Theoretical study of $Z_{cs}(3985)$ with the coupled channel approach

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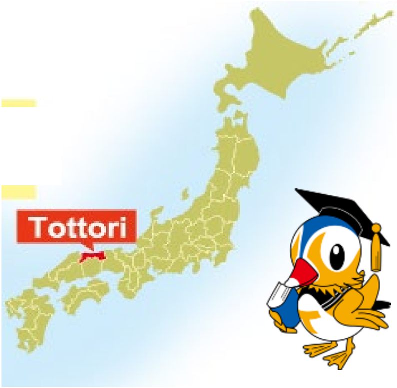


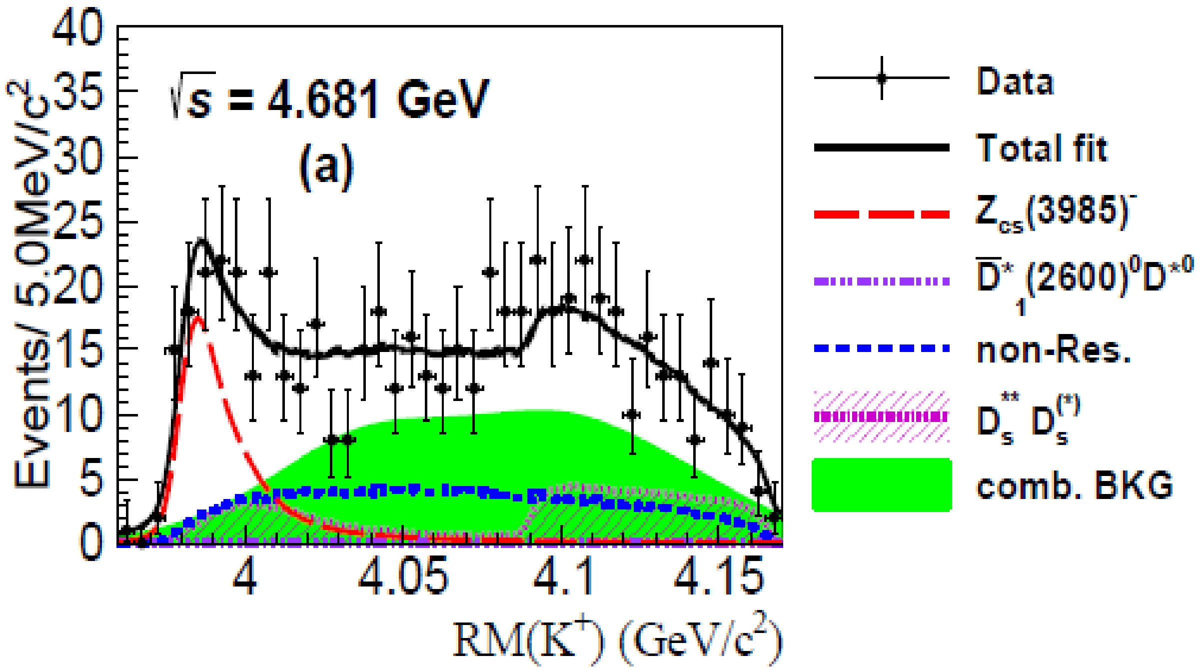
Discovery of $Z_{cs}(3985)$

Phys. Rev. Lett. 126, 102001 (2021)

- In 2020, BESIII reported a new state $Z_{cs}(3985)$
- A peak near threshold in $D_s^{*-}D^0$, $D_s^-D^{*0}$ invariant mass distribution of the $e^+e^- \to K^+(D_s^{*-}D^0 + D_s^- D^{*0})$ reaction
- Mass and width:

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

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



- The state lies about 7 MeV above the $D_s^{*-}D^0$, $D_s^-D^{*0}$ threshold

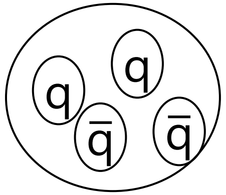
- $Z_{cs}(3985)$ ~ ($D_s^{*-}D^0$) ~ (ccbar s ubar) <=> $Z_c(3900)$ ~ ($D^{*-}D^0$) ~ (ccbar d ubar)

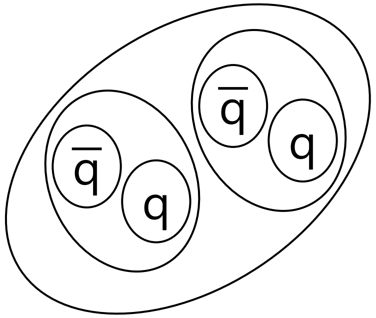
It could be the SU(3) partner of the $Z_c(3900)$ state, where a d quark has been replaced by an s quark.

Theoretical studies of $Z_{cs}(3985)$

Study of $Z_c(3900)$ provided many possible types of hadronic structures

- Tetraquark state $c\bar{c}d\bar{u}$
- Molecular state: $\bar{D}^*D$, $\bar{D}D^*$
- Threshold effect ....





=> Also Interesting to study the nature of $Z_{cs}(3985)$ from the analogy of $Z_c(3900)$

$Z_{cs}(3985) \sim (D_s^{*-}D^0) \sim$ (ccbar s ubar) <=> $Z_c(3900) \sim (D^{*-}D^0) \sim$ (ccbar u dbar)

hidden-charm strange tetraquark

◘ Quark model, Coupled channels, ... etc.

- S.H. Lee, M. Nielsen, U. Wiedner, J. Korean Phys. Soc. 55 (2009) 424.
- L. Meng, B. Wang, S.L. Zhu, arXiv:2011.08656[hep -ph].
- J.Z. Wang, Q.S. Zhou, X. Liu, T. Matsuki, arXiv:2011.08628[hep -ph].
- Z. Yang, X. Cao, F.K. Guo, J. Nieves, M.P. Valderrama, arXiv:2011.08725[hep -ph].
- Z.F. Sun, C.W. Xiao, arXiv:2011.09404[hep -ph]. etc....

Our study

We calculate the $Z_{cs}(3985)$ state with the coupled channel approach

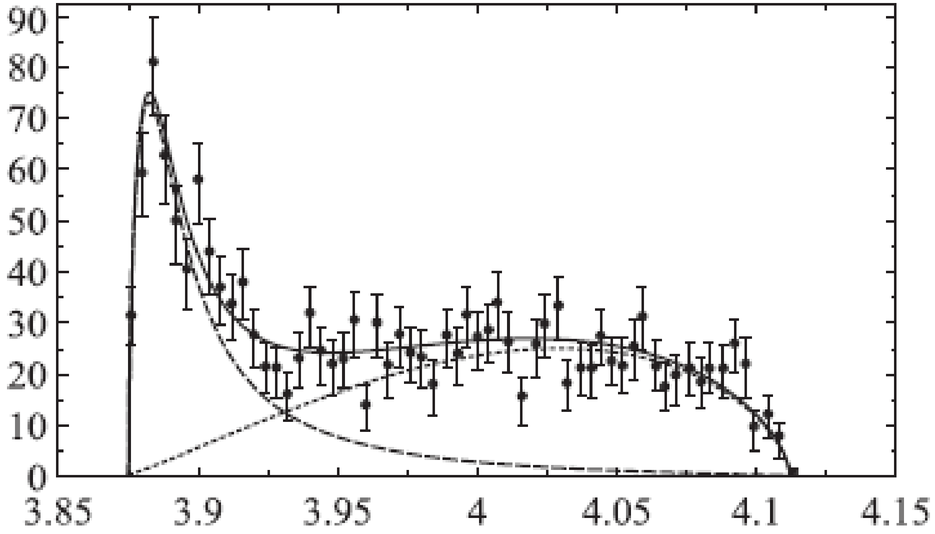
We use a similar formalism which studied $Z_c(3900)$ of

[F. Aceti, M. Bayar, E. Oset, A. Martinez Torres, K.P. Khemchandani, J.M. Dias, F.S. Navarra, M. Nielsen, PRD 90 (2014) 016003]

- One state($D^0 D^{*-}$) very close to threshold and below it

- Data from BESIII Experiment (2014) in the $e^+e^- \to \pi D \bar{D}^*$ reaction

- Peak close to the threshold of $D^0 D^{*-}$ is well reproduced



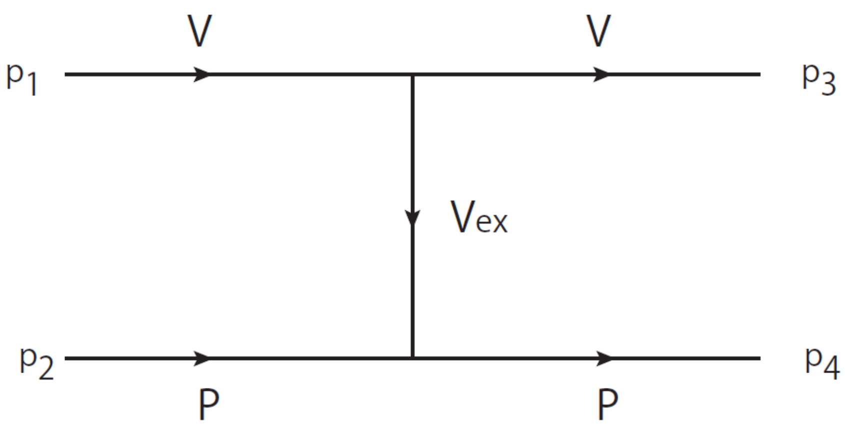
Invariant mass distribution for the $D^0 D^{*-}$

Formalism: Coupled channels approach

- Vector-Pseudoscalar channels (VP)

$$\boxed{J/\psi K^- \,(1),\quad K^{*-}\eta_c\,(2),\quad D_s^{*-}D^0\,(3),\quad D_s^-D^{*0}\,(4)}$$

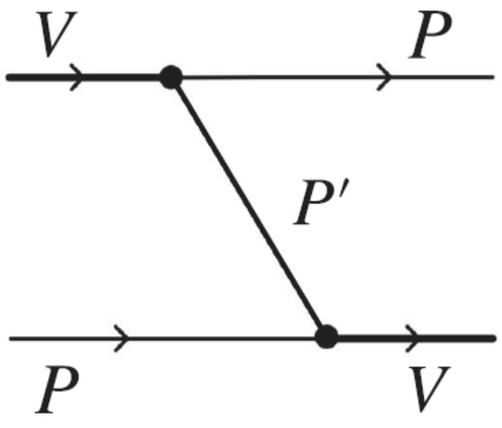
We study the interaction between 4 channels using the local hidden gauge approach.



VP→VP interaction through
the vector mesons exchange

The pseudoscalar exchange is found to give a very small contribution relative to vector meson exchange in Refs.

- J.M. Dias, G. Toledo, L. Roca, E. Oset, Phys. Rev. D103, 16019 (2021)
- F. Aceti, M. Bayar, E. Oset, A. Martinez Torres, K.P. Khemchandani, J.M. Dias, F.S. Navarra, M. Nielsen, PRD 90 (2014) 016003



Formalism: Coupled channels approach

- Vector-Pseudoscalar channels (VP)

$$\boxed{J/\psi K^-\,(1),\quad K^{*-}\eta_c\,(2),\quad D_s^{*-}D^0\,(3),\quad D_s^- D^{*0}\,(4)}$$

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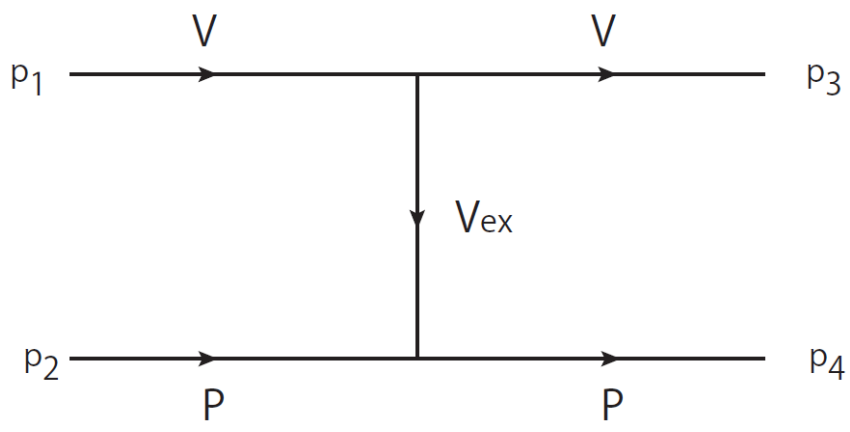


VP→VP interaction through the vector mesons exchange

- local hidden gauge Lagrangians

$$\mathcal{L}_{VPP} = -ig\langle V^\mu[P,\partial_\mu P]\rangle$$

$$\mathcal{L}_{VVV} = ig\langle (V^\mu\partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)V^\nu\rangle$$

$$g = M_V/2f\ \ (M_V = 800\ \text{MeV},\ f = 93\ \text{MeV})$$

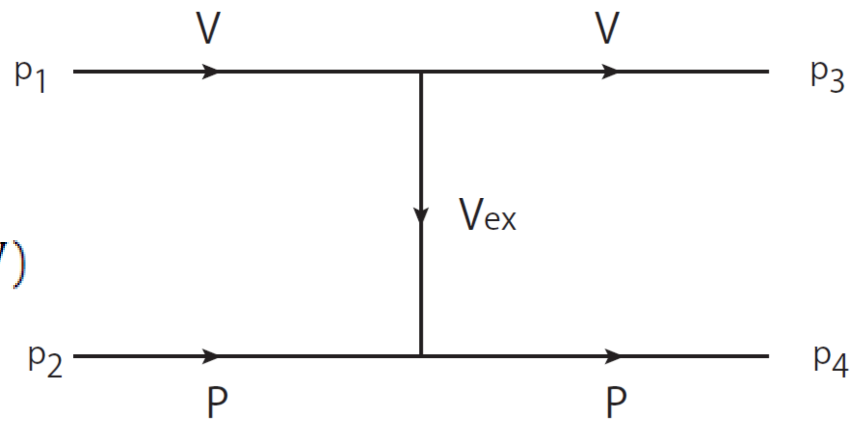
$$P = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}$$

$$V_\mu = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$

Interaction

- The interaction between the channels i, j

$$V_{ij} = C_{ij} g^2 (p_2 + p_4)(p_1 + p_3),$$



$$g = M_V / 2f \;\; (M_V = 800 \text{ MeV}, \; f = 93 \text{ MeV})$$

where the matrix C_{ij} ($C_{ji} = C_{ij}$)

$$\begin{array}{cccc} J/\psi K^- \,(1), & K^{*-}\eta_c \,(2), & D_s^{*-} D^0 \,(3), & D_s^- D^{*0} \,(4) \end{array}$$

$$C_{ij} = \begin{pmatrix} 0 & 0 & \frac{1}{m_{D^*}^2} & \frac{1}{m_{D_s^*}^2} \\ & 0 & \frac{1}{m_{D_s^*}^2} & \frac{1}{m_{D^*}^2} \\ & & -\frac{1}{m_{J/\psi}^2} & 0 \\ & & & -\frac{1}{m_{J/\psi}^2} \end{pmatrix},$$

- We also include the vector propagator

-> projection in *s*-wave

$$V_{ij} = g^2 C_{ij} \frac{1}{2} \left[3M_{12}^2 - (m_1^2 + m_2^2 + m_3^2 + m_4^2) - \frac{1}{M_{12}^2}(m_1^2 - m_2^2)(m_3^2 - m_4^2) \right]$$

where $M_{12}^2 = (p_1 + p_2)^2$

Interaction

- Vector-pseudoscalar channels (VP)

$$J/\psi K^- \,(1),\quad K^{*-}\eta_c\,(2),\quad D_s^{*-}D^0\,(3),\quad D_s^- D^{*0}\,(4)$$

$$\begin{array}{c} \qquad J/\psi K^-\,(1),\; K^{*-}\eta_c\,(2),\; D_s^{*-}D^0\,(3),\; D_s^-D^{*0}\,(4) \\ C_{ij} = \begin{pmatrix} 0 & 0 & \frac{1}{m_{D^*}^2} & \frac{1}{m_{D_s^*}^2} \\ & 0 & \frac{1}{m_{D_s^*}^2} & \frac{1}{m_{D^*}^2} \\ & & -\frac{1}{m_{J/\psi}^2} & 0 \\ & & & -\frac{1}{m_{J/\psi}^2} \end{pmatrix}, \end{array}$$

- Now we consider the combination of states

$$\boxed{A = \frac{1}{\sqrt{2}}(D_s^- D^{*0} + D_s^{*-}D^0)} \qquad \boxed{B = \frac{1}{\sqrt{2}}(D_s^- D^{*0} - D_s^{*-}D^0)}$$

- We use average D and D_s, and D^* and D^*_s masses for the symmetry of this interaction

$$\bar{m}_D = 1916\ \mathrm{MeV}, \quad \bar{m}_{D^*} = 2060\ \mathrm{MeV}.$$

=> The combination A couples to $J/\Psi\ K^-$ and $K^{*-}\eta_c$, while the combination B does not couple.

$$\begin{array}{c} J/\psi K^-\,(1),\; K^{*-}\eta_c\,(2),\; A \\ C_{ij} = \begin{pmatrix} 0 & 0 & \frac{\sqrt{2}}{\bar{m}_{D^*}^2} \\ & 0 & \frac{\sqrt{2}}{\bar{m}_{D^*}^2} \\ & & -\frac{1}{m_{J/\psi}^2} \end{pmatrix} \end{array}$$

Coupled channel

$$\begin{array}{c} J/\psi K^-\,(1),\; K^{*-}\eta_c\,(2),\; B \\ C_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ & 0 & 0 \\ & & -\frac{1}{m_{J/\psi}^2} \end{pmatrix} \end{array}$$

Single channel
⇒ Weak interaction

$C_{AB} = 0$

Interaction: the analogy to Z_c

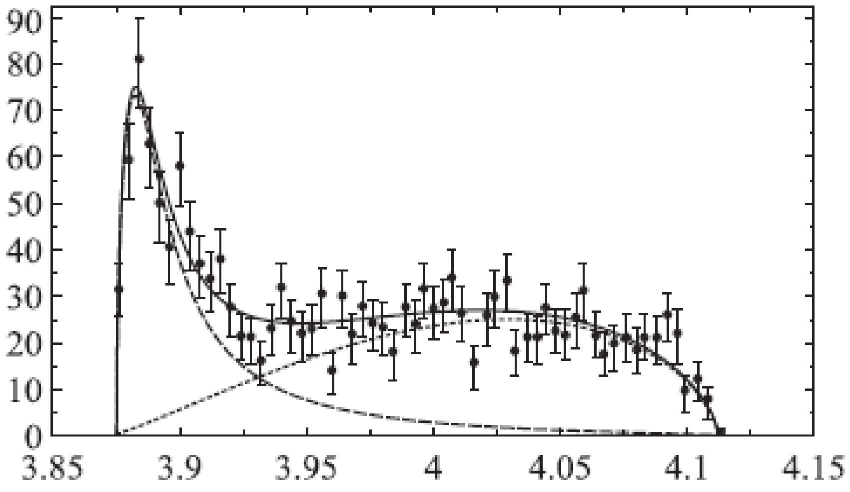
- Within our approach, this combination appears as a consequence of the interaction.

In view of this, we take now the states $\boxed{J/\psi K^- \ (1), \quad K^{*-}\eta_c \ (2), \quad \frac{1}{\sqrt{2}}(D_s^- D^{*0} + D_s^{*-} D^0) \ (3)}$

- The study of Z_c case [F. Aceti, M. Bayar, E. Oset, A. Martinez Torres, K.P. Khemchandani, J.M. Dias, F.S. Navarra, M. Nielsen, PRD 90 (2014) 016003]

$\bar{D} D^* - \bar{D}^* D$ combination did not bind

$\bar{D} D^* + \bar{D}^* D$ combination produced weakly bound states or virtual ones.

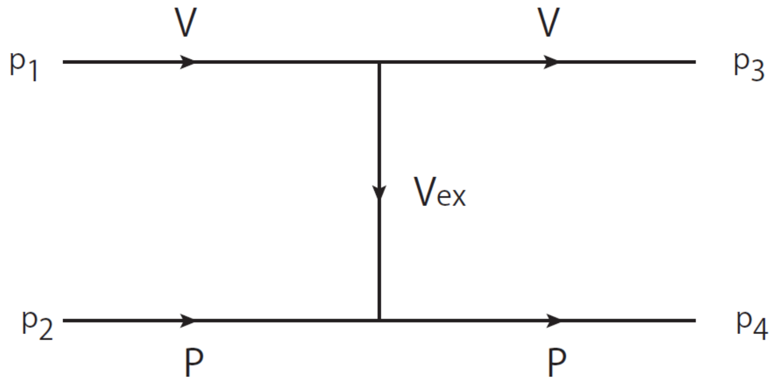


Invariant mass distribution for the $D^0 D^{*-}$

=> In Z_{cs} (3985) case, we expect to get a similar result

Coupled channels approach

$$\boxed{J/\psi K^- \ (1), \quad K^{*-}\eta_c \ (2), \quad \frac{1}{\sqrt{2}}(D_s^- D^{*0} + D_s^{*-} D^0) \ (3)}$$



- Bethe-Salpeter equation: $T = [1 - VG]^{-1} V$

- Interaction between the channels i,j :

$$V_{ij} = g^2 C_{ij} \frac{1}{2} \left[3M_{12}^2 - (m_1^2 + m_2^2 + m_3^2 + m_4^2) - \frac{1}{M_{12}^2}(m_1^2 - m_2^2)(m_3^2 - m_4^2) \right] \qquad C_{ij} = \begin{pmatrix} 0 & 0 & \frac{\sqrt{2}}{\bar{m}_{D^*}^2} \\ & 0 & \frac{\sqrt{2}}{\bar{m}_{D^*}^2} \\ & & -\frac{1}{m_{J/\psi}^2} \end{pmatrix}$$

- Vector-pseudoscalar loop function G:

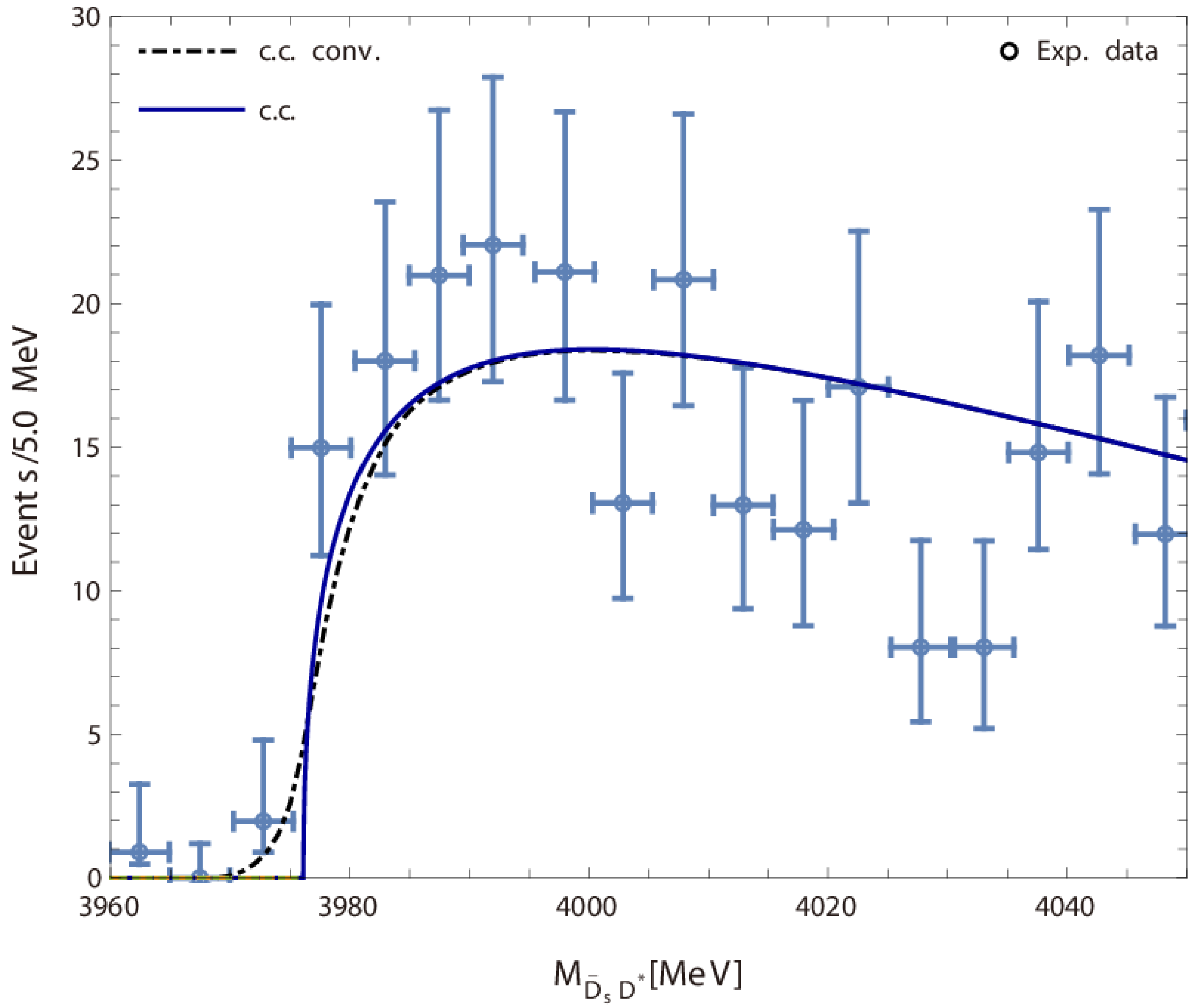
$$G_l = \int \frac{d^3 q}{(2\pi)^3} \frac{\omega_1 + \omega_2}{2\omega_1 \omega_2} \frac{1}{(P^0)^2 - (\omega_1 + \omega_2)^2 + i\epsilon}$$

$$\omega_1 = \sqrt{m^2 + \vec{q}^{\ 2}}, \ \omega_2 = \sqrt{M^2 + \vec{q}^{\ 2}}$$

m, M the pseudoscalar and vector masses of the l channel

The value of q_{max} was taken around 700–850MeV

Differential cross section of the $e^+e^- \to K^+(D_s^{*-}D^0 + D_s^- D^{*0})$ reaction



$$\boxed{\frac{d\sigma}{dM_{\bar{D}_s D^*}} = \frac{1}{s\sqrt{s}}\, p\tilde{q}\; N \;|T_{33}|^2}$$

$\sqrt{s} = 4681$ MeV   *N*: a normalization constant

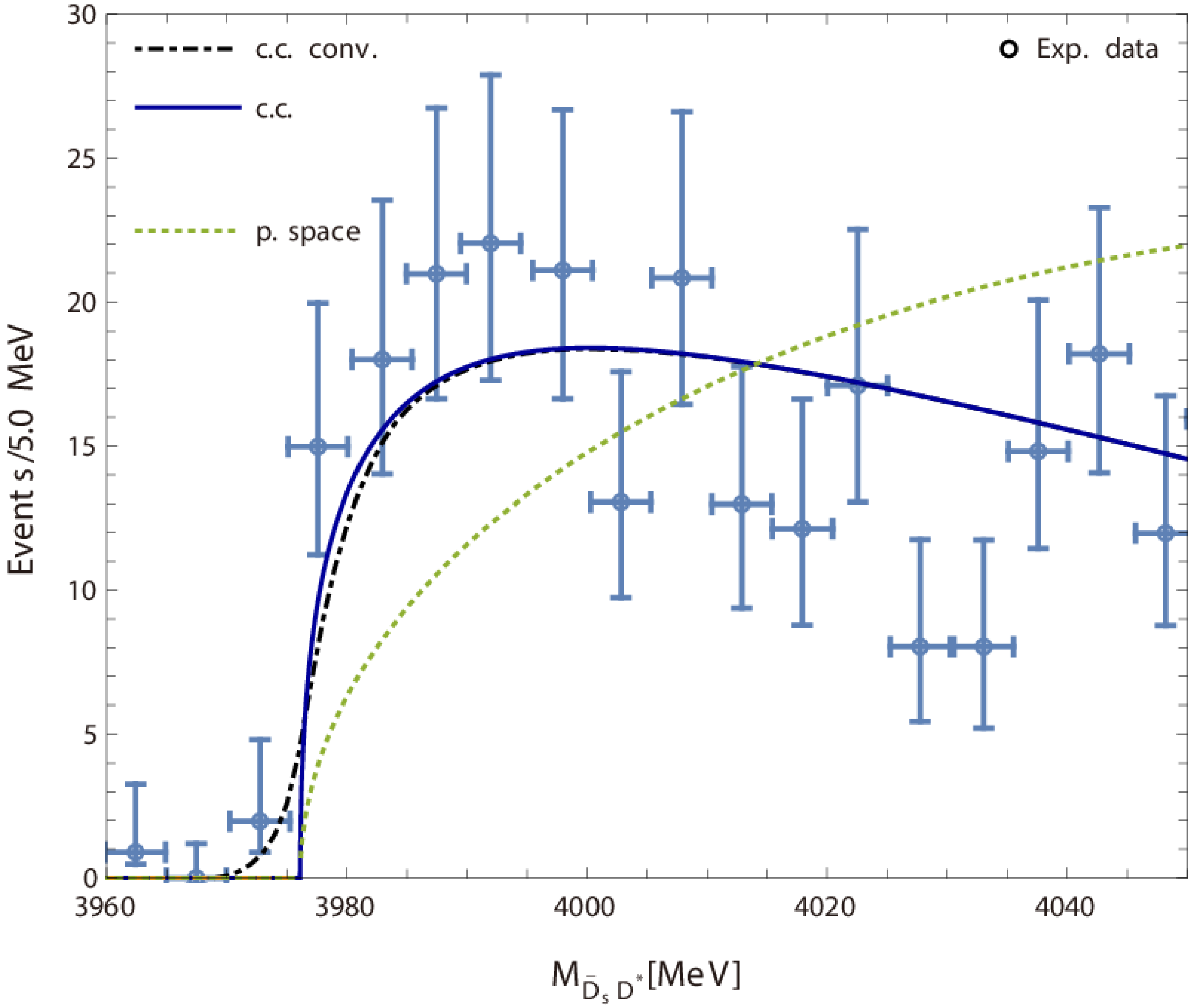
T_{33} : amplitude of $D_s^{*-}D^0 + D_s^- D^{*0} \to D_s^{*-}D^0 + D_s^- D^{*0}$

$$p = \frac{\lambda^{1/2}(s, m_K^2, M^2_{\bar{D}_s D^*})}{2\sqrt{s}}, \qquad \tilde{q} = \frac{\lambda^{1/2}(M^2_{\bar{D}_s D^*}, m^2_{D_s}, m^2_{D^*})}{2M_{\bar{D}_s D^*}}$$

✓ Agreement with the data is sufficiently good.

- Solid line: Result for $D_s^- D^{*0} + D_s^{*-}D^0$ combination with its coupled channels (c.c.).
- Dashed-dotted line: result folded with the experimental resolution (c.c.conv.)

Differential cross section of the $e^+e^- \to K^+(D_s^{*-}D^0 + D_s^- D^{*0})$ reaction



$$\boxed{\frac{d\sigma}{dM_{\bar{D}_s D^*}} = \frac{1}{s\sqrt{s}}\, p\tilde{q}\; N\; |T_{33}|^2}$$

$\sqrt{s} = 4681$ MeV *N*: a normalization constant

T_{33} : amplitude of $D_s^{*-}D^0 + D_s^- D^{*0} \to D_s^{*-}D^0 + D_s^- D^{*0}$

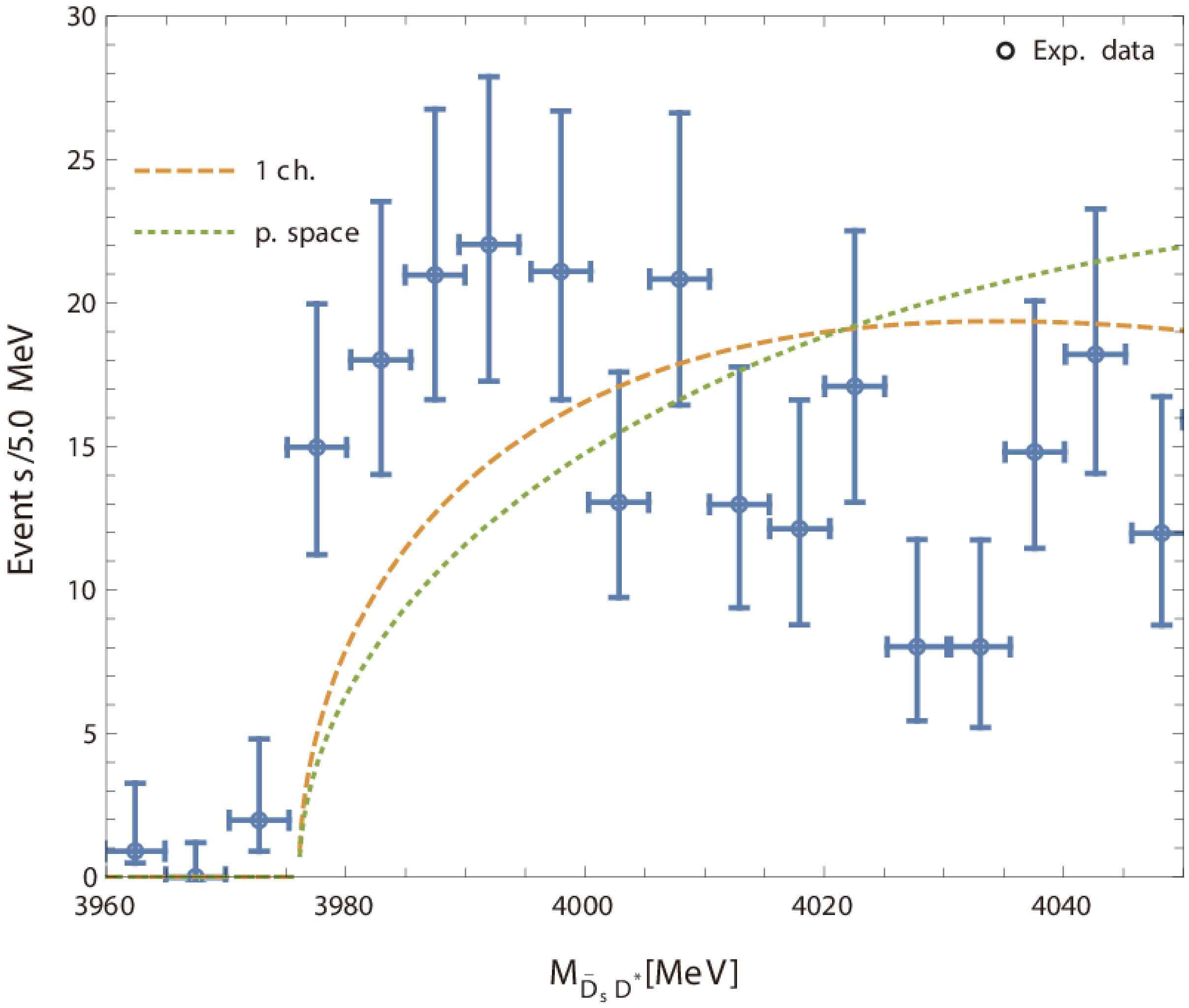
✓ Our model does not produce a bound state nor resonance

✓ The result differs from that of the phase space.

=> This interaction has the effect of accumulating strength close to threshold

- Solid line: Result for $D_s^- D^{*0} + D_s^{*-}D^0$ combination with its coupled channels (c.c.).
- Dashed-dotted line: result folded with the experimental resolution (c.c.conv.)
- Dotted line: phase space.

Differential cross section of the $e^+e^- \to K^+(D_s^{*-}D^0 + D_s^- D^{*0})$ reaction



$$\boxed{\frac{d\sigma}{dM_{\bar{D}_s D^*}} = \frac{1}{s\sqrt{s}}\, p\tilde{q}\, N\, |T_{33}|^2}$$

- single channel $D_s^- D^{*0} - D_s^{*-} D^0$ combination

✓ The result does not differ much from that of the phase space.

✓ It is clearly incompatible with the data.

$\Rightarrow$ The interaction of coupled channels is important to produce the structure of $Z_{cs}(3985)$ close to threshold

- Dashed line: the single channel $D_s^- D^{*0} - D_s^{*-} D^0$ combination (1ch.).
- Dotted line: phase space.

Summary

- We have studied the $e^+e^- \to K^+(D_s^{*-}D^0 + D_s^- D^{*0})$ reaction measured at BESIII, where a new Z_{cs} (3985) state has been reported.

- We considered the interaction of the coupled channels $J/\psi K^-, K^{*-}\eta_c, D_s^- D^{*0}, D_s^{*-}D^0$
  - We found that $D_s^- D^{*0} + D_s^{*-}D^0$ combination couples to other channels,
    but $D_s^- D^{*0} - D_s^{*-}D^0$ combination does not.

- The interaction is not strong to produce a bound state or resonance
- It has sufficient strength to produce the enhancement close to the threshold
  -> Our results agree with the Exp. data.