LHCb实验上奇特强子态的最新进展

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第十届手征有效场论研讨会

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Outline

- Introduction
- $B \to D\bar{D}h(h')$ studies
- One charmonium(like) study
- Pentaquark-related studies
- Summary

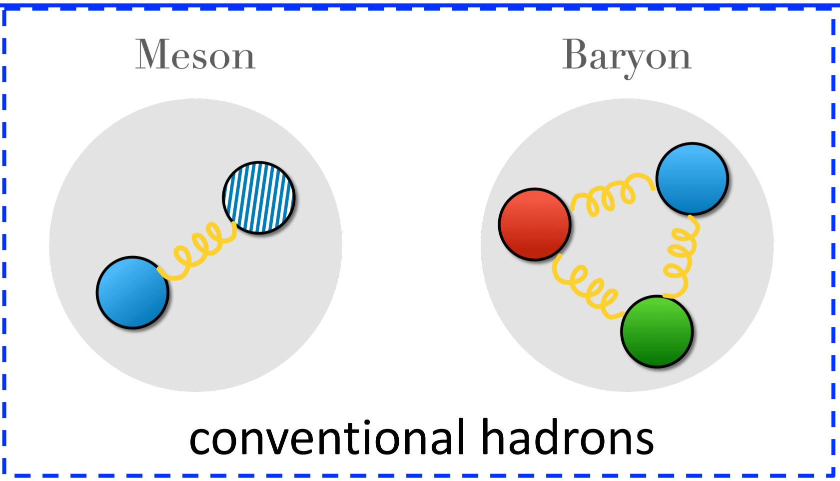
Exotic hadrons for QCD

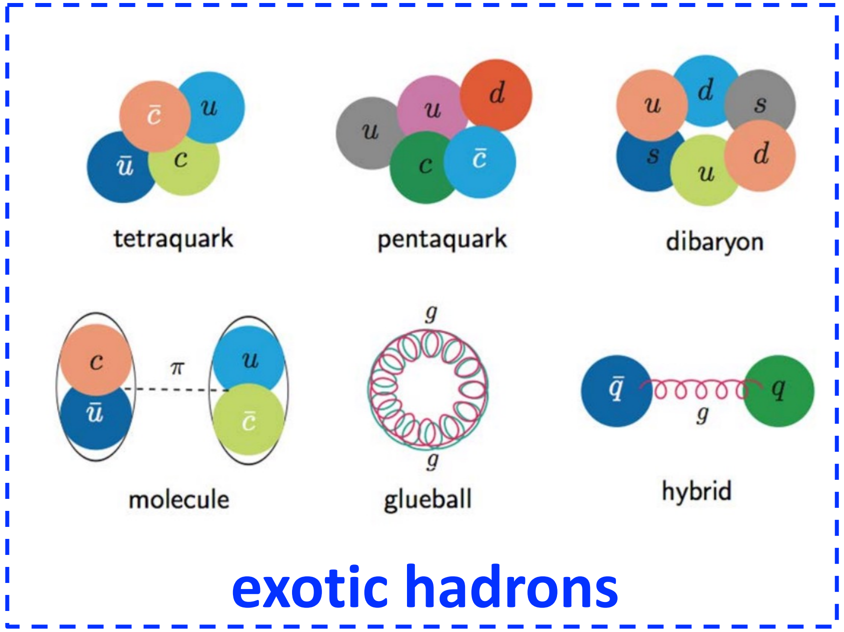
- Exotic hadrons provide a unique probe to study **color confinement** and QCD

- Experimental **signatures** of exotic hadron
  - Exotic quantum numbers for mesons

    $$\boxed{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \text{etc}}$$

  - Heavy flavour tetraquarks and pentaquarks , such as charged charmonium states

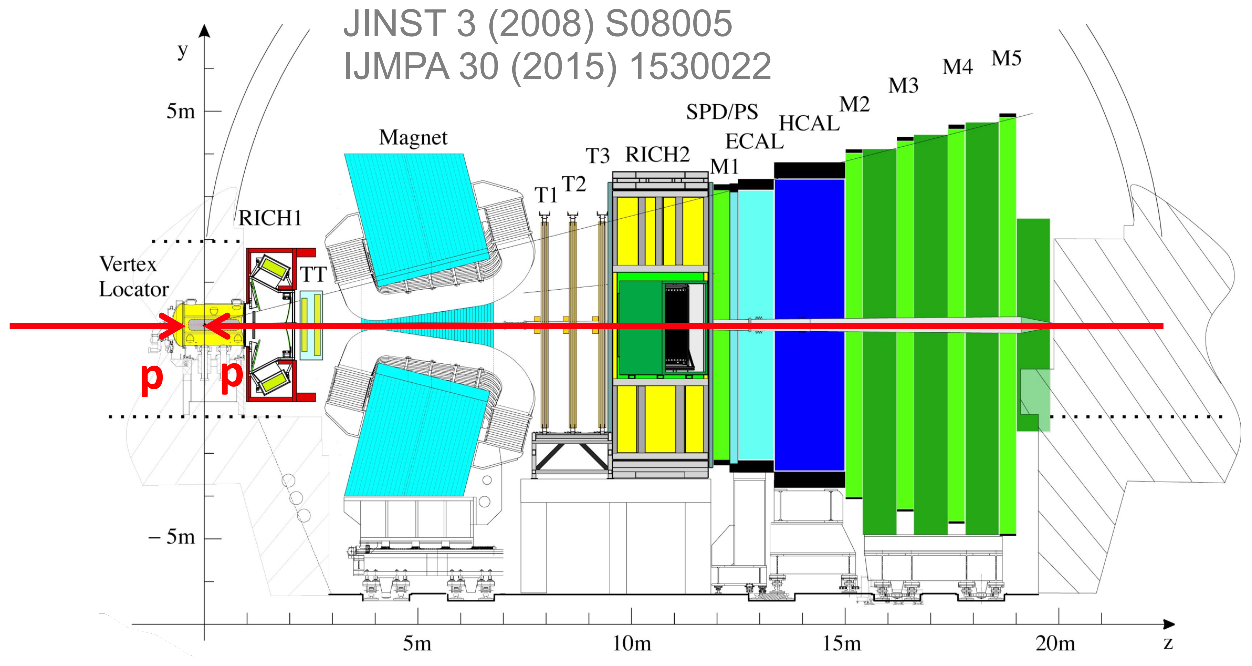


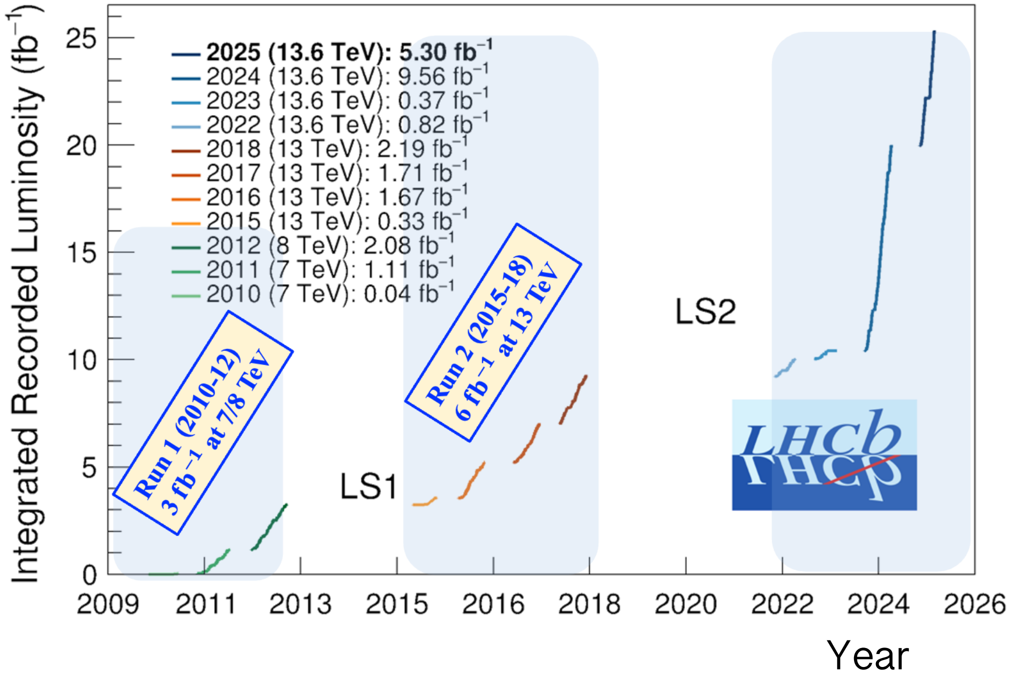


The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - $>10^4 \times$ larger b production rate than the B factories @ $\Upsilon(4S)$
  - 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



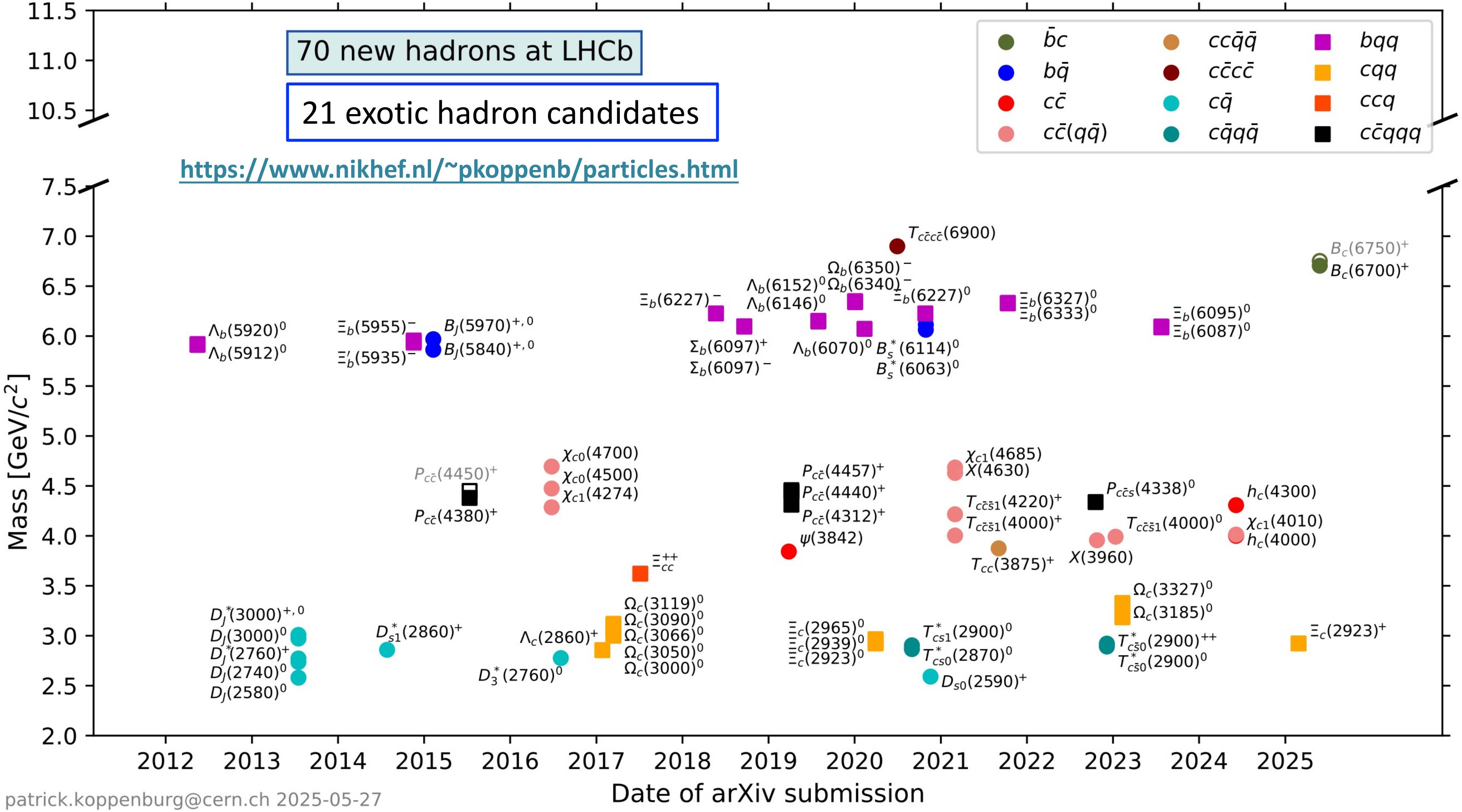


Exotic hadrons at LHCb

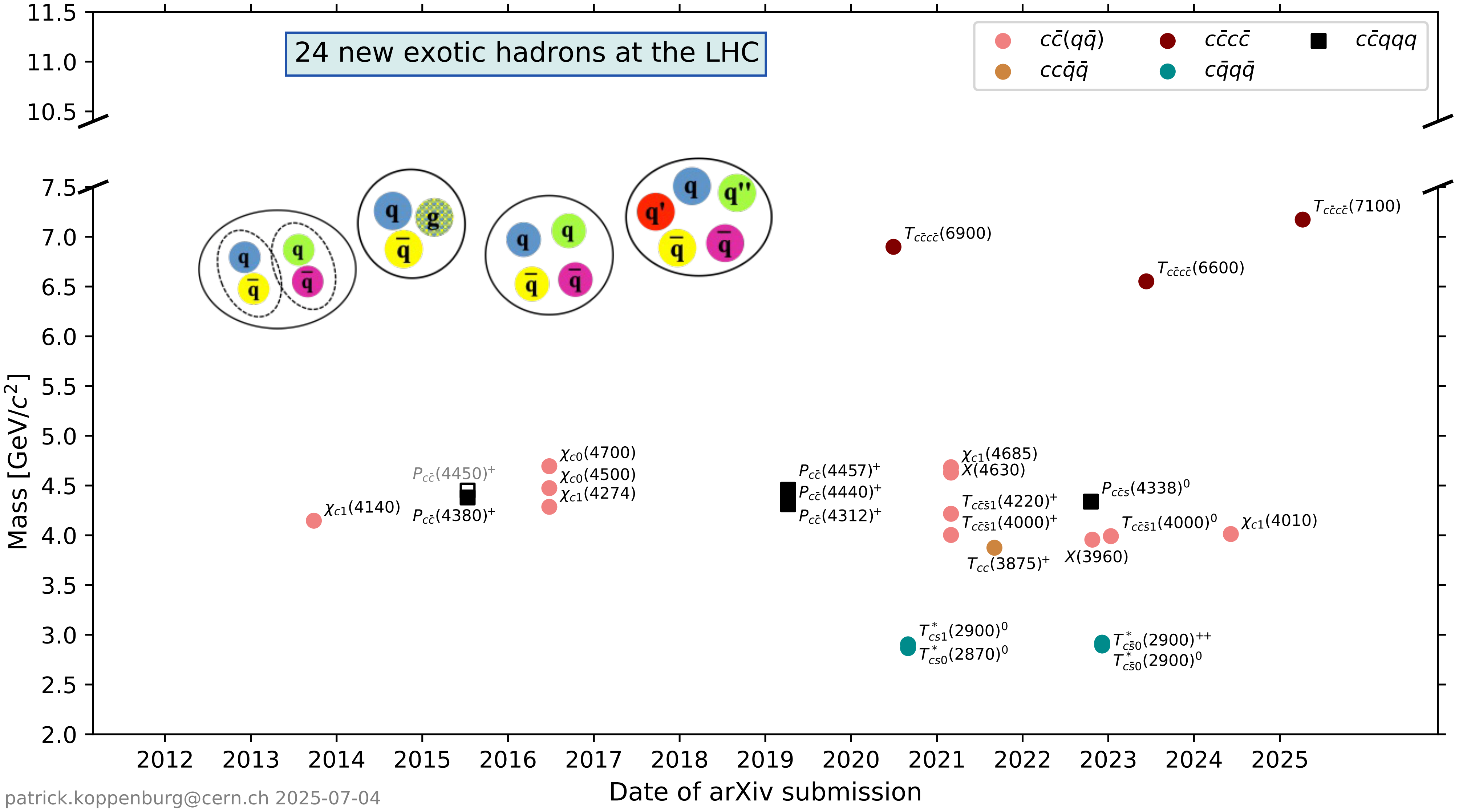
70 new hadrons at LHCb

21 exotic hadron candidates

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



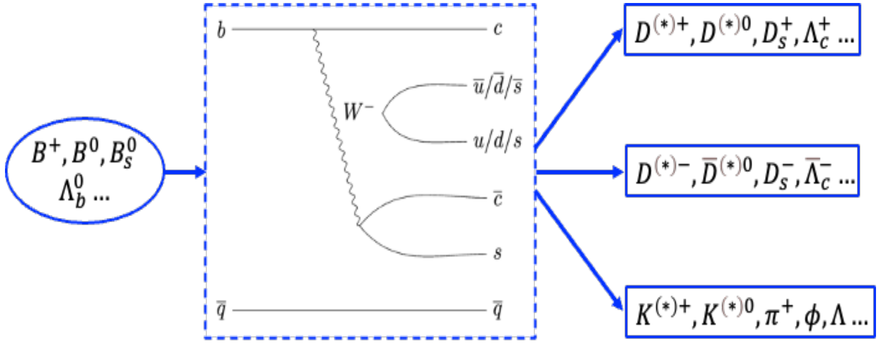
Exotic hadrons at LHC



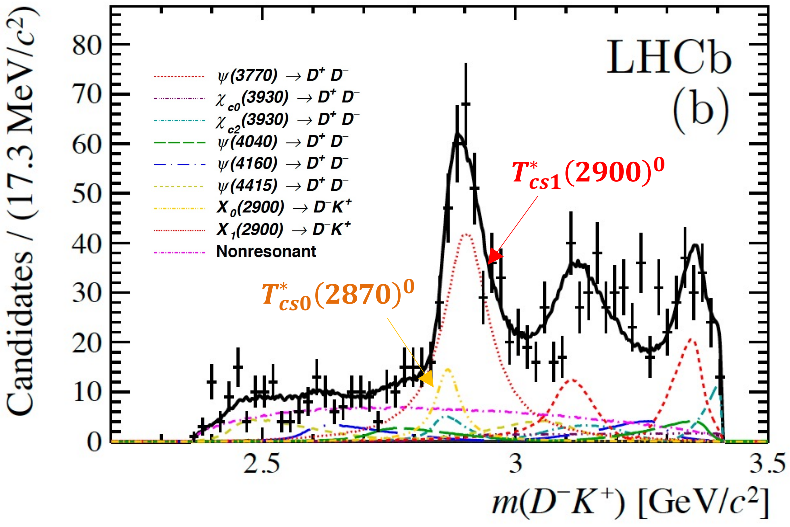
Normal and exotic hadrons in $B \to D\bar{D}h(h')$

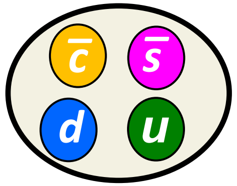
Why $B \to D\bar{D}h(h')$ decays

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



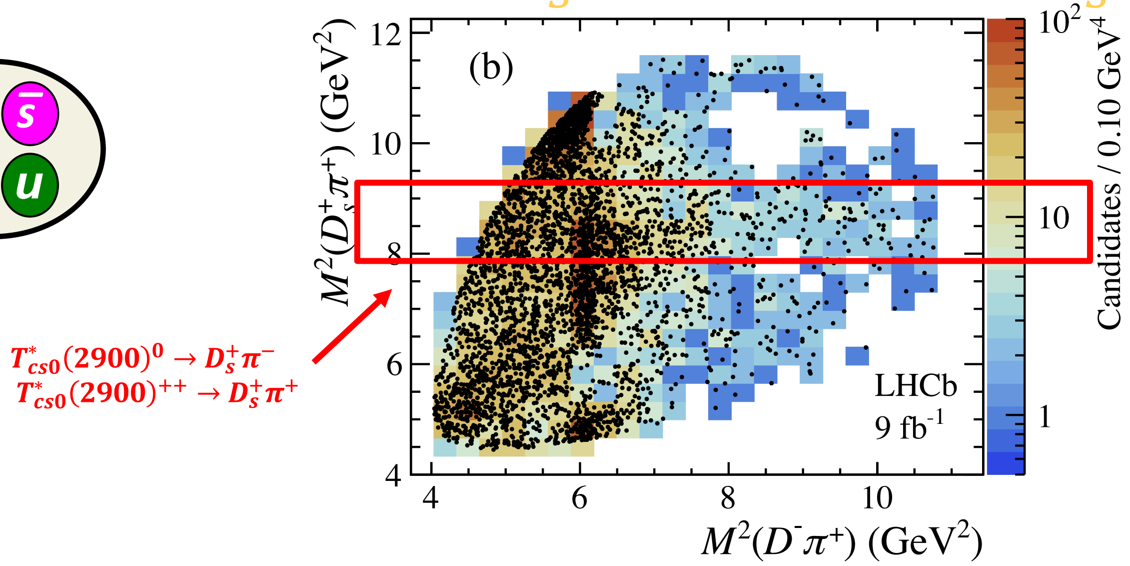
$B^+ \to D^+ D^- K^+$

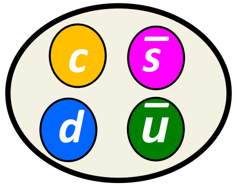




[PRL 125 (2020) 242001]
[PRD 102 (2020) 112003]

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





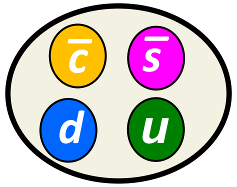
[PRL 131 (2023) 041902]

$B^+ \to D^+\overline{D}^0 K^0$: $T^*_{\bar{c}\bar{s}0}(2870)^0$ new decay mode

[PRL 134 (2025) 101901]

- Amplitude analysis of $B^+ \to D^+\overline{D}^0 K^0_S$ finding $T^*_{\bar{c}\bar{s}0}(2870)^0$, but not $T^*_{\bar{c}\bar{s}1}(2900)^0$ to $D^0 K^0_S$

- $T^*_{cs0}(2870)^0$
  - Significance of 5.3 σ
  - $m = 2883 \pm 11 \pm 8$ MeV
  - $\Gamma = 87^{+22}_{-47} \pm 17$ MeV

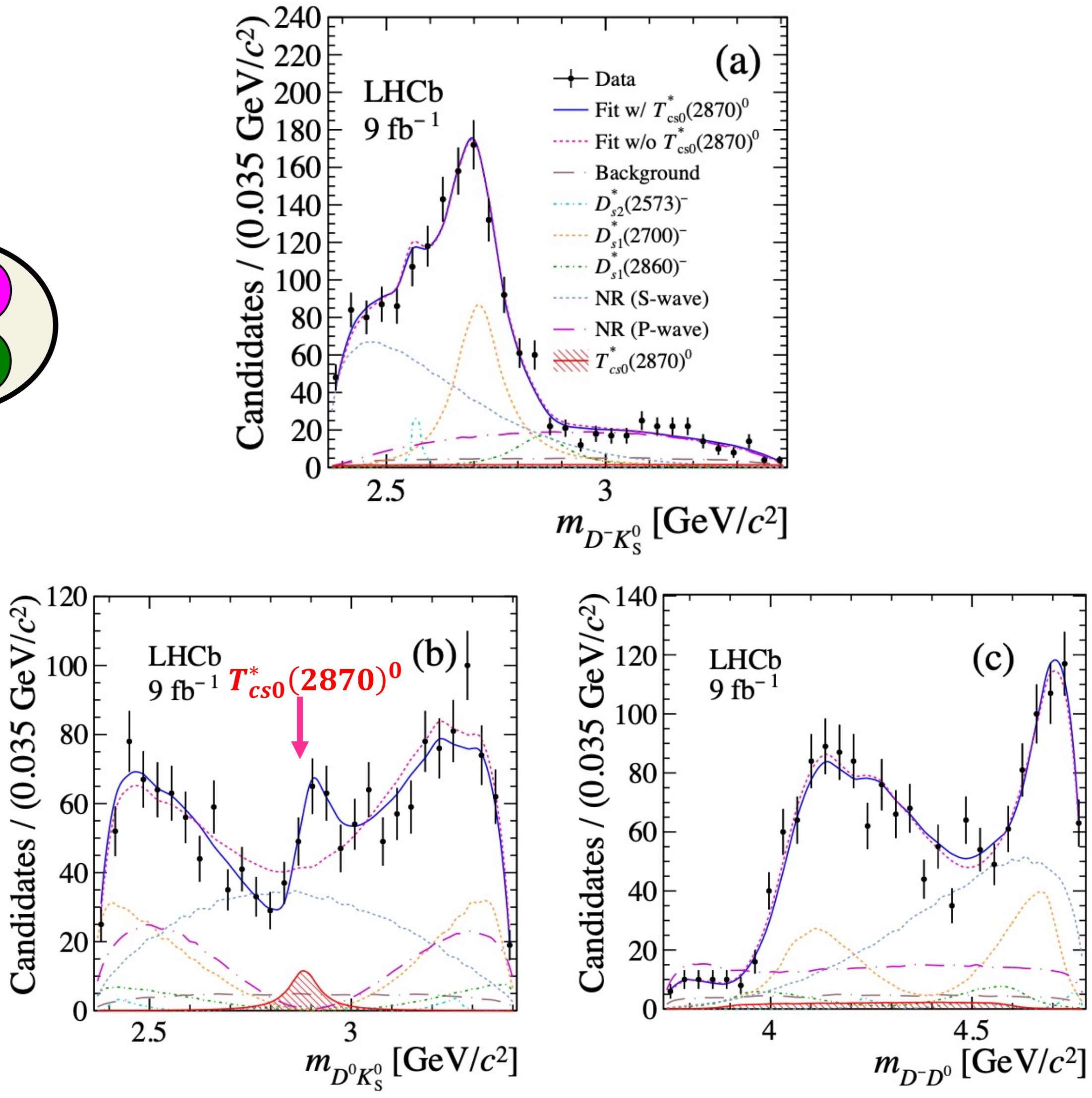


- Branching fraction ratio

$$\frac{T^*_{cs0}(2870)^0 \to D^0\overline{K}^0}{T^*_{cs0}(2870)^0 \to D^+K^-} = 3.3 \pm 1.1 \pm 1.1 \pm 1.1$$

$$\frac{T^*_{cs1}(2900)^0 \to D^0\overline{K}^0}{T^*_{cs1}(2900)^0 \to D^+K^-} = 0.15 \pm 0.15 \pm 0.05 \pm 0.05$$

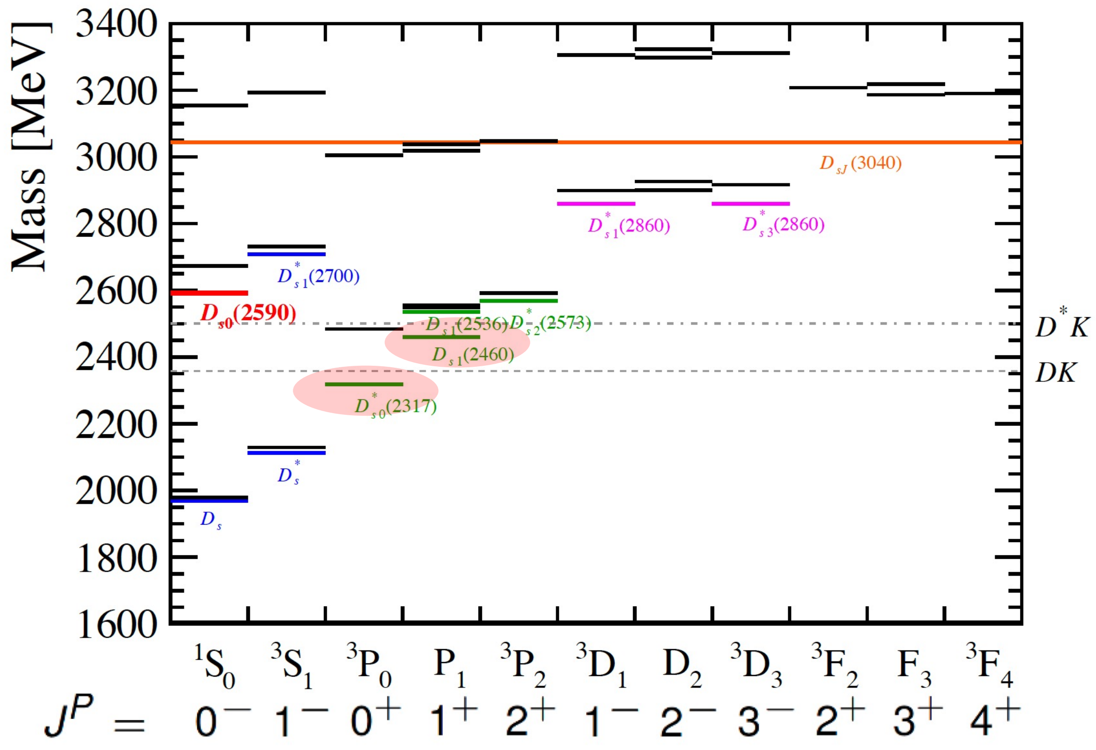
Isospin symmetry: two ratio should be 1



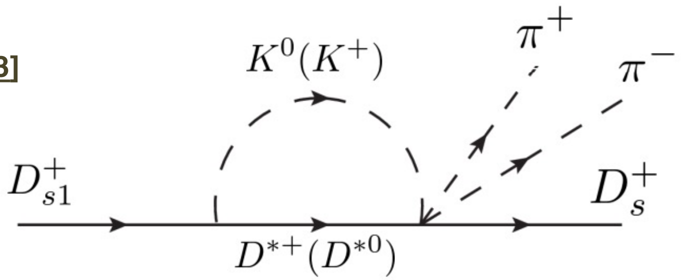
$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ decays

- $D_{s0}^*(2317)$ and $D_{s1}(2460)$ are very special
  - Masses ~100 MeV below expectation
  - Isospin-violating decay $D_s^{(*)+}\pi^0$ dominate

- Propose to study of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$
  - Double-bump lineshape in $m(\pi\pi)$ if $D_{s1}(2460)^+$ is a D^*K hadronic molecule

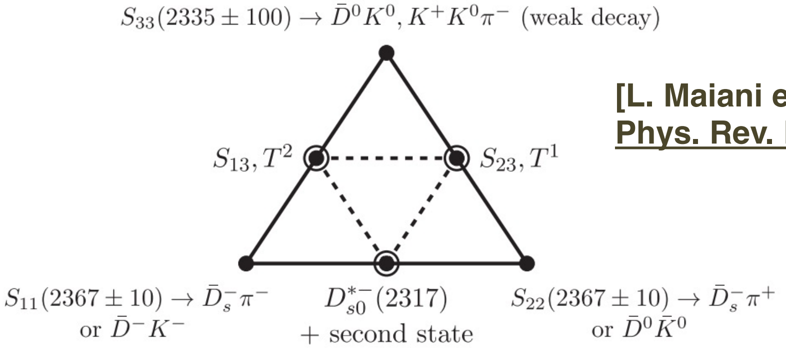


[Tang et. al.
Commun. Theor. Phys. 75 055203]



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

[PRL 131 (2023) 041902]

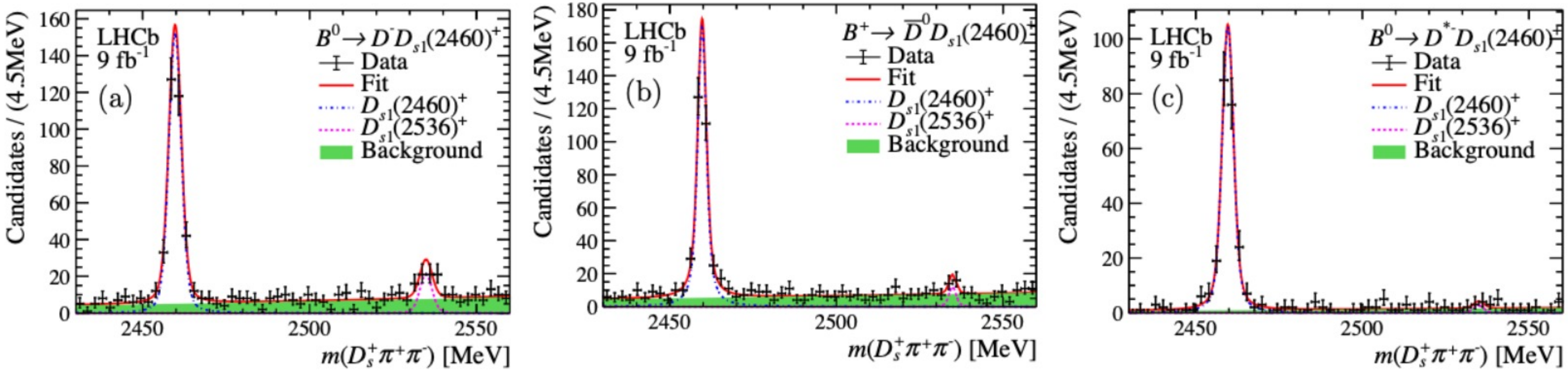


[L. Maiani et. al.
Phys. Rev. D 110, 034014]

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

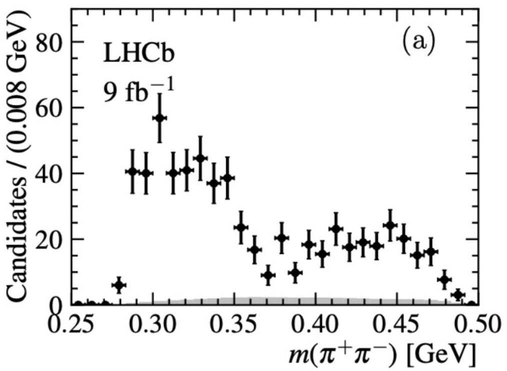
[Sci. Bull. 70 (2025) 1432–1444]

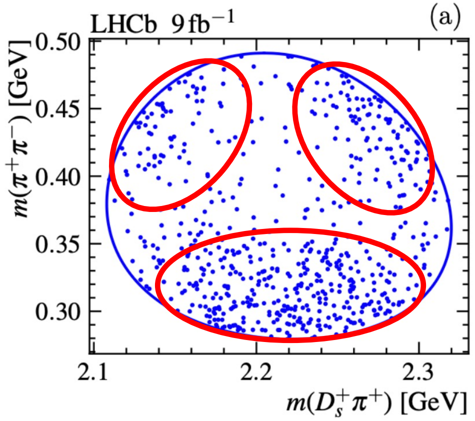
- ~800 $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ from three $B \to D_{s1}(2460)^+\overline{D}^{(*)}$ decays



- 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]



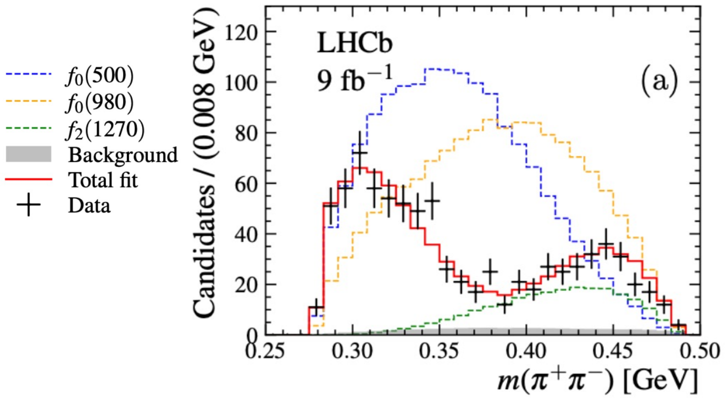


Two resonance models can fit the data well

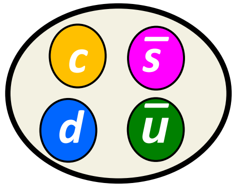
[Sci. Bull. 70 (2025) 1432–1444]

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

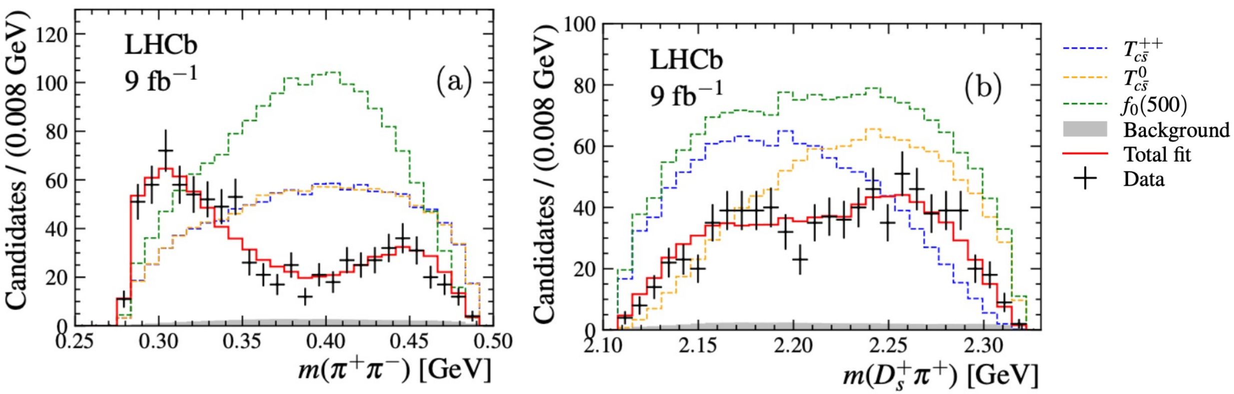
Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$376 \pm 9 \pm 16$	$175 \pm 23 \pm 16$	$197 \pm 35 \pm 23$
$f_0(980)$	945.5	167	$187 \pm 38 \pm 43$
$f_2(1270)$	1275.4	186.6	$29 \pm 2 \pm 1$



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



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

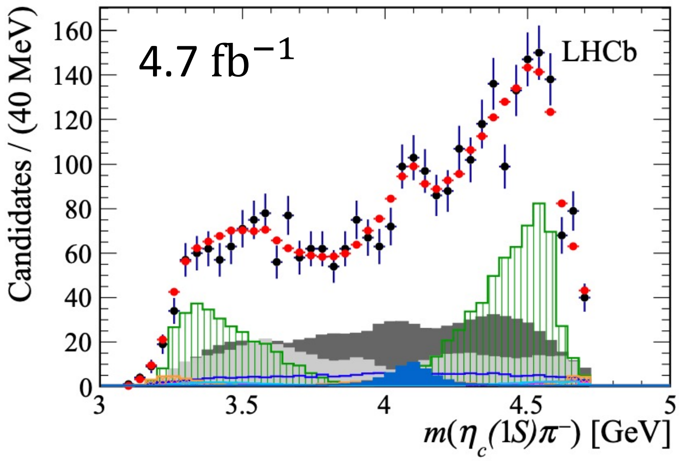


One charmonium(like) study

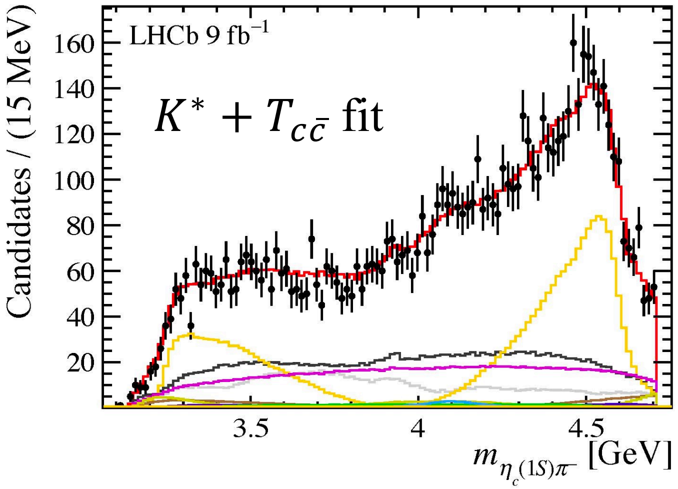
Amplitude analysis of $B^0 \to \eta_c K^+ \pi^-$

- An evidence of $T_{c\bar{c}}(4100)^- \to \eta_c \pi^-$ 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 ± 23 MeV
  - Γ($T_{c\bar{c}}$) = 514 ± 166 MeV
- **$T_{c\bar{c}}(4100)^-$ is not confirmed**

[Eur. Phys. J. C78 (2018) 1019]



[arXiv:2509.03133]



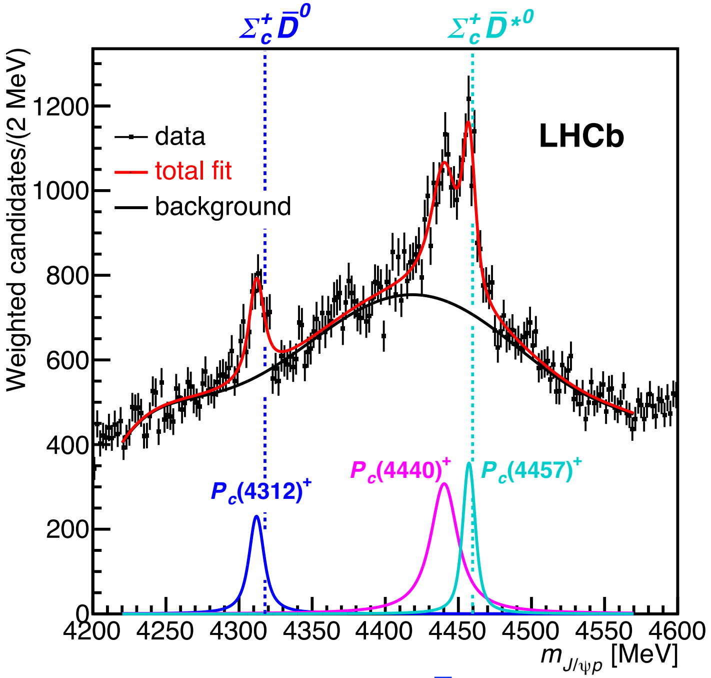
Pentaquark-related studies

Pentaquark study

[PRL 122 (2019) 222001]

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

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

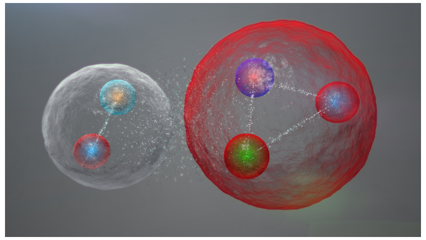


Proximity of $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

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

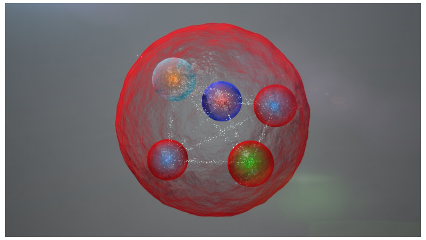
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3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

Hadron molecule



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

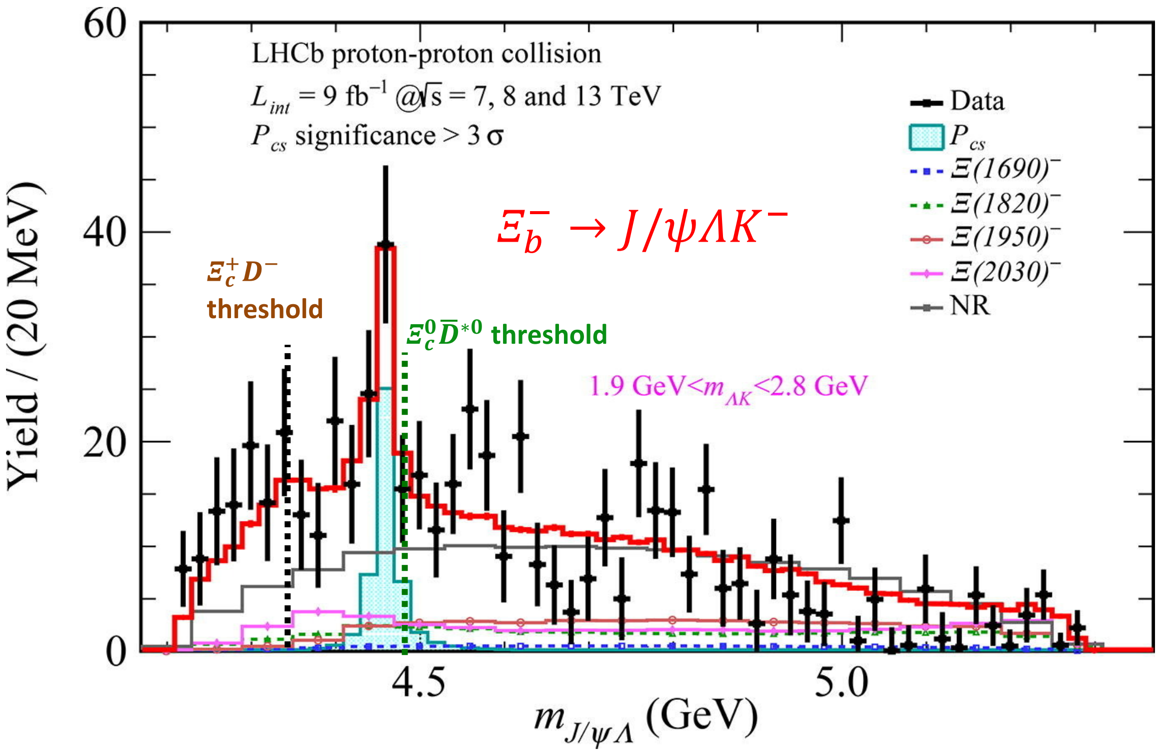
Compact multiquark

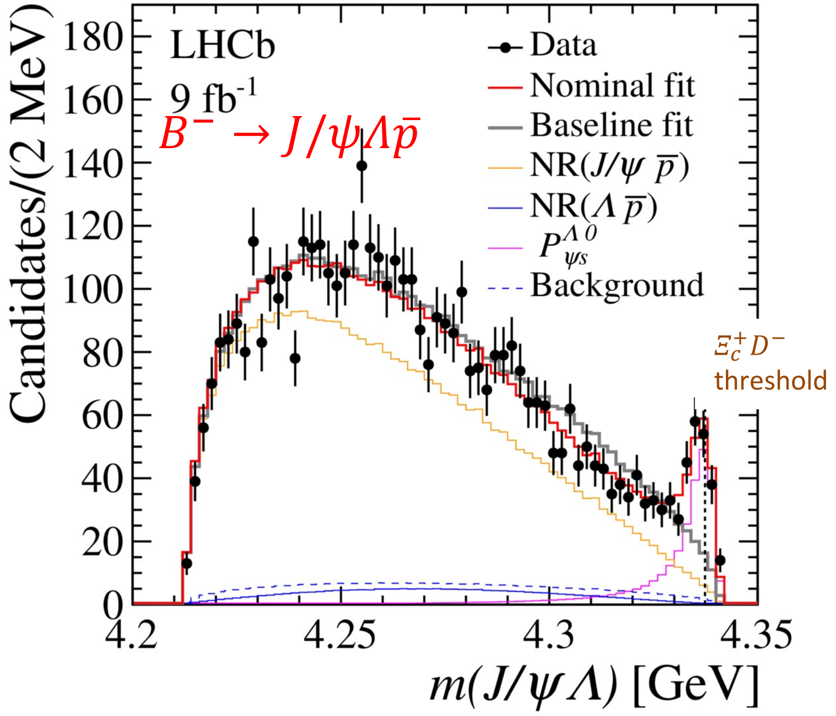


- Mass proximity to threshold **accidental**
- No (strong) hierarchy of couplings

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

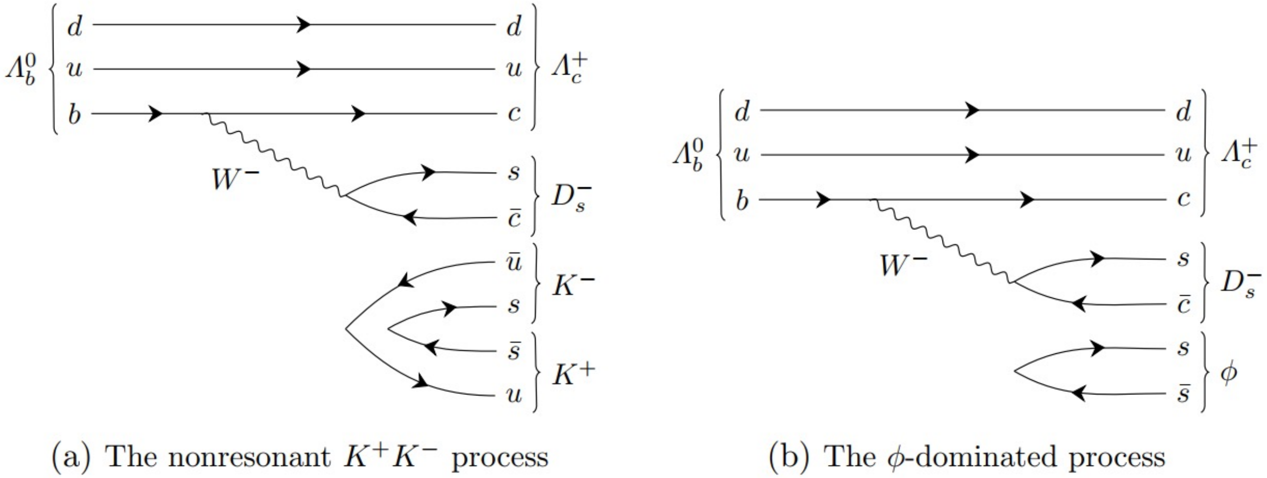
State	M_0 [MeV]	Γ [MeV]	Significance	Threshold	Ref.
$P_{c\bar{c}s}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	3.1σ	$\Xi_c \bar{D}^*$	Science Bulletin 66 (2021) 1278
$P_{c\bar{c}s}(4338)^0$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$	15σ	$\Xi_c \bar{D}$	PRL 131 (2023) 031901





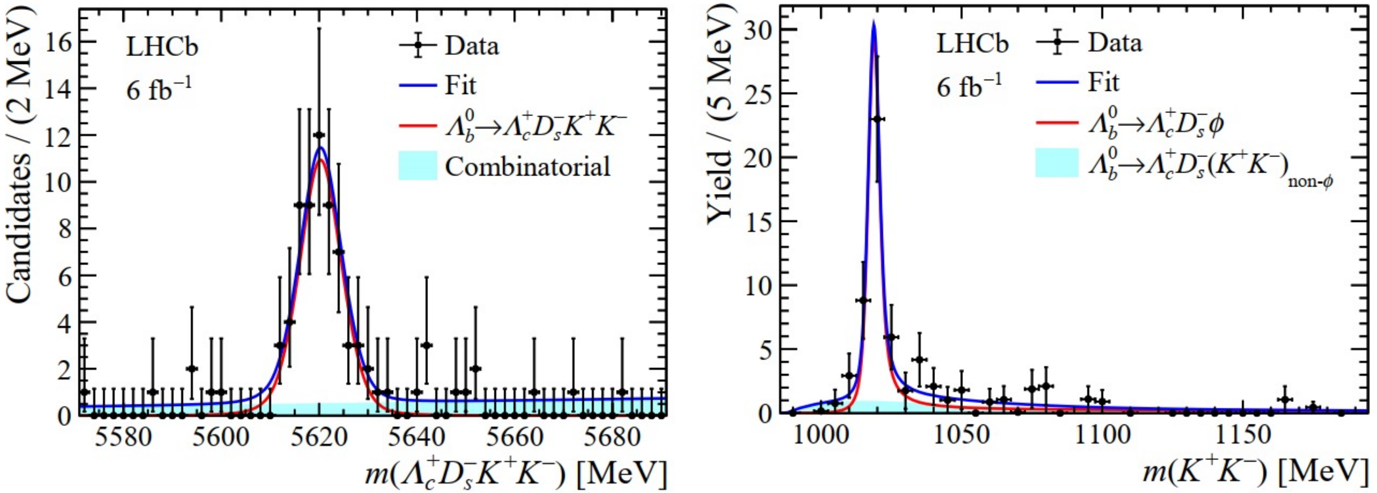
Observation of $\Lambda_b^0 \to \Lambda_c^+ D_s^- K^+ K^-$ decays [arXiv: 2507.10713]

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



- Cut & MVA based selection
  - $61 \pm 8\ \Lambda_b^0$ decays
  - Dominated by $\phi \to K^+K^-$

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



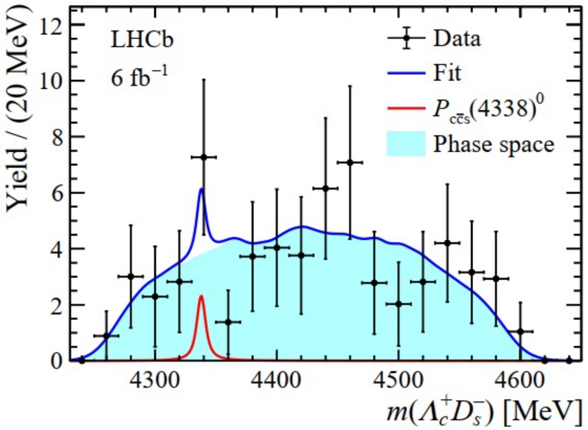
Search for pentaquarks in $\Lambda_c^+ D_s^-$ mass

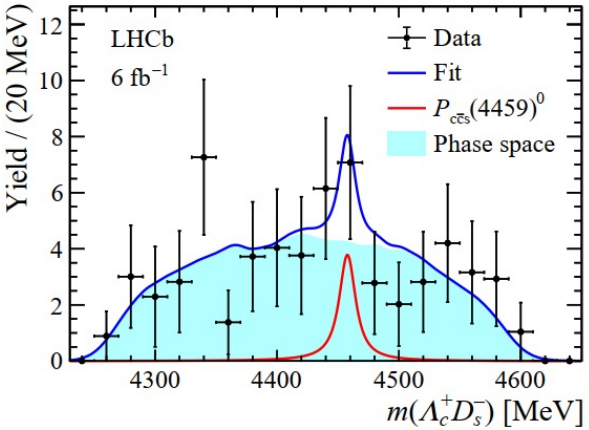
[arXiv: 2507.10713]

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

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

- Widths and masses are Gaussian constrained to their known values





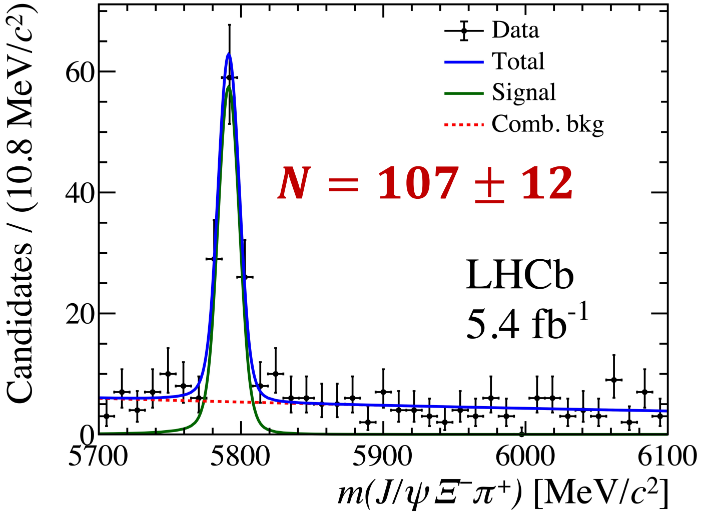
- Upper limits on 90% (95%) CLs:

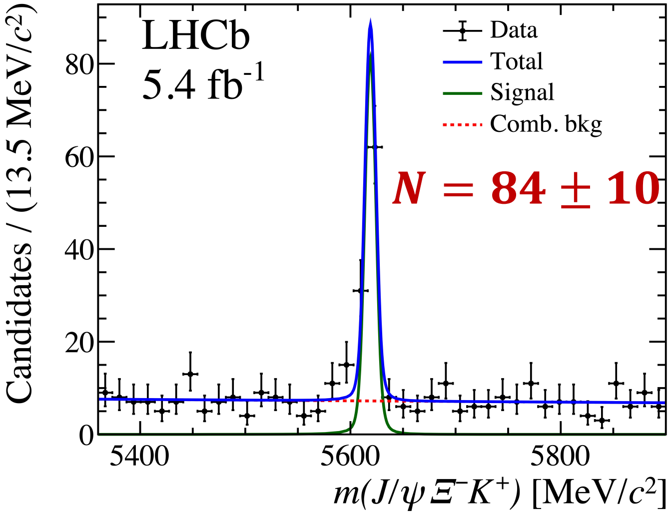
$$\mathcal{R}_{P_{c\bar{c}s}(4338)^0} < 0.10\ (0.12) \quad \text{and} \quad \mathcal{R}_{P_{c\bar{c}s}(4459)^0} < 0.17\ (0.20)$$

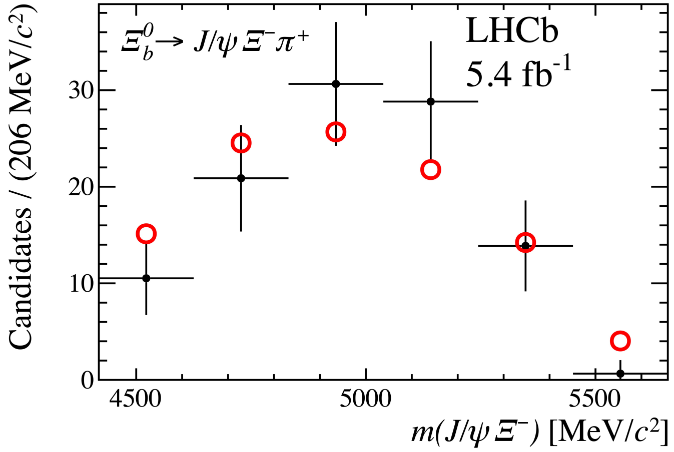
$\Xi_b^0 \to J/\psi \Xi^- \pi^+$ and $\Lambda_b^0 \to J/\psi \Xi^- K^+$

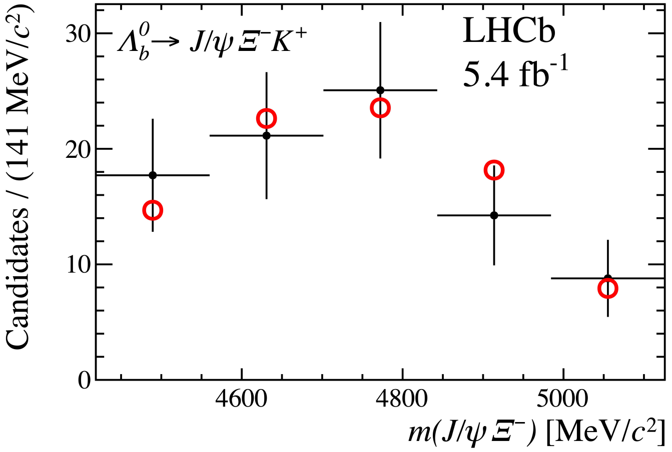
[EPJC 85 (2025) 812]

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









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

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

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

[EPJC 84 (2024) 1062]

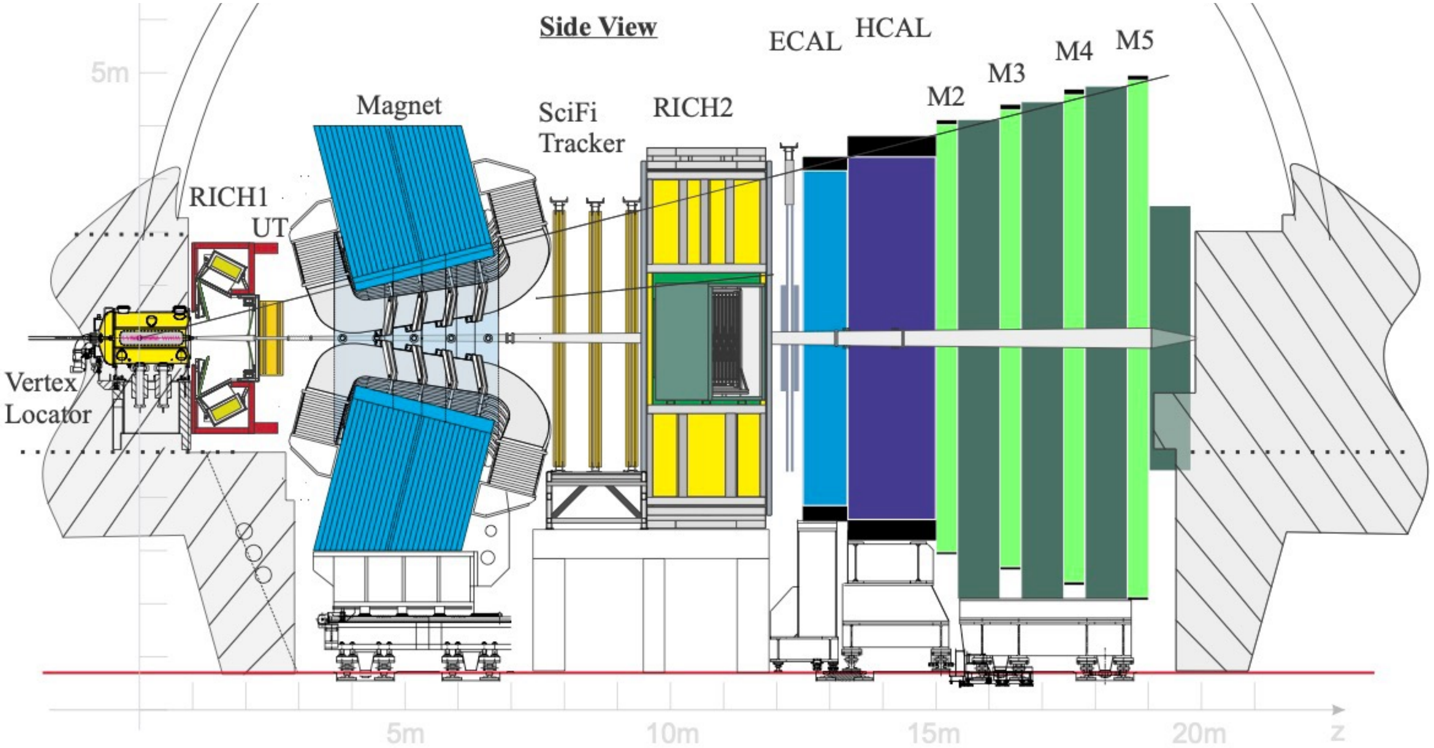
$$\left.\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S) \Lambda)}\right|_{\mathrm{LHCb}} = (2.3 \pm 0.3) \times 10^{-2}$$

- Larger statistics needed for amp. study

Summary

- LHCb keeps making important contributions to heavy hadron spectroscopy with run1 and run2 data
- Run 3 has taken 15 fb^{-1} data with upgraded new detector, about doubled the luminosity of run1&2
- Stay tuned for more exciting results

JINST 19 (2024) P05065



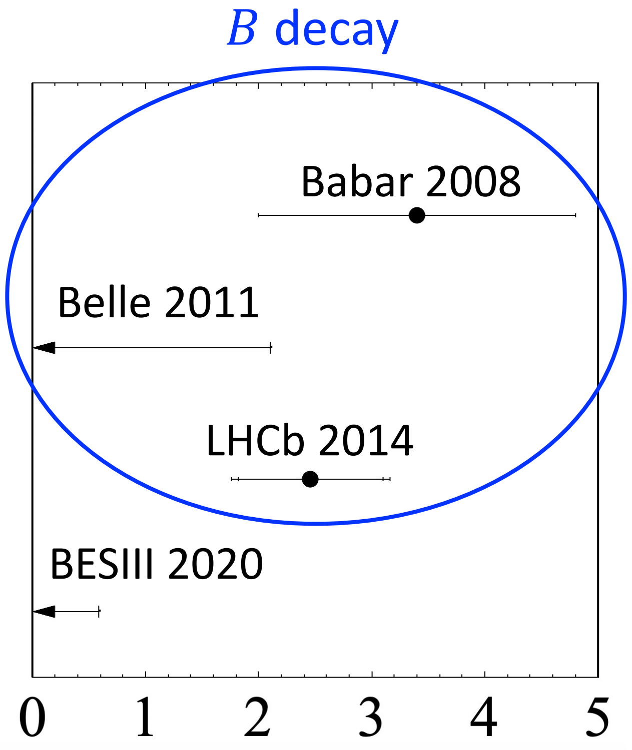
BACKUP

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 $\chi_{c1}(3872) \to \psi(2S)\gamma$ was seen experimentally before

Reference			$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$	
T. Barnes and S. Godfrey	$\gtrsim 1$	[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 *et al.*		[86]	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian *et al.*		[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 *et al.*		[90]	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito		[71]	5.4	$c\bar{c}/vc$
E. S. Swanson	$\ll 1$	[81]	$0.38\,\%$	$D\bar{D}^*$
Y. Dong *et al.*		[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 *et al.*		[82]	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	mixed	[83]	$2 - 10$	$D\bar{D}^*$
E. Cincioglu *et al.*		[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]	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

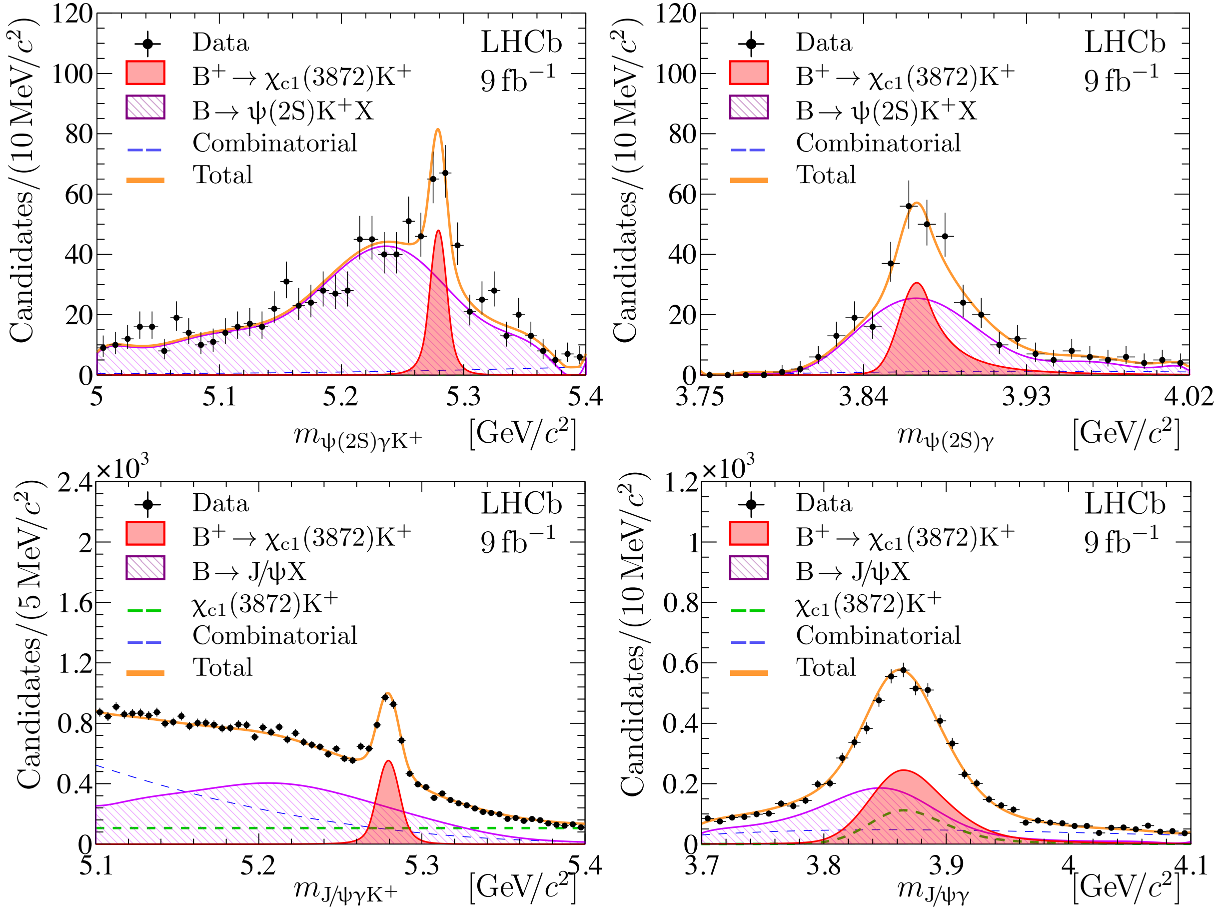


$$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

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

[arXiv: 2406.17006]

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



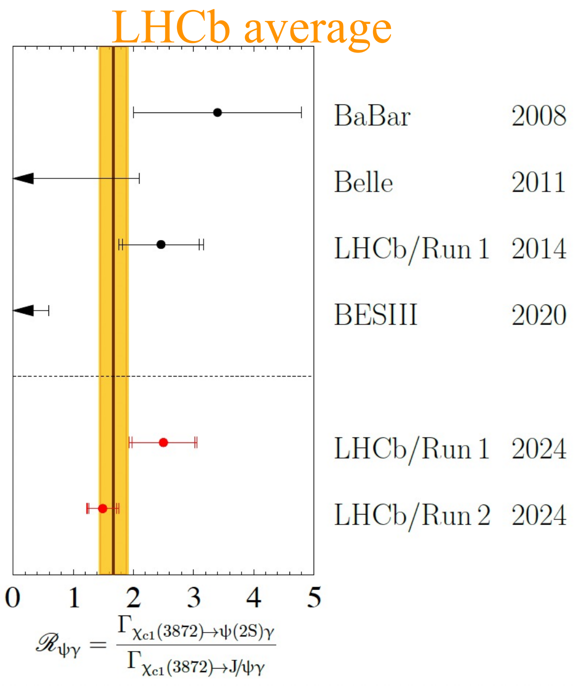
$$\mathscr{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \quad (15\%)$$

LHCb meets theory workshop

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

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

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



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

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

$$\begin{aligned}\mathcal{A}(x) &= \frac{1+d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} c_j A_j(x) + \sum_{k\in R(D^{*-}K^+,\ D^+K^+)} c_k A_k(x)\right\} \Leftarrow B^+ \to D^+D^{*-}K^+ \\ &+ \frac{1-d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} C_j \times c_j A_j(x) + \sum_{l\in R(D^{*+}K^+,\ D^-K^+)} c_l A_l(x)\right\} \Leftarrow B^+ \to D^{*+}D^-K^+\end{aligned}$$

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

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

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

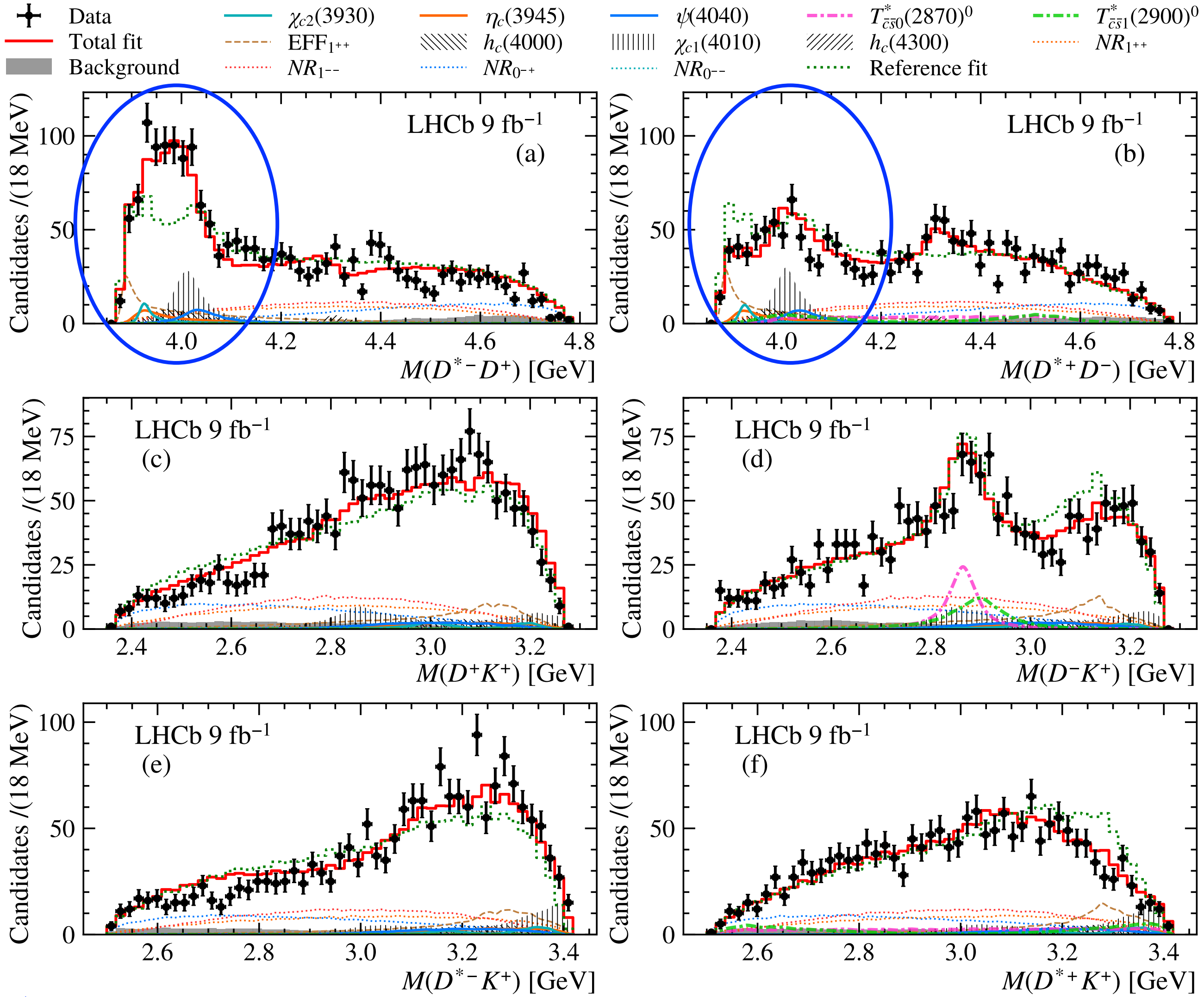
□ Other resonances: Breit-Wigner

□ Nonresonant contributions to $D^{*\pm}D^{\mp}$:
$f_R(m) = e^{(\alpha+\beta i)(m^2-m_0^2)}$ for $NR_{0^{-+}}$; otherwise $f_R(m) = 1$

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

[PRL 133 (2024) 131902]

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



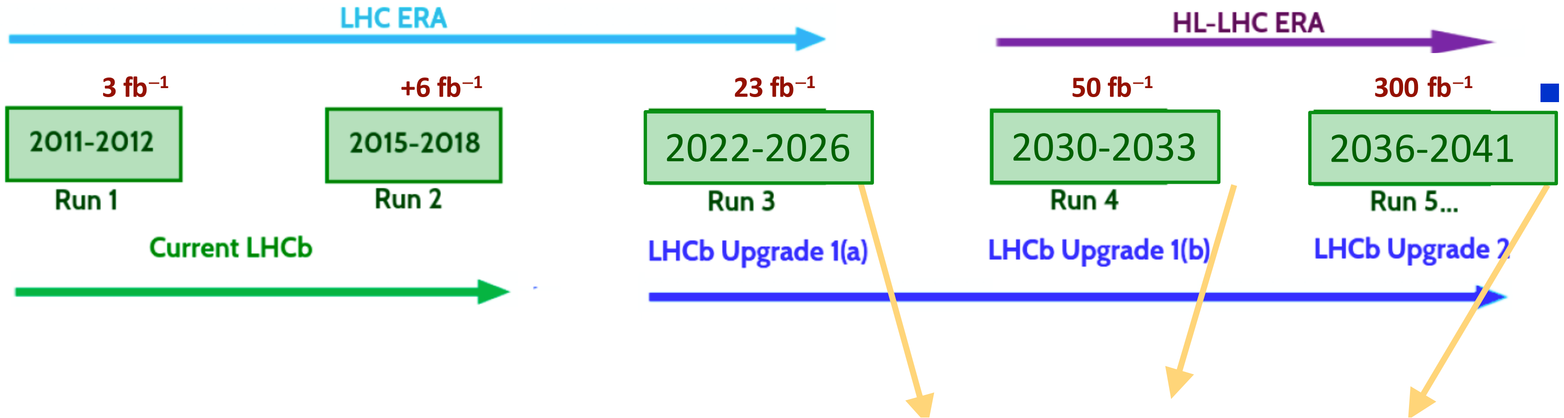
Component	$J^{P(C)}$
$\mathrm{EFF}_{1^{++}}$	1^{++}
$\eta_c(3945)$	0^{-+}
$\chi_{c2}(3930)^\dagger$	2^{++}
$h_c(4000)$	1^{+-}
$\chi_{c1}(4010)$	1^{++}
$\psi(4040)^\dagger$	1^{--}
$h_c(4300)$	1^{+-}
$T^*_{\bar{c}\bar{s}0}(2870)^{0\,\dagger}$	0^+
$T^*_{\bar{c}\bar{s}1}(2900)^{0\,\dagger}$	1^-
$\mathrm{NR}_{1^{--}}(D^{*\mp}D^{\pm})$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

✓clear different interference behaviors

*Fit fractions in paper

Prospects

[arXiv:1808.08865]



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

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

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

$Z_c(4430)$

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

More information for pentaquarks

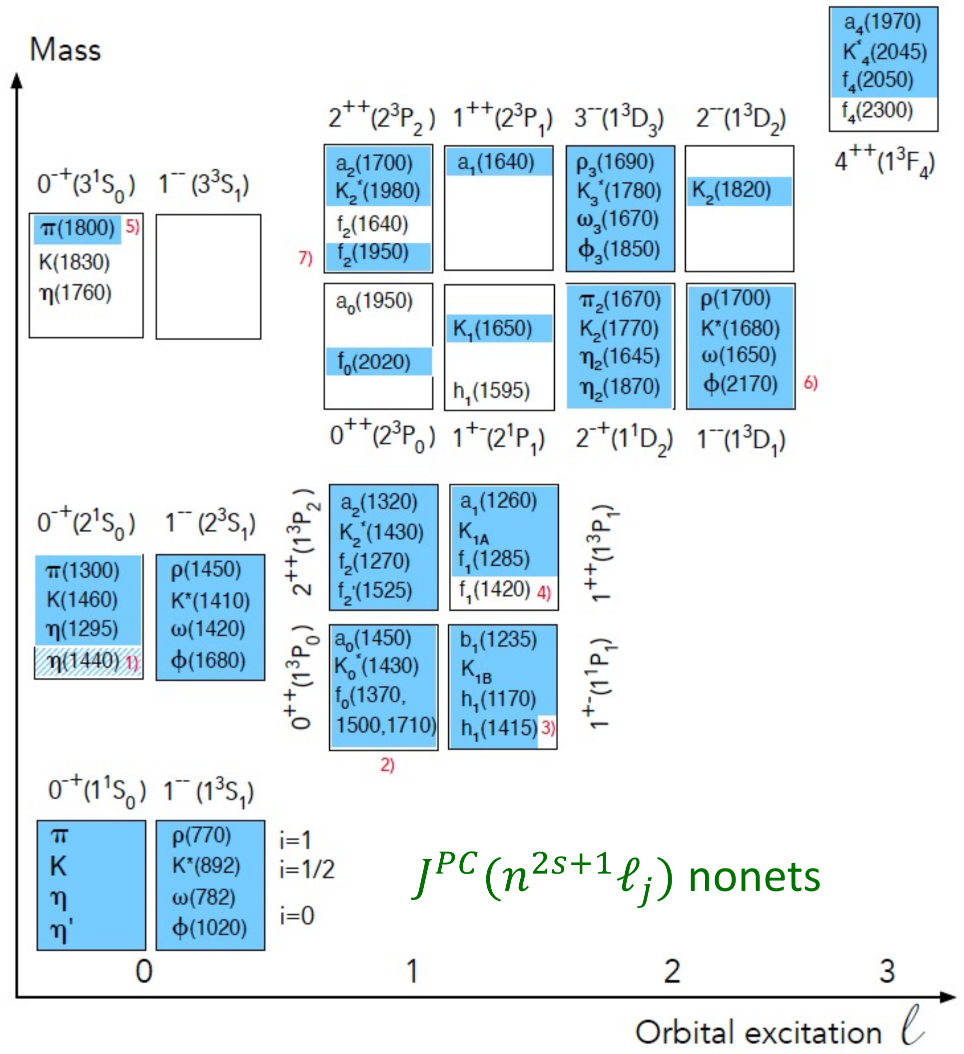
[*] updated according to the latest result

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)

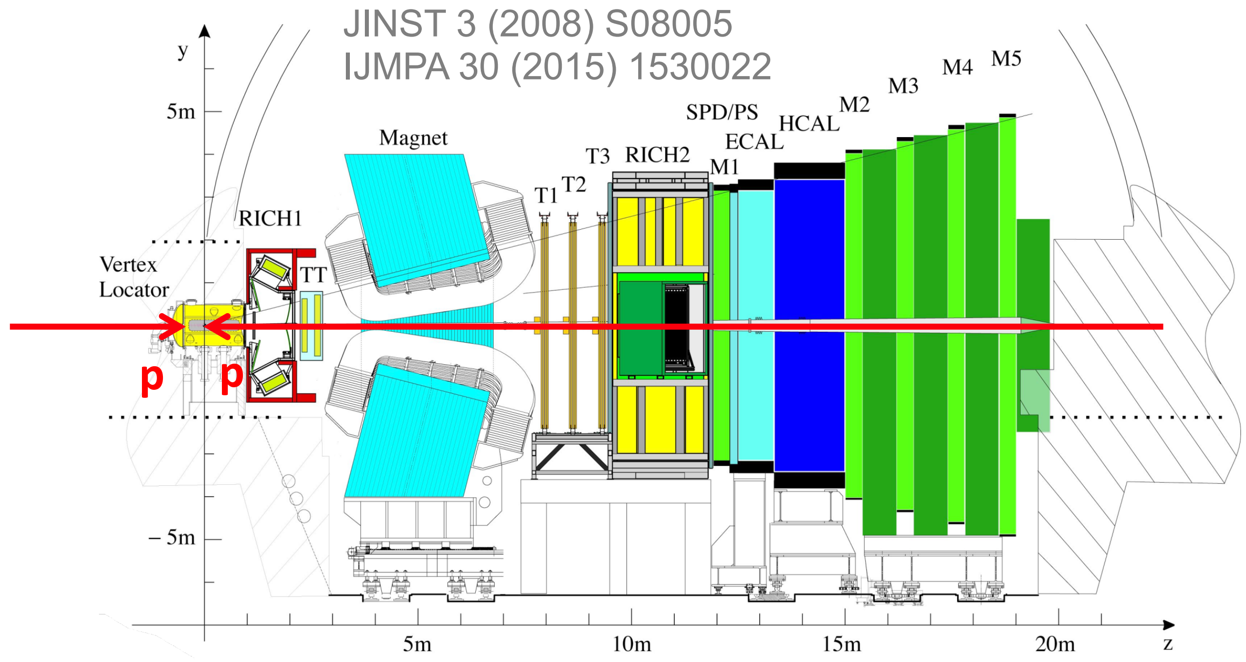
Mass spectrum of $q\bar{q}$ mesons

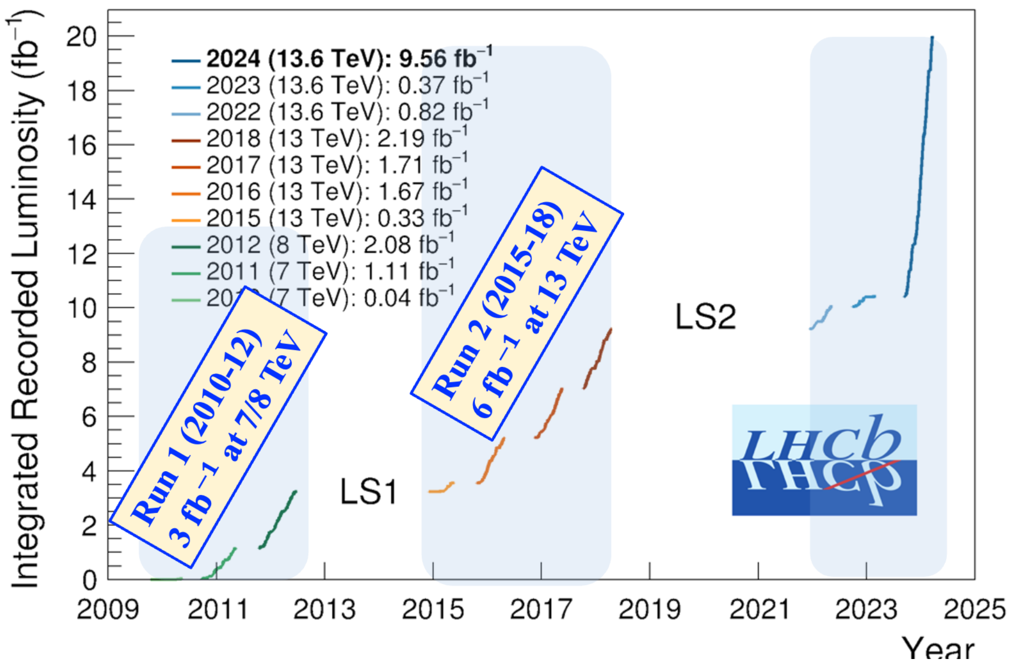


The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - >10^4 $\times$ larger b production rate than the B factories @ $\Upsilon(4S)$
  - 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



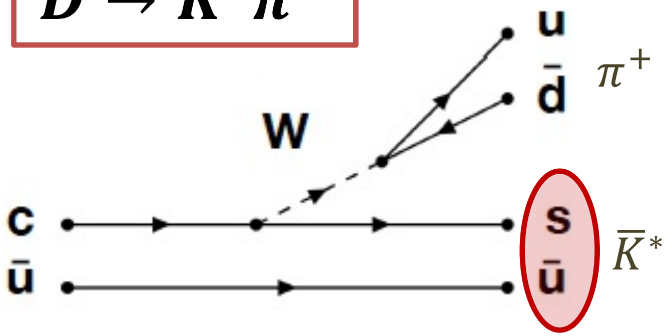


Light-hardon spectroscopy at LHCb

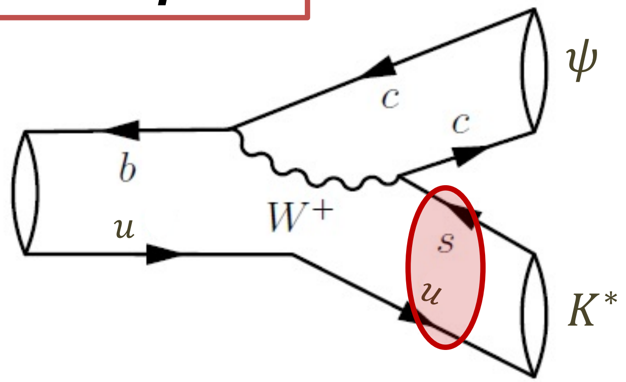
- Amplitude analysis
  - Direct production of light hadrons obviously happens but the multiplicity of tracks is so large that they are covered by large background
  - Rather study resonances in heavy flavored particle decays (D, $B_{(s)}$-hadrons)
  - $B_{(s)}$-decays select pure quark-contents of the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

Strange production

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

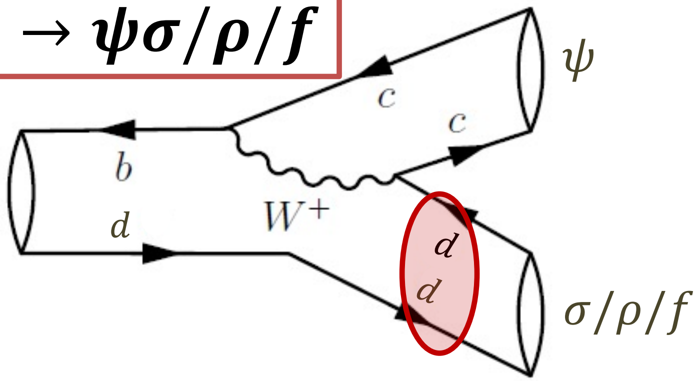


$B \to \psi K^{*}$

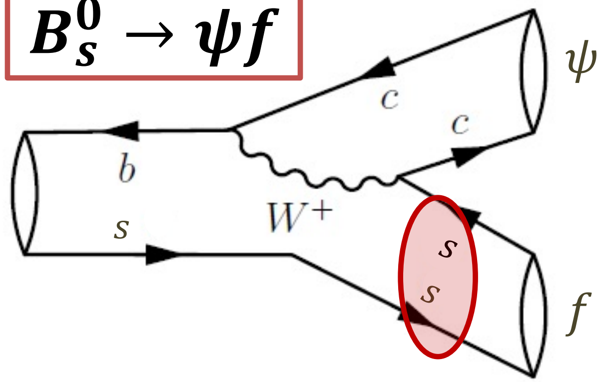


Non-Strange production

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



$B_s^0 \to \psi f$



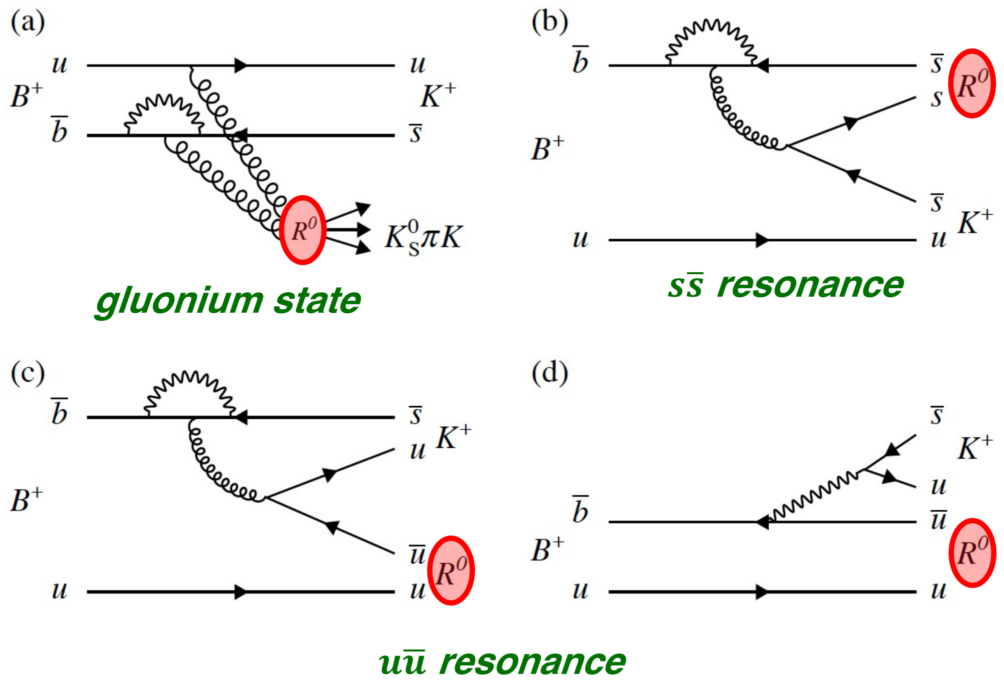
Non-Strange Mesons

Early works on non-strange light mesons

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

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

- The process b → 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 $\eta(1405)$ & $\eta(1475)$

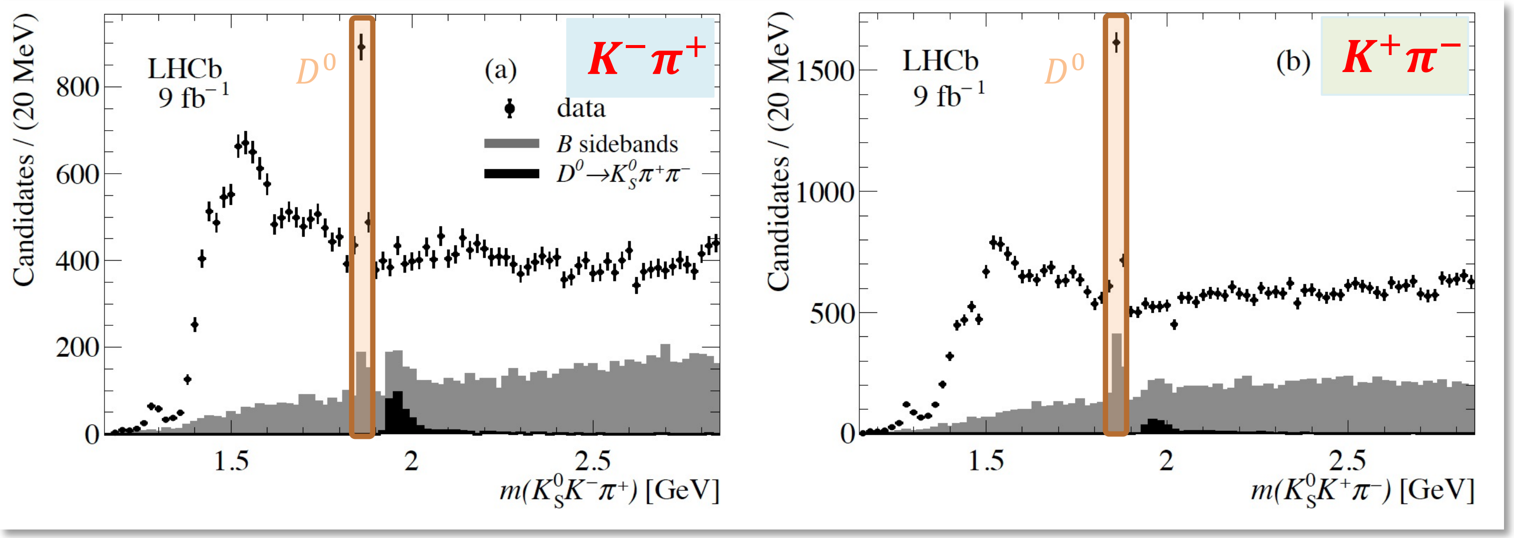
$K_S^0 K^\pm \pi^\mp$ mass spectra

[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
$B^+ \to K_S^0 K^+ K^- \pi^+$	10430	1454	87.8 ± 0.3
$B^+ \to K_S^0 K^+ K^+ \pi^-$	12320	2180	85.0 ± 0.3

- Complex superposition of resonances in the threshold region



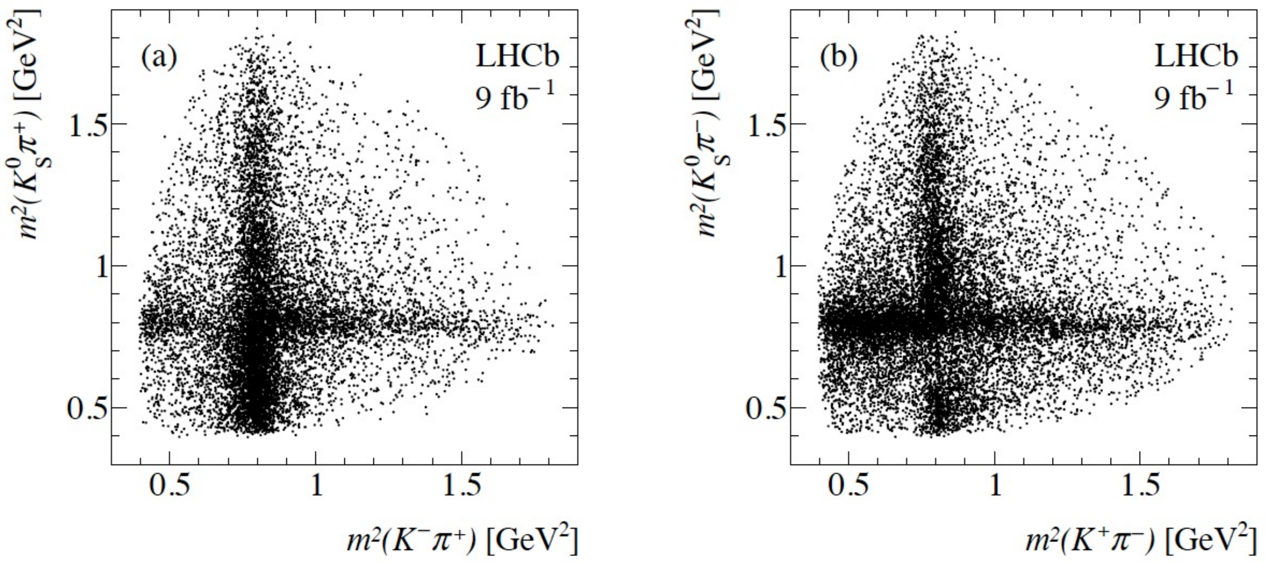
Comparison of two decay modes

[PRD 111 (2025) 092009]

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

$B^+ \to \left(K_S^0 K^- \pi^+\right) K^+$ $\qquad$ $B^+ \to \left(K_S^0 K^+ \pi^-\right) K^+$

$K^{*+}K^-$ vs $\overline{K}^{*0}K^0$



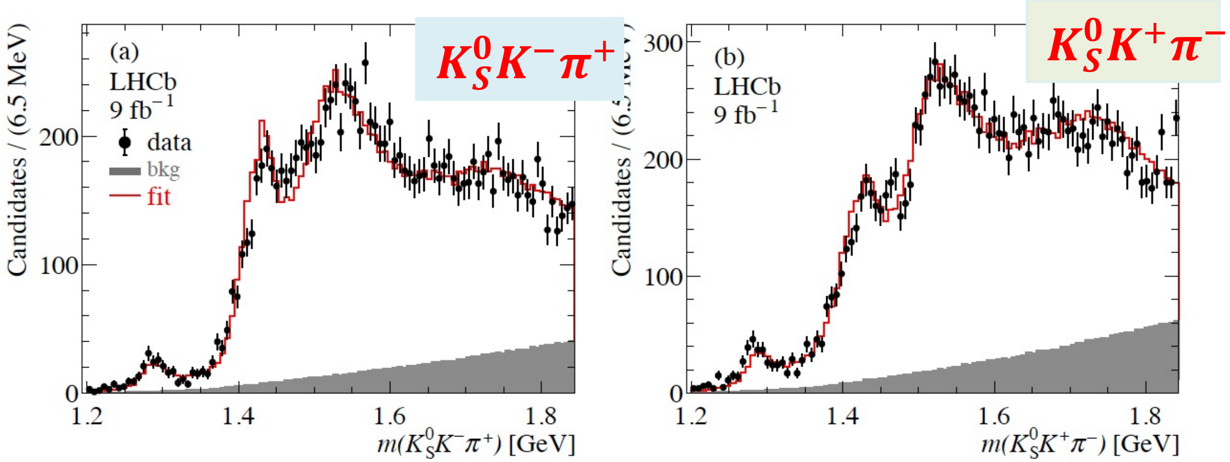
$K^{*-}K^+$ vs $K^{*0}\overline{K}^0$

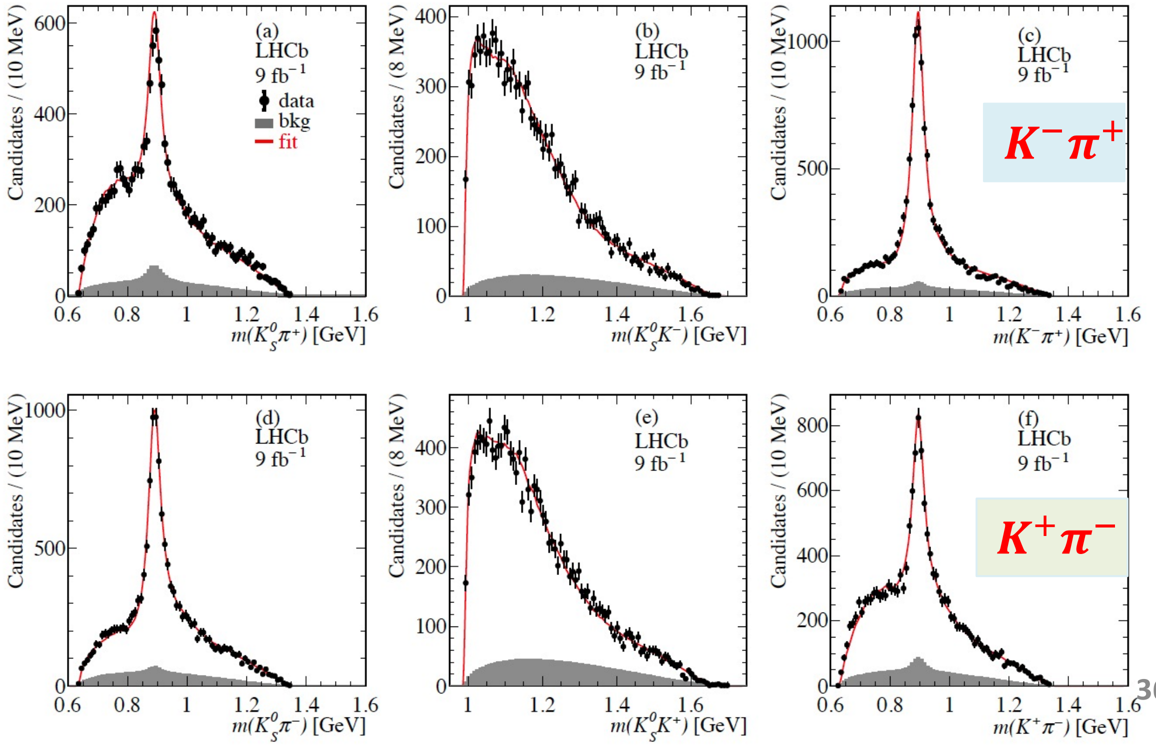
- Asymmetric K^{*+}/K^{*0} distributions
- The Dalitz plots for $B^+ \to \left(K_S^0 K^- \pi^+\right) K^+$ and $B^+ \to \left(K_S^0 K^+ \pi^-\right) K^+$ are different
- Neutral K^{*0} and charged K^{*+} bands are somewhat inverted

Ampitude analysis

[PRD 111 (2025) 092009]

- Decay chains via $a_0(980)\pi$, $K^*(892)\bar{K}$ and direct $K^0K\pi$
- Resonant parameters are fixed to those from PDG
- Reference amplitude is the $J^{PC} = 0^{-+}$ $\eta(1475) \to K^*\bar{K}$, parameter fixed to BESIII analysis on $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$ [JHEP 03 (2023) 121]
- 19 contributions include $J^{PC} = 0^{-+}, 1^{++}, 1^{+-}$ and $\eta_2(1645)$





Fit results

[PRD 111 (2025) 092009]

		$B^+ \to K^0_S K^- \pi^+ K^+$		$B^+ \to K^0_S K^+ \pi^- K^+$	
Contribution	Decay	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