	6701	6745	6754	6773	35.2
HZ [15]	63	6707	6751	6786	6802	55.0

See [arXiv: 2507.02142](https://arxiv.org/abs/2507.02142) for references

Orbitally excited B_c^+ states

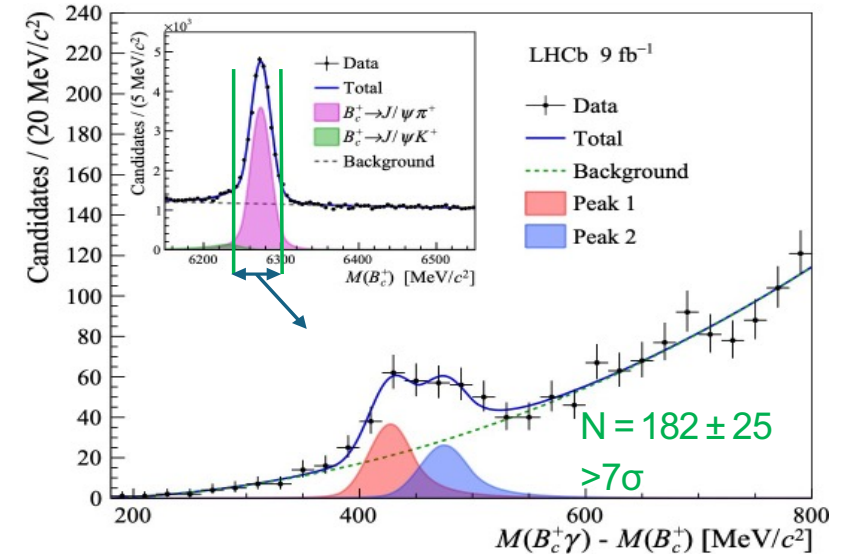
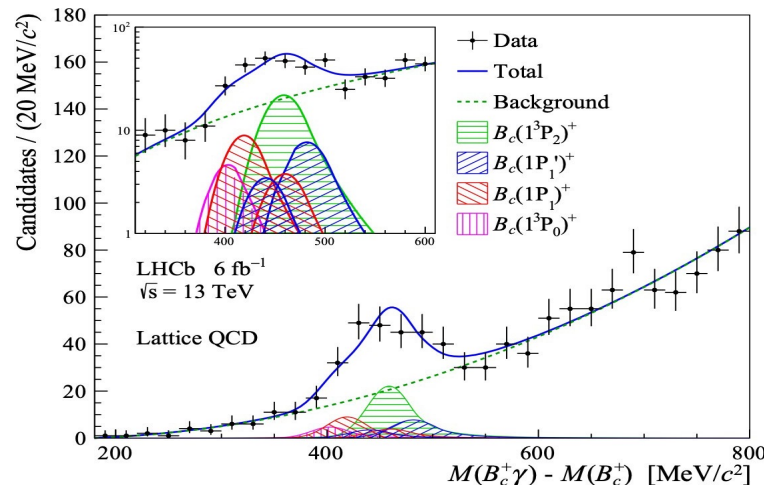
arXiv: 2507.02149 (submitted to PRL)

- $B_c\gamma$ spectrum shows broad excess consistent with multiple overlapping peaks
- Good fit with two peaks, with free masses & widths dictated by resolution

$$M_1 = 6704.8 \pm 5.5 \pm 2.8 \pm 0.3 \text{ MeV}/c^2$$

$$M_2 = 6752.4 \pm 9.5 \pm 3.1 \pm 0.3 \text{ MeV}/c^2$$
- Model-dependent analysis: fit data with inputs from various theory predictions, all give good fit agreement (p-values 15% – 90%)

arXiv: 2507.02142 (submitted to PRD)



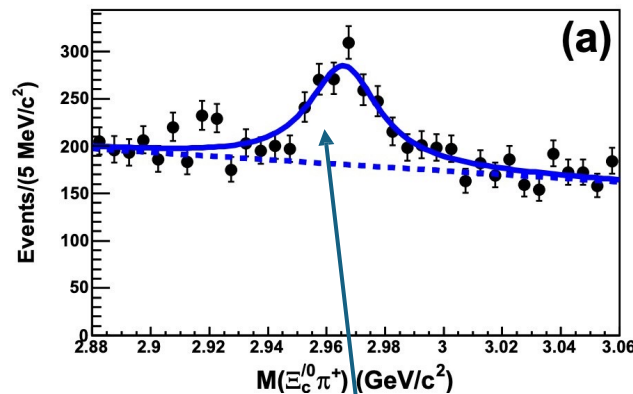
Measure relative production cross-section of $B_c(1P)$ states compared to ground-state:

$$R = 0.20 \pm 0.03 \pm 0.02 \pm 0.03 \text{ (model)}$$

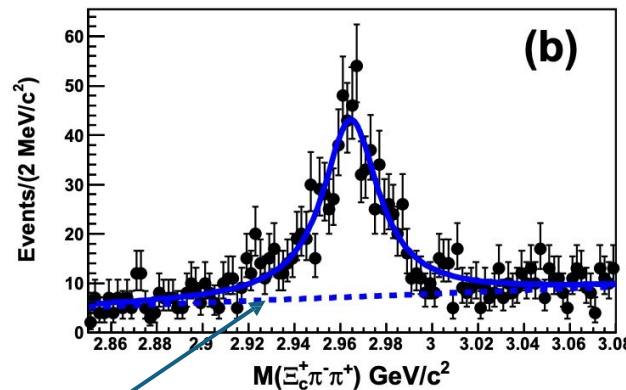
$$(p_T < 20 \text{ GeV}/c \text{ and } 2 < \eta < 4.5)$$

Charmed baryons

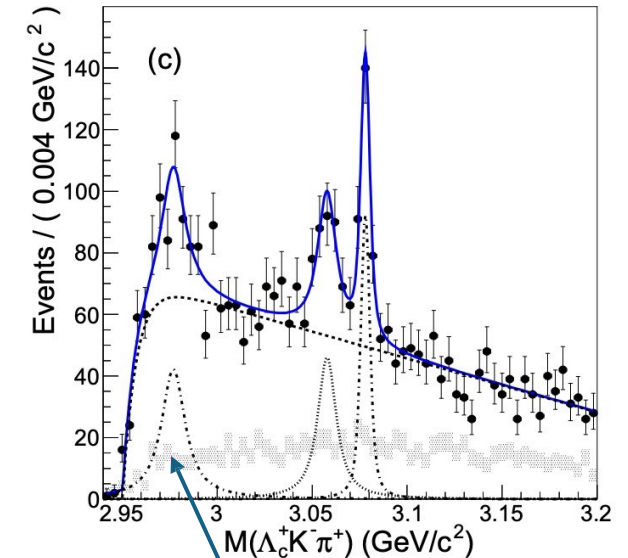
- Charmed baryons exhibit rich spectrum of excited states
- Over 100 $\Xi_c(csu, csd)$ states expected in mass range 2.8 – 3.8 GeV
 - Many experimental results, many puzzles remain
 - e.g. “ $\Xi_c(2970)^+$ ” could be multiple different states
 - $\Rightarrow$ Need more measurements, more decay modes, more precision



“ $\Xi_c(2970)^+$ ” $\rightarrow \Xi_c'^0 \pi^+$ and $\Xi_c^+ \pi^- \pi^+$
 $m = 2966.0 \pm 0.9 \text{ MeV}$
 $\Gamma = 28.1 \pm 3.8 \text{ MeV}$

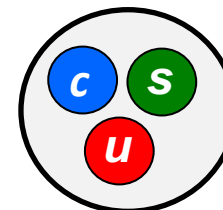


Belle, 2016, [PRD 94, 052011](#)
 ([arXiv:1607.07123](#))



“ $\Xi_c(2970)^+$ ” $\rightarrow \Lambda_c^+ K \pi$
 $m = 2974.9 \pm 2.6 \text{ MeV}$
 $\Gamma = 14.8 \pm 4.8 \text{ MeV}$

Belle, 2013, [PRD 89, 052003](#)
 ([arXiv:1312.1026](#))

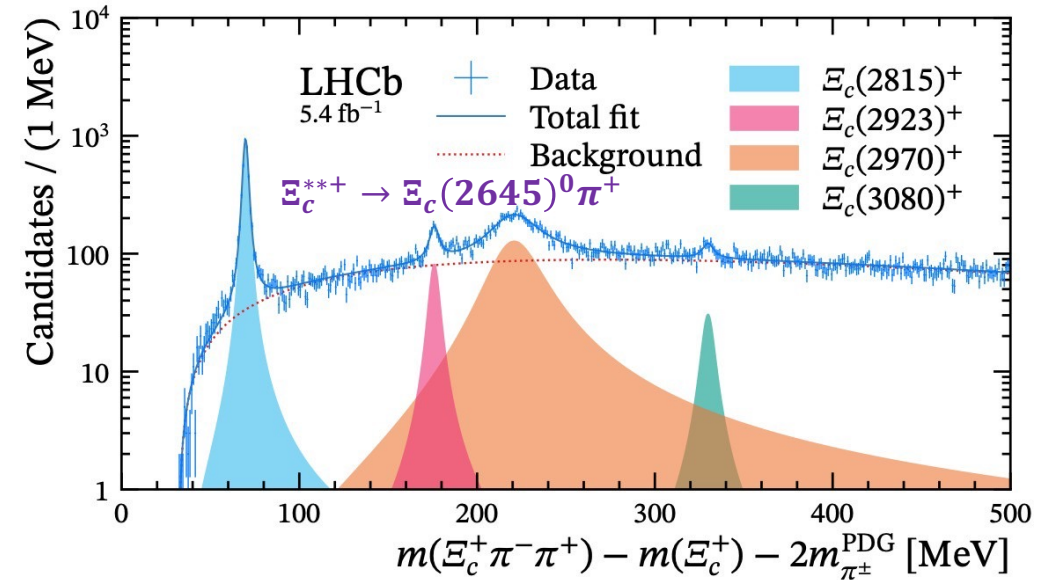
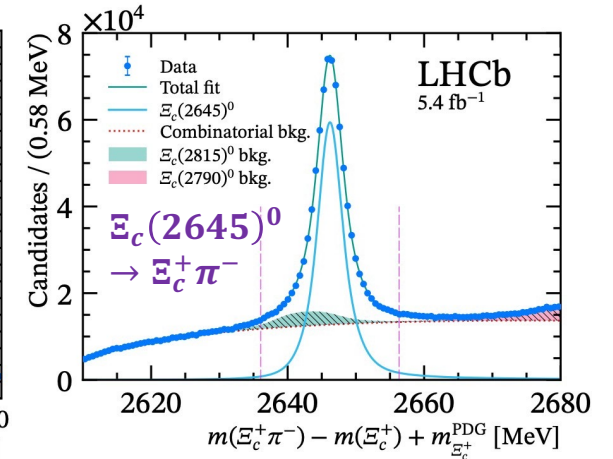
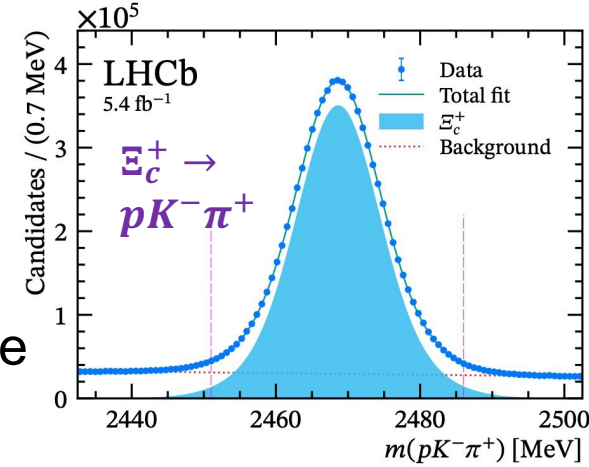
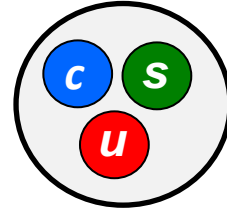


Ξ_c^{**+} states at 2.9-3.1 GeV

[PRL 132 (2025) 161901]

Search with $\Xi_c(2645)^0 \pi^+ \rightarrow \Xi_c^+ \pi^- \pi^+$

- Four peaks with high significance
- $\Xi_c(2923)^+$ observed for 1st time (isospin partner known)
- $\Xi_c(3080)^+$ seen in this decay mode for 1st time
- $\Xi_c(2970)^+$ with ~ 30 MeV width – confirms different to $\Lambda_c K \pi$ peak



$$m[\Xi_c(2815)^+] = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23 \text{ MeV},$$

$$\Gamma[\Xi_c(2815)^+] = 2.07 \pm 0.08 \pm 0.12 \text{ MeV},$$

$$m[\Xi_c(2923)^+] = 2922.8 \pm 0.3 \pm 0.5 \pm 0.2 \text{ MeV},$$

$$\Gamma[\Xi_c(2923)^+] = 5.3 \pm 0.9 \pm 1.4 \text{ MeV},$$

$$m[\Xi_c(2970)^+] = 2968.6 \pm 0.5 \pm 0.5 \pm 0.2 \text{ MeV},$$

$$\Gamma[\Xi_c(2970)^+] = 31.7 \pm 1.7 \pm 1.9 \text{ MeV},$$

$$m[\Xi_c(3080)^+] = 3076.8 \pm 0.7 \pm 1.3 \pm 0.2 \text{ MeV},$$

$$\Gamma[\Xi_c(3080)^+] = 6.8 \pm 2.3 \pm 0.9 \text{ MeV},$$

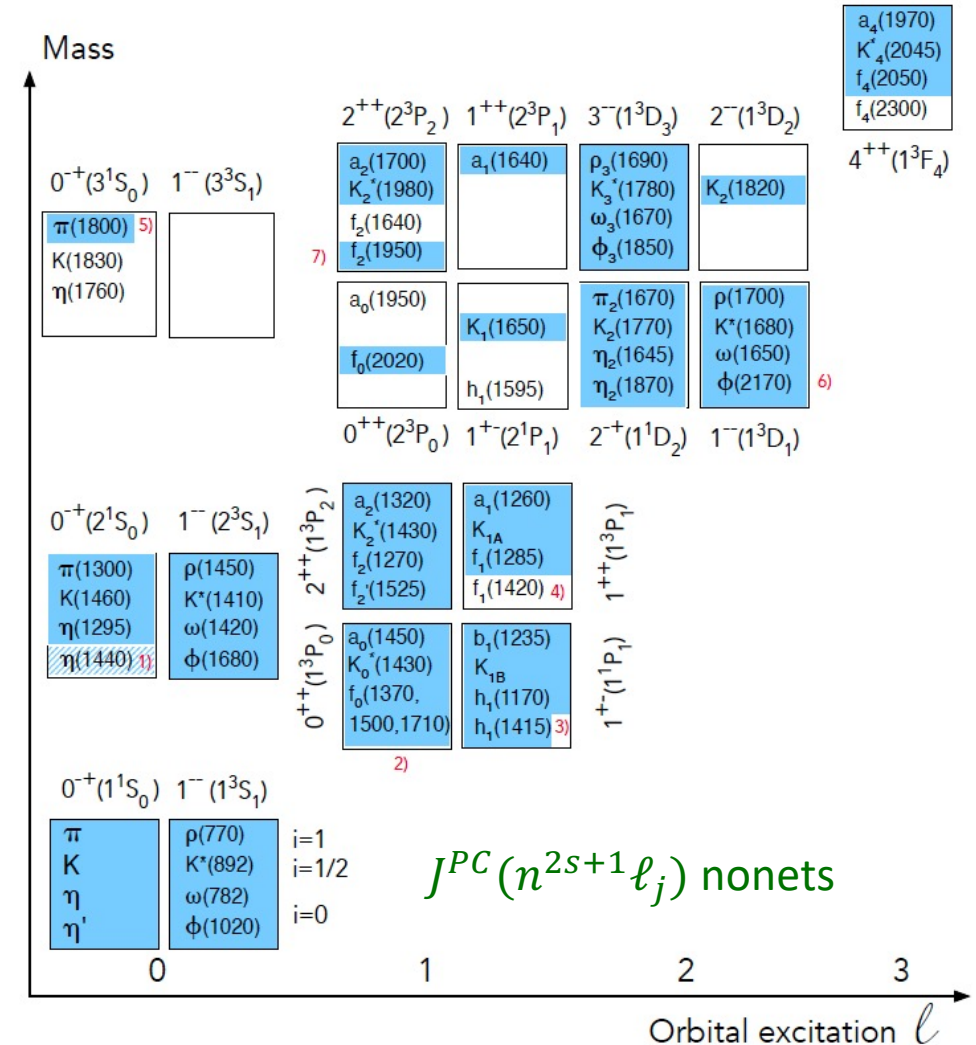
Non-Strange Mesons

Open questions

[PDG review “*Spectroscopy of Light Meson Resonances*”]

- Pseudoscalar $\eta(1440)$ ¹⁾
 - Possibly two states $\eta(1405)$ & $\eta(1475)$
- Difficulty accommodating known light scalars in lower $q\bar{q}$ nonets ²⁾
 - $a_0(980)$, $K_0^*(700)$, $f_0(500)$, $f_0(980)$
- Three observed isoscalars ²⁾
 - $f_0(1370/1500/1700)$
 - The latter two proposed as glueball candidates
- The axial-vector meson $f_1(1420)$ has another candidate $f_1(1510)$ ⁴⁾

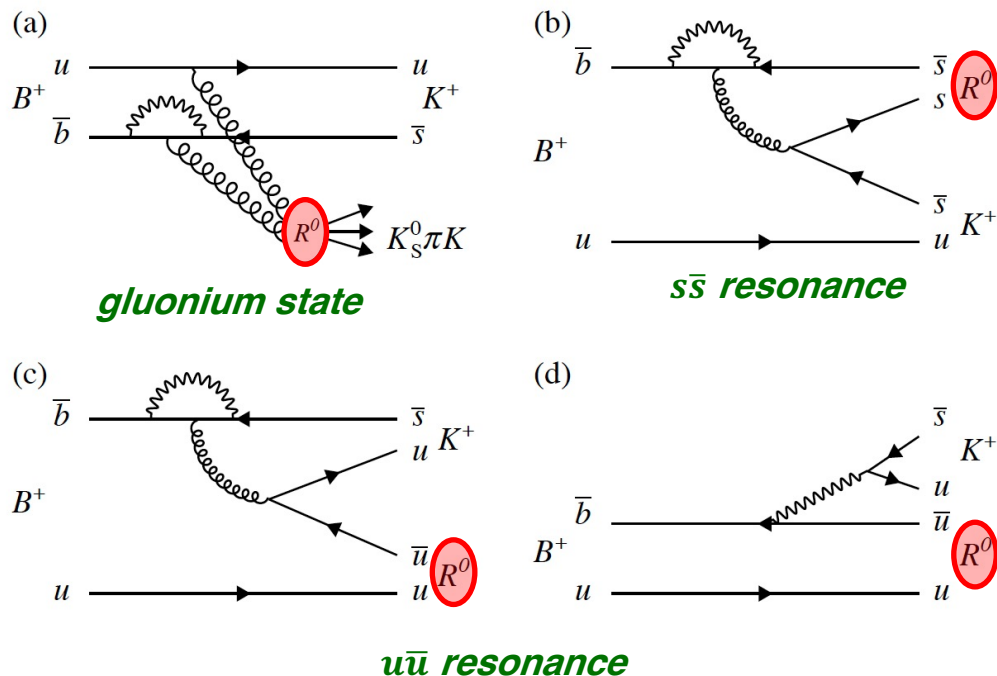
Mass spectrum of $q\bar{q}$ mesons



$R^0 \rightarrow K_S^0 K^\pm \pi^\mp$ system in $B^+ \rightarrow R^0 K^+$ decays

- The process $b \rightarrow s$ gluon has been suggested as possible source of gluonium states
[H. Fritzsch, PLB 415, 83-89 (1997)]

- However contributions from $s\bar{s}$ and $u\bar{u}$ resonances are expected.



- Pseudoscalar glueball:
 - Phenomenological models: ≈ 1.4 GeV
 - Lattice QCD: ≈ 2.5 GeV
[J Phys G40 (2013) 043001]
- Mass region (< 1.6 GeV) can study:
 - Two overlapping 1^{++} states: $f_1(1420)$ and $f_1(1510)$
 - Two states $\eta(1405)$ & $\eta(1475)$

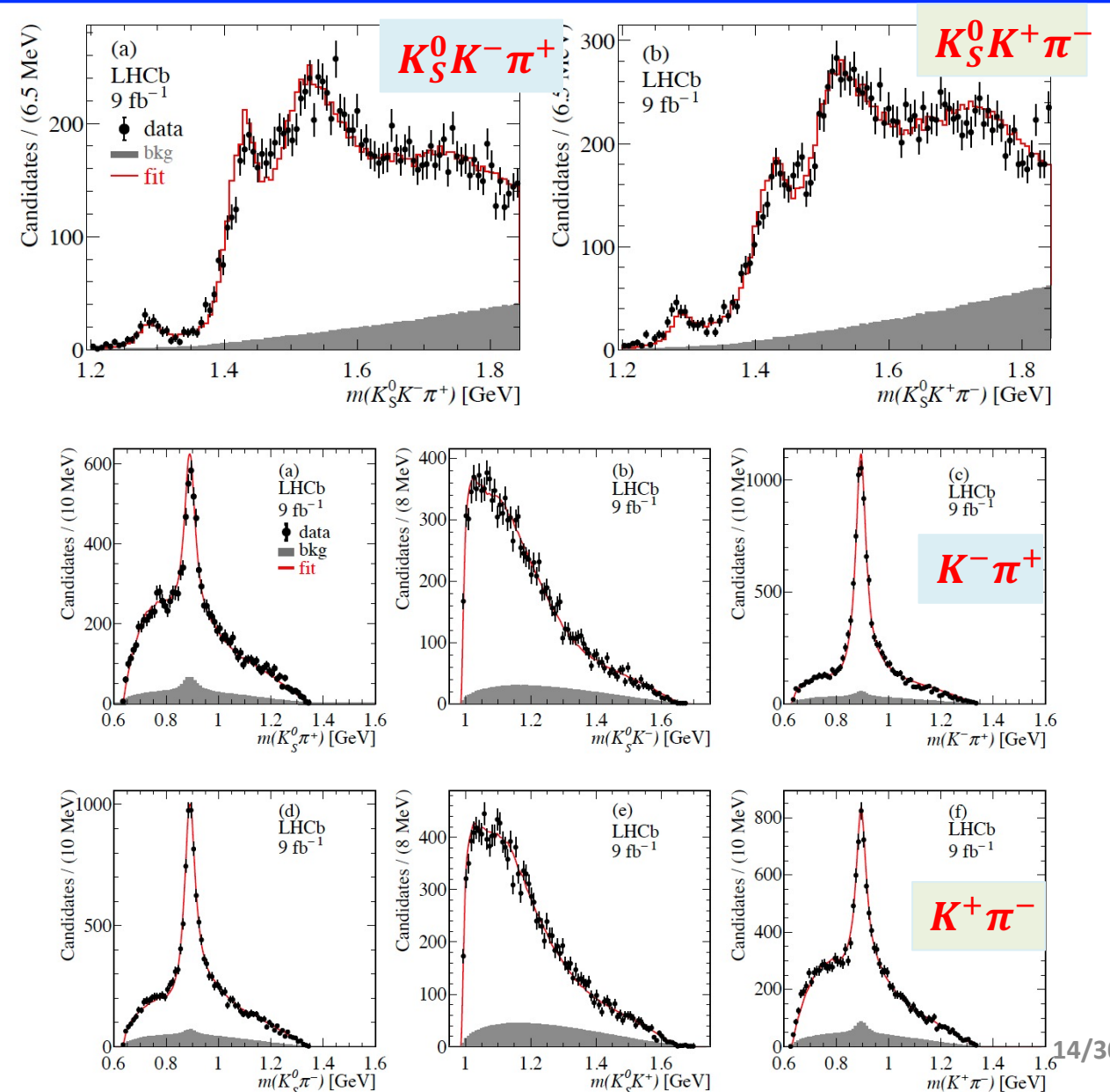
Ampitude analysis

[PRD 111 (2025) 092009]

- Yields for $m(K_S^0 K^\pm \pi^\mp) < 1.85$ GeV (purity $\sim 85\%$)

Final state	Signal Events
$B^+ \rightarrow K_S^0 K^+ K^- \pi^+$	10430
$B^+ \rightarrow K_S^0 K^+ K^+ \pi^-$	12320

- Decay chains via $a_0(980)\pi$, $K^*(892)\bar{K}$ and direct $K^0 K \pi$
- Resonant parameters are fixed to those from PDG
- 19 contributions include $J^{PC} = 0^{-+}, 1^{++}, 1^{+-}$ and $\eta_2(1645)$



Fit results

[PRD 111 (2025) 092009]

Contribution	Decay	$B^+ \rightarrow K_S^0 K^- \pi^+ K^+$		$B^+ \rightarrow K_S^0 K^+ \pi^- K^+$	
		Fraction [%]	Phase [rad]	Fraction [%]	Phase [rad]
$\eta(1475)$	$K^* \bar{K}$	$10.7 \pm 1.1 \pm 1.1$	0	$10.3 \pm 1.1 \pm 1.4$	0
	$a_0 \pi$	$1.4 \pm 0.4 \pm 0.4$	$3.18 \pm 0.19 \pm 0.15$	$1.8 \pm 0.4 \pm 0.4$	$2.92 \pm 0.14 \pm 0.13$
	PS	$15.2 \pm 2.1 \pm 2.1$	$3.33 \pm 0.10 \pm 0.12$	$8.9 \pm 1.4 \pm 2.7$	$3.57 \pm 0.11 \pm 0.13$
	Total	$27.4 \pm 2.4 \pm 2.4$	–	$21.0 \pm 1.8 \pm 3.1$	–
$\eta(1760)$	$K^* \bar{K}$	$1.9 \pm 0.4 \pm 0.3$	$-1.53 \pm 0.16 \pm 0.28$	$3.1 \pm 0.4 \pm 0.5$	$-1.16 \pm 0.13 \pm 0.20$
	$a_0 \pi$	$2.0 \pm 0.4 \pm 0.3$	$2.11 \pm 0.15 \pm 0.20$	$1.7 \pm 0.4 \pm 0.3$	$3.06 \pm 0.12 \pm 0.24$
	PS	$11.9 \pm 1.8 \pm 2.7$	$1.60 \pm 0.10 \pm 0.19$	$23.2 \pm 2.4 \pm 5.1$	$1.92 \pm 0.07 \pm 0.22$
	Total	$15.8 \pm 1.9 \pm 2.7$	–	$27.9 \pm 2.5 \pm 5.1$	–
$\eta(1405)$	$K^* \bar{K}$	$3.5 \pm 0.6 \pm 1.9$	$-0.10 \pm 0.10 \pm 0.20$	$2.3 \pm 0.5 \pm 0.7$	$-0.01 \pm 0.11 \pm 0.18$
	PS	$5.2 \pm 0.5 \pm 0.8$	$1.77 \pm 0.11 \pm 0.28$	$6.4 \pm 0.5 \pm 0.9$	$1.96 \pm 0.13 \pm 0.20$
	Total	$8.7 \pm 0.8 \pm 2.0$	–	$8.6 \pm 0.7 \pm 1.1$	–
$f_1(1285)$	$a_0 \pi$	$2.0 \pm 0.2 \pm 0.2$	$-0.35 \pm 0.13 \pm 0.26$	$2.0 \pm 0.2 \pm 0.2$	$-0.47 \pm 0.11 \pm 0.12$
$f_1(1420)$	$K^* \bar{K}$	$11.4 \pm 0.7 \pm 2.1$	$4.25 \pm 0.08 \pm 0.23$	$6.6 \pm 0.5 \pm 1.7$	$4.67 \pm 0.10 \pm 0.27$
$h_1(1415)$	$K^* \bar{K}[S]$	$10.0 \pm 0.9 \pm 2.0$	$4.59 \pm 0.08 \pm 0.20$	$18.6 \pm 1.2 \pm 3.5$	$1.57 \pm 0.08 \pm 0.55$
	$K^* \bar{K}[D]$	$3.3 \pm 0.3 \pm 0.2$	$-0.13 \pm 0.08 \pm 0.16$	$2.4 \pm 0.3 \pm 0.2$	$-2.57 \pm 0.08 \pm 0.42$
	Total	$13.3 \pm 1.0 \pm 2.0$	–	$21.0 \pm 1.2 \pm 3.6$	–
$f_1(1510)$	$K^* \bar{K}$	$2.9 \pm 0.4 \pm 1.2$	$-3.23 \pm 0.09 \pm 0.47$	$2.6 \pm 0.3 \pm 2.7$	$-2.88 \pm 0.09 \pm 0.23$
$h_1(1595)$	$K^* \bar{K}[S]$	$5.3 \pm 0.8 \pm 1.4$	$1.44 \pm 0.08 \pm 0.19$	$14.8 \pm 1.4 \pm 2.8$	$4.20 \pm 0.06 \pm 0.48$
$\eta_2(1645)$	$K^* \bar{K}$	$1.6 \pm 0.2 \pm 0.8$	$2.28 \pm 0.10 \pm 0.09$	$0.8 \pm 0.2 \pm 0.2$	$2.15 \pm 0.12 \pm 0.09$
PS		$18.2 \pm 2.4 \pm 2.9$	$3.13 \pm 0.09 \pm 0.15$	$25.1 \pm 2.6 \pm 5.0$	$2.85 \pm 0.07 \pm 0.16$
K_{ne}^*		$3.2 \pm 0.4 \pm 0.3$	$-0.87 \pm 0.08 \pm 0.22$	$2.0 \pm 0.3 \pm 0.3$	$-1.36 \pm 0.08 \pm 0.16$
K_{ch}^*		$8.4 \pm 0.7 \pm 0.9$	$-0.86 \pm 0.07 \pm 0.19$	$2.8 \pm 0.4 \pm 1.0$	$-0.82 \pm 0.07 \pm 0.10$
Sum		$118.0 \pm 4.3 \pm 6.2$	–	$135.5 \pm 4.6 \pm 9.7$	–

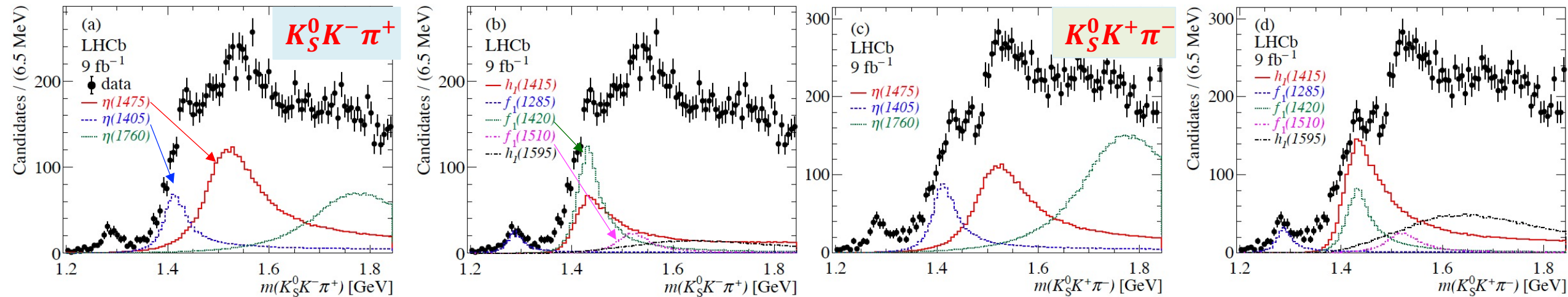
For the two channels

- $J^{PC} = 0^{-+}, 1^{++} K^* K$ contributions are in similar phase.
- $J^{PC} = 1^{+-} K^* K$ contributions are shifted by $\approx \pi$
- These phase differences are responsible for the observed “inversion” of the Dalitz plots

Partial waves contributions

[PRD 111 (2025) 092009]

- Significant 0^{-+} signal has been established, comprising $\eta(1405)$, $\eta(1475)$ and $\eta(1760)$.
- The concurrent observation of these states in both J/ψ radiative decays [*BESIII, JHEP 03 (2023) 121*] and B^+ decays implies potential commonalities in their production mechanisms.
- Presence of $f_1(1420)$ and $f_1(1510)$, both with $I = 0, J^{PC} = 1^{++}$ challenges their physical interpretation, as they both compete for identification as the $s\bar{s}$ member of the axial-vector nonet

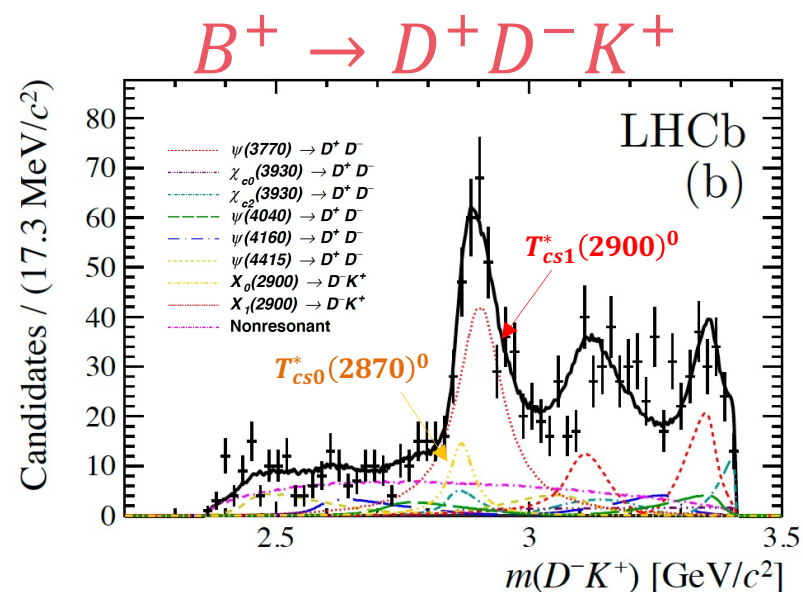
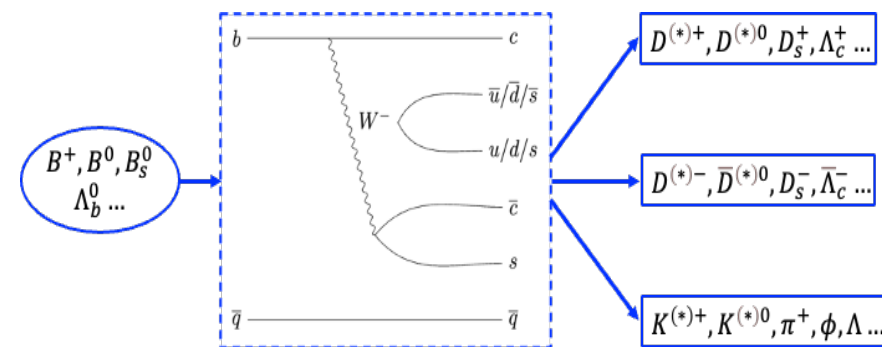


Normal and exotic hadrons in

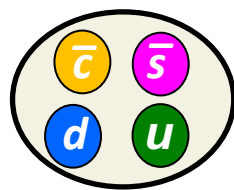
$$B \rightarrow D\bar{D}h(h')$$

Why $B \rightarrow D\bar{D}h(h')$ decays

- Rich opportunities for spectroscopy studies
 - Charmonium(-like) states in $D^{(*)}\bar{D}^{(*)}, \Lambda_c^+\bar{D}^{(*)}, \Lambda_c^+\bar{\Lambda}_c^- \dots$
 - Excited charm states from $D^{(*)}h, \Lambda_c^+h \dots$
 - Open-flavour exotic states from $\bar{D}^{(*)}h, \bar{\Lambda}_c^-h \dots$
- LHCb previous results

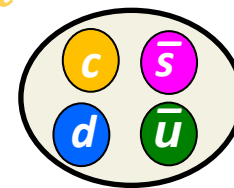
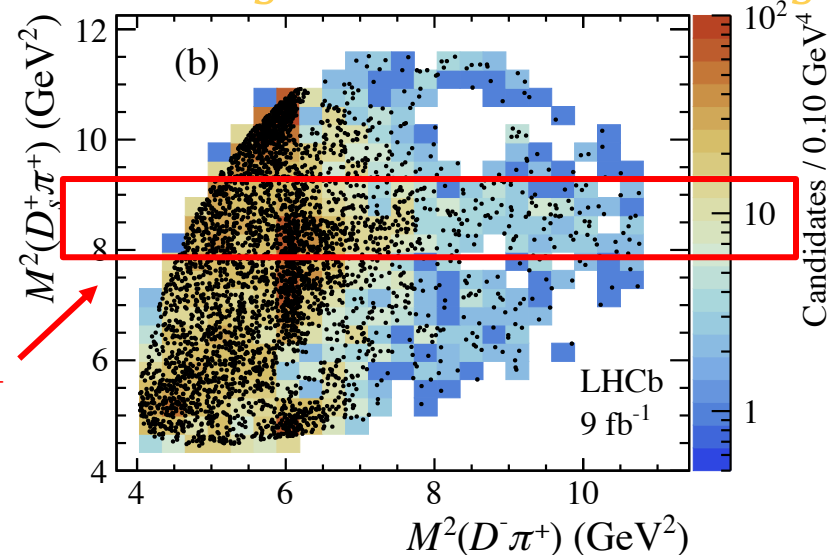


[PRL 125 (2020) 242001]
[PRD 102 (2020) 112003]



$T_{cs0}^*(2900)^0 \rightarrow D_s^+ \pi^-$
 $T_{cs0}^*(2900)^{++} \rightarrow D_s^+ \pi^+$

$B^+ \rightarrow D^- D_s^+ \pi^+$ $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$



[PRL 131 (2023) 041902]

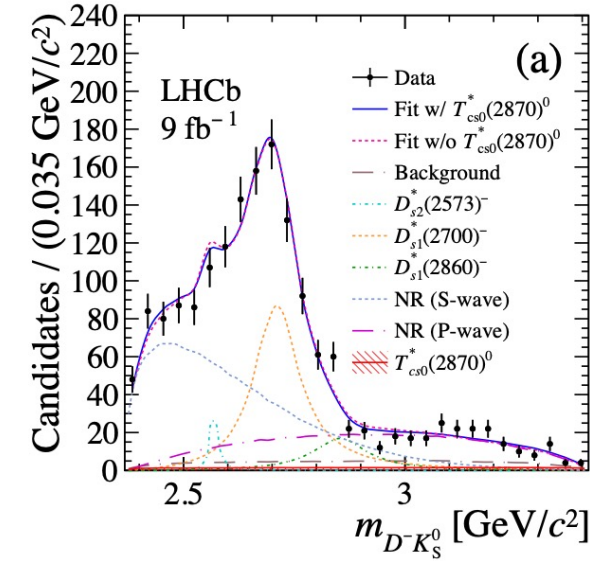
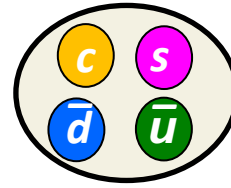
$B^- \rightarrow D^- D^0 \bar{K}^0: T_{cs0}^*(2870)^0$ new decay mode

[PRL 134 (2025) 101901]

- Amplitude analysis of $B^- \rightarrow D^- D^0 K_S^0$ finding $T_{cs0}^*(2870)^0$, but not $T_{cs1}^*(2900)^0$ to $D^0 K_S^0$

- $T_{cs0}^*(2870)^0$

- Significance of 5.3σ
- $m = 2883 \pm 11 \pm 8 \text{ MeV}$
- $\Gamma = 87^{+22}_{-47} \pm 17 \text{ MeV}$

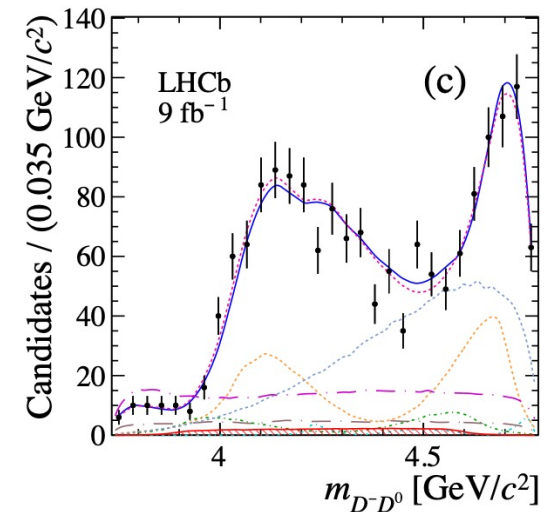
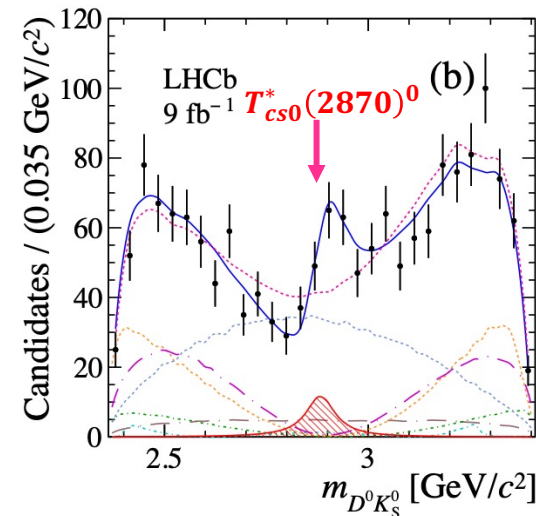


- Branching fraction ratio

$$\frac{T_{cs0}^*(2870)^0 \rightarrow D^0 \bar{K}^0}{T_{cs0}^*(2870)^0 \rightarrow D^+ K^-} = 3.3 \pm 1.1 \pm 1.1 \pm 1.1$$

$$\frac{T_{cs1}^*(2900)^0 \rightarrow D^0 \bar{K}^0}{T_{cs1}^*(2900)^0 \rightarrow D^+ K^-} = 0.15 \pm 0.15 \pm 0.05 \pm 0.05$$

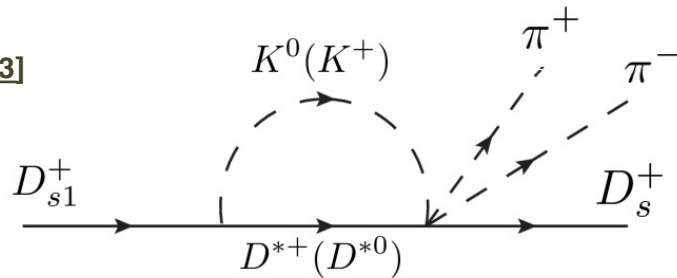
Isospin symmetry: two ratio should be 1



$D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decays

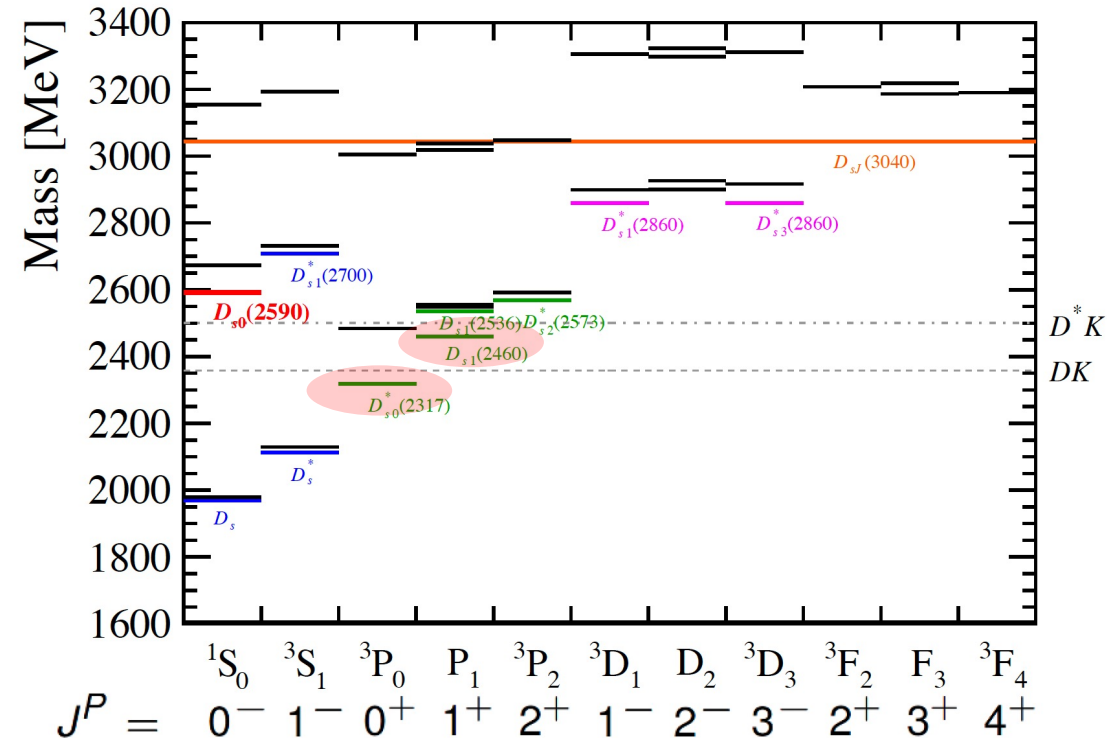
- $D_{s0}^*(2317)$ and $D_{s1}(2460)$ are very special
 - Masses ~ 100 MeV below expectation
 - Isospin-violating decay $D_s^{(*)+} \pi^0$ dominate
- Propose to study of $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$
 - Double-bump lineshape in $m(\pi\pi)$ if $D_{s1}(2460)^+$ is a D^*K hadronic molecule

[Tang et. al.
Commun. Theor. Phys. 75 055203]

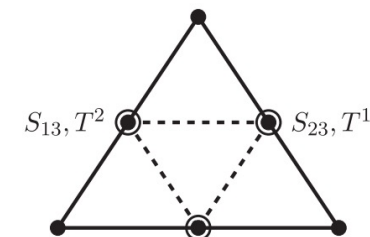


- $I=1$ partners of $D_{s0}^*(2317)$ are proposed
 - Inspired by observation of $I=1$ tetraquark $T_{c\bar{s}}(2900)^{++/0} \rightarrow D_s^+ \pi^\pm$

[PRL 131 (2023) 041902]



$S_{33}(2335 \pm 100) \rightarrow \bar{D}^0 K^0, K^+ K^0 \pi^-$ (weak decay)



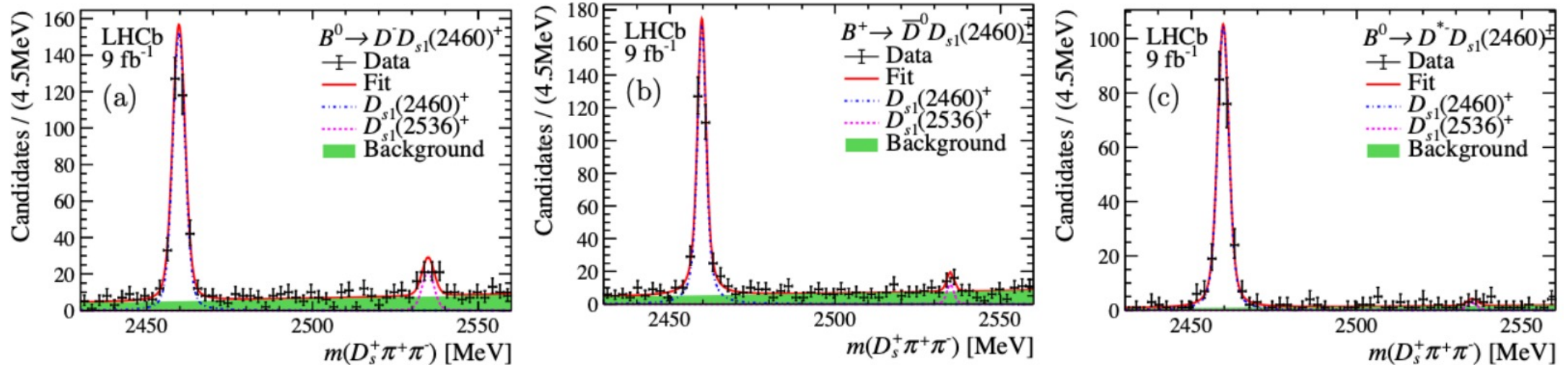
[L. Maiani et. al.
Phys. Rev. D 110, 034014]

$S_{11}(2367 \pm 10) \rightarrow \bar{D}_s^- \pi^-$ or $\bar{D}^- K^-$ $D_{s0}^-(2317)$ + second state $S_{22}(2367 \pm 10) \rightarrow \bar{D}_s^- \pi^+$ or $\bar{D}^0 \bar{K}^0$

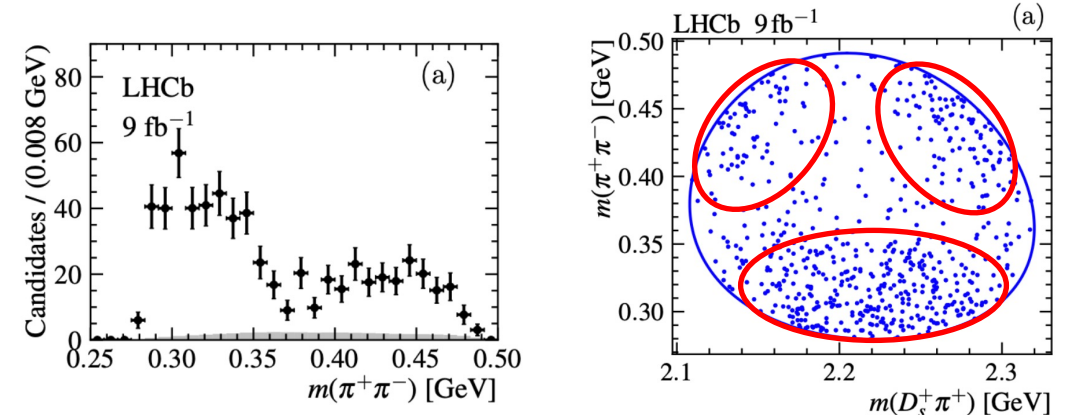
$D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decays

[Sci. Bull. 70 (2025) 1432–1444]

- $\sim 800 D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ from three $B \rightarrow D_{s1}(2460)^+ \bar{D}^{(*)}$ decays



- Double-bump structure in $m(\pi\pi)$
- Amplitude analysis performed
 - $f_0(500) + f_0(980)$ and $\pi\pi$ K-matrix cannot describe the data well
 - The model in paper also cannot describe the data well



[Tang et. al.
Commun. Theor. Phys. 75 055203]

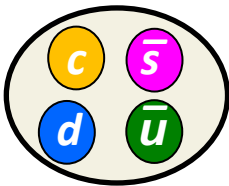
Two resonance models can fit the data well

[Sci. Bull. 70 (2025) 1432–1444]

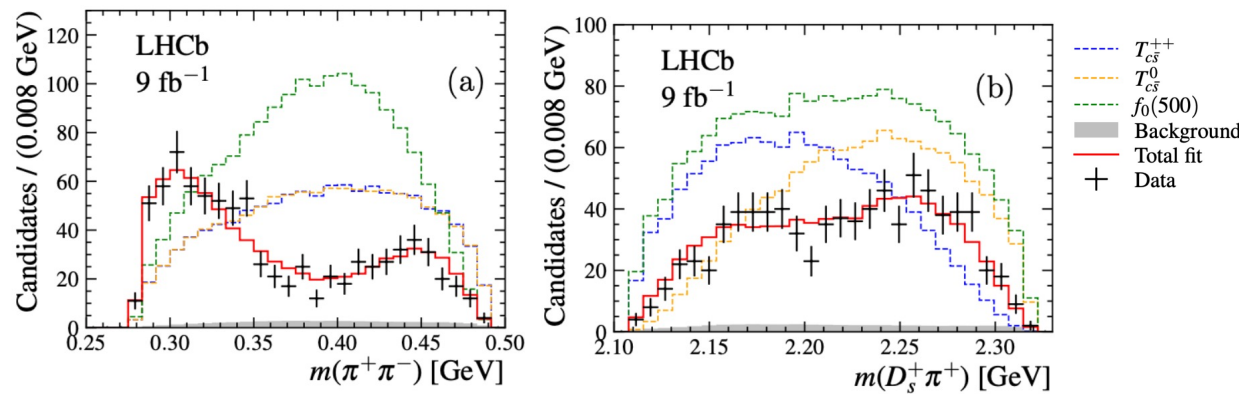
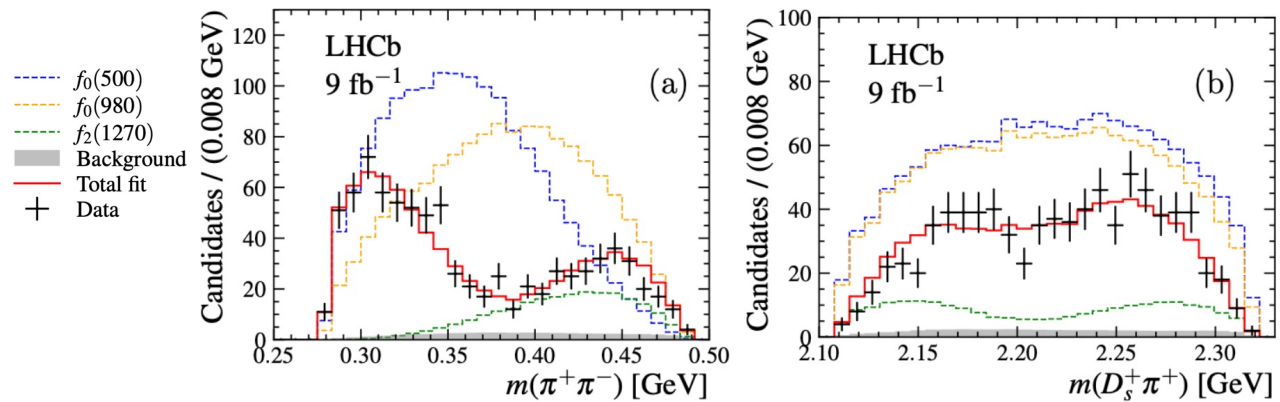
- $f_0(500) + f_0(980) + f_2(1270)$
 - Large contribution from $f_0(980)$ and $f_2(1270)$ above PHSP of $m(\pi\pi)$
 - This model cannot be rejected, but **implausible**

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$376 \pm 9 \pm 16$	$175 \pm 23 \pm 16$	$197 \pm 35 \pm 23$
$f_0(980)$	945.5	167	$187 \pm 38 \pm 43$
$f_2(1270)$	1275.4	186.6	$29 \pm 2 \pm 1$

- $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^0$ (new exotics)



Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$474 \pm 30 \pm 18$	$224 \pm 23 \pm 16$	$248^{+40}_{-54} \pm 39$
$T_{c\bar{s}}$	$2327 \pm 13 \pm 13$	$96 \pm 16 \pm 23$	$156^{+27}_{-38} \pm 25$



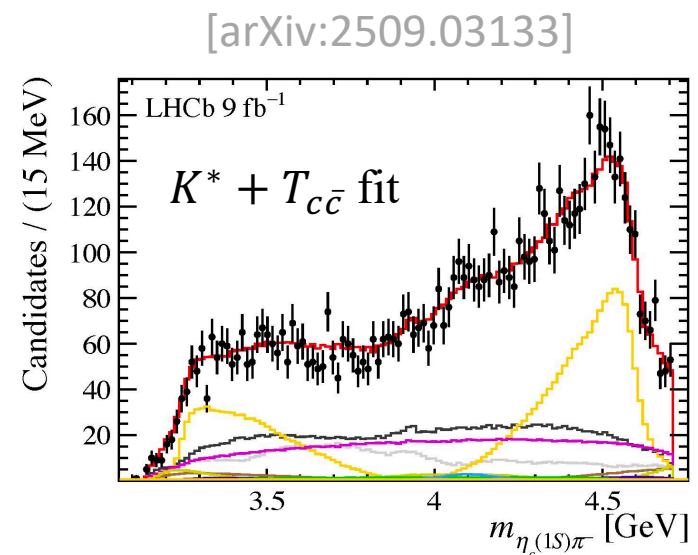
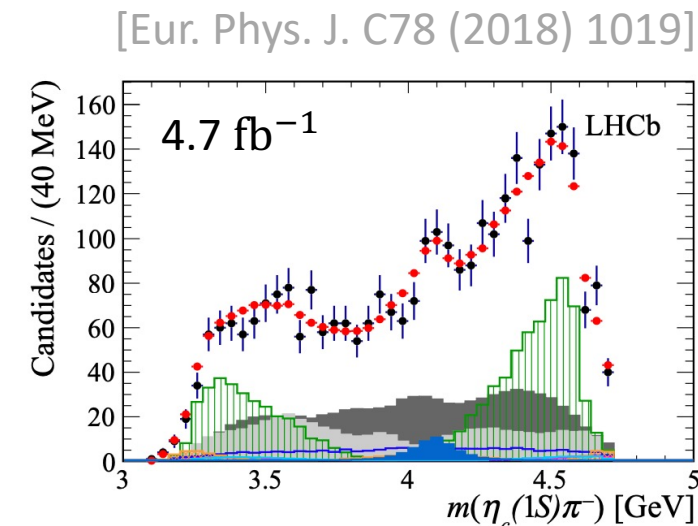
One charmonium(like) study

Amplitude analysis of $B^0 \rightarrow \eta_c K^+ \pi^-$

- An evidence of $T_{c\bar{c}}(4100)^- \rightarrow \eta_c \pi^-$ was reported by LHCb with 4.7 fb^{-1} data (3.4σ)
- Update with full 9 fb^{-1} data
- 5000 signal yields (~ 2.5 of previous publication)
- Amplitude results:

- 3.6σ (2.5σ) significance without (with) systematic uncertainties
- $J^P = 0^+$ disfavoured by 3.2σ compared to 1^- (stat. only)
- $m(T_{c\bar{c}}) = 4106 \pm 23 \text{ MeV}$
- $\Gamma(T_{c\bar{c}}) = 514 \pm 166 \text{ MeV}$

- **$T_{c\bar{c}}(4100)^-$ is not confirmed**

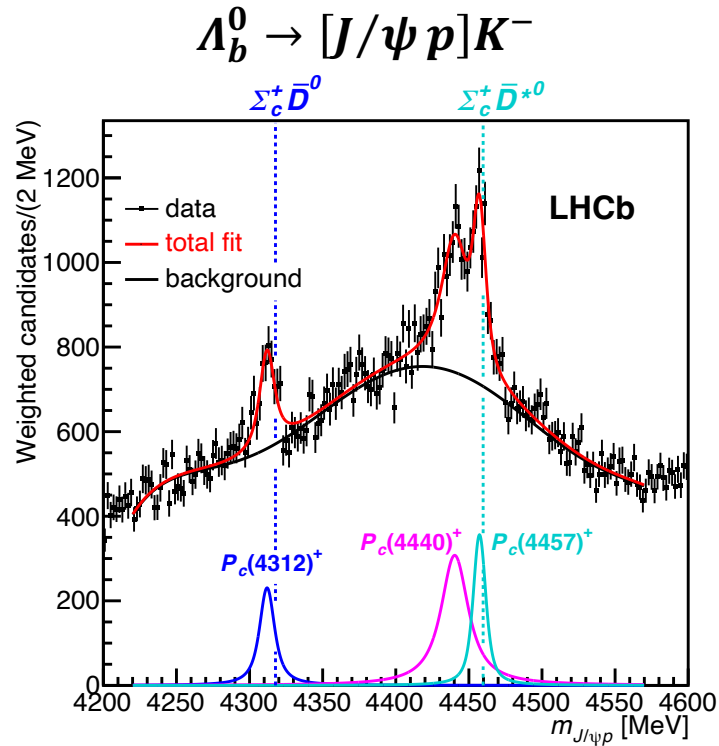


Pentaquark-related studies

Pentaquark study

[PRL 122 (2019) 222001]

- Pentaquark candidates are first observed in 2015, a refined result is presented

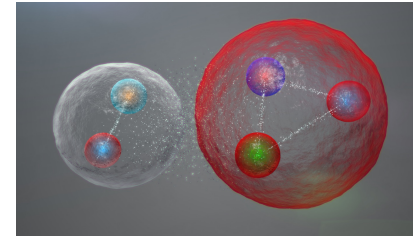


Proximity of $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

Three narrow structures observed in $m(J/\psi p)$

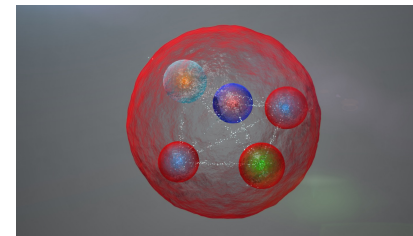
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm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

Hadron molecule



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

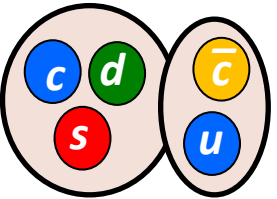
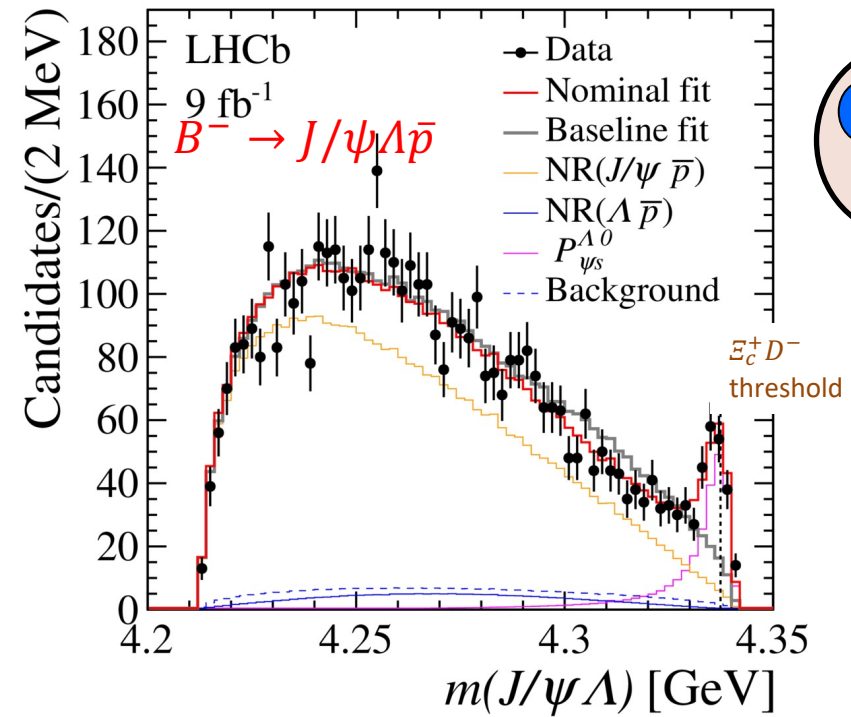
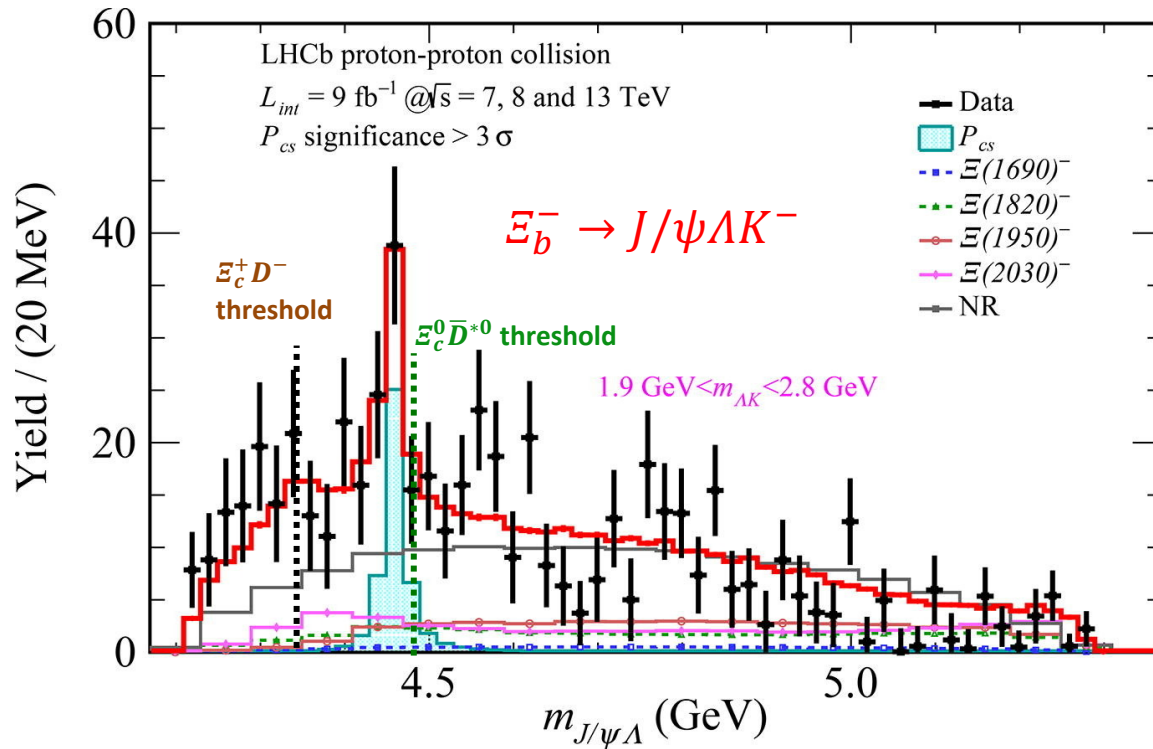
Compact multiquark



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

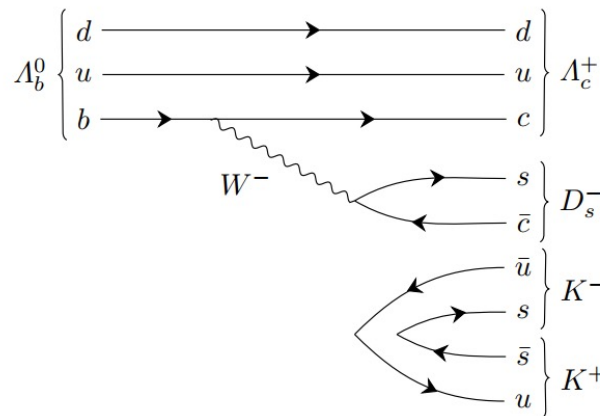
$P_{c\bar{c}s} \rightarrow J/\psi \Lambda$

State	M_0 [MeV]	Γ [MeV]	Significance	Threshold	Ref.
$P_{c\bar{c}s}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	3.1σ	$\bar{E}_c \bar{D}^*$	Science Bulletin 66 (2021) 1278
$P_{c\bar{c}s}(4338)^0$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$	15σ	$\bar{E}_c \bar{D}$	PRL 131 (2023) 031901

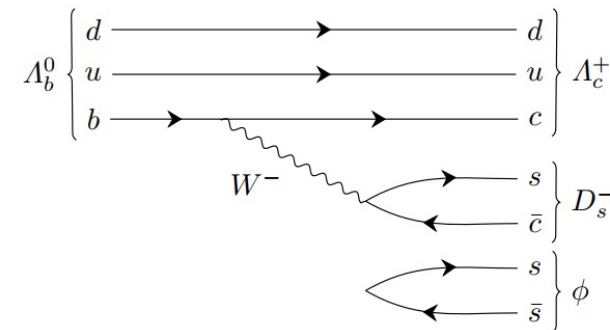


Observation of $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-$ decays [arXiv: 2507.10713]

- Can $P_{c\bar{c}s}$ decay into $\Lambda_c^+ D_s^-$



(a) The nonresonant $K^+ K^-$ process

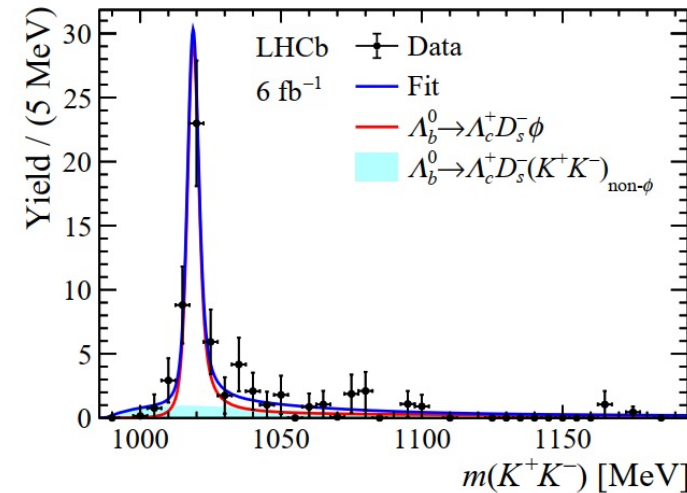
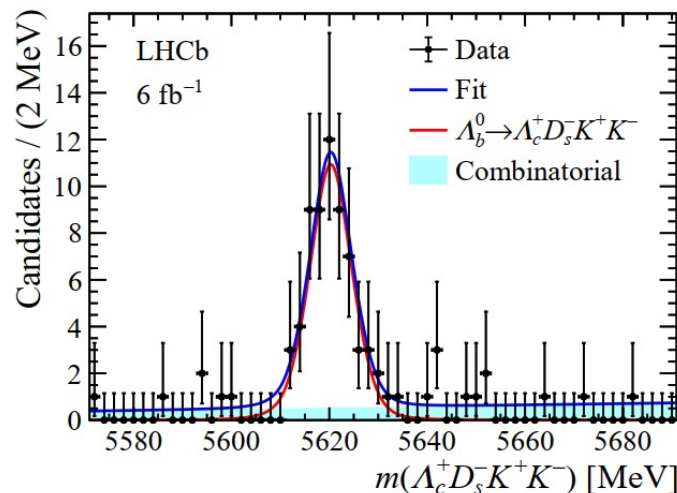


(b) The ϕ -dominated process

- Cut & MVA based selection

- $61 \pm 8 \Lambda_b^0$ decays
- Dominated by $\phi \rightarrow K^+ K^-$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = 0.0141 \pm 0.0019 \pm 0.0012$$



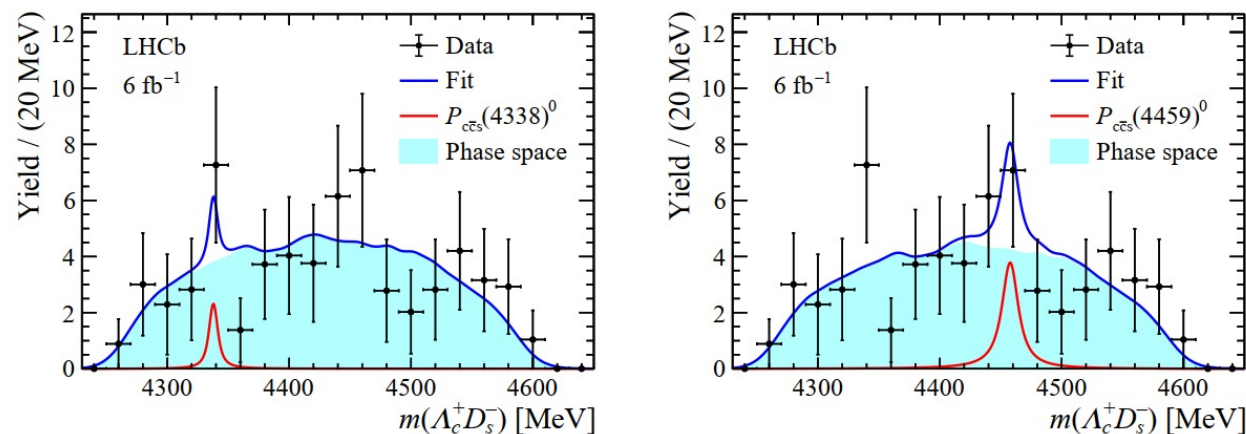
Search for pentaquarks in $\Lambda_c^+ D_s^-$ mass

[arXiv: 2507.10713]

- $P_{c\bar{c}s}$ contributions (fit fractions) derived from fit to background-subtracted data

$$\mathcal{R}_{P_{c\bar{c}s}^0} \equiv \frac{\mathcal{B}(\Lambda_b^0 \rightarrow P_{c\bar{c}s} K^+ K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-)} \cdot \mathcal{B}(P_{c\bar{c}s}^0 \rightarrow \Lambda_c^+ D_s^-)$$

- Widths and masses are Gaussian constrained to their known values



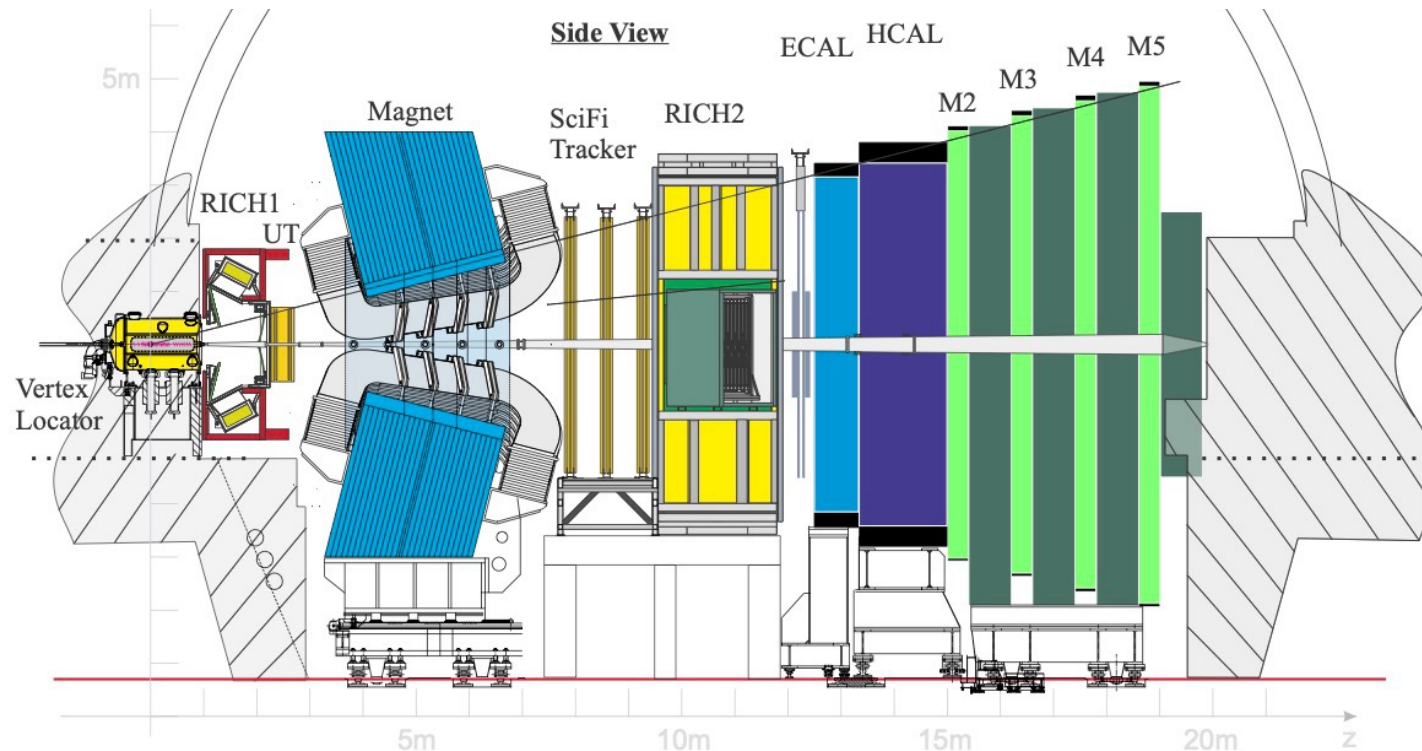
- Upper limits on 90% (95%) CLs:

$$\mathcal{R}_{P_{c\bar{c}s}(4338)^0} < 0.10 \text{ (0.12)} \quad \text{and} \quad \mathcal{R}_{P_{c\bar{c}s}(4459)^0} < 0.17 \text{ (0.20)}$$

Summary

- LHCb keeps making important contributions to heavy hadron spectroscopy with run1 and run2 data
- Run 3 has taken 20 fb^{-1} data with upgraded new detector, about doubled the luminosity of run1&2
- Stay tuned for more exciting results

JINST 19 (2024) P05065



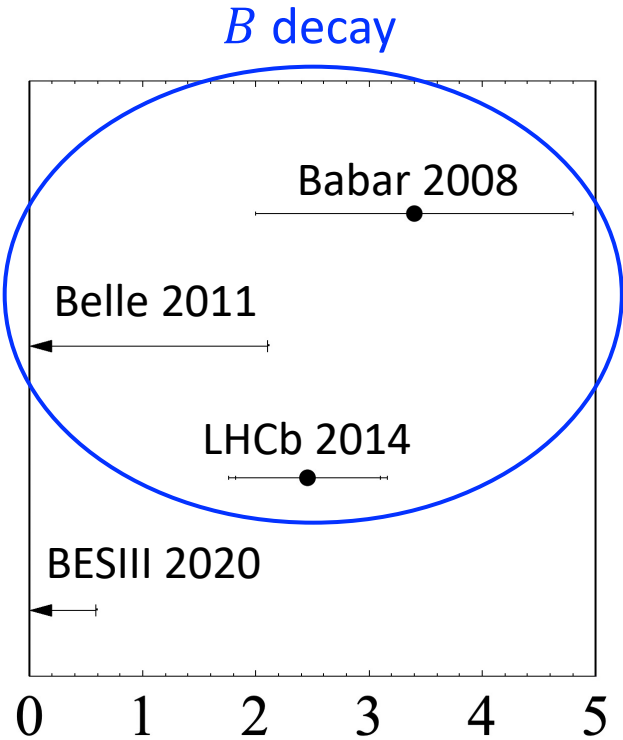
BACKUP

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

[arXiv: 2406.17006]

- Nature of $\chi_{c1}(3872)$ still under debate, while study of radiative decays provides a way to probe it
- Only evidence of $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ was seen experimentally before

Reference	$\mathcal{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872) \rightarrow \psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872) \rightarrow J/\psi\gamma}}$		
T. Barnes and S. Godfrey	67	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	69	2.6	$c\bar{c}$
F. De Fazio	84	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	85	1.3	$c\bar{c}$
Y. Dong <i>et al.</i>	86	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian <i>et al.</i>	87	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto	88	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker	89	2.4	$c\bar{c}$
W. J. Deng <i>et al.</i>	90	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito	71	5.4	$c\bar{c}/\psi c$
E. S. Swanson	81	0.38 %	$D\bar{D}^*$
Y. Dong <i>et al.</i>	86	0.33 %	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai	91	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	92	0.33 %	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	93	3.6 %	$D\bar{D}^*$
F.-K. Guo <i>et al.</i>	82	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	83	$2 - 10$	$D\bar{D}^*$
E. Cincioglu <i>et al.</i>	94	< 4	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu	95	$1.1 - 3.4$	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	93	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$



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

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

[arXiv: 2406.17006]

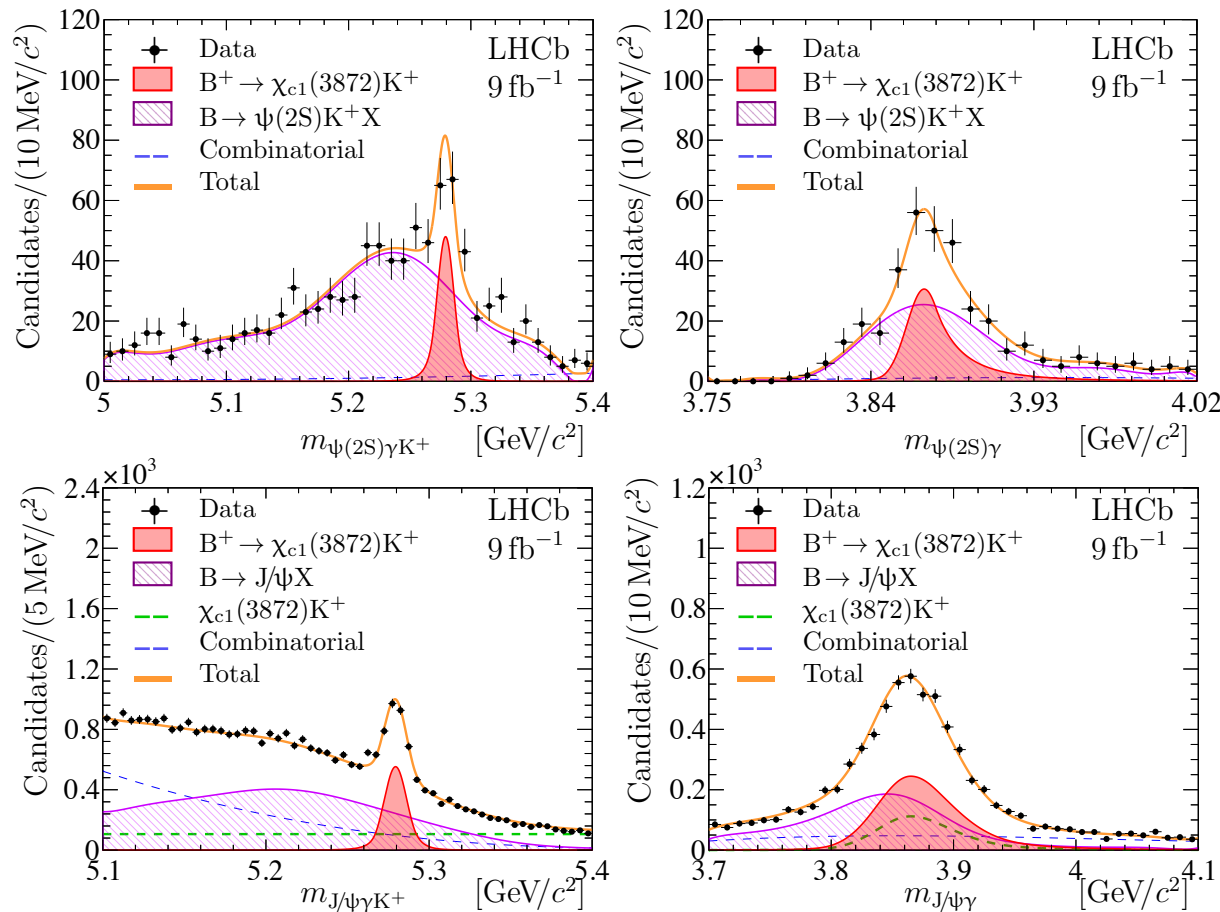
- Update at LHCb using $B^+ \rightarrow \chi_{c1}(3872)K^+$ decay with 9 fb^{-1} Run1+Run2 data

[LHCb meets theory workshop](#)

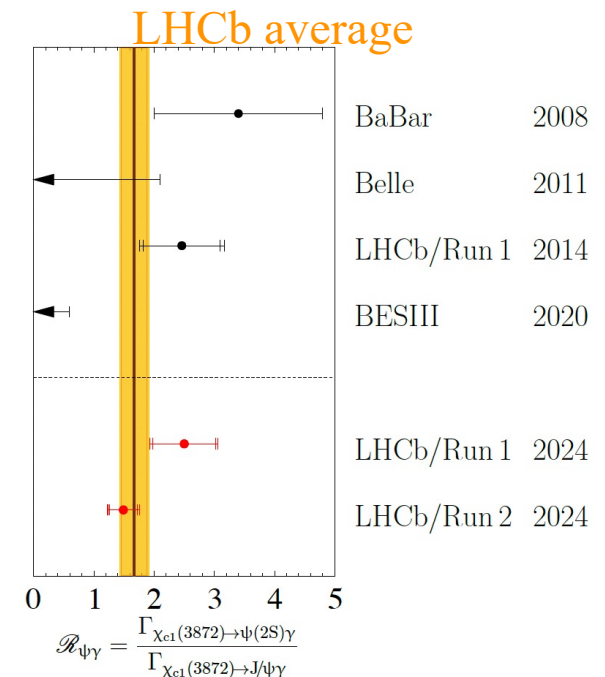
$$\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$$

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

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



$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \quad (15\%)$$



$B^+ \rightarrow D^{*\pm} D^{\mp} K^+$: amplitude analysis

- Amplitudes of $B^+ \rightarrow R(D^{*+} D^-) K^+$ and $B^+ \rightarrow R(D^+ D^{*-}) K^+$ linked by **C-parity**
 $\Rightarrow$ allowing determination of C-parities of R resonances

$$\mathcal{A}(x) = \frac{1+d}{2} \left\{ \sum_{j \in R(D^{*\pm} D^{\mp})} c_j A_j(x) + \sum_{k \in R(D^{*-} K^+, D^+ K^+)} c_k A_k(x) \right\} \quad \leftarrow B^+ \rightarrow D^+ D^{*-} K^+$$

$$+ \frac{1-d}{2} \left\{ \sum_{j \in R(D^{*\pm} D^{\mp})} C_j \times c_j A_j(x) + \sum_{l \in R(D^{*+} K^+, D^- K^+)} c_l A_l(x) \right\} \quad \leftarrow B^+ \rightarrow D^{*+} D^- K^+$$

✓ $d = 1$ for $B^+ \rightarrow D^+ D^{*-} K^+$; $d = -1$ for $B^+ \rightarrow D^{*+} D^- K^+$

□ R resonances with $J^P = 1^+$: S -wave & D -wave

$$f_{R,S/D}(m) = \frac{\gamma_{S/D}}{m_0^2 - m^2 - im_0[\gamma_S^2 \Gamma_S(m) + \gamma_D^2 \Gamma_D(m)]}$$

□ Other resonances: Breit-Wigner

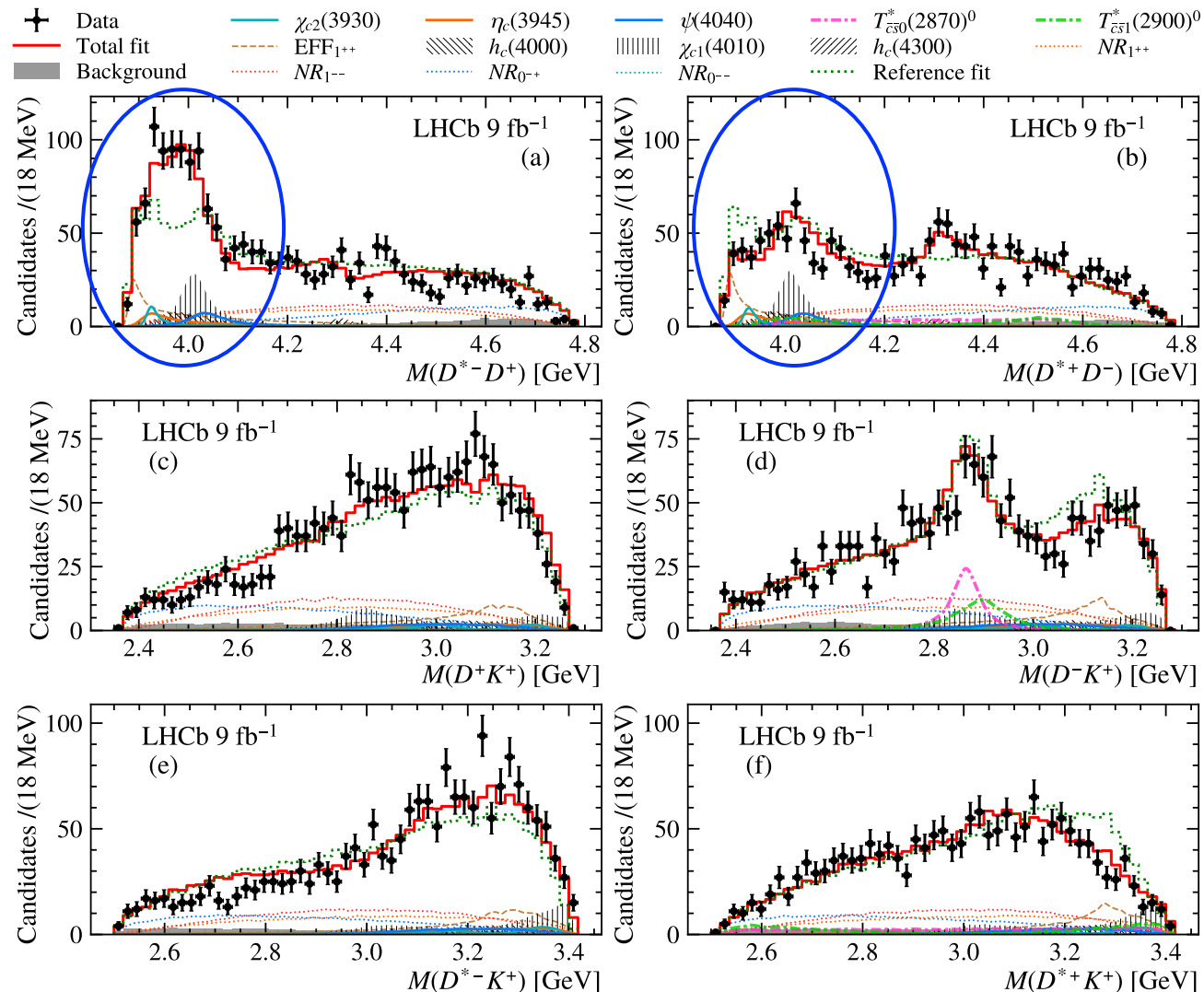
□ Nonresonant contributions to $D^{*\pm} D^{\mp}$:

$$f_R(m) = e^{(\alpha+\beta i)(m^2-m_0^2)} \text{ for } NR_{0-+}; \text{ otherwise } f_R(m) = 1$$

$B^+ \rightarrow D^{*\pm} D^{\mp} K^+$: fit results

[PRL 133 (2024) 131902]

- All components in baseline fit have significance $> 5\sigma$



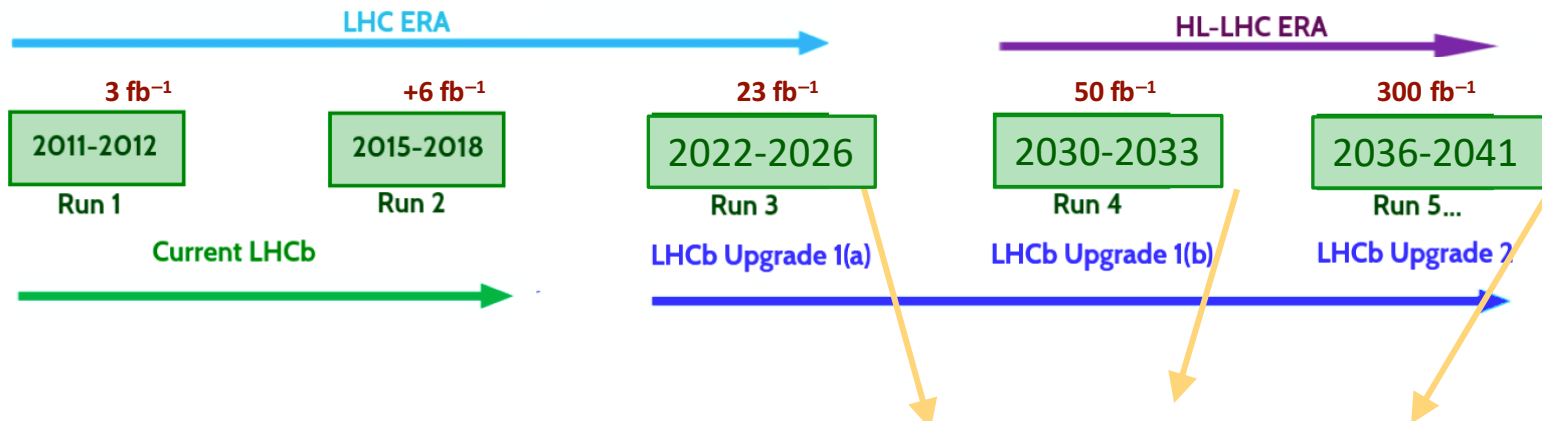
Component	$J^{P(C)}$
EFF ₁₊₊	1^{++}
$\eta_c(3945)$	0^{-+}
$\chi_{c2}(3930)^{\dagger}$	2^{++}
$h_c(4000)$	1^{+-}
$\chi_{c1}(4010)$	1^{++}
$\psi(4040)^{\dagger}$	1^{--}
$h_c(4300)$	1^{+-}
$T_{\bar{c}s0}^{*}(2870)^{0\dagger}$	0^{+}
$T_{\bar{c}s1}^{*}(2900)^{0\dagger}$	1^{-}
NR ₁₋₋ ($D^{*\mp}D^{\pm}$)	1^{--}
NR ₀₋₋ ($D^{*\mp}D^{\pm}$)	0^{--}
NR ₁₊₊ ($D^{*\mp}D^{\pm}$)	1^{++}
NR ₀₊₋ ($D^{*\mp}D^{\pm}$)	0^{-+}

*Fit fractions in paper

✓ clear different interference behaviors

Prospects

[arXiv:1808.08865]



LHCb is now boosting the data to a new level

- Expect to **3x** data (**5x hadronic events**) by 2026
- Opportunity for decays with hadronic final state, such as $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^+$

Decay mode	LHCb		
	23 fb ⁻¹	50 fb ⁻¹	300 fb ⁻¹
$B^+ \rightarrow X(3872)(\rightarrow J/\psi \pi^+ \pi^-) K^+$	14k	30k	180k
$B^+ \rightarrow X(3872)(\rightarrow \psi(2S) \gamma) K^+$	500	1k	7k
$B^0 \rightarrow \psi(2S) K^- \pi^+$	340k	700k	4M
$B_c^+ \rightarrow D_s^+ D^0 \bar{D}^0$	10	20	100
$\Lambda_b^0 \rightarrow J/\psi p K^-$ [*]	680k	1.4M	8M
$\Xi_b^- \rightarrow J/\psi \Lambda K^-$	4k	10k	55k
$\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^+$	23k	58k	390k

$\chi_{c1}(3872)$ lineshape from multi-channels

$Z_c(4430)$

Doubly-charmed tetraquark $\mathcal{T}_{cc\bar{s}}^+ \rightarrow D_s^+ D^0$

More information for pentaquarks

[*] updated according to the latest result

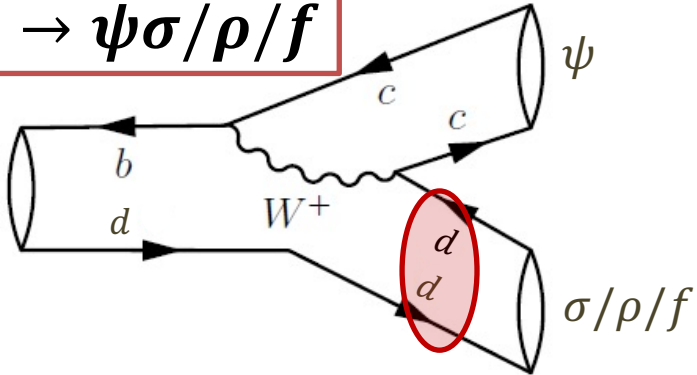
Light-hadron spectroscopy at LHCb

■ Amplitude analysis

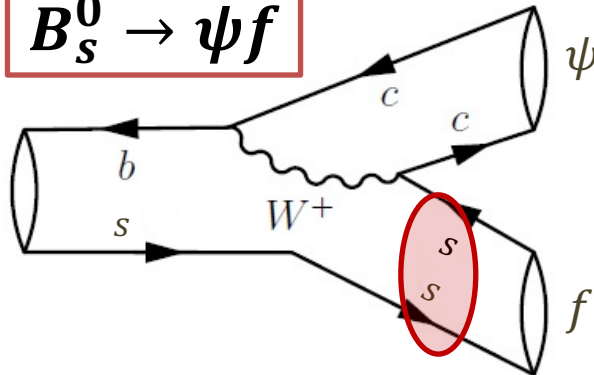
- Direct production of light hadrons obviously happens but the multiplicity of tracks is so large that they are covered by large background
- Rather study resonances in heavy flavored particle decays (D, B_(s)-hadrons)
- B_(s)-decays select pure quark-contents of the light hadron

Non-Strange production

$$B^0 \rightarrow \psi \sigma / \rho / f$$

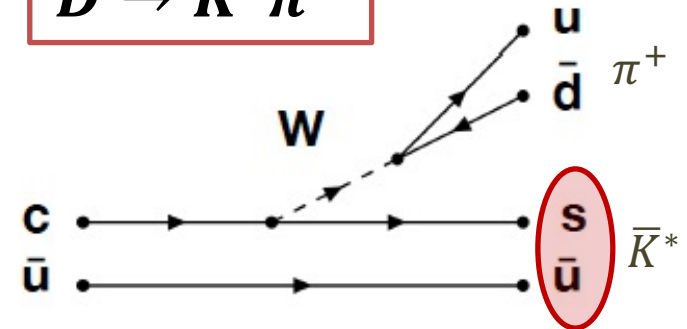


$$B_s^0 \rightarrow \psi f$$

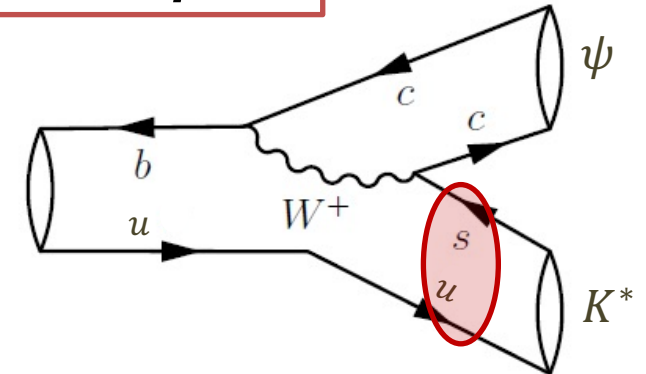


Strange production

$$D \rightarrow \bar{K}^* \pi^+$$



$$B \rightarrow \psi K^*$$



Non-Strange Mesons

Early works on non-strange light mesons

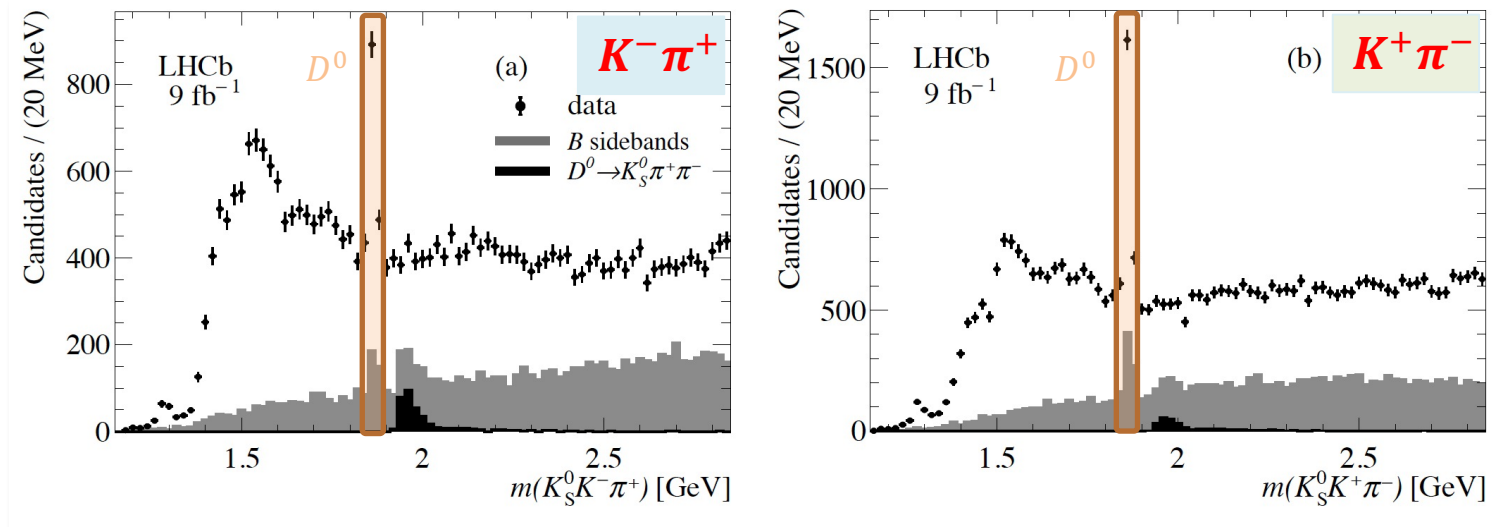
- ❑ LHCb, "Resonances and CP violation in B_s^0 and $\bar{B}_s^0 \rightarrow J/\psi K^+ K^-$ decays in the mass region above the $\phi(1020)$ ", [*JHEP* 08 \(2017\) 037](#).
- ❑ LHCb, "Measurement of the resonant and CP components in $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays", [*PRD* 90 \(2014\) 012003](#).
- ❑ LHCb, "Measurement of resonant and CP components in $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ decays", [*PRD* 89 \(2014\) 092006](#).
- ❑ LHCb, "Observation of $B_{(s)}^0 \rightarrow J/\psi f_1(1285)$ decays and measurement of the $f_1(1285)$ mixing angle", [*PRL* 112 \(2014\) 091802](#).
- ❑ Sheldon Stone and Liming Zhang, "Use of $B \rightarrow J/\psi f_0$ decays to discern the $q\bar{q}$ or tetraquark nature of scalar mesons", [*PRL* 111 \(2013\) 062001](#).
- ❑ LHCb, "Amplitude analysis and branching fraction measurement of $B_s^0 \rightarrow J/\psi K^+ K^-$ ", [*PRD* 87 \(2013\) 072004](#).
- ❑ LHCb, "Analysis of the resonant components in $B^0 \rightarrow J/\psi \pi^+ \pi^-$ ", [*PRD* 87 \(2013\) 052001](#).
- ❑ Liming Zhang and Sheldon Stone, "Time-dependent Dalitz-plot formalism for $B_q^0 \rightarrow J/\psi h^+ h^-$ ", [*PLB* 719 \(2013\) 383-387](#).
- ❑ LHCb, "Analysis of the resonant components in $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ ", [*PRD* 86 \(2012\) 052006](#).
- ❑ LHCb, "Observation of $B_s^0 \rightarrow J/\psi f_2'(1525)$ in $J/\psi K^+ K^-$ final states", [*PRL* 108 \(2012\) 151801](#).
- ❑ LHCb, "First observation of $B_s^0 \rightarrow J/\psi f_0(980)$ decays", [*PLB* 698 \(2011\) 115-122](#).
- ❑ S. Stone and L. Zhang "S-waves and the measurement of CP violating phases in B_s decays", [*PRD* 79 \(2009\) 074024](#).

$K_S^0 K^\pm \pi^\mp$ mass spectra

[PRD 111 (2025) 092009]

- Selection re-optimized in the $K_S^0 K^\pm \pi^\mp$ threshold region
- Event yields for $m(K_S^0 K^\pm \pi^\mp) < 1.85$ GeV

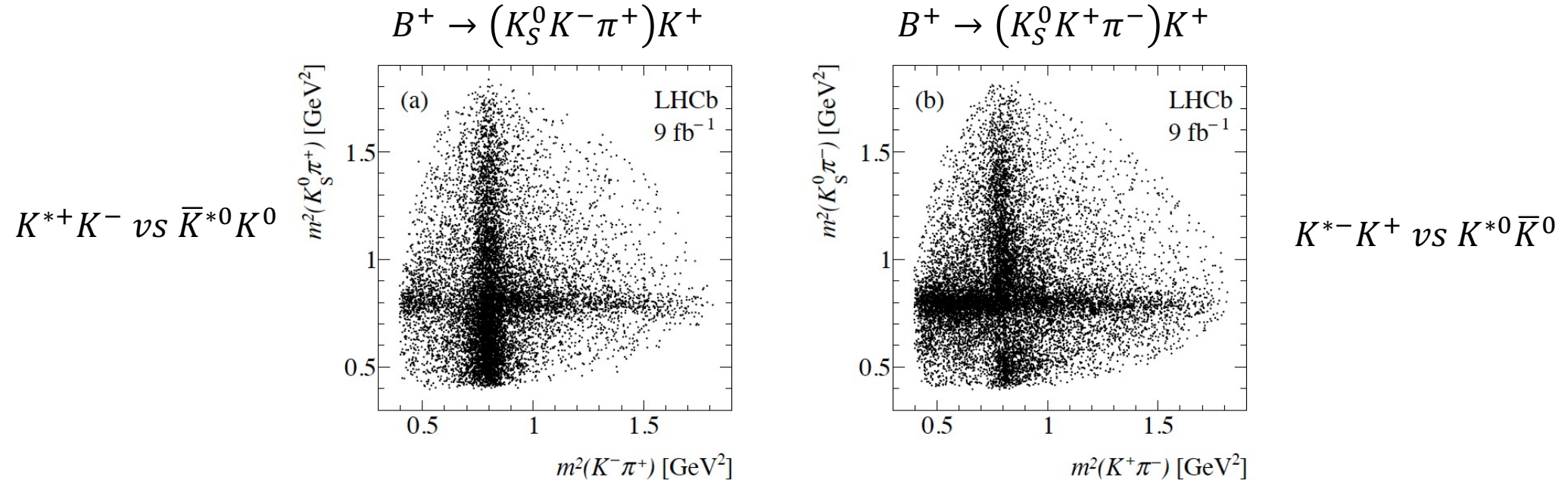
Final state	Signal Events	Background	Purity
$B^+ \rightarrow K_S^0 K^+ K^- \pi^+$	10430	1454	87.8 ± 0.3
$B^+ \rightarrow K_S^0 K^+ K^+ \pi^-$	12320	2180	85.0 ± 0.3



Comparison of two decay modes

[PRD 111 (2025) 092009]

- Dalitz plot for the two different B^+ decays for $1.3 < m(K_S^0 K^\pm \pi^\mp) < 1.85$ GeV



- Asymmetric K^{*+}/K^{*0} distributions
- The Dalitz plots for $B^+ \rightarrow (K_S^0 K^- \pi^+) K^+$ and $B^+ \rightarrow (K_S^0 K^+ \pi^-) K^+$ are different
- Neutral K^{*0} and charged K^{*+} bands are somewhat inverted

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

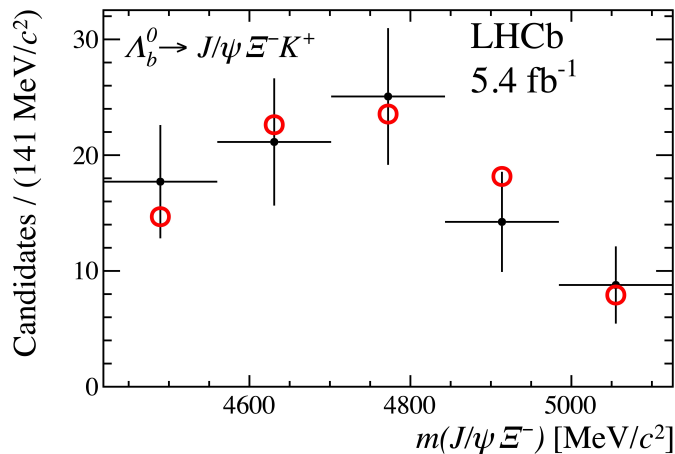
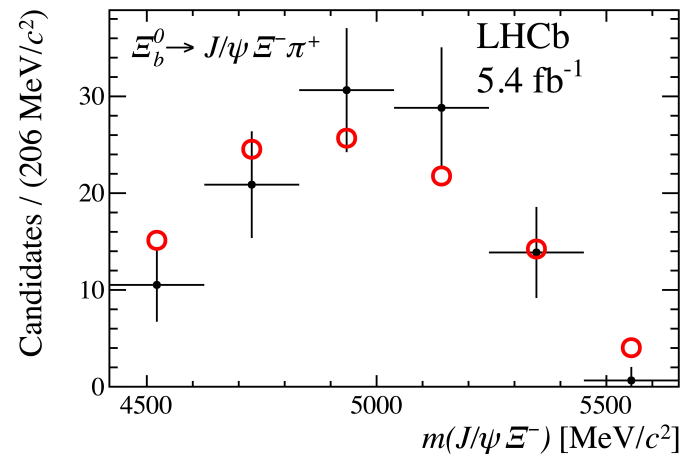
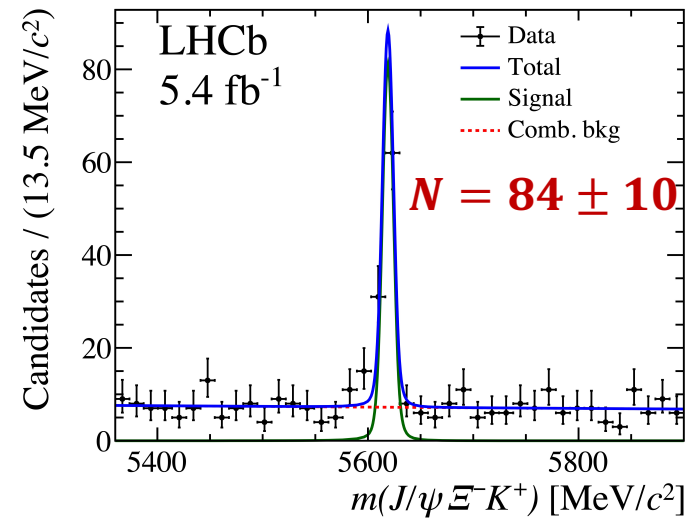
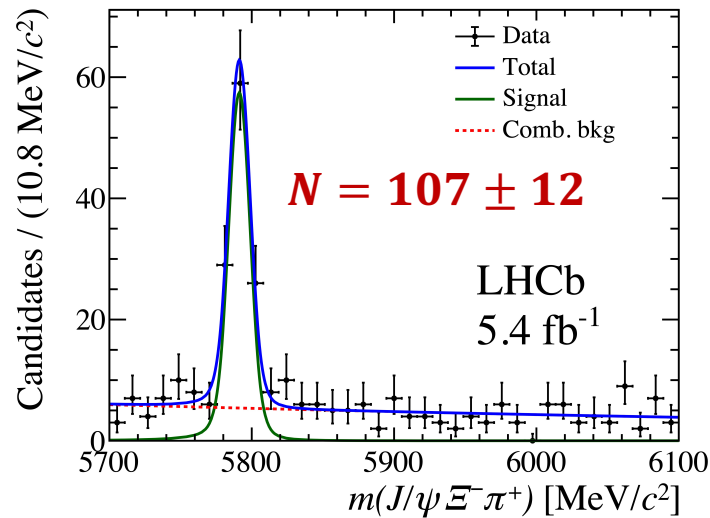
[EPJC 85 (2025) 812]

$J/\psi p \rightarrow c \bar{c} u u d$

$J/\psi \Lambda \rightarrow c \bar{c} \textcolor{red}{s} u d$

?

$J/\psi \Xi \rightarrow c \bar{c} \textcolor{red}{s} s u/d$



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

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

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

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

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

[EPJC 84 (2024) 1062]

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

- Larger statistics needed for amp. study