The $B \to DDh$ analyses in the LHCb experiment

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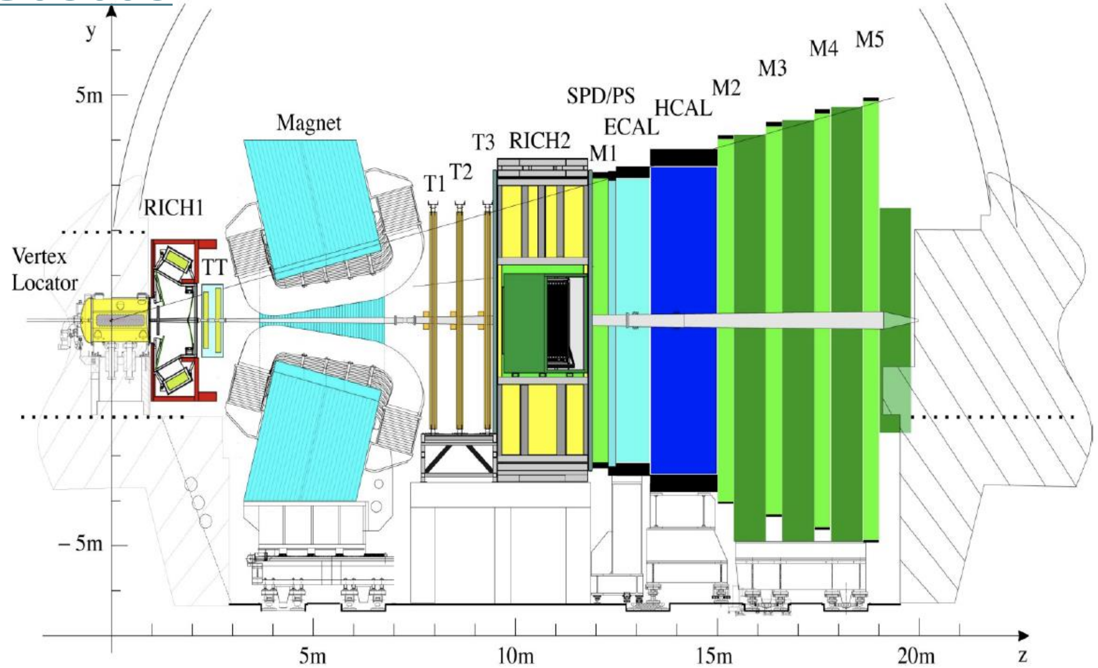
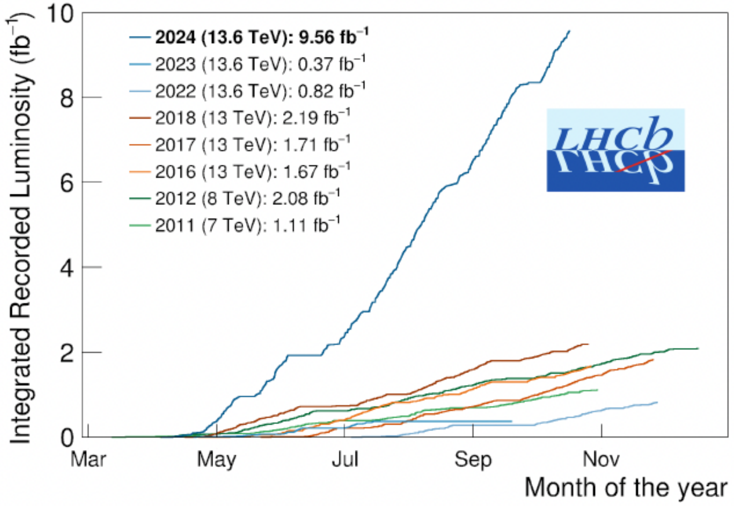
On behalf of the LHCb collaboration

LHCb experiment in Run 1-Run 2

2008 JINST 3 S08005





- Run 1: 3 fb^{-1}
- Run 2: 6 fb^{-1}
- Run 3: almost 9.56 fb^{-1}

Excellent vertex and IP, decay time resolution:
- $\sigma(\mathrm{IP}) \approx 20$ μm for high-p_{T} tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^-\pi^+$ decays

Very good momentum resolution:
- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0,200)$ GeV
- $\sigma(m_B) \approx 24$ MeV for two-body decays

Hadron and Muon identification
- $\epsilon_{K\to K} \approx 95\%$ for $\epsilon_{\pi\to K} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1-3\%$

Data good for analyses
- $> 99\%$

Outline

- **Charm-strange mesons**
- Exotic charm-strange mesons
- Charmonia states

$B^0 \to D^- D^+ K^+ \pi^-$
$\boldsymbol{D_{s0}(2590)^+}$

$B^+ \to D^+ D^- K^+$
$T^*_{cs0}(2870)^0$
$T^*_{cs1}(2900)^0$
$\chi_{c0}(3915)$

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

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

$B^+ \to D^{*+} D^- K^+$
$B^+ \to D^{*-} D^+ K^+$
$h_c(4000), \chi_{c1}(4010), h_c(4300)$
$T^*_{cs0}(2870)^0, T^*_{cs1}(2900)^0$

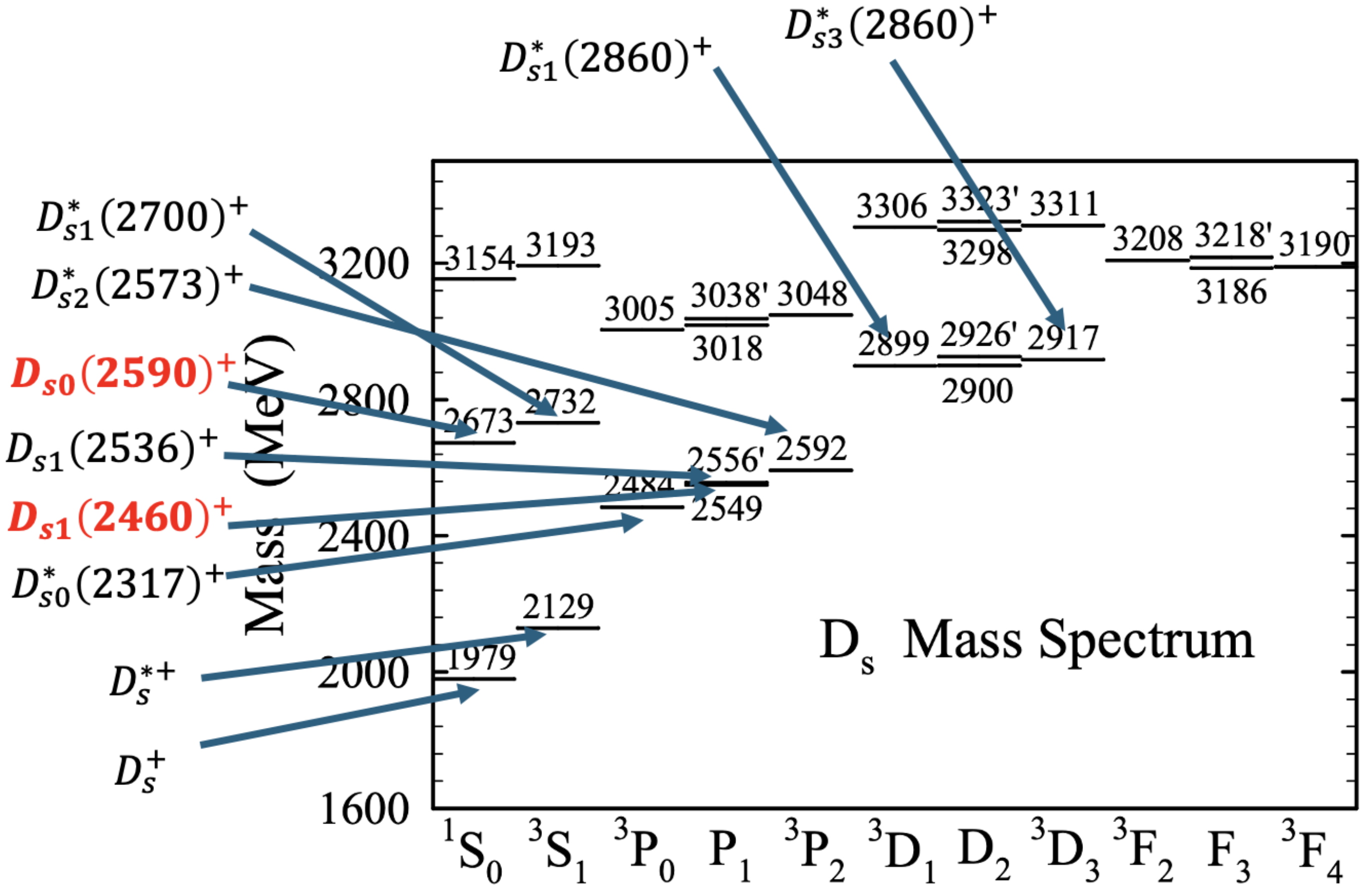
$B^- \to D^- D^0 K_S^0$
$T^*_{cs0}(2870)^0$

$B \to \bar{D}^{(*)} D_s^+ \pi^+ \pi^-$
Double-peak in
$\boldsymbol{D_{s1}(2460)^+} \to D_s^+ \pi^+ \pi^-$

Time

Charm-strange mesons

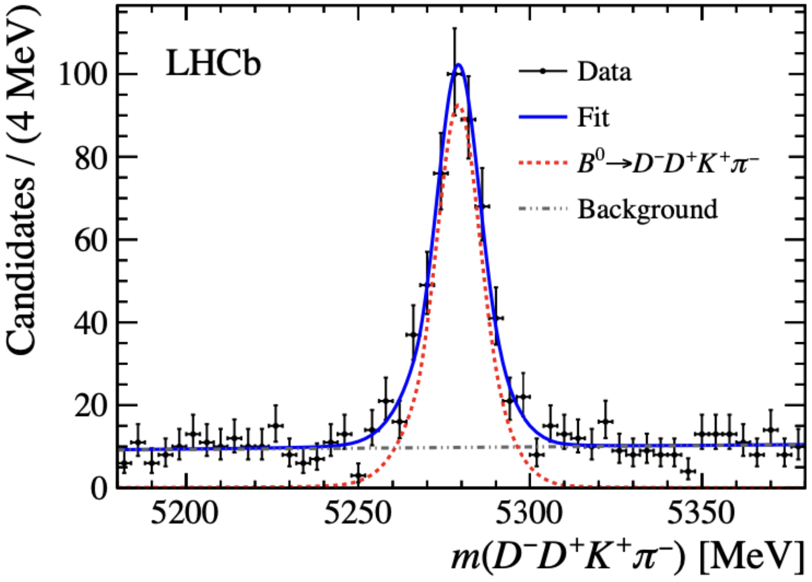
- D_s^{**} spectroscopy
- [Phys. Rev. D 89, 074023]
- Relativistic quark model
- Some discrepancies between predicted and measured masses

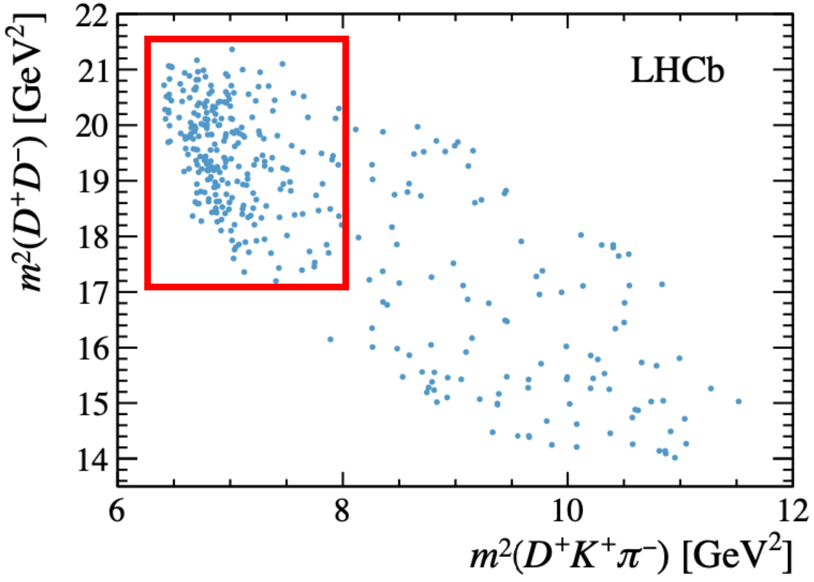


$B^0 \to D^- D^+ K^+ \pi^-$

- Phys. Rev. Lett. 126 (2021) 122002
- Statistics: 5.4 fb^{-1}
- $m(K^+\pi^-) < 750$ MeV
- No D^+D^- structure
- $B^0 \to D^- R(D^+K^+\pi^-)$
- $R(D^+K^+\pi^-) \to D K_0^*(700)^0$

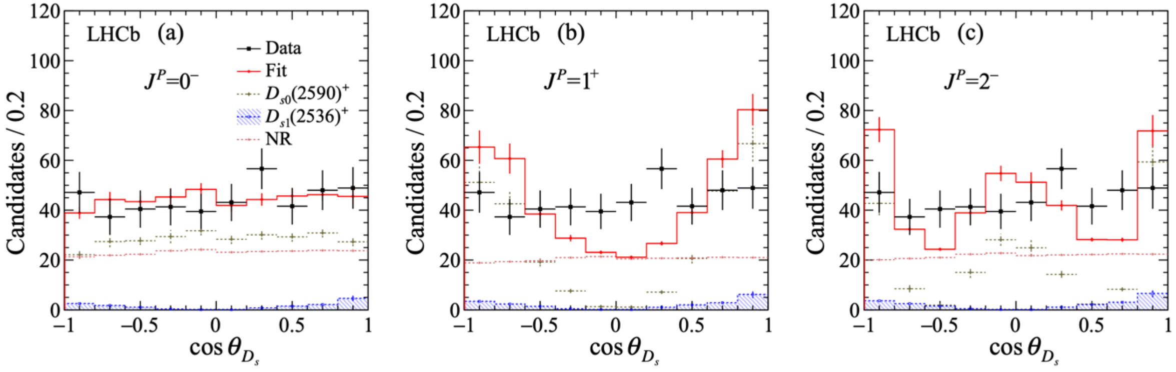
Resonances	J^P
$D_{s1}(2536)^+$	1^+
$D_{s0}(2590)^+$	$?^?$
NR	0^-

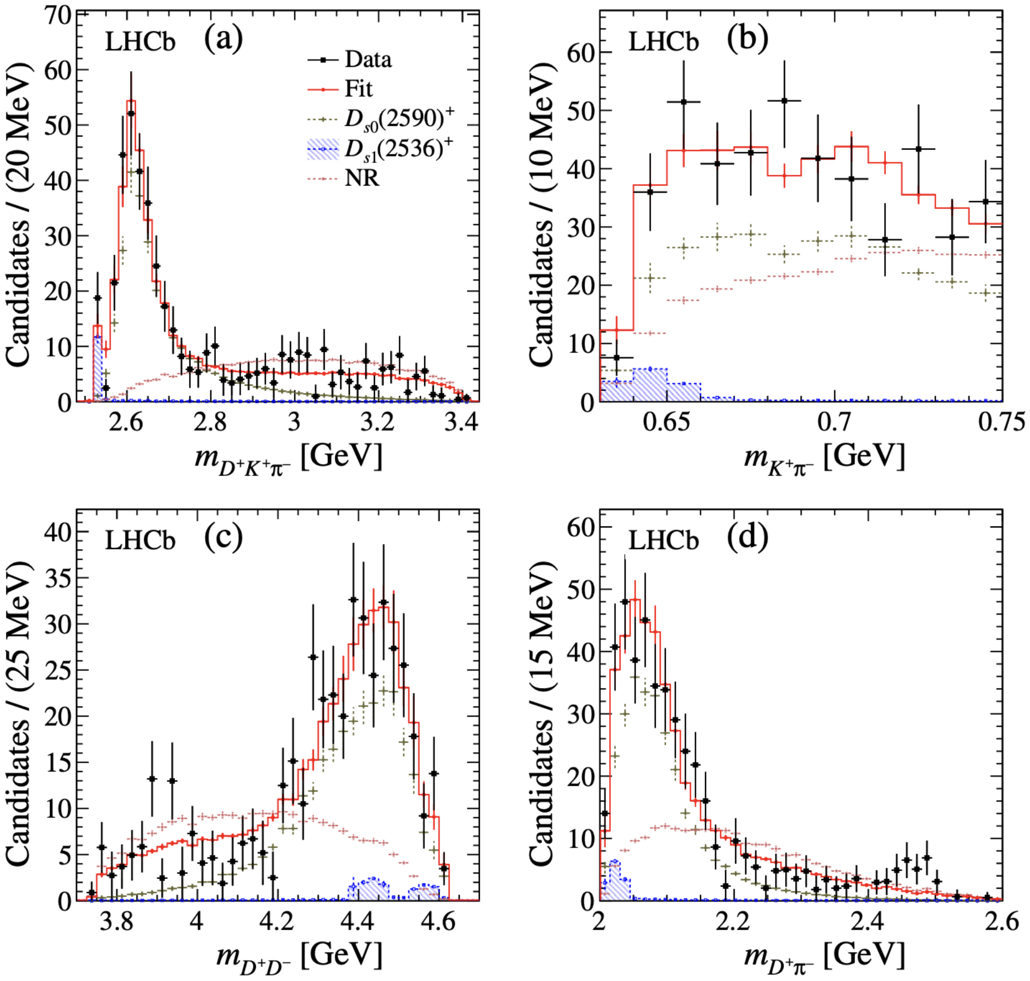




$B^0 \to D^- D^+ K^+ \pi^-$

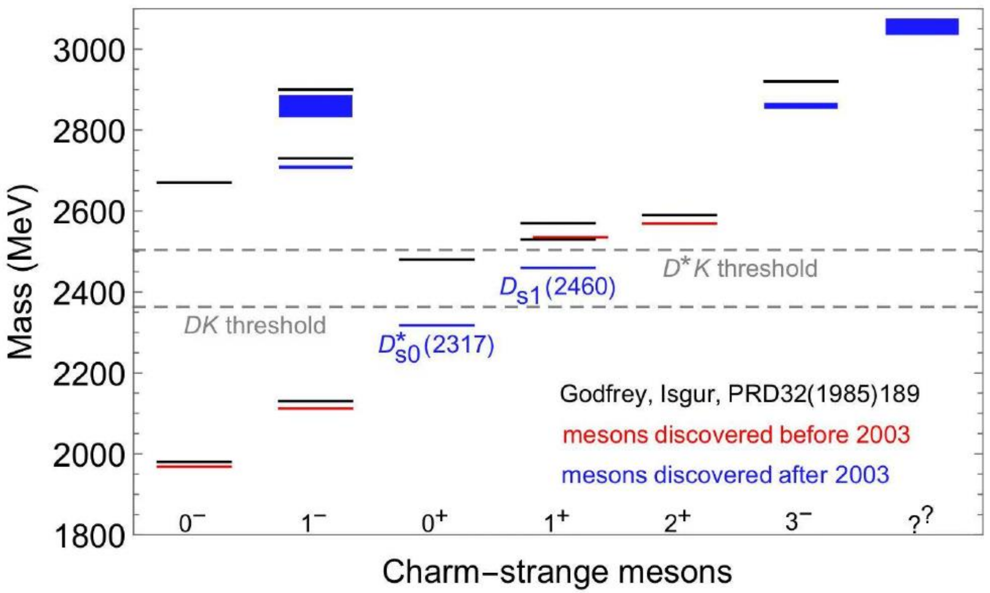
- $D_{s0}(2590)^+ \to D^+ K^+ \pi^-$
- $J^P = 0^-$ >10 σ
- Pole mass: $m_R = 2591 \pm 6 \pm 7$ MeV
- Pole width: $\Gamma_R = 89 \pm 16 \pm 12$ MeV
- θ_{D_s}: Angle between D^+ and the opposite direction of B^0 in the D_{sJ}^+ rest frame
- Strong candidate for $D_s(2^1S_0)$





$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to \bar{D}^{(*)}D_s^+\pi^+\pi^-$

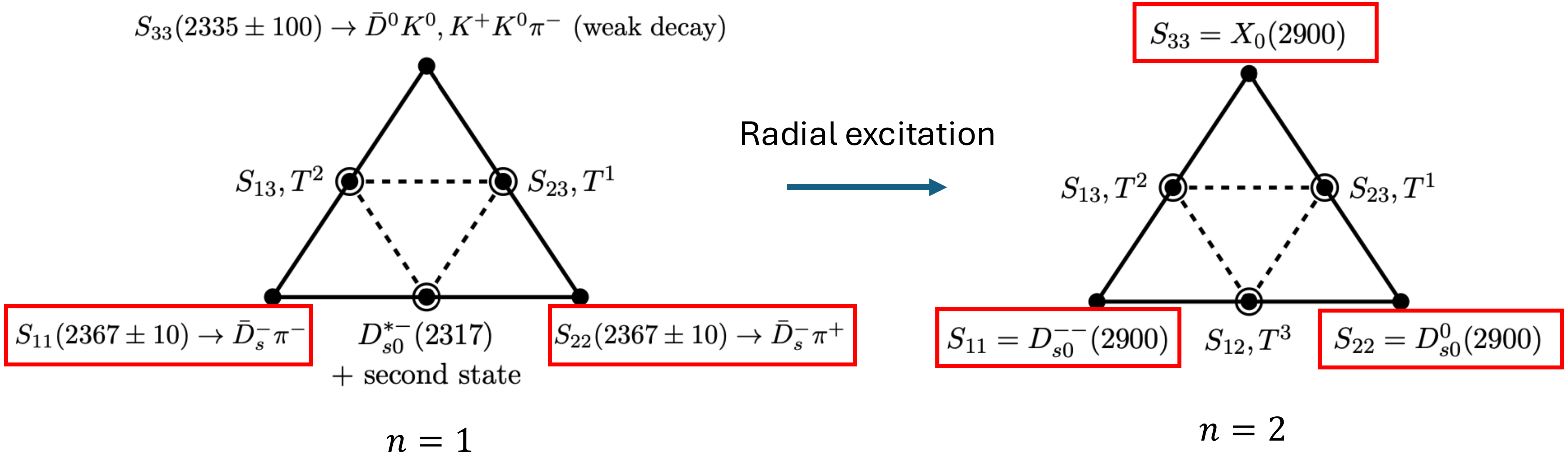
- Babar and CLEO discovered the $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ states
  - Phys. Rev. Lett. **90**, 242001
  - Phys. Rev. D **68**, 032002
- The 100 MeV lower mass compared with quark model prediction
  - Phys. Rev. D, 1985, 32
  - $M(D_{s1}(2460)^+) - M(D_{s0}^*(2317)^+) \approx M(D^*) - M(D)$
- Lower mass makes decaying to $D^{(*)}K$ impossible, dominant isospin violating decay of $D_s^{(*)+}\pi^0$, very small width
- Their nature?
- Isospin conserving decay $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ to a sizable rate



- Rept.Prog.Phys. 80 (2017) 7, 076201
- Hadronic molecule?
- Tetraquark state?
- Charm-strange meson w/ strong couple-channel effect?

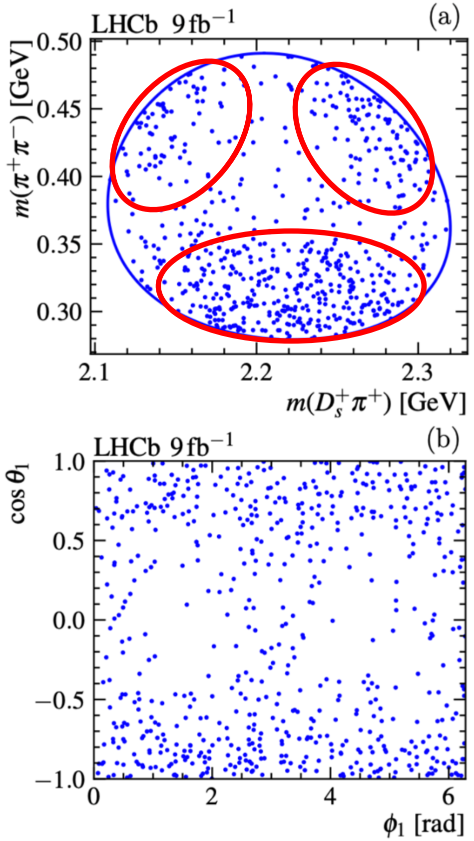
$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to \bar{D}^{(*)}D_s^+\pi^+\pi^-$

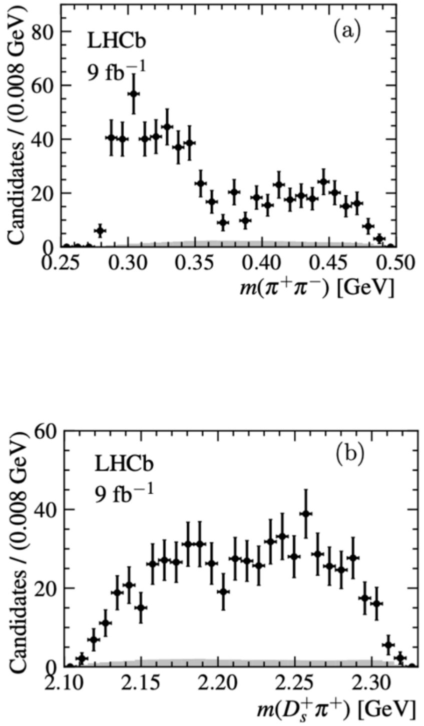
- Double-bump line shape in $m(\pi\pi)$ if $D_{s1}(2460)^+$ is a D^*K hadronic modecule
  - Commun. Theor. Phys. 75 055203
- The multiplet including $T_{c\bar{s}}(2900)^{++}$, $T_{c\bar{s}}(2900)^0$, and $T_{cs0}(2900)^0$ could be the radial excitation of a lighter multiplet containing $D_{s0}^*(2317)^+$
  - $2900 - 2317 = 583$ MeV similar as $M(\psi(2S)) - M(\psi(1S))$
  - Phys. Rev. D **110**, 034014



$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to \bar{D}^{(*)}D_s^+\pi^+\pi^-$

- **arXiv:2411.03399**
- Statistics: 9.0 fb^{-1}
- $B^0 \to D^- D_{s1}(2460)^+$
- $B^+ \to \bar{D}^- D_{s1}(2460)^+$
- $B^0 \to D^{*-} D_{s1}(2460)^+$
- Amplitude fit
  - Isobar approach
  - TF-PWA software link
- The model $f_0(500) + f_0(980)$ 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





$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to \overline{D}^{(*)}D_s^+\pi^+\pi^-$

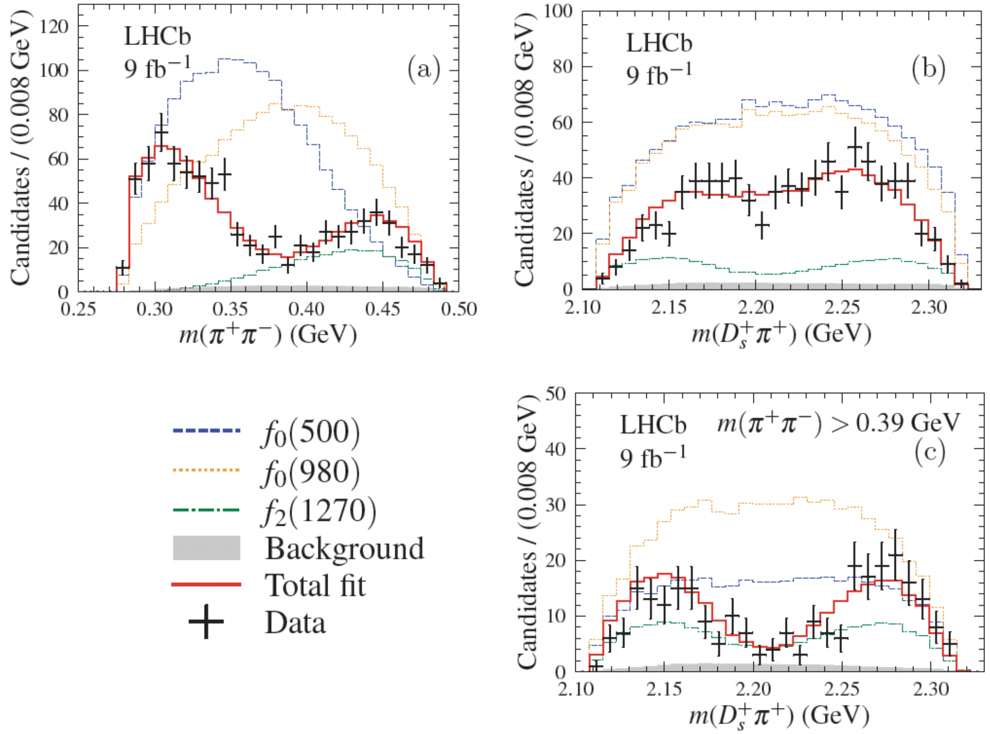
- Model w/o exotic contribution
  - $f_0(500) + f_0(980) + f_2(1270)$
    - $f_0(500)$: relativistic Breit-Wigner (RBW)
    - $f_0(980)$: Flatte model
    - $f_2(1270)$: RBW w/ mass and width fixed
    - Note that the pole of $f_0(980)$ and $f_2(1270)$ are far away from kinematic limit of $m(\pi\pi)$

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

$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to \bar{D}^{(*)} D_s^+\pi^+\pi^-$

- $f_0(500) + f_0(980) + f_2(1270)$
  - Large contribution from $f_0(980)$ and $f_2(1270)$
  - 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 results in other processes

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	$29 \pm 2 \pm 1$



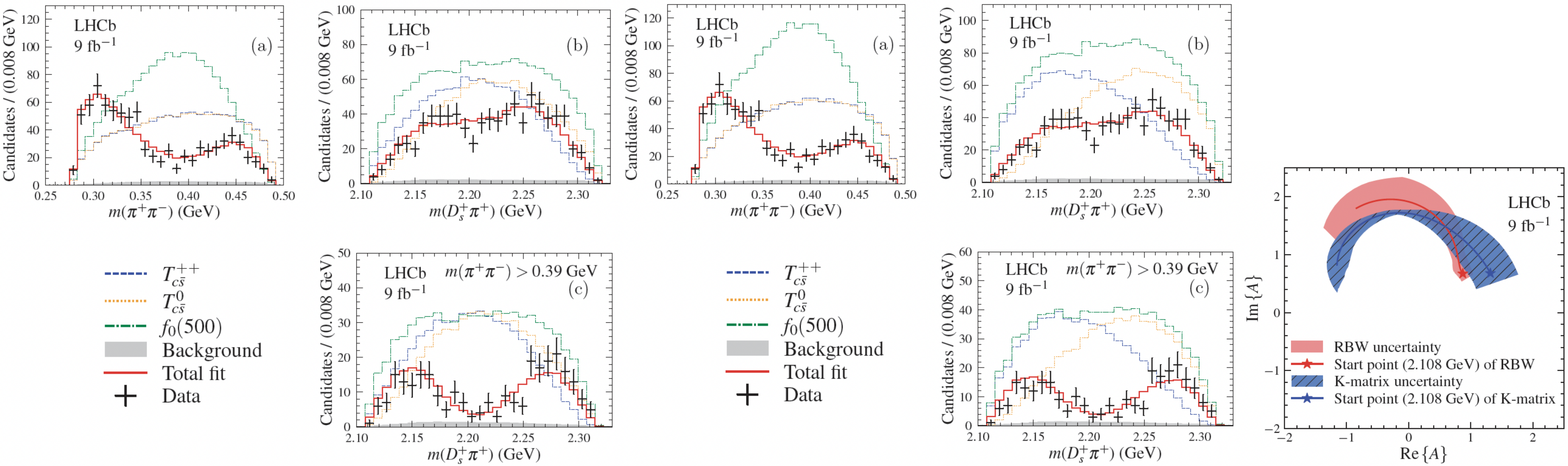
$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to \overline{D}^{(*)}D_s^+\pi^+\pi^-$

- $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^{0}$
  - The mass and width of $f_0(500)$ agree with previous measurement better
  - Pole mass just below DK threshold
  - Scattering length: $-0.86(\pm 0.07) + 0.44(\pm 0.07)i$ fm
  - J^P favours 0^+
  - Significance over $f_0(500) + f_0(980)$ model is larger than 10 σ
  - Isospin symmetry is conserved

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$464 \pm 23 \pm 14$	$214 \pm 28 \pm 8$	$199^{+42}_{-47} \pm 39$
$T_{c\bar{s}}^{++/0}$	$2312 \pm 27 \pm 11$	$264 \pm 46 \pm 21$	$126^{+27}_{-17} \pm 20$

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$474 \pm 30 \pm 18$	$224 \pm 23 \pm 16$	$248^{+40}_{-54} \pm 39$
$T_{c\bar{s}}^{++/0}$	$2327 \pm 13 \pm 13$	$96 \pm 16 \pm 23$	$156^{+27}_{-38} \pm 25$

$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in $B \to \overline{D}^{(*)}D_s^+\pi^+\pi^-$



- Consistent results obtained w/ RBW and K-matrix model except for the width
- Assign large systematic uncertainty for the width
- $T_{c\bar{s}}$: Mass: $2327 \pm 13 \pm 13$ MeV and width: $96 \pm 16^{+170}_{-23}$ MeV

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

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

$B^+ \to D^{*+} D^- K^+$
$B^+ \to D^{*-} D^+ K^+$
$h_c(4000), \chi_{c1}(4010), h_c(4300)$
$T^*_{cs0}(2870)^0, T^*_{cs1}(2900)^0$

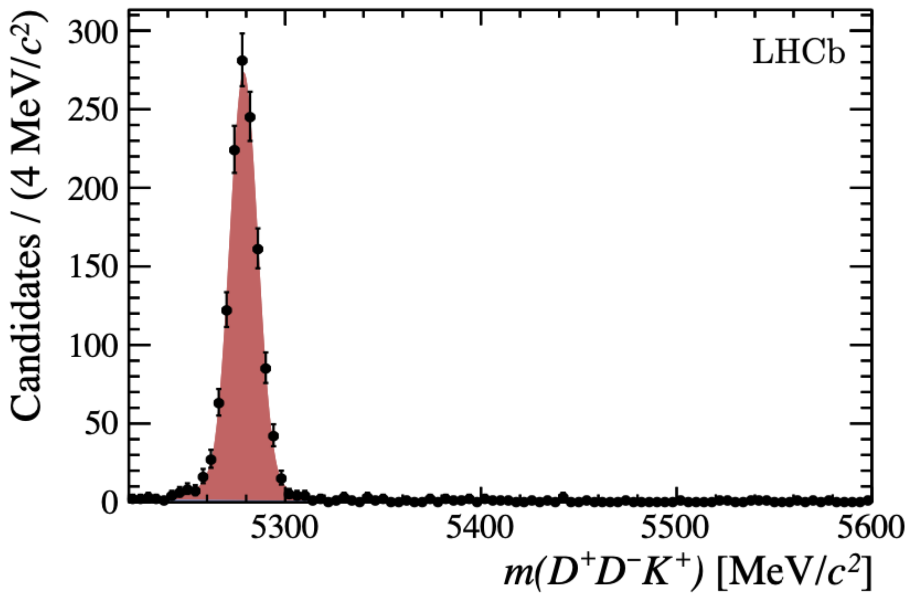
$B^- \to D^- D^0 K_S^0$
$T^*_{cs0}(2870)^0$

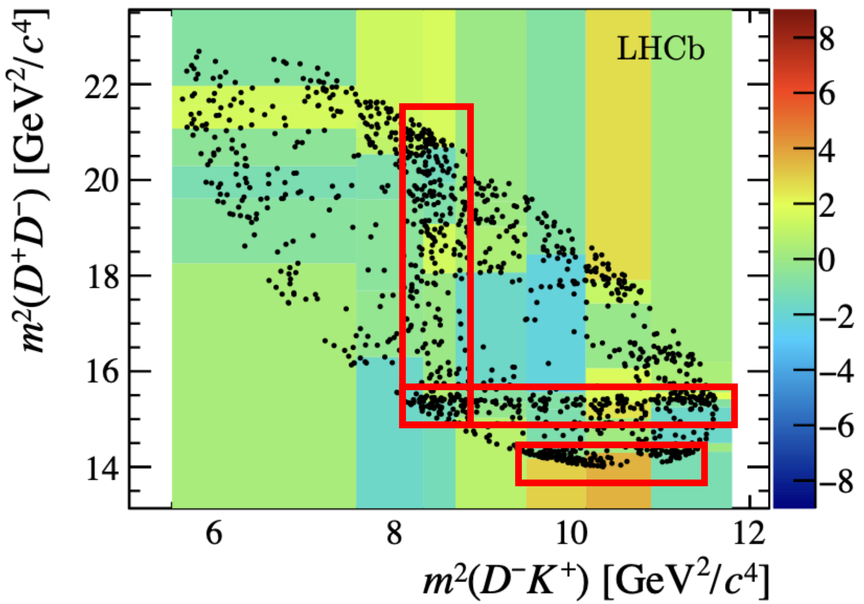
$B \to \bar{D}^{(*)} D_s^+ \pi^+ \pi^-$
Double-peak in
$D_{s1}(2460)^+ \to D_s^+ \pi^+ \pi^-$

Time

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

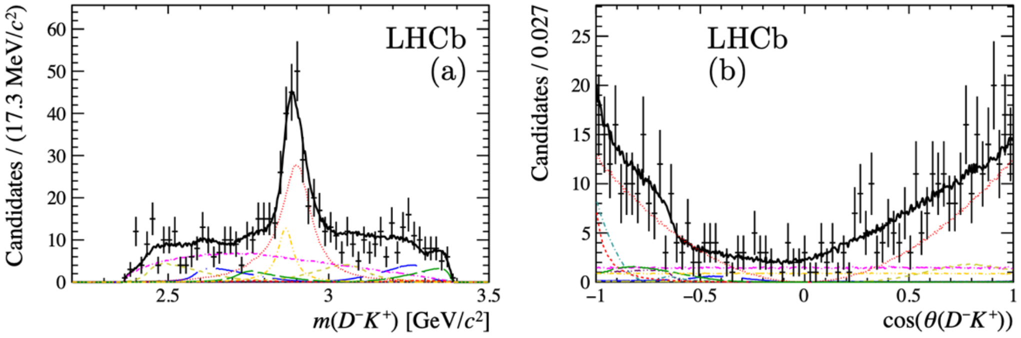
- Phys. Rev. D102 (2020) 112003
- Statistics: 9.0 fb^{-1}
- Various contributions

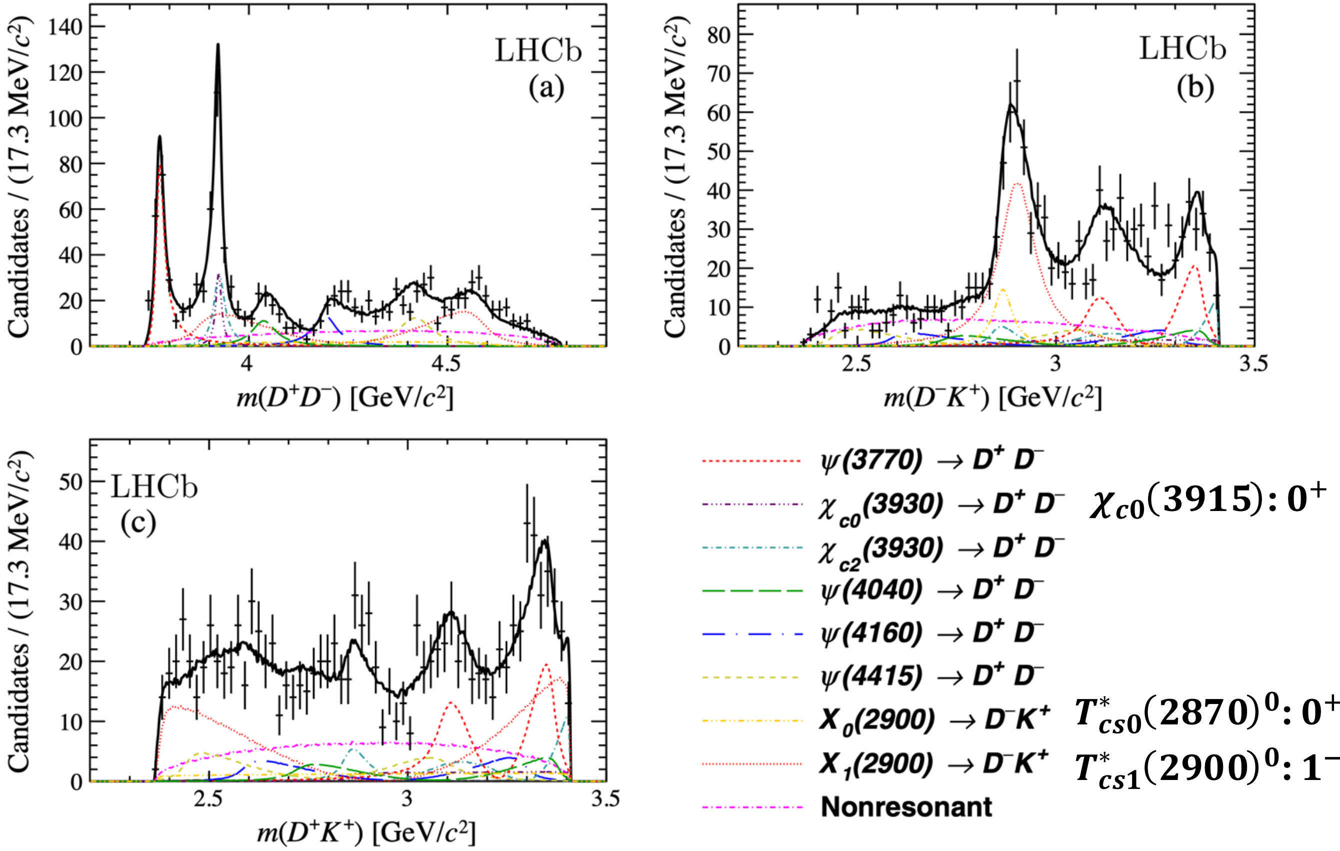




$B^+ \to D^+D^-K^+$

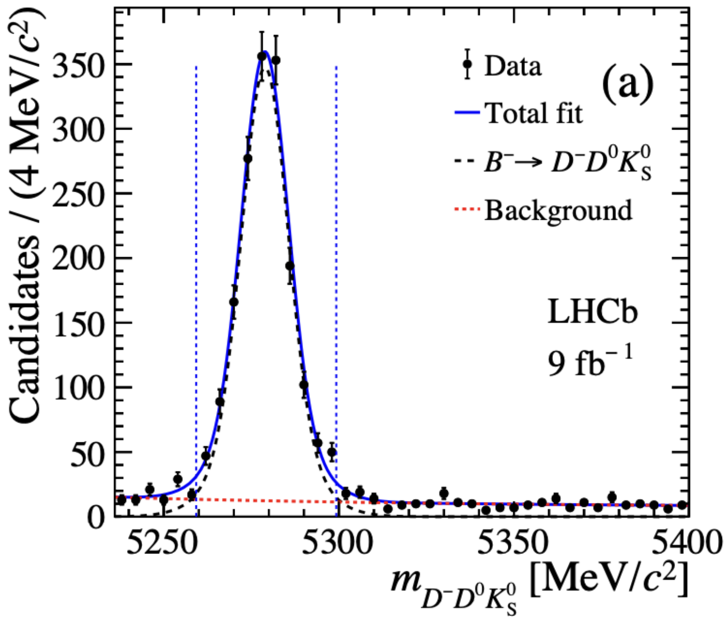
- Two new tetraquark states
  - Quark component: $\bar{c}d\bar{s}u$
  - $T^*_{cs0}(2870)^0$
    - $m = 2866 \pm 7 \pm 2$ MeV
    - $\Gamma = 57 \pm 12 \pm 4$ MeV
  - $T^*_{cs1}(2900)^0$
    - $m = 2904 \pm 5 \pm 1$ MeV
    - $\Gamma = 110 \pm 11 \pm 4$ MeV
- One new charmonium state: $\chi_{c0}(3915)$

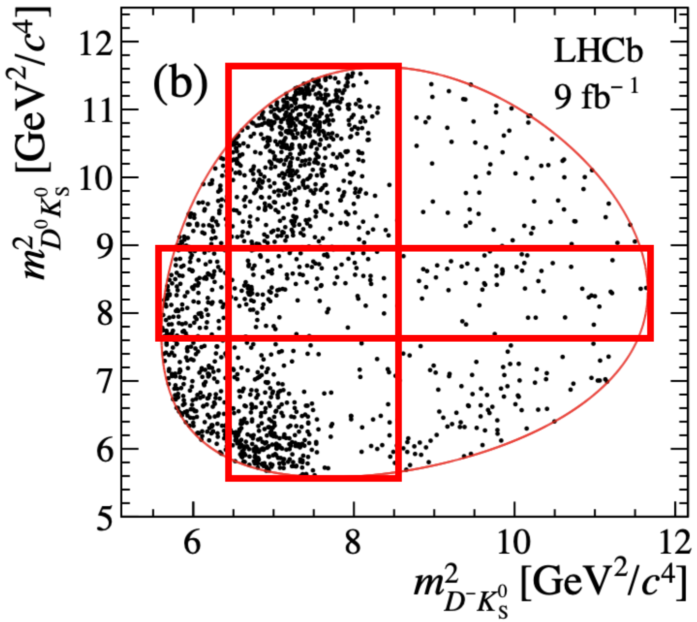




$B^- \to D^- D^0 K_S^0$

- PRL 134 (2025) 101901
- Statistics: 9.0 fb^{-1}
- Contributions from D_{sJ} states and $T_{cs0}^*(2870)^0$

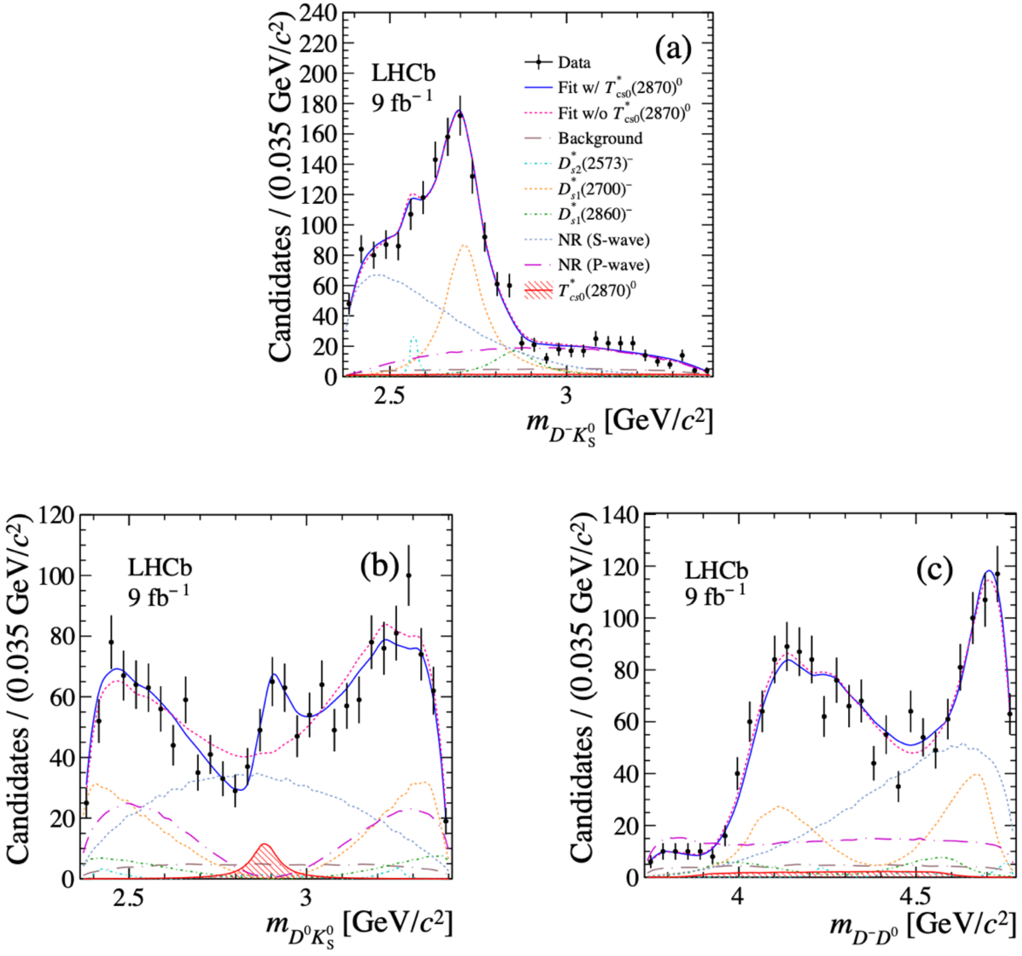




Resonances	J^P
$D_{s2}^*(2573)^-$	0^+
$D_{s1}^*(2700)^-$	1^-
$D_{s1}^*(2860)^-$	2^+
NR (exponential)	0^+
NR (uniform)	1^-
$T_{cs0}^*(2870)^0$	0^+

$B^- \to D^- D^0 K_S^0$

- $T_{cs0}^*(2870)^0$
  - Significance: 5.3 σ
  - $m = 2883 \pm 11 \pm 8$ MeV
  - $\Gamma = 87^{+22}_{-47} \pm 17$ MeV
  - Consistent w/ previous measurement
- Systematics from modelling $m(D^- K_S^0)$
  - K-matrix
  - Higher spin $D_{s3}^*(2860)$
- $R_I[T_{cs0}^*(2870)^0] \equiv \frac{\Gamma(T_{cs0}^*(2870)^0 \to D^0 \bar{K}^0)}{\Gamma(T_{cs0}^*(2870)^0 \to D^+ K^-)} = 3.3 \pm 1.9$
- $R_I[T_{cs1}^*(2900)^0] \equiv \frac{\Gamma(T_{cs1}^*(2900)^0 \to D^0 \bar{K}^0)}{\Gamma(T_{cs1}^*(2900)^0 \to D^+ K^-)} = 0.15 \pm 0.16$
- $\frac{R_I[T_{cs1}^*(2900)^0]}{R_I[T_{cs0}^*(2870)^0]} = 0.044 \pm 0.040$
- Isospin violation
- Needs further explanation

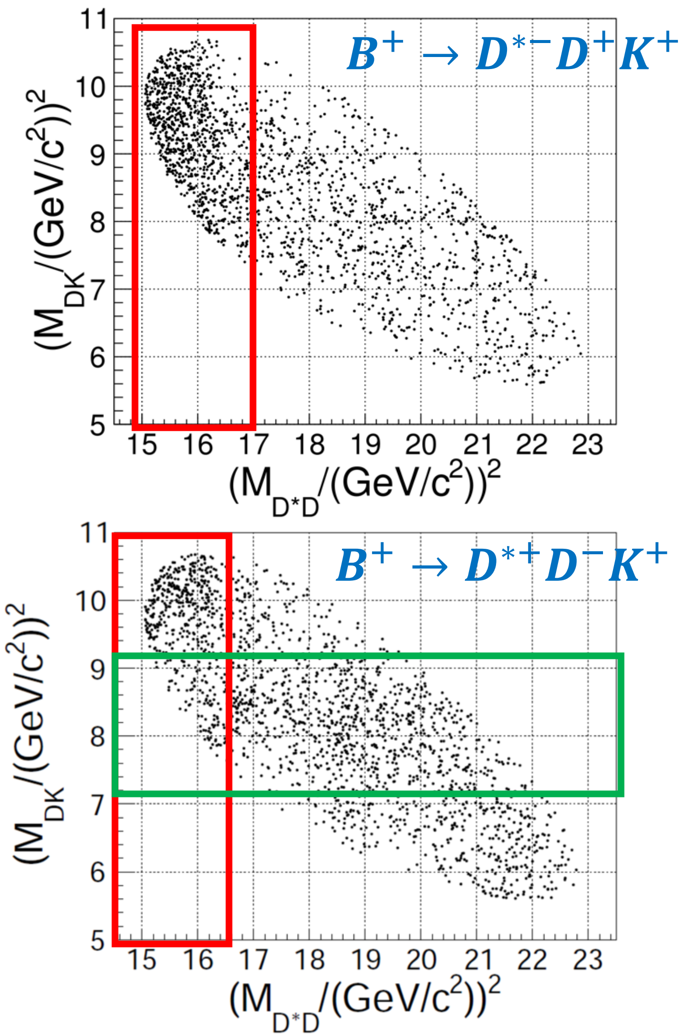


$B^+ \to D^{*+}D^-K^+$ and $B^+ \to D^{*-}D^+K^+$

- PRL 133 (2024) 131902
- Statistics: 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

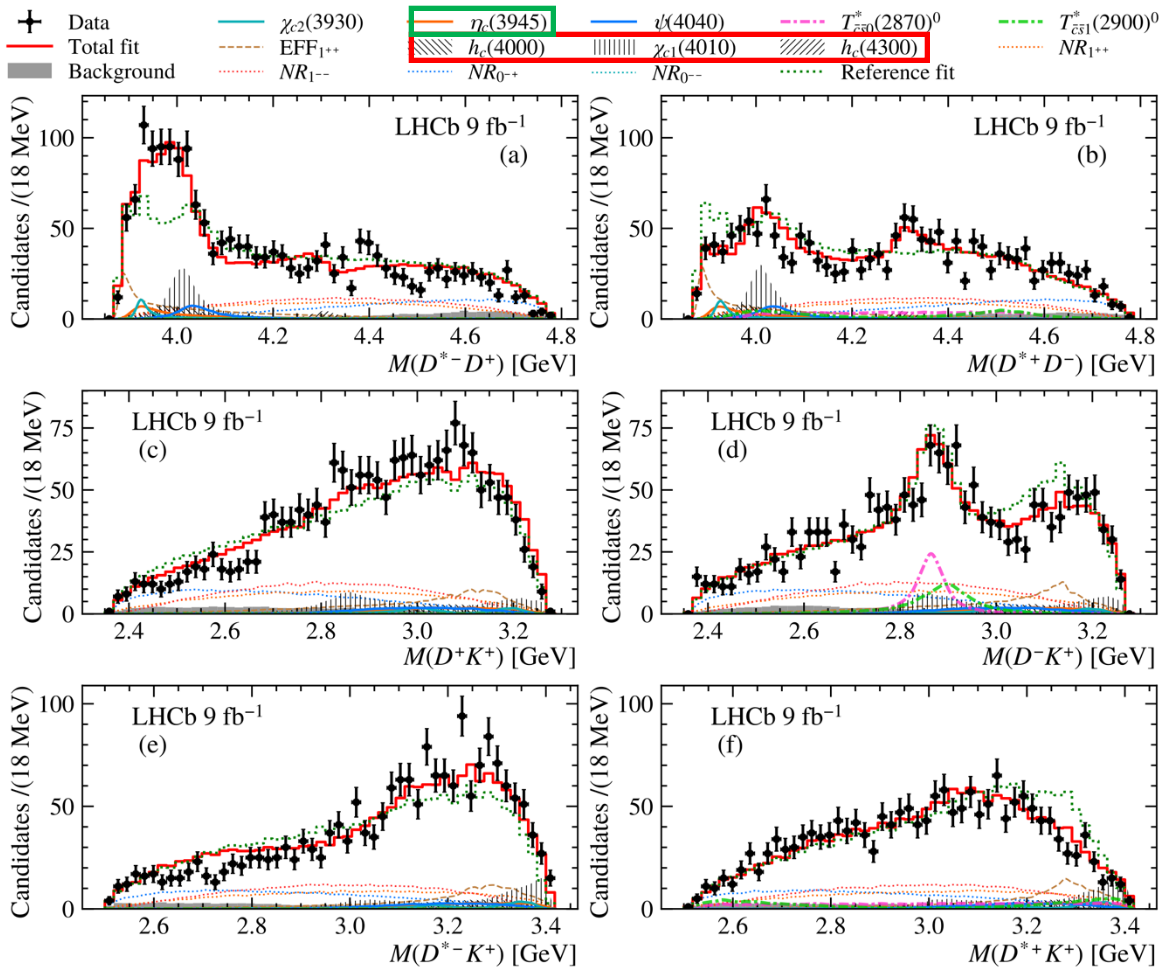
$$\left.\begin{array}{l} B^+ \to D^{*+}D^-K^+ \\ B^+ \to D^{*-}D^+K^+ \end{array}\right\} B^+ \to RK^+, R \to \left\{\begin{array}{l} D^{*+}D^- \\ D^{*-}D^+ \end{array}\right.$$

- $A(x) = \frac{1+d}{2}\left[c_jA_j(x) + c_kA_k(x)\right] + \frac{1-d}{2}\left[C_jc_jA_j(x) + c_lA_l(x)\right]$
  - $j \in R(D^{*\pm}D^{\mp}); k \in R(D^{*-}K^+, D^+K^+); l \in R(D^{*+}K^+, D^-K^+)$
- 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



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

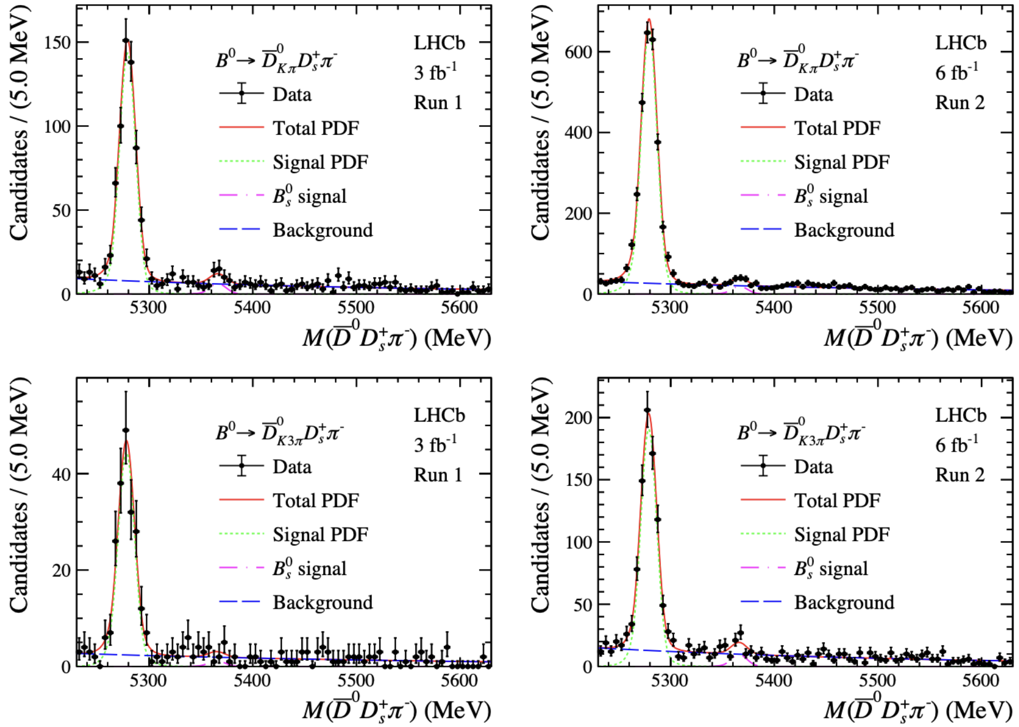
- Contribution from T^*_{cs} seen in one channel
- Some tension in the mass, width and fractions
- $T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^{*-} K^+$ is forbidden by spin-parity conservation
- Upper limits (95% CL)
  - $T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-} K^+, B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^+$: 1.5%
  - $T^*_{\bar{c}\bar{s}1}(2900)^{++} \to D^+ K^+, B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^{++} D^{*-}$: 3.3%

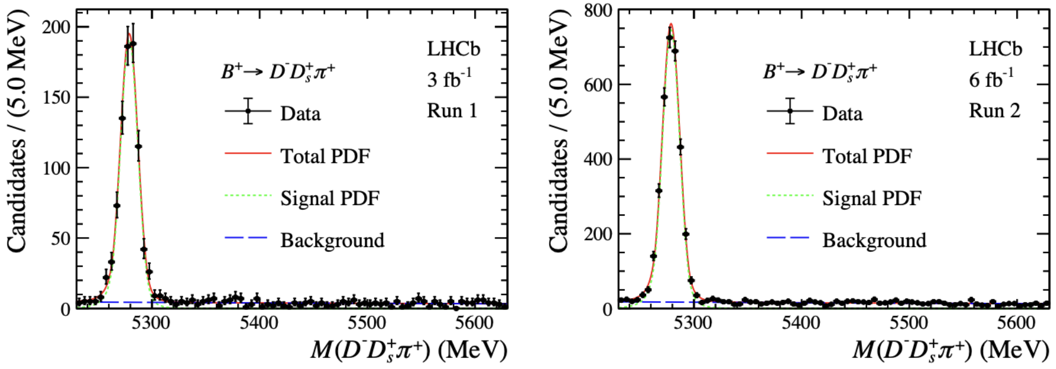


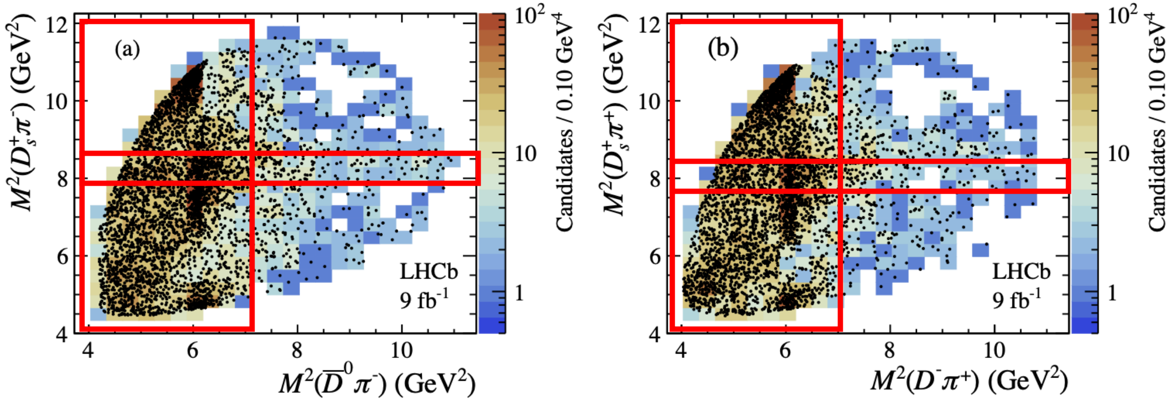
Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	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

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

- Phys.Rev.D 108 (2023) 1
- Statistics: 9.0 fb^{-1}
- Contribution from excited D states and two new tetraquark states

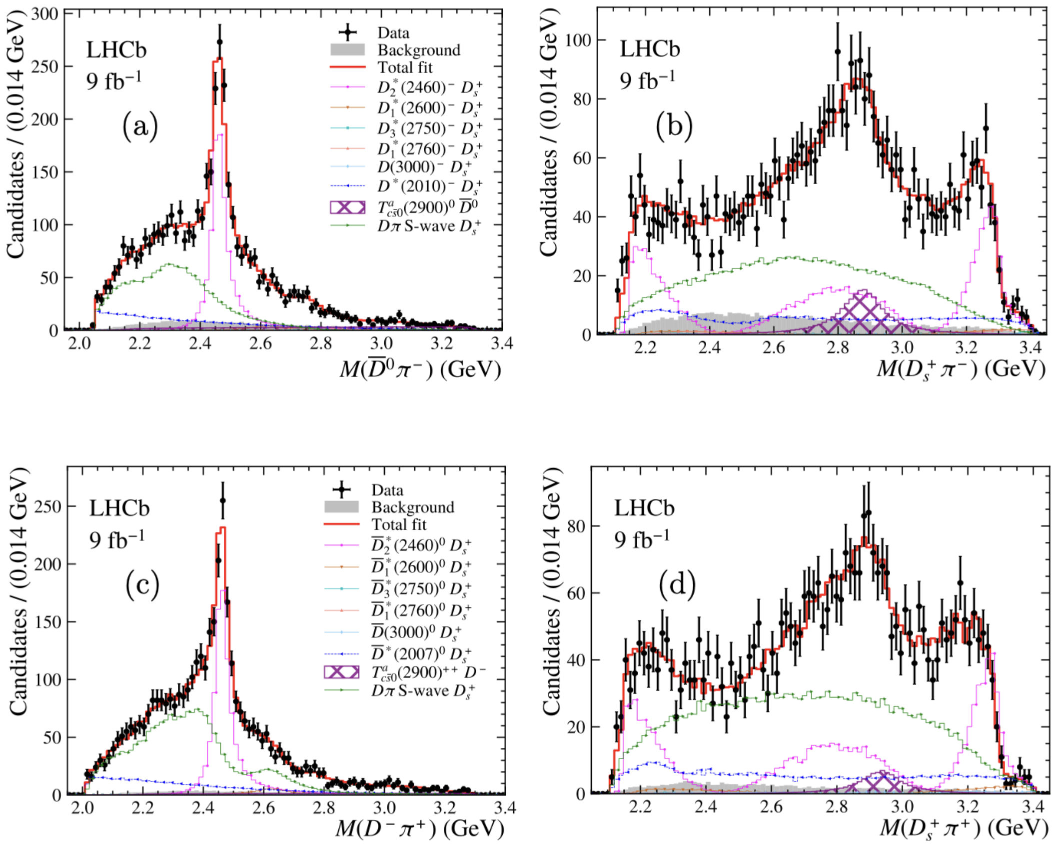






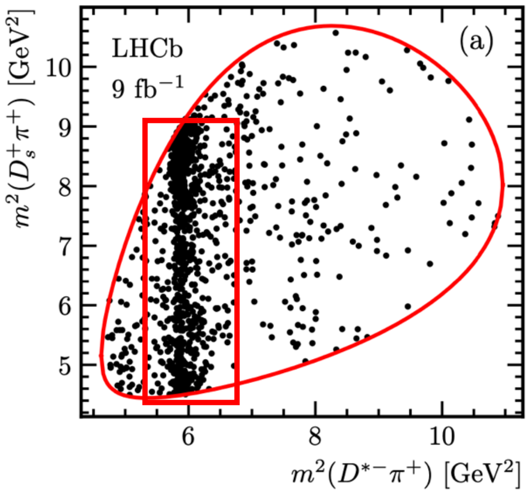
$B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

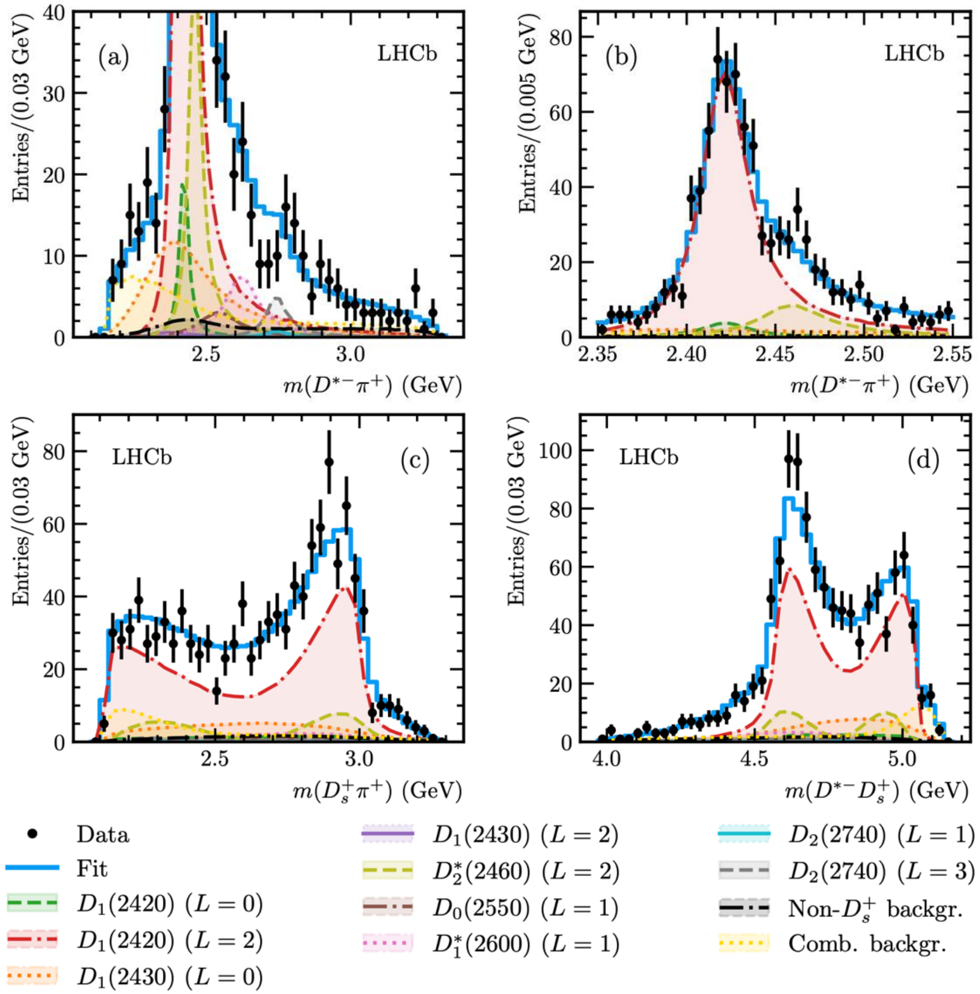
- Two decays are related by isospin symmetry
  - Except for $D^*(2010)^-$ and $\bar{D}^*(2007)^0$
- $T^*_{c\bar{s}0}(2900)^{++}$: $c\bar{s}u\bar{d}$
- $T^*_{c\bar{s}0}(2900)^0$: $c\bar{s}\bar{u}d$
- $J^P = 0^+$
- $m = 2908 \pm 11 \pm 20$ MeV
- $\Gamma = 136 \pm 23 \pm 13$ MeV
- Might belong to an isospin triplet



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

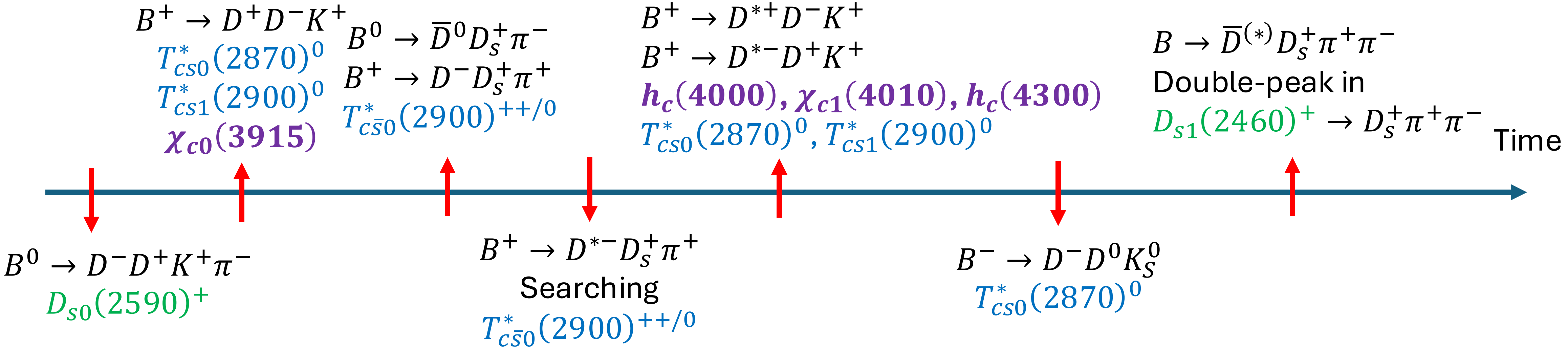
- JHEP08 (2024) 165
- Statistics: 9.0 fb^{-1}
- Main contribution from excited charm meson
- No strong evidence of $T^*_{c\bar{s}0}(2900)^{++}$, an upper limit is set 2.3% @ 90% CL
- The statistics is also limited
- Contributions from excited D decays





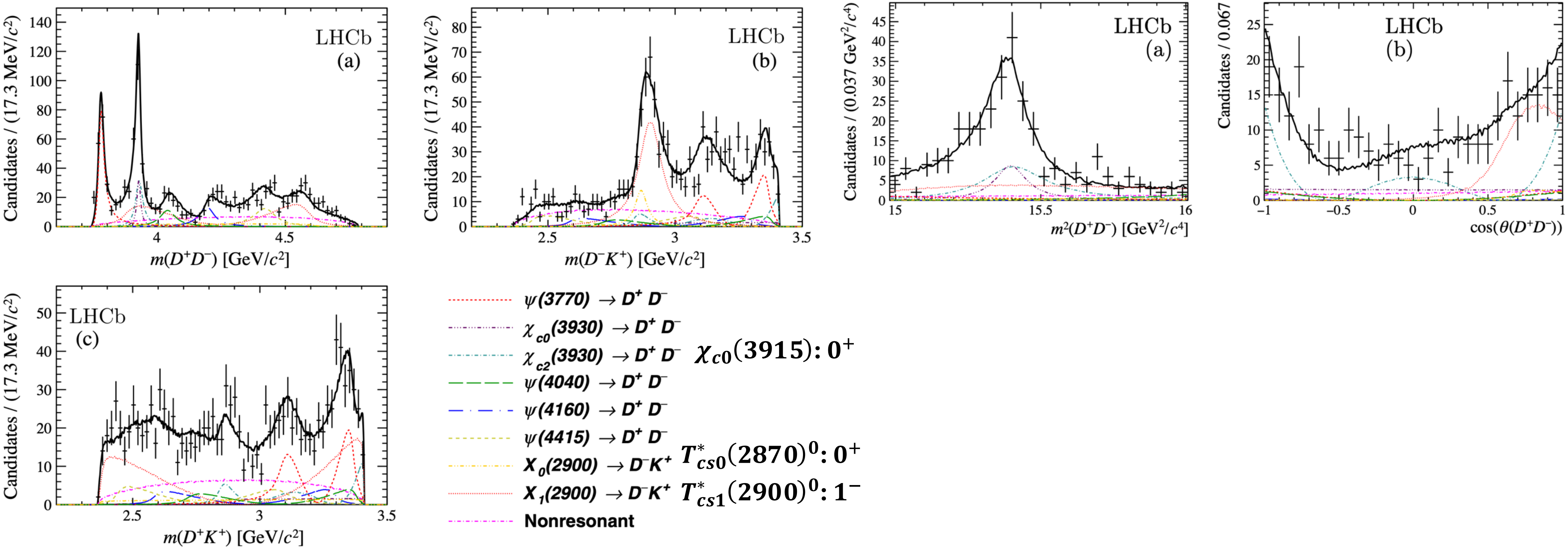
Outline

- Charm-strange mesons
- Exotic charm-strange mesons
- **Charmonia states**



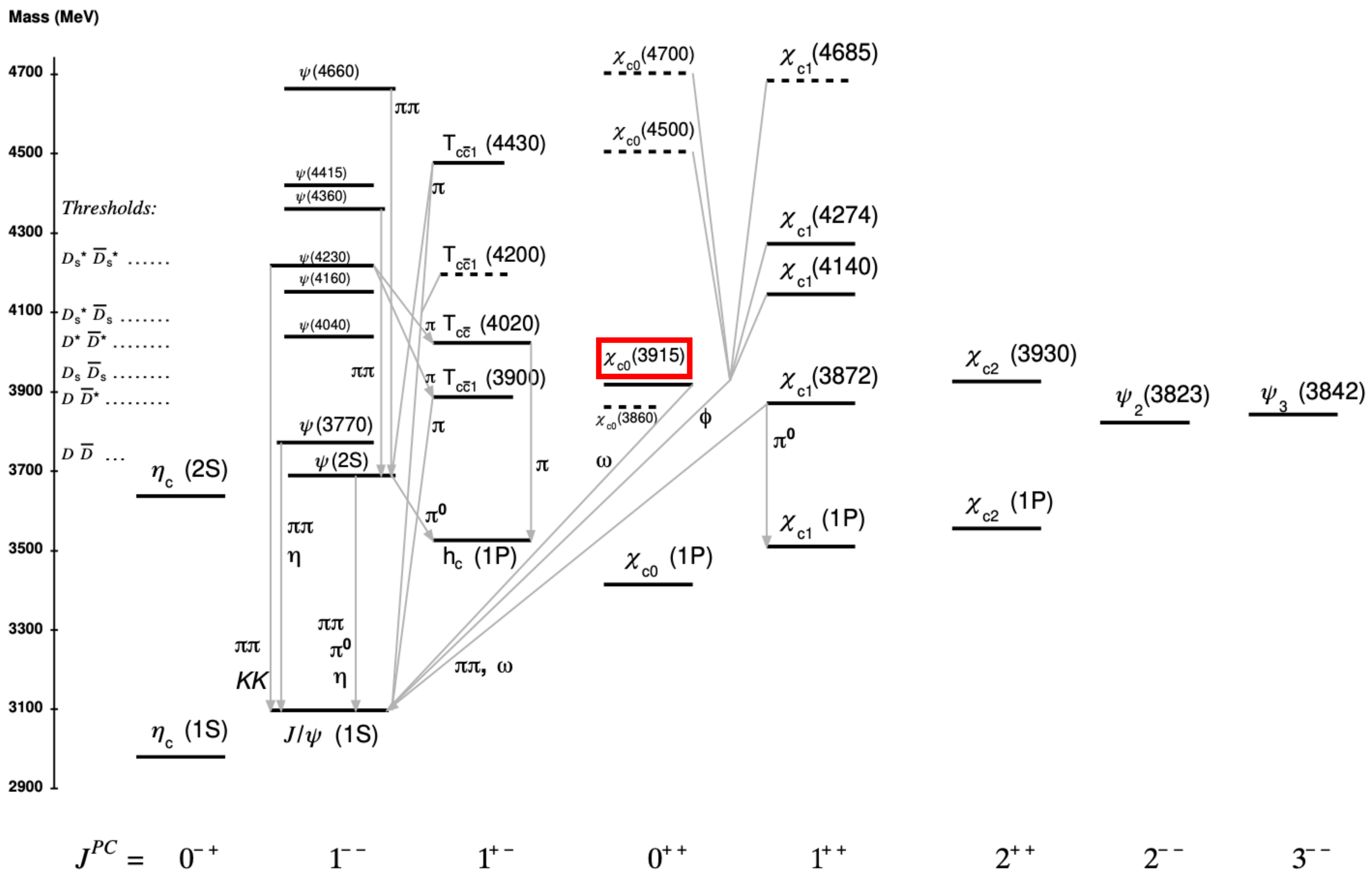
$B^+ \to D^+D^-K^+$

- One new charmonium state: $\chi_{c0}(3915)$



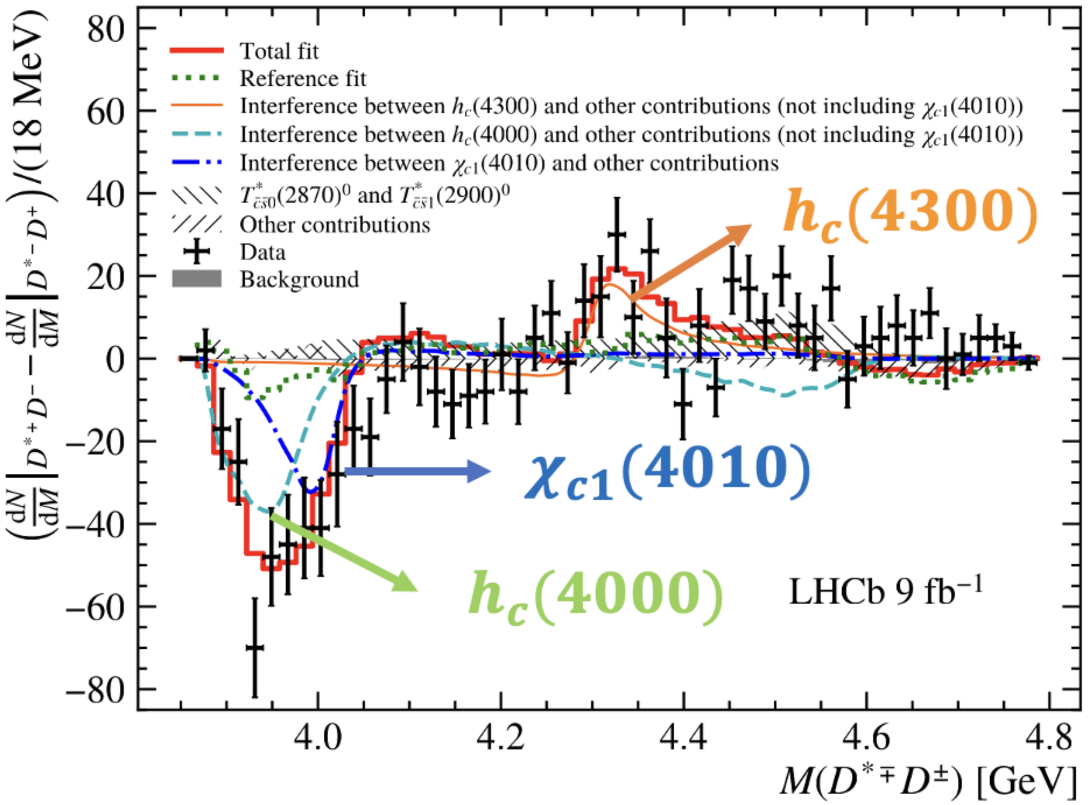
Charmonia spectrum

- PDG



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

- At least three new charmonium states
  - $h_c(4000), \chi_{c1}(4010), h_c(4300)$



$h_c(4000)$: 1^{+-}

$m_0 = 4000^{+17+29}_{-14-22}$ MeV

$\Gamma_0 = 184^{+71+97}_{-45-61}$ MeV

Could be QM Predictions $h_c(2P)$?

$h_c(4300)$: 1^{+-}

$m_0 = 4307.3^{+6.4+3.3}_{-6.6-4.1}$ MeV

$\Gamma_0 = 58^{+28+28}_{-16-25}$ MeV

Could be QM Predictions $h_c(3P)$?

$\chi_{c1}(4010)$: 1^{++}

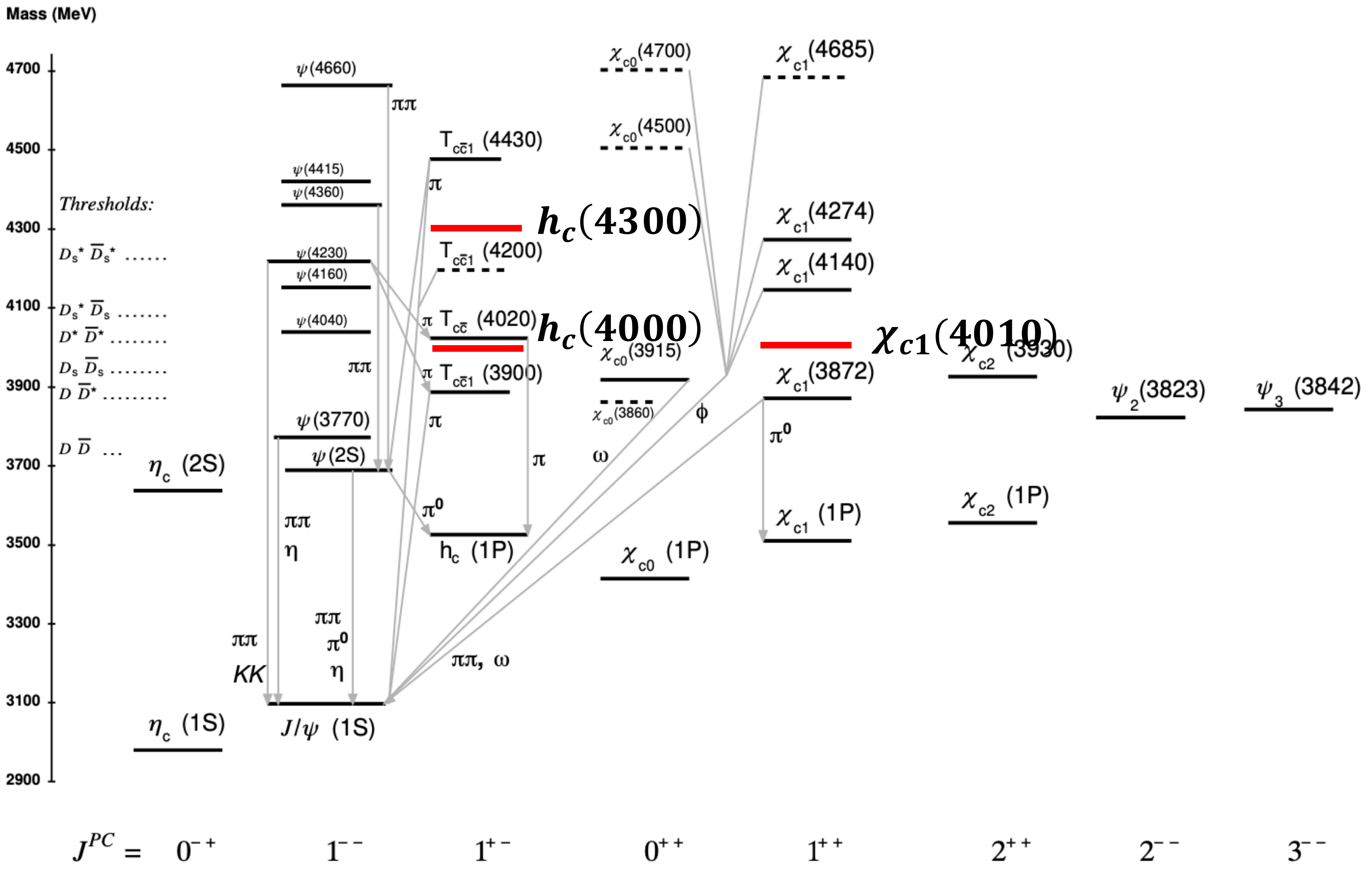
$m_0 = 4012.5^{+3.6+4.1}_{-3.9-3.7}$ MeV

$\Gamma_0 = 62.7^{+7.0+6.4}_{-6.4-6.6}$ MeV

Nature still under debate

Charmonia spectrum

- PDG



Summary

- LHCb experiment has observed many new states through $B \to DDh$ decays w/ data of Run 1-Run 2
- More exotic states and their properties are expected to be observed w/ Run 3 data
- Stay tuned

$D_{s0}(2590)^+$

$T^*_{cs0}(2870)^0$
$T^*_{cs1}(2900)^0$
$\chi_{c0}(3915)$

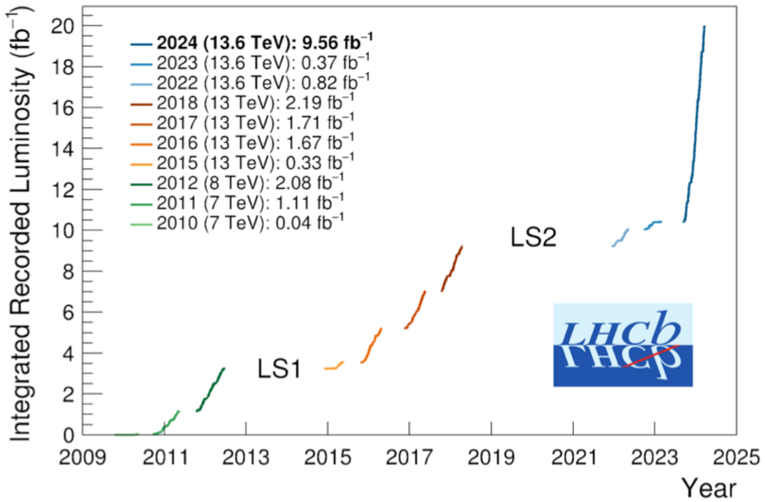
$T^*_{c\bar{s}0}(2900)^{++/0}$

$T^*_{cs0}(2870)^0$

$h_c(4000), \chi_{c1}(4010), h_c(4300)$
$T^*_{cs0}(2870)^0, T^*_{cs1}(2900)^0$

Double-peak in
$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$

More



Thank you!

Back up

$B^0 \to D^- D^+ K^+ \pi^-$

- $A = \sum_k H^{D_{sk}} d_{0,0}^{J_{D_{sk}}}(\theta_{D_s})\, p^{L_{B^0}} B_{L_{B^0}} q^{L_{D_{sk}}} B_{L D_{sk}} BW(m_{K^+\pi^-}) BW(m_{D^+K^+\pi^-})$
- $\Gamma^{D_{sJ}}(m_{DK\pi}) = \Gamma^{D_{sJ}\to D^*K}(m_{DK\pi}) + \Gamma^{D_{sJ}\to DK\pi}(m_{DK\pi})$
- 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
- $r = \Gamma^{D_{sJ}\to DK\pi}(m_0)/\Gamma^{D_{sJ}\to D^*K}(m_0)$
- 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