The threshold effects on $Z_{cs}(3985)$

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Meng-Chuan Du, Qian Wang, and Qiang Zhao, arXiv:2011.09225

Outline

- Introduction
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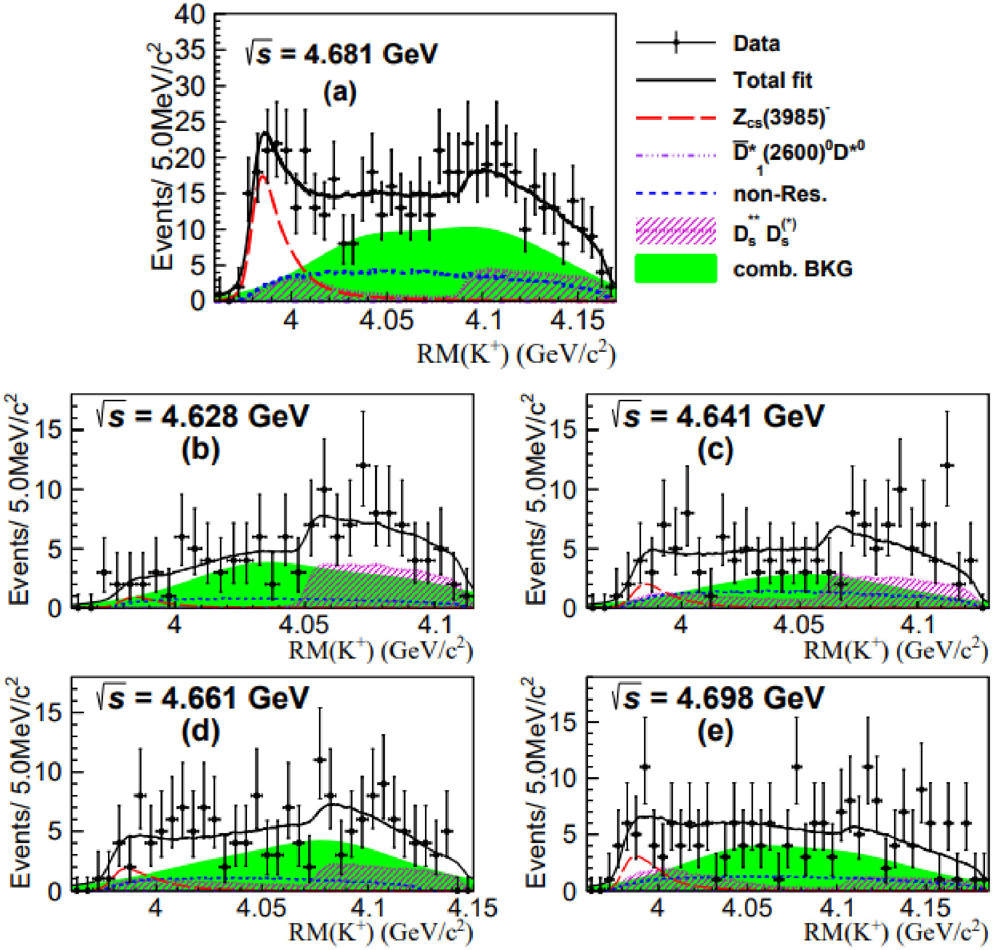
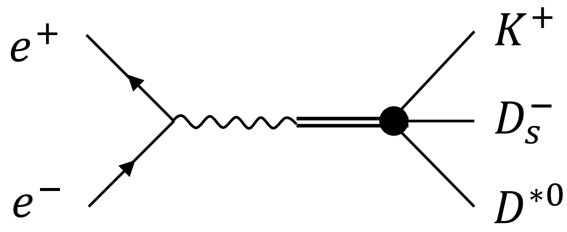
- Parametrization
- Fitted Results
- Summery

The observation of $Z_{cs}^{-}(3985)$





$\sqrt{s}$ = 4.681 GeV

Significance: 5.3σ

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

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

Fig.1. The K^+ recoil-mass spectra in $e^+e^- \to K^+ D_s^- D^{*0}$[1]

[1] M. Ablikim et al. [BESIII], arXiv:2011.07855.

Theoretical studies

[1]Ming-Zhu Liu, Jun-Xu Lu, Tian-Wei Wu, Ju-Jun Xie, Li-Sheng Geng, arXiv:2011,08720.
[2]Jun-Zhang Wang, Xiang Liu, Takayuki Matsuki, arXiv:2011.08501.
[3]Bing-Dong Wan, Cong-Feng Qiao, arXiv:2011.08747.
[4]Jun-Zhang Wang, Qing-Song Zhou, Xiang Liu, Takayuki Matsuki, arXiv:2011.08628.
[5]Zhi-Yang, Feng-Kun Guo, Juan Nieves, Manuel Pavon Valderrama, arXiv:2011.08725
[6]Xu Cao, Jian-Ping Dai, Zhi-Yang, arXiv:2011.09244.
[7]Rui-Chen, Qi Huang, arXiv:2011.09156.
[8]Zhi-Feng Sun, Chu-Wen Xiao, arXiv:2011.09404.
[9]Qi-Nan Wang, Hua-Xing Chen, arXiv:2011.10495.
[10]Bo Wang, Lu Meng, Shi-Lin Zhu, Phys. Rev. D 103 (2021) 2, L021501
[12]Zhi-Gang Wang, arXiv:2011.10959.
[13]K.Azizi, N. Er, arXiv:2011.11488.
[14]Xin Jin, Xue-Jie Liu, Yao-Yao Xue, Hong-Xia Huang, Jia-Lun Ping, arXiv:2011.12230.
[15]Yu. A. Simonov, arXiv:2011.12326.
[16]Natsumi Jkeno, Raquel Molina, Eulogio Oset, arXiv:2011.13425.
[17]Xiang-Kun Dong, Feng-Kun Guo, Bing-Song Zou, arXiv:2011.14517.
[18]Yong-Jiang Xu, Yong-Lu, Chun-Yu Cui, Ming-Qiu Huang, arXiv:2011.14313.
[19]Lu Meng, Bo Wang, Shi-Lin Zhu, arXiv:2012.09813.
[20]Zhi-Hui Guo, J. A. Oller, arXiv:2012.11904.
[21]Xiang-Kun Dong, Feng-Kun Guo, Bing-Song Zou, arXiv:2101.01021.

$Z_c(3900)$ and $Z_c(4020)$

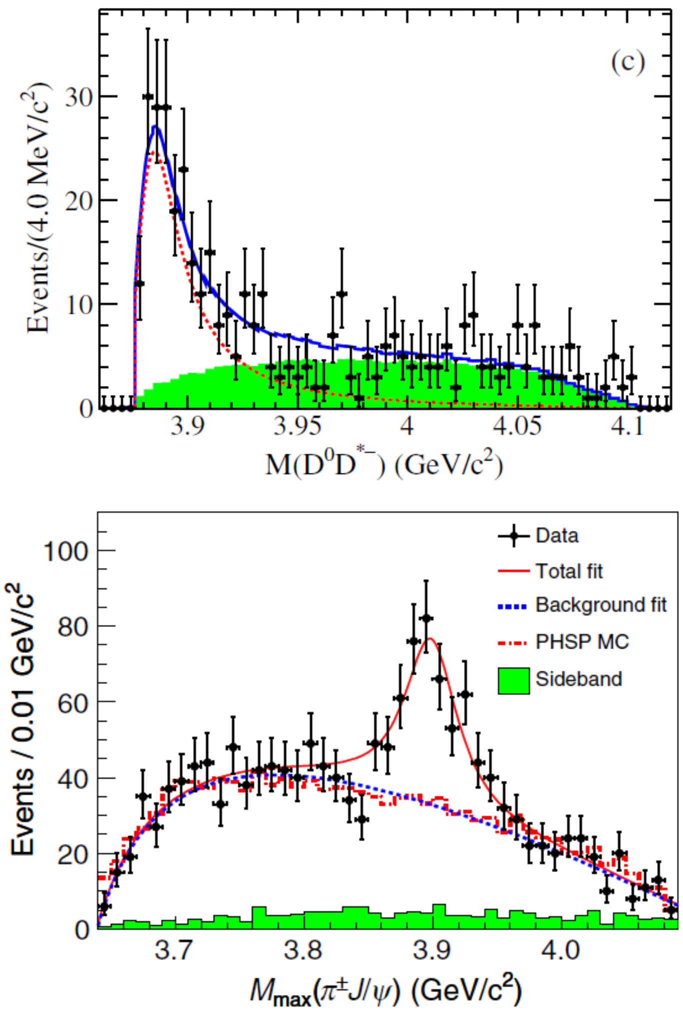


Fig.2. $Z_c(3900)$ observed in $e^+e^- \to D\bar{D}^*\pi$ [1], and $e^+e^- \to J/\psi\pi\pi$ [2].

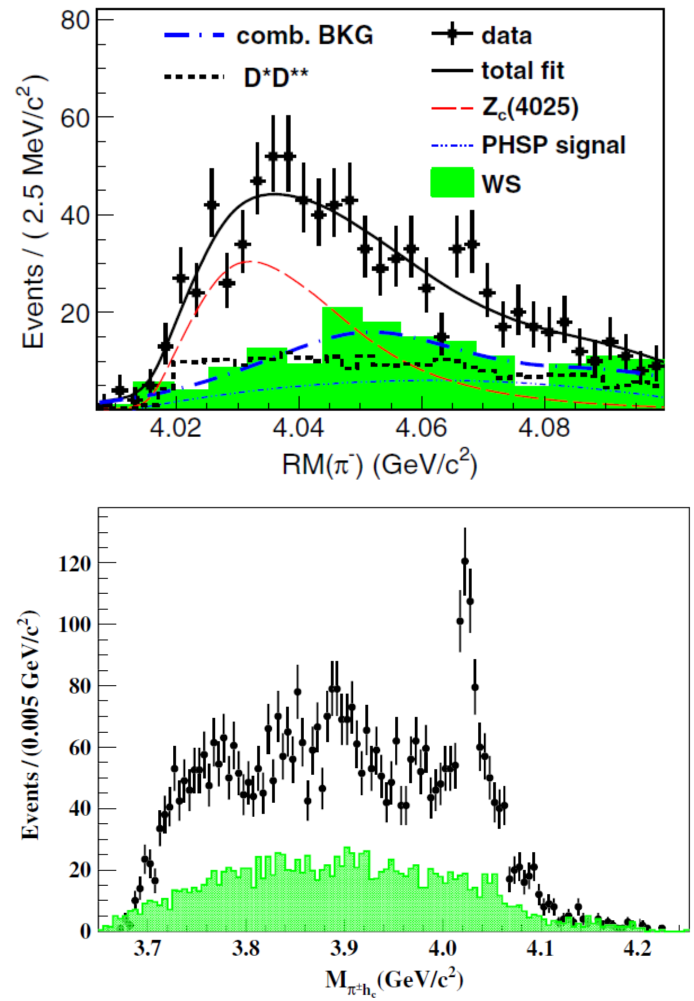
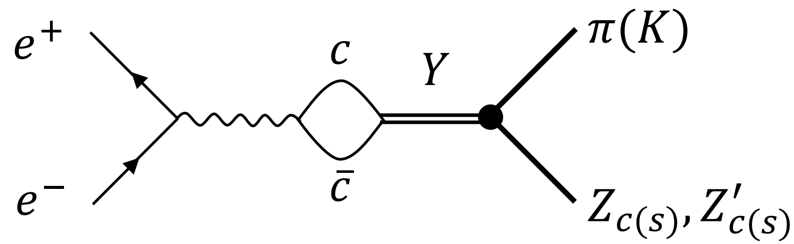


Fig.3. $Z_c(4020)$ observed in $e^+e^- \to D^*\bar{D}^*\pi$ [3], and $e^+e^- \to h_c\pi\pi$ [4]

[1] M. Ablikim et al., PRD 92,092006.
[2] M. Ablikim et al., PRL 110,252001.
[3] M. Ablikim et al., PRL 112,132001.
[4] M. Ablikim et al., PRL 111,242001.

Thresholds for productions of Z_c and Z_{cs}



$$|Y\rangle = \alpha|compact\rangle + \beta|molecule\rangle$$

Thresholds near $Y(4260)$

Thresholds	Mass [MeV]
$D_0(2400)D^*$	4407
$D_1'(2430)\bar{D}$	4295
$D_1(2420)\bar{D}$	4285
$D_2(2460)\bar{D}^*$	4467

Thresholds near $Y(4660)$

Thresholds	Mass [MeV]
$D_{s0}(2317)D_s^*$	4429
$D_{s1}(2460)\overline{D_s}$	4428
$D_{s1}(2536)\overline{D_s}$	4504
$D_{s2}(2573)\overline{D_s}^*$	4685

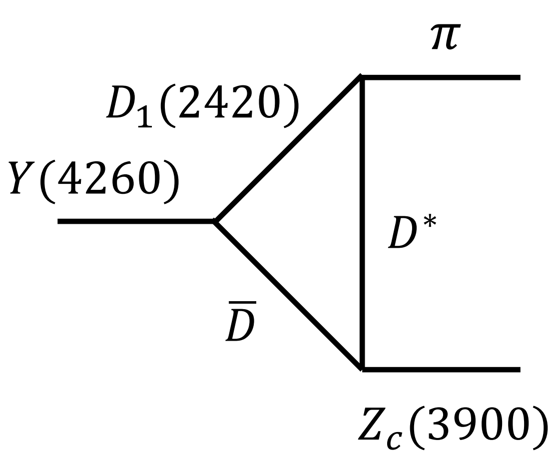
- The production of $D_1(2420)\bar{D}$, $D_2(2460)\bar{D}^*$, $D_{s1}(2536)\overline{D_s}$ and $D_{s2}(2573)\overline{D_s}^*$ thresholds from $^3S_1$ $c\bar{c}$ breaks HQSS.
- HQSS breaking is significant in $|Y\rangle$[1]

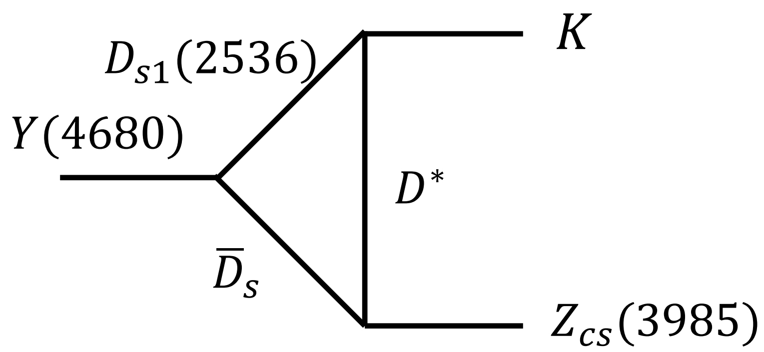
[1] Qiang Wang, Martin Cleven, Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meissner, Xiao-Gang Wu, and Qiang Zhao, Phys. Rev. D89,034001.

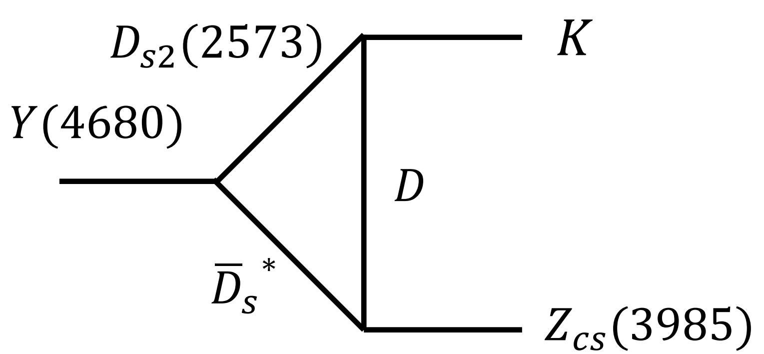
Triangle singularity for Z_c and Z_{cs}

- The presence of TS in heavy meson sector [1].
- TS is essential for $Y(4260)$ and $Z_c(3900)$ [2]

- It is similar for Z_{cs}. For $D_{s0}(2317)\overline{D_s}^*$ and $D_{s1}(2460)\overline{D}_s$ thresholds, see Ref[3]. Ref[4] discussed the effects of the triangle with D_{s2}.

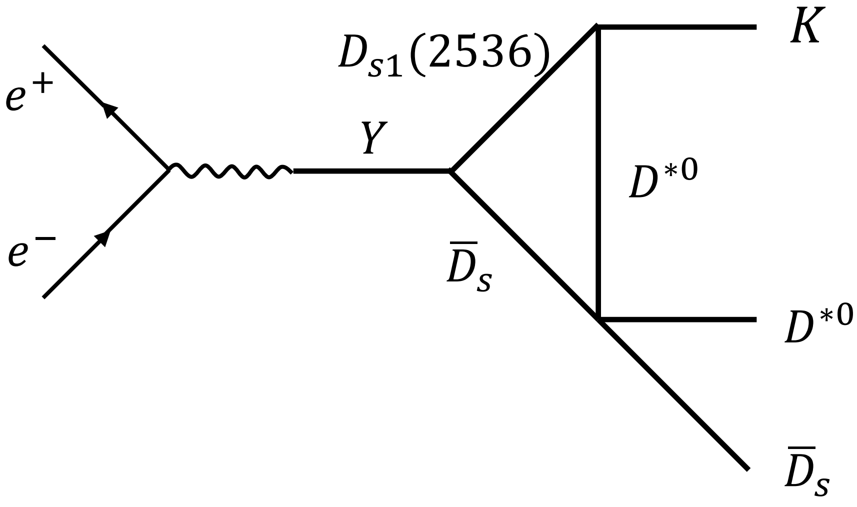


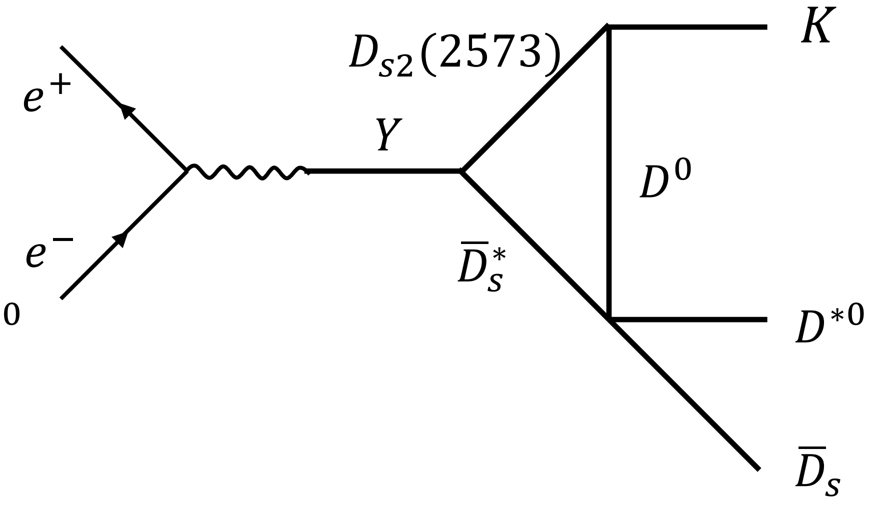




[1] Qian Wang, Christoph Hanhart, and Qiang Zhao, Phys. Lett. B 725,106
[2] Qian Wang, Christoph Hanhart, and Qiang Zhao, Phys. Rev. Lett. 111,132003
[3] Zheng Cao, and Qiang Zhao, Phys. Rev. D 99,014016
[4] Zhi Yang, Xu Cao, Feng-Kun Guo, Juan Nieves, and Manuel Pavon Valderrama, arXiv:2011.08725

As an illustration of the pure kinematics of the triangle singularity, the triangle diagrams induced by $D_{s1}(2536)\bar{D}_s$ and $D_{s2}(2573)\bar{D}_s^*$ are calculated in the framework of the heavy meson effective theory.





- $D_{s1}(2536)\bar{D}_s$ and $D_{s2}(2573)\bar{D}_s^*$ thresholds are produced via D wave $c\bar{c}$, which reflects the HQSS breaking.
- Both the resonance of Y and Z_{cs} are omitted to illustrate the near-threshold kinematic enhancement caused by TS.

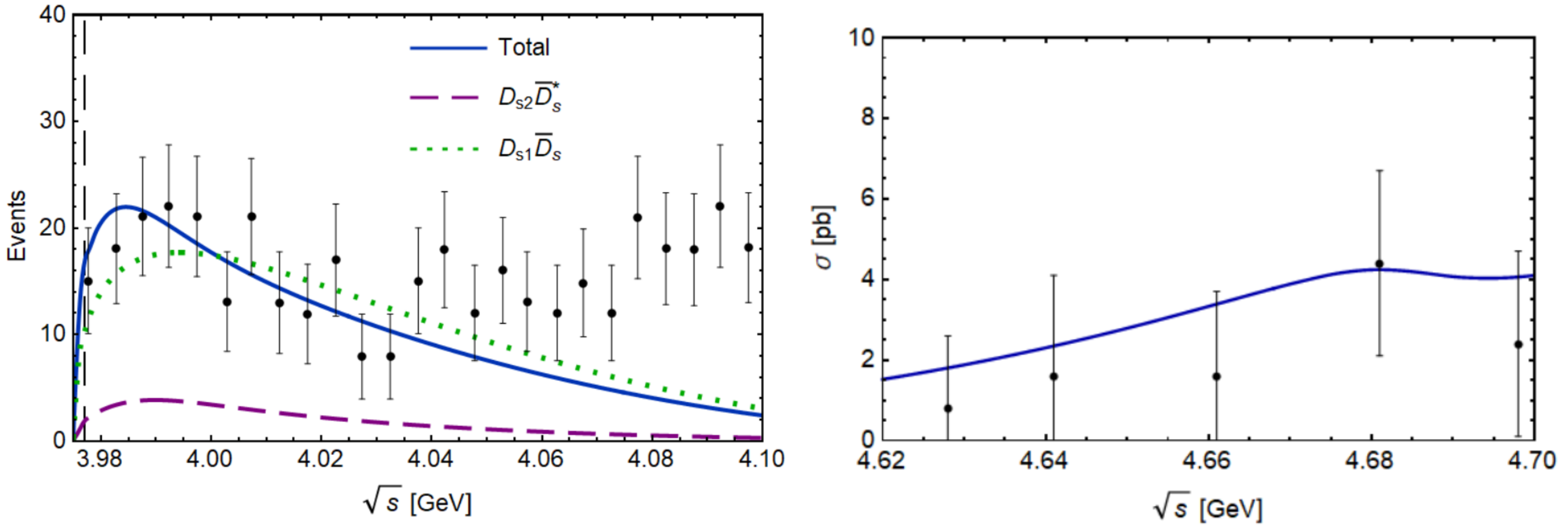


Fig.4. The differential cross sections and the cross section of $e^+e^- \to \bar{D}_s D^* K$, from the triangle diagrams without the poles of $Y(4680)$ and Z_{cs}. The theoretical values are scaled to compare with the data [1].

- The triangle singularity leads to near-threshold enhancement in $\bar{D}_s D^*$ final state.
- The triangle singularity causes enhancement at $D_{s2}(2573)\bar{D}_s^*$ threshold.
- The contribution from $D_{s1}(2536)\bar{D}_s$ threshold is not negligible.
- However, the pole contribution in Y and Z_{cs} cannot be excluded. Both the triangle singularity and the pole are essential for our understanding.

[1] M. Ablikim et al. [BESIII], arXiv:2011.07855.

Parametrization

To illustrate the role play by the pole in a simple way, we adopt the following parametrization

1. For $D\bar{D}^*\pi$ final state:

Bare S-wave π emission vertex:

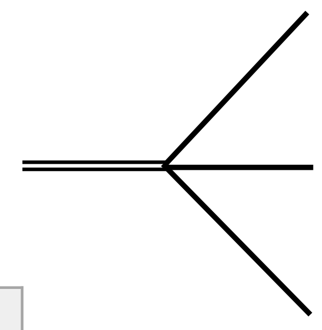
$$\langle D\bar{D}^*\pi_S|\hat{H}|Y\rangle = \mathcal{F}_S^{bare}$$

Compact core
$D_{s0}(2317)D_s^*$
$D_{s1}(2460)\overline{D_s}$

Bare D-wave π emission vertex:

$$\langle D\bar{D}^*\pi_D|\hat{H}|Y\rangle = \mathcal{F}_D^{bare}$$

$D_{s1}(2536)\overline{D_s}$
$D_{s2}(2573)\overline{D_s}^*$



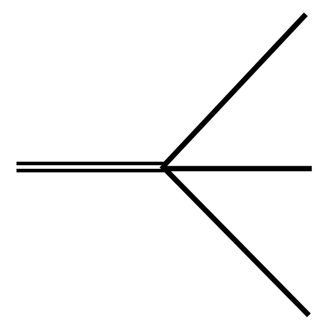
2. For $D^*\bar{D}^*\pi$ final state:

Bare S-wave π emission vertex:

$$\langle D^*\bar{D}^*\pi_S|\hat{H}|Y\rangle = \mathcal{F'}_S^{bare}$$

Bare D-wave π emission vertex:

$$\langle D^*\bar{D}^*\pi_D|\hat{H}|Y\rangle = \mathcal{F'}_D^{bare}$$



- Because of the TS and the resonance of Y, these coupling should have included energy dependence, but they are assumed to be constant for now.

The physical vertex is given by LS equation:

$$\mathcal{A}_L^{phy} = \mathcal{A}_L^{bare}(1 - GV)^{-1}$$

$$\mathcal{A}_L^{phy} \equiv \left(\mathcal{F}_L^{phy} \quad \mathcal{F}'^{phy}_L\right)$$

$$\mathcal{A}_L^{bare} \equiv \left(\mathcal{F}_L^{bare} \quad \mathcal{F}'^{bare}_L\right)$$

The final-state-interaction potentials are given by heavy-light decomposition:

States	**$\vert HL\rangle$ decompositions**	$I(J^{PC})$	**Components**
Z	$\frac{1}{\sqrt{2}}\vert 01\rangle - \frac{1}{\sqrt{2}}\vert 10\rangle$	$1(1^{+-})$	$D\bar{D}^*$
Z'	$\frac{1}{\sqrt{2}}\vert 01\rangle + \frac{1}{\sqrt{2}}\vert 10\rangle$	$1(1^{+-})$	$D^*\bar{D}^*$
W_0	$\frac{1}{2}\vert 00\rangle + \frac{\sqrt{3}}{2}\vert 11\rangle$	$1(0^{++})$	$D\bar{D}$
W_0'	$\frac{\sqrt{3}}{2}\vert 00\rangle - \frac{1}{2}\vert 11\rangle$	$1(0^{++})$	$D^*\bar{D}^*$
W_1	$\vert 11\rangle$	$1(1^{++})$	$D^*\bar{D}^*$
W_2	$\vert 11\rangle$	$1(2^{++})$	$D^*\bar{D}^*$

The calculated potentials are:

$$\begin{pmatrix} \hat{H}_{ZZ} & \hat{H}_{ZZ'} \\ \hat{H}_{Z'Z} & \hat{H}_{Z'Z'} \end{pmatrix} = \begin{pmatrix} \frac{C_1 + C_0}{2} & \frac{C_1 - C_0}{2} \\ \frac{C_1 - C_0}{2} & \frac{C_1 + C_0}{2} \end{pmatrix}$$

$$\begin{pmatrix} \hat{H}_{W_0W_0} & \hat{H}_{W_0W_0'} \\ \hat{H}_{W_0'W_0} & \hat{H}_{W_0'W_0'} \end{pmatrix} = \frac{1}{4}\begin{pmatrix} 3C_1 + C_0 & \sqrt{3}(C_0 - C_1) \\ \sqrt{3}(C_0 - C_1) & 3C_0 + C_1 \end{pmatrix}$$

$$\hat{H}_{W_1W_1} = C_1, \hat{H}_{W_2W_2} = C_1$$

The physical amplitudes are defined by:

$$M_{D\bar{D}^*\pi} = \epsilon_Y^a \epsilon_{\bar{D}^*}^{*b} \left[A_S^{phy} \delta^{ab} + A_D^{phy} \left(p_\pi^a p_\pi^b - \frac{1}{3}\delta^{ab} \right) |\vec{p}_\pi|^2 \right]$$

$$M_{D^*\bar{D}^*\pi} = \frac{i}{\sqrt{2}} \epsilon_Y^a \epsilon^{bcd} \epsilon_{D^*}^{*c} \epsilon_{\bar{D}^*}^{*d} \left[A'^{phy}_S \delta^{ab} + A'^{phy}_D \left(p_\pi^a p_\pi^b - \frac{1}{3}\delta^{ab} \right) |\vec{p}_\pi|^2 \right]$$

$$\sum_{polarizations} |M_{D\bar{D}^*\pi}|^2 = 2\left|\mathcal{F}_S^{phy}\right|^2 + 2Re\left[\mathcal{F}_S^{phy}\mathcal{F}_D^{phy*}\right]\left(\frac{1}{3} - \cos^2\theta\right)p_\pi^2 + \left|\mathcal{F}_D^{phy}\right|^2\left(\frac{5}{9} - \frac{1}{3}\cos^2\theta\right)p_\pi^4$$

Fitted Results

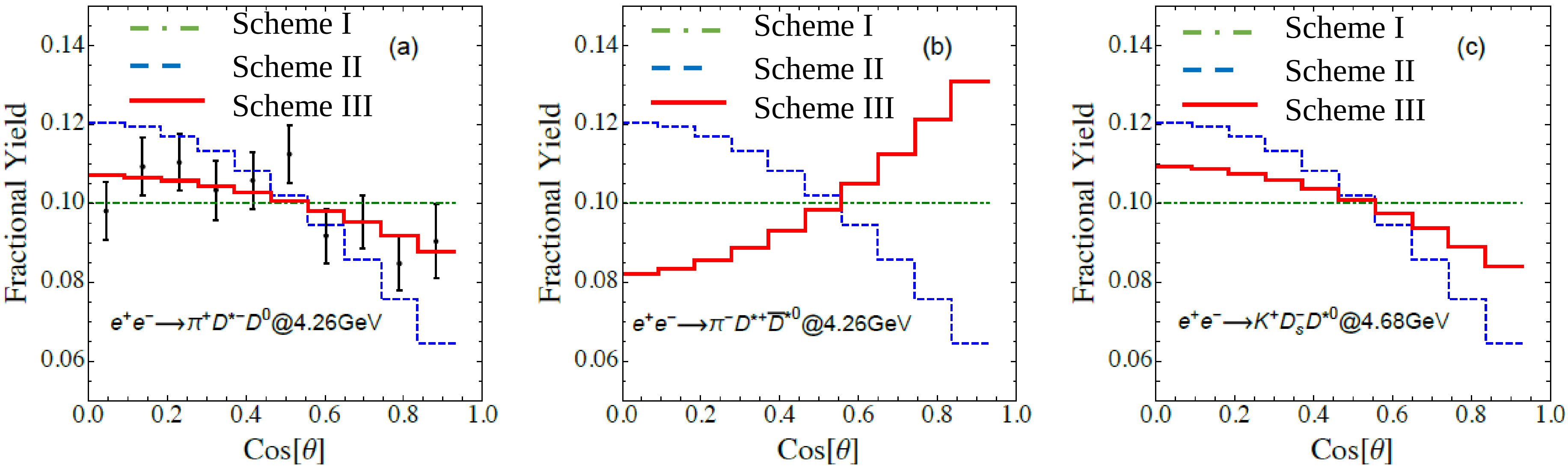


Fig.5. Angular distribution of $\pi(K)$ in $e^+e^- \to \pi^+ D^{*-} D^0$, $e^+e^- \to \pi^- D^{*+} \bar{D}^{*0}$ and $e^+e^- \to K^+ D_s^- D^{*0}$ processes at the first peak position, i.e. the mass region of Z_c, Z_c' and Z_{cs}^-, respectively. The data is taken from Ref[1].

Scheme I: S-wave π emission only $\chi^2/dof = 1.4$

Scheme II: D-wave π emission only $\chi^2/dof = 2.3$

Scheme III: S-wave and D-wave $\chi^2/dof = 1.2$

- Both S and D wave are required.
- π distribution is a sensitive to the interference between the S and D wave.

[1] M. Ablikim et al. [BESIII] PRD 92, 092006

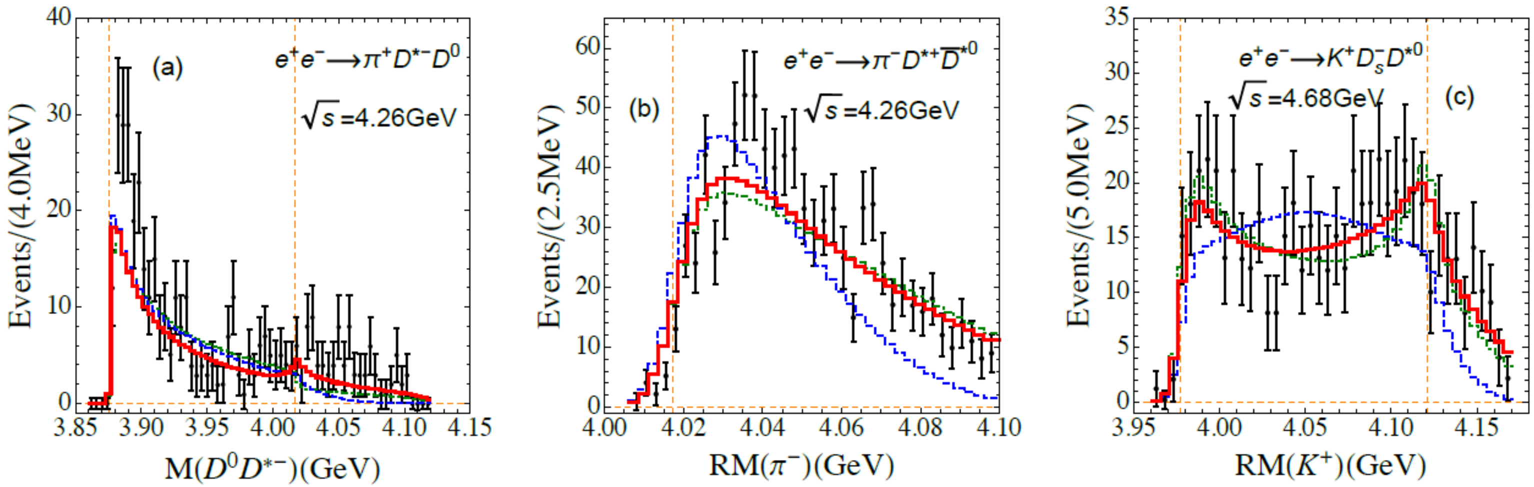


Fig.6. D^0D^{*-}, $D^{*+}\bar{D}^{*0}$ and $\bar{D}_sD^{*0}$ invariant mass spectrum with fitted results. The data are obtained from Ref[1,2,3].

States	Poles		
	Scheme I	Scheme II	Scheme III
Z_c	3873.11_V	3875.76_V	3800.58_B
Z_c'	——	——	——
Z_{cs}	3976.68_V	3979.39_V	3916.19_B
Z_{cs}'	——	——	——
W_{c0}	3734.17_B	3702.63_B	3687.42_B
W_{c0}'	——	$4022.07 \pm 6.58i$	——
W_{c1}	3869.09_B	——	——
W_{c2}	4011.14_B	——	——

Tab.1. The poles on the physical sheets and those close to the physical ones. Those indicated by "— —" are either far away from the corresponding threshold (more than 100MeV) or on a sheet far away from the physical one.

- Bound state poles of Z_c and Z_{cs}
- The constraints of Z_c' from the data is very weak.
- The pole location of W_{c0} is found

[1] M. Ablikim et al. [BESIII], PRD 92, 092006.
[2] M. Ablikim et al. [BESIII], PRL 112, 132001.
[3] M. Ablikim et al. [BESIII], arXiv:2011.07855

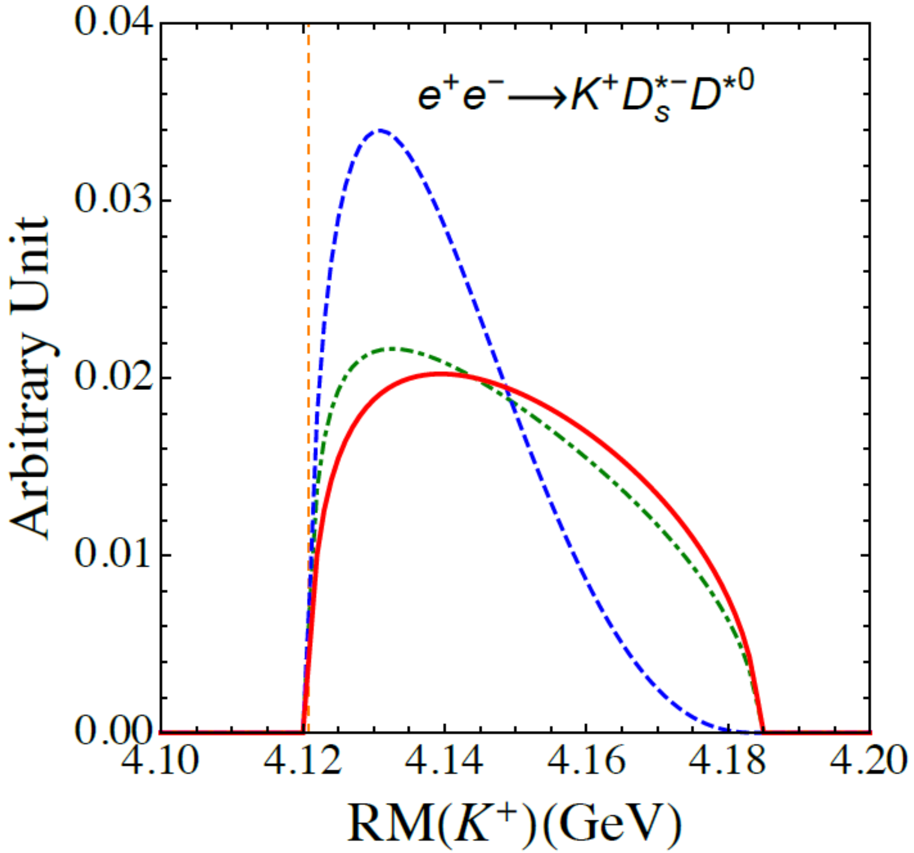


Fig.7. The predicted missing K^+ distribution of $e^+e^- \to K^+ D_s^{*-} D^{*0}$ process at $\sqrt{s} = 4.68$GeV. The blue dashed, green dot-dashed and red curves are for Schemes I,II and III, respectively.

Summery

- Both $Z_c(3900)$ and $Z_{cs}(3985)$ are likely to be genuine states in the fitting, which are enhanced by triangle singularity. A coherent analysis including the triangle singularity is still needed to decode the riddle of Y and Z states.
- The angular distribution of π in $Z_c'\pi$ and $Z_{cs}'K$ channel is sensitive to the interference between S and D wave.
- The $D_s^{*-}D^{*0}$ spectrum is predicted using the fitted parameters.
- e^+e^- spectrum near 4.68 GeV can provide more information for the properties of Y(4660), which in turn can help us understand the production of Z_c and Z_{cs} states.

Thank you