Amplitude analysis of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ decay

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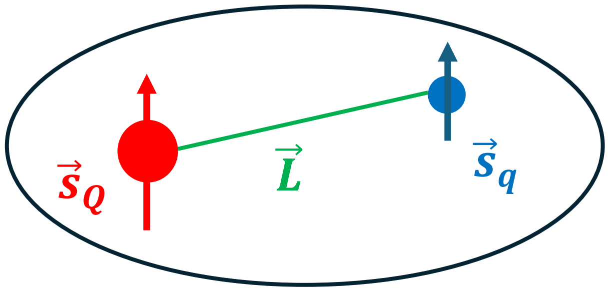
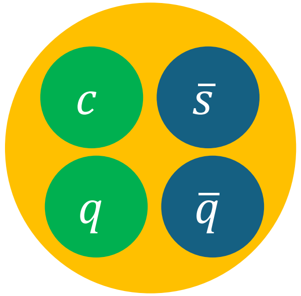
$D_{s1}^{*}(2317)^{+}$ and $D_{s1}(2460)^{+}$

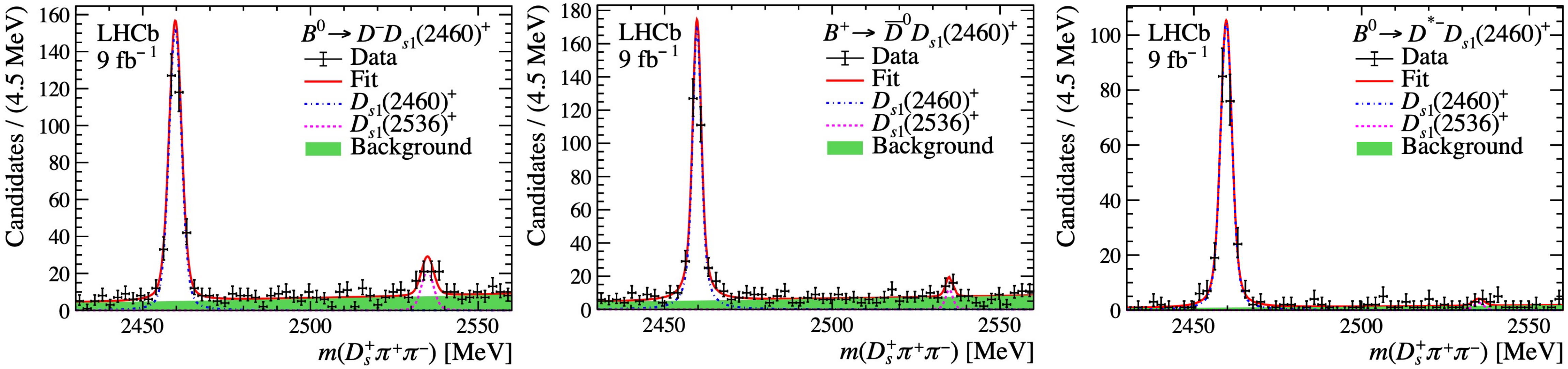




- 20 year-long puzzle
  - Heavy-light quark system? Phys. Rev. D **68**, 054024
  - Tetraquark? Phys. Lett. B **566**, 193 (2003)
  - Hadronic molecule? Phys. Rev. D **68**, 054006
- Width very narrow, low mass
  - Isospin-violating decay: $D_s^{(*)}\pi^0$
  - Isospin-allowed decay occurs at sizable rate: $D_s^+\pi^+\pi^-$ $(4.3 \pm 1.3)\%$
- Not clear whether there exists $I = 1$ state for $D_{s0}^{*}(2317)^{+}$
- Double-bump structure in $m(\pi^+\pi^-)$ if $D_{s1}(2460)^+$ is a D^*K hadronic molecule
  - Commun. Theor. Phys. **75** (2023) 055203
- The multiplet including $T_{c\bar{s}}(2900)^{++}$, $T_{c\bar{s}}(2900)^{0}$ and $T_{cs}(2900)^{0}$ could be the radial excitation of a lighter multiplet containing the $D_{s0}^{*}(2317)^{+}$ state
  - Phys. Rev. D **110**, 034014

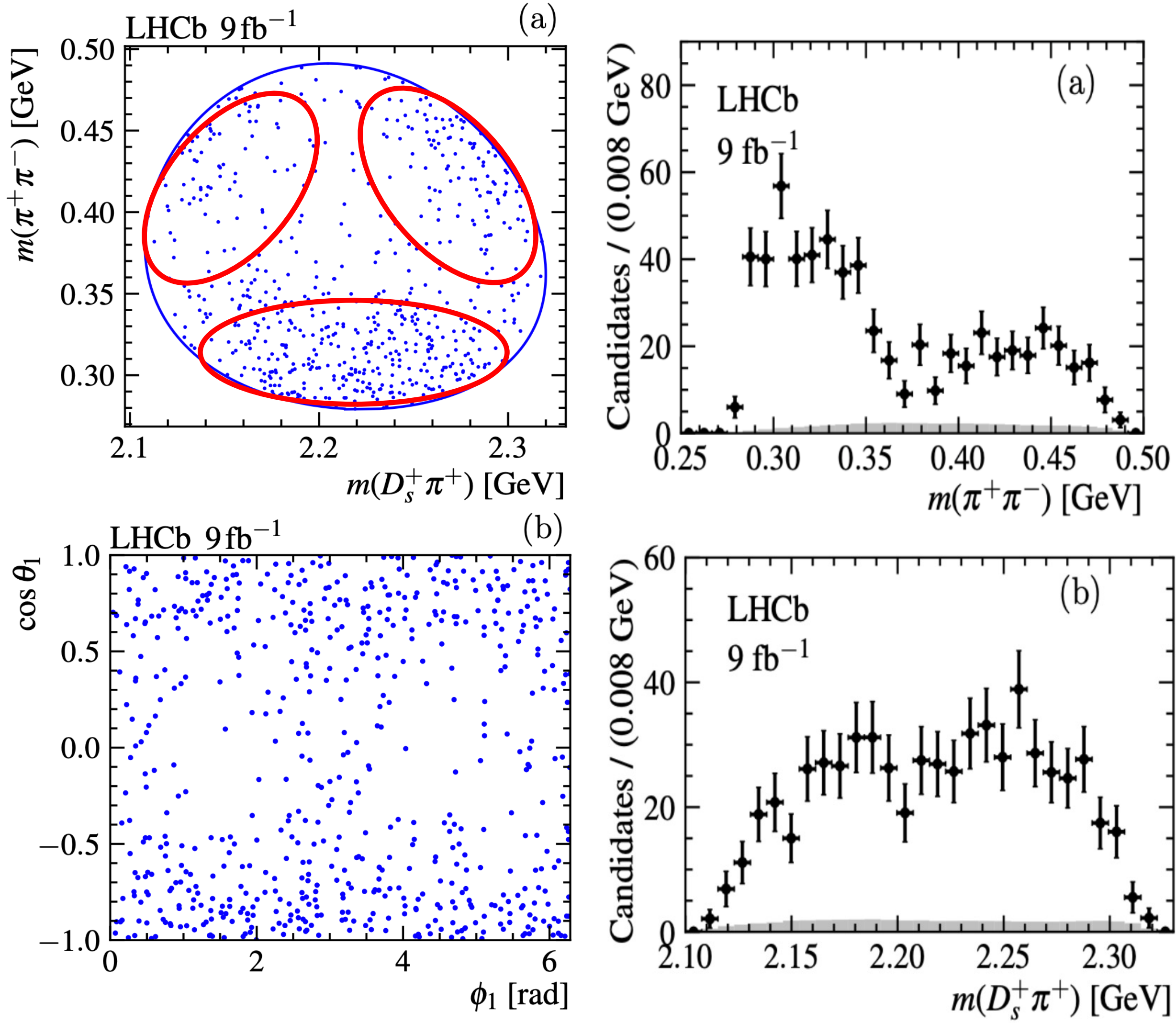
$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ in B decays

- LHCb data 9.0 fb^{-1}
- $B^0 \to D^- D_{s1}(2460)^+$, $B^+ \to \overline{D}^0 D_{s1}(2460)^+$, and $B^0 \to D^{*-} D_{s1}(2460)^+$
- Clear $D_{s1}(2460)^+$ signal, small contribution from $D_{s1}(2536)^+$
- High purity



Data distribution

- Data clusters in three phsp regions
  - Double-peak in $m(\pi^+\pi^-)$
  - Concave structure in $m(D_s^+\pi\ )$
- Amplitude fit
  - Simultaneous fit among three channels
  - Four additional parameters for $B^0 \to D^{*-}D_{s1}(2460)^+$
  - Isobar approach
  - TF-PWA software link

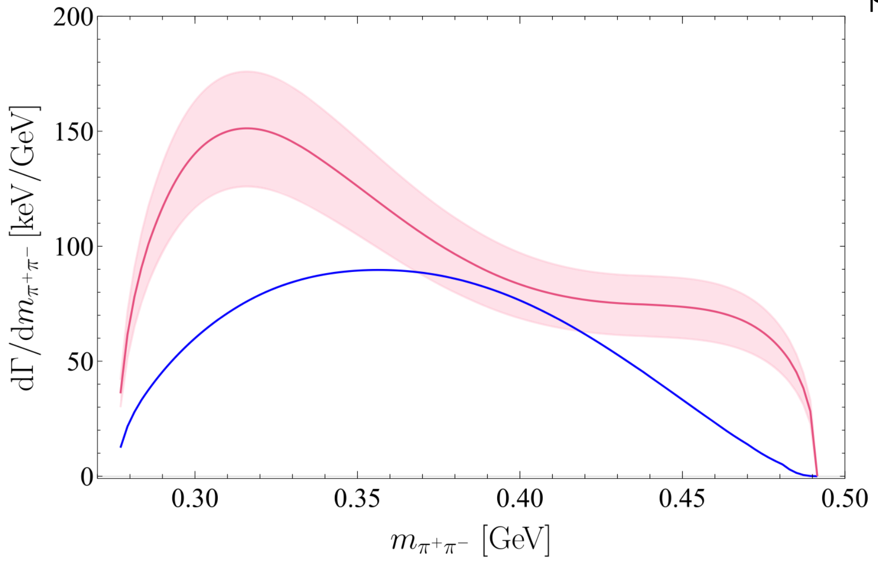


Amplitude fit method

- cfit method
- Model signal and background contribution (extract distribution from candidates in sideband region)
- $-\ln\mathcal{L} = -\sum_{i\in\text{data}}\ln\left[f_{\text{sig}}\mathcal{P}_{\text{sig}}\left(\xi_{i;}\Lambda\right) + (1-f_{\text{sig}})\mathcal{P}_{\text{bkg}}\left(\xi_{i;}\Lambda\right)\right]$
  - $\mathcal{P}_{\text{sig}}\left(\xi_{i;}\Lambda\right) = \frac{|A(\xi_{i};\Lambda)|^2}{\int |A(\xi_{i};\Lambda)|^2\varepsilon(\xi)\mathrm{d}\xi}$
- Fit fraction
  - $F_i = \frac{\int\left|A_i(\xi;\widehat{\Lambda})\right|^2\mathrm{d}\xi}{\int\left|\sum_k A_k(\xi;\widehat{\Lambda})\right|^2\mathrm{d}\xi}$
  - $F_{ij} = \frac{\int 2\mathcal{R}e\left\{A_iA_j^*(\xi;\widehat{\Lambda})\right\}\mathrm{d}\xi}{\int\left|\sum_k A_k(\xi;\widehat{\Lambda})\right|^2\mathrm{d}\xi}$

Naïve models

- Model $f_0(500) + f_0(980)$ and $\pi\pi$ K-matrix model cannot describe well
  - Especially the data with $m(\pi\pi) > 390$ MeV
- The model in paper Commun. Theor. Phys. 75 055203 cannot describe the data well either
  - Detail implimentation in backup



- Red: Hadronic molecule
- Blue: Compact tetraquark

Two models describing 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

Elastic DK

$DK \leftrightarrow D_s\pi$

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

Elastic $D_s\pi$

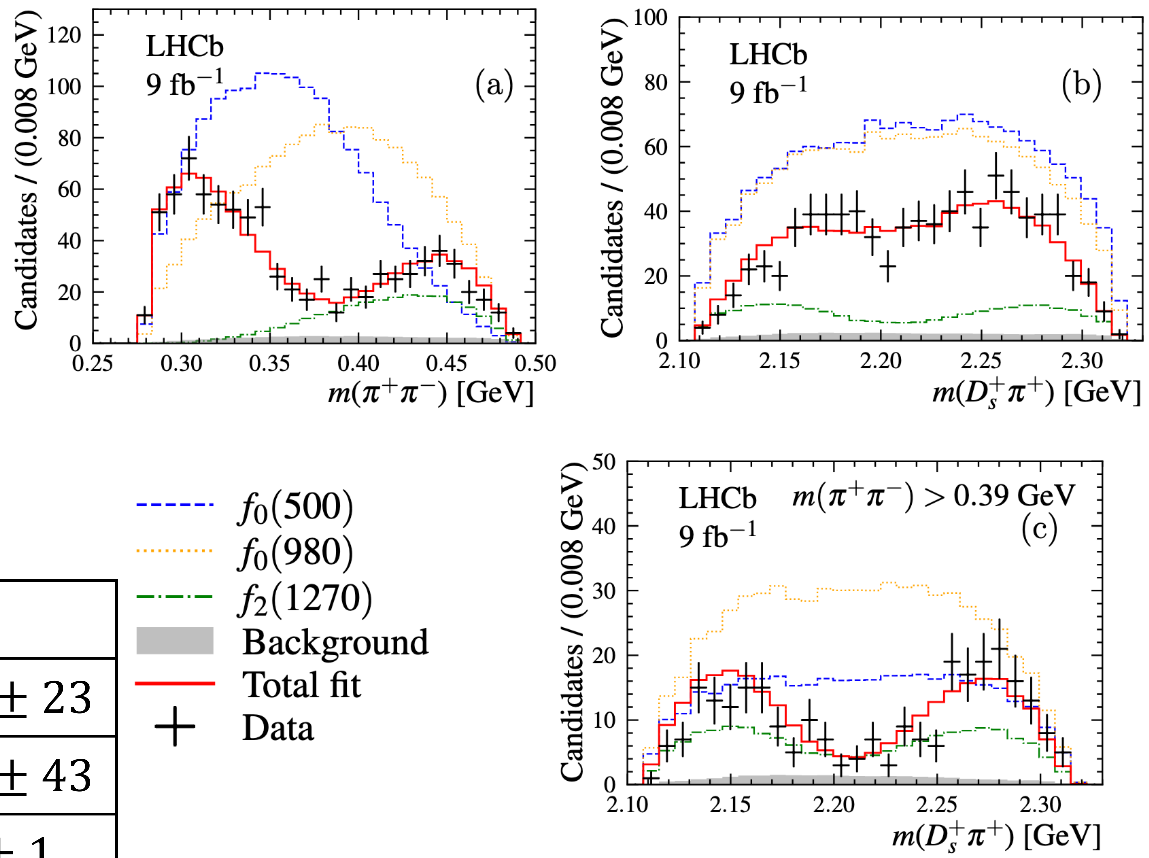
Fixed to 0 in the nominal fit

- ρ contribution is not significant in both models

- 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
    - Lineshae
      - $\dfrac{\beta^2\rho_{DK} + i\gamma_2(i\gamma\rho_{DK} - 1)}{\beta^2\rho_{DK}\rho_{D_s\pi} + (i\gamma\rho_{DK} - 1)(i\gamma_2\rho_{D_s\pi} - 1)}$
    - Scattering length
      - $a = \dfrac{1}{8\pi\sqrt{s_{\mathrm{thr}}}}\left(\gamma + i\beta^2\rho_{D_s\pi}(s_{\mathrm{thr}})\right)$

Model $f_0(500) + f_0(980) + f_2(1270)$

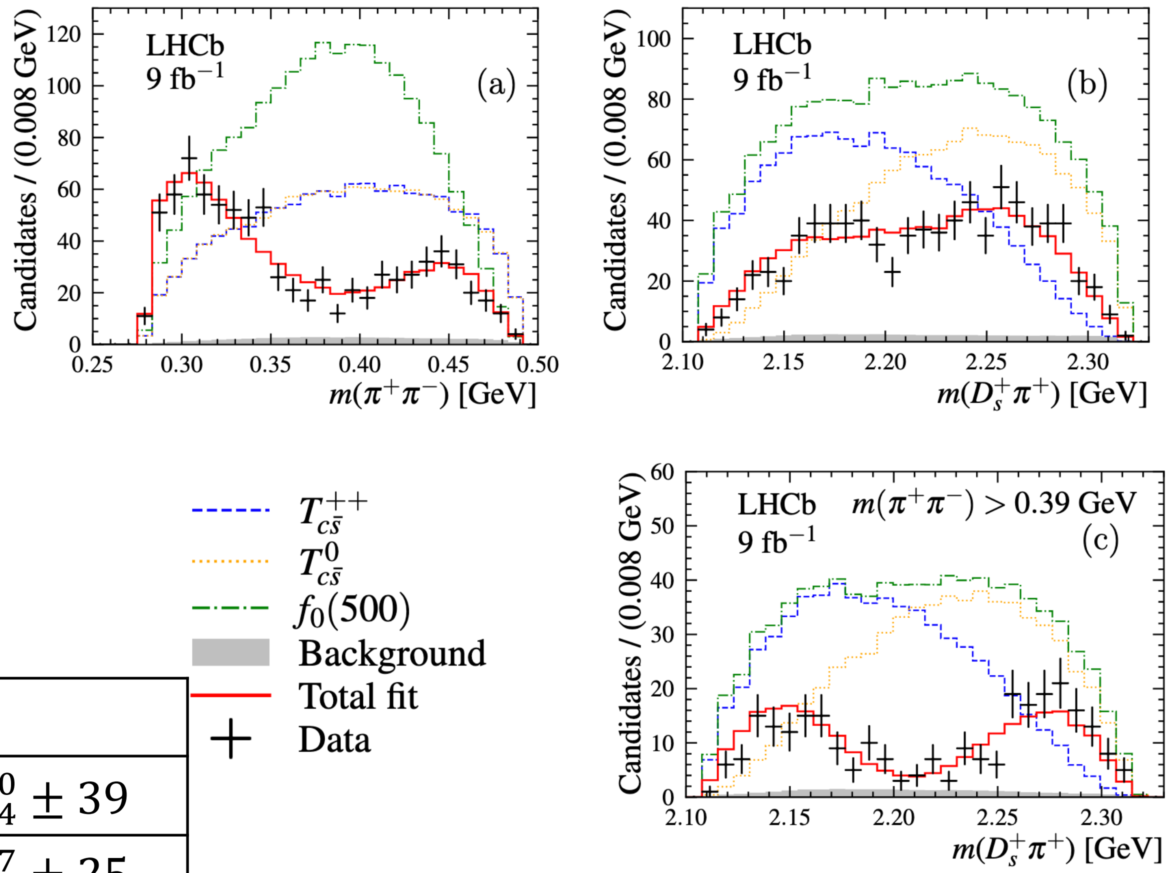
- The large contribution from $f_0(980)$ and $f_2(1270)$
- The large interference between $f_0(500)$ and $f_0(980)$ forming the double bump lineshape in $m(\pi\pi)$
- The mass and width of $f_0(500)$ are different from the known values



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	$29 \pm 2 \pm 1$

Model $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^{0}$

- Isospin symmetry constraint is applied
- Pole mass just below DK threshold
- $a = -0.86(\pm 0.07) + 0.44(\pm 0.07)i$ fm
- Isospin symmetry is conserved
- 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 (%)
$f_0(500)$	$474 \pm 30 \pm 18$	$224 \pm 23 \pm 16$	$248^{+40}_{-54} \pm 39$
$T_{c\bar{s}}$	$2327 \pm 13 \pm 13$	$96 \pm 16^{+170}_{-23}$	$156^{+27}_{-38} \pm 25$

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- $a = -0.86(\pm 0.07) + 0.44(\pm 0.07)i$ fm
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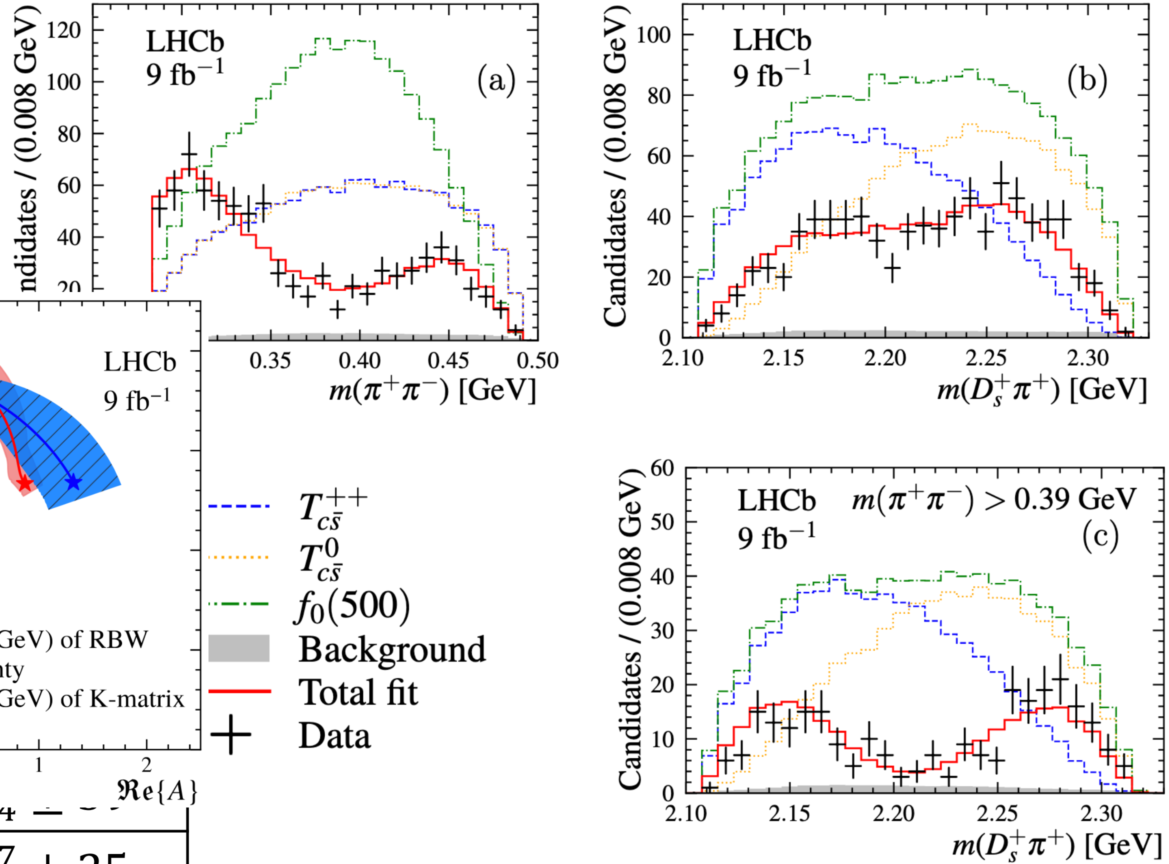
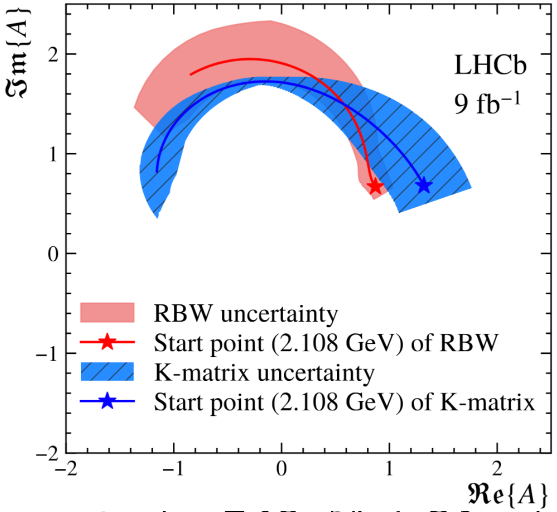
- Consistent results obtained w/ RBW [illegible] matrix model except for the width
- Assign large systematic uncertainty [illegible]





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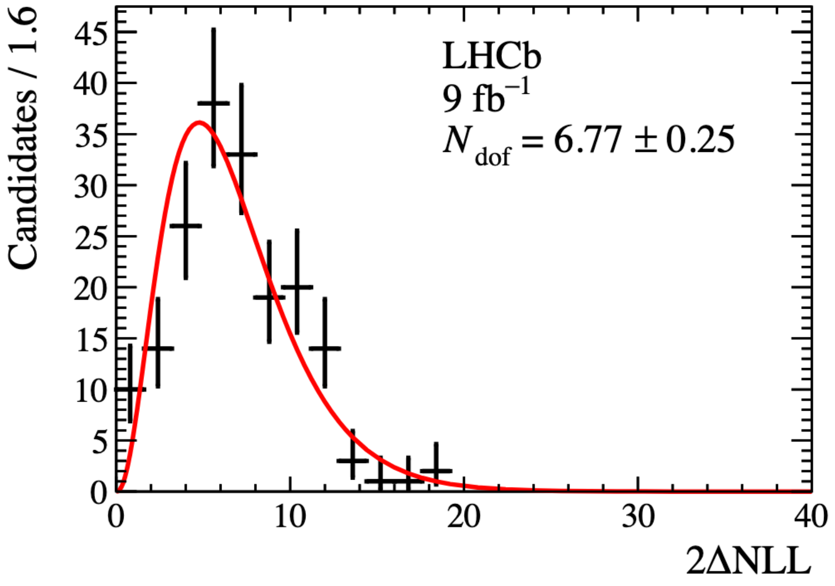
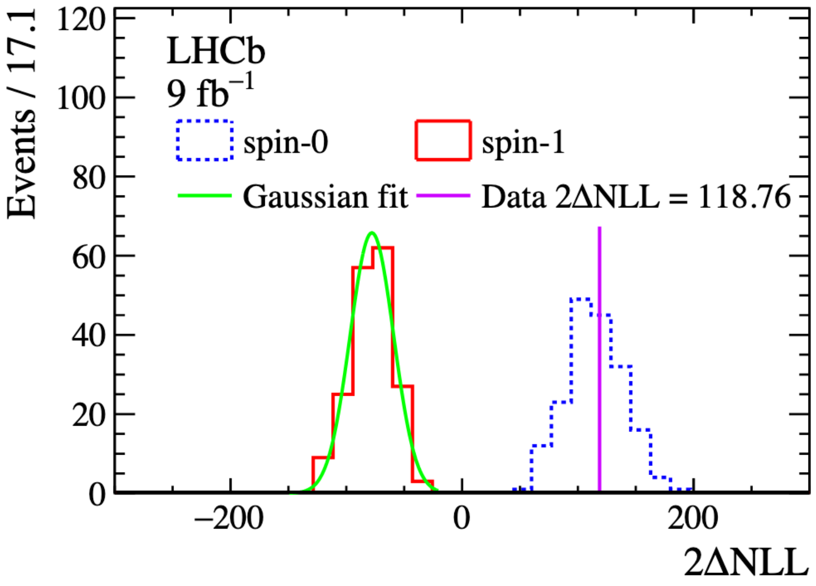
$T_{c\bar{s}}$	$2327 \pm 13 \pm 13$	$96 \pm 16^{+170}_{-23}$	$156^{+27}_{-38} \pm 25$

Model $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^{0}$

- Generate pseudoexperiments to estimate the significance
- Significance over $f_0(500) + f_0(980)$ model is larger than 10 σ
- J^P favours 0^+





Some discussion

- Systematics is dominated by Blatt-Weisskopf factor and model variation
- 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 $f_2(1270)$, their poles far away from the upper limit of $m(\pi\pi)$, 4 times of their widths
  - 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 $T_{c\bar{s}}^{0}$

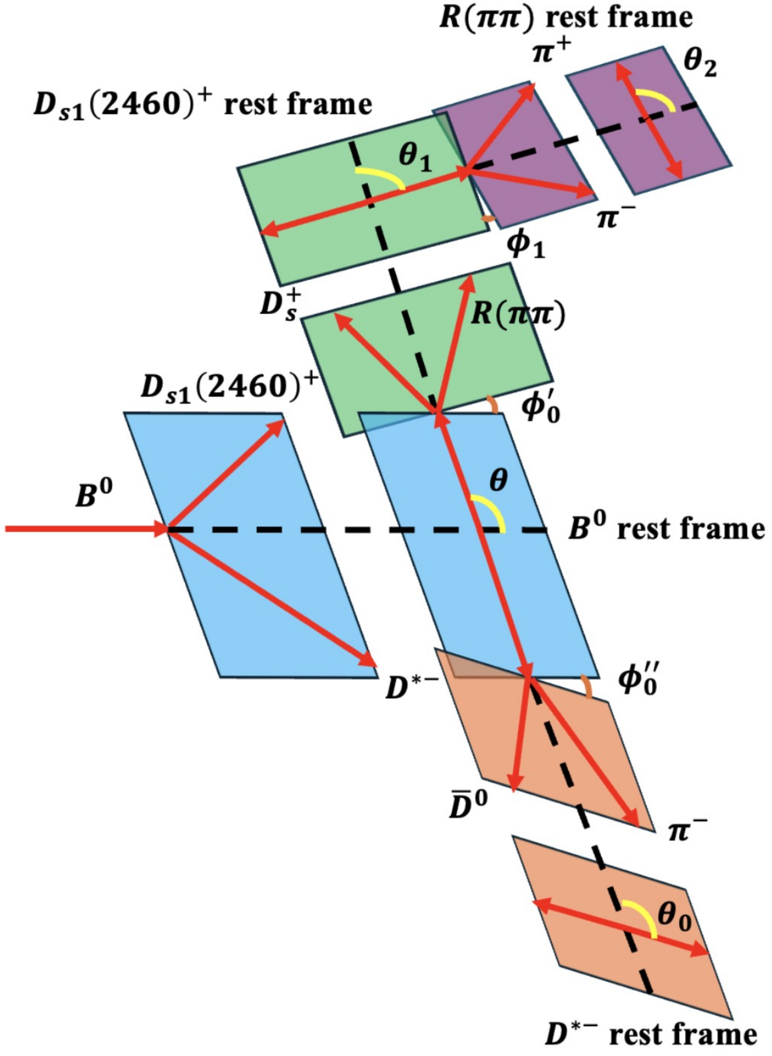
Summary

- An amplitude analysis of the isospin-conserving decay $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ is performed simultaneously in *B* hadronic channels for the first time
- An interesting double-peak structure is seen in $m(\pi\pi)$
  - Two models could describe the data well
  - The first one is physically implausible – The poles for $f_0(980)$ and $f_2(1270)$ are far away from the upper kinematic boundary of $m(\pi\pi)$
  - The second one introduces two new tetraquark states: mass $2327 \pm 13 \pm 13$ MeV, width $96 \pm 16^{+170}_{-23}$ MeV
- This analysis sheds new light on this longstanding puzzles for $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$, also complement those obtained on other T_{cs} and $T_{c\bar{s}}$ hadrons

Backup slides

Kinematics of $B \to \overline{D}^{(*)} D_{s1}(2460)^+$

- $B \to \overline{D} D_{s1}(2460)^+$
  - $m(\pi^+\pi^-), m(D_s^+\pi^+)$
  - $\cos\theta_1, \phi_1$
- $B^0 \to D^{*-} D_{s1}(2460)^+$
  - $m(\pi^+\pi^-), m(D_s^+\pi^+)$
  - $\cos\theta_1, \phi_1$
  - $\cos\theta_0, \phi_0$



$\pi\pi$ K-matrix model

- Total lineshape: $f_u = \sum_{v=1}^{n} [1 - i\hat{K}\rho]_{uv}^{-1} \cdot \hat{P}_v$
- Coupling channels: $\pi\pi$, $K\bar{K}$, 4π, $\eta\eta$, and $\eta\eta'$
- K-matrix: $\hat{K}_{uv}(s) = \left(\sum_{\alpha=1}^{N} \frac{g_u^{(\alpha)} g_v^{(\alpha)}}{m_\alpha^2 - s} + f_{uv}^{\text{scatt}} \frac{m_0^2 - s_0^{\text{scatt}}}{s - s_0^{\text{scatt}}}\right) f_{A_0}(s)$ (poles plus slowly varying parts)
- Production vector: $\hat{P}_v(s) = \sum_{\alpha=1}^{N} \frac{\beta_\alpha g_v^{(\alpha)}}{m_\alpha^2 - s} + f_v^{\text{prod}} \frac{m_0^2 - s_0^{\text{prod}}}{s - s_0^{\text{prod}}}$
- PHSP factor
- $\rho_u = \sqrt{\left[1 - \frac{(m_{1u} + m_{2u})^2}{s}\right]\left[1 - \frac{(m_{1u} - m_{2u})^2}{s}\right]}$
- $\rho_3 = \frac{\rho_u}{1 + \exp\frac{2.8 - s}{3.5}}$
- $\beta_\alpha(\alpha > 1)$ and $f_v^{\text{prod}}(v > 1)$ fixed to 0

Model in paper Commun. Theor. Phys. 75 055203

- Two-dimensional interpolation in $m(\pi\pi) - \cos\theta$ (the helicity angle of $R(\pi\pi)$ decay)
- Different line shapes for different helicity for $D_{s1}(2460)^+$

Flatte model

- $f_{f_0(980)} = \frac{1}{m_0^2 - s - i m_0 (g_{\pi\pi}\rho_{\pi\pi} + g_{KK} F_{KK}^2 \rho_{KK})}$
- PHSP factor
  - $\rho_{\pi\pi} = \frac{2}{3}\sqrt{1 - \frac{4m_{\pi^\pm}^2}{s}} + \frac{1}{3}\sqrt{1 - \frac{4m_{\pi^0}^2}{s}}$, $\rho_{KK} = \frac{1}{2}\sqrt{1 - \frac{4m_{K^\pm}^2}{s}} + \frac{1}{2}\sqrt{1 - \frac{4m_{K^0}^2}{s}}$

Fit goodness