The Z_{cs} and $D^*D^*\bar{K}^*$ states based on the molecular picture

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N. Ikeno, R. Molina and E. Oset, Phys. Lett. B 814, 136120 (2021)
N. Ikeno, R. Molina and E. Oset, Phys. Rev. D 105, 014012 (2022)
N. Ikeno, M. Bayar and E. Oset, Phys. Rev. D 107, 034006 (2023)

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Exotic hadrons

Many exotics have been observed since the discovery of X(3872)

- Z_c(3900), BESIII, 2013: close to $D\bar{D}^*$, $c\bar{q}q\bar{c}$ $(q = u, d)$
- Z_{cs}(3985), BESIII, 2021: close to $\bar{D}_s^* D / \bar{D}_s D^*$, $c\bar{q}s\bar{c}$
- X_0(2900), X_1(2900), LHCb, 2020: close $D^* \bar{K}^*$, $c\bar{q}s\bar{q}$
- T_{cc}(3875), LHCb, 2021: close to DD^*, $c\bar{q}c\bar{q}$
- T_{cs}(2900) LHCb, 2022, $c\bar{s}q\bar{q}$

....

=> Cannot be explained as the ordinary mesons $q\bar{q}$

Many possible types of hadronic structures were proposed:

-Tetraquarks? - Meson-meson molecules? ....

My talk: The studies of the Z_{cs} and $D^*D^*\bar{K}^*$ states based on the molecular picture

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- The Z_{cs} states
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- Molecular states of $D^* D^* \bar{K}^*$ nature

Discovery of $Z_{cs}(3985)$

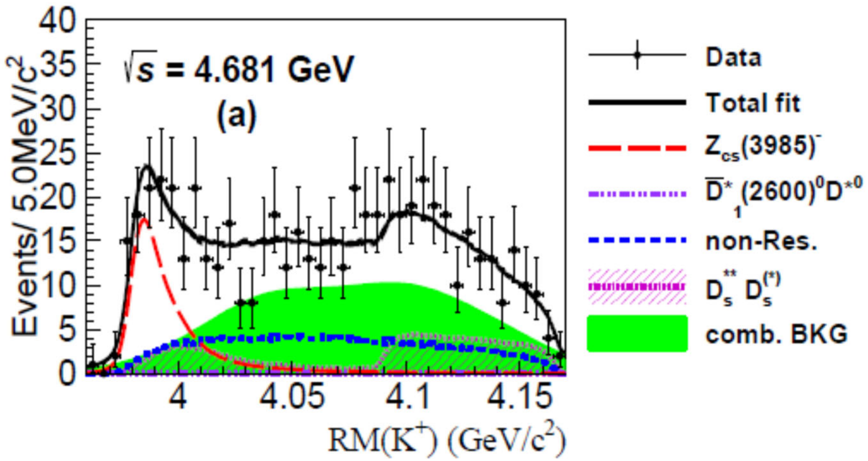
Phys. Rev. Lett. 126, 102001 (2021)

- 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

- $Z_{cs}(3985)$ ~ ($D_s^{*-}D^0$) ~ (cbar s c ubar) : Hidden-charm strange tetraquark

- $Z_c(3900)$ ~ ($D^{*-}D^0$) ~ (cbar d c ubar)

$Z_{cs}(3985)$ could be the SU(3) partner of the $Z_c(3900)$ state, where a d quark has been replaced by an s quark

=> Interesting to study the nature of $Z_{cs}(3985)$

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

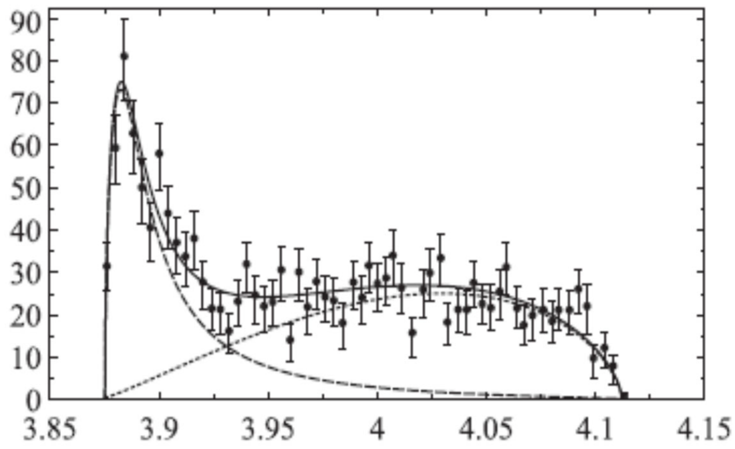
$Z_c(3900)$: BESIII Experiment (2014) in the $e^+e^- \to \pi D \bar{D}^*$ reaction

- $Z_c(3900)$ exists very close to $D\bar{D}^*$ threshold

- $Z_c(3900)$ based on the molecular picture of $D\bar{D}^*$

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

  - Weakly bound state or virtual state is found
  - Peak close to the threshold of $D^0 D^{*-}$ is well reproduced



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

⇒ We use a similar formalism which studied $Z_c(3900)$ and calculate the $Z_{cs}(3985)$ state with the molecular picture

☐ Other studies: Quark model, Coupled channels, … etc.

- S.H. Lee, M. Nielsen, U. Wiedner, J. Korean Phys. Soc. 55, 424 (2009).
- L. Meng, B. Wang, S.L. Zhu, PRD102, 111502(R) (2020).
- J.Z. Wang, Q.S. Zhou, X. Liu, T. Matsuki, EPJC81, 51 (2021).
- Z. Yang, X. Cao, F.K. Guo, J. Nieves, M.P. Valderrama, PRD103, 074029 (2021).
- V. Baru, E.Epelbaum, A.A. Filin, C. Hanhart, A.V. Nefediev, PRD105, 034014 (2022).
- Z.F. Sun, C.W. Xiao, arXiv:2011.09404 [hep -ph]. etc.…

Formalism: Coupled channels approach

$Z_{cs}(3985)$ is dynamically generated from the interaction of the coupled channels (molecular state, … etc.)

- Vector-pseudoscalar channels (VP)

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

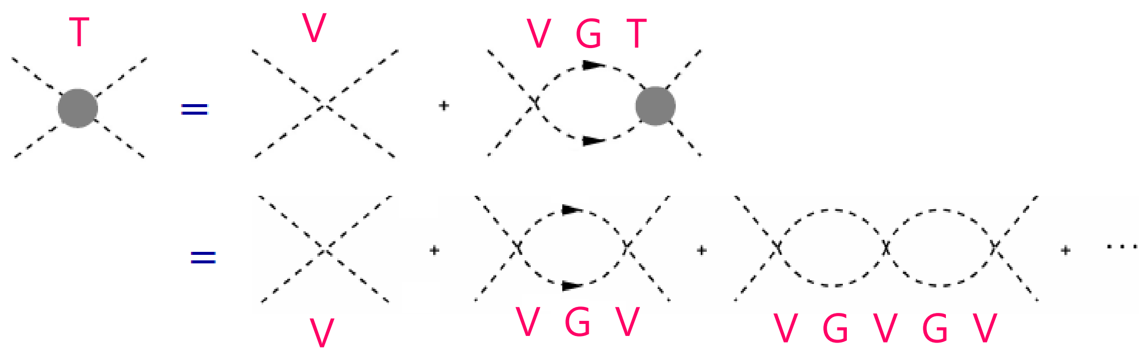
- Bethe-Salpeter equation:

$$T = [1 - VG]^{-1}V$$

T: Scattering matrix

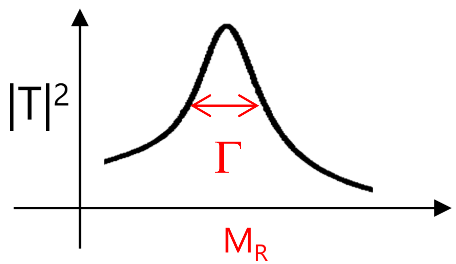
V: Interaction of the coupled channels

G: loop function



- Vector-pseudoscalar loop function G:

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



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

G is regularized with the cutoff parameter q_{max}.

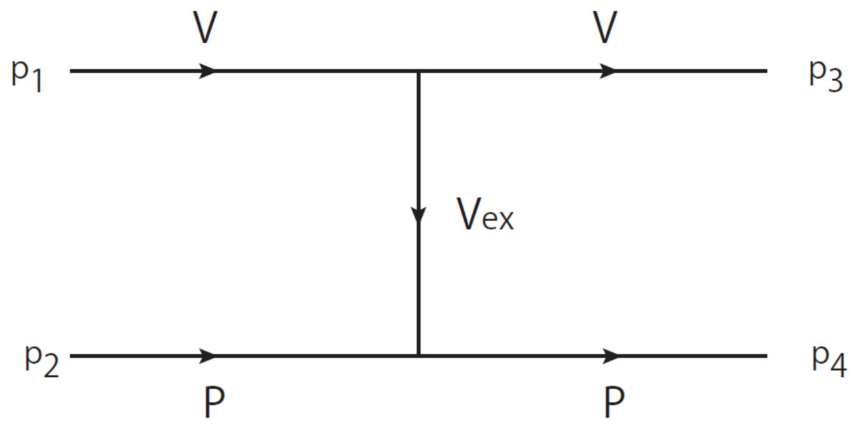
m, M the pseudoscalar and vector masses of the *l*-th channel

q_{max} is around 700–850MeV here

Interaction

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

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



- Local hidden gauge Lagrangians

  Bando, Kugo, Yamawaki, Phys. Rep. 164, (88) 217

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

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

VP→VP interaction through the vector mesons exchange

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

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

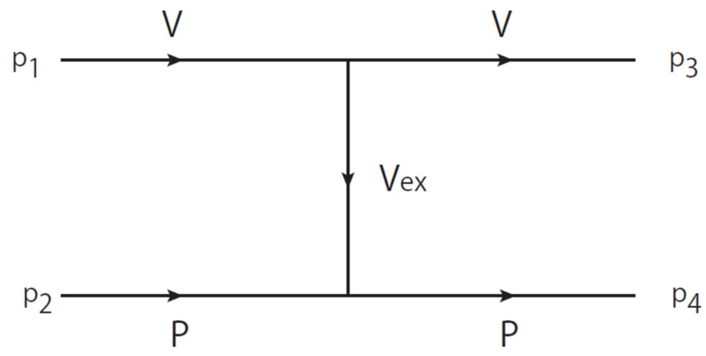
$$V_\mu = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$

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} ($C_{ji} = C_{ij}$)

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

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

- We neglected q^2 in the vector propagator in this expression

- We consider the linear combination of states:

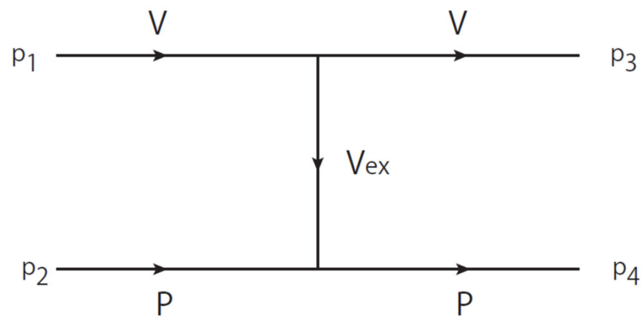
$$A = \frac{1}{\sqrt{2}} (D_s^- D^{*0} + D_s^{*-} D^0) \qquad B = \frac{1}{\sqrt{2}} (D_s^- D^{*0} - D_s^{*-} D^0)$$

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

Interaction for Zcs (the analogy to Z_c)

- We take now the states $J/\psi K^-$ (1), $K^{*-}\eta_c$ (2), A = $\frac{1}{\sqrt{2}}(D_s^- D^{*0} + D_s^{*-} D^0)$ (3)

$$C_{ij} = \begin{pmatrix} 0 & 0 & \frac{\sqrt{2}}{\bar{m}_{D*}^2} \\ & 0 & \frac{\sqrt{2}}{\bar{m}_{D*}^2} \\ & & -\frac{1}{m_{J/\psi}^2} \end{pmatrix}$$



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

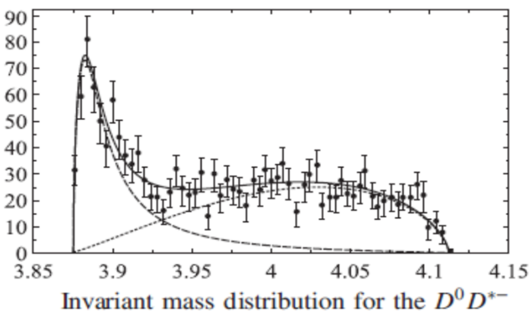
where $M_{12}^2 = (p_1 + p_2)^2$

- In the previous study of Z_c(3900)

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

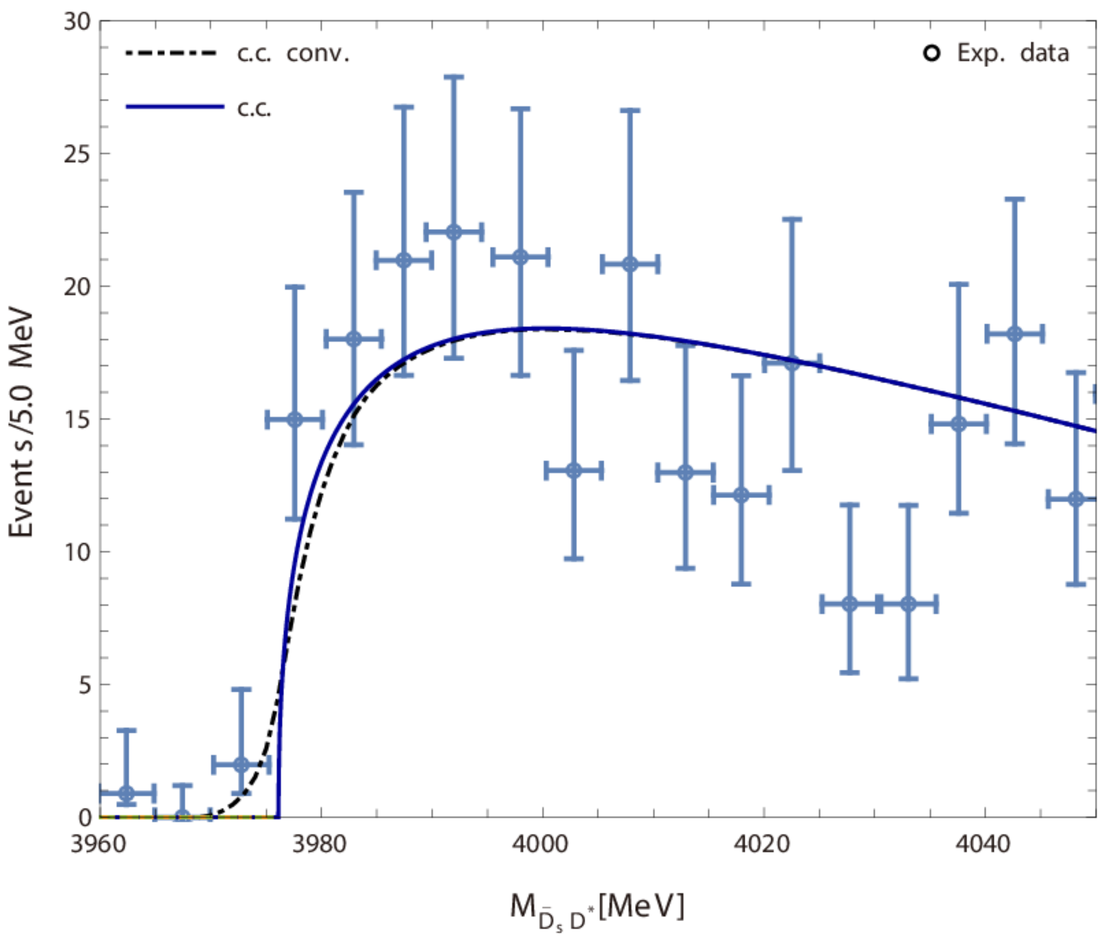
$\bar{D}D^* + \bar{D}^*D$ combination produced weakly bound state or virtual state.



=> We expect to get a similar result in the present Z_{cs}(3985) case

Differential cross section: Zcs

N. Ikeno, R. Molina, E. Oset,
PLB 814, 136120 (2021).



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

$\sqrt{s} = 4681$ MeV

N: a normalization constant

T_{33} : amplitude of

$$D_s^{*-} D^0 + D_s^- D^{*0} \to D_s^{*-} D^0 + D_s^- D^{*0}$$

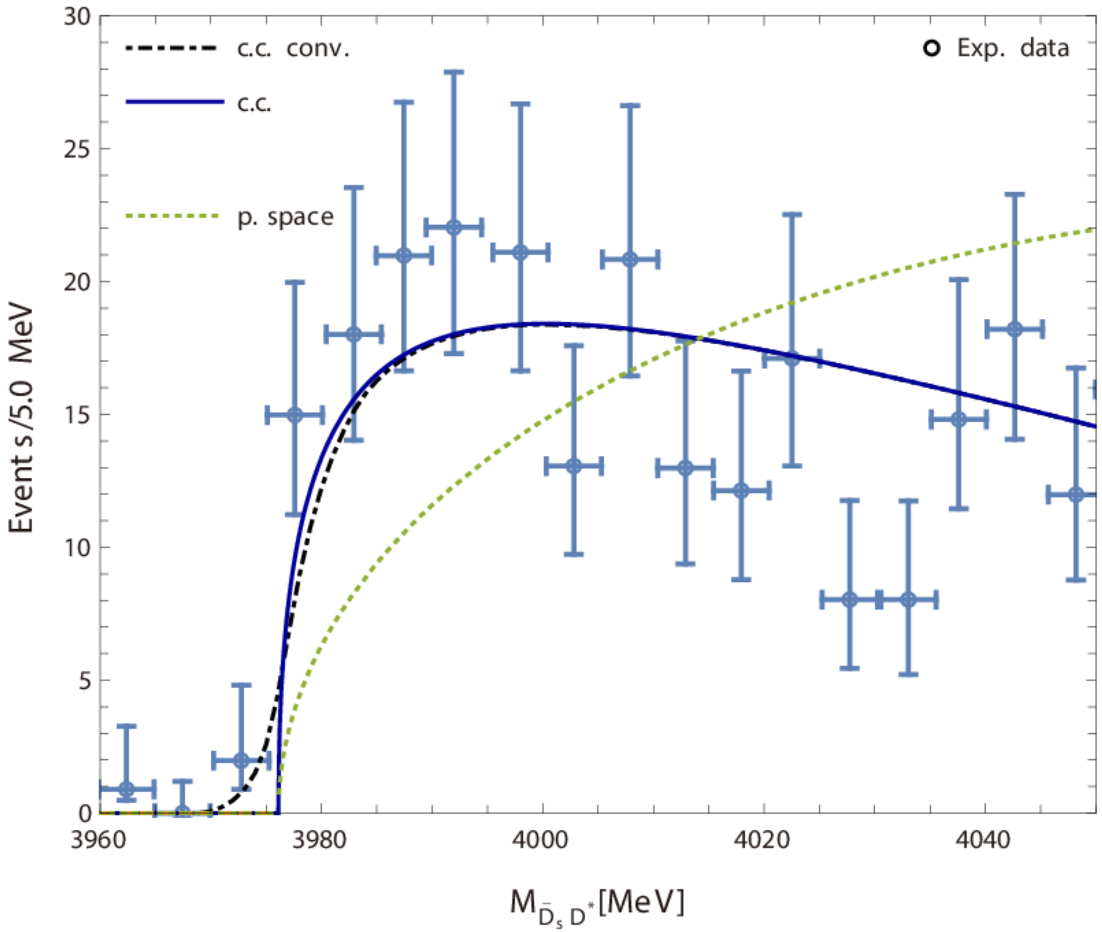
$$p = \frac{\lambda^{1/2}(s, m_K^2, M_{\bar{D}_s D^*}^2)}{2\sqrt{s}}, \quad \tilde{q} = \frac{\lambda^{1/2}(M_{\bar{D}_s D^*}^2, m_{\bar{D}_s}^2, m_{D^*}^2)}{2M_{\bar{D}_s D^*}}$$

✓ 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: Zcs

N. Ikeno, R. Molina, E. Oset,
PLB 814, 136120 (2021).



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

$\sqrt{s} = 4681$ 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.

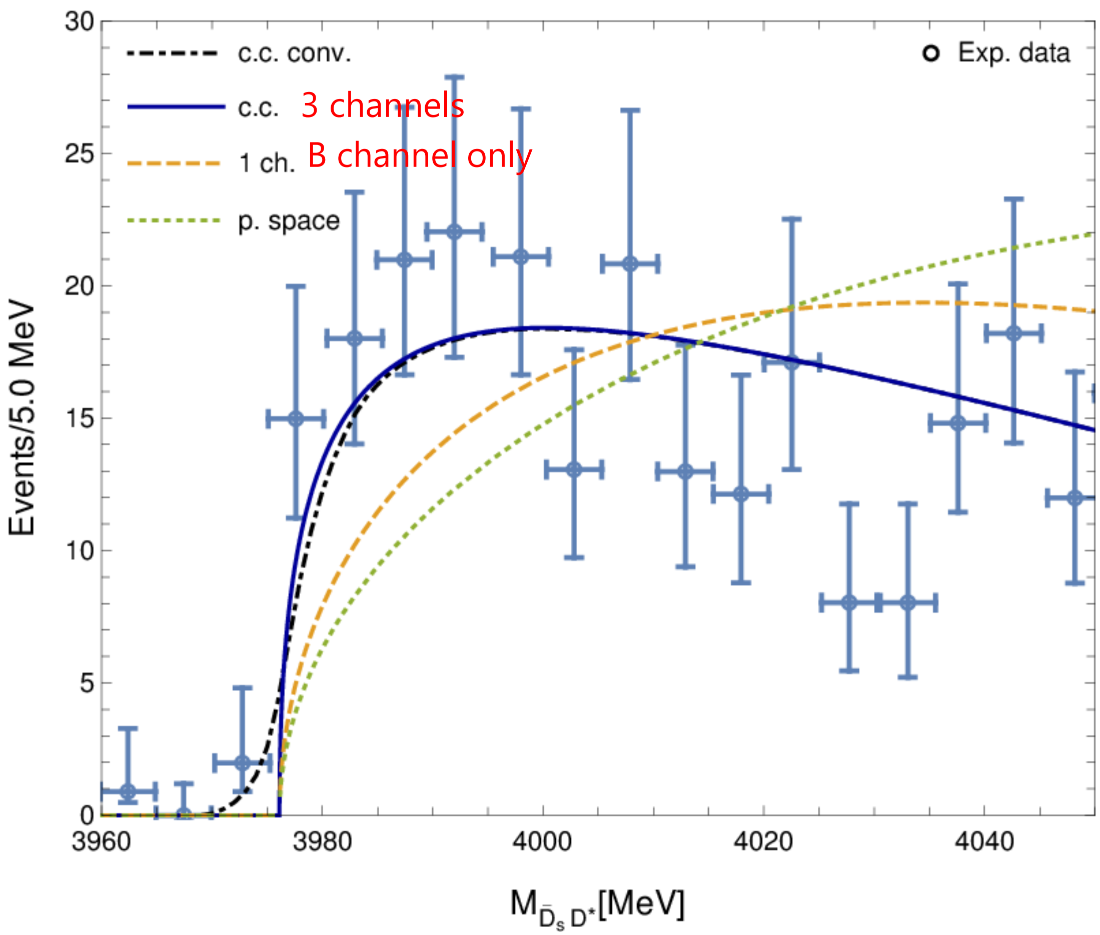
This interaction has the effect of accumulating strength close to threshold

This is strong enough to nearly produce a bound state, which reverts into the production of a virtual state

- 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: Zcs

N. Ikeno, R. Molina, E. Oset,
PLB 814, 136120 (2021).



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

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

✓ The result does not differ much from that of the phase space.
✓ It is clearly incompatible with the data.

The interaction of coupled channels is important to produce the structure of Z_{cs}(3985) 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.)
- Dashed line: the single channel $D_s^- D^{*0} - D_s^{*-} D^0$ combination (1ch.).
- Dotted line: phase space.

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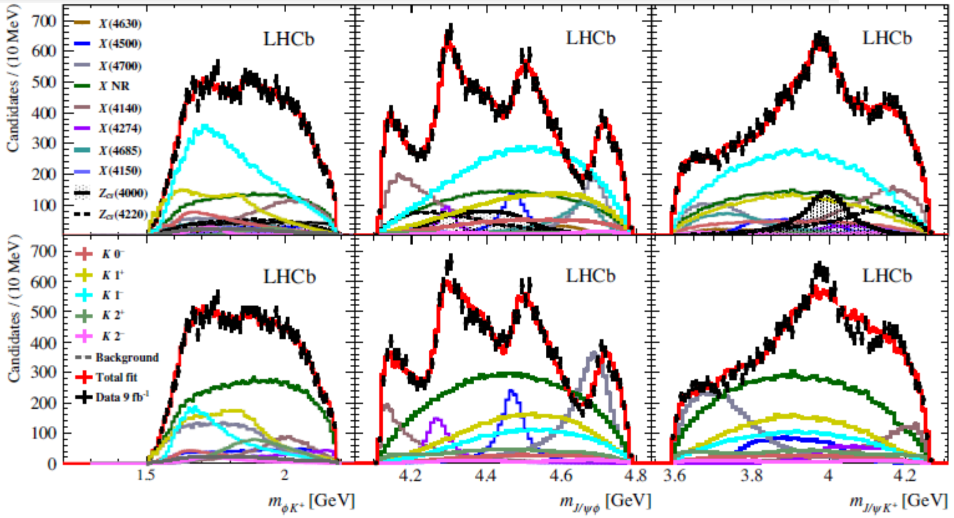
Other Z_{cs} states at LHCb   PRL127, 082001 (2021)

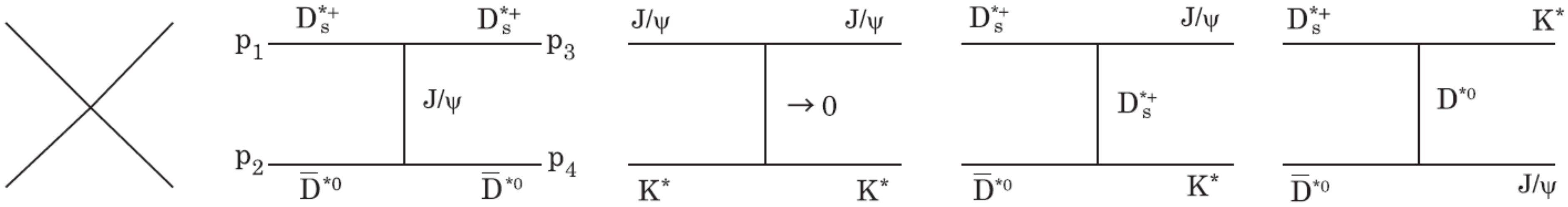
- $Z_{cs}(4000)$ and $Z_{cs}(4220)$ states were observed in the $B^+ \to J/\psi \phi K^+$ reaction at LHCb



=> We study Z_{cs} based on the $D_s^* \bar{D}^*$ molecular state

N. Ikeno, R. Molina and E. Oset, PRD105(2022)014012, PRD106 (2022)099905 (E)

- Vector-vector channels (VV): $D_s^{*+} \bar{D}^{*0}$ (1), $J/\psi K^{*+}$ (2),



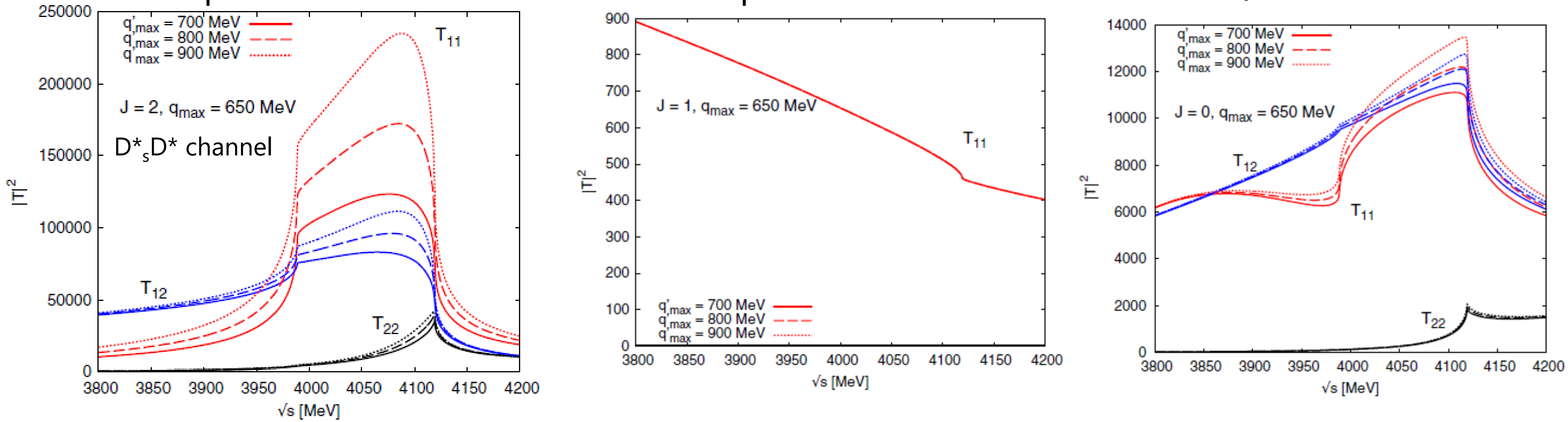
$$\mathcal{L}^{(c)} = \frac{g^2}{2} \langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu \rangle, \quad \mathcal{L}_{VVV} = ig\langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu) V^\nu \rangle$$

Z_{cs} states from $D_s^* \bar{D}^*$

N. Ikeno, R. Molina, E. Oset,
PRD 105, 014012 (2022).

$|T|^2$ for each channel for the different cut-off q_{max} values

- Spin J=2
- Spin J=1
- Spin J=0



=> The system does not develop a bound state, but has enough attraction to create a strong cusp structure (~4120 MeV) with J=2

➢ Recent experimental papers:

- BESIII, Chin. Phys. C47, 033001 (2023)

  Search for hidden-charm tetraquark with strangeness in the reaction of $e^+e^- \to K^+ D_s^{*-} D^{*0} + c.c.$

- LHCb, arXiv:2301.04899 [hep-ex] (2023)

  Evidence of a $J/\psi K^0_s$ structure in $B^0 \to J/\psi \phi K^0_s$ decays

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- **Molecular states of $D^*D^*\bar{K}^*$ nature**

Molecular states of $D^* D^* \bar{K}^*$ nature

$D^* D^* \bar{K}^*$ system [$c\bar{q}c\bar{q}s\bar{q}$] : Very Exotic system with ccs open quarks

- The $D^* \bar{K}^*$ interaction: R. Molina, E. Oset, PLB811 (2020)

  The $J^P = 0^+$ bound state is identified with the $X_0(2900)$

- The $D^* D^*$ interaction: L. R. Dai, R. Molina, E. Oset, PRD 105 (2022)

  Bound state in I = 0 and $J^P = 1^+$

  (using the same q_{max} of D^*D interaction fixed by the T_{cc} data
  A. Feijoo, W. H. Liang, E. Oset, PRD104 (2021).)

=> A search for possible bound states of the three-body system

➢ Recent studies of three body systems of molecular nature:

- DDK T. W. Wu et al., PRD100(2019): A. Martinez Torres, et al., PRD99(2019): Y. Huang et al., PRD101(2020).
- $D\bar{D}^*K$ X. L. Ren et al., PLB785, 112 (2018).
- DD^*K L. Ma et al., , Chin. Phys. C43, 014102 (2019).
- $D\bar{D}K$ T. W. Wu, M. Z. Liu, L.S. Geng, et al., PRD103, L031501 (2021): X. Wei, , Q. H. Shen, J. J. Xie, EPJC82 (2022)

$\Rightarrow$ Contain $cc\bar{s}$ or $\bar{c}\bar{c}s$

Fixed Center Approximation (FCA) to the Faddeev equation

There is a cluster of two bound particles D^*D^* and the third one ($\bar{K}^*$) collides with the components of this cluster without modifying the D^*D^* wave function.

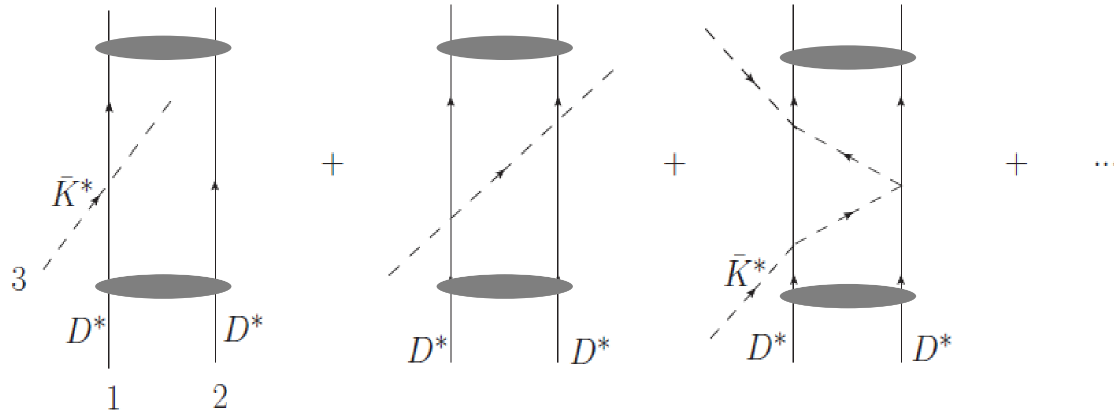
L. Roca and E. Oset, PRD82, 054013 (2010)

Total three-body scattering amplitude T

$$T \equiv T_1 + T_2$$

$$T_1 = t_1 + t_1 G_0 T_2,$$

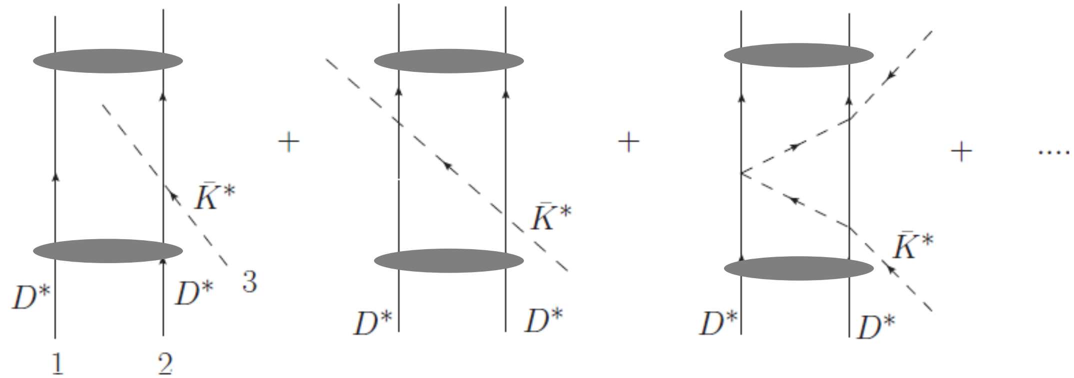
$$T_2 = t_2 + t_2 G_0 T_1,$$



t_i is the scattering amplitude for $D^*(i)\bar{K}^*$bar

G_0 is the $\bar{K}^*$ propagator folded with the cluster wave function

$$G_0 = \frac{1}{2m_C}\int \frac{d^3q}{(2\pi)^3} F(\vec{q}) \frac{1}{q^{0\,2} - \vec{q}^{\,2} - m^2_{\bar{K}^*} + i\epsilon}$$



The form factor F(q) encodes the information about the D^*D^* bound state:

$$F(\vec{q}) = \int d^3\vec{r}\, e^{-i\vec{q}\cdot\vec{r}}\, \Psi_c^2(\vec{r}) = \frac{1}{N}\int_{|\vec{p}-\vec{q}|<q_{\rm max}}^{p<q_{\rm max}} d^3p \frac{1}{m_C - \sqrt{m^2_{D^*}+\vec{p}^{\,2}} - \sqrt{m^2_{D^*}+\vec{p}^{\,2}}}\; \frac{1}{m_C - \sqrt{m^2_{D^*}+(\vec{p}-\vec{q})^2} - \sqrt{m^2_{D^*}+(\vec{p}-\vec{q})^2}}$$

Normalization of the amplitudes

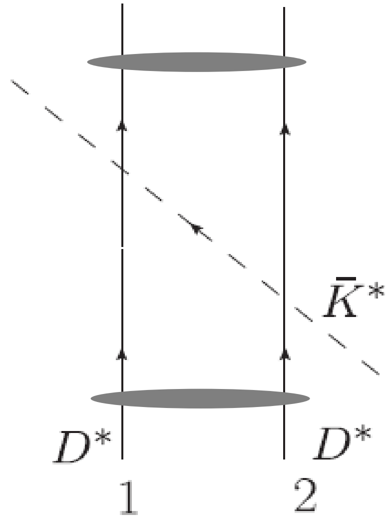
L. Roca and E. Oset, PRD82, 054013 (2010)

- S matrix in the diagram of double scattering:

$$S^{(2)} = -i(2\pi)^4\delta^4(p_{\rm fin}-p_{\rm in})\frac{1}{\mathcal{V}^2}\frac{1}{\sqrt{2\omega_{\bar{K}^*}}}\frac{1}{\sqrt{2\omega_{\bar{K}^*}}}\frac{1}{\sqrt{2\omega_{D^*}}}\frac{1}{\sqrt{2\omega_{D^*}}}\frac{1}{\sqrt{2\omega_{D^*}}}\frac{1}{\sqrt{2\omega_{D^*}}}t_1t_2$$

$$\int\frac{d^3q}{(2\pi)^3}F(\vec{q})\frac{1}{q^{0^2}-\vec{q}^2-m^2_{\bar{K}^*}+i\epsilon}$$

where F(q) is the form factor of the cluster



- Macroscopic perspective of $(D^*(1)D^*(2))_c\ \bar{K}^*$

$$S^{(2)} = -i(2\pi)^4\delta^4(p_{\rm fin}-p_{\rm in})\frac{1}{\mathcal{V}^2}\frac{1}{\sqrt{2\omega_{\bar{K}^*}}}\frac{1}{\sqrt{2\omega_{\bar{K}^*}}}\frac{1}{\sqrt{2\omega_C}}\frac{1}{\sqrt{2\omega_C}}T^{(2)}$$

$$=> \quad T^{(2)} = \frac{2\omega_C}{2\omega_{D^*}}\frac{2\omega_C}{2\omega_{D^*}}\frac{1}{2\omega_C}t_1t_2\int\frac{d^3q}{(2\pi)^3}F(\vec{q})\frac{1}{q^{0^2}-\vec{q}^2-m^2_{\bar{K}^*}+i\epsilon}$$

It is convenient to write the partition functions suited to the macroscopic formalism as

$$\tilde{T}_1 = \tilde{t}_1 + \tilde{t}_1\tilde{G}_0\tilde{T}_2$$
$$\tilde{T}_2 = \tilde{t}_2 + \tilde{t}_2\tilde{G}_0\tilde{T}_1$$

by defining $\tilde{t}_1 = \frac{2m_C}{2m_{D^*}}t_1 \qquad \tilde{t}_2 = \frac{2m_C}{2m_{D^*}}t_2$

In this case, $t_1=t_2$, then $T_1=T_2$

$$\tilde{T}_1=\tilde{t}_1+\tilde{t}_1\tilde{G}_0\tilde{T}_1;\ \ \tilde{T}_1=\frac{1}{\tilde{t}_1^{-1}-\tilde{G}_0};\quad \tilde{T}=\tilde{T}_1+\tilde{T}_2=2\tilde{T}_1$$

Consideration of the isospin and spin of the $D^*\bar{K}^*$ amplitudes

Cluster: D^*D^* bound state in $J^P = 1^+$ and $I = 0$

L. R. Dai, R. Molina, E. Oset, PRD 105 (2022)

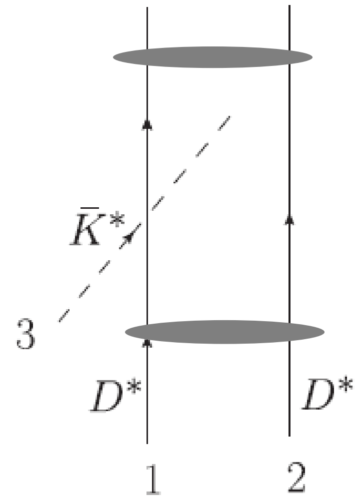
$$|D^*D^*, I=0\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^{*0} - D^{*0}D^{*+})$$

- Isospin considerations:

To make a connection with the $D^*\bar{K}^*$ isospin amplitudes, we combine the third component of $D^*(1)$ with the one of $\bar{K}^*$ to give states of D^*K^* isospin

$|I(D^*(1)\bar{K}^*), I_3(D^*(1)\bar{K}^*)\rangle |I_3(D^*(2))\rangle$ with $I_3 = 1/2$ of $\bar{K}^*$

$$t_1 = \frac{3}{4}t^{I=1}_{D^*\bar{K}^*} + \frac{1}{4}t^{I=0}_{D^*\bar{K}^*}$$



- Spin consideration: three total spins J=0, 1, 2 for $D^*D^*\bar{K}^*$

For J=0 $\quad t_1 = t^{j=1}_{D^*\bar{K}^*}$

For J=1 $\quad t_1 = \frac{1}{4}\left(\frac{4}{3}t^{j=0}_{D^*\bar{K}^*} + t^{j=1}_{D^*\bar{K}^*} + \frac{5}{3}t^{j=2}_{D^*\bar{K}^*}\right).$

For J=2 $\quad t_1 = \frac{1}{4}t^{j=1}_{D^*\bar{K}^*} + \frac{3}{4}t^{j=2}_{D^*\bar{K}^*}$

Consideration of the isospin and spin of the $D^*\bar{K}^*$ amplitudes

Combining the isospin and the spin decomposition of the amplitudes, we find the final contributions

For J=0 $$t_1 = \frac{3}{4} t^{I=1,\ j=1} + \frac{1}{4} t^{I=0,\ j=1}$$

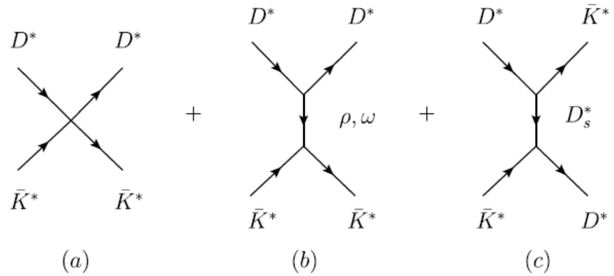
For J=1 $$t_1 = \frac{1}{16}\left\{5t^{I=1,\ j=2} + 3t^{I=1,\ j=1} + 4t^{I=1,\ j=0} + \frac{5}{3}t^{I=0,\ j=2} + t^{I=0,\ j=1} + \frac{4}{3}t^{I=0,\ j=0}\right\}$$

For J=2 $$t_1 = \frac{1}{16}\left\{9t^{I=1,\ j=2} + 3t^{I=1,\ j=1} + 3t^{I=0,\ j=2} + t^{I=0,\ j=1}\right\}$$

- The $D^*\bar{K}^*$ amplitude t for the different I, j states

Bethe-Salpeter eq. $$t_1 = \frac{1}{V^{-1} - G_{D^*\bar{K}^*}}$$

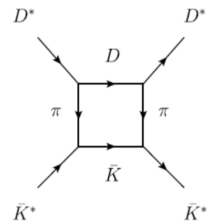
R. Molina, T. Branz, and E. Oset, PRD82(2010) 014010
R. Molina, E. Oset, PLB811 (2020)



The interaction V of $D^*\bar{K}^*$ in I=0 is attractive

$I(J^P)$	M[MeV]	Γ[MeV]	Coupled channels	state
$0(2^+)$	2775	38	$D^*\bar{K}^*$	?
$0(1^+)$	2861	20	$D^*\bar{K}^*$	?
$0(0^+)$	2866	57	$D^*\bar{K}^*$	$X_0(2866)$

Decay width

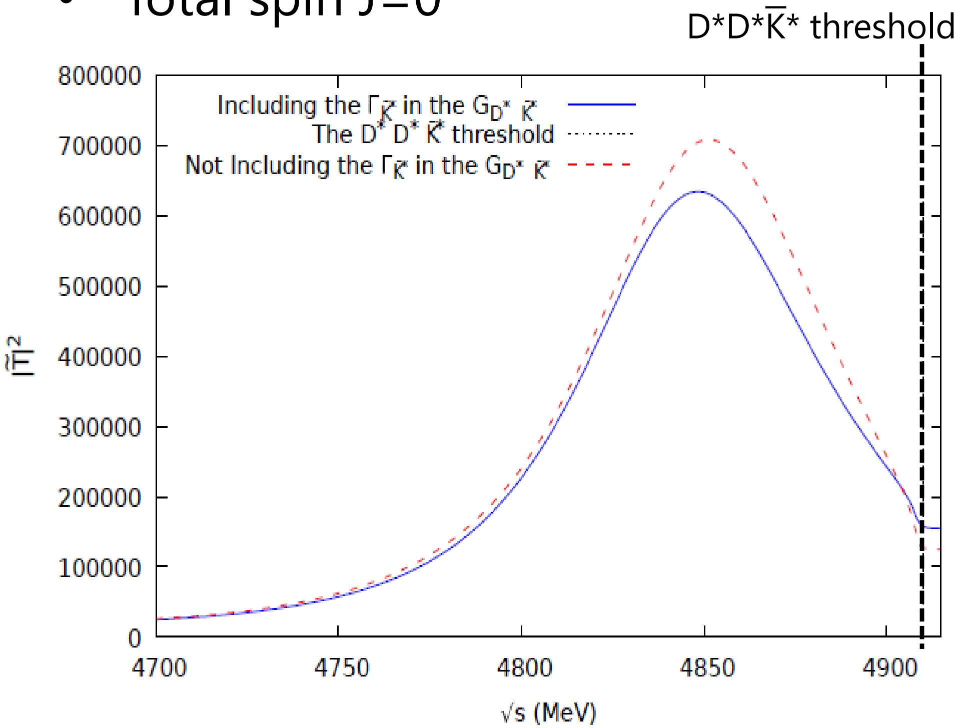


In I = 1, V is repulsive=> No bound state

Bound states of $D^* D^* \bar{K}^*$

N. Ikeno, M. Bayar, E. Oset,
PRD107, 034006 (2023)

- Total spin J=0



- A clear peak around 4845 MeV, about 61 MeV below the $D^*D^*\bar{K}^*$ threshold

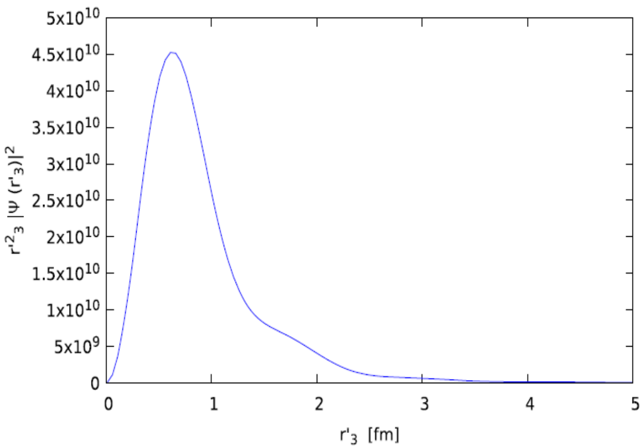
  D*D* is bound by about 4-6 MeV
  D*K̄* is bound by about 30 MeV
  => The interaction of K̄* with two D* would give rise to a binding about twice as big as the one of D*K̄*

- The width is around 80 MeV

  Consideration K̄* decay width by means of a convolution of the loop function

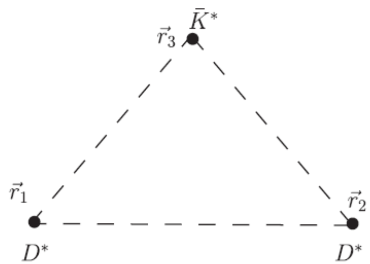
- Wave function for the K̄* in the D*D*K̄* system at rest.

D. Gamermann, J. Nieves, E. Oset,
E. Ruiz Arriola, PRD 81(2010)014029



$$|\Psi(r'_3)|^2 = \int d^3r_1 d^3r_2 (|\phi(\vec{r}_{31})|^2 + |\phi(\vec{r}_{32})|^2)|\phi'(\vec{r}_{12})|^2$$
$$\times \delta^3(m_{D^*}\vec{r}_1 + m_{D^*}\vec{r}_2 + m_{\bar{K}^*}\vec{r}_3),$$

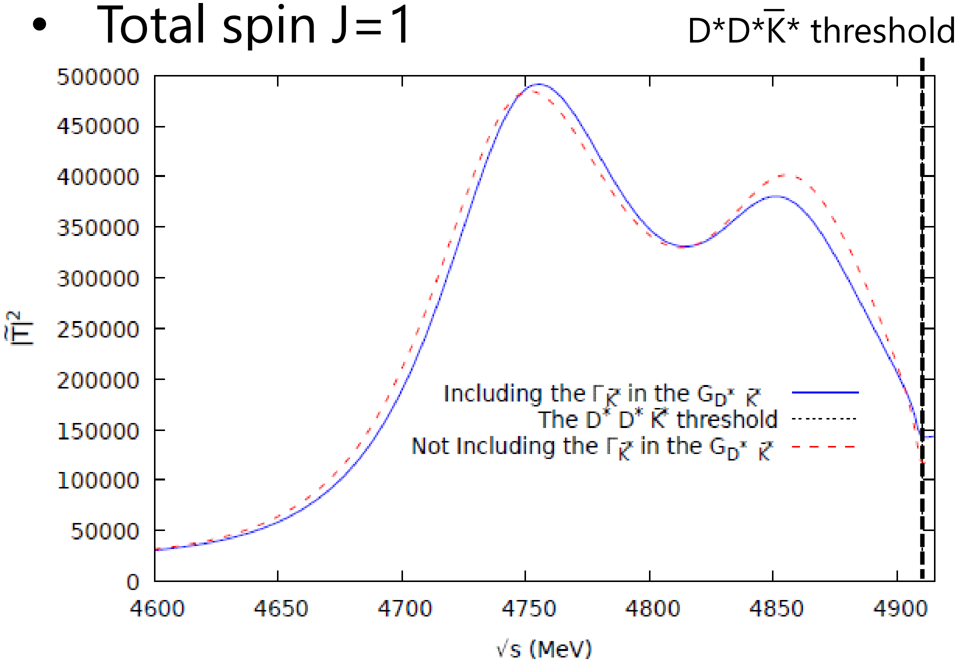
- A peak around 0.7 fm
- The mean square radius ~ 1 fm
  Bigger than that of the proton (0.84 fm),
  Smaller than that of the deuteron (2.1 fm)



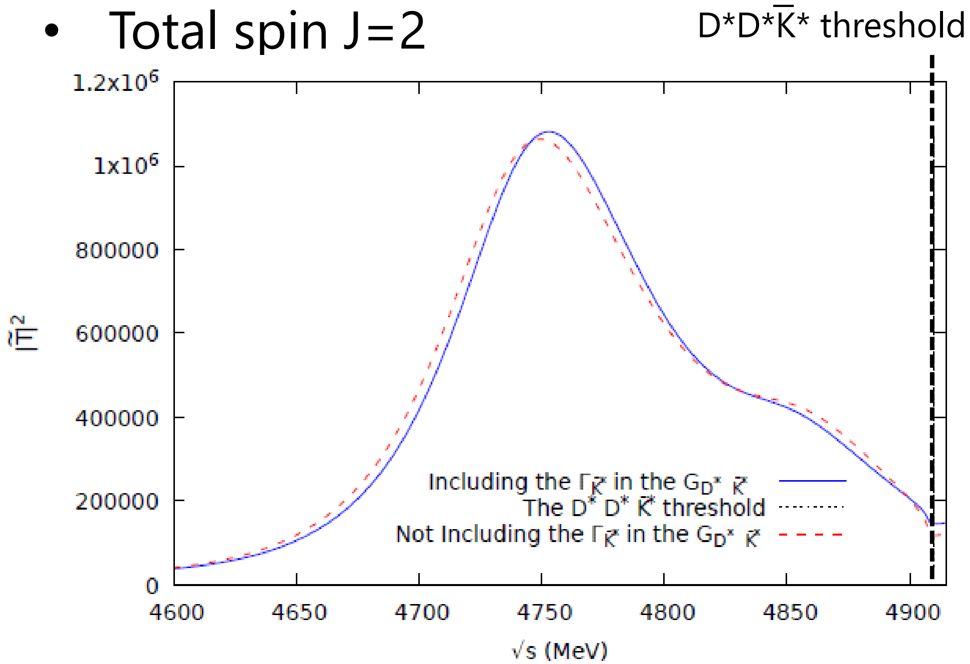
Bound states of $D^* D^* \bar{K}^*$

N. Ikeno, M. Bayar, E. Oset,
PRD107, 034006 (2023)

- Total spin J=1



- Total spin J=2



We see two peaks, indicating two states

=>Easy to trace the origin of the peaks

- Total spin J=1 case

  First peak (higher energy) is due $t^{I=0,j=0,1}$

  Second peak is due to $t^{I=0,j=2}$

- Total spin J=2 case

  First peak (higher energy) is due $t^{I=0,j=1}$

  Second peak is due to $t^{I=0,j=2}$

Spin consideration:

For J=1 $t_1 = \frac{1}{4}\left(\frac{4}{3}t^{j=0}_{D^*\bar{K}^*} + t^{j=1}_{D^*\bar{K}^*} + \frac{5}{3}t^{j=2}_{D^*\bar{K}^*}\right).$

For J=2 $t_1 = \frac{1}{4}t^{j=1}_{D^*\bar{K}^*} + \frac{3}{4}t^{j=2}_{D^*\bar{K}^*}$

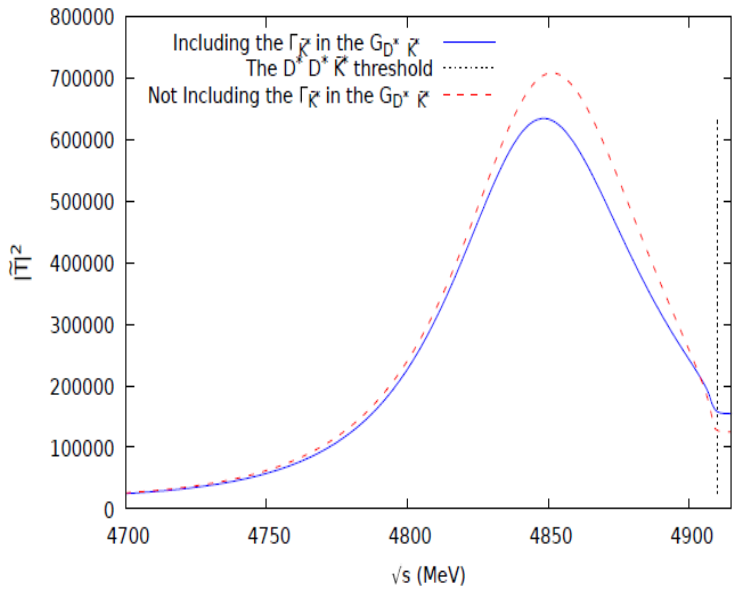
$I(J^P)$	M[MeV]	Γ[MeV]	Coupled channels	state
$0(2^+)$	2775	38	$D^*\bar{K}^*$	?
$0(1^+)$	2861	20	$D^*\bar{K}^*$	?
$0(0^+)$	2866	57	$D^*\bar{K}^*$	$X_0(2866)$

R. Molina, E. Oset, PLB811 (2020)

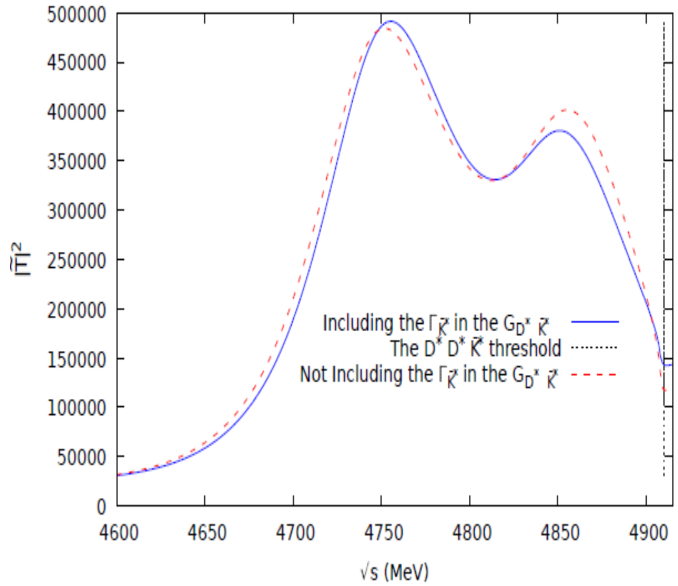
Bound states of $D^* D^* \bar{K}^*$

N. Ikeno, M. Bayar, E. Oset,
PRD107, 034006 (2023)

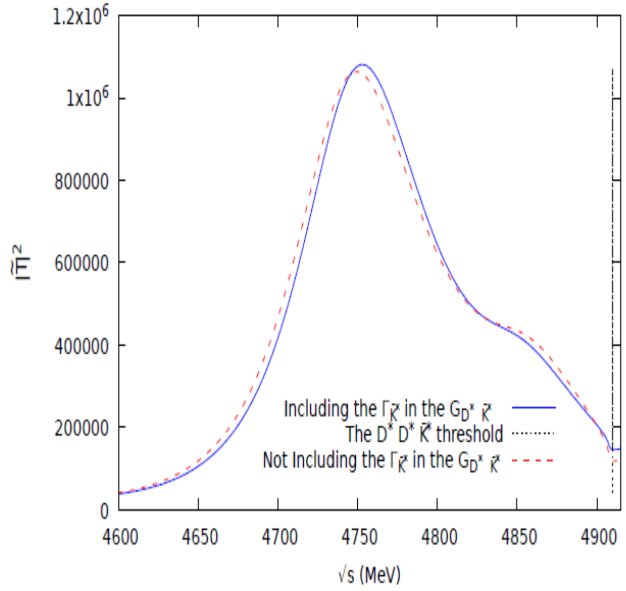
- Total spin J=0



- Total spin J=1



- Total spin J=2



J		M [MeV]	B [MeV]	Γ [MeV]	Main decay mode
0	(State I)	4845	61	80	$D^* D^* \bar{K}$
1	(State I)	4850	56	94	$D^* D \bar{K}$, $D^* D^* \bar{K}$
1	(State II)	4754	152	100	$D^* D \bar{K}$, $D^* D^* \bar{K}$
2	(State I)	4840	66	85	$D^* D^* \bar{K}$
2	(State II)	4755	151	100	$D^* D \bar{K}$, $D^* D^* \bar{K}$

Bound states obtained:
One state for J = 0
two states for J = 1, 2

BE = 56 MeV to 152 MeV
Γ = 80 MeV to 100 MeV

Summary

The Z_{cs} state:

- One of the exotic hadrons with $c\bar{q}s\bar{c}$
- $Z_{cs}(3985)$ at BESIII
  - Threshold effect from the coupled-channel interaction based on the molecular picture of $D_s^* \bar{D} / \bar{D}_s D^*$
- Other Z_{cs} states
  - Another cusp corresponding to the $D_s^* \bar{D}^*$ interaction with J=2

Molecular states of $D^* D^* \bar{K}^*$ nature:

- Very exotic hadron contains ccs open quarks
- We obtained bound states with total spin J = 0, 1, 2 in FCA
- Possible new system B*B*K* containing bbs open quarks

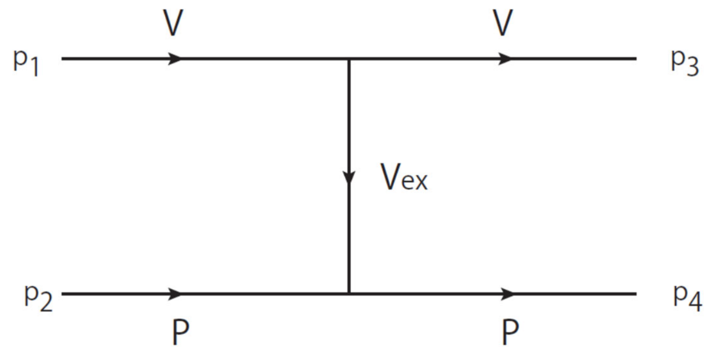
M. Bayar, N. Ikeno and L. Roca, arXiv:2301.07436 [hep-ph], PRD.

Formalism: Coupled channels approach

- Vector-Pseudoscalar channels (VP)

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

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