Hidden-charm molecule with strangeness

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Based on arXiv: 2011.08725

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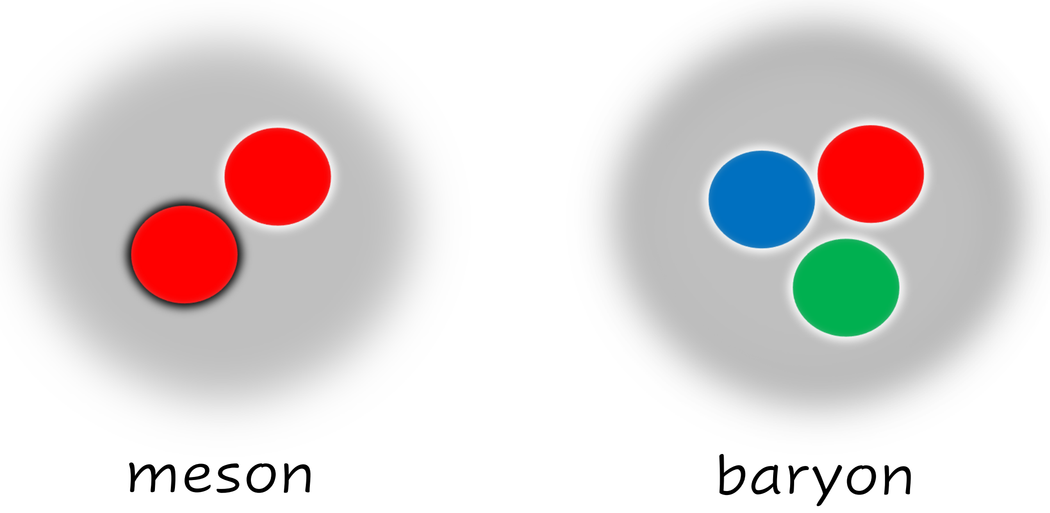
第五届“强子谱和强子结构研讨会”, 2021/1/24

Outline

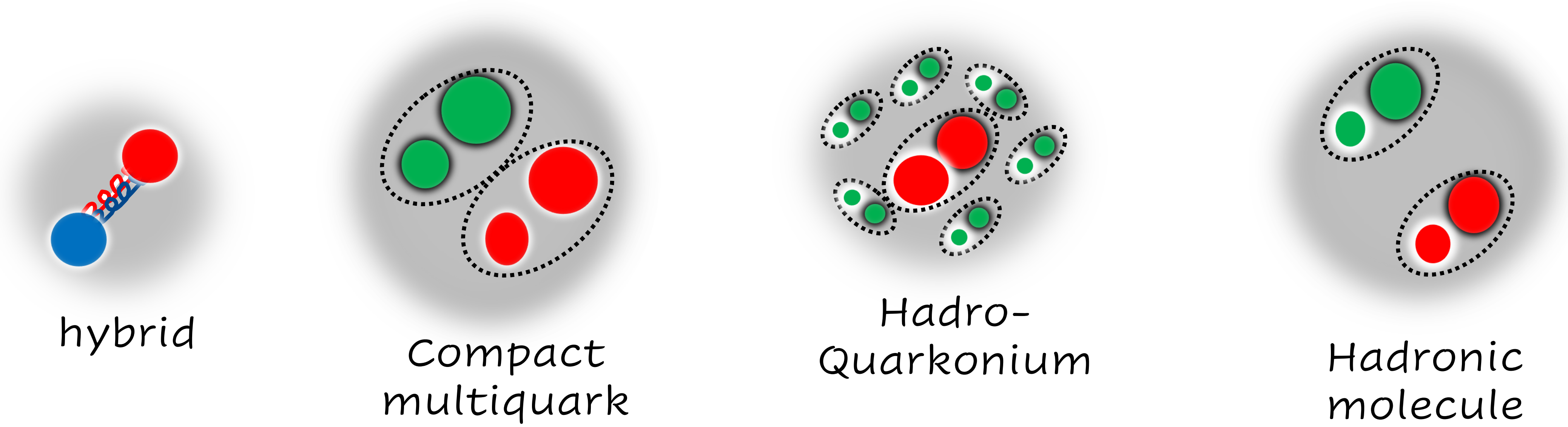
- Hadron structure
- Zc family
- Molecular interpretation of Zc(3900)
- Line shape and pole position of Zcs(3985)
- Summary

Hadron structures

❑ Conventional hadrons



❑ Proposals for the heavy exotic hadrons



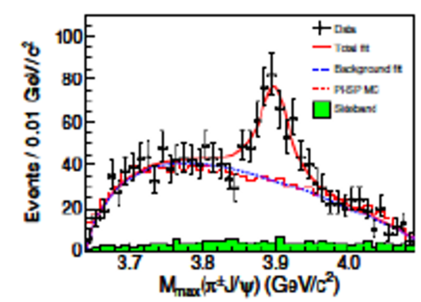
- Hadron structure is a platform to study the QCD in low energy region.
- Quark model classified the hadrons very well.
- However, many new hadrons can not fit into the conventional hadrons (mass and properties).

Exotic hadrons in Zc family

- 2003
- $X(3872)$ observed at Belle
- $X(3872)$ confirmed at D0, CDF
- 2004
- $X(3915)$ [as $Y(3940)$] observed at Belle
- $Y(4260)$ observed at BaBar
- $\chi_{c2}(2P)$ [as $Z(3930)$] observed at Belle
- 2005
- $Y(4260)$ confirmed at CLEO-c
- $X(3940)$, $Y(4008)$, $Y(4660)$ observed at Belle
- $Y(4360)$ observed at BaBar
- 2006
- $Y(4360)$ confirmed at Belle
- $X(3915)$ [as $Y(3940)$] confirmed at BaBar
- $X(3940)$ confirmed at Belle
- 2007
- $Z^{\pm}(4050)$, $X(4160)$, $Z^{\pm}(4250)$, $Z^{\pm}(4430)$, $X(4630)$ observed at Belle
- $Y(4140)$ observed at CDF
- 2008
- $X(3915)$, $X(4350)$, $Y_b(10888)$ observed at Belle
- $\chi_{c2}(2P)$ [as $Z(3930)$] confirmed at BaBar
- $Y(4274)$ observed at CDF
- 2009
- $X(3915)$ confirmed at BaBar
- $Z_b(10610)^{\pm}$ observed and confirmed at Belle
- $Z_b(10650)^{\pm}$ observed and confirmed at Belle
- 2010
- $X(3823)$ [likely $\psi_2(1D)$], $Z_b(10610)^0$ observed and confirmed at Belle
- $Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$ observed at BESIII
- 2011
- $Z_c(3900)^{\pm}$ confirmed at Belle
- $Z_c(3900)^0$ observed at CLEO-c
- $Z_c(4020)^0$ observed at BESIII
- $Y(4140)$ confirmed at D0, CMS
- 2012
- $Y(4274)$ confirmed at CMS
- $Y(4660)$ confirmed at BaBar
- $Z_c(4020)^{\pm}$ confirmed at BESIII
- 2013
- $Z^{\pm}(4200)$ observed at Belle
- $Z^{\pm}(4240)$ observed at LHCb
- $Z^{\pm}(4430)$ confirmed at LHCb
- 2014
- $X(3823)$ [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
- 2015
- $P_c^+(4380)$, $P_c^+(4450)$ observed at LHCb
- $Y_b(10888)$ no longer observed at Belle
- $X(5568)^{\pm}$ observed at D0
- 2016
- $X(5568)^{\pm}$ NOT observed at LHCb
- $Y(4140)$, $Y(4274)$ confirmed at LHCb
- $X(4500)$, $X(4700)$ observed at LHCb

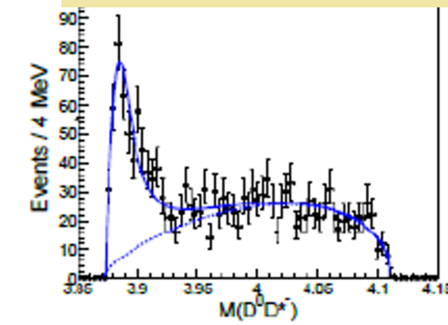
Lebed, Mitchell, Swanson, PPNP93(2017)143

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



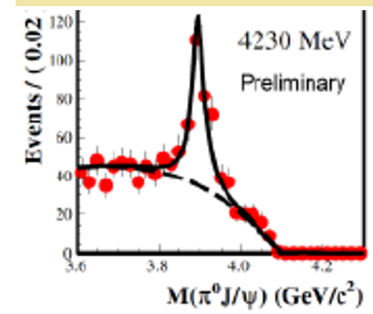
$e^+e^- \to \pi^-\pi^+ J/\psi$

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



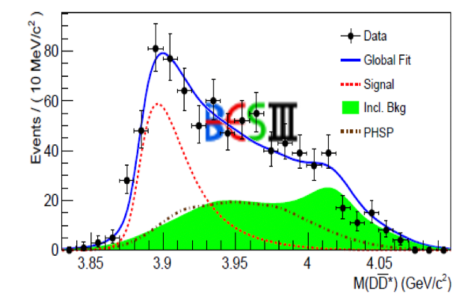
$e^+e^- \to \pi^-(D\bar{D}^*)^+$

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



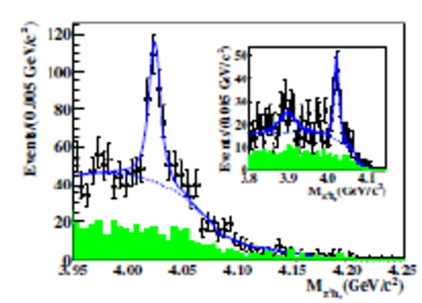
$e^+e^- \to \pi^0\pi^0 J/\psi$

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



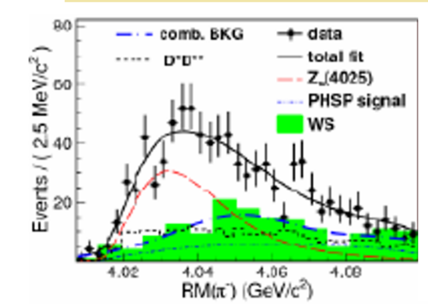
$e^+e^- \to \pi^0(D^*\bar{D})^0$

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



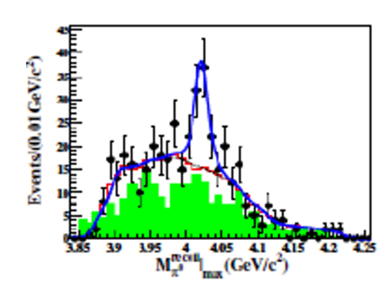
$e^+e^- \to \pi^-\pi^+ h_c$

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



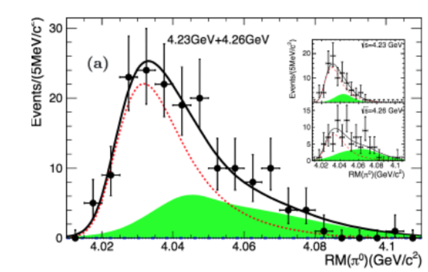
$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

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



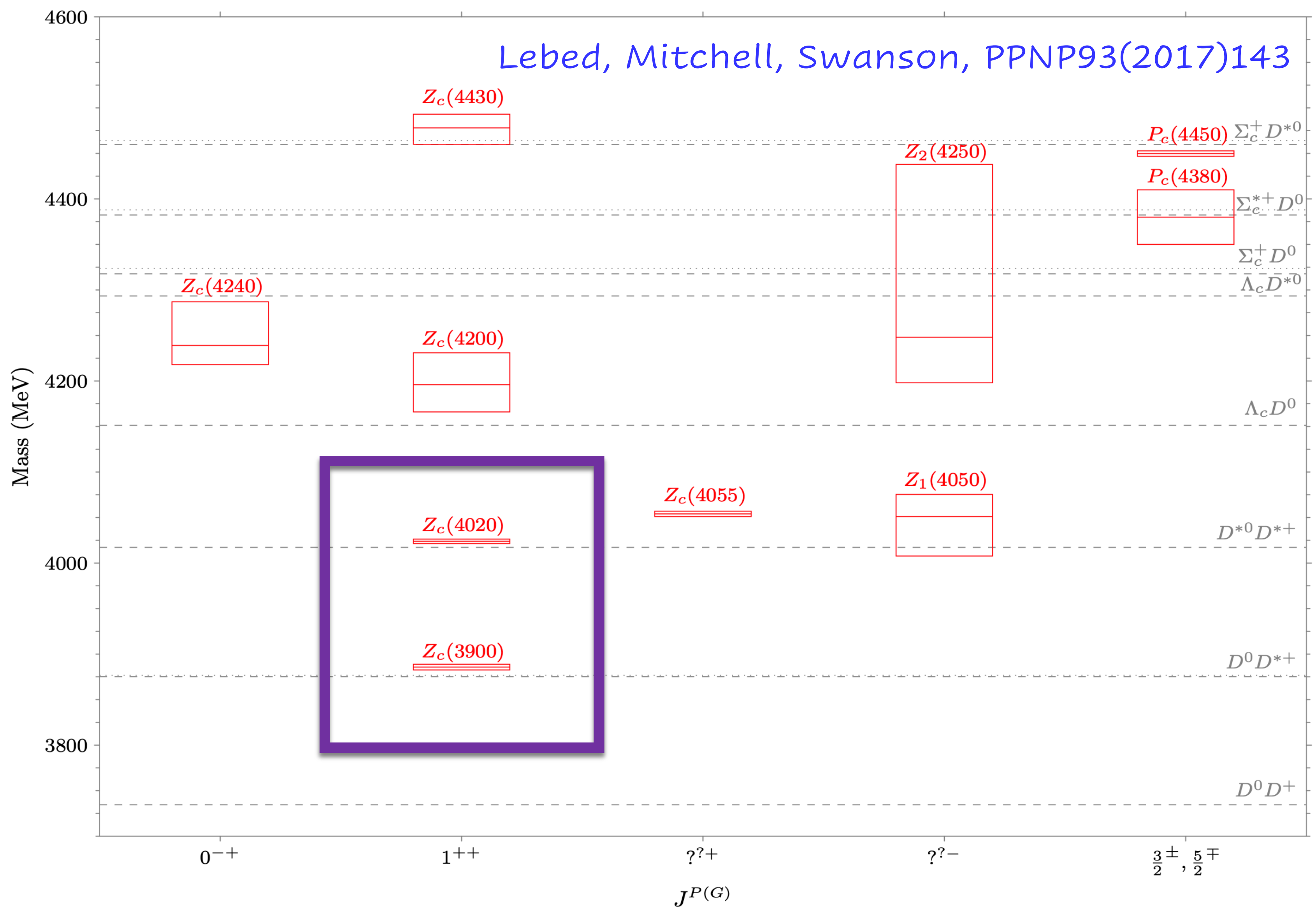
$e^+e^- \to \pi^0\pi^0 h_c$

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



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

Exotic hadrons in Zc family



- Zc states were observed in the hidden- and open-charm channel;
- Unsuccessful searches for Zcs by Belle and BES3 in the hidden channel.

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

Zc(3900): kinematical effect or molecular?

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

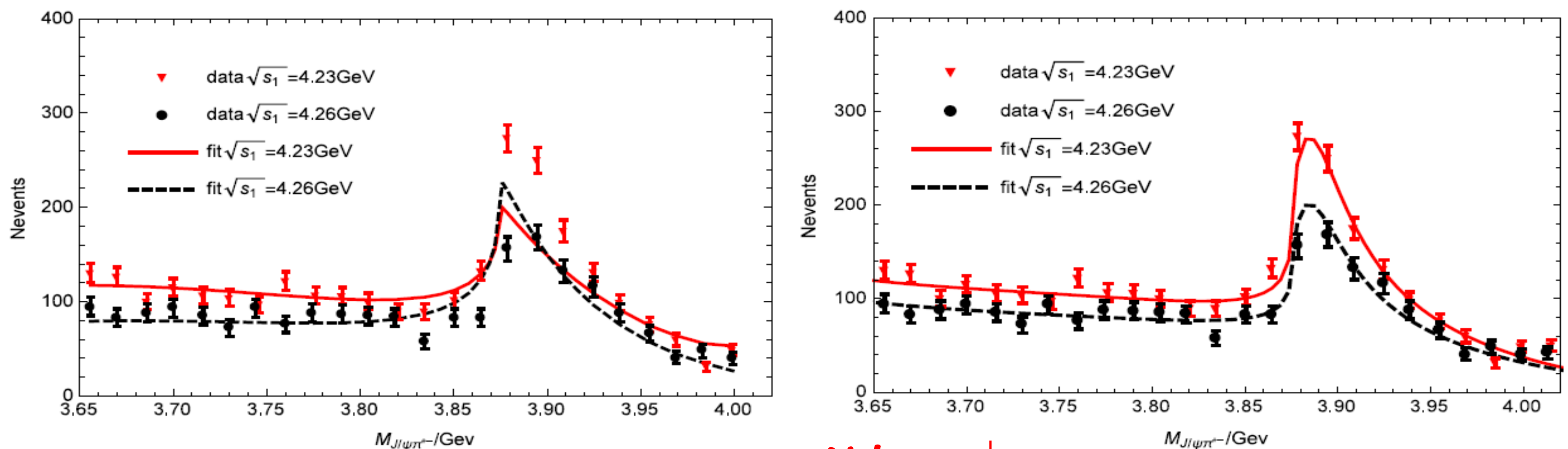
BESIII, PRL110(2013)252001; Belle, PRL110(2013)252002

- 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) Triangle singularity

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

(b) 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.

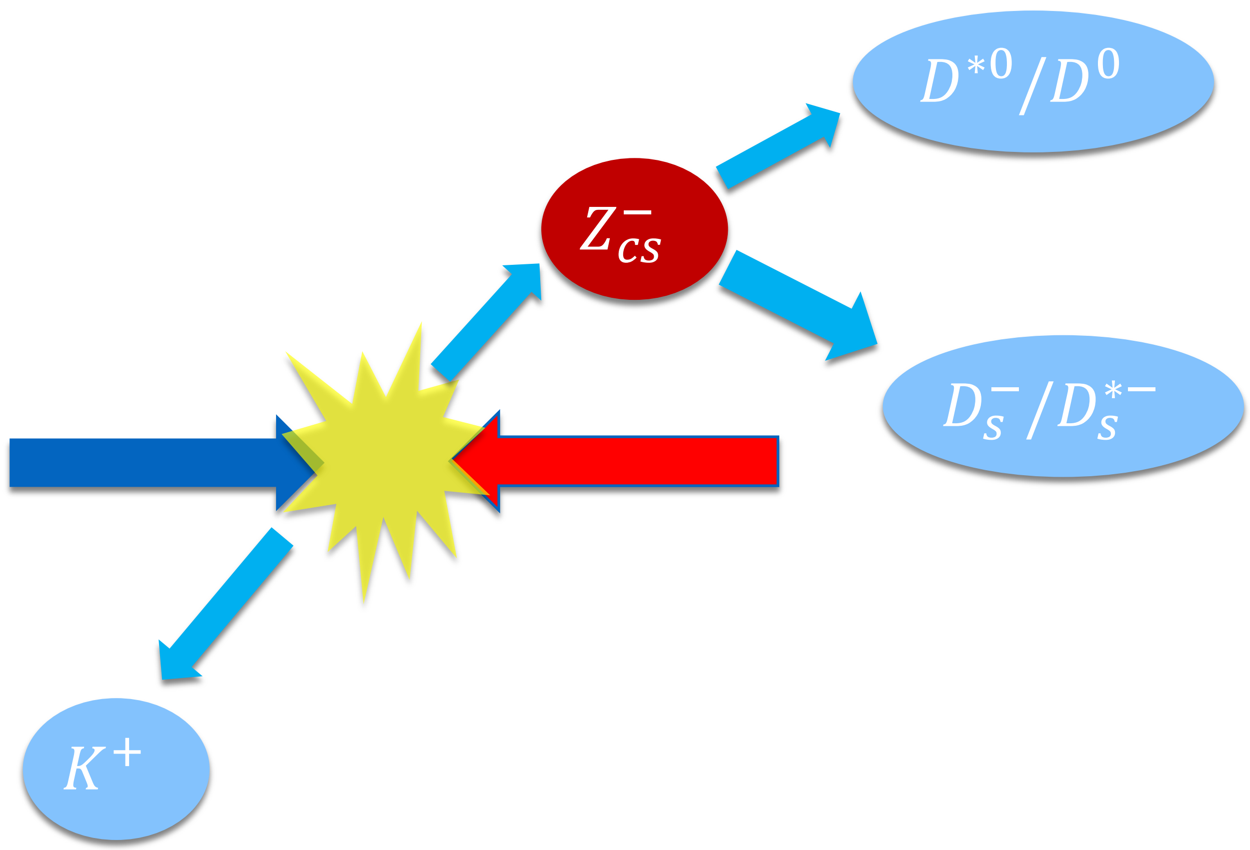
Belle, PRD90(2014)112009

- 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. The isospin of the $Z_c(3900)$ is 1, while for the X(3872) is 0.
- The production of the $D^*\bar{D}$ pair with isospin 1 is highly suppressed in B decays.

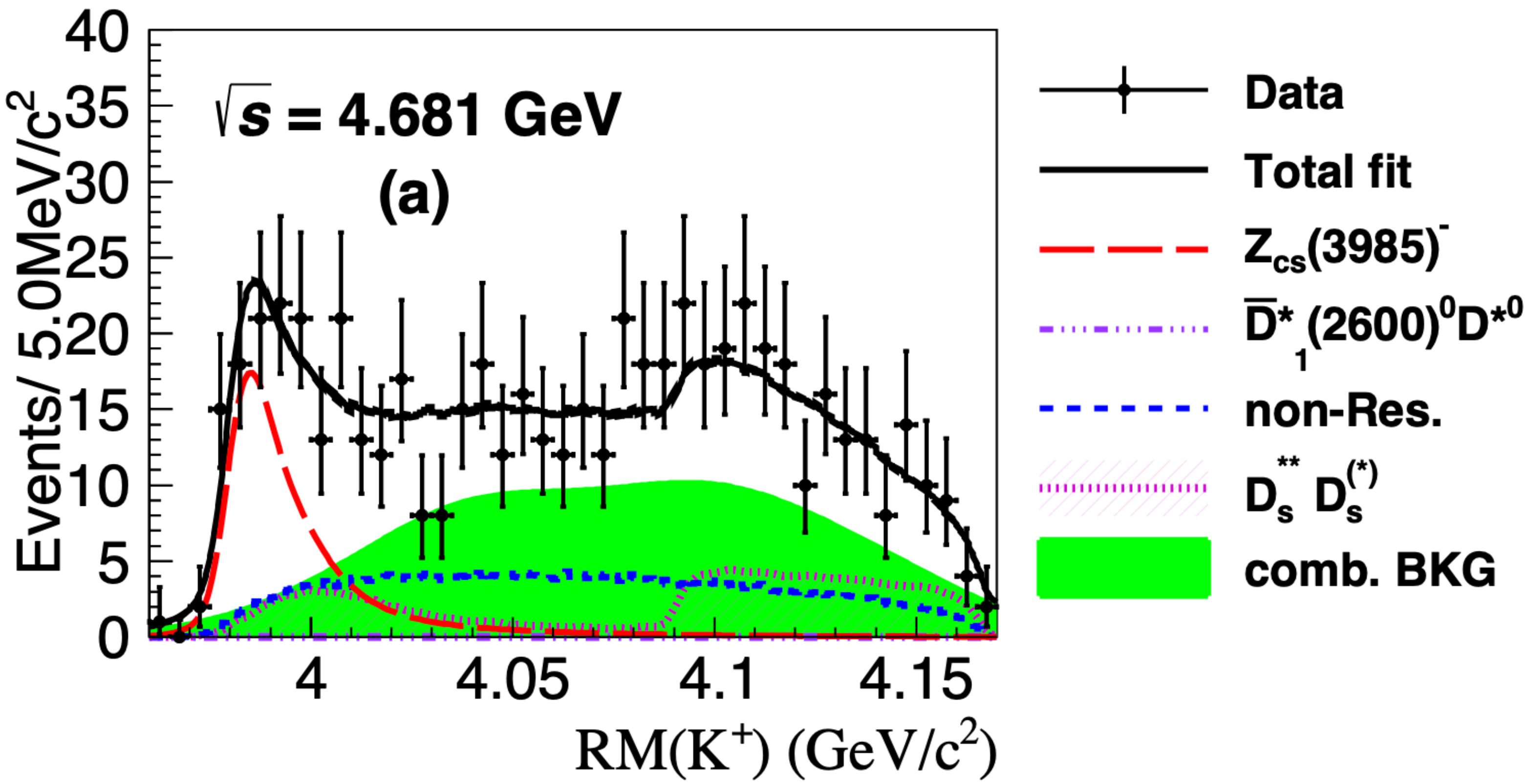
  → The Zc(3900) being a $D^*\bar{D}$ hadronic molecule naturally explains its absence in the B decays.

Yang, Wang and Meissner, PLB775(2017)50

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



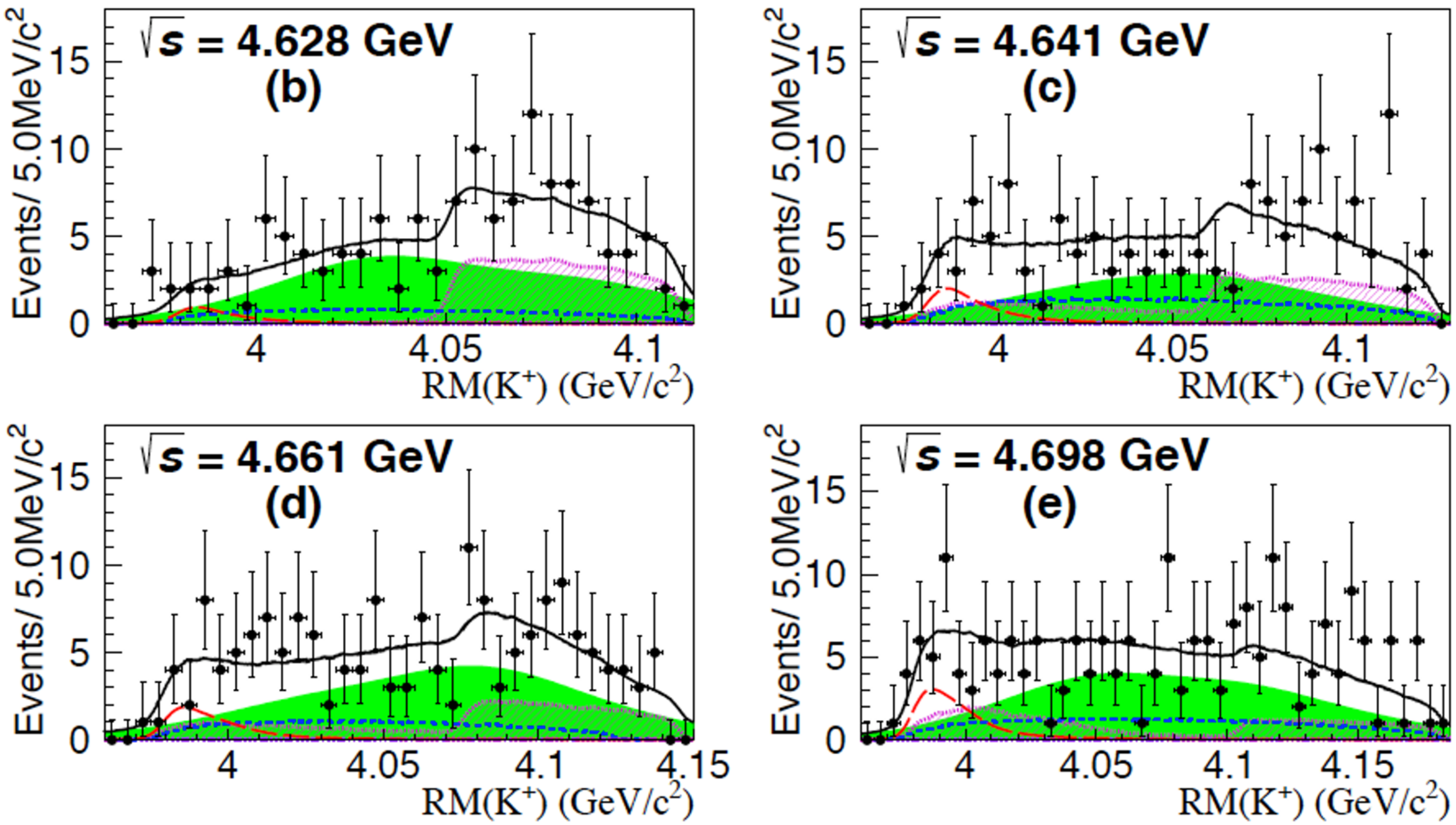
- The recoil mass distribution was studied by BES3;
- A clear peak was found at energy point 4.681GeV;
- Search at other 4 energies was also performed.



arXiv: 2011.07855

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

➢ 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

arXiv: 2011.07855

➢ There exists one particle in the energy range:

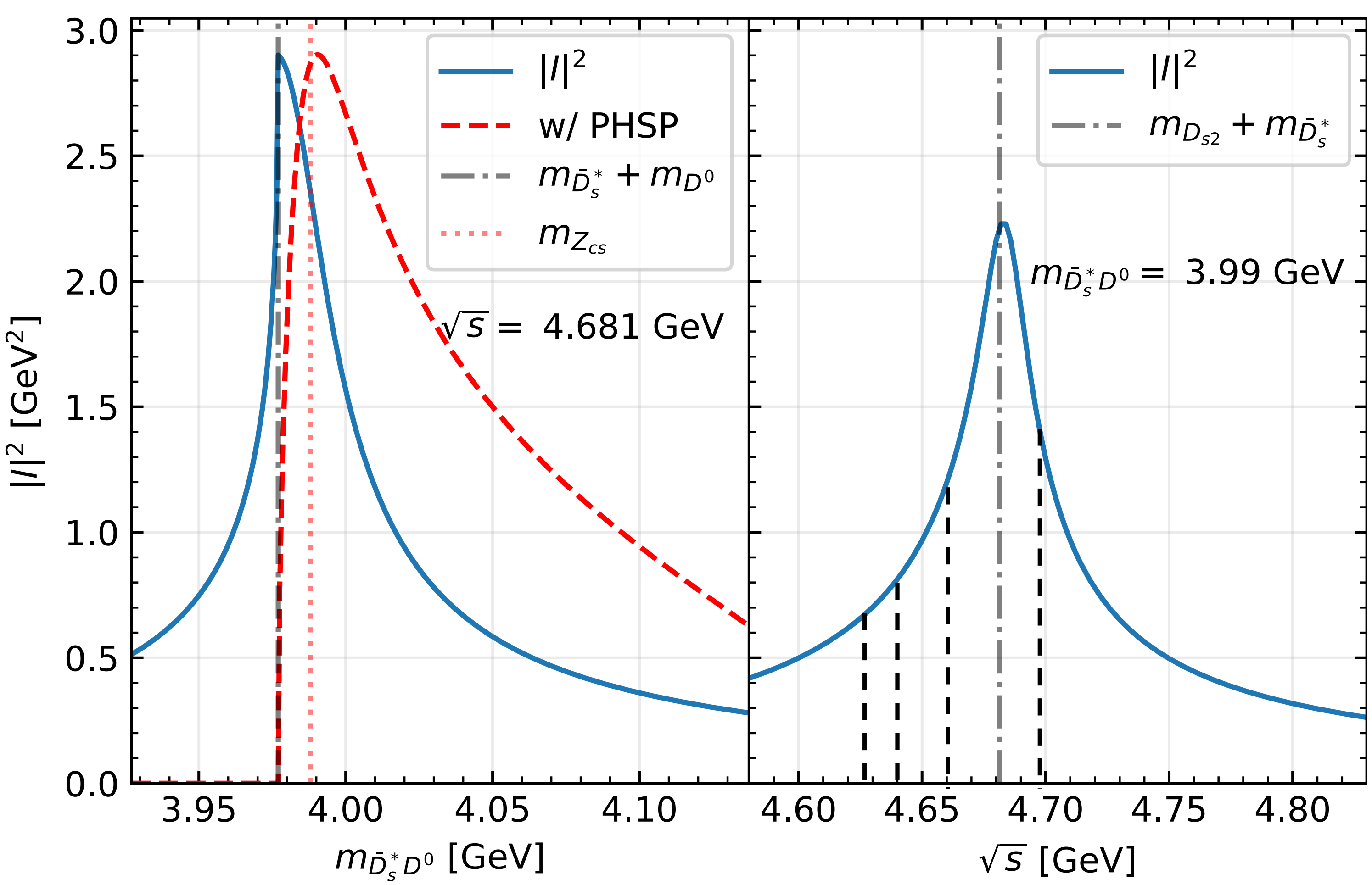
$\psi(4660)$ $\quad I^G(J^{PC}) = 0^-(1^{--})$

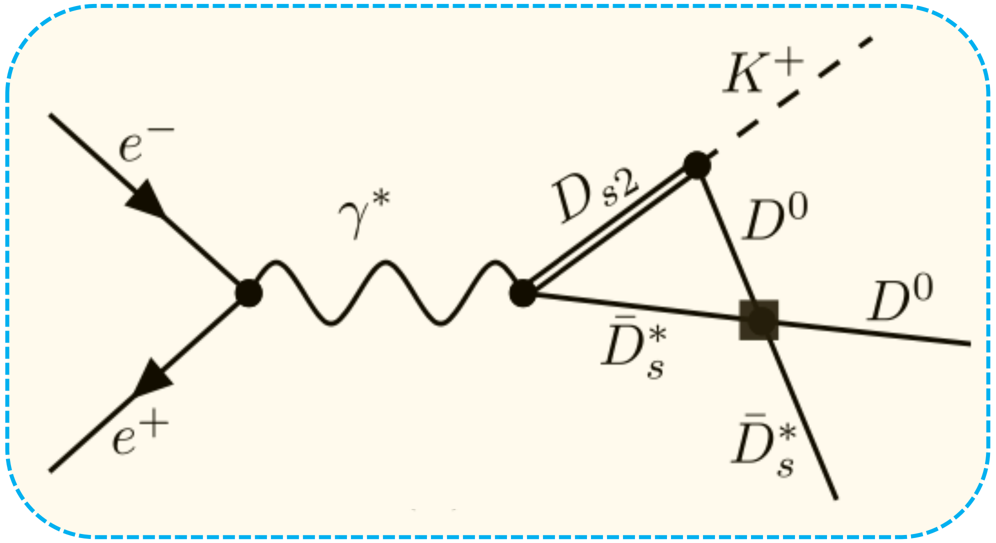
$\psi(4660)$ MASS	4633 ± 7 MeV (S = 1.4)
$\psi(4660)$ WIDTH	64 ± 9 MeV

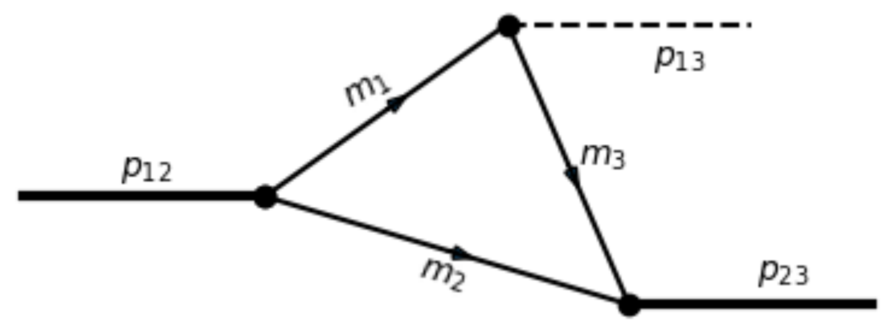
Triangle singularity in Zcs production

- 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, <u>4.681</u>, 4.698] GeV

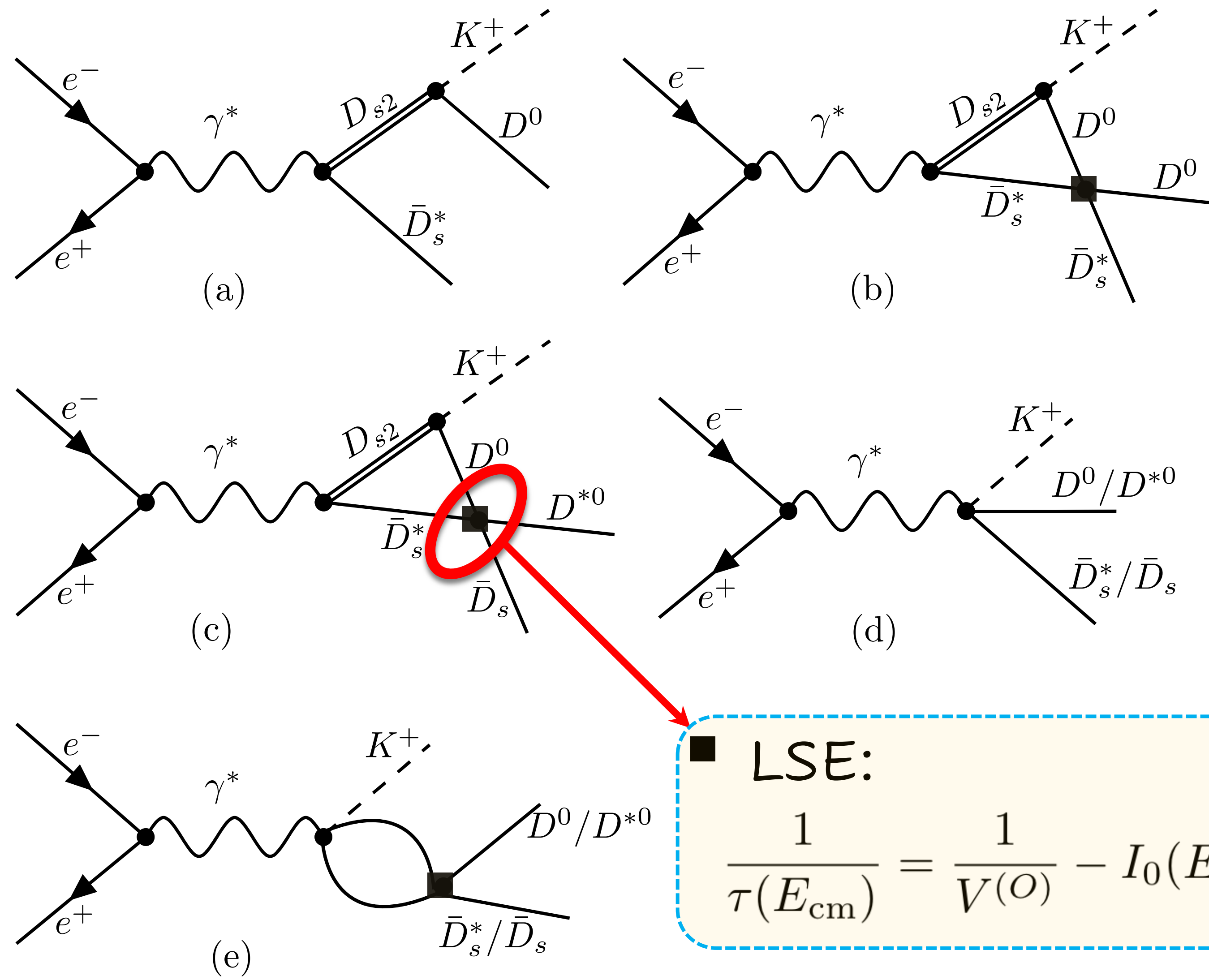
Zcs in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

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

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

- Resonance EFT:

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



- LSE:

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

Other fit parameters:

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

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

$\sqrt{s}$(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	$2.4^{+1.1}_{-1.0} \pm 1.2\,(< 4.7)$

arXiv: 2011.07855

Fits of Zcs line shapes

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

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

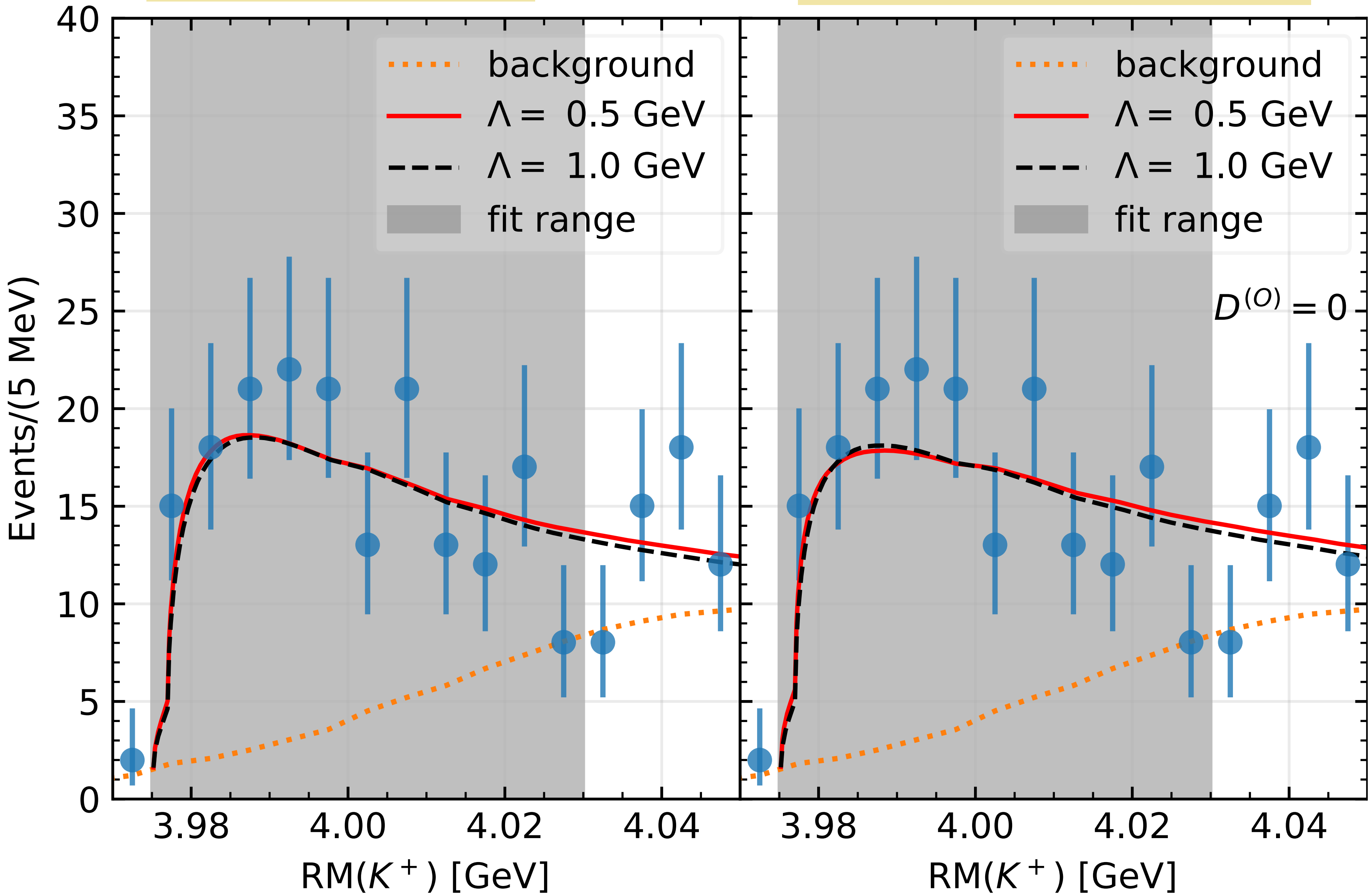
- Resonance EFT:

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

Energy points: 4.681 GeV

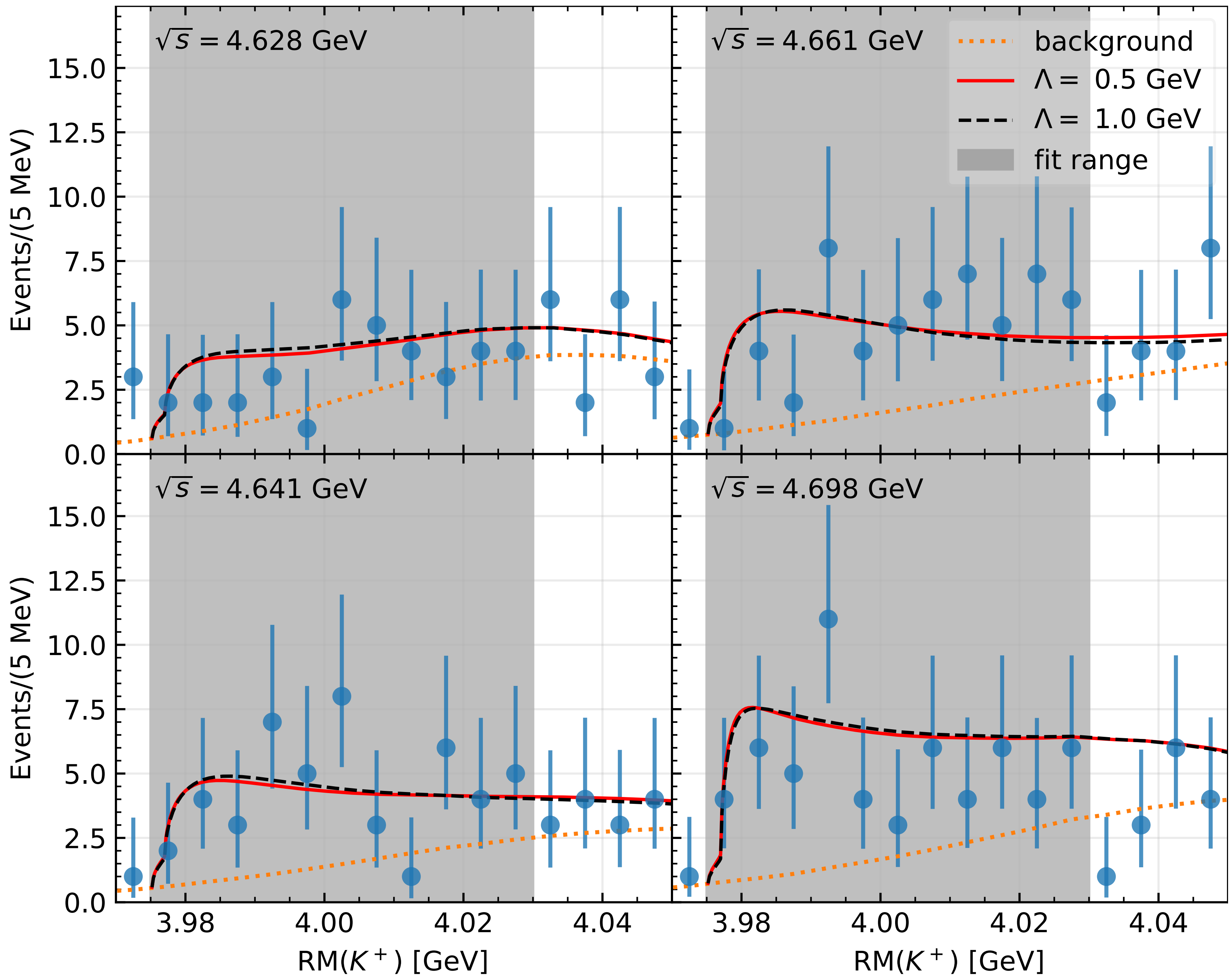
Resonance EFT

Constant-contact EFT



Fits of Zcs line shapes

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



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:

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

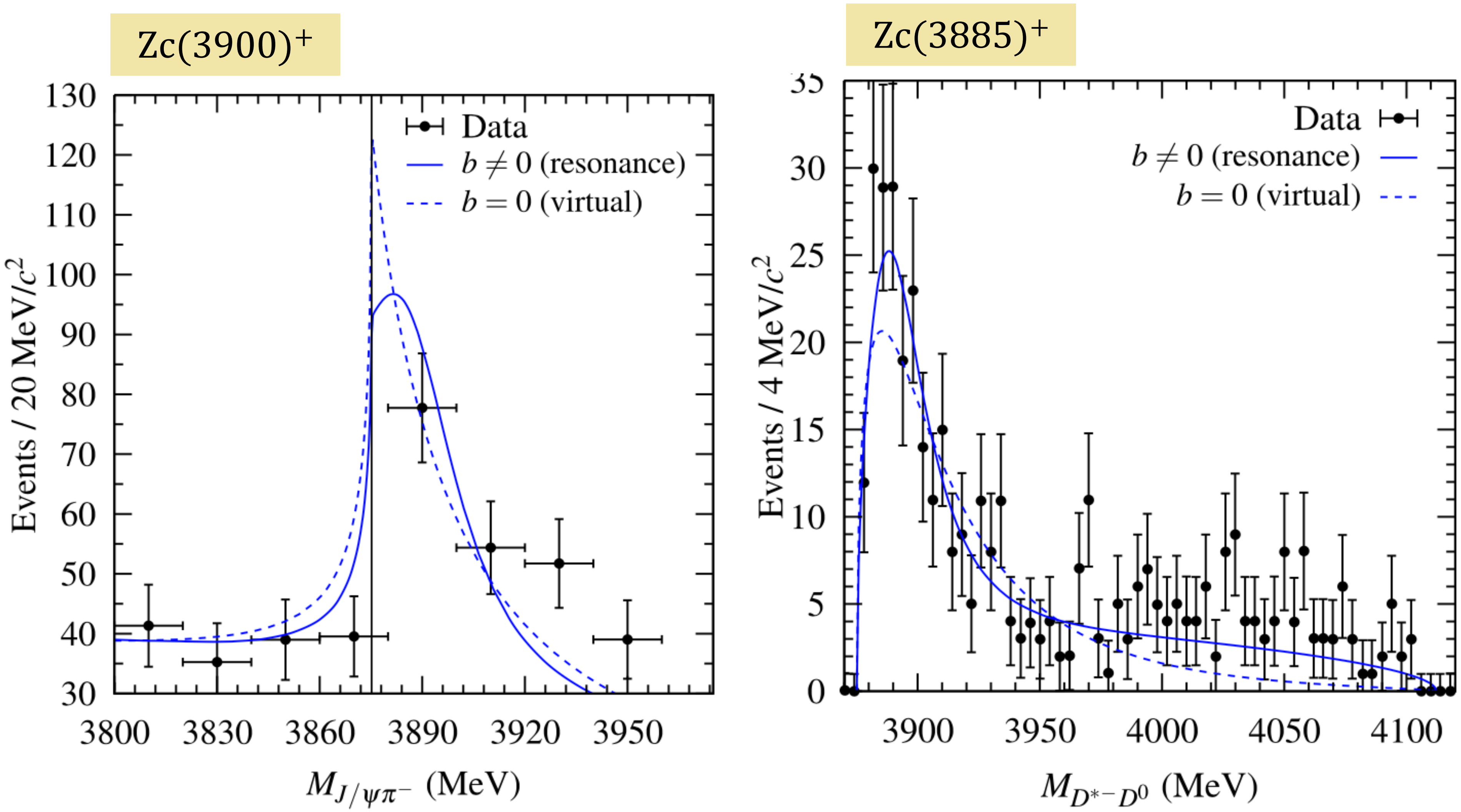
  for resonant EFT:

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

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 ± 2.5 [11]
	$D^*\bar{D}^*$	4017.2	4014^{+2}_{-3}	4012^{+3}_{-6}	4024.1 ± 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 ± 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 ± 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)



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:

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

  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 ± 2.5 [11]
	$D^*\bar{D}^*$	4017.2	3988^{+21}_{-27}	3978^{+25}_{-36}	4024.1 ± 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 ± 2.5 [11]
	$D^*\bar{D}^*$	4017.2	$4025 \pm 4 - i(21 \pm 7)$	$4035 \pm 6 - i(29 \pm 13)$	4024.1 ± 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	$4129 \pm 4 - i(21 \pm 7)$	$4138 \pm 6 - i(28 \pm 12)$	

[19] Albaladejo, Guo, Hidalgo and Nieves, PLB755,337

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!