

# On the $Z_{CS}(3985)$ and $X(3960)$ states

Towards HQSS and  $SU(3)$  multiplet descriptions



**IFIC**  
INSTITUT DE FÍSICA  
CORPUSCULAR

Miguel Albaladejo (IFIC)

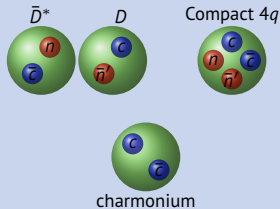
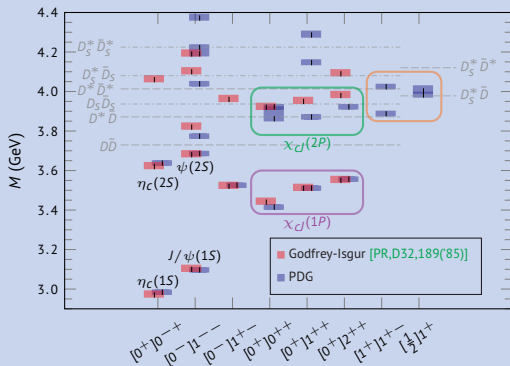
Excited QCD  
Giardini Naxos  
Oct. 24-28, 2022



# Outline

- 1 Introduction
- 2 Interactions [HQSS and  $SU(3)$ ]
- 3  $X(3960)$
- 4 HQSS &  $SU(3)$  multiplets
- 5  $Z_{cs}(3985)$  and  $Z_c(3900)$

## Quark model in the charmonium sector



Appropriate tool: Weinberg's compositeness conditions

- $\chi_{cJ}(1P)$  well established, “very CQM model” state.
- $X(3872)$  discovered by Belle [PRL,91,262001(03)] (also 2003!)  
 $J^{PC} = 1^{++}$  and  $\Gamma \simeq 1$  MeV established by LHCb (e.g. [JHEP,08(2020),123]).
- $\chi_{cJ}(2P)$  Not established. Influence of open thresholds?  $X(3872)$  a molecular state,  $4q, \dots$ ?
- $Z_c/Z_{cs}$  states have  $l = 1$  or  $1/2$ , clearly “tetraquarks” ( $c\bar{c}u\bar{d}, \dots$ )
- Many theoretical and lattice and experimental works: can't cite them properly here!  
 (many references in [2207.08653])

## HQSS and flavour SU(3) LO lagrangian

[Grinstein *et al.*, NP,B380(92); Alfiqy *et al.*, PL,B640(06), ...]

- SU(3) light flavour symmetry:

$$H_a^{(Q)} \sim (Q\bar{u}, Q\bar{d}, Q\bar{s}) \sim (D^0, D^+, D_s^+)$$

- HQSS:  $H_a^{(Q)} = \frac{1 + \gamma_5}{2} (P_{a\mu}^{*(Q)} \gamma^\mu - P_a^{(Q)} \gamma_5)$

$$(\text{with } v \cdot P_a^{*(Q)} = 0)$$

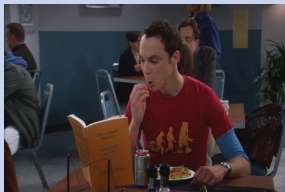
- $H\bar{H} \rightarrow H\bar{H}$  LO lagrangian (S-wave contact interactions):

$$\begin{aligned} \mathcal{L}_{4H} = & \frac{1}{4} \text{Tr} [\bar{H}^{(Q)a} H_b^{(Q)} \gamma_\mu] \text{Tr} [H^{(\bar{Q})c} \bar{H}_d^{(\bar{Q})} \gamma^\mu] (F_A \delta_a^b \delta_c^d + F_A^\lambda \vec{\lambda}_a^b \cdot \vec{\lambda}_c^d) \\ & + \frac{1}{4} \text{Tr} [\bar{H}^{(Q)a} H_b^{(Q)} \gamma_\mu \gamma_5] \text{Tr} [H^{(\bar{Q})c} \bar{H}_d^{(\bar{Q})} \gamma^\mu \gamma_5] (F_B \delta_a^b \delta_c^d + F_B^\lambda \vec{\lambda}_a^b \cdot \vec{\lambda}_c^d), \end{aligned}$$

- **Only 4 constants**, any linear combination can be used

$$C_{0a} = F_A + \frac{10F_A^\lambda}{3}, \quad C_{1a} = F_A - \frac{2}{3}F_A^\lambda,$$

$$C_{0b} = F_B + \frac{10F_B^\lambda}{3}, \quad C_{1b} = F_B - \frac{2}{3}F_B^\lambda.$$



# $D_s^+ D_s^-$ interaction and $B^+ \rightarrow D_s^+ D_s^- K^+$ decay

[Ji, Dong, MA, Du, Guo, Nieves, 2207.08563]

Scattering amplitude:  $T^{-1}(E) = V^{-1} - G(E)$

$$V = 4m_{D_s}^2 \frac{C_{0a} + C_{1a}}{2}$$

$G(E)$ : loop functions, once-subtracted DR,  
 $G(E_{\text{th}}) = G_{\Lambda}(E_{\text{th}})$

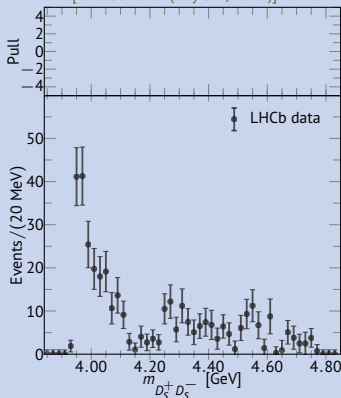
Simple production model:

$$T_B(E) = P + P G(E) T(E) = P \frac{1}{1 - V G(E)}$$

$$\frac{d\Gamma}{dE} = \frac{1}{(2\pi)^3} \frac{k p}{4m_B^2} |T_B(E)|^2$$

[LHCb-PAPER-2022-018,019]

[LHC Seminar (July 5<sup>th</sup>, 2022)]



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- Fit: two solutions (virtual or bound), in both:

$$M_{X(3960)} = 3928(3) \text{ MeV}$$

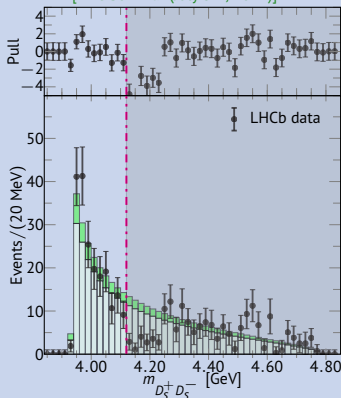
$$2M_{D_s} - M_{X(3960)} = 8(3) \text{ MeV}$$

- LHCb:  $M = 3956(5)(11) \text{ MeV}$ ,  $\Gamma = 43(13)(7) \text{ MeV}$

- [Prelovsek *et al.*, JHEP 06,035(20)]: Bound state  $B = 6.2_{-3.8}^{+2.0} \text{ MeV}$   
(*cf.* also [Bayar, Feijoo, Oset, 2207.08490])

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	Vir. (S-I)		Bou. (S-II)	
	$\Lambda = 0.5 \text{ GeV}$	$\Lambda = 1.0 \text{ GeV}$	$\Lambda = 0.5 \text{ GeV}$	$\Lambda = 1.0 \text{ GeV}$
$C_{D_s^+ D_s^-} (\text{fm}^2)$	$-0.74_{-0.04}^{+0.04}$	$-0.46_{-0.02}^{+0.02}$	$-3.36_{-1.02}^{+0.56}$	$-0.91_{-0.06}^{+0.05}$

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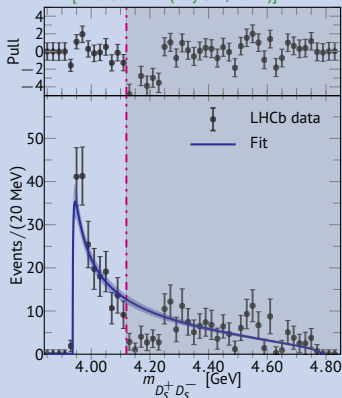
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# Fixing constants

- Lagrangian  $\mathcal{L}$  with HQSS and light-flavour  $SU(3)$  symmetry has 4 constants ( $C_{0a}$ ,  $C_{0b}$ ,  $C_{1a}$ ,  $C_{1b}$ )
- Some relations can be independently useful. Some examples:

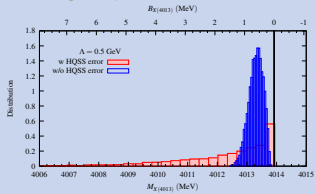
①  $X(3872)$  and  $X_{2^{++}}$

$$\left. \begin{aligned} \langle D\bar{D}^*; 0(1^{++}) | \hat{T} | D\bar{D}^*; 0(1^{++}) \rangle \\ \langle D^*\bar{D}^*; 0(2^{++}) | \hat{T} | D^*\bar{D}^*; 0(2^{++}) \rangle \end{aligned} \right\} = C_{0a} + C_{0b}$$

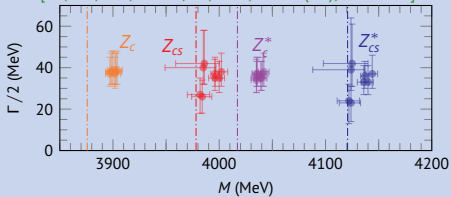
②  $Z_C, Z'_C, Z_{CS}, Z'_{CS}$

$$\left. \begin{aligned} \langle D\bar{D}^*; 1(1^{+-}) | \hat{T} | D\bar{D}^*; 1(1^{+-}) \rangle \\ \langle D_s\bar{D}^*; \frac{1}{2}(1^+) | \hat{T} | D_s\bar{D}^*; \frac{1}{2}(1^+) \rangle \\ \langle D^*\bar{D}^*; 1(1^{+-}) | \hat{T} | D^*\bar{D}^*; 1(1^{+-}) \rangle \\ \langle D_s^*\bar{D}^*; \frac{1}{2}(1^+) | \hat{T} | D_s^*\bar{D}^*; \frac{1}{2}(1^+) \rangle \end{aligned} \right\} = C_{1a} - C_{1b}$$

[MA, Guo, Hidalgo-Duque, Nieves, Pavón, EPJ,C75,547('15)]



[Du, MA, Guo, Nieves, PR,D105,074018('22); see below]





# Fixing all constants

[Ji, Dong, MA, Du, Guo, Nieves, 2207.08563]

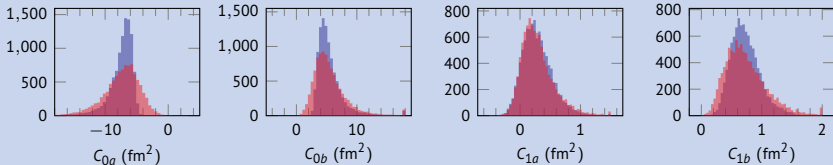
- $X(3960)$ : fixes  $C_{D_s \bar{D}_s} = (C_{0a} + C_{1a}) / 2$  (as previously seen)
- $Z_C(3900)$ : fixes  $C_{1Z} = C_{1a} - C_{1b}$ 
  - Assume virtual state  $M = 3813_{-21}^{+28}$  MeV ([2201.08253; 1512.03638] from a fit to BESIII data)
- $X(3872)$ : fixes  $\begin{cases} C_{0X} = (C_{0a} + C_{0b}) / 2 \\ C_{1X} = (C_{1a} + C_{1b}) / 2 \end{cases}$ 
  - Experimental information:
 

[LHCb, 2204.12597]	$R_{X(3872)}^{\text{exp}} = 0.29(4)$
[LHCb, PR, D 102, 092005(20)]	$B_{X(3872)}^{\text{exp}} = [-150, 0] \text{ keV} \leftarrow M_{X(3872)}^{\text{exp}} = 3871.69_{-0.04}^{+0.00} {}_{-0.13}^{+0.05} \text{ MeV}$
  - Theoretically: [0911.4407; 1210.5431; 1504.00861]

$$V = \frac{1}{2} \begin{pmatrix} C_{0X} + C_{1X} & C_{0X} - C_{1X} \\ C_{0X} - C_{1X} & C_{0X} + C_{1X} \end{pmatrix}, \quad T = (\mathbb{I} - VG)^{-1} V.$$

$$R_{X(3872)} = \frac{\hat{\Psi}_n - \hat{\Psi}_c}{\hat{\Psi}_n + \hat{\Psi}_c}, \quad \hat{\Psi}_n = \frac{1 - (2m_{D^+} + m_{D^{*-}}) G_2 (C_{0X} + C_{1X})}{(2m_{D^+} + m_{D^{*-}}) G_2 (C_{0X} - C_{1X})} = \frac{(2m_{D^0} m_{D^{*0}}) G_1 (C_{0X} - C_{1X})}{1 - (2m_{D^0} m_{D^{*0}}) G_1 (C_{0X} + C_{1X})},$$

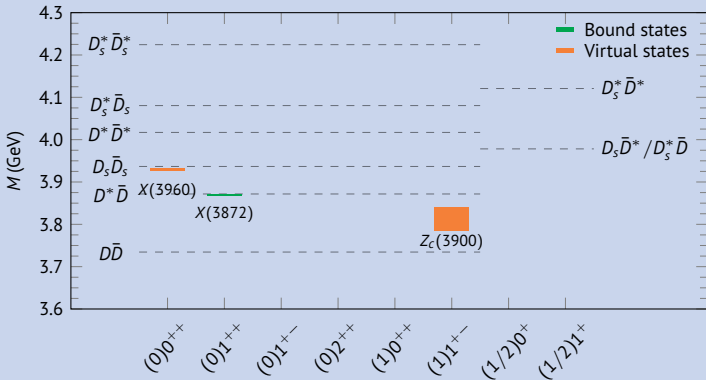
- $SU(3)$  and HQSS **breaking corrections** (30%) are taken into account for the LECs



# Predictions (complete multiplet): $X(3960)$ as virtual

[Ji, Dong, MA, Du, Guo, Nieves, 2207.08563]

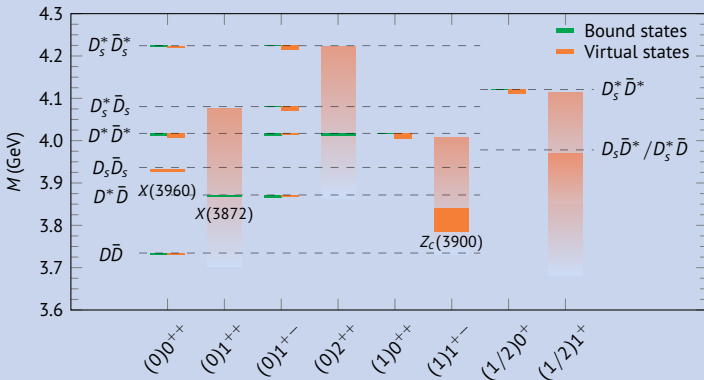
With the **four LECs** ( $C_{0a}$ ,  $C_{0b}$ ,  $C_{1a}$ ,  $C_{1b}$ ) fixed, poles can be looked for in every sector.



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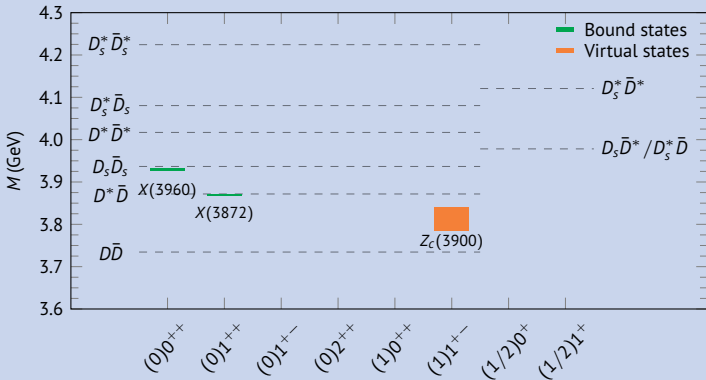
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## Predictions (complete multiplet): $X(3960)$ as bound

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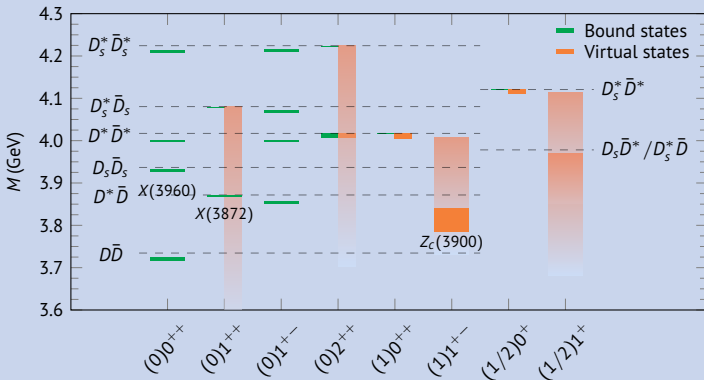
With the **four LECs** ( $C_{0a}$ ,  $C_{0b}$ ,  $C_{1a}$ ,  $C_{1b}$ ) fixed, poles can be looked for in every sector.



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[Ji, Dong, MA, Du, Guo, Nieves, 2207.08563]

With the **four LECs** ( $C_{0a}$ ,  $C_{0b}$ ,  $C_{1a}$ ,  $C_{1b}$ ) fixed, poles can be looked for in every sector.



# A closer look to $Z_C(3900)$ and $Z_{CS}(3985)$

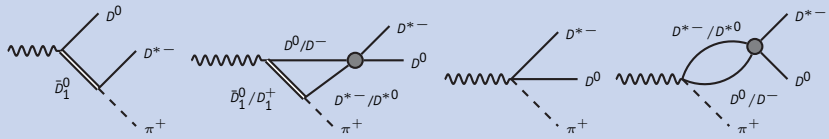
[Du, MA, Guo, Nieves, PR,D105,074018('22)]

- $\langle D\bar{D}^*; 1(1^{+-}) | \hat{T} | D\bar{D}^*; 1(1^{+-}) \rangle = \langle D_s\bar{D}^*; \frac{1}{2}(1^+) | \hat{T} | D_s\bar{D}^*; \frac{1}{2}(1^+) \rangle = C_{1a} - C_{1b} \equiv C_{1Z}$
- Constant  $V$  and single channel: only virtual or bound states (pole condition  $V^{-1} = G$ )
- Extension of the previous approach in two directions [MA, Guo, Hidalgo-Duque, Nieves, PL,B755,337('16)]:

① **Coupled channels**  $\left\{ \begin{array}{l} I = 1 \quad \left( \frac{1}{\sqrt{2}} [D\bar{D}^* - D^*\bar{D}] , J/\psi \pi \right) \\ I = \frac{1}{2} \quad \left( \frac{1}{\sqrt{2}} [D_s\bar{D}^* - D_s^*\bar{D}] , J/\psi K \right) \end{array} \right.$  (also necessary for  $e^+e^- \rightarrow J/\psi\pi\pi$  data)

② **Energy dependence**  $C_{1Z} \rightarrow C_{1Z} + b \frac{s - E_{th}^2}{2E_{th}}$

- Production mechanism (includes triangle singularity!) for  $Y \rightarrow D^0 \bar{D}^{*-} \pi^+$



$$|\overline{\mathcal{A}}_2(s, t)|^2 = \left| \frac{1}{t - m_{D_1}^2} + l(s)T_{22}(s) \right|^2 q_\pi^4(s) + \frac{1}{2} \left| E_\pi(s) \frac{h_S}{h_D} \left[ \frac{1}{t - m_{D_1}^2} + l(s)T_{22}(s) \right] + \beta [1 + G_2(s)T_{22}(s)] \right|^2$$

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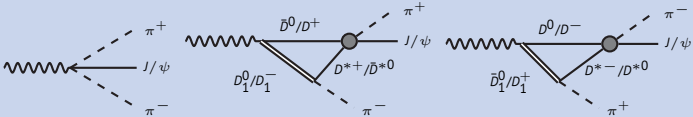
[Du, MA, Guo, Nieves, PR,D105,074018('22)]

- $\langle D\bar{D}^*; 1(1^{+-}) | \hat{T} | D\bar{D}^*; 1(1^{+-}) \rangle = \langle D_s\bar{D}^*; \frac{1}{2}(1^+) | \hat{T} | D_s\bar{D}^*; \frac{1}{2}(1^+) \rangle = C_{1a} - C_{1b} \equiv C_{1Z}$
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- Production mechanism (includes triangle singularity!) for  $Y \rightarrow J/\psi \pi^+ \pi^-$



$$\begin{aligned} |\overline{\mathcal{A}_1(s, t)}|^2 &= |\tau(s)|^2 q_\pi^4(s) + |\tau(t)|^2 q_\pi^4(t) + \frac{3 \cos^2 \theta - 1}{2} [\tau(s)\tau(t)^* + \tau(s)^*\tau(t)] q_\pi^2(s)q_\pi^2(t) \\ &+ \frac{1}{2} \left\{ |\tau'(s)|^2 E_\pi^2(s) + |\tau'(t)|^2 E_\pi^2(t) + [\tau'(s)^*\tau'(t) + \tau'(s)\tau'(t)^*] E_\pi(s)E_\pi(t) \right\} \\ \tau(s) &= \sqrt{2}I(s)T_{12}(s) + \alpha \quad \tau'(s) = \sqrt{2}I(s)T_{12}(s) \times (h_S/h_D) \end{aligned}$$

# Fit to data

[Du, MA, Guo, Nieves, PR,D105,074018('22)]

- Fitted data:
  - $J/\psi\pi^-$  distribution in  $e^+e^- \rightarrow J/\psi\pi^+\pi^-$  [BESIII, PRL,119('17)]
  - $D^0D^{*-}$  distribution in  $e^+e^- \rightarrow D^0D^{*-}\pi^+$  [BESIII,PR, D92('15)]
  - $e^+e^- \rightarrow (D^{*0}D_s^- + D^0D_s^{*-}) K^+$  [BESIII, PRL,126('21)]
- Some production/background/normalization constants are also fitted (not shown here)
- Four schemes:
  - A or B:  $b = 0$  or free
  - I or II:  $h_s = 0$  or not ( $D$ - or  $S$ - and  $D$ -waves)

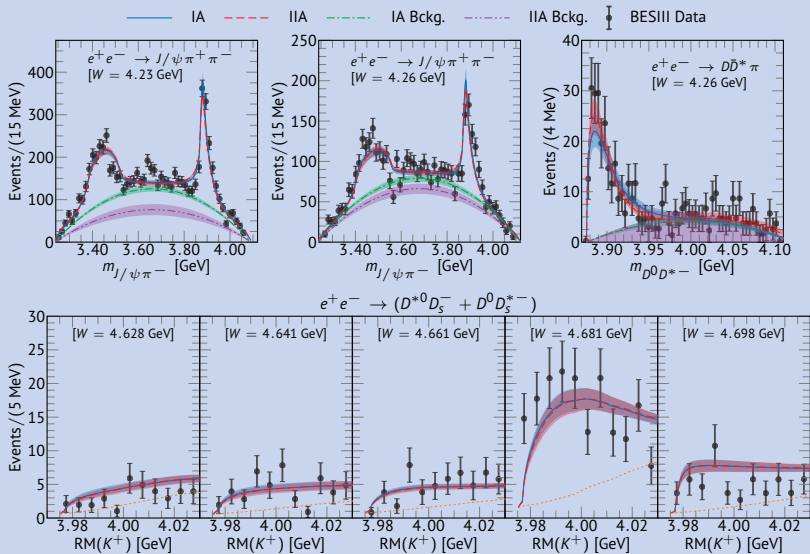
Scheme	$D_1D^*\pi$	$a_2(\mu)$	$\chi^2/\text{dof}$	$C_{12} [\text{fm}^2]$	$C_Z [\text{fm}^2]$	$b [\text{fm}^3]$
IA	$D$	-2.5	1.62	0.005(1)	-0.226(10)	0*
		-3.0	1.62	0.005(1)	-0.177(6)	0*
IIA	$S+D$	-2.5	1.83	0.006(1)	-0.217(10)	0*
		-3.0	1.83	0.006(1)	-0.171(6)	0*
IB	$D$	-2.5	1.24	0.007(4)	-0.222(6)	-0.447(44)
		-3.0	1.21	0.008(1)	-0.177(4)	-0.255(30)
IIB	$S+D$	-2.5	1.37	0.005(1)	-0.203(7)	-0.473(45)
		-3.0	1.27	0.005(1)	-0.171(5)	-0.270(30)





## Fit to data (scheme A)

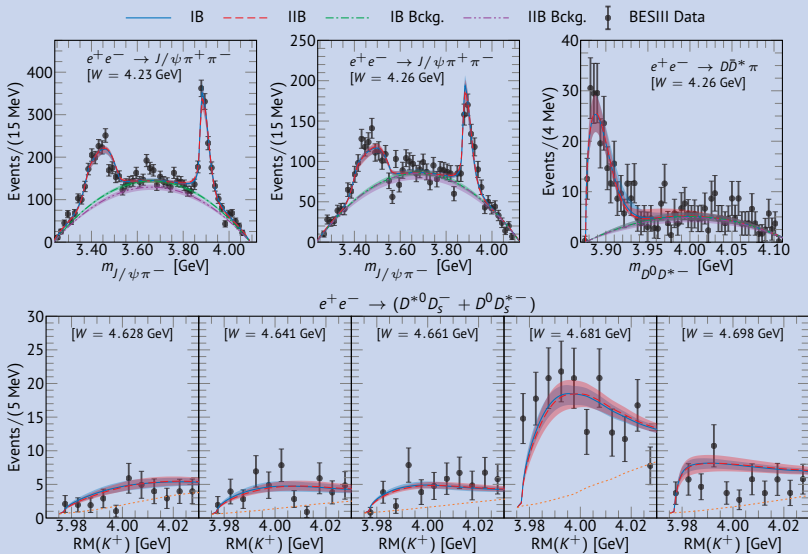
[Du, MA, Guo, Nieves, PR,D105,074018('22)]





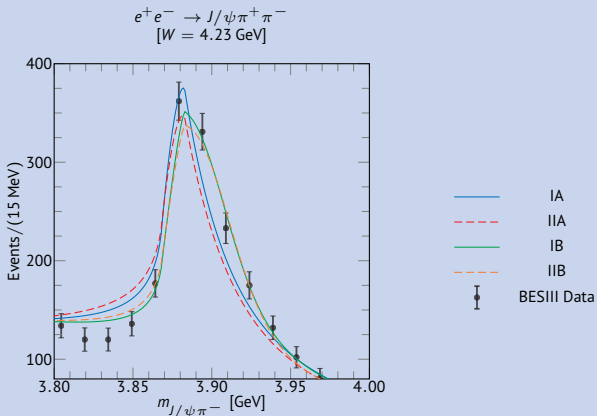
## Fit to data (scheme B)

[Du, MA, Guo, Nieves, PR,D105,074018('22)]





## Not possible to distinguish different scenarios in $J/\psi\pi$ spectrum



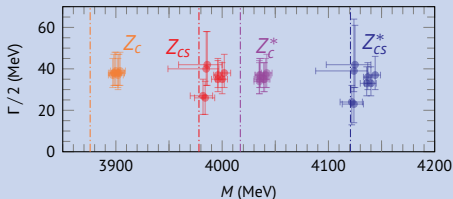
- The effect/peak produced by a **virtual pole** is always at threshold
- The peak of a **resonance** can be shifted from  $\text{Re}\sqrt{s}_{\text{pole}}$
- and in this case the effect is very close to threshold

# $Z_{CS}^{(*)}$ and $Z_C^{(*)}$ poles

[Du, MA, Guo, Nieves, PR,D105,074018('22)]

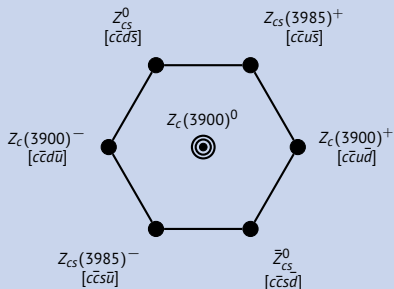
	$D_1 D^* \pi$	$a_2(\mu)$	$Z_C$ [MeV]		$Z_{CS}$ [MeV]		$Z_C^*$ [MeV]		$Z_{CS}^*$ [MeV]	
			Mass	$\Gamma/2$	Mass	$\Gamma/2$	Mass	$\Gamma/2$	Mass	$\Gamma/2$
IA	$D$	-2.5	$3813^{+21}_{-28}$	vir.	$3920^{+18}_{-26}$	vir.	$3962^{+19}_{-25}$	vir.	$4069^{+12}_{-16}$	vir.
		-3.0	$3812^{+22}_{-26}$	vir.	$3924^{+19}_{-23}$	vir.	$3967^{+19}_{-22}$	vir.	$4078^{+17}_{-13}$	vir.
IIA	$S+D$	-2.5	$3799^{+24}_{-33}$	vir.	$3907^{+22}_{-31}$	vir.	$3949^{+22}_{-30}$	vir.	$4057^{+20}_{-28}$	vir.
		-3.0	$3798^{+25}_{-31}$	vir.	$3911^{+17}_{-27}$	vir.	$3955^{+22}_{-27}$	vir.	$4067^{+19}_{-25}$	vir.
IB	$D$	-2.5	$3897^{+4}_{-4}$	$37^{+8}_{-6}$	$3996^{+4}_{-4}$	$37^{+8}_{-6}$	$4035^{+4}_{-4}$	$37^{+8}_{-6}$	$4137^{+4}_{-4}$	$36^{+7}_{-6}$
		-3.0	$3898^{+5}_{-5}$	$38^{+10}_{-7}$	$3996^{+5}_{-6}$	$35^{+9}_{-6}$	$4035^{+4}_{-5}$	$34^{+9}_{-6}$	$4136^{+5}_{-6}$	$33^{+8}_{-6}$
IIB	$S+D$	-2.5	$3902^{+6}_{-6}$	$38^{+9}_{-6}$	$4002^{+6}_{-6}$	$38^{+9}_{-7}$	$4042^{+5}_{-5}$	$38^{+9}_{-7}$	$4144^{+5}_{-6}$	$37^{+9}_{-7}$
		-3.0	$3902^{+5}_{-5}$	$37^{+9}_{-6}$	$4000^{+5}_{-6}$	$35^{+8}_{-7}$	$4039^{+5}_{-6}$	$35^{+8}_{-6}$	$4140^{+5}_{-6}$	$33^{+8}_{-6}$

- $Z_C$  exp.:  $M = 3881.2(4.2)(52.7)$  MeV  
 $\Gamma/2 = 25.9(2.3)(18.0)$  MeV
- $Z_{CS}$  exp.:  $M = 3982.5(2.6)(2.1)$  MeV  
 $\Gamma/2 = 6.4(2.6)(1.5)$  MeV
- [Yang et al., PR,D103('21)] ( $Z_{CS}$  and distribution)
- [Ikeno, Molina, Oset, PL,B814('21)] ( $Z_{CS}$  threshold effect)
- [PAC, PL,B772('17)] Several possibilities for  $Z_C$



- Both schemes (IB and IIB)
- Including  $SU(3)$  breaking effects

## $Z_c$ and $Z_{cs}$ form a $J^{PC} = 1^{+-}$ octet



- $3 \otimes \bar{3} = 8 \oplus 1$
- A  $\bar{Z}_{cs}^0$  has also been found by BESIII  
[PRL,129,112003(22)]
- In the case of  $l = 0$  one cannot make direct identification (mixing vs. coupled channels)

## Summary and conclusions

- We have considered  $D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$  interactions with **HQSS** and  **$SU(3)$  light-flavour symmetry**.
- The  $X(3960)$  structure in LHCb data on  $B^+ \rightarrow D_s^+ D_s^- K^+$  can be explained with a **bound or virtual** state.
- The experimental information coming from  $X(3960)$ ,  $X(3872)$ , and (a virtual)  $Z_C(3900)$  allows to fix the **four constants** appearing in the LO lagrangian.
- Predictions are made based on these constants for **multiplet partners** of these states in other sectors
- Considering a generalization of the interactions, the BESIII data for the  $Z_C$  and  $Z_{CS}$  states can be well reproduced, being  **$Z_C$  and  $Z_{CS}$  flavour partners** within the same **octet**

# On the $Z_{CS}(3985)$ and $X(3960)$ states

Towards HQSS and  $SU(3)$  multiplet descriptions

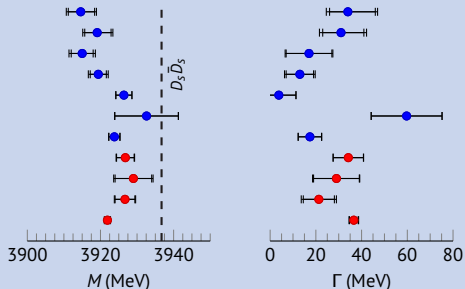


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# $\chi_{c0}(3915)$ and $\chi_{c2}(3930)$ ?



Reaction	Collab.	Ref.
$B^{(+,0)} \rightarrow J/\psi \omega K^{(+,0)}$	BaBar	BaBar:2007vxr
$B^{(+,0)} \rightarrow J/\psi \omega K^{(+,0)}$	BaBar	BaBar:2010wfc
$\gamma\gamma \rightarrow J/\psi \omega$	Belle	Belle:2009and
$\gamma\gamma \rightarrow J/\psi \omega$	BaBar	BaBar:2012nxg
$e^+e^- \rightarrow \gamma J/\psi \omega$	BESIII	BESIII:2019qvy
$B^+ \rightarrow D^+ D^- K^+$	LHCb	LHCb:2020pxc
$B^+ \rightarrow D^+ D^- K^+$	LHCb	LHCb:2020pxc
$\gamma\gamma \rightarrow D\bar{D}$	Belle	Belle:2005rte
$\gamma\gamma \rightarrow D\bar{D}$	BaBar	BaBar:2010jfn
$pp \rightarrow D\bar{D} + \text{anything}$	LHCb	LHCb:2019lnr