Open-charm tetraquark states in $B \rightarrow DDh$ decays at LHCb

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On behalf of LHCb collaboration

HFCPV2025

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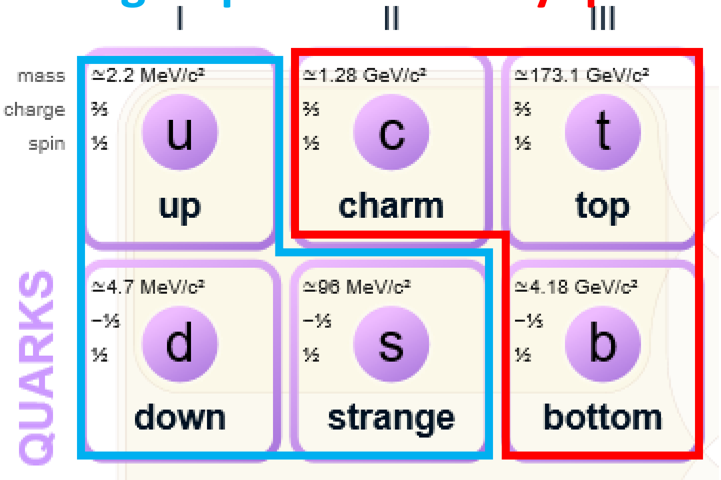
Introduction

Quark model

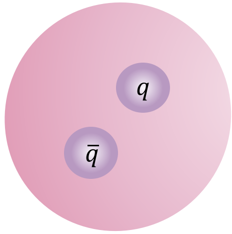
- Hadron: strong interaction system of quark and gluon
- Quark model:
  - proposed by Gell-Mann and Zweig in 1964
  - aim to categorize hadrons
- Classification of hadrons:

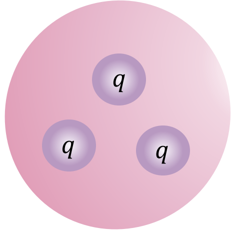
Light quarks   Heavy quarks

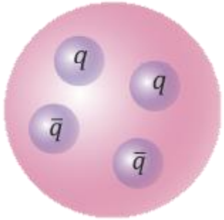


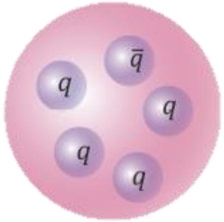
$K, \pi, \ldots$ $p, n, \ldots$

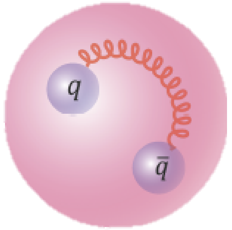
Multiquarks   Gluonic states

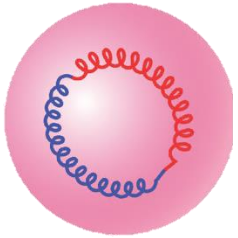












Conventional meson | Conventional baryon | Tetraquark states | Pentaquark states | Hybrid states | Gluonballs | . . .

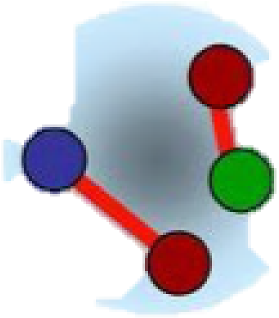
Conventional hadrons

Extensively studied

Exotic hadrons

Less studied

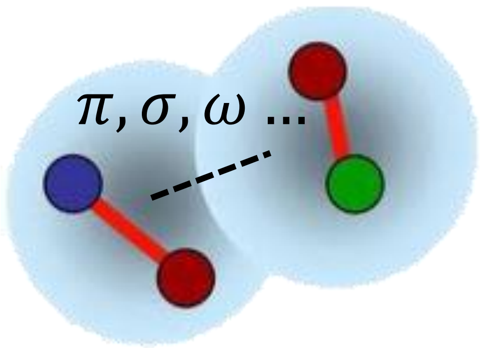
Exotic hadrons



Compact model

$$[qq]_A[\bar{q}\bar{q}]_B$$

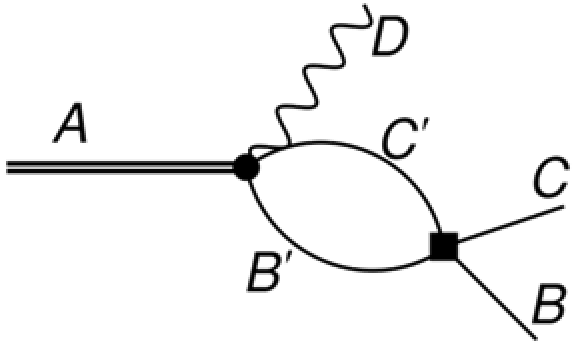
- Tightly bound states
- Isospin partners always predicted



Hadronic molecule

$$[q\bar{q}]_A[q\bar{q}]_B$$

- Loosely bound states
- Low binding energy
- Mass close to two-body thresholds



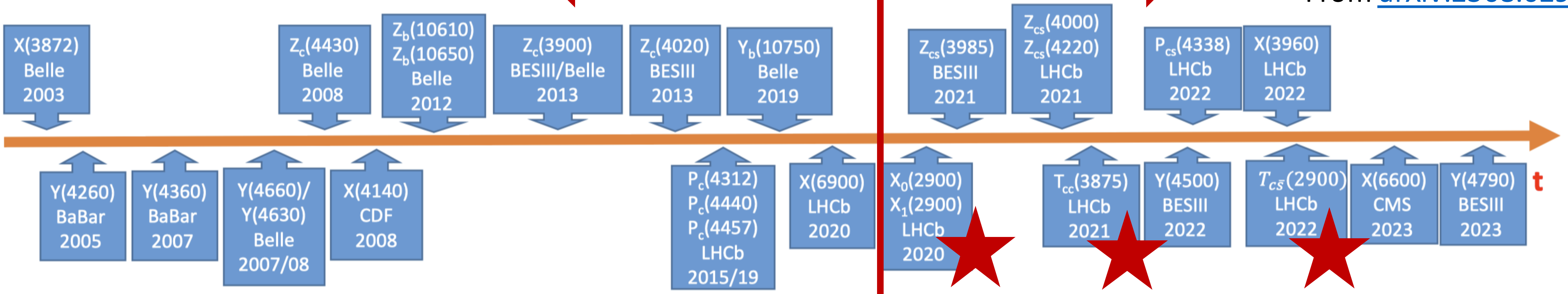
Kinematic effect

- Not a genuine resonance
- Rescattering amplitudes mimicing resonance peaks in mass spectrum

The discovery of exotic hadrons

Since 2020, a new era…

From arXiv:2308.02997



★ All from LHCb!

First discovery of open-charm tetraquark candidate

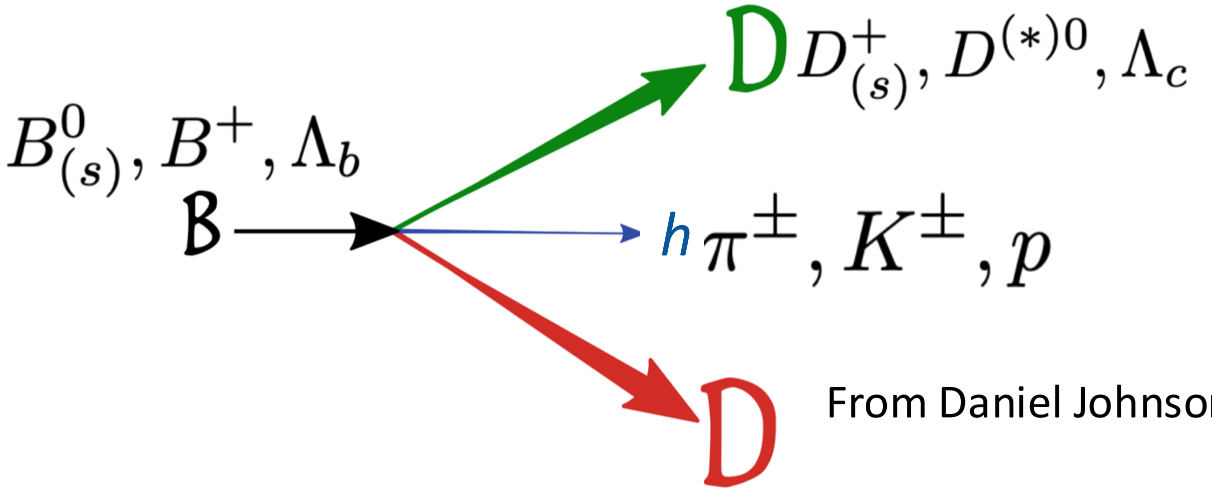
In the past:

- Mostly focused on charmonium-like multiquark ($c\bar{c}q\bar{q}'$)
- Very rich charmonium spectroscopy
- Study of open heavy flavor multiquarks is limited.

Open-charm tetraquark:
with non-zero charm quantum number, manifestly exotic

$B \to DDh$ decays

We looks at "*b*-hadron to two *c*-hadron + *h*" decays:



From Daniel Johnson

Spectroscopy:

- Open-charm exotic channels: $D^{(*)}K^{(*)}(\pi), D_s\pi, K^{(*)}(\pi)\Lambda_c$, ...

By-products
- Charmonium(-like) channels: $D^{(*)}\overline{D}^{(*)}, D^{(*)}\Lambda_c, \Lambda_c\Lambda_c$, ...
- Conventional excited states channels: $D^{(*)}K^{(*)}(\pi), K^{(*)}(\pi)\Lambda_c$, ...

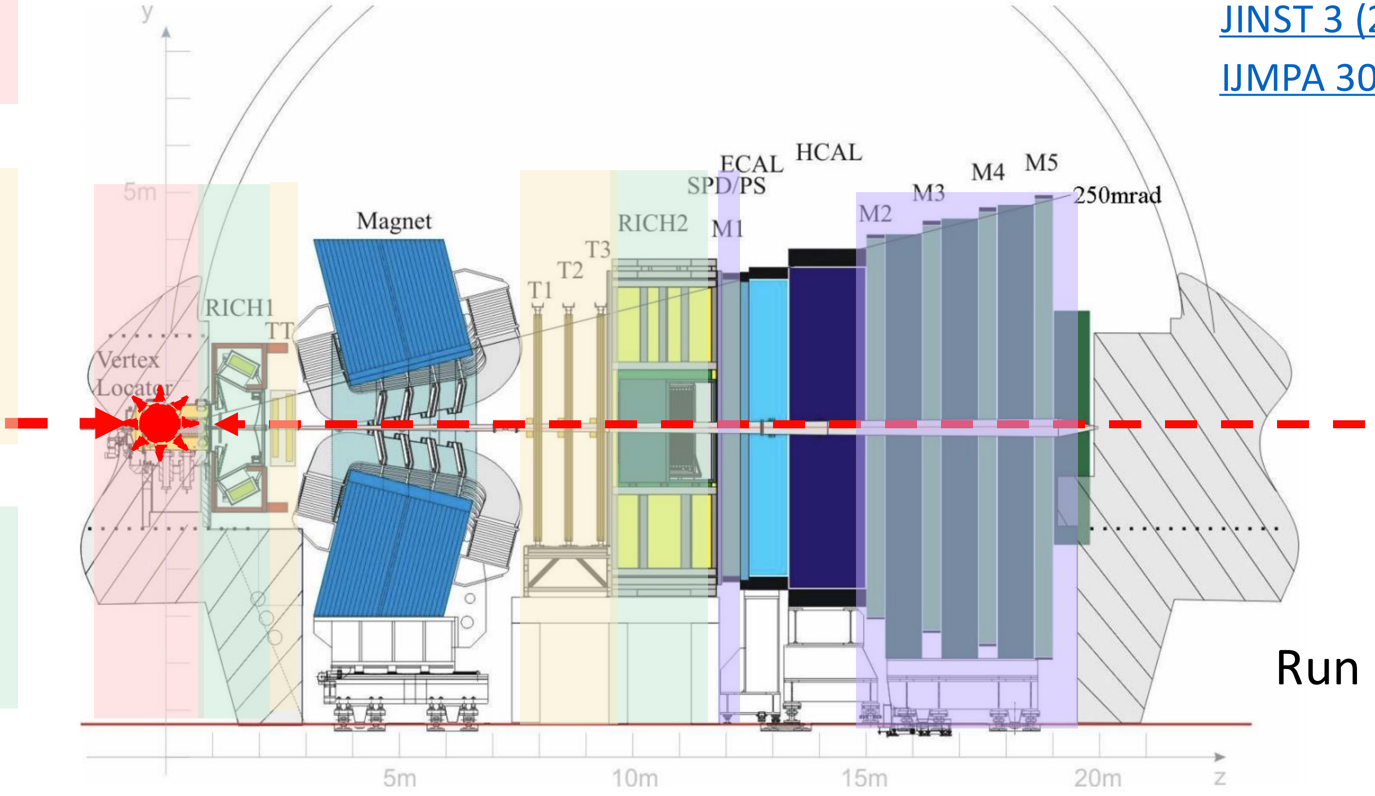
LHCb experiment

- One of the four largest experiments at the LHC
- Designed for heavy flavour physics
- An excellent platform to study $B \to DDh$ decays

High vertex resolution
$\sigma_{\mathrm{IP}} \sim 20\ \mu\mathrm{m}$

Good momentum resolution and tracking efficiency
$\sigma_p/p \sim 0.5\% - 1\%\ (5 - 200\ \mathrm{GeV})$
$\epsilon_{\mathrm{tracking}} \sim 96\%$

Crucial particle identification
$\epsilon(K \to K) \sim 95\%$
mis-ID $\epsilon(\pi \to K) \sim 5\%$



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

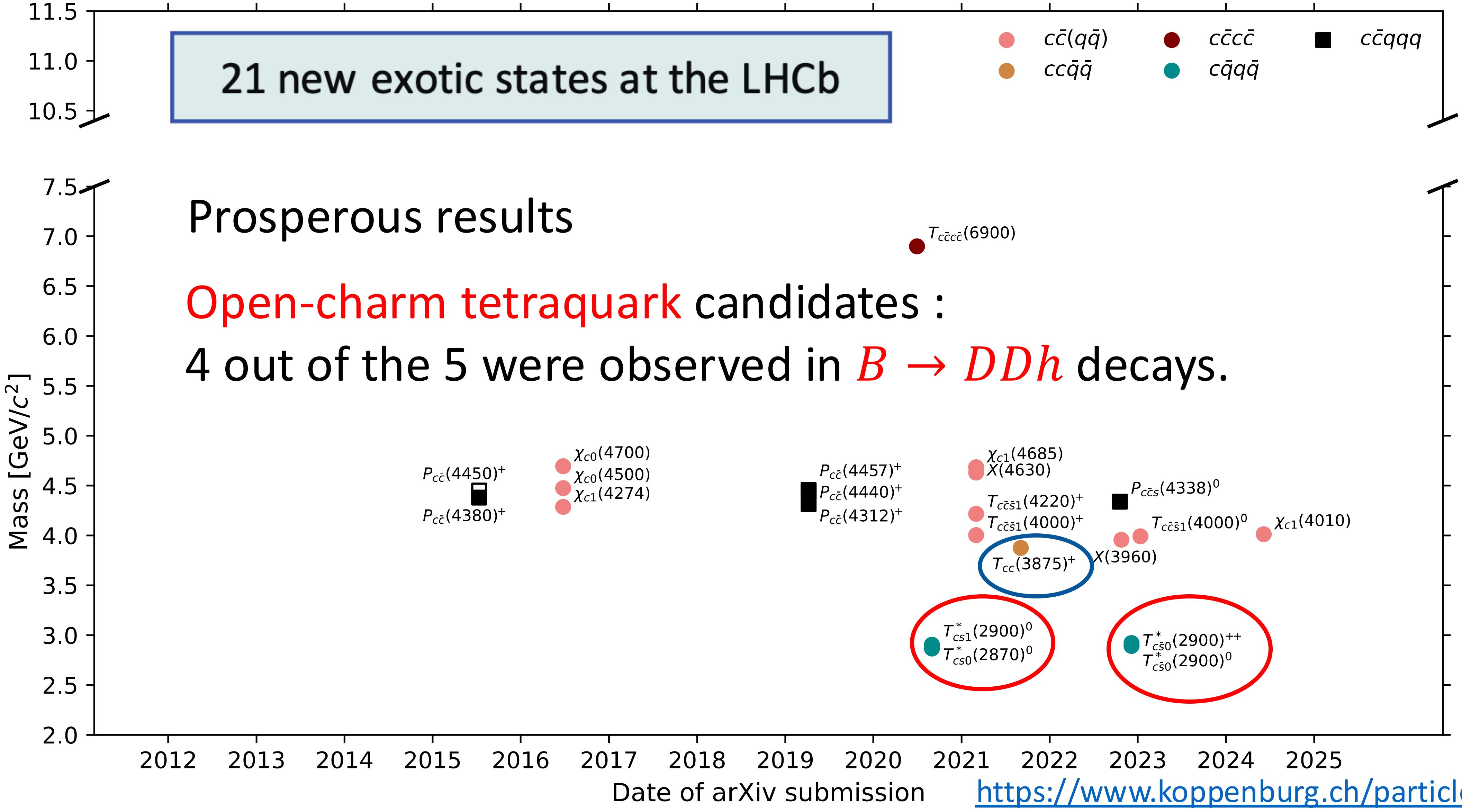
Run 1 and Run 2

Exotic hadrons discovered at LHCb

21 new exotic states at the LHCb

Prosperous results

Open-charm tetraquark candidates :
4 out of the 5 were observed in $B \to DDh$ decays.



https://www.koppenburg.ch/particles.html

Recent results from LHCb

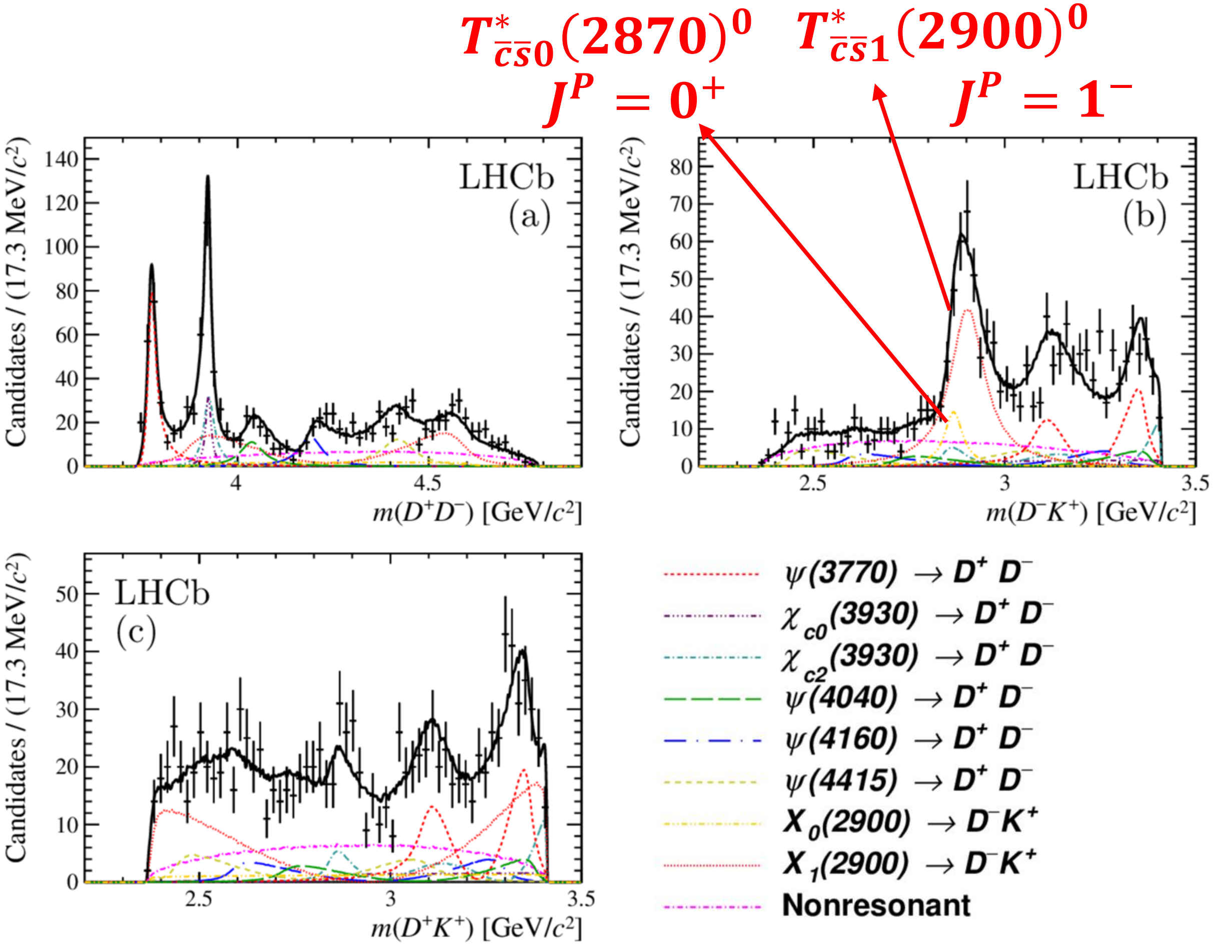
Open-charm tetraquarks observed in $B \to DDh$ decays

- $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ $(cs\bar{u}\bar{d})$ aka $X(2900)$
  - First observation in D^+K^- final states of the $B^- \to D^-D^+K^-$ decay
    Phys. Rev. D 102, 112003 (2020)
    Phys. Rev. Lett. 125, 242001 (2020)
  - Confirmation in D^+K^- final states of $B^- \to D^{*\mp}D^{\pm}K^-$ decays
    Phys. Rev. Lett. 133 (2024) 131902
  - Observation of a new T^{*0}_{cs} decay mode $T^*_{cs0}(2870)^0 \to D^0K^0_S$ in $B^- \to D^-D^0K^0_S$ decays
    Phys. Rev. Lett. 134 (2025) 101901
- $T^*_{c\bar{s}0}(2900)^{++}$ $(c\bar{s}u\bar{d})$ and $T^*_{c\bar{s}0}(2900)^0$ $(c\bar{s}\bar{u}d)$
  - First observation in $D_s\pi$ final states in $B^+ \to D^-D^+_s\pi^+$ and $B^0 \to \bar{D}^0D^+_s\pi^-$ decays
    Phys. Rev. Lett. 131, 041902 (2023)
    Phys. Rev. D 108, 012017 (2023)

Charge conjugation is implied throughout, unless otherwise stated.

$T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ $[cs\bar{u}\bar{d}]$

Phys. Rev. D 102, 112003 (2020)
Phys. Rev. Lett. 125, 242001 (2020)



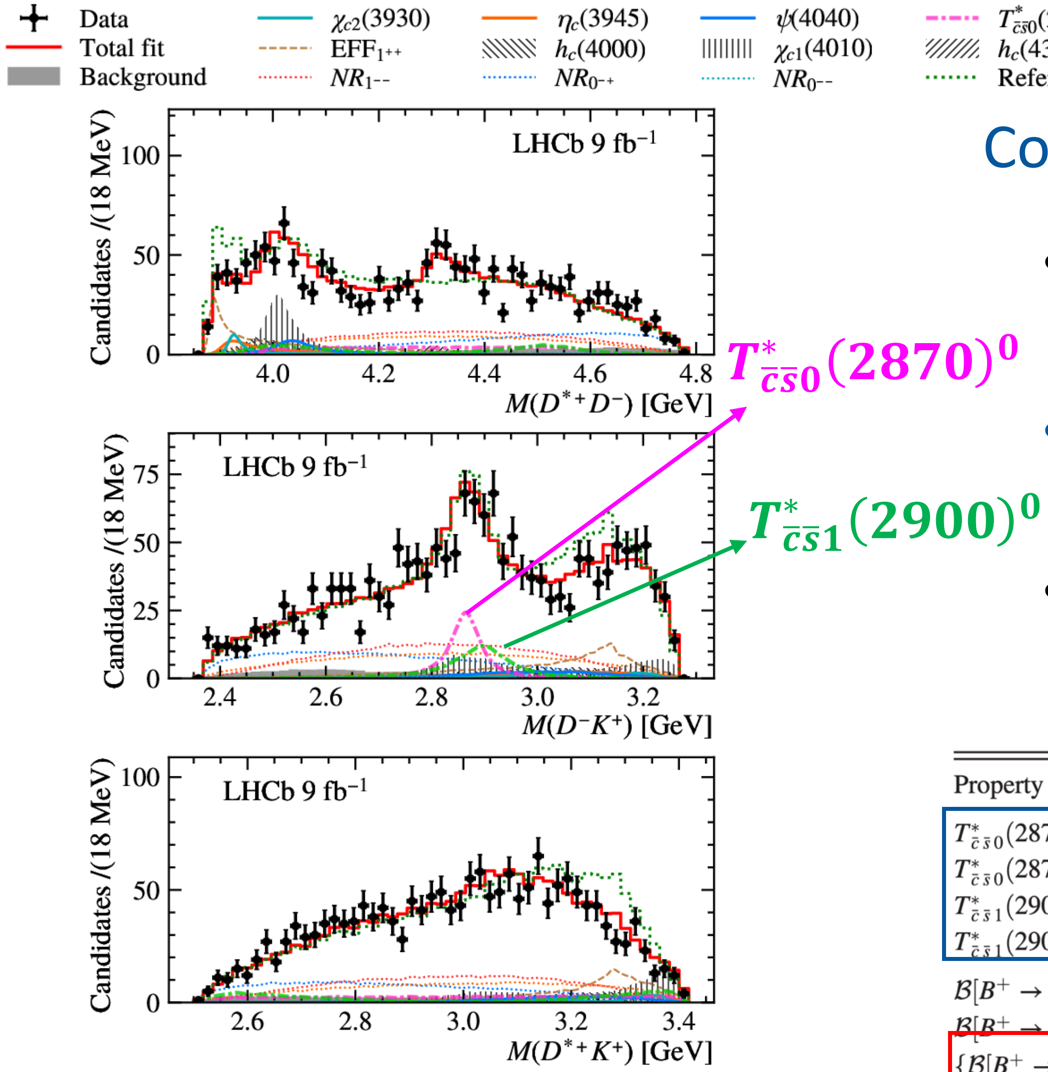
$B^+ \to D^+D^-K^+$

First observation of open-charm tetraquark states

- Amplitude model includes:
  - 6 charmonium states
  - 2 unknown exotics T^{*0}_{cs} (aka $X_{0,1}$)
- First observation of $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ with overwelming significance
- $T^{*0}_{cs0,1}$ $[cs\bar{u}\bar{d}]$, manifestly exotic, strong candidates of tetraquarks
- Masses, widths and fit fractions (FFs) of T^{*0}_{cs} measured

$T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ $[cs\bar{u}\bar{d}]$

Phys. Rev. Lett. 133 (2024) 131902



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

Confirmation in a new production channel $B^+ \to D^{*+}T^{*0}_{\bar{c}\bar{s}}$

- $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ confirmed in $T^{*0}_{\bar{c}\bar{s}} \to D^-K^+$
  FF~6% each for $T^*_{\bar{c}\bar{s}0,1} \to D^-K^+$
- T^{*0}_{cs} masses and widths show ~ 2σ tension with the previous measurement.
- The ratios of production branching fraction $\dfrac{\mathcal{B}[B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0\, D^{(*)+}]}{\mathcal{B}[B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0\, D^{(*)+}]}$ differ in the two processes.

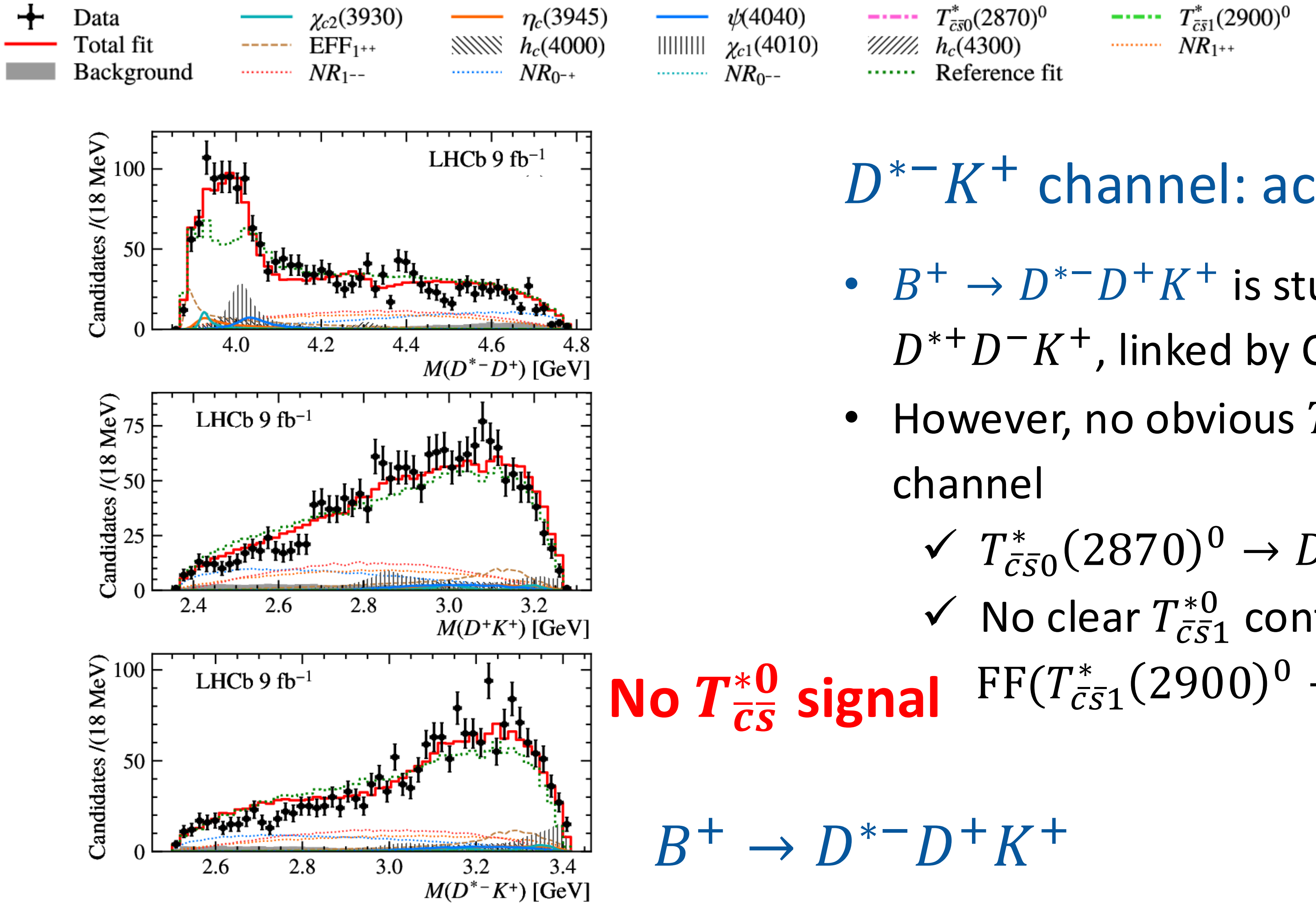
Property	In $B^+ \to D^{*\pm}D^{\mp}K^+$	In $B^+ \to D^+D^-K^+$
$T^*_{\bar{c}\bar{s}0}(2870)^0$, mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$, width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$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

New T^{*0}_{cs} production mechanism?

$1.17 \pm 0.31 \pm 0.48 > 0.18 \pm 0.05$

$T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ $[cs\bar{u}\bar{d}]$

Phys. Rev. Lett. 133 (2024) 131902



$D^{*-}K^+$ channel: access to new J^P for $T^{*0}_{\bar{c}\bar{s}}$ states

- $B^+ \to D^{*-}D^+K^+$ is studied simultaneously with $B^+ \to D^{*+}D^-K^+$, linked by C parity conservation
- However, no obvious $T^{*0}_{\bar{c}\bar{s}}$ signals in the $D^{*-}K^+$ channel
  - ✓ $T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^{*-}K^+$ forbidden by spin-parity
  - ✓ No clear $T^{*0}_{\bar{c}\bar{s}1}$ contribution, $\mathrm{FF}(T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-}K^+) < 1.5\%$ (95% CL)

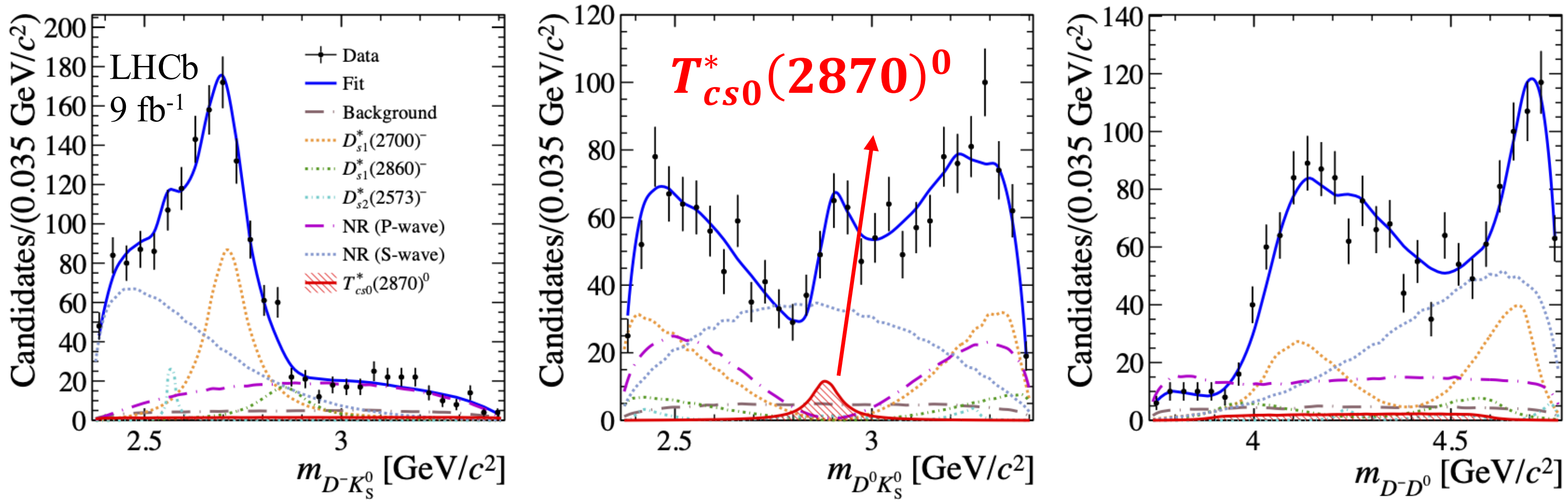
No $T^{*0}_{\bar{c}\bar{s}}$ signal

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

$T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ $[cs\bar{u}\bar{d}]$

Phys. Rev. Lett. 134 (2025) 101901

Observation of a new decay mode of $T^*_{cs0}(2870)^0$



Isospin symmetry with D^+K^- decay mode

$$B^- \to D^- \boxed{D^0 K^0_S}$$

$$M(T^{*0}_{cs0}) = 2883 \pm 11 \pm 8\ \mathrm{MeV}/c^2$$
$$\Gamma(T^{*0}_{cs0}) = 87^{+22}_{-47} \pm 17\ \mathrm{MeV}$$
$$\mathrm{FF}(T^{*0}_{cs0} \to D^0 K^0_S) = (2.6 \pm 1.2 \pm 0.4)\%$$

- $T^*_{cs0}(2870)^0$ observed in a new decay mode $T^*_{cs0}(2870)^0 \to D^0 K^0_S$, at a significance of 5.3σ
- Mass and width of $T^*_{cs0}(2870)^0$ measured, consistent with results from the $B^- \to D^- D^+ K^-$ decay
- $T^*_{cs1}(2900)^0$ also searched for, but without any evidence

$T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ $[cs\bar{u}\bar{d}]$

Phys. Rev. Lett. 134 (2025) 101901

Test of isospin invariance between $T^{*0}_{cs} \to D^+K^-$ and $T^{*0}_{cs} \to D^0\overline{K}^0$

$\overline{K}^0$ reconstructed in mass-eigenstate K^0_S

- Assumption: $T^{*0}_{cs0,1}$ are genuine hadronic states
- Isospin invariance requires:
  - ✓ Relative decay width $R_I(T^{*0}_{cs}) \equiv \frac{\Gamma(T^{*0}_{cs}\to D^0\overline{K}^0)}{\Gamma(T^{*0}_{cs}\to D^+K^-)} \approx 1$
  - ✓ Ratio of fit fractions:

$$R_{\mathrm{FF}}(D^0\overline{K}^0) \equiv \frac{\mathrm{FF}(T^{*0}_{cs1} \to D^0\overline{K}^0)}{\mathrm{FF}(T^{*0}_{cs0} \to D^0\overline{K}^0)}$$

$$R_{\mathrm{FF}}(D^+K^-) \equiv \frac{\mathrm{FF}(T^{*0}_{cs1} \to D^+K^-)}{\mathrm{FF}(T^{*0}_{cs0} \to D^+K^-)}$$

$$R_{\mathrm{FF}}(D^0\overline{K}^0/D^+K^-) = \frac{R_{\mathrm{FF}}(D^0\overline{K}^0)}{R_{\mathrm{FF}}(D^+K^-)} \approx 1$$

agrees with the isospin invariance at current experimental precision

Observable	Result
$R_{\mathrm{I}}(T^*_{cs0}(2870)^0)$	$3.3 \pm 1.1 \pm 1.1 \pm 1.1$
$R_{\mathrm{I}}(T^*_{cs1}(2900)^0)$	$0.15 \pm 0.15 \pm 0.05 \pm 0.05$
$R_{\mathrm{FF}}(D^0\overline{K}^0)/R_{\mathrm{FF}}(D^+K^-)$	$0.044 \pm 0.035 \pm 0.020$

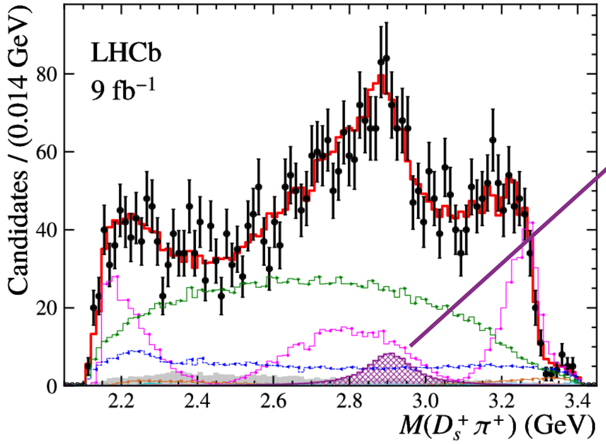
violation of isospin invariance between $T^{*0}_{cs1} \to D^0\overline{K}^0$ and $T^{*0}_{cs1} \to D^+K^-$ decays

Complicated internal structures of $T^*_{cs1}(2900)^0$!

$T^*_{c\bar{s}0}(2900)^{++}[c\bar{s}u\bar{d}]$ and $T^*_{c\bar{s}0}(2900)^0\ [c\bar{s}\bar{u}d]$

Phys. Rev. Lett. 131, 041902 (2023)
Phys. Rev. D 108, 012017 (2023)

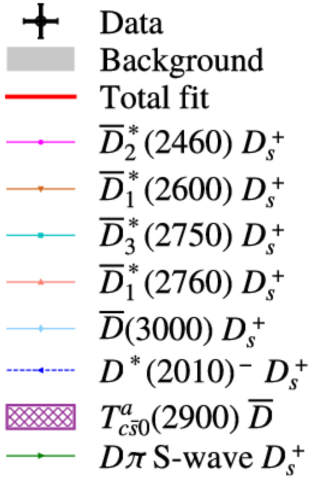
Flavor SU(3) symmetry: $T^*_{cs}\ [cs\bar{u}\bar{d}] \rightarrow T^*_{c\bar{s}}\ [c\bar{s}u\bar{d}\ /\ c\bar{s}\bar{u}d]$?

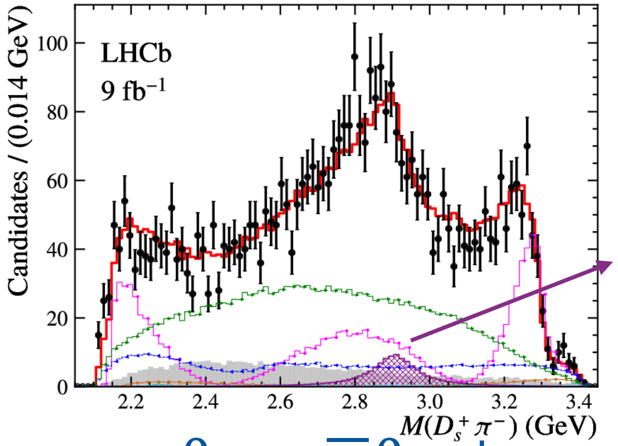


$B^+ \rightarrow D^- D_s^+ \pi^+$

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

$J^P = 0^+$





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

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

$J^P = 0^+$

- Joint amplitude analysis performed linked through isospin symmetry
- Two new exotic states $T^*_{c\bar{s}0}(2900)^{++/0}$ observed in the $D_s\pi$ channel over 5σ
- Enrich the spectroscopy of open-charm tetraquarks
- Also shed light on the long-standing question about D_{sJ} state, i.e., whether they contain two quarks or four quarks

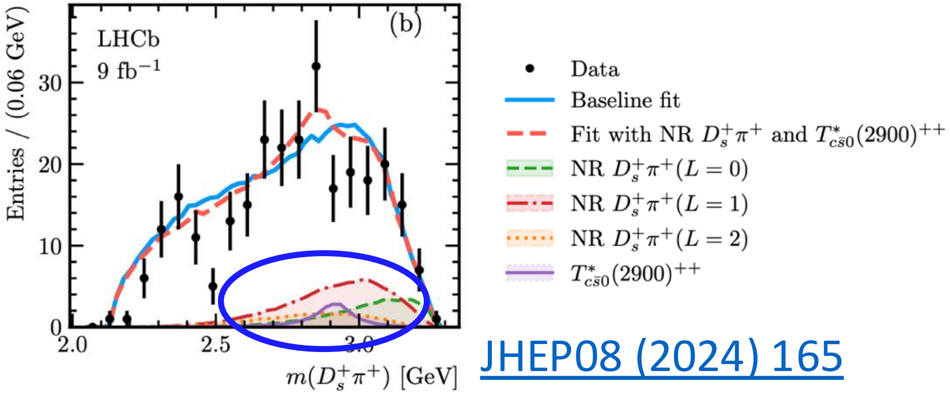
$$M = 2.908 \pm 0.011 \pm 0.020\ \text{GeV}$$

$$\Gamma = 0.136 \pm 0.023 \pm 0.013\ \text{GeV}$$

Other recent researches about $T_{c\bar{s}}^{(*)}[c\bar{s}\bar{u}d]$ states

In $B^+ \to D^{*-}\boldsymbol{D_s^+\pi^+}$ decays:

- no strong evidence
- $\mathrm{FF}(T_{c\bar{s}0}^{*}(2900)^{++} \to D_s^+\pi^+) < 2.3\%$ at 90% CL



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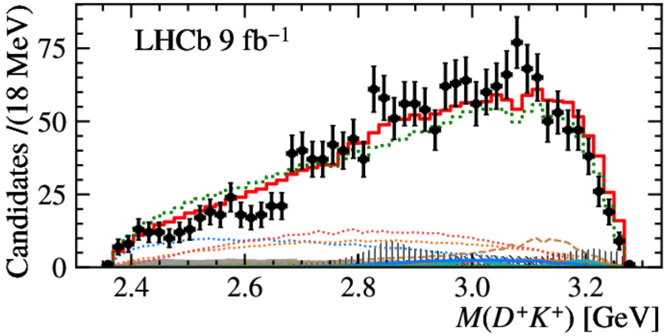
In $B^+ \to D^{*\pm}\boldsymbol{D^{\mp}K^+}$ decays:

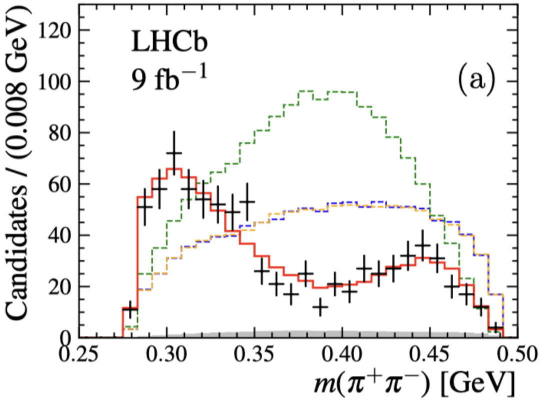
- no strong evidence
- $\mathrm{FF}(T_{c\bar{s}0}^{*}(2900)^{++} \to D^+K^+) < 3.3\%$ at 95% CL

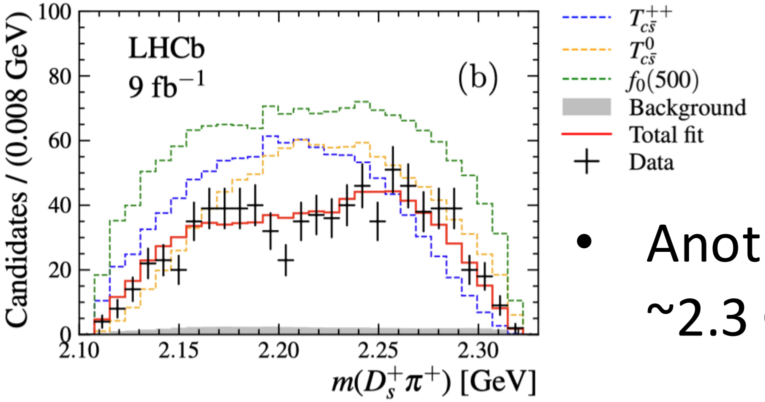


Phys. Rev. Lett. 133 (2024) 131902

No $T_{c\bar{s}0}^{*++}$ signal

In $B \to \bar{D}^{(*)}\boldsymbol{D_s^+\pi^+}\pi^-$ decays: Sci.Bull. 70 (2025) 1432-1444





Further confirmations of $T_{c\bar{s}}^{(*)}$ are needed in new channels!

- Another two $T_{c\bar{s}}^{++/0}$ low excited states observed ~2.3 GeV with $J^P = 0^+$

Summary and prospects

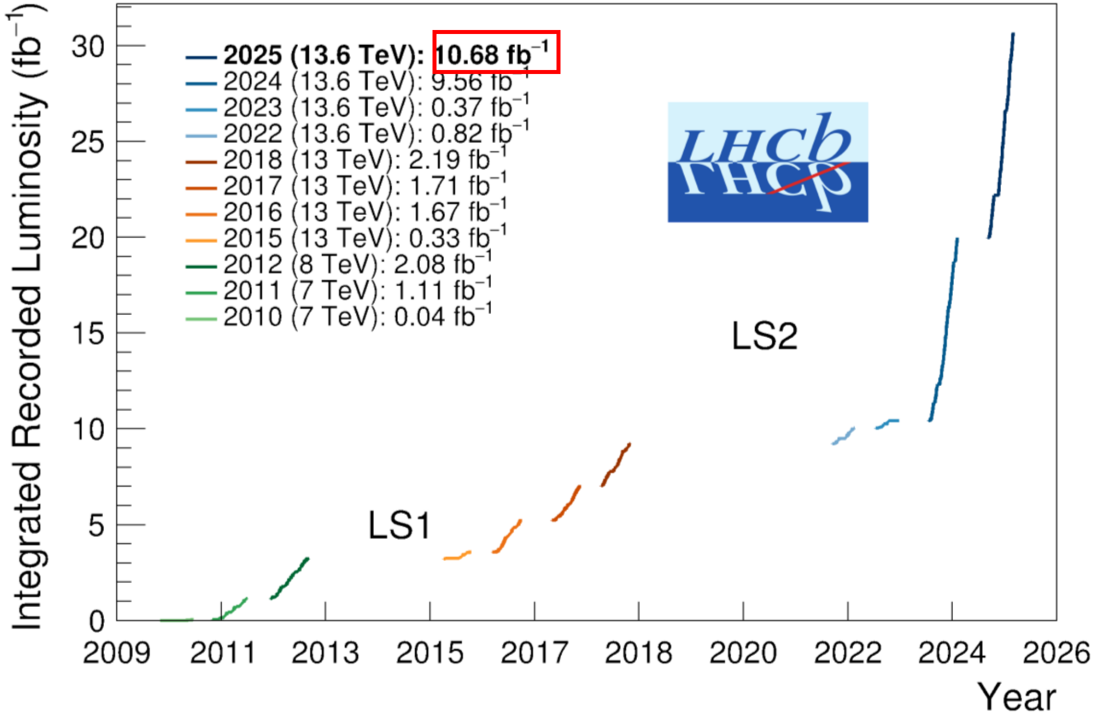
Summary

- Many active studies on exotic hadron spectroscopy with $B \to DDh$ decays at LHCb
- Recent results about open-charm tetraquarks observed in $B \to DDh$ decays:
  - ✓ $T^*_{cs0}(2870)^0$ $(J^P = 0^+)$ and $T^*_{cs1}(2900)^0$ $(J^P = 1^-)$ $[cs\bar{u}\bar{d}]$
  - ✓ $T^*_{c\bar{s}0}(2900)^{++}$ $[c\bar{s}u\bar{d}]$ and $T^*_{c\bar{s}0}(2900)^0$ $[c\bar{s}\bar{u}d]$ $(J^P = 0^+)$
- Further confirmation needed to unveil their nature: compact states, hadronic molecules, or something else?

Prospects

https://lbgroups.cern.ch/online/OperationsPlots/index.htm

- LHCb Run 3 on-going:
  - ✓ Full software trigger and direct lines with fully-hadronic final states to study open-flavor exotics
  - ✓ Increased sensitivity to exotics



With detailed studies on exotic hadrons, our picture on low energy non-perturbative QCD will be greatly improved!

Thanks for your listening!

Backup

Fit fraction

$$\mathcal{A}_{\text{sig}}(\vec{x}) = \sum_{j=1}^{N} c_j F_j(\vec{x})$$

$$\mathcal{F}_j = \frac{\int |c_j F_j(\vec{x})|^2 d\vec{x}}{\int |\mathcal{A}_{\text{sig}}(\vec{x})|^2 d\vec{x}}$$

Test of isospin invariance

Table 3.15 Measurements of the relative rates of decays into the $D^0\overline{K}^0$ and D^+K^- final states for $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ states, $R_{\text{I}}(T^*_{cs0}(2870)^0)$ and $R_{\text{I}}(T^*_{cs1}(2900)^0)$, and the double fit fraction ratio $R_{\text{FF}}(D^0\overline{K}^0)/R_{\text{FF}}(D^+K^-)$. The first, second and third uncertainties are statistical, systematic, and due to the external inputs of $B^- \to D^-D^+K^-$ and $B^- \to D^-D^0K^0_{\text{S}}$ branching fractions, respectively.

Observable	Result
$R_{\text{I}}(T^*_{cs0}(2870)^0)$	$3.3 \pm 1.1 \pm 1.1 \pm 1.1$
$R_{\text{I}}(T^*_{cs1}(2900)^0)$	$0.15 \pm 0.15 \pm 0.05 \pm 0.05$
$R_{\text{FF}}(D^0\overline{K}^0)/R_{\text{FF}}(D^+K^-)$	$0.044 \pm 0.035 \pm 0.020$

Research progesses of $B \to DDh$ decays

- Comprise a relatively large fraction of the total width of the B mesons
- Previous studies mainly focused on the measurement of branching fractions
  - ✓ $B \to \bar{D}^{(*)} D^{(*)} K$ Phys. Rev. D 83, 032004 (2011)
  - ✓ $B^+ \to \bar{D}^0 D^0 K^+$ Phys. Rev. Lett. 100, 092001 (2008)
  - ✓ $B^+ \to D^{(*)+} D^{(*)-} K^+, B^0 \to D^{*-} D^0 K^+$ JHEP 12 (2020) 139
  - ✓ $B^- \to D^0 \bar{D}^0 K^+ \pi^-$ … Phys. Rev. D 102, 051102 (2020)
- Few studies of their resonant structures exist.

Potential processes to search for T_{cs}^* or $T_{c\bar{s}}^*$ isospin partners

$B \to DDh$ decays play a crucial role!

- Ground-state modes:
  - $B^- \to \bar{D}^0 T_{cs}^{*-}, T_{cs}^{*-} \to D^0 K^-$,
  - $\bar{B}^0 \to D^- T_{cs}^{*+}, T_{cs}^{*+} \to D^+ \bar{K}^0$, …

➡ To probe natural J^P states

- Excited-state modes:
  - $B \to DDhh$ four-body decays
  - $B \to DDh$ decays with D^*

➡ To probe unnatural J^P states

What can we do in Run 3?

Search for $T^{*0}_{cs0,1}$ states

- Improve precision in
  - ✓ measuring the properties of T^{*}_{cs} states
  - ✓ isospin invariance test of T^{*0}_{cs} decay
- Further confirmation of $T^{*}_{cs1}(2900)^{0}$
- Search for new T^{*0}_{cs} states with higher spin, as indicated by some theoretical models

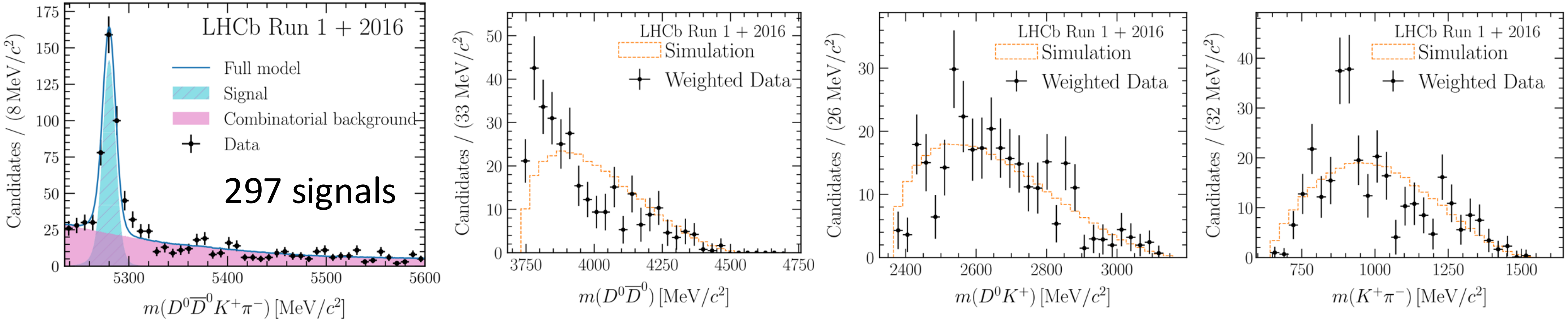
Search for T^{*}_{cs} charged isospin partners

- Potential processes:
  - ✓ $B^{-} \to \bar{D}^{0} T^{*-}_{cs}(\to D^{0}K^{-})$
  - ✓ $\bar{B}^{0} \to D^{-} T^{*+}_{cs}(\to D^{+}\bar{K}^{0})$
- Help distinguish between competing models and better understand their internal structures

Potential processes to search for T_{cs}^* or $T_{c\bar{s}}^*$ or their isospin partners

- One potential decay to be searched for T_{cs}^{*0}: $B^0 \to D^0\bar{D}^0K^+\pi^-$
  - T_{cs}^{*0} in $\bar{D}^0K^+\pi^-$?
  - Also rich conventional charmonium and $D_{(s)}^{**}$ states

[Phys. Rev. D 102, 051102 (2020)](https://doi.org/10.1103/PhysRevD.102.051102)



$\mathcal{B}(B^0 \to D^0\bar{D}^0K^+\pi^-)$ has been measured.

Amplitude model is under developing!

Wait for the LHCb Run 3 data to perform a detailed amplitude analysis.