Threshold and kinematic effects for the exotic resonance-like structures

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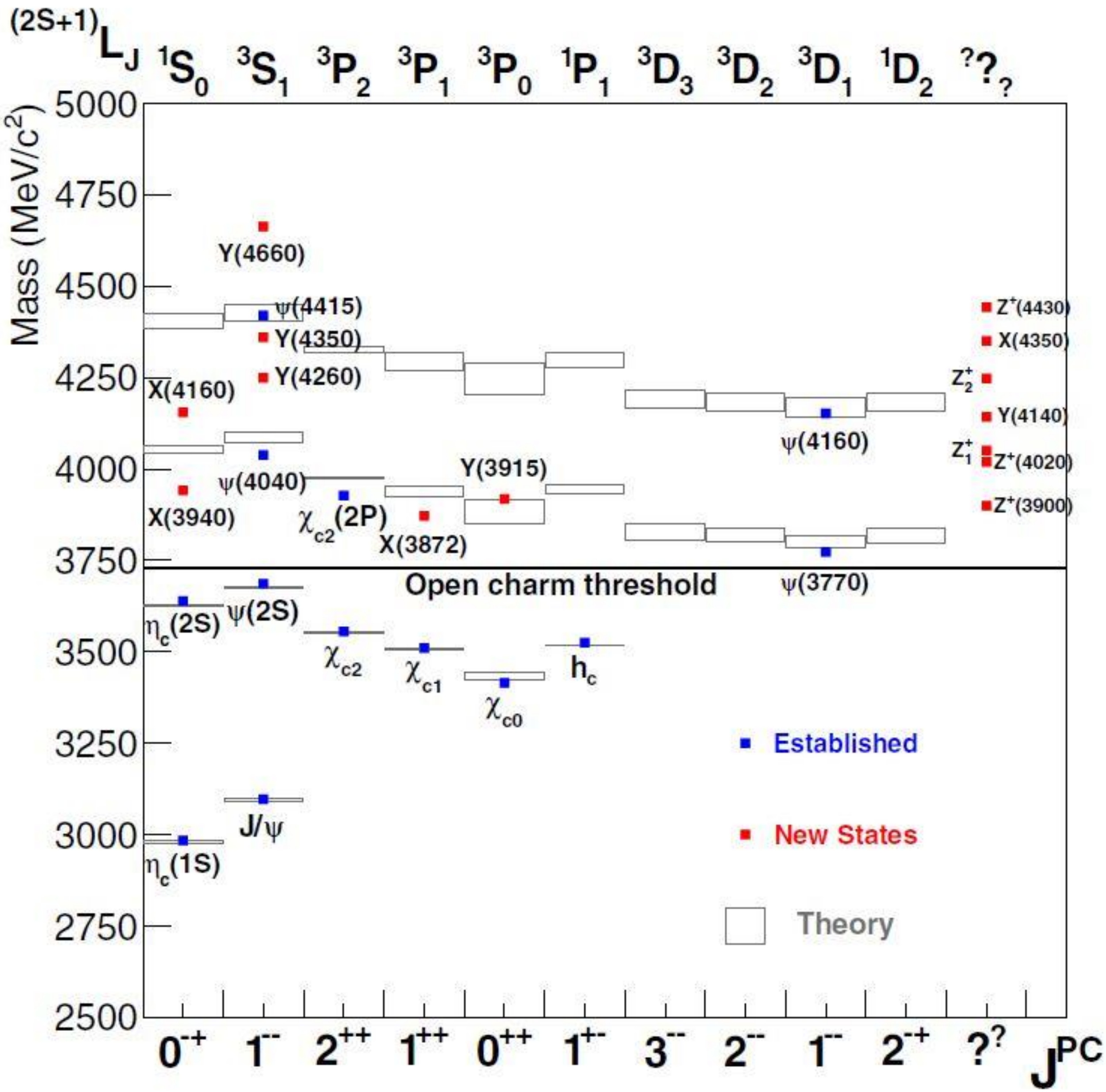
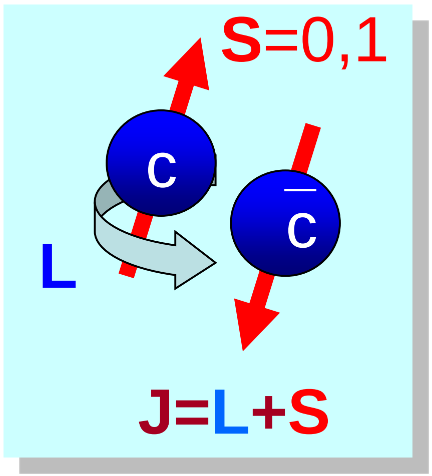
Outline

1. General features about the threshold phenomena in hadron spectra?
2. Definition of anomalous triangle singularity (ATS)
3. Recognition of ATS in physical processes in the study of exotic threshold structures
4. Summary

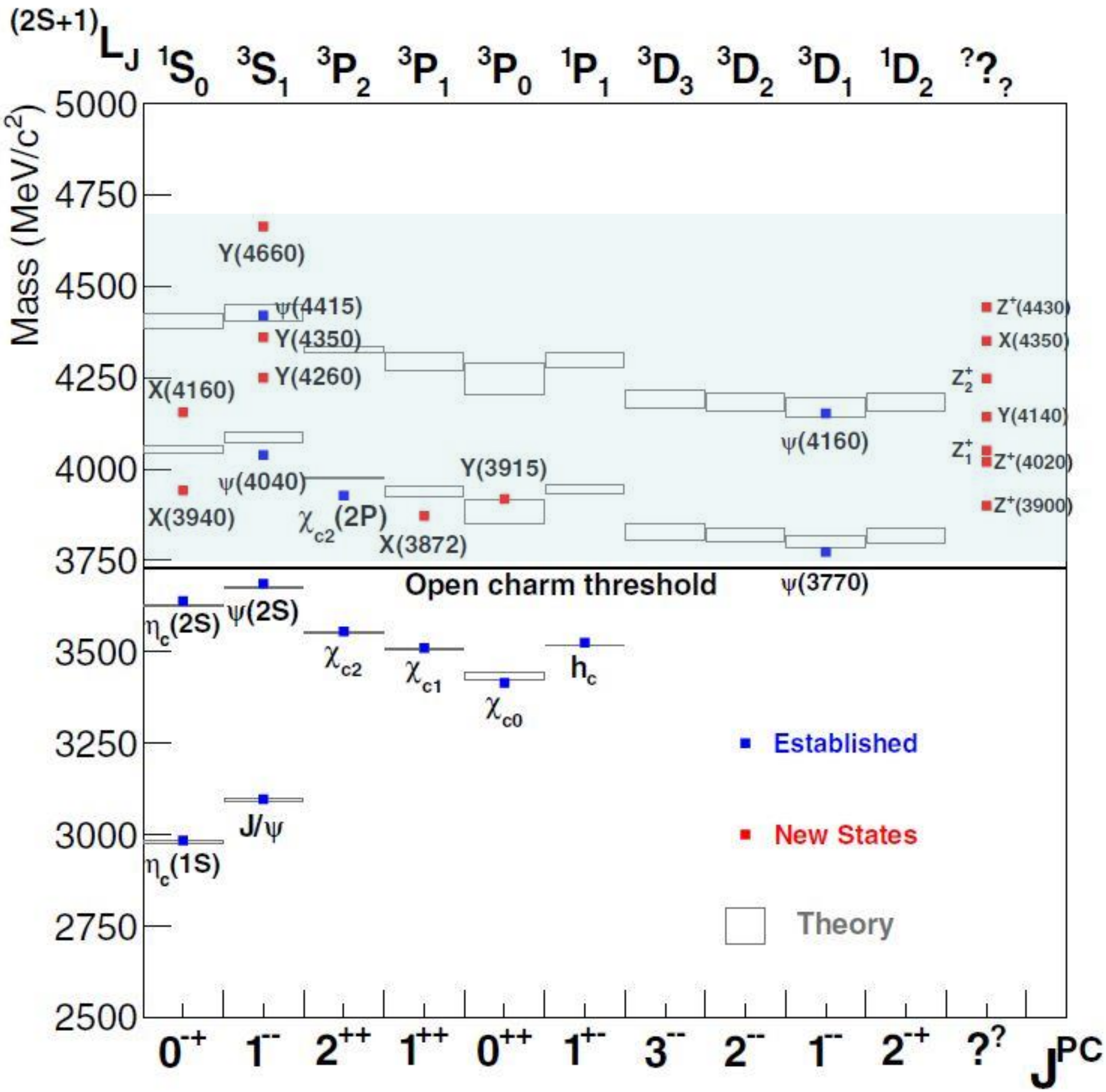
Charmonium Spectrum





New charmonium-like states, i.e. "XYZ" states, are observed in experiment

Charmonium Spectrum

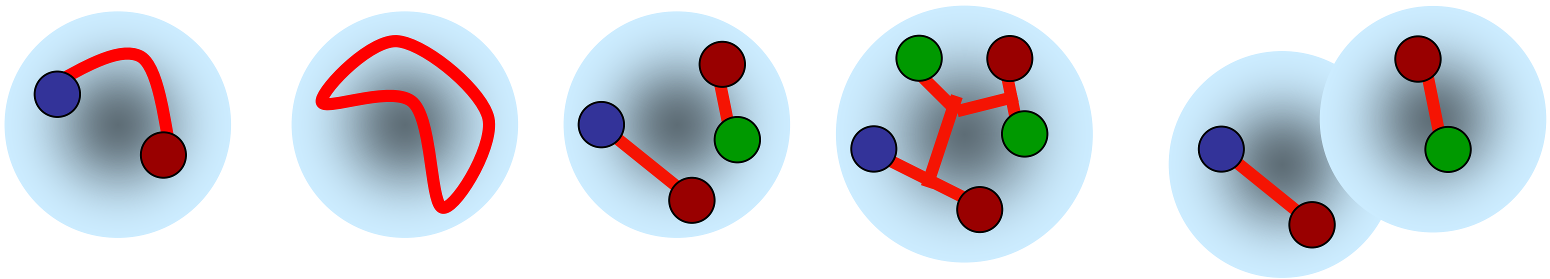


Expected & Unexpected:

- States below open-flavor thres. are well established.
- A large number of excited states, i.e. XYZ states, cannot be accommodated by the conventional QM!
- Full LQCD simulations are unavailable.

Some urgent questions:

- Do we have **indisputable** evidence for exotic hadrons?

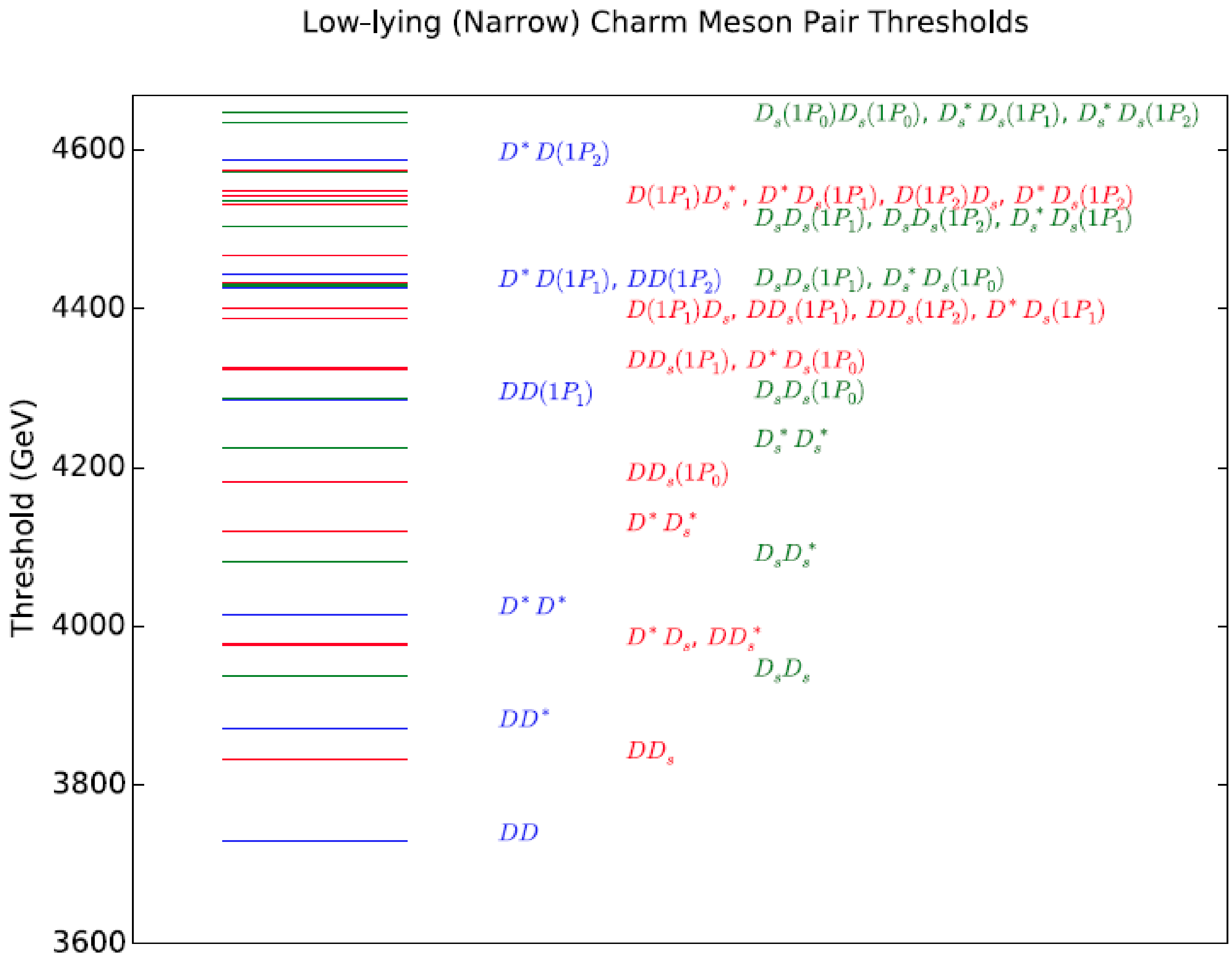


- Do we have **efficient** and **sufficient criteria** for identifying exotic hadrons?

  -- e.g. genuine states vs. kinematic effects ?

- **Where** to look for exotic hadrons?
- … …

Low-lying thresholds



Narrow-Wide Thresholds

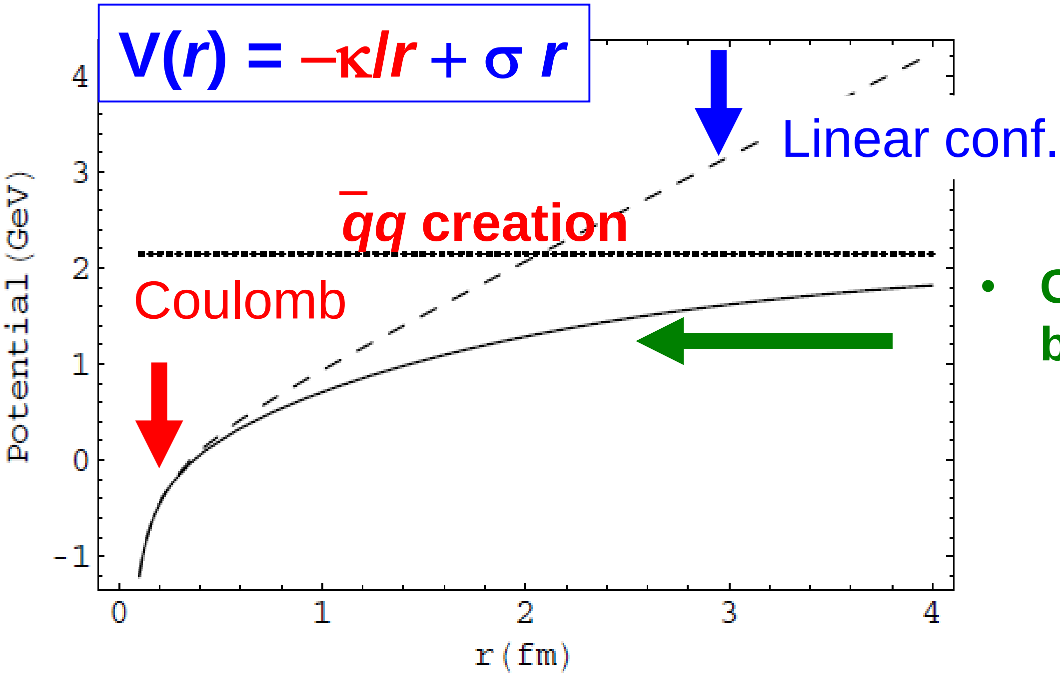
D_s* $D(P_1)$

D_s $D(P_1)$; D_s* $D(P_0)$

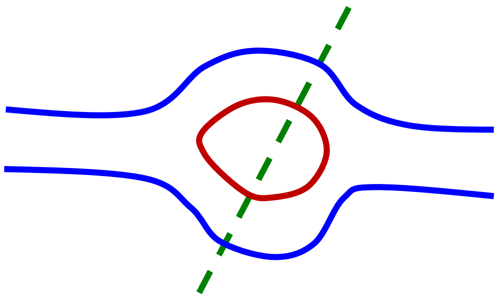
D_s $D(P_0)$; D* $D(P_0)$; D $D(P_1)$

D $D(P_0)$

How the potential QM is broken down



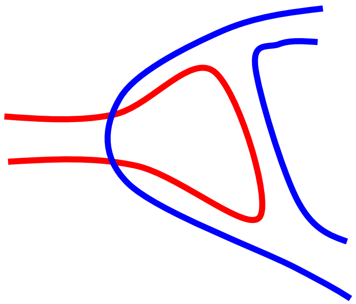
- **Color screening effects? String breaking effects?**



- **The effect of vacuum polarization due to dynamical quark pair creation may be manifested by the strong coupling to open thresholds and compensated by that of the hadron loops, i.e. coupled-channel effects.**

E. Eichten et al., PRD17, 3090 (1987)
B.-Q. Li and K.-T. Chao, Phys. Rev. D79, 094004 (2009);
T. Barnes and E. Swanson, Phys.Rev. C77, 055206 (2008)

Typical processes where the open threshold coupled channels can play a role



$\psi(3770) \to non D\bar{D}$ Y.J. Zhang et al, PRL(2009);

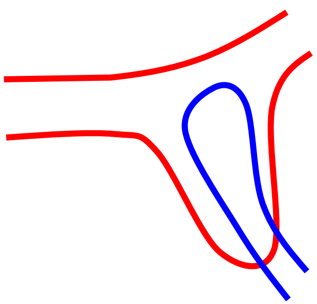
"ρπ puzzle" X. Liu, B. Zhang, X.Q. Li, PLB(2009)

Q. Wang et al. PRD(2012), PLB(2012)

$\chi_{c1} \to VV, \ \chi_{c2} \to VP$ X.-H. Liu et al, PRD81, 014017(2010);

X. Liu et al, PRD81, 074006(2010)

$\eta_c(\eta_c') \to VV$ Q. Wang et al, PRD2012



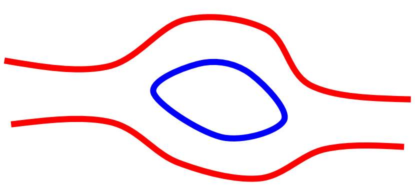
$\psi' \to J/\psi\pi^0, \psi' \to J/\psi\eta$

$\psi' \to \gamma\eta_c, J/\psi \to \gamma\eta_c$

G. Li and Q. Zhao, PRD(2011)074005

F.K. Guo, C. Hanhart, G. Li, U.-G. Meissner and Q. Zhao, PRD82, 034025 (2010); PRD83, 034013 (2011)

F.K. Guo and Ulf-G Meissner, PRL108(2012)112002

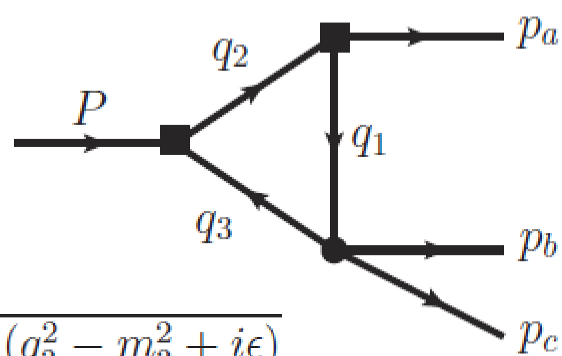


$D_{s1}(2460) - D_{s1}(2536)$

The mass shift in charmonia and charmed mesons, E.Eichten et al., PRD17(1987)3090

X.-G. Wu and Q. Zhao, PRD85, 034040 (2012)

Special kinematic effects from anomalous triangle singularity (ATS)



$$\Gamma_3(s_1, s_2, s_3) = \frac{1}{i(2\pi)^4} \int \frac{d^4 q_1}{(q_1^2 - m_1^2 + i\epsilon)(q_2^2 - m_2^2 + i\epsilon)(q_3^2 - m_3^2 + i\epsilon)}$$
$$= \frac{-1}{16\pi^2} \int_0^1 \int_0^1 \int_0^1 da_1\, da_2\, da_3\, \frac{\delta(1 - a_1 - a_2 - a_3)}{D - i\epsilon},$$

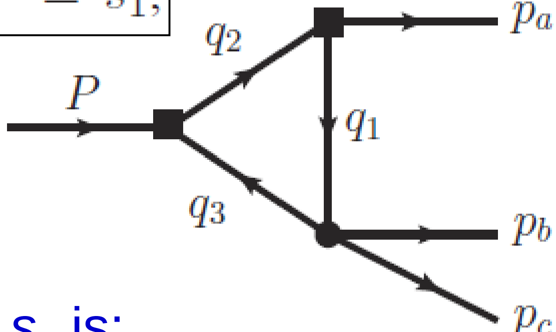
$$D \equiv \sum_{i,j=1}^{3} a_i a_j Y_{ij}, \quad Y_{ij} = \frac{1}{2}\left[m_i^2 + m_j^2 - (q_i - q_j)^2\right]$$

The ATS occurs when all the three internal particles can be simultaneously on shell. It corresponds to

$\partial D / \partial a_j = 0$ for all j=1,2,3. ⇨ $\det[Y_{ij}] = 0$

L. D. Landau, Nucl. Phys. **13**, 181 (1959).
G. Bonnevay, I. J. R. Aitchison and J. S. Dowker, Nuovo Cim. **21**, 3569 (1961).
R.F. Peierls, Phys. Rev. Lett. 6 (1961) 641.
S. Coleman, R.E. Norton, Nuovo Cimento 38 (1965) 438.
P. Landshoff, S. Treiman, Phys. Rev. 127 (1962) 649.
C. Schmid, Phys. Rev. 154 (1967) 1363.

Kinematics :



The ATS condition for fixed s_1, m_j, and s_3 is:

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

Or for fixed s_2, m_j, and s_3 :

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

with $\lambda(x, y, z) \equiv (x - y - z)^2 - 4yz.$

X.-H. Liu, M. Oka and Q. Zhao, PLB753, 297(2016); arXiv:1507.01674 [hep-ph]

Single dispersion relation in s_2 in the complex plane of s_2':

$$\Gamma_3(s_1, s_2, s_3) = \frac{1}{\pi} \int\limits_{(m_1+m_3)^2}^{\infty} \frac{ds_2'}{s_2' - s_2 - i\epsilon} \, \sigma(s_1, s_2', s_3)$$

The spectral function $\sigma(s_1, s_2, s_3)$ can be obtained by means of the Cutkosky's rules (absorptive part of the loop amplitude):

$$\sigma(s_1, s_2, s_3) \; = \; \frac{-1}{16\pi} \int_0^1 \int_0^1 \int_0^1 da_1 \, da_2 \, da_3 \, \delta(1 - a_1 - a_2 - a_3) \delta(D).$$

which reads

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

For fixed s_1, s_3 and m_i, the spectral function $\sigma(s_1, s_2, s_3)$ has logarithmic branch points $s^{\pm}_2$, which correspond to the anomalous thresholds by solving the Landau equation.

How the logarithmic branch points $s^{\pm}_2$ move as s_1 increases from the threshold of $(m_2 + m_3)^2$, with s_3 and m_i fixed?

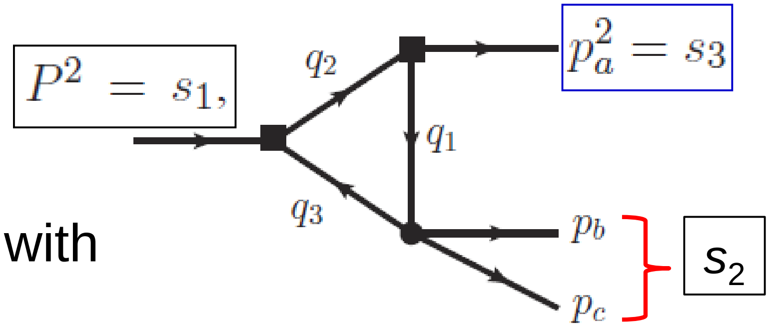
Substituting $s_1 \to s_1 + i\varepsilon$, $s^{\pm}_2$ in the s'-plane are then located at

$$s_2^{\pm}(s_1 + i\epsilon) = s_2^{\pm}(s_1) + i\epsilon\frac{\partial s_2^{\pm}}{\partial s_1},$$

With $\partial s_2^{\pm}/\partial s_1{=}0 \; (\partial s_1^{\pm}/\partial s_2{=}0)$

the normal and critical thresholds for s_1 and s_2 can be determined:

$$s_{1N} = (m_2 + m_3)^2,\; s_{1C} = (m_2 + m_3)^2 + \frac{m_3}{m_1}[(m_2 - m_1)^2 - s_3],$$
$$s_{2N} = (m_1 + m_3)^2,\; s_{2C} = (m_1 + m_3)^2 + \frac{m_3}{m_2}[(m_2 - m_1)^2 - s_3],$$

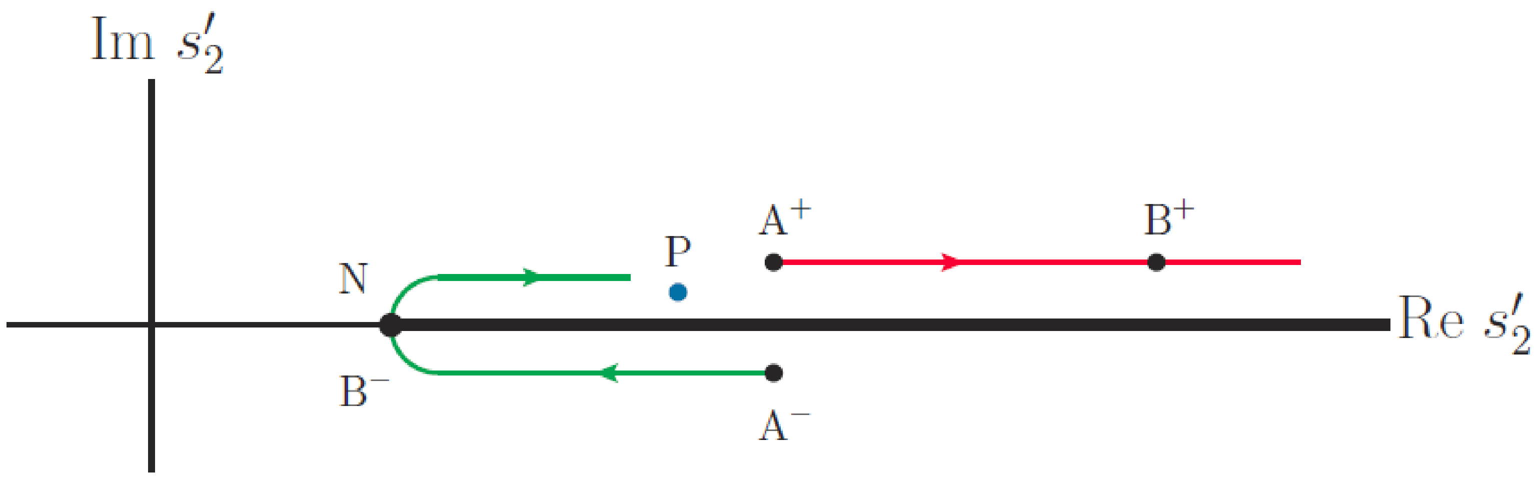


Trajectories of $s^{\pm}_2$ in the complex s'_2-plane with s_1 increasing from $s_{1N} \rightarrow \infty$:

A⁺ :(s_1=s_{1N}, s_2^+=$s_{2C}+i\varepsilon$) → **B⁺** :(s_1=s_{1C}, s_2^+=s_{2N}+$m_3\,\lambda(s_3,m_1^2,m_2^2)/(m_1 m_2)+i\varepsilon$)

A⁻ :(s_1=s_{1N}, s_2^-=$s_{2C}-i\varepsilon$) → **B⁻** :(s_1=s_{1C}, s_2^-=s_{2N})

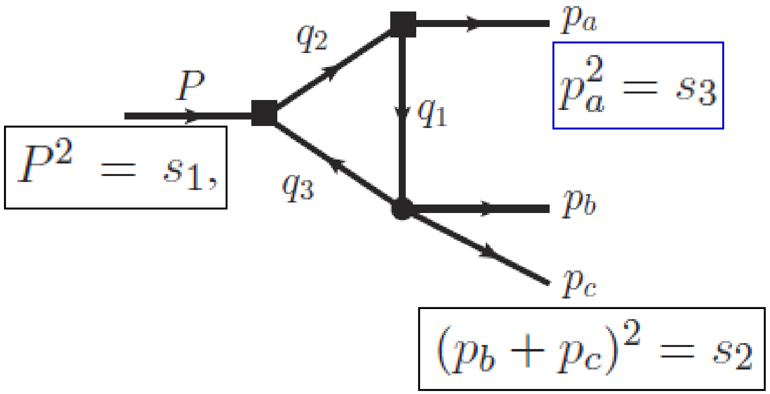
P : $s_2 + i\epsilon.$



$$\Gamma_3(s_1, s_2, s_3) = \frac{1}{\pi} \int_{(m_1+m_3)^2}^{\infty} \frac{ds'_2}{s'_2 - s_2 - i\epsilon}\, \sigma(s_1, s'_2, s_3)$$

The difference between the normal and anomalous thresholds decides the kinematic range of the ATS effects:

$$\Delta_{s_1} = \sqrt{s_1^-} - \sqrt{s_{1N}},$$
$$\Delta_{s_2} = \sqrt{s_2^-} - \sqrt{s_{2N}}.$$



When $s_2=s_{2N}$ ($s_1=s_{1N}$), we will obtain the maximum value of Δs_1 (Δs_2),

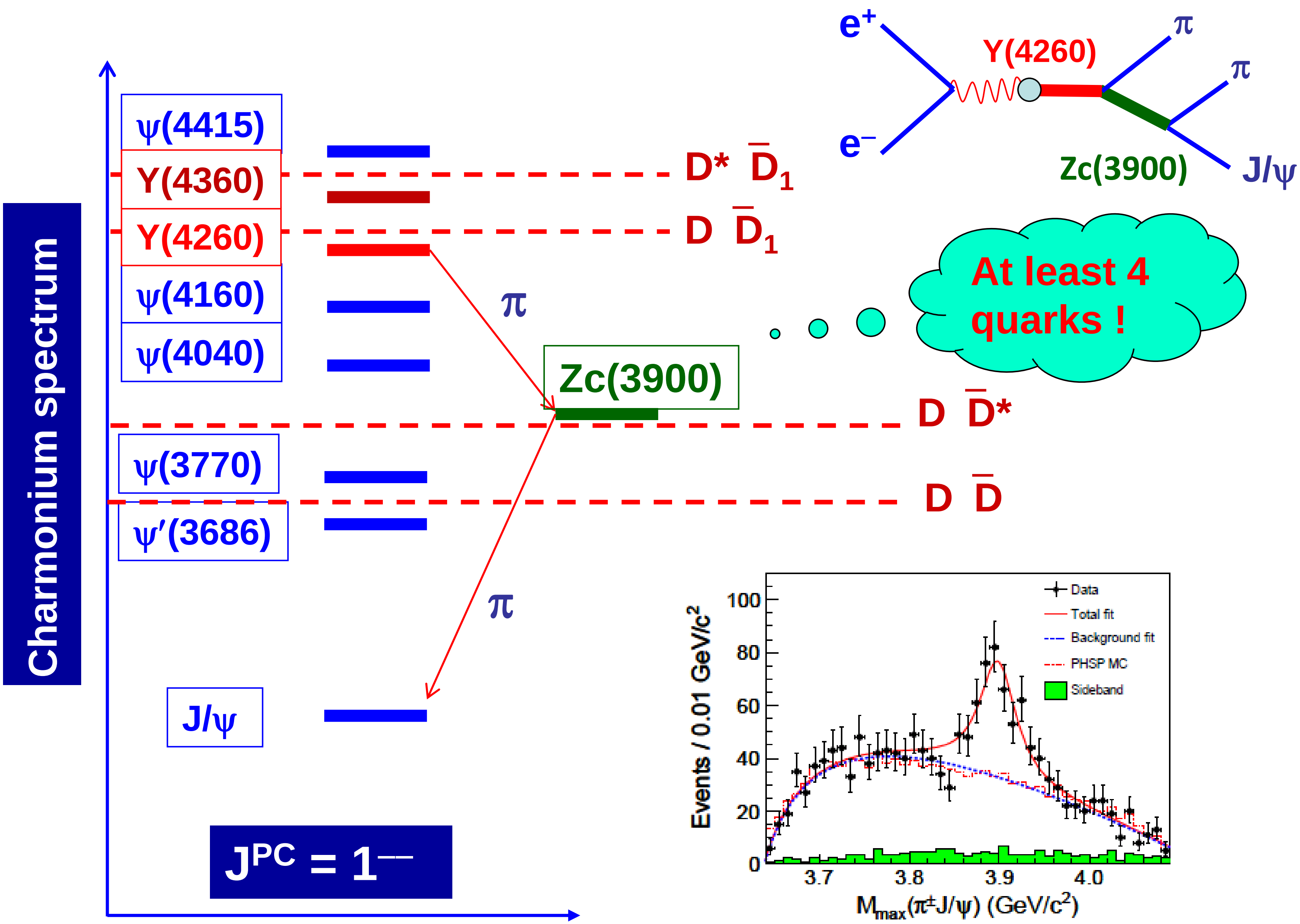
$$\Delta_{s_1}^{\max} = \sqrt{s_{1C}} - \sqrt{s_{1N}} \approx \frac{m_3}{2m_1(m_2+m_3)}[(m_2-m_1)^2 - s_3],$$
$$\Delta_{s_2}^{\max} = \sqrt{s_{2C}} - \sqrt{s_{2N}} \approx \frac{m_3}{2m_2(m_1+m_3)}[(m_2-m_1)^2 - s_3].$$

Larger values of Δ_s^{max} means more significant effects from the ATS mechanism!

Physical cases for recognizing the ATS

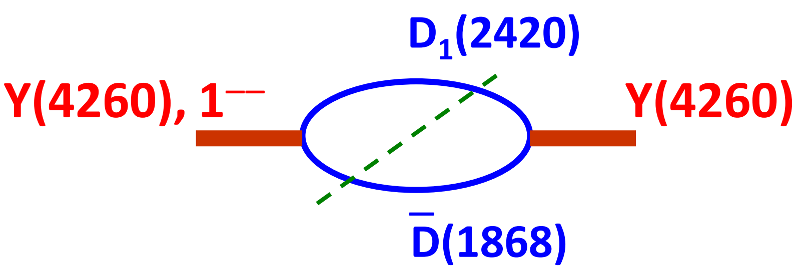
(I) S-wave open flavor threshold in vector channel

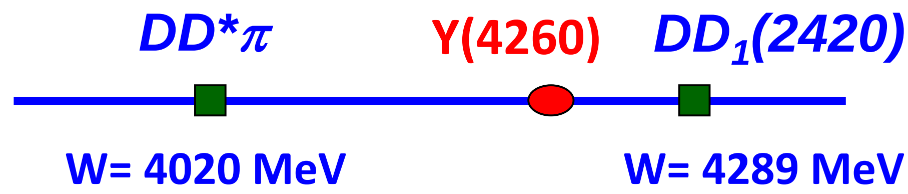
- **Zc(3900) production in Y(4260) decays**

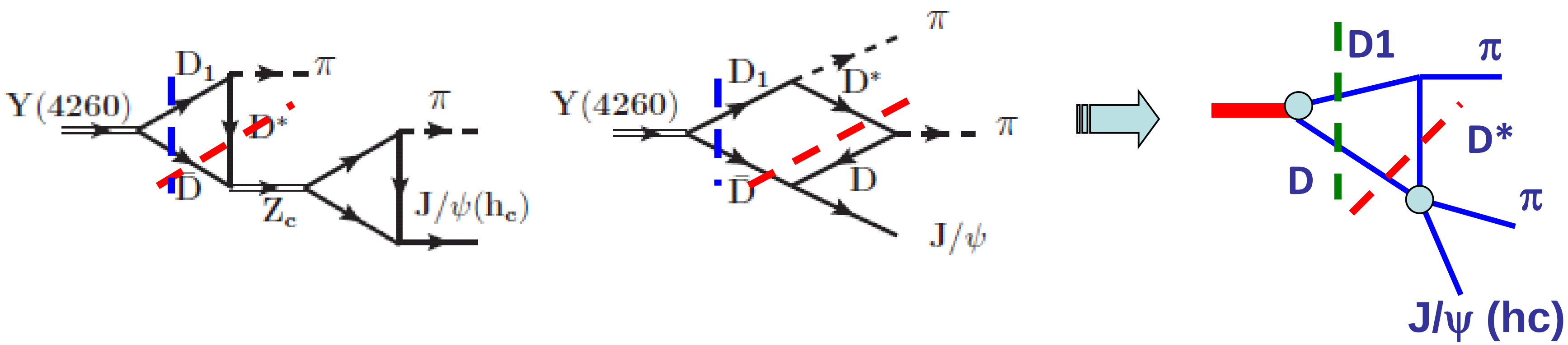


Y(4260) could be a hadronic molecule made of $DD_1(2420)$

"threshold state"



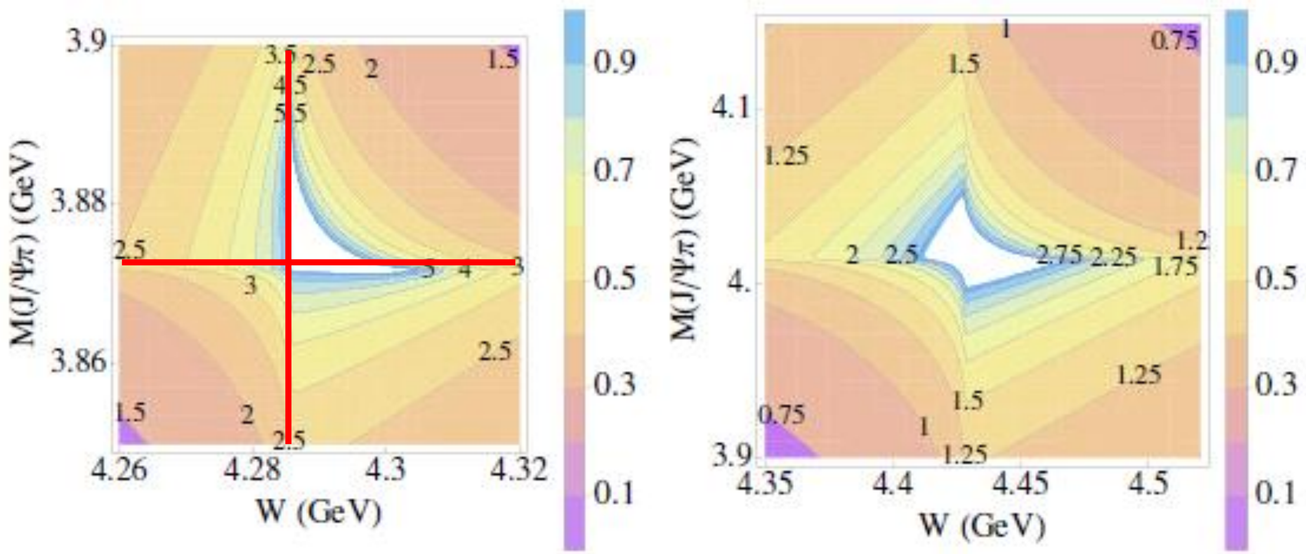




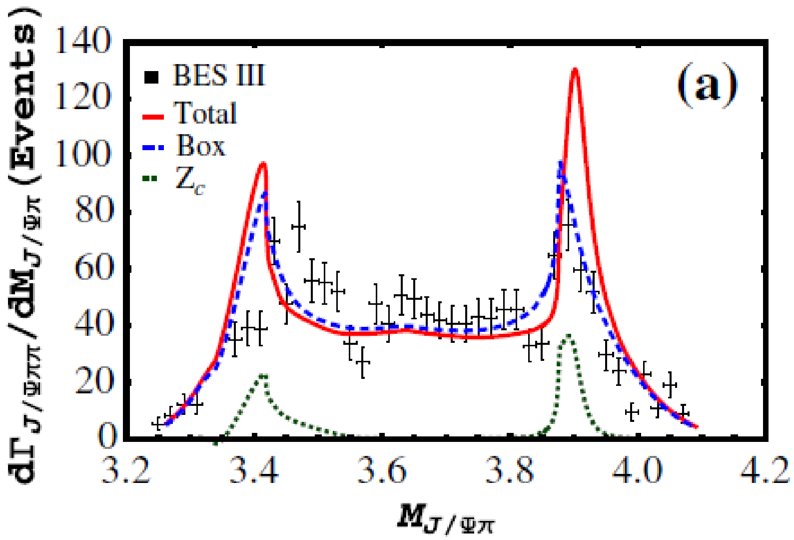
- Zc(3900) can be dynamically generated.
- The peak can also obtain contributions from the ATS mechanism.
- Test of Schmid theorem?

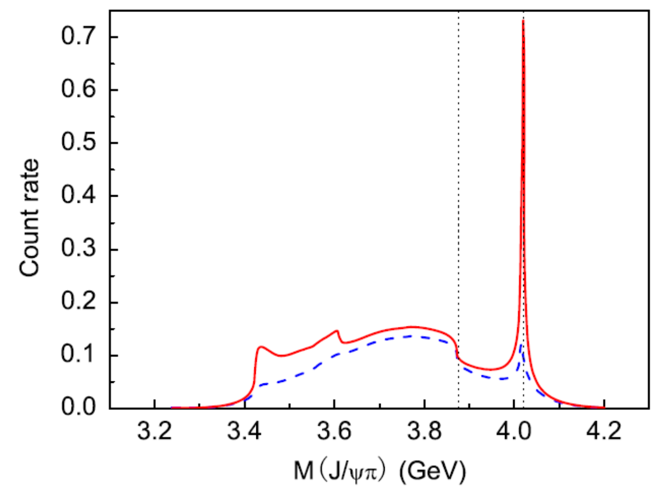
Q. Wang, C. Hanhart, Q.Z., PRL111, 132003 (2013); PLB(2013)
W. Qin, S.R. Xue, Q.Z., arXiv:1605.02407[hep-ph]

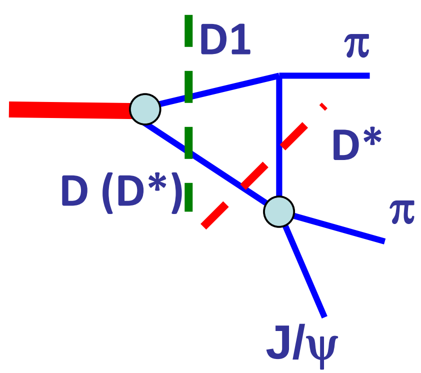
Singularity kinematics in $e^+e^- \to Y(4260)$ / $Y(4360) \to J/\psi\pi\pi$



Q. Wang, C. Hanhart, Q. Zhao, PLB2013; arXiv: 1305.1997[hep-ph];
Liu, Oka, and Q. Zhao, PLB2016; arXiv: 1507.01674[hep-ph]

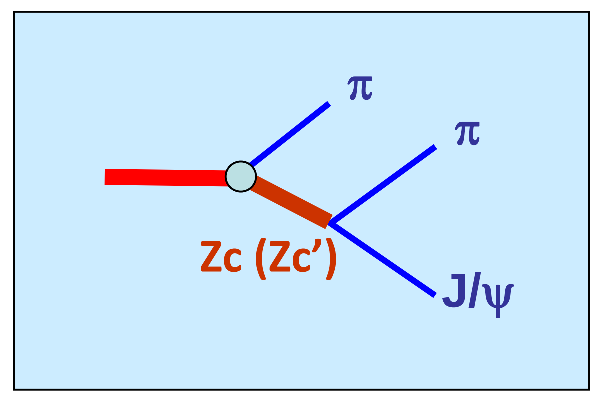






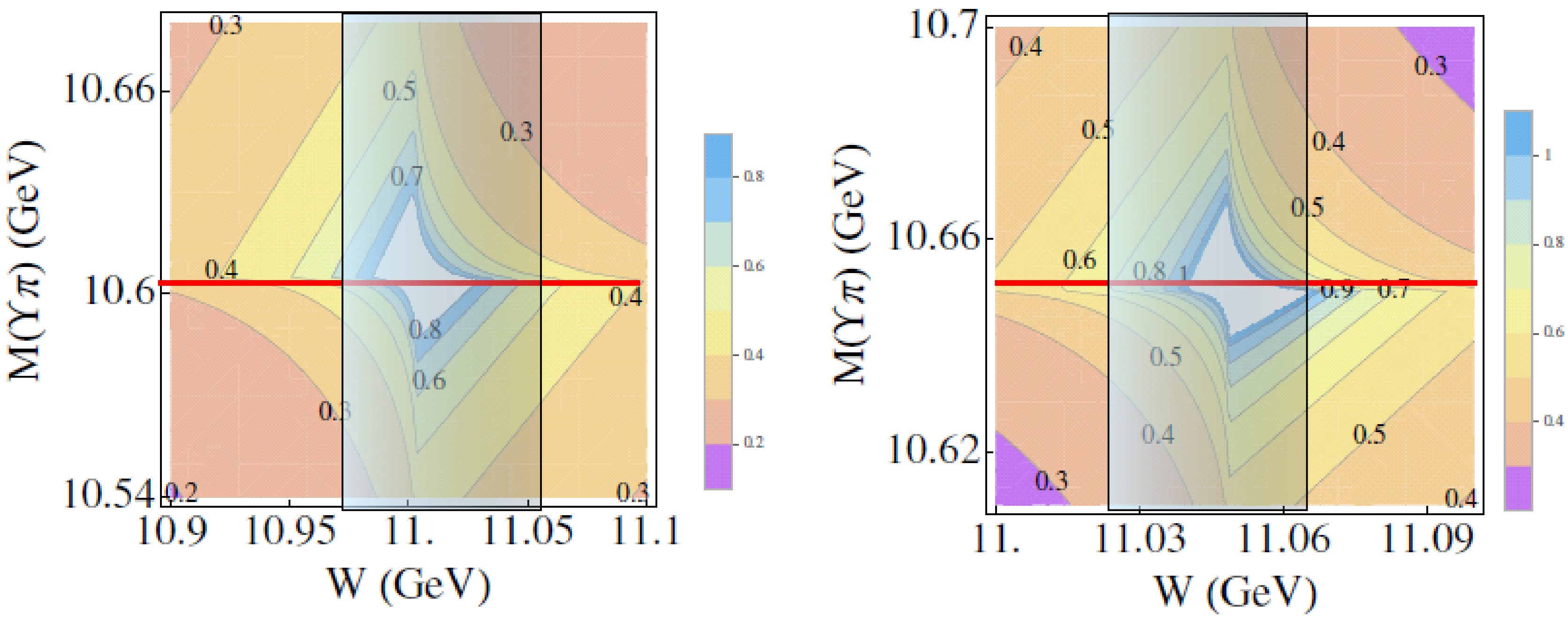
$\Gamma(D_1(2420)) = 27$ MeV

$\Gamma(D^{*0}) = 190$ keV



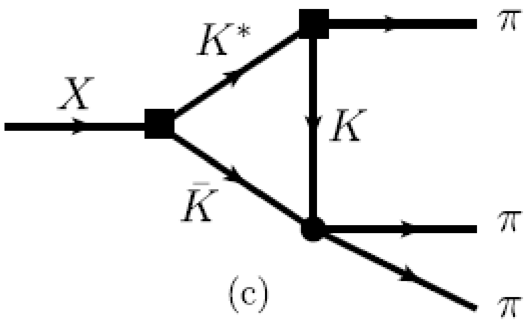
A pole structure can still be present!

Singularity kinematics in $e^+e^- \rightarrow \Upsilon(nS)\,\pi\pi$



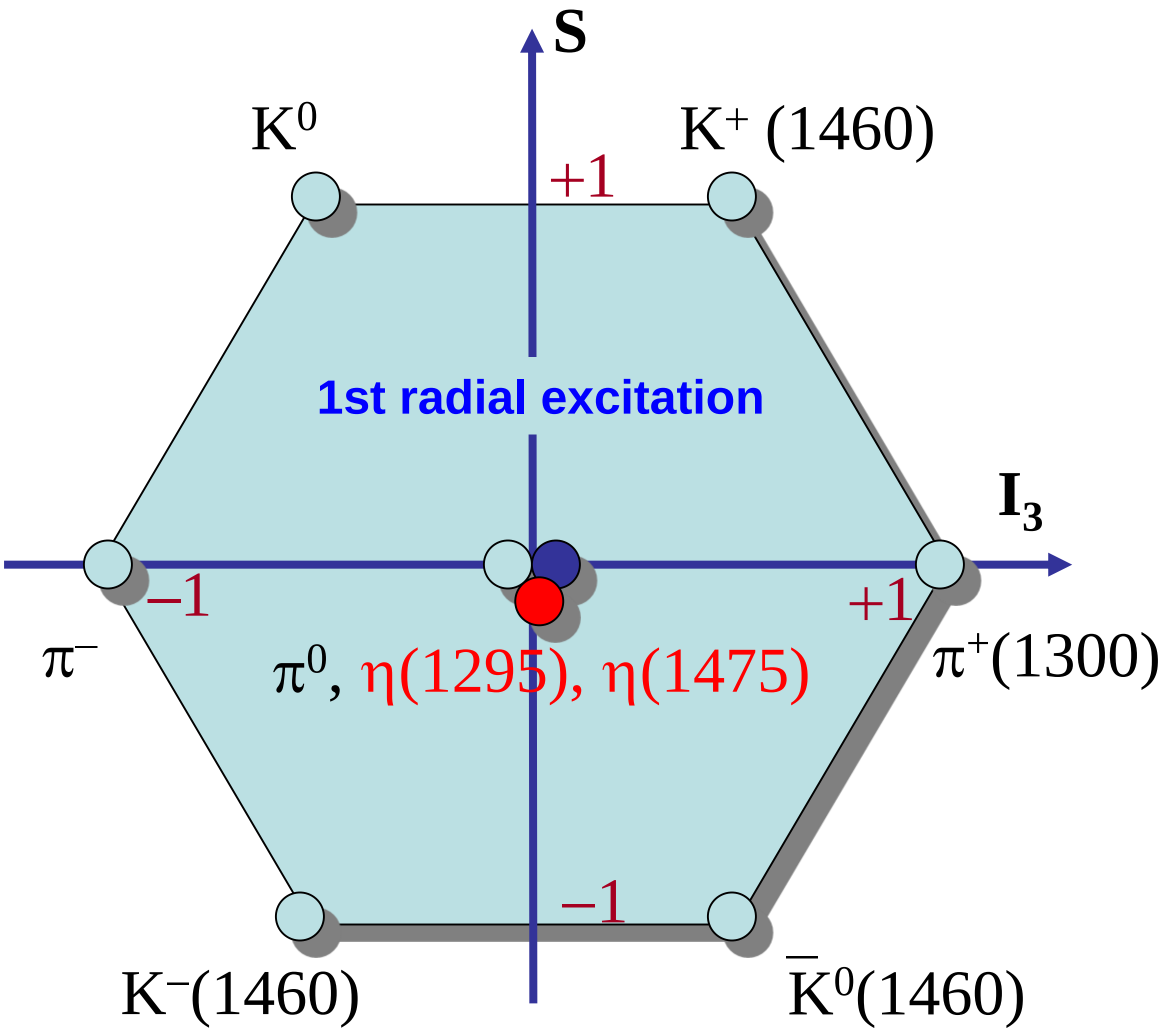
•Two singularity regions by the BB* and B*B* thresholds can appear in the same c.m. energy in the Υ(6S) decays. Two peaks are expected!

Q. Wang, C. Hanhart, Q. Zhao, PLB2013; arXiv: 1305.1997[hep-ph]



(II) The η(1405)/η(1475) puzzle, and $f_1(1420)/a_1(1420)$ problem

The nonet structure repeats itself in the radial excitations in the $\bar{q}q$ meson scenario.



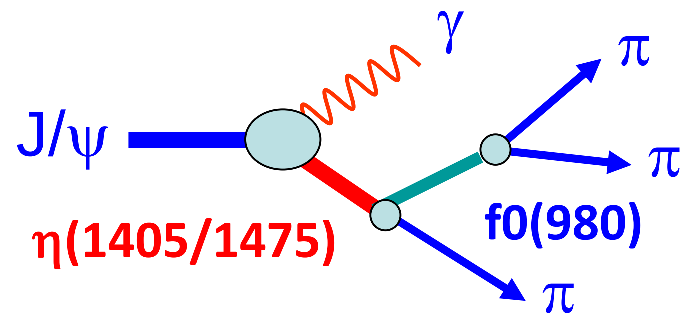
- The abundance of 0^{-+} (I=0) states implies a glueball candidate?

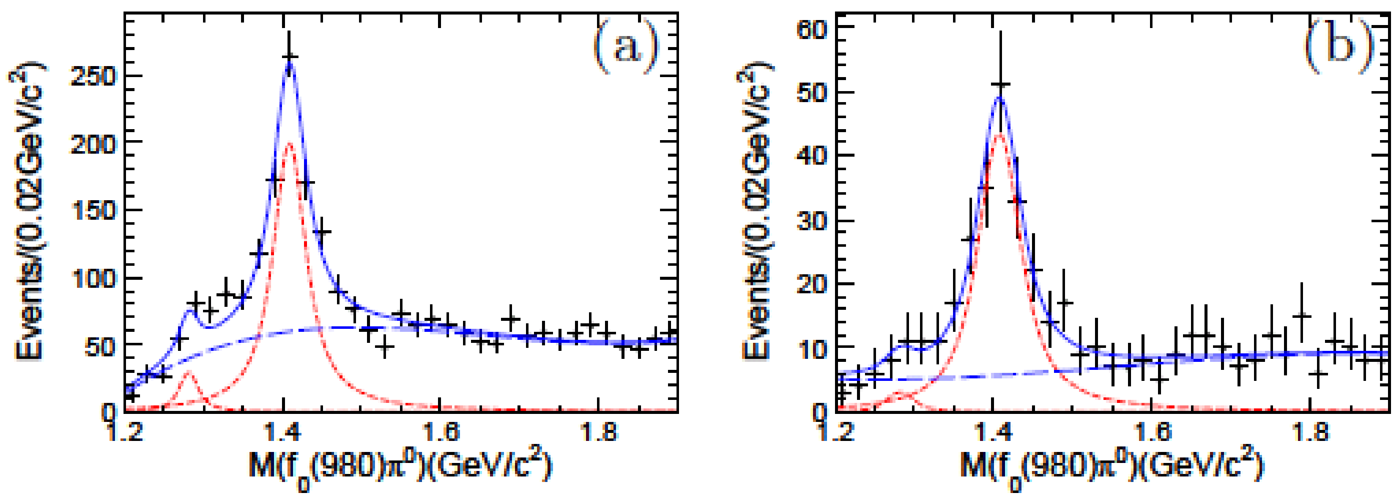
Positive: Flux tube model favors $M_G \cong 1.4$ GeV

Caveat: LQCD (quenched) favors $M_G \cong 2.4$ GeV

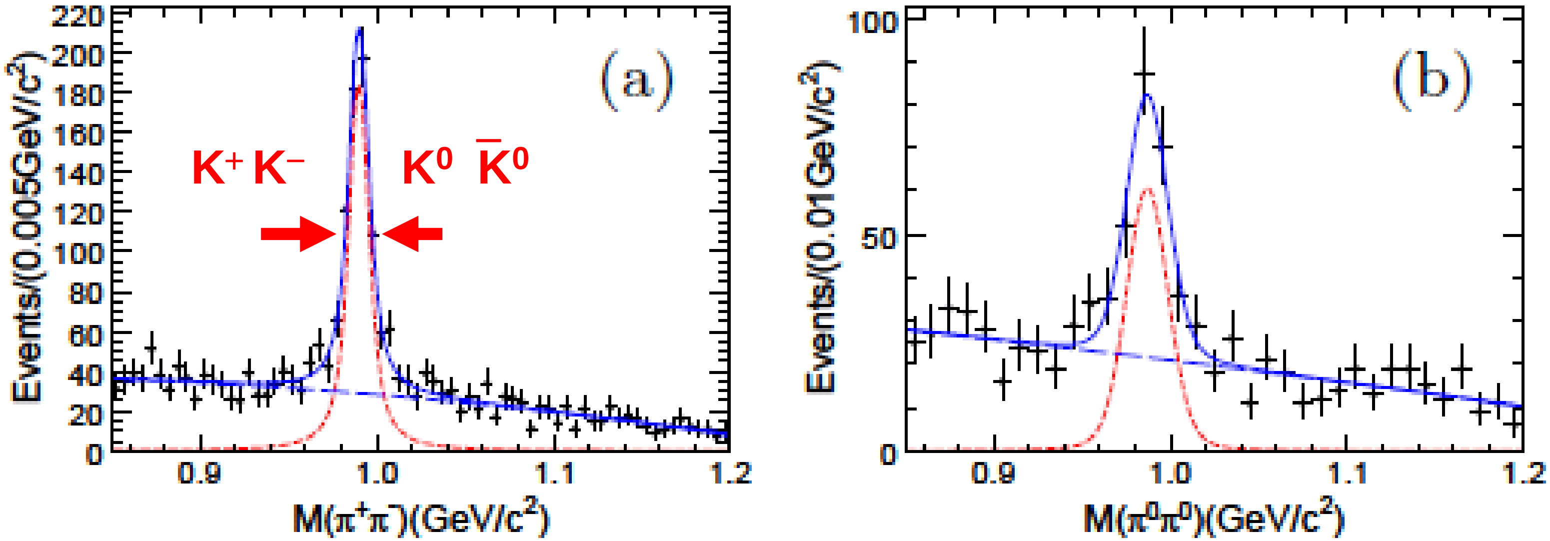
More problems arising from 3 η scenario!

Isospin-violating decay of J/ψ → γπππ





BES-III Collaboration, Phys. Rev. Lett. 108, 182001 (2012)
See also plenary talk by S.S. Fang



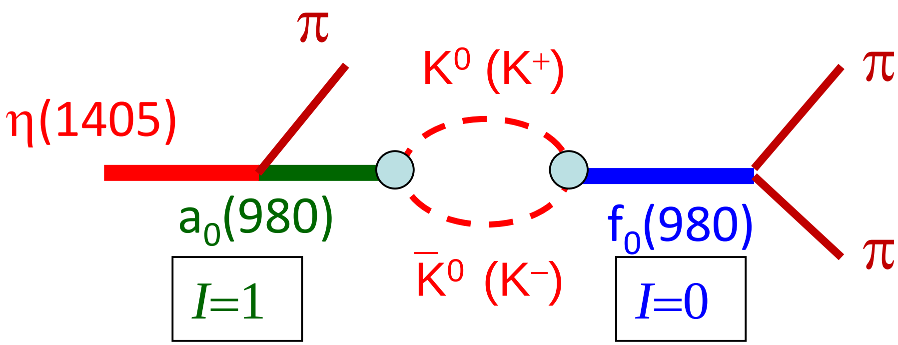
- f_0(980) is extremely narrow: $\Gamma \cong$ 10 MeV !

PDG: $\Gamma \cong$ 40~100 MeV.

- Anomalously large isospin violation!

$$\frac{Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\eta(1405) \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} \cong (17.9 \pm 4.2)\%$$

"$a_0(980)$-$f_0(980)$ mixing" gives only 1% isospin violation effects !

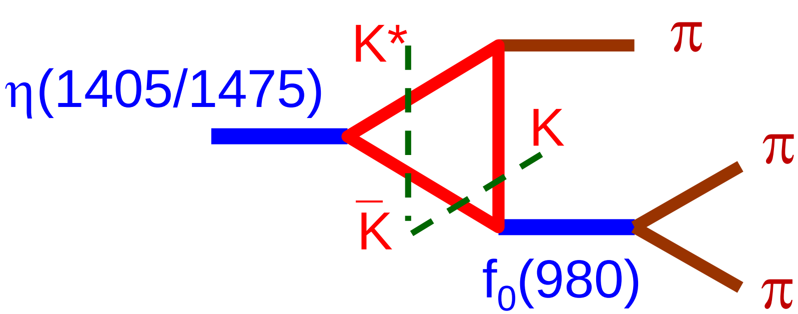


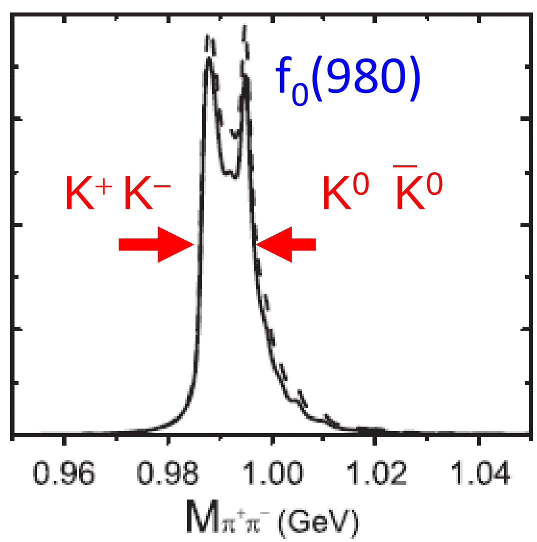
$$g(a_0K^+K^-)\ g(f_0K^+K^-)$$
$$= -g(a_0K^0\ \bar{K}^0)\ g(f_0K^0\ \bar{K}^0)$$

$$M(K^0)-M(K^{\pm}) = m_d-m_u$$

"Triangle singularity"

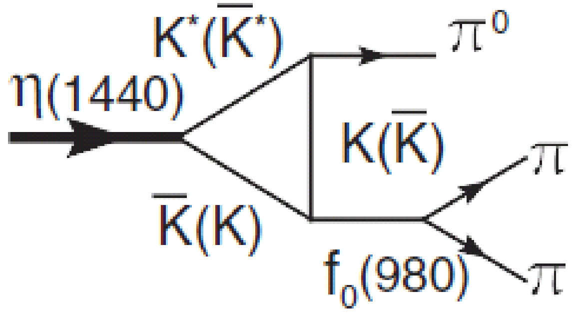
Internal $\bar{K}K^*(K)$ approach the on-shell condition simultaneously!



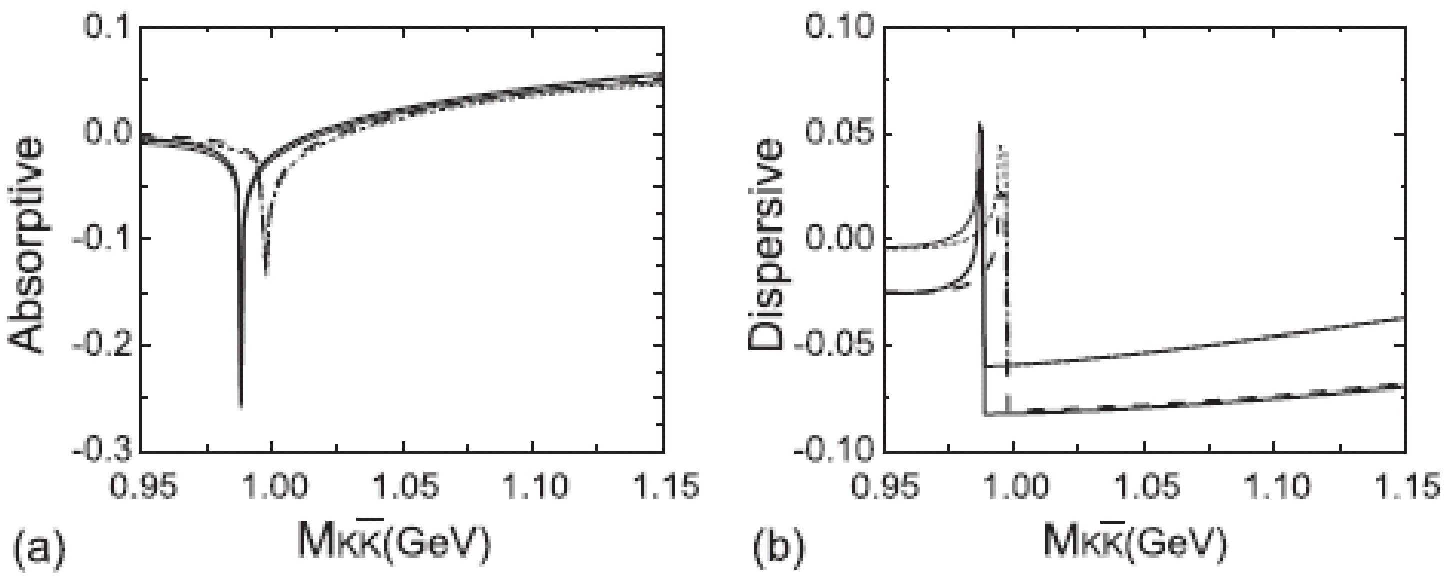


A novel isospin breaking mechanism!

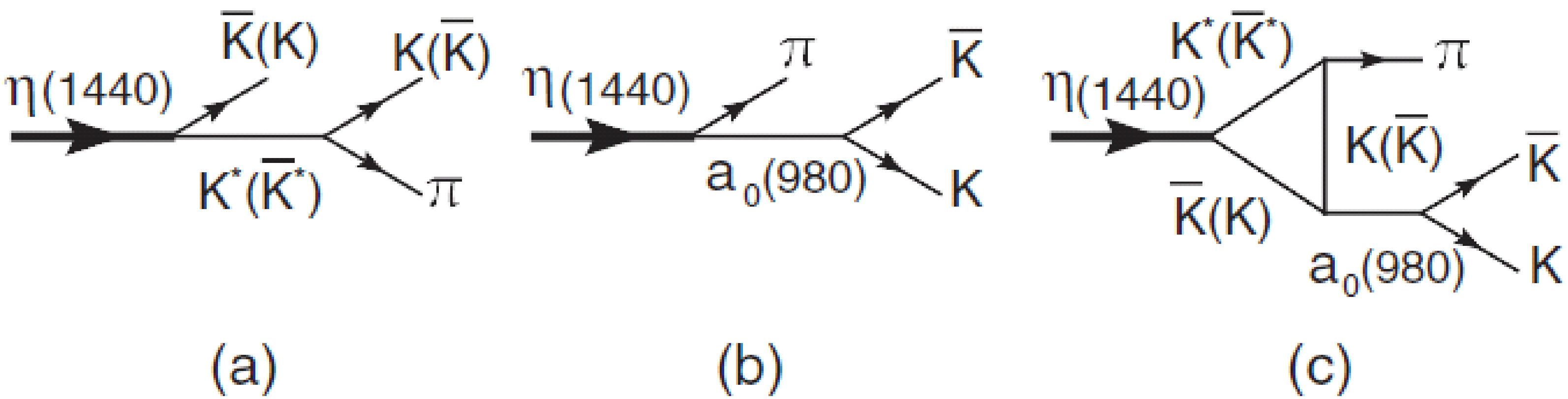
Triangle loop amplitudes:



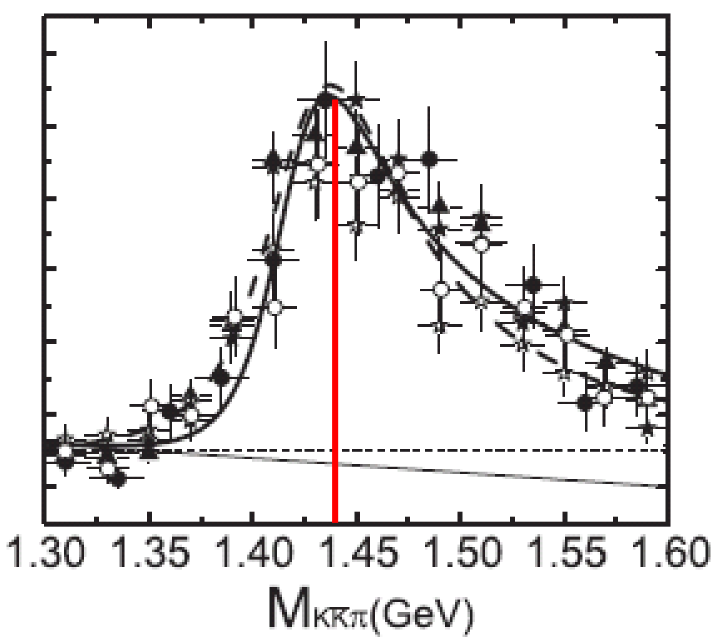
Absorptive amplitudes **Dispersive amplitudes**



$\eta(1440) \rightarrow K\ \bar{K}\ \pi$ decay mechanism:



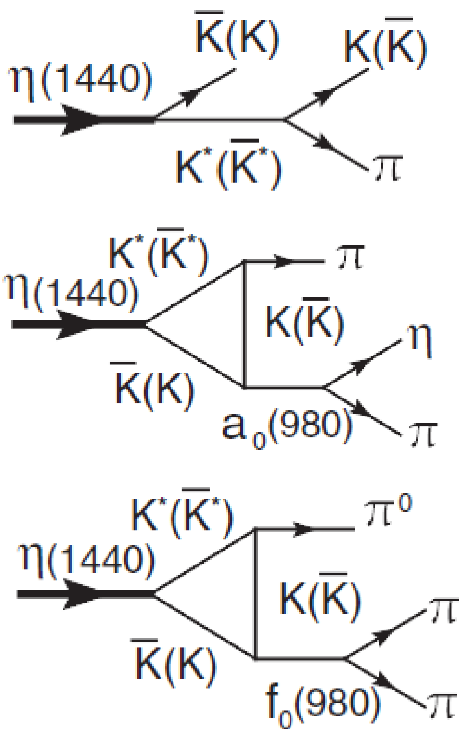
Data from Mark III, BES-I, and DM2

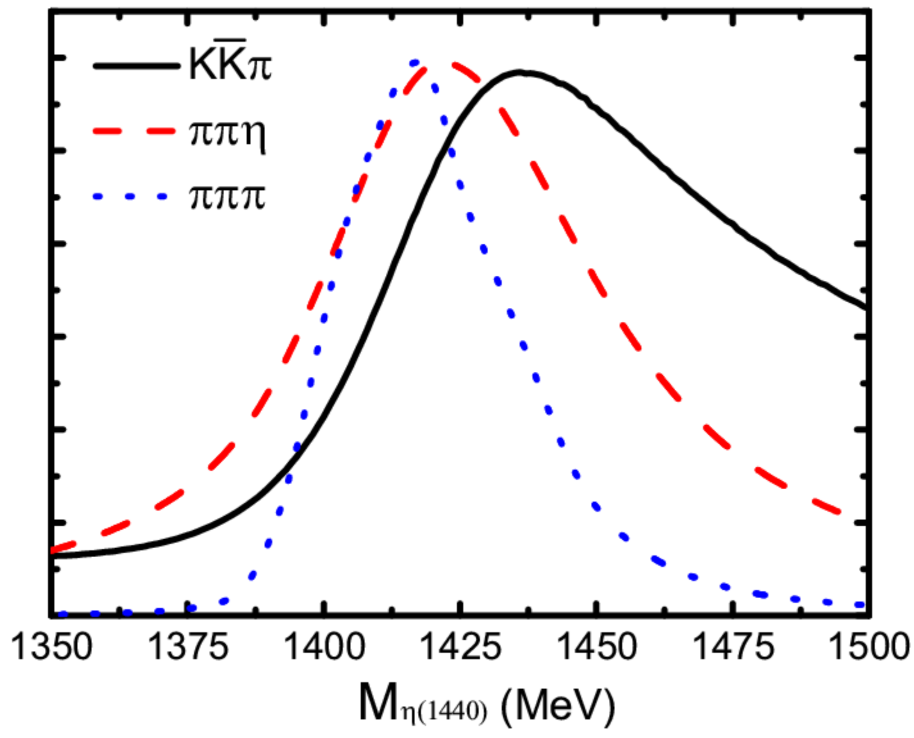


$$\frac{d\Gamma_{J/\psi\to\gamma\eta(1440)\to\gamma ABC}}{d\sqrt{s_0}} = \frac{2s_0}{\pi}\frac{\Gamma_{J/\psi\to\gamma\eta(1440)}(s_0)\Gamma_{\eta(1440)\to ABC}(s_0)}{(s_0-m^2_{\eta(1440)})^2+\Gamma^2_{\eta(1440)}m^2_{\eta(1440)}},$$

J.J. Wu, X.H. Liu, Q.Z. and B.S. Zou, PRL(2012)

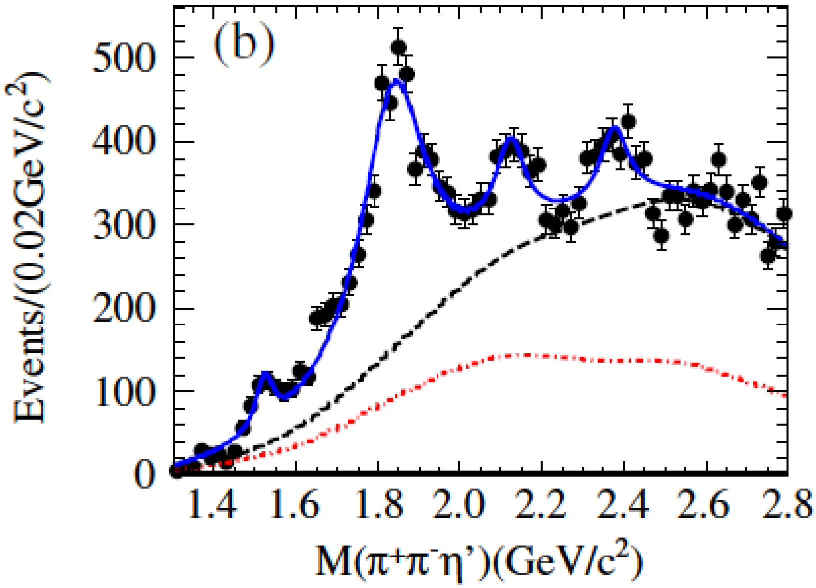
- So far, BESIII do not see two peak signals in any exclusive process.
- The same state has different peak positions and lineshapes in different decay channels.
- η(1405) and η(1475) are likely to be the same state.





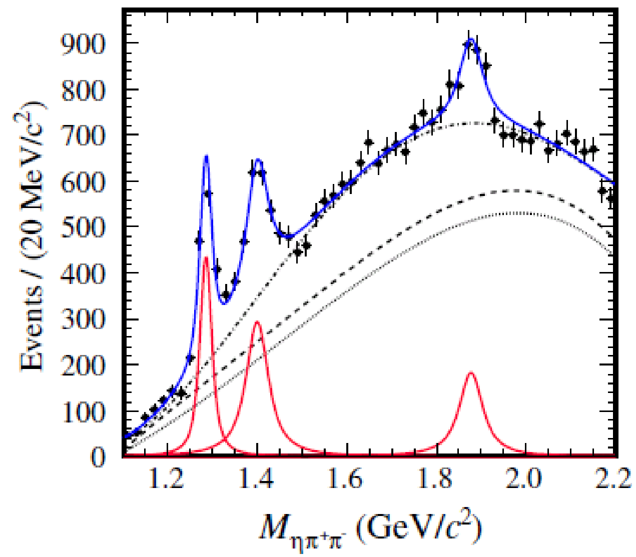
Where to look for pseudoscalar glueball candidate?

$J/\psi \to \gamma\pi^+\pi^-\eta'$



PRL **106,** 072002 (2011)

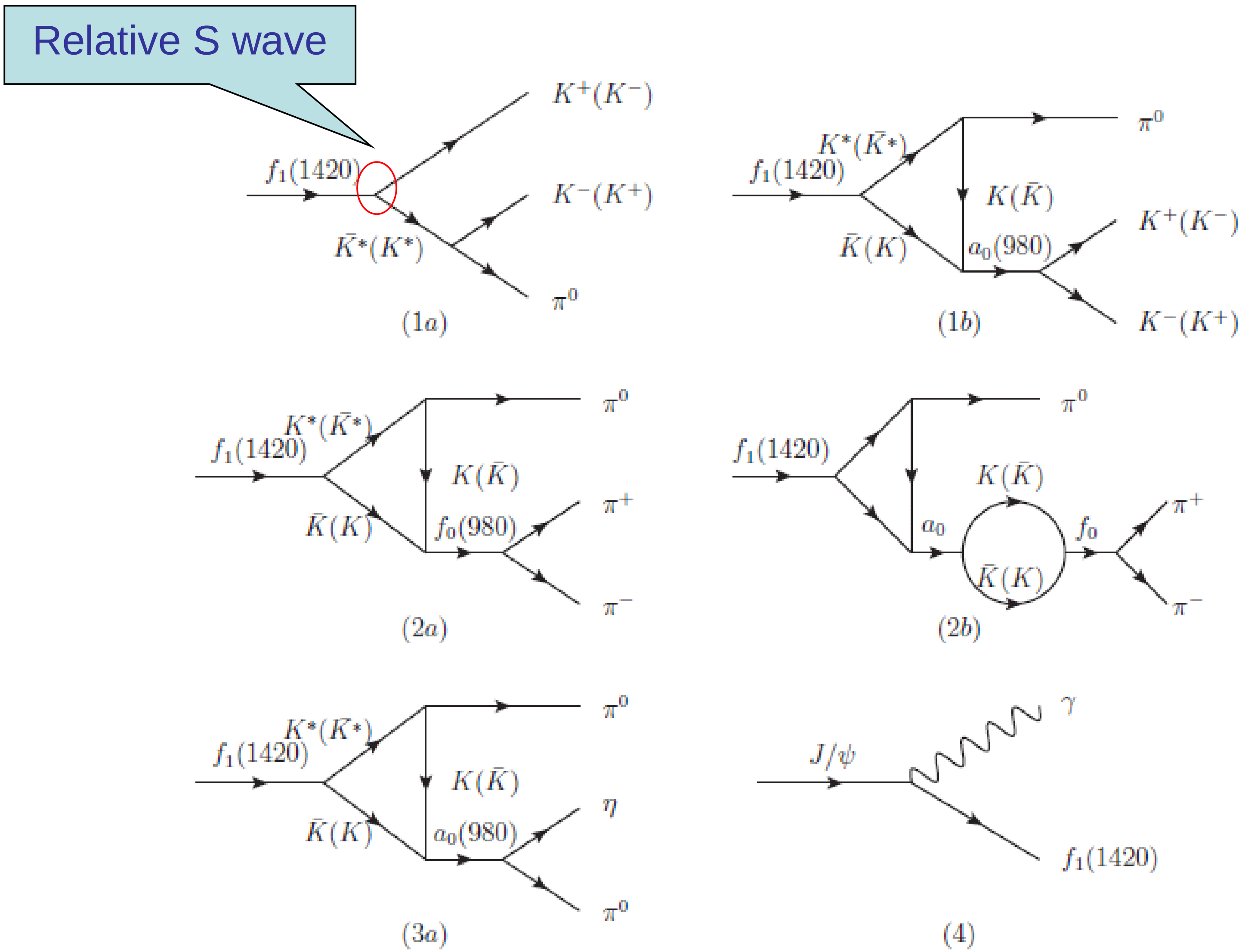
$J/\psi \to \omega\eta\pi^+\pi^-$



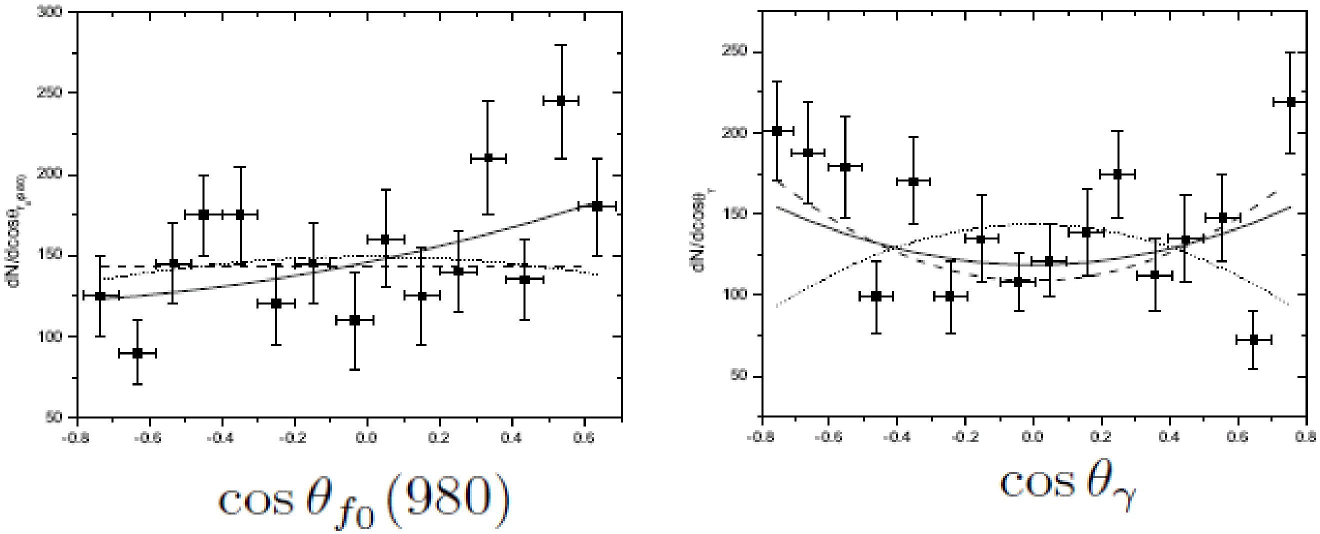
PRL **107,** 182001 (2011)

Pure gauge LQCD: $M_G \cong 2.4$ GeV

The puzzle of $f_1(1420)$ and $a_1(1420)$



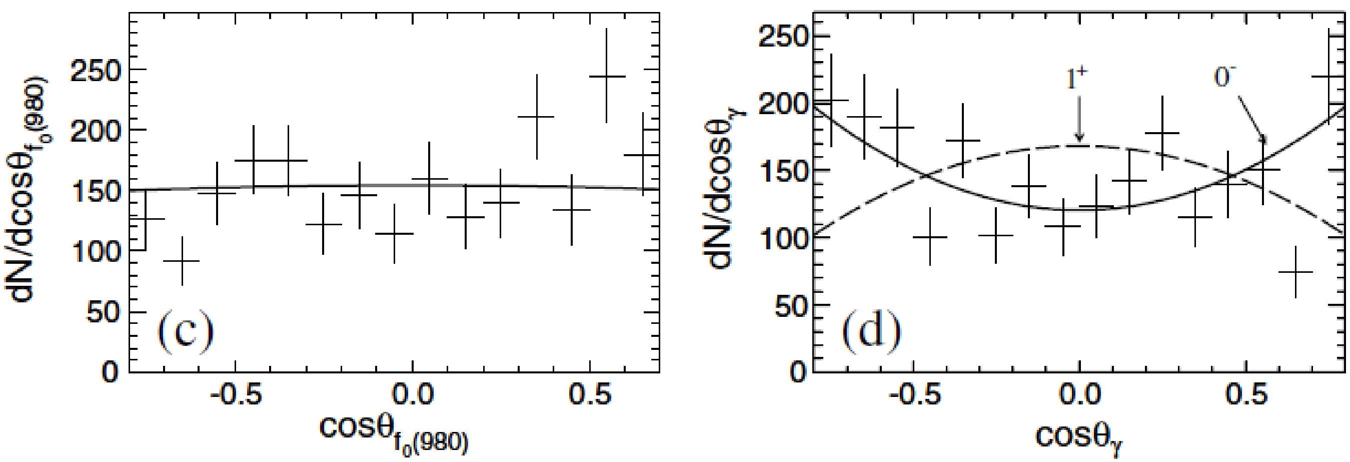
Partial wave analysis of $J/\psi \rightarrow \gamma\ \eta(1405)/f_1(1420) \rightarrow \gamma\ \pi\pi\pi$



Dashed: eta(1440)
Dotted: f1(1420)
Solid: eta(1440) + f1

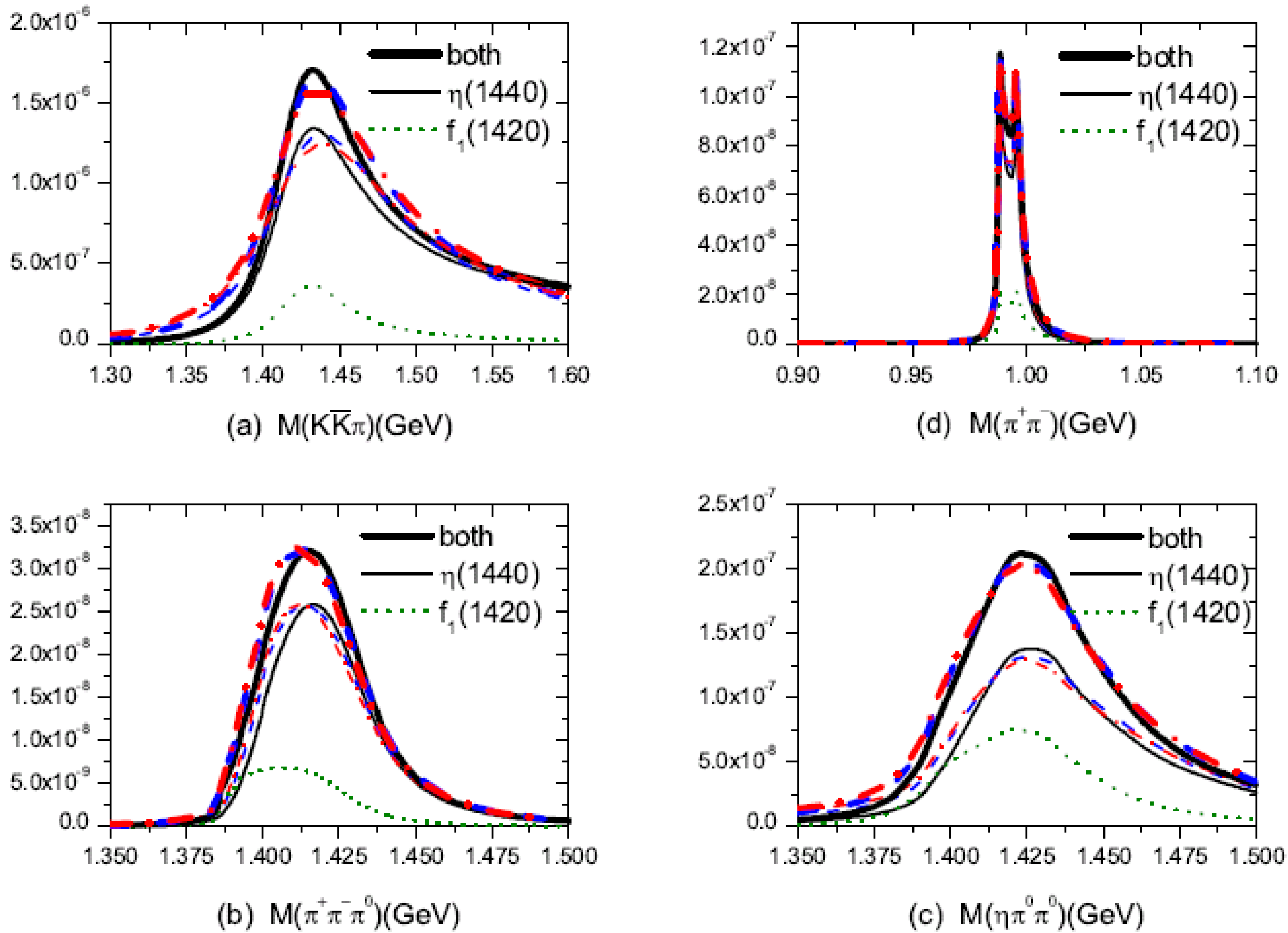
$$\chi^2/d.o.f = 38.3/14; \quad b_\gamma = 118.5 \pm 8.8,\ c = 0.538 \pm 0.312$$

$$\chi^2/d.o.f = 19.8/12; \quad b_{f_0} = 145.7 \pm 10.7,\ c_1 = 0.314 \pm 0.128,\ c_2 = 0.141 \pm 0.317$$

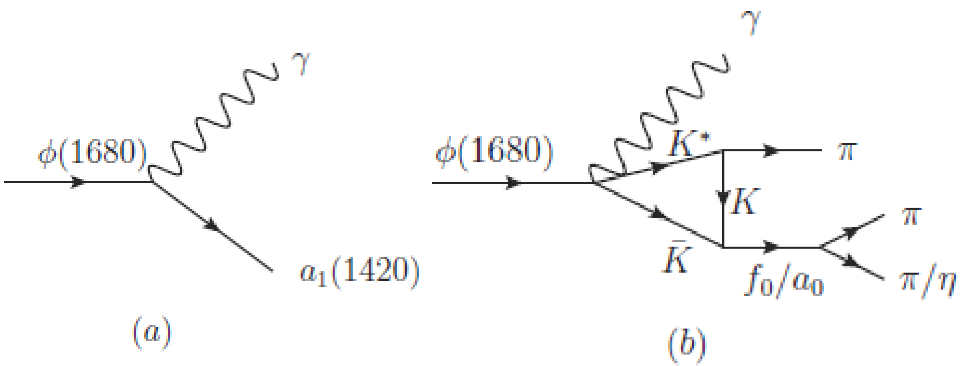


BESIII results:

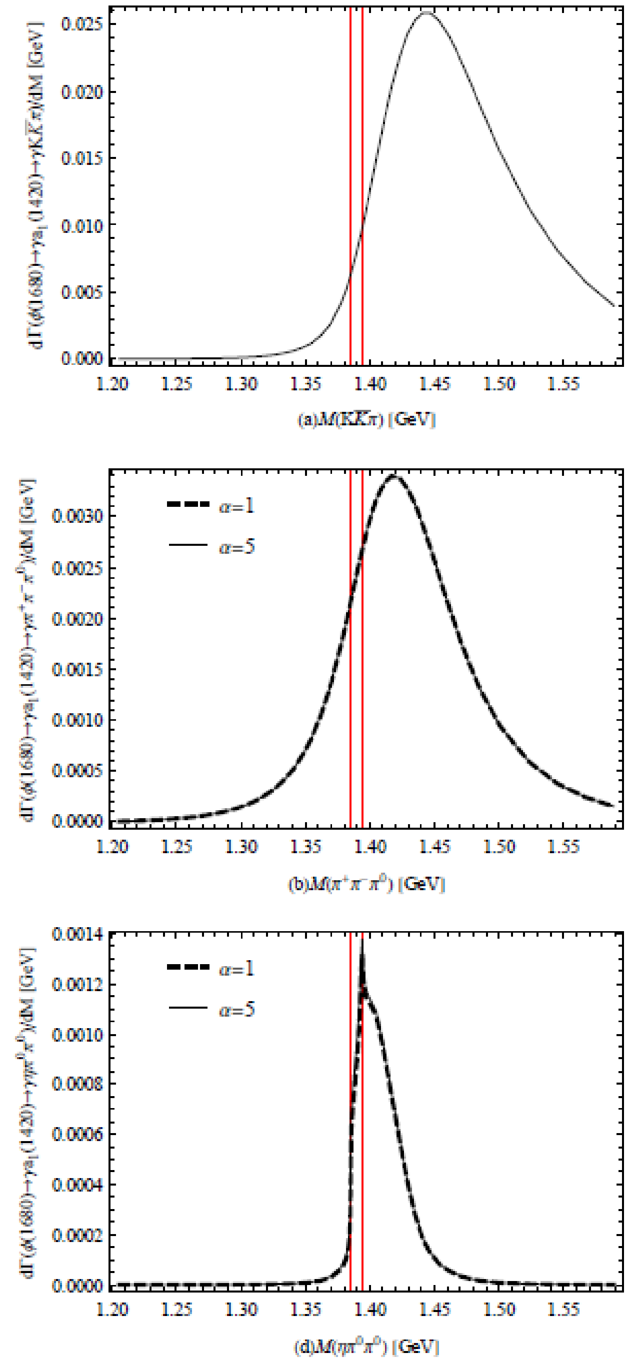
immediate states	$\chi^2/d.o.f$ for $\cos\theta_\gamma$	$\chi^2/d.o.f$ for $\cos\theta_{f_0}$
$\eta(1440)$	40.2/15	26.8/14
$f_1(1420)$	59.0/15	26.4/13
$\eta(1440)$ and $f_1(1420)$	38.3/14	19.8/12



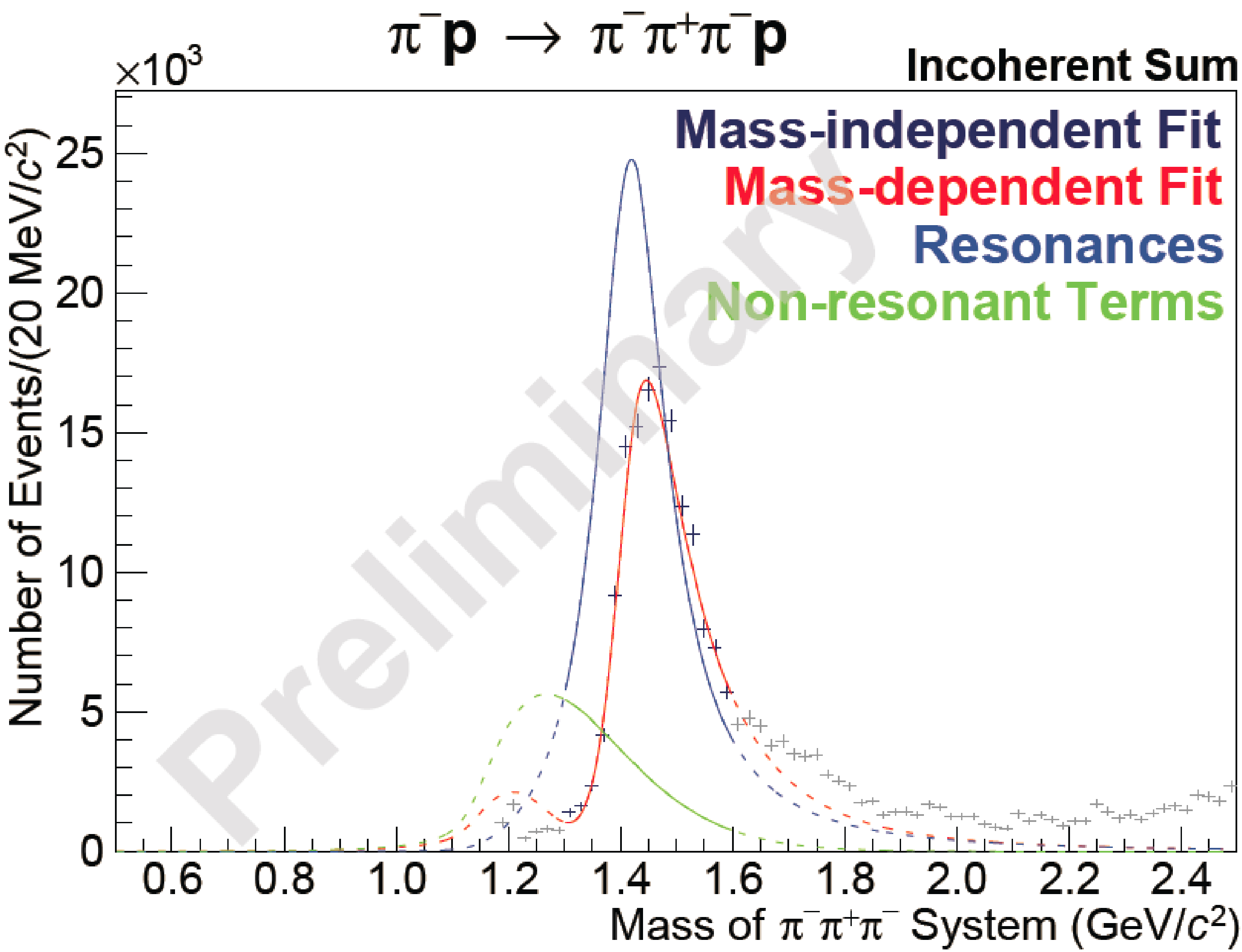
Implication of existence of $a_1(1420)$ in isospin 1 channel



Due to the "triangle singularity", the same "state" produces different resonance-like lineshapes in different channels!

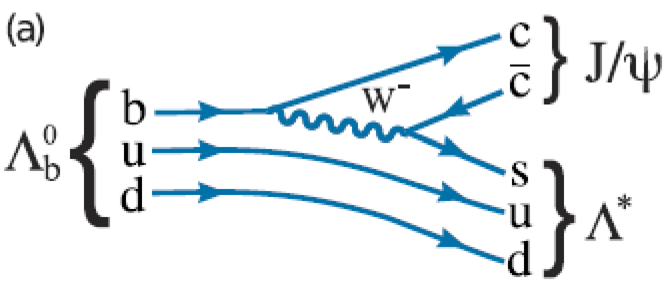


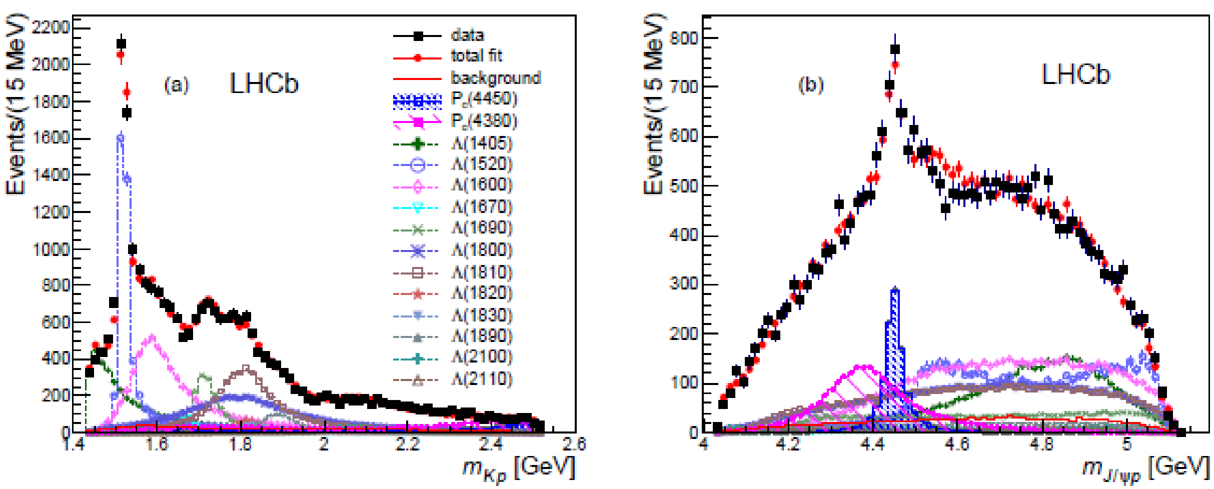
Observation of a new state $a_1(1420)$ at COMPASS



(III) The heavy pentaquark Pc(4380) and Pc(4450) production

Exp. evidence for heavy pentaquarks with hidden charm





M[Pc$^+$(4380)] = (4380±8±29) MeV, Γ= (205±18±86) MeV

M[Pc$^+$(4450)] = (4449.8±1.7±2.5) MeV, Γ=(39±5±19) MeV

J^P = (3/2$^-$, 5/2$^+$) or (3/2$^+$, 5/2$^-$)

Immediate theoretical studies:

1) Molecular states:

R. Chen, X. Liu, X.-Q. Li, S.-L. Zhu, PRL(2015); arXiv:1507.03704[hep-ph]

L. Roca, J. Nieves and E. Oset, arXiv:1507.04249 [hep-ph].

A. Feijoo, V. K. Magas, A. Ramos and E. Oset, arXiv:1507.04640 [hep-ph]

J. He, arXiv:1507.05200 [hep-ph]

U.-G. Meissner, J.A. Oller, arXiv:1507.07478v1 [hep-ph]

2) Multiquark state as an overall color singlet

L. Maiani, A.D. Polosa, and V. Riquer, arXiv:1507.04980 [hep-ph]

R.L. Lebed, arXiv:1507.05867 [hep-ph]

V.V. Anisovich et al., arXiv:1507.07652[hep-ph]

G.-N. Li, X.-G. He, M. He, arXiv:1507.08252 [hep-ph]

3) Soliton model

N.N. Scoccolaa, D.O. Riska, Mannque Rho, arXiv:1508.01172 [hep-ph]

4) Sum rules study

H. X. Chen, W. Chen, X. Liu, T.G. Steele and S. L. Zhu, PRL(2015); arXiv:1507.03717

Z.-G. Wang, arXiv:1508.01468.

Many more …

Some early studies:

J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. **105**, 232001 (2010) [arXiv:1007.0573 [nucl-th]].

J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C **84**, 015202 (2011) [arXiv:1011.2399 [nucl-th]].

J. J. Wu, T.-S. H. Lee and B. S. Zou, Phys. Rev. C **85**, 044002 (2012) [arXiv:1202.1036 [nucl-th]].

Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, Chin. Phys. C **36**, 6 (2012) [arXiv:1105.2901 [hep-ph]].

Alternative solutions? Or some further concerns?

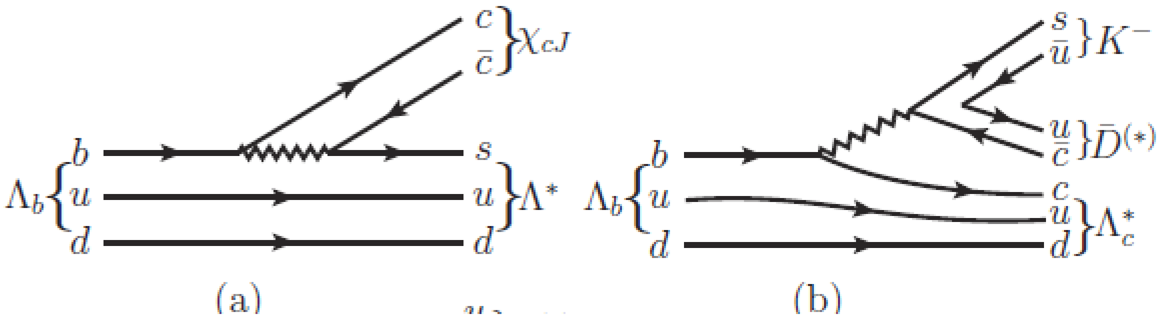
Threshold enhancement produced by anomalous triangle singularity:

F.-K. Guo, U.-G. Meissner, W. Wang, and Z. Yang, arXiv:1507.04950 [hep-ph]

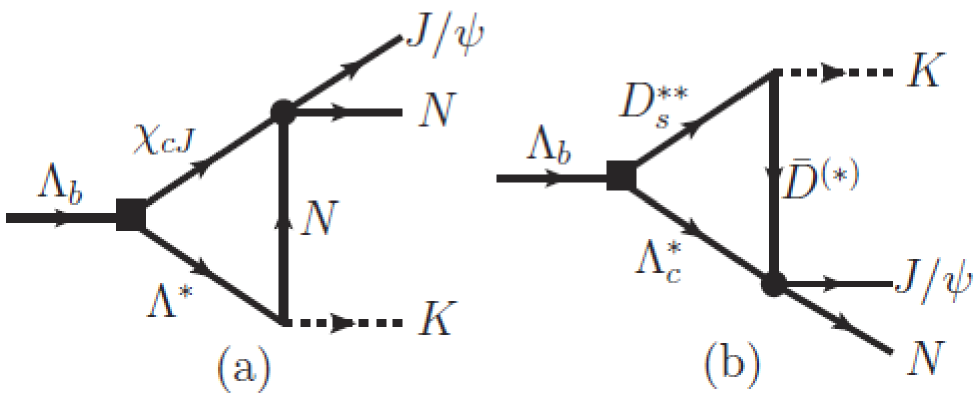
X.-H. Liu, Q. Wang, and Q. Zhao, arXiv:1507.05359 [hep-ph]

M. Mikhasenko, arXiv:1507.06552v1 [hep-ph]

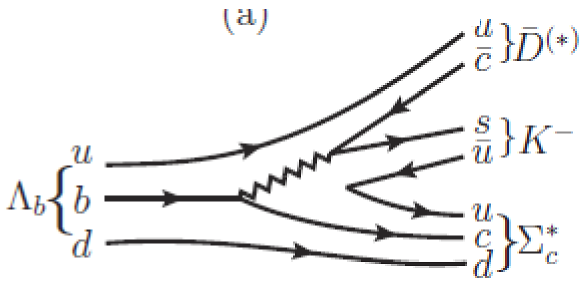
Production mechanism in Λ_b decay



Rescattering via triangle diagrams



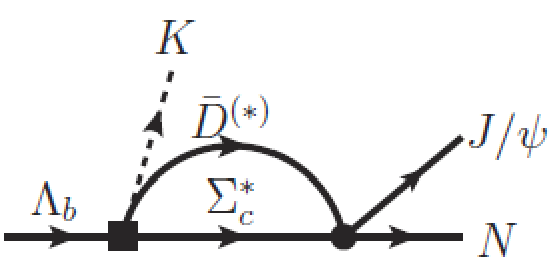
A new leading order mechanism



(c)

$$\langle Y_c \bar{K} \bar{D} | \hat{H}_w | \Lambda_b \rangle_{(c)}$$
$$= \frac{1}{2\sqrt{2}} \left[-\Sigma_c^{++} K^- D^- + \frac{1}{2} \Sigma_c^+ \bar{K}^0 D^- - \frac{1}{2} \Sigma_c^+ K^- \bar{D}^0 + \Sigma_c^0 \bar{K}^0 \bar{D}^0 + \frac{1}{2} \Lambda_c^+ K^- \bar{D}^0 - \frac{1}{2} \Lambda_c^+ \bar{K}^0 D^- \right]$$

Rescattering to generate a pole?



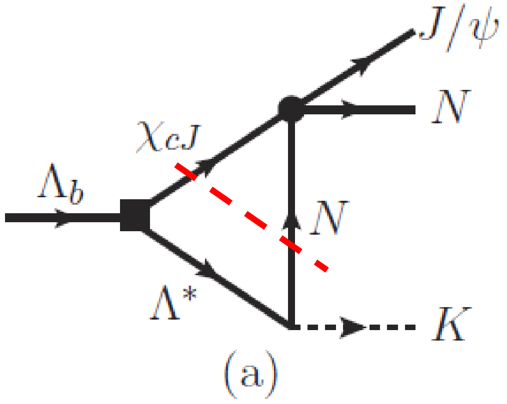
(c)

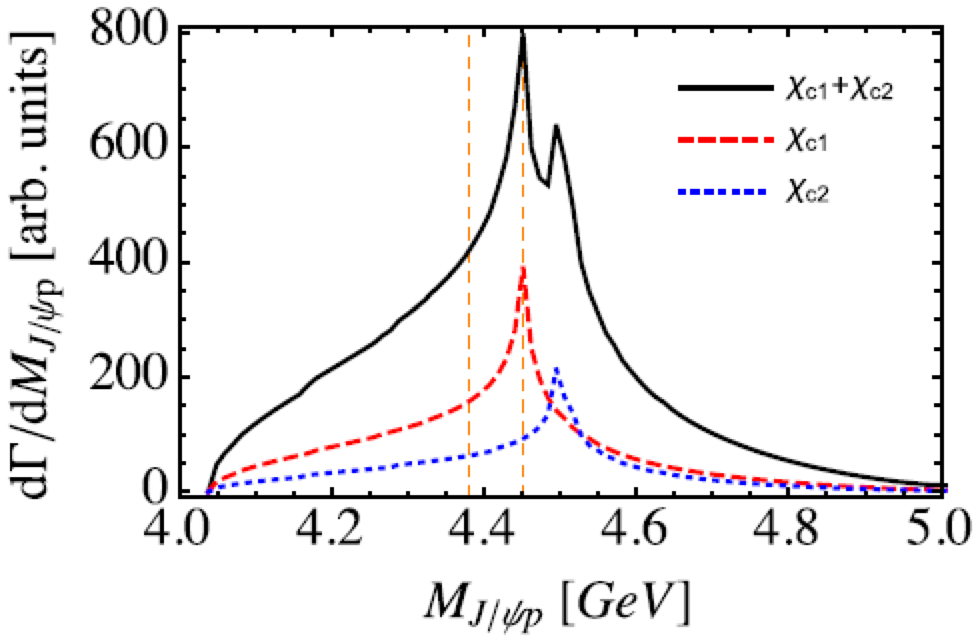
Favored by the molecular picture

X.-H. Liu, Q. Wang, and Q. Zhao, PLB(2016); arXiv:1507.05359 [hep-ph]

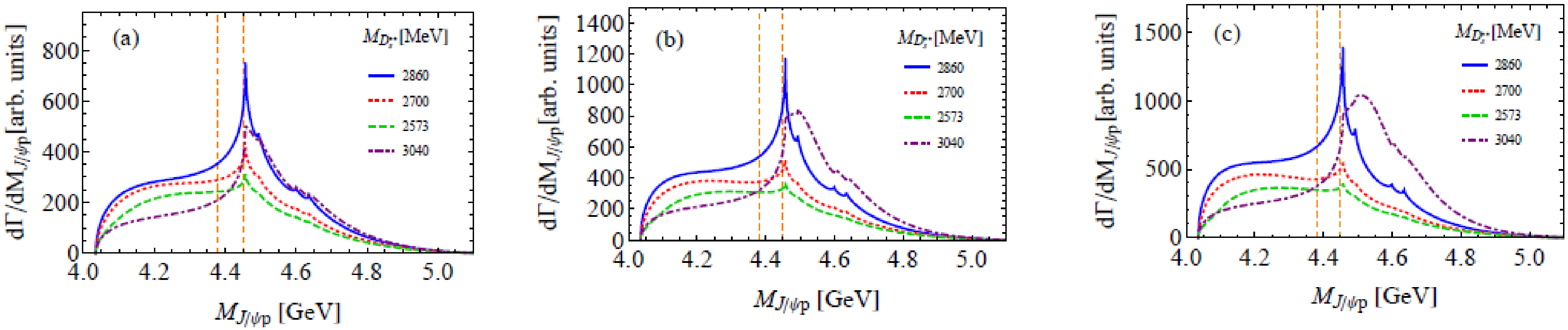
Thresholds for χ_{cJ} p

Threshold masses [MeV]	$\chi_{c0}(1P)\ 0^+$	$\chi_{c1}(1P)\ 1^+$	$\chi_{c2}(1P)\ 2^+$
$p\ 1/2^+$	4353	4449	4494

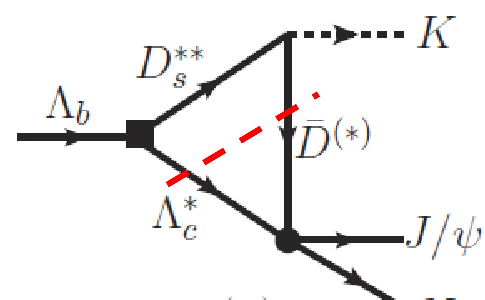




X.-H. Liu, Q. Wang, and Q. Zhao, arXiv:1507.05359 [hep-ph]



Threshold masses [MeV]	$\Lambda_c(2286)\ 1/2^+$	$\Lambda_c(2595)\ 1/2^-$	$\Lambda_c(2625)\ 3/2^-$	$\Lambda_c(2880)\ 5/2^+$
$\bar{D}_s(1968)\ 0^-$	4254	4563	4593	4848
$\bar{D}_s^*(2112)\ 1^-$	4398	4707	4737	4994
$\bar{D}_{s0}(2317)\ 0^+$	4585	4912	4942	5197
$\bar{D}_{s1}(2460)\ 1^+$	4728	5055	5085	5340
$\bar{D}_{s1}(2536)\ 1^+$	4822	5131	5161	5416
$\bar{D}_{s2}(2573)\ 2^+$	4859	5168	5198	5453
$\bar{D}_{s1}(2700)\ 1^-$	4986	5295	5325	5580
$\bar{D}_{sJ}(2860)\ ?^?$	5146	5455	5485	[5740]
$\bar{D}_{sJ}(3040)\ ?^?$	5331	[5636]	[5672]	[5926]



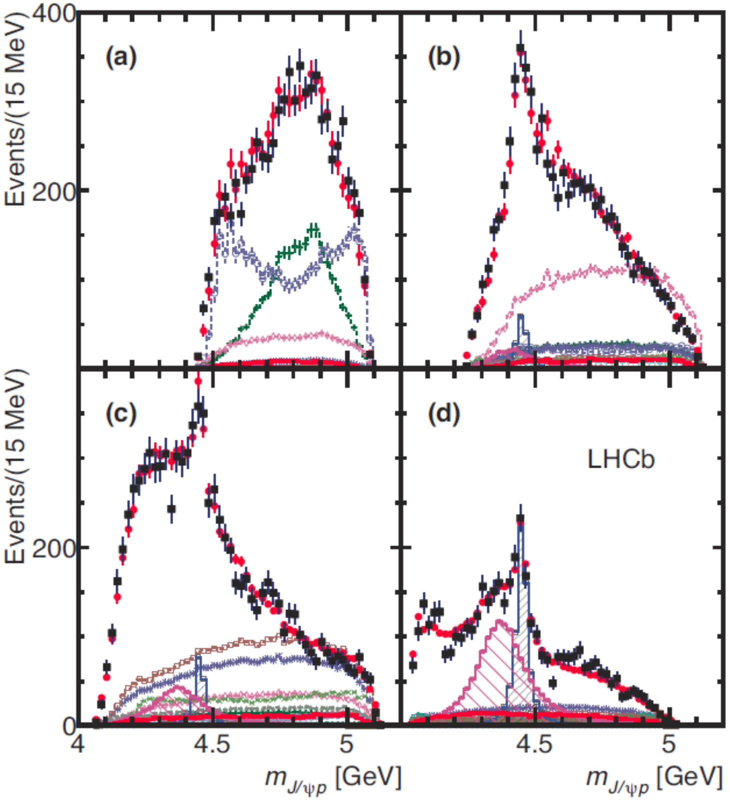
(b)

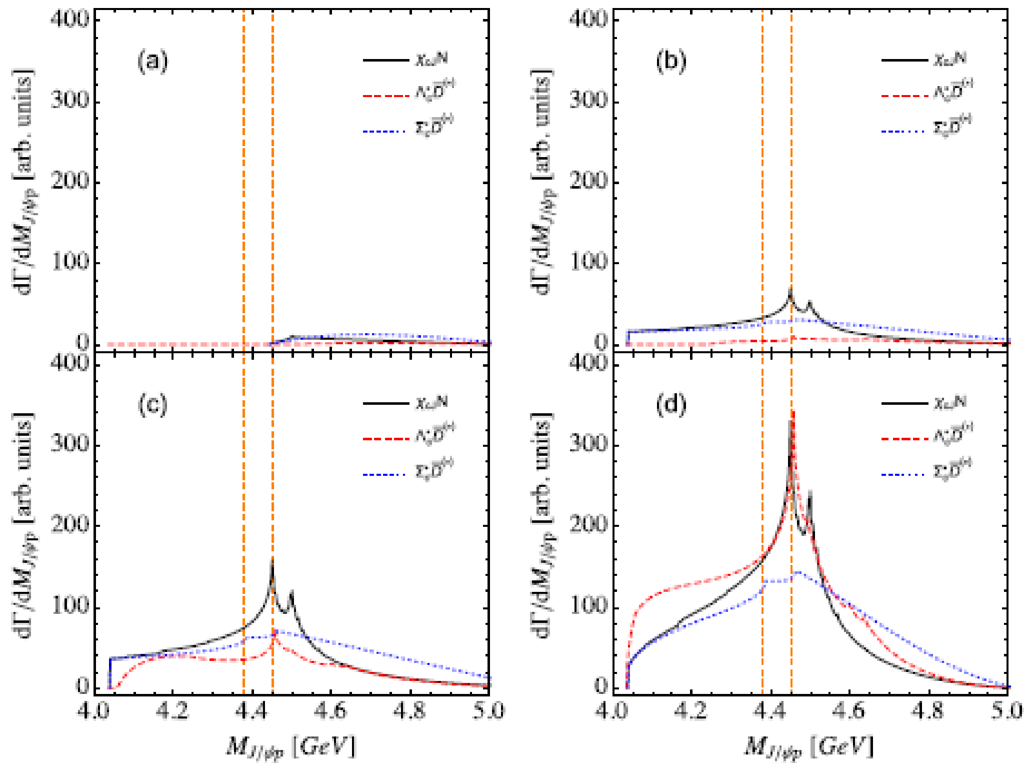
Threshold masses [GeV]	$\Sigma_c(2455)\ 1/2^+$	$\Sigma_c(2520)\ 3/2^+$	$\Sigma_c(2625)\ ?^?$
$\bar{D}(1865)\ 0^-$	4.321	4.385	4.668
$\bar{D}^*(2007)\ 1^-$	4.463	4.527	4.810
$\bar{D}_1(2420)\ 1^+$	4.875	4.939	5.222
$\bar{D}_2(2460)\ 2^+$	4.917	4.981	5.264

Invariant mass distribution of J/ψ p with different K⁻p momentum cuts

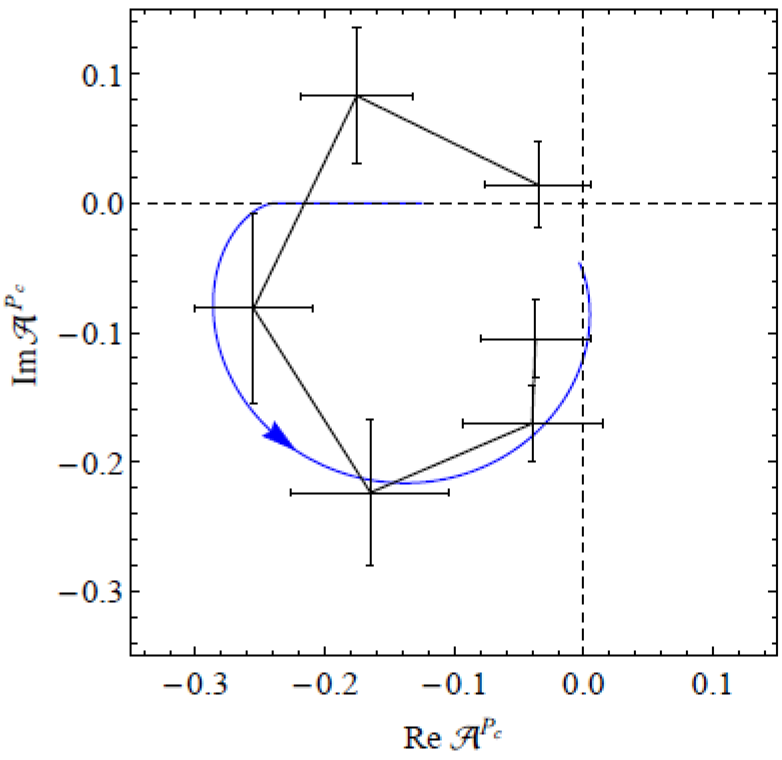
(a) $m_{Kp} < 1.55$ GeV,(b) 1.55 GeV $< m_{Kp} < 1.07$ GeV,

(c) 1.07 GeV $< m_{Kp} < 12.0$ GeV, (d) $m_{Kp} > 2.0$ GeV.



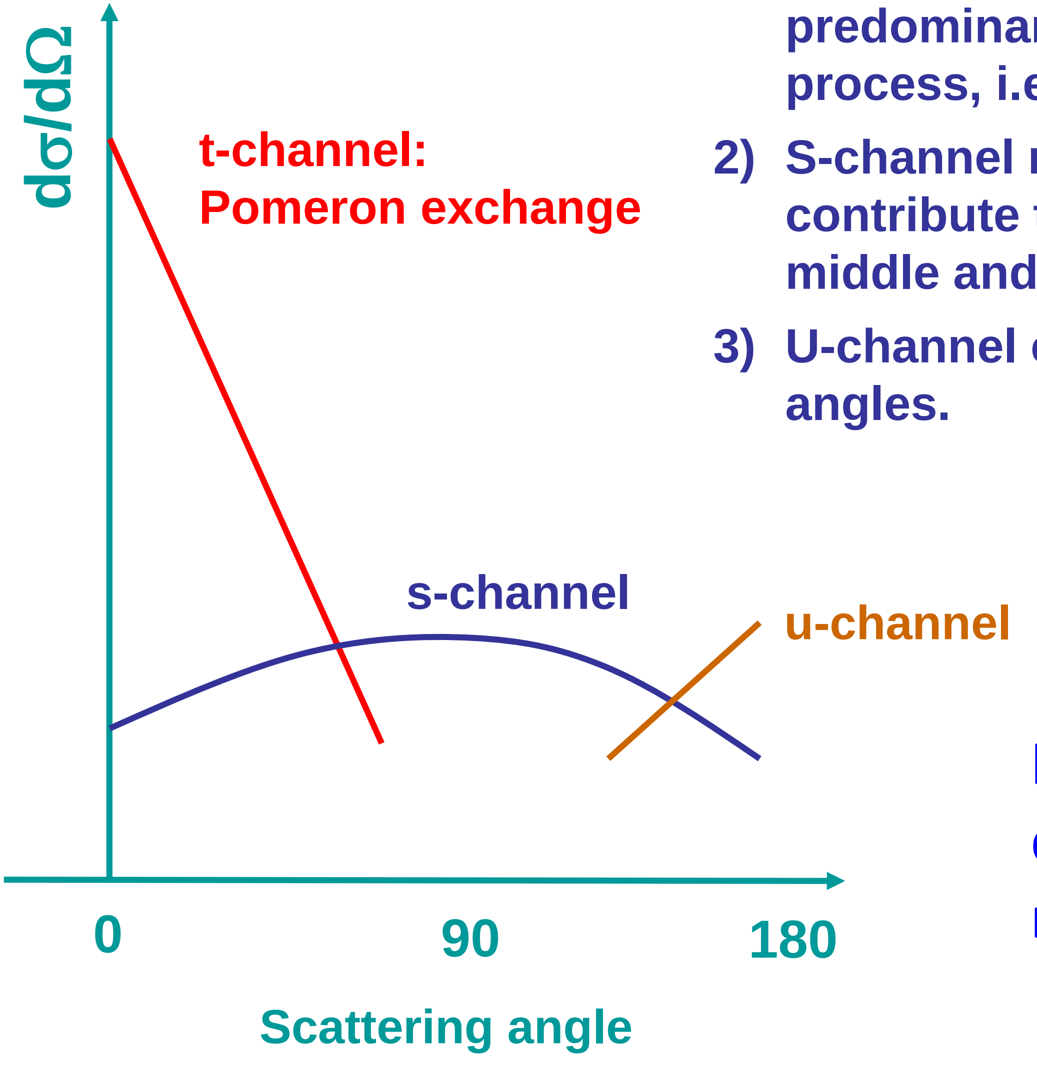


The ATS can mimic a resonance behavior in certain cases



F.-K. Guo, U.-G. Meissner, W. Wang, and Z. Yang, arXiv:1507.04950 [hep-ph]
See also talk by F.-K. Guo

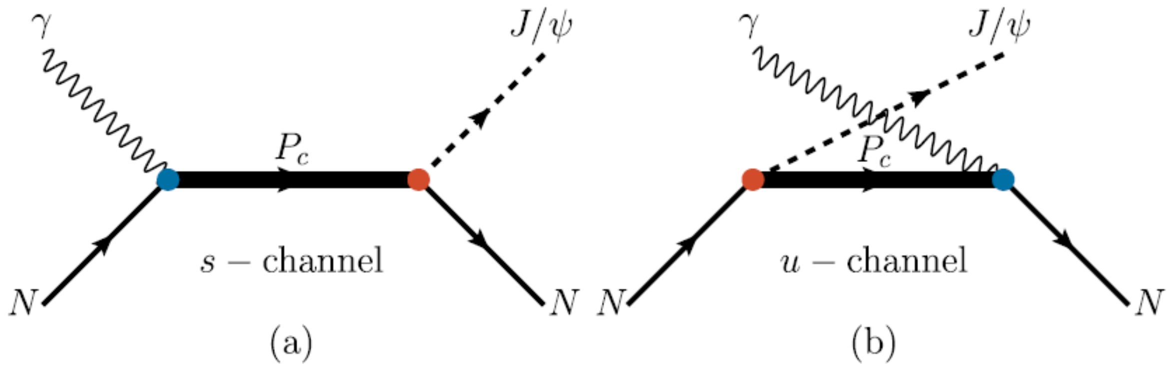
Kinematic features of the production mechanism



1) Forward angle peaking is predominant due to the diffractive process, i.e. Pomeron exchanges.
2) S-channel resonance excitations contribute to the cross sections at middle and backward angles.
3) U-channel contributes to backward angles.

Interferences from different transition mechanisms

s and *u*-channel pentaquark production



Coupling vertices for $\gamma N P_c$:

$$\mathcal{L}^{3/2^\pm}_{\gamma N P_c} = \frac{ieh_1}{2M_N}\bar{N}\Gamma^{(\pm)}_\nu F^{\mu\nu}P_{c\mu} - \frac{eh_2}{(2M_N)^2}\partial_\nu \bar{N}\Gamma^{(\pm)} F^{\mu\nu}P_{c\mu} + \text{H.c.},$$

$$\mathcal{L}^{5/2^\pm}_{\gamma N P_c} = \frac{eh_1}{(2M_N)^2}\bar{N}\Gamma^{(\mp)}_\nu \partial^\alpha F^{\mu\nu}P_{c\mu\alpha} - \frac{ieh_2}{(2M_N)^3}\partial_\nu \bar{N}\Gamma^{(\mp)}_\nu \partial^\alpha F^{\mu\nu}P_{c\mu\alpha} + \text{H.c.}, \qquad \Gamma^{(\pm)}_\mu \equiv \begin{pmatrix} \gamma_\mu\gamma_5 \\ \gamma_\mu \end{pmatrix}, \qquad \Gamma^{(\pm)} \equiv \begin{pmatrix} \gamma_5 \\ \mathbf{1} \end{pmatrix},$$

S. H. Kim, S. i. Nam, Y. Oh and H. C. Kim, PRD 84, 114023 (2011)
Q. Wang, X.-H. Liu, and Q. Zhao, arXiv:1508.00339 [hep-ph]

Coupling vertices for $J/\psi NP_c$:

$$\mathcal{L}^{3/2^\pm}_{P_cN\psi} = -\frac{ig_1}{2M_N}\bar{N}\Gamma^{(\pm)}_\nu\psi^{\mu\nu}P_{c\mu} - \frac{g_2}{(2M_N)^2}\partial_\nu\bar{N}\Gamma^{(\pm)}\psi^{\mu\nu}P_{c\mu} + \frac{g_3}{(2M_N)^2}\bar{N}\Gamma^{(\pm)}\partial_\nu\psi^{\mu\nu}P_{c\mu} + H.c. \; ,$$

$$\mathcal{L}^{5/2^\pm}_{P_cN\psi} = \frac{g_1}{(2M_N)^2}\bar{N}\Gamma^{(\mp)}_\nu\partial^\alpha\psi^{\mu\nu}P_{c\mu\alpha} - \frac{ig_2}{(2M_N)^3}\partial_\nu\bar{N}\Gamma^{(\mp)}\partial^\alpha\psi^{\mu\nu}P_{c\mu\alpha} + \frac{ig_3}{(2M_N)^3}\bar{N}\Gamma^{(\mp)}\partial^\alpha\partial_\nu\psi^{\mu\nu}P_{c\mu\alpha} + H.c.$$

Leading transition matrix elements:

$$\mathcal{M}^{3/2^\pm} = \frac{1}{s-M^2_{P_c}}\frac{eh_1g_1}{(2M_N)2}\epsilon^*_{\psi\nu}\bar{u}_N\Gamma^{(\pm)}_\sigma\Delta_{\beta\alpha}(P_c,k+p)\Gamma^{(\pm)}_\delta(k^\alpha g^{\mu\delta} - k^\delta g^{\alpha\mu})u_N\epsilon_{\gamma\mu} \; ,$$

$$\mathcal{M}^{5/2^\pm} = \frac{1}{s-M^2_{P_c}}\frac{eh_1g_1}{(2M_N)4}\epsilon^*_{\psi\nu}\bar{u}_N q^\sigma(q^\rho g^{\nu\delta} - q^\delta g^{\nu\rho})\Delta_{\rho\sigma;\,\alpha\beta}(P_c,k+p)\Gamma^{(\mp)}_\lambda k^\beta(k^\alpha g^{\mu\lambda} - k^\lambda g^{\alpha\mu})u_N\epsilon_{\gamma\mu}$$

Rarita-Schwinger spin projections:

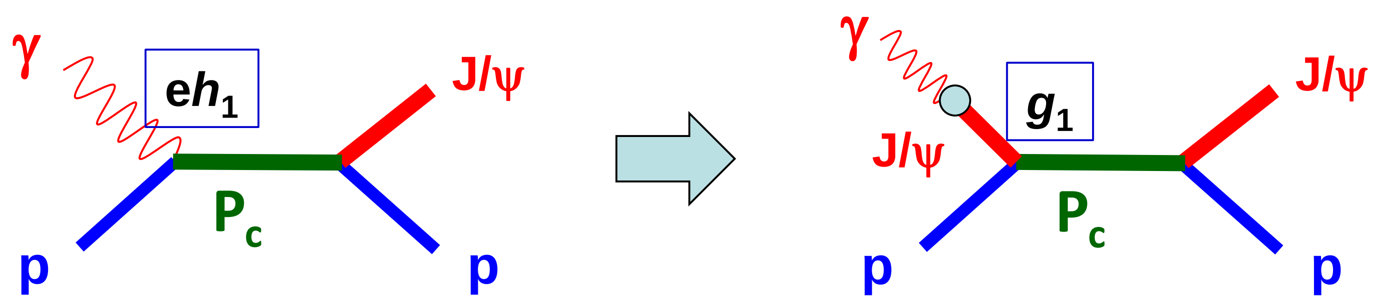
$$\Delta_{\beta\alpha}(B,p) = (\not{p}+M_B)\left[-g_{\beta\alpha} + \frac{1}{3}\gamma_\beta\gamma_\alpha + \frac{1}{3M_B}(\gamma_\beta p_\alpha - \gamma_\alpha p_\beta) + \frac{2}{3M_B^2}p_\beta p_\alpha\right] \; ,$$

$$\Delta_{\rho\sigma;\,\alpha\beta}(B,p) = (\not{p}+M_B)\left[\frac{1}{2}(\bar{g}_{\rho\alpha}\bar{g}_{\sigma\beta} + \bar{g}_{\rho\beta}\bar{g}_{\sigma\alpha}) - \frac{1}{5}\bar{g}_{\rho\sigma}\bar{g}_{\alpha\beta} - \frac{1}{10}(\bar{\gamma}_\rho\bar{\gamma}_\alpha\bar{g}_{\sigma\beta} + \bar{\gamma}_\rho\bar{\gamma}_\beta\bar{g}_{\sigma\alpha} + \bar{\gamma}_\sigma\bar{\gamma}_\alpha\bar{g}_{\rho\beta} + \bar{\gamma}_\sigma\bar{\gamma}_\beta\bar{g}_{\rho\alpha})\right]$$

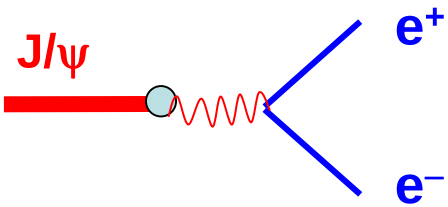
with

$$\begin{cases} \bar{g}_{\alpha\beta} = g_{\alpha\beta} - \dfrac{p_\alpha p_\beta}{M_B^2} \; , \\ \bar{\gamma}_\alpha = \gamma_\alpha - \dfrac{p_\alpha}{M_B^2}\not{p} \; . \end{cases}$$

Vector meson dominance



$$\mathcal{L}_{V\gamma} = \sum_V \frac{eM_V^2}{f_V} V_\mu A^\mu$$



$$eh_1 = -\frac{eM_{J/\psi}^2}{f_{J/\psi}} \frac{ig_1}{k^2 - M_{J/\psi}^2} = i\frac{e}{f_{J/\psi}} g_1$$

By assuming that the J/ψ p saturate the decay widths of the Pc states, we have

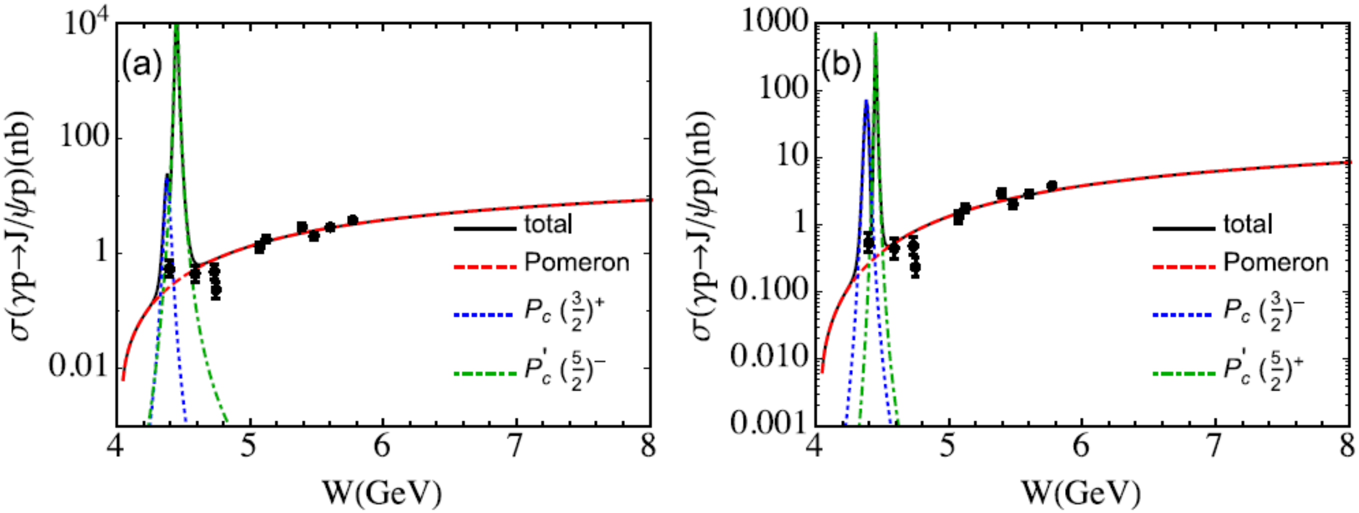
$$g_{\frac{3}{2}^+} = 1.07, \quad g_{\frac{3}{2}^-} = 1.40, \quad g_{\frac{5}{2}^+} = 2.56, \quad g_{\frac{5}{2}^-} = 5.58\ ,$$

A form factor is included:

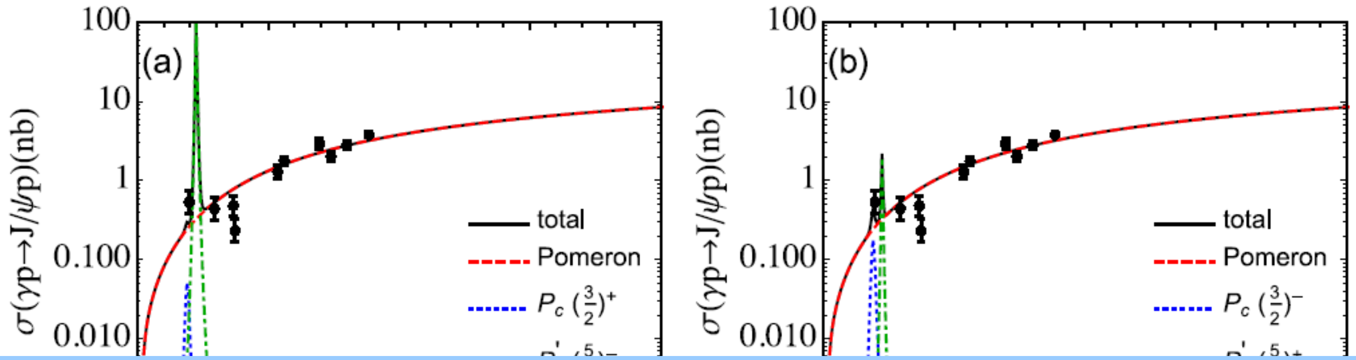
$$\mathcal{F}(p^2) = \frac{\Lambda^4}{\Lambda^4 + (p^2 - M_{P_c}^2)^2}$$

Total cross sections predicted:

Full width prediction



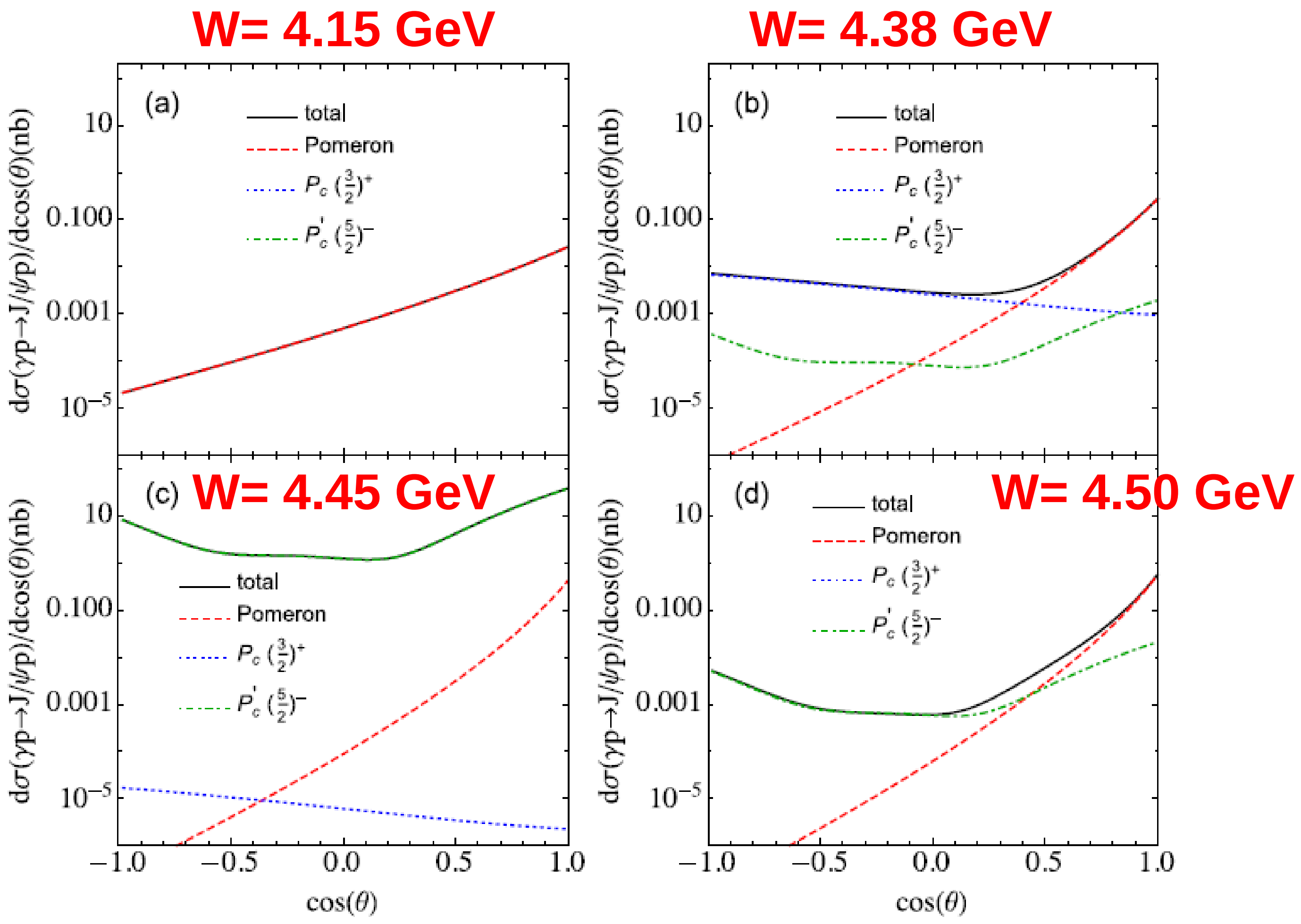
Prediction with 5% of b.r. to J/ψ p:



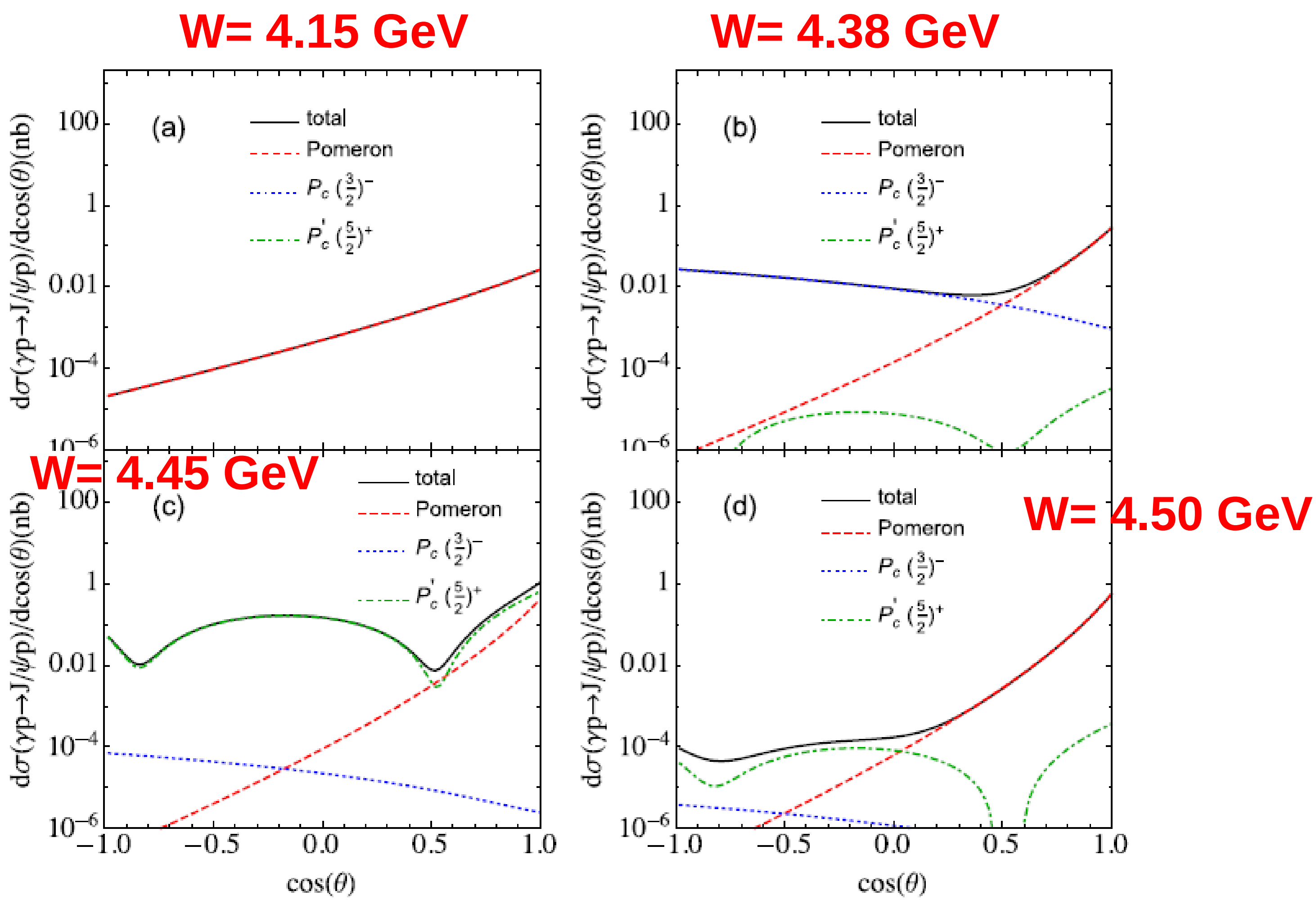
Challenge:

J/psi p CANNOT be the dominant decay channel of these pentaquark candidates!

Predicted differential cross sections at different energies:



Predicted differential cross sections at different energies:



Summary

- The ATS is strongly correlated with threshold phenomena and can produce observable effects when the condition is fulfilled in the physical regime.
- The ATS may mix with the threshold pole structure if a genuine state does exist. So energy-dependence of the threshold peak should be studied.
- An enhancement in elastic channel "almost" implies the existence of a genuine state.
- More criteria for judging the ATS effects and genuine states should be pursued.

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Institute of High Energy Physics

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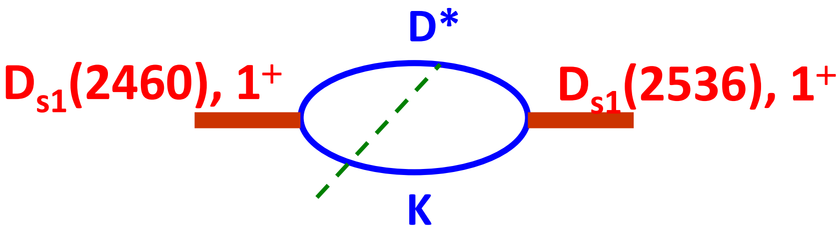
Recent developments on this relevant issue:

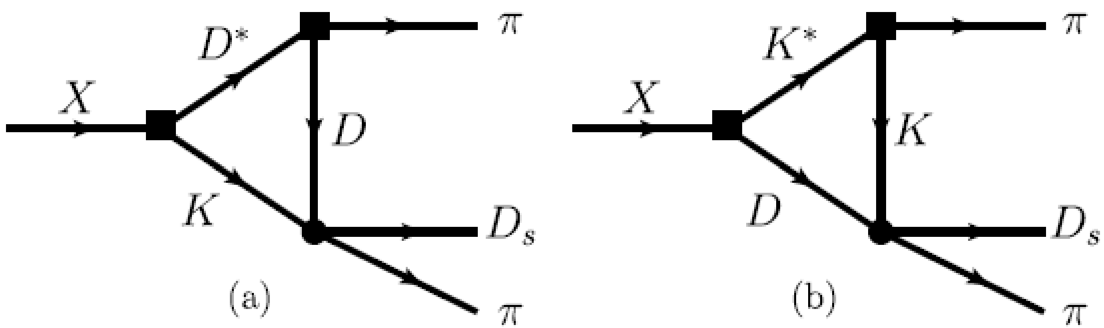
- J.-J. Wu, X.-H. Liu, and Q. Zhao, B.-S. Zou, PRL108, 081003 (2012)
- X.-G. Wu, J.-J. Wu, Q. Zhao, B.-S. Zou, PRD 87, 014023 (2013)
- Q. Wang, C. Hanhart, Q. Zhao, PRL111, 132003 (2013)
- Q. Wang, C. Hanhart, Q. Zhao, PLB725, 106 (2013)
- X.-H. Liu, M. Oka, Q. Zhao, PLB753, 297(2016); arXiv:1507.01674 [hep-ph]
- F.-K. Guo, U.-G. Meissner, W. Wang, and Z. Yang, PRD(2015); arXiv:1507.04950 [hep-ph]
- X.-H. Liu, Q. Wang, and Q. Zhao, PLB(2016); arXiv:1507.05359 [hep-ph]
- X.-H. Liu and M. Oka, NPA 954 (2016) 352; arXiv:1512.05474[hep-ph]
- A. P. Szczepaniak, PLB747, 410 (2015) [arXiv:1501.01691 [hep-ph]]

Thanks for your attention!

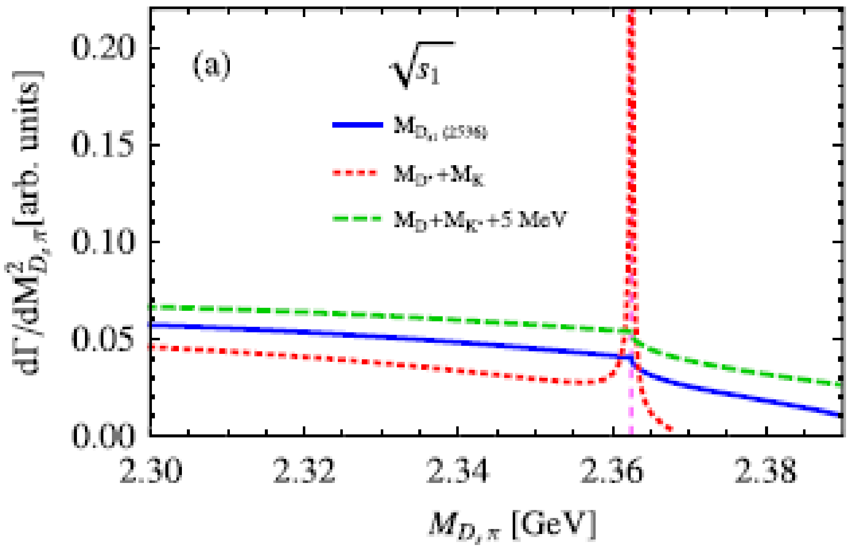
(IV) *Ds*1(2460) or *Ds*1(2536) decays into Ds pipi can go through the ATS process.

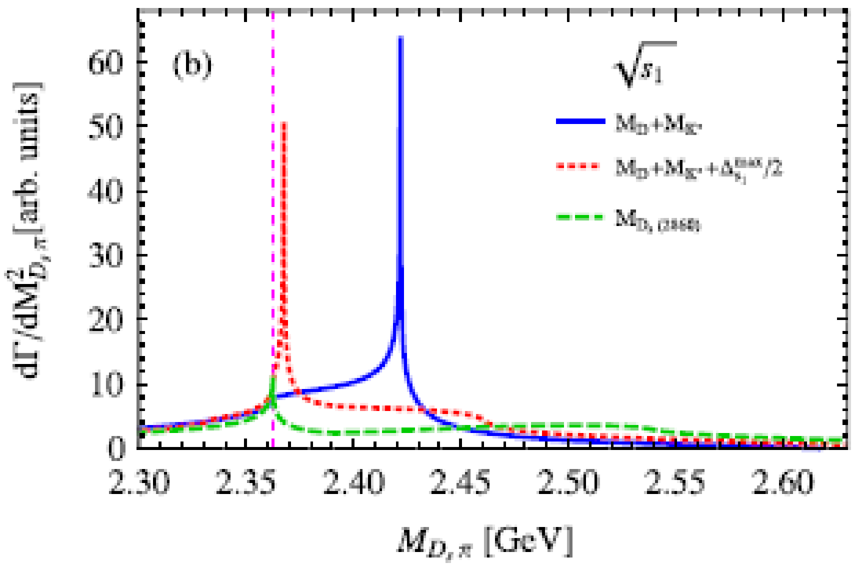


D_{s1}(2460) or D_{s1}(2536) are mixture of $3P_1$ and $1P_1$.



The ATS peaks appear at different energies





References:

•J.-J. Wu, X.-H. Liu, and Q. Zhao, B.-S. Zou, PRL108, 081003 (2012)
•X.-G. Wu, J.-J. Wu, Q. Zhao, B.-S. Zou, PRD 87, 014023 (2013)
•Q. Wang, C. Hanhart, Q. Zhao, PRL111, 132003 (2013)
•Q. Wang, C. Hanhart, Q. Zhao, PLB725, 106 (2013)
•X.-H. Liu, M. Oka, Q. Zhao, PLB753, 297(2016); arXiv:1507.01674 [hep-ph]
•F.-K. Guo, U.-G. Meissner, W. Wang, and Z. Yang, PRD(2015); arXiv:1507.04950 [hep-ph]
•X.-H. Liu, Q. Wang, and Q. Zhao, PLB(2016); arXiv:1507.05359 [hep-ph]
•X.-H. Liu and M. Oka, arXiv:1512.05474[hep-ph]
•A. P. Szczepaniak, PLB747, 410 (2015) [arXiv:1501.01691 [hep-ph]]

Lagrangians in the NREFT

- **Y(4260)D_1D coupling:**

$$\mathcal{L}_Y = i\frac{y}{\sqrt{2}}\left(\bar{D}_a^{\dagger}Y^i D_{1a}^{i\dagger} - \bar{D}_{1a}^{i\dagger}Y^i D_a^{\dagger}\right) + \text{H.c.},$$

$$|y| = (3.28^{+0.25}_{-0.28} \pm 1.39)\ \ \text{GeV}^{-1/2}$$

- **Zc(3900)DD* coupling:**

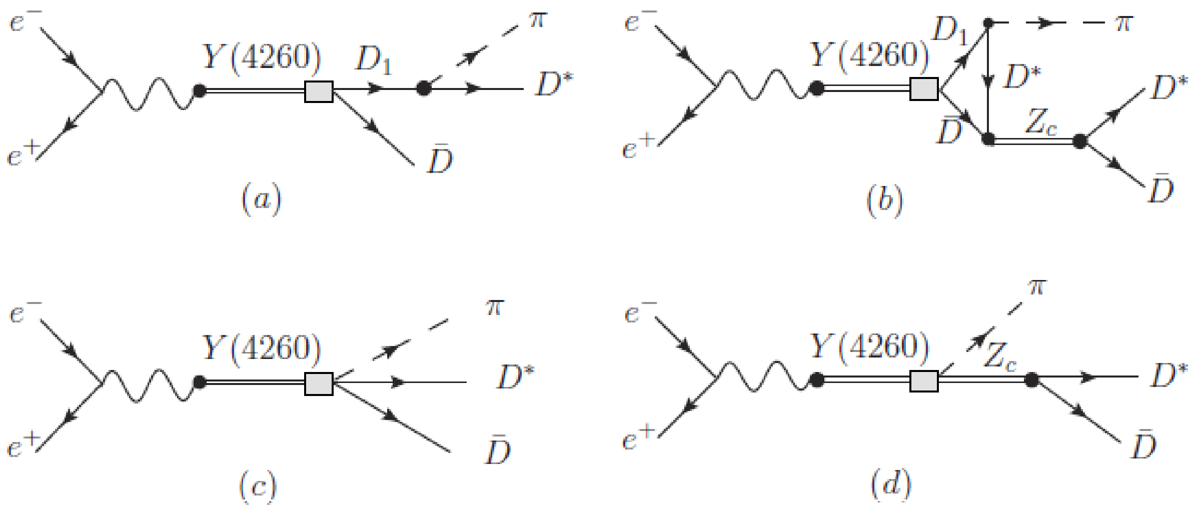
$$\mathcal{L}_Z = \frac{z}{\sqrt{2}}\left[\bar{V}^{\dagger i}Z^i P^{\dagger} - \bar{P}^{\dagger}Z^i V^{\dagger i}\right] + \text{H.c.}\ ,$$

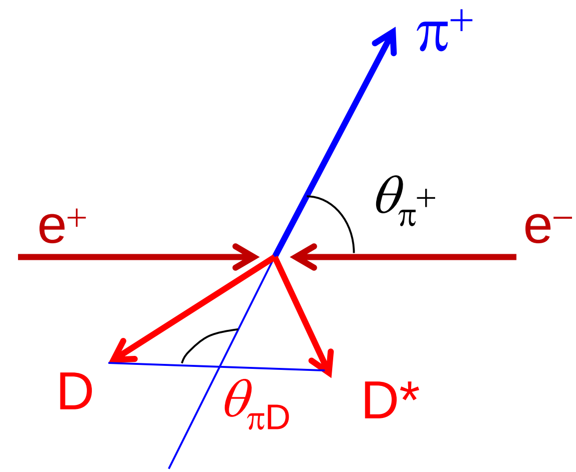
$$Z_{ba}^i = \begin{pmatrix} \frac{1}{\sqrt{2}}Z^{0i} & Z^{+i} \\ Z^{-i} & -\frac{1}{\sqrt{2}}Z^{0i} \end{pmatrix}_{ba} \qquad P(V) = \left(D^{(*)0}, D^{(*)+}\right)$$

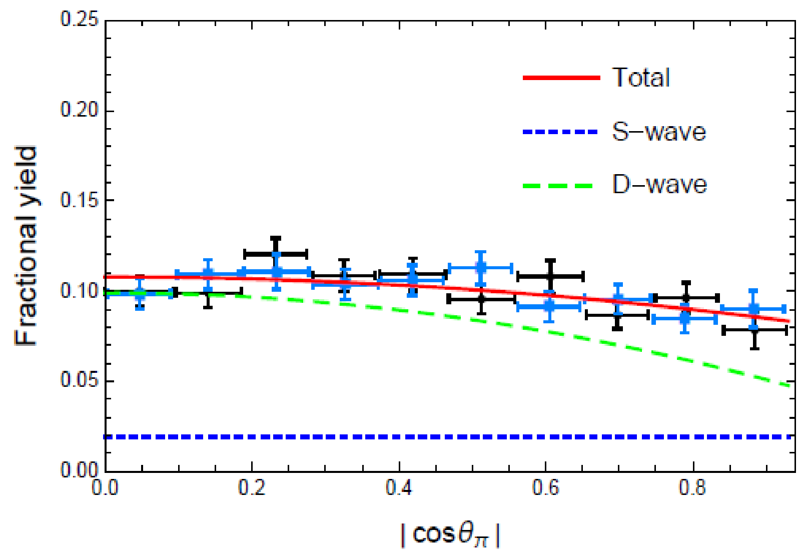
- **D1D*pi coupling:**

$$\mathcal{L}_{D_1} = i\frac{h'}{f_\pi}\Big[3D_{1a}^i(\partial^i\partial^j\phi_{ab})D_b^{*\dagger j} - D_{1a}^i(\partial^j\partial^j\phi_{ab})D_b^{*\dagger i}$$
$$-3\bar{D}_a^{*\dagger i}(\partial^i\partial^j\phi_{ab})\bar{D}_{1b}^j + \bar{D}_a^{*\dagger i}(\partial^j\partial^j\phi_{ab})\bar{D}_{1b}^i\Big] + \text{H.c.}, (2)$$

Q. Wang, C. Hanhart, QZ, PRL111, 132003 (2013); PLB(2013)

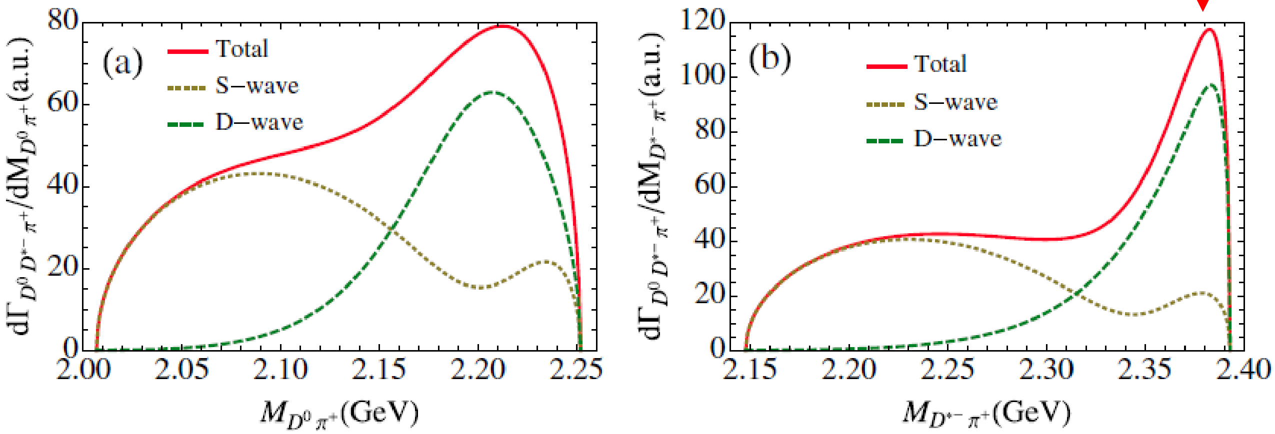




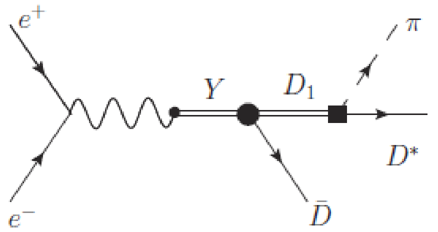


Q. Wang, C. Hanhart, Q.Z., PRL111, 132003 (2013); PLB(2013)
W. Qin, S.R. Xue, Q.Z., arXiv:1605.02407[hep-ph]
See talk by Si-Run Xue in Parallel Section: B-2/26-M-1, July 26, 2016

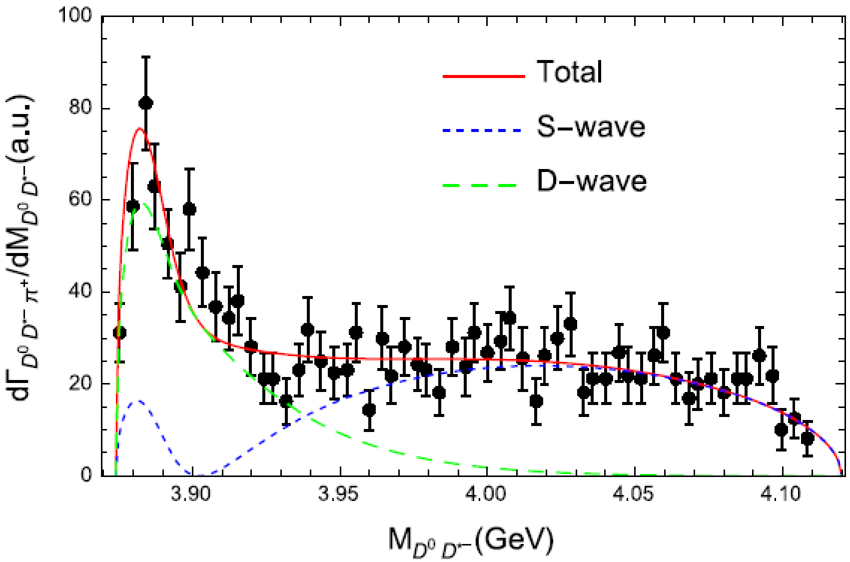
Invariant mass spectra for Dπ, D*π, and $\bar{D}$D*



Signature for D_1(2420) via the tree diagram.



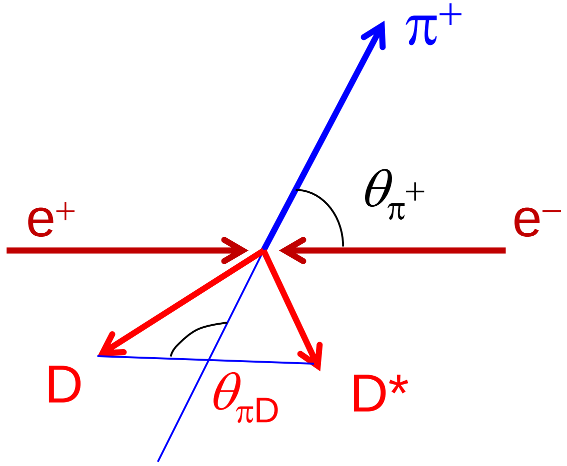
The Zc(3900) could have a pole below the DD* threshold.



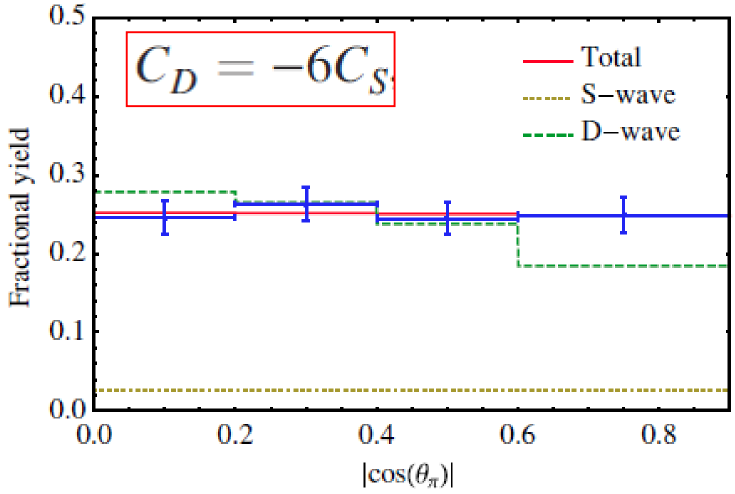
How a D wave can be present?

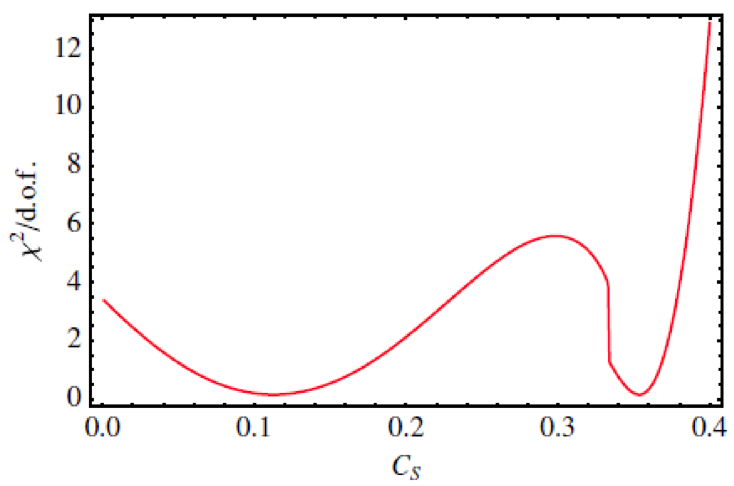
$$\mathcal{M} = \epsilon_Y^a \epsilon_{Z_c}^b \left(C_S \delta^{ab} + C_D \left(\hat{q}^a \hat{q}^b - \frac{1}{3} \delta^{ab} \right) \right).$$

$$\sum_{\text{polarizations}} |\mathcal{M}|^2 = 2C_S^2 - 2C_S C_D \cos^2\theta_\pi + \frac{2C_S C_D}{3} - \frac{C_D^2 \cos^2\theta_\pi}{3} + \frac{5C_D^2}{9}$$

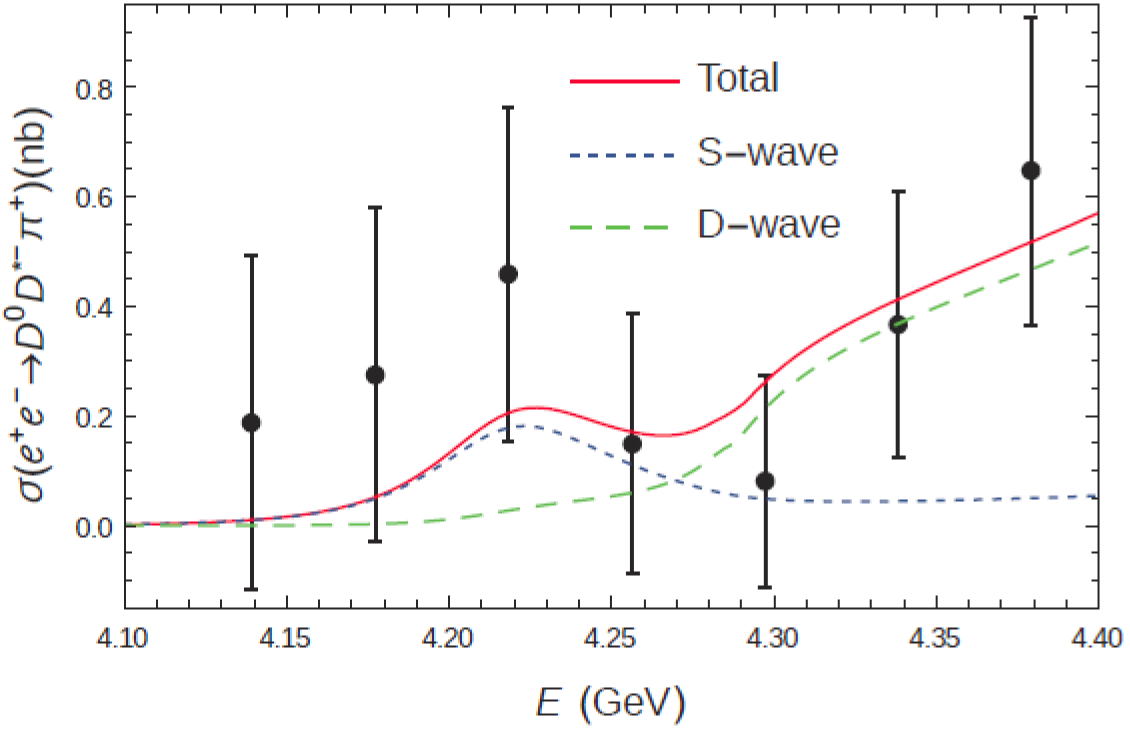


$$\sum_{\lambda=1,2} \epsilon_Y^{\lambda a} \epsilon_Y^{*\lambda b} = \delta^{ab} - \delta^{a3}\delta^{b3}, \qquad \sum_{\lambda=1,2,3} \epsilon_{Z_c}^{\lambda a} \epsilon_{Z_c}^{*\lambda b} = \delta^{ab}$$

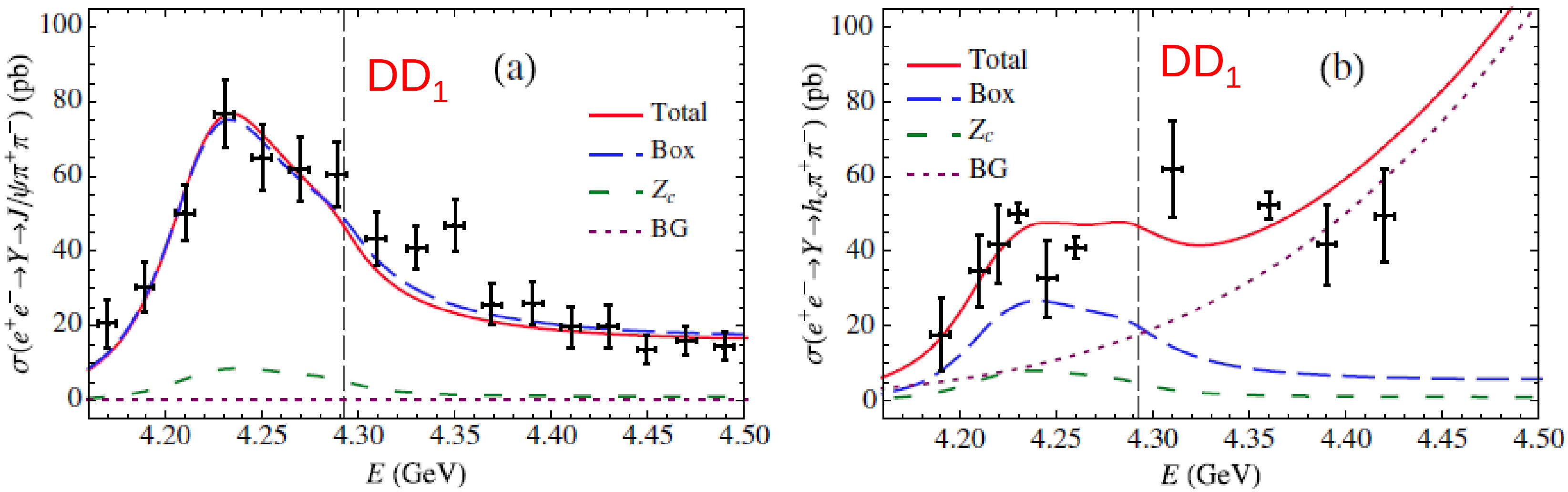




Non-BW lineshape around the Y(4260) mass region as an evidence for the molecular feature of Y(4260):

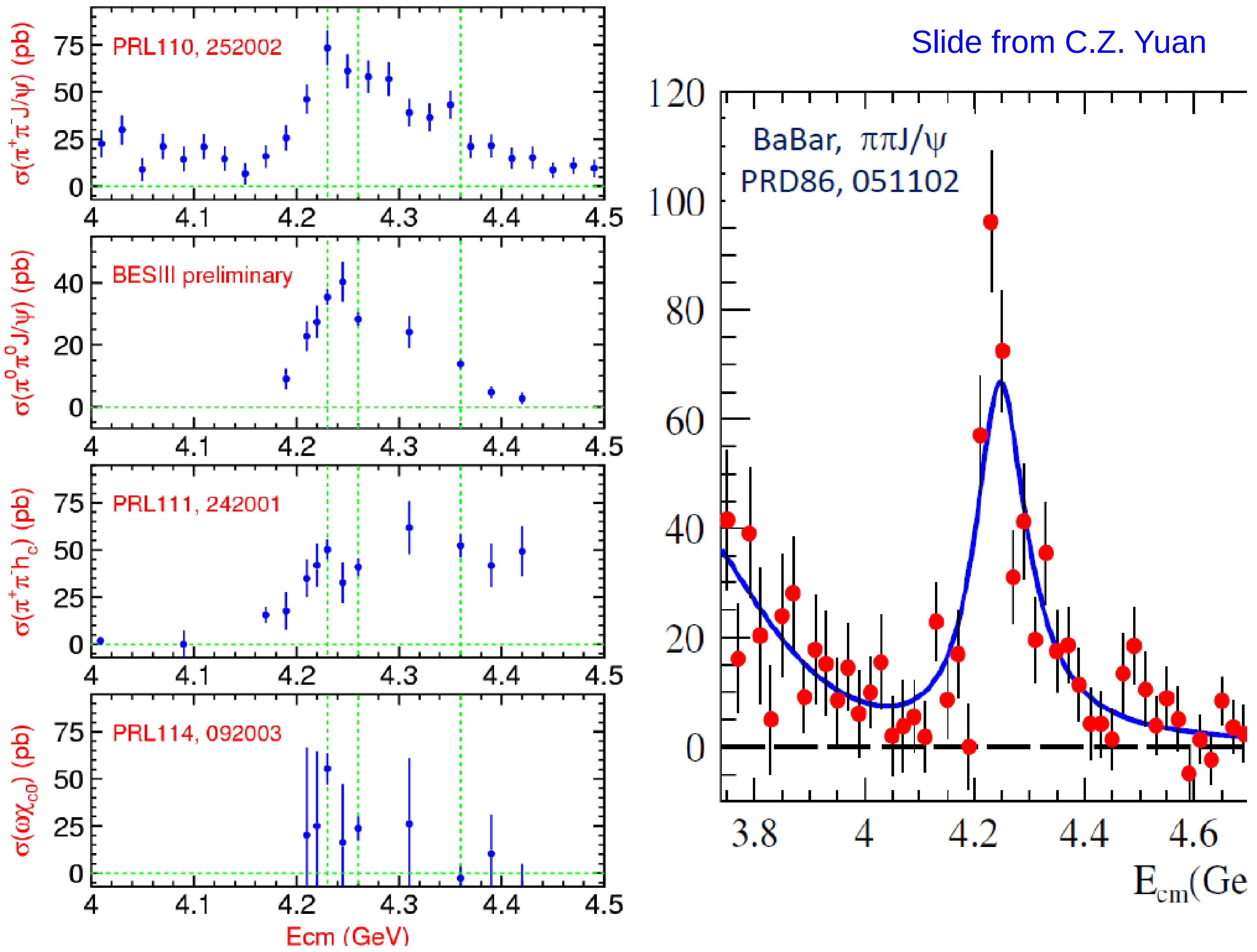


$e^+e^- \to J/\psi\pi^+\pi^-$ $\qquad$ $e^+e^- \to h_c\pi^+\pi^-$



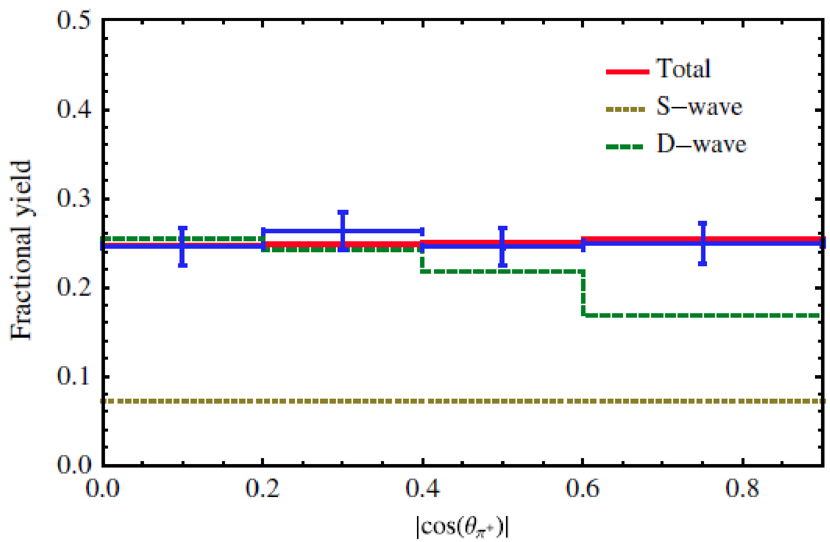
- **Where is the peak position and pole position of Y(4260)?**
- **Is the J/psi pipi the dominant decay channel for Y(4260)?**
- **How to understand the non-trivial lineshape of the hc pipi channel?**
- **Could the exclusive channel cross section lineshape provide more information about the nature of Y(4260)?**
- **……**

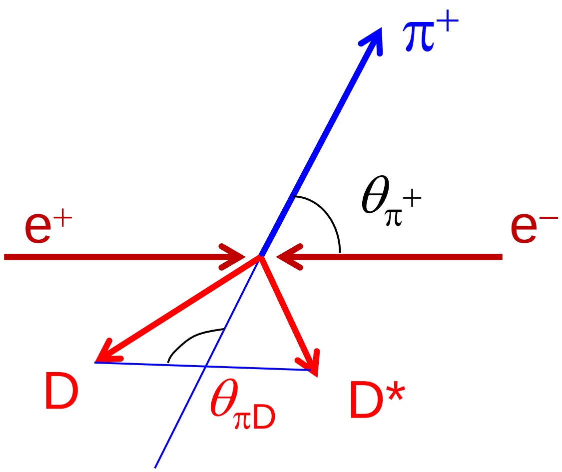
M. Cleven, Q. Wang, C. Hanhart, U.-G. Meissner, and Q. Zhao, 1310.2190; PRD90, 074039 (2014)

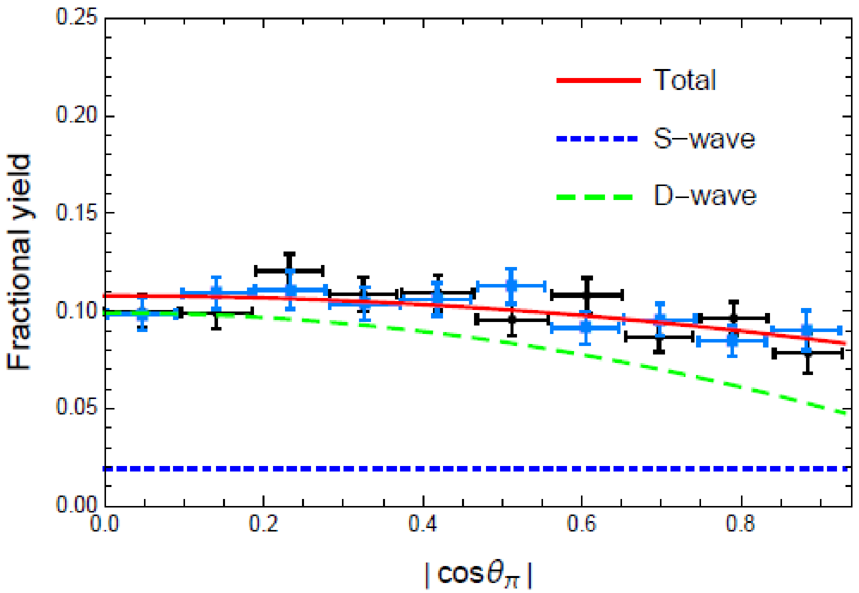


PRL110, 252002
BESIII preliminary
PRL111, 242001
PRL114, 092003
Ecm (GeV)
Slide from C.Z. Yuan
BaBar, ππJ/ψ
PRD86, 051102

Angular distribution analysis







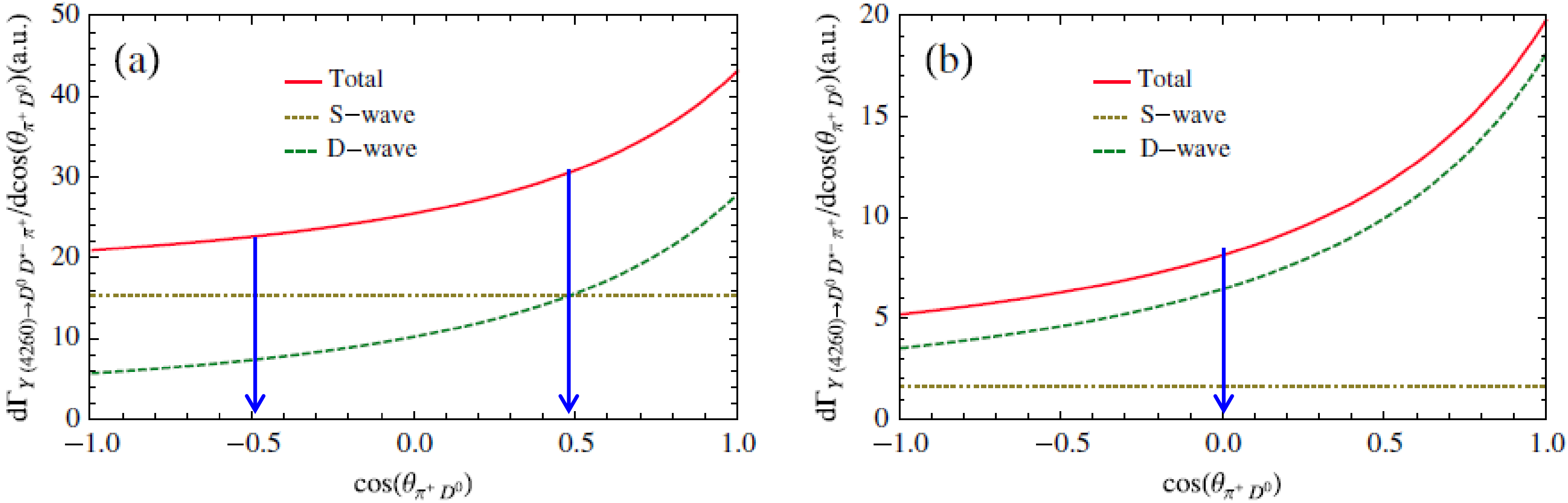
Updated data from BESIII, PRD 92 (2015) 092006

The asymmetry of events between $|\cos(\theta_{\pi D})| > 0.5$ and $|\cos(\theta_{\pi D})| < 0.5$,

$$\mathcal{A} = \frac{n_{>0.5} - n_{<0.5}}{n_{>0.5} + n_{<0.5}} = (0.12 \pm 0.06)$$

A =

0.0	S wave
0.11	D wave
0.05	S+D



Forward–backward asymmetry for the DD* peak:

$$\mathcal{A}_{fb} = \frac{n_{>0} - n_{<0}}{n_{>0} + n_{<0}}. =$$

0.0	S wave
0.37	D wave
0.16	S+D