# Hidden-charm molecule with strangeness

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第七届XYZ粒子研讨会, 2021/5/17

# Outline

- Hadron structure
- Zc family
- Molecular interpretation of Zc(3900)
- Line shape and pole position of Zcs(3985)

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

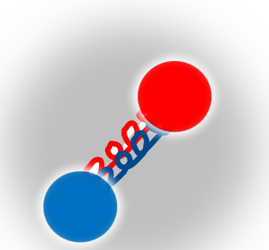
# Hadron structures

- ❑ Conventional hadrons

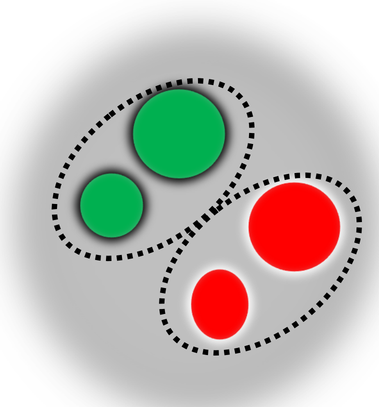
meson

baryon

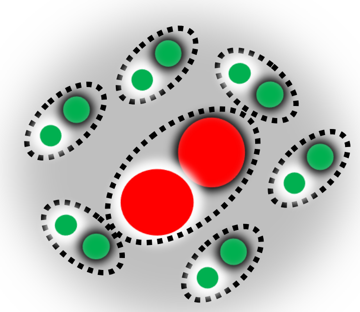
- ❑ Proposals for the heavy exotic hadrons



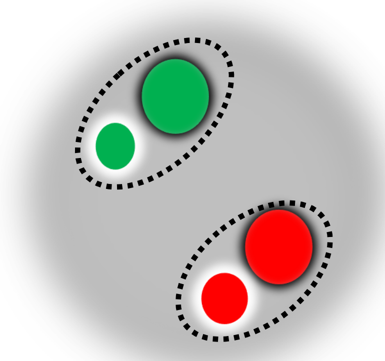
hybrid



Compact multiquark



Hadro-Quarkonium



Hadronic molecule

- Hadron structure is a platform to study the QCD in low energy region.
- Quark model classified the hadrons very well.
- However, many new hadrons can not fit into the conventional hadrons (mass and properties).

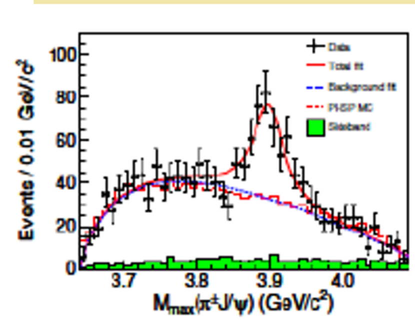
# Exotic hadrons in Zc family

2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016

- $X(3872)$ observed at Belle
- $X(3872)$ confirmed at D0, CDF
- $X(3915)$ [as $Y(3940)$] observed at Belle
- $Y(4260)$ observed at BaBar
- $\chi_{c2}(2P)$ [as $Z(3930)$] observed at Belle
- $Y(4260)$ confirmed at CLEO-c
- $X(3940)$, $Y(4008)$, $Y(4660)$ observed at Belle
- $Y(4360)$ observed at BaBar
- $Y(4360)$ confirmed at Belle
- $X(3915)$ [as $Y(3940)$] confirmed at BaBar
- $X(3940)$ confirmed at Belle
- $Z^{\pm}(4050)$, $X(4160)$, $Z^{\pm}(4250)$, $Z^{\pm}(4430)$, $X(4630)$ observed at Belle
- $Y(4140)$ observed at CDF
- $X(3915)$, $X(4350)$, $Y_b(10888)$ observed at Belle
- $\chi_{c2}(2P)$ [as $Z(3930)$] confirmed at BaBar
- $Y(4274)$ observed at CDF
- $X(3915)$ confirmed at BaBar
- $Z_b(10610)^{\pm}$ observed and confirmed at Belle
- $Z_b(10650)^{\pm}$ observed and confirmed at Belle
- $X(3823)$ [likely $\psi_2(1D)$], $Z_b(10610)^0$ observed and confirmed at Belle
- $Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$ observed at BESIII
- $Z_c(3900)^{\pm}$ confirmed at Belle
- $Z_c(3900)^0$ observed at CLEO-c
- $Z_c(4020)^0$ observed at BESIII
- $Y(4140)$ confirmed at D0, CMS
- $Y(4274)$ confirmed at CMS
- $Y(4660)$ confirmed at BaBar
- $Z_c(4020)^{\pm}$ confirmed at BESIII
- $Z^{\pm}(4200)$ observed at Belle
- $Z^{\pm}(4240)$ observed at LHCb
- $Z^{\pm}(4430)$ confirmed at LHCb
- $X(3823)$ [likely $\psi_2(2D)$], $Z_c(3900)^0$, $Z_c(4020)^0$ confirmed at BESIII
- $Z_c(4055)^{\pm}$ observed at Belle
- $Y(4230)$ observed at BESIII
- $P_c^+(4380)$, $P_c^+(4450)$ observed at LHCb
- $Y_b(10888)$ no longer observed at Belle
- $X(5568)^{\pm}$ observed at D0
- $X(5568)^{\pm}$ NOT observed at LHCb
- $Y(4140)$, $Y(4274)$ confirmed at LHCb
- $X(4500)$, $X(4700)$ observed at LHCb

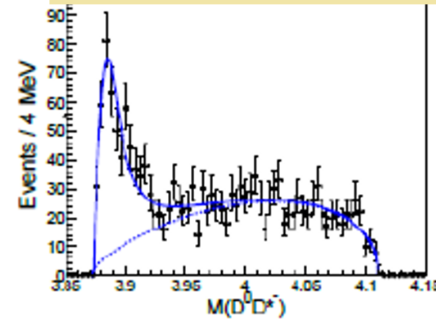
Lebed, Mitchell, Swanson, PPNP93(2017)143

Zc(3900)$^+$
PRL 110, 252001 (2013)



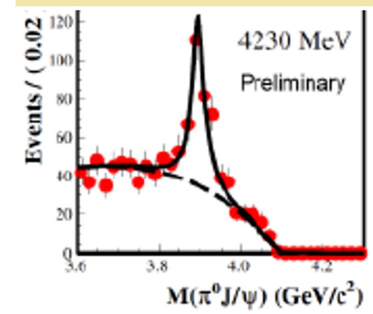
$e^+e^- \to \pi^-\pi^+ J/\psi$

Zc(3885)$^+$
PRL 112, 022001(2014)



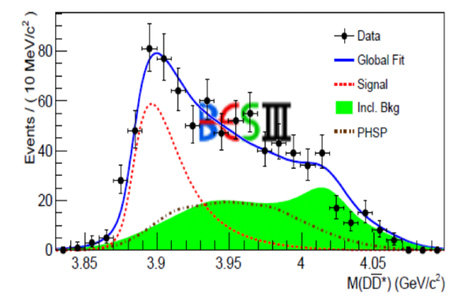
$e^+e^- \to \pi^-(D\bar{D}^*)^+$

Zc(3900)$^0$
PRL 115, 112003 (2015)



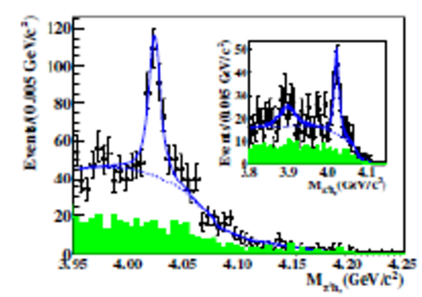

$e^+e^- \to \pi^0\pi^0 J/\psi$

Zc(3885)$^0$
PRL115, 222002 (2015)



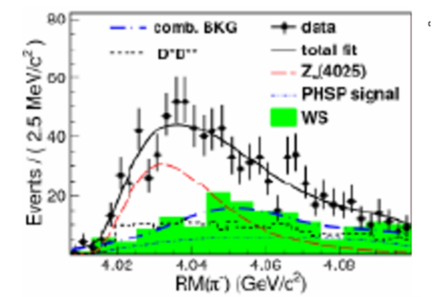
$e^+e^- \to \pi^0(D^*\bar{D})^0$

Zc(4020)$^+$
PRL 111, 242001(2013)



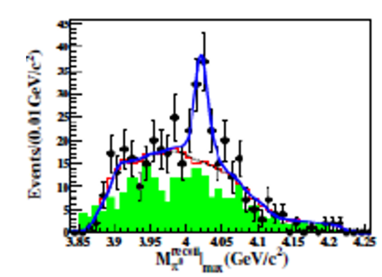
$e^+e^- \to \pi^-\pi^+ h_c$

Zc(4025)$^+$
PRL 112, 132001 (2014)



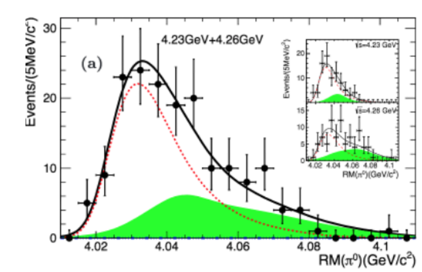
$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

Zc(4020)$^0$
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0 h_c$

Zc(4025)$^0$
PRL115, 182002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

# Zc(3900): kinematical effect or molecular?

- The charged one was observed in $J/\psi\pi^{\pm}$ mass distribution by BESIII and Belle.

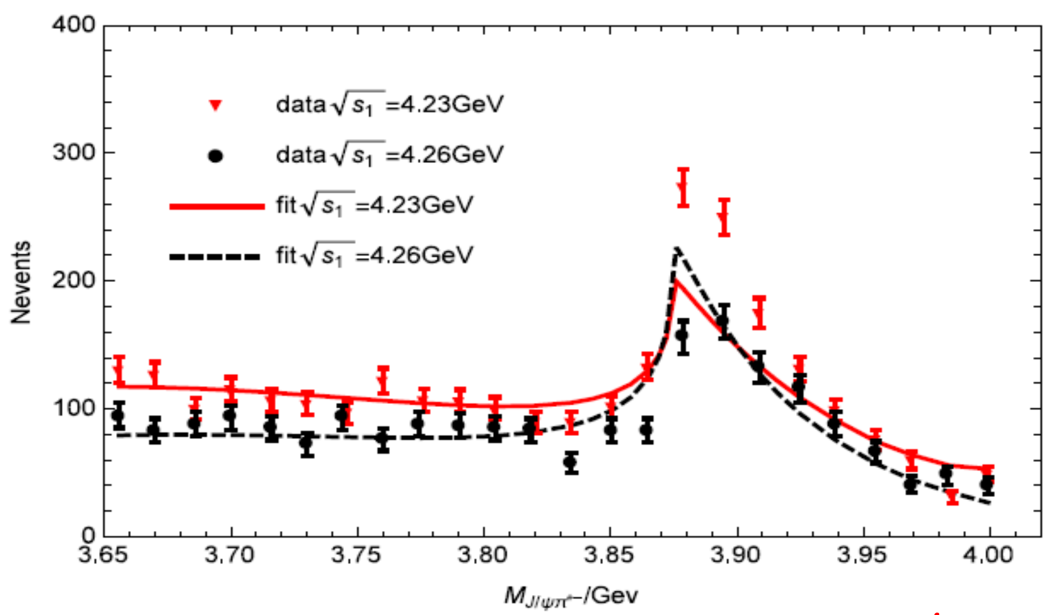
BESIII, PRL110(2013)252001; Belle, PRL110(2013)252002

- Must contain at least 4 quarks, $c\bar{c}u\bar{d}$, slightly above the $D^{*}\bar{D}$ threshold, mainly $D^{*}\bar{D}$ molecular? Or tetraquark, hybrid...?
- Kinematical cusp effect? In this scenario, it is not self consistent.

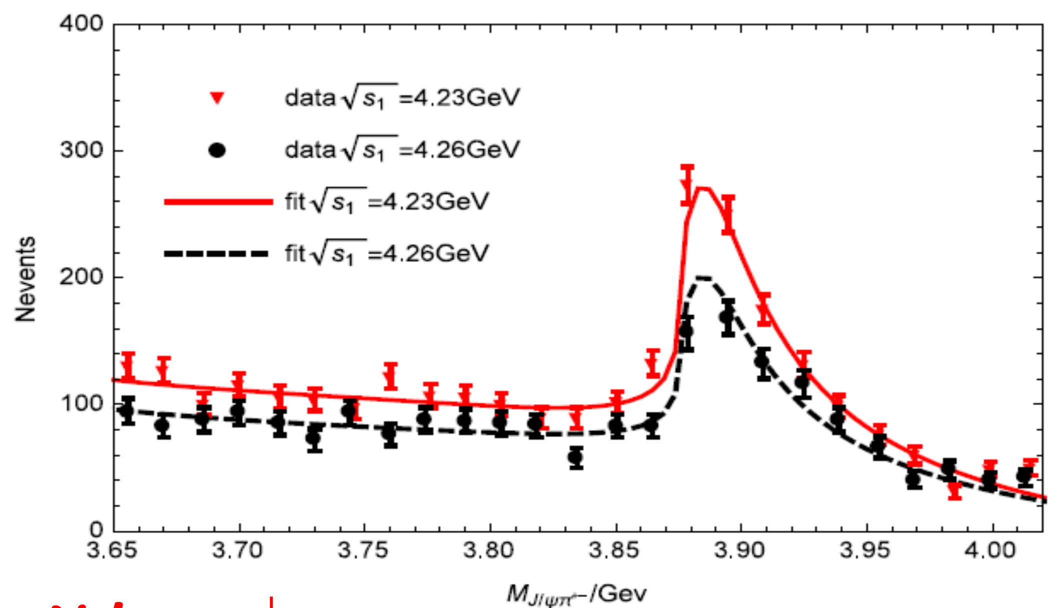
Guo, Hanhart, Wang and Zhao, PRD91(2015)051504

- Hadronic molecule, not triangle singularity

Gong, Pang, Wang and Zheng, EPJC78 (2018)276




(a)




(b)

$e^+e^- \to J/\psi\pi^-\pi^+$

Triangle singularity

Hadronic molecule

# Zc(3900): absence in B decay

- The $Z_c(3900)$ was found through $e^+e^- \to J/\psi\pi\pi$ and $D^*\bar{D}\pi$.
- However, it was not found in the $B \to KZc(Z_c \to J/\psi\pi)$ decay.

  Instead, the $Z_c(4200)$ and $Z_c(4430)$ were found.

Belle, PRD90(2014)112009

- The absence may have something to do with its internal structure.
- Under the hadronic molecular picture, both X(3872) and $Z_c(3900)$ have $D^*\bar{D}$ constituent, with isospin 0 and 1, respectively.
- The production of the $D^*\bar{D}$ pair with isospin 1 is highly suppressed in B decays.

  → <u>The Zc(3900) being a $D^*\bar{D}$ hadronic molecule naturally explains its absence in the B decays.</u>

Yang, Wang and Meissner, PLB775(2017)50

# Zcs studies before 2020

**Theoretical predictions:**

- Molecule picture using QCD sum rule

  Lee, Nielsen and Wiedner, J. Korean Phys. Soc. 55, 424 (2009)

- Hadrocharmonium Voloshin, PLB798,135022 (2019); Ferretti and Santopinto, JHEP04,119

- Single kaon emission model Chen, Liu and Matsuki, Phys.Rev.Lett.110,232001

**Experimental measurements:**

- Unsuccessful searches for Zcs by Belle and BES3 in the hidden channel in $e^+e^- \to J/\psi K^+K^-$.

  PRD77, 011105(2008); PRD89,072015(2014); PRD97, 071101(2018)

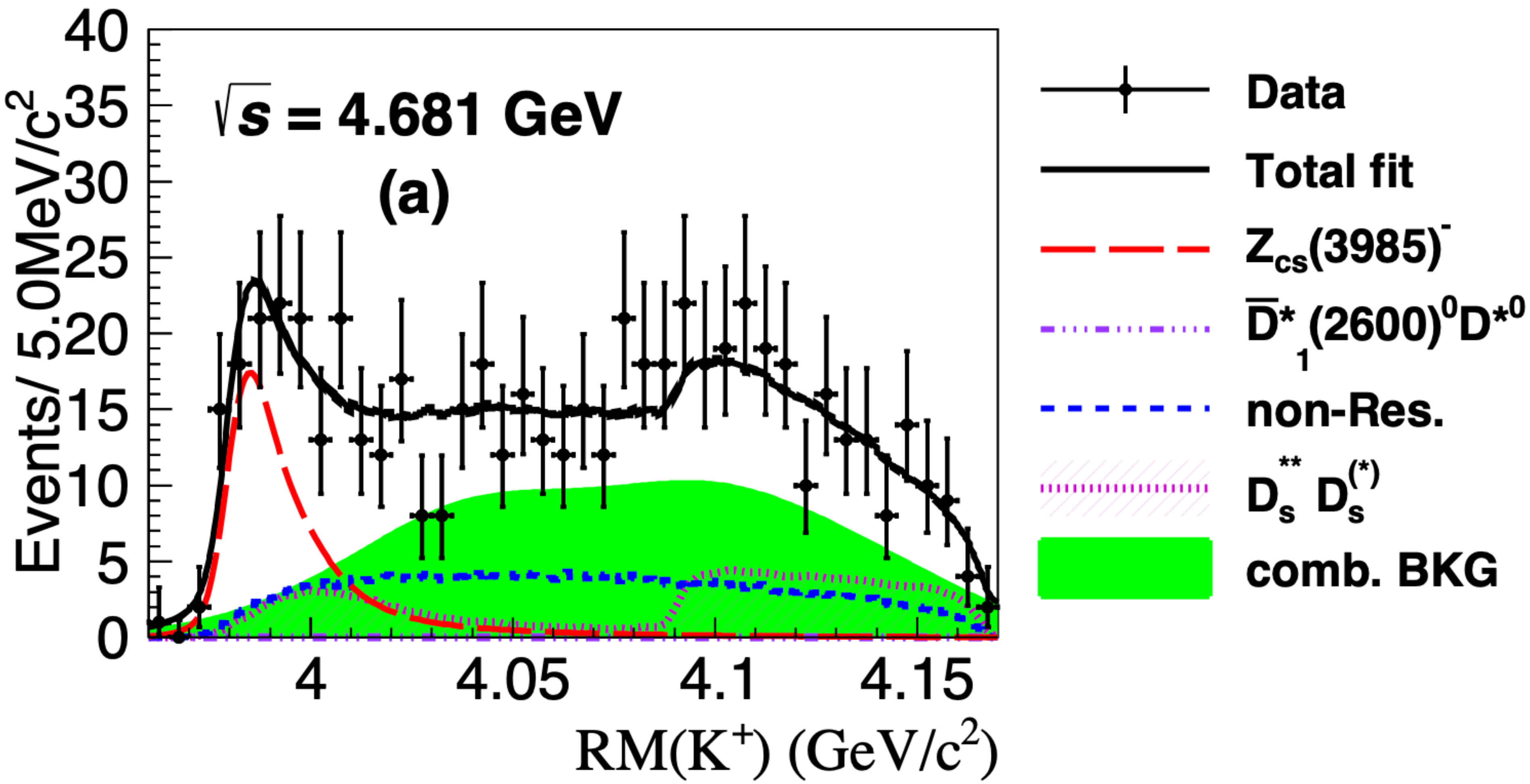
- No signal in LHCb measurement of $\bar{B}_s^0 \to J/\psi K^+K^-$.

  Phys.Rev.D 87, 072004(2013)

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

- The recoil mass distribution was studied by BES3;
- A clear peak was found at energy point 4.681GeV:

$M[Z_{cs}(3985)] = 3982.5^{+2.8}_{-3.3}\, MeV,\ \Gamma[Z_{cs}(3985)] = 12.8^{+6.1}_{-5.3}\, MeV$




BES3,Phys.Rev.Lett.126.102001

# Theoretical explanation of Zcs

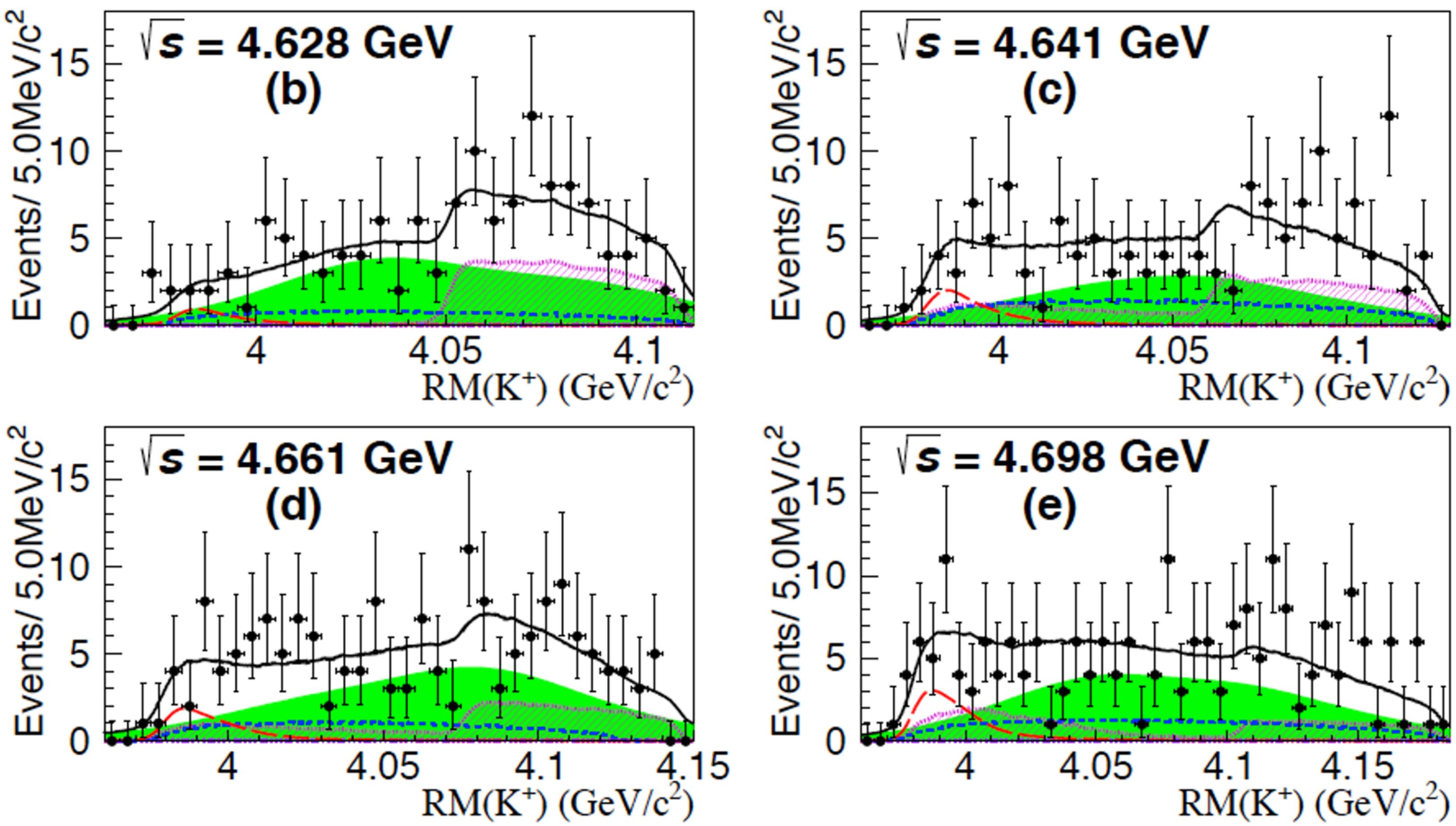
- Kinematic effect: two-body reflection/triangle singularity;
- Molecule;
- Tetraquark;

.......


L Meng, Bo Wang, Shi-Lin Zhu, Phys.Rev.D 102 (2020) 11, 111502;
Bing-Dong Wan, Cong-Feng Qiao, arXiv:2011.08747;
Jun-Zhang Wang, Qing-Song Zhou, Xiang Liu, Takayuki Matsuki, Eur.Phys.J.C81(2021)1,51;
Rui Chen, Qi Huang, Phys.Rev.D103(2021)3,034008;
Meng-Chuan Du, Qian Wang, Qiang Zhao, arXiv:2011.09225;
Zhi-Feng Sun, Chu-Wen Xiao, arXiv:2011.09404;
Qi-Nan Wang, Wei Chen, Hua-Xing Chen, arXiv:2011.10495;
Bo Wang, Lu Meng, Shi-Lin Zhu, Phys.Rev.D103(2021)2,L021501;
Zhi-Gang Wang, arXiv:2011.10959;
K. Azizi, N. Er, Eur.Phys.J.C81(2021)1,61;
Xin Jin, Xuejie Liu, Yaoyao Xue, Hongxia Huang. Jialun Ping, arXiv:2011.12230;
Yu A. Simonov, JHEP04(2021)051;
J.Y. Sungu, A. Turkan, H.Sundu, E. Veli Veliev, arXiv:2011.13013;
Natsumi Ikeno, Raquel Molina, Eulogio Oset, Phys.Lett.B814(2021)136120;
Xiang-Kun Dong, Feng-Kun Guo, Bing-Song Zou, Phys.Rev.Lett.126(2021)15,152001;
Yong-Jiang Xu, Chun-Yu Cui, Ming-Qiu Huang, arXiv:2011.14313;
..........

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

➢ The Zcs structure was also observed in other four energy points.




| $\sqrt{s}$(GeV) | $\mathcal{L}_{\rm int}$(pb$^{-1}$) |
|---|---|
| 4.628 | 511.1 |
| 4.641 | 541.4 |
| 4.661 | 523.6 |
| 4.681 | 1643.4 |
| 4.698 | 526.2 |

**BES3,Phys.Rev.Lett.126.102001**

➢ There exists one particle in the energy range:

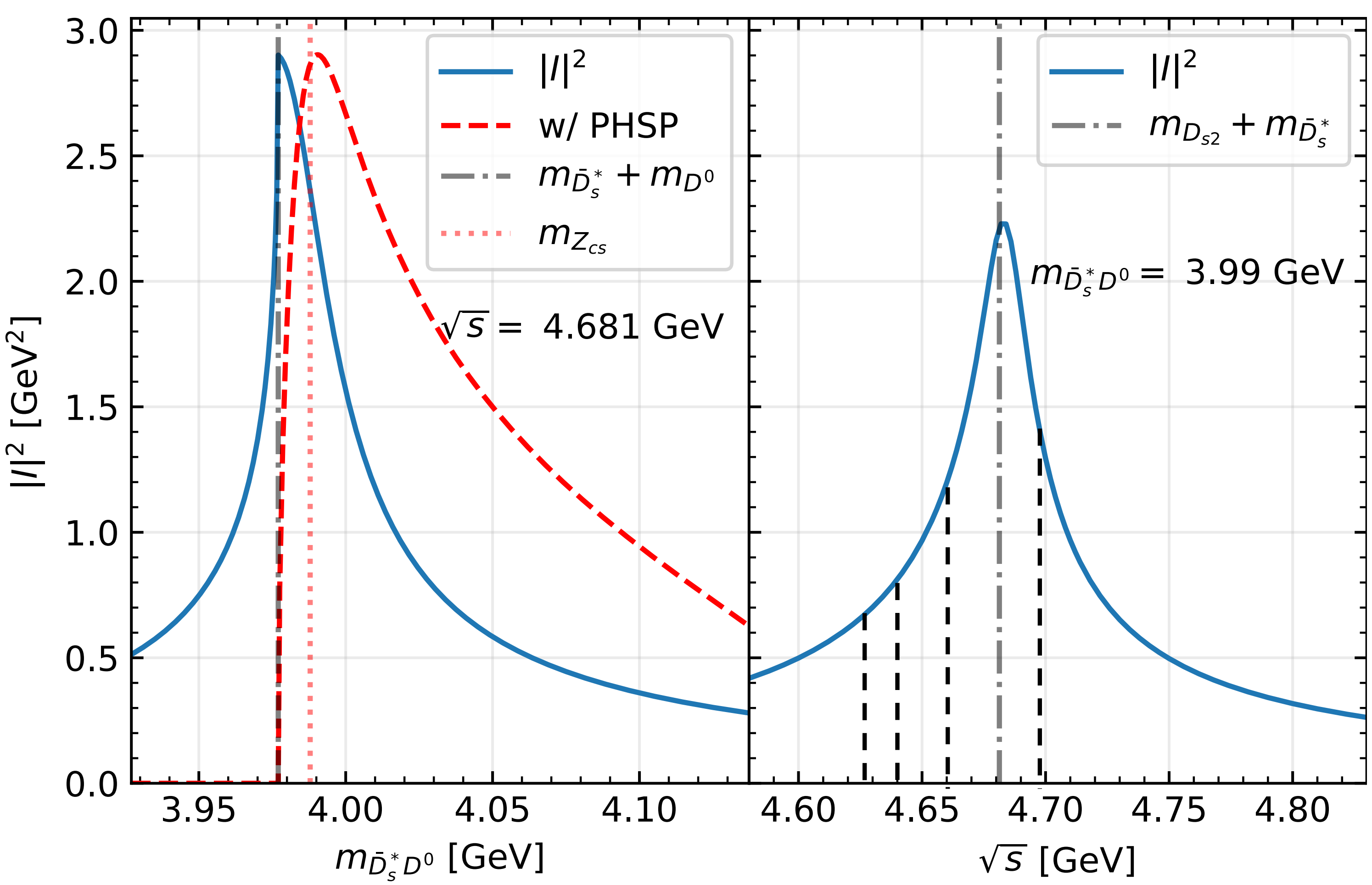
$\psi(4660)$ $I^G(J^{PC}) = 0^-(1^{--})$

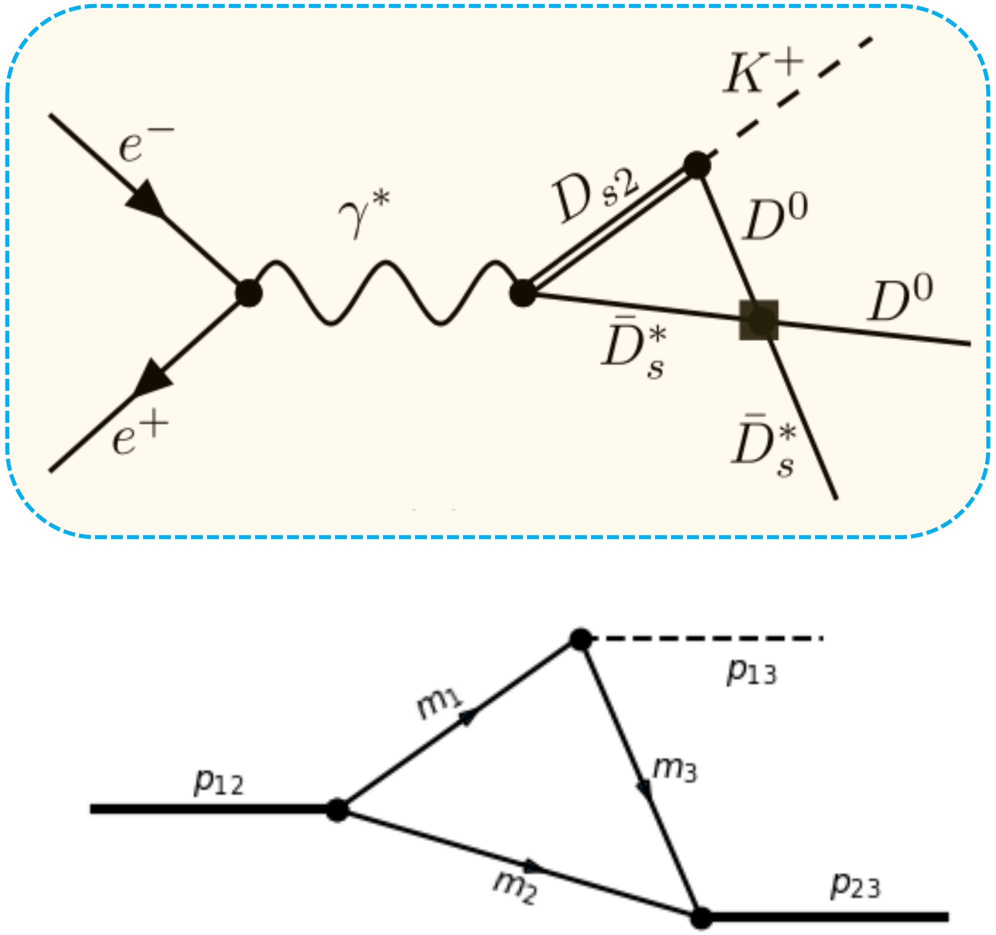
| | |
|---|---|
| $\psi(4660)$ MASS | $4633 \pm 7$ MeV (S = 1.4) |
| $\psi(4660)$ WIDTH | $64 \pm 9$ MeV |

# Triangle singularity in Zcs production

- There is such triangle diagram which appears as peak around threshold at c.m. energy 4.681 GeV;
- It can enhance the production of near-threshold hadronic molecules.

Guo, Liu and Sakai, PPNP112,103757; Guo, Hanhart, Meissner, Wang, Zhao and Zou, RMP90,015004




$$= I(m_1, m_2, m_3, p_{13}, p_{12}, p_{23})$$

Energy points: [4.628, 4.641, 4.661, 4.681, 4.698] GeV

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

- Constant-contant EFT:
  (for virtual/bound state)

$$V^{(O)}_{\rm virtual} = C^{(O)}$$

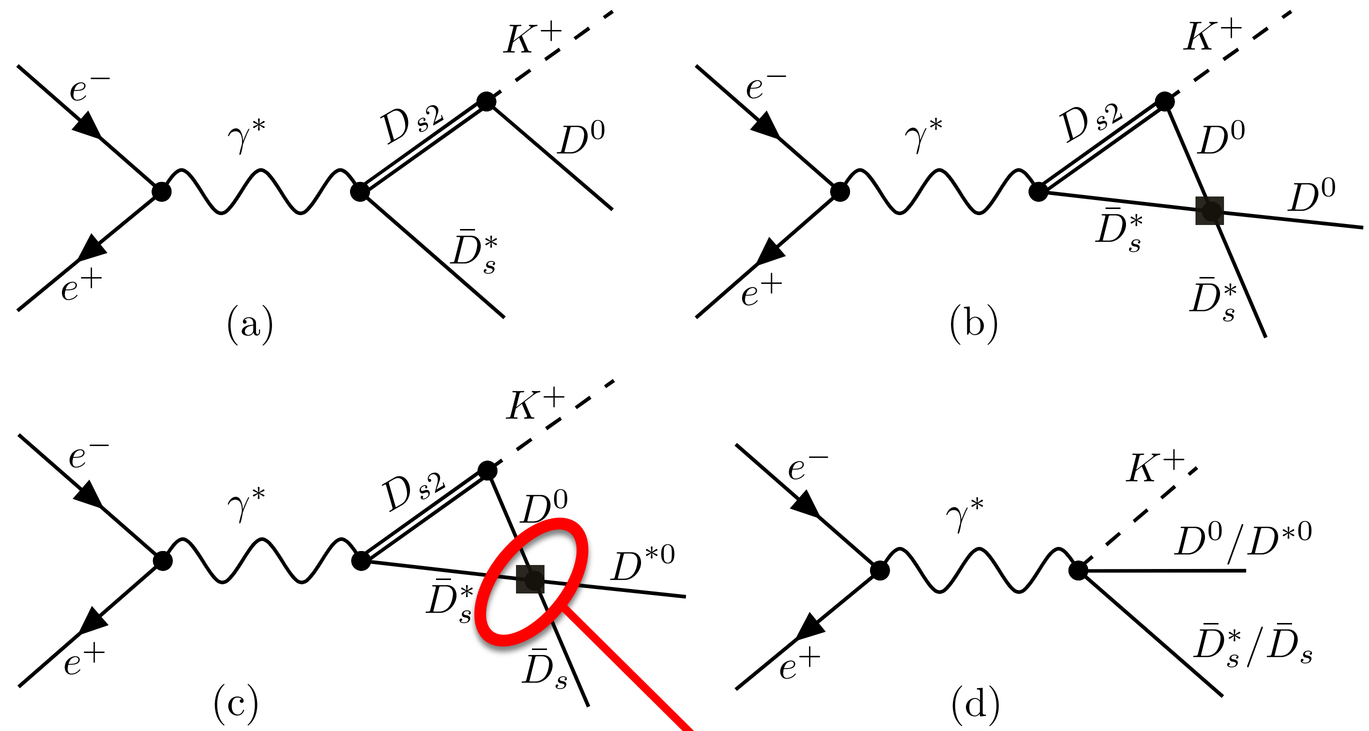
- Resonance EFT:

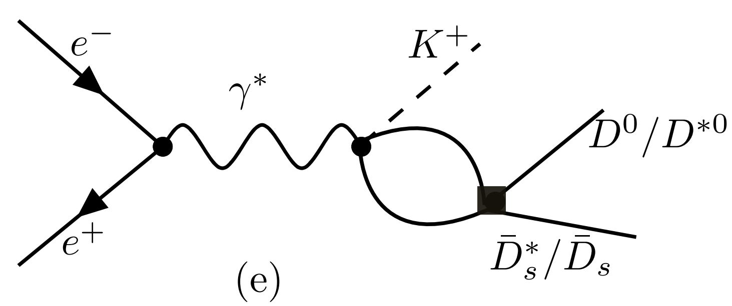
$$V^{(O)}_{\rm res} = C^{(O)} + 2D^{(O)}\,k^2$$

Other fit parameters:

- N: overall constant (e+e- vertex);
- r: relative weight between diagrams (d,e) and diagrams (a,b,c) ;

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




- LSE:

$$\frac{1}{\tau(E_{\rm cm})} = \frac{1}{V^{(O)}} - I_0(E_{\rm cm};\Lambda)$$

| $\sqrt{s}$(GeV) | $\mathcal{L}_{\rm int}$(pb$^{-1}$) | $n_{\rm sig}$ | $f_{\rm corr}\bar{\varepsilon}$(%) | $\sigma^B\cdot\mathcal{B}$ (pb) |
|---|---|---|---|---|
| 4.628 | 511.1 | $4.2^{+6.1}_{-4.2}$ | 1.03 | $0.8^{+1.2}_{-0.8}\pm 0.6\,(<3.0)$ |
| 4.641 | 541.4 | $9.3^{+7.3}_{-6.2}$ | 1.09 | $1.6^{+1.2}_{-1.1}\pm 1.3\,(<4.4)$ |
| 4.661 | 523.6 | $10.6^{+8.9}_{-7.4}$ | 1.28 | $1.6^{+1.3}_{-1.1}\pm 0.8\,(<4.0)$ |
| 4.681 | 1643.4 | $85.2^{+17.6}_{-15.6}$ | 1.18 | $4.4^{+0.9}_{-0.8}\pm 1.4$ |
| 4.698 | 526.2 | $17.8^{+8.1}_{-7.2}$ | 1.42 | $2.4^{+1.1}_{-1.0}\pm 1.2\,(<4.7)$ |

BES3,Phys.Rev.Lett.126.102001

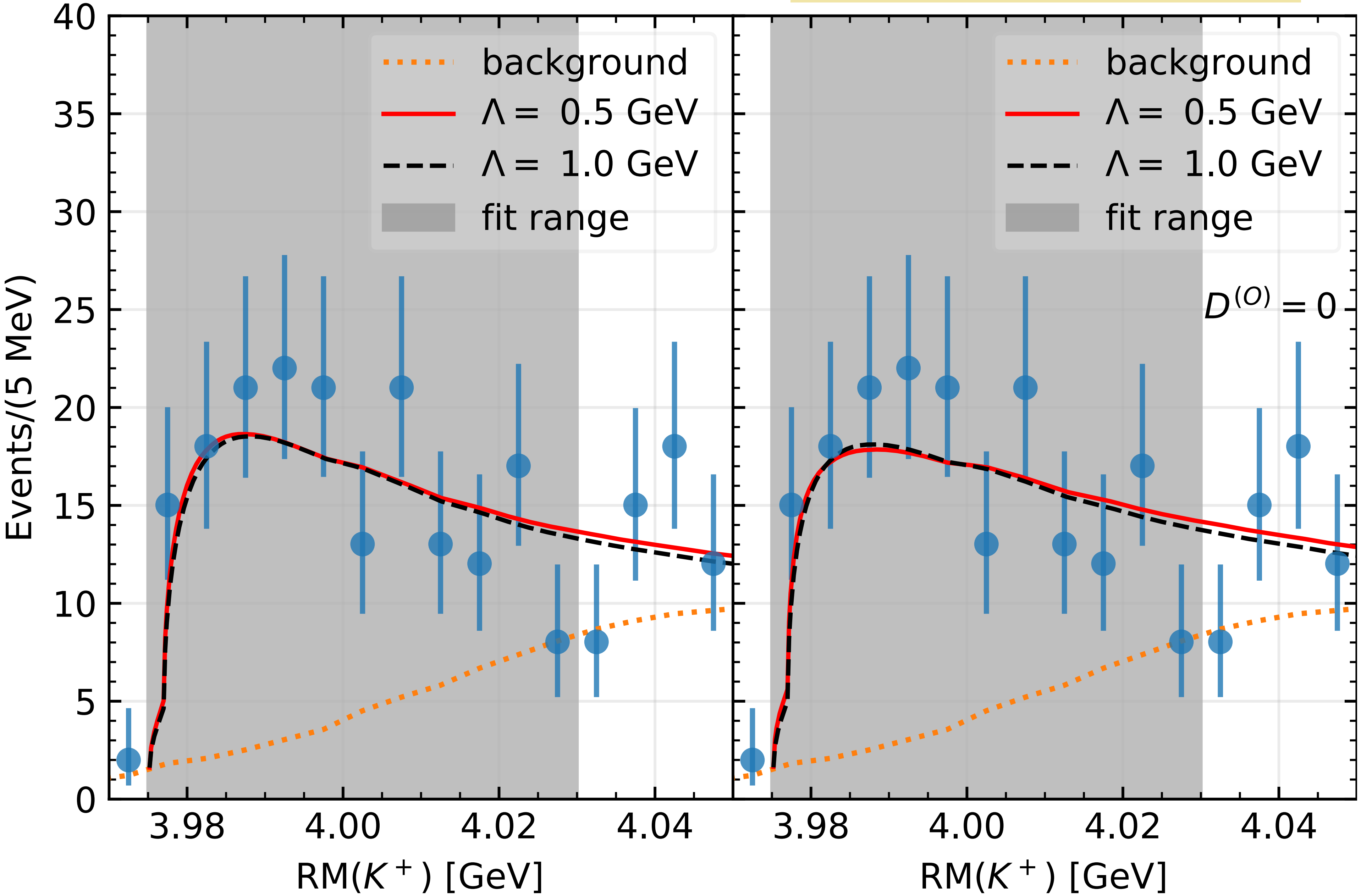
# Fits of Zcs line shapes

- The fits are quite well, $\chi^2/dof \approx 0.6$ for both cases.

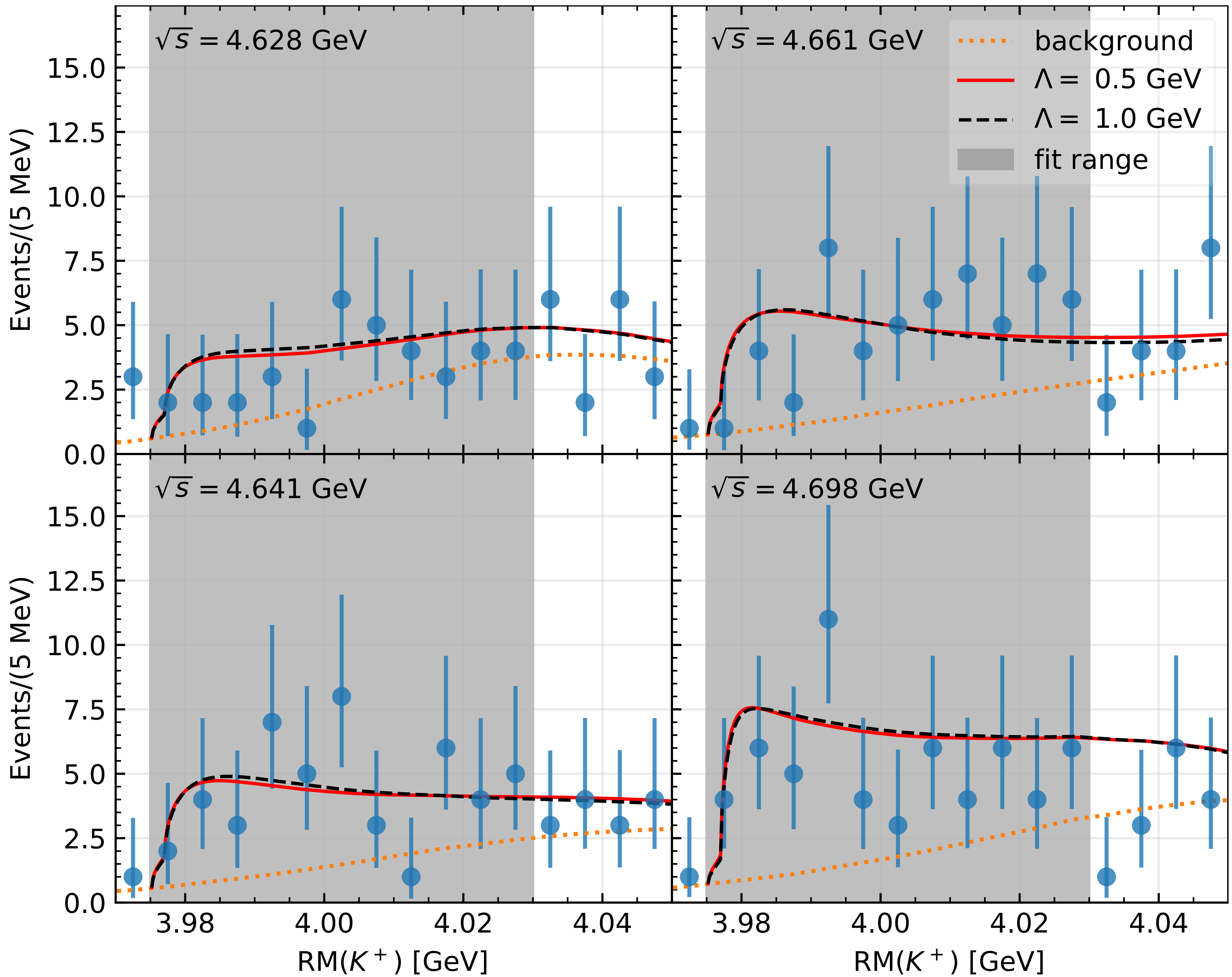
Energy points: 4.681 GeV

Resonance EFT

Constant-contact EFT



# Fits of Zcs line shapes




Resonance EFT

Energy points: [4.628, 4.641, 4.661, 4.698] GeV

# LECs and Poles

➢ The LECs in fitting Zcs line shapes:

for constant-contact EFT:

$$C^{(O)}(\Lambda) = -0.77^{+0.12}_{-0.10} \left(-0.45^{+0.05}_{-0.04}\right) \text{ fm}^2 ,$$

for resonant EFT:

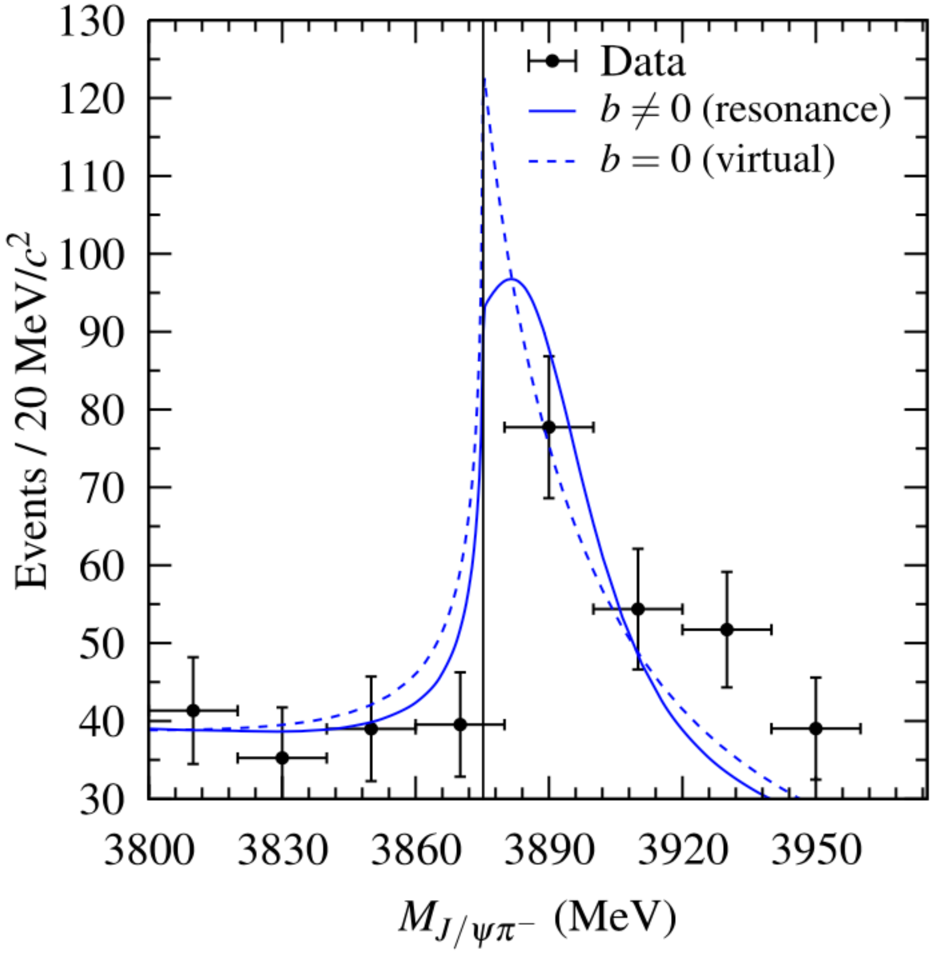
$$C^{(O)}(\Lambda) = -0.72^{+0.18}_{-0.13} \left(-0.44^{+0.06}_{-0.05}\right) \text{ fm}^2 ,$$
$$D^{(O)}(\Lambda) = -0.17^{+0.21}_{-0.21} \left(-0.025^{+0.066}_{-0.049}\right) \text{ fm}^4 ,$$

| Potential | States | Thresholds | Masses ($\Lambda = 0.5$ GeV) | Masses ($\Lambda = 1$ GeV) | Experiment |
|---|---|---|---|---|---|
| $V^{(O)}_{\text{virtual}}$ | $\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$ | 3875.8 | $3871^{+2}_{-3}$ | $3867^{+4}_{-7}$ | $3884.4 \pm 2.5$ [11] |
| | $D^*\bar{D}^*$ | 4017.2 | $4014^{+2}_{-3}$ | $4012^{+3}_{-6}$ | $4024.1 \pm 1.9$ [11] |
| | $D\bar{D}^*_s$-$D^*\bar{D}_s$ | 3979.4, 3976.9 | $3974^{+2}_{-3}$ | $3971^{+3}_{-6}$ | |
| | $D^*\bar{D}^*_s$ | 4120.8 | $4117^{+3}_{-5}$ | $4115^{+3}_{-6}$ | |
| Potential | States | Thresholds | Masses ($\Lambda = 0.5$ GeV) | Masses ($\Lambda = 1$ GeV) | Experiment |
| $V^{(O)}_{\text{res}}$ | $\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$ | 3875.8 | $3861^{+20}_{-0} - i6^{+14}_{-6}$ (R/V) | $3861^{+16}_{-35} - i0^{+29}_{-0}$ (R/V) | $3884.4 \pm 2.5$ [11] |
| | $D^*\bar{D}^*$ | 4017.2 | $4004^{+18}_{-0} - i0^{+20}_{-0}$ (R/V) | $4006^{+10}_{-37} - i0^{+28}_{-0}$ (R/V) | $4024.1 \pm 1.9$ [11] |
| | $D\bar{D}^*_s$-$D^*\bar{D}_s$ | 3979.4, 3976.9 | $3963^{+20}_{-0} - i3^{+16}_{-3}$ (R/V) | $3966^{+12}_{-36} - i0^{+20}_{-0}$ (R/V) | $3982.5^{+2.8}_{-3.3} - i25.6^{+12.1}_{-10.6}$ [4] |
| | $D^*\bar{D}^*_s$ | 4120.8 | $4110^{+14}_{-0} - i0^{+19}_{-0}$ (R/V) | $4111^{+9}_{-25} - i0^{+15}_{-0}$ (R/V) | |

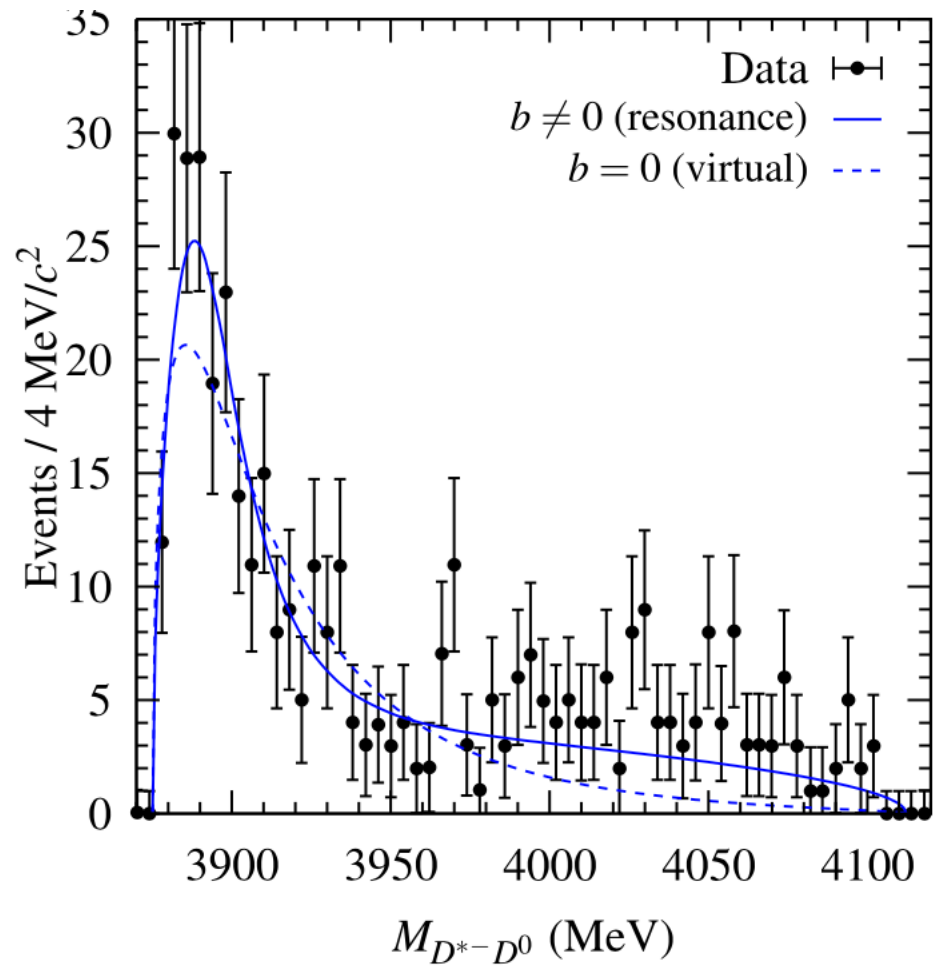
# Zc(3900): line shape in $J/\psi\pi$ and $D^{*-}D^0$ channels

Albaladejo, Guo, Hidalgo and Nieves, PLB755,337(2016)

Zc(3900)$^+$




Zc(3885)$^+$




| $M_{Z_c}$ (MeV) | $\Gamma_{Z_c}/2$ (MeV) | Ref. | Final state |
|---|---|---|---|
| $3894 \pm 6 \pm 1$ | $30 \pm 12 \pm 6$ | $\Lambda_2 = 1.0$ GeV | $J/\psi\ \pi$, $\bar{D}^*D$ |
| $3886 \pm 4 \pm 1$ | $22 \pm 6 \pm 4$ | $\Lambda_2 = 0.5$ GeV | $J/\psi\ \pi$, $\bar{D}^*D$ |
| $3831 \pm 26^{+7}_{-28}$ | virtual state | $\Lambda_2 = 1.0$ GeV | $J/\psi\ \pi$, $\bar{D}^*D$ |
| $3844 \pm 19^{+12}_{-21}$ | virtual state | $\Lambda_2 = 0.5$ GeV | $J/\psi\ \pi$, $\bar{D}^*D$ |

# LECs and Poles from Zc(3900) case

- The LECs in reproducing the pole position of Zc(3900):

  for constant-contact EFT: [19] Albaladejo, Guo, Hidalgo and Nieves, PLB755,337

$$C^{(O)}(\Lambda) = -0.29^{+0.15}_{-0.32}\ \left(-0.28^{+0.08}_{-0.39}\right)\ \mathrm{fm}^2\ ;$$

  for resonant EFT:

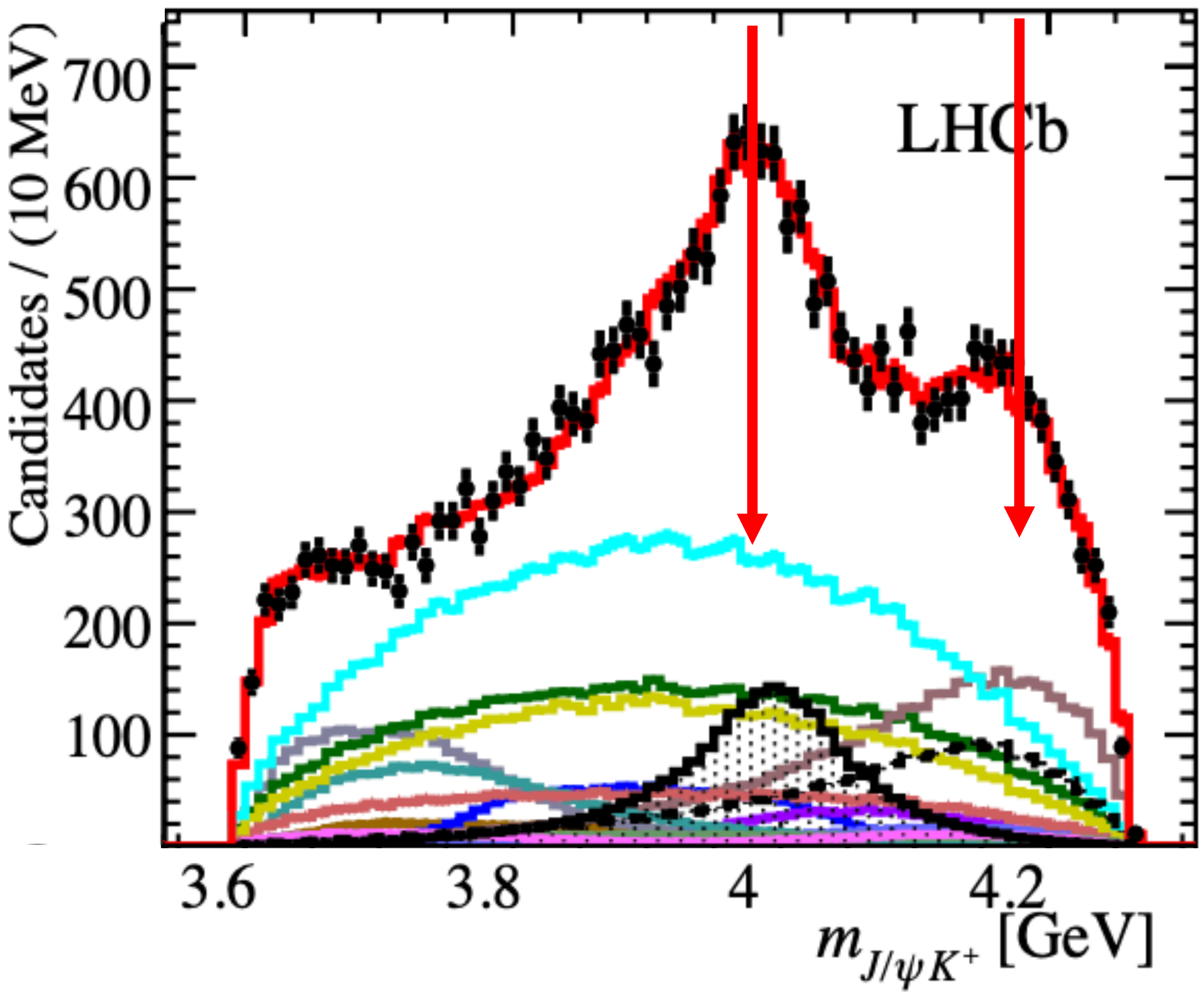
$$C^{(O)}(\Lambda) = -0.06^{+0.24}_{-0.16}\ \left(-0.22^{+0.10}_{-0.06}\right)\ \mathrm{fm}^2\ ,$$
$$D^{(O)}(\Lambda) = -0.31^{+0.10}_{-0.17}\ \left(-0.09^{+0.03}_{-0.07}\right)\ \mathrm{fm}^4\ .$$

| Potential | States | Thresholds | Masses ($\Lambda = 0.5$ GeV) | Masses ($\Lambda = 1$ GeV) | Experiment |
|---|---|---|---|---|---|
| $V^{(O)}_{\mathrm{virtual}}$ | $\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$ | 3875.8 | Input [19] | Input [19] | $3888.4 \pm 2.5$ [11] |
| | $D^*\bar{D}^*$ | 4017.2 | $3988^{+21}_{-27}$ | $3978^{+25}_{-36}$ | $4024.1 \pm 1.9$ [11] |
| | $D\bar{D}_s^*/D^*\bar{D}_s$ | 3979.4/3976.9 | $3948^{+22}_{-27}$ | $3937^{+25}_{-36}$ | |
| | $D^*\bar{D}_s^*$ | 4120.8 | $4092^{+21}_{-26}$ | $4083^{+24}_{-35}$ | |
| Potential | States | Thresholds | Masses ($\Lambda = 0.5$ GeV) | Masses ($\Lambda = 1$ GeV) | Experiment |
| $V^{(O)}_{\mathrm{res}}$ | $\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})$ | 3875.8 | Input [19] | Input [19] | $3888.4 \pm 2.5$ [11] |
| | $D^*\bar{D}^*$ | 4017.2 | $4025 \pm 4 - i(21 \pm 7)$ | $4035 \pm 6 - i(29 \pm 13)$ | $4024.1 \pm 1.9$ [11] |
| | $D\bar{D}_s^*/D^*\bar{D}_s$ | 3979.4/3976.9 | $3986 \pm 4 - i(22 \pm 7)$ | $3996 \pm 6 - i(30 \pm 13)$ | $3982.5^{+2.8}_{-3.3} - i25.6^{+12.1}_{-10.6}$ [4] |
| | $D^*\bar{D}_s^*$ | 4120.8 | $4129 \pm 4 - i(21 \pm 7)$ | $4138 \pm 6 - i(28 \pm 12)$ | |

# Zcs signal in $J/\psi K$ channel through pp collider

➢ LHCb measurement of $B^+ \to J/\psi\phi K^+$:

arXiv:2103.01803




Ying-Hui Ge, Xiao-Hai Liu, Hong-wei Ke, arXiv:2103.05282;
Xiaoyun Chen, Yue Tan, Yuan Chen, arXiv:2103.07347;
Ortega, Entem, Fernandez, arXiv:2103.07871;
Hua-Xing Chen, arXiv:2103.08586;
Maiani, Polosa, Riquer, arXiv:2103.08331;
Xuejie Liu, Hongxia Huang, Jialun Ping, Dianyong Chen, Xiemei Zhu, arXiv:2103.12425;
U.Ozdem, A.Karadeniz Yildirim, arXiv:2104.13074;
Pan-Pan Shi, Fei Huang, Wen-Ling Wang, arXiv:2105.02397;
……

$M[Z_{cs}(4000)] = 4003 \pm 6^{+4}_{-14}\ MeV,$

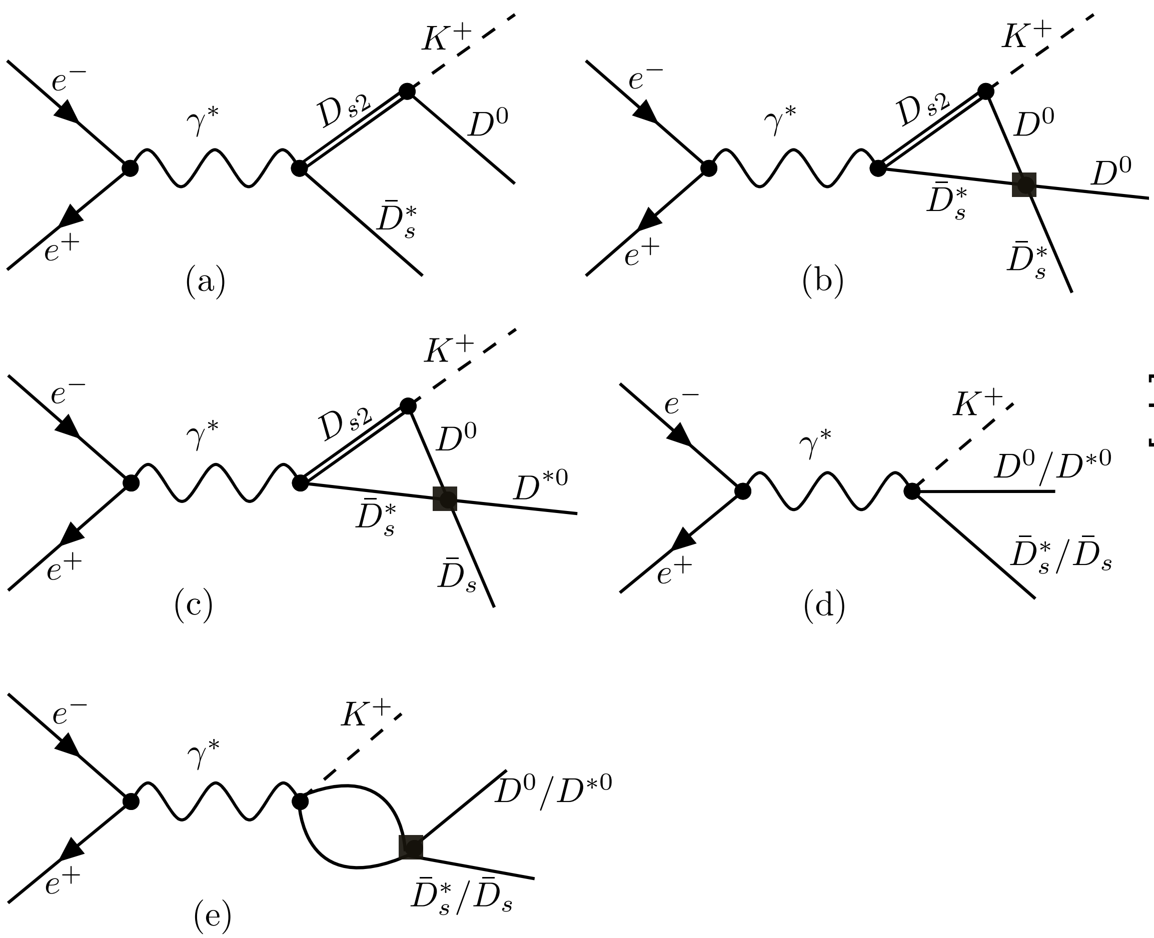
$\Gamma[Z_{cs}(4000)] = 131 \pm 15 \pm 26\ MeV$

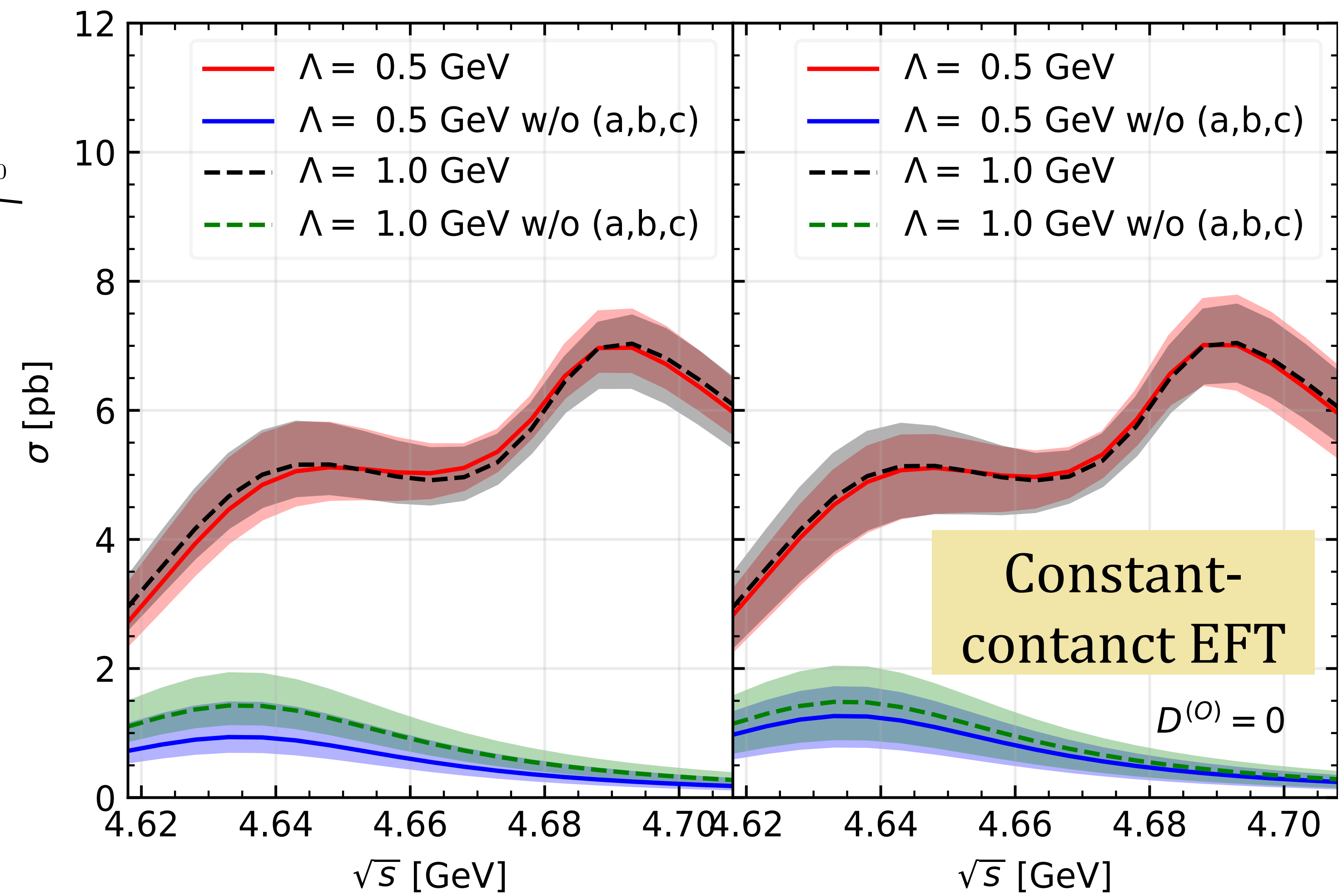
$M[Z_{cs}(4220)] = 4216 \pm 24^{+43}_{-30}\ MeV,$

$\Gamma[Z_{cs}(4220)] = 233 \pm 52^{+97}_{-73} MeV$

# Outlook: Zcs cross section from T-matrix?

- Our cross section and Zcs production cross section of BES3:




| $\sqrt{s}$( GeV) | $\sigma^B \cdot \mathcal{B}$ (pb) |
|---|---|
| 4.628 | $0.8^{+1.2}_{-0.8} \pm 0.6\,(< 3.0)$ |
| 4.641 | $1.6^{+1.2}_{-1.1} \pm 1.3\,(< 4.4)$ |
| 4.661 | $1.6^{+1.3}_{-1.1} \pm 0.8\,(< 4.0)$ |
| 4.681 | $4.4^{+0.9}_{-0.8} \pm 1.4$ |
| 4.698 | $2.4^{+1.1}_{-1.0} \pm 1.2\,(< 4.7)$ |

# Summary

- Two EFTs correspond to two origins: virtual/bound and resonance states. Both can fit the line shapes very well.
- Triangle singularity plays an important role.
- Zc and Zcs are partners in SU(3)-flavor symmetry with molecular configurations.
- High statistic measurements from different channels or energies are needed to:
  - classify the origin of Zcs;
  - reduce the error of pole position.

# Thank you!