Are the $Z_{cs}(3985)$ and $Z_{cs}(4000)$ the same state?

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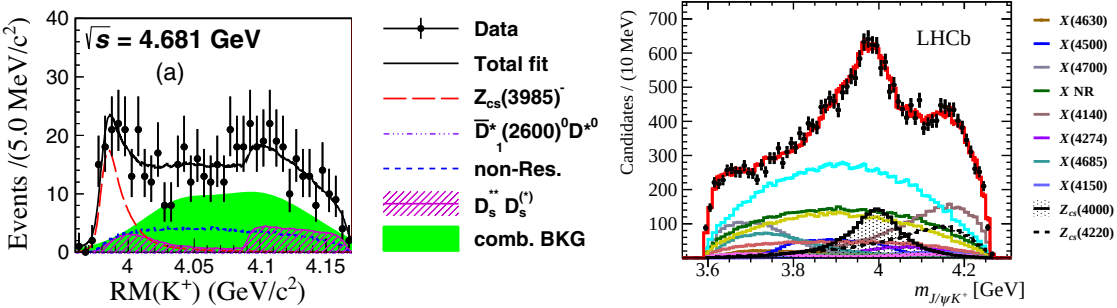
Based on arXiv:2104.08469, PRD103, L021501, PRD102,111502(R)

Contents

Experimental results from BESIII and LHCb



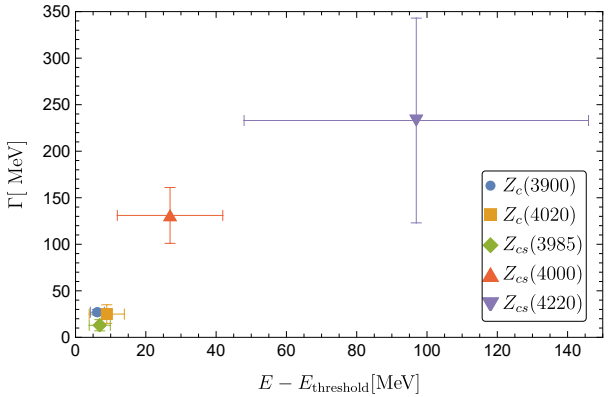
- BESIII: $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ at $\sqrt{s} = 4.681$ GeV
- LHCb:$Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ in the $J/\psi K^+$ of the $B^+ \to J/\psi\phi K^+$ 2103.01803

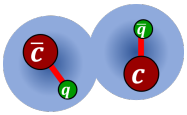
$$(M, \Gamma): \quad (3982.5, 12.8)\ \text{MeV} \quad \text{VS} \quad (4003, 131)\ \text{MeV}$$

- Width difference: 10 times.Whether they are the same states?
- Molecular scheme: symmetries (and their possible breaking)+ effective field theory (EFT)

Theoretical interpretation of $Z_{cs}(3985)$ state

$Z_{cs}(3985)$ state





Composed of two color singlet hadrons (during most of its lifetime)

- Near-threshold resonances

$Z_c(3900)$	$D^*\bar{D}/D\bar{D}^*$
$Z_c(4020)$	$D^*\bar{D}^*$
$Z_{cs}(3985)$	$D_s\bar{D}^*/D_s^*\bar{D}$

- A natural explanation:
  - $\Rightarrow$ $Z_{cs}(3985)$: SU(3) partner of $Z_c(3900)$
    PRD103,074029; 2011.09404; 2011.10495; 2011.09225...
  - $\Rightarrow$ Z_c, Z_c', Z_{cs}: molecular resonances
- Hadronic molecule: PRL67,556; RMP90,015004
  - $\Rightarrow$ loosely bound states
  - $\Rightarrow$ near-threshold di-hadron resonances

SU(3) flavor limit

- $\bar{\mathrm{P}}\mathrm{V}/\bar{\mathrm{V}}\mathrm{P}$ di-meson wave functions

$$|C=-\eta\rangle = |G=\eta\rangle = \frac{1}{\sqrt{2}}\left(|\bar{D}D^*\rangle + \eta|\bar{D}^*D\rangle\right)^{I=1}$$

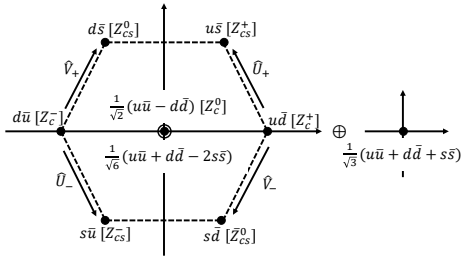
- $Z_c(3900): G=+1 \Rightarrow \eta=+1$
- $\hat{G}_U = \hat{C}e^{i\hat{U}_2\pi}, \hat{G}_V = \hat{C}e^{i\hat{V}_2\pi}$

$$|G_U=+1\rangle = \frac{1}{\sqrt{2}}\left(|D_s^- D^{*+}\rangle + |D_s^{*-}D^+\rangle\right)$$

- $Z_{cs}(3985)^-$: U-spin partner of $Z_c(3900)^-$
- General notation:

$$|\bar{\mathrm{P}}\mathrm{V}/\bar{\mathrm{V}}\mathrm{P},\pm\rangle = \tfrac{1}{\sqrt{2}}\left(|\bar{\mathrm{P}}\mathrm{V}\rangle \pm |\bar{\mathrm{V}}\mathrm{P}\rangle\right)$$

- Mxing: odd and even $G_{U/V}$ when ~~SU(3)$_f$~~



SU(2) subgroups		
$u,d\,(I)$	$d,s\,(U)$	$u,s\,(V)$

Heavy quark spin symmetry (HQSS)

- $V^{\text{spin-space}} = v_1 + v_2 \boldsymbol{s}_q \cdot \boldsymbol{s}_{\bar{q}} +$ HQSS breaking terms
  - $\Rightarrow$ The heavy part: spectator
  - $\Rightarrow$ Heavy spin and light spin are conserved
- $\langle V \rangle$: HQSS partner states

$$\langle V^s_{q\bar{q}} \rangle^{1^+}_{\{\bar{\mathtt{V}}\mathtt{V}\}} = \langle V^s_{q\bar{q}} \rangle^{1^+}_{\{\bar{\mathtt{P}}\mathtt{V}/\bar{\mathtt{V}}\mathtt{P},+\}}$$
$$\langle V^s_{q\bar{q}} \rangle^{2^+}_{\{\bar{\mathtt{V}}\mathtt{V}\}} = \langle V^s_{q\bar{q}} \rangle^{1^+}_{\{\bar{\mathtt{P}}\mathtt{V}/\bar{\mathtt{V}}\mathtt{P},-\}}$$

- Rearrangement and selection rules: $|(\bar{c}q_1)_{j_1}(c\bar{q}_2)_{j_2}; J^P\rangle \Rightarrow |(\bar{c}c)_h(\bar{q}_1 q_2)_l; J^P\rangle$
- Example

$$|\bar{\mathtt{P}}\mathtt{V}/\bar{\mathtt{V}}\mathtt{P},+\rangle = \frac{1}{\sqrt{2}}\left(|0^-_{\bar{c}c}, 1^-_{q_1\bar{q}_2}; 1^+\rangle - |1^-_{\bar{c}c}, 0^-_{q_1\bar{q}_2}; 1^+\rangle\right)$$
$$Z_c(3900) \sim |\bar{D}D^*/\bar{D}^*D,+\rangle \sim \frac{1}{\sqrt{2}}\left(|\eta_c\rho\rangle - |J/\psi\pi\rangle\right)$$

Calculation: Masses and widths

- Coupled-channel Lippmann-Schwinger equations (LSEs):$T = V + VGT$

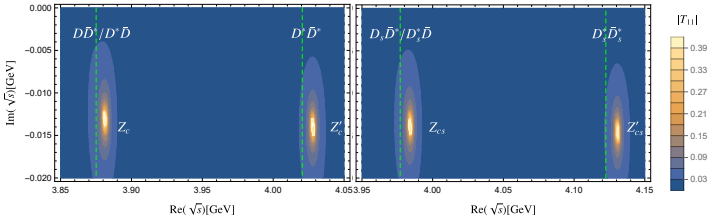
Channel	1	2	3
Z_c/Z_c'	$J/\psi\pi$	$\bar{D}D^*/\bar{D}^*D$	$\bar{D}^*D^*$
Z_{cs}/Z_{cs}'	$J/\psi K$	$\bar{D}_sD^*/\bar{D}_s^*D$	$\bar{D}_s^*D^*$

- Interaction

$$V_{ij} = \begin{bmatrix} 0 & v_{12} & v_{12} \\ v_{12} & C_d + \frac{C_d'}{2}(\boldsymbol{p}^2 + \boldsymbol{p}'^2) & v_{23} \\ v_{12} & v_{23} & C_d + \frac{C_d'}{2}(\boldsymbol{p}^2 + \boldsymbol{p}'^2) \end{bmatrix}$$

- Masses and widths of $Z_c(3900)$ and $Z_c(4020)$ as input

Calculation: Masses and widths



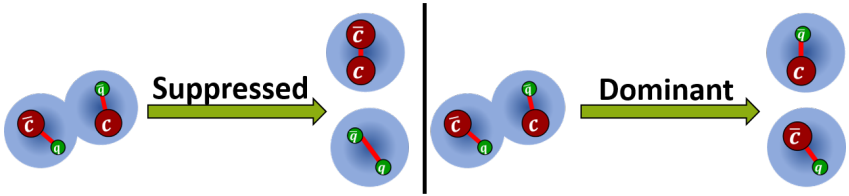
(M, Γ)	This work	Exp
Z_{cs}	$(3984, 27)$	$(3982.5, 12.8)$
Z'_{cs}	$(4130, 29)$	

- $Z_{cs}(3985)$: agree with the experiment results well PRD102,111502(R)
- Predict $Z_{cs}(4130)$, SU$(3)_F$ partner of $Z_c(4020)$ and HQSS partner of $Z_{cs}(3985)$

Calculation: Decays

Z_c/Z_{cs}	$\frac{\Gamma_2}{\Gamma_1} > 10$	
Z_c'/Z_{cs}'	$\frac{\Gamma_3}{\Gamma_1} > 10$	$\frac{\Gamma_3}{\Gamma_2} \sim 1$

- $Z_{c(s)} \to \bar{D}_{(s)} D^* / \bar{D}^*_{(s)} D$ is dominant: fall apart
- $Z_{c(s)} \to J/\psi\pi(K)$ is suppressed: recluster the heavy quarks
- $Z_{c(s)}$:$\bar{D}_{(s)} D^* / \bar{D}^*_{(s)} D$ interaction is not attractive enough but confine them for a finite time

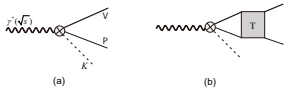


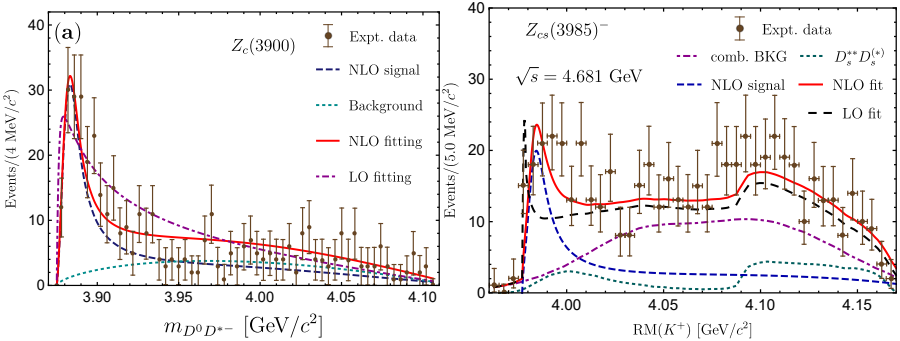
- Coupled-channel effect from $J/\psi\pi(K)$ is tiny

PRD102,111502(R)

Calculation: Productions

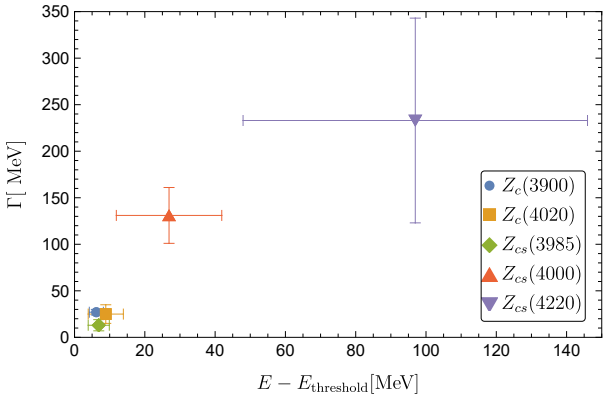
- The parameters are extracted from the $Z_c(3900)$ data PRD102,114019; PRD92,092006
- The event distribution of $Z_{cs}(3985)$ are consistent with the experimental results PRD103, L021501





Theoretical analysis in two-state scheme

If the $Z_{cs}(3985)$ and $Z_{cs}(4000)$ are two different states



- Bad $SU_F(3)$ symmetry
  - $\Rightarrow$ Only one Z_c state with $J^P = 1^+$ near the $\bar{D}D^*/\bar{D}^*D$ threshold
  - $\Rightarrow$ Two Z_{cs} states (narrower one and broader one) with $J^P = 1^+$ near the $\bar{D}_sD^*/\bar{D}_s^*D$ threshold
- Good HQSS: $Z_c(3900)$ and $Z_c(4020)$

broad, $Z_{cs}(4000)$	Corresponding?	$\lvert\bar{\rm P}{\rm V}/\bar{\rm V}{\rm P},+\rangle$	HQSS	$\lvert\bar{\rm V}{\rm V},1^+\rangle$
narrow, $Z_{cs}(3985)$	Mixing?	$\lvert\bar{\rm P}{\rm V}/\bar{\rm V}{\rm P},-\rangle$	HQSS	$\lvert\bar{\rm V}{\rm V},2^+\rangle$

- Neglect the $J/\psi\pi$ and $J/\psi K$ channels

Heavy quark spin symmetry violation effect

$$V^{1^+}_{\{\bar{\mathtt{P}}\mathtt{V},\bar{\mathtt{V}}\mathtt{P}\}} = \frac{1}{2\Lambda}\begin{bmatrix} c_a^+ + c_a^- & c_a^+ - c_a^- \\ c_a^+ - c_a^- & c_a^+ + c_a^- + 4\delta c_a \end{bmatrix} + \text{NLO term}$$

$$V^{1^+}_{\{\bar{\mathtt{P}}\mathtt{V}/\bar{\mathtt{V}}\mathtt{P},+-\}} = \begin{bmatrix} \frac{c_a^+ + \delta c_a}{\Lambda} & \frac{\delta c_a}{\Lambda} \\ \frac{\delta c_a}{\Lambda} & \frac{c_a^- + \delta c_a}{\Lambda} \end{bmatrix} + \begin{bmatrix} \frac{c_b^+(\boldsymbol{p}^2+\boldsymbol{p}'^2)}{\Lambda^3} & \\ & \frac{c_b^-(\boldsymbol{p}^2+\boldsymbol{p}'^2)}{\Lambda^3} \end{bmatrix}$$

- δc_a HQSS breaking effect, inducing the mixing of $|\mathtt{PV}/\mathtt{VP}, +\rangle$ and $|\mathtt{PV}/\mathtt{VP}, -\rangle$
- 5 LECs, 4 input: masses and widths of $Z_{cs}(3985)$ and $Z_{cs}(4000)$
- Set $\delta c_a = 0$ and determine the other 4 LECs
- Varying δc_a to make $-0.4 < R_{\text{HQSSB}} < 0.4$

$$R_{\text{HQSSB}} = \frac{4\delta c_a}{|c_a^+ + c_a^-|}$$

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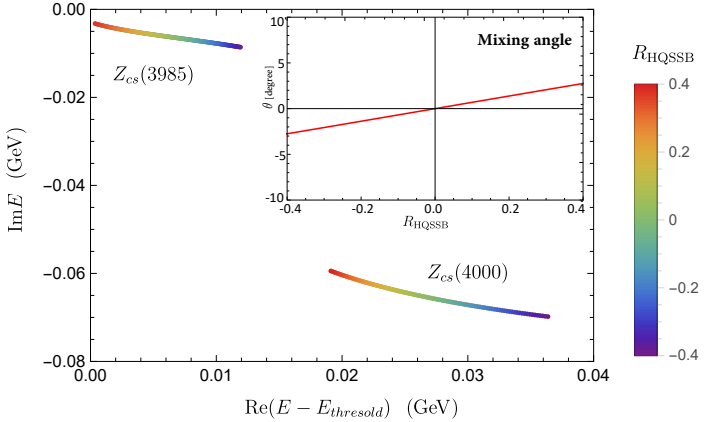
Mixing effect is not significant



- Relative orders for M and Γ do not change
- Mixing angle of $|\mathtt{PV}/\mathtt{VP}, +\rangle$ and $|\mathtt{PV}/\mathtt{VP}, -\rangle$ is tiny

2104.08469

Dimeson components of two states

broad, $Z_{cs}(4000)$	Corresponding ⇌ tiny mixing	$\|\bar{\mathrm{P}}\mathrm{V}/\bar{\mathrm{V}}\mathrm{P},+\rangle$	HQSS ⟷	$\|\bar{\mathrm{V}}\mathrm{V},1^+\rangle$	←	$Z_{cs}(4220)$,broad state
narrow, $Z_{cs}(3985)$		$\|\bar{\mathrm{P}}\mathrm{V}/\bar{\mathrm{V}}\mathrm{P},-\rangle$	HQSS ⟷	$\|\bar{\mathrm{V}}\mathrm{V},2^+\rangle$	←	Prediction

- $|Z_{cs}(4000)\rangle$=$|\bar{D}_s^* D/\bar{D}_s D^*,+\rangle$ and $Z_{cs}(3985) = |\bar{D}_s^* D/\bar{D}_s D^*,-\rangle$

$$\mathcal{R}(Z_{cs} \to \bar{D}_s^* D/Z_{cs} \to \bar{D}_s D^*) \approx 0.5$$

- Tensor $\bar{D}_s^* D^*$ state as the HQSS partner of $Z_{cs}(3985)$.

$$M = 4126 \pm 3 \text{ MeV}, \quad \Gamma = 13 \pm 6 \text{ MeV}.$$

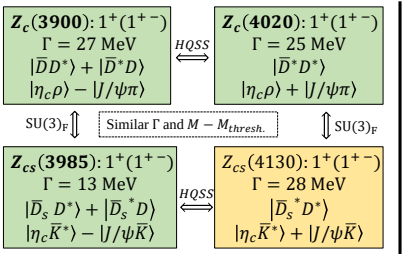
- $Z_{cs}(3985) \to J/\psi K$ is suppressed compared with $Z_{cs}(4000) \to J/\psi K$ in the HQSS limit.

$$|\bar{\mathrm{P}}\mathrm{V}/\bar{\mathrm{V}}\mathrm{P},+\rangle = \frac{1}{\sqrt{2}}\left(|0^-_{\bar{c}c}, 1^-_{q_1\bar{q}_2}; 1^+\rangle - |1^-_{\bar{c}c}, 0^-_{q_1\bar{q}_2}; 1^+\rangle\right)$$
$$|\bar{\mathrm{P}}\mathrm{V}/\bar{\mathrm{V}}\mathrm{P},-\rangle = |1^-_{\bar{c}c}, 1^-_{q_1\bar{q}_2}; 1^+\rangle$$

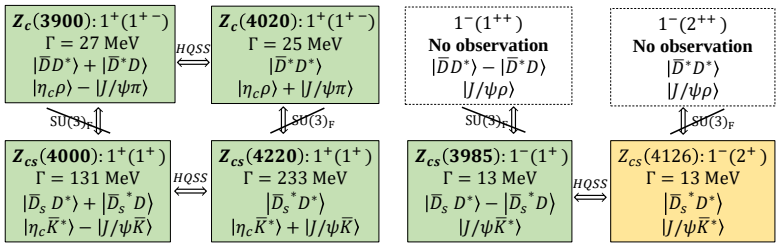
Summary

Summary

- Based on molecule scheme



(a) $Z_{cs}(3985)$ as the $SU(3)_F$ partner of $Z_c(3900)$.



(b) Implications $Z_{cs}(3985)$ and $Z_{cs}(4000)$ as two different states.

- Take home messages

  $\Rightarrow$ $Z_{cs}(3985) \to J/\psi K$ in suppressed in the two states schemes

  $\Rightarrow$ Tensor $Z_{cs}(4126)$ in two states schemes

- Compact tetraquark scheme: predict more states (two nonets)

2103.08331

Thanks for your attention!