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Is $Z_{cs}(3982)$ a molecular partner of $Z_c(3900)$ and $Z_c(4020)$?

Vadim Baru

Institut für Theoretische Physik II, Ruhr-Universität Bochum Germany

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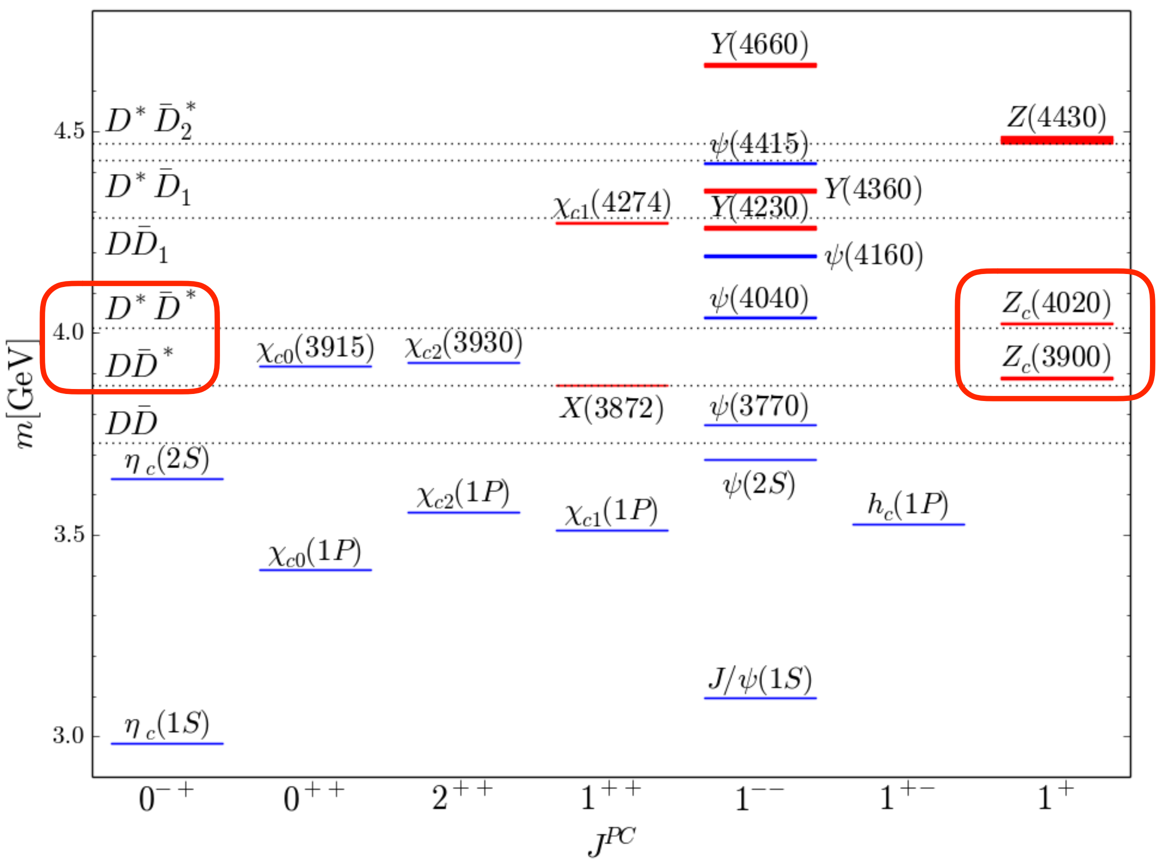
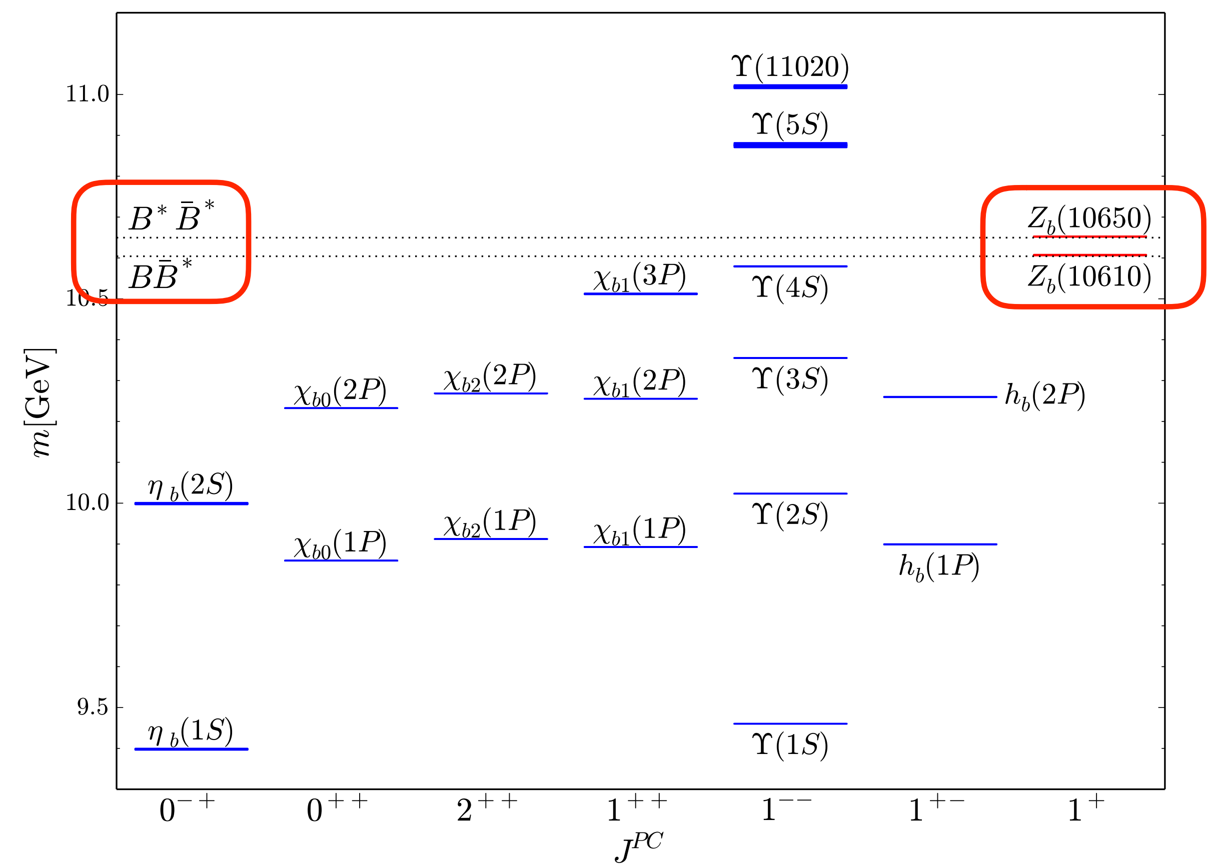
in collaboration with

E. Epelbaum, A.A. Filin, C. Hanhart, and A.V. Nefediev

Key Ref: PRD 105, 034014 (2022)

"Tetraquarks" in quarkonium spectrum





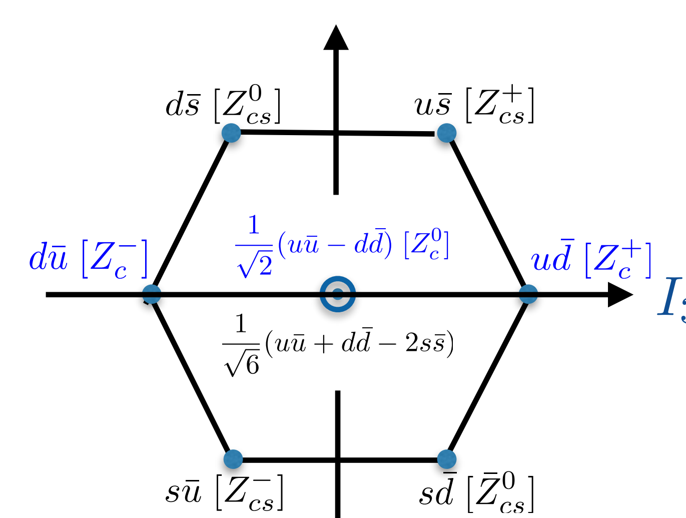
- Twin I=1 nearthreshold states $Z_b(10610)/Z_b(10650)$ by Belle and $Z_c(3900)/Z_c(4020)$ by BES III
  - clearly exotic: seen in charged modes $\pi^{\pm}h_b(mP),\ \pi^{\pm}\Upsilon(nS)$ Belle $\Longrightarrow b\bar{b}u\bar{d},\ldots$
  - $J^{PC}=1^{+-}$ $\pi^{\pm}J/\psi,\ \pi^{\pm}\Psi(2S)$ BES III $\Longrightarrow c\bar{c}u\bar{d},\ldots$

    Isospin-1

- Natural candidates for hadronic molecules

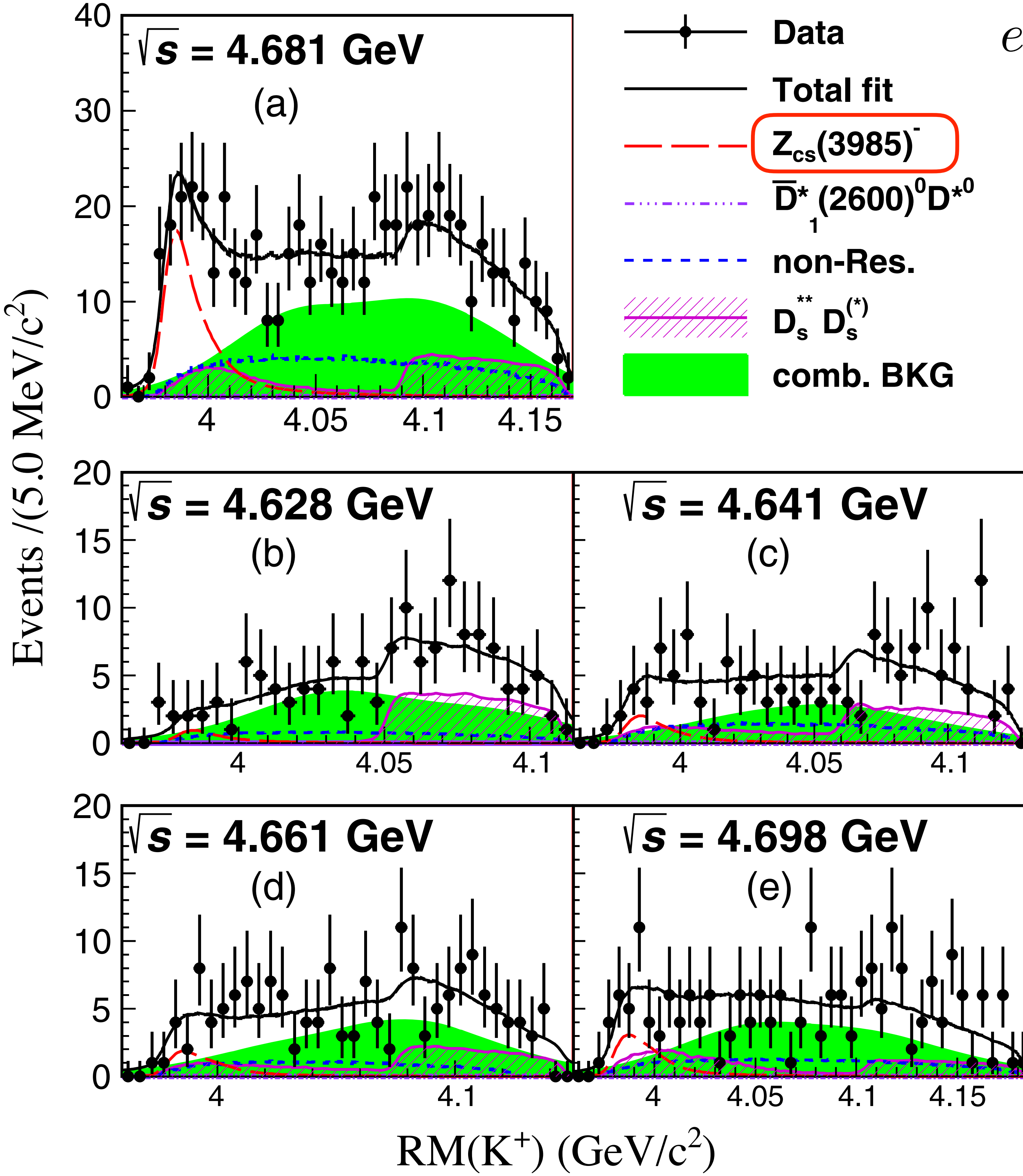
$\Longrightarrow$ Flavour SU(3) and heavy-quark spin (HQSS) partners must exist

our works (2016-2022), Hidalgo-Duque et al.(2013), Guo et al (2015), Meng et al 2020, …



$Z_{cs}(3982)$ — $c\bar{c}s\bar{u}$ state by BESIII

PRL 126 (2021), 102001



$$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$$

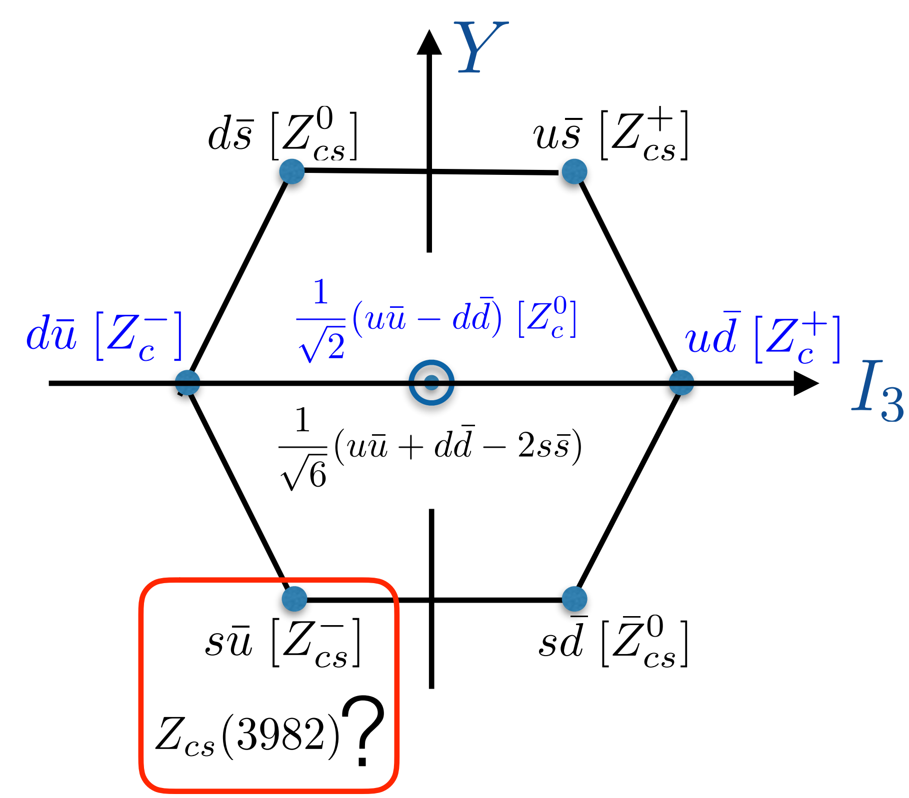
Breit-Wigner type fit:

$$M = 3982.5^{+1.8}_{-2.6} \pm 2.1 \text{ MeV}$$

$$\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0 \text{ MeV}$$

Near $D_s^- D^{*0} + D_s^{*-} D^0$ thr.

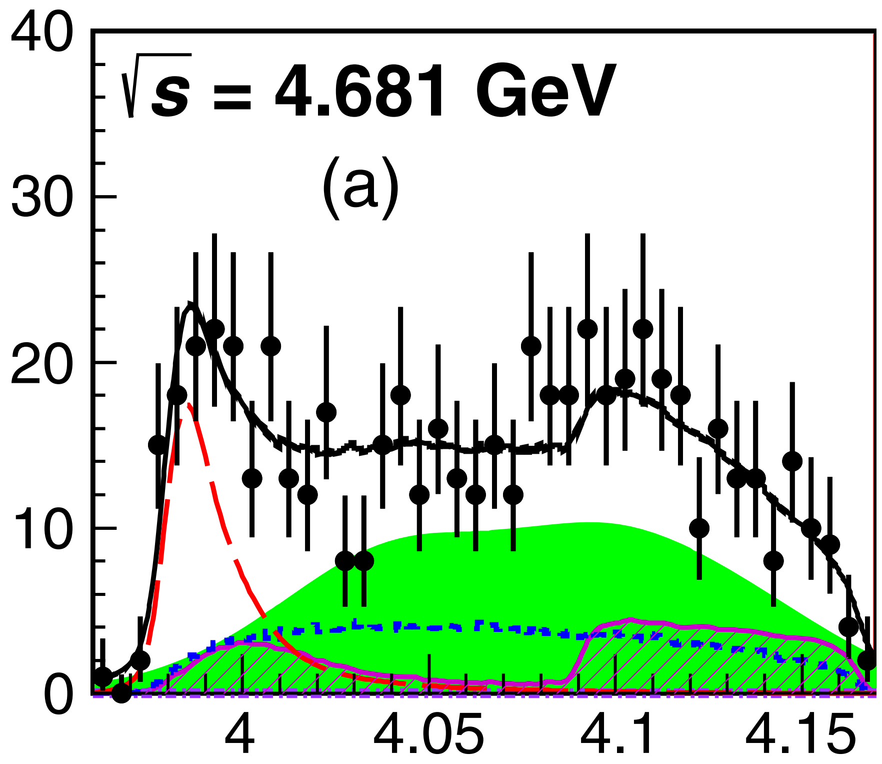
$I = 1/2, \ J^P = 1^+$



Appealing possibility that Z_{cs} is a strange molecular partner of $Z_c(3900)$

Properties of Z_{cs} : A coupled-channel EFT analysis of the line shape is needed!

From $Z_{cs}(3982)$ to molecular nature of vector mesons

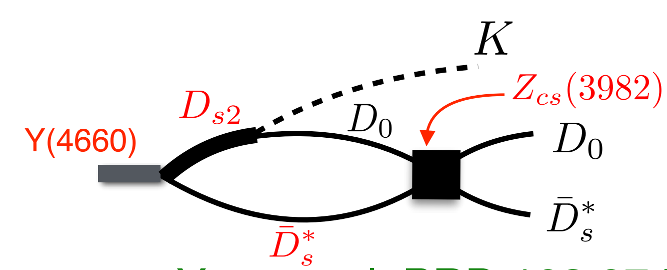


BESIII

- BESIII data are measured in the energy range 4.628-4.698

  $\Longrightarrow$ Excitation of $J^{PC}=1^{--}$ Y(4660) $\Gamma = 62^{+9}_{-7}$ MeV

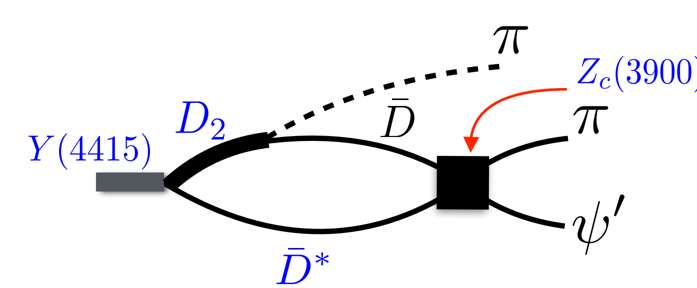
- $D_{s2}(2573)$ and $D_{s1}(2536)$ are important parts of the background



- Triangle singularity from $D_{s2}D_s{}^*D$ is near $\sqrt{s} = 4.681$ GeV

Yang et al. PRD 103,074029('21)
VB et al. PRD 105,034014('22)

$\Longrightarrow$ Y(4660) should have sizeable coupling to $D_{s2}D_s{}^*$ $\Longrightarrow$ $D_{s2}D_s{}^*$ molecule!



- Complete analogy to Z_c: BESIII observation of Z_c at 4415 MeV

  suggests Y(4415) is a D_2D^* molecule

Similar argument for Y(4230): Wang et al. PRL111,132003('13), Cleven at al. PRD90,074039('14)

> If Z_{cs} is a strange molecular partner of $Z_c(3900)$
>
> $\Longrightarrow$ Y(4660) is likely to be a strange partner of Y(4415)

Contact SU(3) flavour and HQSS Lagrangian

- $H\bar{H} \to H\bar{H}$ LO contact Lagrangian

$$\mathcal{L} = -\frac{C_{00}}{4}\mathrm{Tr}[\bar{H}_a^\dagger H_a^\dagger H_b \bar{H}_b] - \frac{C_{01}}{4}\mathrm{Tr}[\bar{H}_a^\dagger \sigma^i H_a^\dagger H_b \sigma^i \bar{H}_b]$$
$$-\frac{C_{10}}{4}\mathrm{Tr}[\bar{H}_a^\dagger \lambda^A_{aa'} H_{a'}^\dagger H_b \lambda^A_{bb'} \bar{H}_{b'}] - \frac{C_{11}}{4}\mathrm{Tr}[\bar{H}_a^\dagger \lambda^A_{aa'} \sigma^i H_{a'}^\dagger H_b \lambda^A_{bb'} \sigma^i \bar{H}_{b'}]$$

Al Fiky et al. PLB640('06)

Grinstein *et al.*, NPB380('92);

- SU(3) flavour symmetry: $H_a \sim (Q\bar{u}, Q\bar{d}, Q\bar{s}) \sim (D^0, D^+, D_s^+)$

- HQSS: $H_a = P_a + V_a^i \sigma^i$ $\quad\bar{H}_a = \bar{P}_a - \bar{V}_a^i \sigma^i$

$P = D, D_s$
$V = D^*, D_s^*$

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$P = D, D_s$
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- 4 Param's in general, but only two are relevant for (I=1/2) Z_{cs} and (I=1) Z_c

$$\mathcal{C}_d = \frac{1}{8}(C_{11} + C_{10}), \quad \mathcal{C}_f = \frac{1}{8}(C_{11} - C_{10})$$

- Resulting effective potentials to be used in the dynamical equations

Z_{cs} $\quad 1^+ : \{\bar{D}_s D^*, D\bar{D}_s^*, D^*\bar{D}_s^*\}$

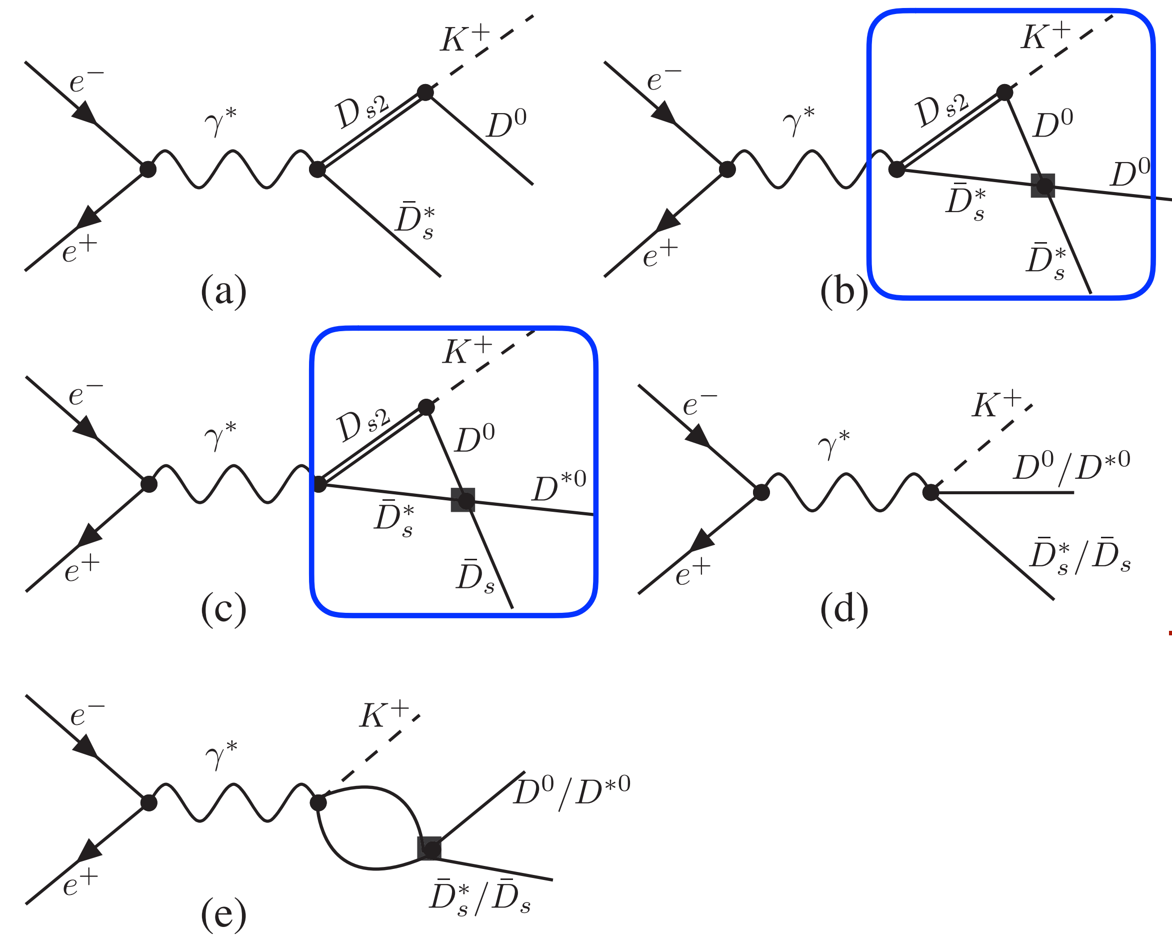
$$V^{\mathrm{CT}}[1^+] = \begin{pmatrix} \mathcal{C}_d + \frac{1}{2}\mathcal{C}_f & \frac{1}{2}\mathcal{C}_f & -\frac{1}{\sqrt{2}}\mathcal{C}_f \\ \frac{1}{2}\mathcal{C}_f & \mathcal{C}_d + \frac{1}{2}\mathcal{C}_f & \frac{1}{\sqrt{2}}\mathcal{C}_f \\ -\frac{1}{\sqrt{2}}\mathcal{C}_f & \frac{1}{\sqrt{2}}\mathcal{C}_f & \mathcal{C}_d \end{pmatrix}$$

Z_c $\quad 1^{+-} : \left\{\frac{D\bar{D}^* - D^*\bar{D}}{\sqrt{2}}, D^*\bar{D}^*\right\}$

$$V^{\mathrm{CT}}[1^{+-}] = \begin{pmatrix} \mathcal{C}_d & \mathcal{C}_f \\ \mathcal{C}_f & \mathcal{C}_d \end{pmatrix}$$

An analysis by Yang et al.

Yang, Cao, Guo, Nieves, and Valderrama
Phys.Rev. D 103 (2021), 074029

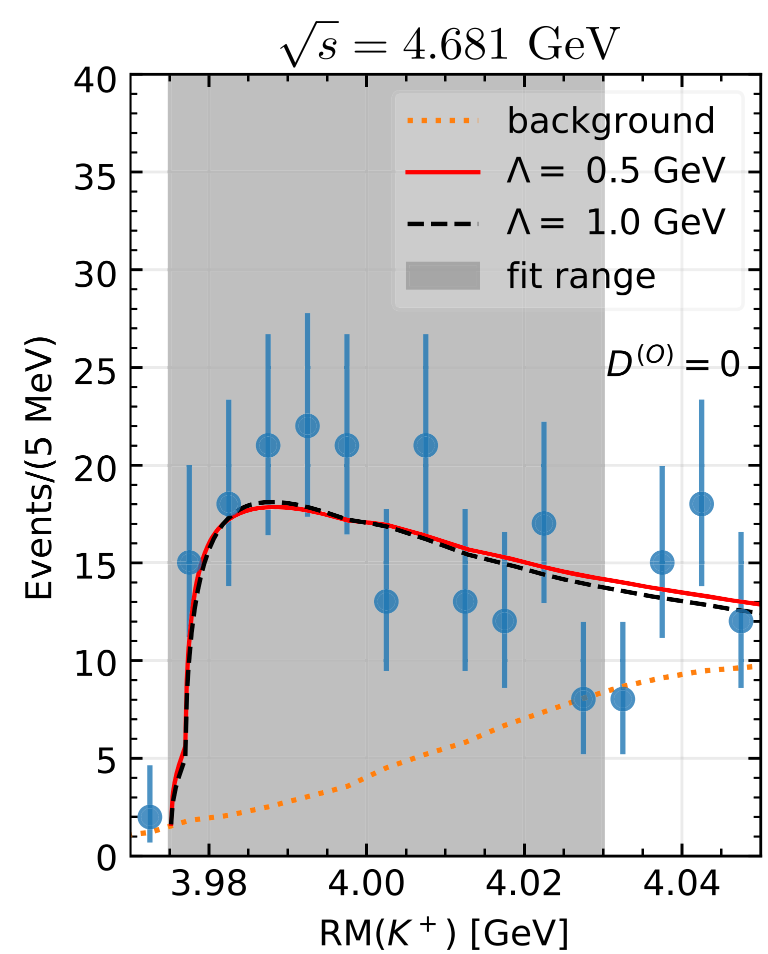


Production

- Triangle singularity from $D_{s2}D_s^*D_0$ is nearby
- Pointlike production

—Contact EFT neglecting coupled-ch. to $D_s^*D^*$ and D^*D^*

—Limited energy range in fits, 50 MeV above D_sD^*/D_s^*D



⟹ Extracted poles are consistent with that Z_{cs} is the SU(3) flavour partner of $Z_c(3900)$

—Supported by a combined $Z_c(3900)$ and Z_{cs} analysis by Du et al. PRD105, 074018('22)]

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$$V^{\rm CT}[1^+] = \begin{pmatrix} \mathcal{C}_d + \frac{1}{2}\mathcal{C}_f & \frac{1}{2}\mathcal{C}_f & -\frac{1}{\sqrt{2}}\mathcal{C}_f \\ \frac{1}{2}\mathcal{C}_f & \mathcal{C}_d + \frac{1}{2}\mathcal{C}_f & \frac{1}{\sqrt{2}}\mathcal{C}_f \\ -\frac{1}{\sqrt{2}}\mathcal{C}_f & \frac{1}{\sqrt{2}}\mathcal{C}_f & \mathcal{C}_d \end{pmatrix}$$

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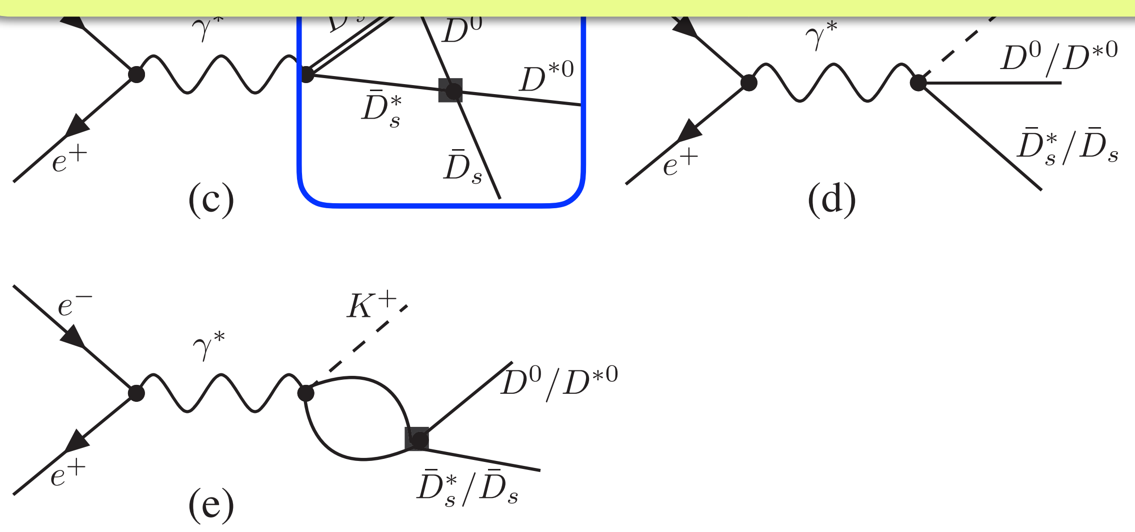

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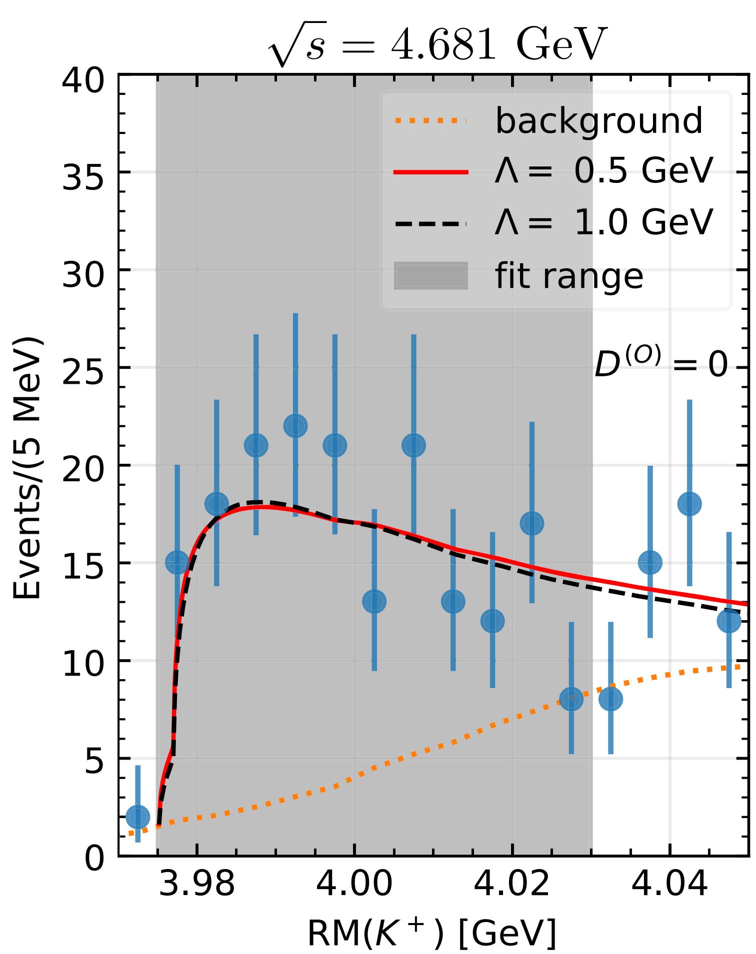

$\Longrightarrow$ Extracted poles are consistent with that Z_{cs} is the SU(3) flavour partner of $Z_c(3900)$

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Goals of our study

- Include all coupled channels, i.e. $\bar{D}_s D^*, D\bar{D}_s^*, D^*\bar{D}_s^*$
- Complete analysis in the whole energy range covered by the BES III data

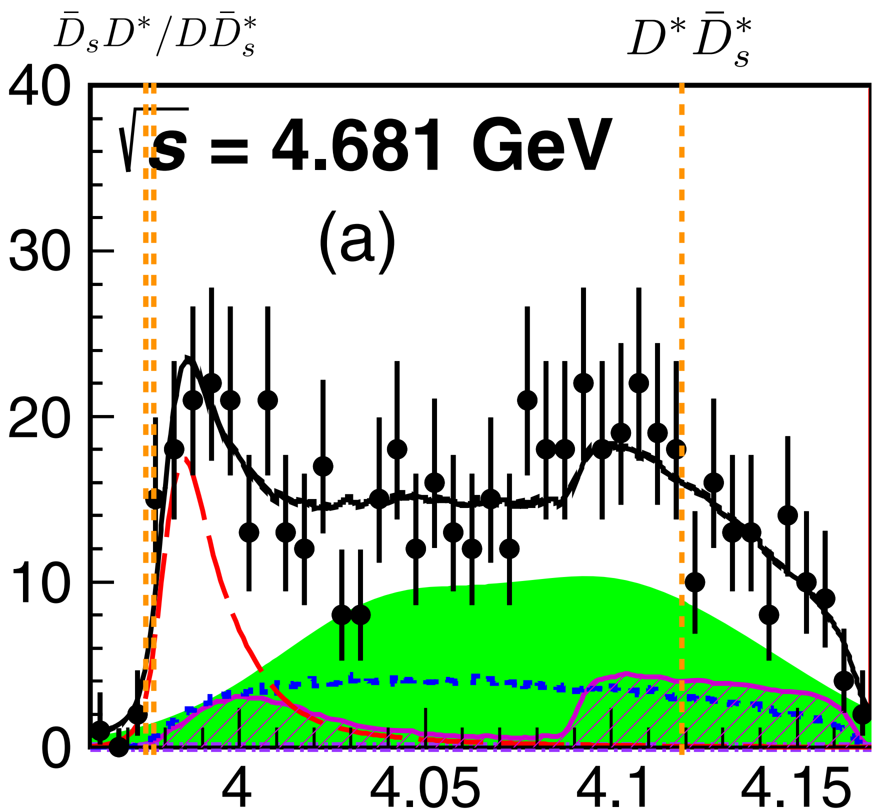
$\Longrightarrow$ reliable prediction for a possible spin partner state near $D^*D_s^*$

- Include missing production mechanisms:

— the role of D_{s1}

— triangle singularities from $D_{s2}D_s^*D$, $D_{s2}D_s^*D^*$ and $D_{s1}D_s^*D^*$

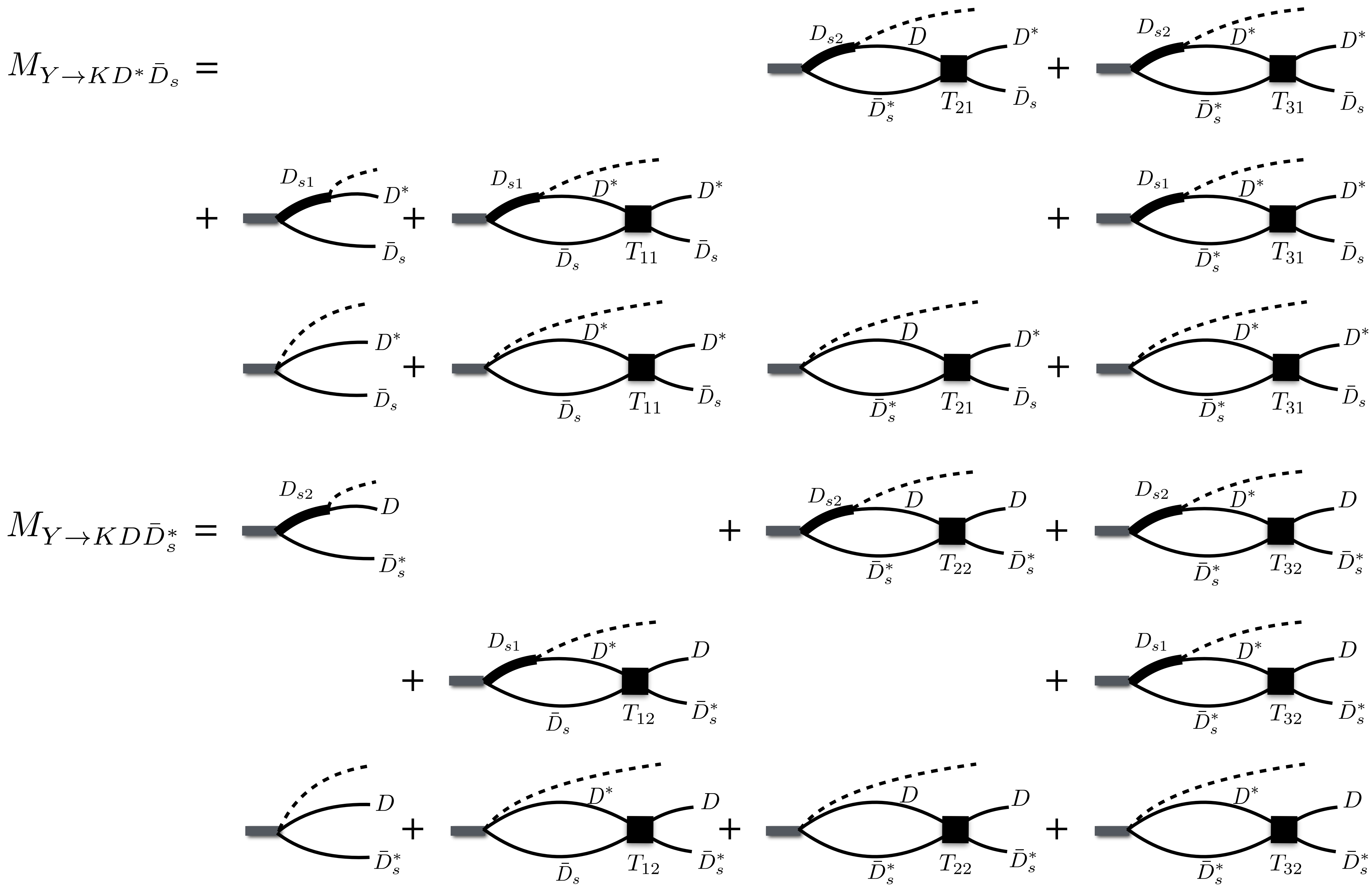
All in the range of BESIII data!



<u>Not covered by our analysis</u>

- — possible SU(3) breaking due to lightest pseudoscalar GB octet
- — combined analysis of $Z_c(3900)/Z_c(4020)$ and $Z_{cs}(3982)$ data

Coupled-channel production $e^+e^- \to Y(4660) \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

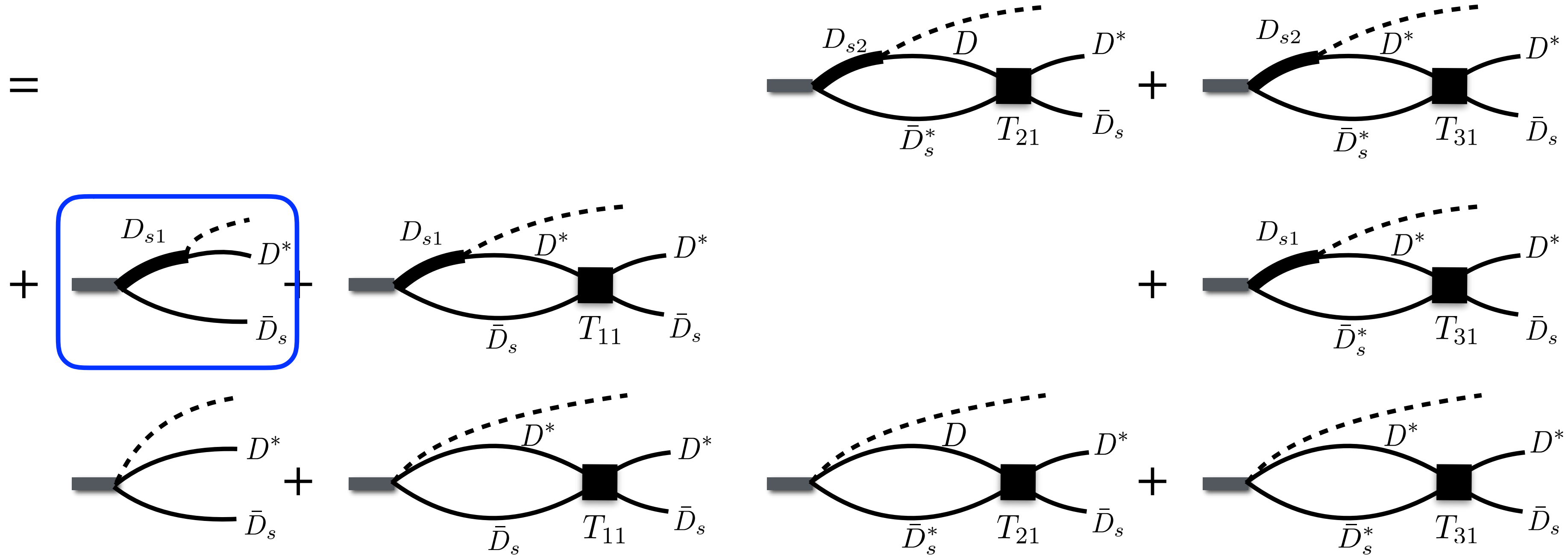


– $Z_{cs}(3982)$ is a pole in the coupled-channel $\{\bar{D}_s D^*, D\bar{D}_s^*, D^*\bar{D}_s^*\}$ scattering amplitude

$$T_{\alpha\beta}(\sqrt{s},p,p') = V_{\alpha\beta}(p,p') - \sum_\gamma \int \frac{d^3q}{(2\pi)^3} V_{\alpha\gamma}(p,q) G_\gamma(\sqrt{s},q) T_{\gamma\beta}(\sqrt{s},q,p')$$

Coupled-channel production $e^+e^- \to Y(4660) \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

$M_{Y\to K D^* \bar{D}_s} =$



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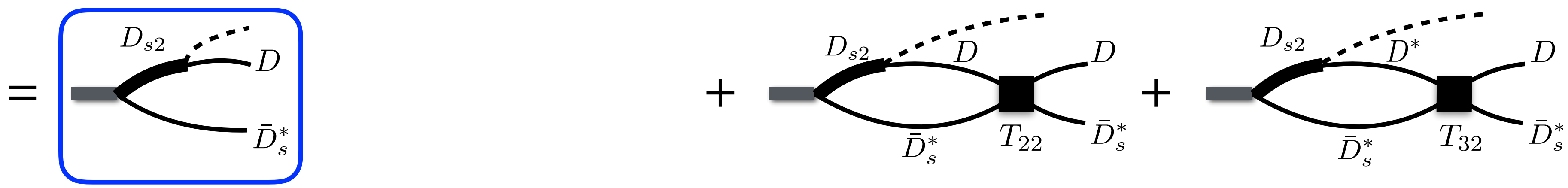
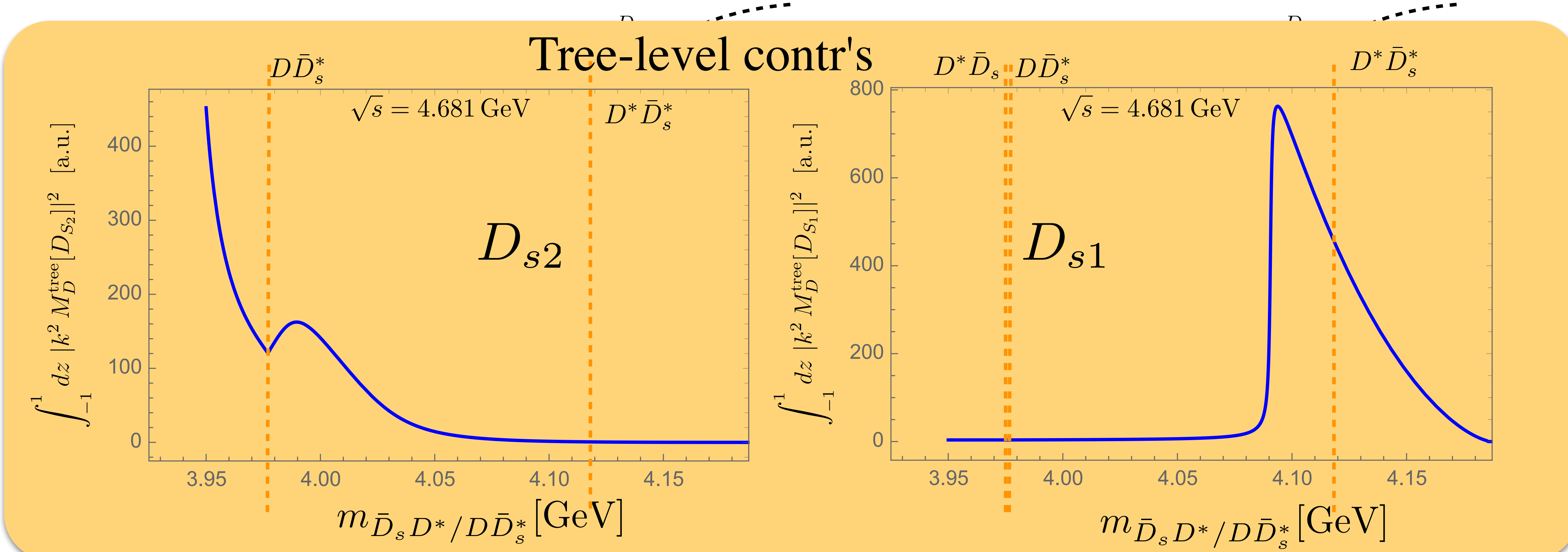
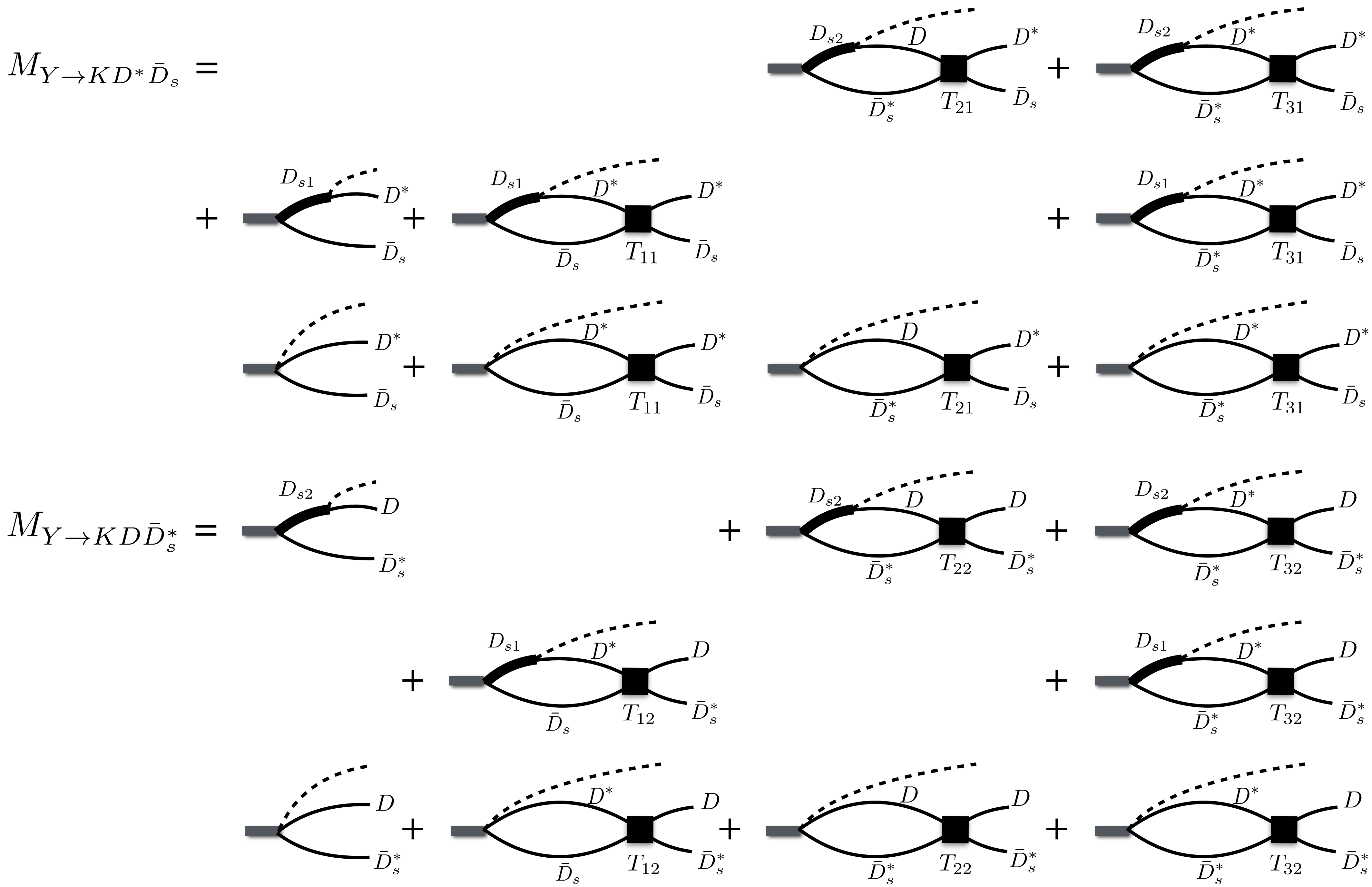




Coupled-channel production $e^+e^- \to Y(4660) \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



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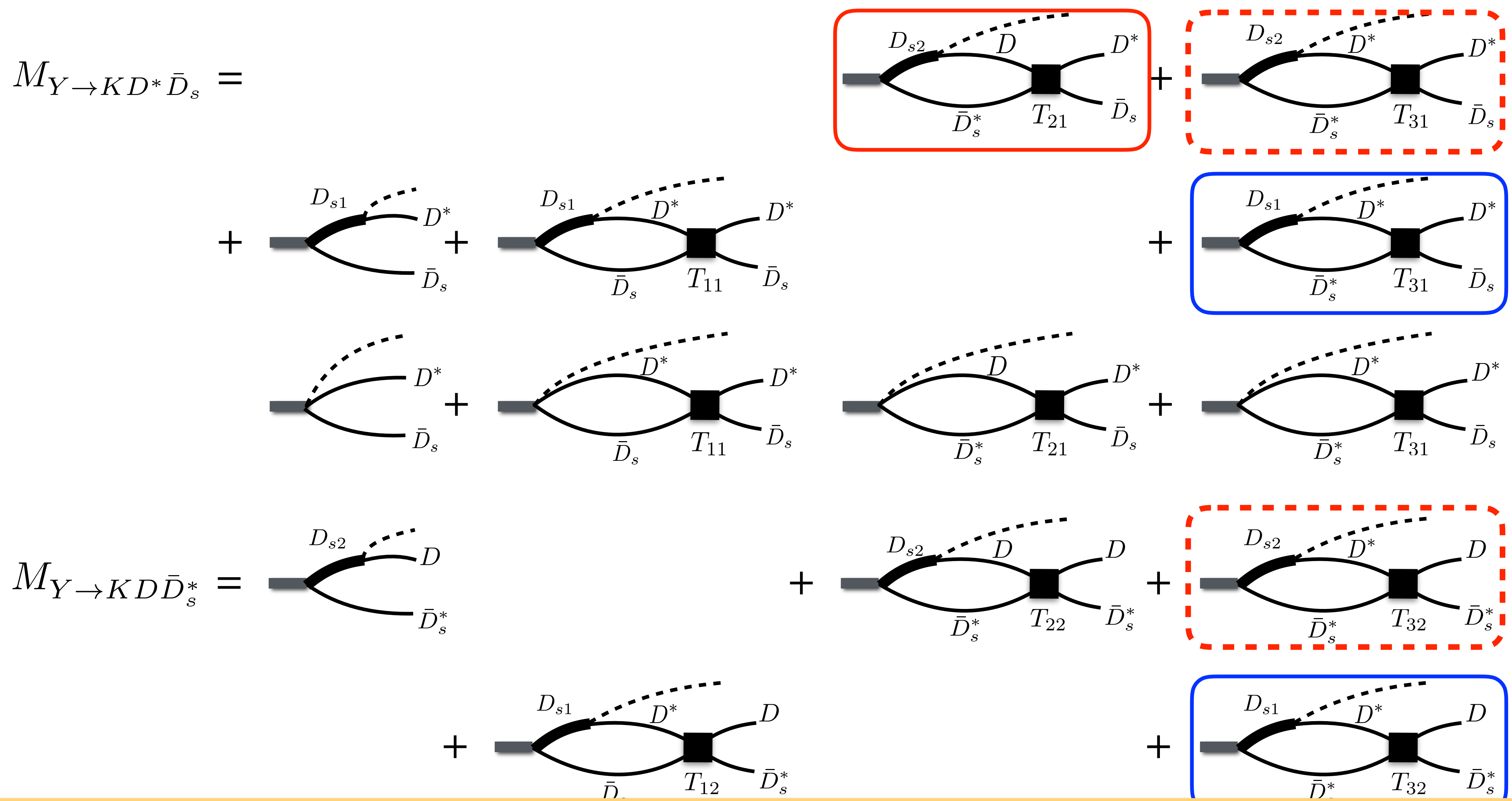
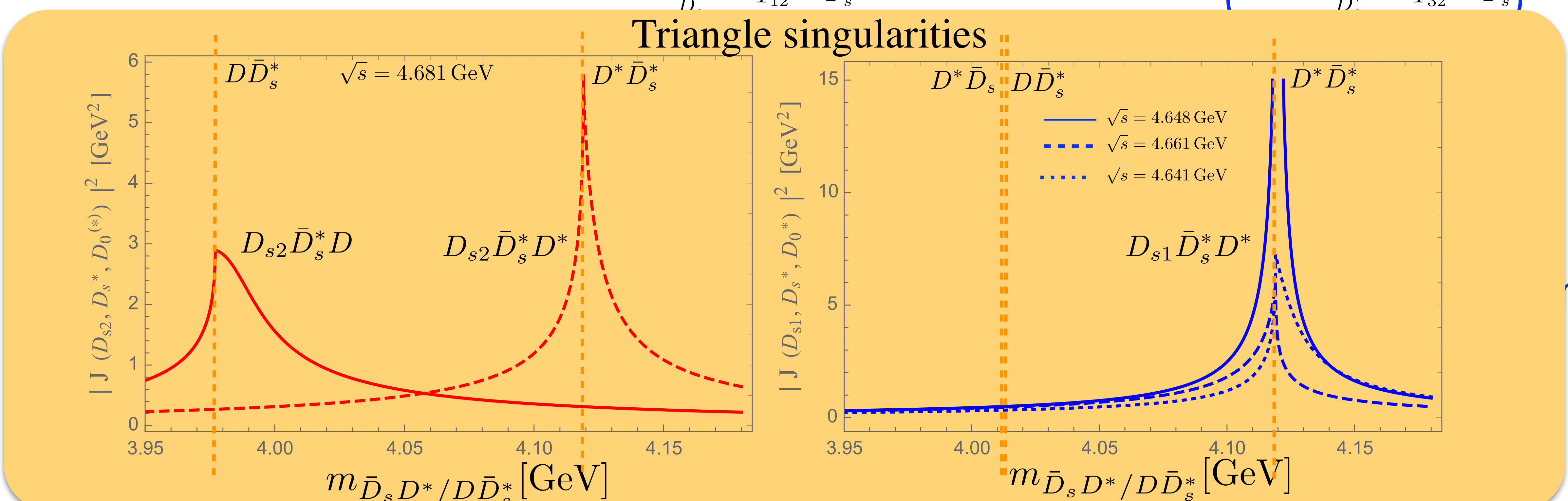




nplitude

From amplitudes to observables

- Differential cross section

$$\frac{d\sigma}{dm_{23}} = \mathcal{N}\left|\frac{2m_Y}{s-m_Y^2+im_Y\Gamma_Y}\right|^2 \sum_{\alpha=1}^{2} \frac{k\,q^{(23)}[\alpha]}{s}\int_{-1}^{1}\frac{dz}{2}\left[k^4\left|M_D[\alpha]\right|^2+\left|M_S[\alpha]\right|^2\right]$$

$$\alpha = 1 \equiv \bar{D}_s D^*$$
$$\alpha = 2 \equiv \bar{D}_s^* D$$

- Number of events

$$\frac{dN}{dm_{23}} = \frac{d\sigma}{dm_{23}}\bar{\epsilon}\,\mathcal{L}_{\rm int}\,f_{\rm corr}$$

$\bar{\epsilon}$ — efficiency,

$\mathcal{L}_{\rm int}$ — integrated luminocity,

$f_{\rm corr}$ — radiative & vacuum polarisation

- Maximum likelihood

$$-2\log\mathcal{L} = 2\sum_i\left(\mu_i - n_i + n_i\log\frac{n_i}{\mu_i}\right)$$

- Combined fit of 5 distributions with 5 parameters:

— 2 LO contact terms C_d and C_f

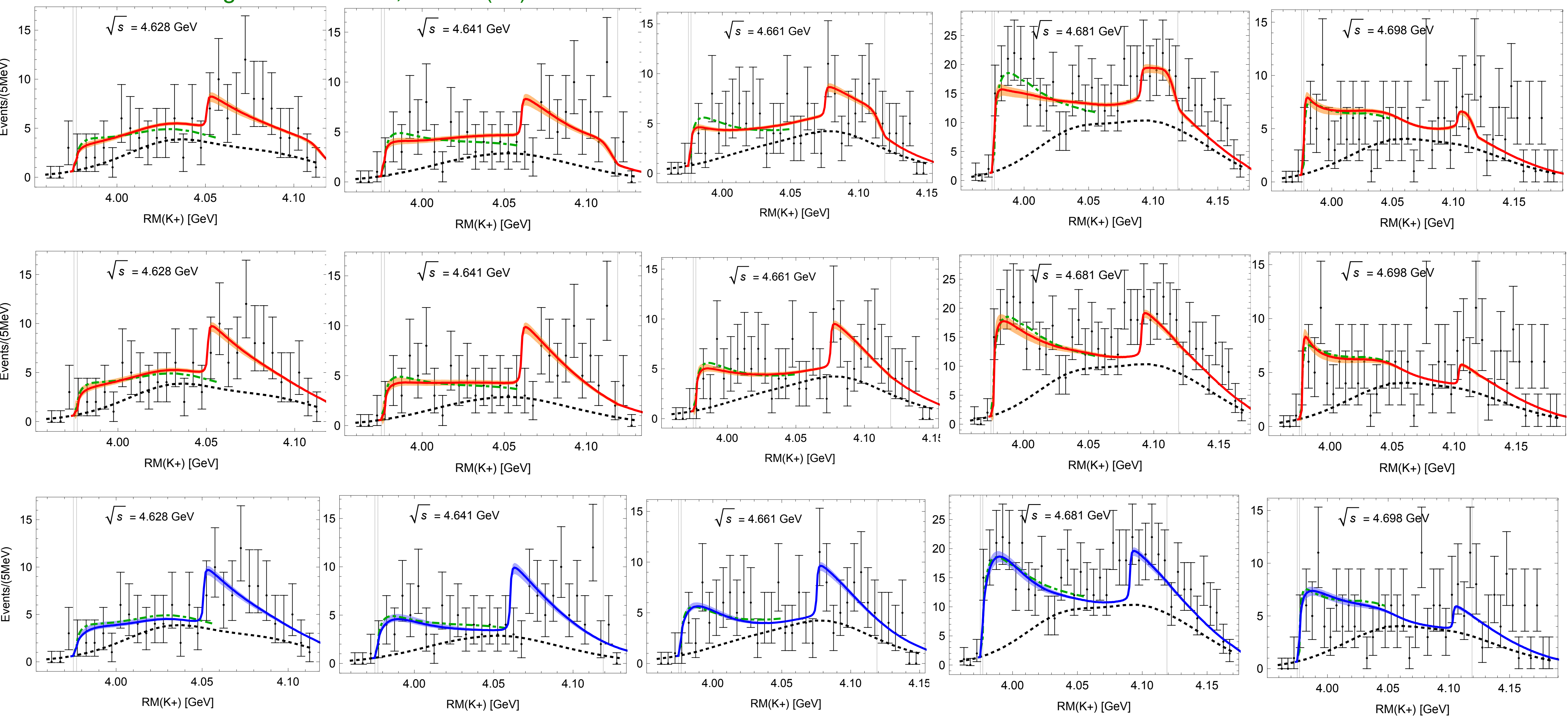
— 2 ratios of production couplings

— Overal Norm

Two classes of Solutions

Class 1: minor coupled-ch. effects—fits 1 and 1’ Class 2: large coupled-ch. effects—fit 2

similar to Yang et al. PRD103,074029(21)



Upper, middle, lower row for fit 1, fit 1′, fit 2, respectively

5 parameter fits

Fit	$\mathcal{C}_d$, fm^2	$\mathcal{C}_f$, fm^2	$g_{D_{s1}}/g_{D_{s2}}$	$g/g_{D_{s2}}$	$\mathcal{N}$, $10^{-2}\,\frac{\text{pb}}{\text{GeV}}$	$-2\log\mathcal{L}$
fit 1	-0.51 ± 0.02	0.18 ± 0.02	0.26 ± 0.02	-2.5 ± 0.3	0.46 ± 0.05	138
fit 1′	-0.24 ± 0.05	-0.1 ± 0.05	0.37 ± 0.03	-2.8 ± 0.6	0.35 ± 0.04	144
fit 2	0.50 (fixed)	-1.04 ± 0.01	-0.44 ± 0.03	-6.5 ± 2.5	0.28 ± 0.03	146

← Global minimum (fit 1)

Lessons from this study

Pole positions

$J^{P(C)}$	State	Threshold, MeV		RS	Poles fit 1	RS	Poles fit 2
1^+	$Z_{cs}(3982)$	$\bar{D}_s D^*/\bar{D}_s^* D$	$3975.2/3977.0$	$(+++)$	3942 ± 11	$(+++)$	3954 ± 2
1^+	$Z_{cs}(3982)$	$\bar{D}_s D^*/\bar{D}_s^* D$	$3975.2/3977.0$	$(--+)$	3971 ± 2	$(--+)$	$3959 \pm 7 - (47 \pm 16)i$
1^+	Z'_{cs}	$\bar{D}_s^* D^*$	4119.1	$(--+)$	$4115 \pm 2 - (10 \pm 2)i$		No state/not spin partner
1^{+-}	$Z_c(3900)$	$(D\bar{D}^*, -)$	3871.7	$(++)$	3841 ± 11	$(-+)$	$3864 \pm 7 - (58 \pm 13)i$
1^{+-}	$Z_c(4020)$	$\bar{D}^* D^*$	4013.7	$(-+)$	$4009 \pm 18 - (9 \pm 2)i$		Not spin partner
1^{++}	W_{c1}	$(D\bar{D}^*, +)$	3871.7	$(-)$	3864 ± 2	$(+)$	3852 ± 2
2^{++}	W_{c2}	$\bar{D}^* D^*$	4013.7	$(-)$	4009 ± 2	$(+)$	3990 ± 2

fit 1 (1'): — bound (virtual) state, amplified by the $D_{s2}D_s^*D$ triangle singularity

$Z_{cs}(3982)$ $\Longrightarrow$ strong enhancement near the D_s^*D threshold

— SU(3) partner of $Z_c(3900)$

— has a HQSS partner near $D_s^*D^*$ threshold Z_{cs}' — SU(3) partner of $Z_c(4020)$

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— has a HQSS partner near $D_s^*D^*$ threshold Z_{cs}' — SU(3) partner of $Z_c(4020)$

fit 2: — may be quite broad resonance state, amplified by the $D_{s2}D_s^*D$ triangle singularity

$Z_{cs}(3982)$ $\Longrightarrow$ strong enhancement near the D_s^*D threshold

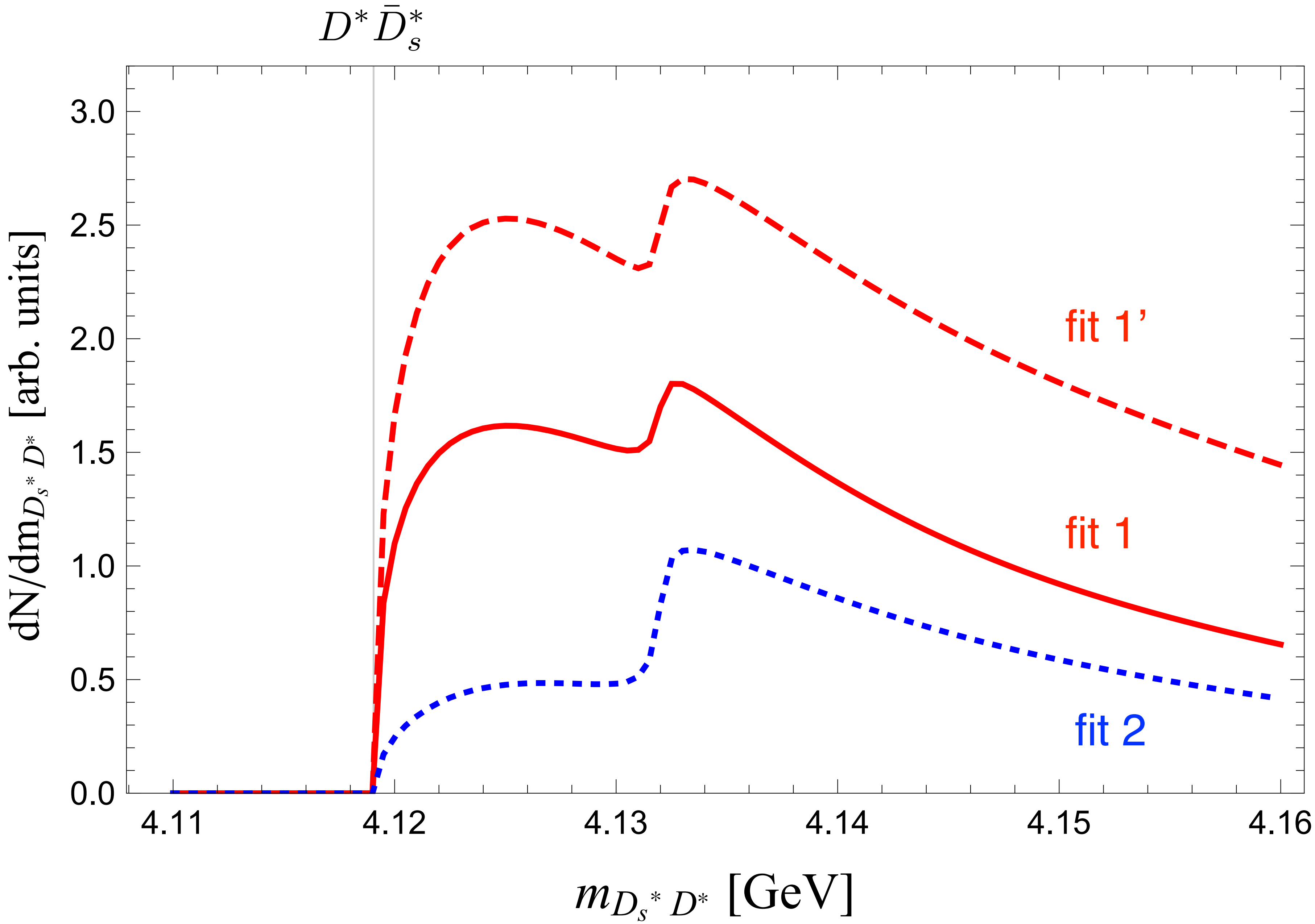
— may still be an SU(3) partner of $Z_c(3900)$

— No HQSS partners near $D_s^*D^*$ and D^*D^* thresholds

$\Longrightarrow$ $Z_c(4020)$ must have a different origin

How to discriminate?

Predictions for $e^+e^- \to K^+ D_s^{*-} D^{*0}$

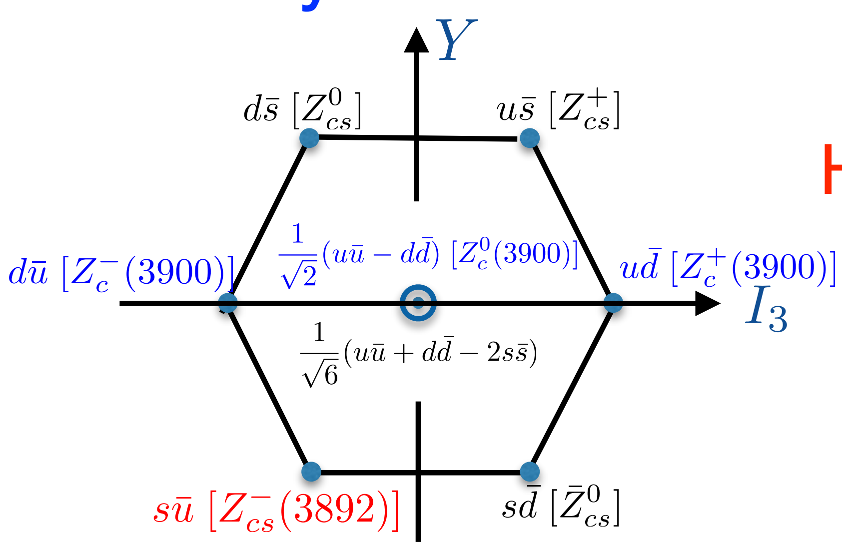


- Strong enhancement near $D_s^*D^*$ threshold in fits 1 (1'), because of Z_{cs}' pole
- No Z_{cs}' pole in fit 2 $\Longrightarrow$ only smooth phase space
- Structure near 4.133 is due to D_{s1}

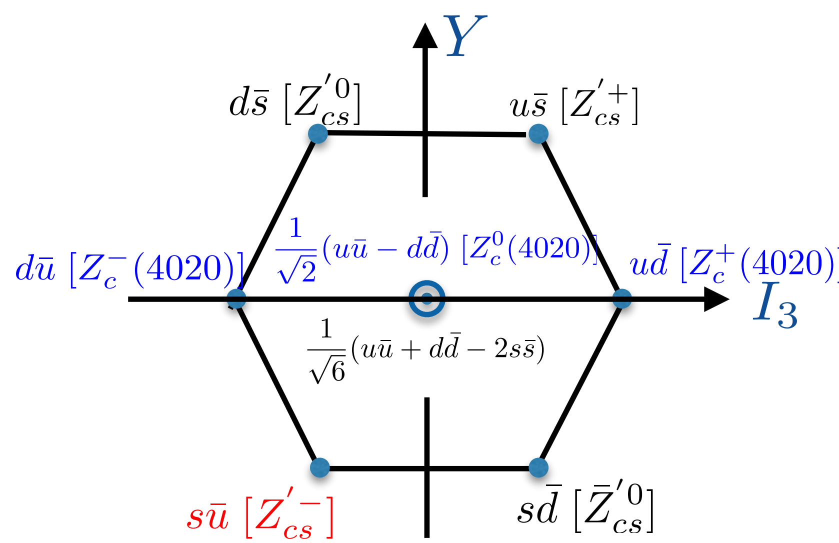
Conclusions

- BES III lineshapes $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ are analysed :
  - — an EFT approach with LO contact interactions
  - — SU3 and HQSS ⇒ multiplets of particles
  - — Various production mechanisms including triangle singularities

- Two very different scenarios:

1. 

HQSS ⟹



All states: bound/virtual

consistent with Yang et al.('21), Du et al.('22)

2. $Z_{cs}(3982)$— may be a strange partner of $Z_c(3900)$, if both are resonances but no HQSS partners

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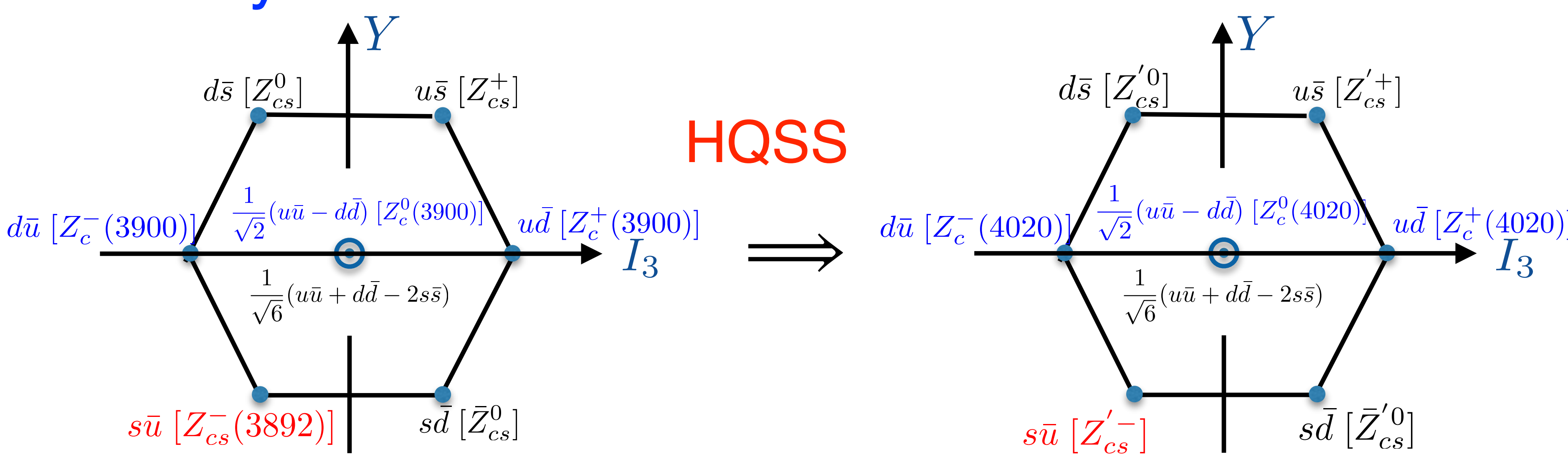
- Two very different scenarios:

1.



All states: bound/virtual

consistent with Yang et al.('21), Du et al.('22)

2. $Z_{cs}(3982)$— may be a strange partner of $Z_c(3900)$, if both are resonances but no HQSS partners

⇒ Precise data in $D_s D^* + D_s^* D$ and $D_s^* D^*$ needed!

⇒ Role of pseudosclar GB octet to be understood

⇒ Possible connection of the $Z_{cs}(3982)$ with the structures by LHCb

Ortega et al. ('21)
Meng et al. (21')

Thanks for your attention!