
Charm spectroscopy and exotic hadrons at LHCb

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On behalf of 

12th International Workshop on Charm Physics

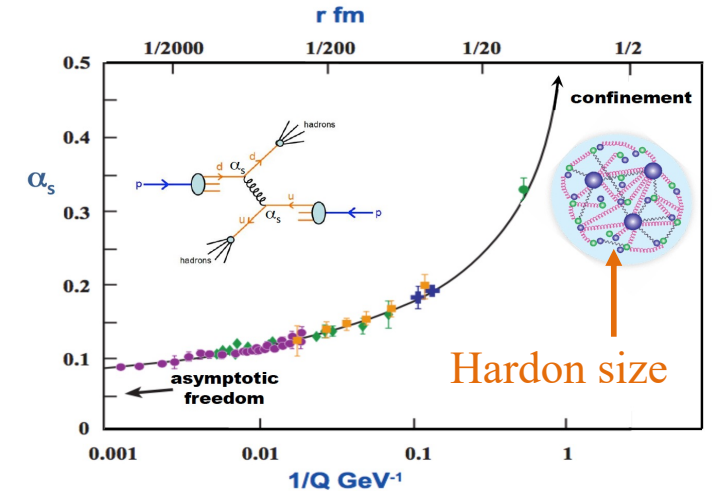
12-16 May 2025, Tsung-Dao Lee Institute, Shanghai

Outline

- Introduction
- Charm spectroscopy with $B \rightarrow D\bar{D}h$ decays
- Quarkonium(-like) states
- Charm baryon spectroscopy
- Summary

Introduction

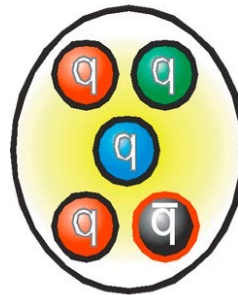
- Hadron spectroscopy provides opportunities to study QCD in non-perturbative region
 - Extensive and precise spectroscopy combined with a thorough theoretical analysis add substantially to our knowledge of QCD
- Exotic hadrons provide unique probe to QCD
 - Predicted in quark model
 - Strong experimental evidence in last years



Mesonic
molecule ?



Tetraquark ?



Pentaquark ?



Hybrid ?

EXOTIC

...



Meson

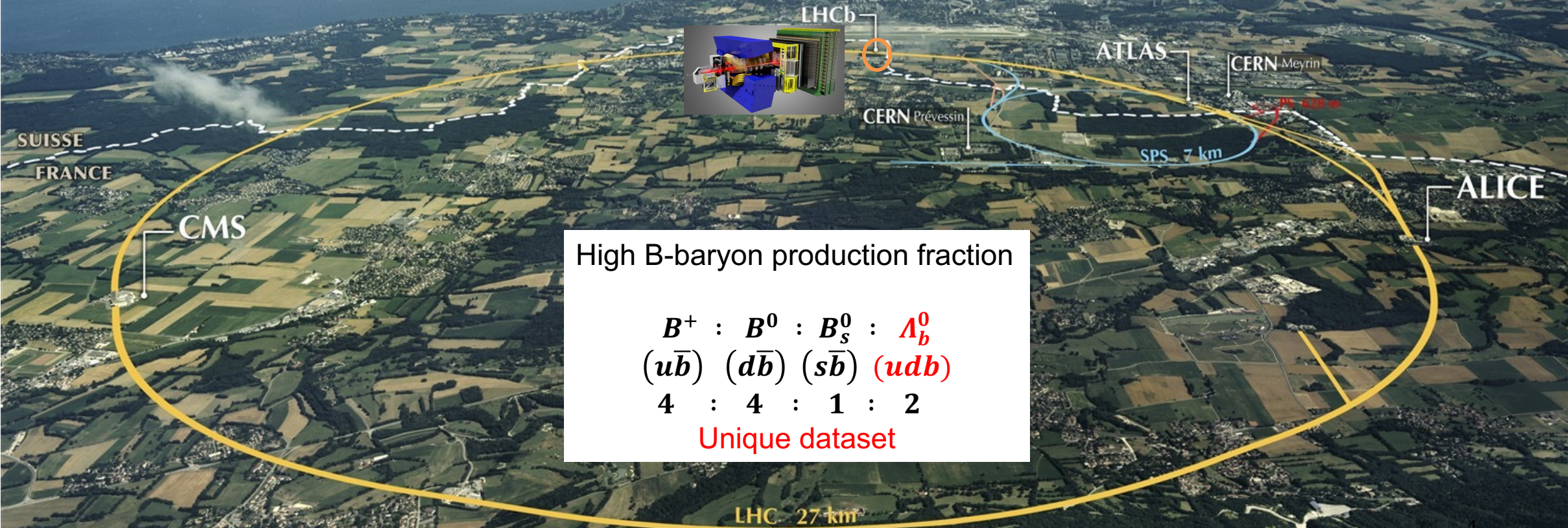


Baryon

CONVENTIONAL

The LHCb 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

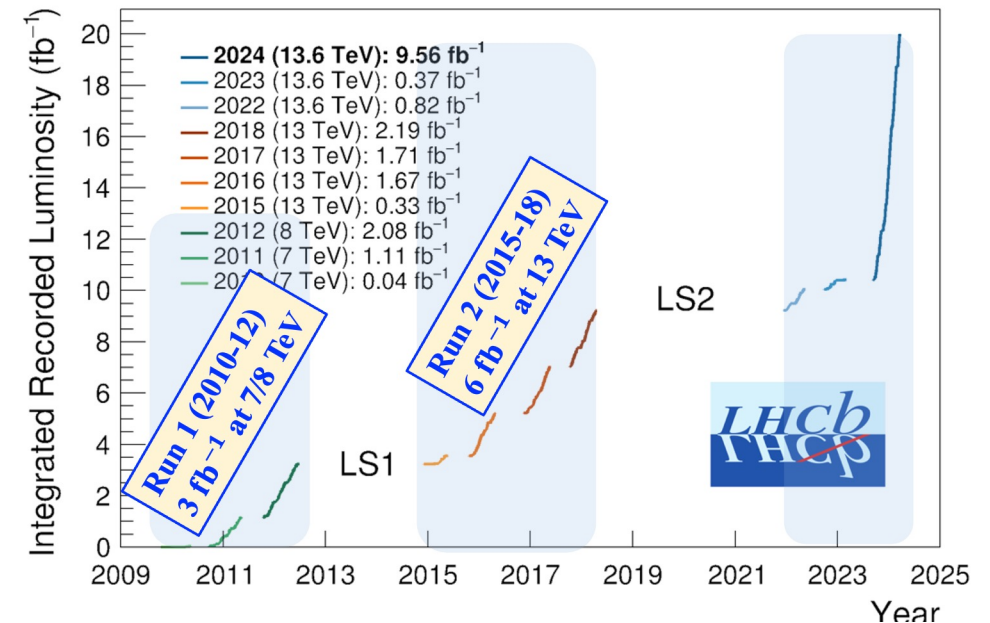
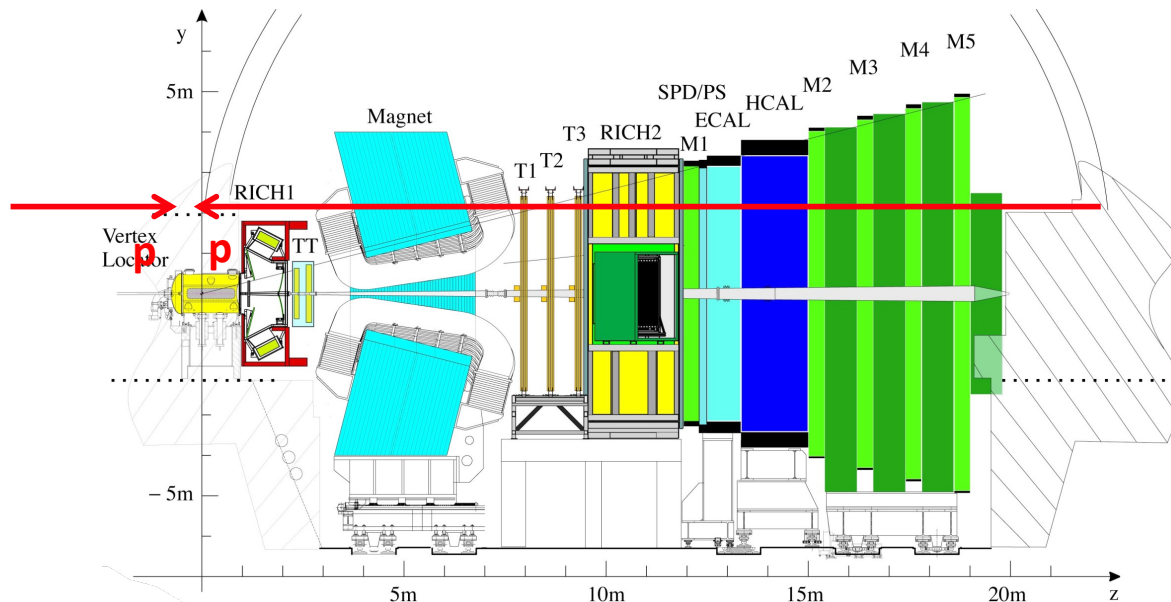
B^+	B^0	B_s^0	Λ_b^0
$(u\bar{b})$	$(d\bar{b})$	$(s\bar{b})$	$(ud\bar{b})$
4	4	1	2
Unique dataset			

The LHCb Experiment

- LHCb is a dedicated flavor physics experiment at the LHC
 - $>10^4 \times$ larger b production rate than the B factories @ Y(4S)
 - Access to all c -hadrons: D^+ , D^0 , D_s^+ , c -baryons
- Ideal also to study hadron spectroscopy including exotics
- Acceptance optimized for forward $Q\bar{Q}$ production

➤ All results in this talk based on full or part of run-1/2 datasets

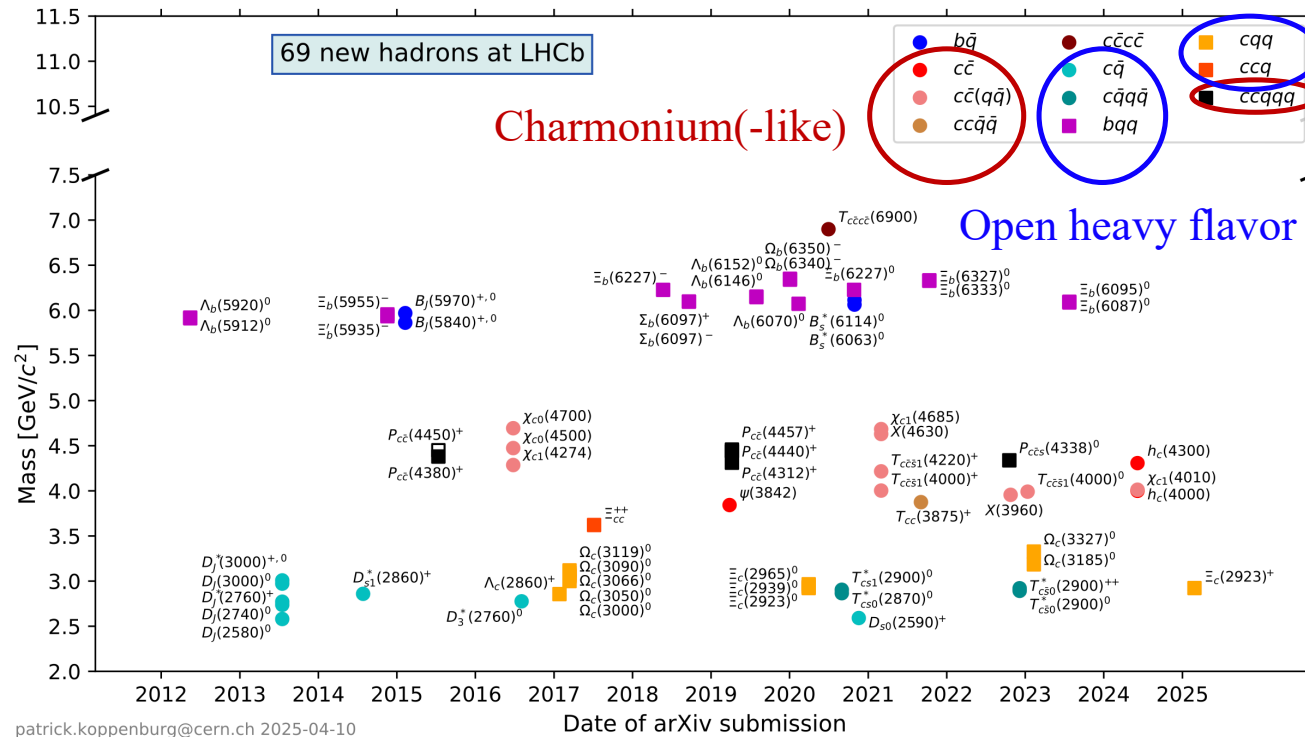
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



New particles in a glance

69 new hadrons discovered by LHCb!

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

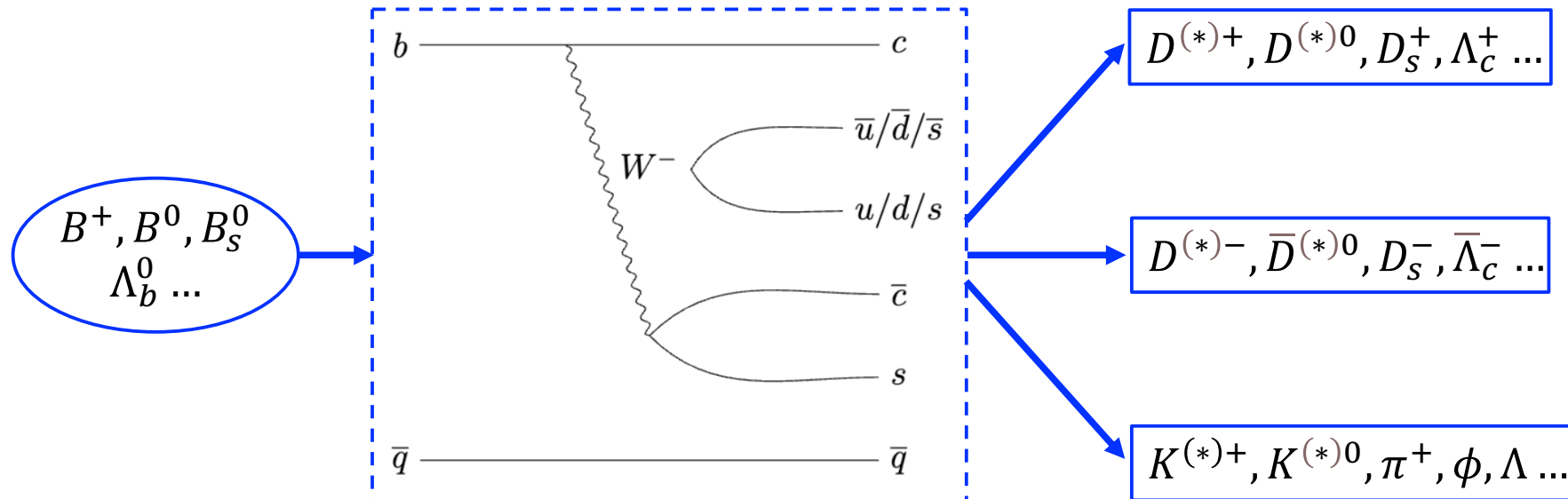


Exotic hadron naming convention: [PDG2024](#)

Charm spectroscopy with $B \rightarrow D\bar{D}h$ decays

Why $B \rightarrow D\bar{D}h$ decays

- Rich opportunities for spectroscopy
 - Excited $D^+, D^0, D_s^+, \Lambda_c^+$ states from $D^{(*)}h, \Lambda_c^+ h \dots$
 - Charmonium(-like) states in $D^{(*)}\bar{D}^{(*)}, \Lambda_c^+\bar{D}^{(*)}, \Lambda_c^+\bar{\Lambda}_c^- \dots$
 - Open-heavy-flavor exotic states from $\bar{D}^{(*)}h, \bar{\Lambda}_c^- h \dots$
- Improve previous studies by B-factories with higher signal and lower background



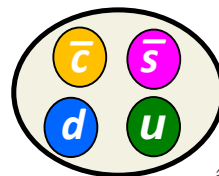
$T_{cs0,1}^*$ in $B^- \rightarrow D^- D^+ K^-$ decays

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

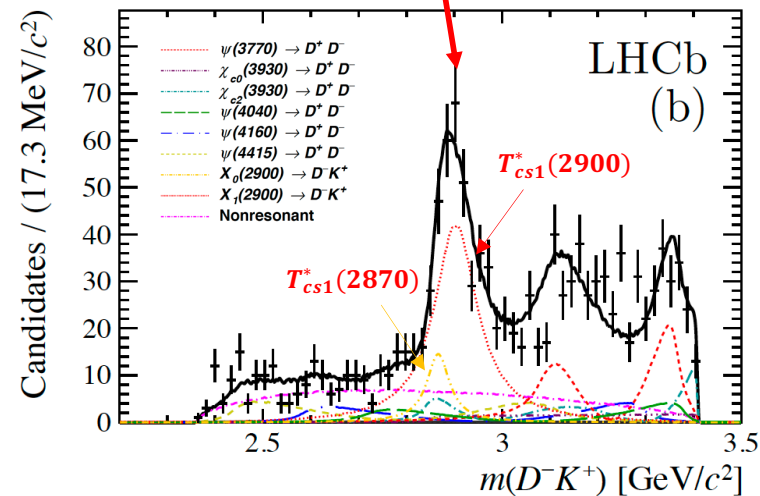
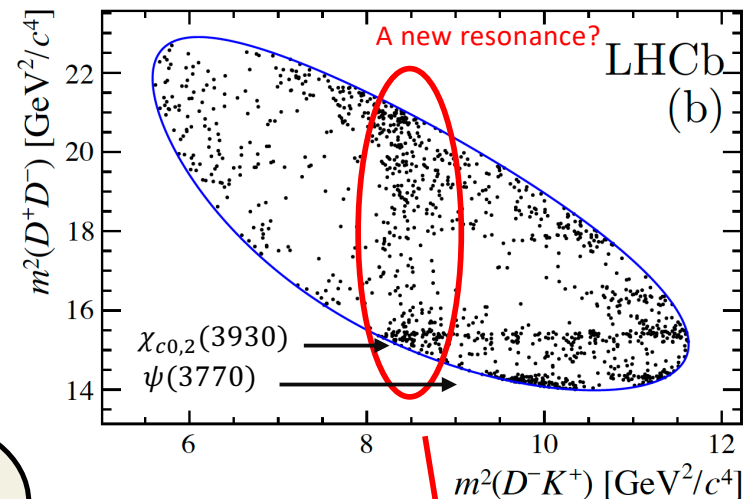
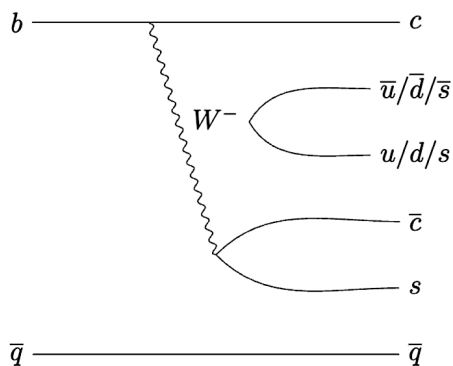
$$T_{cs0,1}^*(2900)^0 \rightarrow D^+ K^-$$

$$\chi_{c0,2}(3930) \rightarrow D^+ D^-$$

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



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



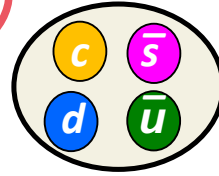
$T_{c\bar{s}0}^*$ in $B \rightarrow \bar{D} D_s^+ \pi^\pm$ decays

[PRL 131 (2023) 041902]

$$\begin{aligned} T_{c\bar{s}0}^*(2900)^{++} &\rightarrow D_s^+ \pi^+ \\ T_{c\bar{s}0}^*(2900)^0 &\rightarrow D_s^+ \pi^- \end{aligned}$$

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

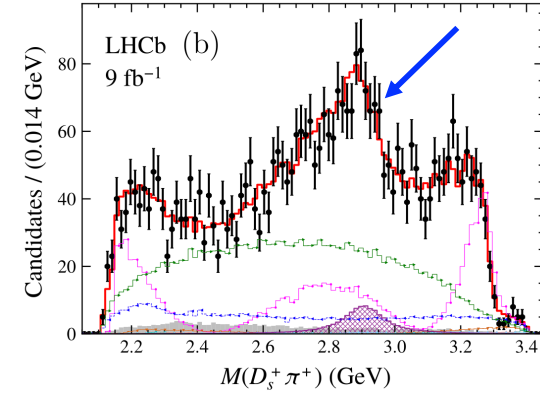
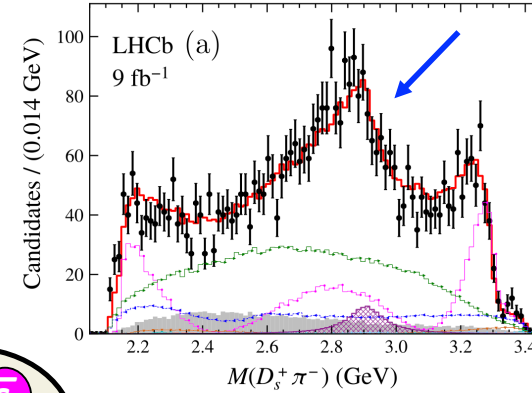
$$T_{cs0,1}^*(2900), \chi_{c0,2}(3930)$$



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

&

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

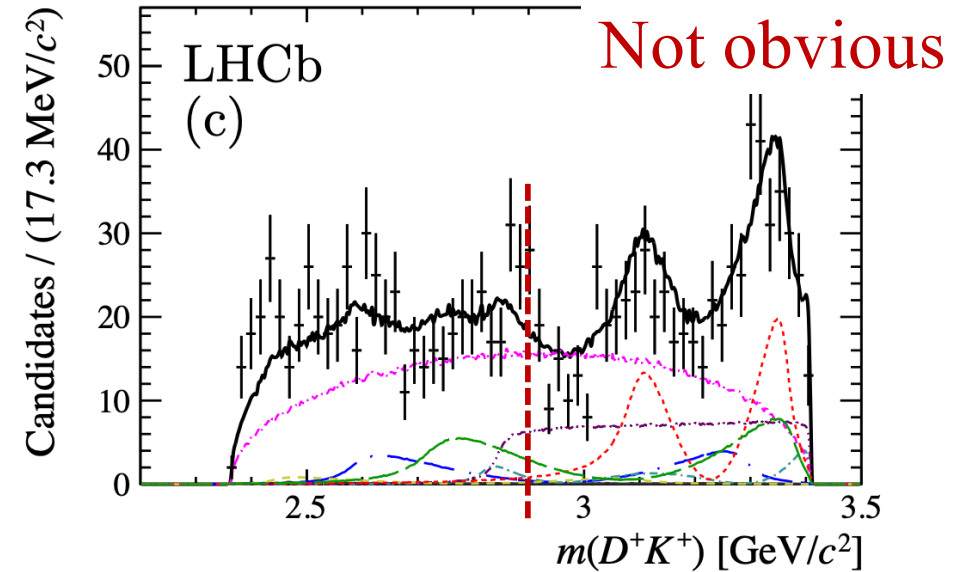
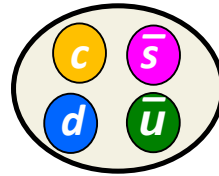
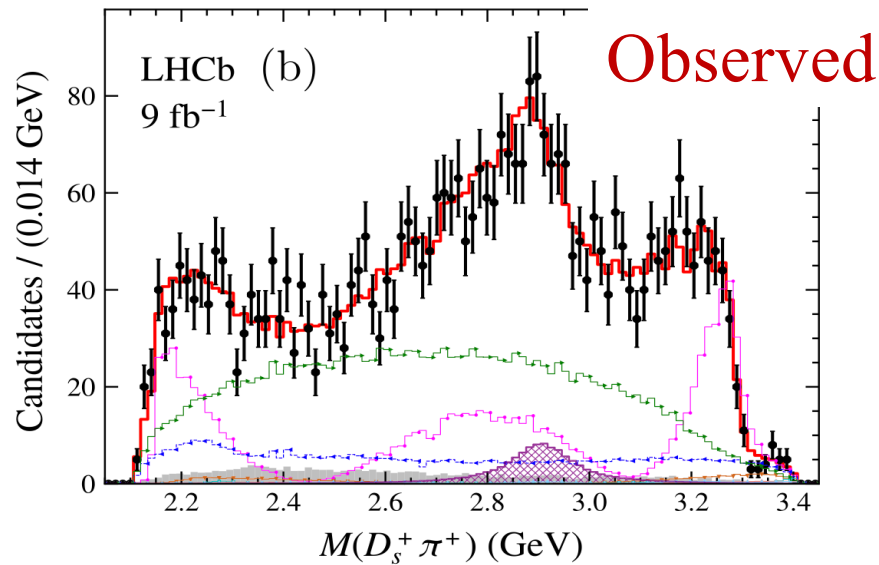
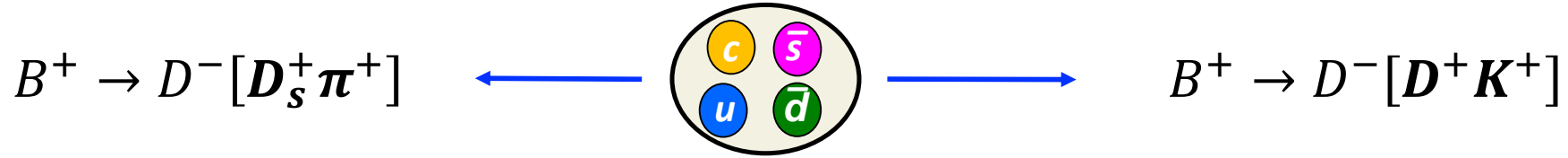


Puzzle for $T_{c\bar{s}0}^*(2900)$

[PRL 131 (2023) 041902]

[PRD 102 (2020) 112003]

$$B^+ \rightarrow D^- T_{c\bar{s}0}^*(2900)^{++}$$



$$B^0 \rightarrow \bar{D}^0 T_{c\bar{s}0}^*(2900)^0 \rightarrow \bar{D}^0 D_s^+ \pi^- \text{ and } \bar{D}^0 D^0 K^0 ?$$

$X_0(3960)$ in $B \rightarrow D_s^+ D_s^- K^+$ decays

[PRL 131 (2023) 071901]

$$B^+ \rightarrow D_s^+ D_s^- K^+$$

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

$T_{cs0,1}^*(2900), \chi_{c0,2}(3930)$

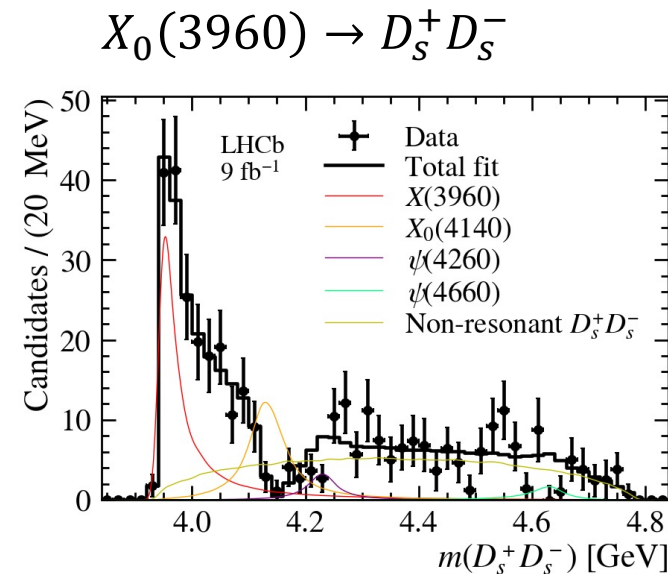
$$B^+ \rightarrow D^- D_s^+ \pi^+$$

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

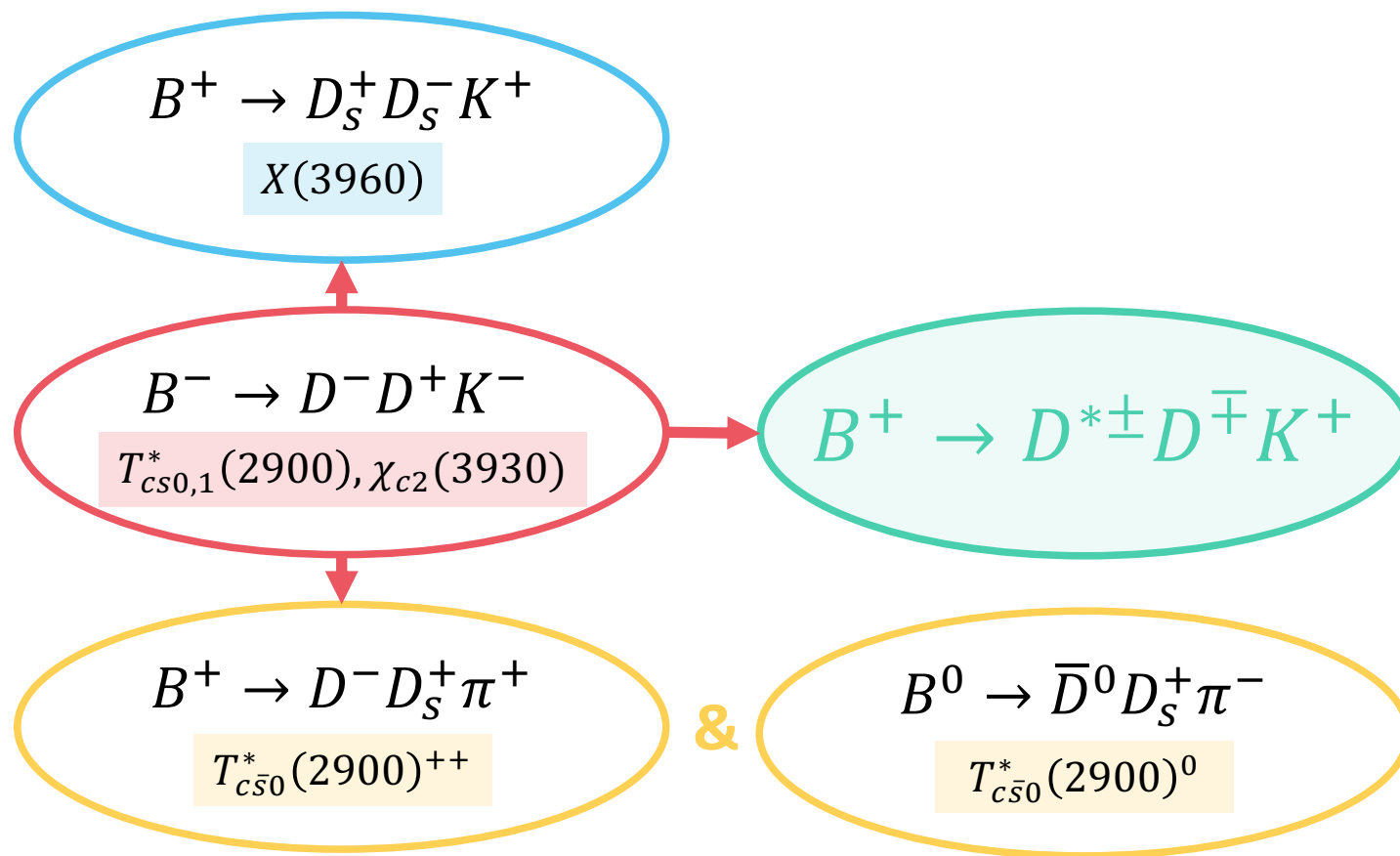
&

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

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



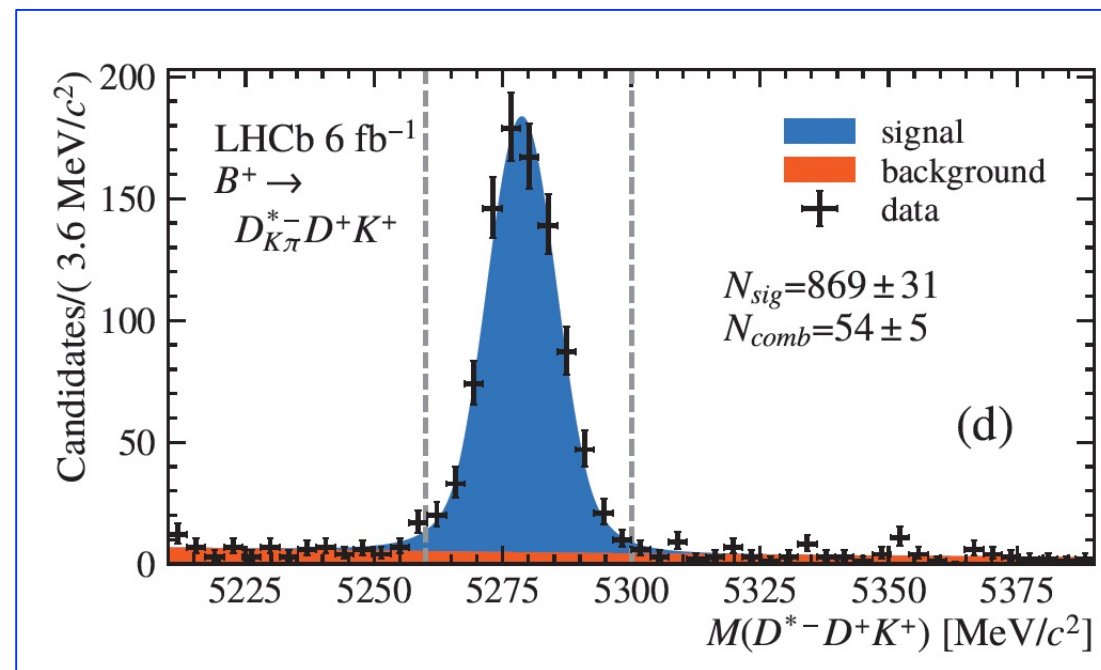
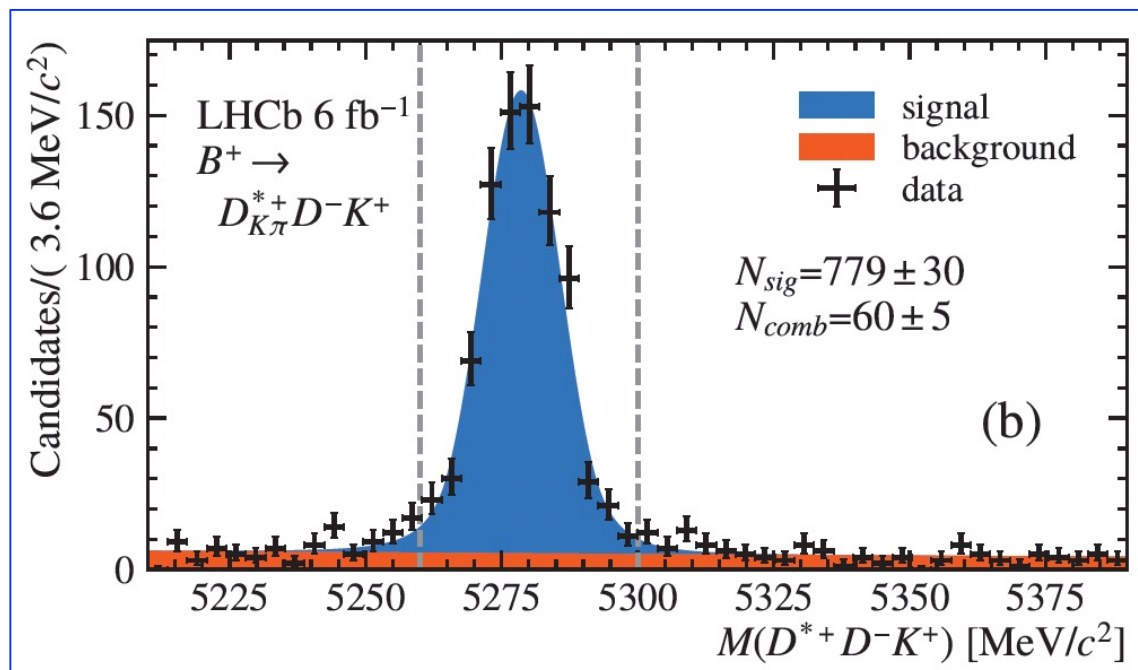
New states in $B^+ \rightarrow D^{*\pm} D^{\mp} K^+$ decays



$B^+ \rightarrow D^{*\pm} D^{\mp} K^+$: signal yields

[PRL 133 (2024) 131902]

- Full LHCb Run1&2 dataset of 9 fb^{-1} : $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+ \& K^-\pi^+\pi^+\pi^-)\pi^+$



Signal yields:

- ✓ $B^+ \rightarrow D^{*+} D^- K^+$: ~ 1636
- ✓ $B^+ \rightarrow D^+ D^{*-} K^+$: ~ 1772

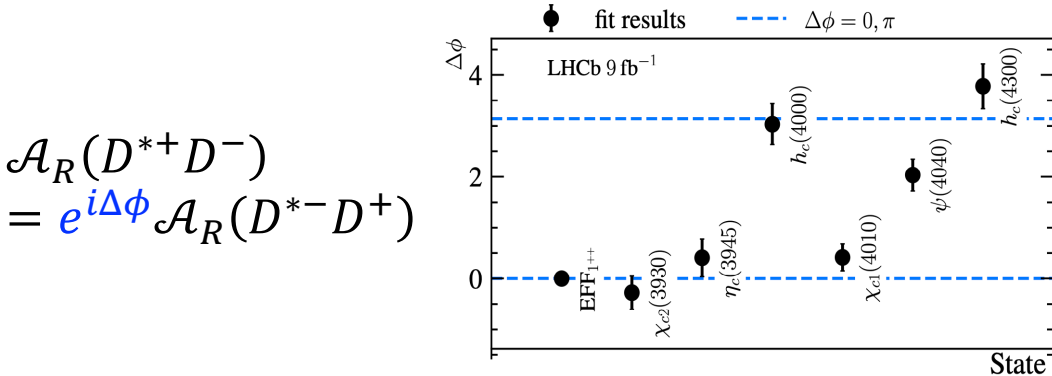
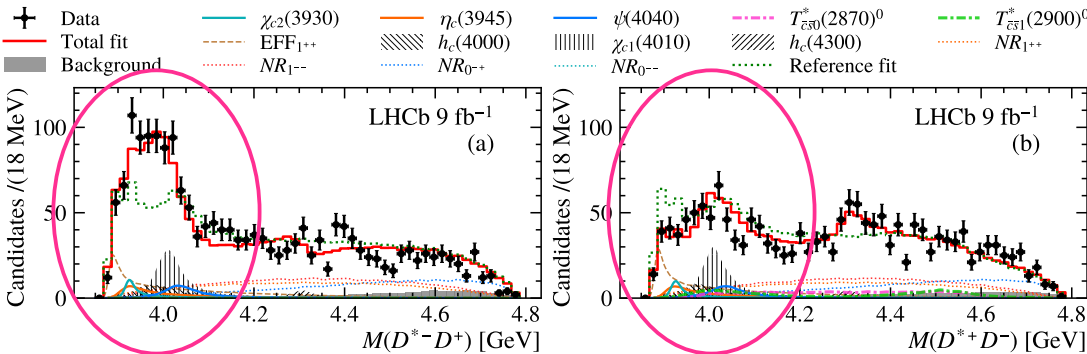
$B^+ \rightarrow D^{*\pm} D^\mp K^+$: amplitude analysis

[PRL 133 (2024) 131902]

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

C-even: $\mathcal{A}_R(D^{*+} D^-) = +\mathcal{A}_R(D^{*-} D^+)$

C-odd: $\mathcal{A}_R(D^{*+} D^-) = -\mathcal{A}_R(D^{*-} D^+)$



$$\mathcal{A}_R(D^{*+} D^-) = e^{i\Delta\phi} \mathcal{A}_R(D^{*-} D^+)$$

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 ⁻⁺

- New charmonium(-like) states decaying to $D^* \bar{D}$ observed ($> 6.1\sigma$)
- J^{PC} determined ($> 5.7\sigma$)
- Exotics or charmonium? Isospin could shed light

Open charm tetraquarks

[PRL 133 (2024) 131902]

- $T_{c\bar{s}0,1}^*$ states, observed in $B^- \rightarrow D^- D^+ K^-$, confirmed in $B^- \rightarrow D^{*-} D^+ K^-$ decays

$$\frac{\mathcal{B}(B^+ \rightarrow T_{c\bar{s}0}^*(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \rightarrow T_{c\bar{s}1}^*(2900)^0 D^{(*)+})}$$

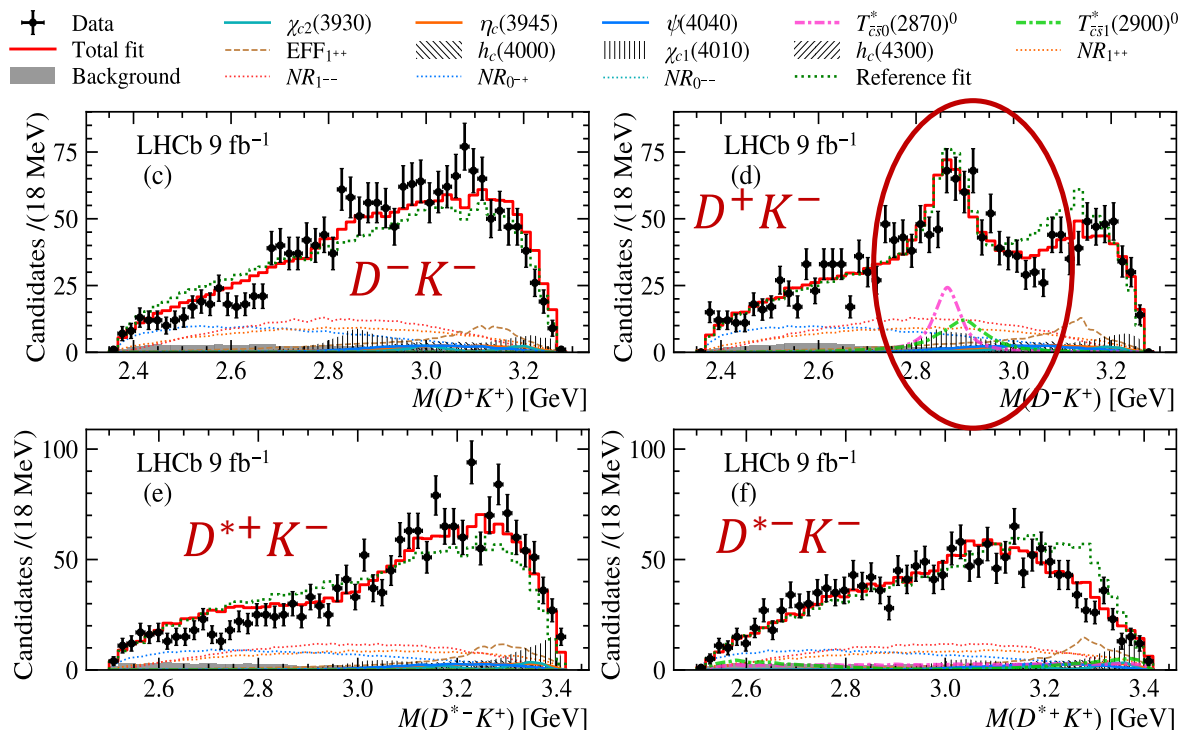
$$B^- \rightarrow D^{*-} D^+ K^-$$

$$1.17 \pm 0.31 \pm 0.48$$

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

$$0.18 \pm 0.05$$

- No obvious structure in $D^{*\pm} K^-$ and $D^- K^-$ spectra

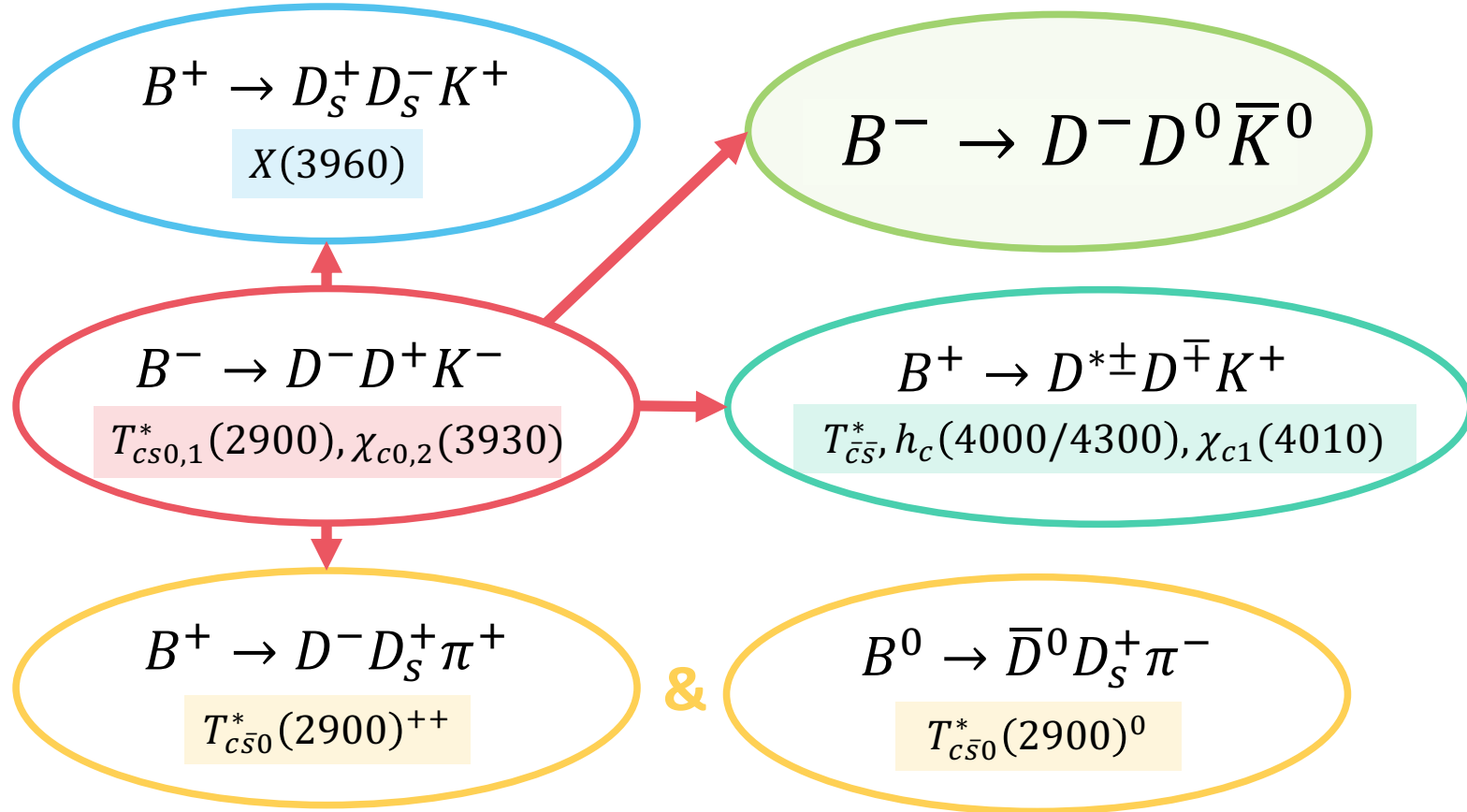


Component	$J^{P(C)}$
EFF ₁₊₊	1 ⁺⁺
$\eta_c(3945)$	0 ⁻⁺
$\chi_{c2}(3930)^\dagger$	2 ⁺⁺
$h_c(4000)$	1 ⁺⁻
$\chi_{c1}(4010)$	1 ⁺⁺
$\psi(4040)^\dagger$	1 ⁻⁻
$h_c(4300)$	1 ⁺⁻
$T_{c\bar{s}0}^*(2870)^{0\dagger}$	0 ⁺
$T_{c\bar{s}1}^*(2900)^{0\dagger}$	1 ⁻
NR ₁₋₋ ($D^{*\mp} D^\pm$)	1 ⁻⁻
NR ₀₋₋ ($D^{*\mp} D^\pm$)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

11σ

9.2σ

T_{cs}^* in $B^- \rightarrow D^- D^0 \bar{K}^0$ decays



$T_{cs0}^*(2870)^0$ new decay mode

[PRL 134 (2025) 101901]

- Amplitude analysis of $B^- \rightarrow D^- D^0 K_S^0$
Significant $T_{cs0}^*(2870)^0 \rightarrow D^0 K_S^0 (5.3\sigma)$

No obvious $T_{cs1}^*(2900)^0 \rightarrow D^0 K_S^0$

$$T_{cs}^*[cs\bar{u}d] \rightarrow D^+ K^-, D^0 \bar{K}^0$$

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

$$m = 2883 \pm 11 \pm 6 \text{ MeV}$$

$$\Gamma = 87_{-47}^{+22} \pm 6 \text{ MeV}$$

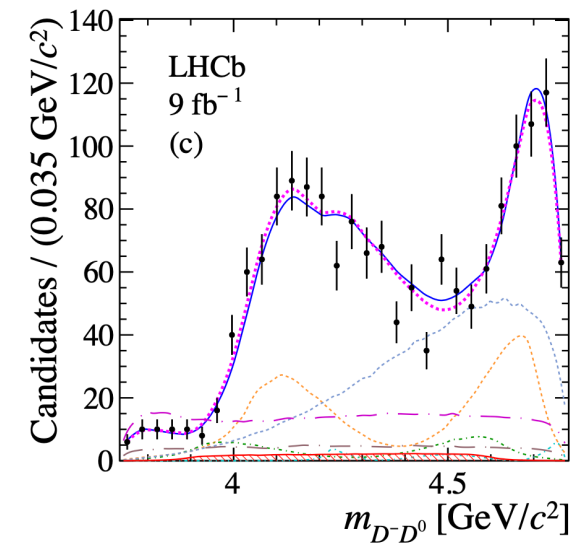
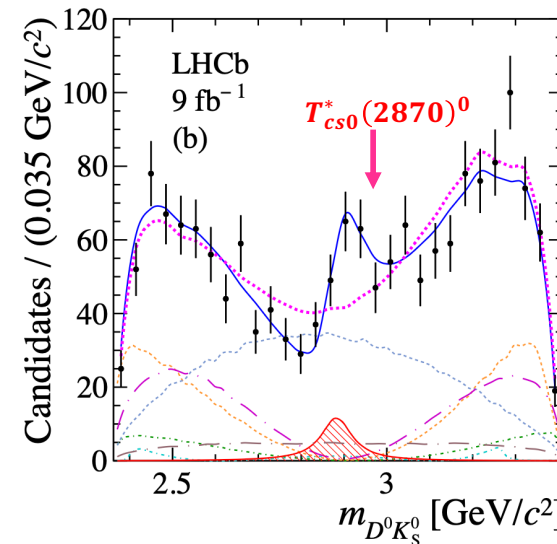
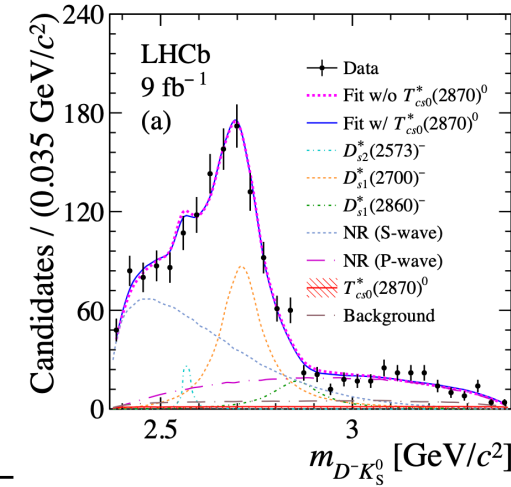
Consistent with $B^- \rightarrow D^- D^+ K^-$

- Isospin tests:

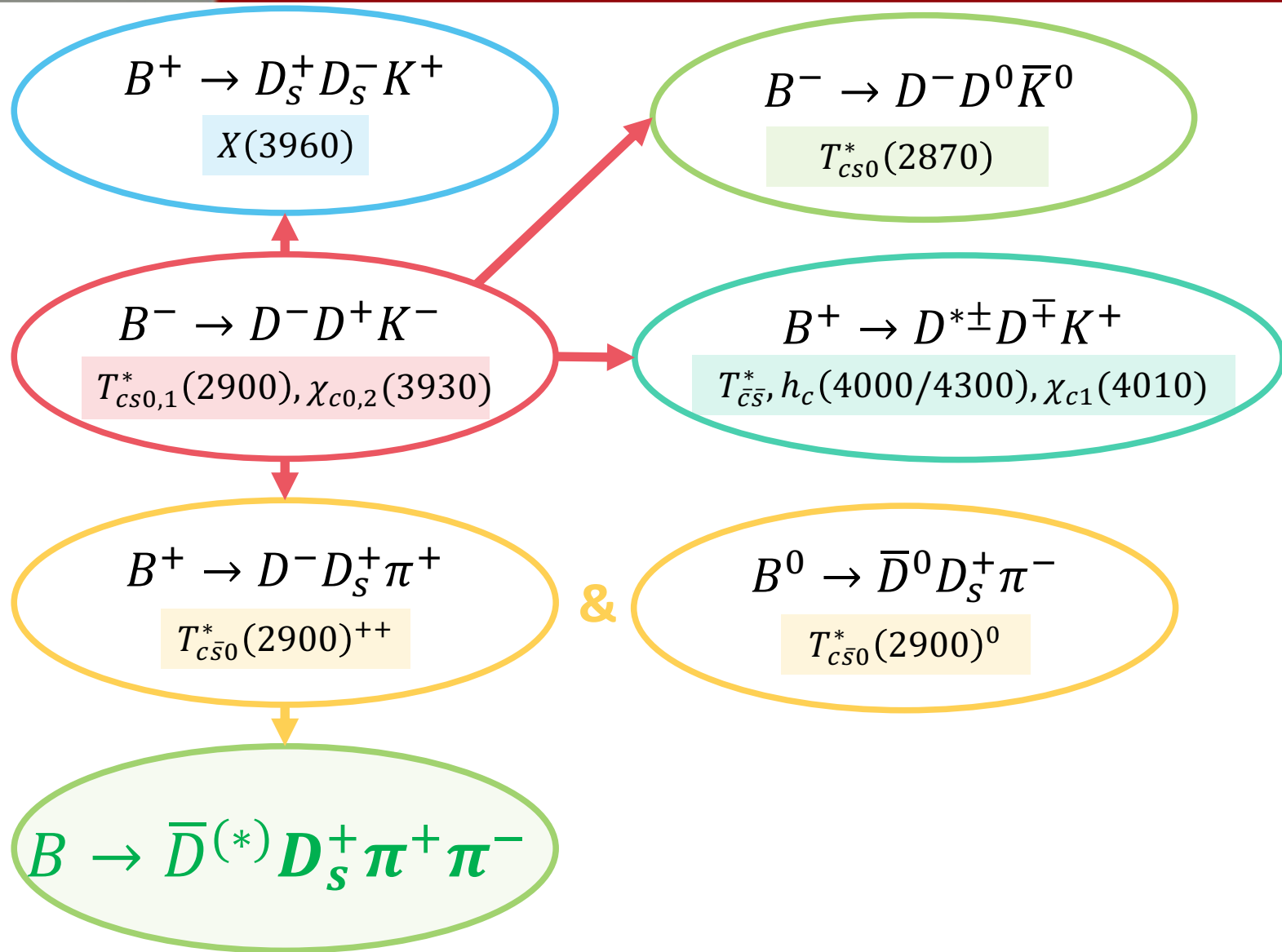
$$\frac{T_{cs0}^*(2870)^0 \rightarrow D^0 \bar{K}^0}{T_{cs0}^*(2870)^0 \rightarrow D^+ K^-} = 3.3 \pm 1.9$$

$$\frac{T_{cs1}^*(2900)^0 \rightarrow D^0 \bar{K}^0}{T_{cs1}^*(2900)^0 \rightarrow D^+ K^-} = 0.15 \pm 0.17$$

Isospin symmetry: ratio close 1



Excited D_s^+ state in $B \rightarrow \bar{D} D_s^+ \pi^+ \pi^-$ decays



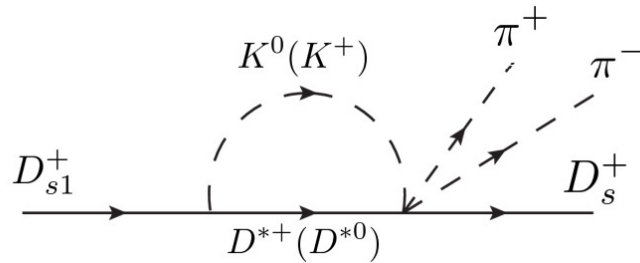
Study of $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decay

- Unexpected properties for $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$

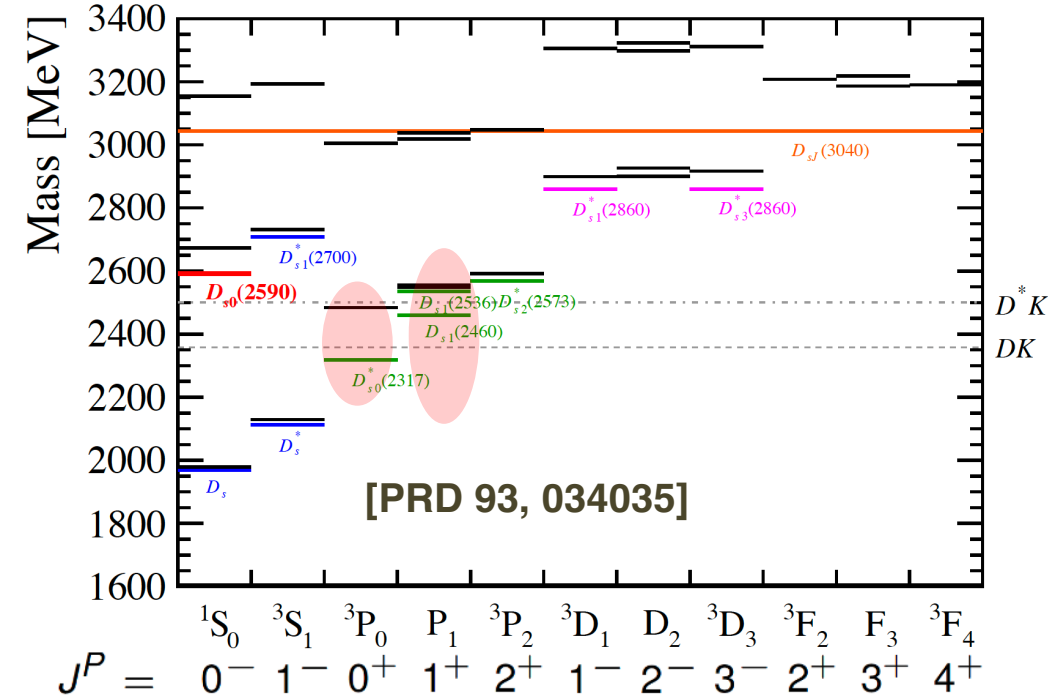
- Masses ~ 100 MeV below prediction
- Isospin-violating decay $D_s^{(*)+} \pi^0$ dominate

- 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



[Commun. Theor. Phys.
75 055203]



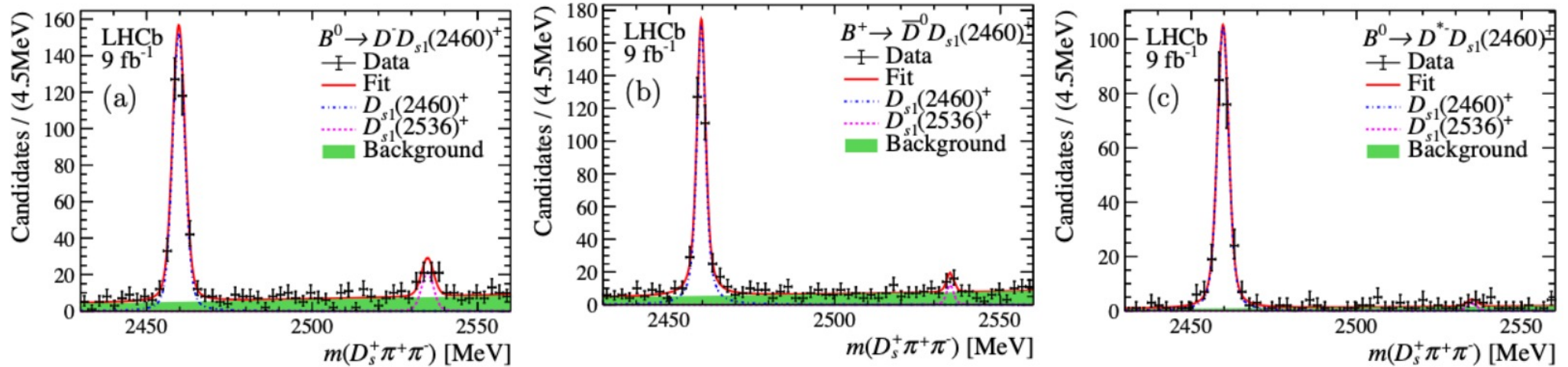
- $D_{s0}^*(2317)^+$ as tetraquark: isospin partners proposed inspired by observation $T_{c\bar{s}}(2900)^{++/0} \rightarrow D_s^+ \pi^{+/0}$

[PRD 110, 034014]

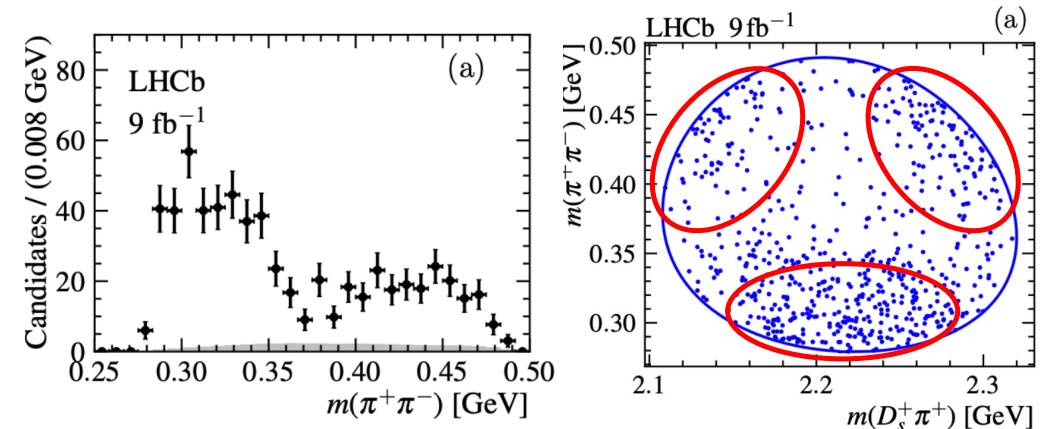
Study of $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decay

[arXiv:2411.03399]

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



- Double-bump structure in $m(\pi\pi)$
- Amplitude analyses performed
 - $f_0(500) + f_0(980)$, or $\pi\pi$ K-matrix cannot describe data well
 - Model directly from theory cannot describe data well either



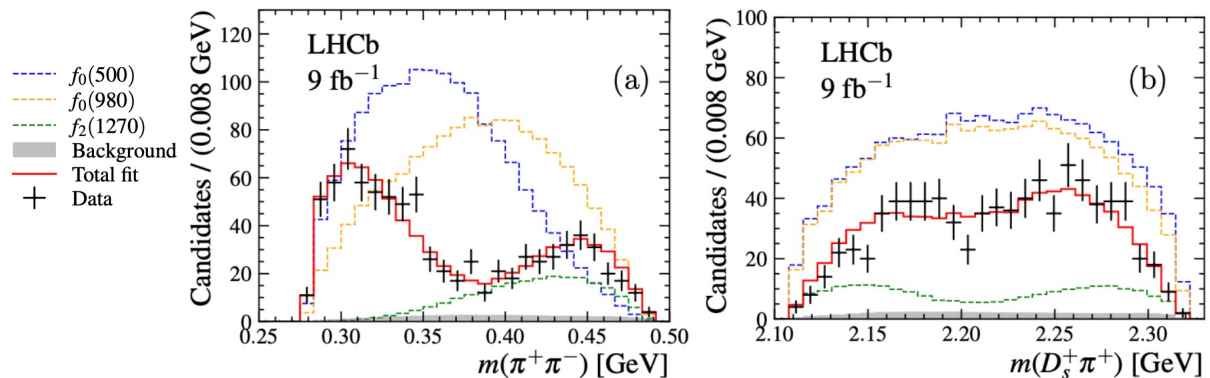
[Commun. Theor. Phys. 75 055203]

Two models can fit the data well

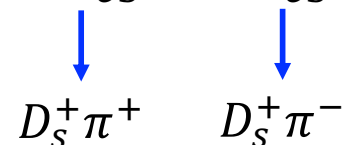
[arXiv:2411.03399]

- $f_0(500) + f_0(980) + f_2(1270)$
 - Large contribution from $f_0(980)$ and $f_2(1270)$ despite beyond phase space limit
 - Can't 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	$29 \pm 2 \pm 1$



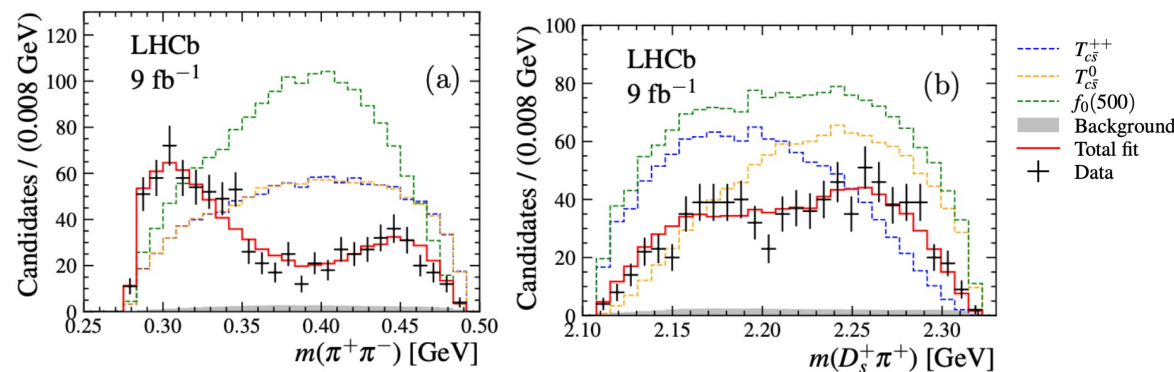
- $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^0$ (new exotics)



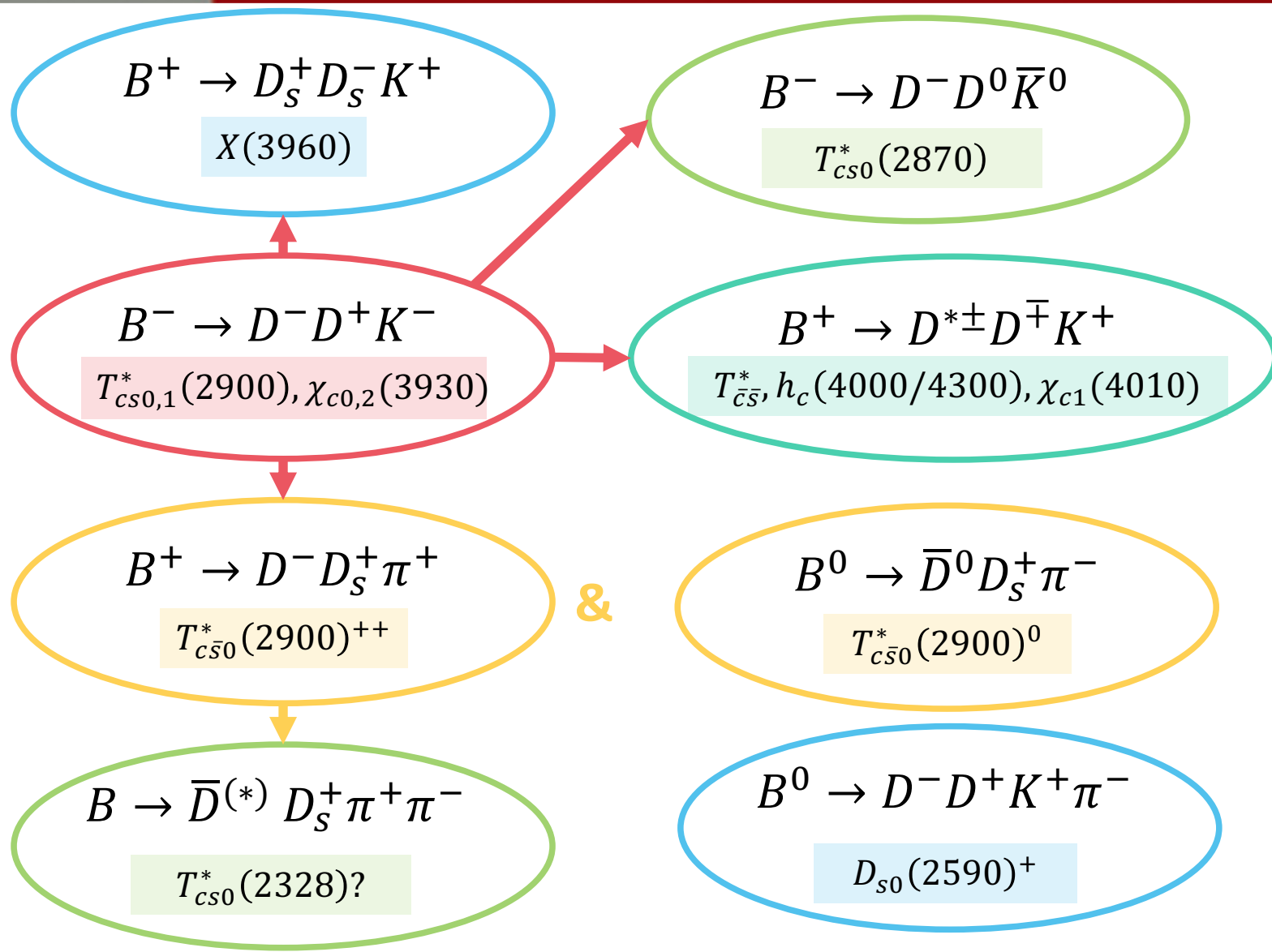
Consistent with isospin symmetry

$T_{c\bar{s}}$ masses $\sim D_{s0}^*(2317)^+$, but different widths

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$472 \pm 32 \pm 19$	$226 \pm 24 \pm 18$	$237^{+51}_{-43} \pm 42$
$T_{c\bar{s}}$	$2328 \pm 12 \pm 12$	$96 \pm 16^{+170}_{-23}$	$151^{+31}_{-33} \pm 25$



Excited D_s^+ in $B^0 \rightarrow D^- D^+ K^+ \pi^-$ decays



$D_{s0}(2590)^+$ in $B^0 \rightarrow D^- D^+ K^+ \pi^-$ decay

- Enhancement around 2.6 GeV in $D^+ K^+ \pi^-$ mass spectrum
- Amplitude fit for low $m(K^+ \pi^-)$ mass region

$K^+ \pi^-$ dominated by $K_0^*(700)^0$ S-wave

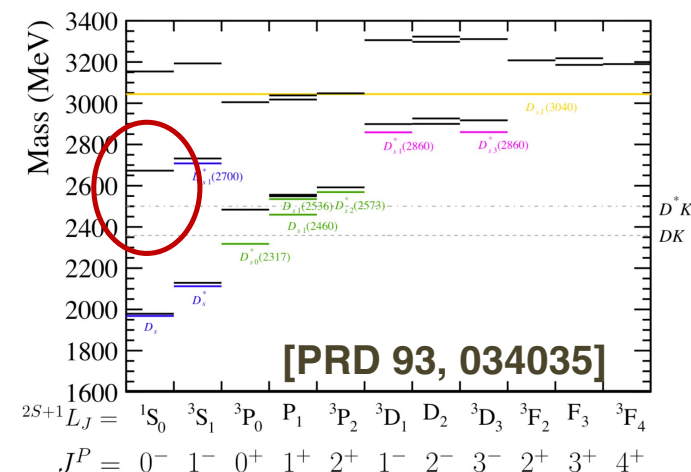
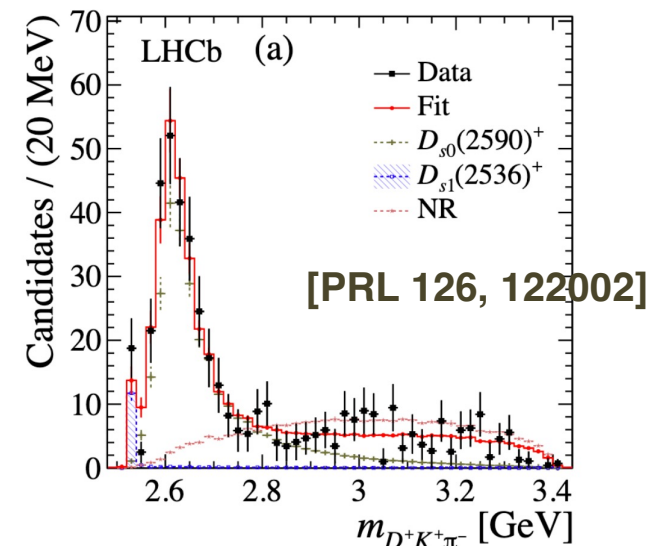
- Observation of $D_s(2590)^+$

$J^P = 0^-$ preferred, $1^+, 2^-$ rejected by $>15\sigma$

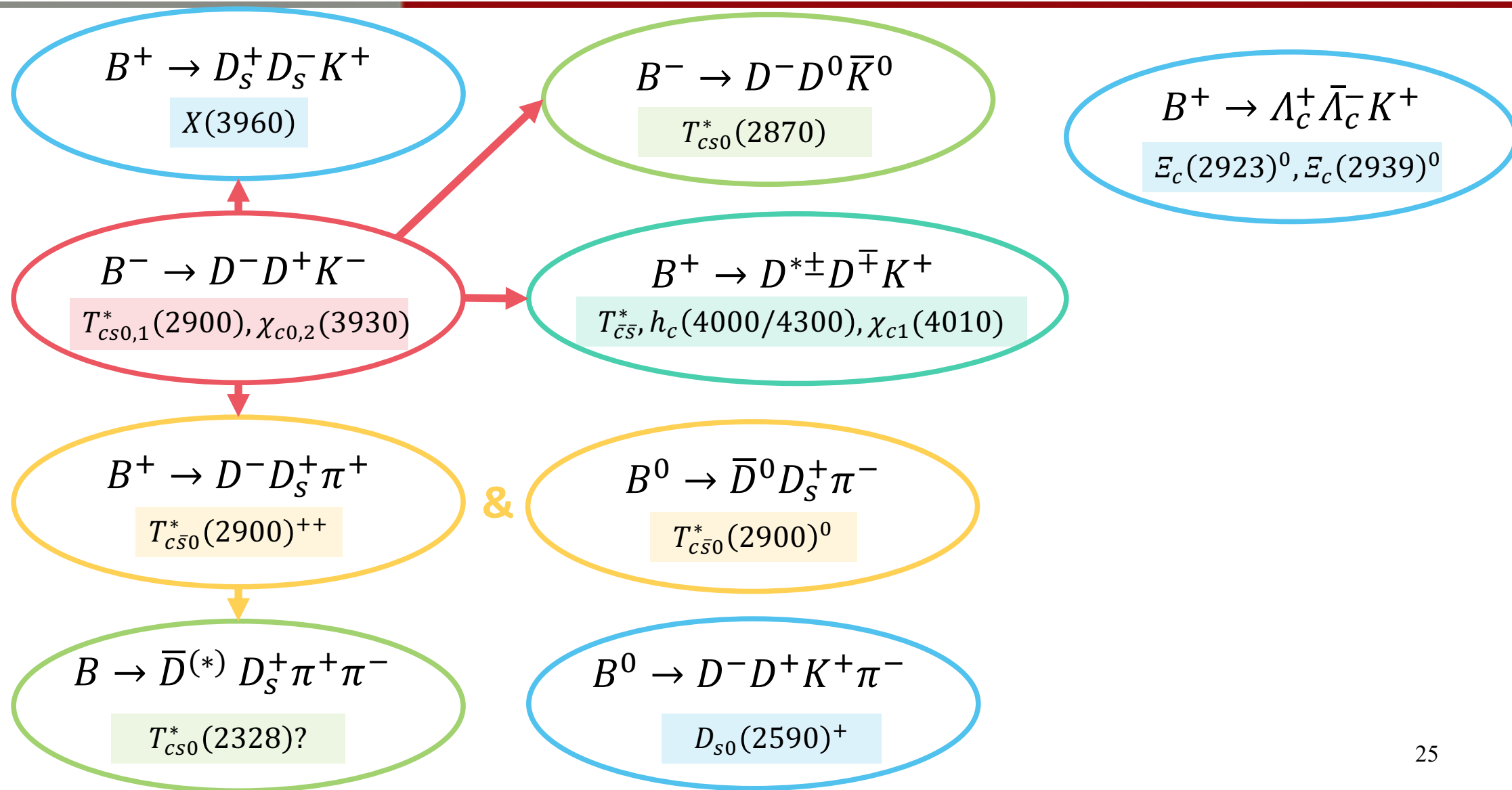
$m = 2591 \pm 6 \pm 7$ MeV

$\Gamma = 89 \pm 16 \pm 12$ MeV

- Consistent with the $D_s(2^1S_0)^+$ state, but mass 80 MeV lower than prediction, but width is compatible
- Amplitude fit in full phase space ongoing



States in $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$ decay



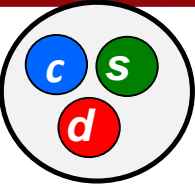
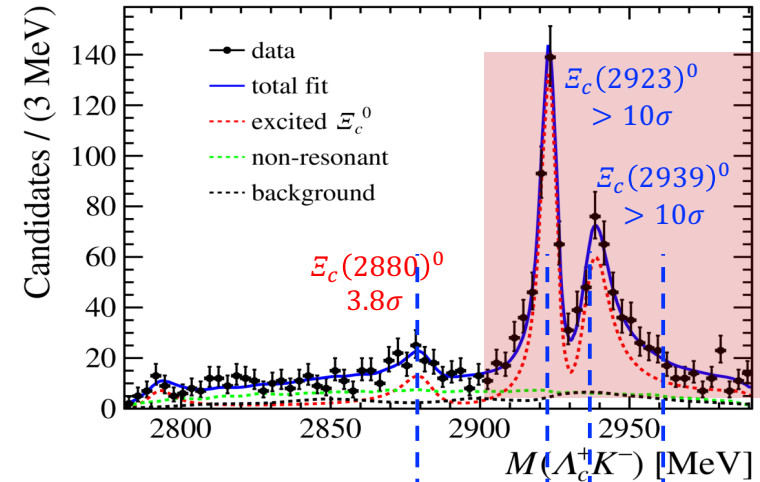
Observing Ξ_c state in $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$ decay

- Interesting for conventional & exotic studies
 - $\Xi_c^{0**} \rightarrow \Lambda_c^+ K^-$; exotics in $\Lambda_c^+ \bar{\Lambda}_c^-$ and $\bar{\Lambda}_c^- K^-$?
- High-purity sample, with $N_{\text{sig}} = 1365 \pm 42$
- $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ baryons confirmed
- Evidence of a new $\Xi_c(2880)^0$

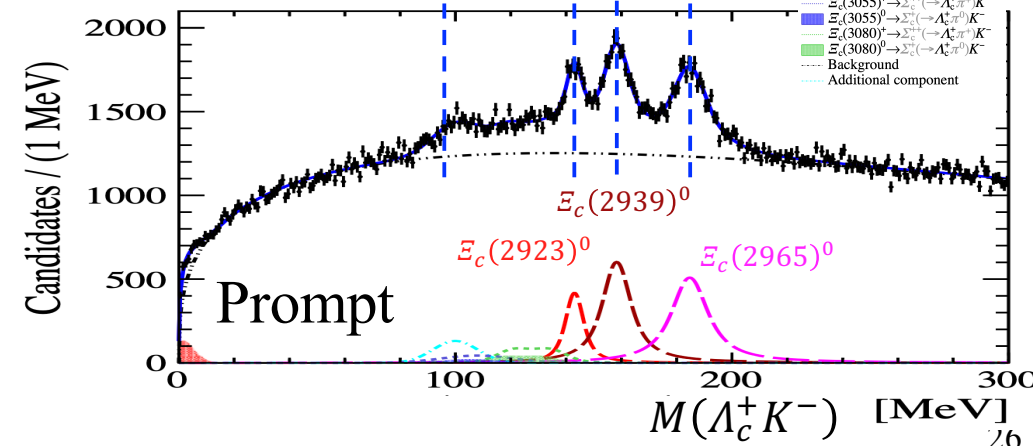
State	Mass (MeV)	Width (MeV)
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$

- No significant hint for exotic hadrons in $\Lambda_c^+ \bar{\Lambda}_c^-$ or $\bar{\Lambda}_c^- K^-$ mass spectra
- (In)consistency with prompt production
 - Missing states, different relative yields

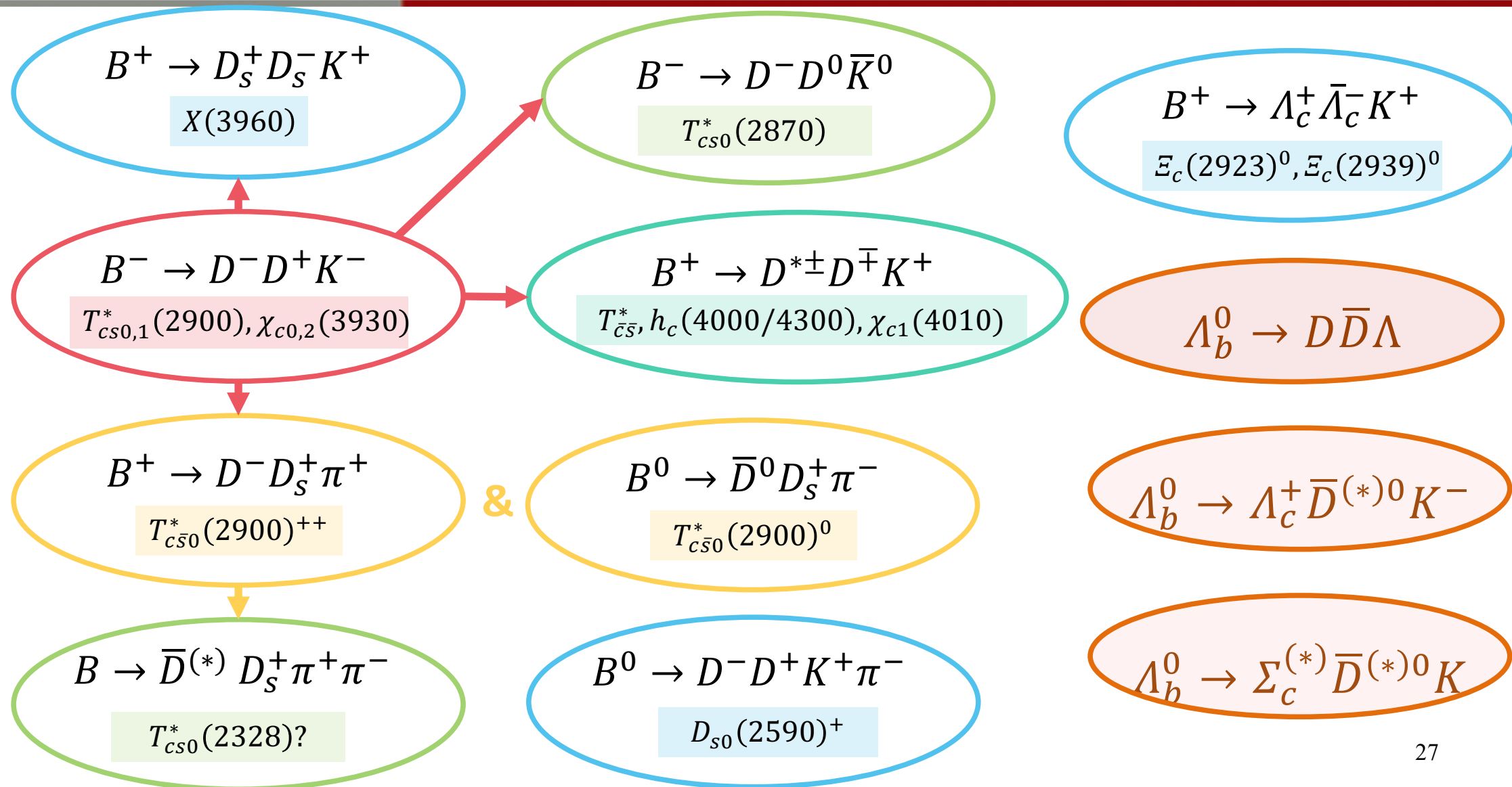
[PRD 108 (2023) 012020]



[PRL 124 (2020) 222001]



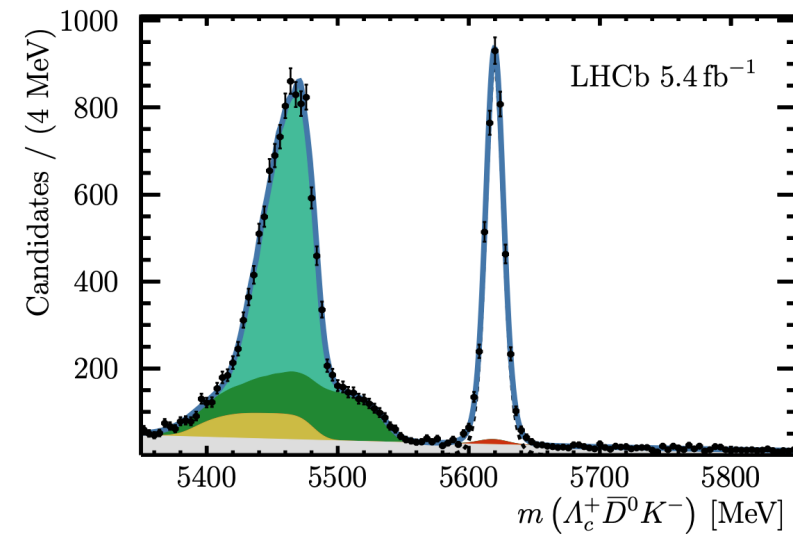
Beauty baryon decays



Observation of $\Lambda_b^0 \rightarrow c\bar{c}s$ decays

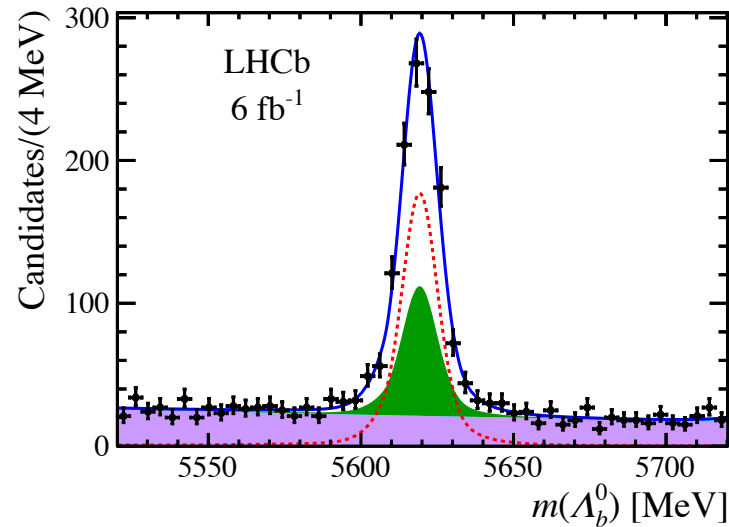
- Pave way for hidden- or open-charm pentaquarks

$$\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^-$$



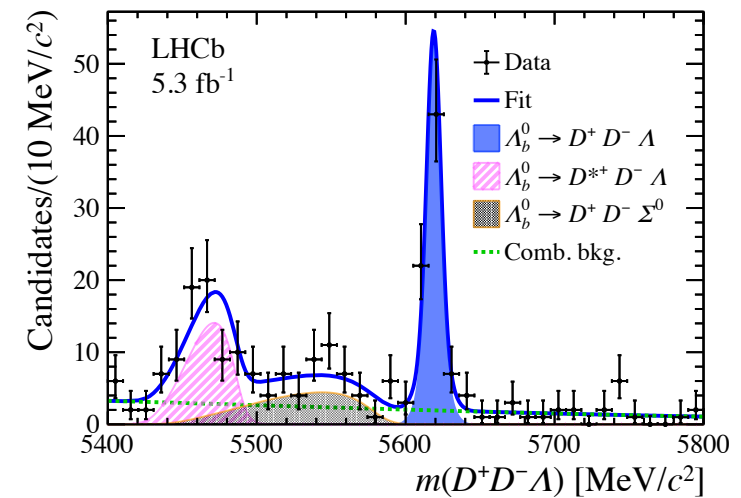
[EPJC 84 (2024) 575]

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



[PRD 110 (2024) L031104]

$$\Lambda_b^0 \rightarrow D^+ D^- \Lambda$$



[JHEP 07 (2024) 140]

Quarkonium(-like) states

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

- Nature of $\chi_{c1}(3872)$ still under debate, radiative decays sensitive to structure
- Only evidence of $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ was seen experimentally

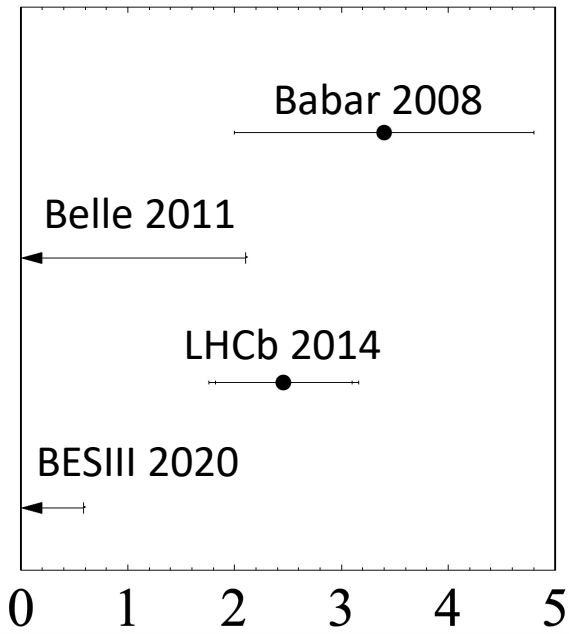
Reference		$\mathcal{R}_{\psi\gamma}$	
T. Barnes and S. Godfrey	67	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	69	2.6	$c\bar{c}$
F. De Fazio	84	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	85	1.3	$c\bar{c}$
Y. Dong <i>et al.</i>	86	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian <i>et al.</i>	87	(0.8 ± 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	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

$\gtrsim 1$

$\ll 1$

mixed

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



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

[JHEP 11 (2024) 121]

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

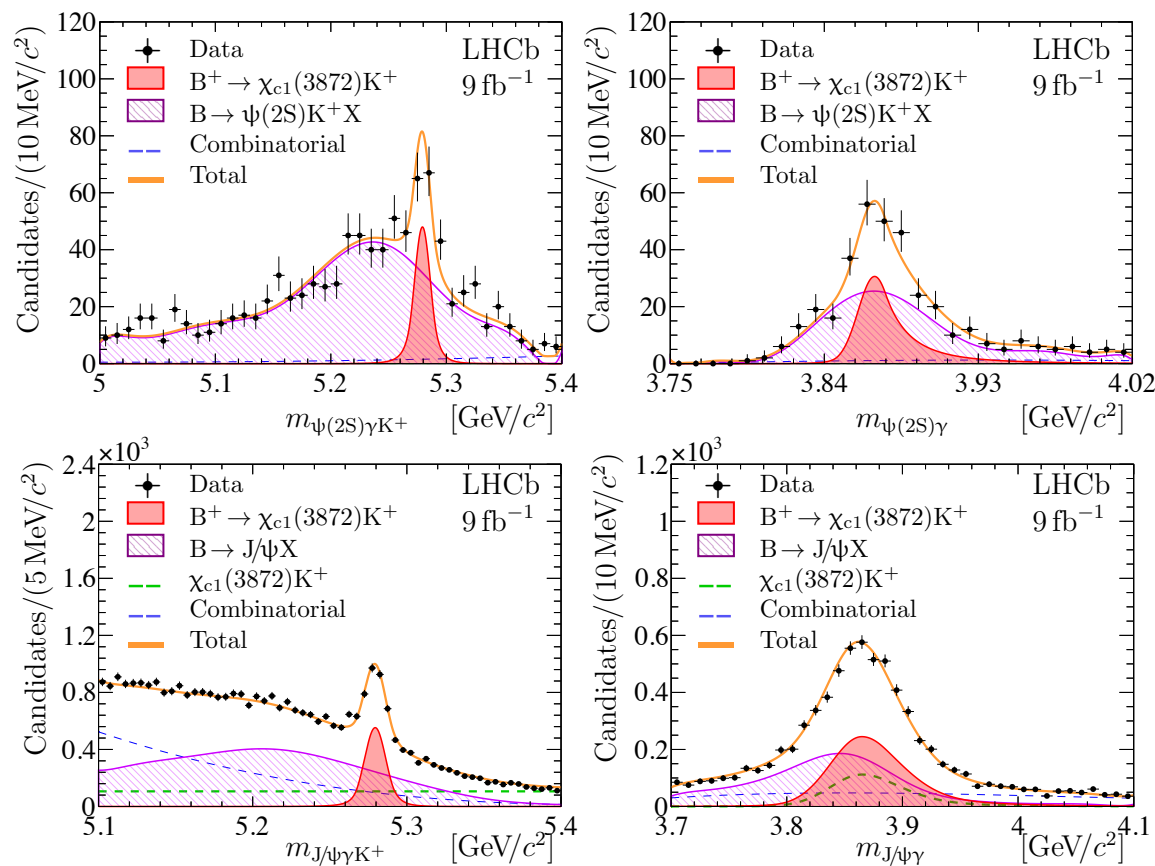
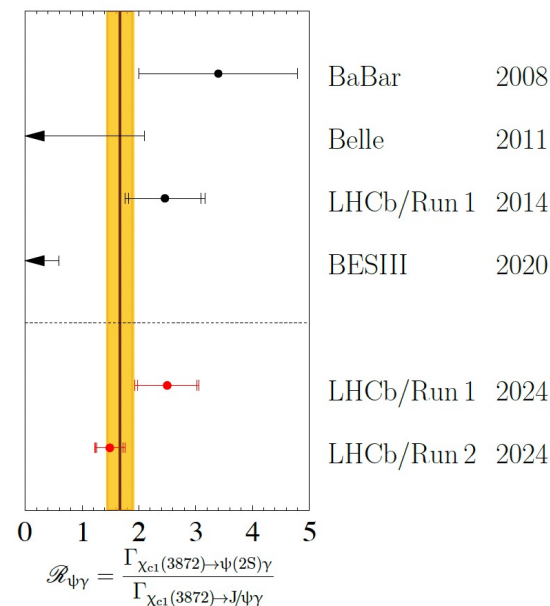
$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \quad (15\%)$$

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

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

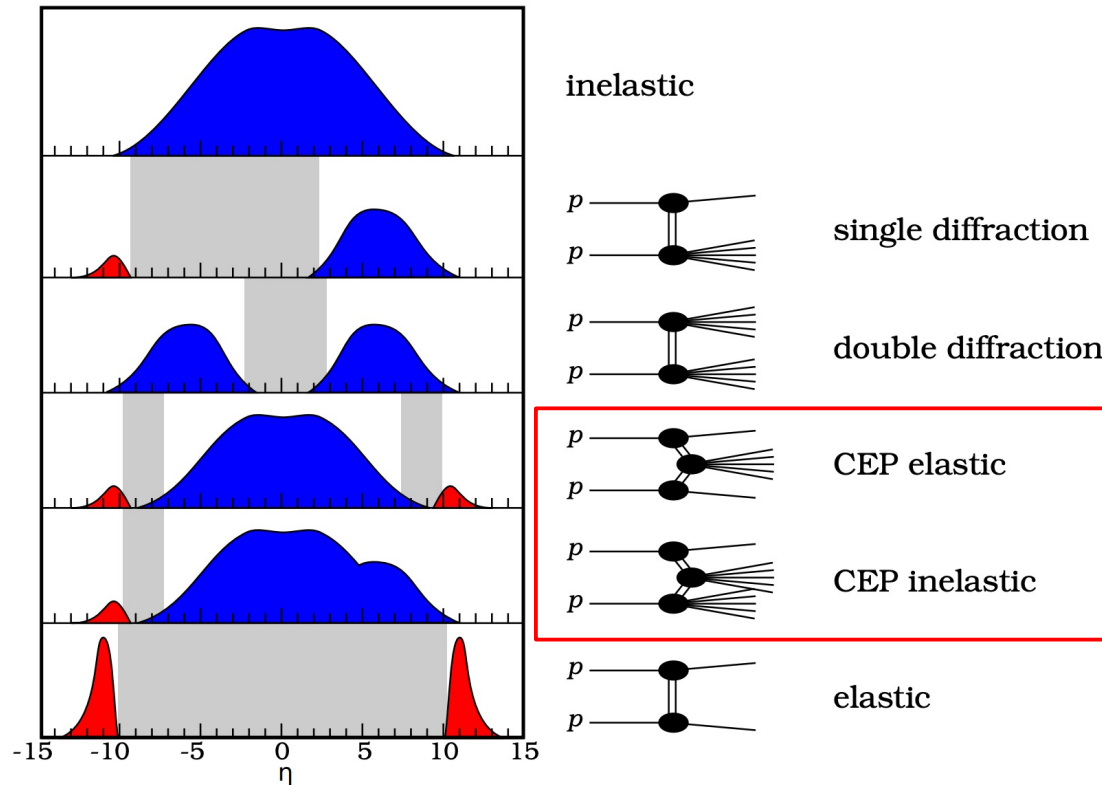
$$\text{Run2: } N = 63 \pm 10; 6.7\sigma$$

LHCb average

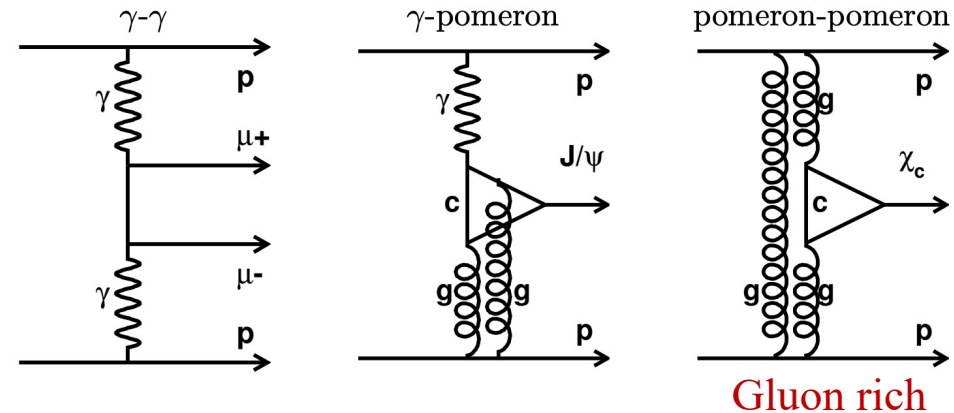


Central exclusive production (CEP)

■ Study $J/\psi\phi$ resonances in CEP

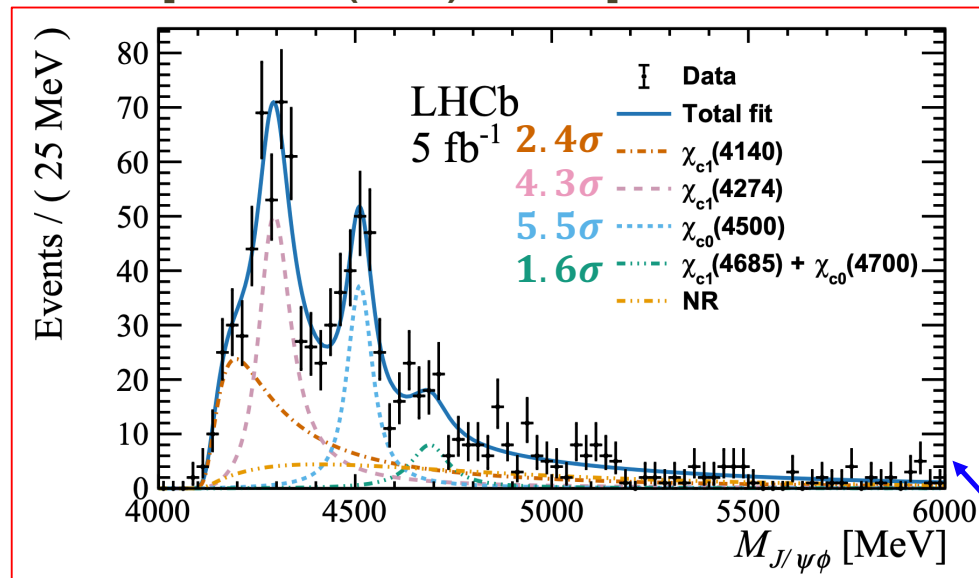


- ✓ Experimentally clean even @LHC
- ✓ Spin-parity option narrowed down
- ✗ Much smaller rate



$X \rightarrow J/\psi\phi$ in central exclusive production

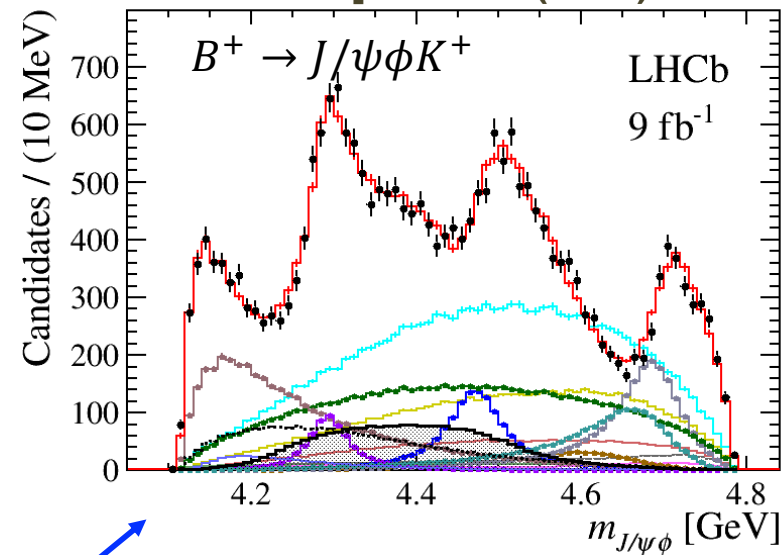
[PRL 134 (2025) 031902]



- First observation of exotics in CEP events
- Mass and width measurements

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

[PRL 127 (2021) 082001]



- Cross-section measurements

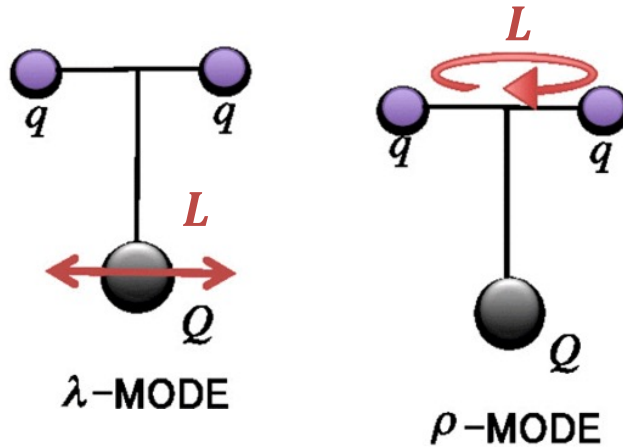
$$\begin{aligned}
 \sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} &= (0.80 \pm 0.15 \pm 0.28) \text{ pb}, \\
 \sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} &= (0.73 \pm 0.08 \pm 0.17) \text{ pb}, \\
 \sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} &= (0.42^{+0.09}_{-0.08} \pm 0.06) \text{ pb}, \\
 \sigma_{\chi_{c1}(4685) + \chi_{c0}(4700)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4685) + \chi_{c0}(4700)} &= (0.14^{+0.07}_{-0.06} \pm 0.06) \text{ pb}, \\
 \sigma_{\text{NR}} \times \mathcal{B}_{\text{eff}}^{\text{NR}} &= (0.43^{+0.24}_{-0.18} \pm 0.20) \text{ pb},
 \end{aligned}$$

Charm baryon spectroscopy

More details in talk by Guanyue WAN (Thursday afternoon)

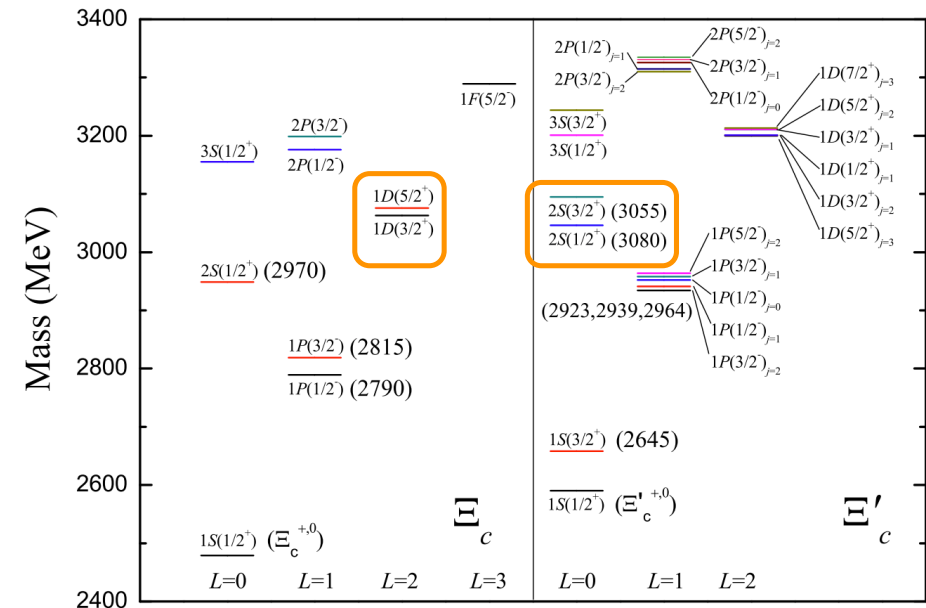
Singly heavy baryons

- Qqq baryons well described by heavy-quark light-diquark $Q[qq]$ model
- ✓ λ -mode can cope with almost all observed states
- ✓ ρ -mode: no firm assignment yet



[PRD 92 (2015) 114029]

- Spin-parity of most states not measured, limiting proper assignment in spectroscopy

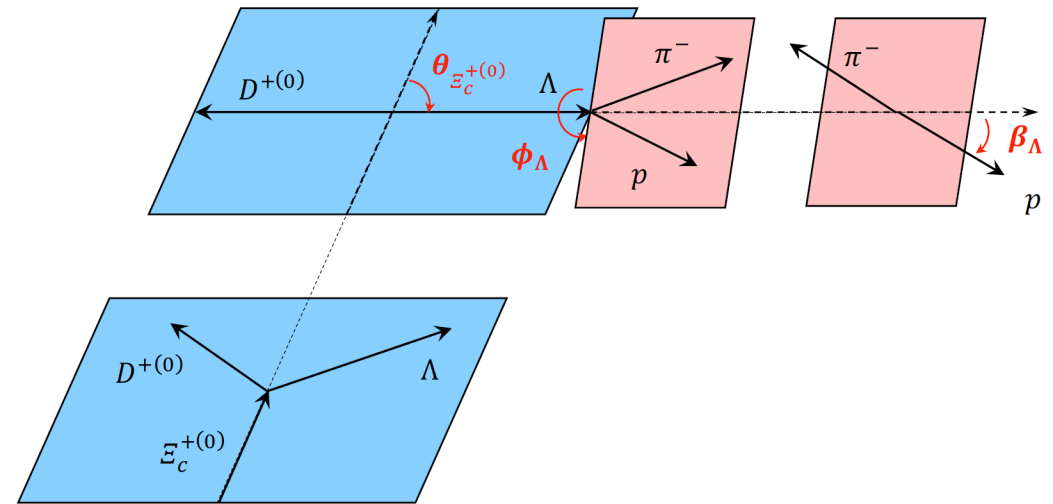
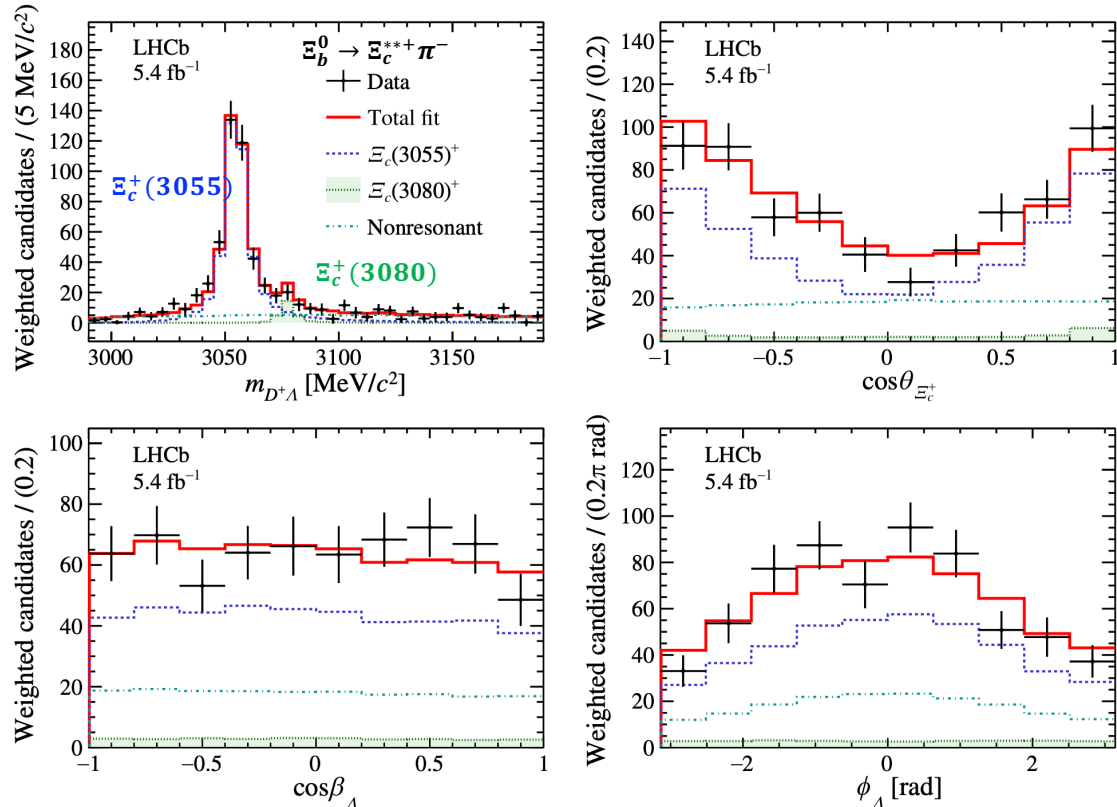
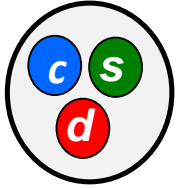


Chinese Phys. C 47 (2023) 073105

Determination of J^P for $\Xi_c(3055)^{+,0}$

[PRL 134 (2025) 081901]

- First observation $\Xi_b^{0(-)} \rightarrow \Xi_c(3055)^{+,0}(\rightarrow D\Lambda)\pi^-$ decays, also evidence for $\Xi_c(3080)$
- Used to study of the properties of $\Xi_c(3055)^{+,0}$ baryons
- Amplitude analysis performed to four observables ($m_{D\Lambda}$, θ_{Ξ_c} , β_Λ , θ_Λ)



1st determination of J^P for $\Xi_c(3055)^{+,0}$

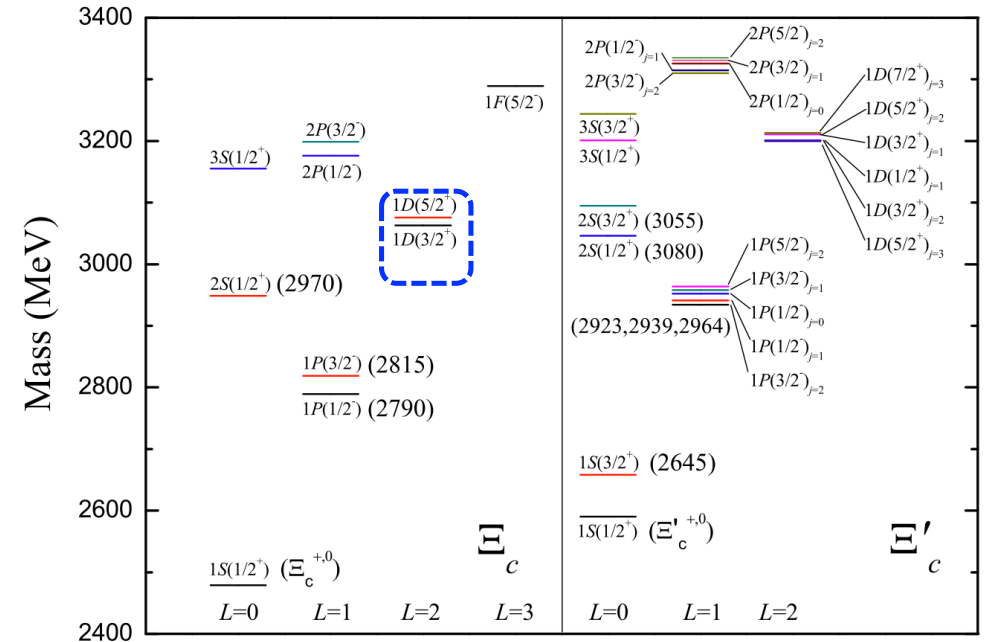
- $J^P = 3/2^+$ determined for $\Xi_c(3055)^{+,0}$ with significances of more than 6.5σ (3.5σ)

J^P and narrow width favor $\Xi_c(3055)$ as
as a 1D λ -mode excitation of flavor antitriplet

- Mass, width, decay parameter and relative rate between $\Xi_c(3080)$ and $\Xi_c(3055)$

Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
m [MeV/ c^2]	$3054.52 \pm 0.36 \pm 0.17$	$3061.00 \pm 0.80 \pm 0.23$
Γ [MeV/ c^2]	$8.01 \pm 0.76 \pm 0.34$	$12.4 \pm 2.0 \pm 1.1$
α	$-0.92 \pm 0.10 \pm 0.05$	$-0.92 \pm 0.16 \pm 0.22$
R_B	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$

[PRL 134 (2025) 081901]



[CPC 47 (2023) 073105]

Hadronic two-body decays of Ω_c^0 baryon

- First observation of Cabibbo-suppressed decays $\Omega_c^0 \rightarrow \Omega^- K^+$ and $\Omega_c^0 \rightarrow \Xi^- \pi^+$

$$\frac{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- \pi^+)} = [6.08 \pm 0.51 (\text{stat}) \pm 0.40 (\text{syst})]\%,$$

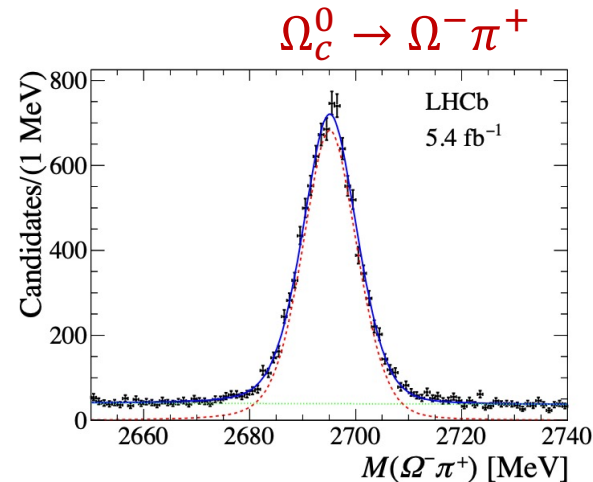
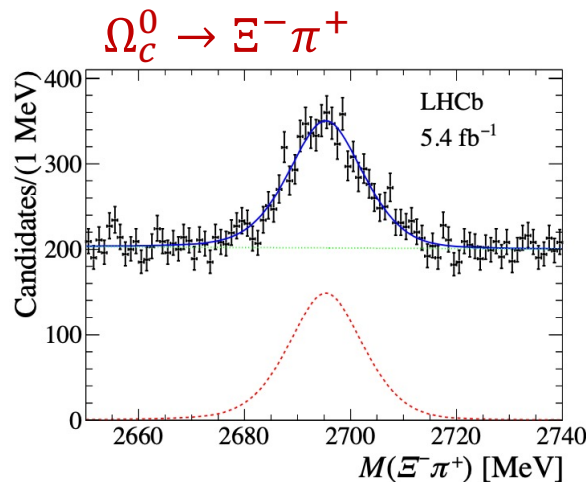
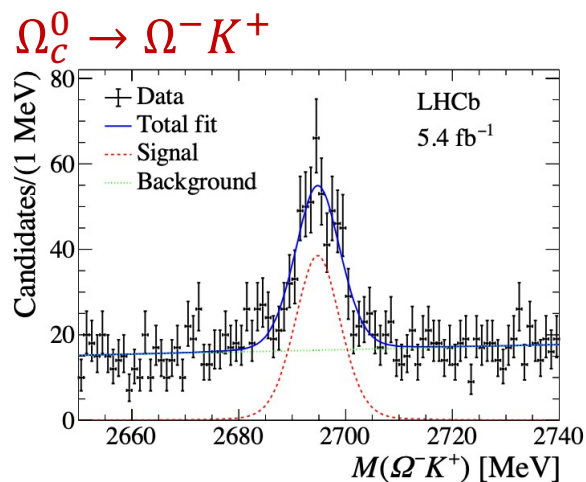
$$\frac{\mathcal{B}(\Omega_c^0 \rightarrow \Xi^- \pi^+)}{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- \pi^+)} = [15.81 \pm 0.87 (\text{stat}) \pm 0.44 (\text{syst}) \pm 0.16 (\text{ext})]\%.$$

[PRL 132 (2024) 081802]

- Precision measurement of Ω_c^0 mass using $\Omega_c^0 \rightarrow \Omega^- \pi^+$

$$M(\Omega_c^0) = 2695.28 \pm 0.07 (\text{stat}) \pm 0.27 (\text{syst}) \pm 0.30 (\text{ext}) \text{ MeV}$$

World average improved by $\times 4$



$\Lambda_b^0, \Lambda_c^+, \Lambda$ decay parameters

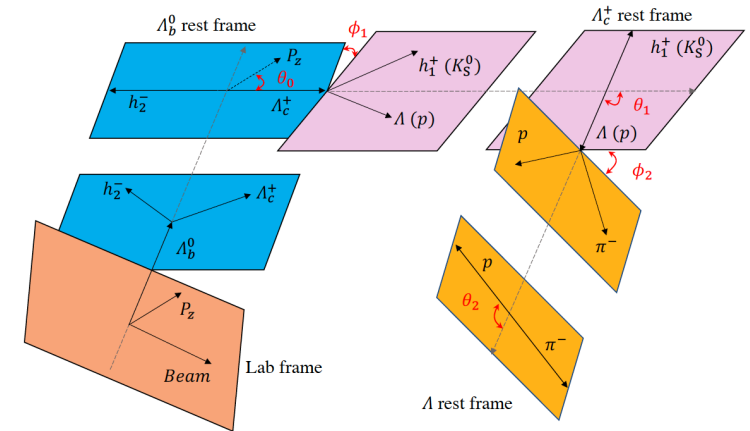
[PRL 133 (204) 261804]

- $B \rightarrow BP$ decay parameters: first proposed by Lee and Yang to search for parity violation, defined by S- and P-wave amplitudes

$$\alpha \equiv \frac{2\Re(s^*p)}{|s|^2 + |p|^2}, \quad \beta \equiv \frac{2\Im(s^*p)}{|s|^2 + |p|^2}, \quad \gamma \equiv \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2}, \quad \alpha^2 + \beta^2 + \gamma^2 = 1$$

- $\Lambda_b^0 \rightarrow \Lambda_c^+ h^- (h = \pi, K)$ decays,
with $\Lambda_c^+ \rightarrow \Lambda h^+, \Lambda_c^+ \rightarrow p K_S^0$
 $\Lambda \rightarrow p \pi^-$

- Decay parameters encoded in angular distributions
 - Λ_b^0 measured to be unpolarized by previous study



$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi_2} \propto (1 + \alpha_{\Lambda_b^0} \alpha_{\Lambda_c^+} \cos\theta_1 + \alpha_{\Lambda_c^+} \alpha_{\Lambda} \cos\theta_2 + \alpha_{\Lambda_b^0} \alpha_{\Lambda} \cos\theta_1 \cos\theta_2 - \alpha_{\Lambda_b^0} \gamma_{\Lambda_c^+} \alpha_{\Lambda} \sin\theta_1 \sin\theta_2 \cos\phi_2 + \alpha_{\Lambda_b^0} \beta_{\Lambda_c^+} \alpha_{\Lambda} \sin\theta_1 \sin\theta_2 \sin\phi_2)$$

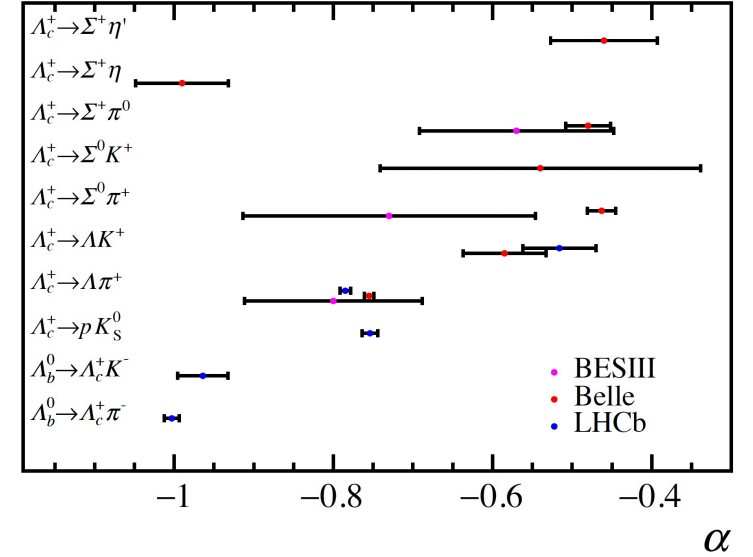
$\Lambda_b^0, \Lambda_c^+, \Lambda$ decay parameters

[PRL 133 (204) 261804]

- α parameters for Λ_b^0, Λ_c^+ and Λ decays
- $\alpha(\Lambda_b^0)$ compatible with most calculations, $\alpha(\Lambda_c^+)$ constrains models

$$\alpha \equiv \frac{2\Re(s^*p)}{|s|^2 + |p|^2}$$

Decay	Körner	Xu	Cheng	Ivanov	Żenczykowski	Sharma	Zou	Geng
$\Lambda_c^+ \rightarrow \Lambda \pi^+$	-0.70	-0.67	-0.99	-0.95	-0.95	-0.99	-0.93	-0.87 ± 0.10
$\Lambda_c^+ \rightarrow p \bar{K}^0$	-1.0	0.51	-0.90	-0.49	-0.97	-0.66	-0.75	$-0.89^{+0.26}_{-0.11}$



- β, γ and phase Δ for $\Lambda_c^+ \rightarrow \Lambda \pi^+$ decays

$$\beta \equiv \frac{2\Im(s^*p)}{|s|^2 + |p|^2}, \quad \gamma \equiv \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2},$$

- Inputs for global fit

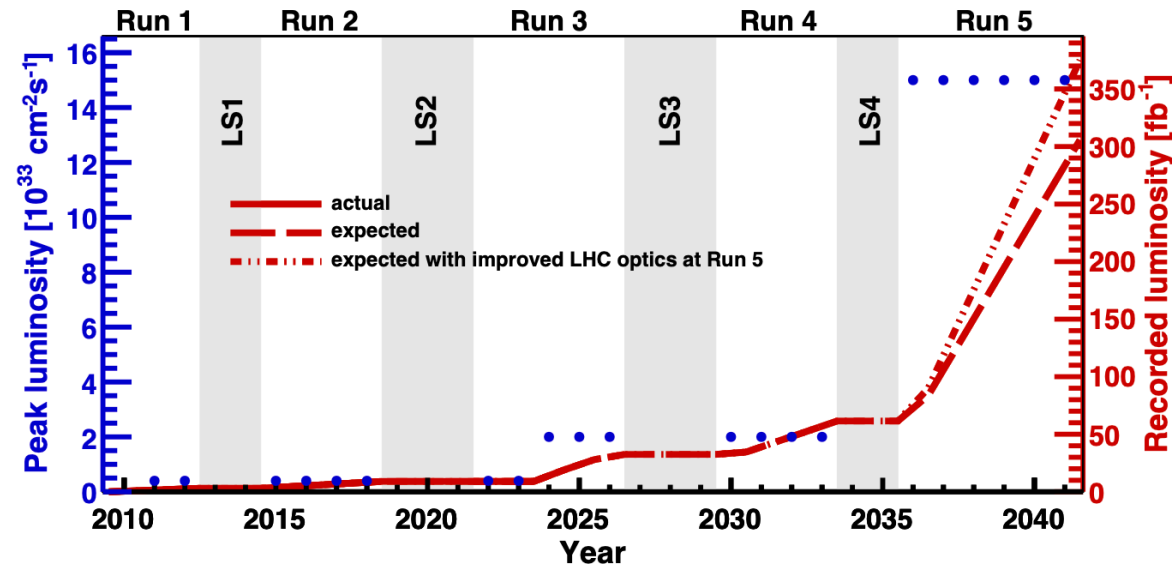
PRD111 (2025) 034011

Decay	$\Lambda_c^+ \rightarrow \Lambda \pi^+$	$\Lambda_c^+ \rightarrow \Lambda K^+$
β	$0.368 \pm 0.019 \pm 0.008$	$0.35 \pm 0.12 \pm 0.04$
$\bar{\beta}$	$-0.387 \pm 0.018 \pm 0.010$	$-0.32 \pm 0.11 \pm 0.03$
γ	$0.502 \pm 0.016 \pm 0.006$	$-0.743 \pm 0.067 \pm 0.024$
$\bar{\gamma}$	$0.480 \pm 0.016 \pm 0.007$	$-0.828 \pm 0.049 \pm 0.013$
Δ (rad)	$0.633 \pm 0.036 \pm 0.013$	$2.70 \pm 0.17 \pm 0.04$
$\bar{\Delta}$ (rad)	$-0.678 \pm 0.035 \pm 0.013$	$-2.78 \pm 0.13 \pm 0.03$

Summary

- New important contributions to heavy hadron spectroscopy with run1 and run2 data
 - New charm states with $B \rightarrow DDh$ decays
 - Charmonium like states
 - New charm baryons and measurements
- Run 3 collection ongoing, much more data foreseen
- Stay tuned for more exciting results

LHCB-TDR-026



Enjoy the landscapes of exotic states

[arXiv:2410.06923]



BACKUP

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

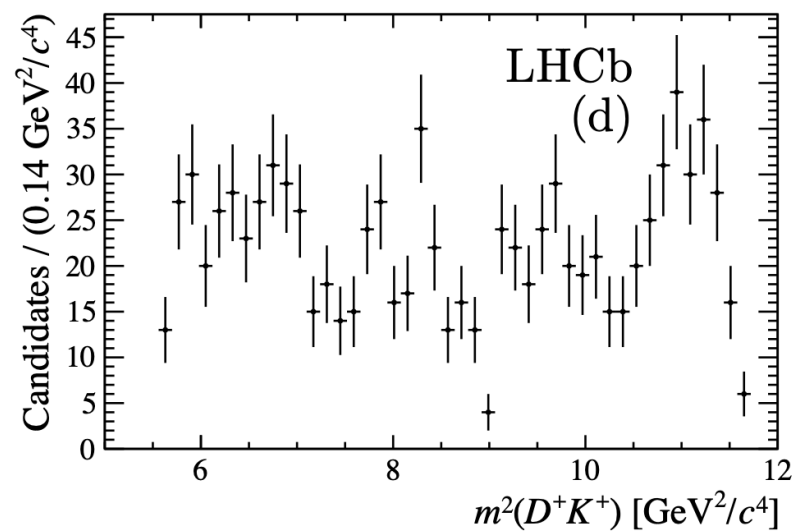
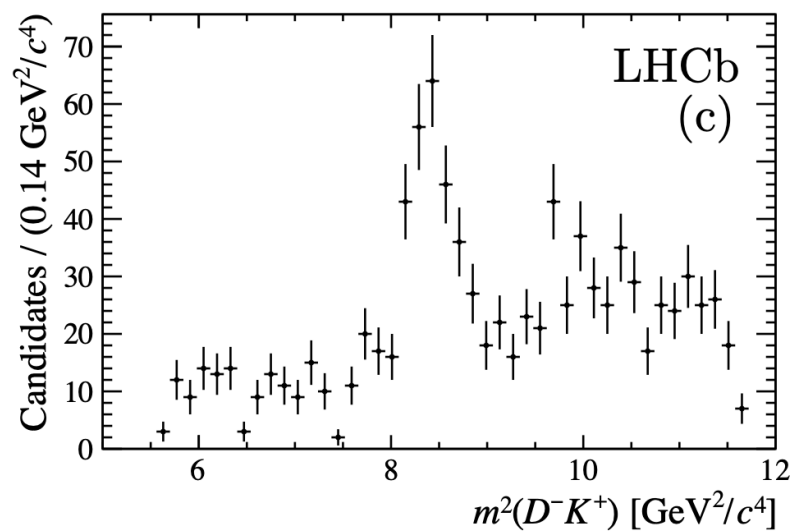
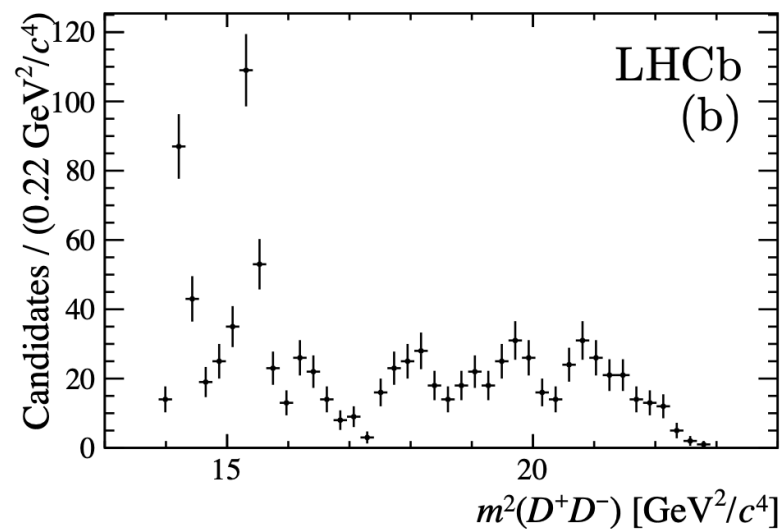
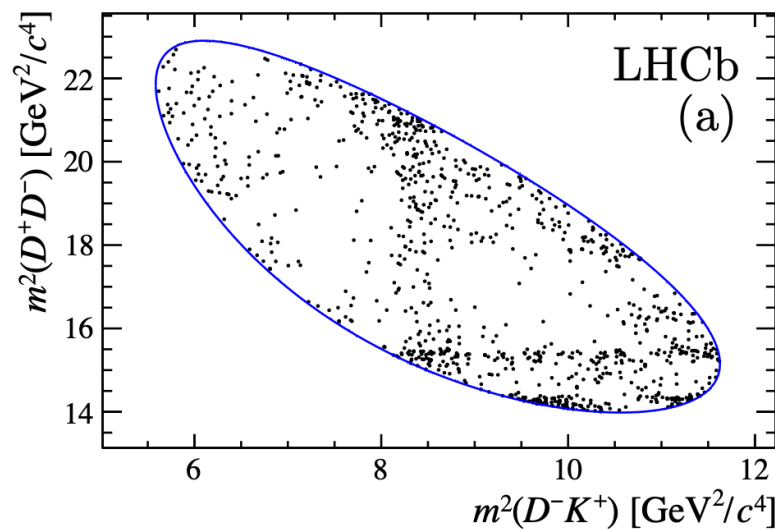
$$f_{R,S/D}(m) = \frac{\gamma_{S/D}}{m_0^2 - m^2 - im_0[\gamma_S^2 \Gamma_S(m) + \gamma_D^2 \Gamma_D(m)]}$$

□ Other resonances: Breit-Wigner

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

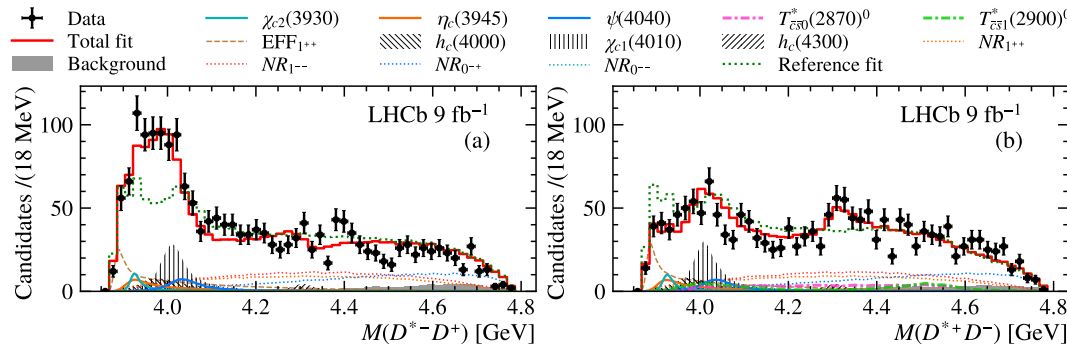
$$f_R(m) = e^{(\alpha+\beta i)(m^2-m_0^2)} \text{ for } NR_{0-+}; \text{ otherwise } f_R(m) = 1$$

$B^- \rightarrow D^- D^+ K^-$ structures

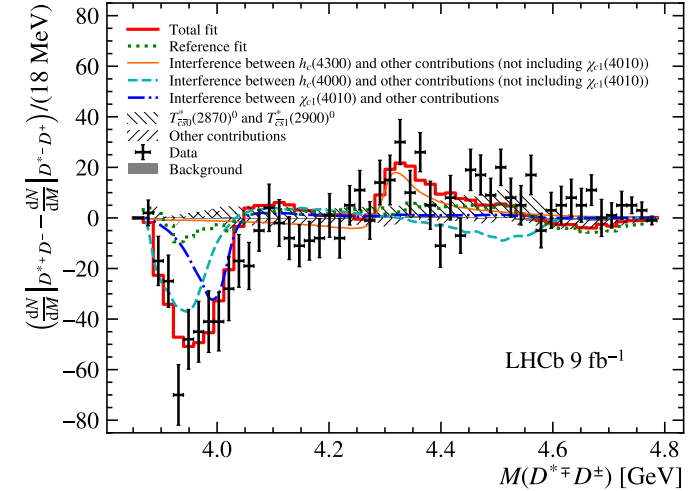


$B^+ \rightarrow D^{*\pm} D^{\mp} K^+ : D^{*\pm} D^{\mp}$ system

[PRL 133 (2024) 131902]



- Significances for those charmonium(-like) states $>6.1\sigma$
- J^{PC} for each state is determined to be $>5.7\sigma$ better than other hypotheses



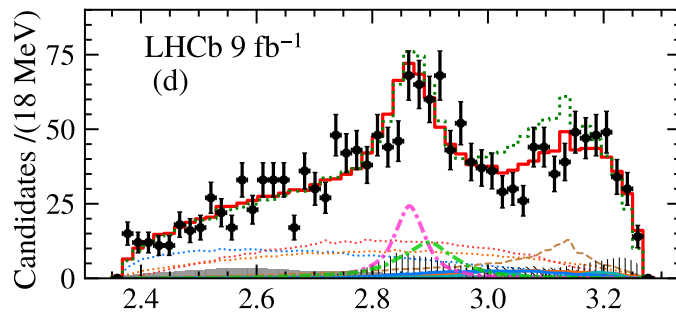
This work		Known states [6]		$c\bar{c}$ prediction [34]
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9, 10]	$J^{PC} = ?^{??}$	$\eta_c(3S)$ $J^{PC} = 0^{-+}$
$m_0 = 3945^{+28+37}_{-17-28}$	$\Gamma_0 = 130^{+92+101}_{-49-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37^{+27}_{-17}$	$m_0 = 4064$ $\Gamma_0 = 80$
$h_c(4000)$	$J^{PC} = 1^{+-}$	$T_{c\bar{c}}(4020)^0$ [35]	$J^{PC} = ?^{? -}$	$h_c(2P)$ $J^{PC} = 1^{+-}$
$m_0 = 4000^{+17+29}_{-14-22}$	$\Gamma_0 = 184^{+71+97}_{-45-61}$	$m_0 = 4025.5^{+2.0}_{-4.7} \pm 3.1$	$\Gamma_0 = 23.0 \pm 6.0 \pm 1.0$	$m_0 = 3956$ $\Gamma_0 = 87$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$			$\chi_{c1}(2P)$ $J^{PC} = 1^{++}$
$m_0 = 4012.5^{+3.6+4.1}_{-3.9-3.7}$	$\Gamma_0 = 62.7^{+7.0+6.4}_{-6.4-6.6}$			$m_0 = 3953$ $\Gamma_0 = 165$
$h_c(4300)$	$J^{PC} = 1^{+-}$			$h_c(3P)$ $J^{PC} = 1^{+-}$
$m_0 = 4307.3^{+6.4+3.3}_{-6.6-4.1}$	$\Gamma_0 = 58^{+28+28}_{-16-25}$	$\chi_c(4274)$ [36]	$J^{PC} = 1^{++}$	$m_0 = 4318$ $\Gamma_0 = 75$
		$m_0 = 4294 \pm 4^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$\chi_{c1}(3P)$ $J^{PC} = 1^{++}$
				$m_0 = 4317$ $\Gamma_0 = 39$

- States can fit into Charmonia, and mass more consistent with the prediction with unquenched quark model [arXiv: 2312.10296]
- $\chi_{c1}(4010)$ could be the partner of $\chi_{c1}(3872)$, predicted both in the unquenched model and Lattice [arXiv:2402.14541]

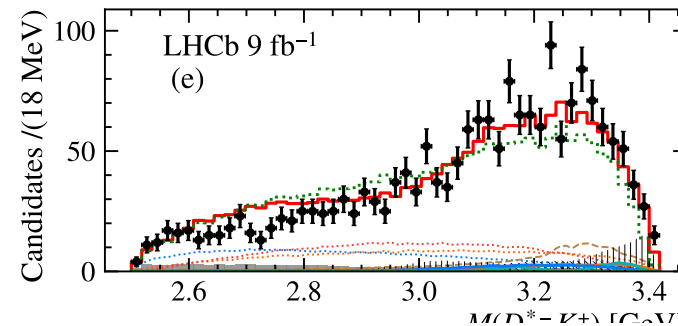
$B^+ \rightarrow D^{*\pm} D^{\mp} K^+ : T_{\bar{c}\bar{s}}^*$ states

[PRL 133 (2024) 131902]

➤ $B^+ \rightarrow D^{*+} D^- K^+$



➤ $B^+ \rightarrow D^{*-} D^+ K^+$



	Property	This work	Previous work
11σ	$T_{\bar{c}\bar{s}0}^*(2870)^0$ 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
9.2σ	$T_{\bar{c}\bar{s}1}^*(2900)^0$ 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
	$\mathcal{B}(B^+ \rightarrow T_{\bar{c}\bar{s}0}^*(2870)^0 D^{(*)+})$	$(4.5^{+0.6}_{-0.8} {}^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
	$\mathcal{B}(B^+ \rightarrow T_{\bar{c}\bar{s}1}^*(2900)^0 D^{(*)+})$	$(3.8^{+0.7}_{-1.0} {}^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
	$\frac{\mathcal{B}(B^+ \rightarrow T_{\bar{c}\bar{s}0}^*(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \rightarrow T_{\bar{c}\bar{s}1}^*(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

✓ $T_{\bar{c}\bar{s}0}^*(2870)^0 \rightarrow D^{*-} K^+$ forbidden

✓ $\mathcal{B}(T_{\bar{c}\bar{s}1}^*(2900)^0 \rightarrow D^{*-} K^+) / \mathcal{B}(T_{\bar{c}\bar{s}1}^*(2900)^0 \rightarrow D^- K^+) < 0.21$ @ 95% CL

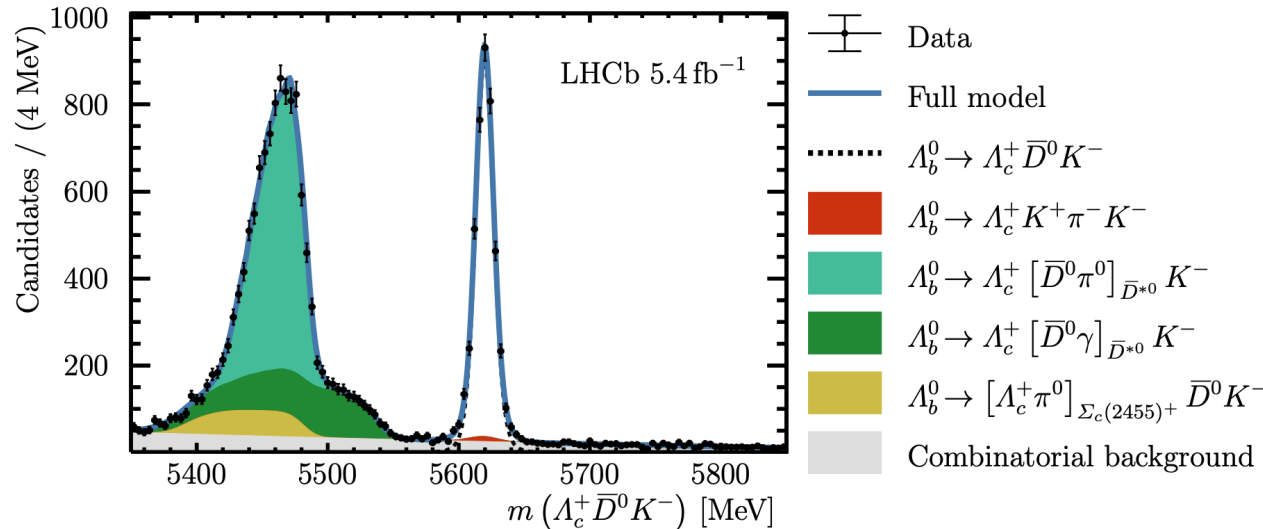
Observations of $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^-$ decays

[EPJC 84 (2024) 575]

- Pave the way for future P_c^+ search in $\Lambda_c^+ \bar{D}^{(*)0}$ systems
 - Open-charm equivalent of $J/\psi p$ decay
 - $\bar{D}^{*0}$ is partially reconstructed with missing π^0/γ

$$N_{\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-} = 4010 \pm 70,$$

$$N_{\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-} = 10\,560_{-290}^{+310}$$



- Branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = (19.08_{-0.34-0.18}^{+0.36+0.16} \pm 0.38)\%$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = (58.9_{-1.7-1.8}^{+1.8+1.7} \pm 1.2)\%$$

- Relative to $\Lambda_b^0 \rightarrow J/\psi p K^-$

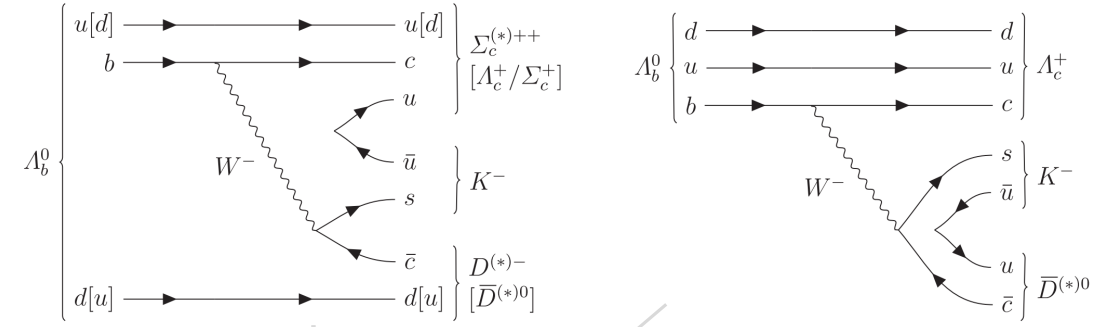
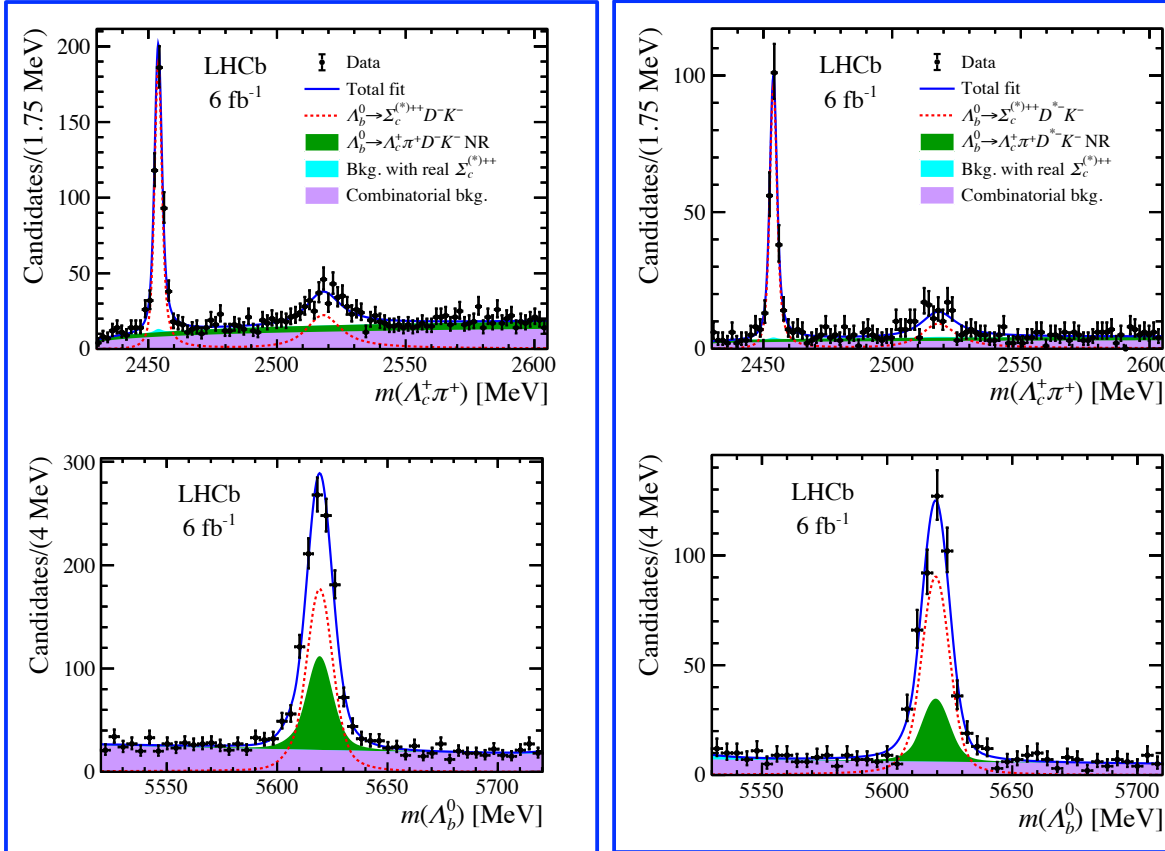
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)} = (15.2_{-2.8}^{+3.2})\%$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-)} = (4.9_{-0.9}^{+1.1})\%$$

$\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$: observation

[PRD 110 (2024) L031104]

- Four $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$ modes observed with overwhelming significance



$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)} = 0.282 \pm 0.016 \pm 0.016 \pm 0.005,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 0.460 \pm 0.052 \pm 0.028,$$

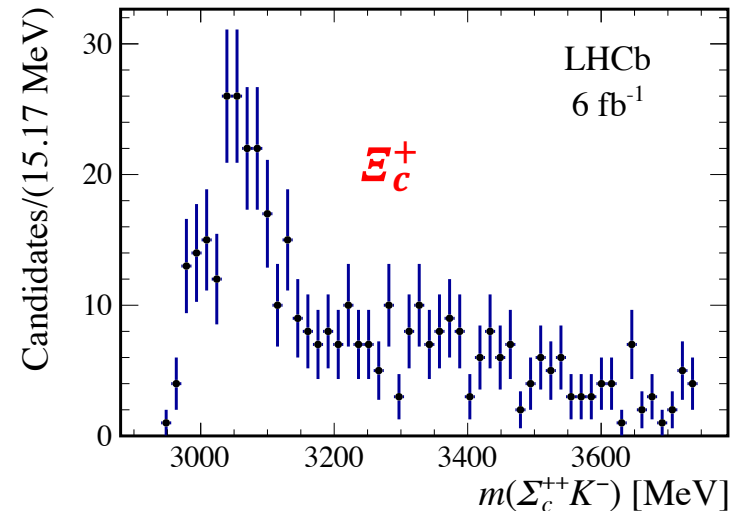
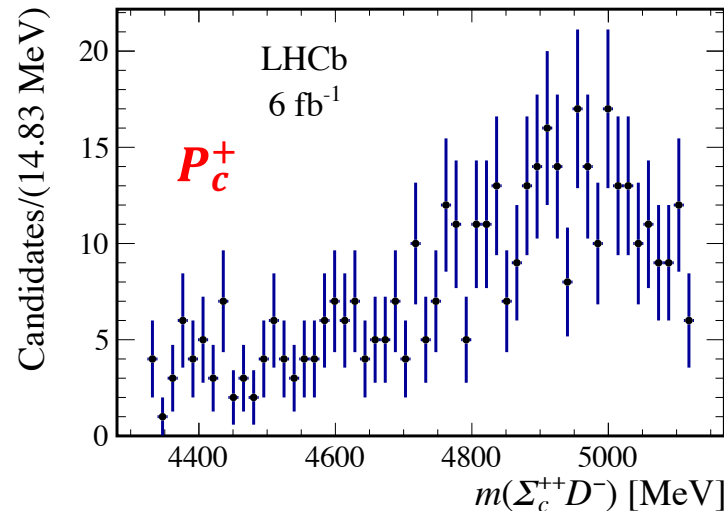
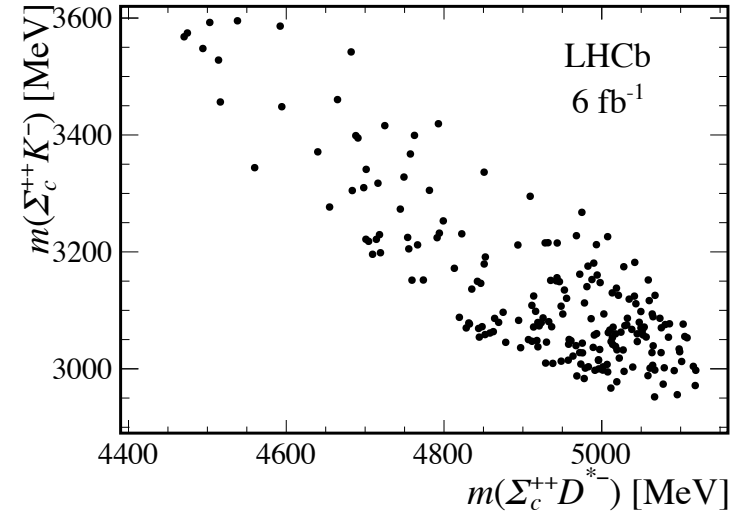
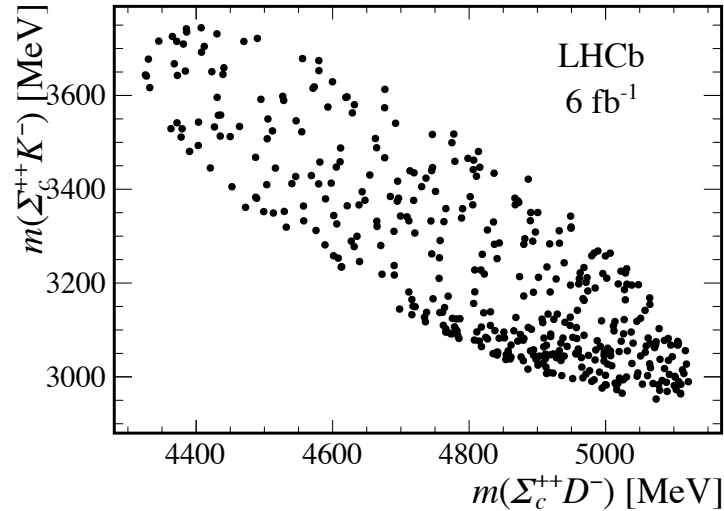
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 2.261 \pm 0.202 \pm 0.129 \pm 0.046,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 0.896 \pm 0.137 \pm 0.066 \pm 0.018,$$

$\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$: intermediate states

[PRD 110 (2024) L031104]

- Larger dataset needed to draw a definitive conclusion



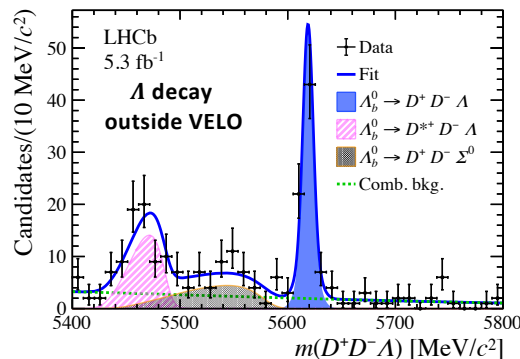
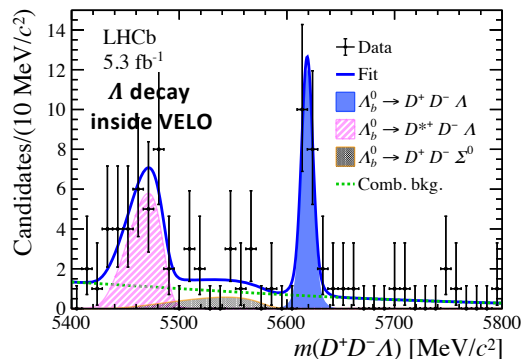
Observation of $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$

[JHEP 07 (2024) 140]

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

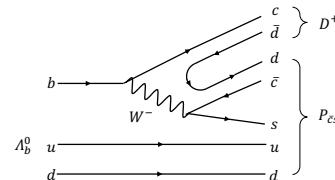
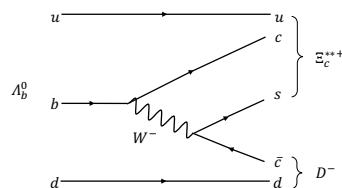
$N = 19 \pm 5$

$N = 73 \pm 9$

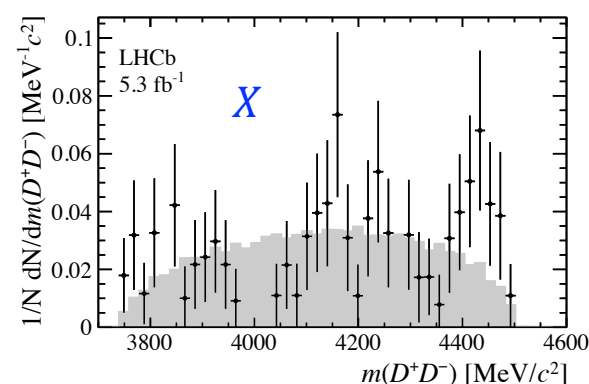
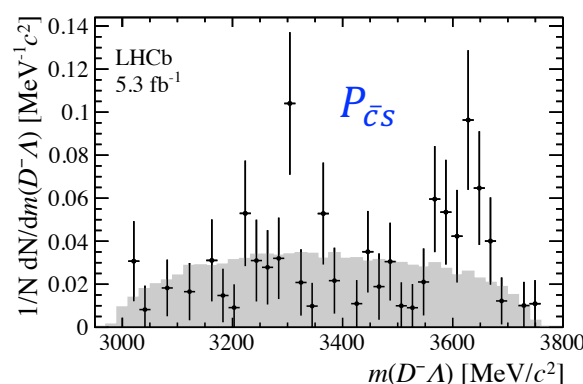
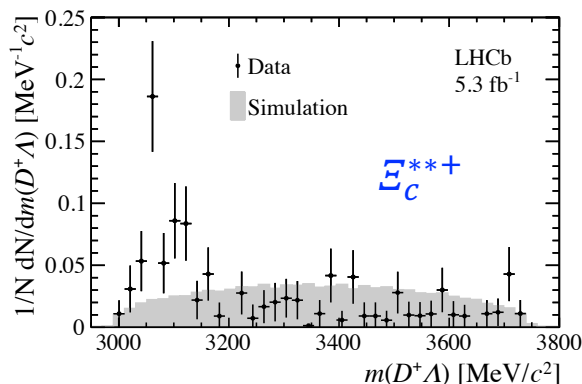
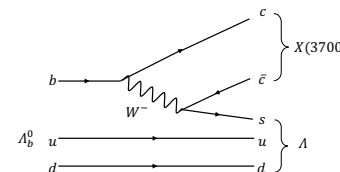


$$\frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^+ D^- \Lambda)}{\mathcal{B}(B^0 \rightarrow D^+ D^- K_S^0)} = 0.179 \pm 0.022 \pm 0.014$$

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

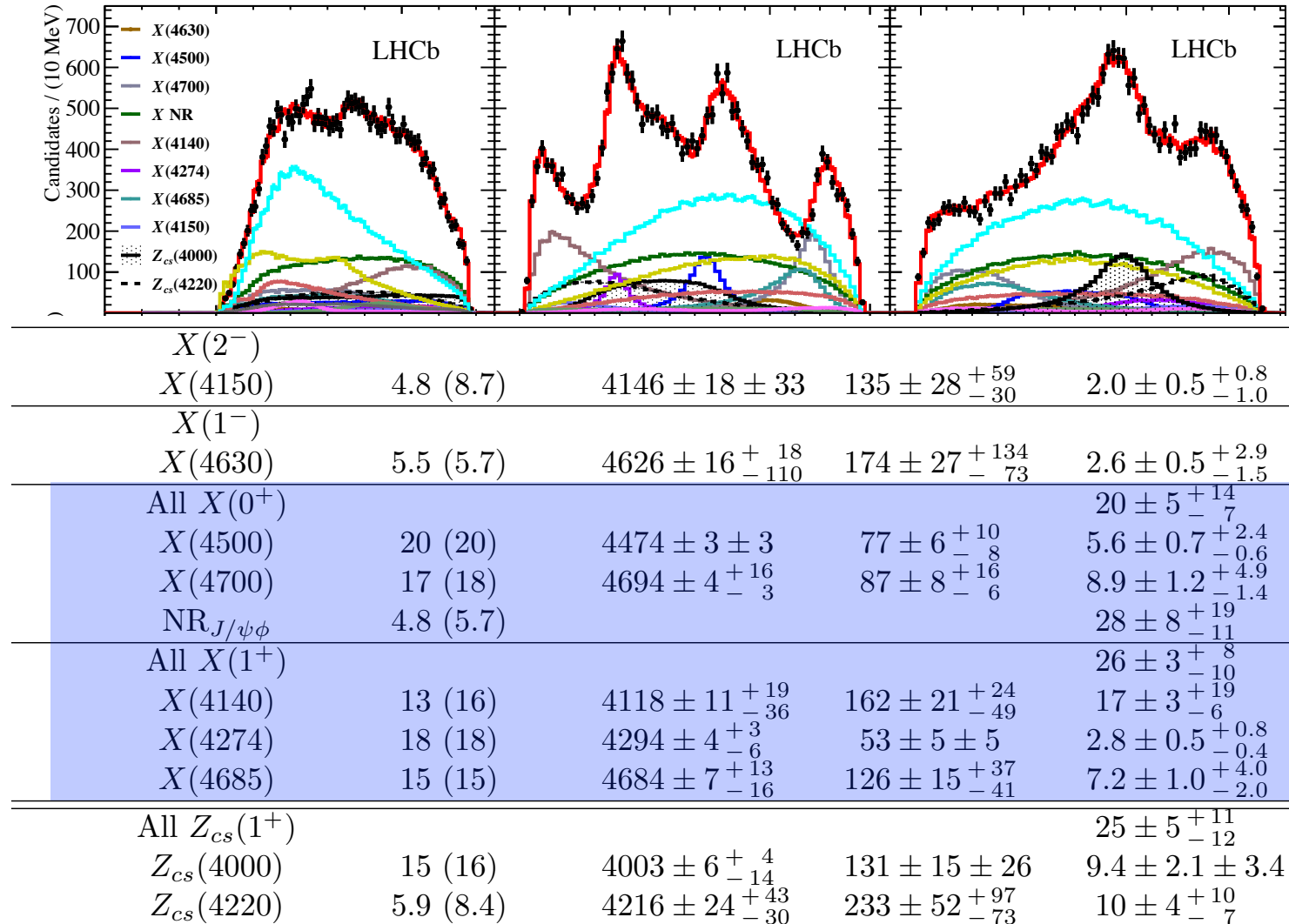


[PRD 103 (2021) 114013]



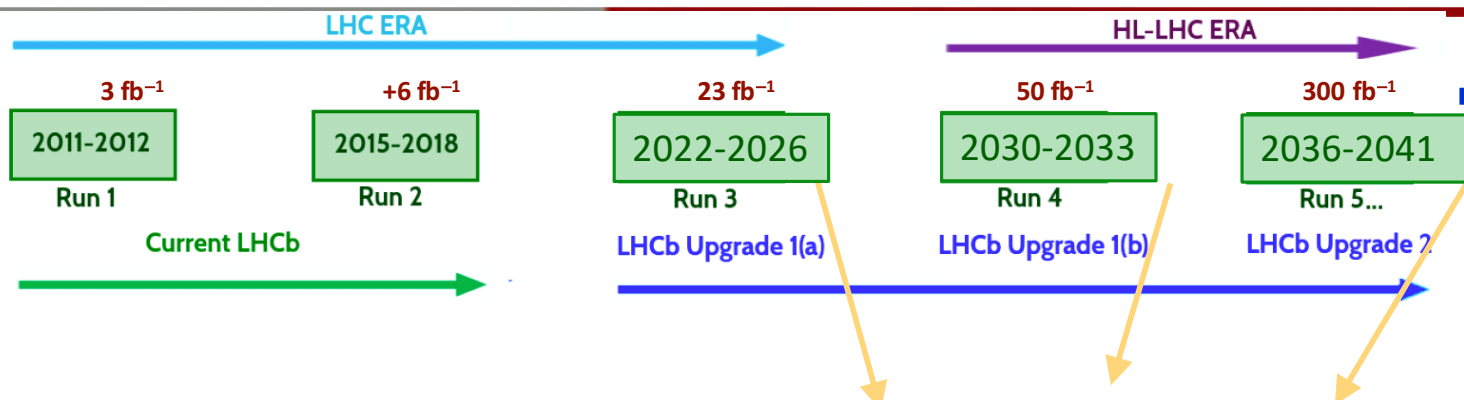
X states in $B^+ \rightarrow J/\psi\phi K^+$ decays

[PRL 127 (2021) 082001]



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

$D_s(2460)^+ \rightarrow D_S^+ \pi^+ \pi^-$ fit

Model	ΔNLL	Number of fit parameters
Chiral dynamics	252.4	5
K-matrix $\pi\pi$ S-wave	249.0	6
$f_0(500) + f_0(980)$	245.2	8
$f_0(500) + f_0(980) + \rho(770)^0$	148.0	12
$f_0(500) + f_0(980) + f_2(1270)$	3.7	12
$f_0(500) + f_0(980) + f_2(1270) + \rho(770)^0$	-2.8	16
K-matrix $\pi\pi$ S-wave + $f_2(1270)$	5.9	10
$f_0(500) + \text{RBW } T_{c\bar{s}}(0^+)$	3.5	10
$f_0(500) + \text{K-matrix } T_{c\bar{s}}(0^+)$	0.0	10
$f_0(500) + f_0(980) + \text{RBW } T_{c\bar{s}}(0^+)$	-3.0	12
$f_0(500) + \rho(770)^0 + \text{RBW } T_{c\bar{s}}(0^+)$	-1.1	14
$f_0(500) + f_2(1270) + \text{RBW } T_{c\bar{s}}(0^+)$	-4.3	14
$f_0(500) + \text{RBW } T_{c\bar{s}}(1^-)$	62.9	12

Search for pentaquarks via open charm

[PRD 110 (2024) 032001]

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

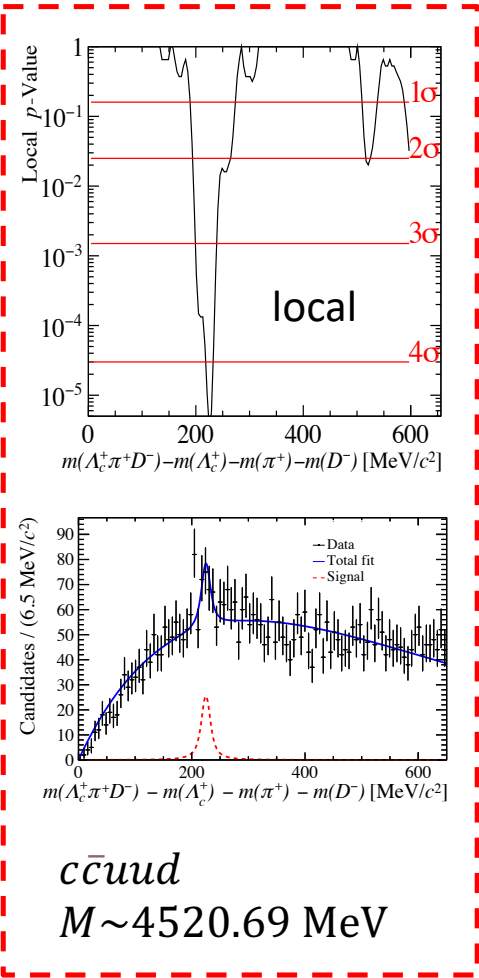
✓ hidden-charm pentaquarks

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

✓ doubly-charmed pentaquarks & excited E_{cc}

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

*10 modes too statistically limited to set upper limits



- No significant signals are found
- Upper limits set on $R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\epsilon_{\Lambda_c^+}}{\epsilon_{P_c}} \rightarrow \frac{\sigma(P_c) \times \mathcal{B}(P_c \rightarrow \Lambda_c^+ D(\pi)) \times \mathcal{B}(D)}{\sigma(\Lambda_c^+)}$
- Largest significant modes:

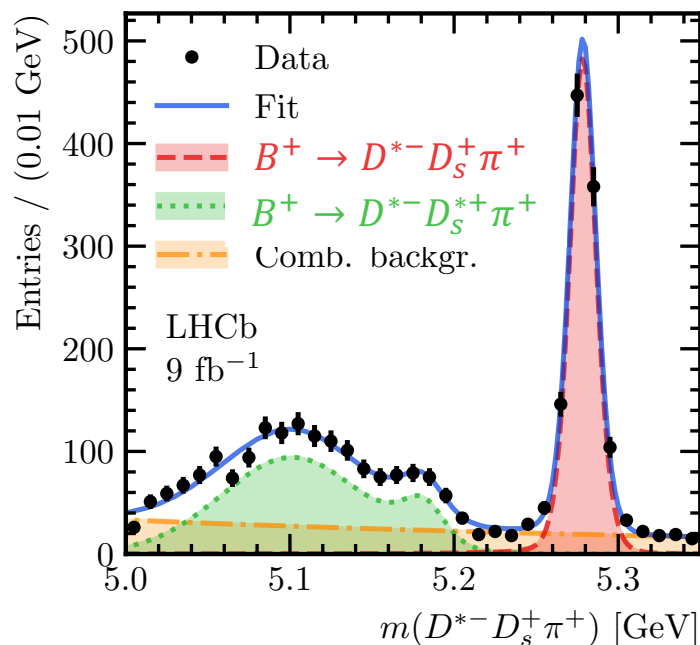
*Complete list in paper

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

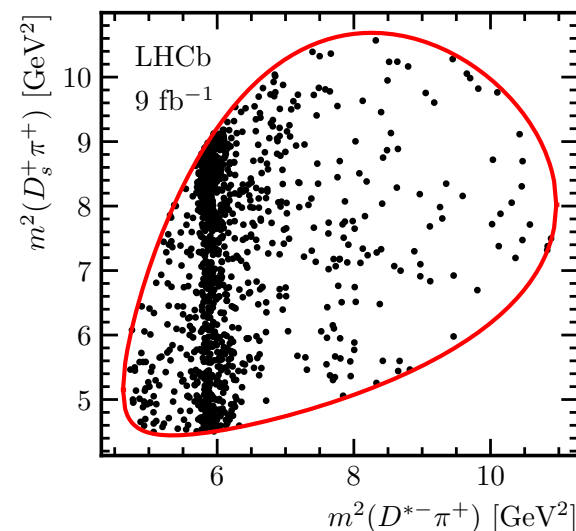
$B^+ \rightarrow D^{*-} D_s^{(*)+} \pi^+ : \text{branching fractions}$

[arXiv: 2405.00098]

- Measurement performed using the full LHCb dataset of 9 fb^{-1}



$$|m(D^{*-} D_s^+ \pi^+) - m_{B^+}| < 30 \text{ MeV}$$



$$\mathcal{R} = \frac{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^+ \pi^+)}{\mathcal{B}(B^0 \rightarrow D^{*-} D_s^+)} = 0.173 \pm 0.006 \pm 0.010$$

$$\mathcal{R}^* = \frac{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^{*+} \pi^+)}{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^+ \pi^+)} = 1.32 \pm 0.07 \pm 0.14$$

$B^+ \rightarrow D^{*-} D_s^+ \pi^+$: amplitude analysis

[arXiv: 2405.00098]

■ Baseline fit with $\bar{D}^{**0} \rightarrow D^{*-} \pi^+$ contributions

Resonance	J^P	Mass [MeV]	Width [MeV]
$D_1(2420)$	1^+	2422.1 ± 0.6	31.3 ± 1.9
$D_1(2430)$	1^+	2412 ± 9	314 ± 29
$D_2^*(2460)$	2^+	$2461.1^{+0.7}_{-0.8}$	47.3 ± 0.8

6.5 σ

$D_0(2550)$ 0^- 2549 ± 19 165 ± 24

6.8 σ

$D_1^*(2600)$ 1^- 2627 ± 10 141 ± 23

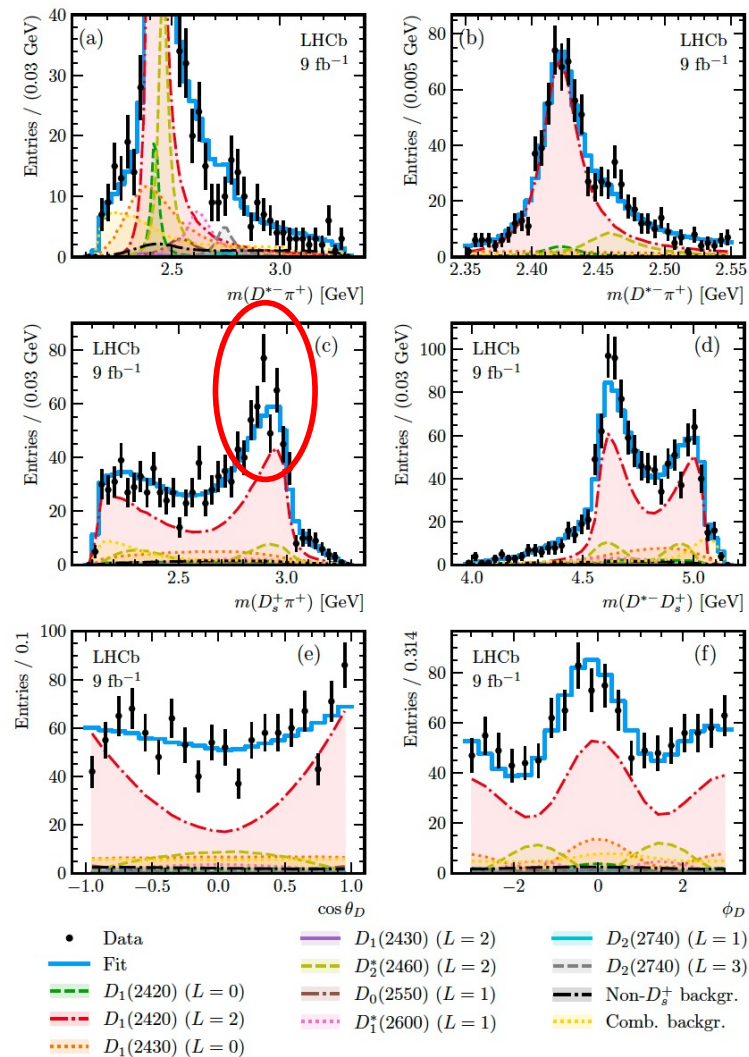
4.6 σ

$D_2(2740)$ 2^- 2747 ± 6 88 ± 19

$D_3^*(2750)$ 3^- 2763.1 ± 3.2 66 ± 5

Component	Fit fraction [%]	Phase [rad]
$D_1(2420)$ S-wave	$3.8 \pm 1.7 \pm 0.8^{+1.3}_{-0.1}$	$-1.96 \pm 0.16 \pm 0.10^{+0.17}_{-0.05}$
$D_1(2420)$ D-wave	$71.0 \pm 4.4 \pm 4.6^{+0.0}_{-6.0}$	0 (fixed)
$D_1(2430)$ S-wave	$14.2 \pm 2.5 \pm 2.4^{+3.1}_{-2.0}$	$+0.14 \pm 0.11 \pm 0.13^{+0.06}_{-0.18}$
$D_1(2430)$ D-wave	$0.5 \pm 0.9 \pm 1.5^{+0.2}_{-0.5}$	$-2.99 \pm 0.42 \pm 0.84^{+0.23}_{-0.55}$
$D_2^*(2460)$	$11.7 \pm 1.4 \pm 0.8^{+0.0}_{-0.7}$	$+3.14 \pm 0.11 \pm 0.14^{+0.05}_{-0.04}$
$D_0(2550)$	$2.3 \pm 0.8 \pm 0.7^{+0.3}_{-1.7}$	$-2.24 \pm 0.21 \pm 0.26^{+0.05}_{-0.25}$
$D_1^*(2600)$	$4.8 \pm 1.0 \pm 0.9^{+1.1}_{-2.0}$	$+0.32 \pm 0.16 \pm 0.16^{+0.37}_{-0.01}$
$D_2(2740)$ P-wave	$0.4 \pm 0.4 \pm 0.2^{+0.1}_{-0.1}$	$-0.02 \pm 0.56 \pm 0.32^{+0.16}_{-0.59}$
$D_2(2740)$ F-wave	$2.3 \pm 0.7 \pm 0.9^{+0.4}_{-0.1}$	$-0.09 \pm 0.27 \pm 0.21^{+0.08}_{-0.23}$

Sum of fit fractions | $111.0 \pm 5.2 \pm 4.2$

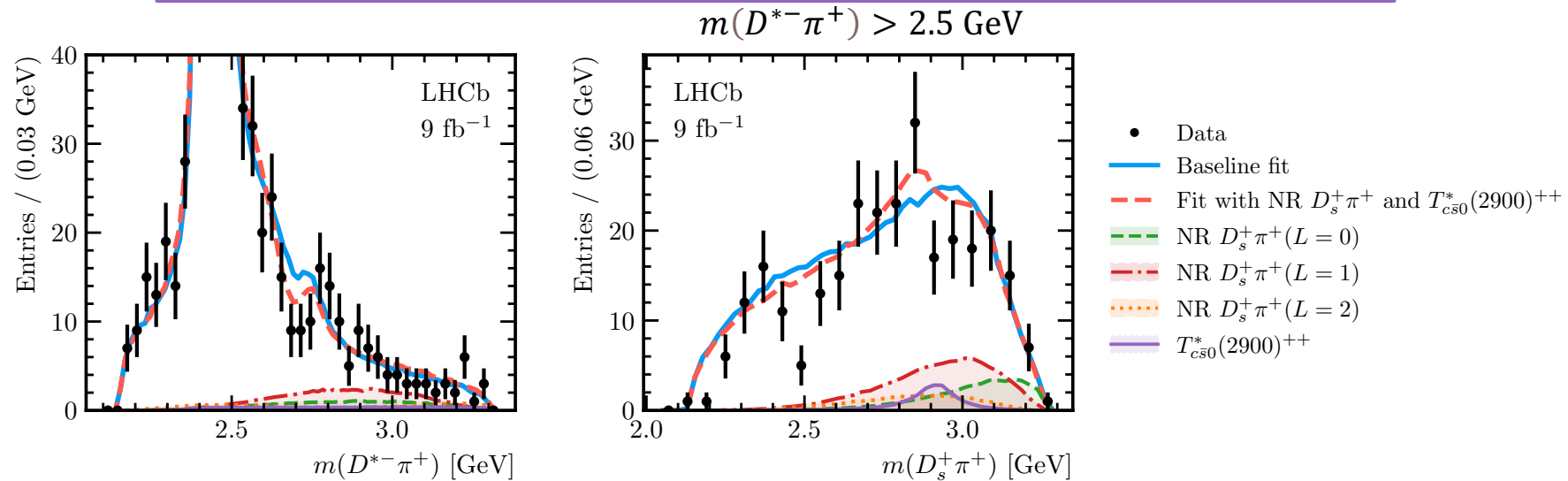


$B^+ \rightarrow D^{*-} D_s^+ \pi^+$: amplitude analysis

[arXiv: 2405.00098]

- Fits incorporating $D_s^+ \pi^+$ amplitudes
 - best fit: $T_{c\bar{s}0}^a(2900)^{++} + \text{nonresonant vector}$

2.6 σ , fit fraction = **$1.2 \pm 0.8\%$** , upper limit 2.3(2.7)% at 90(95)% CL
 • consistent with **$(2.25 \pm 0.67 \pm 0.77)\%$** in $B^+ \rightarrow D^- D_s^+ \pi^+$

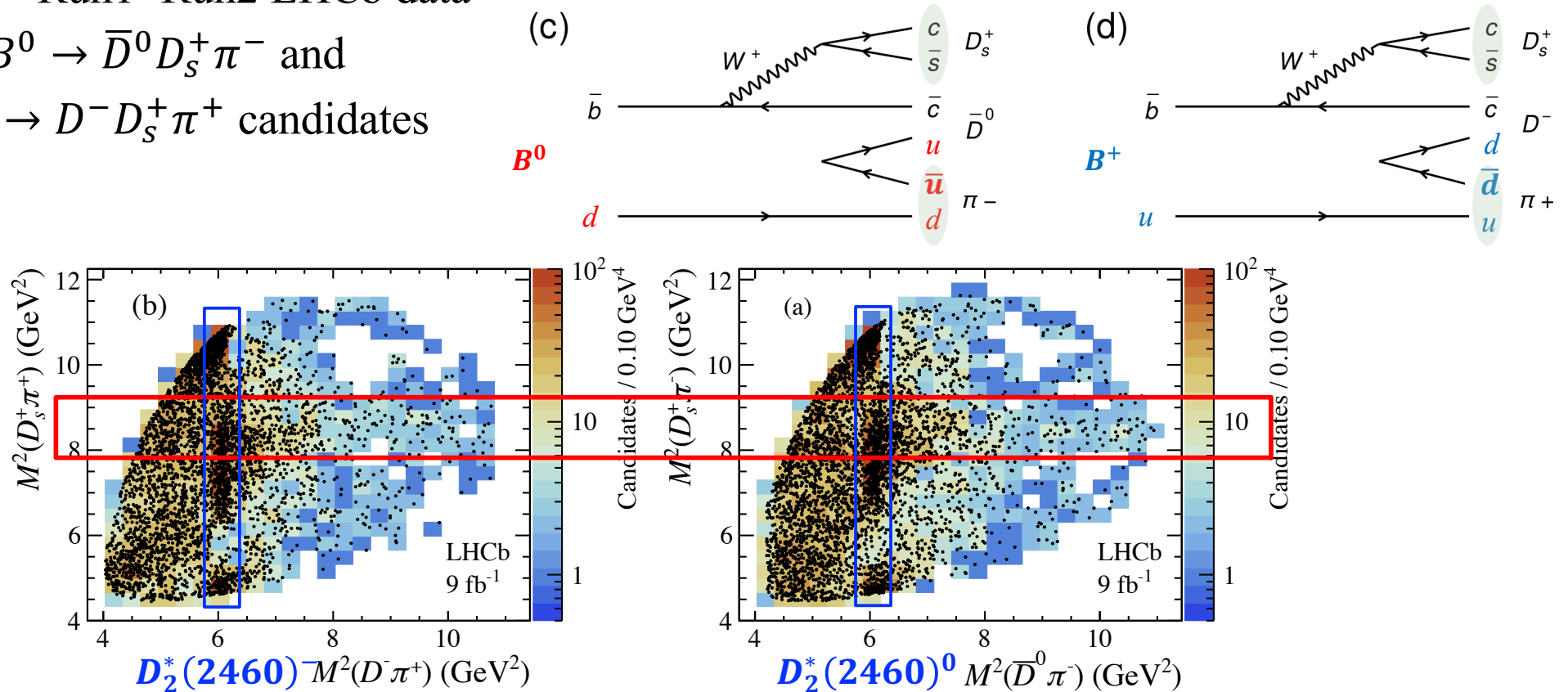


- Fits incorporating $D^{*-} D_s^+$ amplitudes: none provides a physical description

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

[PRL 131 (2023) 041902]

- Full 9 fb^{-1} Run1+Run2 LHCb data
 $\Rightarrow 4420 B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and
 $3940 B^+ \rightarrow D^- D_s^+ \pi^+$ candidates

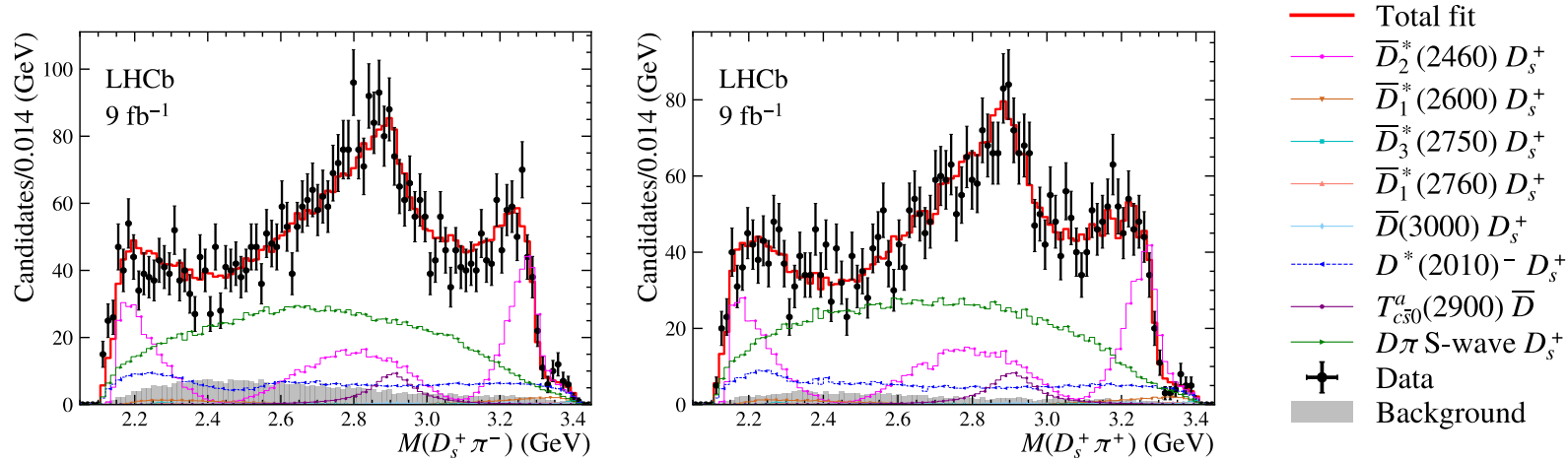


$\Rightarrow$ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

Observation of $T_{c\bar{s}0}^a(2900)^{0/++}$

- Fit with two $D_s^+ \pi$ states sharing resonance parameters

[PRL 131 (2023) 041902]



➤ $T_{c\bar{s}0}^a(2900)^0 \rightarrow D_s^+ \pi^-$ & $T_{c\bar{s}0}^a(2900)^{++} \rightarrow D_s^+ \pi^+$ **significance $> 9\sigma$**

✓ A second $1^- D_s^+ \pi$ state yields significance of only 1.3σ

✓ Additional $D\pi, D_s^+ \pi, DD_s^+$ resonances disfavored

➤ $J^P = 0^+$ favored over other spin-parity by more than 7.5σ

$$M = 2.908 \pm 0.011 \pm 0.020 \text{ GeV}$$

$$\Gamma = 0.136 \pm 0.023 \pm 0.011 \text{ GeV}$$

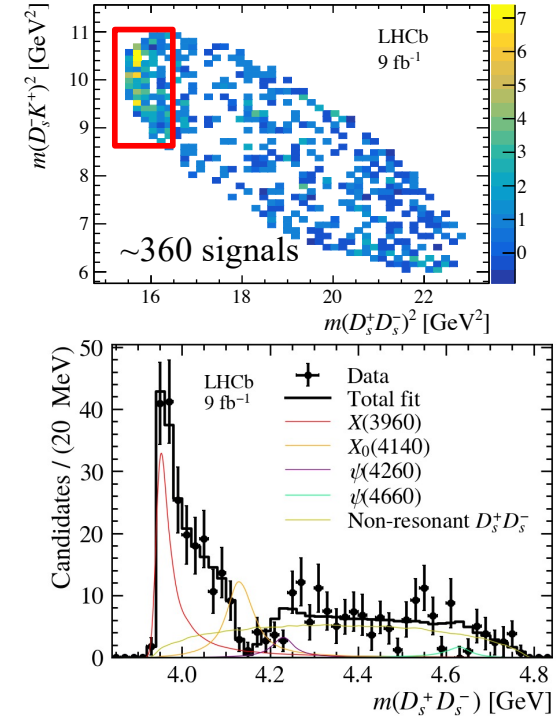
$$\text{Fit fraction} = (2.45 \pm 0.65 \pm 0.84)\%$$

$X(3960)$ in $B^+ \rightarrow D_s^+ D_s^- K^+$ decays

[PRL 131 (2023) 071901]

- Strong threshold enhancement found in $D_s^+ D_s^-$ system
- Amplitude analysis is performed
- **$X(3960)$** : threshold enhancement
 - $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ
 - Could be a $c\bar{c}s\bar{s}$ tetraquark predicted by Lattice QCD
- Resonance parameters are consistent with $\chi_{c0}(3930)$ within 3σ
- More data need to study the lineshape for $X(3960)$

[JHEP 06 (2021) 035]

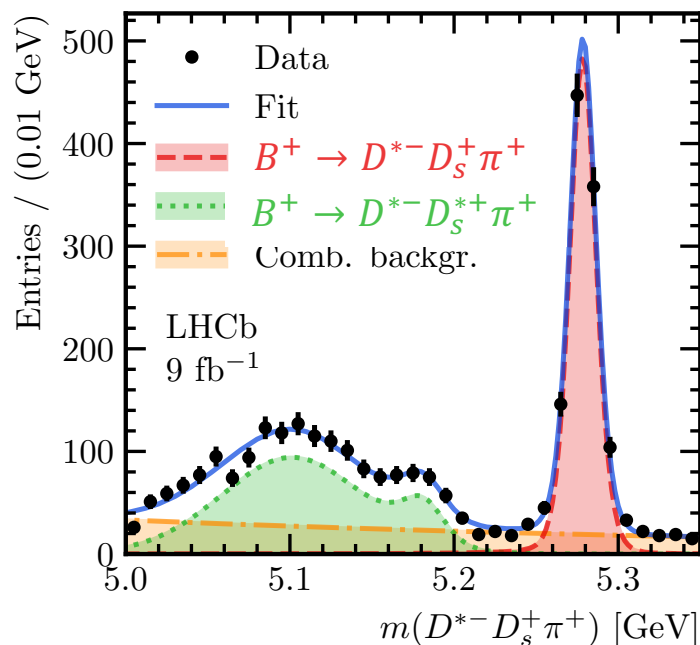


Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 [62]	55 [62]	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 [32]	64 [32]	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

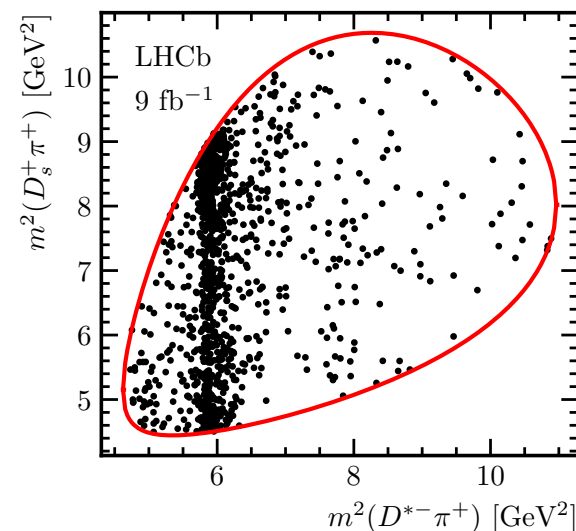
$B^+ \rightarrow D^{*-} D_s^{(*)+} \pi^+ : \text{branching fractions}$

[arXiv: 2405.00098]

- Measurement performed using the full LHCb dataset of 9 fb^{-1}



$$|m(D^{*-} D_s^+ \pi^+) - m_{B^+}| < 30 \text{ MeV}$$



$$\mathcal{R} = \frac{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^+ \pi^+)}{\mathcal{B}(B^0 \rightarrow D^{*-} D_s^+)} = 0.173 \pm 0.006 \pm 0.010$$

$$\mathcal{R}^* = \frac{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^{*+} \pi^+)}{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^+ \pi^+)} = 1.32 \pm 0.07 \pm 0.14$$

$B^+ \rightarrow D^{*-} D_s^+ \pi^+$: amplitude analysis

[arXiv: 2405.00098]

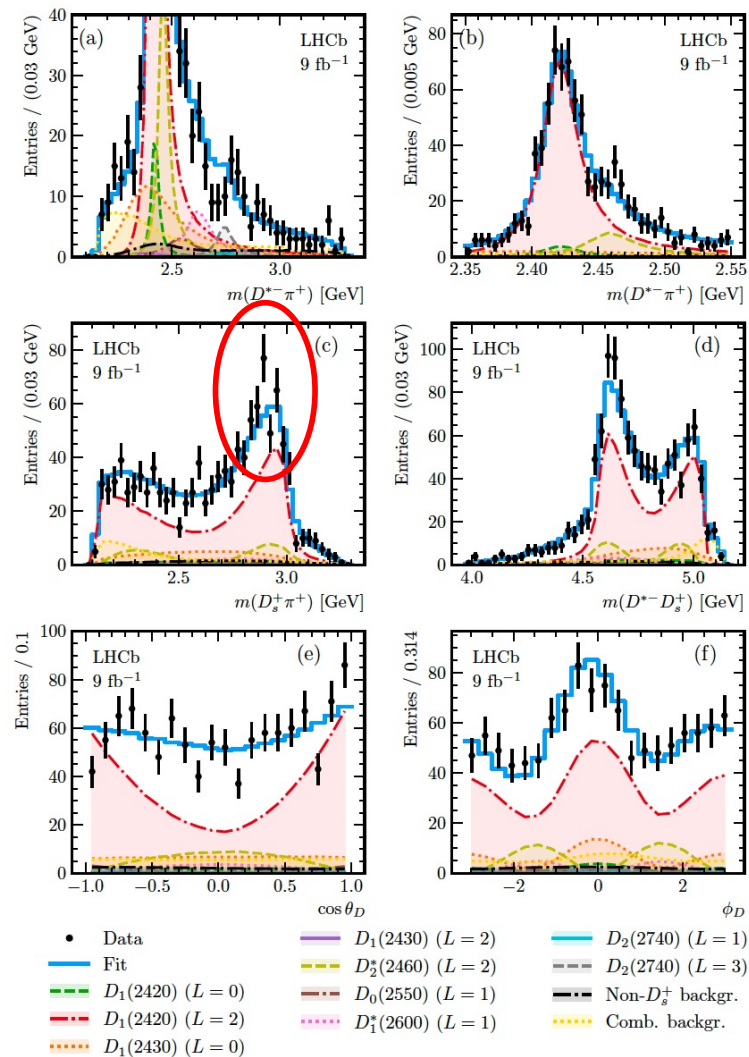
■ Baseline fit with $\bar{D}^{**0} \rightarrow D^{*-} \pi^+$ contributions

Resonance	J^P	Mass [MeV]	Width [MeV]
$D_1(2420)$	1^+	2422.1 ± 0.6	31.3 ± 1.9
$D_1(2430)$	1^+	2412 ± 9	314 ± 29
$D_2^*(2460)$	2^+	$2461.1^{+0.7}_{-0.8}$	47.3 ± 0.8

6.5σ	$D_0(2550)$	0^-	2549 ± 19	165 ± 24
6.8σ	$D_1^*(2600)$	1^-	2627 ± 10	141 ± 23
4.6σ	$D_2(2740)$	2^-	2747 ± 6	88 ± 19
	$D_3^*(2750)$	3^-	2763.1 ± 3.2	66 ± 5

Component	Fit fraction [%]	Phase [rad]
$D_1(2420)$ S-wave	$3.8 \pm 1.7 \pm 0.8^{+1.3}_{-0.1}$	$-1.96 \pm 0.16 \pm 0.10^{+0.17}_{-0.05}$
$D_1(2420)$ D-wave	$71.0 \pm 4.4 \pm 4.6^{+0.0}_{-6.0}$	0 (fixed)
$D_1(2430)$ S-wave	$14.2 \pm 2.5 \pm 2.4^{+3.1}_{-2.0}$	$+0.14 \pm 0.11 \pm 0.13^{+0.06}_{-0.18}$
$D_1(2430)$ D-wave	$0.5 \pm 0.9 \pm 1.5^{+0.2}_{-0.5}$	$-2.99 \pm 0.42 \pm 0.84^{+0.23}_{-0.55}$
$D_2^*(2460)$	$11.7 \pm 1.4 \pm 0.8^{+0.0}_{-0.7}$	$+3.14 \pm 0.11 \pm 0.14^{+0.05}_{-0.04}$
$D_0(2550)$	$2.3 \pm 0.8 \pm 0.7^{+0.3}_{-1.7}$	$-2.24 \pm 0.21 \pm 0.26^{+0.05}_{-0.25}$
$D_1^*(2600)$	$4.8 \pm 1.0 \pm 0.9^{+1.1}_{-2.0}$	$+0.32 \pm 0.16 \pm 0.16^{+0.37}_{-0.01}$
$D_2(2740)$ P-wave	$0.4 \pm 0.4 \pm 0.2^{+0.1}_{-0.1}$	$-0.02 \pm 0.56 \pm 0.32^{+0.16}_{-0.59}$
$D_2(2740)$ F-wave	$2.3 \pm 0.7 \pm 0.9^{+0.4}_{-0.1}$	$-0.09 \pm 0.27 \pm 0.21^{+0.08}_{-0.23}$

Sum of fit fractions | $111.0 \pm 5.2 \pm 4.2$

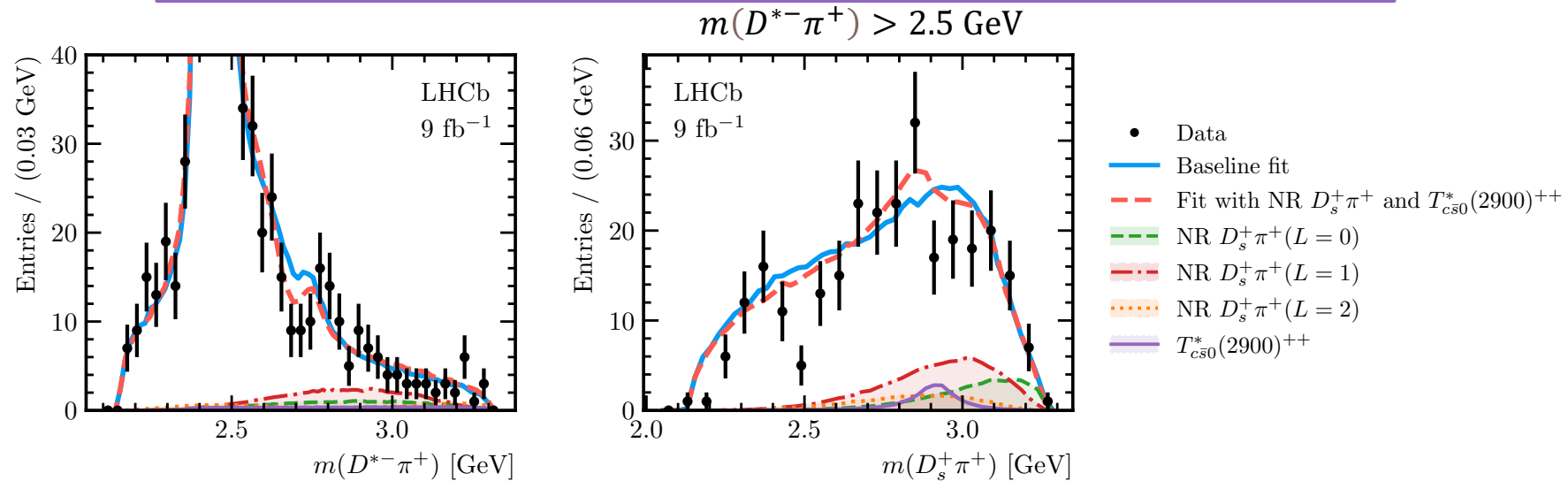


$B^+ \rightarrow D^{*-} D_s^+ \pi^+$: amplitude analysis

[arXiv: 2405.00098]

- Fits incorporating $D_s^+ \pi^+$ amplitudes
 - best fit: $T_{c\bar{s}0}^a(2900)^{++} + \text{nonresonant vector}$

2.6 σ , fit fraction = **$1.2 \pm 0.8\%$** , upper limit 2.3(2.7)% at 90(95)% CL
 • consistent with **$(2.25 \pm 0.67 \pm 0.77)\%$** in $B^+ \rightarrow D^- D_s^+ \pi^+$



- Fits incorporating $D^{*-} D_s^+$ amplitudes: none provides a physical description