Production of Near Threshold States in e^+e^- Annihilations

CRC110 B.3 Project

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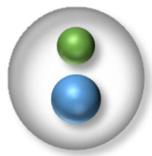
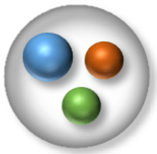
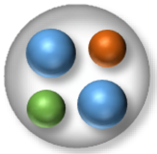
Constituent QM & Hadron Exotics

- *Constituent quark model*

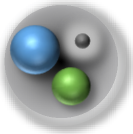
Mesons 

Baryons 

- *Hadron exotics*

Tetraquarks 

Loosely bound molecules 

Hybrids 

"*XYZ*" States and Nearby Thresholds

- *Most of the heavily flavored "**XYZ**" states are intimately related to the nearby S-wave thresholds:*

$\vdots$

Charmonium-like

$X(4274)$ $Y(4260)$ [1]	$D_1\overline{D}$
$Y(4008)$ $Z_c(4020)$ [2]	$D^*\overline{D^*}$
$X(3872)$ $Z_c(3900)$ [3]	$D\overline{D^*}$

$\vdots$

Bottomonium-like

$Z_b(10650)$ [4]	$B^*\overline{B^*}$
$Z_b(10610)$ [4]	$B\overline{B^*}$

[1] B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 95 (2005) 142001
[2] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 111, no. 24, 242001
[3] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 110, 252001
[4] A. Bondar et al. [Belle Collaboration], Phys. Rev. Lett. 108 (2012) 122001

Two Nearby Thresholds by Spin Splitting

- *Equal spin splitting of mass of meson doublets with same light degree of freedom:*

$$m_{D_{s1}} - m_{D_{s0}} = 142\text{ MeV} \qquad m_{D_s^*} - m_{D_s} = 144\text{ MeV}$$

(1/2)+ (1/2)+ (1/2)- (1/2)-

mass of $D_{s1}D_s$ = 4.428 GeV mass of $D_{s0}D_s^*$ =4.430 GeV

- *Same splitting in the beauty-strange meson doublets:*

$$m_{B_{s1}} - m_{B_{s0}} = m_{B_s^*} - m_{B_s} + O(1\text{ MeV}) \approx 48\text{ MeV}$$

Dynamically Generated States

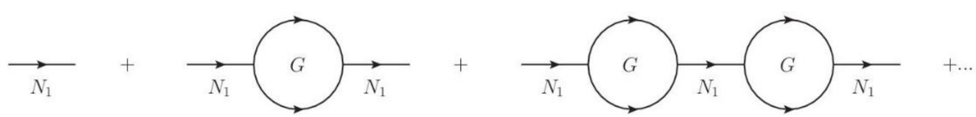
- In Godfrey-Isgur quark model, both $\psi(4S)$ and $\psi(2D)$ have masses close to $D_{s1}D_S$ and $D_{s0}D_s^*$ thresholds and can couple to them in S-wave:

$$m_{\psi(4S)} = 4.45\text{GeV} \qquad m_{\psi(2D)} = 4.194\text{GeV}$$

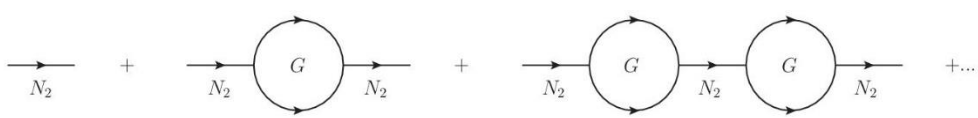
- With the strong interaction of these two thresholds, the propagator of $\psi(4S)$ and $\psi(2D)$ can be taken as [1]:

$$G = \frac{1}{D_1 D_2 - |D_{12}|^2}\begin{pmatrix} D_1 & D_{12} \\ D_{21} & D_2 \end{pmatrix} = \frac{G_{12}}{\det[G_{12}]}$$

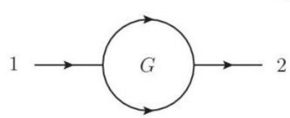
Where

$\frac{i}{D_1} =$ 

$= \frac{i}{m_a^2 - s - iB_{11}}$

$\frac{i}{D_2} =$ 

$= \frac{i}{m_b^2 - s - iB_{22}}$

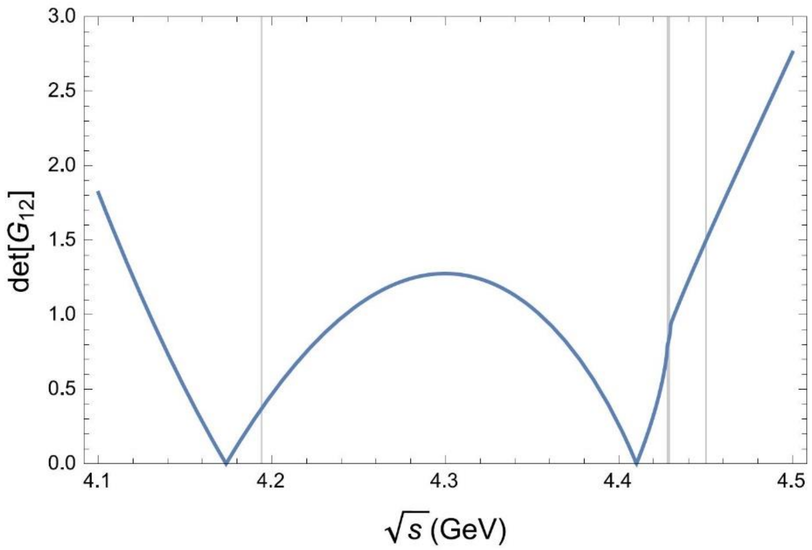
$D_{12} =$ 

$= iB_{12}$

[1] N.N.Achasov, A.V.Kiselev, Phys. Lett.B534,83

Finding Physical Poles

- *Since* $G = \frac{G_{12}}{|G_{12}|}$, *finding the physical poles is equivalent to set* $|G_{12}| = 0$ *and solve* $\sqrt{s}$.



Pole 1 = $4.17\ \mathrm{GeV} \approx m_{\psi(4160)}$

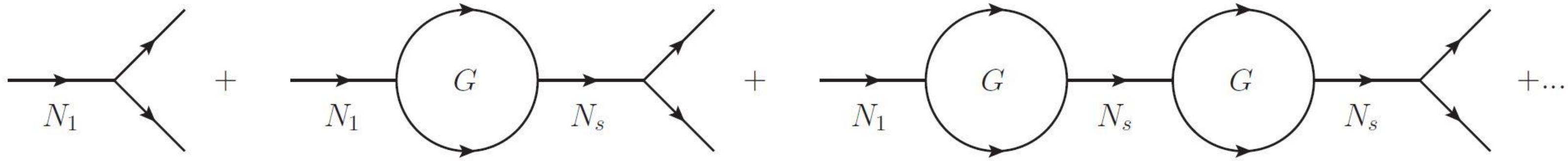
Pole 2 = $4.41\ \mathrm{GeV} \approx m_{\psi(4415)}$

with $\mathrm{g}=7\ \mathrm{GeV}^{-1/2}$

- *So we regard* $\psi(4415)$ *and* $\psi(4160)$ *can be mixing states between the dynamically generated states of the strong S-wave interactions with thresholds and the quark model states* $\psi(4S)$ *and* $\psi(2D)$.

Physical Propagator of $\psi(4415)$

- *Physical propagator of* $\psi(4415)$:

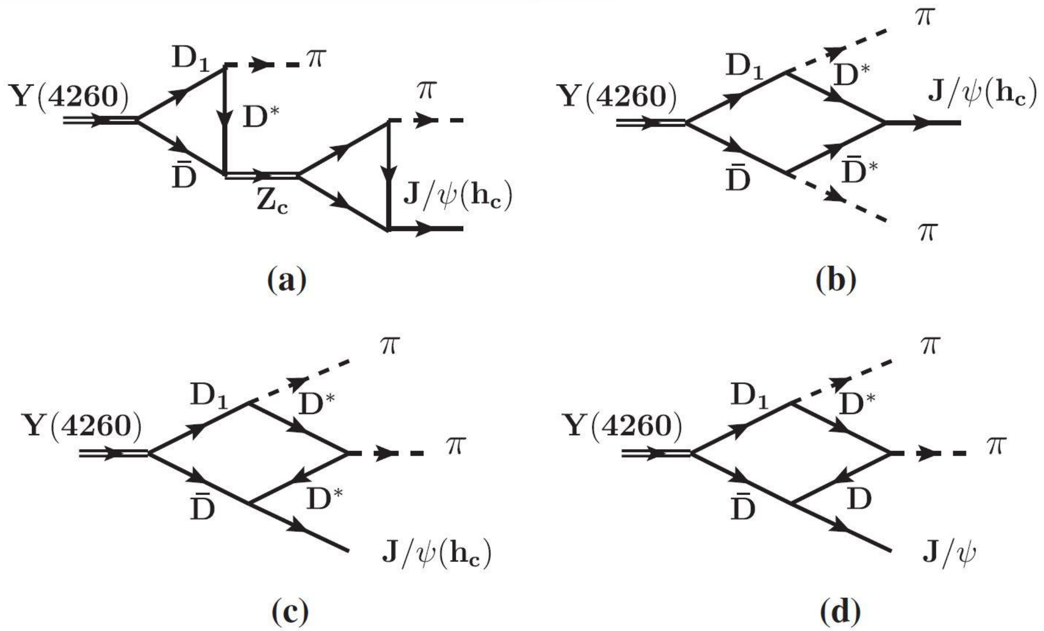


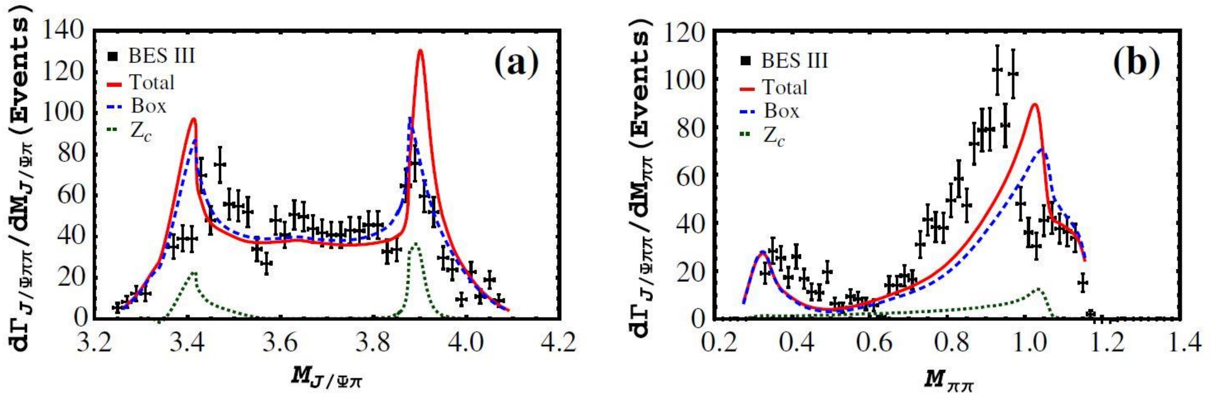
$$
\begin{aligned}
\frac{i}{N_{1p}} &= \frac{i}{N_1} G \frac{i}{N_s} + \frac{i}{N_1} G \frac{i}{N_s} G \frac{i}{N_s} + \ldots \\
&= \frac{i}{N_1} / (1 - G \frac{i}{N_s}) \\
&= \frac{i}{2m_1(E - m_1 - \Sigma_1(E))},
\end{aligned}
$$

- *To get the physical pole at $m_{1p,}$ expand $\Sigma_1(E)$ at m_{1p} to the first order:*

$$
\begin{aligned}
\frac{2m_1 i}{N_{1p}} &= \frac{i}{E - m_1 - \Sigma_1(E)} \\
&= \frac{iZ}{E - m_1 p - Z\widetilde{\Sigma}_1(E)}
\end{aligned}
$$

The Study of $Z_c(3900)$

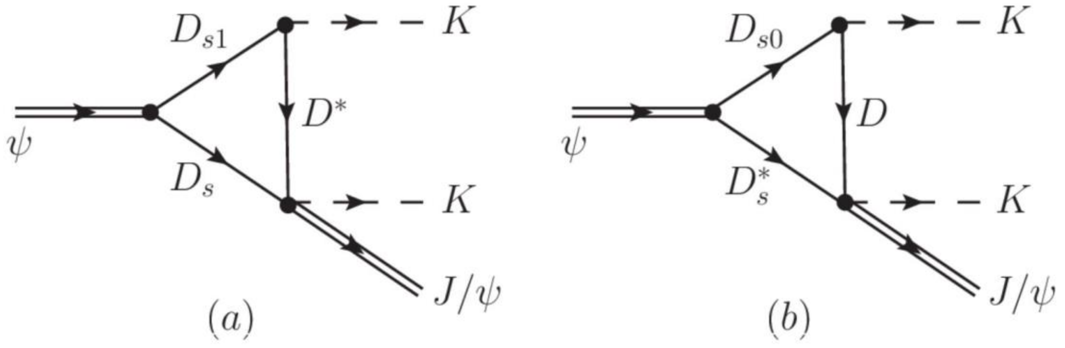




Q. Wang, C. Hanhart and Q. Zhao, Phys. Rev. Lett. 111, 132003

Cusp Effects in $\psi(4415)$

- *Possible triangle diagrams of* $\psi(4415) \to J/\psi KK$:



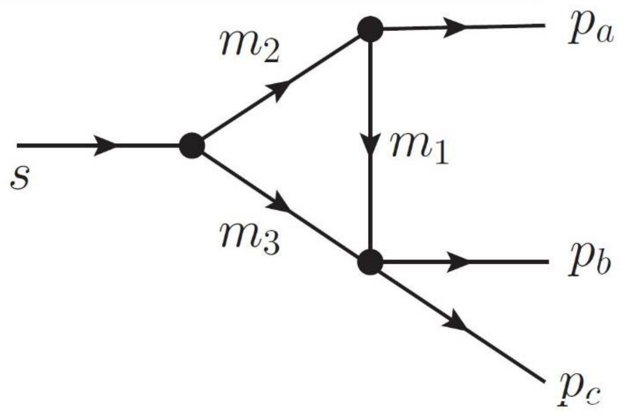
- *Lagrangians in ChPT:*

$$\mathcal{L}_1 = g_S \langle J \bar{S}_a^{\dagger} \bar{H}_a + J \bar{H}_a^{\dagger} \bar{S}_a \rangle$$

$$\mathcal{L}_2 = ih \langle \bar{H}_a S_b \gamma_\mu \gamma_5 \mathcal{A}_{ba}^{\mu} \rangle$$

$$\mathcal{L}_3 = C_S \langle J \bar{H}_b^{\dagger} \gamma_\mu \gamma_5 \bar{H}_a \mathcal{A}_{ba}^{\mu} \rangle$$

Triangle Singularity



- *We define* $s_2 = (p_b + p_c)^2, s_3 = p_a^2$
- *The scalar 3-point loop* $\Gamma_3(s_1, s_2, s_3)$

$$= \frac{1}{i(2\pi)^4} \int \frac{d^4 q_1}{(q_1^2 - m_1^2 + i\epsilon)(q_2^2 - m_2^2 + i\epsilon)(q_3^2 - m_3^2 + i\epsilon)}$$

- *With the location of TS at*

$$s^{\pm} = (m_2 + m_3)^2 + \frac{1}{2m_1^2}[(m_1^2 + m_2^2 - s_3)(s_2 - m_1^2 - m_3^2) - 4m_1^2 m_2 m_3 \pm \lambda^{1/2}(s_2, m_1^2, m_3^2)\lambda^{1/2}(s_3, m_1^2, m_2^2)],$$

$$s_2^{\pm} = (m_1 + m_3)^2 + \frac{1}{2m_2^2}[(m_1^2 + m_2^2 - s_3)(s - m_2^2 - m_3^2) - 4m_2^2 m_1 m_3 \pm \lambda^{1/2}(s, m_2^2, m_3^2)\lambda^{1/2}(s_3, m_1^2, m_2^2)].$$

- *And the TS region depending on* s_3*:*

$$s_N = (m_2 + m_3)^2,\ \ s_C = (m_2 + m_3)^2 + \boxed{\frac{m_3}{m_1}[(m_2 - m_1)^2 - s_3],}$$

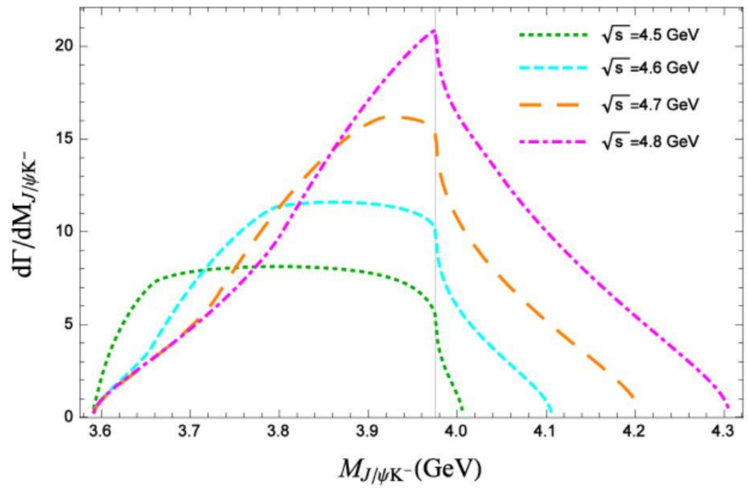
$$s_{2N} = (m_1 + m_3)^2,\ \ s_{2C} = (m_1 + m_3)^2 + \boxed{\frac{m_3}{m_2}[(m_2 - m_1)^2 - s_3].}$$

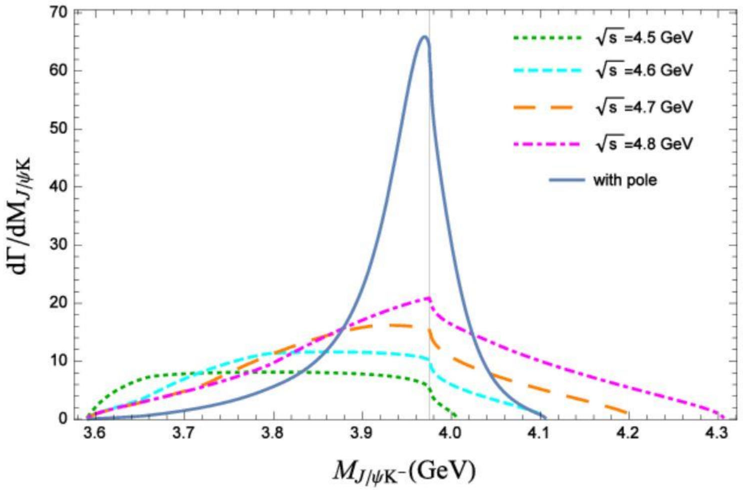
L. D. Landau, Nucl. Phys. 13 (1959) 181
X. H. Liu, M. Oka and Q. Zhao, Phys. Lett. B 753

Cusp Effects in $\psi(4415)$

- *Since the mass of D_{s1} is slightly smaller than that of D^*K, and the mass of D_{s0} is slightly smaller than that of DK, only the lower-order singularity can happen here.*

- *Invariant mass spectrum of $J/\psi K$ in $\psi(4415) \to J/\psi KK$*



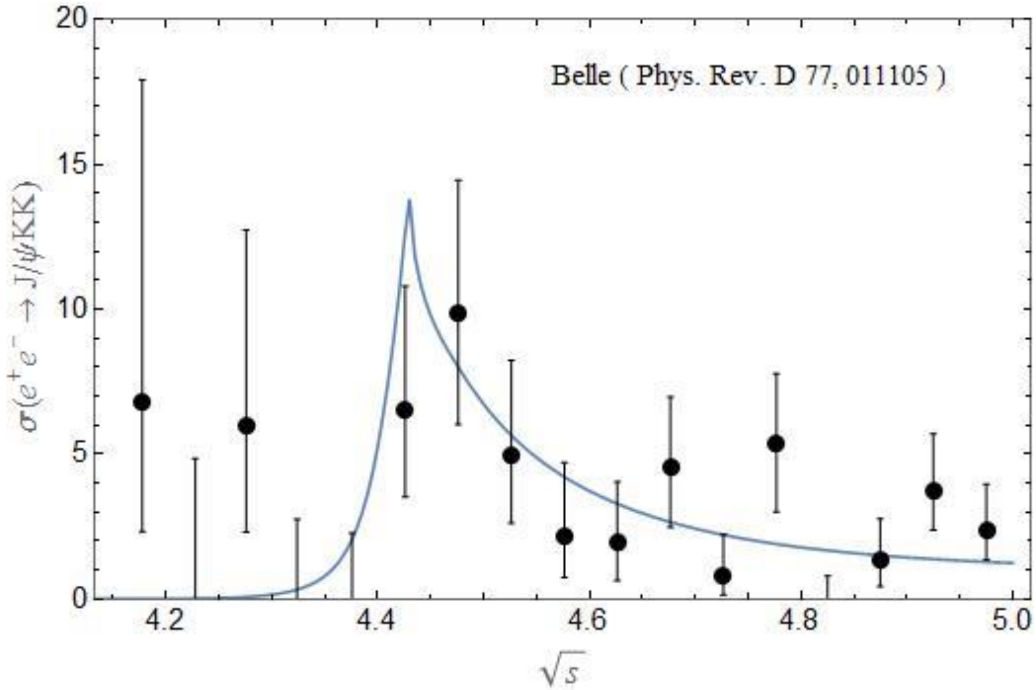


Left one: Cusp effects at different initial energy from 4.5 *to* 4.8 GeV

Right one: Compare with a introduced physical pole with $\Gamma = 100$ MeV

Total Cross Section

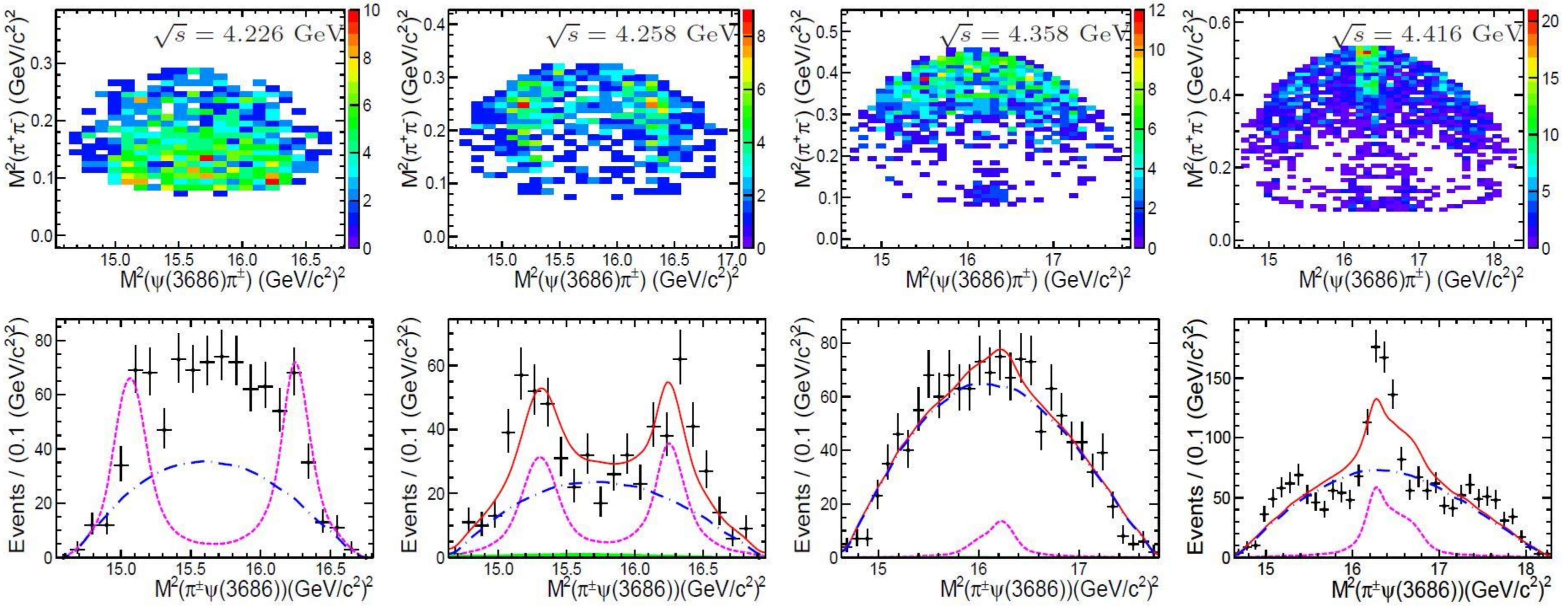
- *Total cross section of* $\psi(4415) \to J/\psi KK$



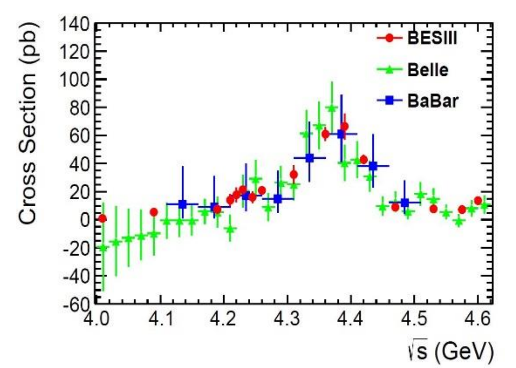
- *Total cross section effected by the physical pole at* 4.42 GeV *can be taken as a prediction for future experiments.*

Recent BESIII Results on $e^+e^- \to \psi(2S)\pi\pi$

- $e^+e^- \to \psi(3686)\pi^+\pi^-$ *in* BESIII



- *Recently*, BESIII *study the process* $e^+e^- \to \psi(2S)\pi\pi$ *at center-of-mass energies* $\sqrt{s}$ *from* 4.008 *to* 4.600 GeV, *with a total structure near* 4.4 GeV.



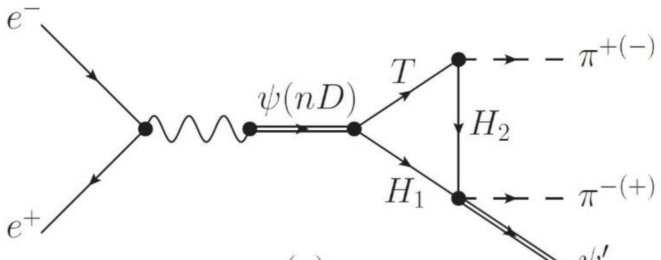
Born cross section of $e^+e^- \to \pi^+\pi^-\psi(3686)$

BESIII, arXiv: 1703.08787

Our Proposal

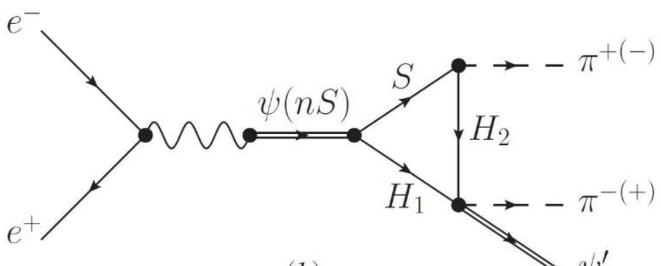
- *Loop ingredients:*

$[D_1(2420), D^*, D^*]$ $[D_1(2420), D, D^*]$
$[D_2, D^*, D^*]$ $[D_2, D^*, D]$



(a)

$[D_1(2430), D^*, D^*]$ $[D_1(2430), D, D^*]$
$[D_0, D^*, D]$



(b)

- *Lagrangians:*

$$
\begin{aligned}
\mathcal{L}_{J_D T H} &= g_D < J^{\mu\nu} \bar{H}_a^\dagger \gamma_\nu \bar{T}_{a\mu} - J^{\mu\nu} \bar{T}_{a\mu}^\dagger \gamma_\nu \bar{H}_a >, \\
\mathcal{L}_{J_S S H} &= g_S < J \bar{S}_a^\dagger \bar{H}_a + J \bar{H}_a^\dagger \bar{S}_a >, \\
\mathcal{L}_{THA} &= i \frac{h'}{\Lambda_\chi} < \bar{H}_a T_b^\mu \gamma^\nu \gamma_5 (D_\mu \mathcal{A}_\nu + D_\nu \mathcal{A}_\mu)_{ba} >, \\
\mathcal{L}_{SHA} &= ih < \bar{H}_a S_b \gamma_\mu \gamma_5 \mathcal{A}_{ba}^\mu >, \\
\mathcal{L}_{HHJA} &= C_S < J \bar{H}_b^\dagger \gamma_\mu \gamma_5 \bar{H}_a \mathcal{A}_{ba}^\mu > .
\end{aligned}
$$

Individual Channel Contribution

$[D_1(2420), D^*, D^*]$

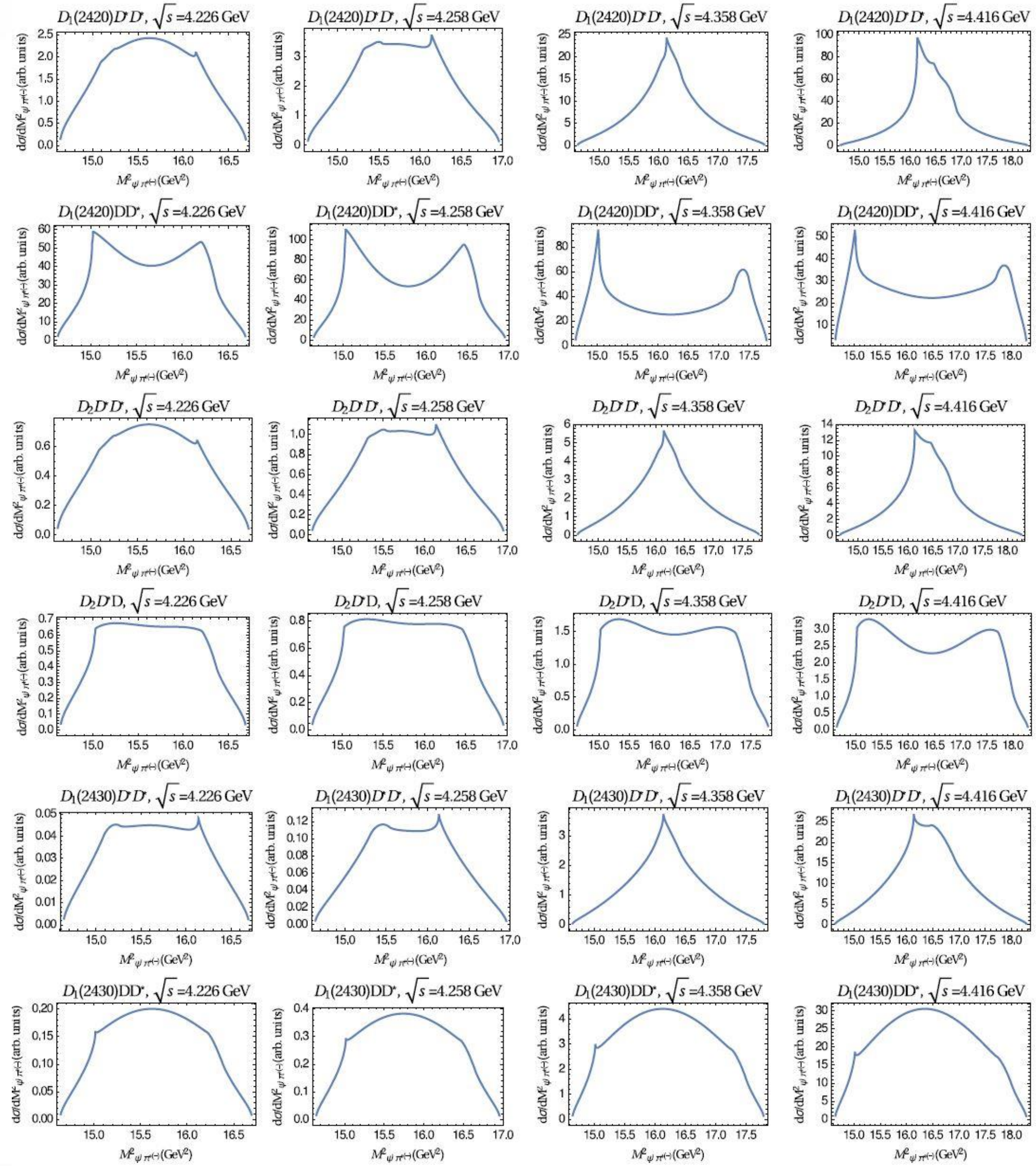
$[D_1(2420), D, D^*]$

$[D_2, D^*, D^*]$

$[D_2, D^*, D]$

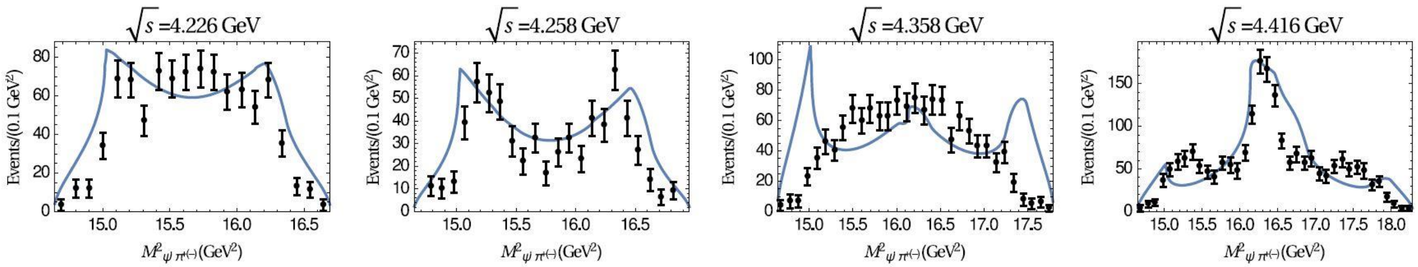
$[D_1(2430), D^*, D^*]$

$[D_1(2430), D, D^*]$



Total Line Shapes

- *Adding up the contributions from all channels with one free parameter between the* [THH] *and* [SHH] *sets we get:*



The diagrams for $e^+e^- \to \psi'\pi\pi$ via intermediate triangle D meson loops.

- *Though the third diagram at* $\sqrt{s} = 4.358$ GeV *differs from the experimental data more significantly, the total trend of the line shapes as* $\sqrt{s}$ *increases still keeps. From this point of view, it's clear that the impact from thresholds effects plays essential role in line shapes of the* $\psi'\pi$ *2-body invariant mass spectrum.*

Summary

- By investigating the very closely lied $D_{s1}D_S$ and $D_{s0}D_S^*$ thresholds at about $4.43\ \mathrm{GeV}$ we show that the $\psi(4415)$ and $\psi(4160)$ can be mixing states between the dynamically generated states of the strong S-wave interactions with thresholds and the quark model states $\psi(4S)$ and $\psi(2D)$.
- We continue to investigate the $e^+e^- \to J/\psi KK$ final states spectrum and the invariant mass spectrum of $J/\psi K$ to search for signals from this mixing mechanism. We show that a pole structure would be different from open threshold CUSP effects and the measurement of the cross section line shape of $J/\psi KK$ can be sensitive to the dynamically generated state and clarify the impact from such strong S-wave open thresholds.
- With different thresholds we also investigate the $e^+e^- \to \psi'\pi\pi$ final states to see the line shapes of $\psi'\pi$ invariant mass spectrum with different $\sqrt{s}$. We find that the impact from threshold effects brings the key features like the experiments of BESIII showed recently.

Thanks for your attention!