The Z_{cs} states based on the molecular picture

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Raquel Molina, Eulogio Oset

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)

20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023), June 5- 9th 2023

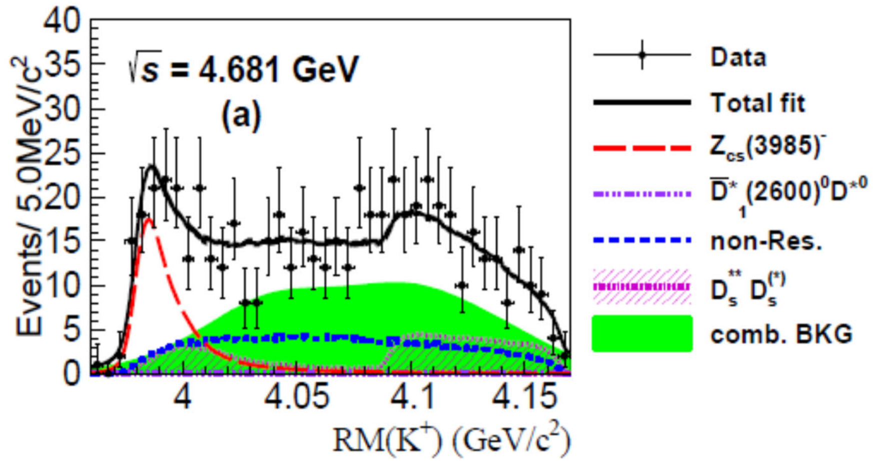
Discovery of $Z_{cs}(3985)$

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:

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

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



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$Z_{cs}(3985)$ could be the SU(3) partner of the $Z_c(3900)$ state, where a d quark has been replaced by an s quark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

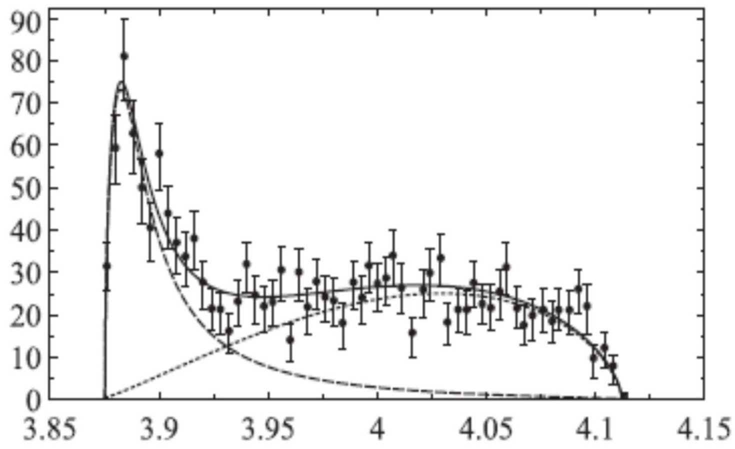
$Z_c(3900)$: BESIII Experiment (2014) in the $e^+e^- \to \pi D\bar{D}^*$ reaction

- $Z_c(3900)$ 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 $D^0 D^{*-}$

$\Rightarrow$ 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)

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

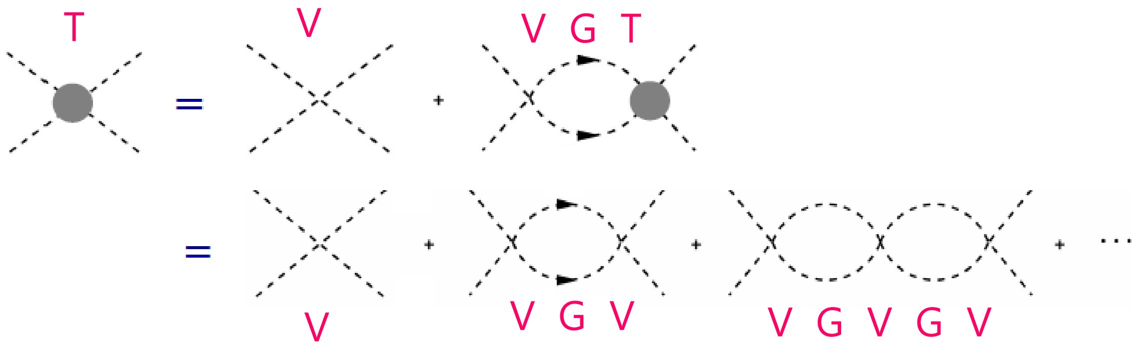
- Bethe-Salpeter equation:

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

T: Scattering matrix

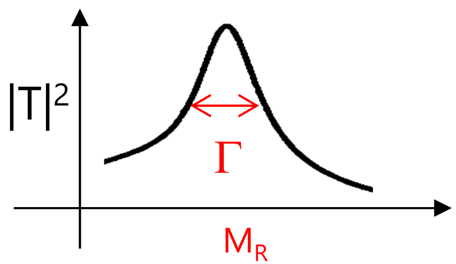
V: Interaction of the coupled channels

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}.

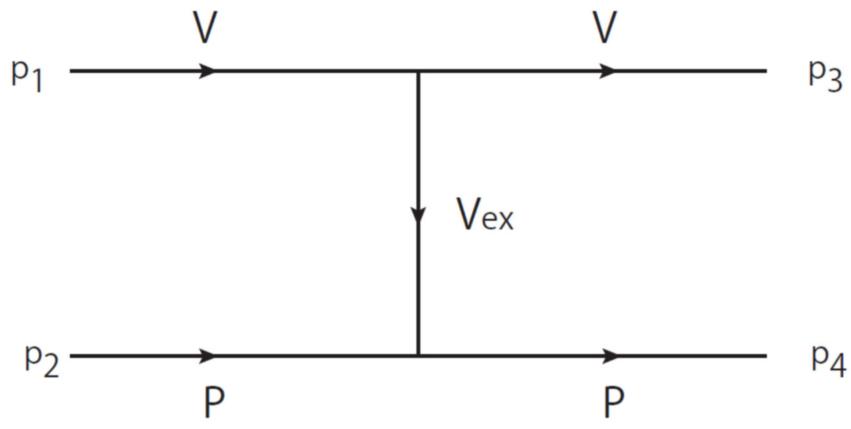
m, M the pseudoscalar and vector masses of the l-th channel

q_{max} is around 700–850MeV here

Interaction

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

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



- 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

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

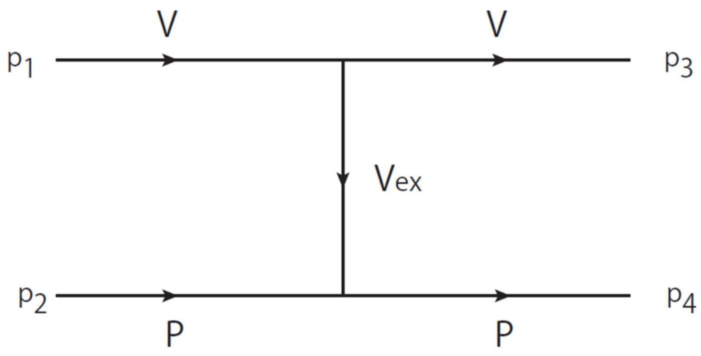
$$P = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix} \quad V_\mu = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$

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:

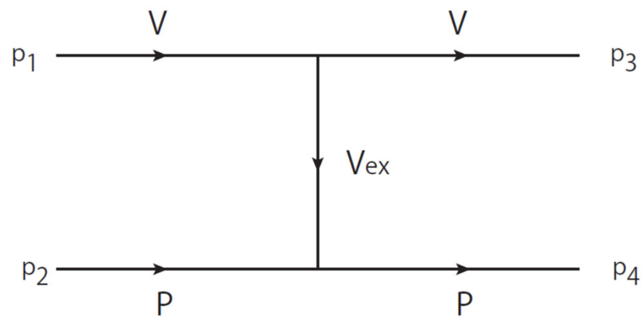
$$\boxed{A = \frac{1}{\sqrt{2}}(D_s^- D^{*0} + D_s^{*-} D^0)} \qquad \boxed{B = \frac{1}{\sqrt{2}}(D_s^- D^{*0} - D_s^{*-} D^0)}$$

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

Interaction for Z_{cs} (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)

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



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

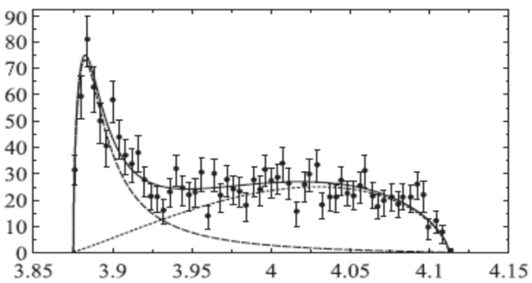
where $M_{12}^2 = (p_1 + p_2)^2$

- 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.

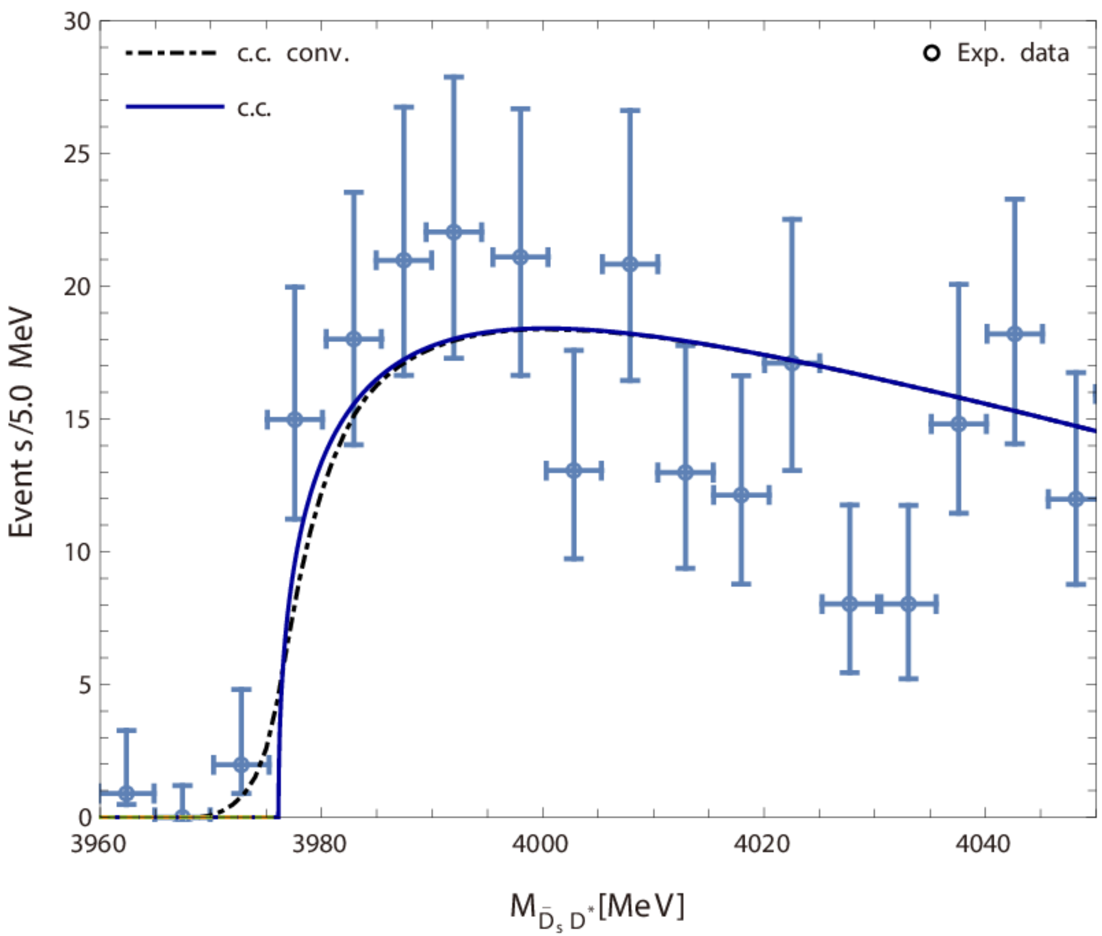


Invariant mass distribution for the $D^0 D^{*-}$

=> 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

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

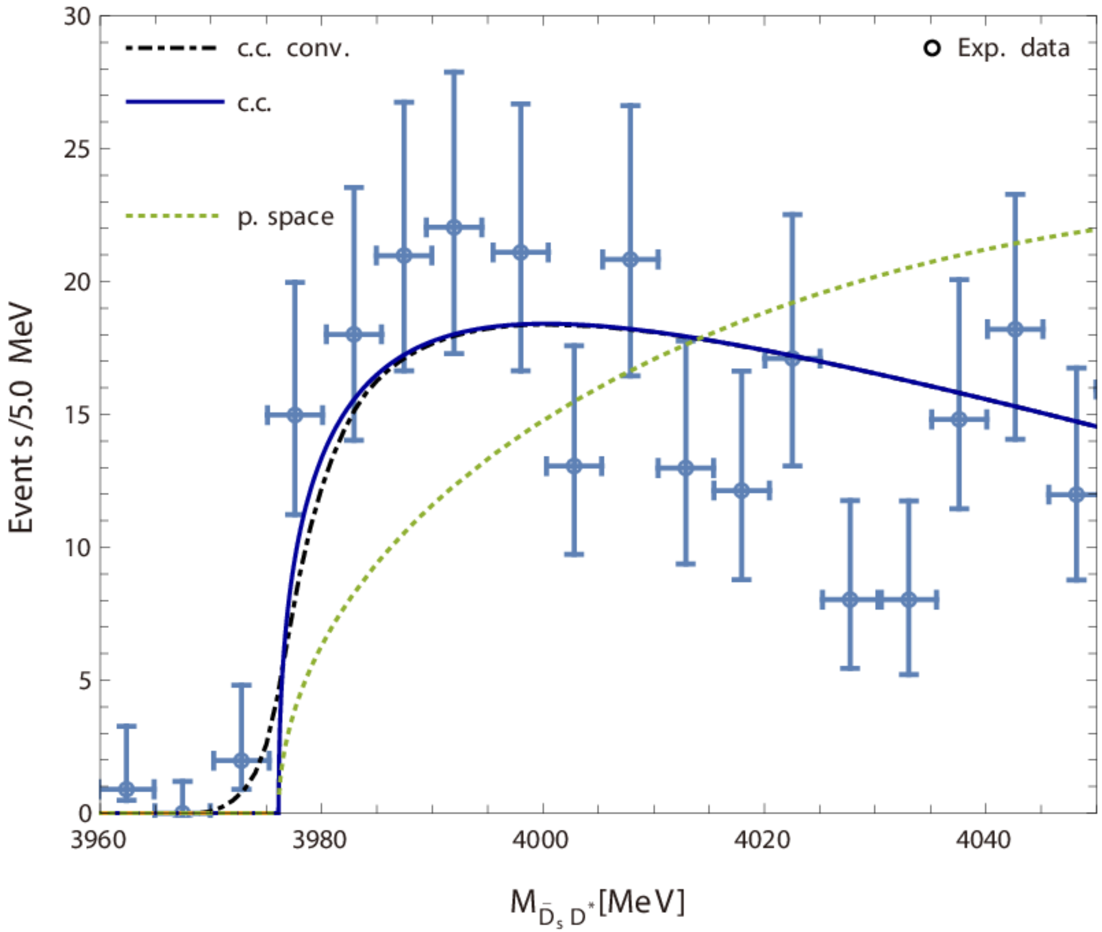
$$p = \frac{\lambda^{1/2}(s, m_K^2, M_{\bar{D}_s D^*}^2)}{2\sqrt{s}}, \quad \tilde{q} = \frac{\lambda^{1/2}(M_{\bar{D}_s D^*}^2, m_{\bar{D}_s}^2, m_{D^*}^2)}{2M_{\bar{D}_s D^*}}$$

✓ 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.

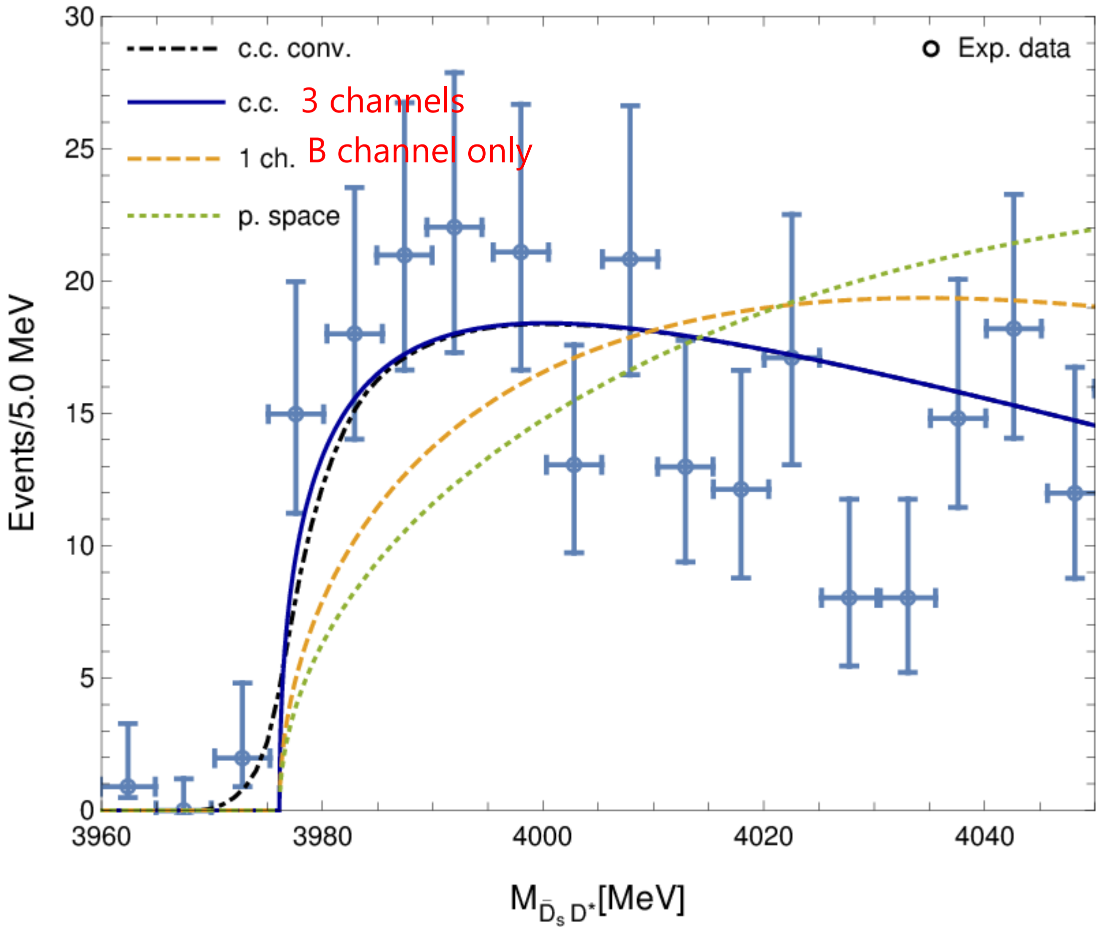
This interaction has the effect of accumulating strength close to threshold

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 $D_s^- D^{*0} - D_s^{*-} D^0$

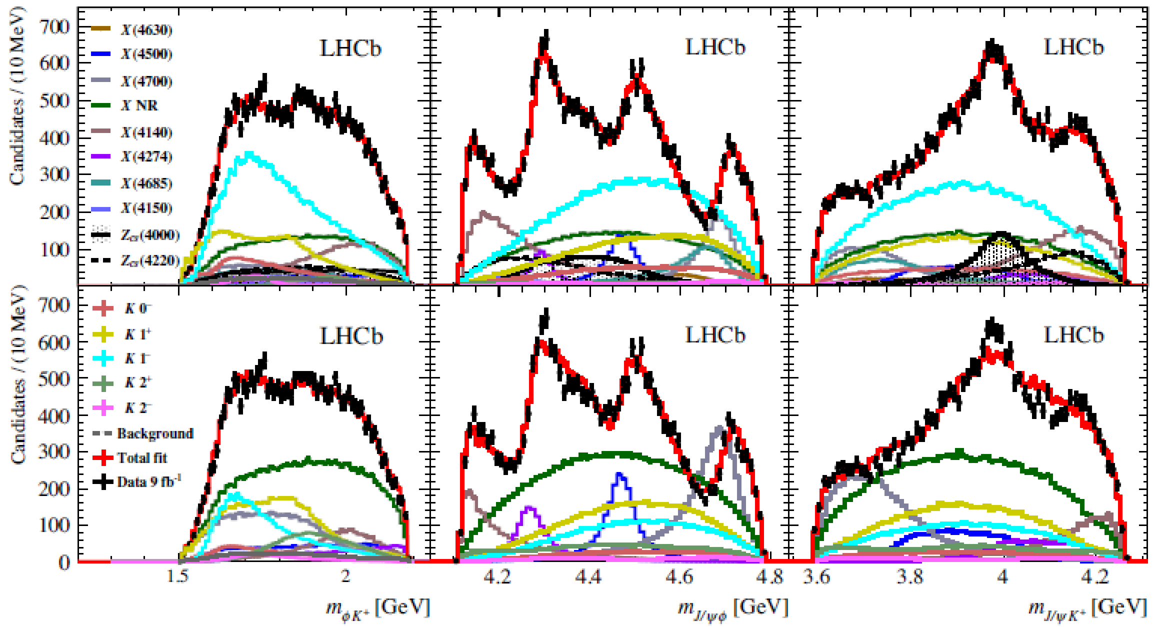
✓ The result does not differ much from that of the phase space.
✓ It is clearly incompatible with the data.

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.

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



- 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)

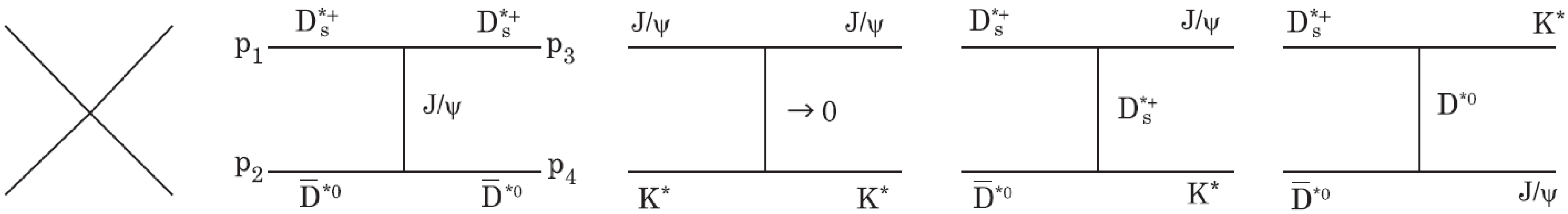
  Evidence of a $J/\psi K^0_s$ structure in $B^0 \to J/\psi \phi K^0_s$ decays

=> 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)

The Z_{cs} state based on the $D_s^*\bar{D}^*$ molecular state

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



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

- The interaction is different for the different spin channels J

- Contact term for the interaction

$$V^{(c)} = g^2\begin{pmatrix} 2 & -4 \\ -4 & 0 \end{pmatrix}, \qquad J = 0,$$

$$V^{(c)} = g^2\begin{pmatrix} 3 & 0 \\ 0 & 0 \end{pmatrix}, \qquad J = 1,$$

$$V^{(c)} = g^2\begin{pmatrix} -1 & 2 \\ 2 & 0 \end{pmatrix}, \qquad J = 2.$$

- Exchange term for the interaction

$$V^{(\mathrm{ex})} = g^2\begin{pmatrix} -\frac{(p_1+p_3)\cdot(p_2+p_4)}{M^2_{J/\psi}} & -\frac{3s-\sum M_i'^2}{D} \\ -\frac{3s-\Sigma M_i'^2}{D} & 0 \end{pmatrix}, \qquad J = 0, 2$$

$$V^{(\mathrm{ex})} = g^2\begin{pmatrix} -\frac{(p_1+p_3)\cdot(p_2+p_4)}{M^2_{J/\psi}} & 0 \\ 0 & 0 \end{pmatrix}, \qquad J = 1.$$

The diagonal terms are repulsive or zero for J = 0, 1, but attractive for J = 2.

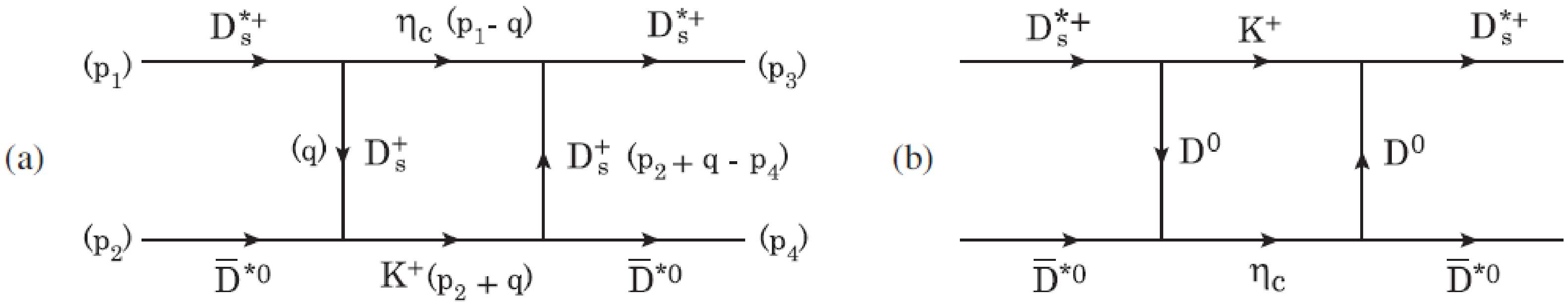
$$\Sigma M_i'^2 = M^2_{D_s^*} + M^2_{\bar{D}^{*0}} + M^2_{J/\psi} + M^2_{K^*}$$

$$D = M^2_{J/\psi} - 2\bar{M}_{D^*}E_{J/\psi}$$

Decay channels

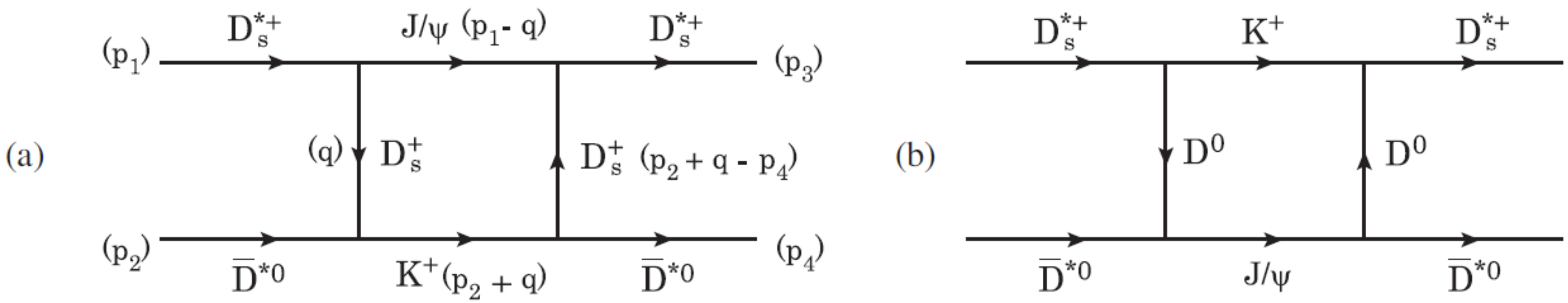
The $J/\psi K^*$ state is 129 MeV below the $D_s^*\bar{D}^*$ threshold
We only study the decay channels of the $D_s^*\bar{D}^*$ component

Diagram for $D_s^{*+}\bar{D}^{*0}$ decay to $\eta_c K^+$



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

Diagram for $D_s^{*+}\bar{D}^{*0}$ decay to $J/\psi K$.



$$\mathcal{L} = \frac{G'}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\langle\partial_\mu V_\nu \partial_\alpha V_\beta P\rangle$$

Finally, we include all these decay channels taking for the $D_s^{*+}\bar{D}^{*0} \to D_s^{*+}\bar{D}^{*0}$ transition

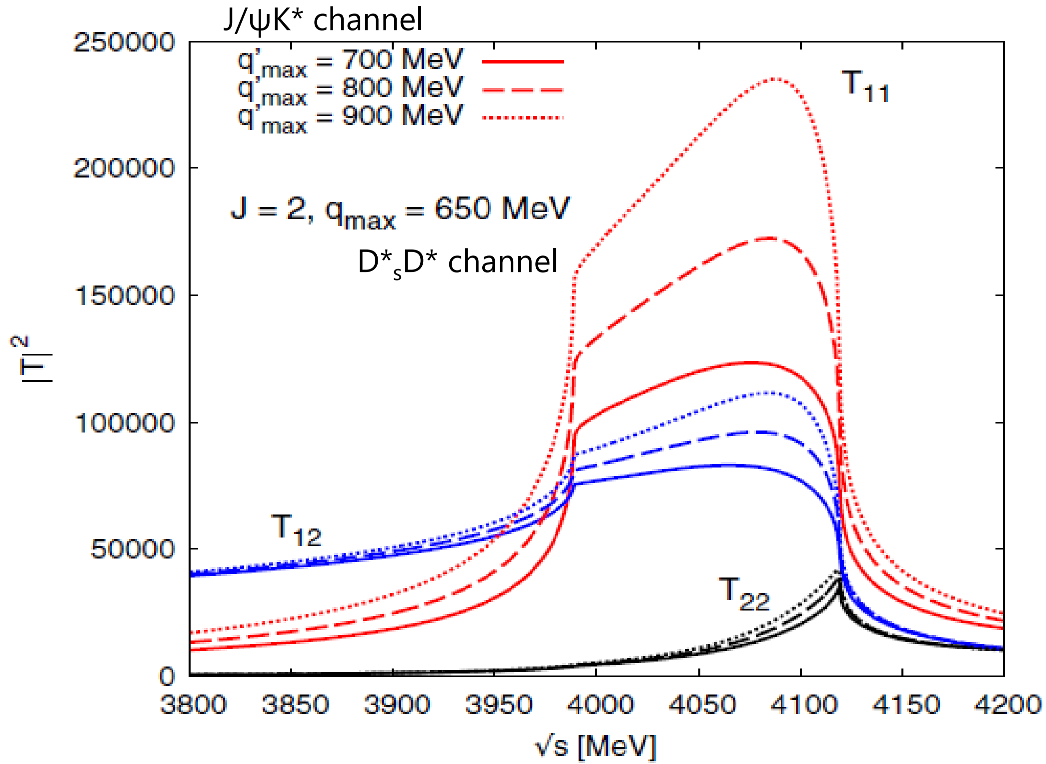
$$V_{D_s^{*+}\bar{D}^{*0} \to D_s^{*+}\bar{D}^{*0}} + i\mathrm{Im}V^{(a)} + i\mathrm{Im}V^{(b)} + i\mathrm{Im}V'^{(a)} + i\mathrm{Im}V'^{(b)}$$

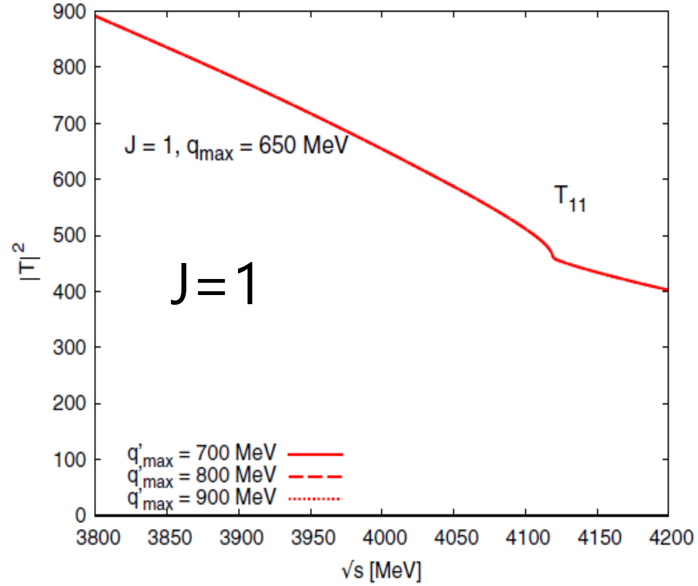
Z_{cs} states from $D_s^* \bar{D}^*$ and $J/\psi K^*$ coupled channels

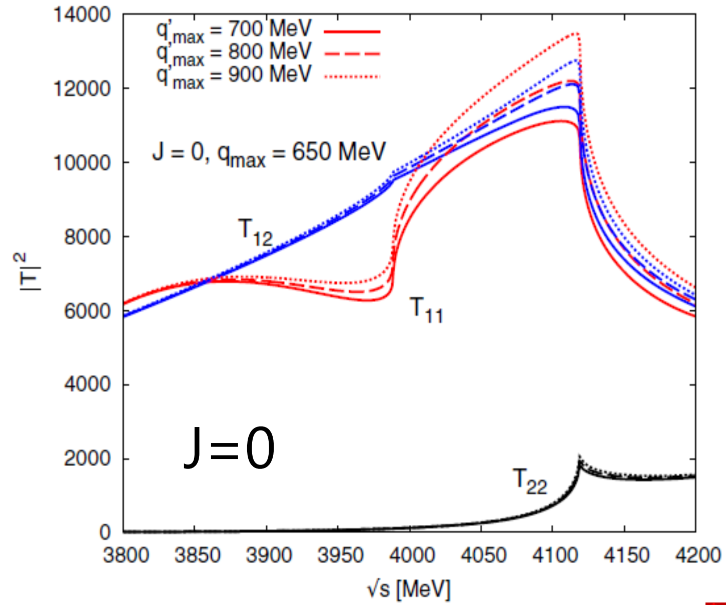
N. Ikeno, R. Molina, E. Oset,
PRD 105, 014012 (2022).

$|T|^2$ for each channel for the different cut-off q_{max} values of $J/\psi K^*$ channel

J=2







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

$J/\psi K$ distribution in $B^+ \to J/\psi \phi K^+$ decay

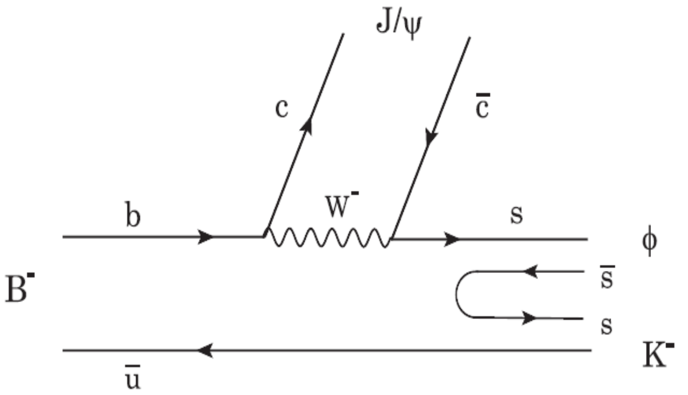


FIG. 5. A mechanism for $B^- \to J/\psi\phi K^-$ decay based on internal emission.

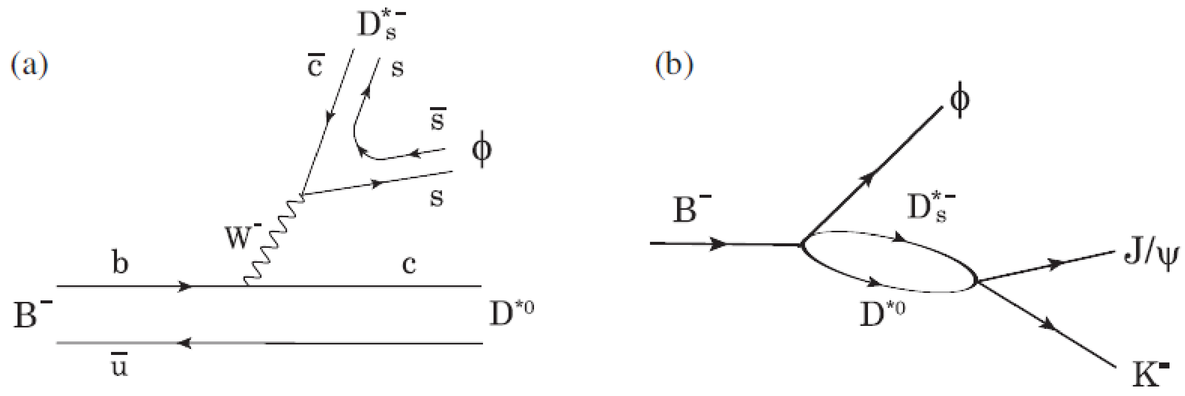
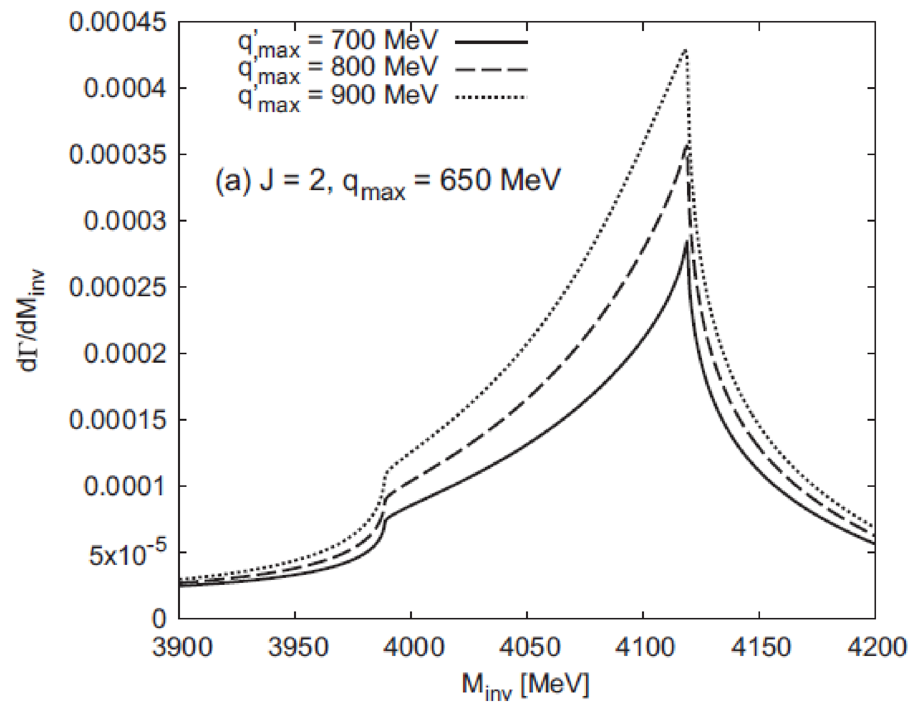


FIG. 6. (a) Mechanism for $B^- \to \phi D_s^{*-} D^{*0}$; (b) Rescattering mechanism leading to $\phi J/\psi K$.

The mass distribution

$$\frac{d\Gamma}{dM_{\rm inv}(J/\psi K)} = \frac{1}{(2\pi)^3}\frac{1}{4M_B^2}\, p_\phi \tilde{p}_K |t|^2$$

$$p_\phi = \frac{\lambda^{1/2}(M_B^2, M_\phi^2, M_{\rm inv}^2(J/\psi K))}{2M_B} \qquad \tilde{p}_K = \frac{\lambda^{1/2}(M_{\rm inv}^2(J/\psi K), M_{J/\psi}^2, M_K^2)}{2M_{\rm inv}(J/\psi K)}$$



We see a pronounced sharp peak around the $D_s^* \bar{D}^*$ threshold (~4120 MeV)

=> Further measurements around this region is required

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 $D_s^*\bar{D}/\bar{D}_s D^*$

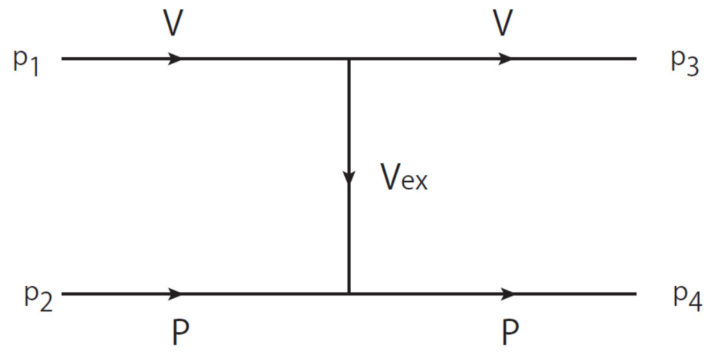
- Other Z_{cs} states
  - We have studied Z_{cs} states with coupled channels of $D_s^*\bar{D}^*$ and $J/\psi K^*$
  - The J=2 channel has enough attraction to create a strong cusp structure that shows up in the $J/\psi K$ invariant mass distribution in the B decay at the $D_s^*\bar{D}^*$ threshold.

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