# TWO TOPICS ON CHARMONIUM-LIKE STATES

**Zhi-Yong Zhou** 周智勇
**Southeast University** 东南大学

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# TOPIC I: COULD X(3915) AND X(3930) BE THE SAME TENSOR STATE?

Zhi-Yong Zhou, Zhiguang Xiao, Hai-Qing Zhou.

**Phys.Rev.Lett. 115.022001(2015)** arXiv:1501.00879

# MOTIVATION

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pdgLive Home > $\chi_{c0}(2P)$ was $X(3915)$

**2014 Review of Particle Physics.**
Please use this CITATION: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).

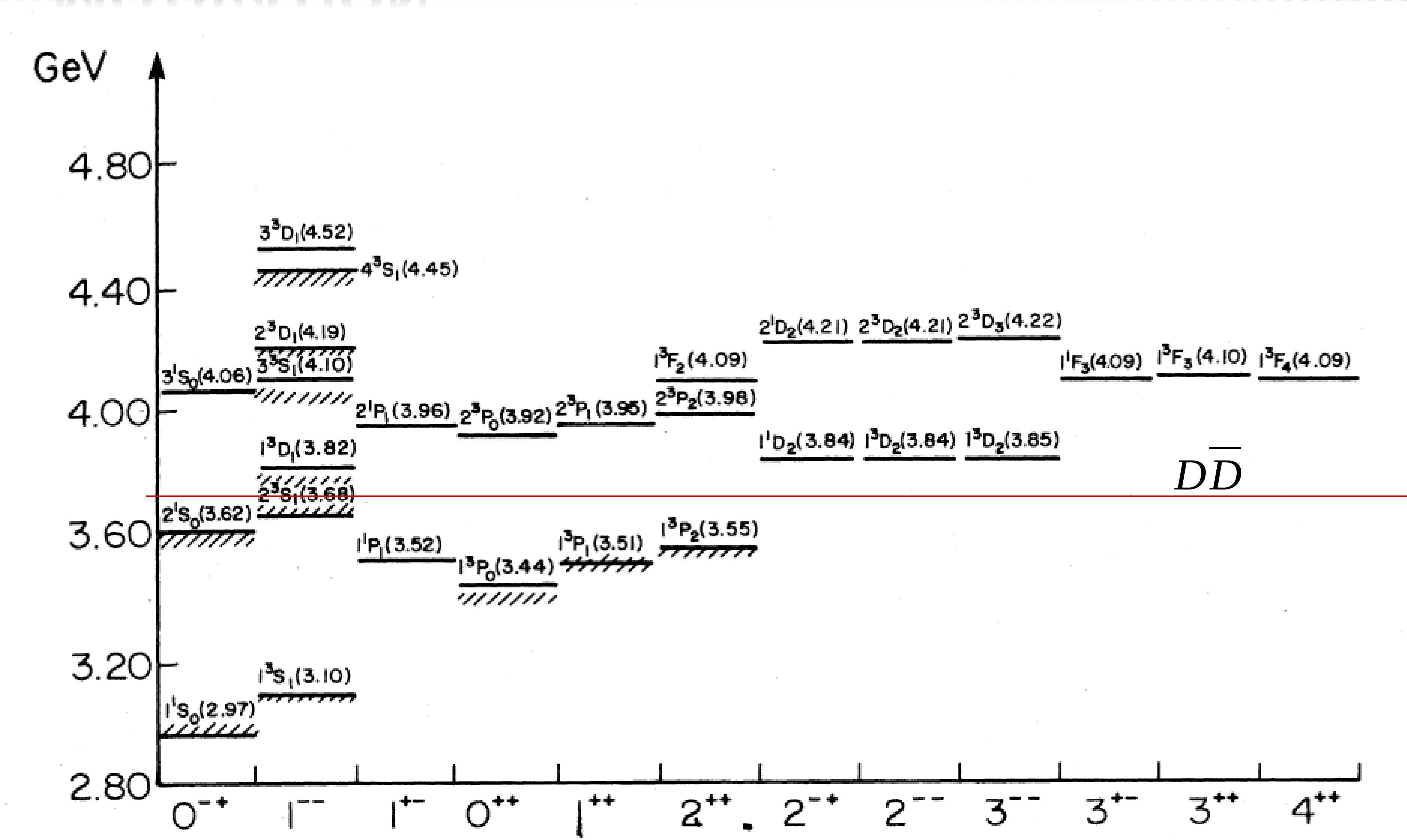
## $\chi_{c0}(2P)$ was $X(3915)$

INSPIRE search

| | |
|---|---|
| $\chi_{c0}(2P)$ MASS | $3918.4 \pm 1.9$ MeV |
| $\chi_{c0}(2P)$ WIDTH | $20 \pm 5$ MeV (S = 1.1) |

- ***The famous Godfrey-Isgur model (PRD 32,189(1985)) predict the mass of $\chi_{c0}(2P)$ to be about 3915MeV, but the predicted mass values of this model are usually higher than the observed values for the states above the open-flavor threshold.***

# MOTIVATION


GeV
4.80
4.40
4.00
3.60
3.20
2.80
3³D₁(4.52)
4³S₁(4.45)
2³D₁(4.19)
3³S₁(4.10)
3¹S₀(4.06)
1³D₁(3.82)
2³S₁(3.68)
2¹S₀(3.62)
1³S₁(3.10)
1¹S₀(2.97)
2¹P₁(3.96)
1¹P₁(3.52)
2³P₀(3.92)
1³P₀(3.44)
2³P₁(3.95)
1³P₁(3.51)
1³F₂(4.09)
2³P₂(3.98)
1³P₂(3.55)
2¹D₂(4.21)
1¹D₂(3.84)
2³D₂(4.21)
1³D₂(3.84)
2³D₃(4.22)
1³D₂(3.85)
1¹F₃(4.09)
1³F₃(4.10)
1³F₄(4.09)
$D\overline{D}$
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
2⁻⁺
2⁻⁻
3⁻⁻
3⁺⁻
3⁺⁺
4⁺⁺

# MOTIVATION

- ***The properties of X(3915) is far beyond the expectations to $\chi_{c0}(2P)$. Why it does not couple to the OZI-allowed channel? Why the mass splitting between $\chi_{c0}(2P)$*)[X(3915)?]* **and $\chi_{c2}(2P)$ )[X(3930)]** ***is so small?***

  **Guo and Meissner, PRD 86,091501.**

- ***Olsen argued that this assignment implies a conflictions between the branch fraction of*** $\chi_{c0}(2P) \to J/\psi\omega$ ***from different experiment processes.***

  ***Olsen,* PRD 91, 057501.**

***We wish to solve this puzzle in a different aspect.***

# EXAMINING THE EXPERIMENTS

- ***Belle reported this state in $\gamma\gamma \to J/\psi\omega$ first, and they claimed that both the $J^{PC} = 0^{++}$ and $2^{++}$ are both possible.***

  **PRL 104,092001**

- ***BaBar confirmed this observation, and made an angular distribution analysis of final leptonic and pionic states. They claim the angular distribution data highly prefer the $J^{PC} = 0^{++}$ assignment based on the helicity-2-dominance assumption. It is the only experiment to identify its quantum numbers.***

  **PRD 86,072002**

- ***The PDG table quotes the X(3915) as $\chi_{c0}(2P)$.***

# QUESTIONS

- *Helicity-2 dominance is a result of the quark model,* (**Krammer and Krasemann, PLB 73, 58(1978). Li et al., PRD 43,2161(1991).**)
  ***but above the open-flavor thresholds, the predictions of quark model is not consistent with the observed values, which means that it is hard to regard them to be pure qqbar states. However, the states above the open-flavor thresholds could be described well by the coupled-channel models.***

  **Eichten et al., PRD 17, 3090(1978). PRD 21, 203(1980).**
  **Heikkila et al., PRD 29,110(1984) Van Beveren et al., Z.Phy.C19,275(1983)**
  **Pennington and Wilson, PRD 76,077502(2007) Zhou, Xiao, EPJA 50,165(2014)**

- ***The only experiment to verify the helicity-2 dominance assumption for the states above the open-flavor threshold is the measurements of the*** $2^{++}$ ***X(3930) in*** $\gamma\gamma \to D\bar{D}$ ***processes by Belle and BaBar. It is like a circular reasoning.***
- ***It urges us to check whether the experiment analyses are over-restricted.***
- ***Whether the helicity-2 amplitude is dominant or not should be determined by data.***

# THE THEORETICAL FRAME

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2\rho(s)s}(|\mathcal{M}_{++}|^2 + |\mathcal{M}_{+-}|^2), \qquad (1)$$

where $\rho(s) = \sqrt{(s-4m_D^2)/s}$. The partial wave expansions of $\mathcal{M}_{+\pm}$ are [16]

$$\mathcal{M}_{++}(s,\cos\theta) = 16\pi \sum_{J\geq 0}(2J+1)F_{J0}(s)d^J_{0,0}(\cos\theta),$$
$$\mathcal{M}_{+-}(s,\cos\theta) = 16\pi \sum_{J\geq 2}(2J+1)F_{J2}(s)d^J_{2,0}(\cos\theta), (2)$$

Thus, the helicity amplitudes of $\gamma\gamma \to D\bar{D}$ are represented phenomenologically as

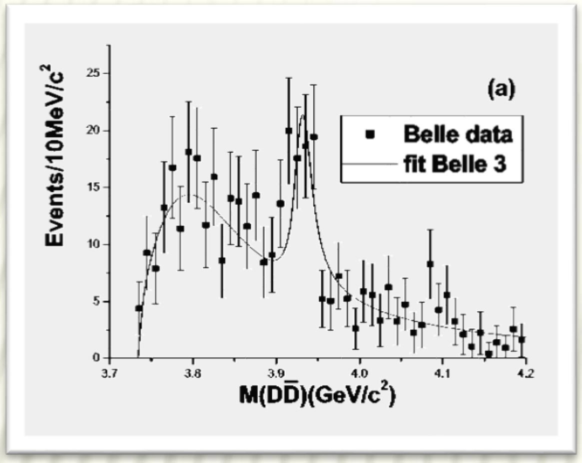
$$\mathcal{M}_{++} = 16\pi(\mathcal{A}_0(s) + \beta_1 e^{i\phi_1}\mathcal{A}_2(s) \times 5 \times d^2_{0,0}(\cos\theta)),$$
$$\mathcal{M}_{+-} = 16\pi(\beta_2 e^{i\phi_2}\mathcal{B}_2(s) \times 5 \times d^2_{2,0}(\cos\theta)), \qquad (4)$$

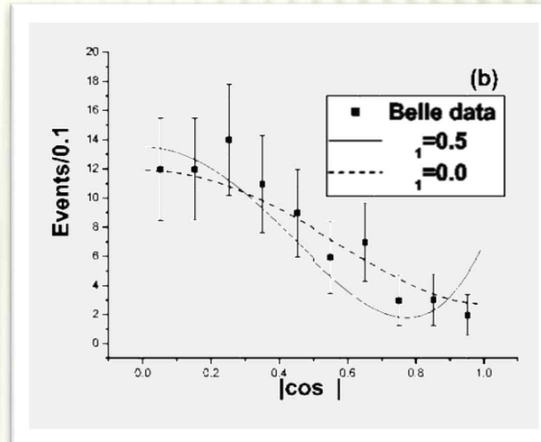
where $\mathcal{A}_0(s) = \frac{M_{\chi_{c0'}}\Gamma_{\chi_{c0'}}(s)}{M^2_{\chi_{c0'}} - s - iM_{\chi_{c0'}}\Gamma_{\chi_{c0'}}(s)}$, $\mathcal{A}_2(s) = \mathcal{B}_2(s) = \frac{M_{\chi_{c2'}}\Gamma_{\chi_{c2'}}(s)}{M^2_{\chi_{c2'}} - s - iM_{\chi_{c2'}}\Gamma_{\chi_{c2'}}(s)}$. One could use these amplitudes

# CHECK THE NECESSITY OF ASSUMPTION OF HELICITY-2 DOMINANCE

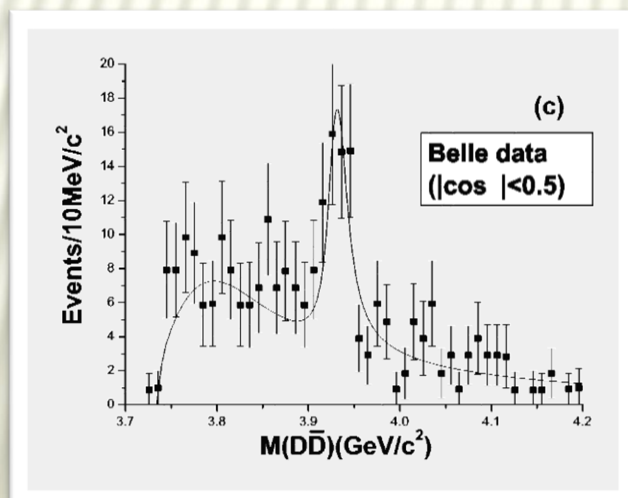
***With an appropriate parametrization method***

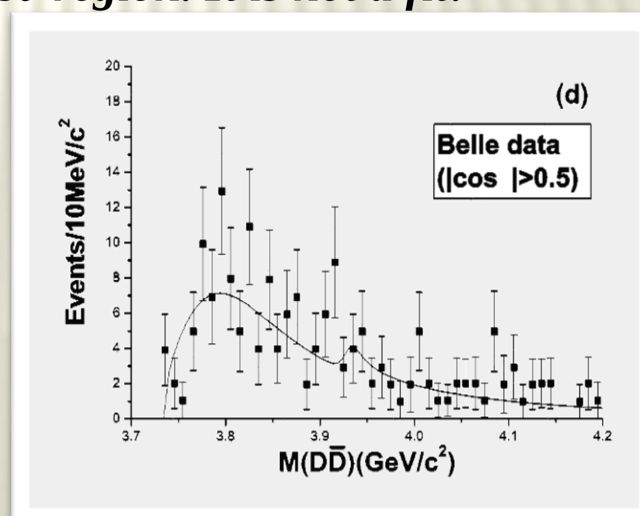
**Belle data of** $\gamma\gamma \to D\bar{D}$



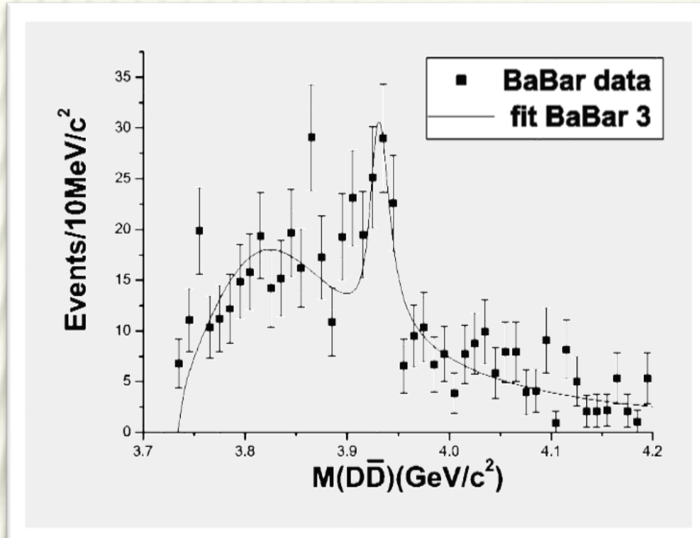

***Reproduce the mass distributions in different cos$\theta$ region. It is not a fit!***

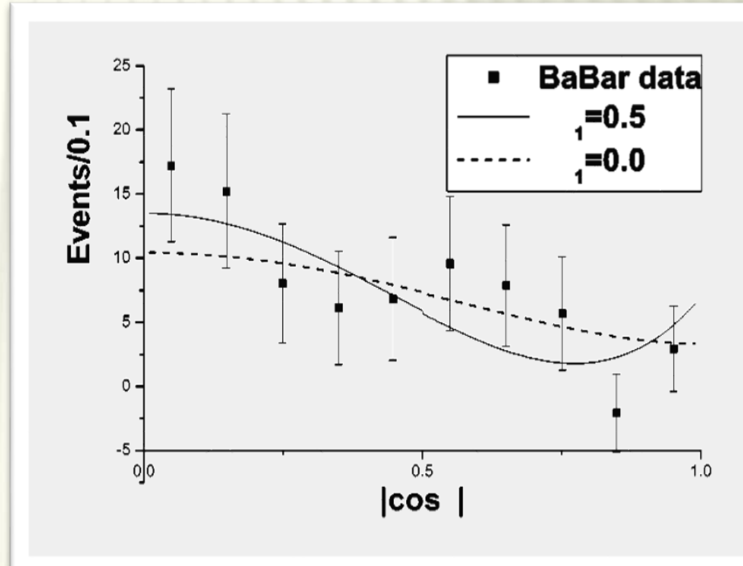


# CHECK THE NECESSITY OF ASSUMPTION OF HELICITY-2 DOMINANCE

**BaBar data of** $\gamma\gamma \to D\bar{D}$



# FIT PARAMETERS

| Parameters | "fit Belle 1" | "fit Belle 2" | "fit Belle 3" | "fit BaBar 1" | "fit BaBar 2" | "fit BaBar 3" |
|---|---|---|---|---|---|---|
| $\chi^2/d.o.f$ | 44.8/(47+10−9) | 45.2/(47+10−7) | 55.5/(47+10−8) | 71.9/(47+10−9) | 73.7/(47+10−7) | 73.1/(47+10−8) |
| $M_{\chi_{c0'}}$(GeV) | $3.817 \pm 0.009$ | $3.814 \pm 0.006$ | $3.820 \pm 0.009$ | $3.853 \pm 0.009$ | $3.851 \pm 0.009$ | $3.853 \pm 0.009$ |
| $\Gamma_{\chi_{c0'}}$(GeV) | $0.163 \pm 0.033$ | $0.155 \pm 0.020$ | $0.201 \pm 0.019$ | $0.229 \pm 0.031$ | $0.227 \pm 0.032$ | $0.233 \pm 0.030$ |
| $M_{\chi_{c2'}}$(GeV) | $3.925 \pm 0.003$ | $3.925 \pm 0.005$ | $3.924 \pm 0.009$ | $3.932 \pm 0.001$ | $3.932 \pm 0.001$ | $3.932 \pm 0.001$ |
| $\Gamma_{\chi_{c2'}}$(GeV) | $0.035 \pm 0.005$ | $0.036 \pm 0.005$ | $0.031 \pm 0.005$ | $0.021 \pm 0.004$ | $0.021 \pm 0.005$ | $0.020 \pm 0.004$ |
| $\beta_1$ | $\boxed{0.147 \pm 0.201}$ | 0 | 0.5 | $\boxed{0.290 \pm 0.237}$ | 0 | 0.5 |
| $\phi_1$(Rad) | $2.850 \pm 0.513$ | | $3.653 \pm 0.389$ | $3.713 \pm 1.326$ | | $3.700 \pm 0.597$ |
| $\beta_2$ | $0.559 \pm 0.077$ | $0.586 \pm 0.051$ | $0.388 \pm 0.086$ | $0.514 \pm 0.151$ | $0.599 \pm 0.056$ | $0.330 \pm 0.101$ |

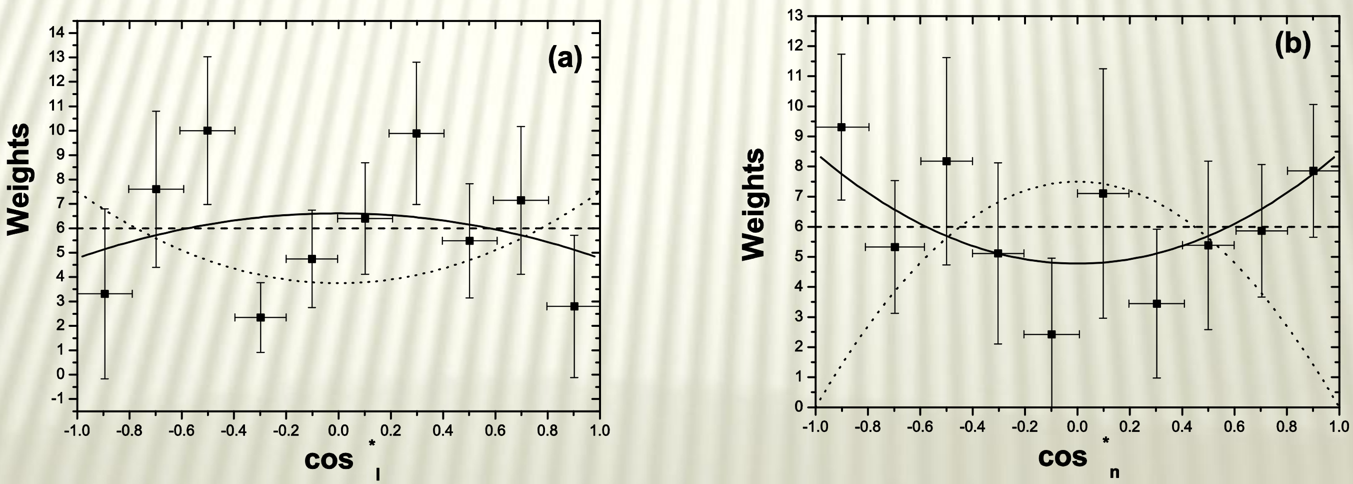
***<u>Large errorbars</u> imply that this experiment do not verify the helicity-2 dominance. Belle and BaBar's analyses might be over-restricted by using this assumption.***

***To check this assumption again, by fixing the $\beta_1$ value, one obtains fit results with similar qualities. This means the helicity-2 dominance assumption is not necessary in determining the X(3930), and the related experiment can not be regarded as the evidence of this assumption.***

# ANGULAR DISTRIBUTIONS

***Coupled-channel unitarity could give a constraint to the helicity ratios of different channels at the pole position.***

***The angular distribution of the final leptons, pions, and the angle between leptons and pions of X(3915) signal. A combined fit of*** $\gamma\gamma \to D\bar{D}, J/\psi\omega$ ***data favors*** $\beta_1/\beta_2 = 0.48/0.30$***,which means a sizable helicity-0 contribution. The fit also provide a better description to the angular-distribution data.***



# SUMMARY I

- *We pointed out that, by abandoning the helicity-2 assumption, the experimental data prefer the X(3915) to be a $J^{PC}=2^{++}$ state than a $J^{PC}=0^{++}$ state . Its mass and width are coinciding with those of the X(3930) state. X(3915) and X(3930) are the same tensor state.*
- *It may suggest a sizable non-qqbar components of the X(3930) state, as other states above the open-flavor thresholds.*
- *Further experimental measurements are suggested.*
- *Several theoretical efforts on coupled-channel models predict*

*$\chi_{c0}$(2P) at about 3850GeV*

**Pennington and Wilson, PRD 6,077502(2007)**
**Danilkin and Simonov, PRL 105,102002(2010)**
**Zhou, Xiao, EPJA 50,165(2014)**

# TOPIC II: DISTINGUISHING CUSP EFFECTS AND NEAR-THRESHOLD-POLE EFFECTS

In collaboration with Zhiguang Xiao(肖志广) USTC

arXiv:1505.05761

# MOTIVATION

- ***More and more near-threshold charmonium-like and bottomonium-like structures, dubbed $Z_c$'s and $Z_b$'s, are observed.***
- ***Since these signals are near thresholds, there are debates on the origin of these signals.***

***The threshold cusp effects.***

**Bugg, EPL 96,11002(2011) Chen et.al., PRD 84,034032(2011) Swanson, PRD 91,034009(2015)**

***Importance of higher-order contributions***

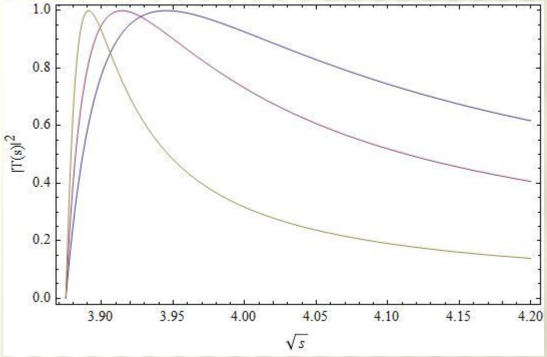
**Guo et.al., PRD91,051504(2015)**

***No pole even including higher-order contributions.***

**Swanson, arXiv:1504.07952**

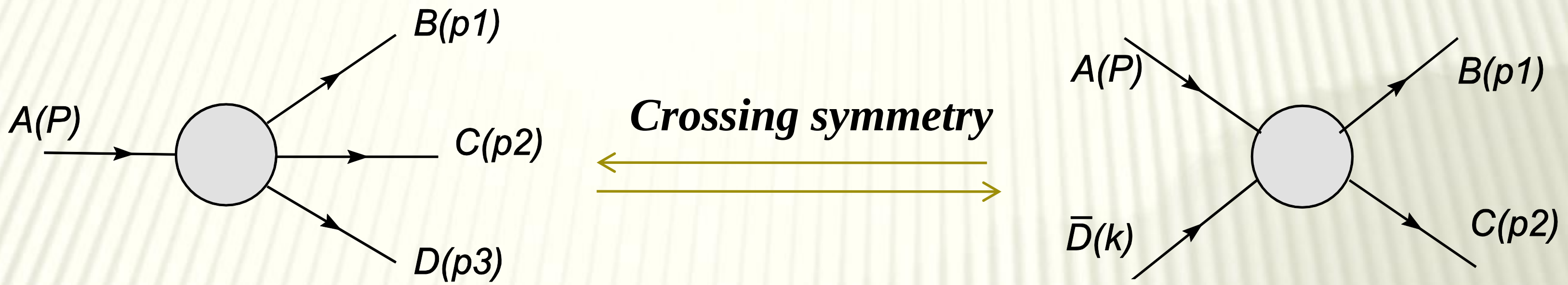
# OUR OPINION

- ***Threshold cusps come from the unitarity cut. It always be there. How to distinguish the threshold cusp effect and the near-threshold-pole effects? Establishing a model with correct general properties and determining the signal by data.***




- ***Unitarity and analyticity play important roles in non-perturbative analyses. Coupled-channel unitarity also put more constraints to the model parameters. It also provides us a chance to analyze the data with different final states at the same time.***
- ***Summing up higher-order diagrams is a consensus of theorists in studying nonperturbative problems.***

# THE MODEL




***Crossing symmetry requires that the decay amplitude and the scattering amplitude are the same functions with the Mandelstam variables in different physical regions.***

$$s=(p_1+p_2)^2, t=(p_1+p_3)^2, u=(p_2+p_3)^2,$$

$$where \qquad s+t+u=m_A^2+m_B^2+m_C^2+m_D^2.$$

***We build a factorization form for a two-body scattering process first.***

# THE MODEL

***Factorization form of T matrix in "Argand unit"***

$$T = G^{+}\Sigma G$$

***in a matrix form***

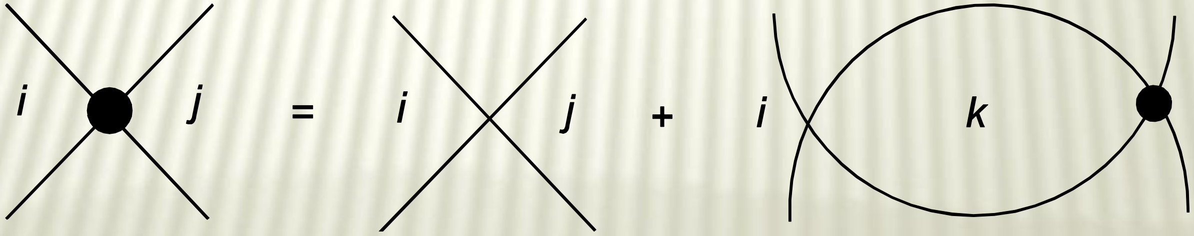
$$G = \begin{pmatrix} G_1(s) & 0 & 0 & \\ 0 & G_2(s) & 0 & \\ 0 & 0 & G_3(s) & \\ & & & \ddots \end{pmatrix}$$

*where* $G_n(s) = \sqrt{\rho_n(s)}\, f_n(s)\theta(s - s_{th,n})$

$\Sigma$ ***satisfies several iterative equations in a matrix form***

$$\Sigma = \lambda + \lambda \Pi \Sigma$$

***which could be represented pictorially as***




***It could be regarded as a Simplification of Lippmann-Schwinger equation.***

**Kaiser, Siegel, Weise, NPA594,325(1995 )  Oller and Oset, NPA620,438(1997)**

# THE MODEL

***Coupled-channel unitarity leads to***

$$\mathrm{Im}\,\Sigma^{-1} = -GG^{+}$$

$$\Sigma^{-1} = \lambda^{-1}(I - \lambda\Pi)$$

$$\mathrm{Im}\,\Pi = GG^{+}$$

***which means the imaginary part of Π***

$$\mathrm{Im}\,\Pi_n = \rho_n(s) f_n^2(s)\theta(s - s_{th,n}).$$

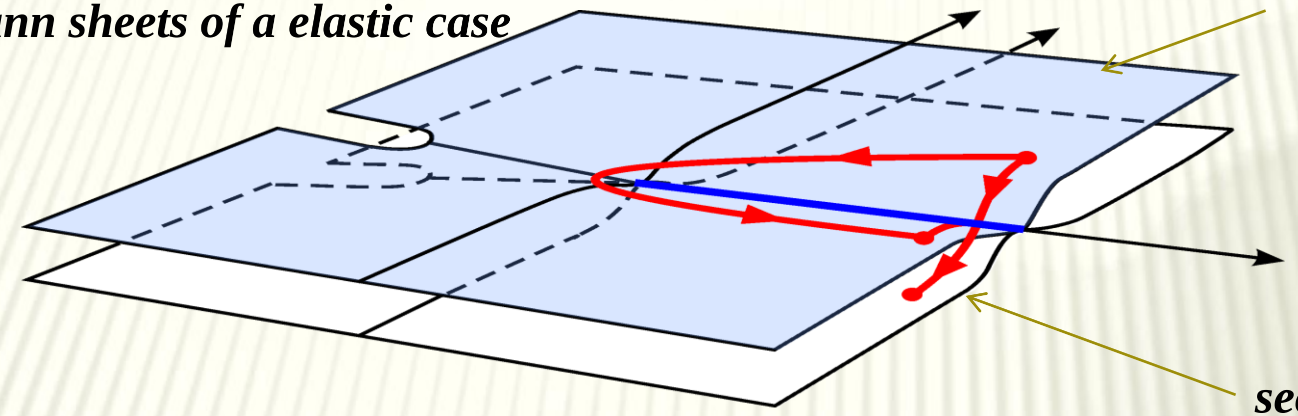
***The real part of Π could be represented by a dispersion relation***

$$\mathrm{Re}\,\Pi_n = \frac{1}{\pi}\int_{s_{th,n}}^{\infty} \frac{\mathrm{Im}\,\Pi_n(s)}{z-s} dz.$$

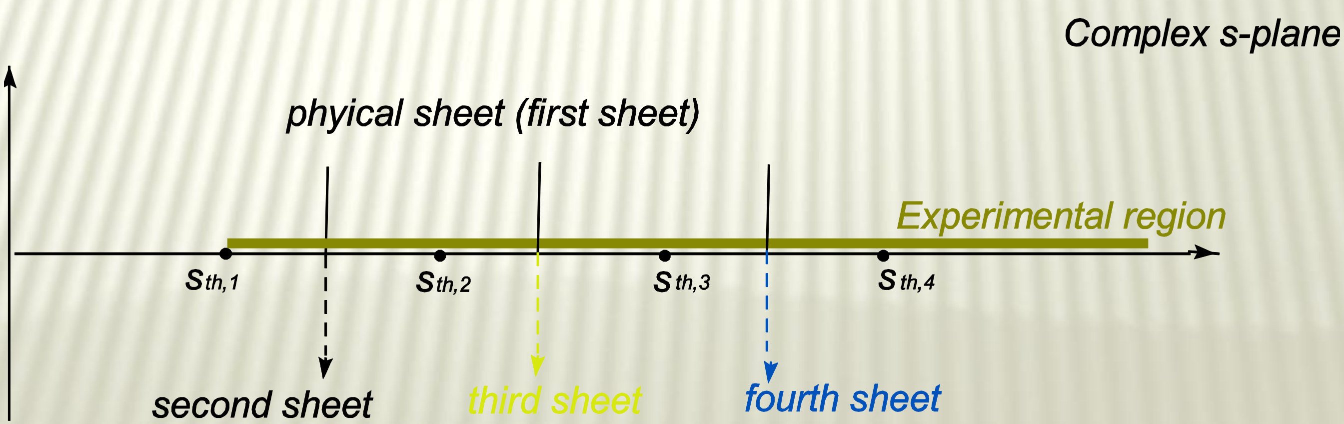
***One can easily analytically continue the amplitudes to complex s-plane and study its analytic structure.***

# ANALYTIC STRUCTURE

***Riemann sheets of a elastic case***




***For a n-channel case, there are $2^n$ Riemann sheets, but only the closest sheets are important.***



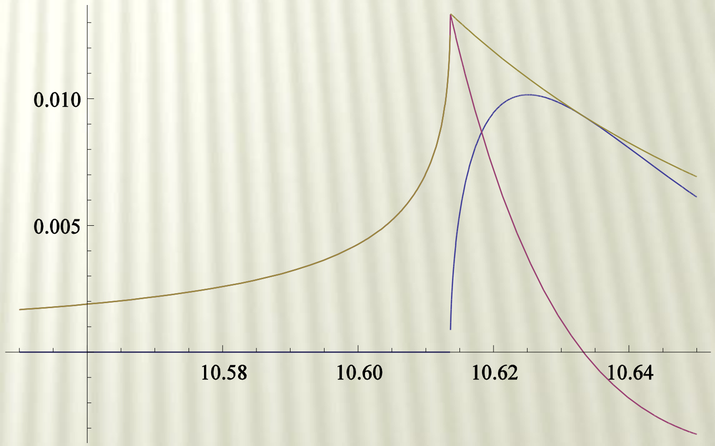
# PICTURE

*The poles appear at the zero points of determinant of* $(I-\lambda\Pi)$ *, since*

$$\Sigma^{-1}=\lambda^{-1}(I-\lambda\Pi)$$

***For a elastic case (only one channel), if the coupling constant is stronger than Π($s_{th}$), there exists a bound-state pole on the first sheet. When the coupling becomes weaker, the pole moves to the threshold, crosses it, and become a virtual-state pole on the second sheet.***

***For a inelastic case, the poles usually move to the complex s-plane and become resonance poles.***

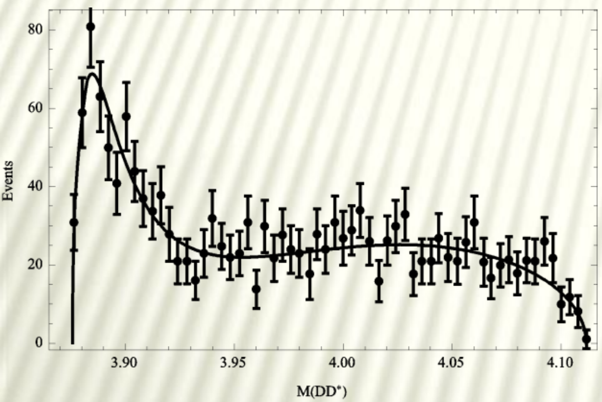


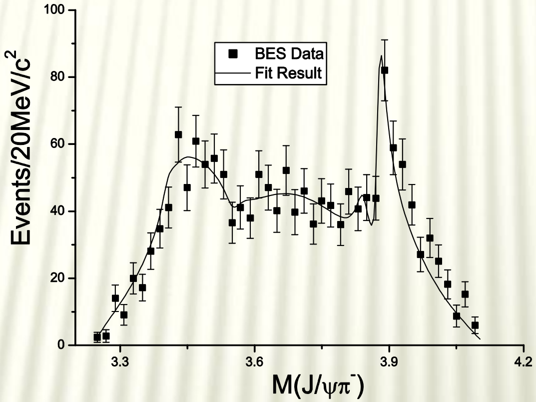

***Typical behavior of ReΠ, ImΠ, and |Π|***

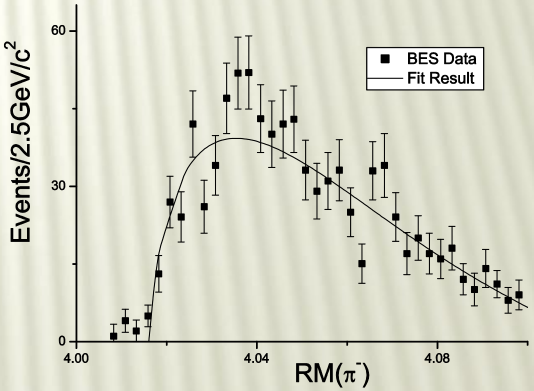
# NUMERICAL RESULTS OF A COMBINED FIT

***We consider a four-channel case. The channels $J/\psi\pi$, $DD^*$, $D^*D^*$, and $X(4260)\pi$ are referred to channel "1", "2", "3", and "4". The channel $X(4260)\pi$ is always virtual, but it provides a background contribution.***

***A perfect fit to the experimental data for charged $DD^*$, $D^*D^*$, and $J/\psi\pi$ mass-distribution data at the same time in $e^+e^-$ collision at about $s^{1/2}$=4.26GeV.***




$$\frac{\chi^2}{d.o.f} = 1.03$$

# NUMERICAL RESULTS

*Two nearby poles are found* $s^{II} = (3.846 \pm 0.019i)^2 GeV^2,$

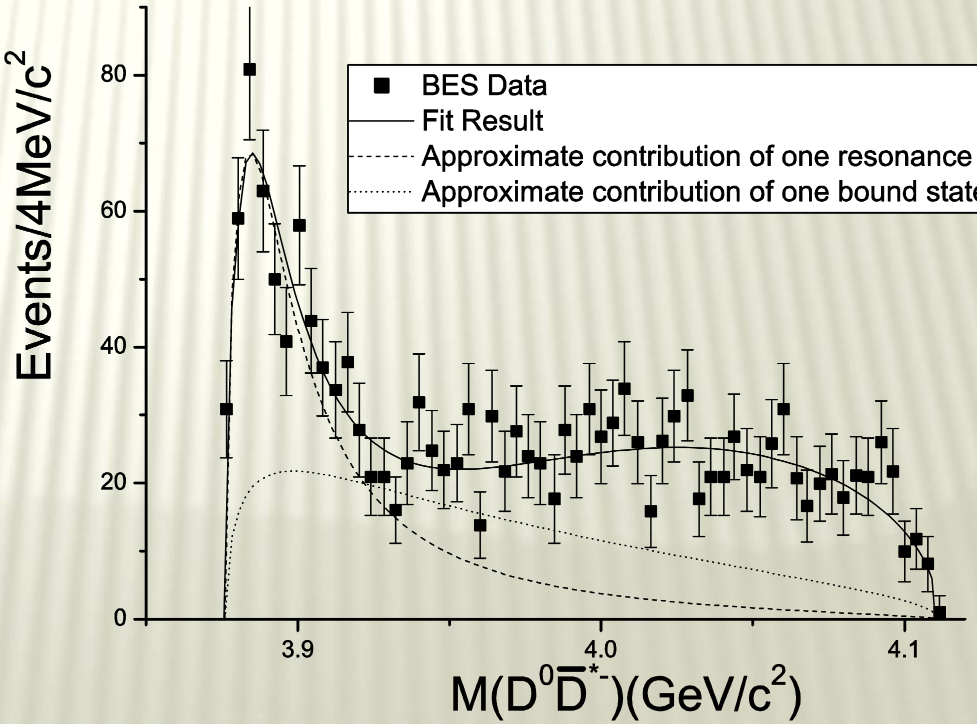
$$s^{III} = (3.875 \pm 0.016i)^2 GeV^2.$$

***No nearby pole is found near the $D^*D^*$ threshold.***

***There is no method to precisely isolate the contribution of a pole in multichannel scattering .***

***We propose that the third-sheet pole might contribute dominantly. If we omit the $J/\psi\pi$ threshold, the number of Riemann sheet become 8. A third-sheet pole will become a second-sheet pole. We might use a second-sheet pole of the PKU factorization form (Zheng et al., NPA 733, 235(2004)) to mimick the contribution of***

$$s^{III} = (3.875 \pm 0.016i)^2 GeV^2.$$



# SUMMARY II

- ***The model could perfectly reproduce the mass distribution data of different final states of X(4260) at the same time.***
- ***The best numerical result of a combined analysis prefers the Zc(3900) signal is formed by the combined effect of two poles and the DD*** **threshold. Although the two poles are "shadow" poles, the third-sheet one at*** $s^{III}=(3.875\pm0.016i)^2 GeV^2$ ***contributes dominantly.***
- ***However, no pole related to the Zc(4025) in $D^*D^*$ mass distribution.***
- ***This scheme satisfies the coupled –channel unitarity and the higher-order contributions are included. Its analytic structure is easily analyzed. The scheme is simply operated. It may be generalized and used in experiment analyses.***
- ***Combined analyses are suggested, which will provide more informations.***

# THANKS FOR YOUR PATIENCE!

Reference: Phys.Rev.Lett. 115.022001(2015)
arXiv:1501.00879
arXiv:1505.05761