Discovery potential of charmonium 2*P* states through the $e^+e^- \to \gamma D\bar{D}$ processes

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PRD 111, 054021 (2025)

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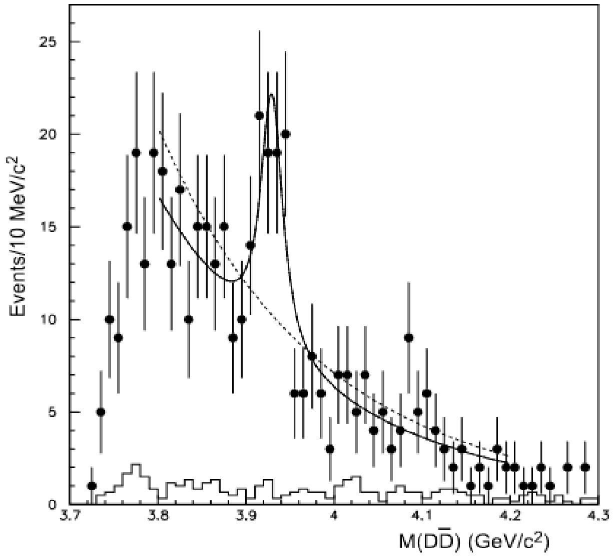
Outlook

- **Background**
- **The production of the $\chi_{c0,2}(2P)$ by $e^+e^- \to \gamma D\bar{D}$**
- **Numerical result**
- **Summary**

Background

$X(3915)$ & $Z(3930)$



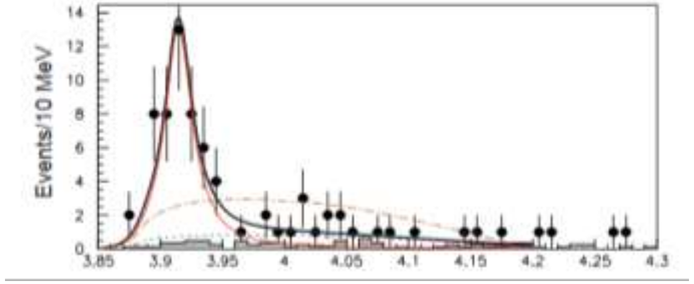
Belle PRL 96, 082003 (2006)

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

$Z(3930)$

2^{++}

$\chi_{c2}(2P)$ candidate

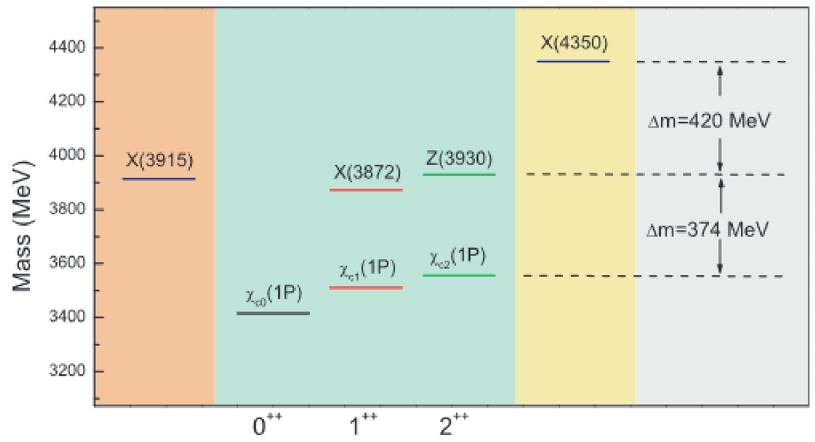


Belle PRL 104, 092001 (2010)

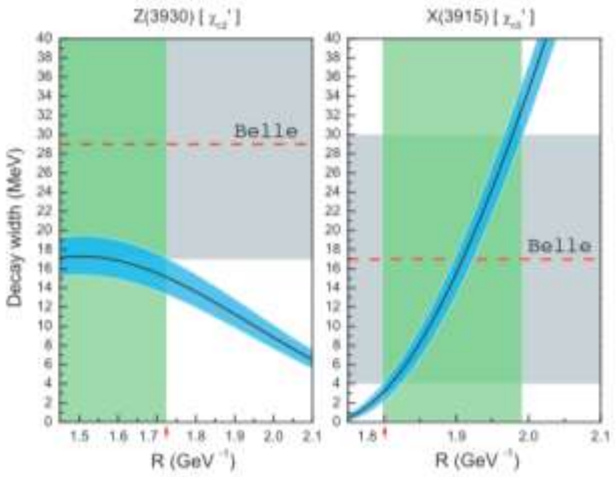
$\gamma\gamma \to J/\psi\omega$

$X(3915)$

0^{++} or 2^{++}



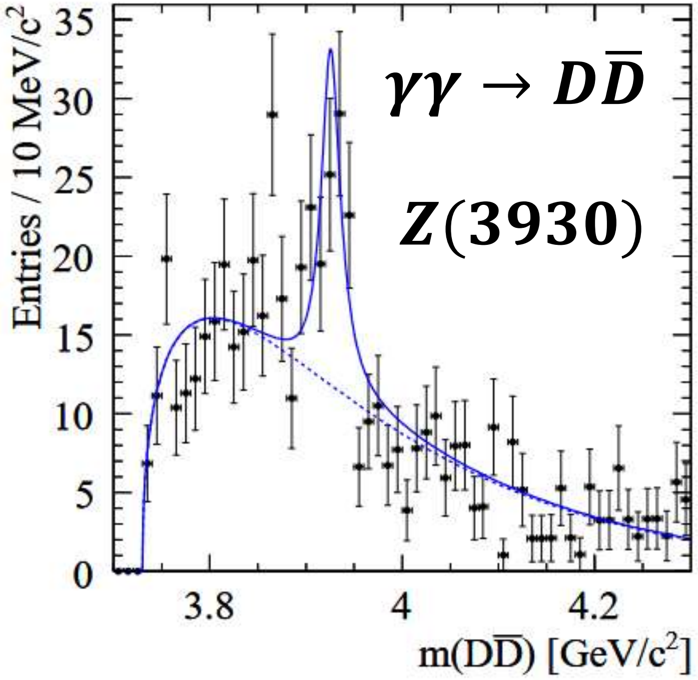
Xiang Liu, Luo-Zhi Gang and Zhi-Feng Sun
PRL 104, 122001 (2010)



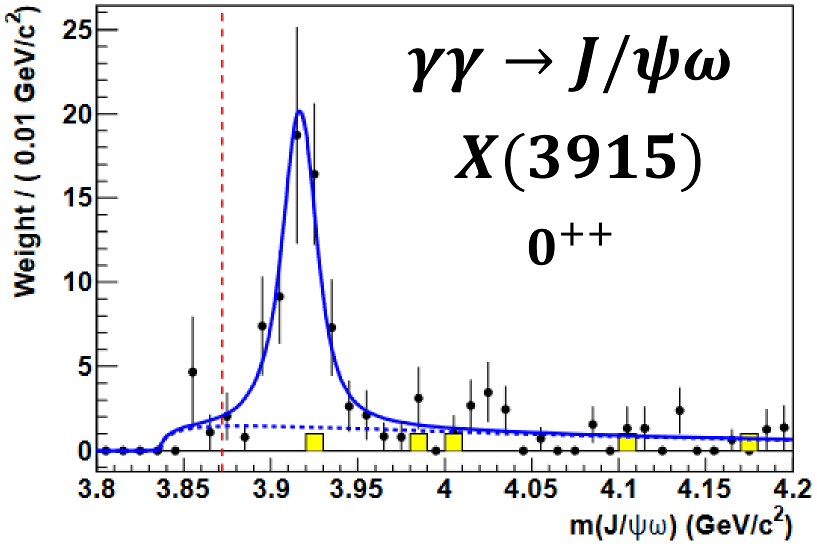
Consistent with Belle

$X(3915) \equiv \chi_{c0}(2P)$
$X(3872) \equiv \chi_{c1}(2P)$
$Z(3930) \equiv \chi_{c2}(2P)$

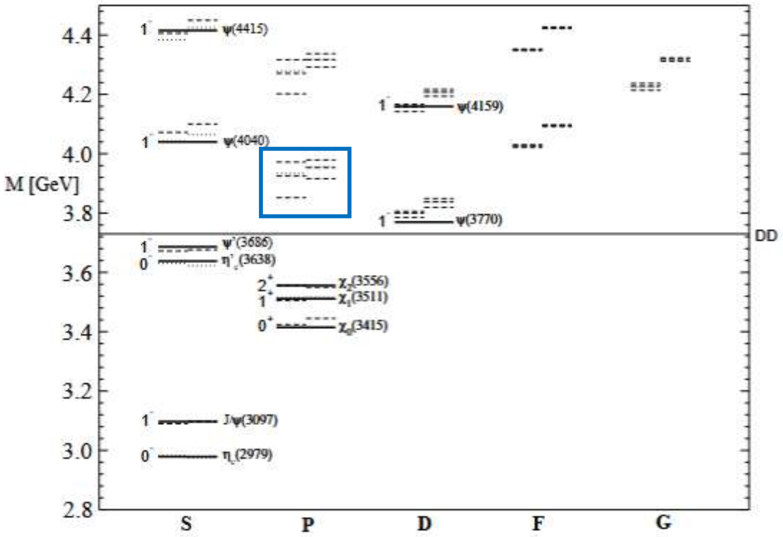
Three questions



Babar PRD 81, 092003 (2010)



Babar PRD 86, 072002 (2012)

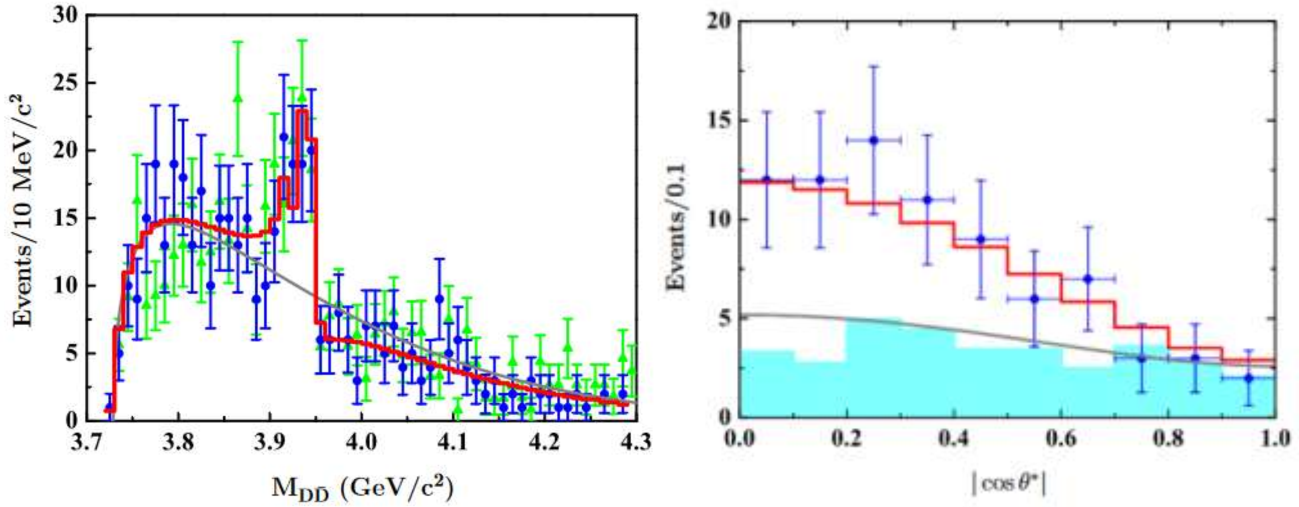


T. Barnes, S. Godfrey, and E. S. Swanson
PRD 72, 054026 (2005)

- **Why is there no evidence for $X(3915) \to D\bar{D}$ decays?**
- **Why is the partial width for $X(3915) \to J/\psi\omega$ large?**
- **Why is the mass gap between $X(3915)$ and $Z(3930)$ so small?**

Three answers

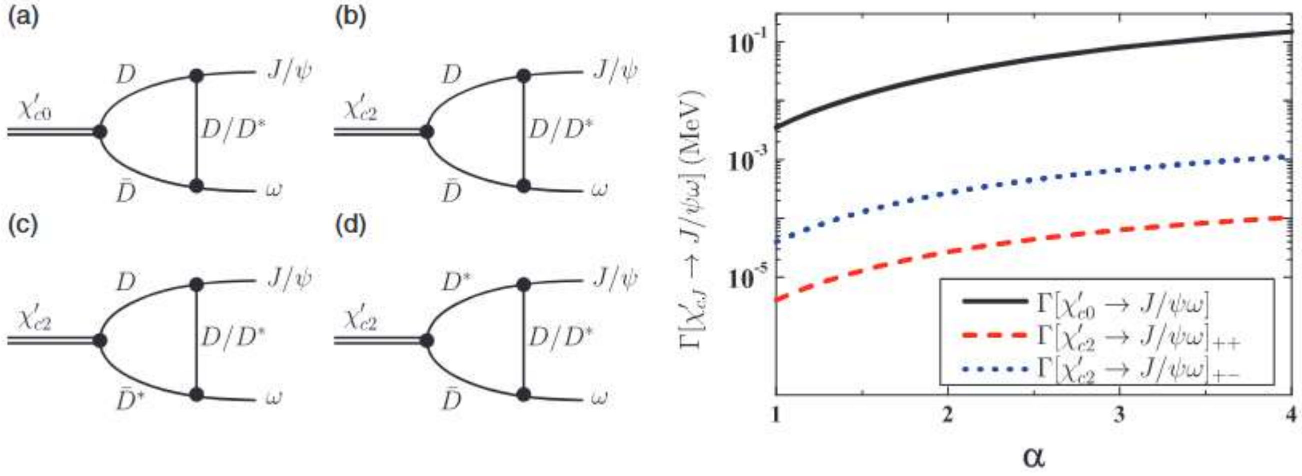
①



The $Z(3930)$ enhancement structure in $\gamma\gamma \to D\bar{D}$ may contain two *P*-wave higher charmonia $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$.

Dian-Yong Chen, Jun He, Xiang Liu and Takayuki Matsuki EPJC 72, 2226(2012)

②

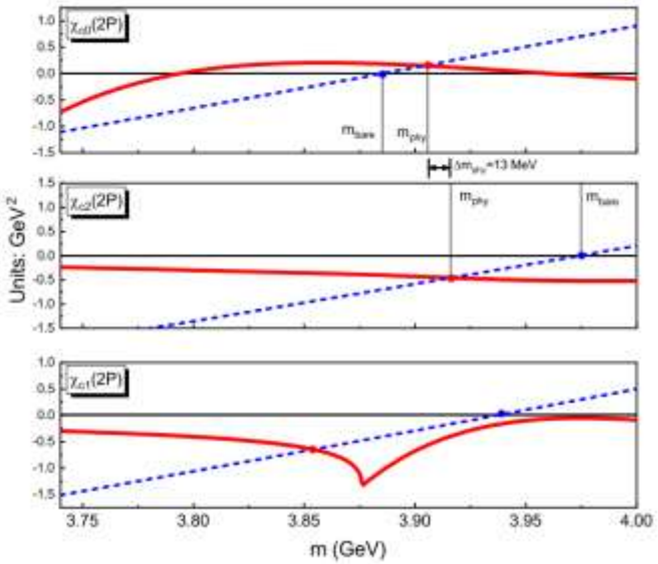


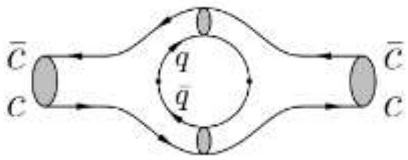
Consistent with the experimental measurements.

Dian-Yong Chen, Jun He, Xiang Liu and Takayuki Matsuki PTEP 043B05(2015)

Three answers

③





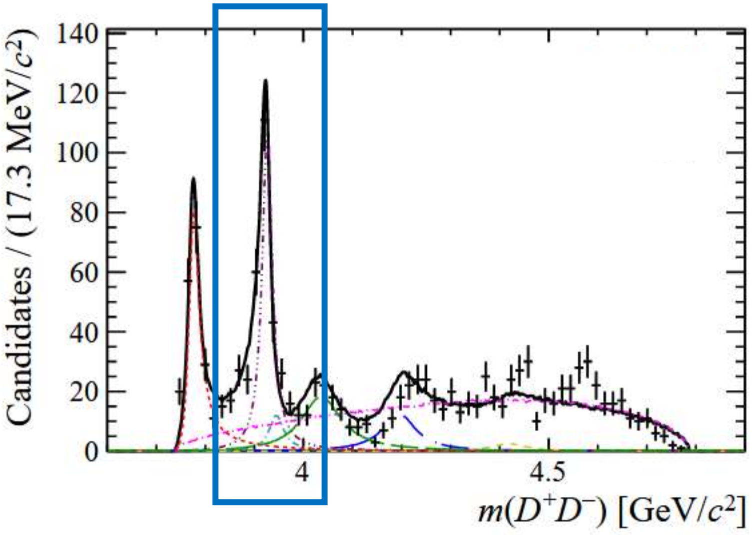
State	m_{bare} (MeV)	m_{phy} (MeV)	δm (MeV)	Γ (MeV)
$\chi_{c0}(2P)$	3885	3904	+19	23
$\chi_{c1}(2P)$	3936	3855	-81	0
$\chi_{c2}(2P)$	3974	3917	-57	26

narrow

Small mass gap can be well reproduced.

Ming-Xiao Duan, Si-Qiang Luo, Xiang Liu and Takayuki Matsuki PRD 101, 054029 (2020)

EXP

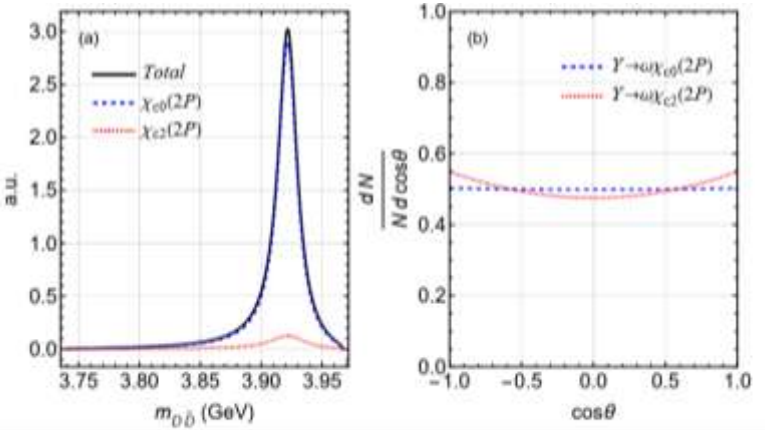


LHCb PRD 102, 112003 (2020)

- **The establishment of the $X(3915)$ as the $\chi_{c0}(2P)$ was ultimately achieved.**
- **The $D\bar{D}$ channel plays a crucial role in identifing the properties of the $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$.**

The production of the $\chi_{c0,2}(2P)$ by $e^+e^- \to \gamma D\bar{D}$

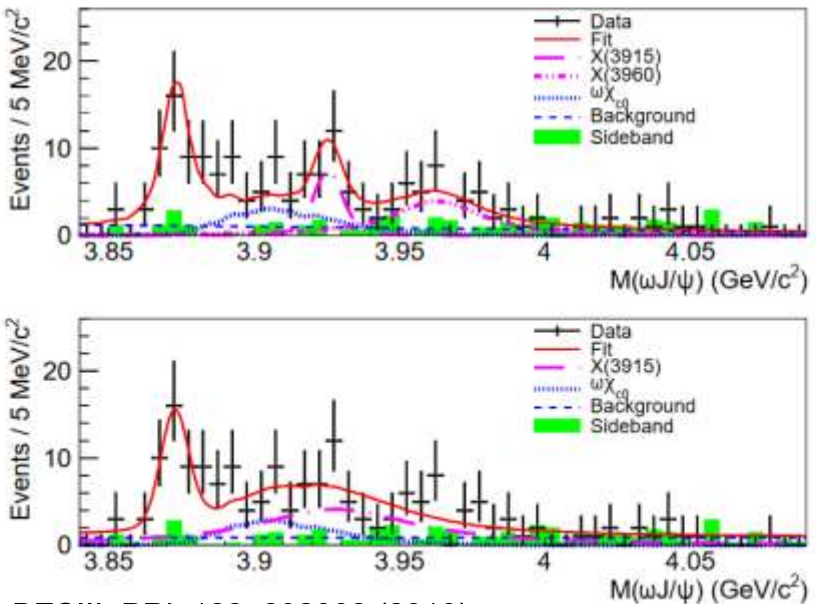
Additional production mechanisms



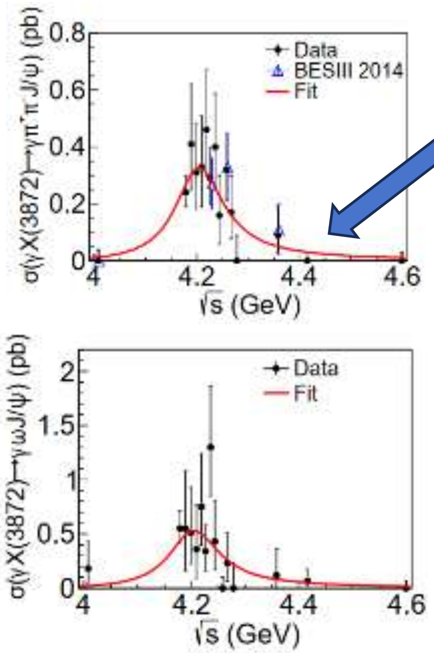
The process $e^+e^- \to \omega D\bar{D}$ may serve as a new avenue for accessing the charmonium states $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$.

Ri-Qing Qian and Xiang Liu PRD 108, 094046 (2023)

Similarly



BESIII PRL 122, 232002 (2019)

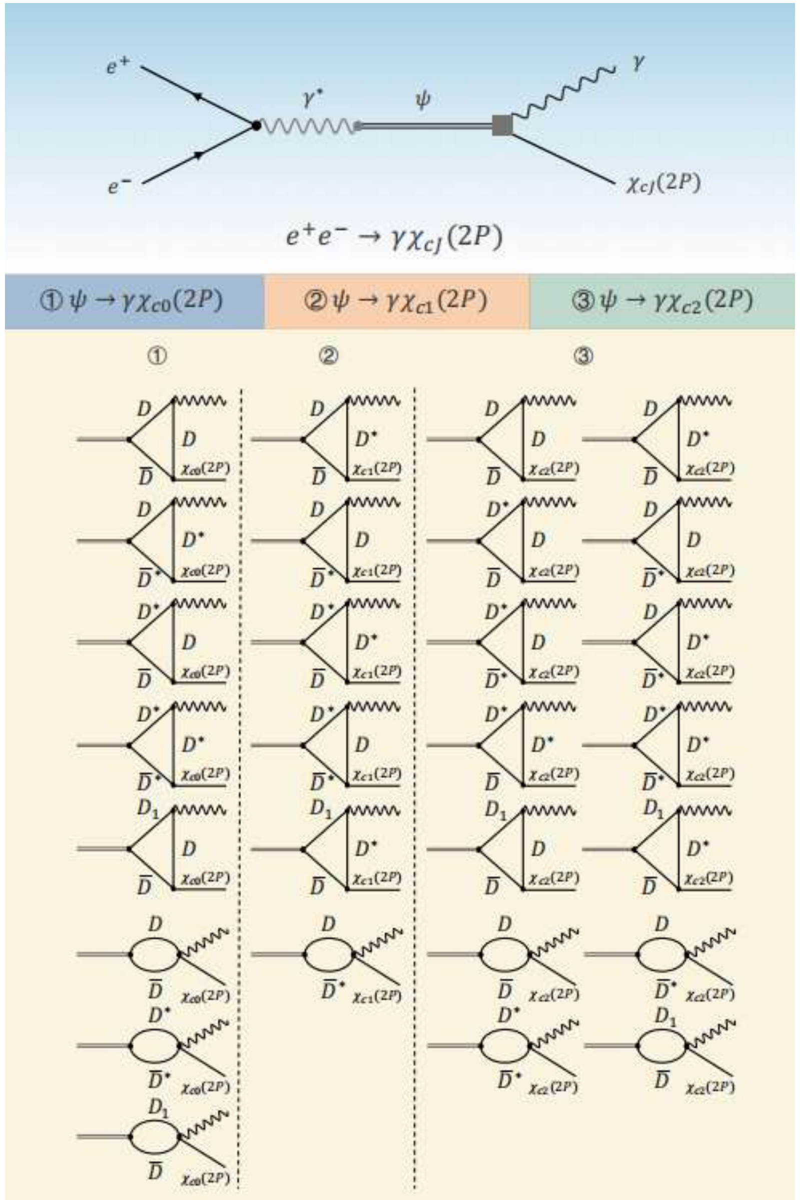


Contribution from $\psi(4230)$.

$$e^+e^- \to \psi(4230) \to \gamma\chi_{c1}(3872)$$

$$e^+e^- \to \psi \to \gamma\chi_{c0,2}(2P) \to \gamma D\bar{D}$$

Analyse of $e^+e^- \to \gamma\chi_{cJ}(2P)$



$$\sigma(e^+e^- \to \psi \to \gamma\chi_{cJ}(2P)) = \frac{12\pi\Gamma_\psi^{e^+e^-}\Gamma_{\gamma\chi_{cJ}}}{|s-m_\psi^2+im_\psi\Gamma_\psi|^2}$$

$$\sigma[\gamma\chi_{c0}(2P)] : \sigma[\gamma\chi_{c1}(2P)] : \sigma[\gamma\chi_{c2}(2P)] = \Gamma_{\gamma\chi_{c0}} : \Gamma_{\gamma\chi_{c1}} : \Gamma_{\gamma\chi_{c2}}$$

Coupled-channel effects: hadronic loops mechanism.

$$\mathcal{L}_S = ig_S Tr[S^{(Q\bar{Q})}\bar{H}^{(\bar{Q}q)}\gamma^\mu \overleftrightarrow{\partial}_\mu \bar{H}^{(Q\bar{q})}] + h.c.$$

$$\mathcal{L}_P = ig_P Tr[P^{(Q\bar{Q})\mu}\bar{H}^{(\bar{Q}q)}\gamma_\mu \bar{H}^{(Q\bar{q})}] + h.c.$$

...

$$\mathcal{M}^{\rm Tri} = \int \frac{d^4q}{(2\pi)^4}\frac{\mathcal{V}_1\mathcal{V}_2\mathcal{V}_3}{D(q_1,m_{q_1})D(q_2,m_{q_2})D(q,m_q)}\mathcal{F}^2(q^2)$$

$$\mathcal{F}(q^2) = \left(\frac{m_E^2-\Lambda^2}{q^2-\Lambda^2}\right)^2 \qquad \Lambda = m_E + \alpha\Lambda_{\rm QCD}$$

$$\mathcal{M}^{\rm Cont} = \int \frac{d^4q_1}{(2\pi)^4}\frac{\mathcal{V}_1\mathcal{V}_2}{D(q_1,m_{q_1})D(q_2,m_{q_2})}\mathcal{F}^2_{\rm cont}(q_1^2)$$

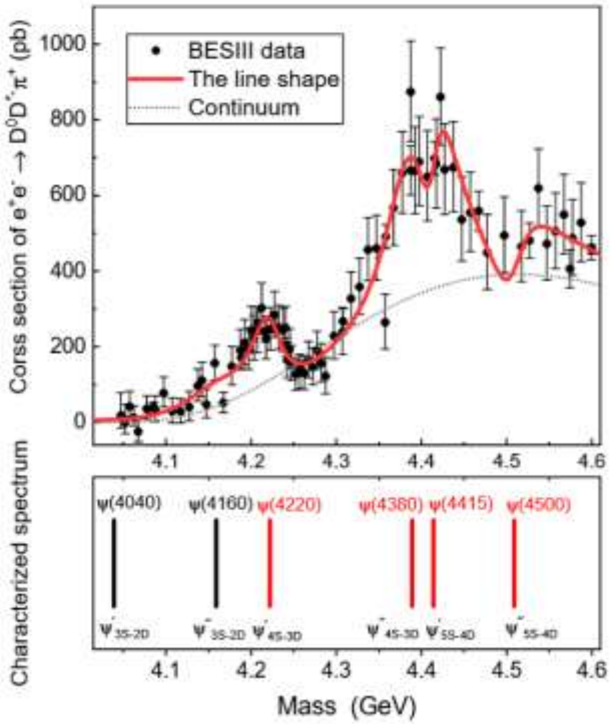
Gauge invariance

$$\mathcal{M}^{\rm Tot} = \epsilon_\gamma^\mu \mathcal{M}_\mu^{\rm Tot}$$

$$p_\gamma^\mu \mathcal{M}_\mu^{\rm Tot} = 0$$

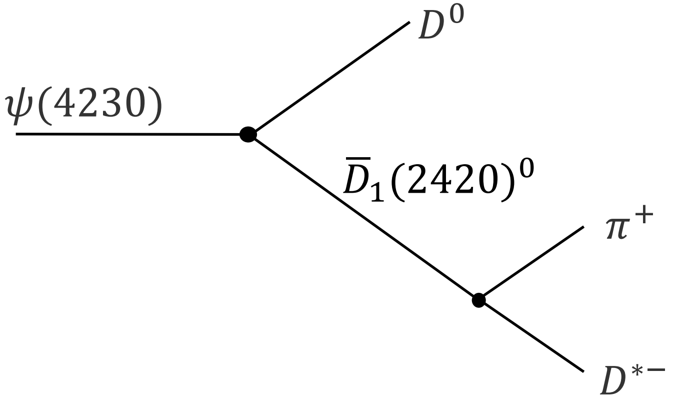
$$\Gamma_{\gamma\chi_{cJ}} = \frac{1}{3}\frac{1}{8\pi}\frac{|\boldsymbol{P}_1|}{m_\psi^2}|\mathcal{M}^{\rm Tot}_{\gamma\chi_{cJ}}|^2$$

The coupling constants



Jun-zhang Wang and Xiang Liu
PLB 849, 138456(2024)

$$R_{\psi(4230)} = \Gamma^{e^+e^-}_{\psi(4230)} \cdot \mathcal{BR}(\psi(4230) \to \pi^+ D^{*-} D^0) = 2.70\ \text{eV}$$



$$g_{\max} = 10.19\ \text{GeV}^{-1/2}$$

Additional intermediate states contribute to $\pi^+ D^{*-} D^0$, including $D^{*-} D_0^*(2300)^+$, $D^0 \bar{D}_1(2430)$ and $D^0 \bar{D}_2^*(2460)^0$.

Significant couplings

Zi-Long Man, Si-Qiang Luo, Zi-Yue Bai and Xiang Liu
PLB 868, 139644 (2025)

$$g_{\psi D_1 D} = g_{\max}/4 = 2.55\ \text{GeV}^{-1/2}$$

$$g_{\psi DD} = 0.765, \quad g_{\psi D^* D} = 0.054\ \text{GeV}^{-1}, \quad g_{\psi D^* D^*} = 1.320.$$

$$g_{D^0 \bar{D}^{*0} \gamma} = 2.0\ \text{GeV}^{-1}, \quad g_{D^+ D^{*-} \gamma} = -0.5\ \text{GeV}^{-1},$$

$$g_{D_1^0 \bar{D}^0 \gamma} = 1.446\ \text{GeV}^{-1/2}, \quad g_{D_1^+ D^- \gamma} = 0.466\ \text{GeV}^{-1/2},$$

$$g_{D_1^0 \bar{D}^{*0} \gamma} = 0.610, \quad g_{D_1^+ \bar{D}^{*-} \gamma} = 0.200.$$

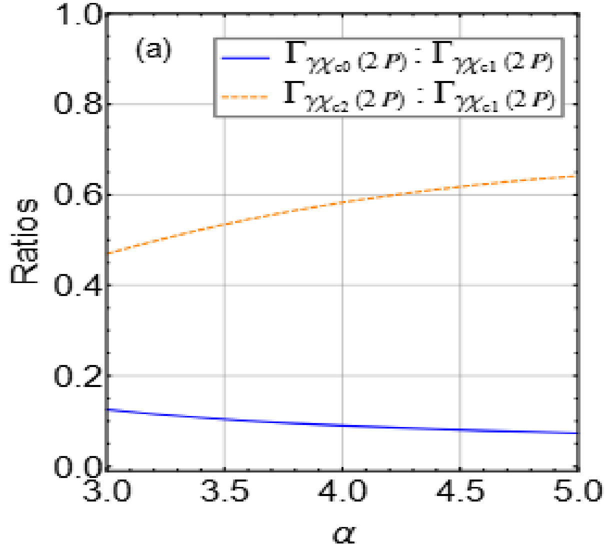
$$\frac{g_{\chi_{c0} DD}}{\sqrt{3} m_D} = \frac{\sqrt{3} g_{\chi_{c0} D^* D^*}}{m_{D^*}} = 2\sqrt{m_{\chi_{c0}}} g_p,$$

$$g_{\chi_{c1} DD^*} = 2\sqrt{2}\sqrt{m_D m_{D^*} m_{\chi_{c1}}} g_p,$$

$$g_{\chi_{c2} DD} m_D = g_{\chi_{c2} DD^*} \sqrt{m_D m_{D^*} m_{\chi_{c2}}} = \frac{g_{\chi_{c2} D^* D^*}}{4 m_{D^*}} = \sqrt{m_{\chi_{c2}}} g_p.$$

Numerical result

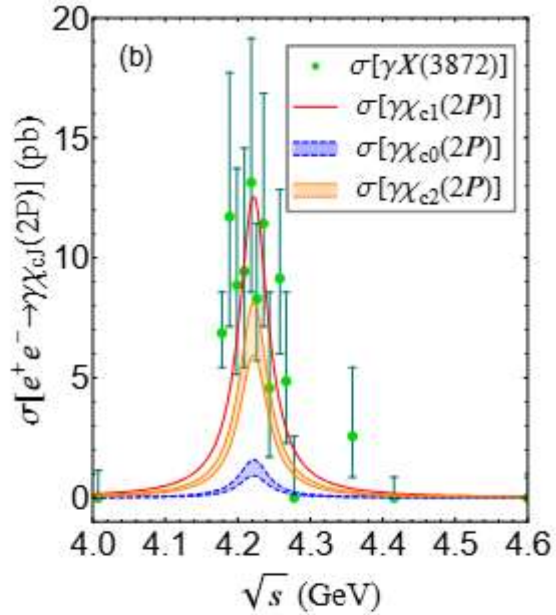
The cross section



$$\Gamma_{\gamma\chi_{c0}} : \Gamma_{\gamma\chi_{c1}} = 0.07 \sim 0.13\,,$$
$$\Gamma_{\gamma\chi_{c2}} : \Gamma_{\gamma\chi_{c1}} = 0.47 \sim 0.64\,.$$

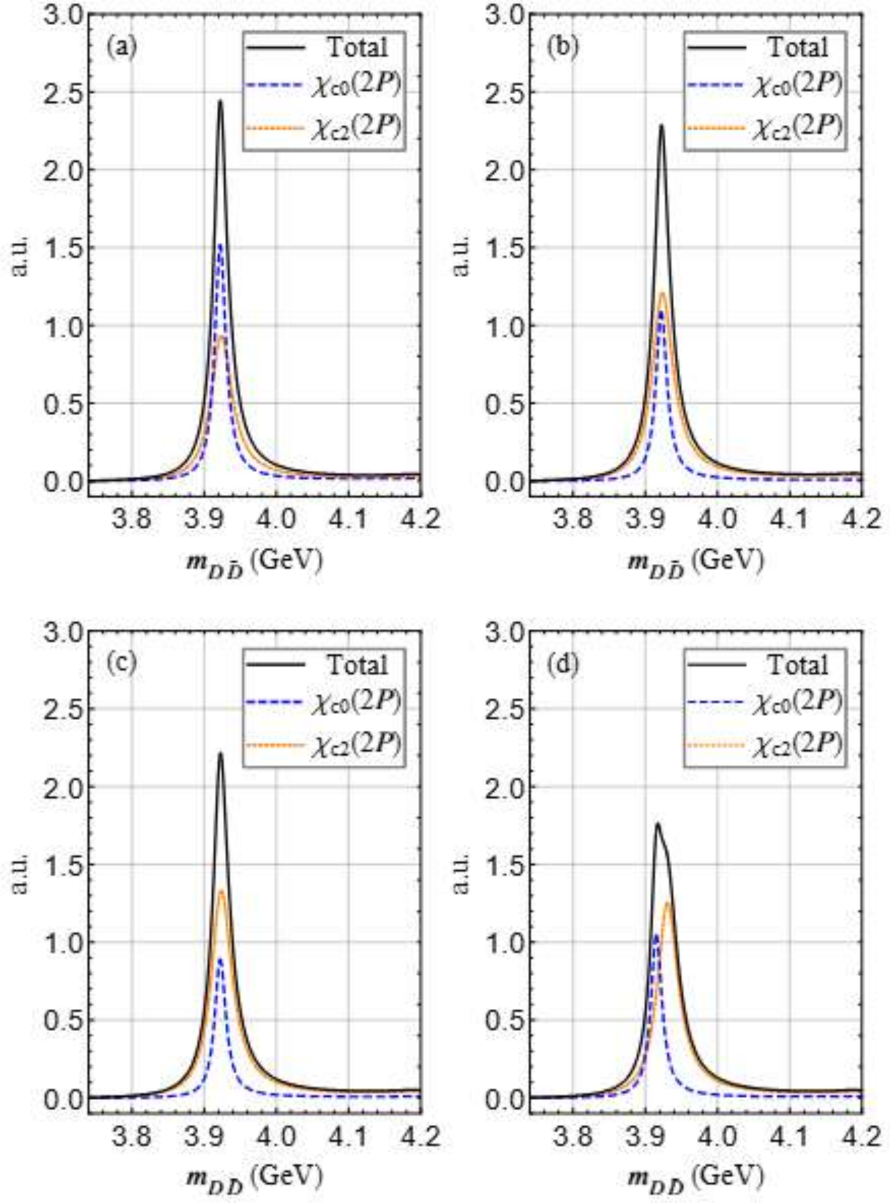
The ratios vary smoothly with α.

$$\sigma(e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi) = \sigma[\gamma X(3872)] \times \underbrace{\mathcal{BR}(X(3872) \to \pi^+\pi^- J/\psi)}_{3.5\%}$$



The cross sections $\sigma[\gamma\chi_{c1}(2P)]$ and $\sigma[\gamma\chi_{c2}(2P)]$are sufficiently large to be measured experimentally, with $\sigma[\gamma\chi_{c2}(2P)]$<$\sigma[\gamma\chi_{c1}(2P)]$, while $\sigma[\gamma\chi_{c0}(2P)]$ is relatively hard to be measured.

The $D\bar{D}$ invariant mass spectrum



$$\mathcal{BR}(\chi_{c0}(2P) \to D\bar{D}) \approx 100\%$$

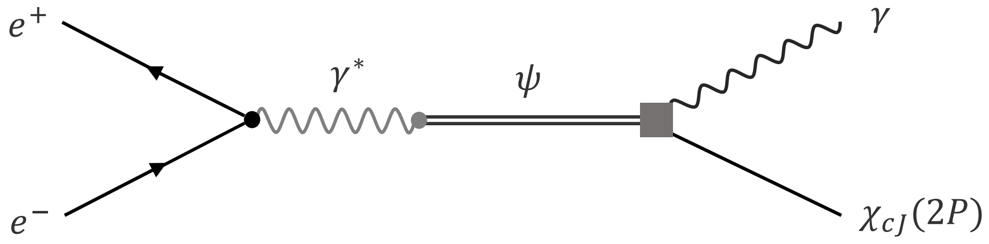
$$\mathcal{BR}(\chi_{c2}(2P) \to D\bar{D}) \approx 60\%$$

(a)-(c) The predicte $D\bar{D}$ invariant mass spectrum for $e^+e^- \to \gamma D\bar{D}$ with the cut-off parameter α set to 3, 4, and 5, respectively.

(d) Revisiting the $D\bar{D}$ invariant mass spectrum of $e^+e^- \to \gamma D\bar{D}$ for $\alpha = 4$ with a slightly increased mass gap.

Although both states show significant amplitudes in the $D\bar{D}$ invariant mass spectrum, the small mass gap between $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ presents a challenge in distinguishing them.

The angular distributions



$$\rho_\psi = \frac{1}{2}\sum_{m=\pm1} |1,m\rangle\langle 1,m|$$

$$\frac{dN}{N d\cos\theta} \propto 1 + \beta_{0,2}\cos^2\theta$$

For $\chi_{c0}(2P)$

$$\frac{d\Gamma_{\gamma\chi_{c0}}}{d\Omega} \propto \sum_{m,m'}\sum_{\mu=\pm1} \rho_{m,m'} D^{j*}_{m\mu}(\phi,\theta,0) D^{j}_{m'\mu}(\phi,\theta,0) T^{j*}_{\mu} T^{j}_{\mu} = \frac{1}{2}|T_1|^2(1+\cos^2\theta)$$

$\boldsymbol{\beta_0 = 1}$, **independent of the model.**

For $\chi_{c2}(2P)$

$$\frac{d\Gamma_{\gamma\chi_{c2}}}{d\Omega} = \frac{1}{32\pi^2}\frac{|\boldsymbol{p}_1|}{m_\psi^2}|\mathcal{M}^{\mathrm{Tot}}_{\gamma\chi_{c2}}|^2$$

TABLE III. β_2 for different values of α.

α	3	4	5
β_2	0.109	0.110	0.112

$$\frac{\beta_0}{\beta_2} \approx 9$$

We hope that these results will be useful in experimentally distinguishing between the $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ states.

Summary

- The calculated cross sections for $e^+e^- \to \gamma\chi_{c0}(2P)$ and $e^+e^- \to \gamma\chi_{c2}(2P)$ are fall within the measurable range of future experiments.

- Both $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ show significant amplitudes in the $D\bar{D}$ invariant mass spectrum of $e^+e^- \to \gamma D\bar{D}$.

- The ratio between angular distributions parameters β_0 and β_2 is approximately 9 for $\psi \to \gamma\chi_{c0,2}(2P)$ systems.

The $e^+e^- \to \gamma D\bar{D}$ process offers an opportunity to observe the $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ states.

Thanks