Influence of threshold effects induced by heavy flavor meson rescattering

Xiao-Hai Liu

Tokyo Institute of Technology

For Hadrons & Hadron Interactions in QCD 2015 (HHIQCD2015)

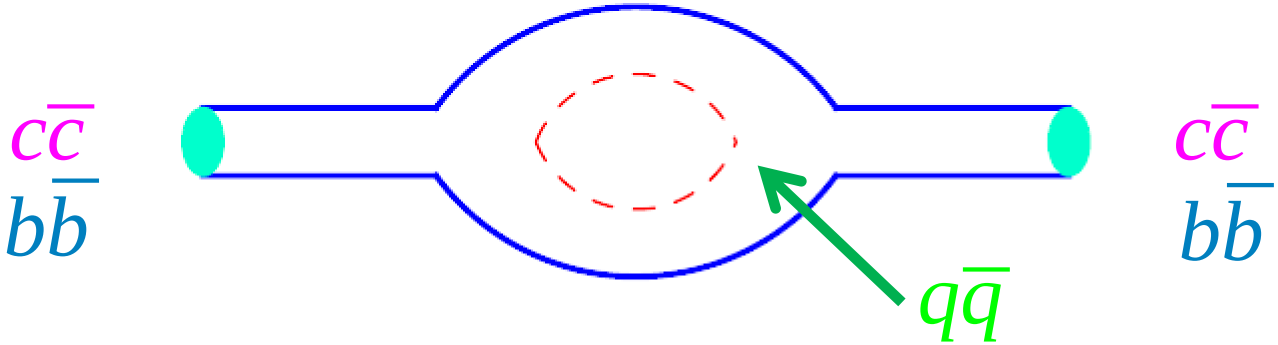
YITP, Kyoto, 2015.03.03

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

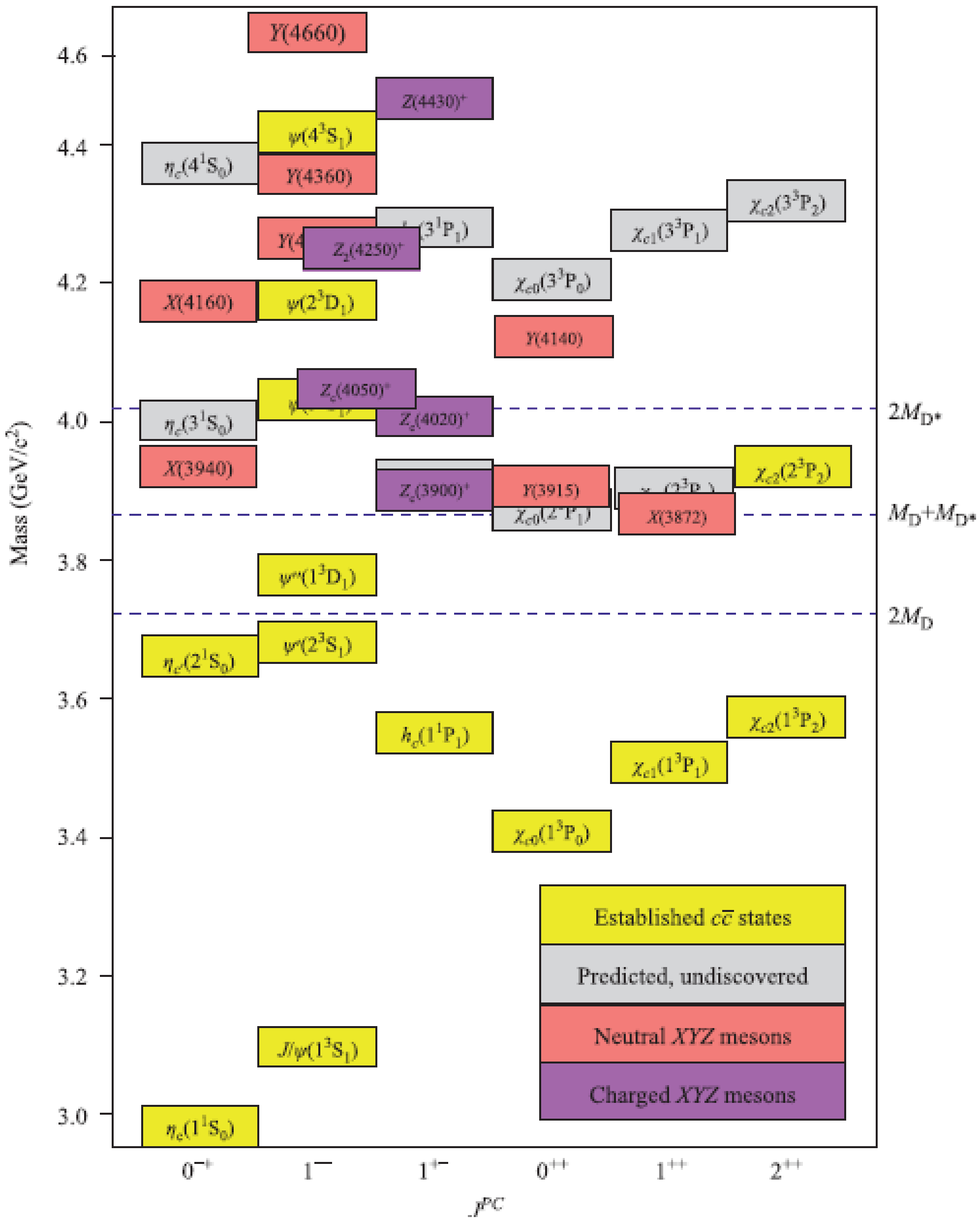
- ✓ **Observations of XYZ particles;**
- ✓ **Discrepancy between conventional quenched quark model predictions and experimental data;**
- ✓ **Coupled-channel effects will largely affect the mass and decay properties of heavy quarkonia;**

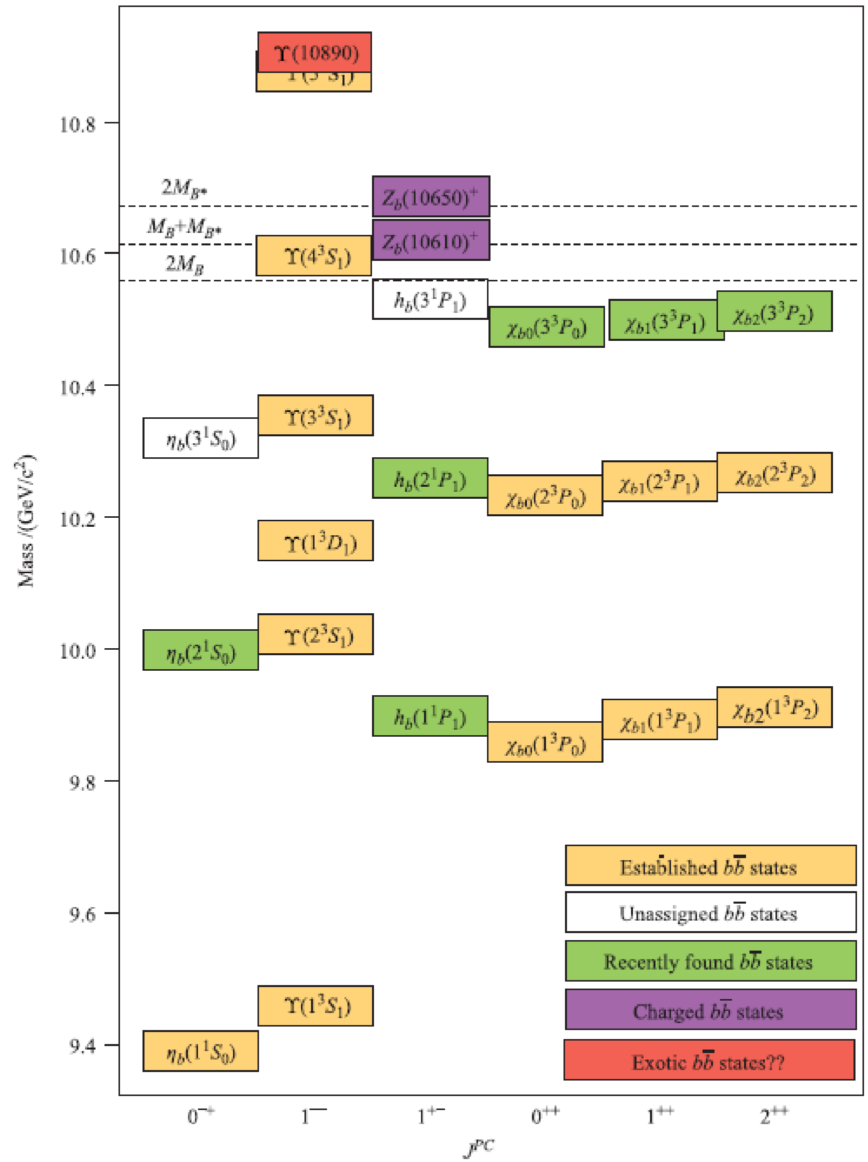


Coupled-channel effects

- ✓ 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





arXiv:1411.7738

Status of searches for new states

arXiv:1411.5957

Table 11. Status of searches for the new states in B decays, for several final states f, updated with respect to Drenska *et al.*[78] Final states where each exotic state was observed (S: "seen") or excluded (NS: "not seen") are indicated; F is reserved to final states which have been searched and not seen, but are forbidden by quantum numbers not known at the time of the analysis. A final state is marked as NP ("not performed") if the analysis has not been performed in a given mass range and with MF ("missing fit") if the spectra are published but a fit to a given state has not been performed. Finally "—" indicates that the known quantum numbers or available energy forbid the decay; and "hard" that an analysis is experimentally too challenging. As explained in Sec. 3.6, we consider a state $Y(3915)$ decaying into $J/\psi\omega$, seen both in B decays and in $\gamma\gamma$ fusion, and a state $X(3940)$ seen in double charmonium production and decaying into $D\bar{D}^*$. "Vectors" indicates the 1^{--} states discovered via ISR not explicitly mentioned in the table.

$B \to \mathcal{X}K$, $\mathcal{X} \to f$

State	J^{PC}	$\psi\pi\pi$	$\psi\omega$	$\psi\gamma$	$\psi\phi$	$\psi\eta$	$\psi'\pi\pi$	$\psi'\omega$	$\psi'\gamma$	$\chi_c\gamma$	$p\bar{p}$	$\Lambda_c\bar{\Lambda}_c$	$D\bar{D}$	$D\bar{D}^*$	$D^*\bar{D}^*$	$D_s^{(*)}\bar{D}_s^{(*)}$	$\gamma\gamma$
$X(3872)$	1^{++}	S	S	S	—	F	—	—	S	F	NS	—	—	S	—	—	F
$Y(3915)$	0^{++}	MF	S	NS	—	—	—	—	MF	—	MF	—	MF	NS	—	NP	NP
$Z(3930)$	2^{++}	MF	MF	NS	—	—	—	—	MF	—	MF	—	MF	MF	—	NP	NP
$Y(4140)$	J^{P+}	MF	MF	NP	S	—	NP	—	NP	—	MF	—	MF	NP	NP	NP	NP
$X(4160)$	0^{P+}	MF	MF	NP	MF	—	NP	—	NP	—	MF	—	MF	NP	NP	NP	NP
$X(4350)$	J^{P+}	MF	MF	NP	MF	—	NP	NP	NP	—	MF	—	NP	NP	NP	NP	NP
$Y(4260)$	1^{--}	NS	—	—	—	MF	NP	—	—	NP	MF	—	NP	NP	NP	NP	—
vectors	1^{--}	MF	—	—	—	MF	NP	—	—	NP	MF	—	NP	NP	NP	NP	—
$Y(4660)$	1^{--}	NP	—	—	—	MF	NP	—	—	NP	MF	MF	NP	NP	NP	NP	—

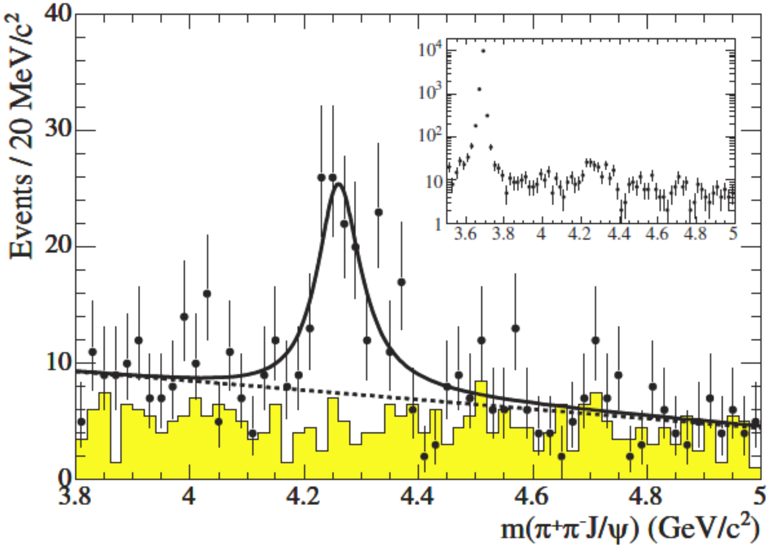
Table 12. Status of searches for the new states in ISR produtcion for several final states f, updated with respect to Drenska *et al.*[78] In this table we consider the $Y(4630)$ decaying into $\Lambda_c\bar{\Lambda}_c$ and the $Y(4660)$ decaying into $\psi'\pi\pi$ to be the same state. The meaning of the symbols is explained in the caption of Table 11.

$e^+e^- \to \gamma_{ISR}\mathcal{X}$, $\mathcal{X} \to f$

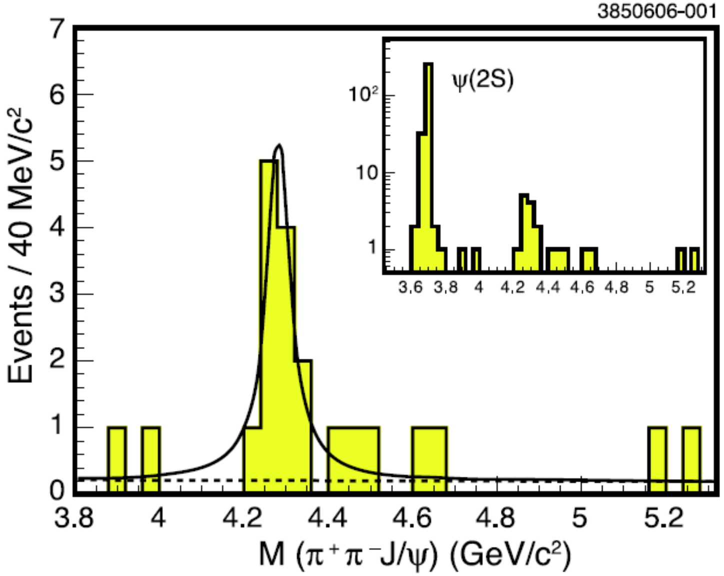
State	J^{PC}	$\psi\pi\pi$	$\psi'\pi\pi$	$h_c\pi\pi$	$\psi\eta$	$\chi_c\gamma$	$\chi_c\omega$	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	$D\bar{D}$	$D\bar{D}^*$	$D^*\bar{D}^*$	$D_s^{(*)}\bar{D}_s^{(*)}$
$Y(4008)$	1^{--}	S	MF	MF	MF	MF	—	MF	MF	—	MF	MF	MF	MF
$Y(4220)$	1^{--}	MF	MF	S	MF	MF	S	MF	MF	—	MF	MF	MF	MF
$Y(4260)$	1^{--}	S	NS	NS	NS	NS	NS	NS	MF	—	NS	NS	NS	NS
$Y(4290)$	1^{--}	MF	NS	S	NS	NS	NS	MF	MF	—	MF	MF	MF	MF
$Y(4360)$	1^{--}	NS	S	MF	MF	MF	MF	MF	MF	—	MF	MF	MF	MF
$Y(4660)$	1^{--}	NS	S	NP	MF	MF	MF	MF	MF	S	MF	MF	MF	MF

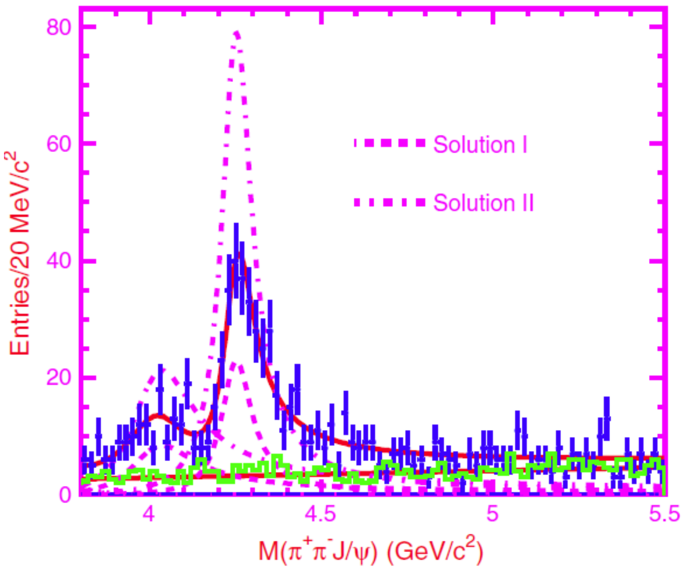
Y(4260)

BABAR 2005



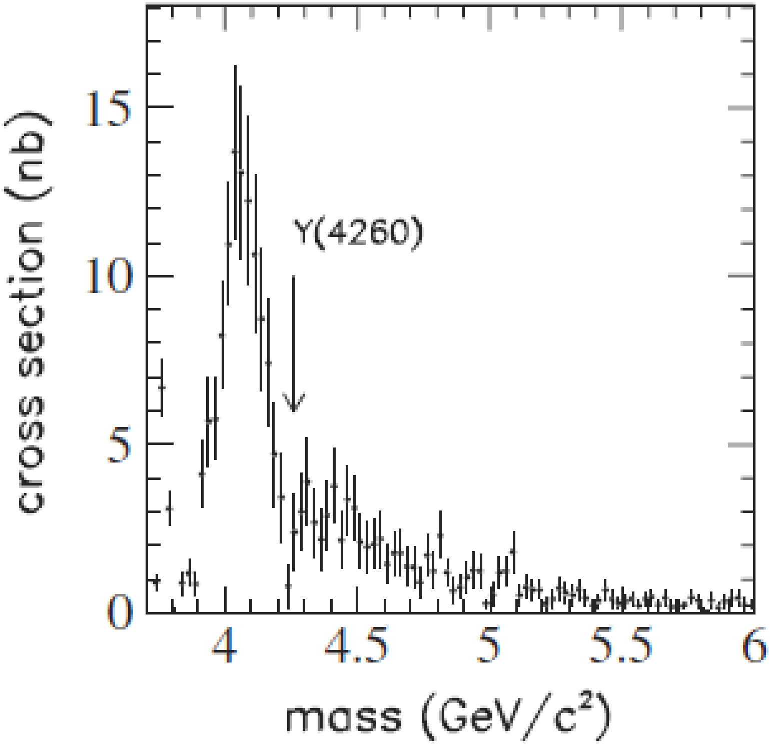
CLEO 2006





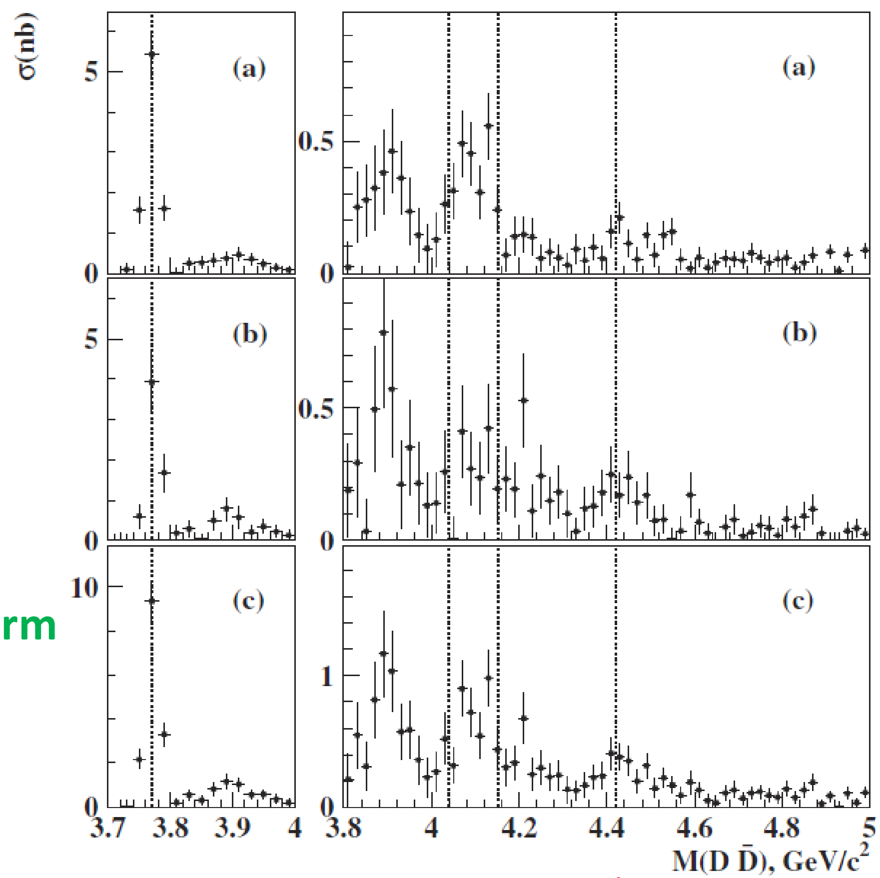
Belle, 2007

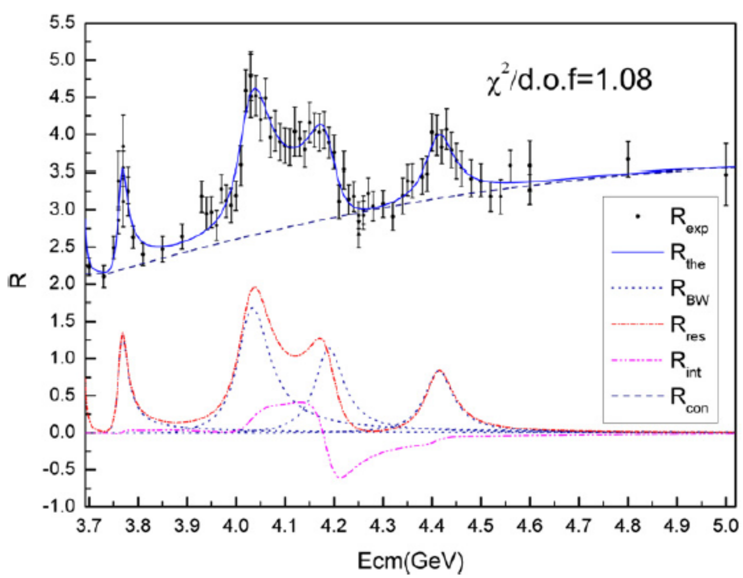
observed in J/ψππ



Belle, PRD79,092001; sum of e+e-→open charm

Belle 2008 e+e- → $\bar{D}D$





Dip at Y4260 !

R-value Scan, BES, 2007

Y(4260)

Theoretical explanation

- ✓**Hybrid** S.L. Zhu;Close&Page;Kou &Pene
- ✓**Tetraquark** Ebert et al; Maiani et al
- ✓**Baryonium of Λ_c anti-Λ_c** C.F. Qiao
- ✓**$\chi_{c0}\rho$, $\chi_{c1}\omega$ molecule, sizeable coupling with $\chi_{c0}\omega$** Liu et al; Yuan et al; Dai et al
- ✓**Interference of other charmonium** Chen et al
- ✓**D_1D, D_0D^* molecular state** Close et al; Kalashnikova et al; G.J. Ding
- ✓……

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 $j^P=1/2^-,1/2^+,3/2^+$

$$
\begin{aligned}
H_a &= \frac{1+\not{v}}{2}[\mathcal{D}^*_{a\mu}\gamma^\mu - \mathcal{D}_a\gamma_5]\,, \\
S_a &= \frac{1+\not{v}}{2}\left[\mathcal{D}'^{\mu}_{1a}\gamma_\mu\gamma_5 - \mathcal{D}^*_{0a}\right]\,, \\
T^\mu_a &= \frac{1+\not{v}}{2}\Bigg\{\mathcal{D}^{\mu\nu}_{2a}\gamma_\nu \\
&\quad - \sqrt{\frac{3}{2}}\mathcal{D}_{1a\nu}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\Bigg\}\,,
\end{aligned}
$$

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

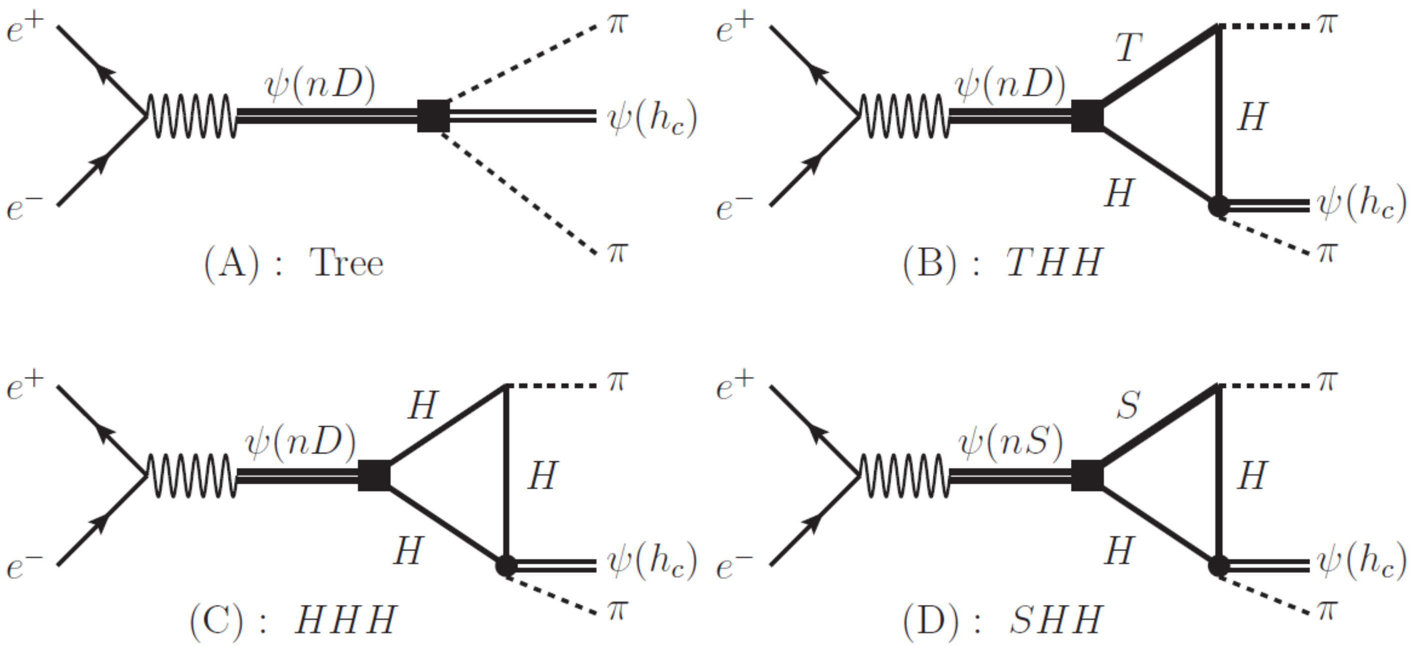
According to HHChPT power counting

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

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

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

Dipion Transitions



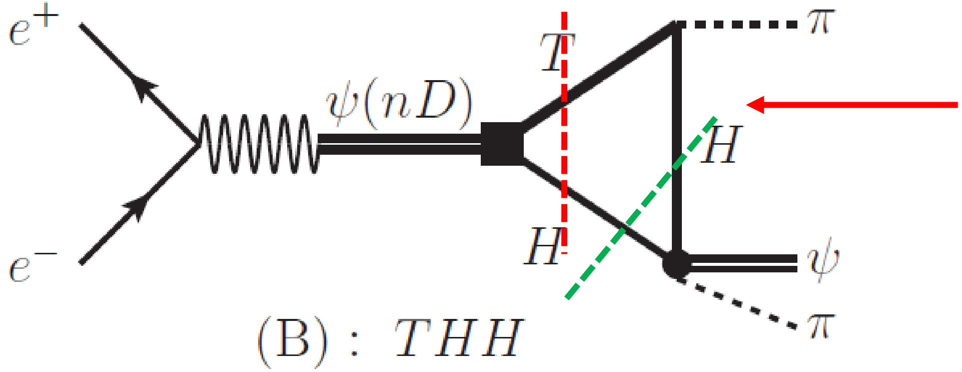
ψ(4160) as the input ψ(nD):

- ✓ **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

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

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

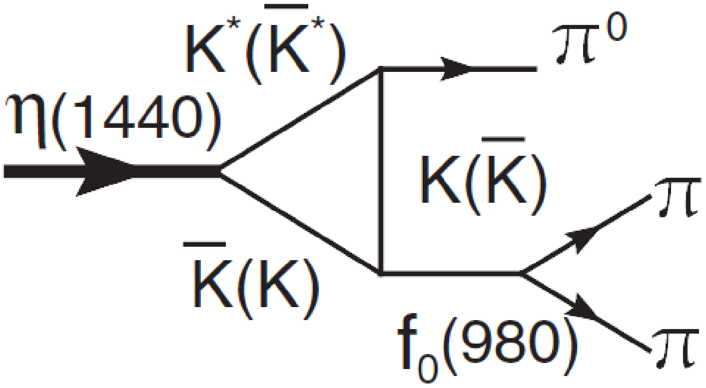
$$\text{III)}\quad \{D_2 D^*\,[D]\},$$

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

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



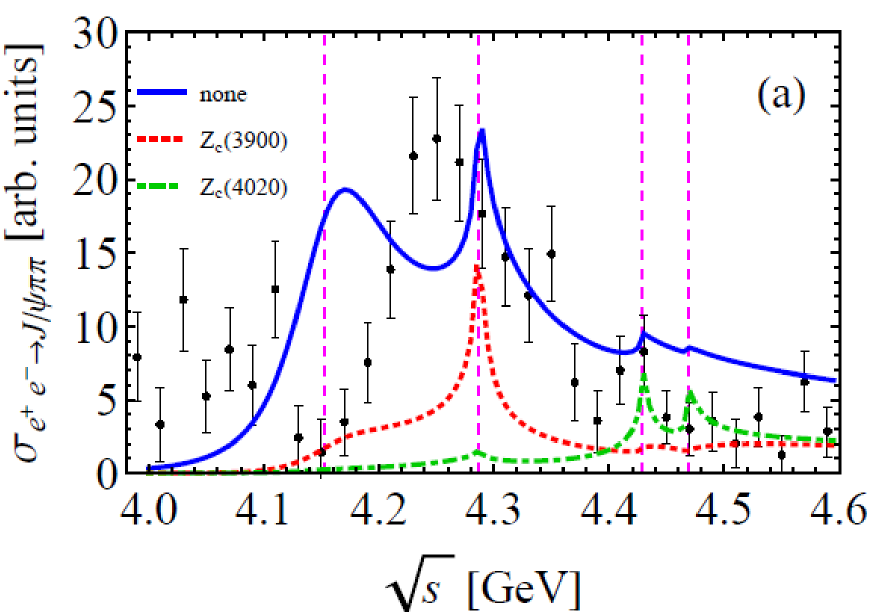
Largely isospin violation in η(1405/1475)→3π

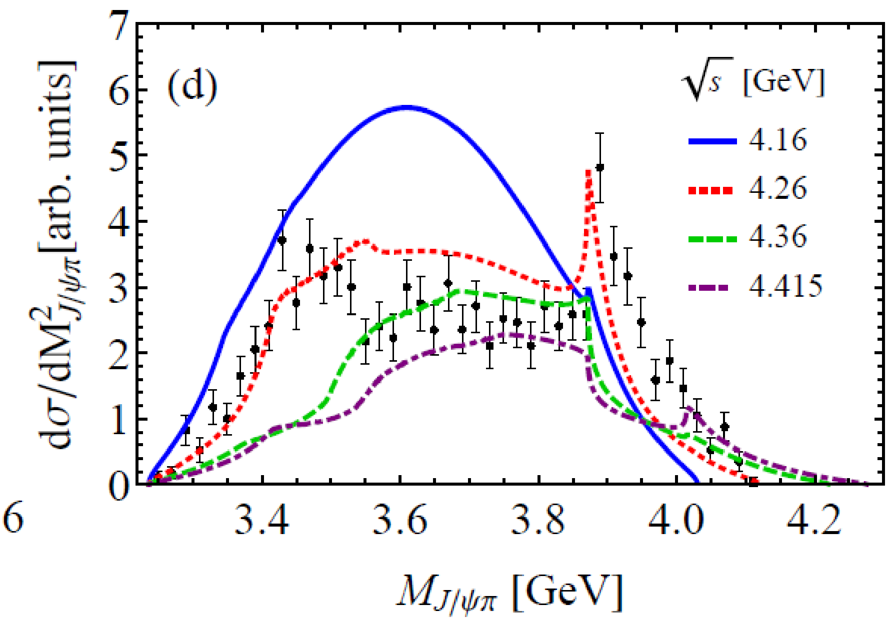
Br~10%, [BESIII, PRL108,182001 (2012)]

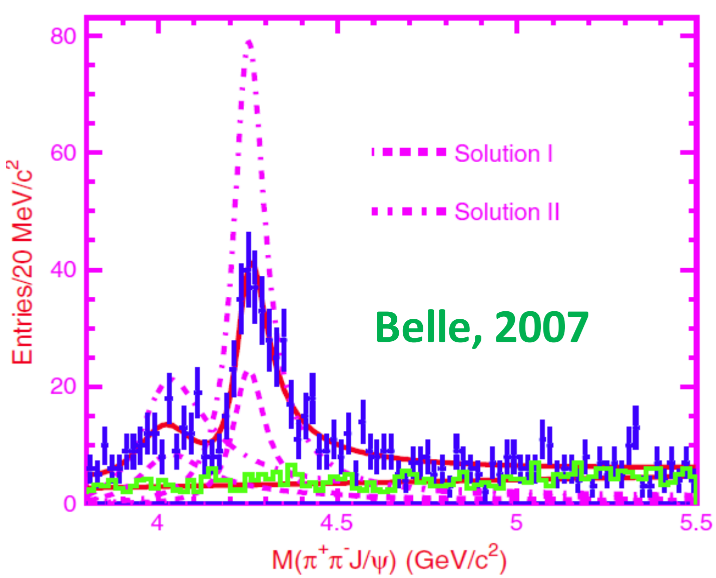
Wu,Liu,Zhao&Zou, PRL108,081803(2012)

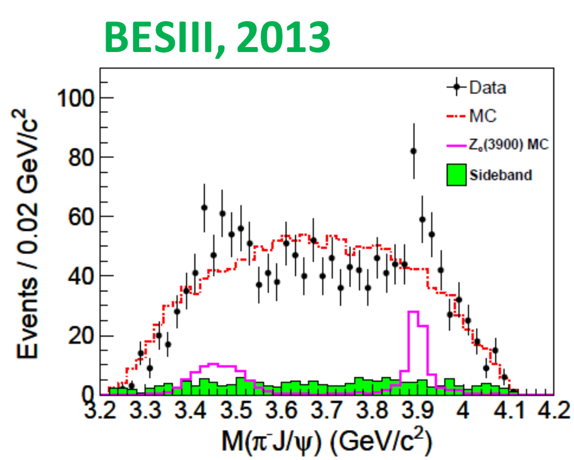
References:
Landshoff and Treiman, Phys.Rev. 127,649(1962)
Landshoff and Treiman, Nuovo Cimento 19,1249(1961)
Eden et al., <<The Analytic S-Matrix>>, 1966
…………

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

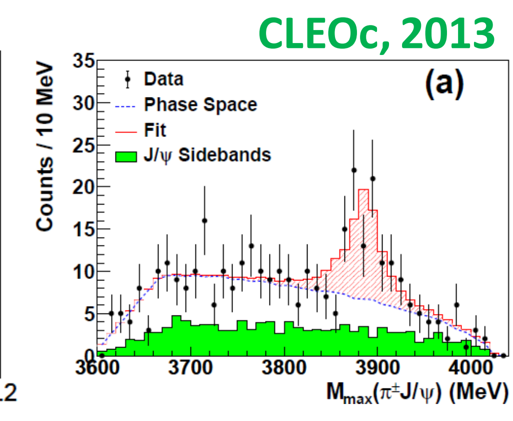






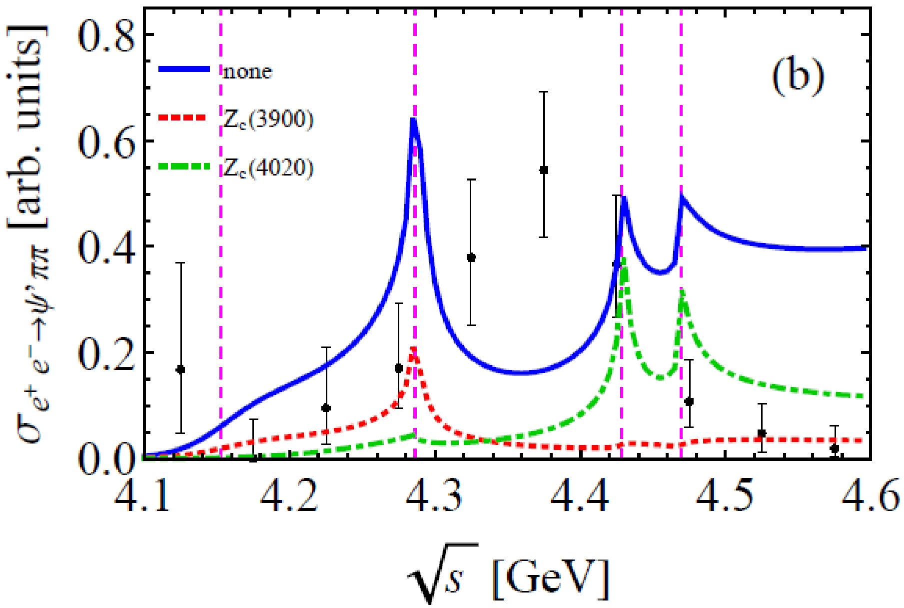


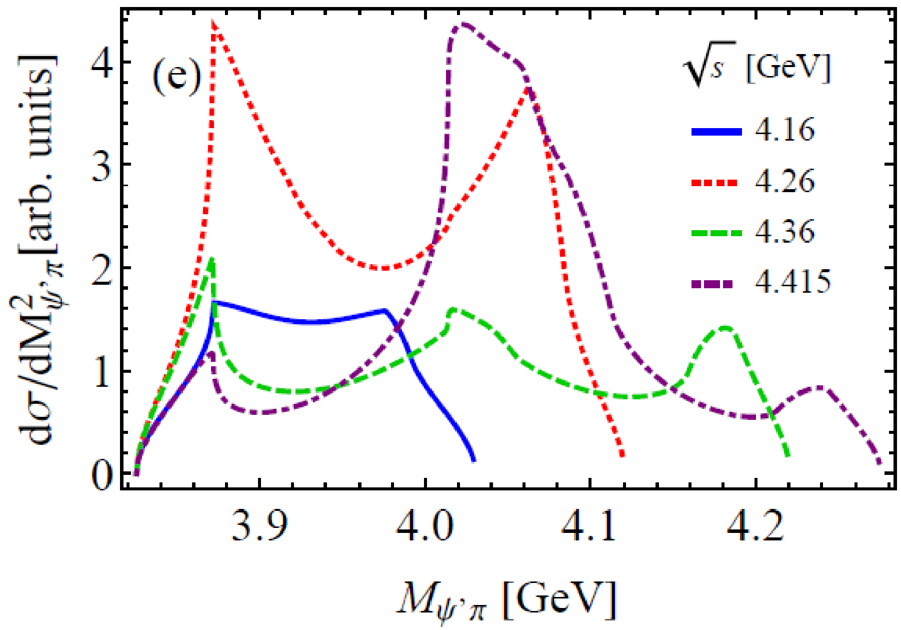
$\sqrt{s}$=4.26 GeV

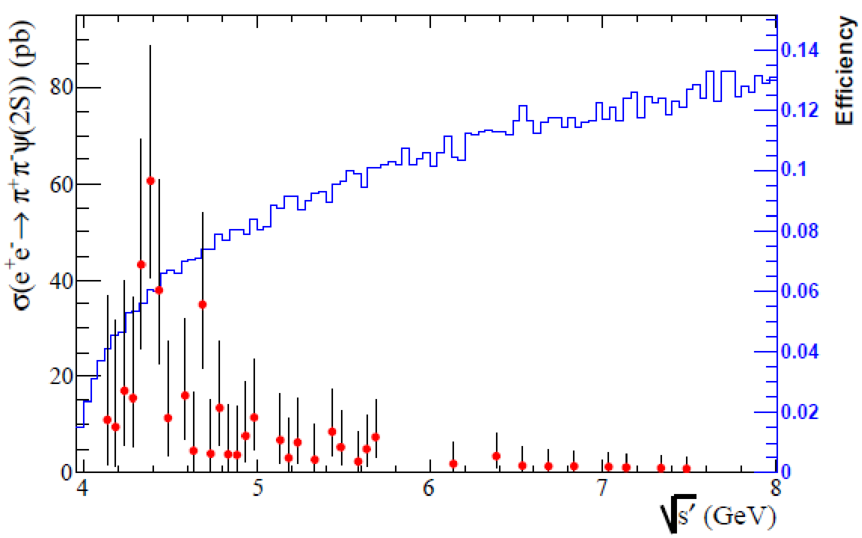


$\sqrt{s}$=4.17 GeV

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



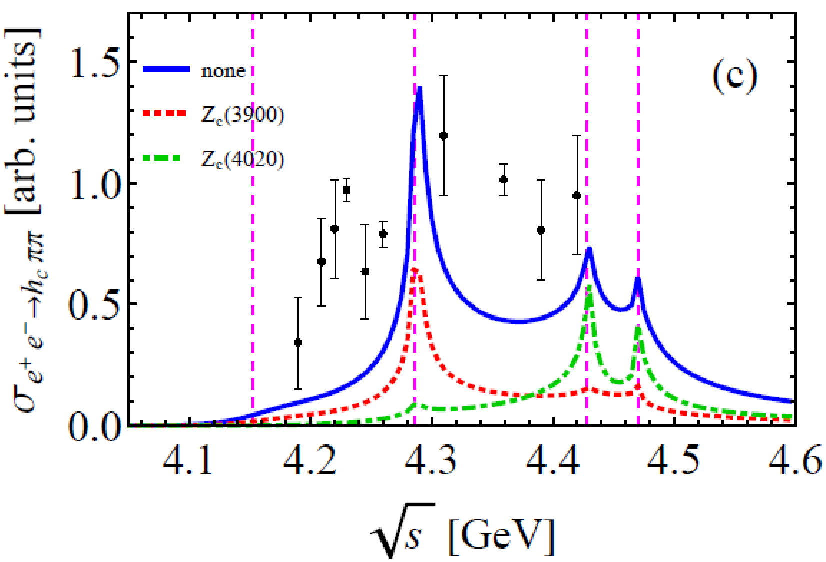


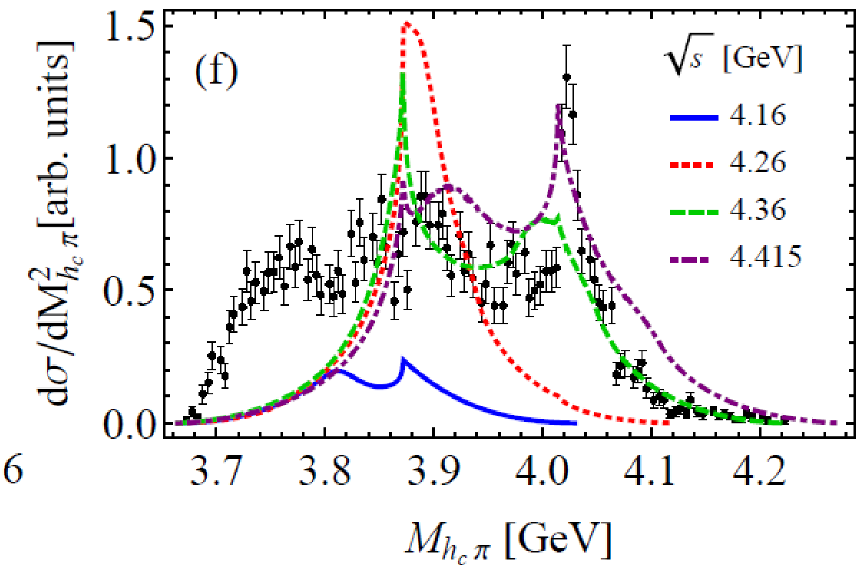


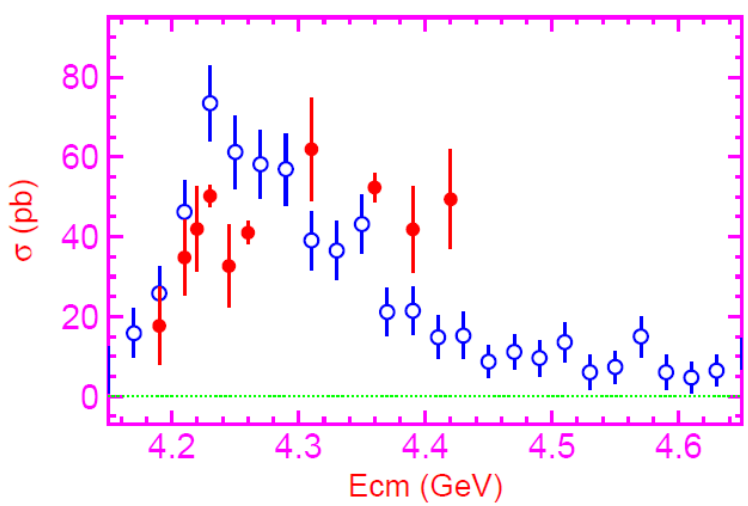
BarBar, PRL98,212001(2007)

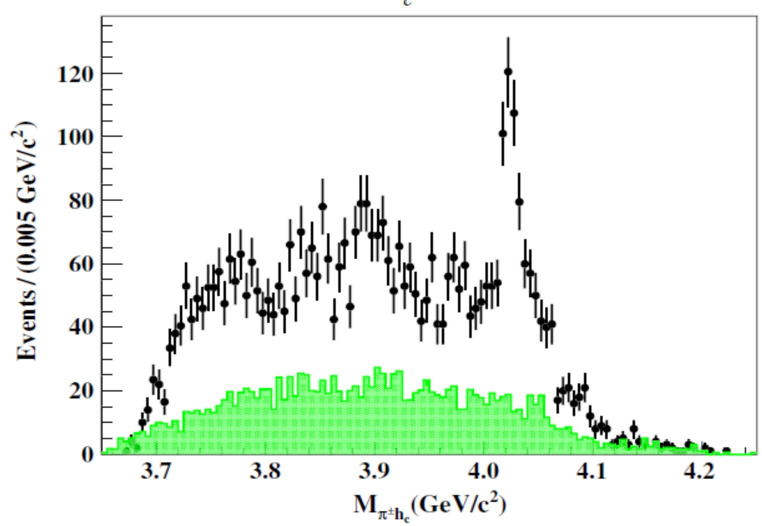
- ✓ **Results are sensitive to kinematics**
- ✓ **Same dynamics, different kinematics**
- ✓ **Direct prediction to check the mechanism**

$e^+e^- \to h_c\pi\pi$ 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:

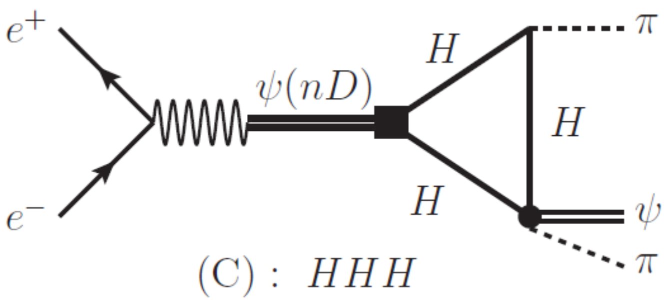
✓ D_1D, D_0D^* molecular state, F. Close et al, PRL102,242003(2009), PRD81,074033(2010); Kalashnikova and Nefediev, PRD77,054025(2008);

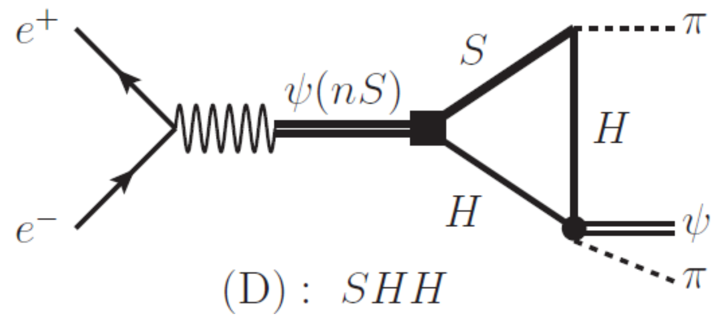
✓ Potential model, G.J. Ding PRD79,014001(2009)

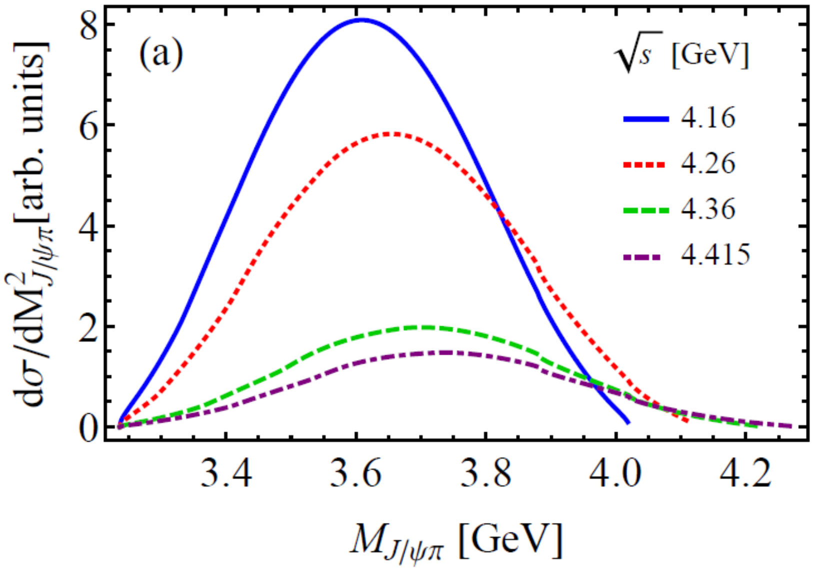
✓ Connection with Zc(3900), Wang, Zhao and Hanhart, PRL111,132003(2013); X.H. Liu and G.Li, PRD88,014013(2013)

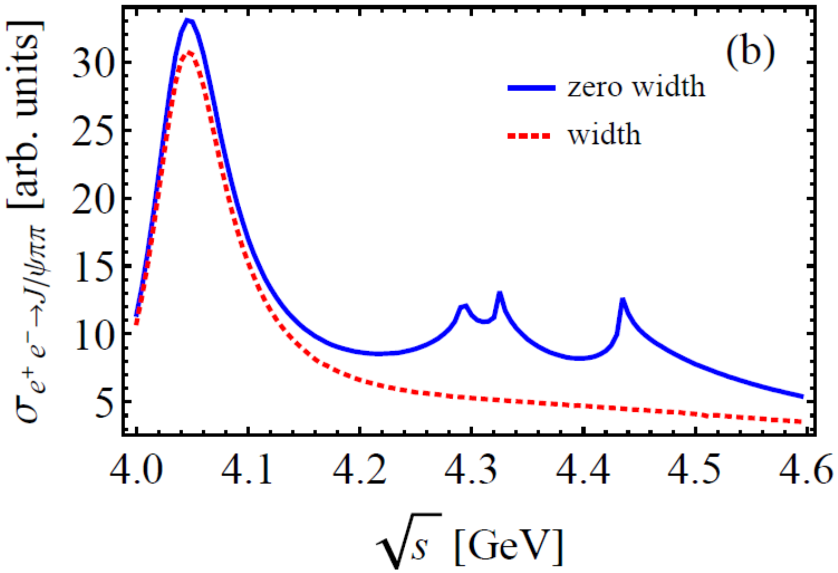
✓ ……

HHH Loop and SHH Loop





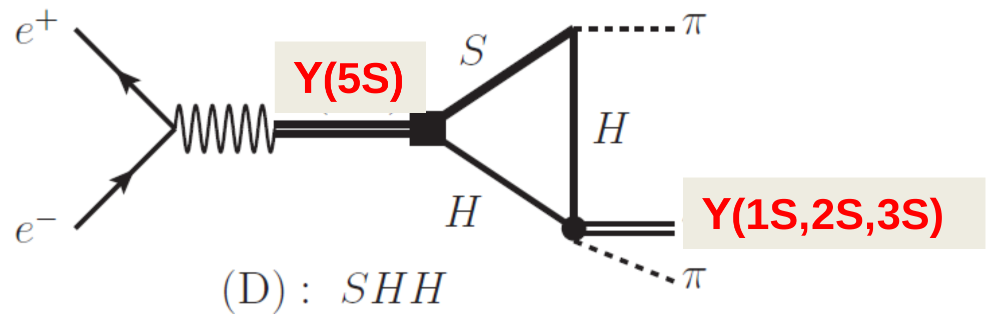


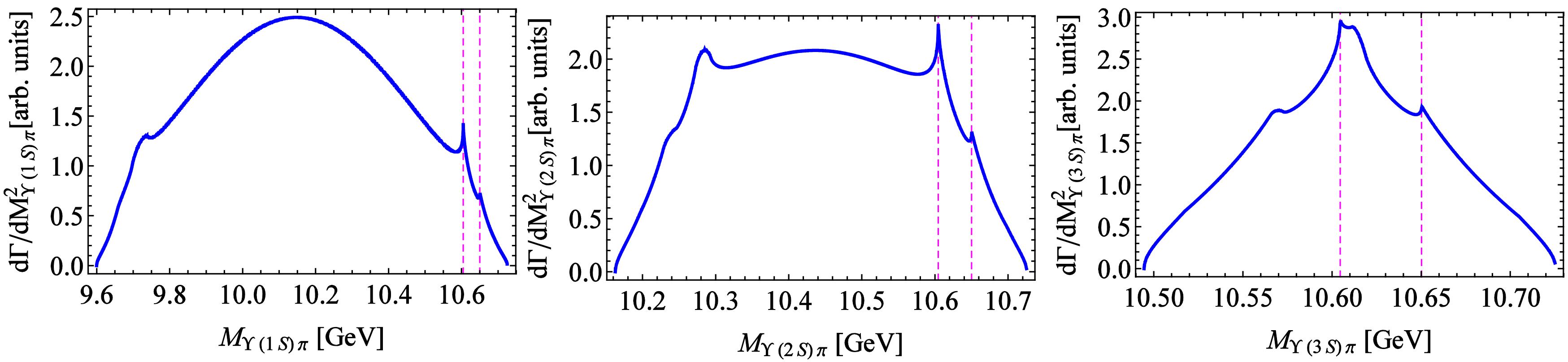


No obvious cusp around 3.9GeV, inconsistent with CLEOc result

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

Zb Production

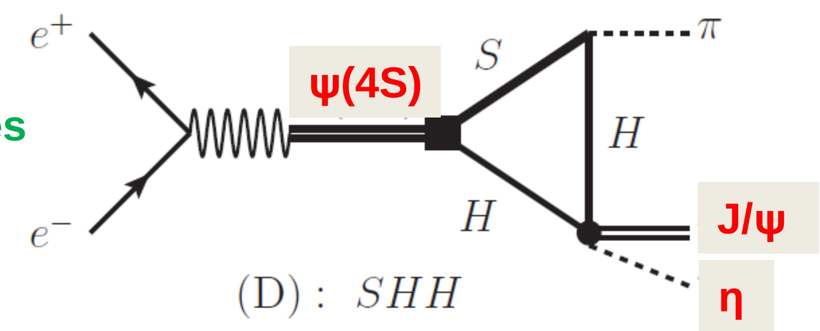


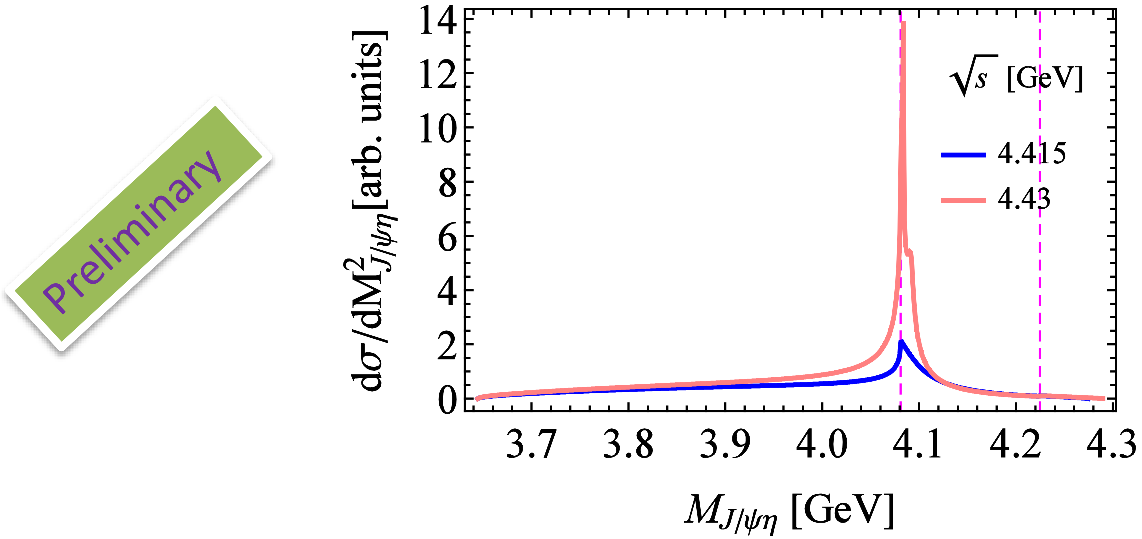


Cusps at BB* and B*B* thresholds ⟺ Production of Zb(10610) and Zb(10650)

Hunting For Partners of Y4160 &Y4274

Isospin violation processes





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

$$D = 0,$$

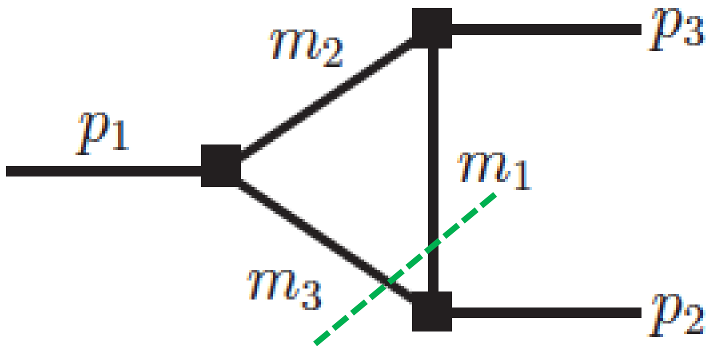
$$either \;\; a_j = 0 \;\; or \;\; \boxed{\frac{\partial D}{\partial a_j} = 0.}$$

Leading singularity

The position of the singularity is obtained by solving

$$\det Y_{ij} = 0$$

Anomalous Threshold Singularity



$$s_1 = p_1^2,\ s_2 = p_2^2,\ s_3 = p_3^2$$

Normal threshold $\quad s_{2n} = (m_1 + m_3)^2$

Anomalous threshold

$$s_2^{\pm} = (m_1 + m_3)^2 + \frac{1}{2m_2^2}[2m_2m_3(m_1^2 + m_2^2 - s_3) - 4m_2^2m_1m_3 \pm \lambda^{1/2}(s_1, m_2^2, m_3^2)\lambda^{1/2}(s_3, m_1^2, m_2^2)]$$

Anomalous Threshold Singularity

Single dispersion relation

$$\Gamma(s_1, s_2, s_3) = \frac{1}{\pi} \int_{(m_1+m_3)^2}^{\infty} \frac{ds_2'}{s_2' - s_2 - i\epsilon} \sigma_2(s_1, s_2', s_3)$$

$$\sigma_2 = \sigma_+ - \sigma_-$$

$$\begin{aligned} \sigma_\pm(s_1, s_2, s_3) \; = \; & \frac{1}{16\pi\lambda^{1/2}(s_1, s_2, s_3)} \log[-s_2(s_1 + s_3 - s_2 + m_1^2 + m_3^2 - 2m_2^2) \\ & - \; (s_1 - s_3)(m_1^2 - m_3^2) \pm \lambda^{1/2}(s_1, s_2, s_3)\lambda^{1/2}(s_2, m_1^2, m_3^2)] \end{aligned}$$

Brach points of the log function is at $s_2^\pm$

Work in the kinematical region

$$s_1 \; \leq \; (m_2 + m_3)^2, \; s_3 \; \leq \; (m_2 - m_1)^2$$

Anomalous Threshold Singularity

Double dispersion relation

Landau type contribution

$$\Gamma(s_1, s_2, s_3) = \int_{(m_2+m_3)^2}^{\infty} \frac{ds'_1}{\pi(s'_1 - s_1 - i\epsilon)} \int_{s_2^-(s'_1)}^{s_2^+(s'_1)} \frac{ds'_2}{\pi(s'_2 - s_2 - i\epsilon)} \Delta(s'_1, s'_2, s_3)$$

$$+ \, 2\int_{s_1^0}^{\infty} \frac{ds'_1}{\pi(s'_1 - s_1 - i\epsilon)} \int_{s_2^+(s'_1)}^{s_2^L(s'_1)} \frac{ds'_2}{\pi(s'_2 - s_2 - i\epsilon)} \Delta(s'_1, s'_2, s_3)$$

Non-Landau type contribution

Double spectral function can be obtained according to Cutkosky rule

$$\Delta(s_1, s_2, s_3) = \frac{1}{16\lambda^{1/2}(s_1, s_2, s_3)}$$

Anomalous Threshold Singularity

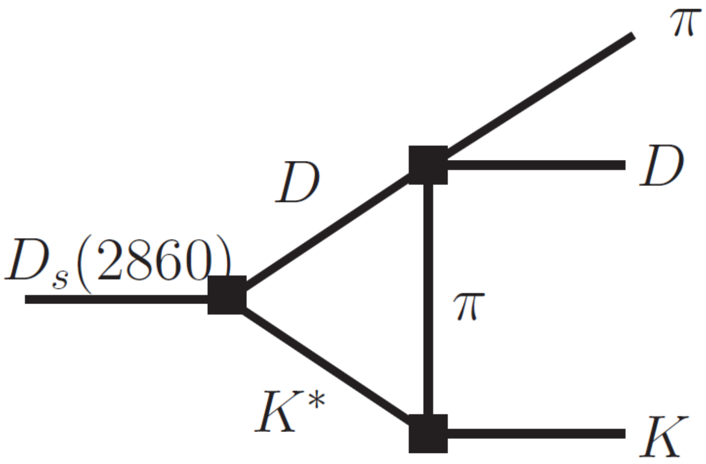
When $s_1 = (m_2 + m_3)^2$

$$s_2^{\pm} = (m_1 + m_3)^2 + \frac{m_3}{m_2}[(m_2 - m_1)^2 - s_3]$$

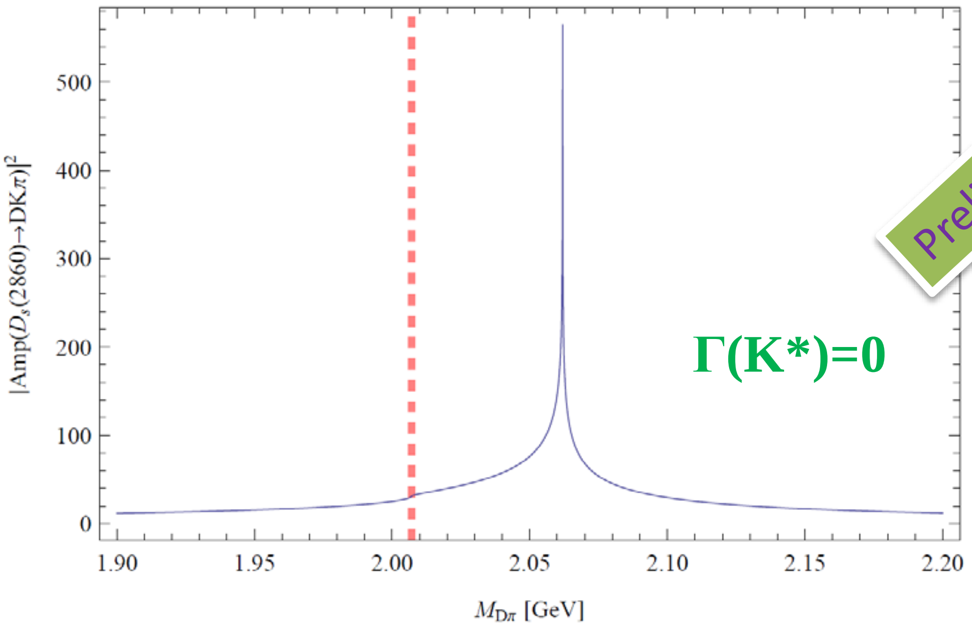
How to amplify the discrepancy between normal and anomalous threshold?

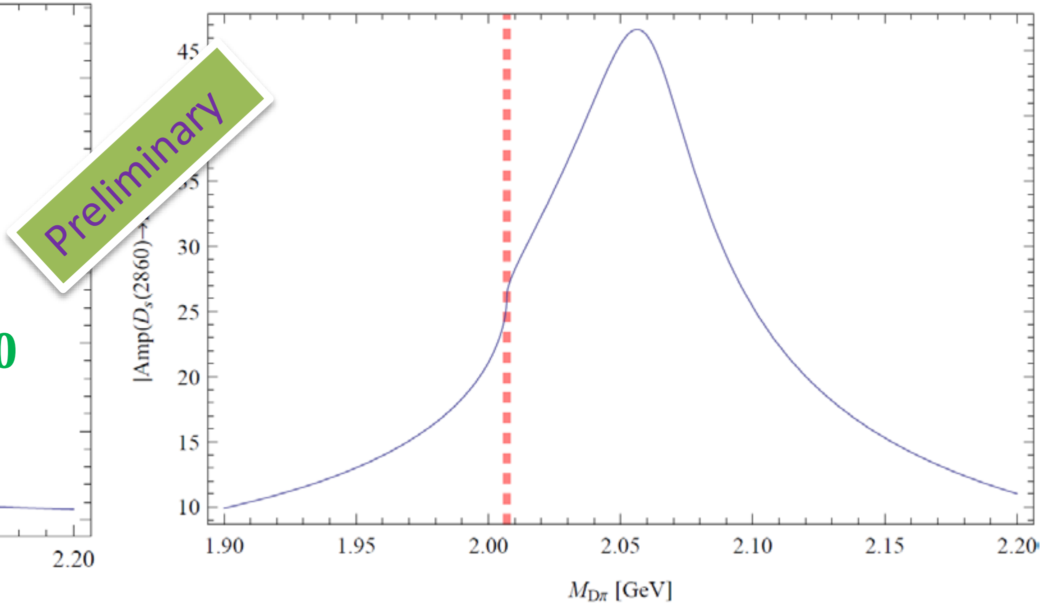
If the discrepancy is larger, it could be used to distinguish the cusp effects and molecular states.

Anomalous Threshold Singularity

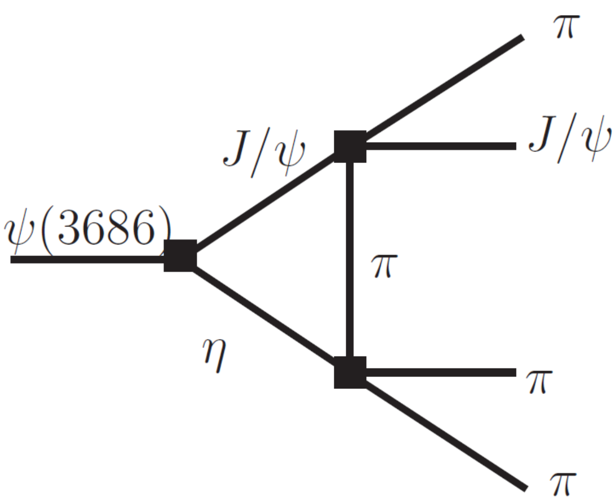


$$D_s(2860) \to DK^*[\pi] \to DK\pi$$



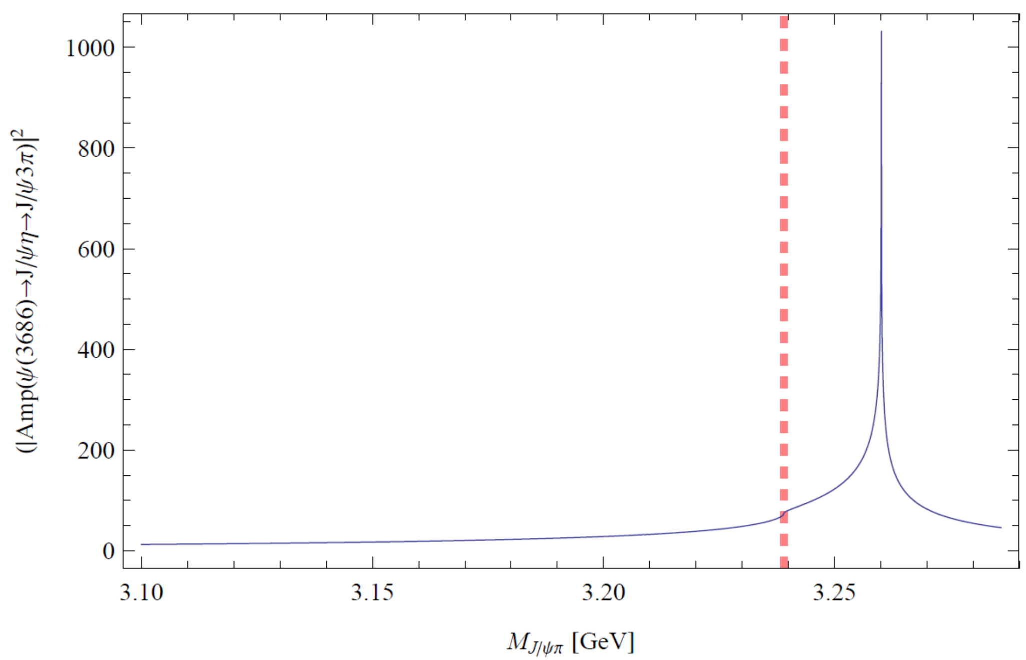


Anomalous Threshold Singularity



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.**

Thanks!