Influence of threshold effects induced by charmed meson rescattering

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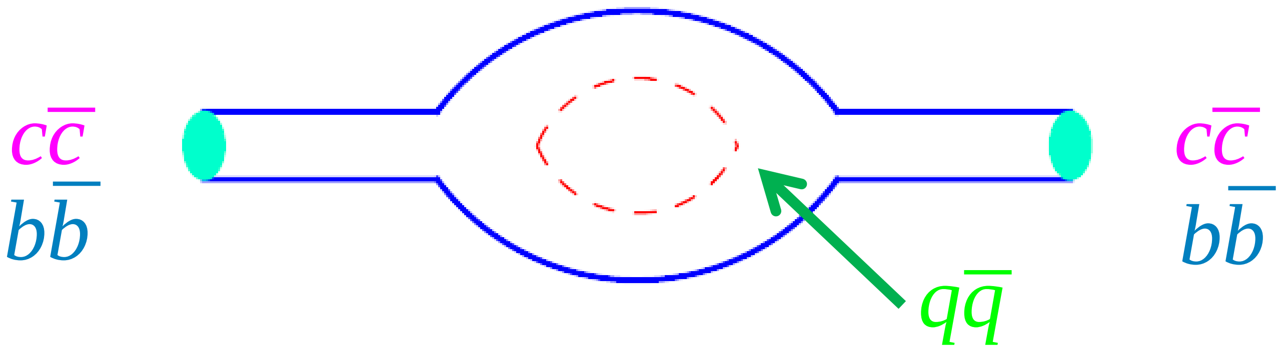
Outline

- **Motivation**
- **Coupled-channel effects and threshold enhancement phenomena**
  - ✓ **Dipion transitions $e^+e^- \rightarrow J/\psi\pi\pi$, $\psi'\pi\pi$,$h_c\pi\pi$**
  - ✓ **Zb production, hunting for some XYZ particles**
  - ✓ **Anomalous threshold singularity**
- **Summary**

Motivation

- ✓ **Observations of XYZ particles;**
- ✓ **Discrepancy between conventional quenched quark model predictions and experimental data;**
- ✓ **Coupled-channel effects will largely affect the mass and decay properties of heavy quarkonia;**



Coupled-channel effects

- ✓ E. Eichten et al, PRD17,3090(1978), PRD73,104014(2006);
- ✓ M.R. Pennington, D.J. Wilson, PRD76,077502(2008);
- ✓ T. Barnes, E.S. Swanson, PRC77,055206(2008);
- ✓ B.Q. Li, C.Meng, K.T. Chao, PRD80,014012(2009);
- ✓ F.K. Guo et al; PRD83,034013(2011);
- ✓ Z.Y. Zhou, Z. Xiao, arXiv:1309.1949;
- ✓ ……

Unconventional states in heavy quarkonium region

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	<1.2	$1^{++}/2^{-+}$	$B\to K(\pi^+\pi^- J/\psi)$	Belle [36, 37] (12.8), BABAR [38] (8.6)	2003	OK
				$p\bar{p}\to(\pi^+\pi^- J/\psi)+\ldots$	CDF [39–41] (np), DØ [42] (5.2)		
				$B\to K(\omega J/\psi)$	Belle [43] (4.3), BABAR [23] (4.0)		
				$B\to K(D^{*0}\bar{D}^0)$	Belle [44, 45] (6.4), BABAR [46] (4.9)		
				$B\to K(\gamma J/\psi)$	Belle [47] (4.0), BABAR [48, 49] (3.6)		
				$B\to K(\gamma\psi(2S))$	BABAR [49] (3.5), Belle [47] (0.4)		
				$pp\to(\pi^+\pi^- J/\psi)+\ldots$	LHCb [50] (np)		
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	$0/2^{?+}$	$B\to K(\omega J/\psi)$	Belle [51] (8.1), BABAR [52] (19)	2004	OK
				$e^+e^-\to e^+e^-(\omega J/\psi)$	Belle [53] (7.7), BABAR [23] (np)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$	Belle [54] (6.0)	2007	NC!
				$e^+e^-\to J/\psi(\ldots)$	Belle [20] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^-\to\gamma(D\bar{D})$	BABAR [55] (np), Belle [56] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^- J/\psi)$	Belle [57] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle [58] (5.0), BABAR [59] (1.1)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF [60, 61] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^-\to J/\psi(D\bar{D}^*)$	Belle [54] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B\to K(\pi^+\chi_{c1}(1P))$	Belle [58] (5.0), BABAR [59] (2.0)	2008	NC!
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^- J/\psi)$	BABAR [62, 63] (8.0)	2005	OK
					CLEO [64] (5.4), Belle [57] (15)		
				$e^+e^-\to(\pi^+\pi^- J/\psi)$	CLEO [65] (11)		
				$e^+e^-\to(\pi^0\pi^0 J/\psi)$	CLEO [65] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B\to K(\phi J/\psi)$	CDF [61] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}$	$13.3^{+18.4}$	$0/2^{++}$	$e^+e^-\to e^+e^-(\phi J/\psi)$	Belle [66] (3.2)	2009	NC!
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	BABAR [67] (np), Belle [68] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B\to K(\pi^+\psi(2S))$	Belle [69, 70] (6.4), BABAR [71] (2.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$	Belle [72] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$	Belle [68] (5.8)	2007	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^+	$\Upsilon(5S)\to\pi^-(\pi^+[b\bar{b}])$	Belle [73, 74] (16)	2011	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^+	$\Upsilon(5S)\to\pi^-(\pi^+[b\bar{b}])$	Belle [73, 74] (16)	2011	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^-\to(\pi^+\pi^-\Upsilon(nS))$	Belle [75, 76] (2.0)	2010	NC!

arXiv:1010.5827

Coupled-channel effects with P-wave states involved

- ✓ **Combinations of S- and P-wave charmed mesons are very close to some conventional higher charmonia(ψ(4160), ψ(4415)) and Y(4260), Y(4360), Z(4430) ……);**
- ✓ **The coupling with the parity-odd charmonia could be S-wave, supposed to be strong;**

	D_0D^*	$D_1'D$	$D_1'D^*$	D_1D	D_1D^*	D_2D	D_2D^*	$D_{s0}D_s^*$	$D_{s1}D_s$
Threshold [MeV]	4325	4292	4434	4286	4428	4327	4470	4430	4424

Connections between coupled channel effects and XYZ?

Model based on HHChPT

Doublets with light degrees of freedom j^P=1/2$^-$,1/2$^+$,3/2$^+$

$$H_a = \frac{1+\not{v}}{2}[\mathcal{D}^*_{a\mu}\gamma^\mu - \mathcal{D}_a\gamma_5] ,$$

$$S_a = \frac{1+\not{v}}{2}\left[\mathcal{D}'^{\mu}_{1a}\gamma_\mu\gamma_5 - \mathcal{D}^*_{0a}\right] ,$$

$$T^\mu_a = \frac{1+\not{v}}{2}\left\{\mathcal{D}^{\mu\nu}_{2a}\gamma_\nu - \sqrt{\frac{3}{2}}\mathcal{D}_{1a\nu}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\} ,$$

HQSS allowed coupling (LDOF will also be conserved)

	HH	SH	TH
ψ(nS)	P-wave	S-wave	D-wave
ψ(nD)	P-wave	D-wave	S-wave

Leading Order Effective Lagrangian

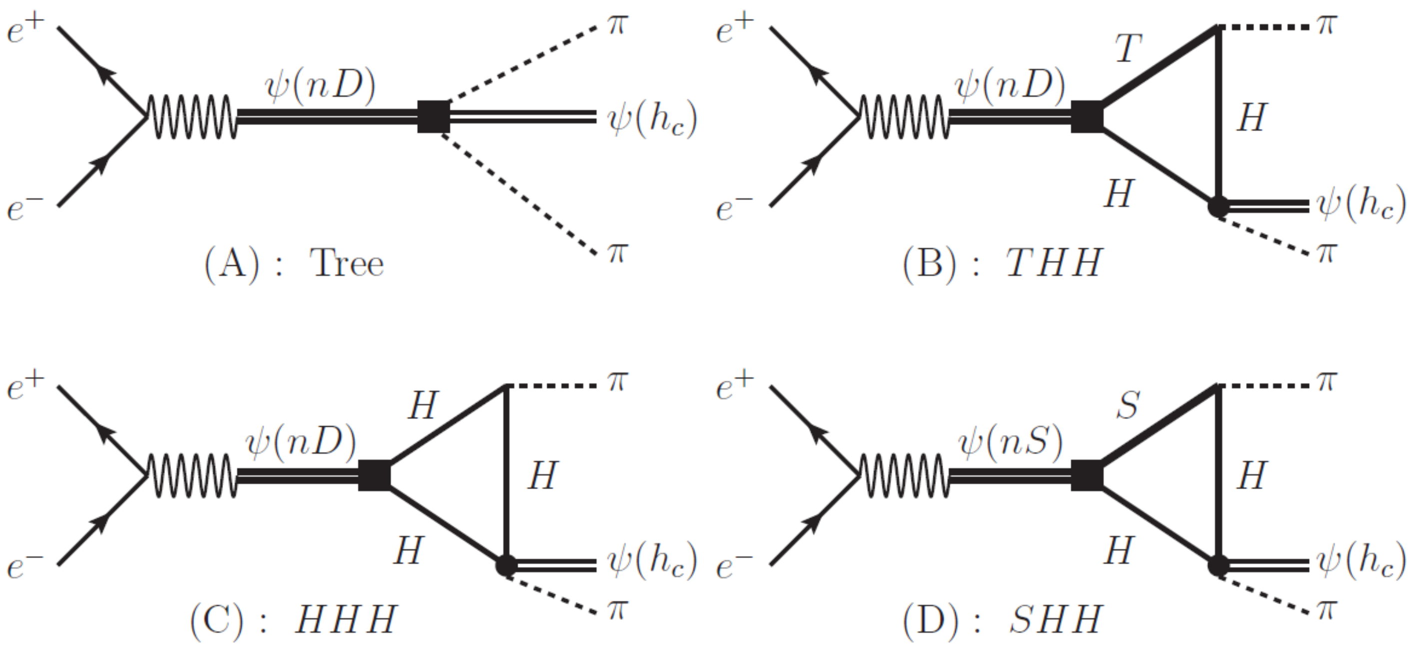
According to HHChPT power counting

$$
\begin{aligned}
\mathcal{L}_1 &= \frac{g_T}{\sqrt{2}} < J^{\mu\nu} \bar{H}_a^\dagger \gamma_\nu \bar{T}_{a\mu} - J^{\mu\nu} \bar{T}_{a\mu}^\dagger \gamma_\nu \bar{H}_a > \\
&+ i g_H < J^{\mu\nu} \bar{H}_a^\dagger \gamma_\mu \overleftrightarrow{\partial}_\nu \bar{H}_a > \\
&+ g_S < J \bar{S}_a^\dagger \bar{H}_a + J \bar{H}_a^\dagger \bar{S}_a > \\
&+ C_S < J \bar{H}_b^\dagger \gamma_\mu \gamma_5 \bar{H}_a \mathcal{A}_{ba}^\mu > \\
&+ i C_P < J^\mu \bar{H}_b^\dagger \sigma_{\mu\nu} \gamma_5 \bar{H}_a \mathcal{A}_{ba}^\nu > + h.c., \\
\mathcal{L}_2 &= i \frac{h'}{\Lambda_\chi} < \bar{H}_a T_b^\mu \gamma^\nu \gamma_5 (D_\mu \mathcal{A}_\nu + D_\nu \mathcal{A}_\mu)_{ba} > \\
&+ i h < \bar{H}_a S_b \gamma_\mu \gamma_5 \mathcal{A}_{ba}^\mu > + i g < H_b \gamma_\mu \gamma_5 \mathcal{A}_{ba}^\mu \bar{H}_a > .
\end{aligned}
$$

$$
J = \frac{1+\not{v}}{2}[\psi(nS)^\mu \gamma_\mu]\frac{1-\not{v}}{2}, \; J^\mu = \frac{1+\not{v}}{2}[h_c(nP)^\mu \gamma_5]\frac{1-\not{v}}{2}
$$

$$
J^{\mu\nu} = \frac{1+\not{v}}{2}\left\{\psi(nD)_\alpha \left[\frac{1}{2}\sqrt{\frac{3}{5}}[(\gamma^\mu - v^\mu) g^{\alpha\nu} + (\gamma^\nu - v^\nu) g^{\alpha\mu}] - \sqrt{\frac{1}{15}}(g^{\mu\nu} - v^\mu v^\nu)\gamma^\alpha\right]\right\} \frac{1-\not{v}}{2}
$$

Dipion Transitions



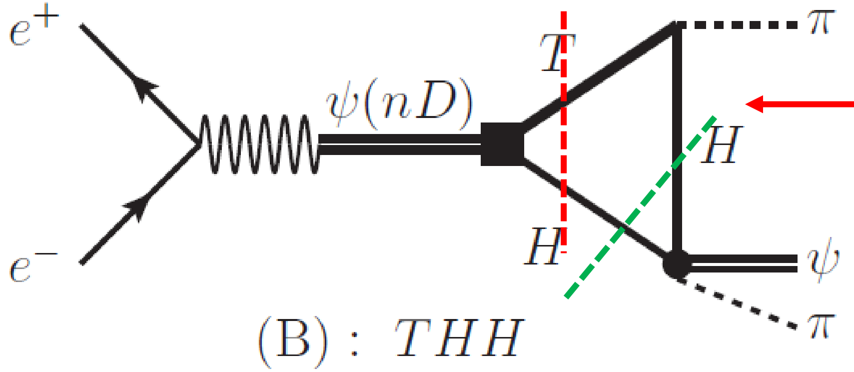
ψ(4160) as the input ψ(nD):

- ✓ **Widely accepted as a conventional 2^3D_1 charmonia**
- ✓ **Couple to TH via S-wave, respect HQSS**
- ✓ **Close to Y(4260)**

M=4153±3 MeV, Γ =103±8 MeV **PDG averaged**
M=4191.7±6.5 MeV, Γ =71.8±12.3 MeV **BES, PLB660,315(2008)**
M=4193±7 MeV, Γ =79±14 MeV **X.H. Mo et al, PRD82,077501(2010)**

Γ_{ee}=0.83±0.07 KeV, **not small**

THH Loop



Triangle singularity (TS) may occur under special kinematic configurations

$$\text{I)} \quad \{D_1 D \, [D^*]\},$$

$$\text{II)} \quad \{D_1 D^* \, [D^*]\},$$

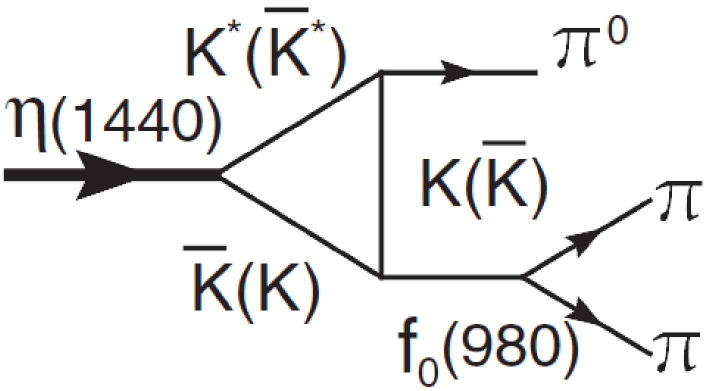
$$\text{III)} \quad \{D_2 D^* \, [D]\},$$

$$\text{IV)} \quad \{D_2 D^* \, [D^*]\},$$

In the heavy quark limit

$$\mathcal{M}^I : \mathcal{M}^{II} : \mathcal{M}^{III} : \mathcal{M}^{IV} = 1 : \frac{1}{2} : -\frac{1}{5} : \frac{3}{10} \; .$$

Triangle Singularity



Largely isospin violation in η(1405/1475)→3π

Br~10%, [BESIII, PRL108,182001 (2012)]

Wu,Liu,Zhao&Zou, PRL108,081803(2012)

References:

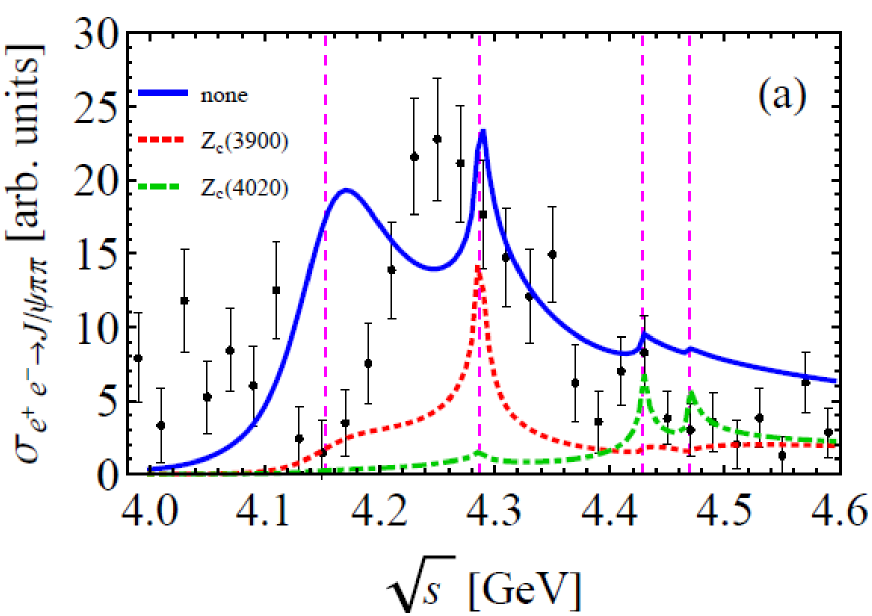
Landshoff and Treiman, Phys.Rev. 127,649(1962)

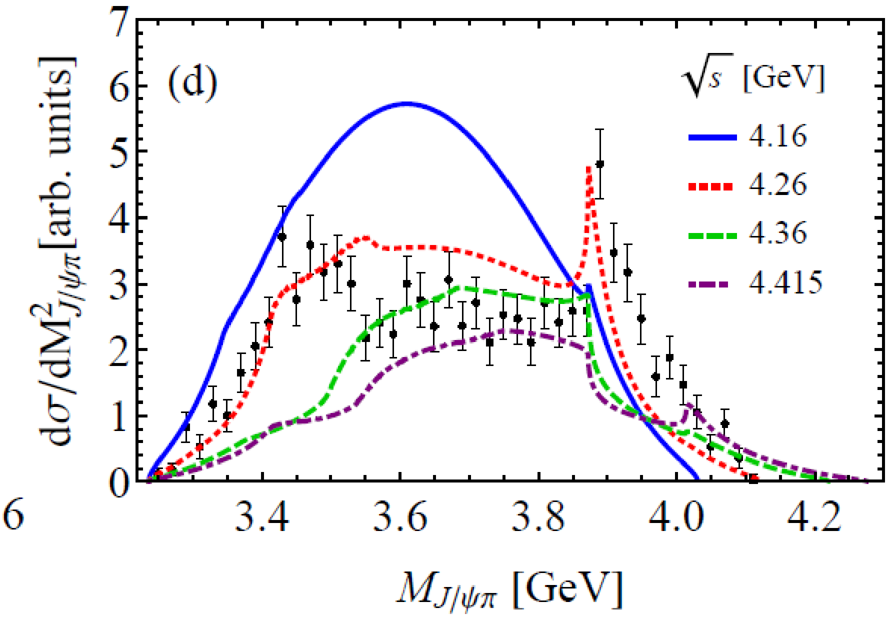
Landshoff and Treiman, Nuovo Cimento 19,1249(1961)

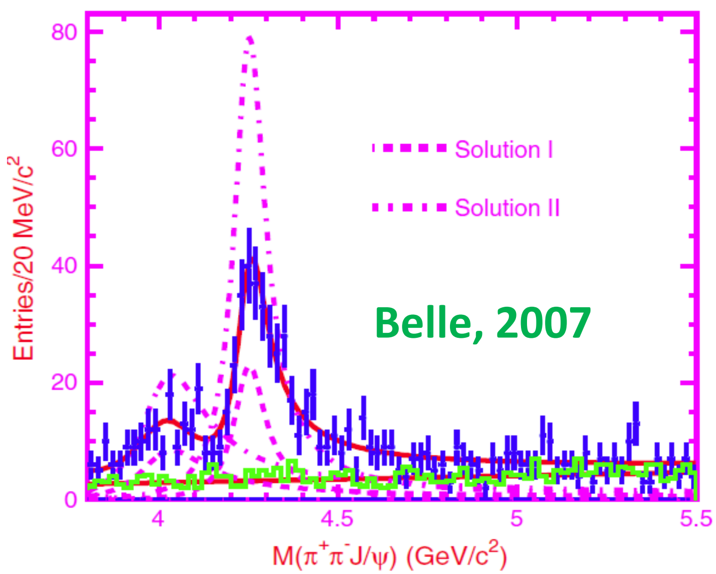
Eden et al., <<The Analytic S-Matrix>>, 1966

…………

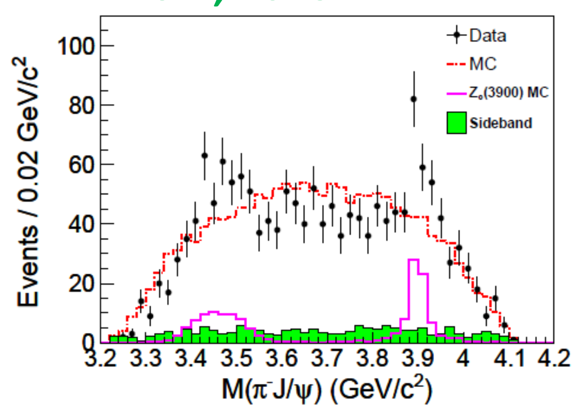
$e^+e^- \to J/\psi\pi\pi$ via ψ(4160) and THH loops





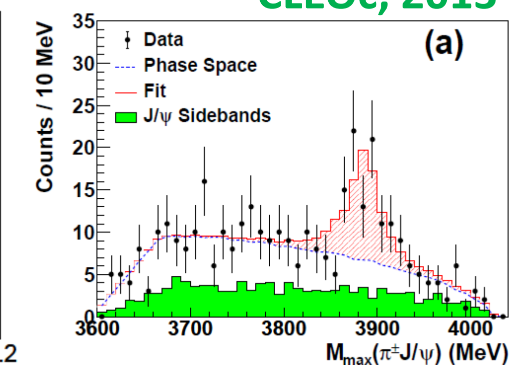


BESIII, 2013



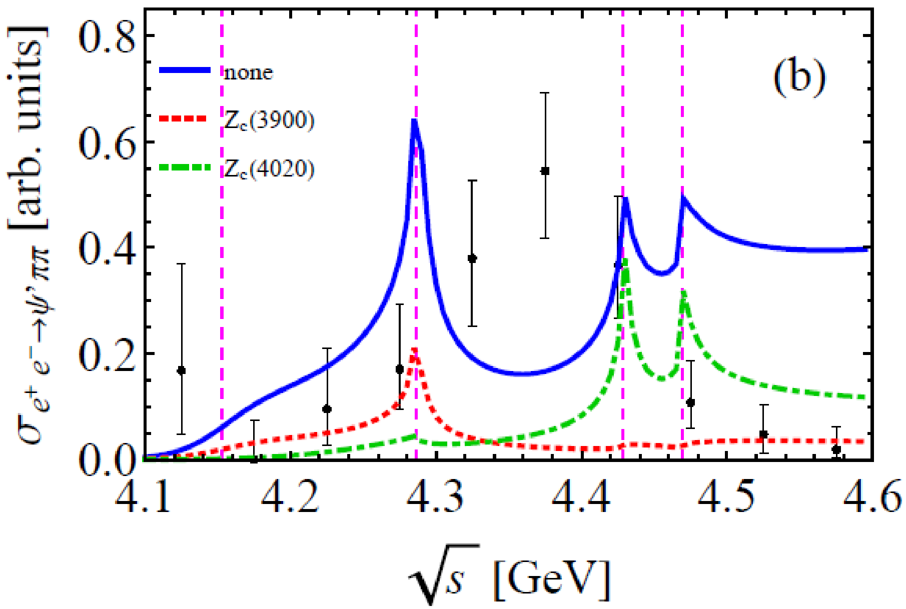
$\sqrt{s}$=4.26 GeV

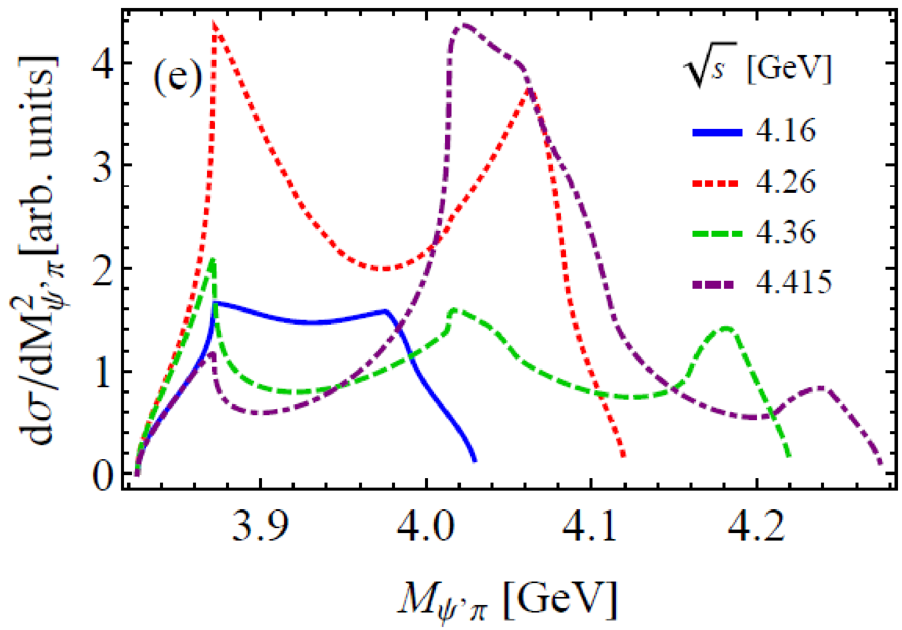
CLEOc, 2013

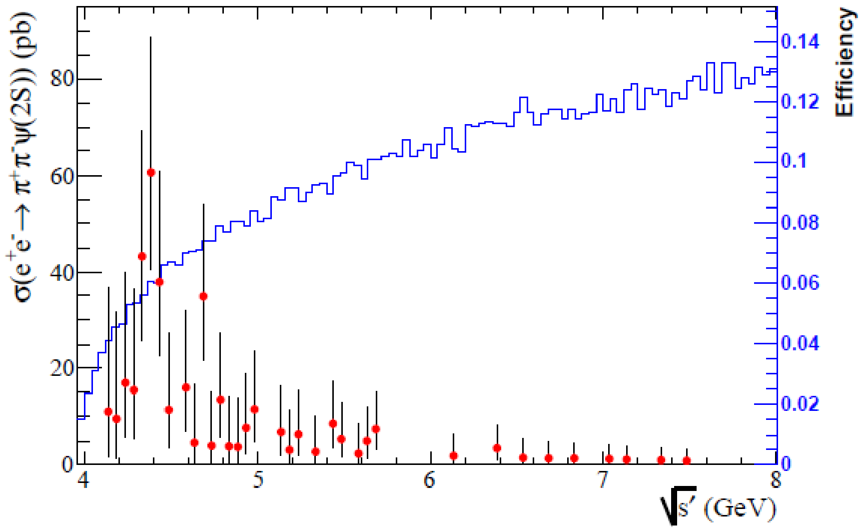


$\sqrt{s}$=4.17 GeV

$e^+e^- \to \psi'\pi\pi$ via ψ(4160) and THH loops



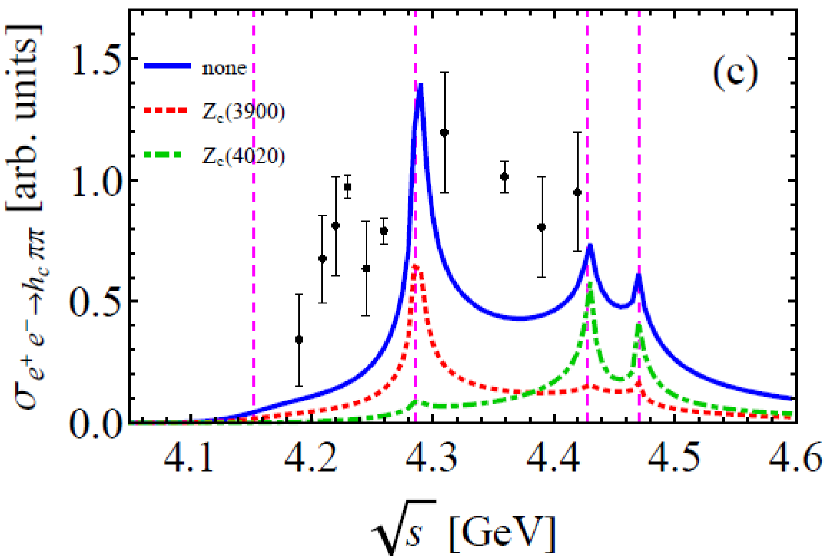


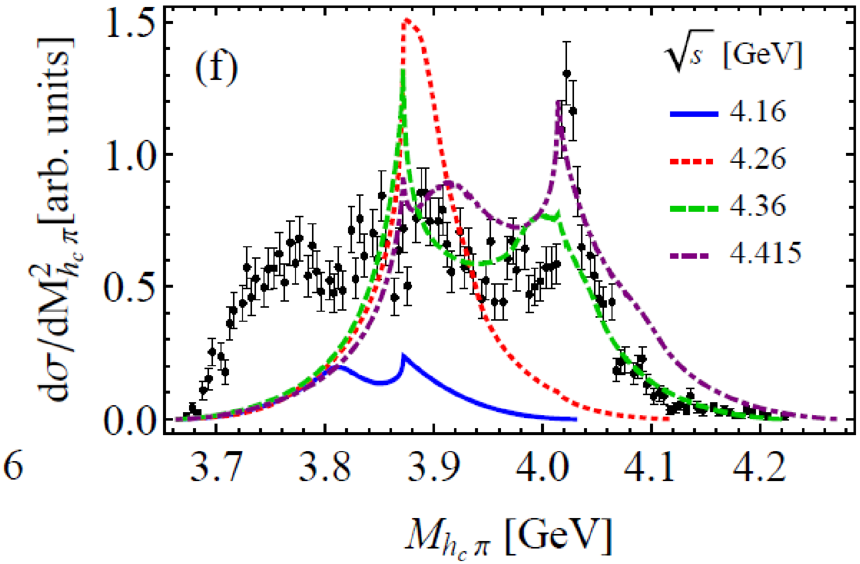


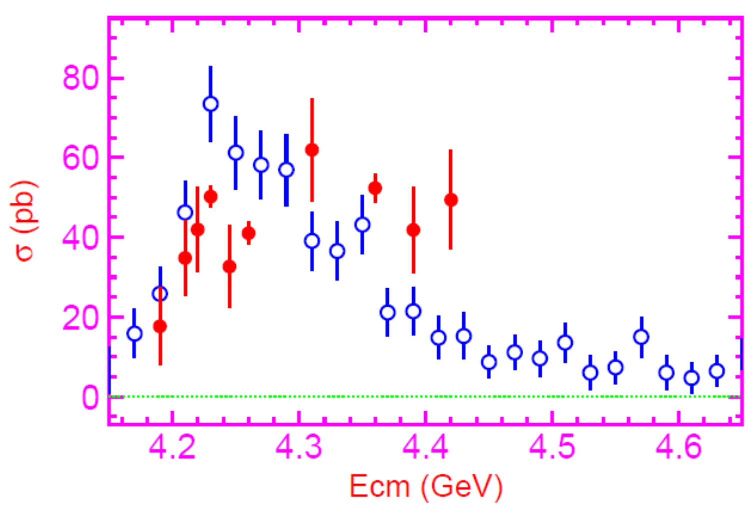
BarBar, PRL98,212001(2007)

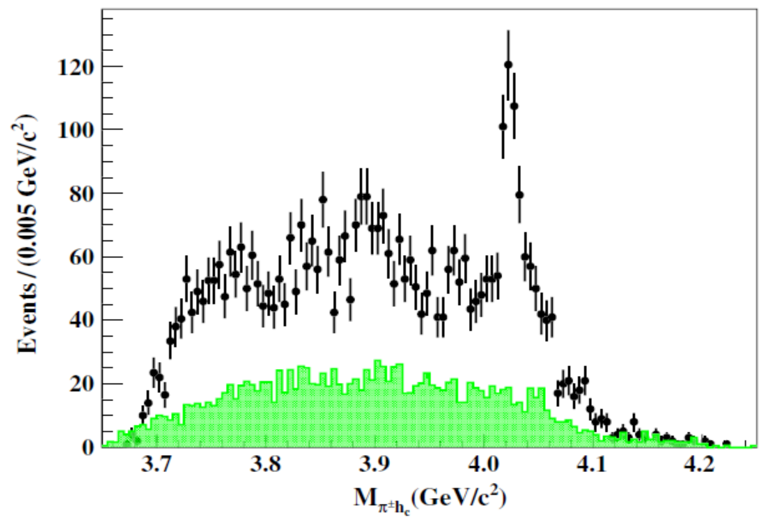
- ✓ **Results are sensitive to kinematics**
- ✓ **Same dynamics, different kinematics**
- ✓ **Direct prediction to check the mechanism**

$e^+e^- \to h_c\pi\pi$ via ψ(4160) and THH loops









Sum of energy points from 3.9 to 4.42

C.Z. Yuan, arXiv:1312.6399

Belle, PRL111,242001(2013)

Comparison with Molecule Ansatz

✓Similar points: kinematics, singularities of rescattering loops

✓ Different points:

- Incorporates the D_1D, D_1D^* , D_2D^* combinations in a single Lagrangian with the relative phase and coupling strength fixed in the heavy quark limit;
- No matter whether the molecular state exist or not, it seems to be natural to suppose the coupled channel effects should exist physically

Y(4260) as molecular state:

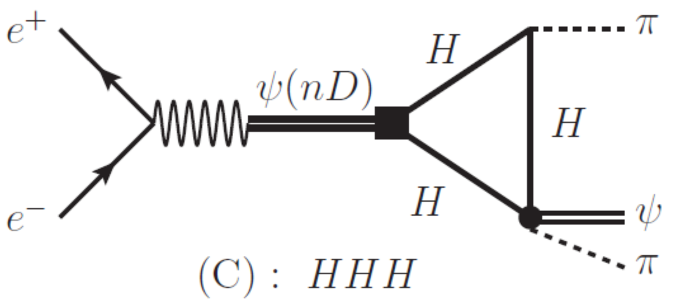
✓ D_1D, D_0D^* molecular state, F. Close et al, PRL102,242003(2009), PRD81,074033(2010); Kalashnikova and Nefediev, PRD77,054025(2008);

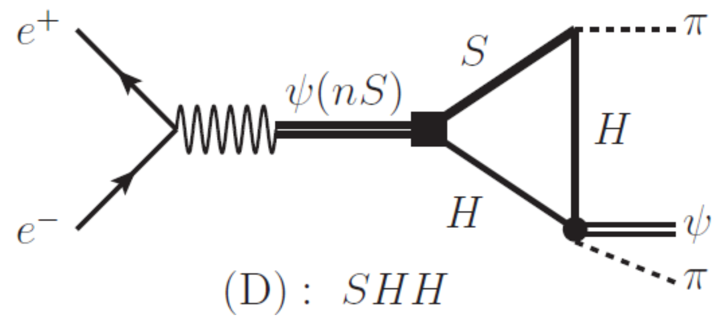
✓ Potential model, G.J. Ding PRD79,014001(2009)

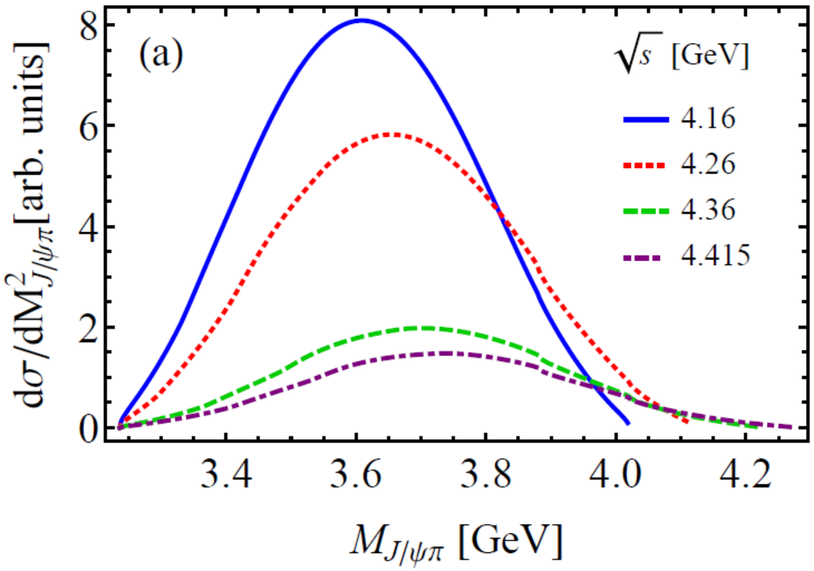
✓ Connection with Zc(3900), Wang, Zhao and Hanhart, PRL111,132003(2013); X.H. Liu and G.Li, PRD88,014013(2013)

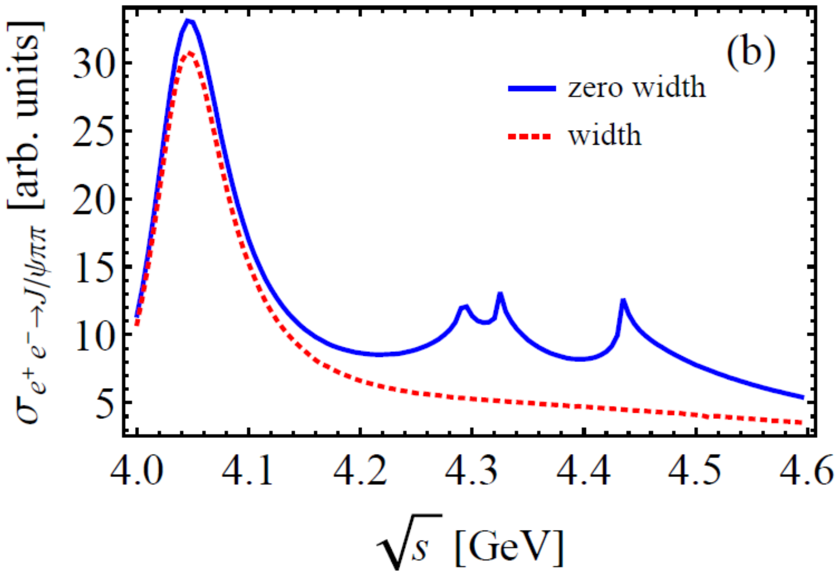
✓ ......

HHH Loop and SHH Loop





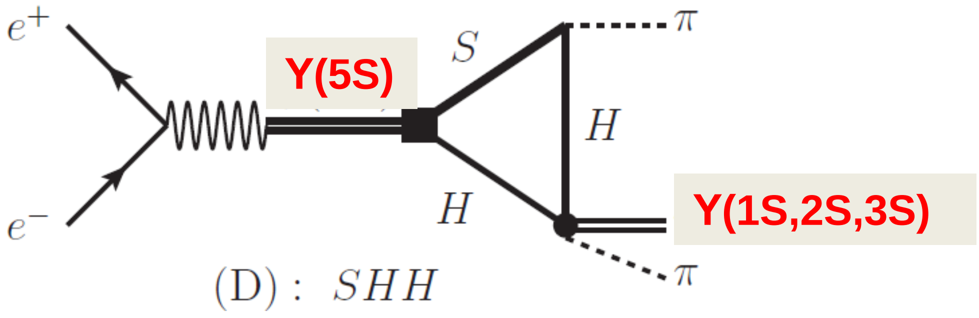


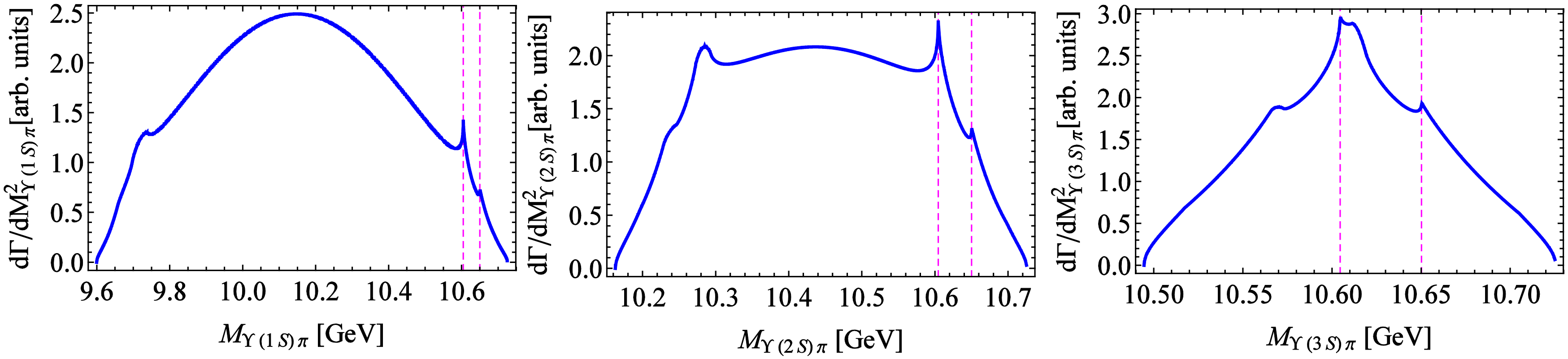


No obvious cusp around 3.9GeV, inconsistent with CLEOc result

Broad width of D_0 and D_1' will lower the amplitude and smooth the cusps

Zb Production

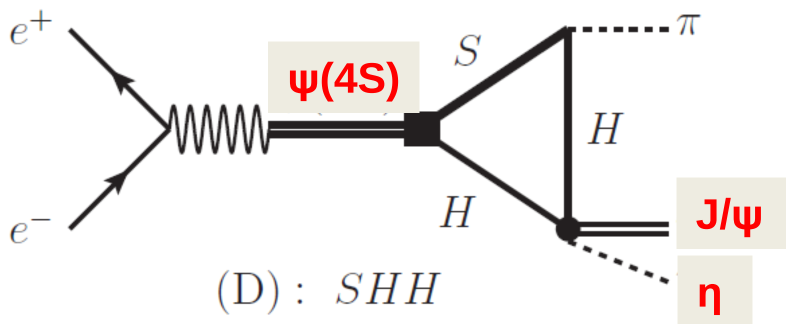




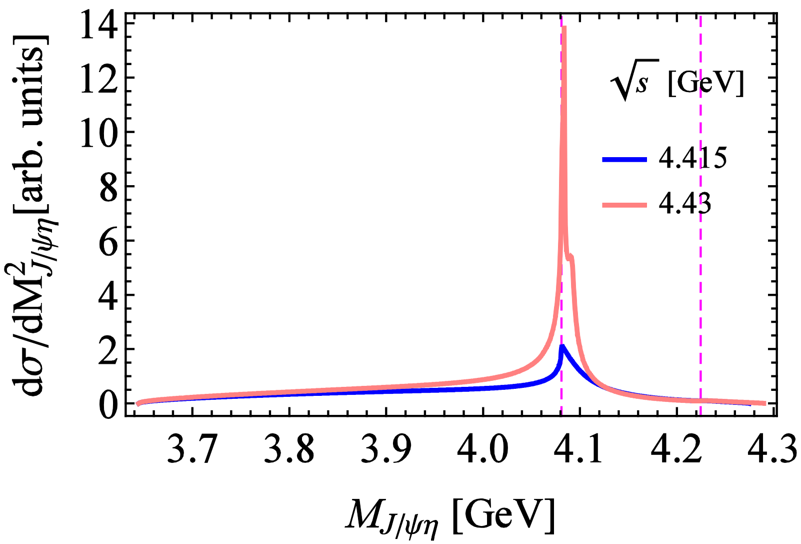
Cusps at BB* and B*B* thresholds ⟺ Production of Zb(10610) and Zb(10650)

Hunting For Partners of Y4160 &Y4274

Isospin violation processes



Preliminary



Cusps at D_sD_s* and D_s*D_s* thresholds
(C=-1)

⟺

Production of partners of Y(4160) and Y(4274)
(observed in J/ψφ, C=+1)

Anomalous Threshold Singularity

✓ **Singularity in the complex space**

Landau Equation

$$I_3 = \prod_{i=1}^{3} \int_0^1 d\, a_k \frac{\delta(1 - \sum_k a_k)}{D - i\epsilon}$$

$$D = \sum_{i,j} a_i a_j Y_{ij}, \quad Y_{ij} = \frac{1}{2}\left[m_i^2 + m_j^2 - (q_{i-1} - q_{j-1})^2\right]$$

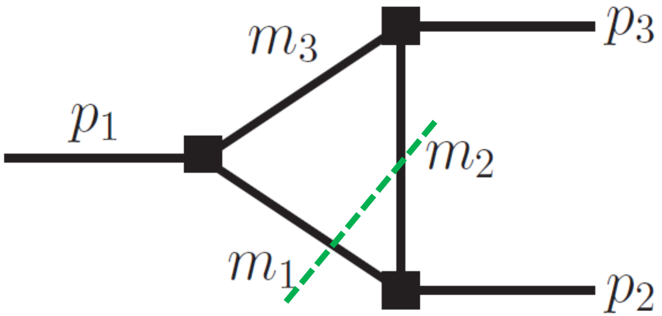
Necessary conditions

$$D = 0,$$

$$either \;\; a_j = 0 \;\; or \;\; \boxed{\frac{\partial D}{\partial a_j} = 0.}$$

Leading singularity

Anomalous Threshold Singularity



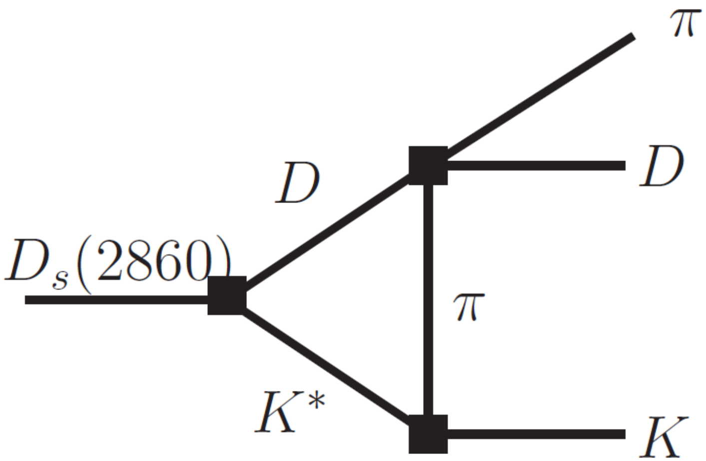
$$p_1^2 = W^2, p_2^2 = s_2,\ p_3^2 = m^2.$$

Normal threshold $\quad s_n = (m_1 + m_2)^2$

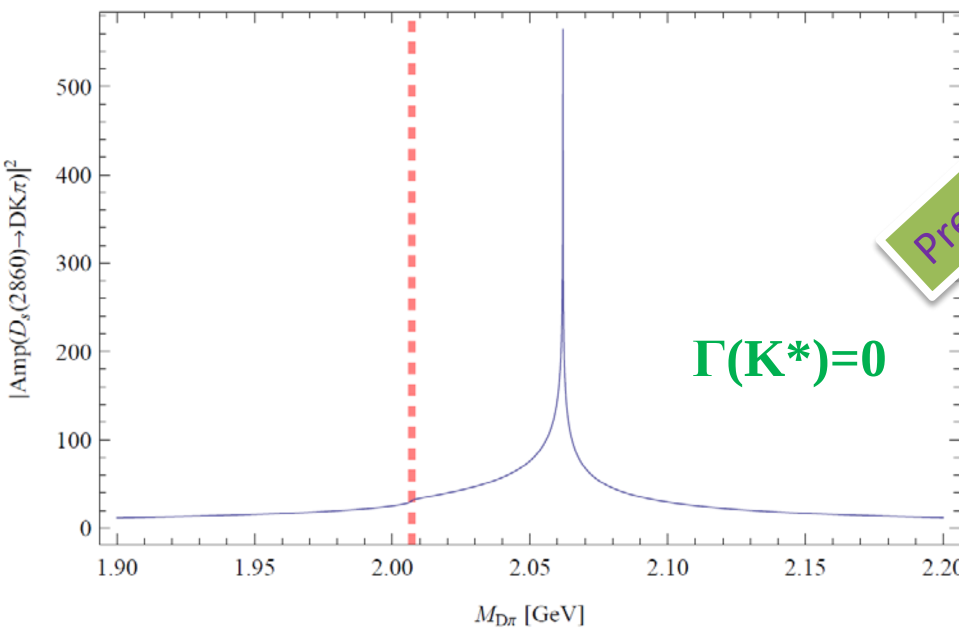
Anomalous threshold $\quad \bar{s}_2 = s_n + \frac{m_1}{m_3}[(m_2 - m_3)^2 - m^2],$

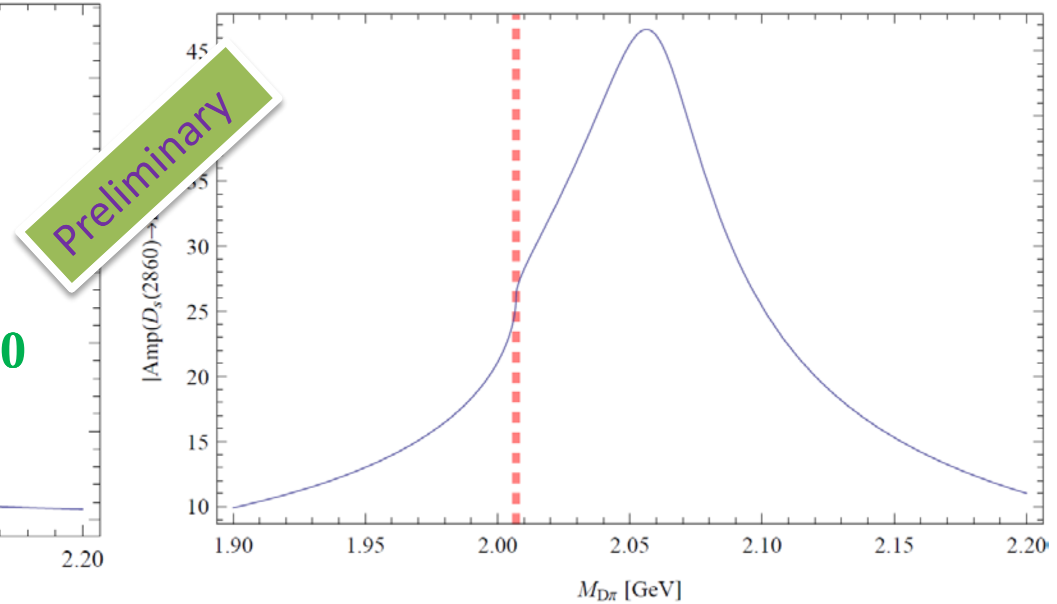
when $\quad W = m_1 + m_3,$

Anomalous Threshold Singularity

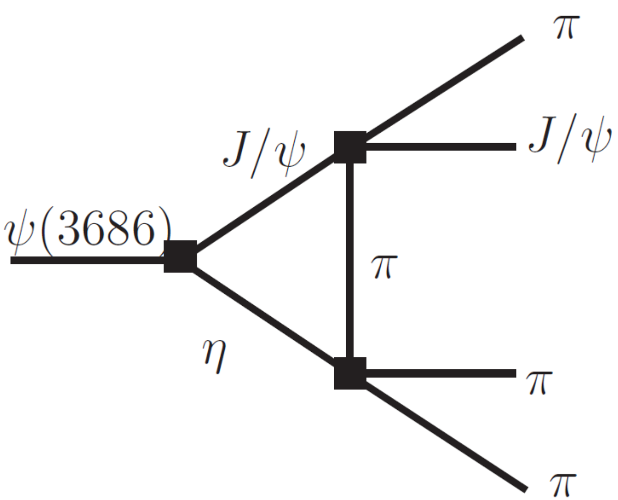


$$D_s(2860) \to DK^*[\pi] \to DK\pi$$



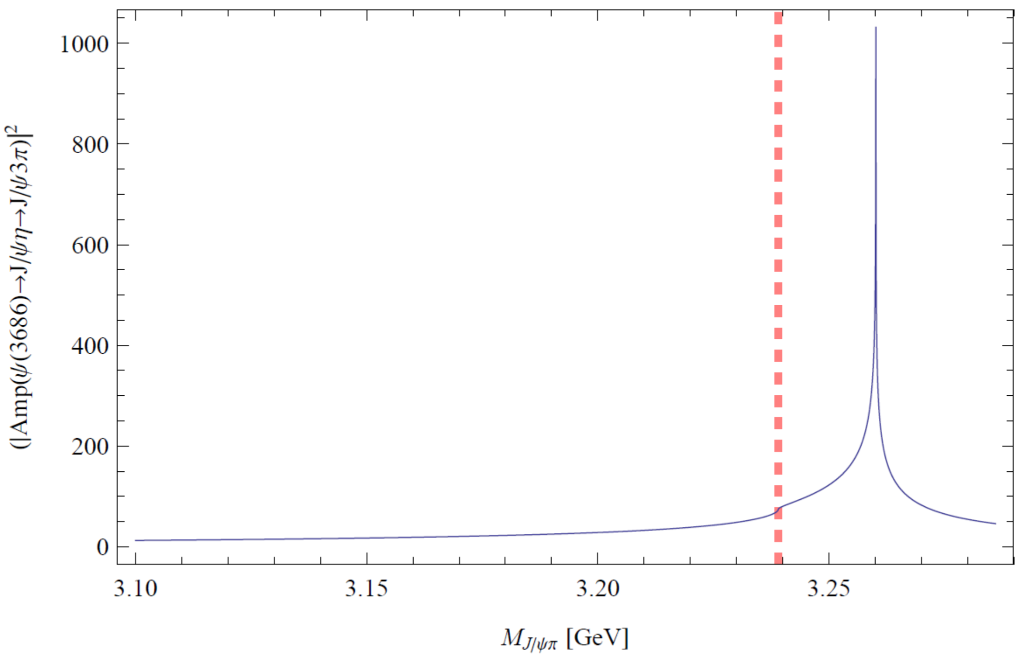


Anomalous Threshold Singularity



For investigating J/ψπ interaction

Preliminary



Summary

- **The lineshape behavior of the cross sections and distributions for the dipion transitions are studied. Couple-channel effects may largely affect the threshold behavior, especially that induced by the couplings between D-wave charmonia and TH charmed mesons, taking into account these leading order S-wave couplings will respect HQSS.**
- **Some interesting cusps are obtained, which may have some underlying connections with the XYZ states observed around the TH and HH thresholds.**
- **Kinematics plays a crucial role in generating the cusps.**
- **Anomalous threshold singularity would be used to discriminate coupled-channel effects and genuine resonances.**