Zc states in a Chiral Quark Model

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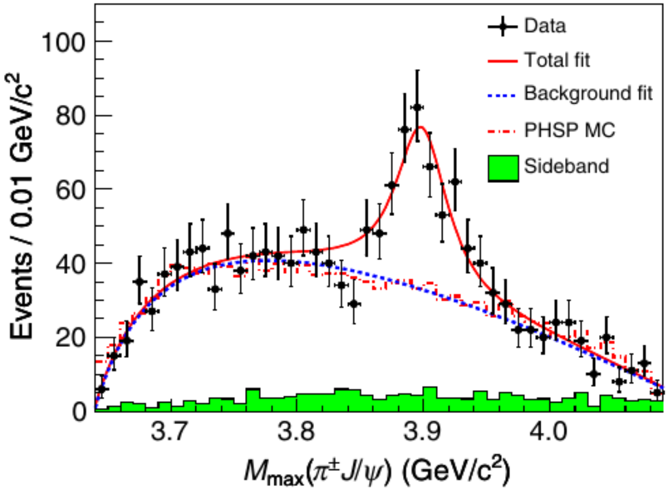
Introduction

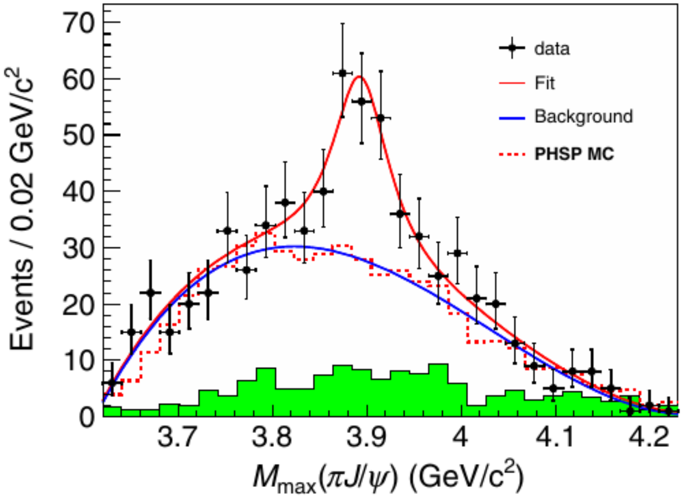
- *From the November revolution in 1974 up to the discovery of the X(3872) in 2003 all the heavy mesons were well accommodated in the naive quark model*
- *For the X(3872) the ratio* $\frac{\Gamma(\omega J/\psi)}{\Gamma(\pi^+\pi^- J/\psi)} = 0.8 \pm 0.3$ *is difficult to understand as a pure* $c\bar{c}$ *state*
- *The ratio can be easily explained in the molecular picture due to the mass difference between the charged and neutral D and D* mesons.*
- *The Ds0(2317) and Ds1(2460) are predicted by most quark models at energies aroung 2.5 GeV*
- *In 2011 the charged Zb(10610) and Zb(10650) mesons were discovered which are evidences of non naive quark model states*
- *Later in 2013 the analogs in the charmonium sector were found*

Zc(3900) state

$e^+e^- \to \pi^+\pi^- J/\psi$ Charged $Z_c^\pm$

BESIII, Phys. Rev. Lett. 110, 252001 | *Belle, Phys. Rev. Lett. 110, 252002*





$M = (3899.0 \pm 3.6)\ \mathrm{MeV/c^2}$

$\Gamma = (46 \pm 10)\ \mathrm{MeV}$

$M = (3894.5 \pm 6.6 \pm 4.5)\ \mathrm{MeV/c^2}$

$\Gamma = (63 \pm 24 \pm 26)\ \mathrm{MeV}$

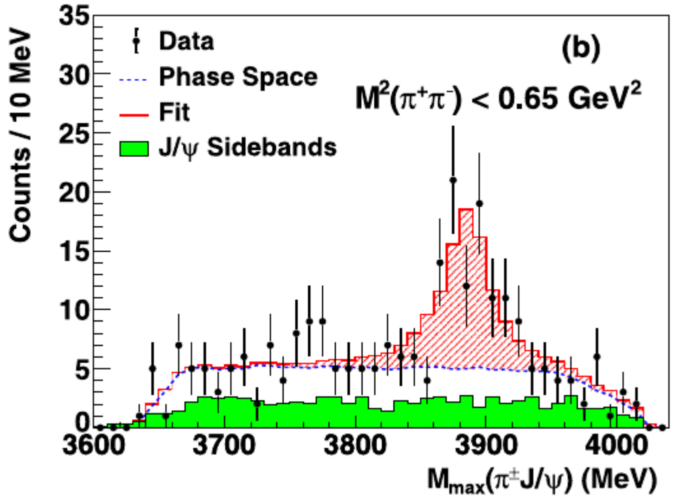
$\sqrt{s} = 4.26\ \mathrm{GeV}\ Y(4260)$

Zc(3900) state

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

Analysis of CLEO-c data, Phys. Lett. B727, 366 (2013)

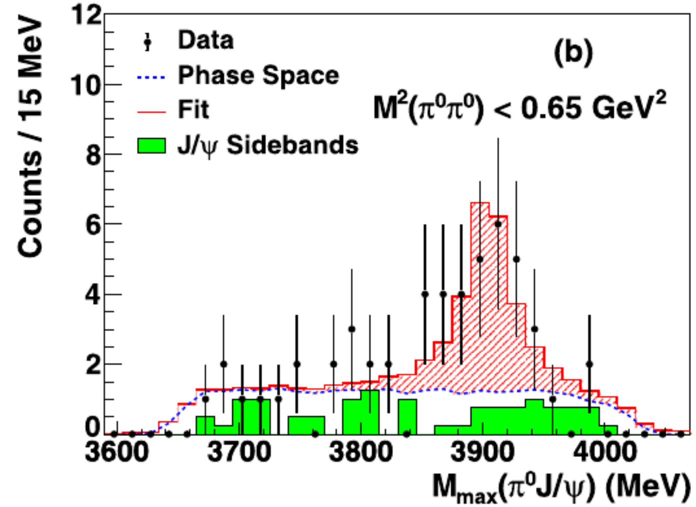
Charged



$M = (3886.0 \pm 4 \pm 2)\ \mathrm{MeV/c^2}$

$\Gamma = (37 \pm 4 \pm 8)\ \mathrm{MeV}$

Neutral (confirmed by BESIII 2015)



$M = (3904 \pm 9 \pm 5)\ \mathrm{MeV/c^2}$

$\Gamma = 37\ \mathrm{MeV}\ \text{(fixed)}$

$\sqrt{s} = 4.17\ \mathrm{GeV}$ $Y(4260)$? *Different energy*

Zc(3900)/Zc(3885) state

- *Confirmed by BESIII in* $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ *compatible with* $J^P = 1^+$
- *It was labelled as* $Z_c(3885)$ $M = (3883.9 \pm 1.5 \pm 4.2)$ MeV$/c^2$

  $$\Gamma = (24.8 \pm 3.3 \pm 11.0) \text{ MeV}$$
- *BESIII, Phys. Rev. Lett. 119, 072001 (2017) determined* $J^P = 1^+$ *for the*

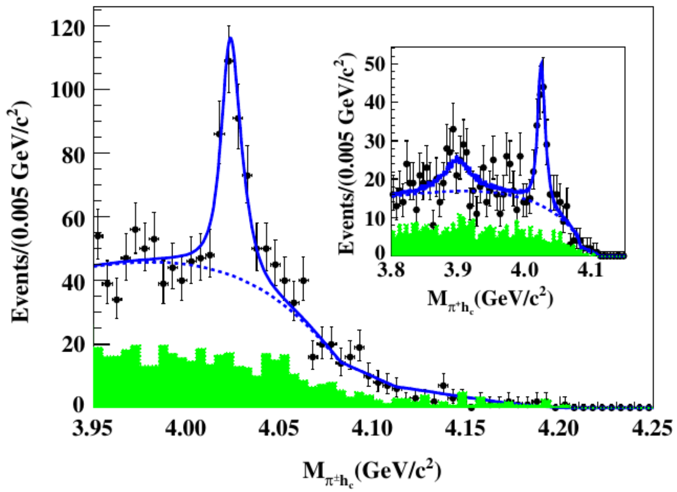
  $$Z_c(3900) \; M = (3881.2 \pm 4.2 \pm 52.7) \text{ MeV}/c^2$$

  $$\Gamma = (51.8 \pm 4.6 \pm 36.0) \text{ MeV}$$
- *They are seen as the same state*

Zc(4020) state

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

BESIII, Phys. Rev. Lett. 111, 242001



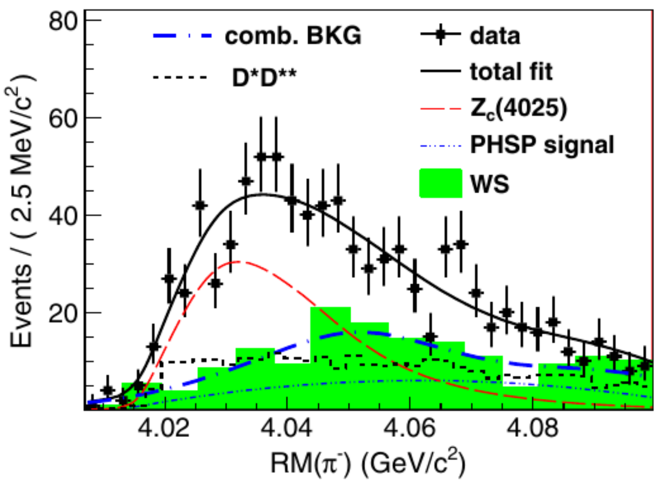
$$M = (4022.9 \pm 0.8 \pm 2.7)\ \mathrm{MeV/c^2}$$

$$\Gamma = (7.9 \pm 2.7 \pm 2.6)\ \mathrm{MeV}$$

$$\sqrt{s} = 4.23, 4.26, 4.36\ \mathrm{GeV}$$

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

BESIII, Phys. Rev. Lett. 112, 132001



$$M = (4026.3 \pm 2.6 \pm 3.7)\ \mathrm{MeV/c^2}$$

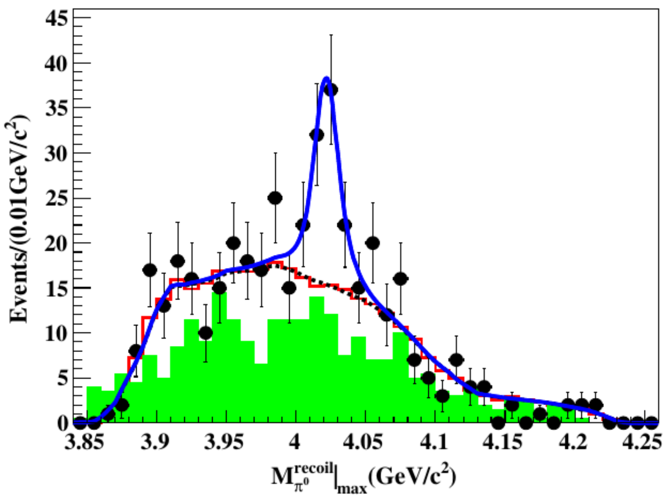
$$\Gamma = (24.8 \pm 5.6 \pm 7.7)\ \mathrm{MeV}$$

$$\sqrt{s} = 4.26\ \mathrm{GeV}$$

Zc(4020) state

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

BESIII, Phys. Rev. Lett. 113, 212002



Neutral state confirmed

$$M = (4023.9 \pm 2.2 \pm 2.8)\ \mathrm{MeV/c^2}$$

$$\Gamma = (7.9 \pm 2.6)\ \mathrm{MeV}\ \mathrm{(fixed)}$$

$$\sqrt{s} = 4.23, 4.26, 4.36\ \mathrm{GeV}$$

Theoretical interpretation

- *Since the states are charged they can not be pure quark-antiquark states*
- *More complex structures are needed*
- *The closest thresholds are* $D\bar{D}^*$ and $D^*\bar{D}^*$
- *They could be*
  - *Hadron molecules*

F.-K. Guo, C. Hidalgo-Duque, J. Nieves, and M. P. Valderrama, Phys. Rev. **D88**, 054007 (2013), arXiv:1303.6608 [hep-ph].

J. He, X. Liu, Z.-F. Sun, and S.-L. Zhu, Eur. Phys. J. **C73**, 2635 (2013), arXiv:1308.2999 [hep-ph].
X.-H. Liu, L. Ma, L.-P. Sun, X. Liu, and S.-L. Zhu, Phys. Rev. **D90**, 074020 (2014), arXiv:1407.3684 [hep-ph].

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  - *Tetraquarks*

A. Esposito, A. L. Guerrieri, F. Piccinini, A. Pilloni, and A. D. Polosa, Int. J. Mod. Phys. **A30**, 1530002 (2015), arXiv:1411.5997 [hep-ph].
J. M. Dias, F. S. Navarra, M. Nielsen, and C. M. Zanetti, Phys. Rev. **D88**, 016004 (2013), arXiv:1304.6433 [hep-ph].
S. S. Agaev, K. Azizi, and H. Sundu, Phys. Rev. **D96**, 034026 (2017), arXiv:1706.01216 [hep-ph].
Z.-G. Wang and T. Huang, Phys. Rev. **D89**, 054019 (2014), arXiv:1310.2422 [hep-ph].
C.-F. Qiao and L. Tang, Eur. Phys. J. **C74**, 3122 (2014), arXiv:1307.6654 [hep-ph].
C. Deng, J. Ping, and F. Wang, Phys. Rev. **D90**, 054009 (2014), arXiv:1402.0777 [hep-ph].

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  - *Tetraquarks*
  - *Threshold effects*

E. S. Swanson, Phys. Rev. **D91**, 034009 (2015), arXiv:1409.3291 [hep-ph].
E. S. Swanson, Int. J. Mod. Phys. **E25**, 1642010 (2016), arXiv:1504.07952 [hep-ph].

Theoretical interpretation

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  - *Hadron molecules*
  - *Tetraquarks*
  - *Threshold effects*
  - *LQCD studies*

S. Prelovsek, C. B. Lang, L. Leskovec, and D. Mohler, Phys. Rev. **D91**, 014504 (2015), arXiv:1405.7623 [hep-lat].
S. Prelovsek and L. Leskovec, Phys. Lett. **B727**, 172 (2013), arXiv:1308.2097 [hep-lat].
Y. Chen *et al.*, Phys. Rev. **D89**, 094506 (2014), arXiv:1403.1318 [hep-lat].
Y. Chen *et al.* (CLQCD), Phys. Rev. **D92**, 054507 (2015), arXiv:1503.02371 [hep-lat].
S.-h. Lee, C. DeTar, H. Na, and D. Mohler (Fermilab Lattice, MILC), (2014), arXiv:1411.1389 [hep-lat].
Y. Ikeda, S. Aoki, T. Doi, S. Gongyo, T. Hatsuda, T. Inoue, T. Iritani, N. Ishii, K. Murano, and K. Sasaki (HAL QCD), Phys. Rev. Lett. **117**, 242001 (2016), arXiv:1602.03465 [hep-lat].

Theoretical interpretation

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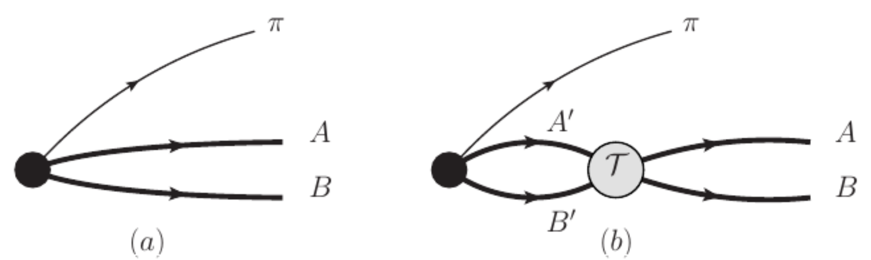
Works on Effective Field Theories

- *F.-K. Guo et al. (Phys. Rev. D 91, 051504) showed the pronounced peak needs a virtual or molecular state*
- *F. Aceti et al. (Phys. Rev. D 90, 016003) found a I=1 barely* $D\bar{D}^*$ *bound state with a mass around 3869-3875 MeV*
- *M. Albaladejo et al. (Phys. Lett. B755, 337) found more likely to be a threshold nearby resonance or virtual state and a bound state was disfavored*
- *J. He at al. (Eur. Phys. J. C 78, 94) found a virtual state*

Works on Lattice QCD

- *S. Prelovsek et al. (Phys. Rev. D91, 014504) does not found a candidate*
- *Y. Chen et al. (Phys. Rev. D89, 094506) does not support a shallow bound state*
- *Y. Ikeda et al. (Phys. Rev. Lett. 117, 242001) found that the interaction is dominated by off-diagonal terms supporting a threshold cusp*

Line shapes



$$A + B = \{\pi J/\psi,\ \rho\eta_c,\ D\bar{D}^*,\ D^*\bar{D}^*\}$$

Mass distribution

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{k_{AB}k_{\pi Z_c}}{4\,s}|\mathcal{M}^\beta(m_{AB})|^2 dm_{AB}$$

Production amplitude only in S-waves

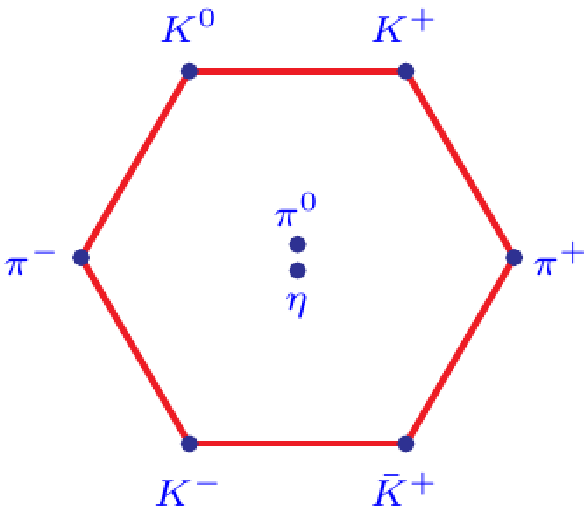
$$\mathcal{M}^\beta(m_{AB}) = \left(\mathcal{A}^\beta - \sum_{\beta'}\mathcal{A}^{\beta'}\int d^3p\frac{t^{\beta'\beta}(p,k^\beta,E)}{p^2/2\mu - E - i0}\right)$$

Number of events

$$N(m_{AB}) = \mathcal{N}_{AB}\times\frac{d\Gamma}{dm_{AB}}$$

The Chiral Quark model

- *Spontaneous Chiral Symmetry Breaking*
  Pseudo-goldstone boson exchange
- *One gluon exchange*
- *Confinement*



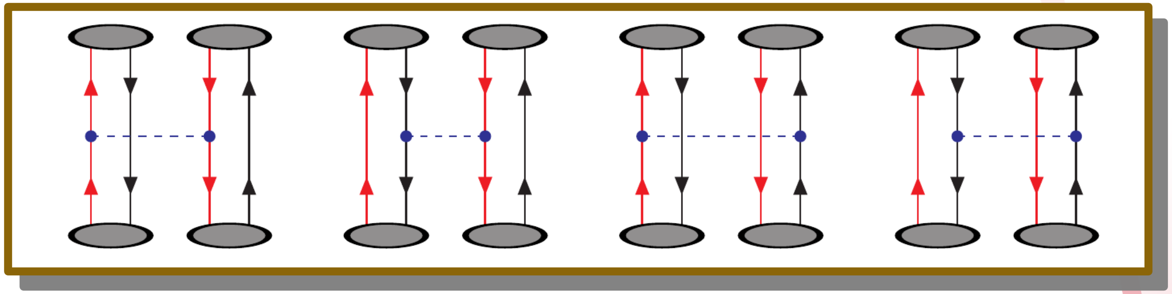
$$V_{q_i q_j} = \begin{cases} q_i q_j = nn \Rightarrow V_{CON} + V_{OGE} + V_{GBE} + V_{SBE} \\ q_i q_j = nQ \Rightarrow V_{CON} + V_{OGE} \\ q_i q_j = QQ \Rightarrow V_{CON} + V_{OGE} \end{cases}$$

A. Manohar and H. Georgi, Nucl. Phys. B 324 (1984)
F. Fernández et al., J. Phys. G 19 (1993)

Two meson dynamics

Direct terms:

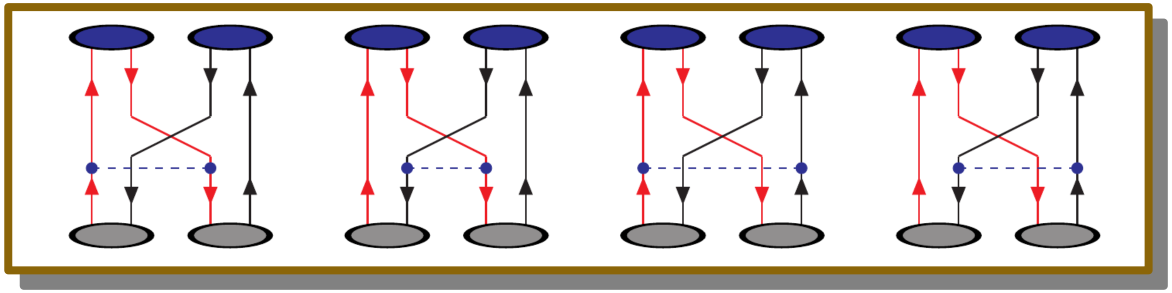
- *No change of quark content*
- *Cancel for color interactions*



$D^{(*)}\bar{D}^{*} \to D^{(*)}\bar{D}^{*}$ *No contribution for* $\pi J/\psi \to \pi J/\psi$

Rearrangement process:

- *Change quark content*
- *Color interactions contribute*



$D^{(*)}\bar{D}^{*} \to \pi J/\psi$ *Non-diagonal terms*

Results

$$I^G(J^{PC}) = 1^+(1^{+-})$$

We include the closest thresholds and the $\pi J/\psi$

$$\pi J/\psi\ (3234.19\ \mathrm{MeV}/c^2)$$

$$\rho\eta_c\ (3755.79\ \mathrm{MeV}/c^2)$$

$$D\bar{D}^*\ (3875.85\ \mathrm{MeV}/c^2)$$

$$D^*\bar{D}^*\ (4017.24\ \mathrm{MeV}/c^2)$$

We do a χ^2 *fit to the data*

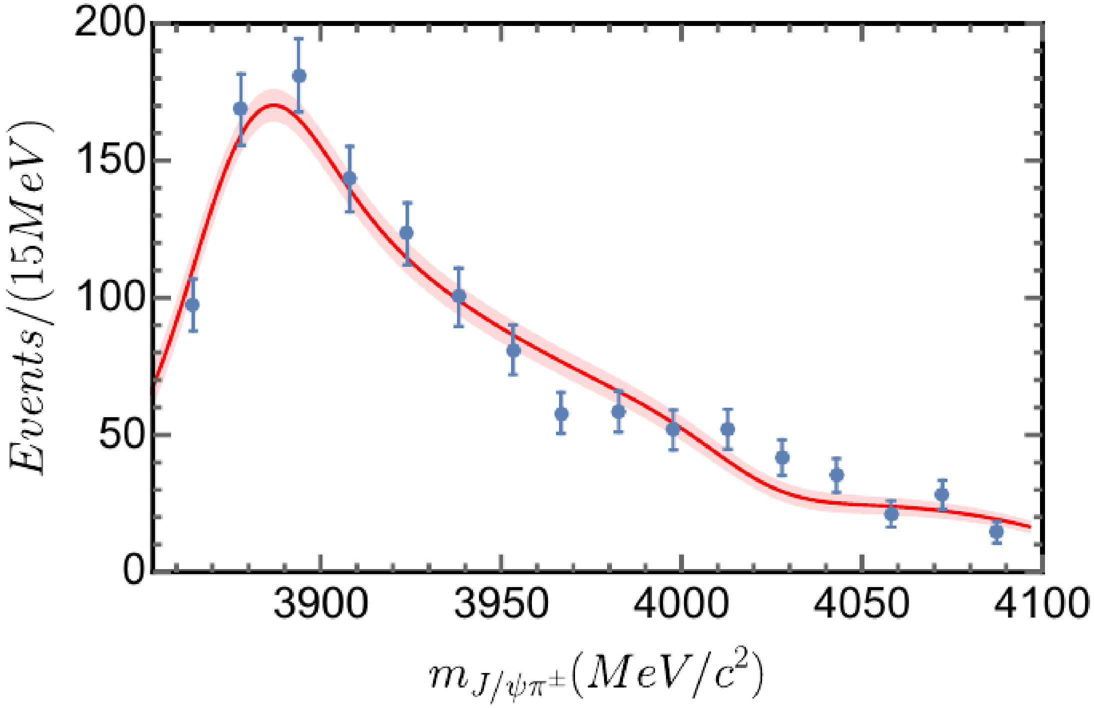
$$\chi^2(\{\mathcal{A},\mathcal{N}\}) = \sum_i \left(\frac{N^{\mathrm{the}}(x_i) - N^{\exp}(x_i)}{\sigma_i^{\exp}}\right)^2$$

Channel	$\mathcal{N}_{AB}(\times 10^7)$	$\mathcal{A}_{AB}$
$\pi J/\psi$	3.76 ± 0.09	0.34 ± 0.01
$D\bar{D}^*$	0.80 ± 0.04	0.76 ± 0.01
$D^*\bar{D}^*$	19.33 ± 0.7	0.66 ± 0.01
$\rho\eta_c(1S)$		-1.00 ± 0.04
$\chi^2_{\min}/\mathrm{d.o.f.}$	1.89	

Lineshapes for πJ/ψ

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

$\sqrt{s} = 4.26\ \mathrm{GeV}$

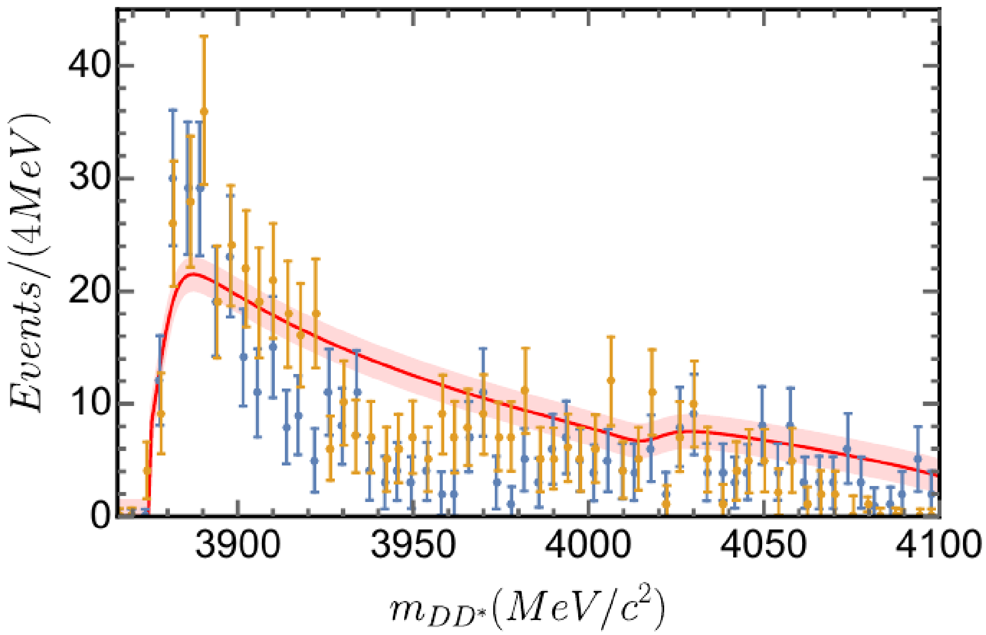


Data from BESIII Phys. Rev. Lett. 119, 072001 (2017)

Lineshapes for DD*

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

$\sqrt{s} = 4.26\ \text{GeV}$

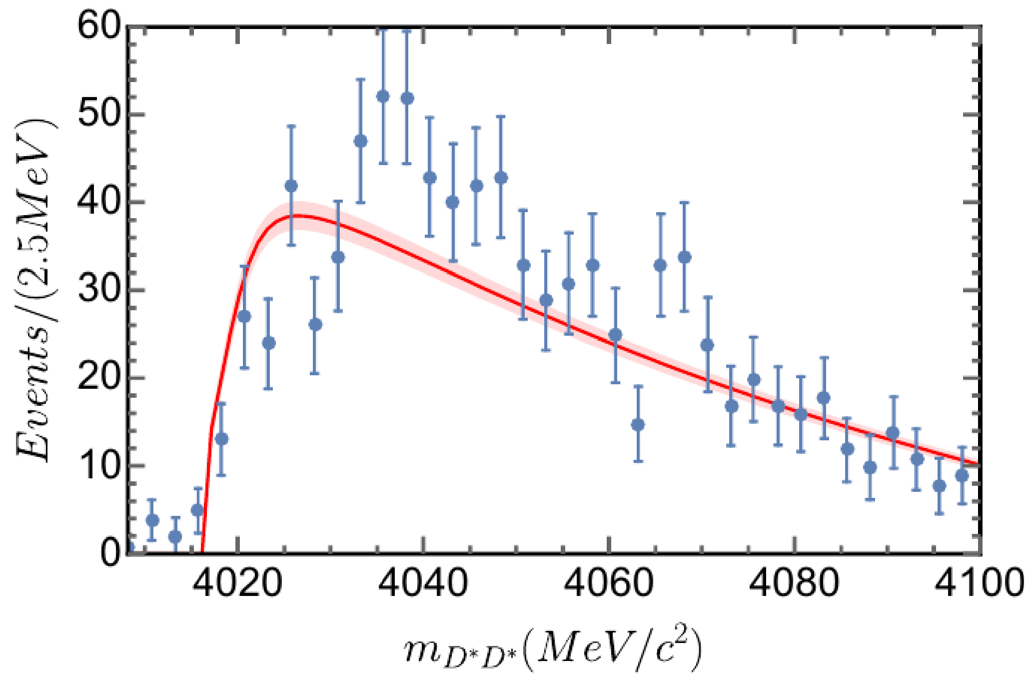


Data from BESIII Phys. Rev. D 92, 092006 (2015)

Lineshapes for D*D*

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

$\sqrt{s} = 4.26\ \mathrm{GeV}$

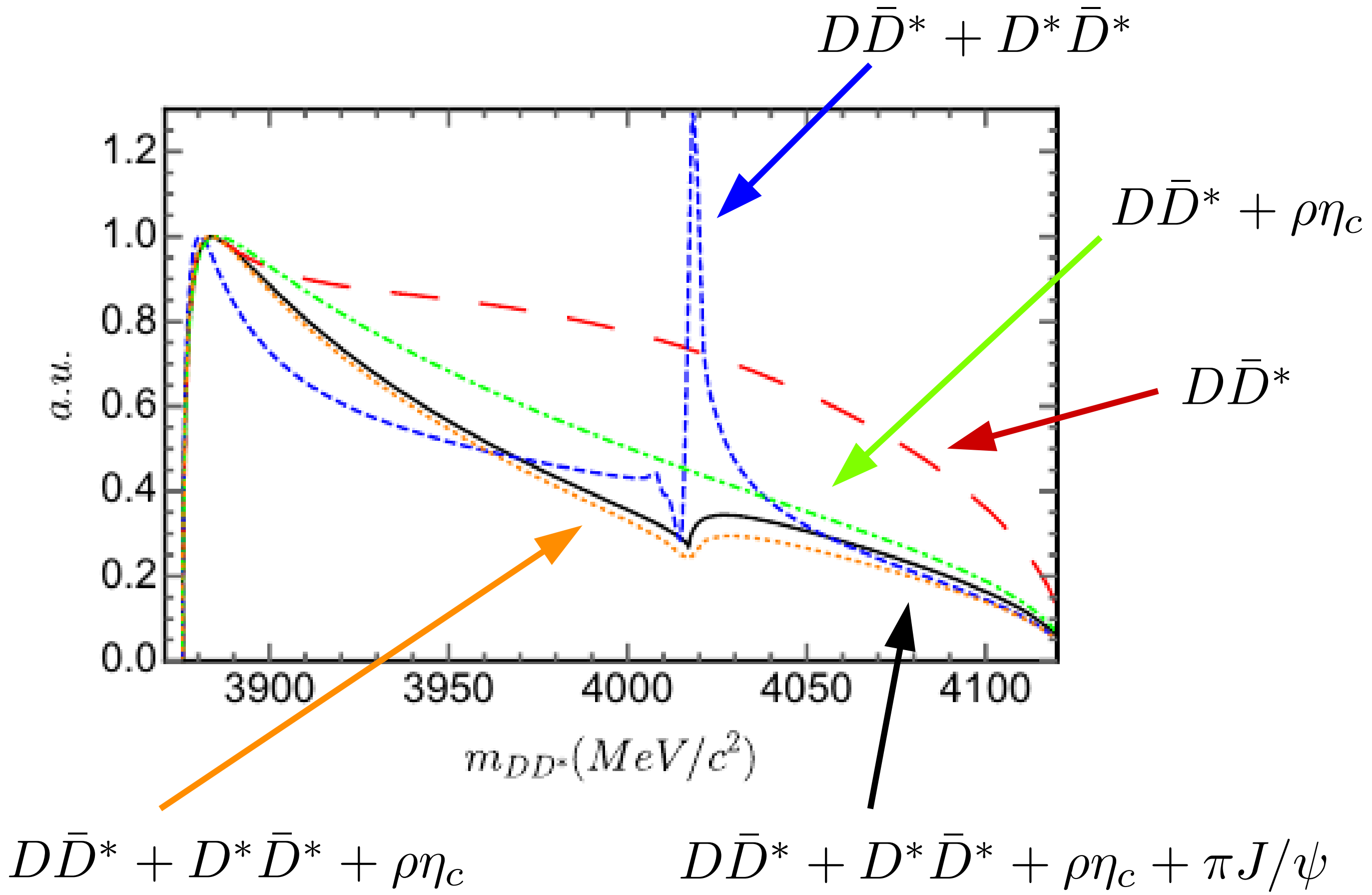


Data from BESIII Phys. Rev. Lett. 112, 132001 (2014)

Virtual states

Calculation	$Z_c(3900)$ pole	RS	$Z_c(4020)$ pole	RS
$D\bar{D}^*$	$3871.37 - 2.17\,i$	(S)	-	-
$D\bar{D}^* + D^*\bar{D}^*$	$3872.27 - 1.85\,i$	(S,F)	$4014.16 - 0.10\,i$	(S,S)
$\rho\eta_c + D\bar{D}^*$	$3871.32 - 0.00\,i$	(S,S)	-	-
$\rho\eta_c + D\bar{D}^* + D^*\bar{D}^*$	$3872.07 - 0.00\,i$	(S,S,F)	$4013.10 - 0.00\,i$	(S,S,S)
$\pi J/\psi + \rho\eta_c + D\bar{D}^* + D^*\bar{D}^*$	$3871.74 - 0.00\,i$	(S,S,S,F)	$4013.21 - 0.00\,i$	(S,S,S,S)

Lineshapes for DD*



Virtual states

Calculation	$Z_c(3900)$	type
This work	3871.74	virtual
F. Aceti et al.	$3878 - 23\,i$	resonance
M. Albaladejo et al.	$3894 \pm 6 \pm 1 - 30 \pm 12 \pm 6\,i$	resonance
	$3886 \pm 4 \pm 1 - 22 \pm 6 \pm 4\,i$	resonance
	$3831 \pm 26^{+7}_{-28}$	virtual
	$3844 \pm 19^{+12}_{-21}$	virtual
Y. Ikeda et al.	$3709 \pm 94 - 183(46)\,i$	virtual
	$3748 \pm 76 - 157(32)\,i$	virtual
	$3686 \pm 56 - 44(27)\,i$	virtual
J. He et al.	$3876 - 5\,i$	resonance
Calculation	$Z_c(4020)$	**type**
This work	4013.21	virtual
F. Aceti et al.	$(3990 - 4000) - 50\,i$	bound/virtual

Summary

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- *We have analyzed the invariant mass distributions for the reactions*

$$e^+e^- \to \pi^+\pi^- J/\psi$$
$$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$$
$$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$$

- *We fit the data with a χ^2/d.o.f=1.89*
- *The production amplitude is assumed to be a phenomenological vertex that produce a pion and other two mesons*
- *We use the Chiral Quark Model for the final state interaction*
- *We obtain two virtual states close to the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds for the Zc(3900)/Zc(3885) and Zc(4020) with quantum numbers*

$$I^G(J^{PC}) = 1^+(1^{+-})$$