Conventional and exotic charm meson spectroscopy (experiment)

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on behalf of LHCb Collaboration

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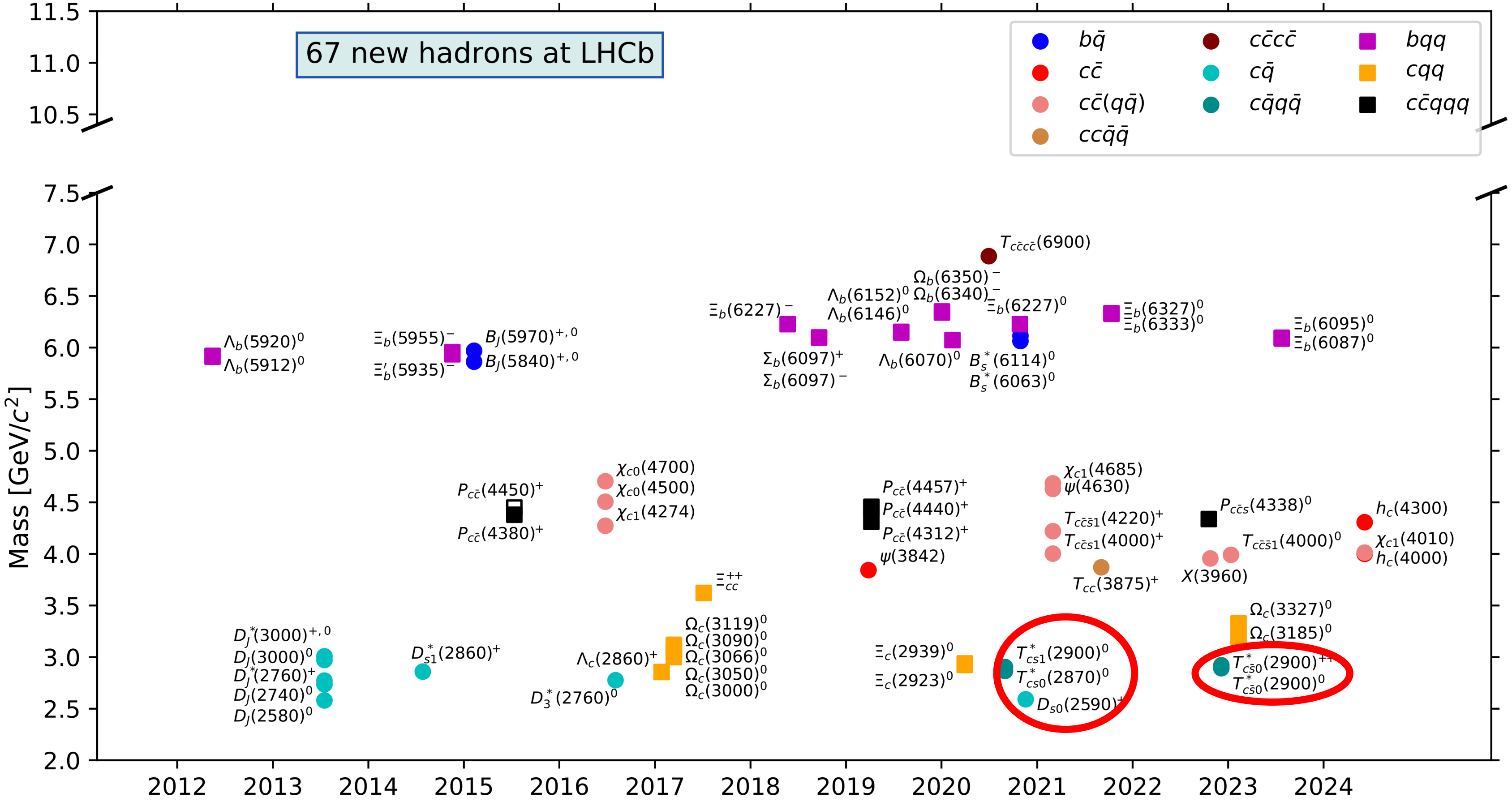
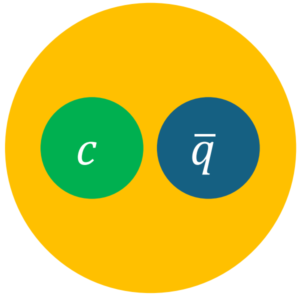
Hadrons discovered at LHCb experiment

- Link
- Mass vs discovery date
- Focus on $c\bar{q}$ and $c\bar{q}q\bar{q}$
- Discovered through $B \to DDX$ decays
- Full reconstruction of all final-state particles

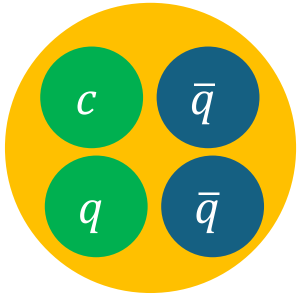


Outline

- Conventional charm-strange meson
  - $D_{s0}(2590)^+$



- Exotic charm-strange meson
  - $T^*_{cs1}(2900)^0$
  - $T^*_{cs0}(2870)^0$
  - $T^*_{c\bar{s}0}(2900)^{++}$
  - $T^*_{c\bar{s}0}(2900)^0$



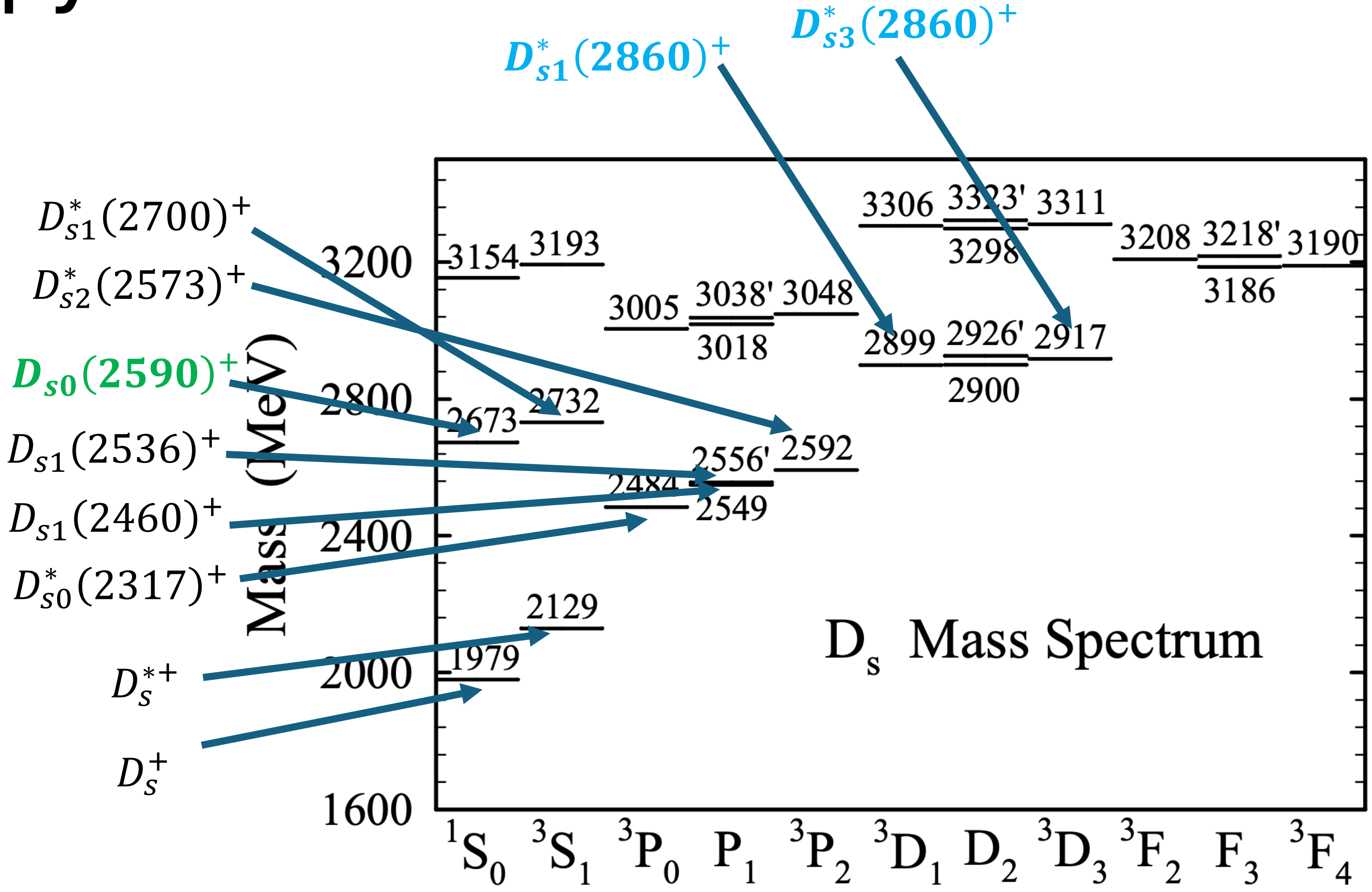
- Controversy on $D^*_{s0}(2317)$ and $D_{s1}(2460)^+$

- Will focus on the most recent results
- Inclusion of charge-conjugate processes is implied throughout the talk

D_s^{**} spectroscopy

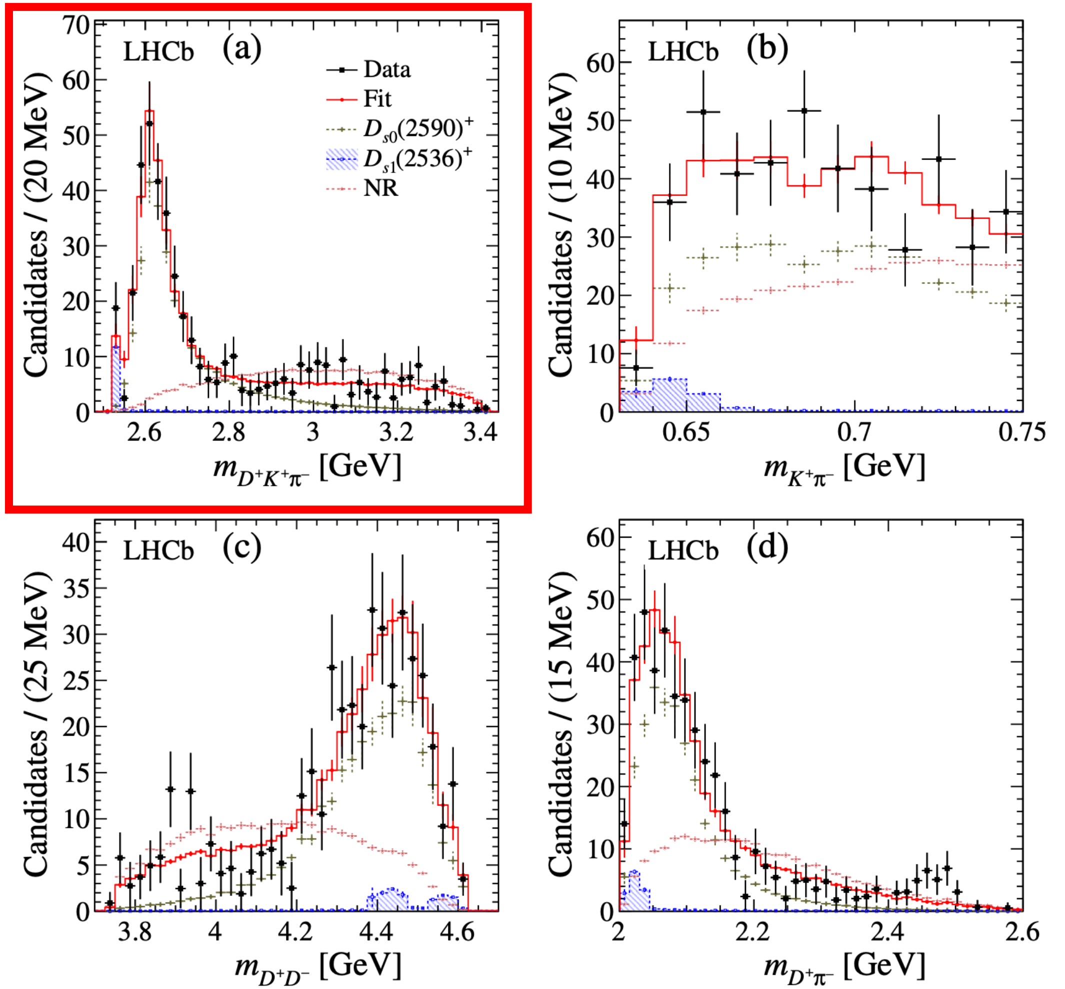
- Relativistic quark model
- Some discrepancies between predicted and measured masses
- Blue: states discovered in LHCb
- Green: states discovered in LHCb and to be introduced in the talk

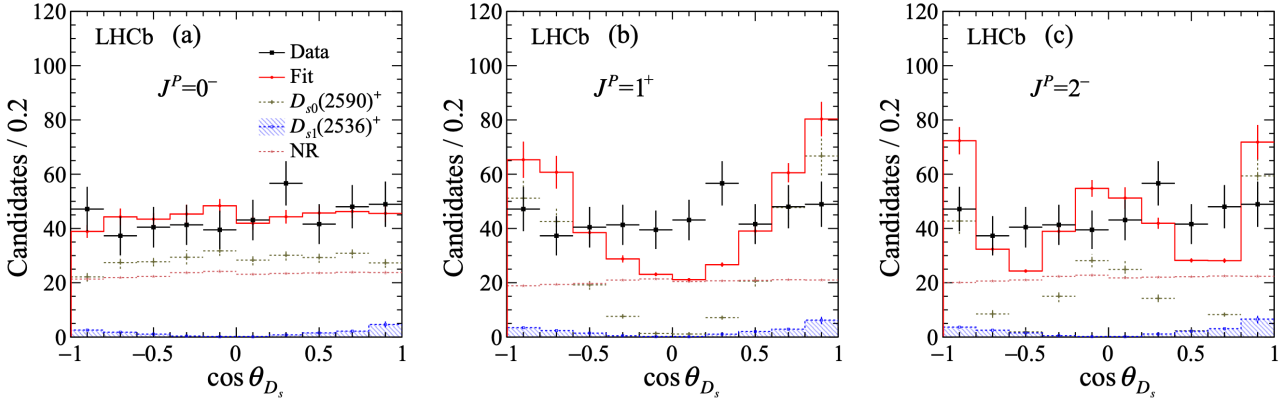
Phys. Rev. D 89, 074023



$D_{s0}(2590)^+$: strong candidate for $D_s^+(2^1S_0)$

- 5.4 fb^{-1}
- $B^0 \to D^-D^+K^+\pi^-$; $D_{s0}(2590)^+ \to D^+K^+\pi^-$
- $m(K^+\pi^-) < 750$ MeV: dominantly S-wave ($J^P = 0^+$), any $R(D^+K^+\pi)$ should have unnatural $J^P = (-1)^{J+1}$
- Pole mass and pole width
  - $m_R = 2591 \pm 6 \pm 7$ MeV; $\Gamma_R = 89 \pm 16 \pm 12$ MeV
- $J^P = 0^-$ >10 σ
- θ_{D_s}: Angle between D^+ and the opposite direction of B^0 in the D_s^+ rest frame





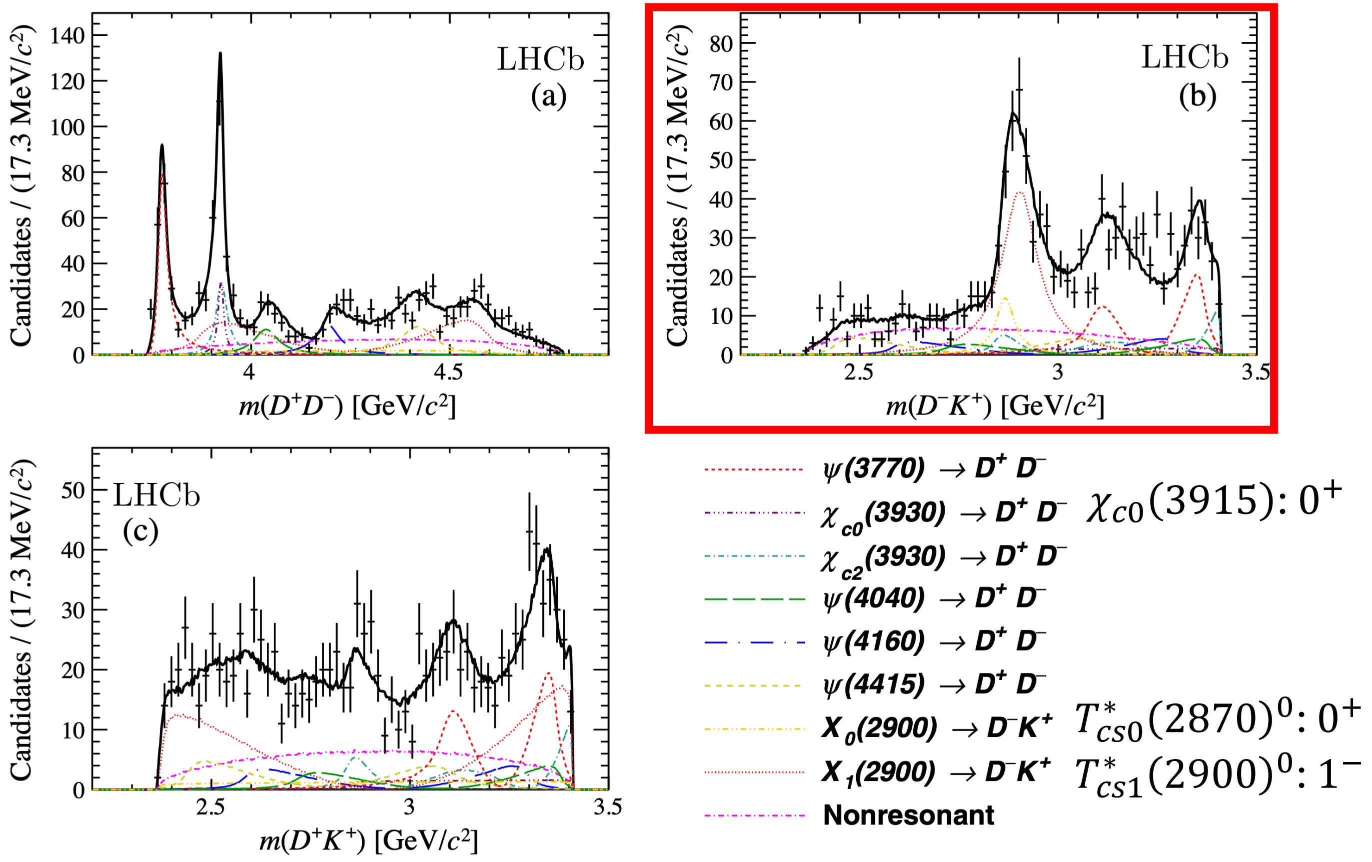
Phys. Rev. Lett. 126 (2021) 122002

Exotic charm-strange mesons

States	Quark compnent	Mass (MeV)	Width (MeV)	Discovery channel
$T^*_{cs0}(2870)^0$	$\bar{c}d\bar{s}u$	2866 ± 7	57 ± 13	$B^+ \to D^+D^-K^+$ $B^- \to D^-D^0K_S^0$ $B^+ \to D^{*+}D^-K^+$
$T^*_{cs1}(2900)^0$	$\bar{c}d\bar{s}u$	2904 ± 5	110 ± 12	$B^+ \to D^+D^-K^+$ $B^+ \to D^{*+}D^-K^+$
$T^*_{c\bar{s}0}(2900)^{++}$	$c\bar{s}u\bar{d}$	2921 ± 26	140 ± 40	$B^+ \to D^-D_s^+\pi^+$
$T^*_{c\bar{s}0}(2900)^0$	$c\bar{s}\bar{u}d$	2892 ± 21	119 ± 29	$B^0 \to \bar{D}^0D_s^+\pi^-$

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

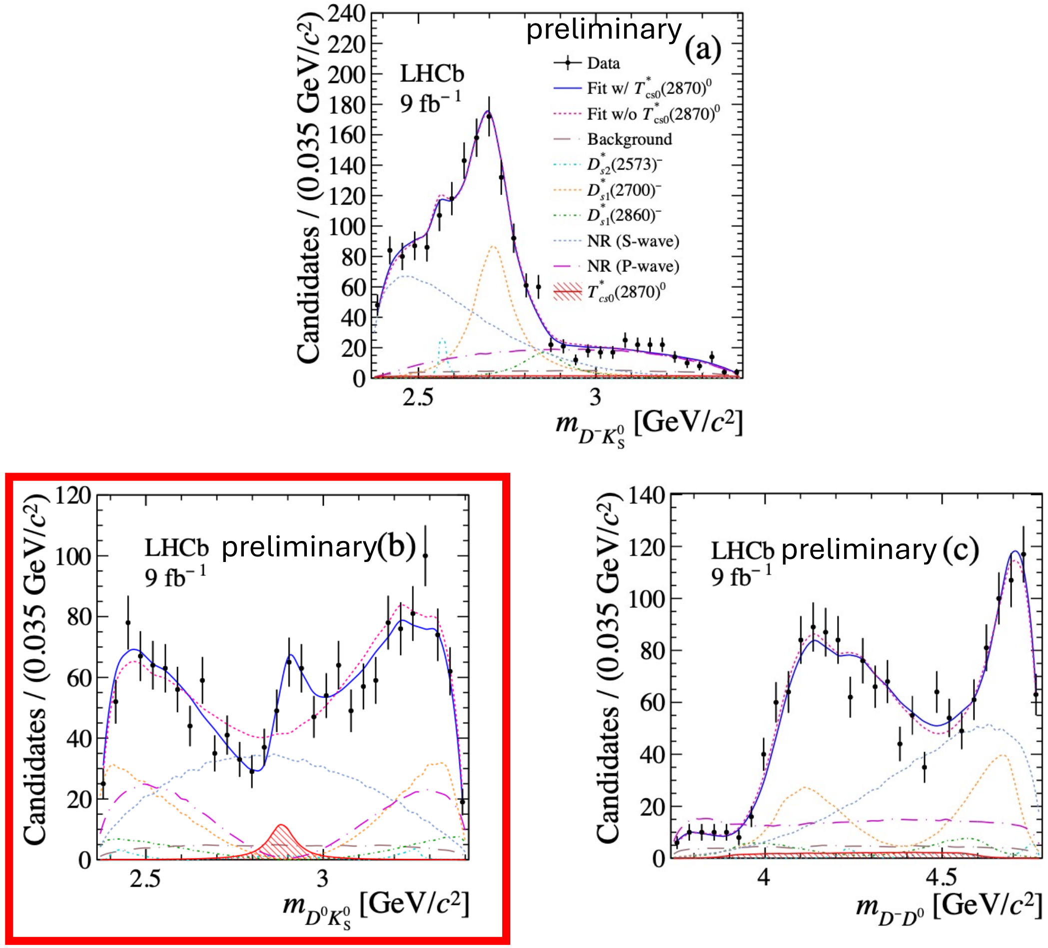
- $9.0\ \text{fb}^{-1}$
- $B^+ \to D^+ D^- K^+$
- Two new tetraquark states: $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$
  - $\bar{c}d\bar{s}u$
  - $m = 2866 \pm 7 \pm 2$ MeV
  - $\Gamma = 57 \pm 12 \pm 4$ MeV
  - $m = 2904 \pm 5 \pm 1$ MeV
  - $\Gamma = 110 \pm 11 \pm 4$ MeV
- One new state: $\chi_{c0}(3915)$



Phys. Rev. D102 (2020) 112003

$T_{cs0}^{*}(2870)^0$ in $B^- \to D^- D^0 K_S^0$ preliminary

- 9.0 fb^{-1}
- $T_{cs0}^{*}(2870)^0$ (Significance of 5.3 σ)
  - $m = 2883 \pm 11 \pm 6$ MeV
  - $\Gamma = 87^{+22}_{-47} \pm 6$ MeV
- Use D_{sJ} states to model $m(D^- K_S^0)$
  - K-matrix: overlap between $D_{s1}^{*}(2700)$ and $D_{s1}(2860)$
  - Higher spin $D_{s3}^{*}(2860)$
- $T_{cs1}^{*}(2900)^0$ not significant
- $\frac{\Gamma(T_{cs0}^{*}(2870)^0 \to D^0 \bar{K}^0)}{\Gamma(T_{cs0}^{*}(2870)^0 \to D^+ K^-)} = 3.3 \pm 1.9$
- $\frac{\Gamma(T_{cs1}^{*}(2900)^0 \to D^0 \bar{K}^0)}{\Gamma(T_{cs1}^{*}(2900)^0 \to D^+ K^-)} = 0.15 \pm 0.16$
- Phys. Rev. D103 (2021) 014004
  - $T_{cs1}^{*}(2900)^0$ is caused by triangle singularities of $B^- \to D^{(*)0} D_{sJ}^{(*)-} (\to D^- K^{(*)0})$ decays with final-state rescattering
  - The state does not have a definite isospin



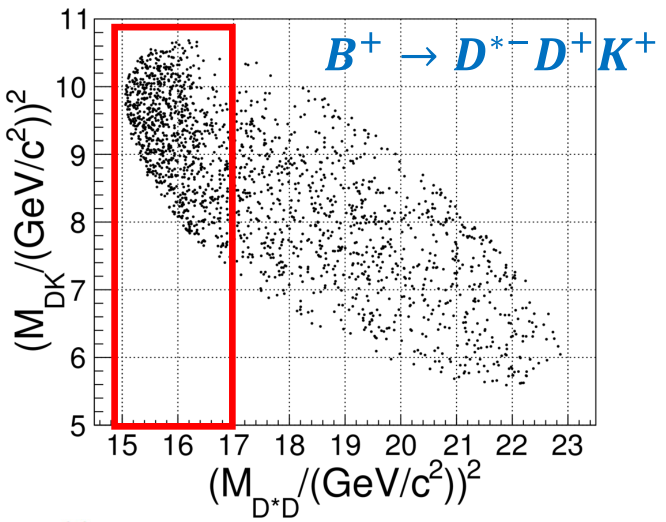
LHCB-PAPER-2024-040

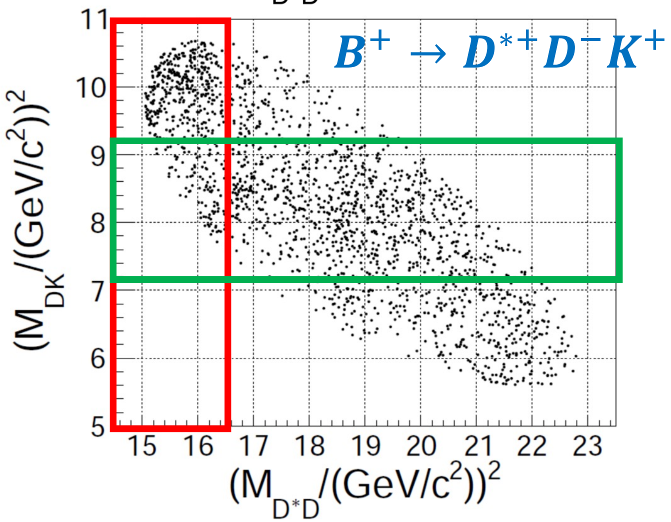
$T_{cs0}^{*}(2870)^0$ and $T_{cs1}^{*}(2900)^0$ in $B^+ \to D^{*\pm} D^{\mp} K^+$

- 9.0 fb^{-1}
- $B^+ \to D^{*+} D^- K^+$ and $B^+ \to D^{*-} D^+ K^+$
- $B^+ \to R(D^{*\pm} D^{\mp}) K^+$ The amplitude is related by C parity

$$\left.\begin{array}{l} B^+ \to D^{*+} D^- K^+ \\ B^+ \to D^{*-} D^+ K^+ \end{array}\right\} B^+ \to X K^+, X \to \left\{\begin{array}{l} D^{*+} D^- \\ D^{*-} D^+ \end{array}\right.$$

- $A(x) = \frac{1+d}{2}\left[c_j A_j(x) + c_k A_k(x)\right] + \frac{1-d}{2}\left[C_j c_j A_j(x) + c_l A_l(x)\right]$
- It is the first time that amplitude analysis can determine the C-parity of the resonances
- Clear difference due to interference of different C-parities
- At least three new states: $h_c(4000)$, $\chi_{c1}(4010)$, $h_c(4300)$



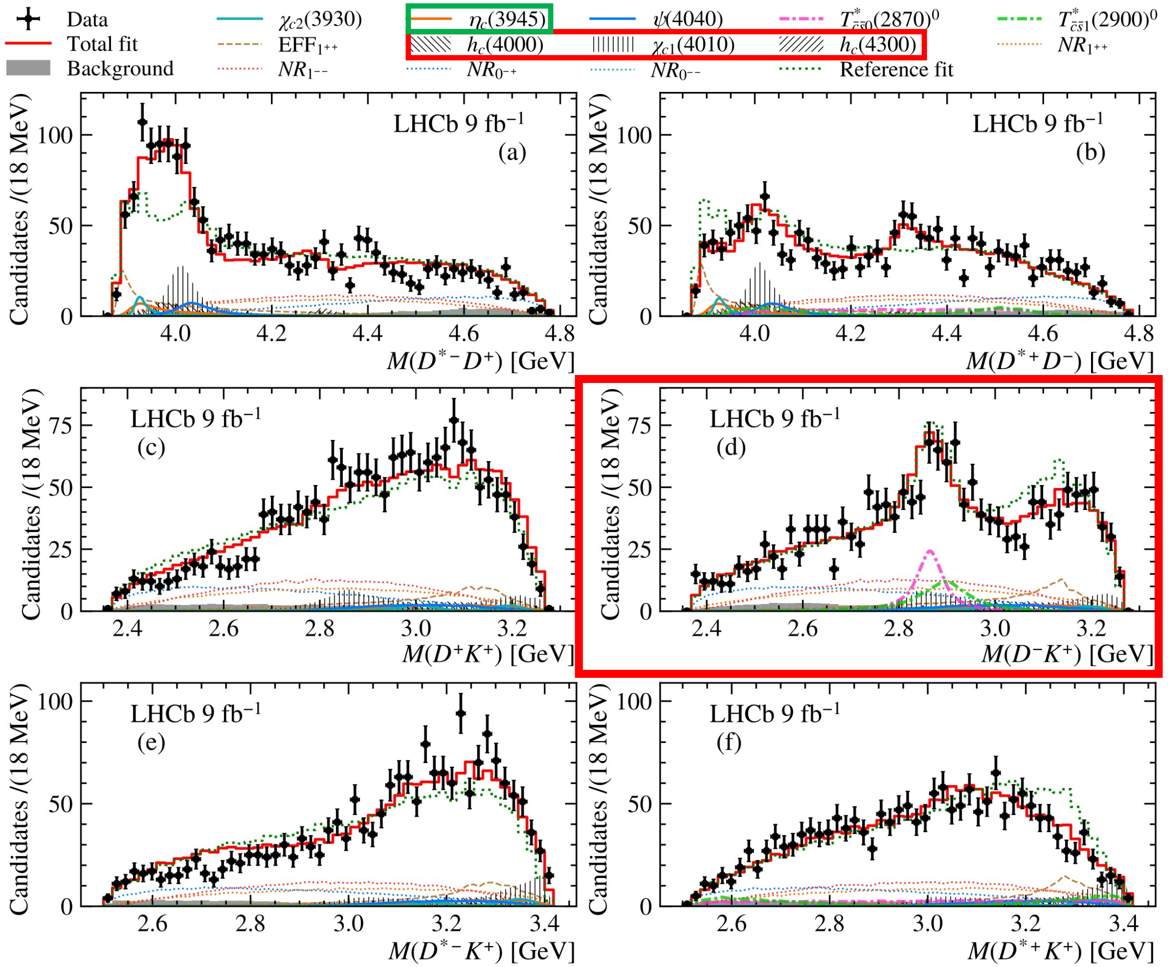


Phys. Rev. Lett. 133 (2024) 131902

$T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ in $B^+ \to D^{*\pm} D^{\mp} K^+$

- Contribution from T^*_{cs} seen in one channel
- Some tension in the mass, width and fractions
- $T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^{*-}K^+$ is forbidden
- The processes $B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^+$, $T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-}K^+$ and $B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^{++} D^{*-}$, $T^*_{\bar{c}\bar{s}1}(2900)^{++} \to D^+K^+$ are not obvious

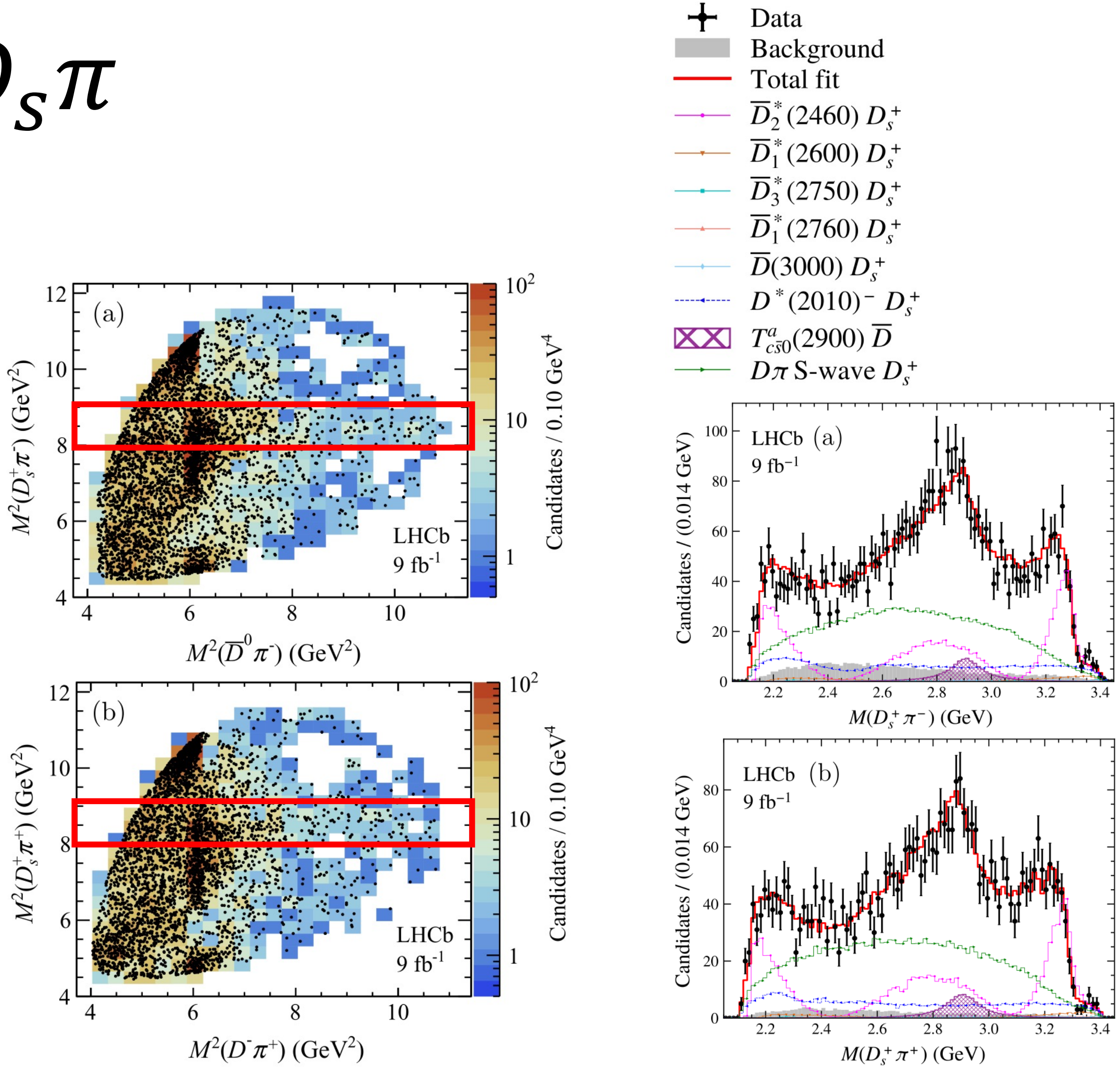
Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm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



$T^*_{c\bar{s}0}(2900)$ in $B \to D D_s \pi$

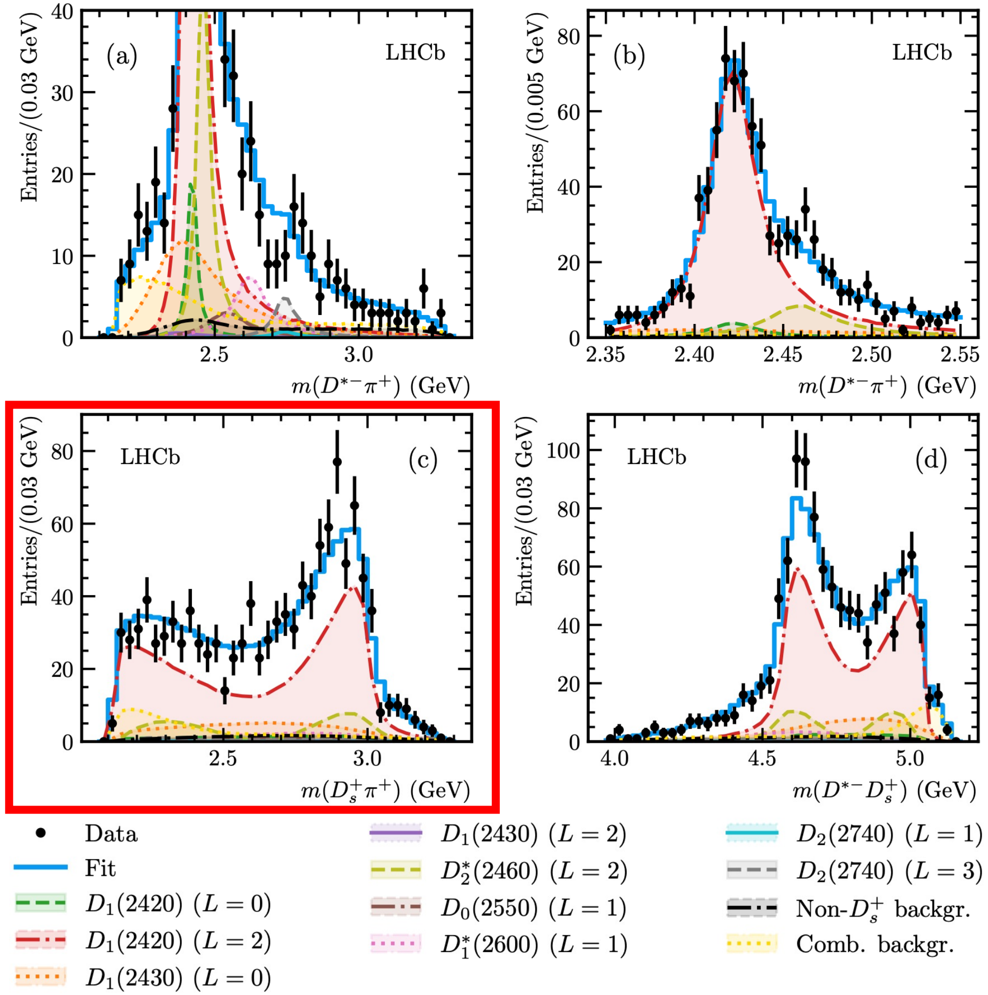
- 9.0 fb^{-1}
- $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$
- Isospin symmetry
- $T^*_{c\bar{s}0}(2900)^{++}$: $c\bar{s}u\bar{d}$
- $T^*_{c\bar{s}0}(2900)^{0}$: $c\bar{s}\bar{u}d$
- $J^P = 0^+$
- $m = 2908 \pm 11 \pm 20$ MeV
- $\Gamma = 136 \pm 23 \pm 13$ MeV
- Might belong to an isospin triplet

Phys. Rev. Lett. 131 (2023) 041902



Search for $T^*_{c\bar{s}0}(2900)^{++}$ in $B^+ \to D^{*-} D_s^+ \pi^+$

- 9.0 fb^{-1}
- $B^+ \to D^{*-} D_s^+ \pi^+$
- Main contribution from excited charm meson
- No strong evidence of $T^*_{c\bar{s}0}(2900)^{++}$, an upper limit is set 2.5% @ 90% CL
- The statistics is limited



JHEP08 (2024) 165

$D_{s1}(2460)^+$ in B decays

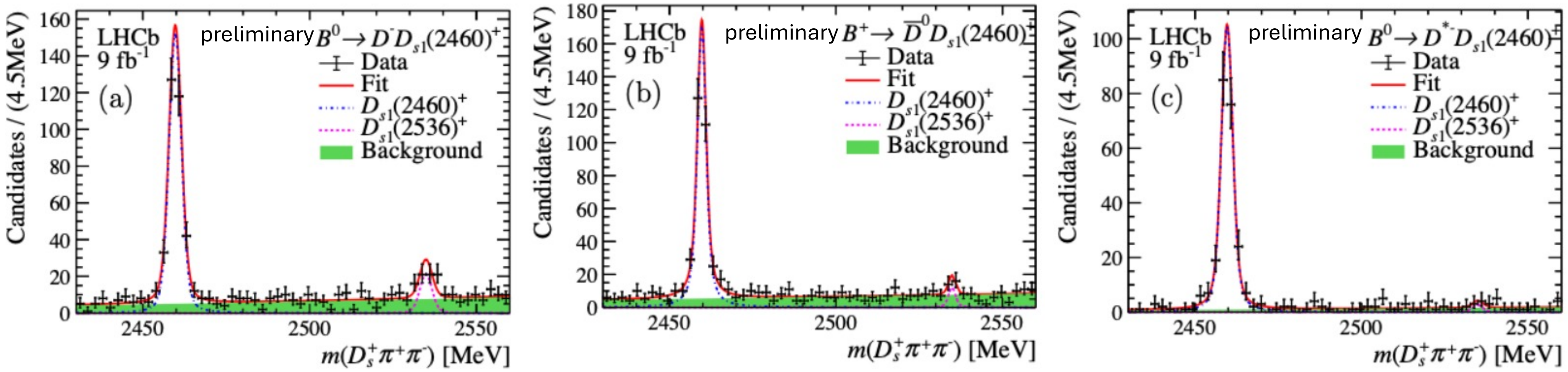
LHCB-PAPER-2024-033

- The nature of $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ has been discussed extensively without a firm conclusion
- Their masses are 100 MeV lower than the quark model expectation
- Lower mass makes decaying to D^*K impossible, dominant isospin violating decay of $D_s^{(*)+}\pi^0$
- Isospin conserving decay $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ at a sizable rate
- Double-bump lineshape in $m(\pi\pi)$ if $D_{s1}(2460)^+$ is a D^*K hadronic molecule
  - Commun. Theor. Phys. 75 055203
  - The multiplet including $T_{c\bar{s}}(2900)^{++}$, $T_{c\bar{s}}(2900)^0$, and $T_{cs0}(2900)^0$ could be the radial excitation of a lighter multiplet containing $D_{s0}^*(2317)^+$
  - Phys. Rev. D **110**, 034014

$D_{s1}(2460)^+$ in B decays

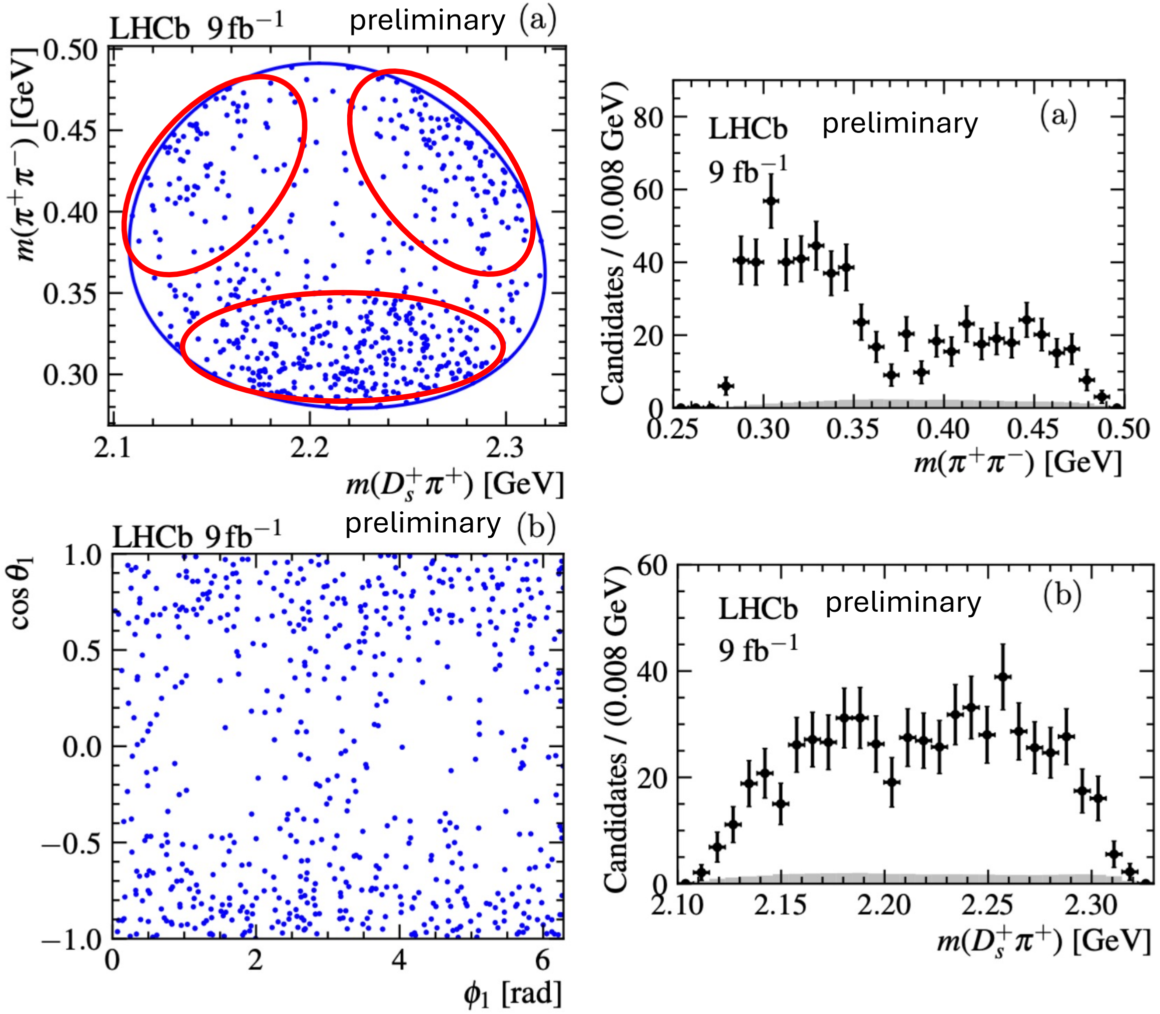
preliminary

- $9.0\ \mathrm{fb}^{-1}$
- $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to \overline{D}^{(*)}D_s^+\pi^+\pi^-$
- $B^0 \to D^-D_{s1}(2460)^+$, $B^+ \to \overline{D}^0 D_{s1}(2460)^+$, and $B^0 \to D^{*-}D_{s1}(2460)^+$



$D_{s1}(2460)^+$ in B decays

- Double-bump structure in $m(\pi\pi)$
- Amplitude fit
  - Isobar approach
  - TF-PWA software [link]
- The models $f_0(500) + f_0(980)$ and $\pi\pi$ K-matrix cannot describe the data well
- The model in paper [Commun. Theor. Phys. 75 055203] also cannot describe the data well



$D_{s1}(2460)^+$ in B decays

- Two models can describe the data well
- One w/o exotic contribution
  - $f_0(500) + f_0(980) + f_2(1270)$
    - $f_0(500)$: relativistic Breit-Wigner (RBW)
    - $f_0(980)$: Flatte model
    - $f_2(1270)$: RBW w/ mass and width fixed
- ρ contribution is not significant

- One w/ exotic contribution
  - $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^{0}$
  - $T_{c\bar{s}}$ tested with two models
    - RBW
    - K-matrix (scattering length approxmation)
    - Describes the rescattering between $D_s\pi$ and DK channel
    - Natural parametrisation of the DK molecular state

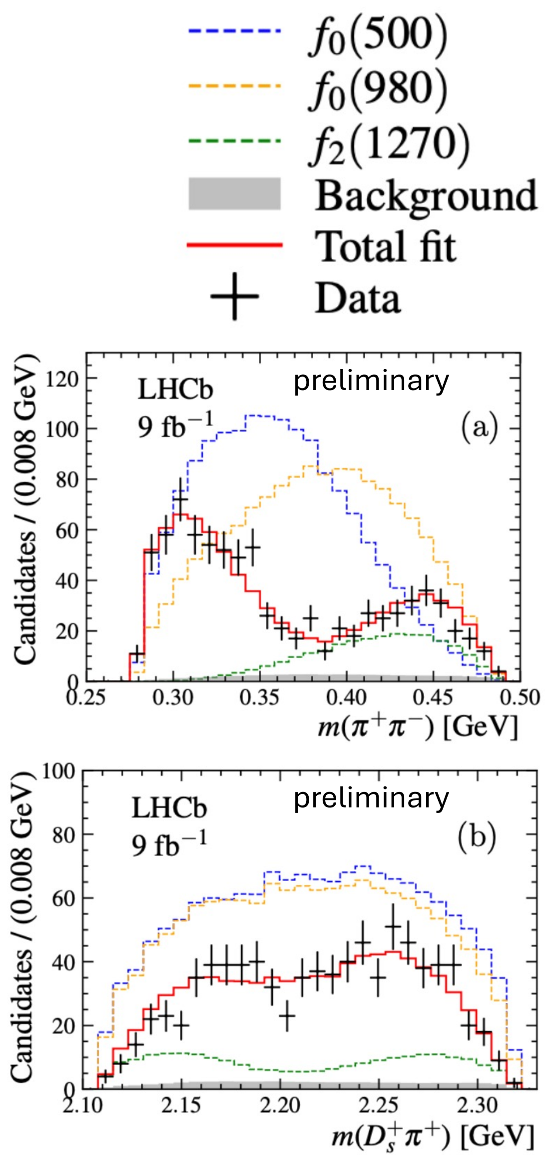
Elastic DK **$DK \leftrightarrow D_s\pi$**

$$K = \begin{pmatrix} \gamma & \beta \\ \beta & \gamma_2 \end{pmatrix}$$

Elastic $D_s\pi$

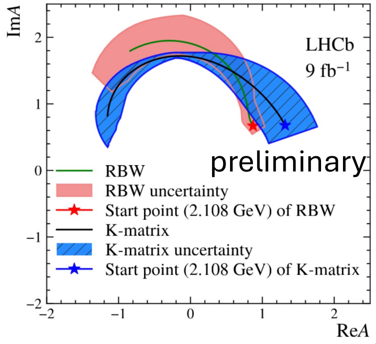
$D_{s1}(2460)^+$ in B decays

- $f_0(500) + f_0(980) + f_2(1270)$
  - The large contribution from $f_0(980)$ and $f_2(1270)$
  - The large interference between $f_0(500)$ and $f_0(980)$ forming the double bump lineshape in $m(\pi\pi)$
  - The mass and width of $f_0(500)$ are different from the known values



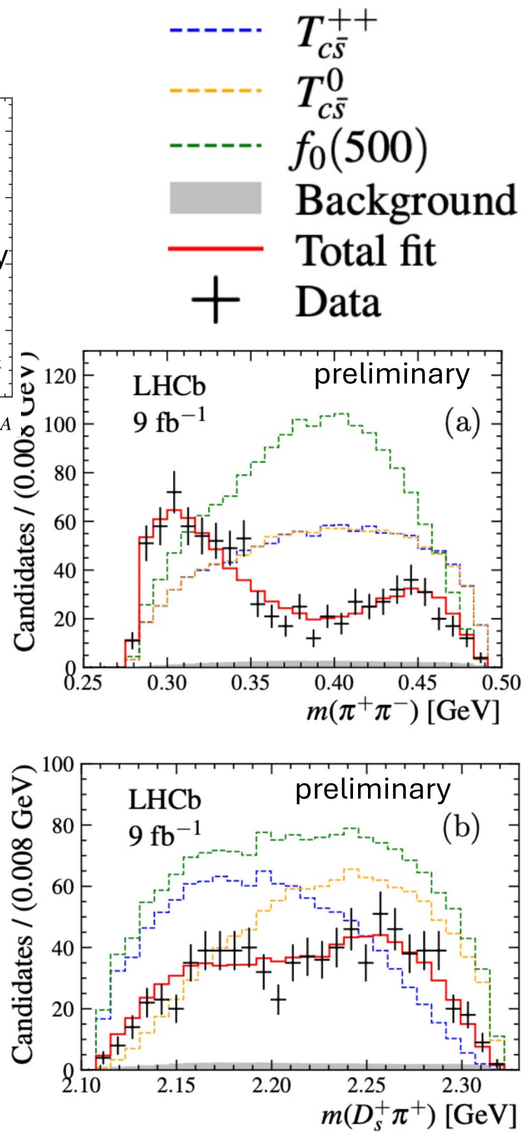
Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$376 \pm 9 \pm 16$	$175 \pm 23 \pm 16$	$197 \pm 35 \pm 23$
$f_0(980)$	945.5	167	$187 \pm 38 \pm 43$
$f_2(1270)$	1275.4	186.6	$29 \pm 2 \pm 1$

$D_{s1}(2460)^{+}$ in B decays



- $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^{0}$
  - Pole mass just below DK threshold
  - Isospin symmetry is conserved
  - J^P favours 0^+
  - Significance over $f_0(500) + f_0(980)$ model is larger than 10 σ
  - Consistent results obtained w/ RBW and K-matrix model except for the width
  - Assign large systematic uncertainty for the width

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



$D_{s1}(2460)^+$ in B decays

- Some discussion
  - Large interference is inevitable since narrow phase space
  - Two models could describe the data well
  - The first one only with $R(\pi\pi)$ contribution
    - Large contribution from $f_0(980)$ and $f_2(1270)$ far away from the upper limit of $m(\pi\pi)$
    - The mass and width for $f_0(500)$ not consistent with PDG
    - We cannot fully reject this model, but we find it implausible.
  - The second one with exotic charm meson contribution
    - $T_{c\bar{s}}^{++}$ and its isopin partner $T_{c\bar{s}}^{0}$

Summary

- LHCb has discovered multiple conventional and exotic charm meson over the past few years
- Need more data to understand the production mechanism of newly observed tetraquark states and find their isospin partners
- New results on the $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ decay shed light on the open question regarding the structure of the D_{sJ} states.

Thank you!

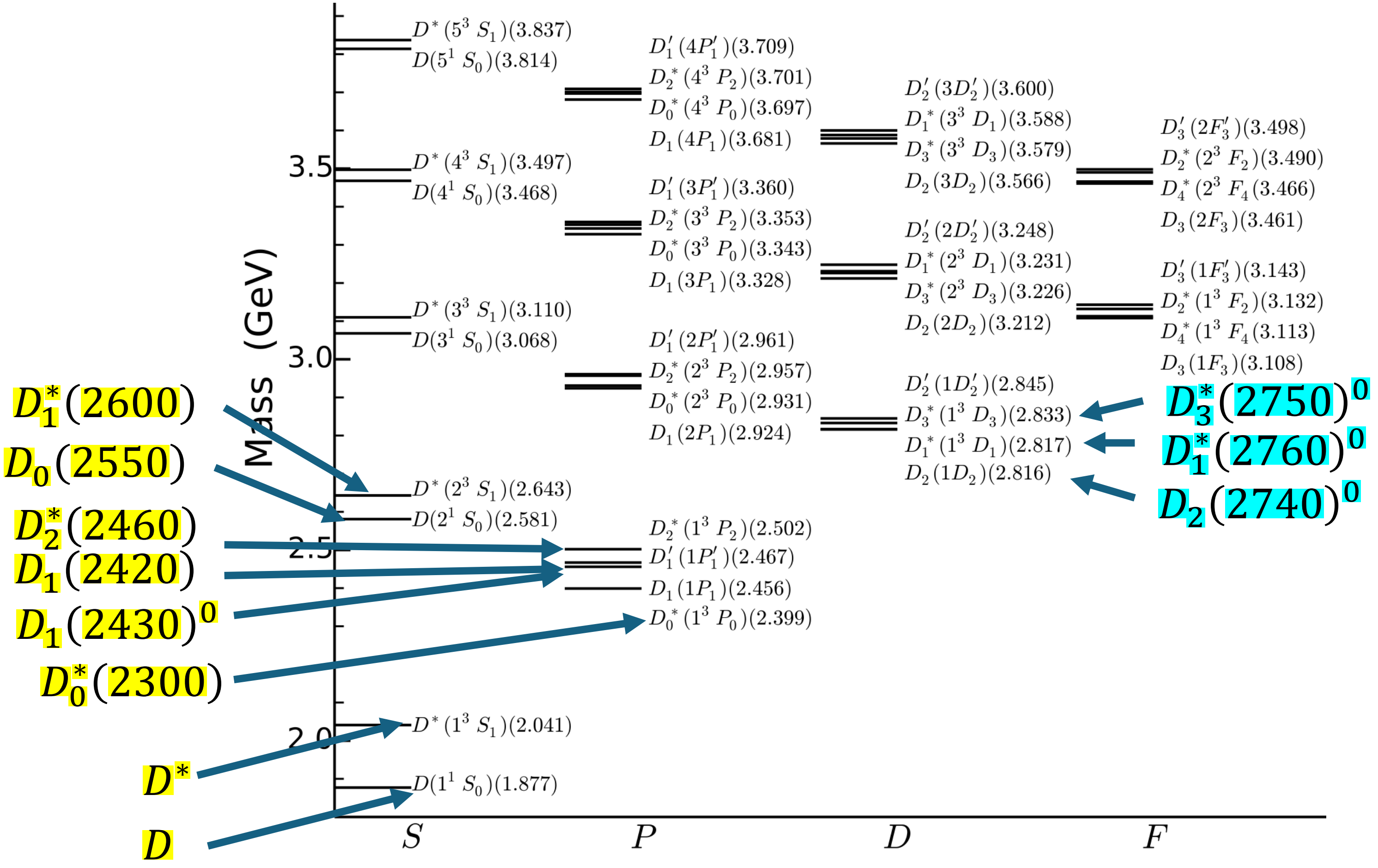
Backup slides

D^{**} spectroscopy

- Relativistic quark model
- Some discrepancies between predicted and measured masses
- Blue: states discovered in LHCb
- Link

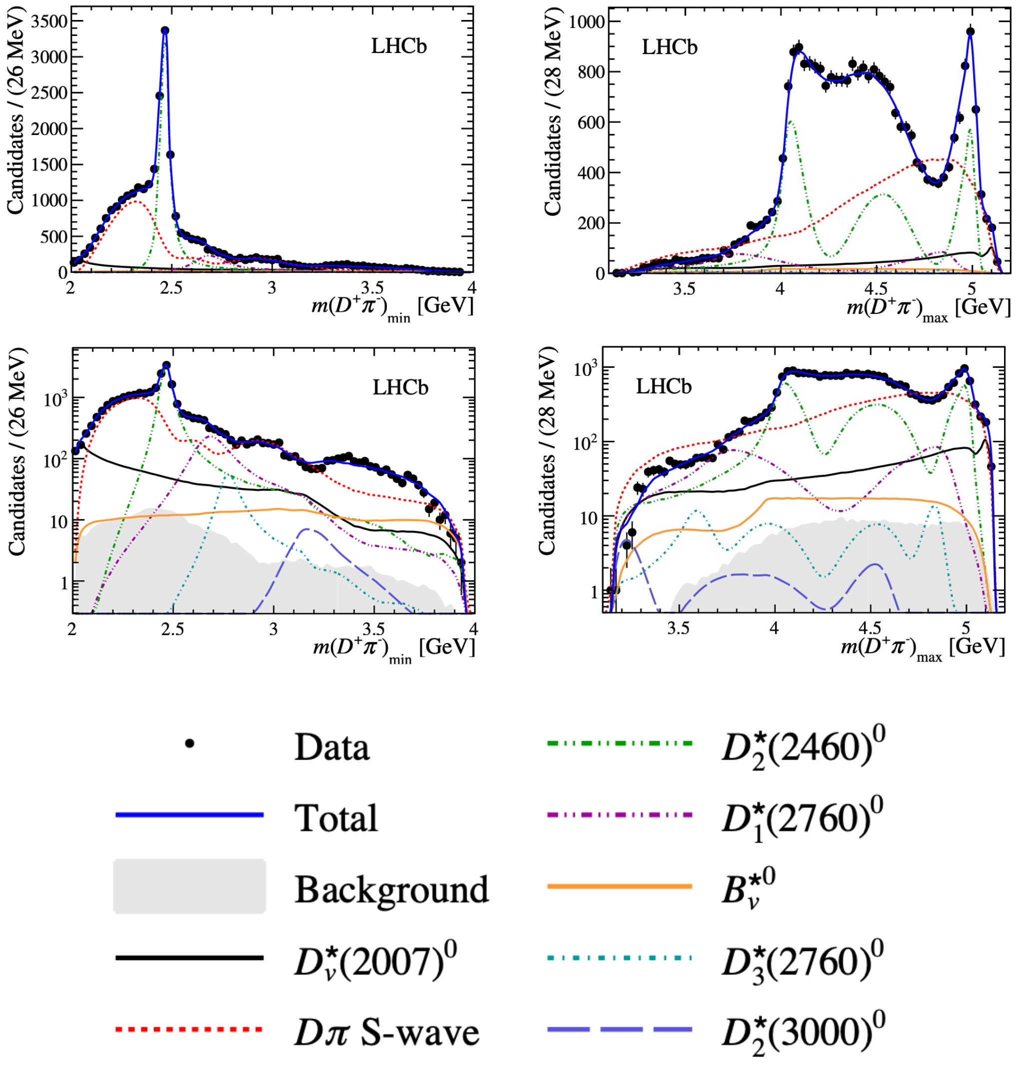
$D^*(2640)^{\pm}$?

$D(3000)^0$?



Observation of $D_3^*(2750)^0, D(3000)^0$

- $3.0\ \text{fb}^{-1}$
- Amplitude analysis of $B^+ \to D^-\pi^+\pi^+$
- Significant contribution from $D_2^*(2460)^0, D_1^*(2680)^0,\ D_3^*(2750)^0, D(3000)^0$
- $D_1^*(2680)^0$: Both 2S and 1D states with spin-parity $J^P = 1^-$ are expected in this region
- $D_3^*(2750)^0$: a member of 1D family
- $D(3000)^0$: a member of 2P or 1F family
- No spin-parity preference

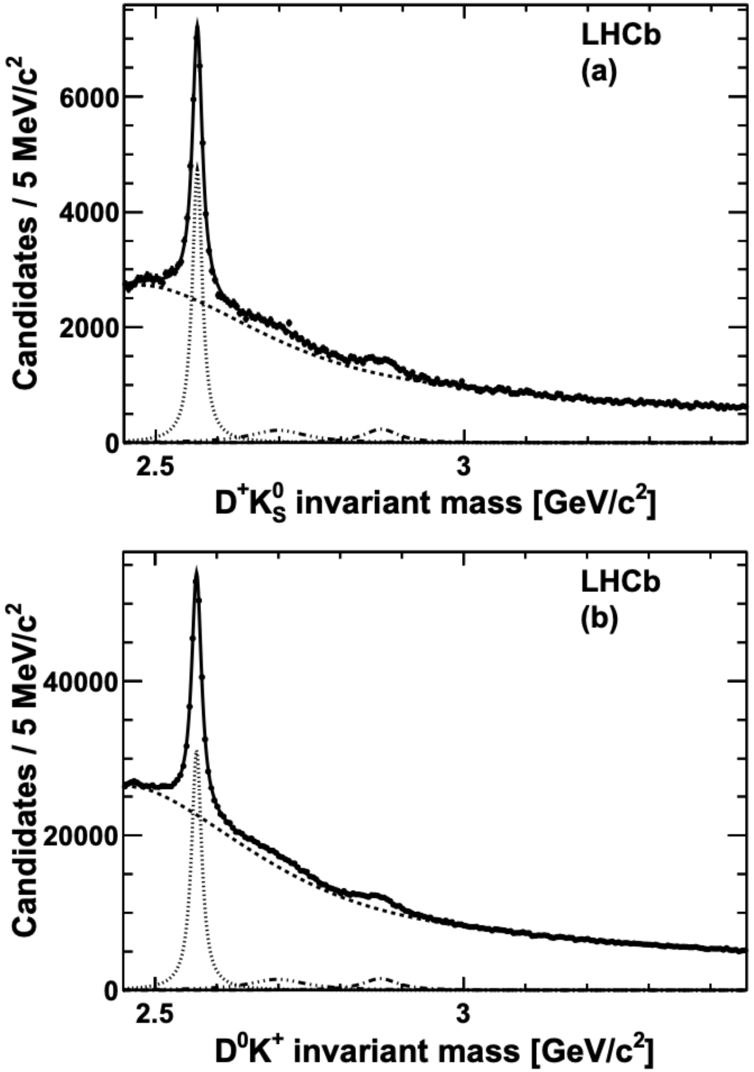


Phys. Rev. D94 (2016) 072001

Confirmation of $D_{s1}^{*}(2700)^{+}$ and $D_{sJ}^{*}(2860)^{+}$

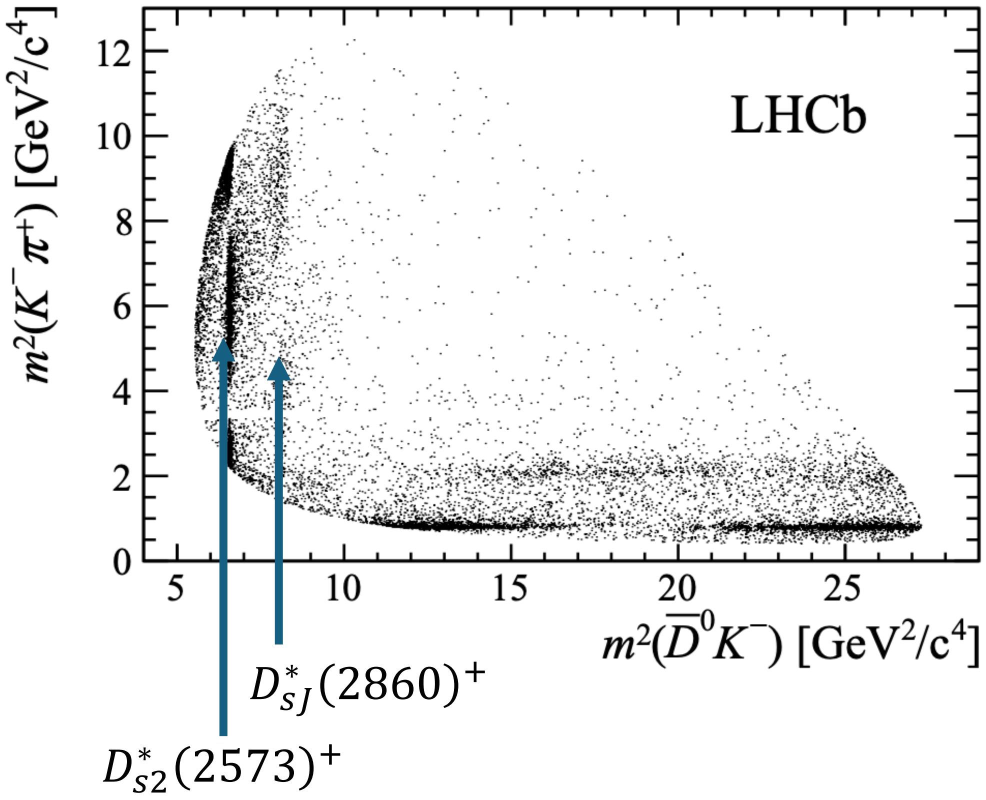
- $3.0\ \mathrm{fb}^{-1}$
- $pp \to D^{+}K_{S}^{0} + X$ and $pp \to D^{0}K^{+} + X$
- $m(D_{s1}^{*}(2700)^{+}) = 2709.2 \pm 1.9 \pm 4.5$ MeV
- $\Gamma(D_{s1}^{*}(2700)^{+}) = 115.8 \pm 7.3 \pm 12.1$ MeV
- $m\left(D_{sJ}^{*}(2860)^{+}\right) = 2866.1 \pm 1.0 \pm 6.3$ MeV
- $\Gamma\left(D_{sJ}^{*}(2860)^{+}\right) = 69.9 \pm 3.2 \pm 6.6$ MeV

JHEP 10 (2012) 151



Resolve the J^P of $D_{s1}^*(2860)^+$ and $D_{s3}^*(2860)^+$

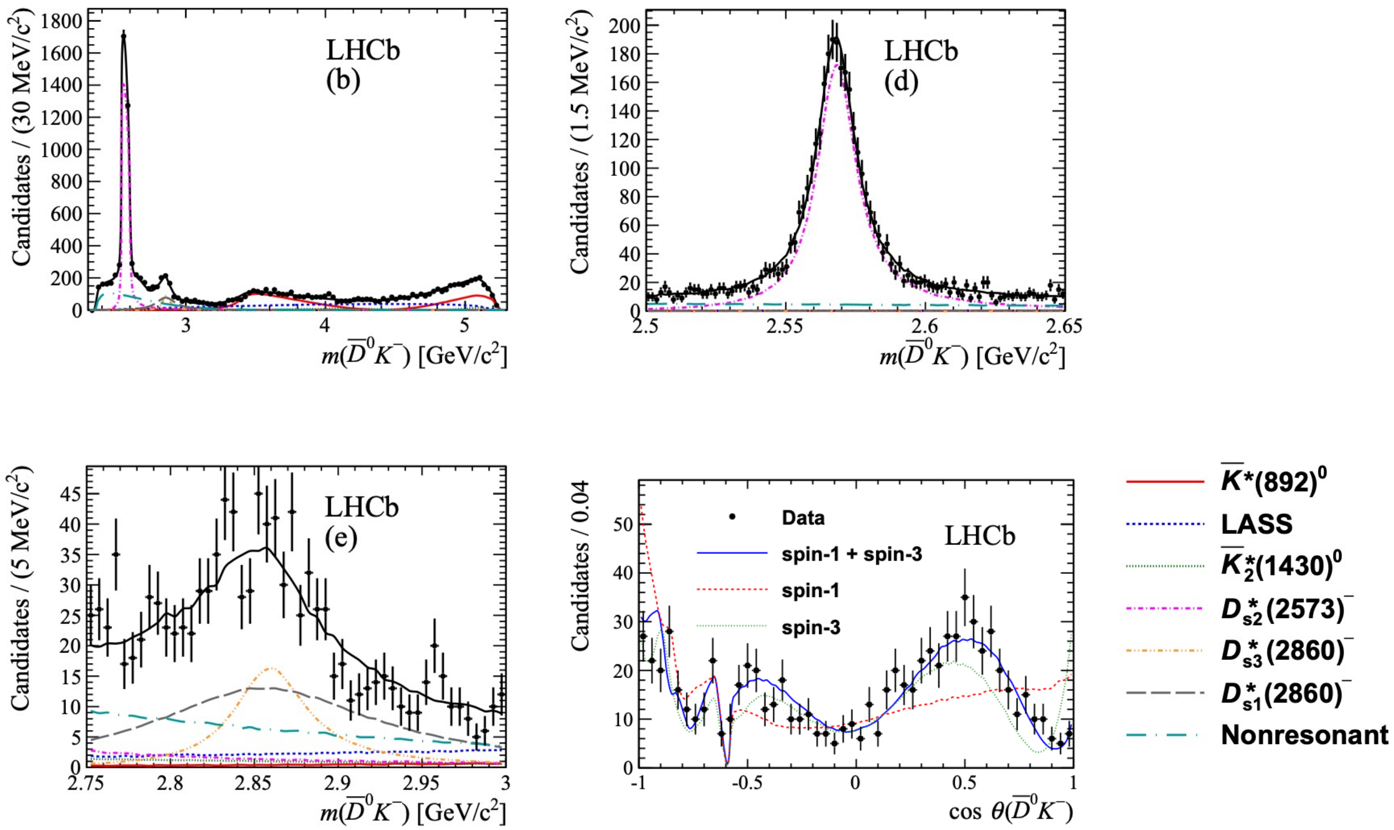
- $3.0\ \mathrm{fb}^{-1}$
- $B_s^0 \to \overline{D}^0 K^- \pi^+$
- Dalitz plot distribution in the signal region



Phys. Rev. Lett. 113 (2014) 162001

Resolve the J^P of $D^*_{s1}(2860)^+$ and $D^*_{s3}(2860)^+$

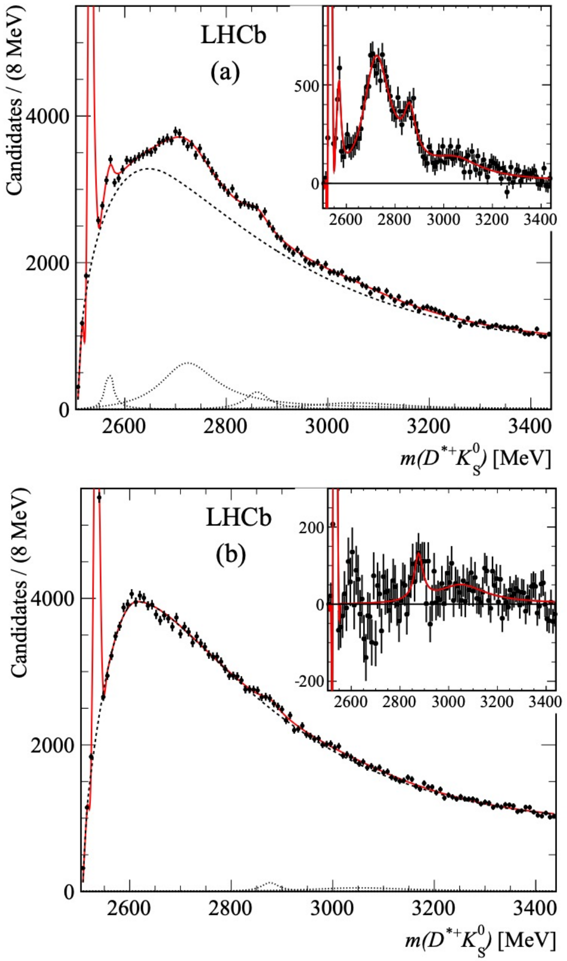
- $m(D^*_{s2}(2573)^+) = 2568.39 \pm 0.29 \pm 0.19 \pm 0.18$ MeV
- $\Gamma(D^*_{s2}(2573)^+) = 16.9 \pm 0.5 \pm 0.4 \pm 0.4$ MeV
- $m(D^*_{s1}(2860)^+) = 2859 \pm 12 \pm 6 \pm 23$ MeV
- $\Gamma(D^*_{s1}(2860)^+) = 159 \pm 23 \pm 27 \pm 72$ MeV
- $m(D^*_{s2}(2573)^+) = 2860.5 \pm 2.6 \pm 2.5 \pm 6.0$ MeV
- $\Gamma(D^*_{s2}(2573)^+) = 53 \pm 7 \pm 4 \pm 6$ MeV
- The angle between π^+ and $\overline{D}^0$ meson momenta in the $\overline{D}^0 K^-$ rest frame



Confirmation of $D_{s1}^*(2700)^+$ and $D_{s3}^*(2860)^+$

- $3.0\ \mathrm{fb}^{-1}$
- $pp \to D^{*+}K_S^0 + X$ and $pp \to D^{*0}K^+ + X$
- Significant $D_{s1}(2573)^+$
- Hint of $D_{sJ}(3040)^+$
- $m(D_{s1}^*(2700)^+) = 2732.3 \pm 4.3 \pm 5.8$ MeV
- $\Gamma(D_{s1}^*(2700)^+) = 136 \pm 19 \pm 24$ MeV
- $m(D_{s3}^*(2860)^+) = 2867.1 \pm 4.3 \pm 1.9$ MeV
- $\Gamma(D_{s3}^*(2860)^+) = 50 \pm 11 \pm 13$ MeV
- θ_{H}: angle between π and K_S^0 in the $D^{*+}K_S^0$ rest frame

JHEP 02 (2016) 133

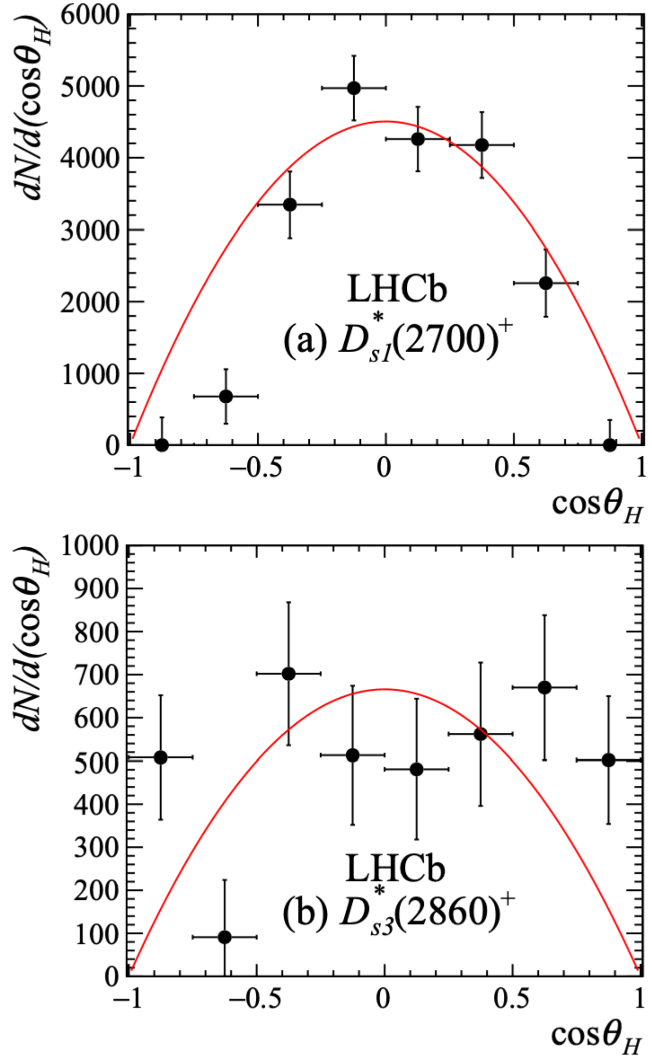


NP sample $|\cos\theta_{\mathrm{H}}| < 0.5$

UP sample $|\cos\theta_{\mathrm{H}}| > 0.5$

$D_{s1}^{*}(2700)^{+}$ and $D_{s3}^{*}(2860)^{+}$

- Spin-parity analysis
- $J^{P} = 1^{-}$: $D_{s1}^{*}(2700)^{+}$
- $J^{P} = 3^{-}$: $D_{s3}^{*}(2860)^{+}$
- Mainly $D_{s3}^{*}(2860)^{+}$ contribution



$D_{s0}(2590)^+$: strong candidate for $D_s(2^1S_0)$

- $\Gamma^{D_{sJ}}(m_{DK\pi}) = \Gamma^{D_{sJ}\to D^*K}(m_{DK\pi}) + \Gamma^{D_{sJ}\to DK\pi}(m_{DK\pi})$
- Two-body mass-dependent width
- $\Gamma^{D_{sJ}\to D^*K}(m_{DK\pi}) = \Gamma^{D_{sJ}\to D^*K}(m_0) \cdot \left(\frac{q}{q_0}\right)^{2L+1} \cdot \frac{m_0}{m_{DK\pi}} \cdot B_L'(q, q_0, d)^2$
- Constant
- $r = \Gamma^{D_{sJ}\to DK\pi}(m_0)/\Gamma^{D_{sJ}}(m_0)$
- Almost equally good fit quality and the same $D^+K^+\pi^-$ mass lineshape are found for different width fractions *r* in the range 0 to 1
- *r* cannot be determined with the current data, and is fixed to 0.5 in the fit

K-matrix for $T_{c\bar{s}}$ model

- $\begin{pmatrix} \gamma & \beta \\ \beta & \gamma_2 \end{pmatrix}$
- Lineshape
  - $\frac{\beta^2 \rho_{DK} + i\gamma_2(i\gamma\rho_{DK} - 1)}{\beta^2 \rho_{DK}\rho_{D_s\pi} + (i\gamma\rho_{DK} - 1)(i\gamma_2\rho_{D_s\pi} - 1)}$
- Scattering length
  - $a = \frac{1}{8\pi\sqrt{s_{\mathrm{thr}}}}\left(\gamma + i\beta^2\rho_{D_s\pi}(s_{\mathrm{thr}})\right)$