Could the $X(3915)$ and the $X(3930)$ be the same tensor state?

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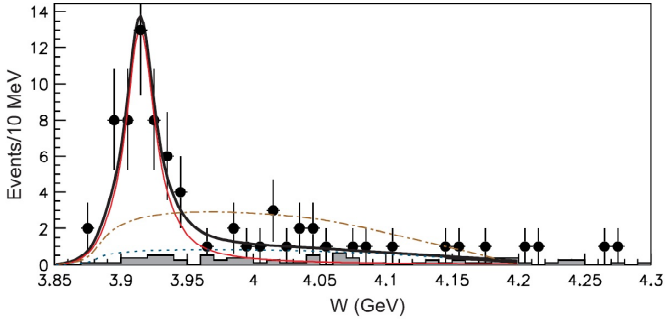
X(3915)

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

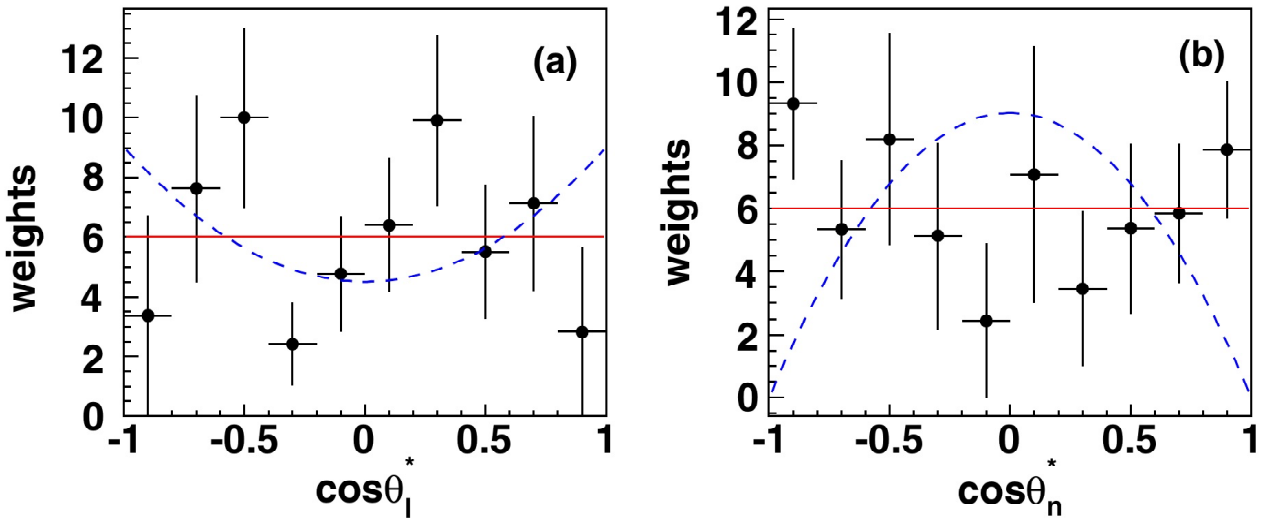
$\chi_{c0}(2P)$ MASS	3918.4 ± 1.9 MeV
$\chi_{c0}(2P)$ WIDTH	20 ± 5 MeV (S = 1.1)
$\chi_{c0}(2P)\ \Gamma(\mathrm{i})\Gamma(\gamma\gamma)/\Gamma(\mathrm{total})$	

- X(3915) observed by Belle (PRL,104,092001,(2010)), $\gamma\gamma \to J/\psi\omega$. It was not determined whether it is 0^+ or 2^+.
- Interpretation:
  $\chi_{c0}(2P)$: Xiang Liu et.al., PRL104,122001(2010).
  $\chi_{c2}(2P)$: T.Branz et.al., PRD83,114015(2011).



X(3915)

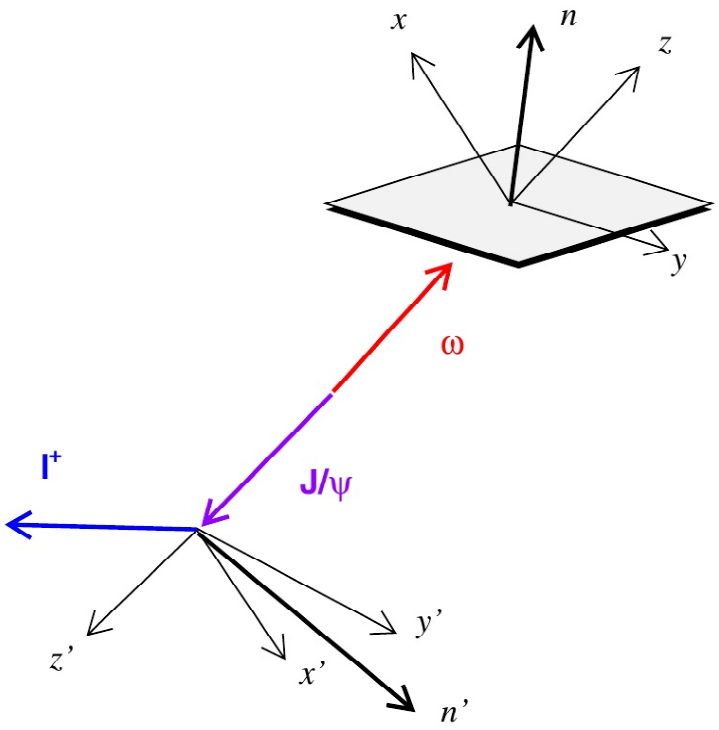
BABAR PRD86,072002(2012):
Search for $X(3915)$ in $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^- J/\psi\omega$,
$J/\psi \to \ell^+\ell^-$, $(\ell = e, \mu)$, $\omega \to \pi^+\pi^-\pi^0$.
$\gamma\gamma$ quasi-real, $J^P = 0^{\pm+}, 2^{\pm+}, 4^{\pm+}, \ldots; 3^{++}, 5^{++}, \ldots$



Prefer $J^{PC} = 0^{++}$

X(3915)

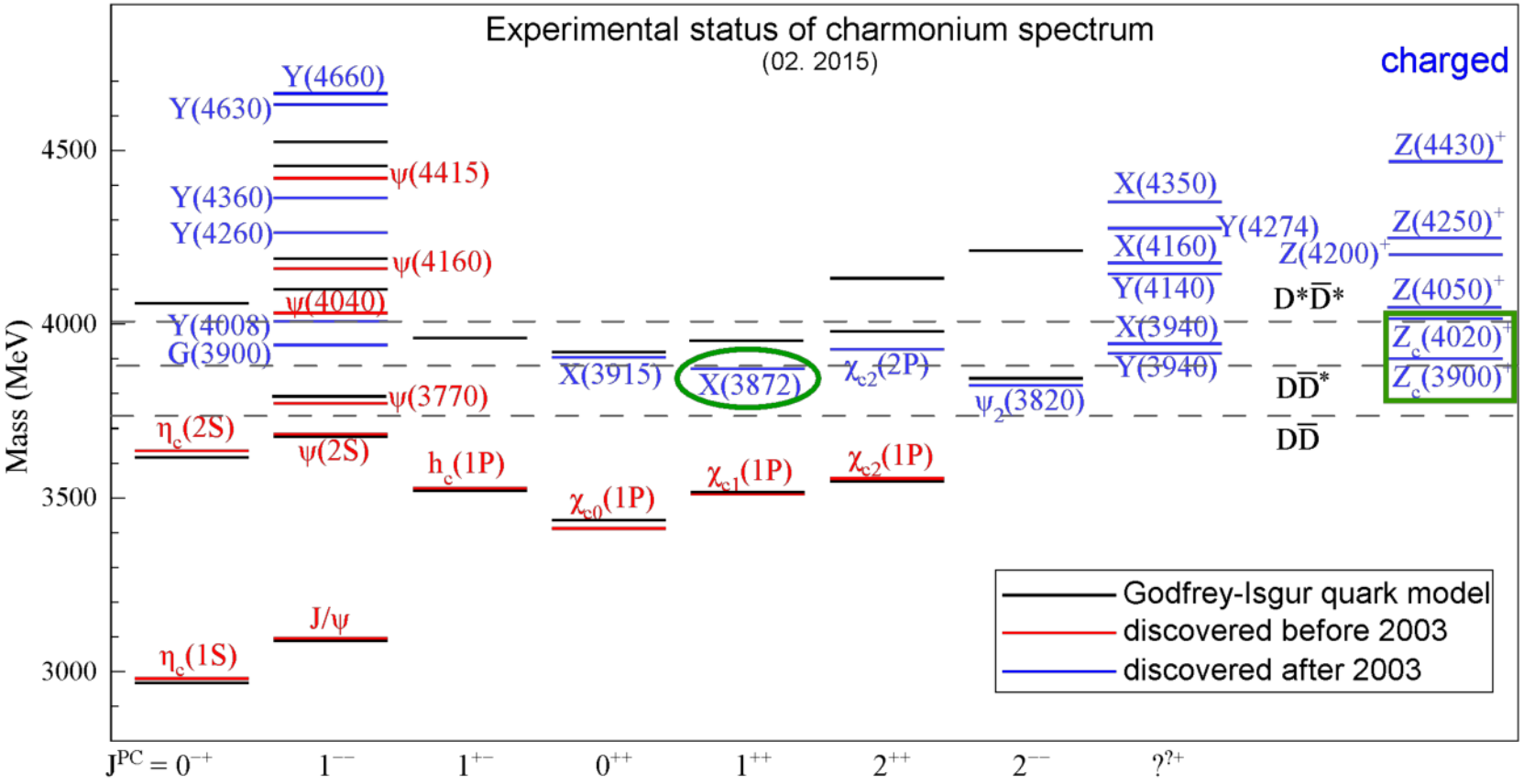
- θ_ℓ^*: angle between the ℓ^+ from J/ψ and the two photon axis (the same as the e^+e^- beam).
- θ_n^*: angle between the normal of the ω decay plane $\vec{n}$ and the two photon axis.



X(3915): THE QUANTUM NUMBER

$J^{PC} = 0^{++}$? Is it really the $\chi_{c0}(2P)$?

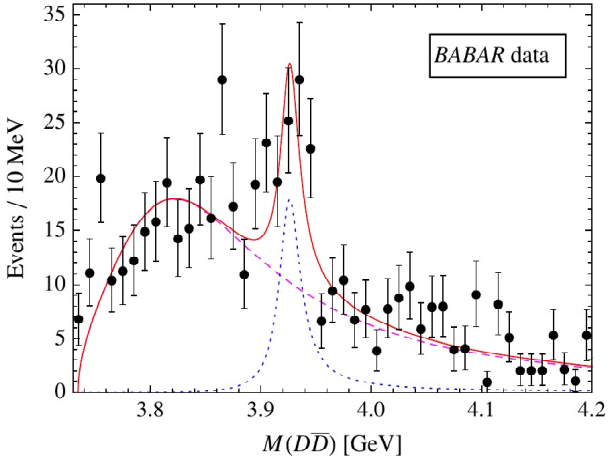
- Godfrey-Isgur model (PRD 32,189(1985)): predicts the mass of $\chi_{c0}(2P)$ to be about 3915MeV, but for states above open-flavor threshold, GI's predictions are usually higher than the observed values.

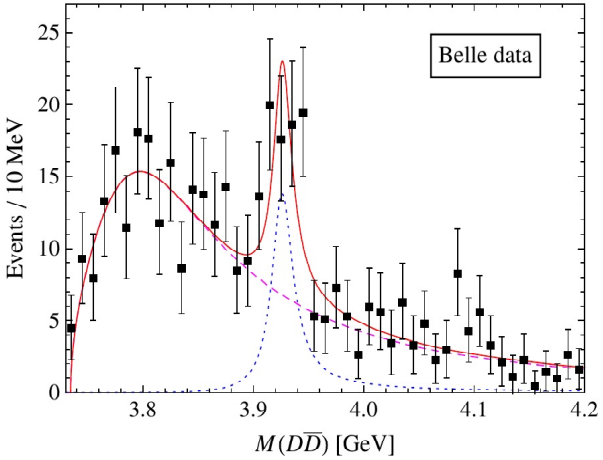

Experimental status of charmonium spectrum
(02. 2015)
charged
Mass (MeV)
4500
4000
3500
3000
Y(4660)
Y(4630)
ψ(4415)
Y(4360)
Y(4260)
ψ(4160)
ψ(4040)
Y(4008)
G(3900)
ψ(3770)
η_c(2S)
ψ(2S)
J/ψ
η_c(1S)
h_c(1P)
X(3915)
χ_c0(1P)
X(3872)
χ_c1(1P)
χ_c2(2P)
χ_c2(1P)
ψ_2(3820)
X(4350)
Y(4274)
X(4160)
Y(4140)
X(3940)
Y(3940)
Z(4200)^+
D*D̄*
DD̄*
DD̄
Z(4430)^+
Z(4250)^+
Z(4050)^+
Z_c(4020)^+
Z_c(3900)^+
Godfrey-Isgur quark model
discovered before 2003
discovered after 2003
J^PC = 0^-+
1^--
1^+-
0^++
1^++
2^++
2^--
?^?+

X(3915): THE QUANTUM NUMBER

Questioned: $X(3915) = \chi_{c0}(2P)$?

- Guo and Meissner (PRD,86,091501): propose that $\chi_{c0}(2P)$ should be a broad resonance around 3840.
  - $\chi_{c0}(2P) \to J/\psi\omega$ is OZI suppressed, but with $> 1MeV$ partial width for $X(3915)$, too large.
  - $\chi_{c0}(2P) \to D\bar{D}$ is OZI allowed, but lack of evidence for $X(3915) \to D\bar{D}$.
  - The mass diffrence between $X(3915)$, $\chi_{c0}(2P)$ and $X(3930)$, $\chi_{c2}(2P)$ is too small. For 1P: $\chi_{c2} - \chi_{c0} \sim 141\text{MeV}$.





- Olsen (Phys. Rev. D 91, 057501): The upper limit of the $\mathscr{B}(\chi_{c0}(2P) \to \omega J/\psi)$ implied by $\gamma\gamma \to X(3915)$ is lower than the lower bound infered from $B \to KX(3915)$.

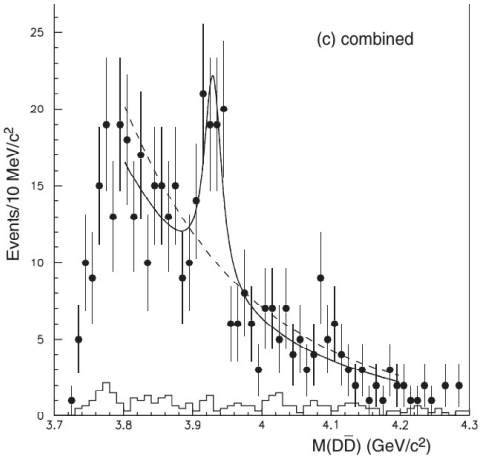
X(3930)

$\chi_{c2}(2P)$

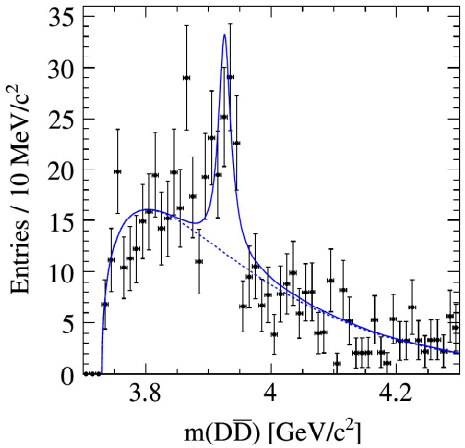
$\chi_{c2}(2P)$ MASS	3927.2 ± 2.6 MeV
$\chi_{c2}(2P)$ WIDTH	24 ± 6 MeV

in $\gamma\gamma \to D\bar{D}$, Belle Phys.Rev.Lett. 96 (2006) 082003;
BABAR, Phys.Rev. D81 (2010) 092003.

BELLE



BABAR



Main decay modes: $X(3930) \to D\bar{D}, D^+D^-, \gamma\gamma$.

Helicity-2 dominance

Is it possible that the $X(3930)$ and $X(3915)$ are the same resonance?

- In determinating the quantum number of $X(3915)$, BABAR uses the helicity 2 dominance assumption of the tensor resonance.
  $\gamma\gamma \to X(3915) \to J/\psi\omega$, two onshell massless γ, helicity-2 or 0.
- The helicity-2 dominance comes from the calculation for $Q\bar{Q}$ states under the quark model (Krammer & Krasemann, PLB73,58(1978), Z.Li, F.Close, and T Barne, PRD43,2161).

Helicity-2 dominance

- However, above open flavor threshold, the resonances described by quark model $Q\bar{Q}$ is not quite consistent with the experiment. And these states could be described better by couple-channeled 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)).
- If $X(3915)$ is not composed purely of $Q\bar{Q}$ state or the open-flavor effects should be included, then this helicity-2 dominance assumption may not be good.
- In fact, the helicity 2 dominance assumption should also be tested by experimental data. The data $X(3930)$ can be used to test this assumption.

Outline of Our work

- Examine : $\gamma\gamma \to D\bar{D}$ mass and angular distributions, to see whether the helicity-2 dominance is neccesary to reproduce the X(3930) data — the answer is negative.
  - Assuming a broad 0^{++} resonance around 3830 MeV to simulate the background, and a narrow 2^{++} resonance around 3.93 GeV.
  - Partly incorporate the unitarity in the parameterization of the helicity amplitude to take into account the open-flavor effect.
- Abandoning the helicity-2 dominance assumption, we analyse the angular distribution of $X(3915)$ from BABAR to see whether the experiment data can be reproduced.

Basic framework

The differential cross section of $\gamma\gamma \to D\bar{D}$ in terms of helicity amplitudes $\mathcal{M}_{+\pm}$: $\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2\rho(s)s}(|\mathcal{M}_{++}|^2 + |\mathcal{M}_{+-}|^2)$,
Partial wave expansion:

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

From unitarity, the partial wave amplitude can be parameterized as (Au, Morgan, Pennington *PhysRevD.35.1633*)

$$\begin{aligned} F_{J\lambda}(\gamma\gamma \to D\bar{D}; s) &= \alpha_{1;J\lambda}(s)T_J(D\bar{D} \to D\bar{D}; s) \\ &+ \alpha_{2;J\lambda}(s)T_J(J/\psi\omega \to D\bar{D}; s), \\ F_{J\lambda}(\gamma\gamma \to J/\psi\omega; s) &= \alpha_{1;J\lambda}(s)T_J(D\bar{D} \to J/\psi\omega; s) \\ &+\alpha_{2;J\lambda}(s)T_J(J/\psi\omega \to J/\psi\omega; s), \end{aligned} \quad (2)$$

$\alpha_{i;J\lambda}$: no right-hand cut, smooth real functions in the physical region.

Basic framework:Strong amplitude

- We use the Breit-Wigner amplitudes combined with the Blatt-Weisskopf factors to parameterize the strong amplitudes, which are also used in the BABAR's original analysis:

$$T_L(s) = \frac{M\Gamma(s)}{M^2 - s - iM\Gamma(s)},\ \Gamma(s) = \Gamma(\frac{p}{p_0})^{2L+1}\frac{M}{\sqrt{s}}F_L^2(s),$$

  where $F_0 = 1$ and $F_2 = \frac{\sqrt{9+3(p_0R)^2+(p_0R)^4}}{\sqrt{9+3(pR)^2+(pR)^4}}$, with $R = 1.5\mathrm{GeV}^{-1}$
- Two Breit-Wigner: a S-wave, 0^{++} broad resonance pole to parameterize the background, and a D-wave, 2^{++} narrow pole ($X(3930)$).
- 0^{++} contributes to $\mathcal{M}_{++}$; 2^{++} contributes to $\mathcal{M}_{++}$ and $\mathcal{M}_{+-}$

$\gamma\gamma \to D\bar{D}$ PROCESS

First, we look at the $\gamma\gamma \to D\bar{D}$ process:

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

$$\mathcal{A}_0(s) = \frac{M_{\chi_{c0'}}\Gamma_{\chi_{c0'}}(s)}{M^2_{\chi_{c0'}} - s - iM_{\chi_{c0'}}\Gamma_{\chi_{c0'}}(s)},$$

$$\mathcal{A}_2(s) = \mathcal{B}_2(s) = \frac{M_{\chi_{c2'}}\Gamma_{\chi_{c2'}}(s)}{M^2_{\chi_{c2'}} - s - iM_{\chi_{c2'}}\Gamma_{\chi_{c2'}}(s)}.$$

- We can fit the $\gamma\gamma \to D\bar{D}$ mass and angular distribution simultaneously.
- The fit parameters are $M_{\chi_{c0'}}$, $\Gamma_{\chi_{c0'}}$, $M_{\chi_{c2'}}$, $\Gamma_{\chi_{c2'}}$, β_1, ϕ_1, and β_2.

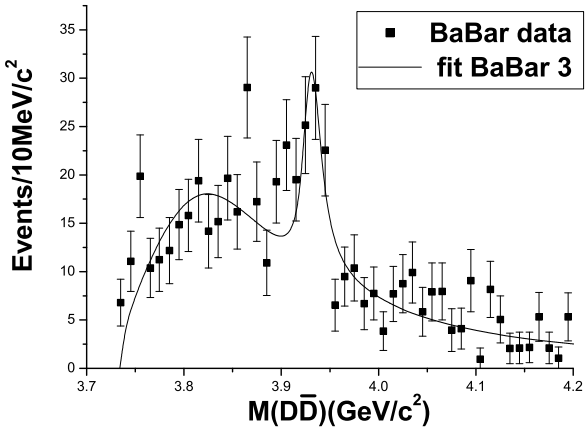
$\gamma\gamma \to D\bar{D}$: TESTING THE HELICITY-2 DOMINANCE

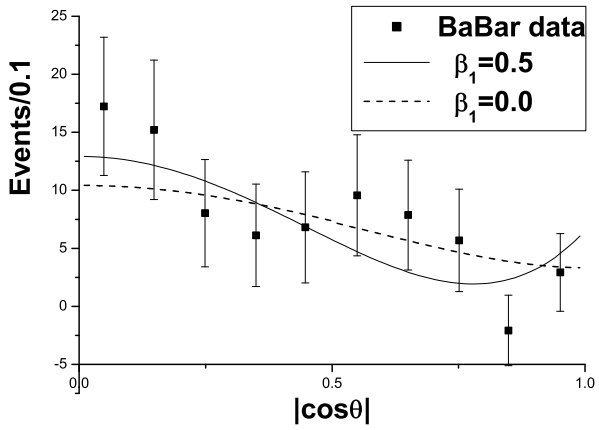
β_2/β_1: denotes the relative strength of the helicity-2 and helicity-0 contributions from the tensor resonance.

Three sets of fits:

- All parameters free. "fit Belle 1", "fit BABAR 1"
- Only Helicity-2 contribution: "fit Belle 2", "fit BABAR 2"
- Fix helicity-0 contribution to be large $\beta_1 = 0.5$: "fit Belle 3", "fit BABAR 3"

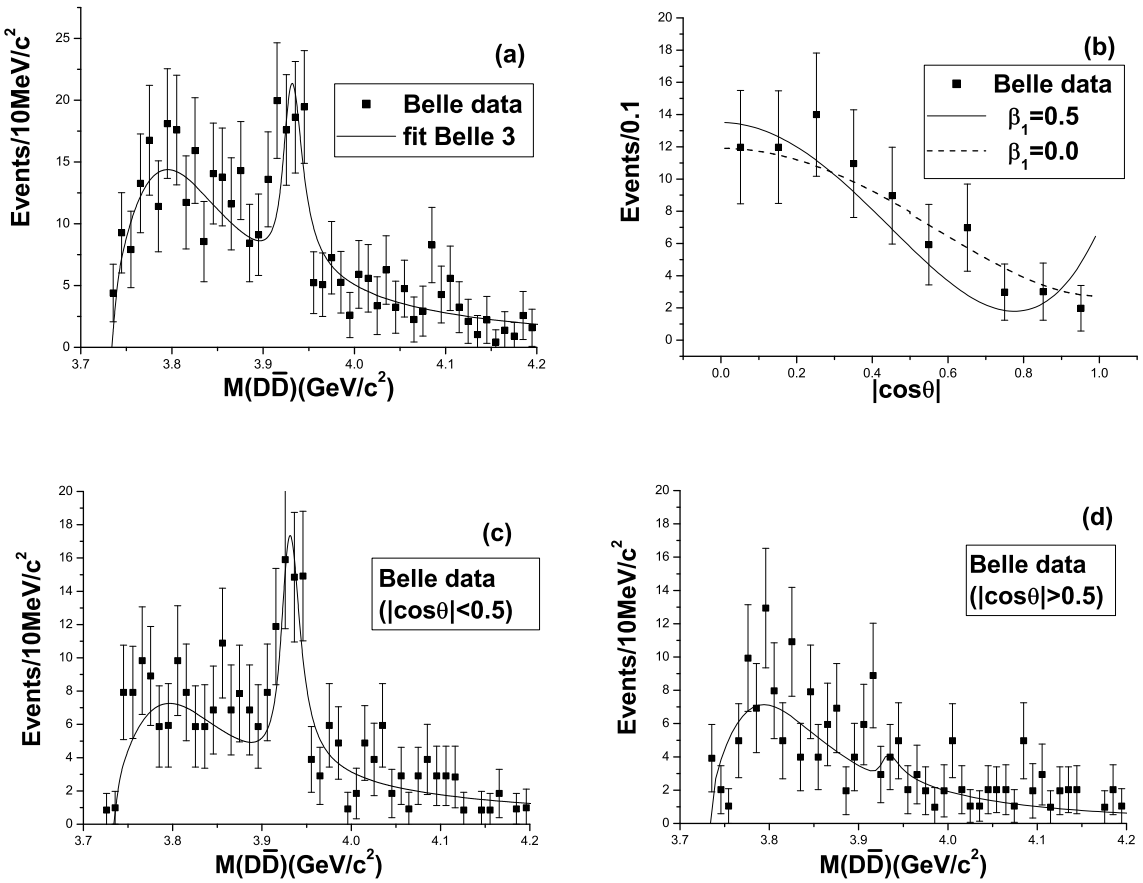
BABAR:





$\gamma\gamma \to D\bar{D}$ PROCESS

BELLE



The lower two diagrams are predictions, consistent with the data well.

Testing the helicity-2 dominance

Parameters	"fit Belle 1"	"fit Belle 2"	"fit Belle 3"
$\chi^2/d.o.f$	0.93	0.9	1.13
$M_{\chi_{c0'}}$(GeV)	3.817 ± 0.009	3.814 ± 0.006	3.820 ± 0.009
$\Gamma_{\chi_{c0'}}$(GeV)	0.163 ± 0.033	0.155 ± 0.020	0.201 ± 0.019
$M_{\chi_{c2'}}$(GeV)	3.925 ± 0.003	3.925 ± 0.005	3.924 ± 0.009
$\Gamma_{\chi_{c2'}}$(GeV)	0.035 ± 0.005	0.036 ± 0.005	0.031 ± 0.005
β_1	0.147 ± 0.201	0	0.5
ϕ_1(Rad)	2.850 ± 0.513		3.653 ± 0.389
β_2	0.559 ± 0.077	0.586 ± 0.051	0.388 ± 0.086

Parameters	"fit BaBar 1"	"fit BaBar 2"	"fit BaBar 3"
$\chi^2/d.o.f$	1.50	1.47	1.49
$M_{\chi_{c0'}}$(GeV)	3.853 ± 0.009	3.851 ± 0.009	3.853 ± 0.009
$\Gamma_{\chi_{c0'}}$(GeV)	0.229 ± 0.031	0.227 ± 0.032	0.233 ± 0.030
$M_{\chi_{c2'}}$(GeV)	3.932 ± 0.001	3.932 ± 0.001	3.932 ± 0.001
$\Gamma_{\chi_{c2'}}$(GeV)	0.021 ± 0.004	0.021 ± 0.005	0.020 ± 0.004
β_1	0.290 ± 0.237	0	0.5
ϕ_1(Rad)	3.713 ± 1.326		3.700 ± 0.597
β_2	0.514 ± 0.151	0.599 ± 0.056	0.330 ± 0.101

Testing the helicity-2 dominance

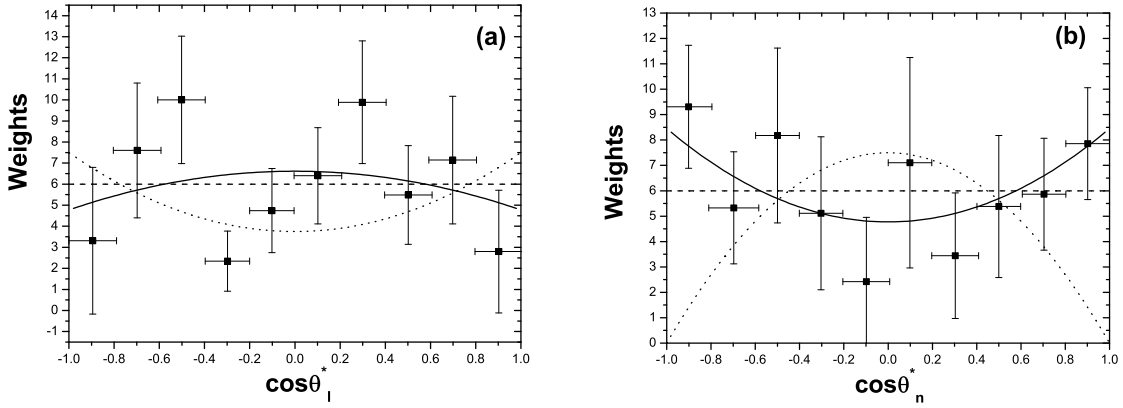
- The fit quality of these fits are similar: especially the fits for *BABAR*. The fit quality with larger helicity-0 "fit BABAR 3" and "fit Belle 3" is still acceptable.
- Free fit: large β_1 errorbar, there can be large helicity 0 contributions.
- The narrow $\chi_{c2'}$ pole position is not sensitive to whether the helicity-2 is dominant or not.

This means the helicity-2 dominance assumption is not necessary in determining the X(3930).

Angular distribution for $\gamma\gamma \to J/\psi\omega$

Re-examine BABAR's angular distribuation for $\gamma\gamma \to J/\psi\omega$.

- We then do not impose the helicity-2 dominance.
- Assuming the $X(3915)$ and $X(3930)$ are the same tensor state.
- Narrow resonance dominant assumption: β_1/β_2 is roughly the same as in $\gamma\gamma \to D\bar{D}$.
- Global fit to both $\gamma\gamma \to D\bar{D}$ mass distribution and $\gamma\gamma \to J/\psi\omega$ angular distribution.
- The fit qualities for the $\cos\theta_n^*$ and $\cos\theta_l^*$ are improved compared with the 0^{++} assignment of $X(3915)$.
- $\beta_1 : \beta_2 = 0.48 : 0.31$: a large helicity-0 contribution.



Conclusion

- We tested the helicity-2 dominance assumption in the $\gamma\gamma \to D\bar{D}$ process, and found that this assumption is not necessary in reproducing the experimental data for $X(3930)$.
- Without this assumption and assuming $X(3915)$ and $X(3930)$ to be the same tensor state, we reanalyses the angular distribution in for $X(3915)$, and found that this assignment is more consistent with the present BABAR data than assigning the $X(3915)$ to be 0^{++}.
- The helicity-0 contribution is large for this state, which means that it could not be a pure $Q\bar{Q}$ state.

Thank you!

Backup: narrow pole dominance assumption

We assume the narrow pole for the $X(3915)$. Under the pole dominance assumption, if the pole's couplings to the two channels are parameterized by $g_{D\bar{D}}$ and $g_{J/\psi\omega}$, respectively, for s near the pole position, we have

$$\begin{aligned}\frac{F_{J\lambda}(\gamma\gamma \to D\bar{D}; s)}{F_{J\lambda}(\gamma\gamma \to J/\psi\omega; s)} &= \frac{\alpha_{1;J\lambda}(s)\frac{g^*_{D\bar{D}}g_{D\bar{D}}}{s-s_{pole}} + \alpha_{2;J\lambda}(s)\frac{g^*_{J/\psi\omega}g_{D\bar{D}}}{s-s_{pole}}}{\alpha_{1;J\lambda}(s)\frac{g^*_{D\bar{D}}g_{J/\psi\omega}}{s-s_{pole}} + \alpha_{2;J\lambda}(s)\frac{g^*_{J/\psi\omega}g_{J/\psi\omega}}{s-s_{pole}}} \\ &= \frac{g_{D\bar{D}}}{g_{J/\psi\omega}}, \end{aligned} \tag{3}$$

which means

$$\frac{F_{20}(\gamma\gamma \to D\bar{D}; s)}{F_{20}(\gamma\gamma \to J/\psi\omega; s)} = \frac{F_{22}(\gamma\gamma \to D\bar{D}; s)}{F_{22}(\gamma\gamma \to J/\psi\omega; s)} \tag{4}$$

therefore,

$$\frac{F_{20}(\gamma\gamma \to D\bar{D}; s)}{F_{22}(\gamma\gamma \to D\bar{D}; s)} = \frac{F_{20}(\gamma\gamma \to J/\psi\omega; s)}{F_{22}(\gamma\gamma \to J/\psi\omega; s)} \tag{5}$$

at the pole position.