中国科学院高能物理研究所
Institute of High Energy Physics

中国科学院
CHINESE ACADEMY OF SCIENCES

Some insights into the charmonium-like XYZ states

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Outline

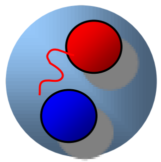
1. Multi-face of QCD?
2. Open threshold phenomena in the charmonium energy region?
3. How and what we can learn from charmonium production and decay?
4. Summary

1. Multi-face of QCD?

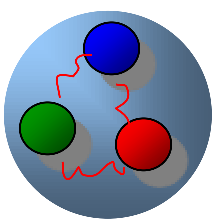
Quantum Chromo-Dynamics (QCD)
-- so far the most successful theory for strong interactions

Conventional hadron

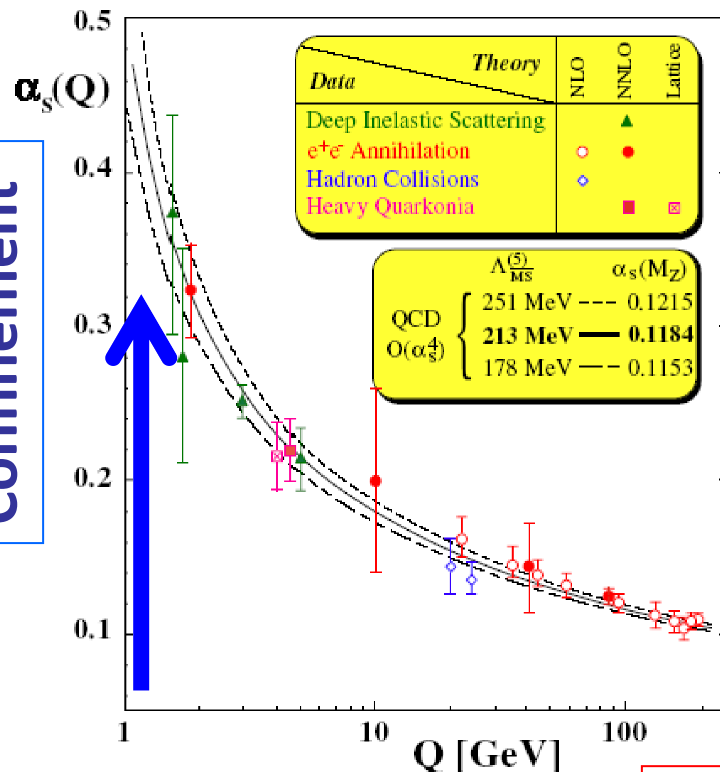
Meson

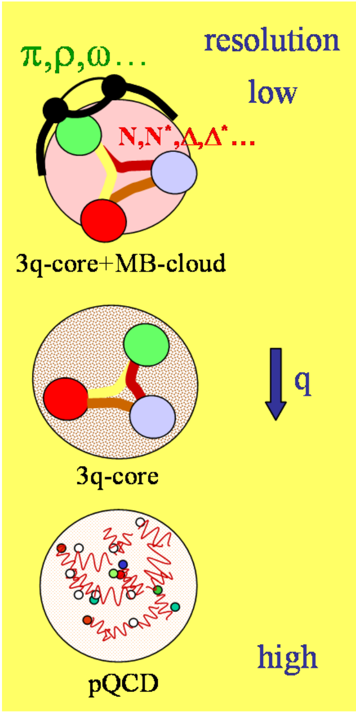


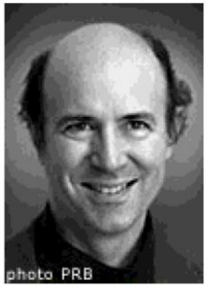
Baryon



Confinement





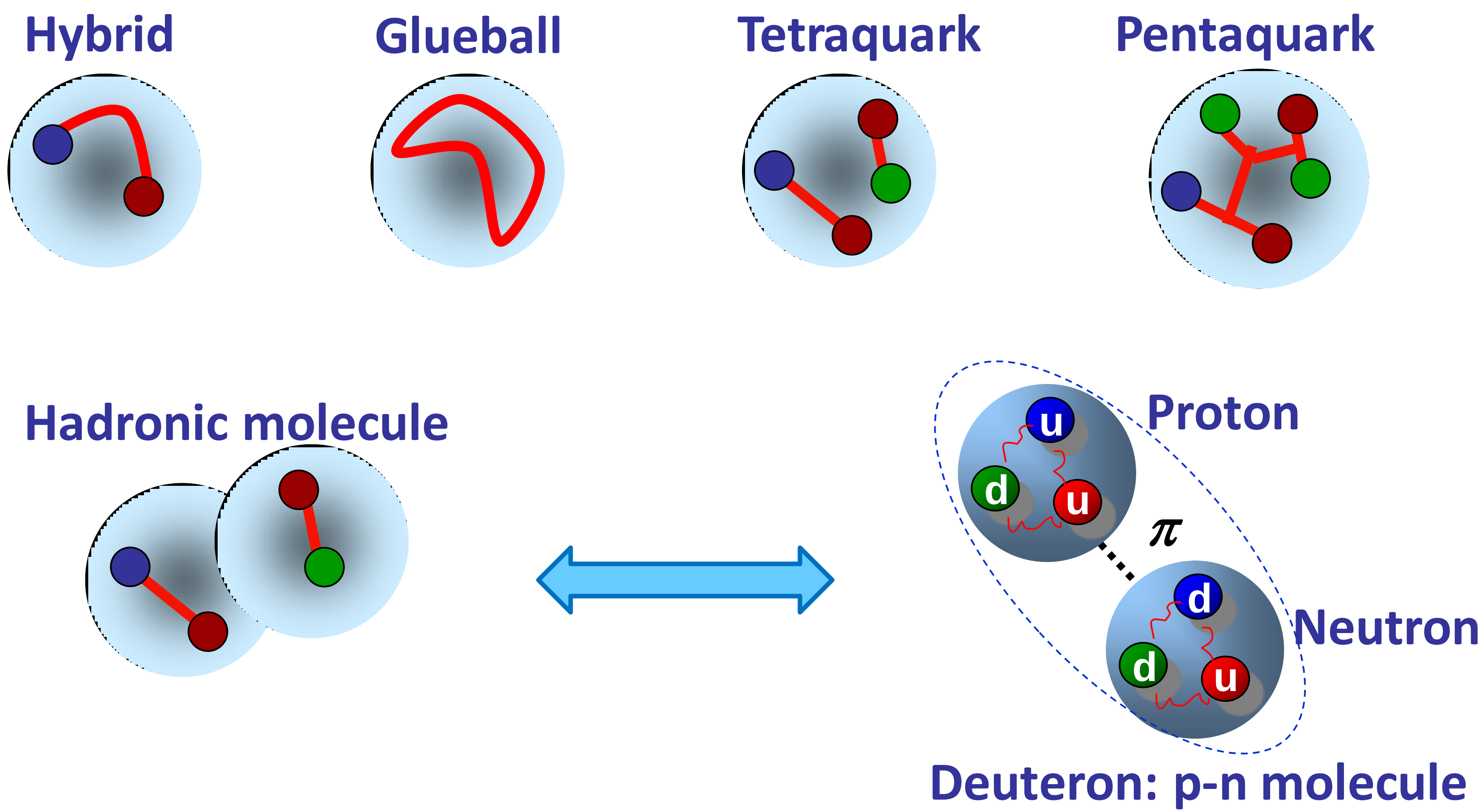


David J. Gross H. David Politzer Frank Wilczek

2004

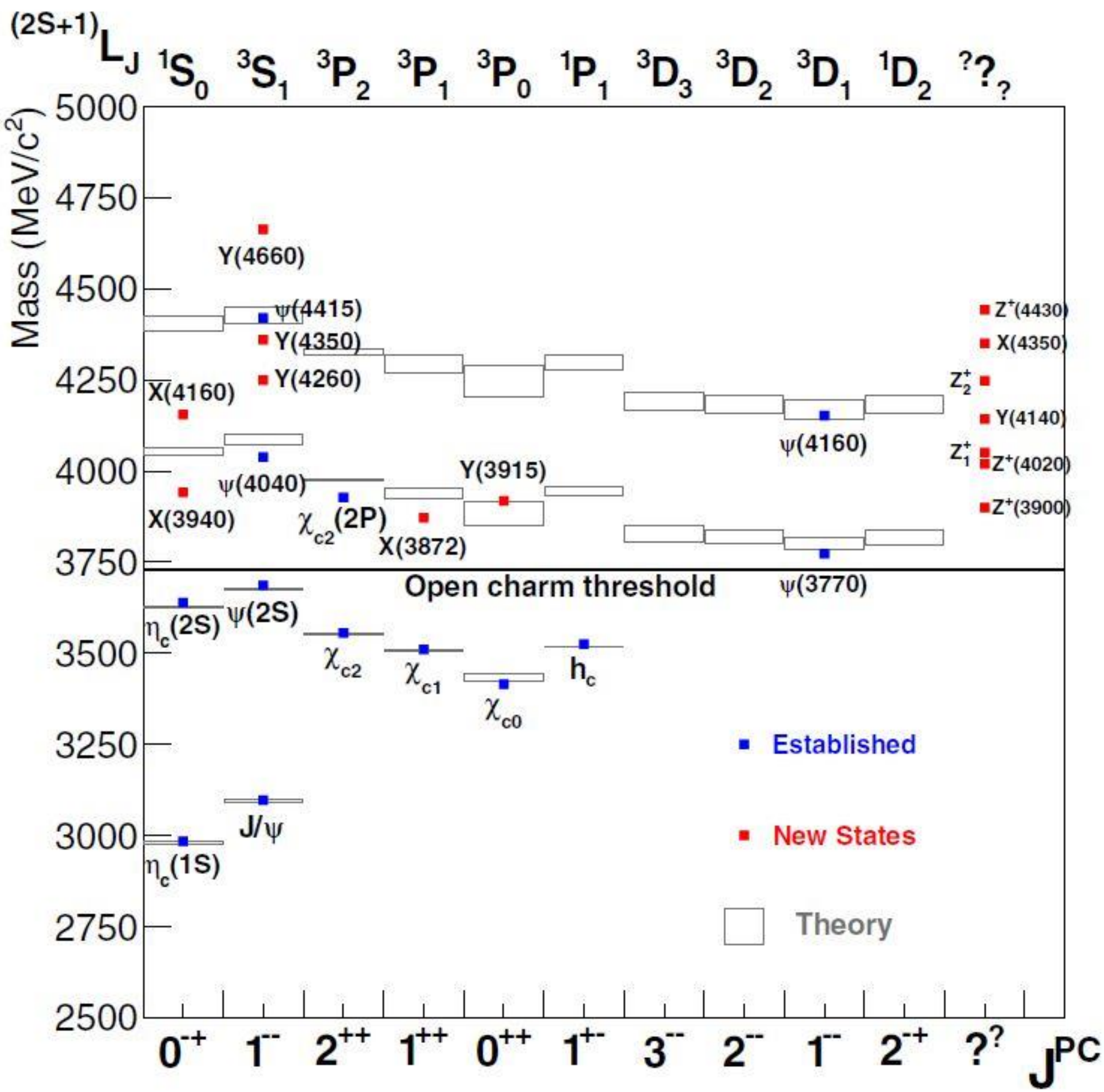
Asymptotic freedom

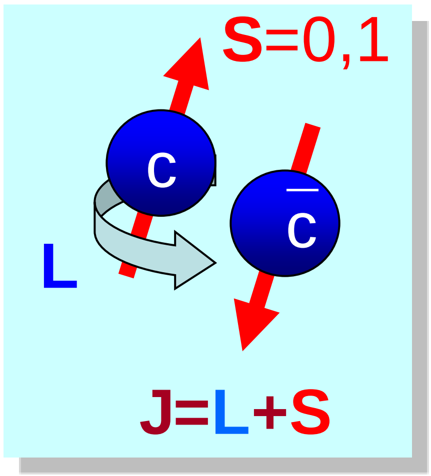
Multi-faces of QCD: Exotic hadrons



Evidence for QCD exotic states is a missing piece of knowledge about the Nature of strong QCD.

Charmonium Spectrum





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

Expected and unexpected:

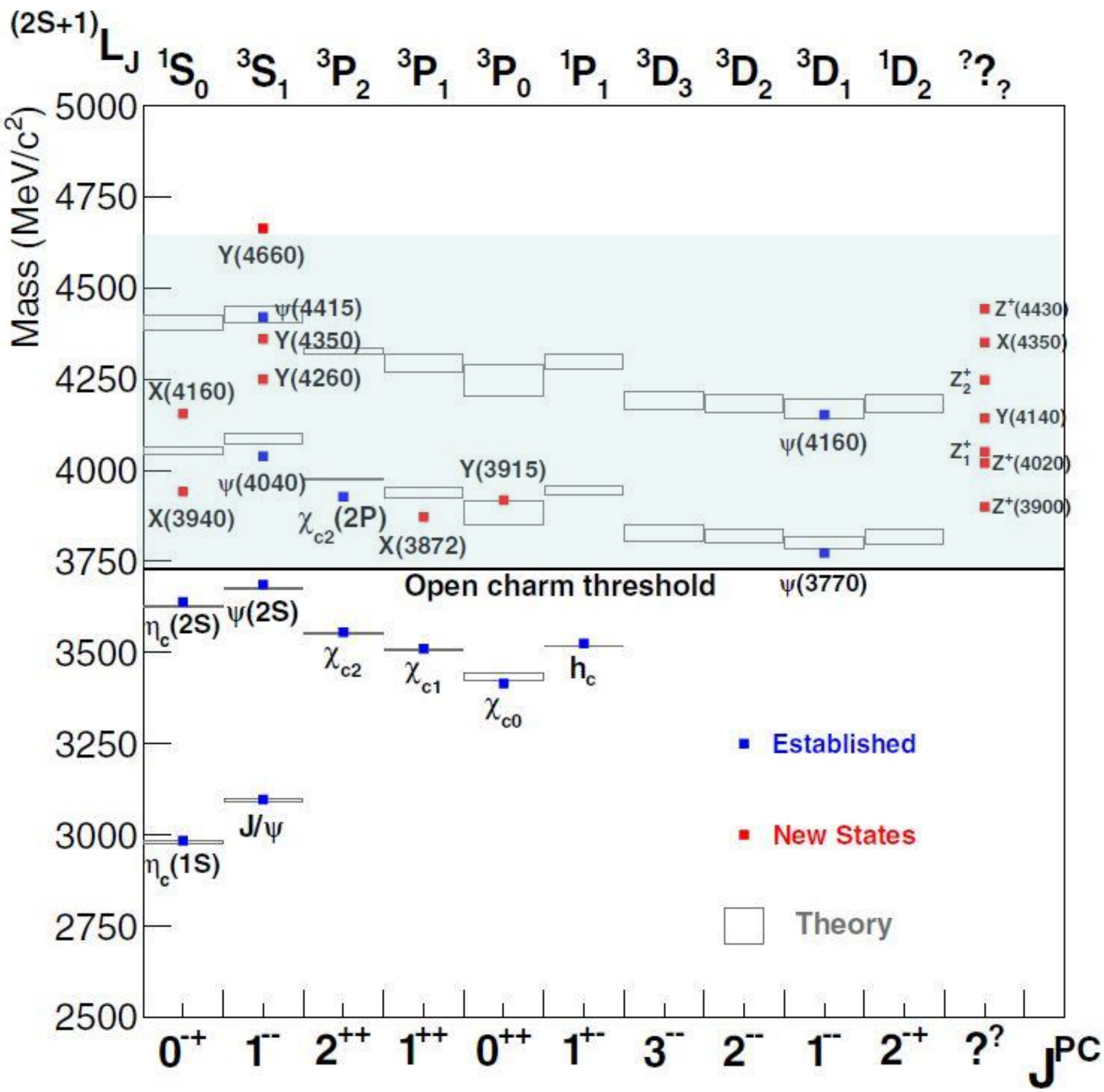
- Ground states and states below open-flavor threshold are well established.
- A large number of excited states, i.e. XYZ states, cannot be accommodated by the conventional quark model!
- Lattice QCD still cannot provide a full quantitative description of the hadron spectroscopy.

Some urgent questions:

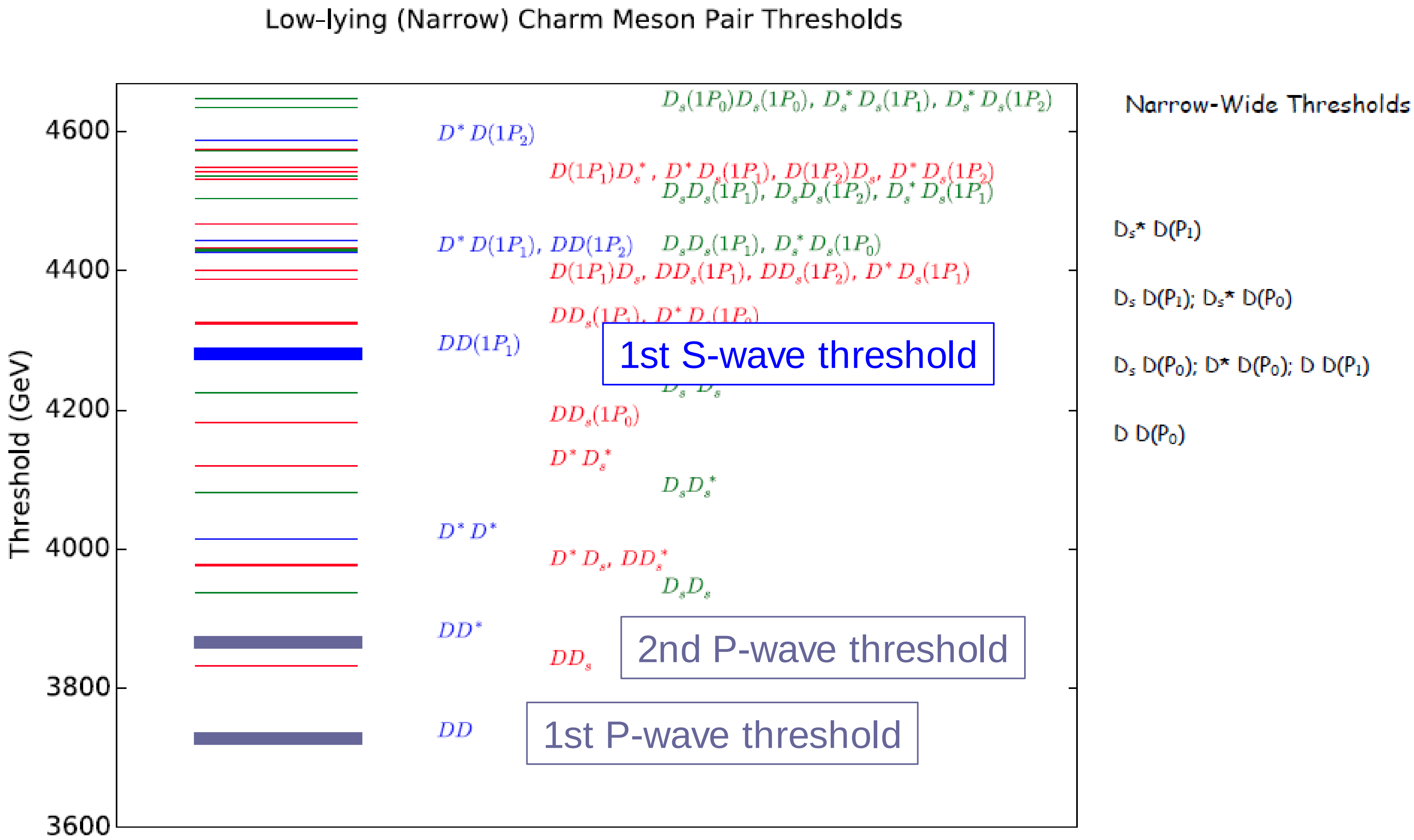
- Do we have indisputable evidence for exotic hadrons?
- Do we have efficient and sufficient criteria for identifying exotic hadrons?
- Where to look for exotic hadrons?
- … …

2. Open threshold phenomena in the charmonium energy region?

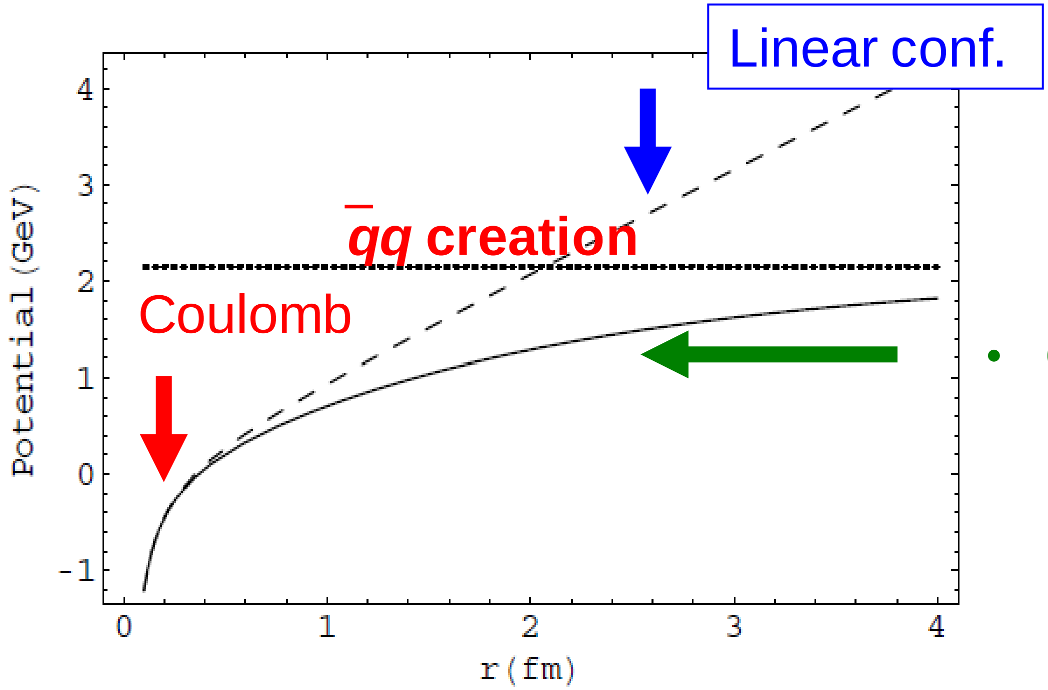
Charmonium Spectrum



Low-lying thresholds

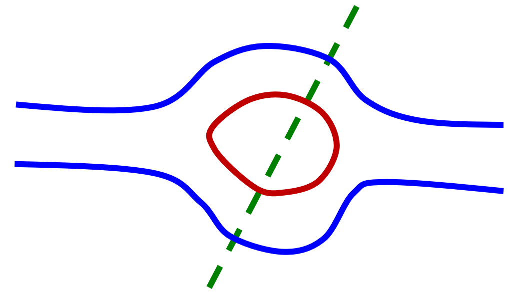


Breakdown of potential quark model



$$V(r) = -\kappa / r + \sigma r$$

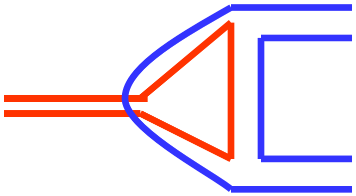
- **Color screening effects? String breaking effects?**



- **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)

• **In case that the open threshold coupled channels play a role, typical ways to include such an effect are via hadron loops in hadronic transitions**



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

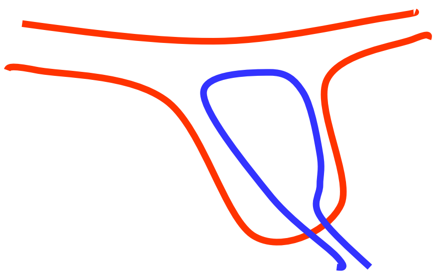
"ρπ puzzle" X. Liu, B. Zhang, X.Q. Li, PLB(2009)

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



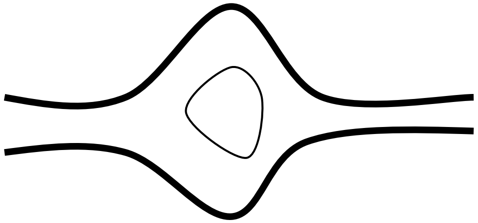
$\psi' \to J/\psi\pi^0, \psi' \to J/\psi\eta$

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

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

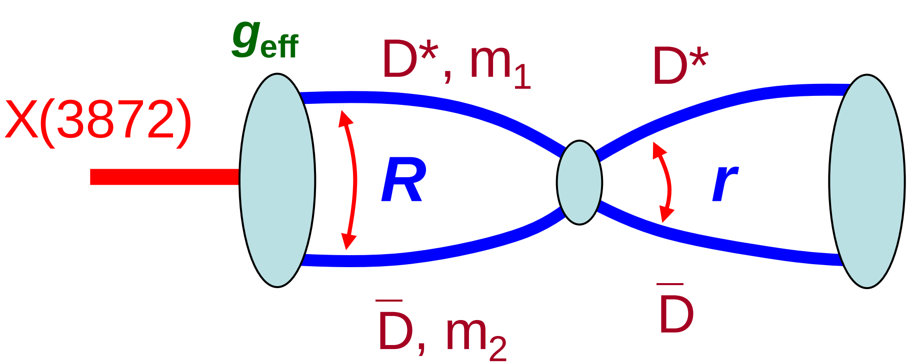


$D_{s1}(2460) - D_{s1}(2536)$

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

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

- Charm quark is heavy enough to allow the implementation of non-relativistic treatment for the $c\bar{c}$ system.
- Heavy quark motions are much slower than the gauge field which act as an averaged potential.
- The physics can be described by systematic expansions in terms of the heavy quark velocity in NRQCD, or in terms of $1/m_Q$ in HQEFT.



a) Scale separation:

Shallow bound state： $R >> r$

R: size of hadron, e.g. X(3872)
r: interaction range
p: typical momentum of const. hadrons
$R \sim 1/p \sim 1/(2\mu E_B)^{1/2}$

→ Separate short and long-range interactions

b) Power counting:

$p/m = v << 1$; $2E/m = p^2/m^2 \sim O(v^2)$; $1/(E-p^2/2m) \sim O(v^{-2})$

Even better for bottomed system!

However, it is the interplay between perturbative and non-perturbative regimes that helps us understand better the nature of strong QCD.

- ◆ Relativistic corrections?
- ◆ Coupled channel corrections?
- ◆ Isospin violations?
- ◆ … …

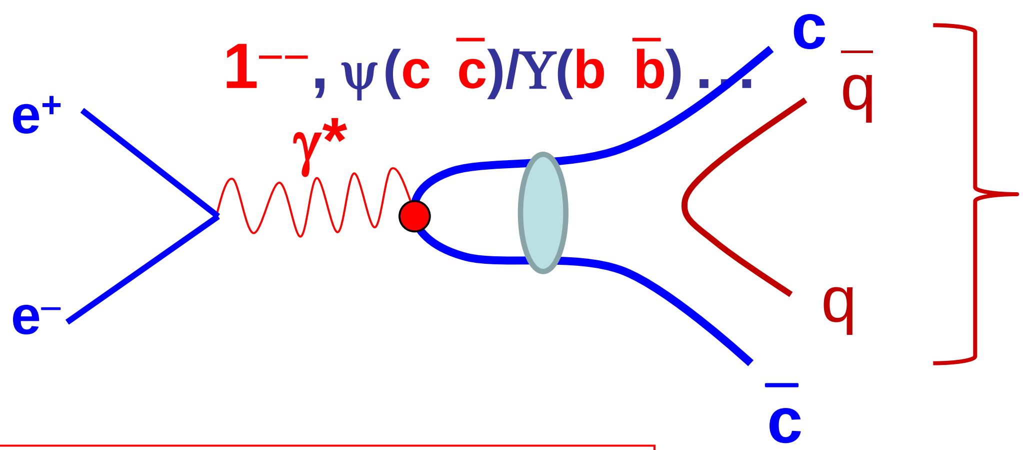
- □ State mixings?
- □ Exotic states?
- □ Kinematic effects?
- □ … …

3. How and what we can learn from charmonium production and decay?

- 1st open charm threshold (P wave)
- 2nd open charm threshold (P wave)
- 1st S-wave open charm threshold

→ Better understanding of the open thresholds is needed!

Vector charmonium production in e^+e^- annihilations

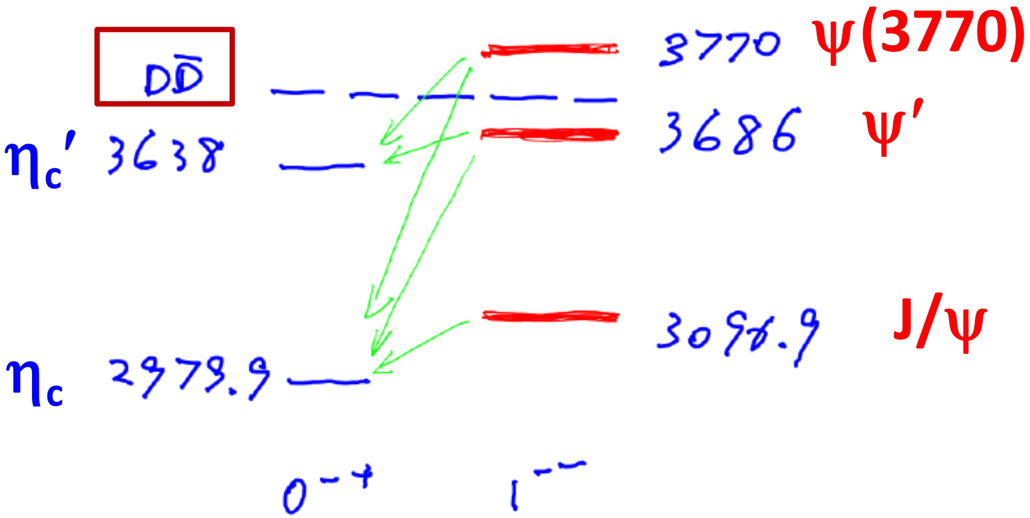


Charmed meson pair production, i.e.
$D(0^-)\bar{D}(0^-)$,
$D^*(1^-)\bar{D}^*(1^-)$,
$D^*\bar{D} + \bar{D}D^*$...

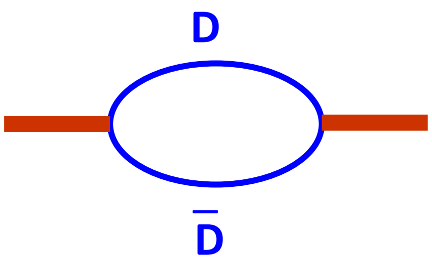
Belle, BaBar, and BESIII

- Direct production of vector charmonium ($J^{PC}=1^{--}$) states.
- Dynamics for vector charmonium interactions with final states.
- Signals for vector exotics, e.g. Y(4260)? Or exotics produced in vector charmonium decays, e.g. X(3872) and Zc(3900)?
- ......

(I) The vicinity of the first open charm threshold



The open threshold will not only affect the masses of the charmonium states, but also affect the transitions.



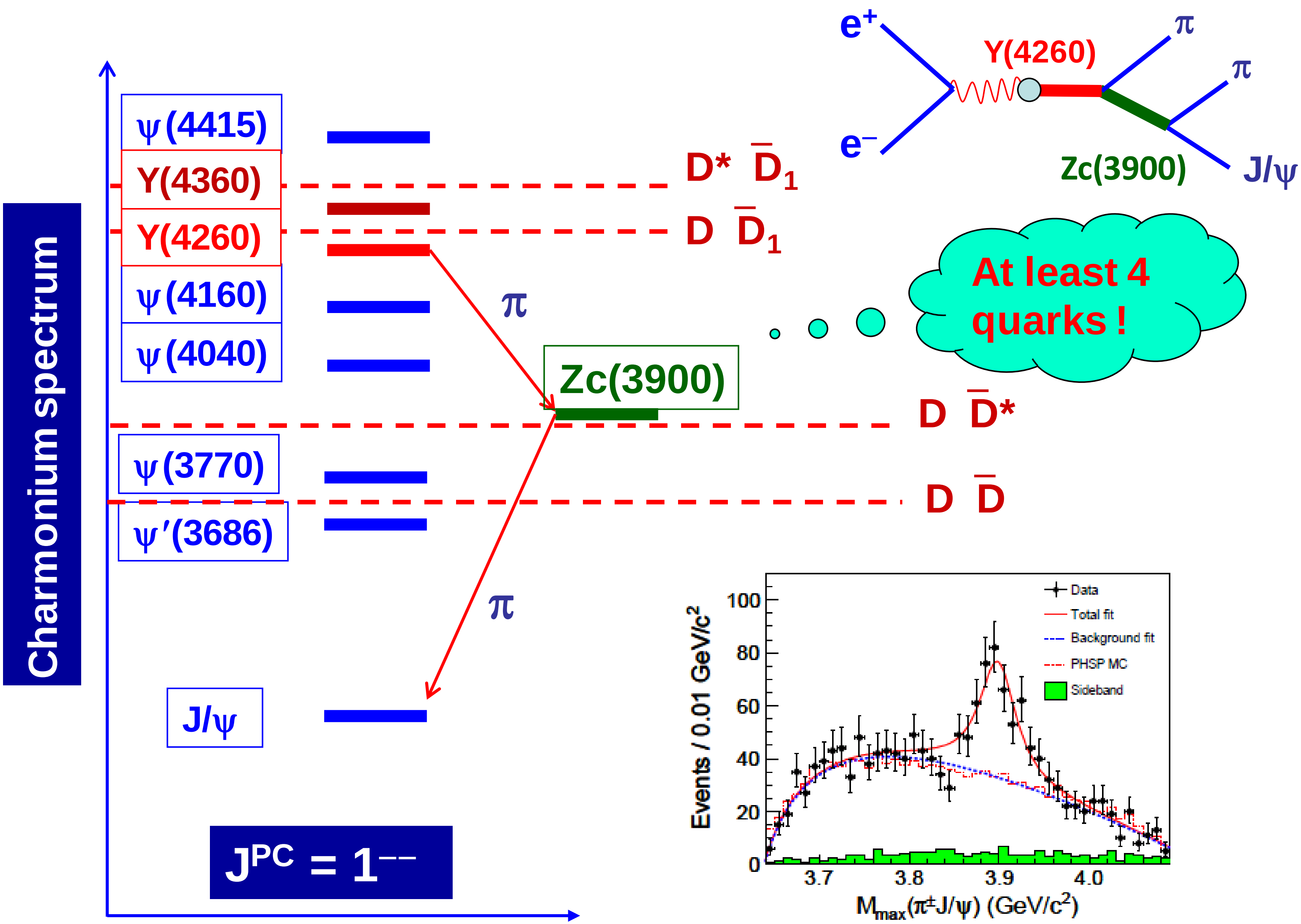
State	Mass	Centroid	Splitting (potential)	Splitting (induced)
1^1S_0	2979.9[a]	3067.6[b]	−90.5[e]	+2.8
1^3S_1	3096.9[a]		+30.2[e]	−0.9
2^1S_0	3638[a]	3674[b]	−50.1[e]	+15.7
2^3S_1	3686.0[a]		+16.7[e]	−5.2

E. Eichten, K. Lane, C. Quigg, PRD73, 014014 (2006)

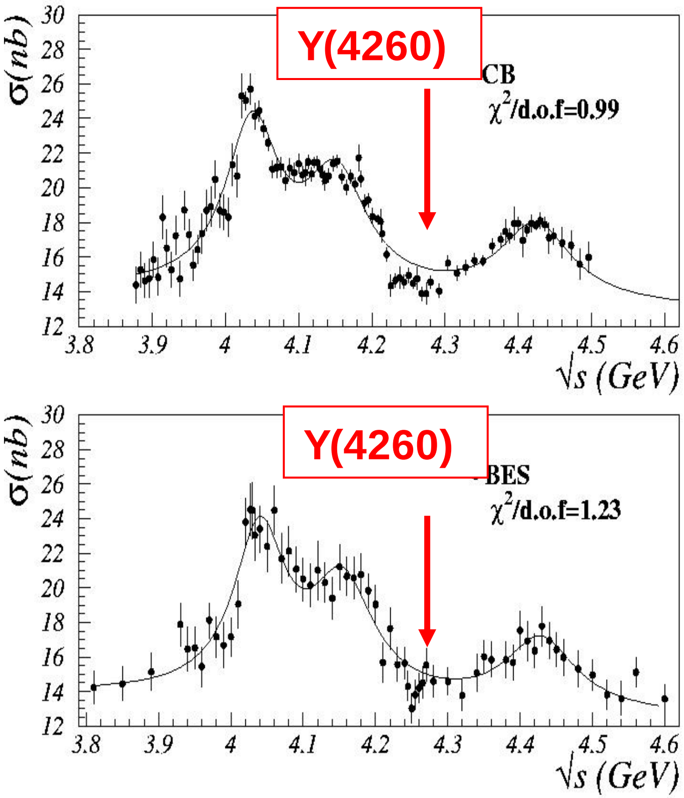
Some existing puzzles in the vicinity of the 1st open charm threshold ($D\bar{D}$) :

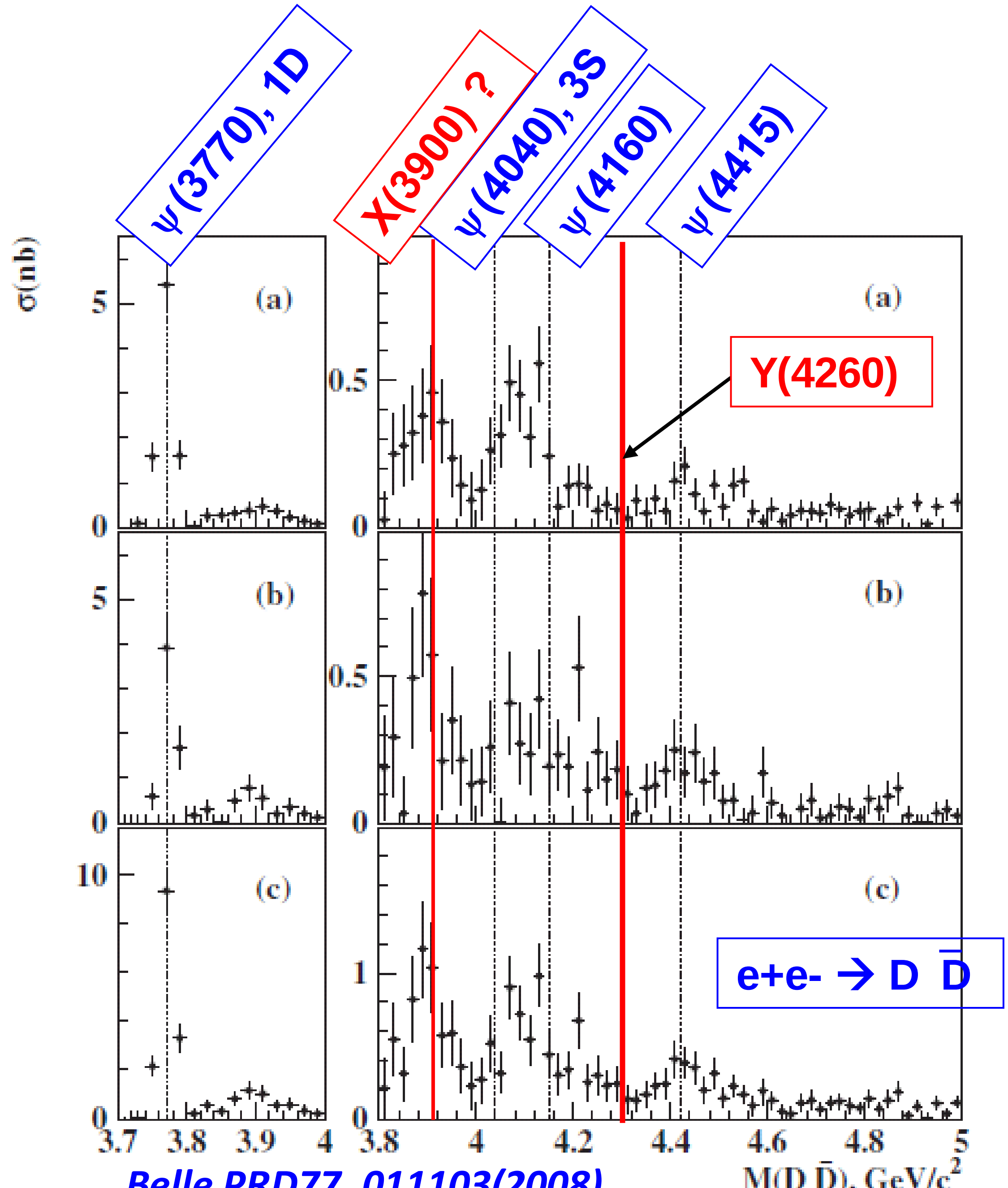
- **“$\rho\pi$ puzzle”**
- **$\psi(3770)$ non-$D\bar{D}$ decays**
- **Lineshape of $\psi(3770)$**
- **J/ψ and ψ' M1 transition problem**
- **ψ' and $\psi(3770)$ E1 transition puzzle**
- **……**

(III) The first S-wave open charm threshold in vector channel



$\sigma(e^+e^- \to$ hadrons$)$

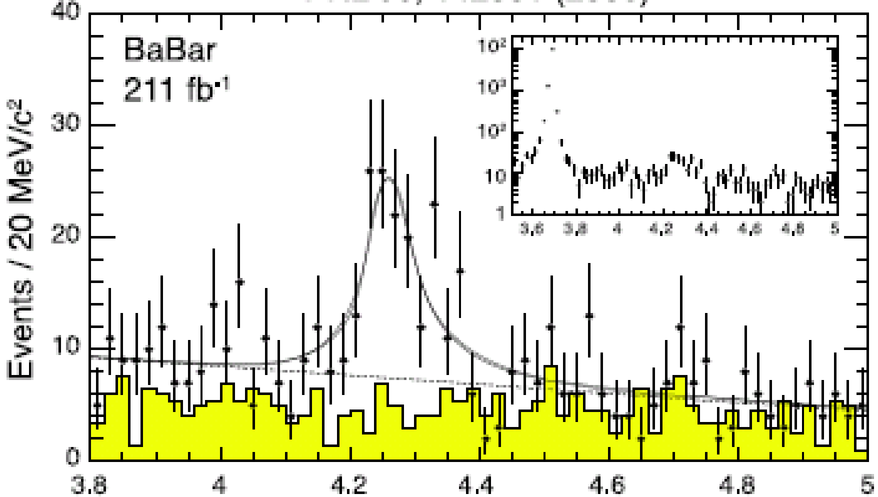




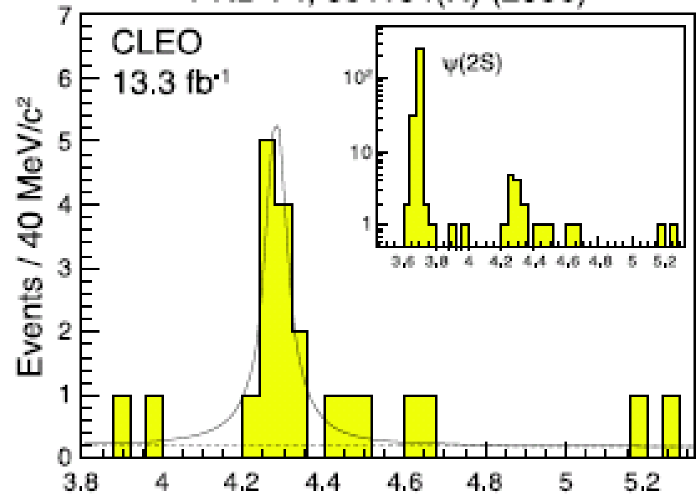
Belle PRD77, 011103(2008).

Observation of Y(4260) in J/ψ ππ spectrum

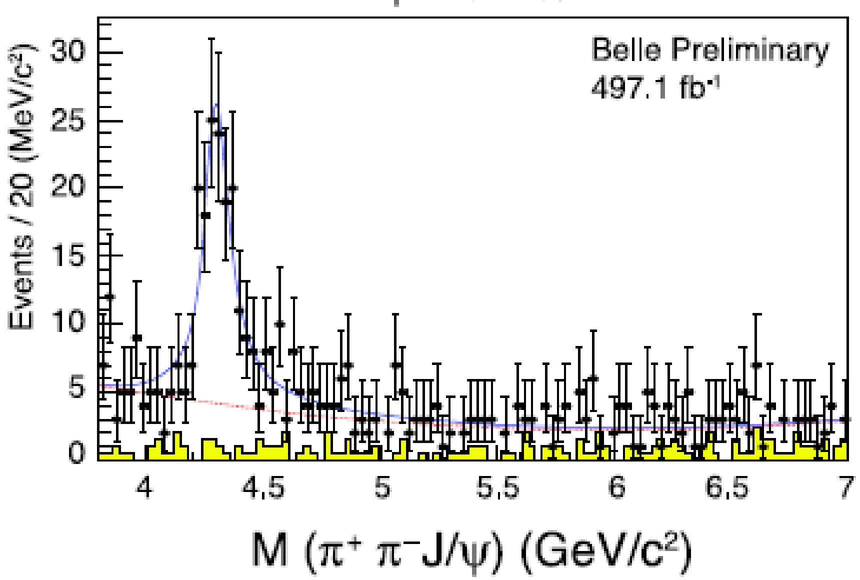
PRL 95, 142001 (2005)



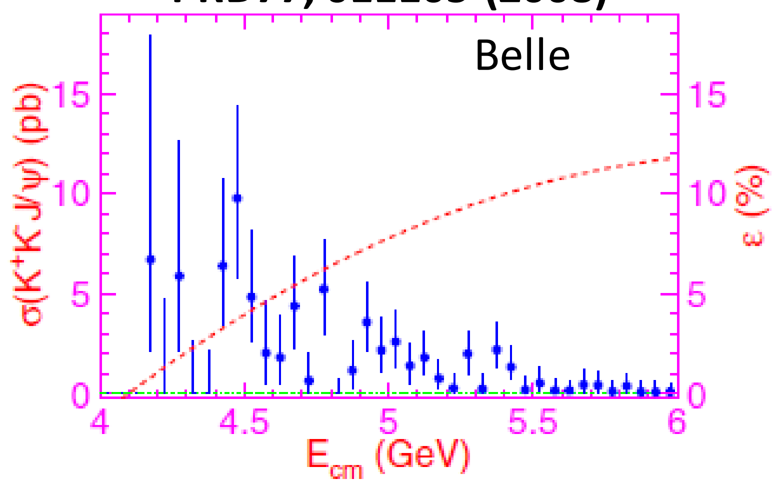
PRD 74, 091104(R) (2006)



hep-ex/0612006



PRD77, 011105 (2008)

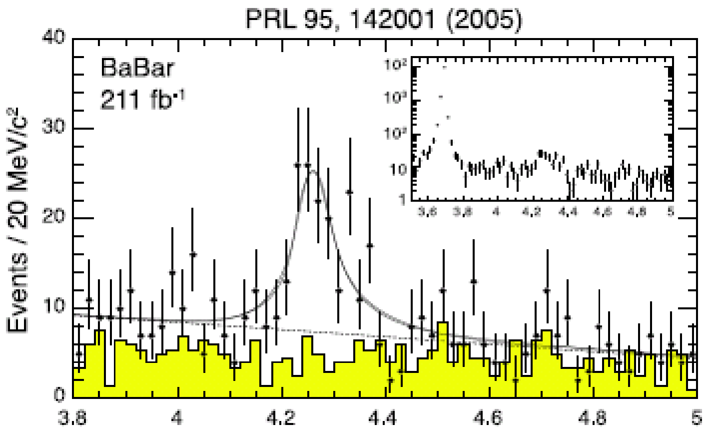


• Opportunities for a better understanding the nature of Y(4260)

Cited 485 times!

Theoretical prescriptions:

- Hybrid
- Tetraquark
- Glueball
- Hadronic molecules
- Interference effects



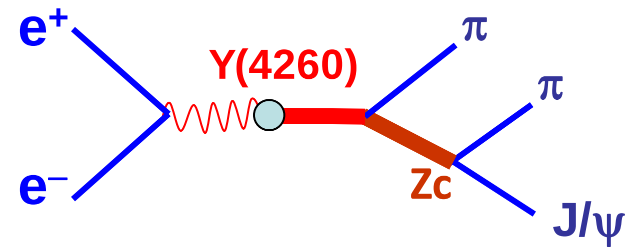
Calculations done by various approaches:

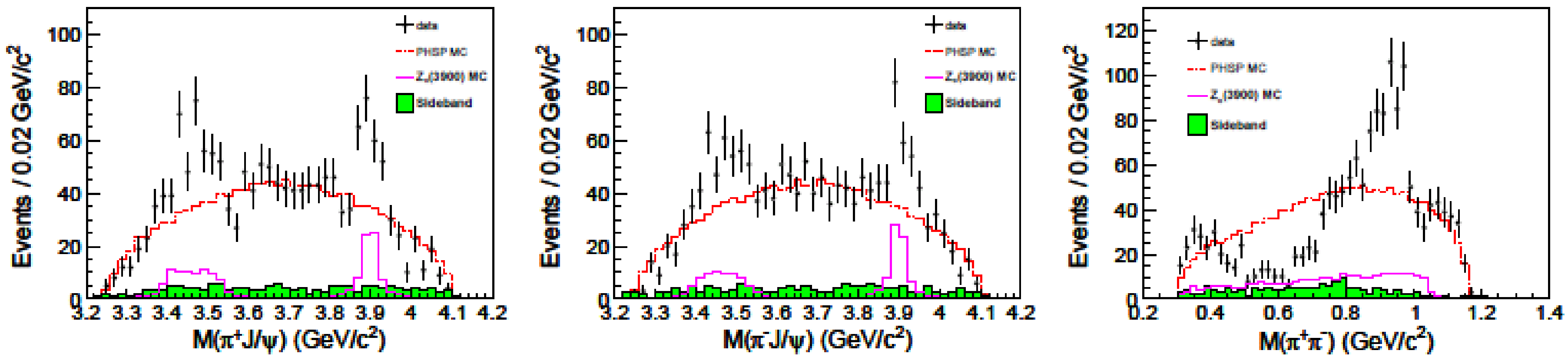
- Quark model
- Hadron interaction with effective potentials
- QCD sum rules
- Lattice QCD

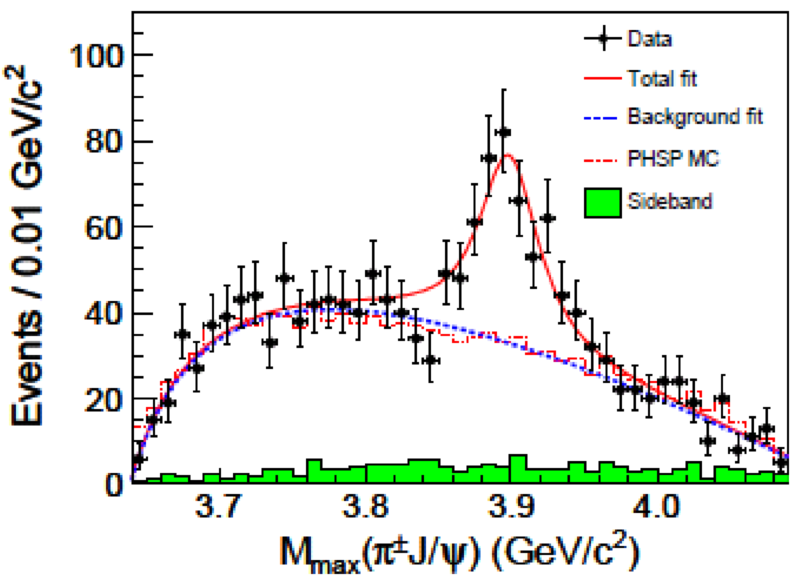
See 1010.5827[hep-ph] for a recent review.

- Hybrid state, F.E.Close and P.R.Page, PLB28(2005)215; S.L.Zhu, PLB625(2005)212; E. Kou and O. Pene, PLB631(2005)164
- Radial excitation of a diquark-antidiquark state analogous to X(3872), L.Maiani, F.Piccinini, A.D. Polosa and V. Riquer, PRD71(2005)014028
- D_1 D molecular state, G.J.Ding, PRD79(2009)014001; F. Close and C. Downum, PRL102(2009)242003; A.A.Filin, A. Romanov, C. Hanhart, Yu.S. Kalashnikova, U.G. Meissner and A.V. Nefediev, PRL105(2010)019101
- Strongly couple to $X_{c0}\omega$, M. Shi, D. L. Yao and H.Q. Zheng, hep-ph/1301.4004
- Hadro-quarkonium, M. Voloshin
- Inference effects, X. Liu et al
- ……

Observation of a charged charmoniumlike structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV



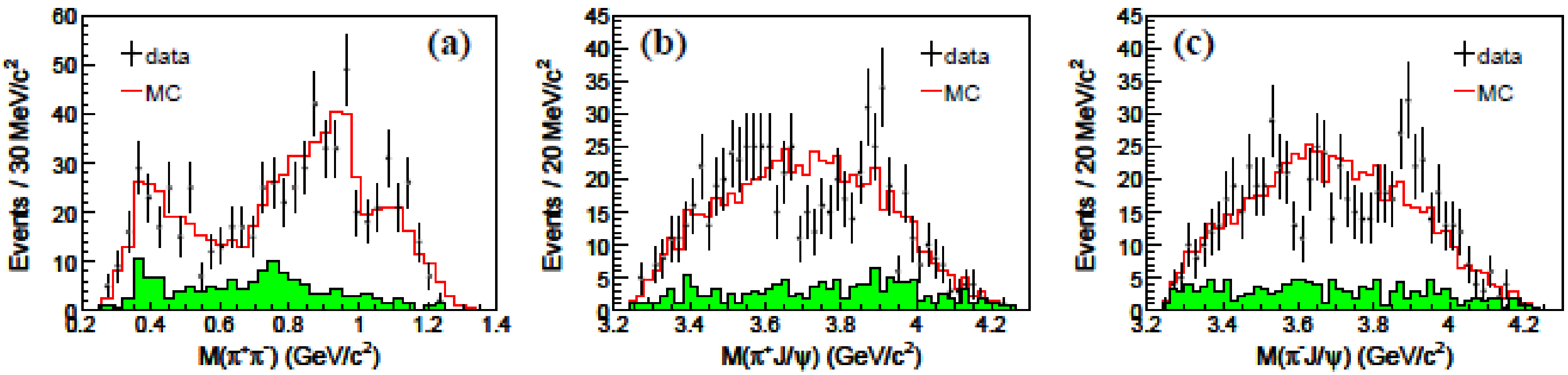




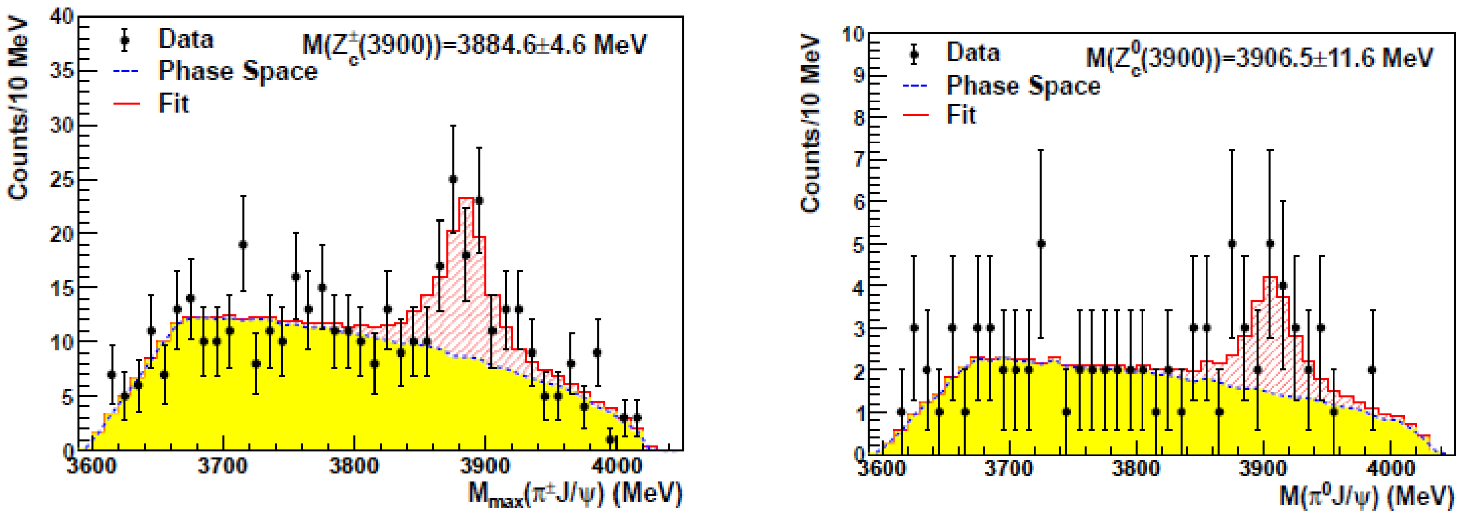
- The mass of the charged charmonium-like structure **Zc(3900)** is about 3.899 GeV, close to **DD* threshold**!
- It could be an opportunity for understanding the mysterious **Y(4260)**.

BESIII, PRL110, 252001 (2013) [arXiv:1303.5949 [hep-ex]]

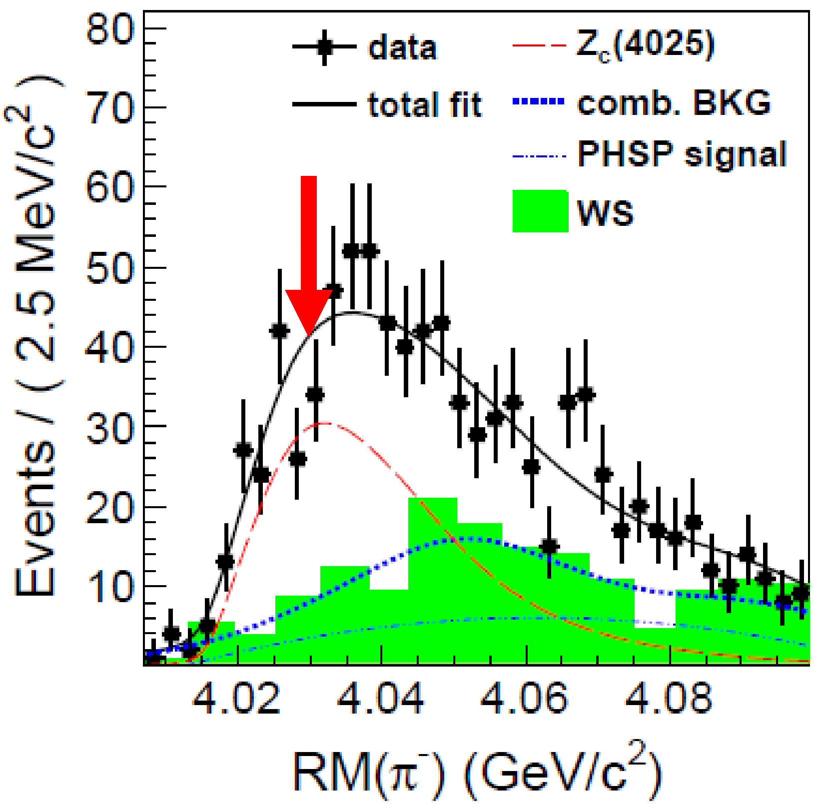
Belle, PRL110, 252002 (2013) [arXiv:1304.0121v1 [hep-ex]]



Xiao et al., arXiv:1304.3036v1 [hep-ex]



$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$



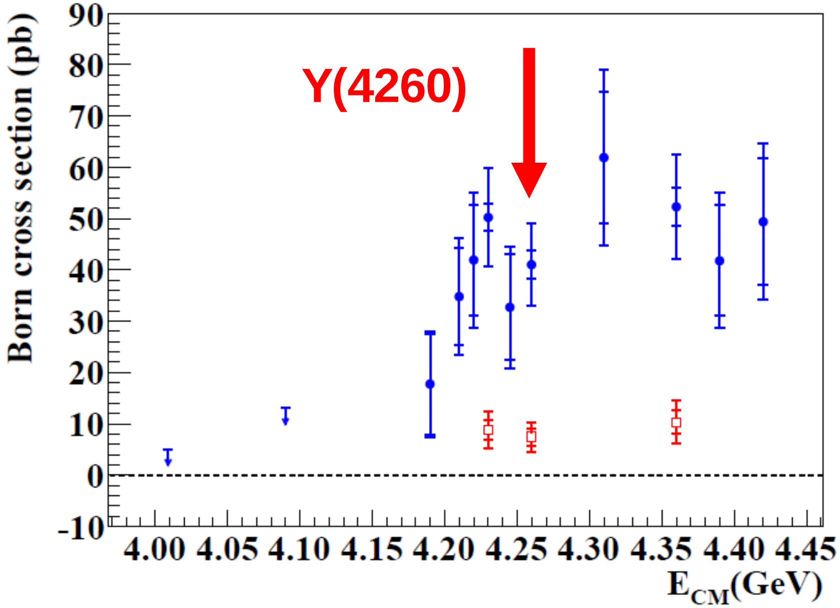
$\sqrt{s} = 4.26\,\text{GeV}$

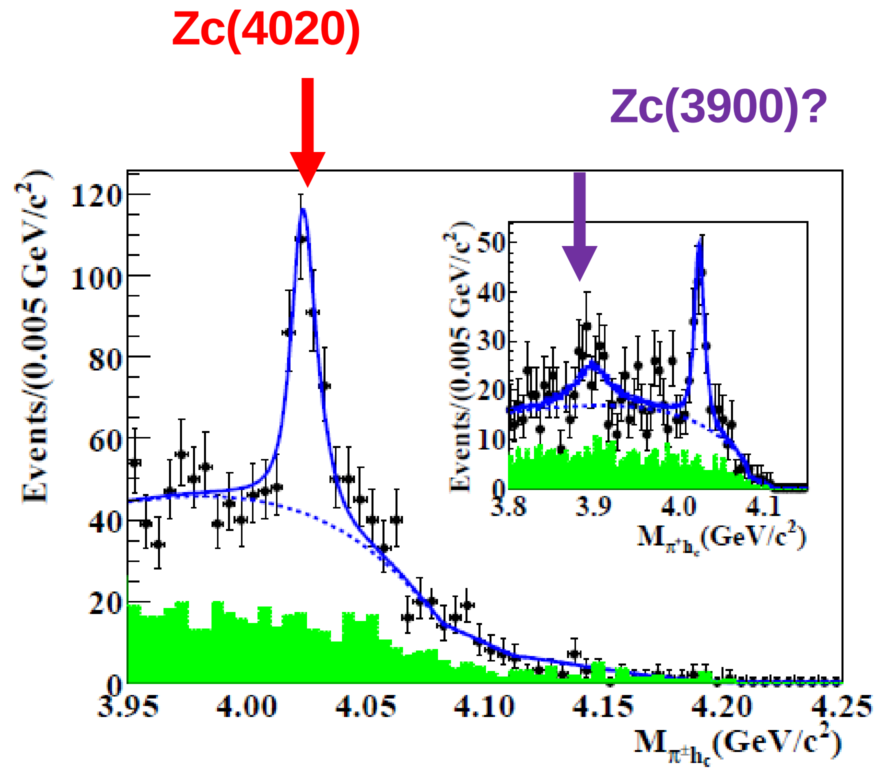
$m(Z_c^+(4025)) = (4026.3 \pm 2.6)\,\text{MeV}/c^2,$

$\Gamma(Z_c^+(4025)) = (24.8 \pm 5.6)\,\text{MeV}.$

BESIII Collaboration, arXiv:1308.2760 [hep-ex]

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





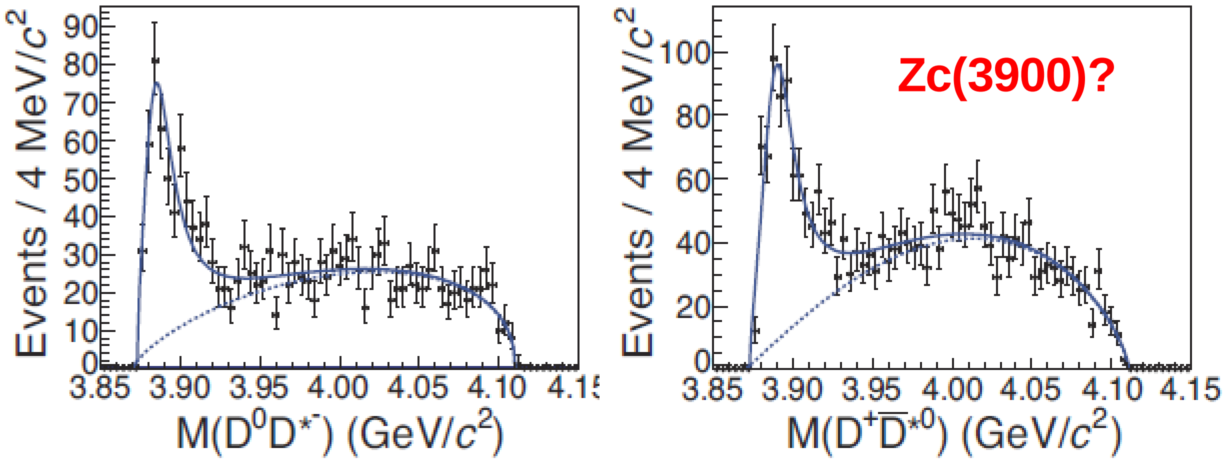
m(Zc(4020)) = $(4022.9 \pm 0.8 \pm 2.7)\ \mathrm{MeV}/c^2$

Γ(Zc(4020)) = $(7.9 \pm 2.7 \pm 2.6)\ \mathrm{MeV}$

Both Zc(4025) and Zc(4020) are close to the $\bar{D}^*D^*$ threshold. Are they the same state?

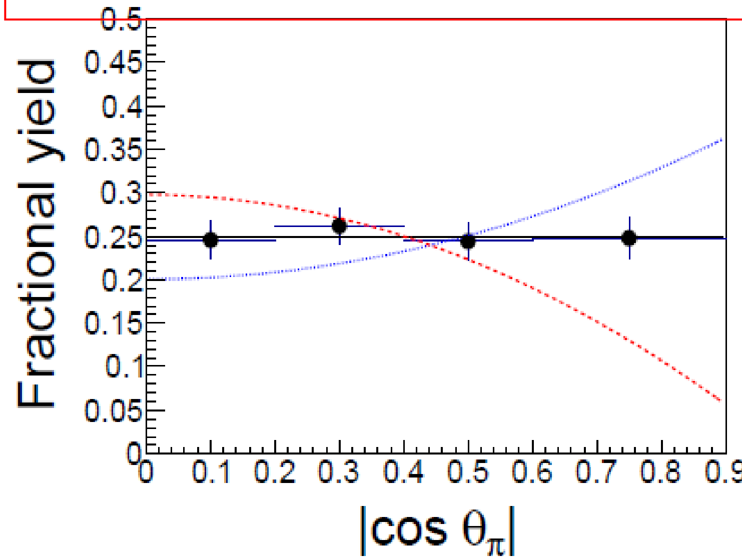
BESIII Collaboration, arXiv:1309.1896 [hep-ex]

$$e^+e^- \to \pi D\bar{D}^* \text{ at } \sqrt{s} = 4.26 \text{ GeV}$$



Tag	$M_{\text{pole}}(\text{MeV}/c^2)$	$\Gamma_{\text{pole}}(\text{MeV})$
π^+D^0	3882.3 ± 1.5	24.6 ± 3.3
π^-D^+	3885.5 ± 1.5	24.9 ± 3.2

Direct determination of the spin-parity!



$J^P = 1^-$

$J^P = 1^+$

$J^P = 0^-$

BESIII Collaboration, arXiv:1310.1163 [hep-ex]

BESIII, PRL110, 252001 (2013) [arXiv:1303.5949 [hep-ex]]

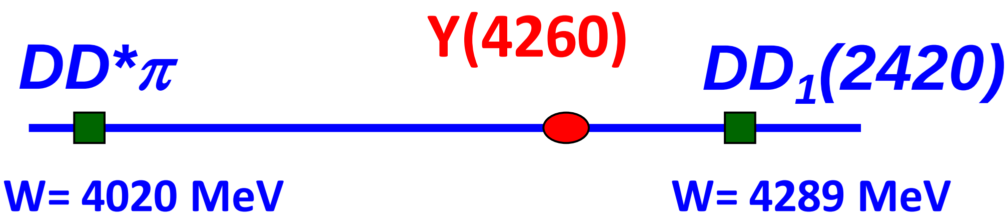
Cited 138 times and significantly contributed by Chinese theorists! (HQEFT, QCDSR, QM, preli. LQCD, …)

Theoretical interpretations:

- **Hadro-quarkonium (M. Voloshin *et al*.)**
- **Tetraquark (L. Maiani *et al.*)**
- **Born-Oppenheimer tetraquark (E. Braaten)**
- **Hadron loops (X. Liu *et al*.)**
- **Hadronic molecule produced in a singularity condition (Q. Wang, C. Hanhart, Q.Z.)**
- **… …**

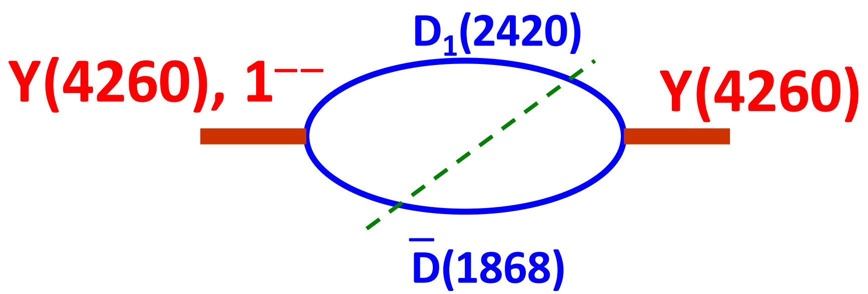
- **Would Zc(3900) and Zc'(4020/4025) be an analogue of the Zb and Zb' in the charm sector?**
- **How those states are formed? Are there always "thresholds" correlated?**
- **What is the dominant decay channel of Zc and Zc' ?**
- **What can we learn about the production mechanism for Zc and Zc' from the lineshape measurement of J/psi pipi and hcpipi ?**
- **How to distinguish various proposed scenarios?**
- **… …**

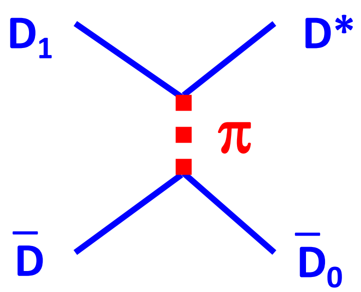
Y(4260) could be a hadronic molecule made of $DD_1(2420)$



- $D\ (c\bar{q}),\ J^P=0^-$;
- $D^*(c\bar{q}),\ J^P=1^-$;
- $D_1\ (c\bar{q}),\ J^P=1^+$.

"threshold state"

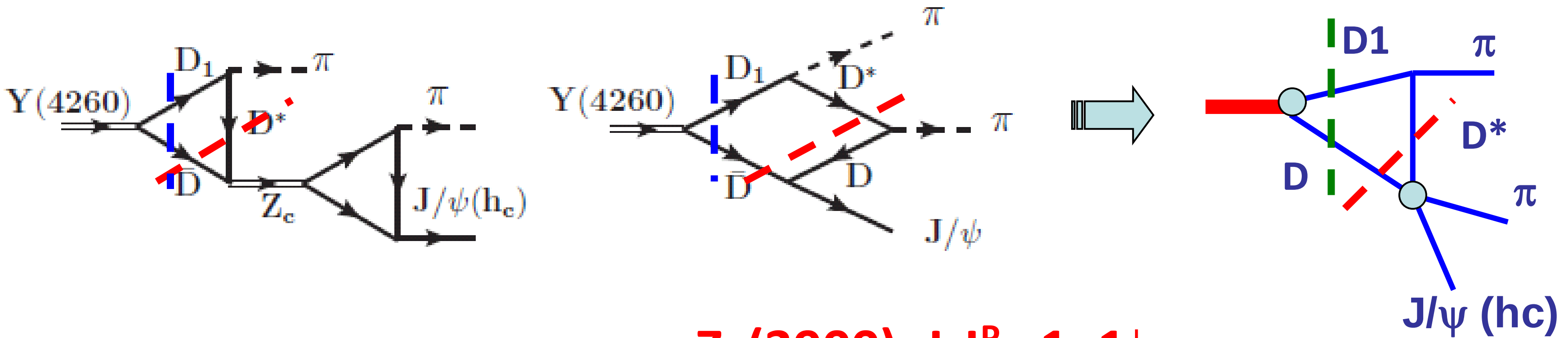




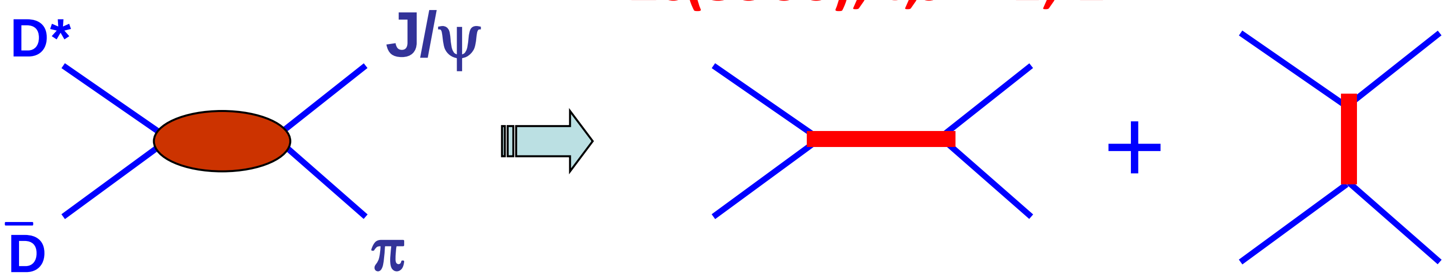
Q. Wang, C. Hanhart, QZ, PRL111, 132003 (2013); PLB(2013)

- The signature of Y(4260) could be revealed by the associated Zc(3900) near the DD* threshold via "triangle singularity"!

[J.-J. Wu, X.-H. Liu, B.-S. Zou, and Q. Zhao, PRL108, 081003 (2012)]



Zc(3900), $I, J^P = 1, 1^+$



$M(Zc) \cong M(D) + M(D^*) = 3.876$ GeV

A systematic study of the singularity regions in e+e- → J/psi pipi, hc pipi and DD*pi is necessary.

Lagrangians in the NREFT

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

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

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

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

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

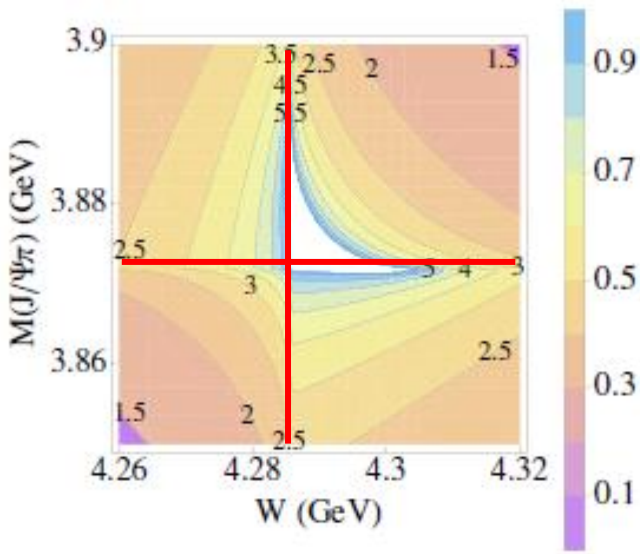
$$Z_{ba}^i = \begin{pmatrix} \frac{1}{\sqrt{2}} Z^{0i} & Z^{+i} \\ Z^{-i} & -\frac{1}{\sqrt{2}} Z^{0i} \end{pmatrix}_{ba} \qquad P(V) = \left(D^{(*)0}, D^{(*)+}\right)$$

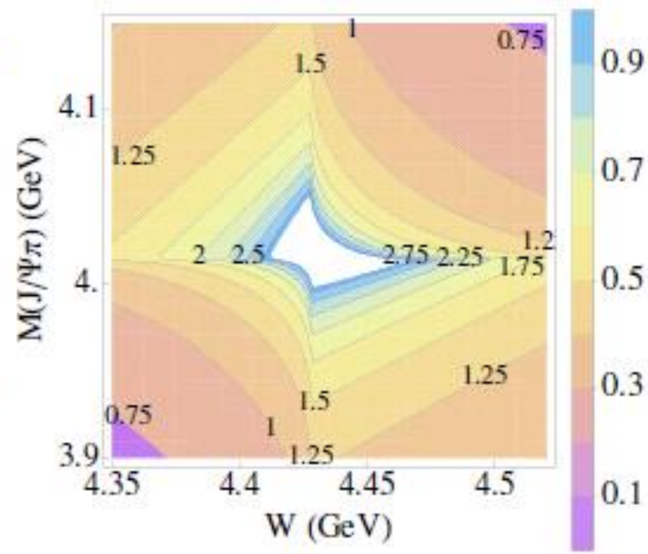
- **D1D*pi coupling:**

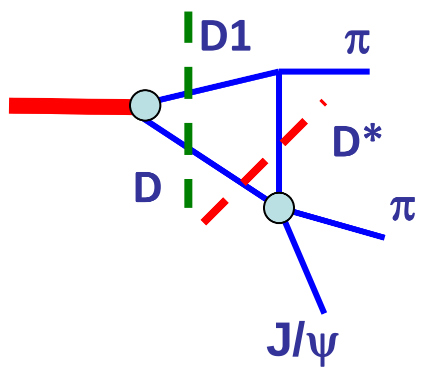
$$\mathcal{L}_{D_1} = i\frac{h'}{f_\pi}\Big[3D_{1a}^i(\partial^i\partial^j\phi_{ab})D_b^{*\dagger j} - D_{1a}^i(\partial^j\partial^j\phi_{ab})D_b^{*\dagger i}$$
$$-3\bar{D}_a^{*\dagger i}(\partial^i\partial^j\phi_{ab})\bar{D}_{1b}^j + \bar{D}_a^{*\dagger i}(\partial^j\partial^j\phi_{ab})\bar{D}_{1b}^i\Big]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

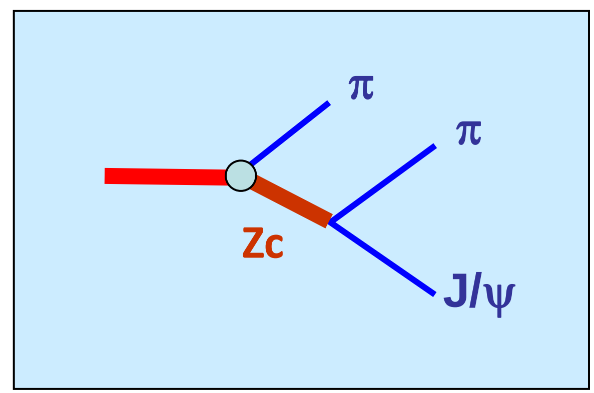
Q. Wang, C. Hanhart, QZ, PRL111, 132003 (2013); PLB(2013)

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







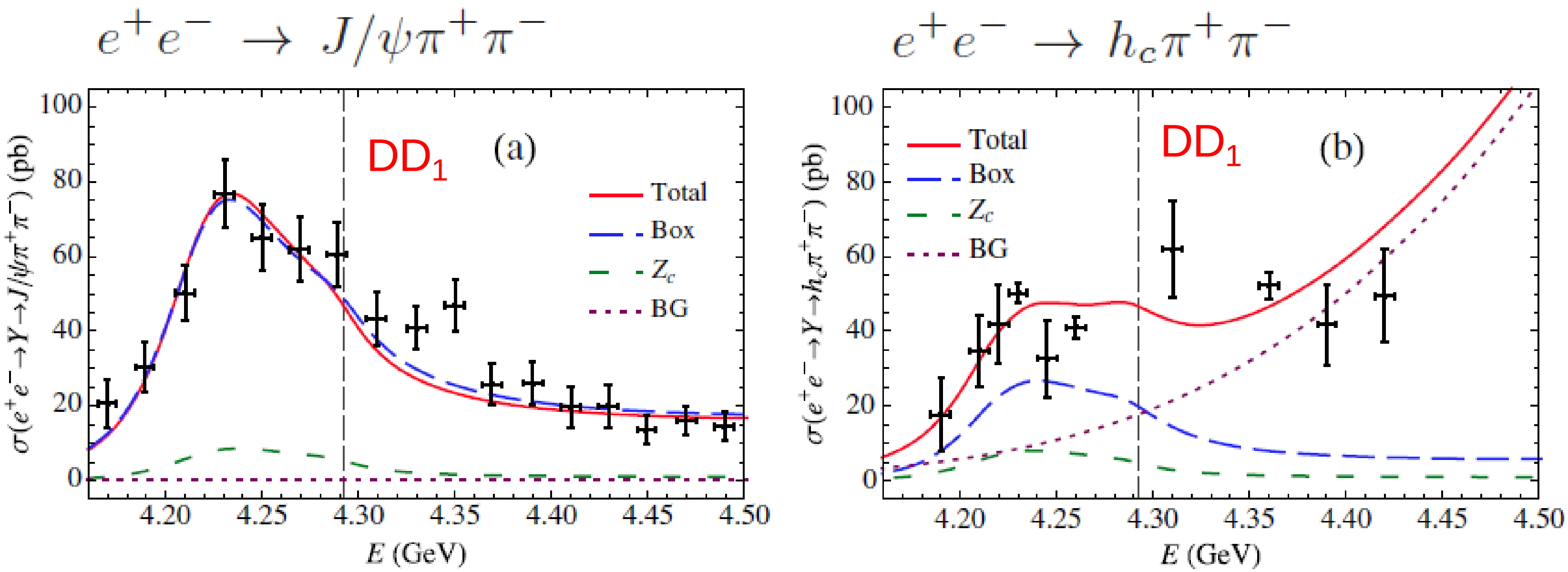


$\Gamma(D_1(2420)) = 27$ MeV

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

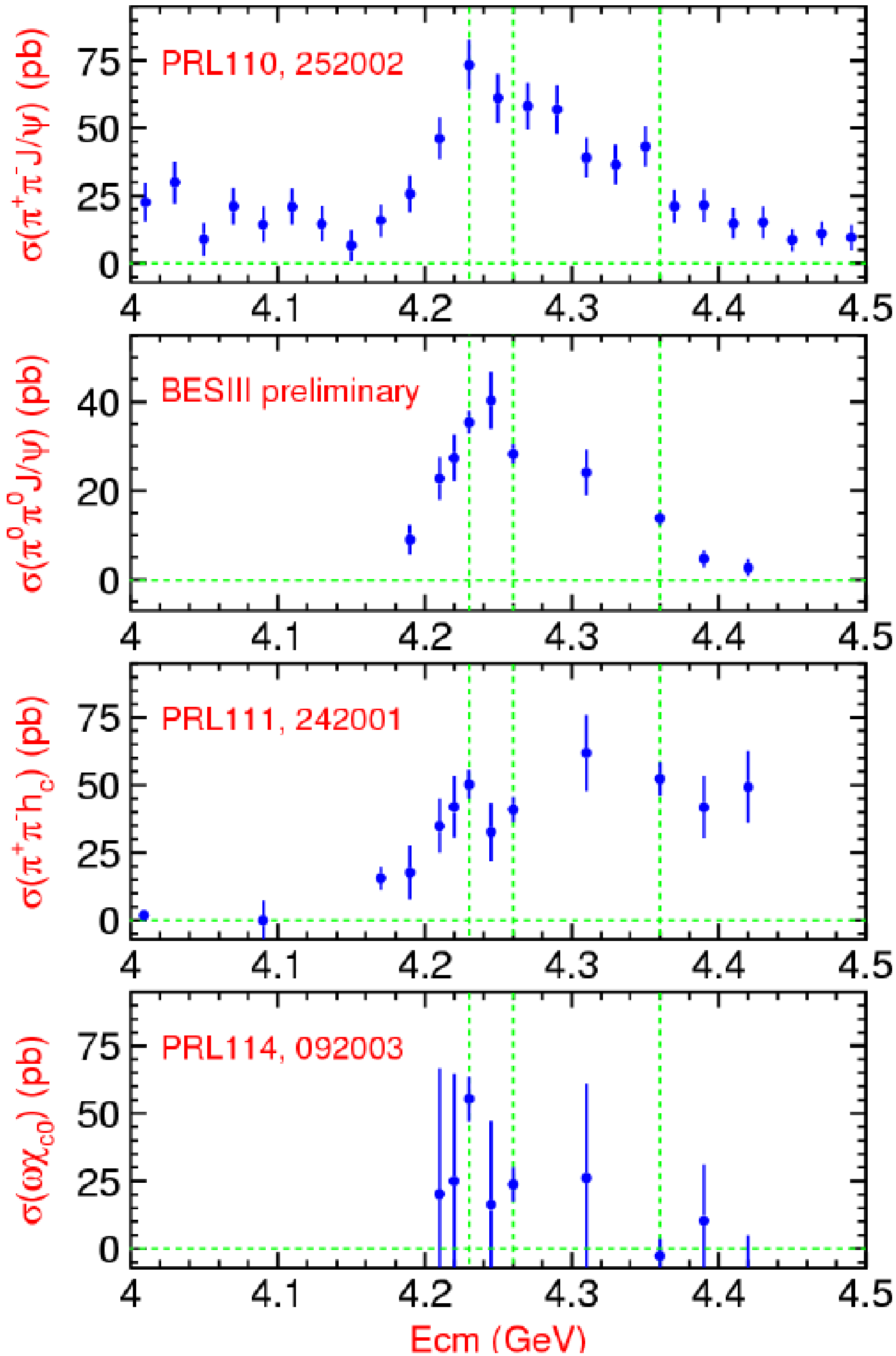
Q. Wang, C. Hanhart, Q. Zhao, PLB2013; arXiv: 1305.1997[hep-ph];

Liu, Oka, and Q. Zhao, arXiv: 1507.01674[hep-ph]

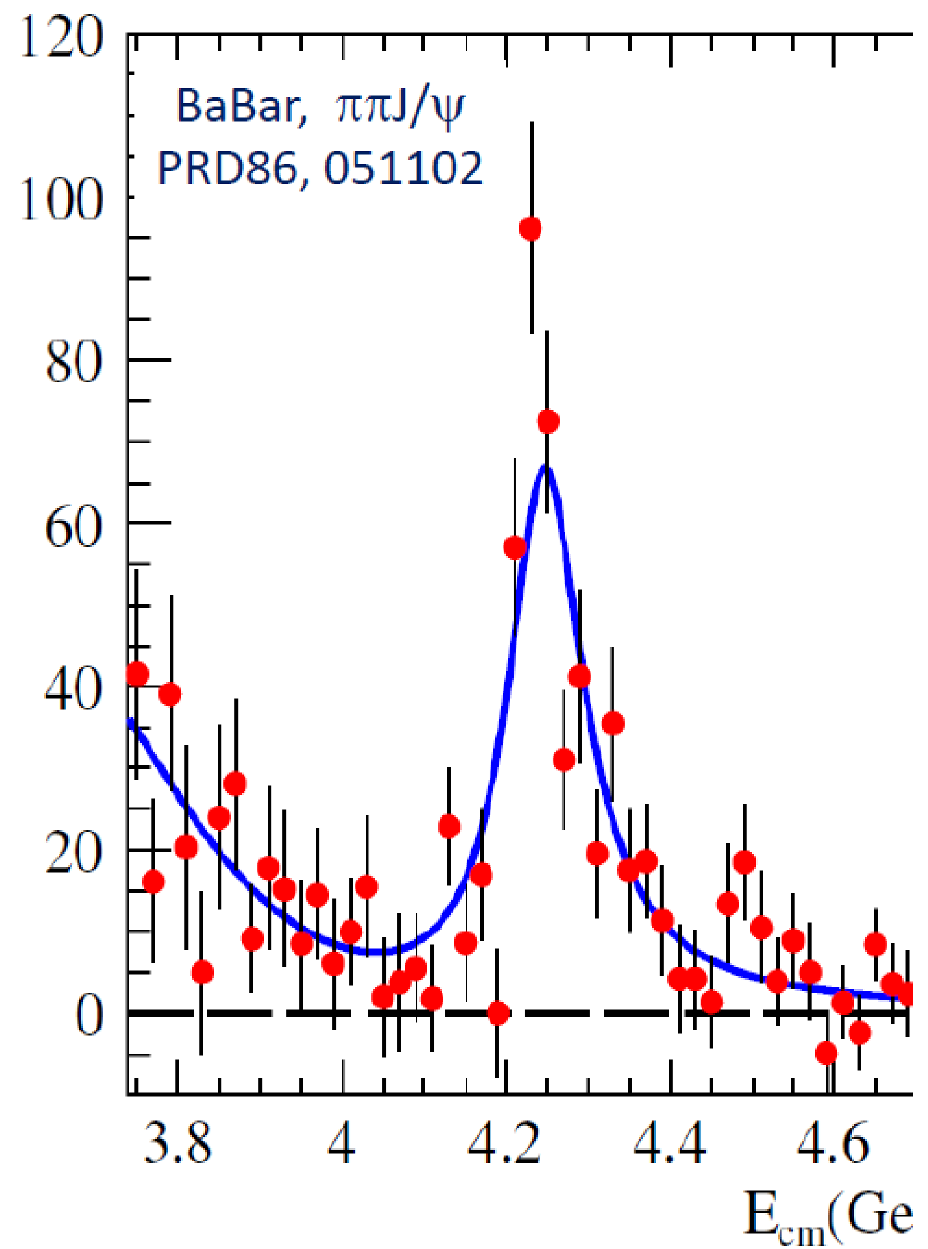


- **Where is the peak position and pole position of Y(4260)?**
- **Is the J/psi pipi the dominant decay channel for Y(4260)?**
- **How to understand the non-trivial lineshape of the hc pipi channel?**
- **Could the exclusive channel cross section lineshape provide more information about the nature of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

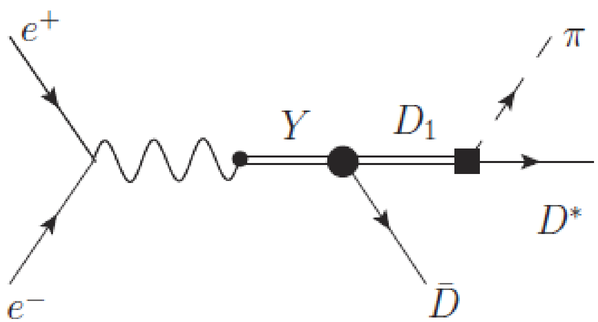
M. Cleven, Q. Wang, C. Hanhart, U.-G. Meissner, and Q. Zhao, 1310.2190; PRD90, 074039 (2014)

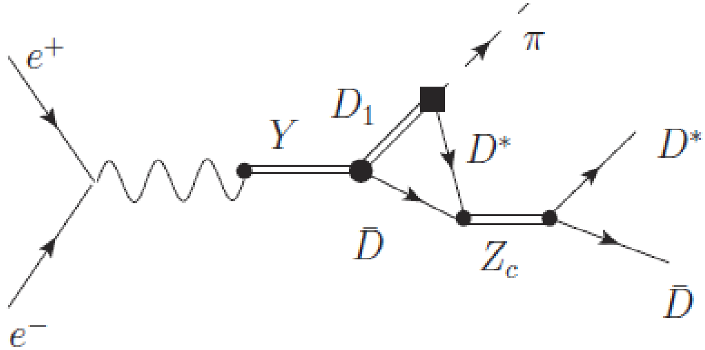


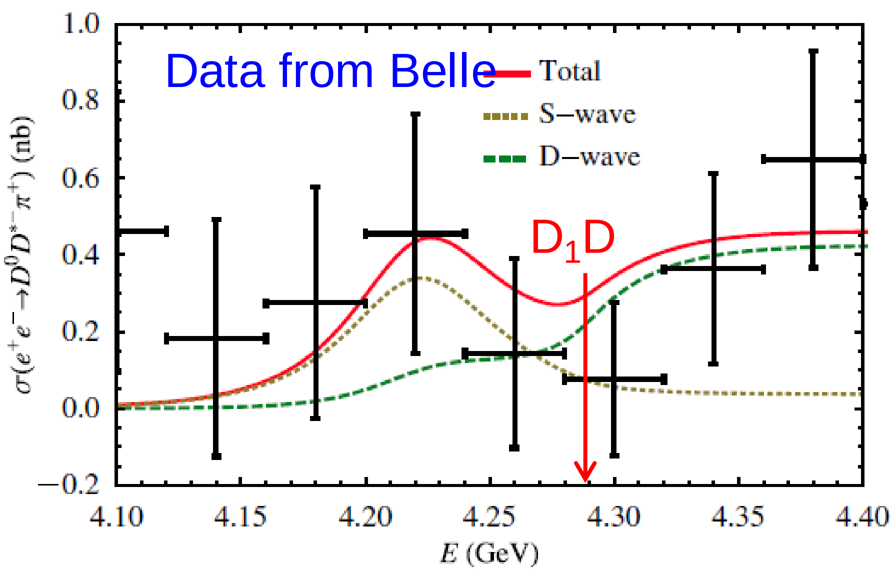
Slide from C.Z. Yuan



If a hadronic molecule component exists: the DD*pi should be the dominant decay channel with a non-trivial lineshape!



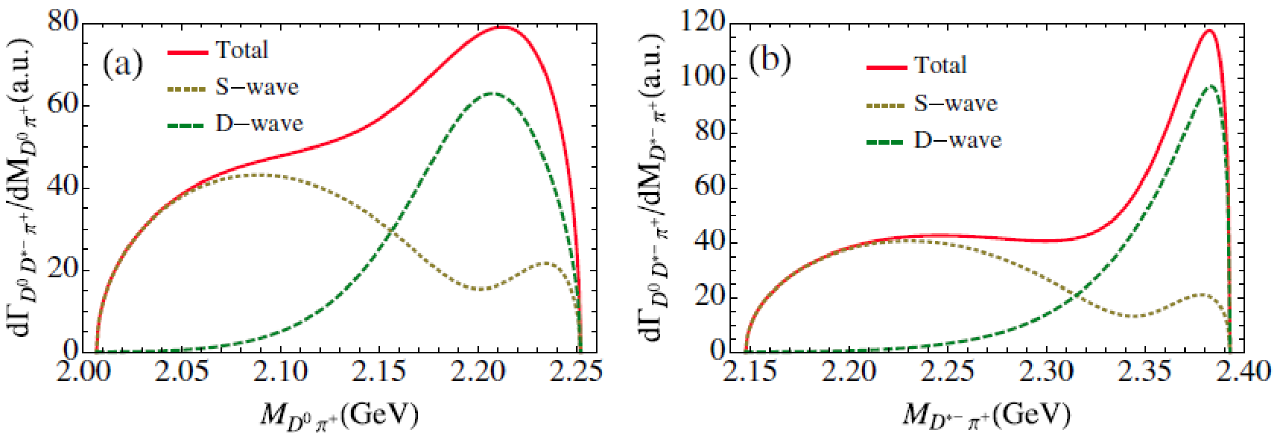




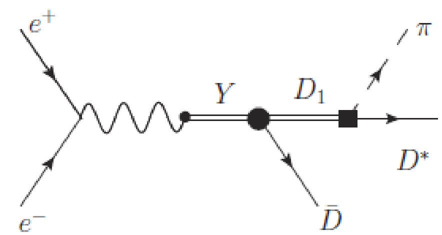
The **narrow** D1(2420) decay into D* pi is dominantly via a **D wave**.

$$\mathcal{M}_{D\bar{D}^*\pi} = \epsilon_Y^a \epsilon_{\bar{D}^*}^b \Big[C_S \delta^{ab} + C_D(E, M_{D\bar{D}^*}, M_{\bar{D}^*\pi}) \times \left(\hat{q}^a \hat{q}^b - \frac{1}{3}\delta^{ab} \right) \Big]$$

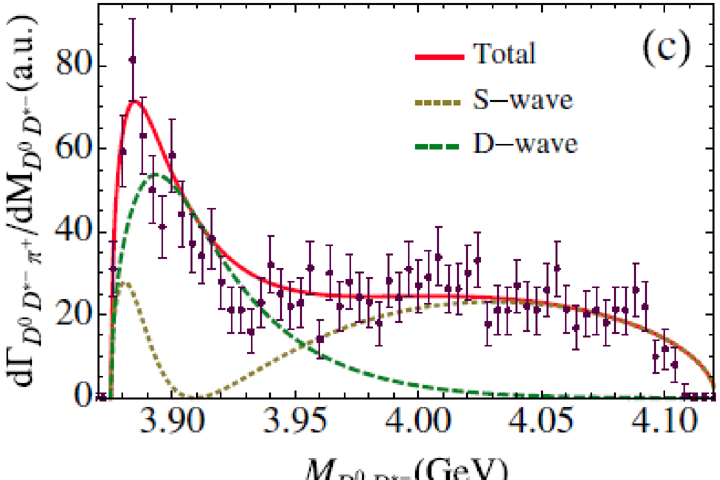
Invariant mass spectra for $D\pi$, $D^*\pi$, and $\bar{D}D^*$



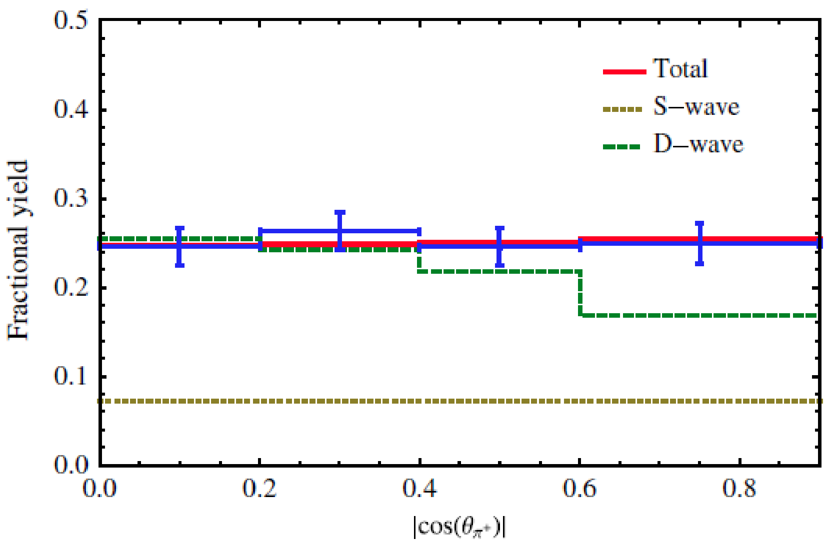
Signature for $D_1(2420)$ via the tree diagram.

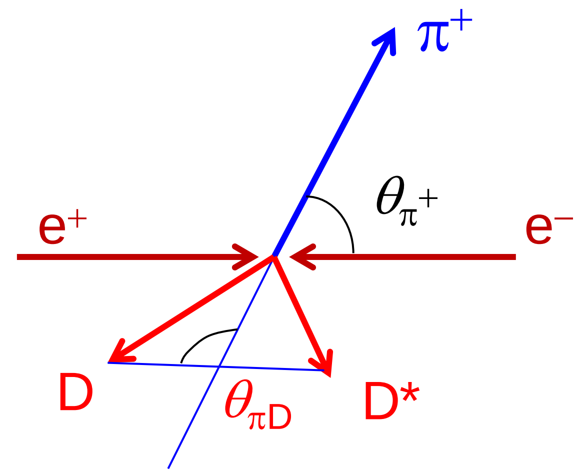


The Zc(3900) could have a pole below the DD* threshold.

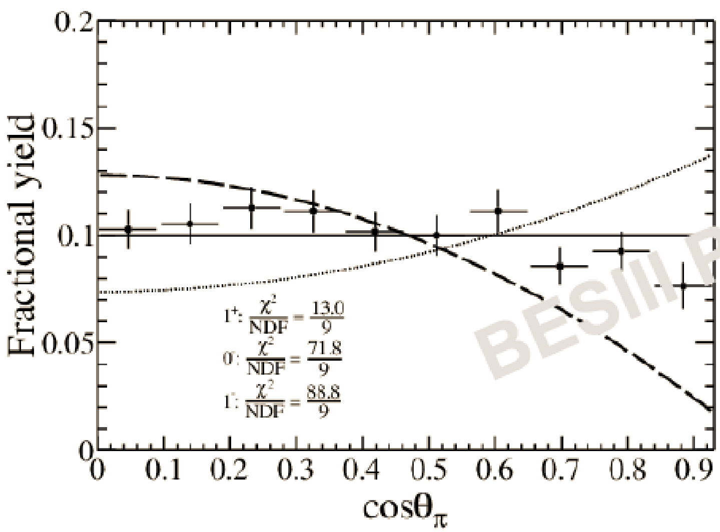


Angular distribution analysis

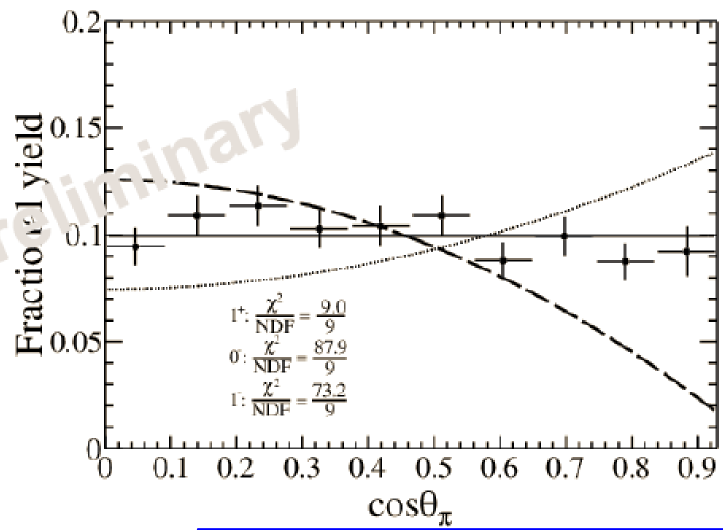




$e^+e^- \to \pi^+(D^0D^{*-})$.



$e^+e^- \to \pi^+(D^-D^{*0})$.



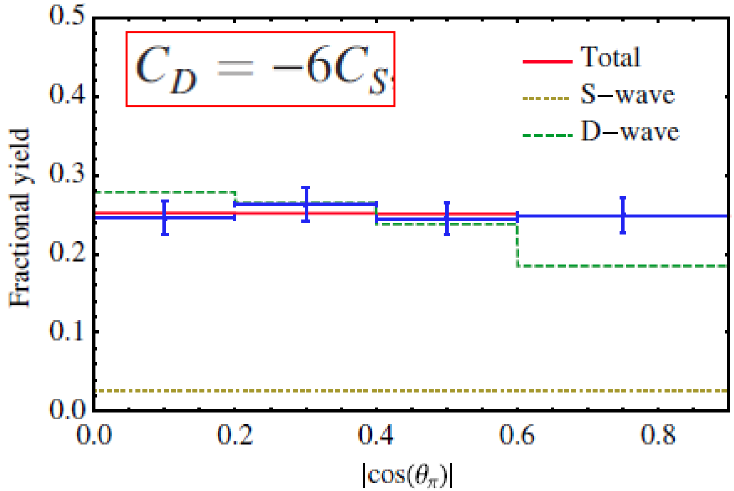
Yuping Guo, talk at QCD Exotics

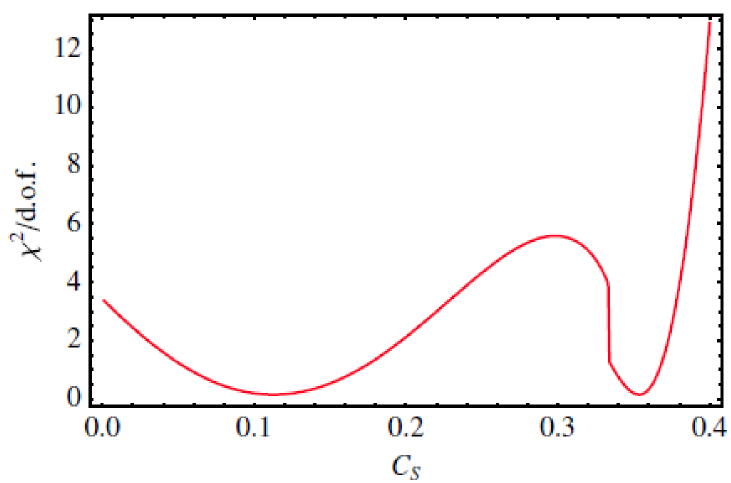
How a D wave can be present?

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

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

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

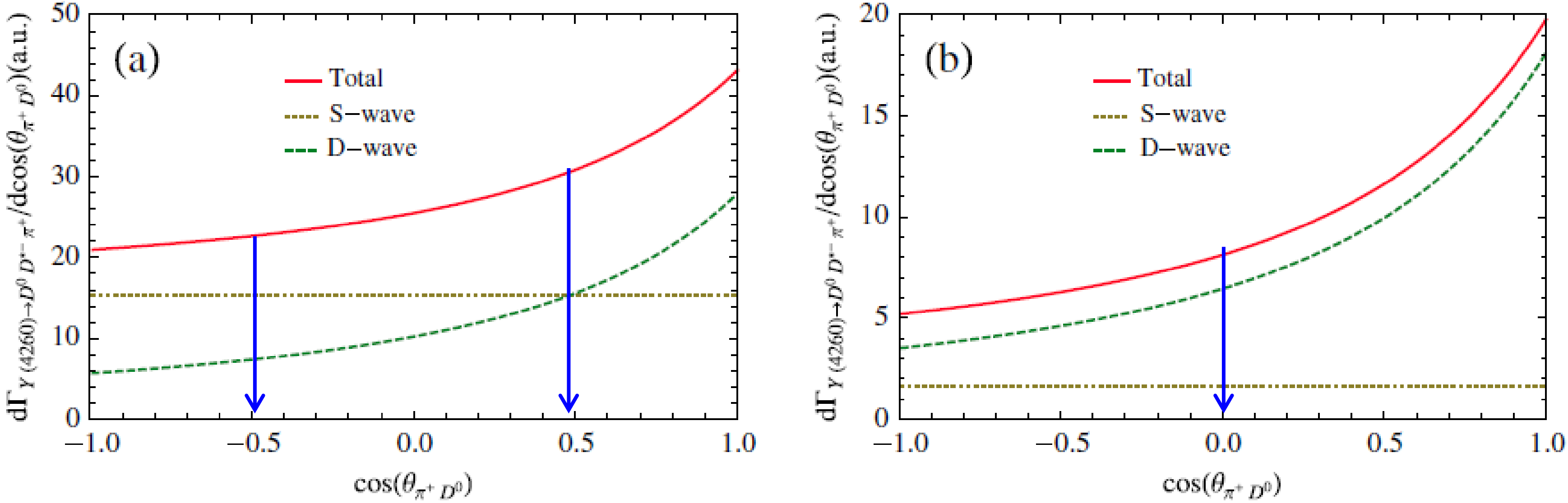




The asymmetry of events between $|\cos(\theta_{\pi D})| > 0.5$ and $|\cos(\theta_{\pi D})| < 0.5$,

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

A = { 0.0 S wave; 0.11 D wave; 0.05 S+D }



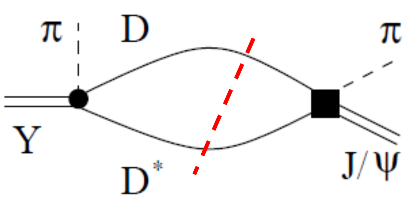
Forward–backward asymmetry for the DD* peak:

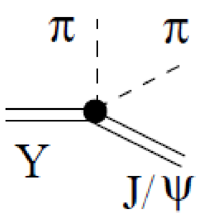
$$\mathcal{A}_{fb} = \frac{n_{>0} - n_{<0}}{n_{>0} + n_{<0}}.$$

= { **0.0** S wave; **0.37** D wave; **0.16** S+D }

(IV) How to distinguish a near-threshold pole from kinematic effects

One loop diag. **Contact interaction**



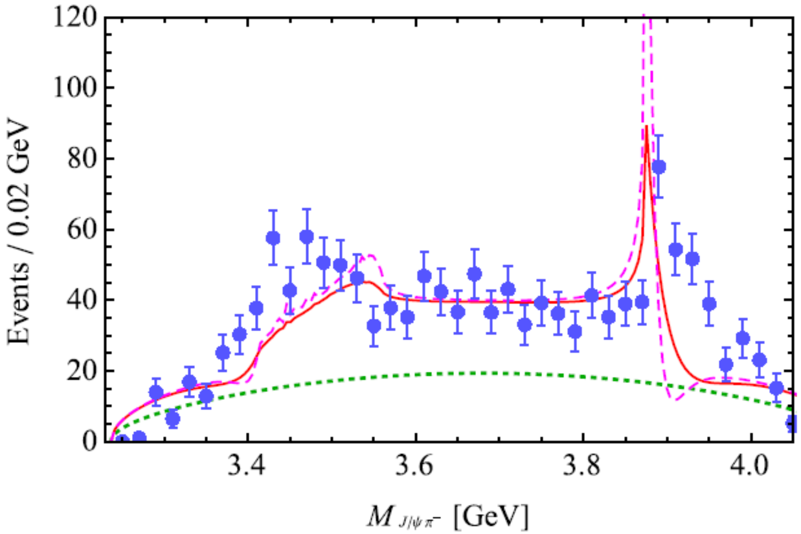


$$\mathcal{L}_I = g_{\psi Y}\psi^{\mu\dagger}\pi\pi Y_\mu + g_\psi \psi^{\mu\dagger}\pi D\bar{D}^*_\mu$$

$$T_1 = g_{\psi Y} - g_Y G_\Lambda(E) g_\psi$$

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3}\frac{f_\Lambda(\vec{q}^{\,2})}{E - m_1 - m_2 - \vec{q}^{\,2}/(2\mu)}$$

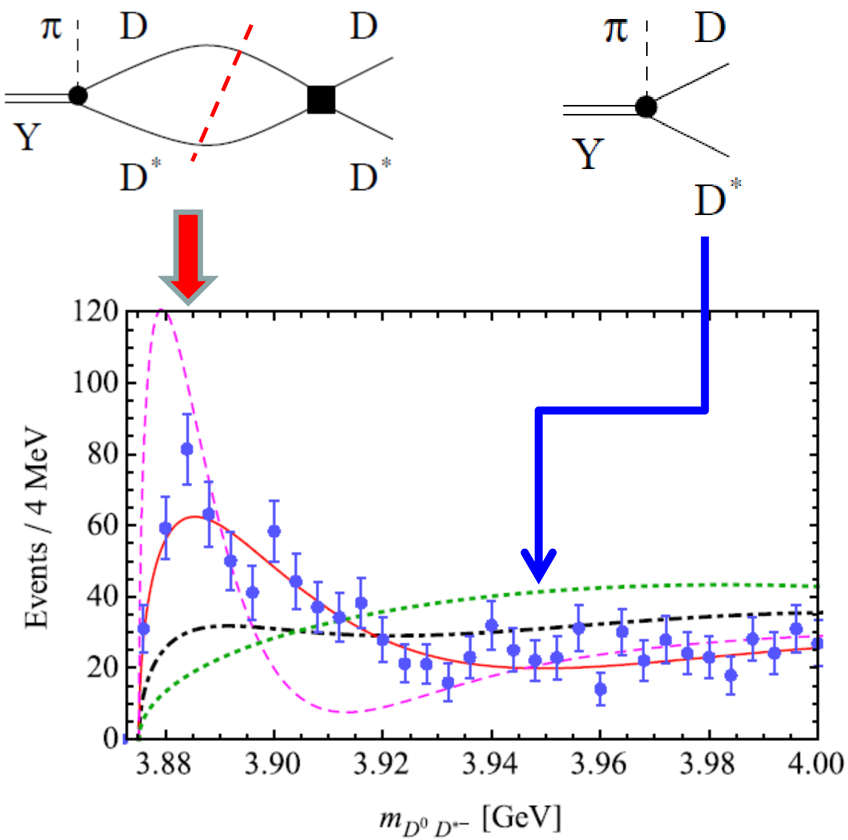
$$f_\Lambda(\vec{p}^{\,2}) = \exp\left(-2\vec{p}^{\,2}/\Lambda^2\right)$$



- **Can Zc(3900) be caused by pure kinematic effects?**
- **Can Zc(3900) be a genuine state?**
- **How to judge the parameters physically meaningful or not?**

See also talk by Q. Wang

One loop diag. **Contact interaction**



$$\mathcal{L}_I = g_Y \pi (D\bar{D}^*_\mu)^\dagger Y^\mu + \frac{C}{2}(D\bar{D}^*)^\dagger (D\bar{D}^*)$$

$$T_1 = g_Y \left[1 - G_\Lambda(E)C\right]$$

$$T_2 = g_Y \left[1 - G_\Lambda(E)C + (G_\Lambda(E)C)^2\right]$$

…

Strong elastic scattering amp. requires summation of all bubble diagrams which will inevitably generate a pole:

$$T = g_Y / [1 + G_\Lambda(E)\, C]$$

Guo, Hanhart, Wang and Zhao, PRD (2015), arXiv:1411.5584[hep-ph]

(V) Prospects from different scenarios

Theoretical models for XYZ states:

- Hadro-quarkonium (Voloshin)
- Tetraquark (Maiani, Polosa, et al.)
- Born-Oppenheimer tetraquark (Braaten)
- Hadron loop CUSP (Bugg, Swanson, Liu, et al.)
- Hadronic molecule produced in a singularity condition for hadron loops

See e.g. M. Cleven, F.-K. Guo, C. Hanhart, Q. Wang, Q.Z., arXiv:1505.01771 [hep-ph]

4. Summary

Huge puzzling questions on charmonium-like states!

Theory:

- Self-consistent method
- Systematic analysis of various processes
- Better understanding of threshold structures

Experiment:

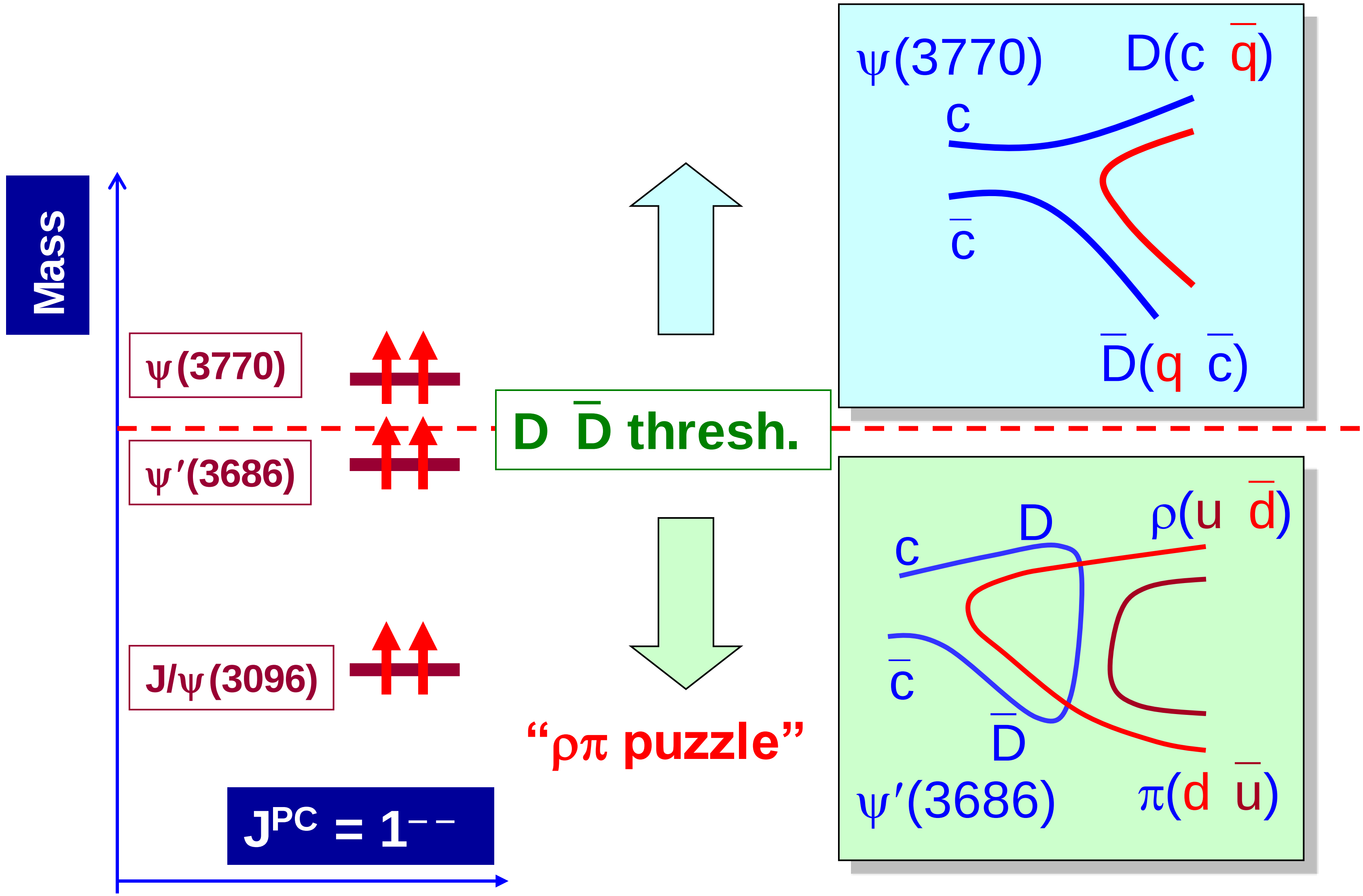
- Detailed lineshape measurement
- Angular distributions of exclusive channels

→ **Large data sample with detailed energy scan**

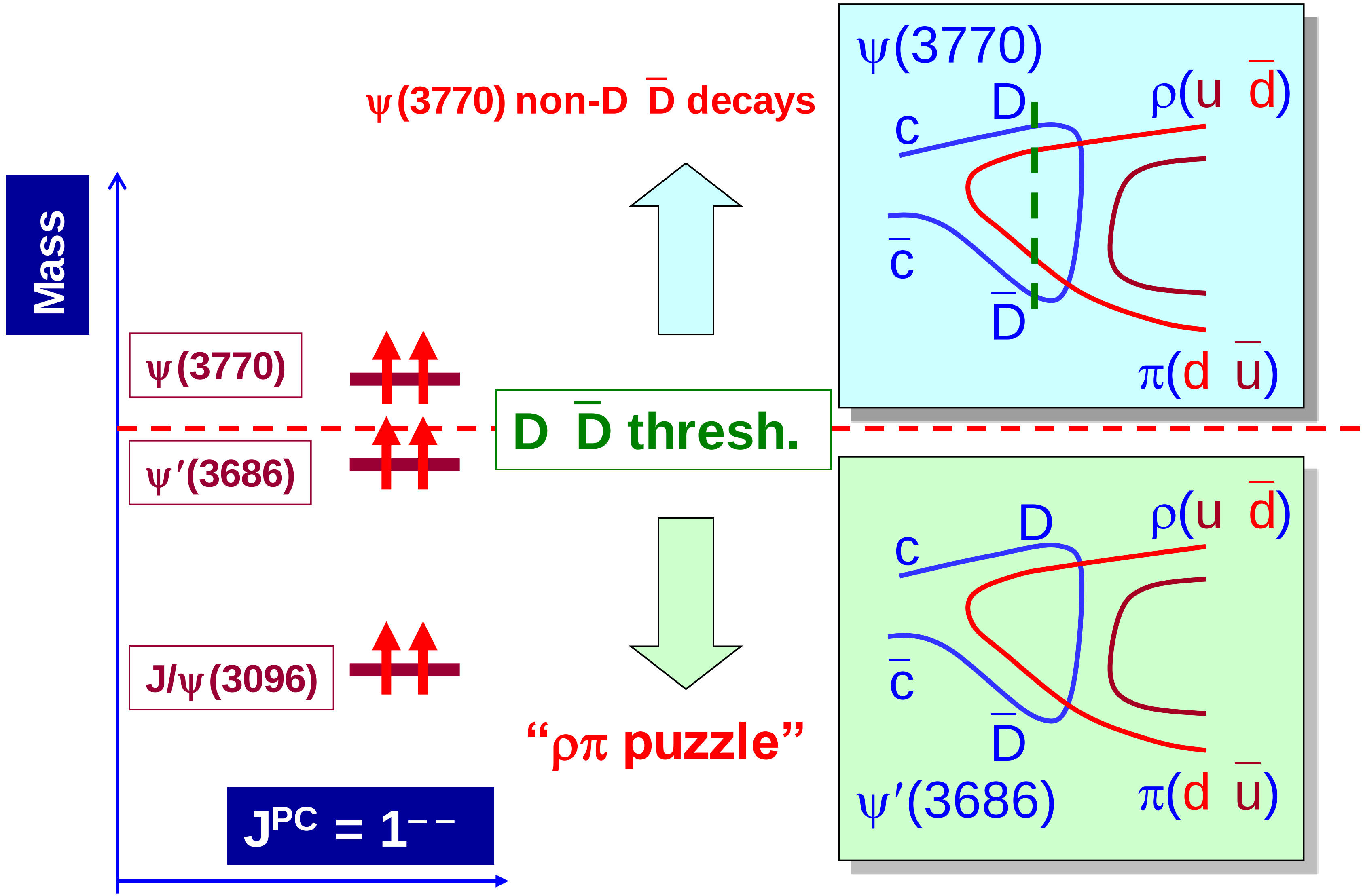
→ **Reliable extraction of dynamic information**

Thanks for your attention!

The ψ(3686) and ψ(3770) will experience or suffer the most from the $D\bar{D}$ open channel effects. Such effects behave differently in the kinematics below or above the threshold.



The ψ(3686) and ψ(3770) will experience or suffer the most from the $D\bar{D}$ open channel effects. Such effects behave differently in the kinematics below or above the threshold.



Further hint for D $\bar{D}$ threshold effects:

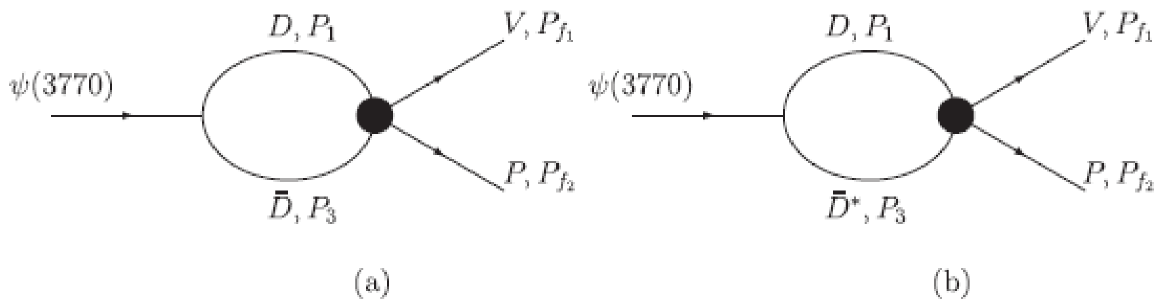
- M1 transition discrepancies between quark model and experimental data for the hindered process $\psi(2S) \to \gamma\eta_c$.
- A precise measurement of the $\psi(3770) \to \gamma\eta_c, \gamma\eta_c'$ is necessary.
- Correlation between E1 transitions of $\psi(3770) \to \gamma\chi_{cJ}$ and $\psi(2S) \to \gamma\chi_{cJ}$.
- Hadronic transitions, e.g. η or $\pi\pi$ emissions.

Initial meson	$J/\psi(1^3S_1)$	$\psi'(2^3S_1)$		$\psi''(1^3D_1)$	
Final meson	$\eta_c(1^1S_0)$	$\eta_c'(2^1S_0)$	$\eta_c(1^1S_0)$	$\eta_c'(2^1S_0)$	$\eta_c(1^1S_0)$
Γ_{M1}^{NR} (keV)	2.9	0.21	9.7	$\cdots$	$\cdots$
Γ_{M1}^{GI} (keV)	2.4	0.17	9.6	$\cdots$	$\cdots$
Γ_{IML} (keV)	$0.08^{+0.13}_{-0.06}$	$0.02^{+0.02}_{-0.01}$	$2.78^{+5.73}_{-1.96}$	$1.82^{+1.95}_{-1.19}$	$17.14^{+22.93}_{-12.03}$
Γ_{all} (keV)	$1.58^{+0.37}_{-0.37}$	$0.08^{+0.03}_{-0.03}$	$2.05^{+2.65}_{-1.75}$	$1.82^{+1.95}_{-1.19}$	$17.14^{+22.93}_{-12.03}$
Γ_{exp} (keV)	1.58 ± 0.37 [4]	$0.143 \pm 0.027 \pm 0.092$ [34]	0.97 ± 0.14 [16]	< 55	< 19
Γ_{LQCD} (keV)	2.51 ± 0.08	$\cdots$	0.4 ± 0.8	$\cdots$	10 ± 11

G. Li and Q. Zhao, PRD84, 074005 (2011)

BESIII, PRD 89, 112005 (2014)

ψ(3770) hadronic non-D D̄ decays via intermediate D meson loops



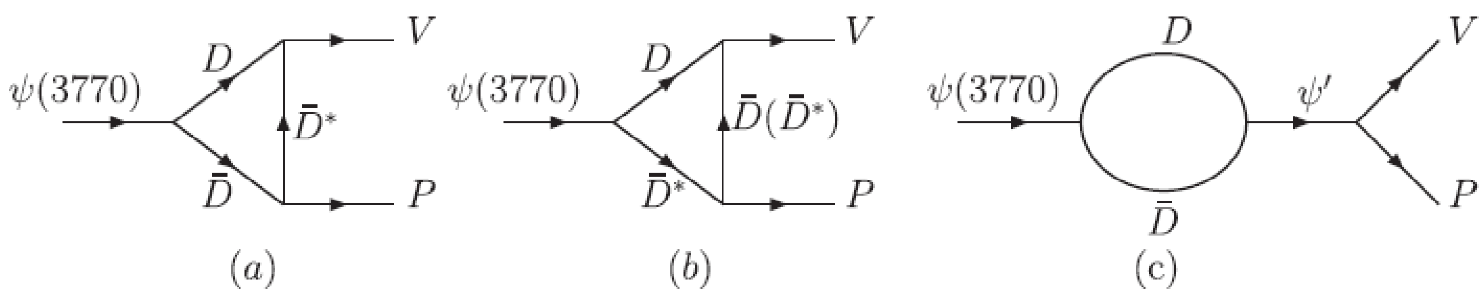
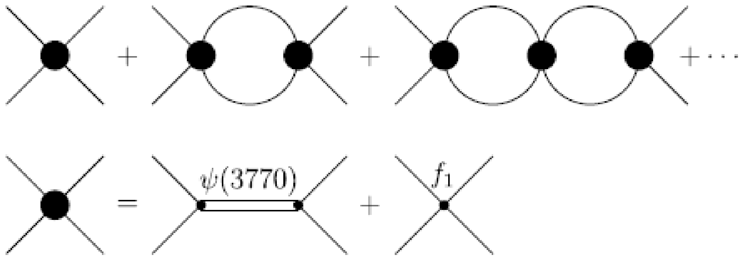


FIG. 2. The t- [(a) and (b)] and s-channel (c) meson loops in $\psi(3770) \to VP$.

Quantitative study of ψ(3770) → VP is possible.

Y.-J. Zhang, G. Li and Q. Zhao, PRL102, 172001 (2009)

Lineshape of psi(3770)

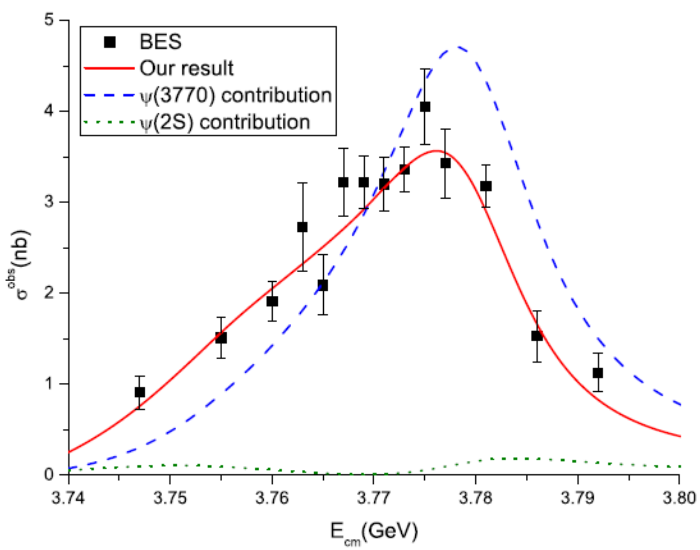


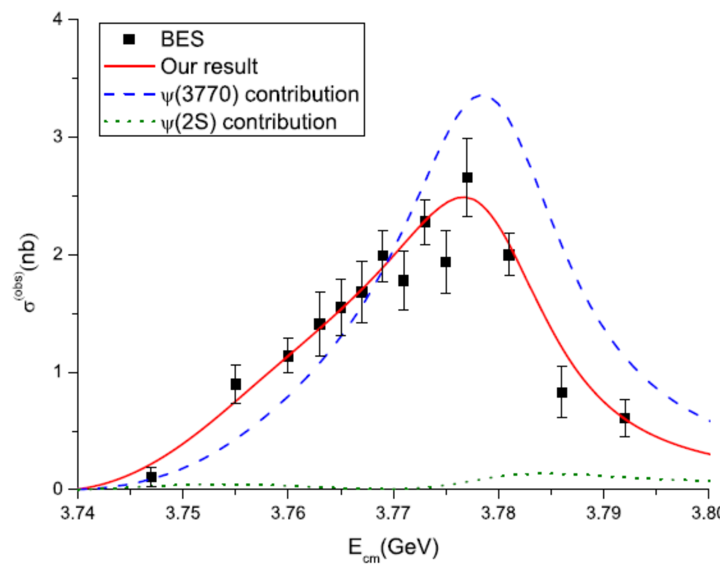
$$\delta\mathcal{L} = \mathcal{L}_{\psi D\bar{D}} + \mathcal{L}_{(D\bar{D})^2},$$

$$\mathcal{L}_{\psi D\bar{D}} = ig_{\psi D\bar{D}}\{D^\dagger\nabla\bar{D} - \nabla D^\dagger\bar{D}\}\cdot\psi$$
$$+ ig_{\psi D\bar{D}}\{\bar{D}^\dagger\nabla D - \nabla\bar{D}^\dagger D\}\cdot\psi,$$

$$\mathcal{L}_{(D\bar{D})^2} = f_1\{D^\dagger\nabla\bar{D} - \nabla D^\dagger\bar{D}\}\cdot\{\nabla\bar{D}^\dagger D - \bar{D}^\dagger\nabla D\}$$
$$+ f_3\{D^\dagger\tau^i\nabla\bar{D} - \nabla D^\dagger\tau^i\bar{D}\}\cdot\{\nabla\bar{D}^\dagger\tau^i D - \bar{D}^\dagger\tau^i\nabla D\}$$
$$+\cdots,$$

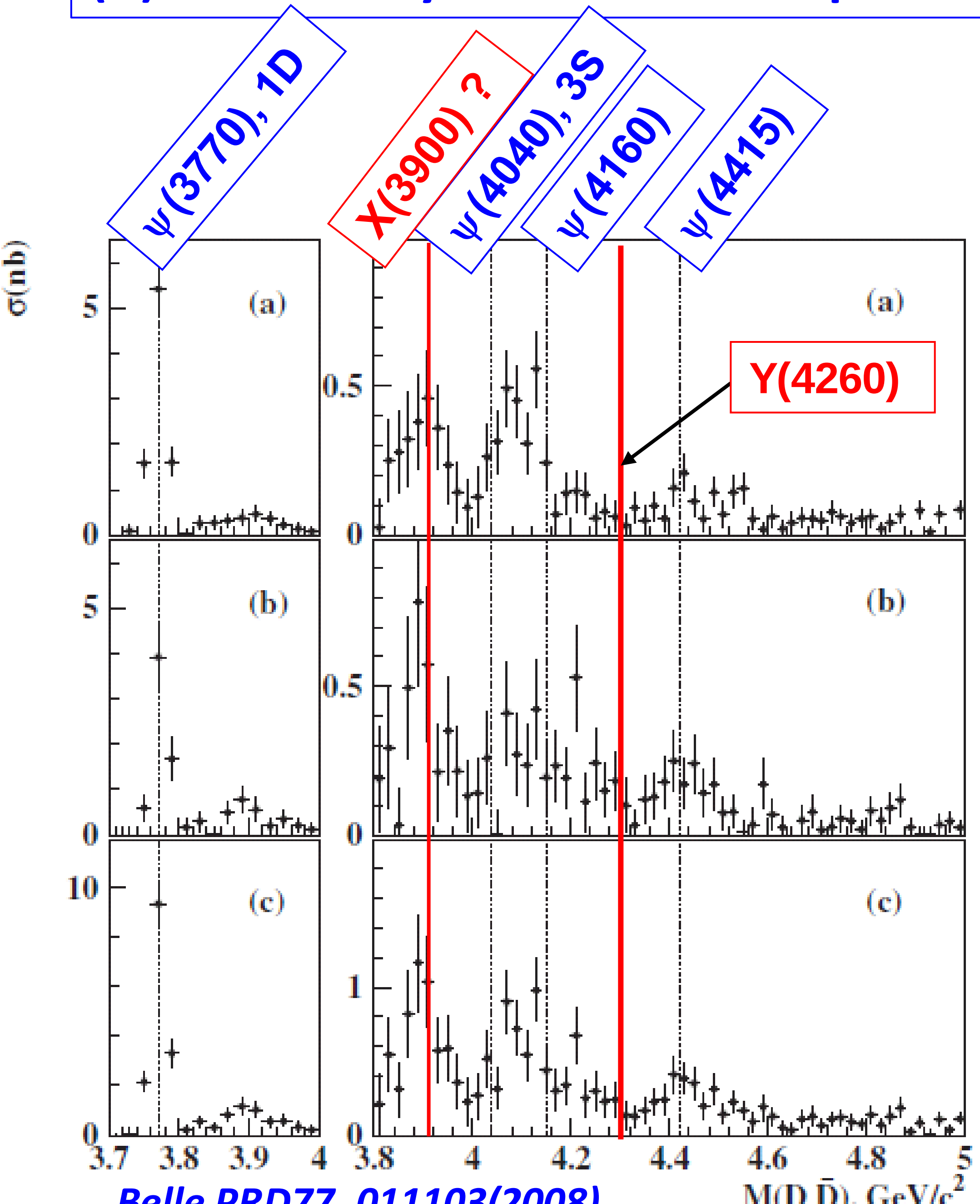
with $D = \begin{pmatrix} D^0 \\ D^+ \end{pmatrix}$, $\bar{D} = \begin{pmatrix} \bar{D}^0 \\ D^- \end{pmatrix}$,





Y.J. Zhang, Q. Z., PRD 81 (2010) 034011; H.B. Li, X.S. Qin, M.Z. Yang, PRD 81 (2010) 011501; G.-Y. Chen, Q. Z., PLB 718 (2013) 1369

(II) The vicinity of the second open charm threshold



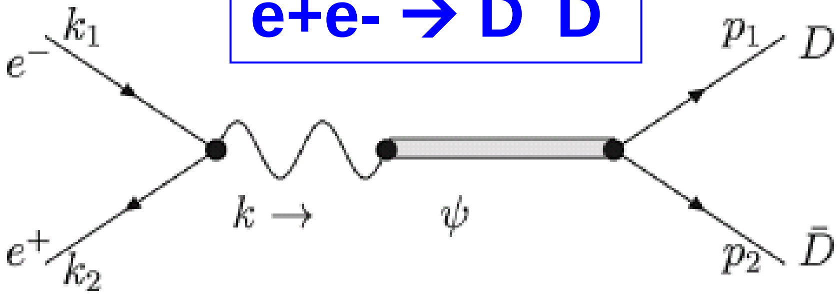
Belle PRD77, 011103(2008).

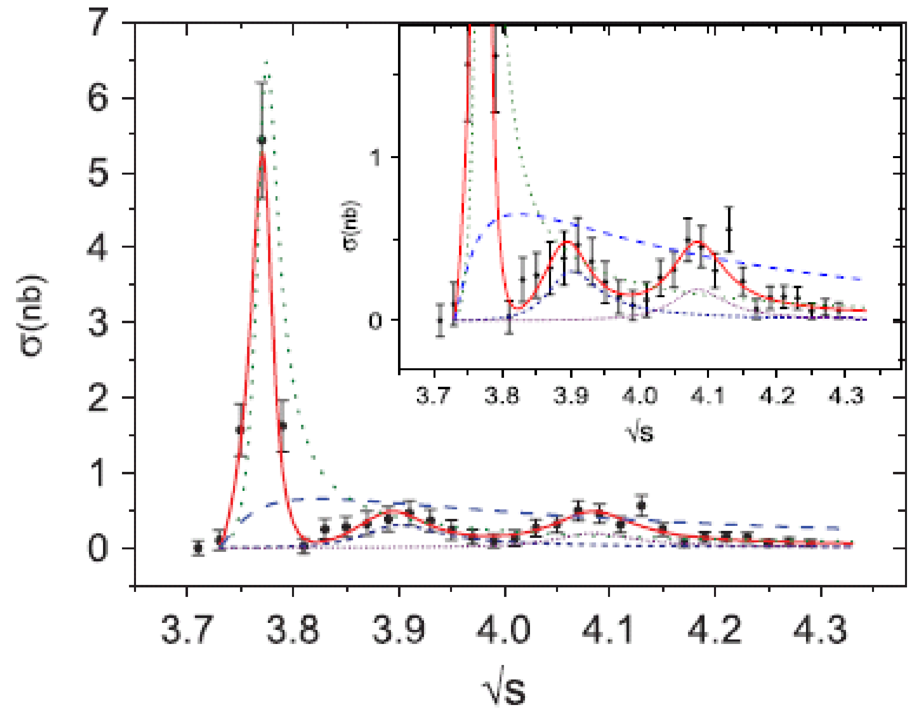
e+e- → D D̄

- What is X(3900)? (see Wang et al., PRD84, 014007 (2011))
- X(3900) has not been inlcuded in *PDG*.
- Not in charmonium spectrum
- Interpreted as D D̄* scattering state (Eichten et al.)
- … …

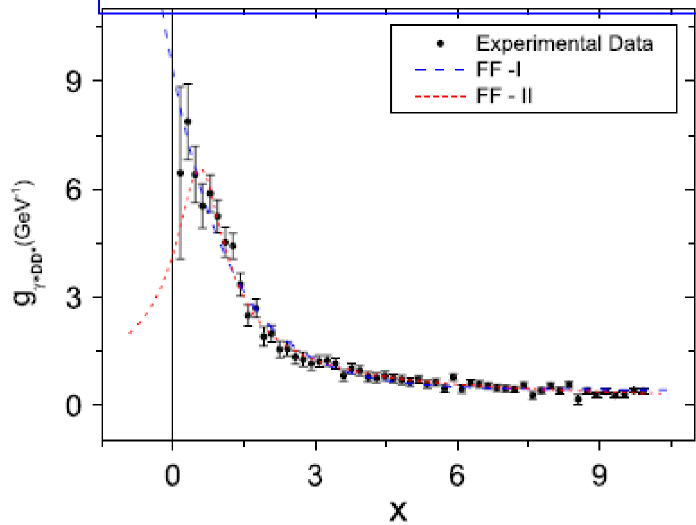
X(3900) can be fitted by either BW or DD* rescattering. Can the DD* P-wave interaction generate a pole?

e+e- → D $\bar{D}$

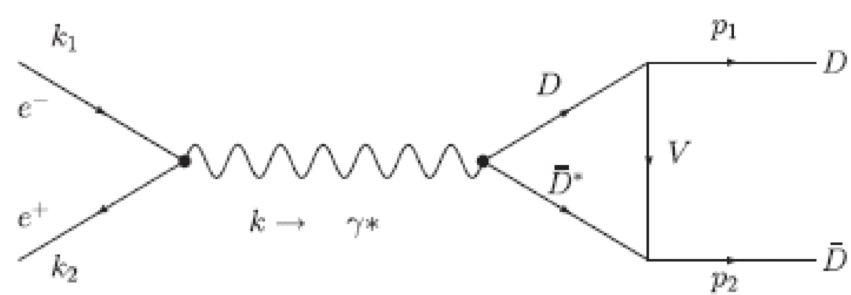




e+e- → D $\bar{D}$* + c.c.

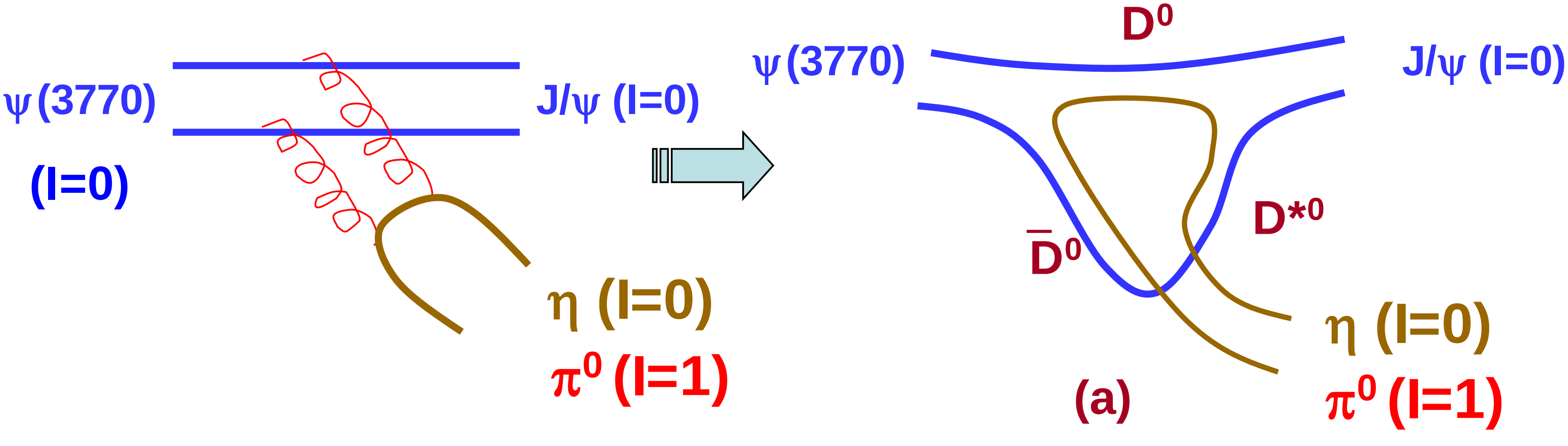


D $\bar{D}$* open threshold may explain:



Y.J. Zhang and QZ, PRD81, 034011 (2010)

ii) Direct evidence for open charm effects in $e^+e^- \rightarrow J/\psi\,\eta$, $J/\psi\,\pi^0$

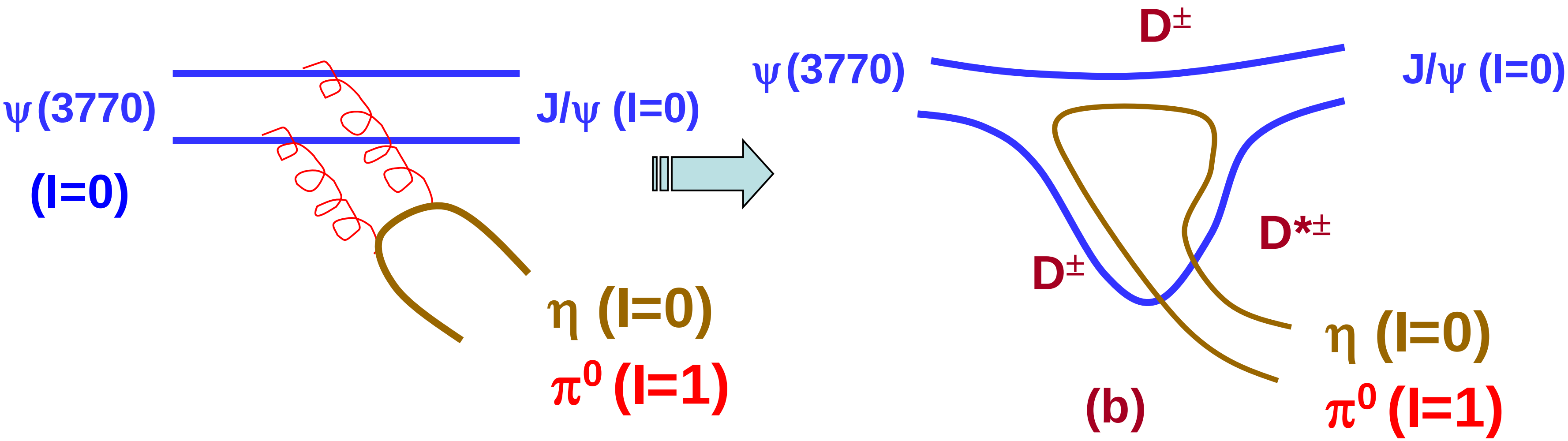


For the isospin-violating $J/\psi\pi^0$ production:

If $m_u = m_d$,
→ $m(D^0) = m(D^\pm)$
(a) + (b) = 0

If $m_u \neq m_d$,
→ $m(D^0) \neq m(D^\pm)$
(a) + (b) ≠ 0

ii) Direct evidence for open charm effects in $e^+e^- \rightarrow J/\psi\,\eta,\ J/\psi\,\pi^0$

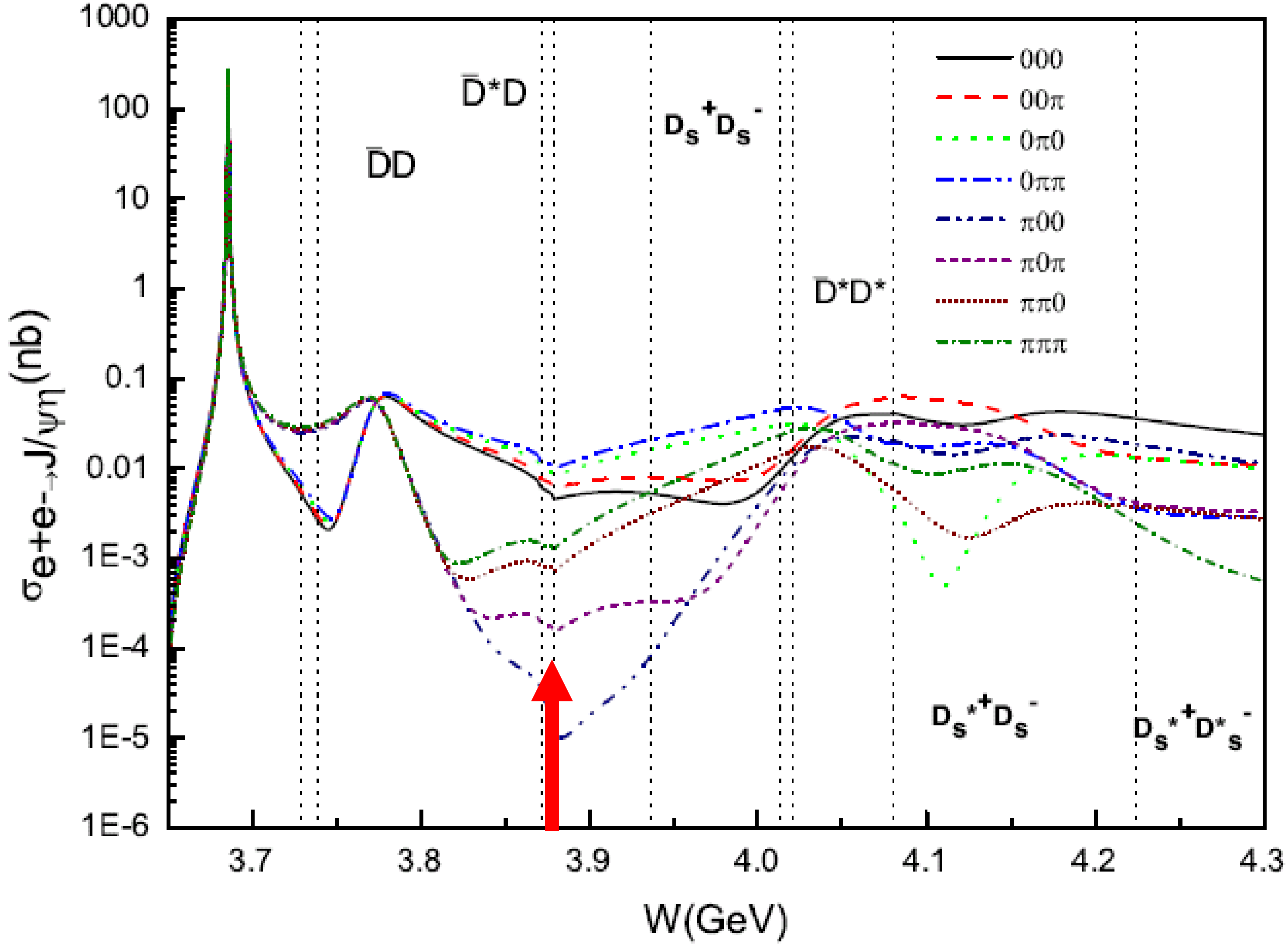


For the isospin-violating $J/\psi\pi^0$ production:

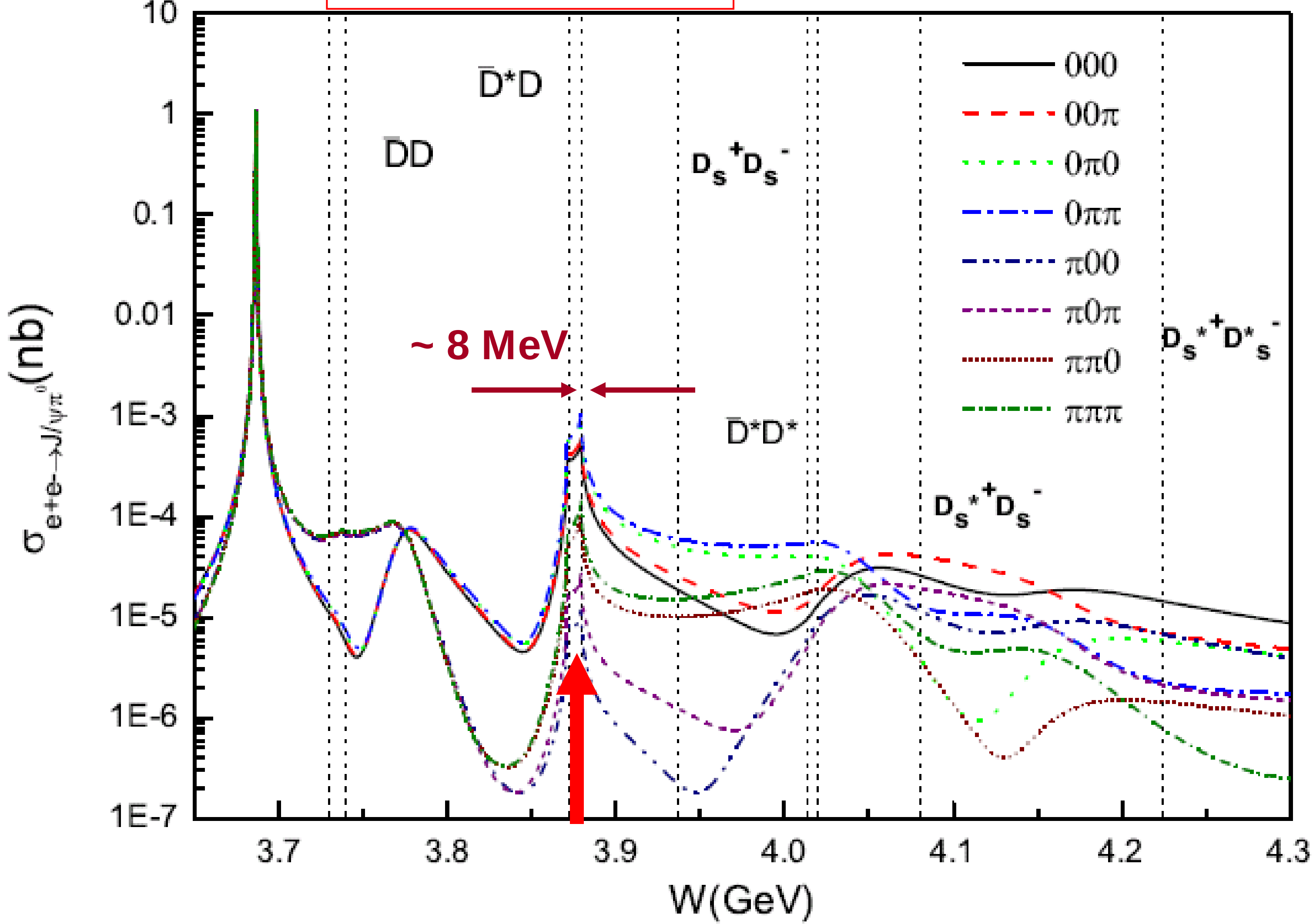
If $m_u = m_d$,
$\rightarrow m(D^0) = m(D^\pm)$
(a) + (b) = 0

If $m_u \neq m_d$,
$\rightarrow m(D^0) \neq m(D^\pm)$
(a) + (b) $\neq$ 0

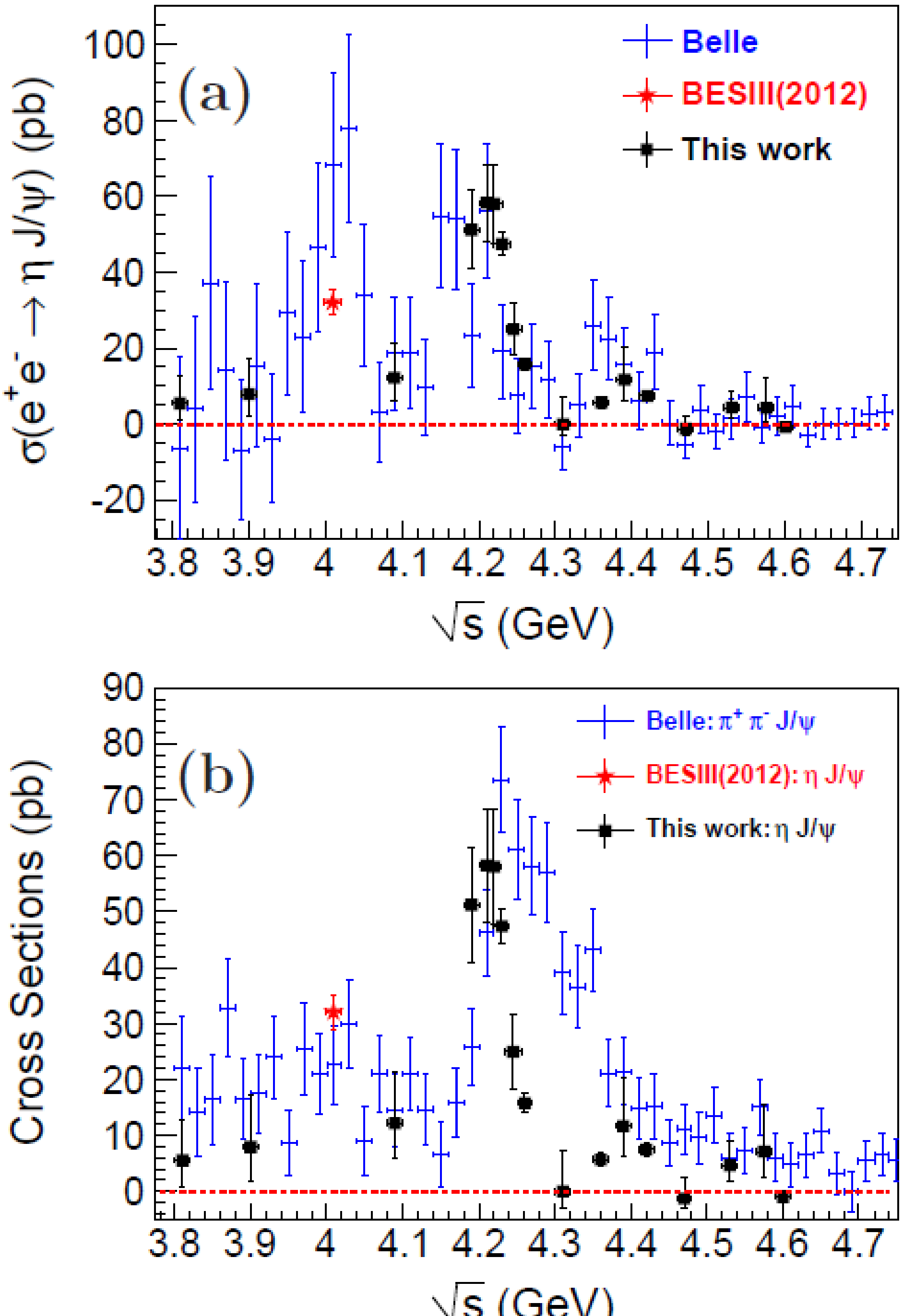
- **Cross section lineshape of** $e^+e^- \rightarrow J/\psi\ \eta$



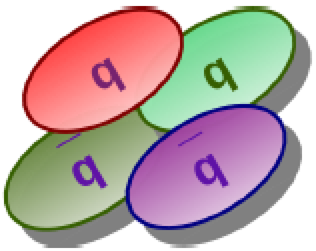
• Direct evidence for open charm effects in the cross section lineshape of $e^+e^- \rightarrow J/\psi\ \pi^0$



Wang, Liu, Zhao, 1103.1095[hep-ph], PRD84, 014007(2011)

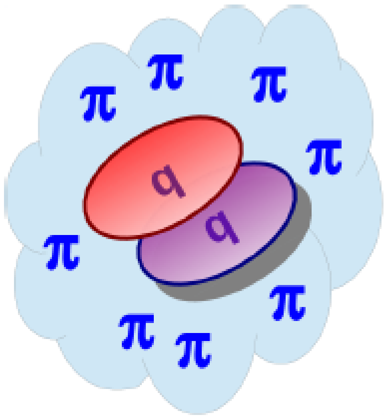


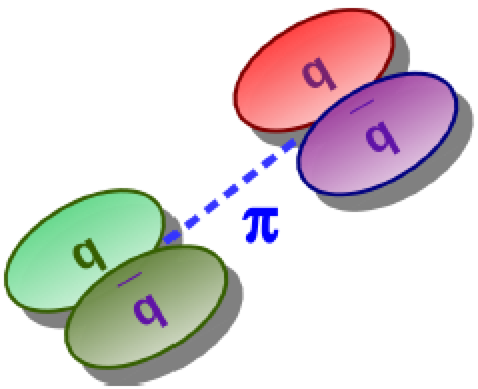
BESIII, arXiv:1503.06644 [hep-ex]



Tetraquark
Compact state of four quarks

Hadrocharmonium
Heavy Quarkonium Core
Surrounded by pion cloud





Hadronic Molecule
Formed from interactions of two hadrons
Classic Example for Baryons: Deuteron

In the heavy quark spin symmetry (HQSS) limit these models have different predictions for the spectrum.

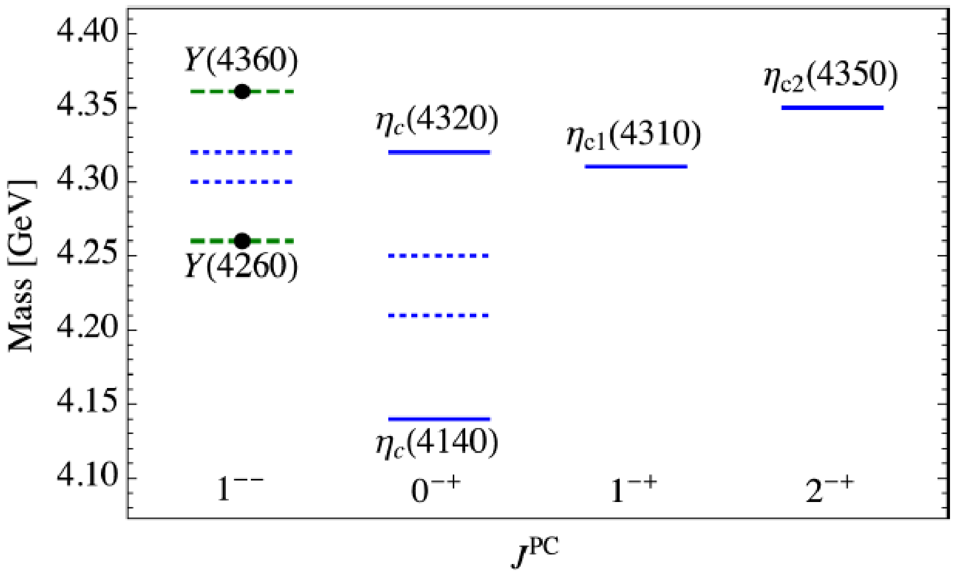
Slide from talk by M. Cleven

- **Hadro-quarkonium states**

$$\begin{pmatrix} Y(4260) \\ Y(4360) \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_3 \end{pmatrix} \quad \theta \sim 40^0$$

$$\begin{cases} \psi_1 \sim h_c \times (0^{-+})_{q\bar{q}} \\ \psi_3 \sim \psi' \times (0^{++})_{q\bar{q}} \end{cases}$$

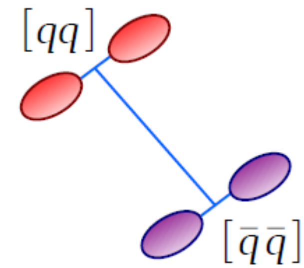
Heavy spin doublets: (h_c, χ_{cJ}), (ψ, η_c)



- Possible decay channel: $\eta_c\pi\pi$, $\chi_{cJ}\pi\pi$
- Exotic quantum number: $J^{PC}=1^{-+}$
- Two η_c states

M. Cleven, F.-K. Guo, C. Hanhart, Q. Wang, Q.Z., arXiv:1505.01771 [hep-ph]

- **Tetraquark states**

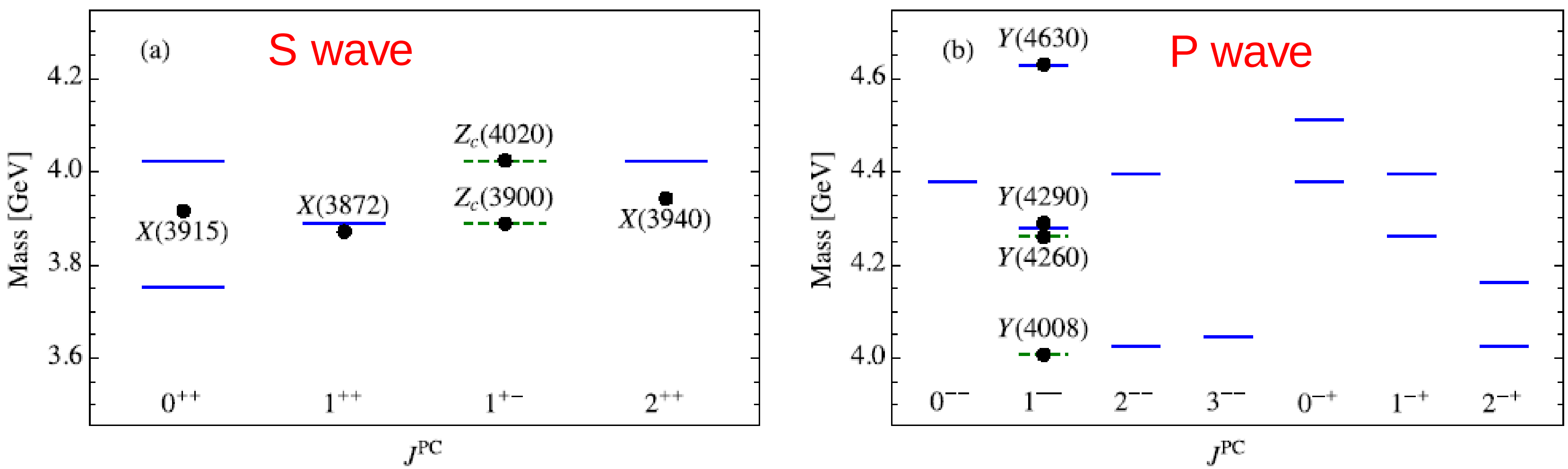


The mass of a tetraquark is given by

$$M = M_{00} + B_c \frac{\boldsymbol{L}^2}{2} - 2a\boldsymbol{L}\cdot\boldsymbol{S} + 2\kappa_{cq}\left[(\boldsymbol{s}_q\cdot\boldsymbol{s}_c + (\boldsymbol{s}_{\bar{q}}\cdot\boldsymbol{s}_{\bar{c}}))\right]$$

For a state with given ***J***, the mass can be estimated:

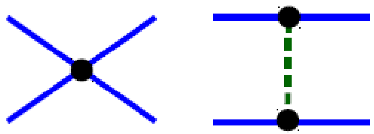
$$M = M_{00} + B_c \frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}\left[s(s+1) + \bar{s}(\bar{s}+1) - 3\right]$$



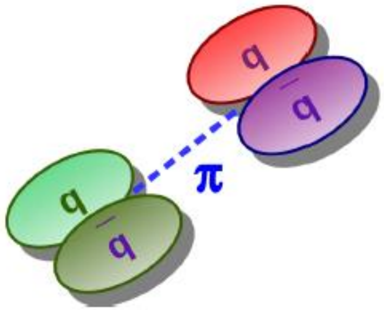
Extremely rich spectrum is predicted!

Hadronic molecules

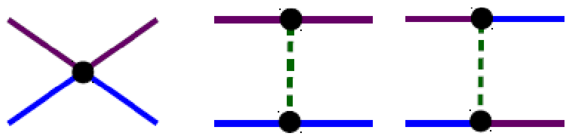
- $(D,D^*) + (D,D^*)$



$J^{PC} = 0^{++}, 1^{++}, 1^{+-}, 2^{++}$



- $(D_1,D_2) + (D,D^*)$

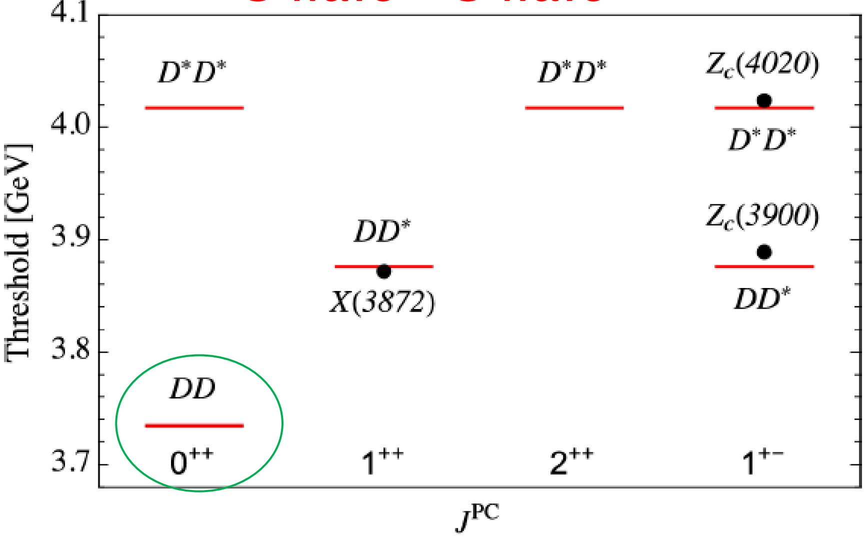


$J^{PC} = 1^{--}, 1^{-+}$

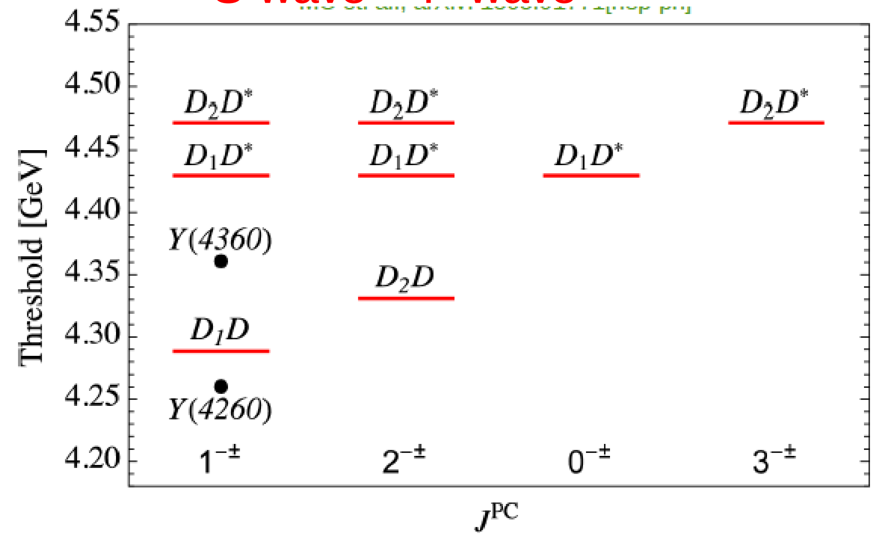
- Long-range pion exchange;
- Isoscalar and isovector may not bind simultaneously;

$$\langle I, I_3 | \vec{\tau}_{(1)} \cdot \vec{\tau}_{(2)} | I, I_3 \rangle = 2\left[I(I+1) - 3/2 \right] = \begin{cases} -3 & I = 0 \\ 1 & I = 1 \end{cases}$$

S wave – S wave



S wave – P wave

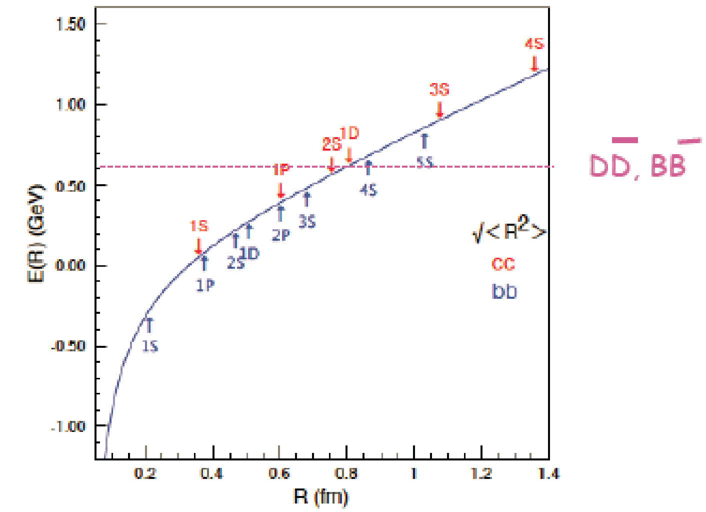


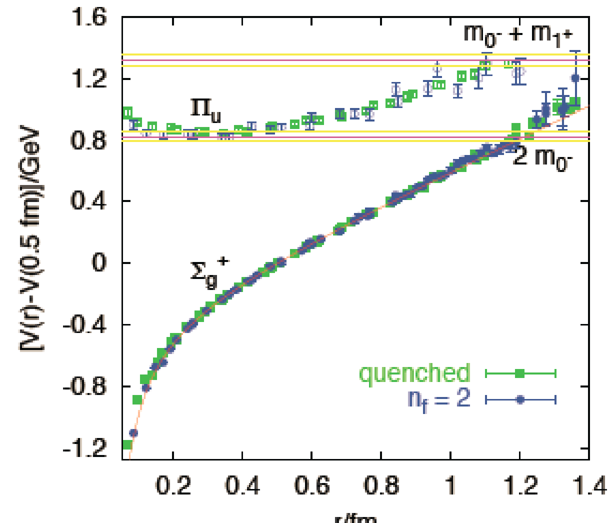
- States appear at **S-wave** thresholds;
- The **J=3** state has significantly higher mass than for tetraquarks;
- Only one $J^{PC}=0^{-+}$ state is predicted;
- Scalar state of $\bar{D}D$ may not exist;
- Exotic partners of $J^{PC}= 1^{--}$;
- ……

QCD Multipole Expansion (QCDME)

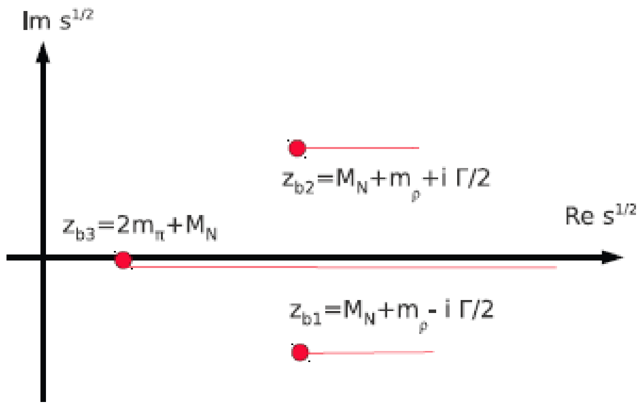
- When should the QCDME work well ?
  - Transitions between tightly bound quarkonium states
  - Small radius ($R \ll \Lambda_{QCD}$)
    - bottomium 1S, 1P, 2S, 1D, 2P, 3S, ...
    - charmonium 1S, 1P, ...
  - Small contributions from excitations involving QCD additional degrees of freedom.
    - This is essential to the factorization assumption !
- Above threshold
  - light quark pairs
    - $D^{(*)} \overline{D}^{(*)}$ thresholds in 1D to 3S region
    - $B^{(*)} \overline{B}^{(*)}$ thresholds in 4S region
  - gluonic string excitations
    - Hybrid states will appear in the spectrum associated with the potentials Π_u, ...
    - In the static limit this occurs at separation $r \approx 1.2$ fm.
      - Between the 3S and 4S in (cc) system
      - Just above the 5S in the (bb) system
- New mechanisms can be expected for hadronic transitions above threshold.

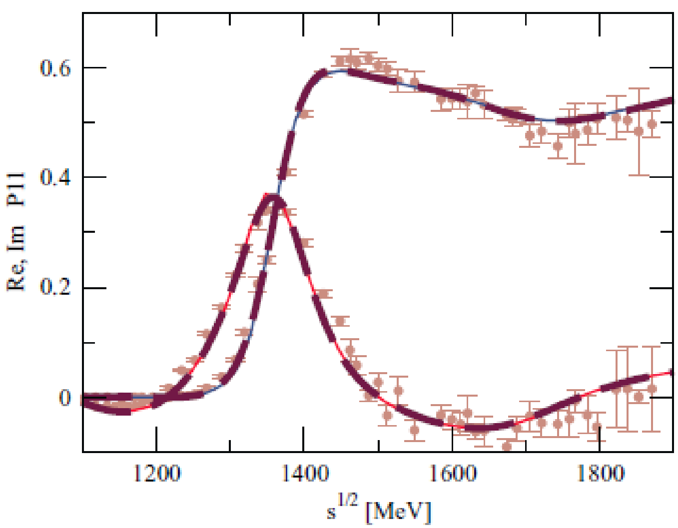
Cornell Potential Model





Not every bump is a resonance ...





In the complex plane there are

- $\rightarrow$ poles = states
- $\rightarrow$ branch points
  - ▷ on the real axis = channel with stable particles
  - ▷ in the complex plane = channel with un-stable particles
- $\rightarrow$ triangle-singularities

See talk by Xiao-Hai Liu

Analysis without ρN–channel gives pole at 1698-130 i MeV

S. Ceci et al. PRC84 (2011) 015205

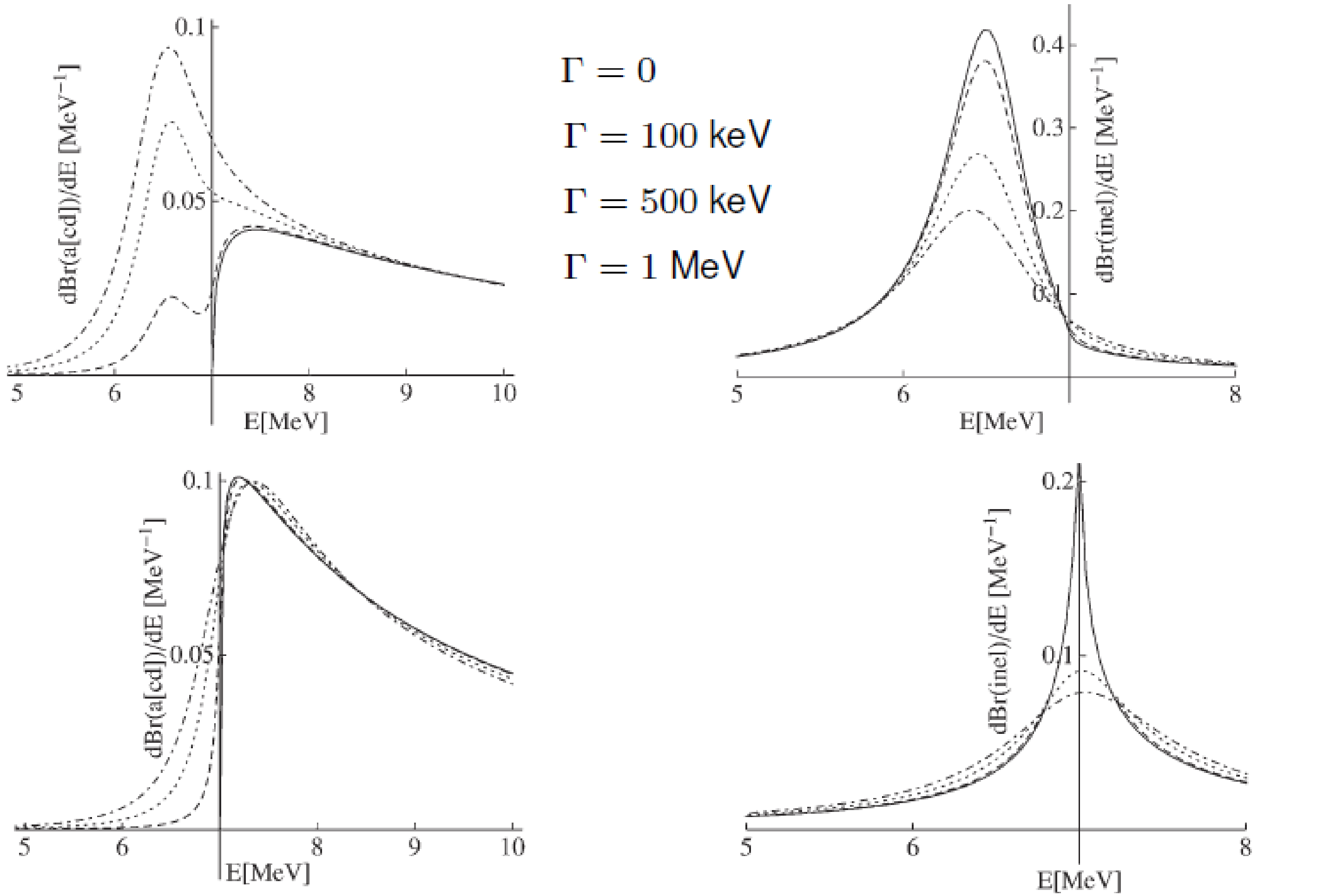
Lineshapes of near threshold states

Braaten & Lu PRD76 (2007) 094028; C.H. et al. PRD81(2010)094028

Direct channel | Inelastic channel

bound state:

virtual state:

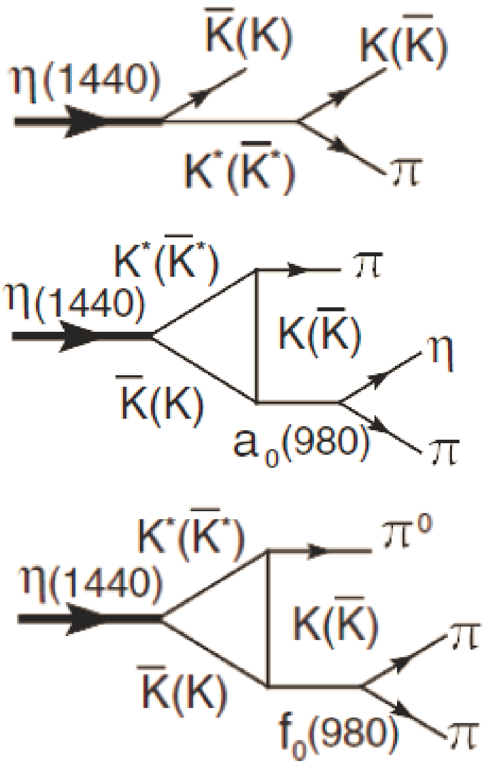


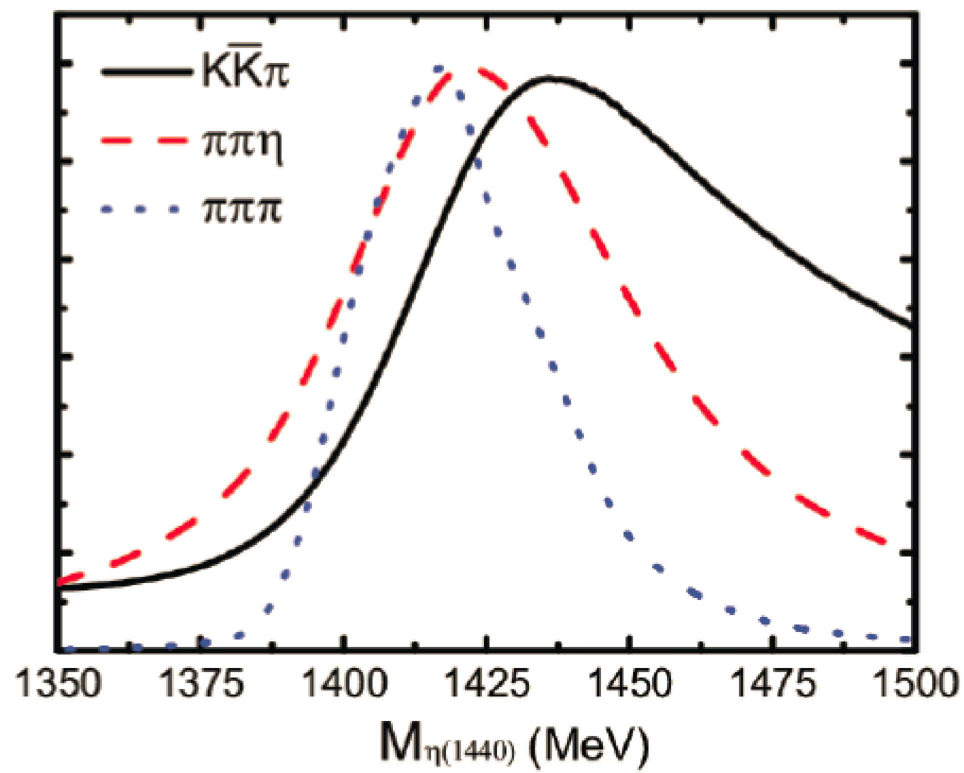
Only molecules can appear as virtual states!

Only poles are physical

Line shapes and peak positions are channel dependent

Only pole–locations are physical!





J. J. Wu et al., PRL108, 081803 (2012)

Scalar puzzle (I): Scalars below 1 GeV:

Pay less price to create a 0^- ($q\bar{q}$) pair instead to orbitally excite a ($q\bar{q}$)?

$\bar{q}q$ tensor nonet

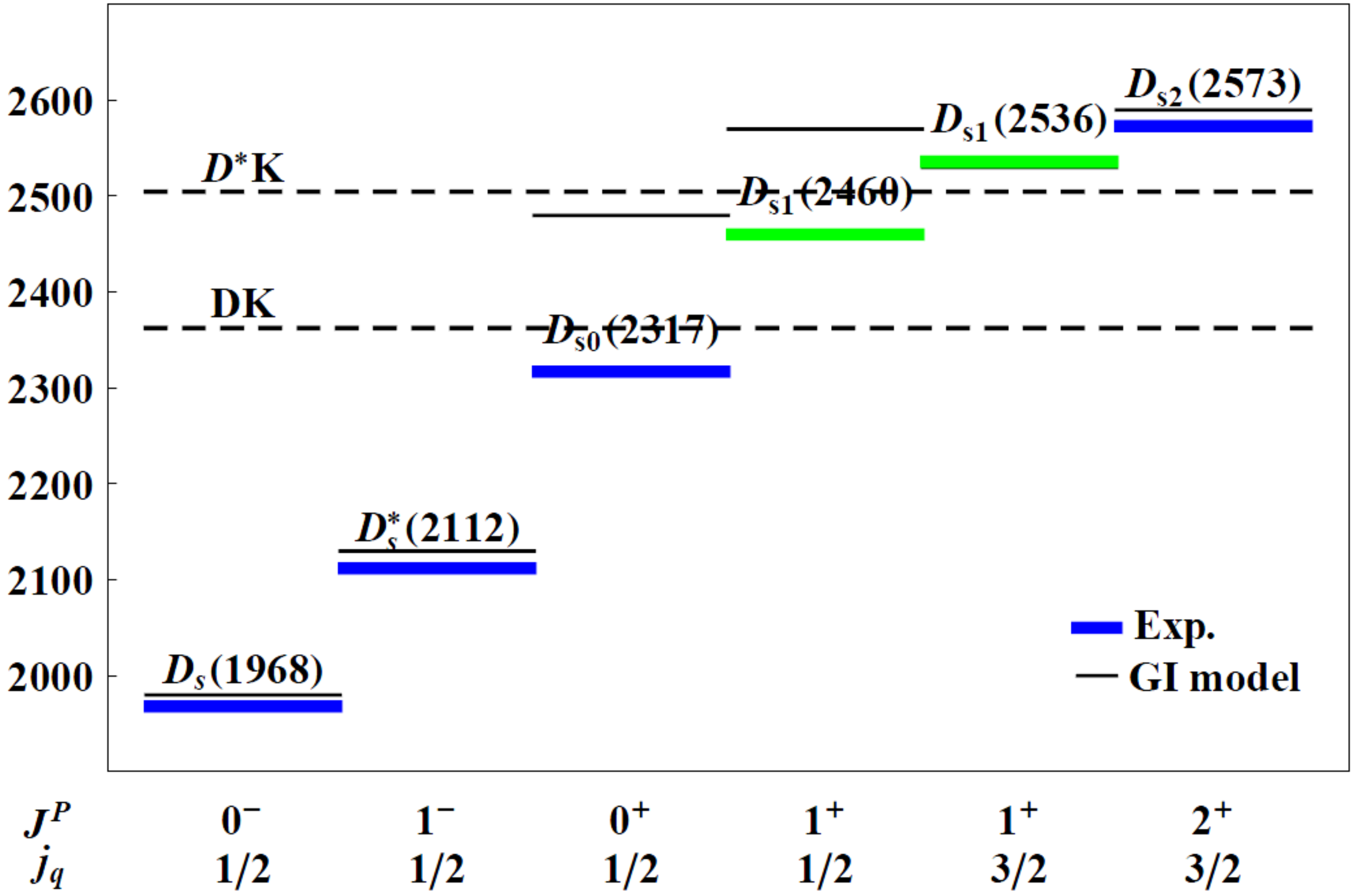
$f'_2(1525)$	$\bar{s}s$
$K_2(1430)$	$\bar{s}d$
$a_2(1320)$	$\bar{u}u - \bar{d}d$
$f_2(1270)$	$\bar{u}u + \bar{d}d$

puzzling scalar nonet

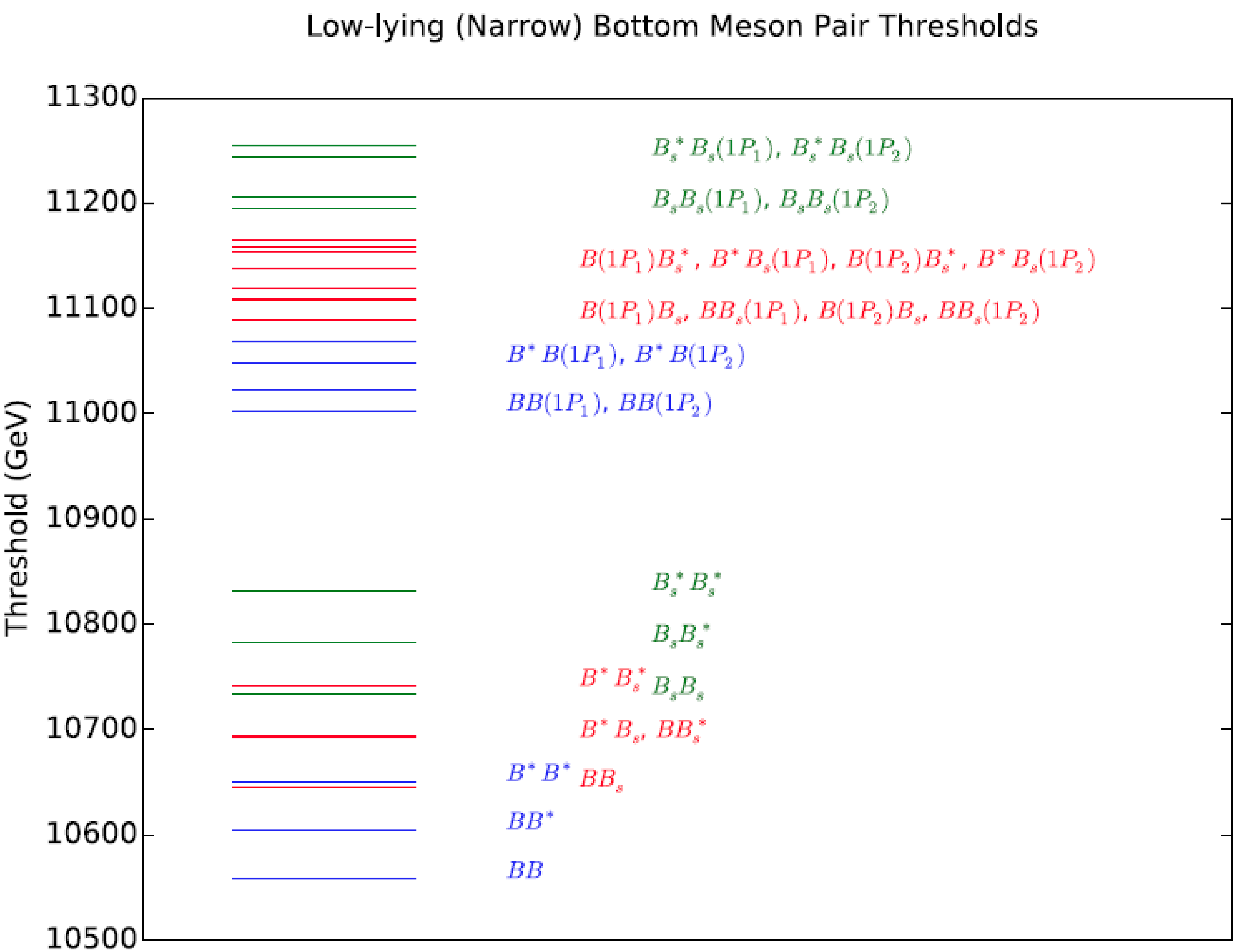
$a_0(980)$	$\bar{u}u - \bar{d}d$,	[$\bar{u}s\ \bar{s}u - \bar{d}s\ \bar{s}d$]
$f_0(980)$	$\bar{s}s$,	[$\bar{s}u\ \bar{u}s + \bar{s}d\ \bar{d}s$]
$\kappa(800)$	$\bar{s}d$,	[$\bar{s}u\ \bar{u}d$]
$f_0(600)$	$\bar{u}u + \bar{d}d$,	[$\bar{u}d\ \bar{d}u$]

$\bar{q}q$, $\bar{q}^2q^2$, meson molecule ?

D_s spectrum in comparison with potential model calculations



Low-lying thresholds



Narrow-Wide Thresholds

B_s^* $B(P_1)$

B_s^* $B(P_0)$; B_s $B(P_1)$

B $B(P_1)$; B_s $B(P_0)$

B* $B(P_0)$

B $B(P_0)$