Recent progress on charmonium-like states

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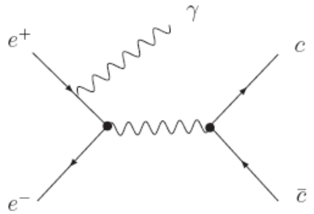
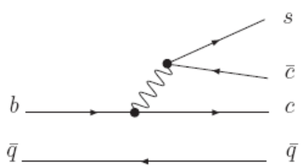
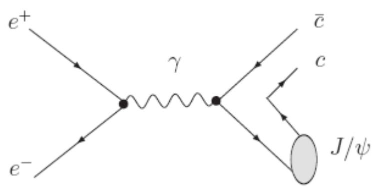
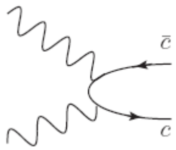
Outline

- Charmonium-like states X, Y, Z
- Experimental status: X(3915) X(4350)
  X(3872) Z(3930)
- Mass spectrum analysis
- Two-body strong decay
- Numerical result
- Summary

Charmonium-like states X, Y, Z

$(e^+ + e^-)_{\rm ISR} \to (c\bar{c})$	$b \to s(c\bar{c})$	$e^+ + e^- \to J/\psi + (c\bar{c})$	$\gamma\gamma$ fusion
			
$Y(4260)$ $Y(4008)$ $Y(4320)$ $Y(4664)$ $X(3773)$¶	$X(3872)$ $Y(3940)$ $Z^+(4430)$ $Z^+(4051)$ $Z^+(4248)$ $Y(4140)$	$X(3940)$ $X(4160)$	$Z(3930)$ $Y(3915)$ $Y(4350)$

In the past seven years, about 16 charmonium-like states were observed.

BaBar, Belle, CLEO, CDF

Production mechanism: Four

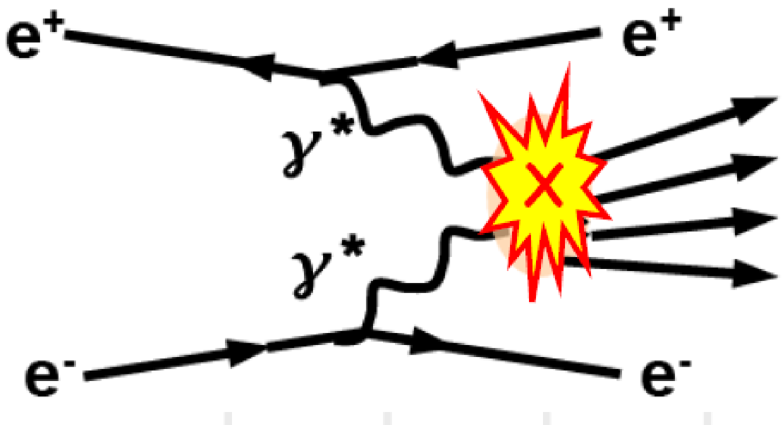
		Hidden charm						Open charm		
	state	$J/\psi\pi\pi$	$J/\psi K\bar{K}$	$J/\psi\omega$	$\psi(2S)\pi\pi$	$\chi_{c1}\pi^+$	$\psi(2S)\pi^+$	$D^0\bar{D}^{*0}$	$D\bar{D}$	$D^*\bar{D}^*$
	$X(3872)$	■		■				■		
	$Y(4260)$	■	■							
	$Y(4320)$				■					
	$Y(3940)$			■						
neutral	$X(3940)$ §							■		
	$Z(3940)$								■	
	$Y(4008)$	■								
	$X(4160)$									■
	$X(4664)$				■					
	$Z^+(4430)$						■			
charge	$Z^+(4050)$					■				
	$Z^+(4248)$					■				

Observed in **hidden-charm** decay channel or **open-charm** decay channel

Understand the underlying properties of the observed charmonium-like states

Conventional charmonium + Exotic states + …

Experimental status: X(3915) X(4350) Z(3930) X(3872)



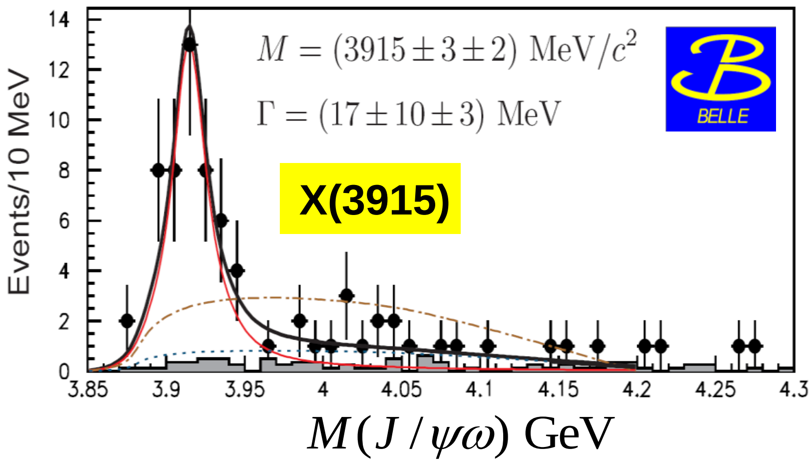
Z(3930)	Belle + BaBar
X(3915)	Belle
X(4350)	Belle

J^{PC} quantum number of the charmonium-like state observed in $\gamma\gamma$ fusion process favors

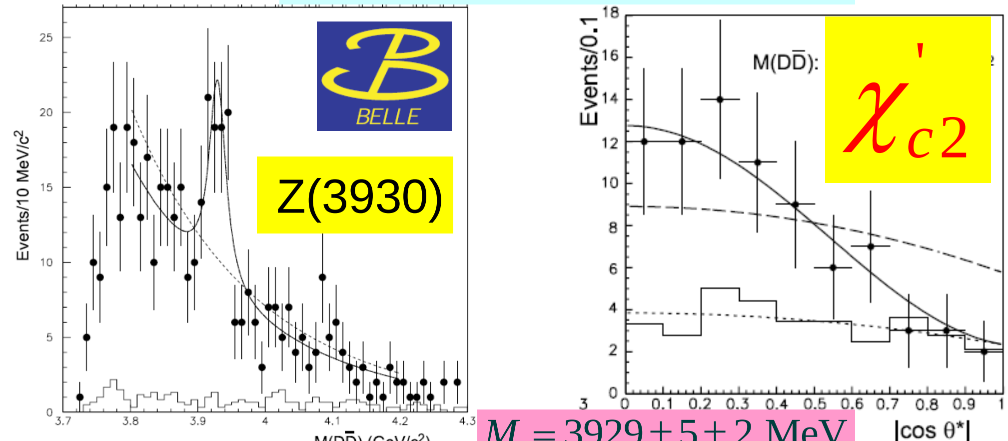
0^{++} or 2^{++}

The charmonium-like states in $\gamma\gamma$ fusion process

Phys.Rev.Lett.104:092001,2010



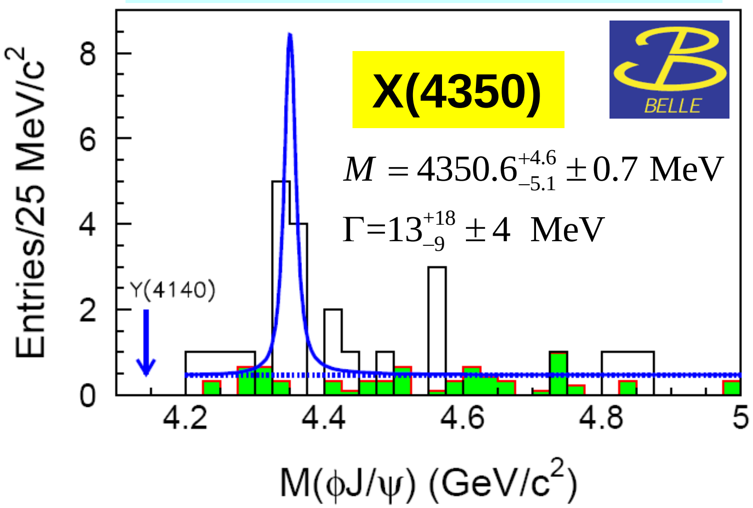
Phys.Rev.Lett.96:082003,2006



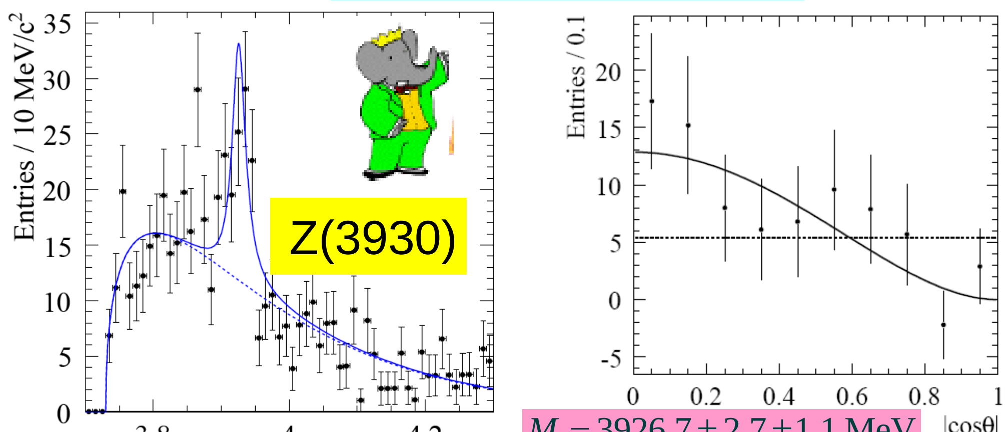
$M = 3929 \pm 5 \pm 2$ MeV

$\Gamma = 29 \pm 10 \pm 2$ MeV

Phys.Rev.Lett.104:112004,2010



arXiv:1002.0281 [hep-ex]



$M = 3926.7 \pm 2.7 \pm 1.1$ MeV

$\Gamma = 21.3 \pm 6.8 \pm 3.6$ MeV

The experimental mesurement of X(3872)

	Decay modes								
	$J/\psi\pi^+\pi^-$	$J/\psi\pi^+\pi^-\pi^0$ ($J/\psi\omega$)	$J/\psi\eta$	$D^0\bar{D}^0\pi^0$	$D^{*0}\bar{D}^0$	$\gamma J/\psi$	$\gamma\psi'$	Mass (MeV)	J^{PC}
Belle-1	■							$3872.0 \pm 0.6 \pm 0.5$	
Belle-2		■				■		–	
Belle-3				■				$3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$	
Belle-4	■							$3871.46 \pm 0.37 \pm 0.07$	
Belle-5					■			$3872.9^{+0.3+0.5}_{-0.6-0.5}$	
BaBar-1	■							3873.4 ± 1.4	
BaBar-2			□					–	
BaBar-3	■							–	
BaBar-4	■							$3871.3 \pm 0.6 \pm 0.1$ (B^-) $3868.6 \pm 1.2 \pm 0.2$ (B^0)	
BaBar-5				■				–	
BaBar-6						■		–	
BaBar-7					■			$3875.1^{+0.5}_{-0.7} \pm 0.5$	
BaBar-8	■							$3871.4 \pm 0.6 \pm 0.1$ (B^+) $3868.7 \pm 1.5 \pm 0.4$ (B^0)	
BaBar-9						■	■	–	
BaBar-10		■						$3873.0^{+1.8}_{-1.6} \pm 1.3$	2^{-+}
CDF-1	■							$3871.3 \pm 0.7 \pm 0.4$	
CDF-2	■							–	
CDF-3	■							–	$1^{++}/2^{-+}$
CDF-4	■							$3871.61 \pm 0.16 \pm 0.19$	
D0	■							$3871.8 \pm 3.1 \pm 3.0$	

$m(D^0D^{*0}) = 3871.81 \pm 0.36$ MeV

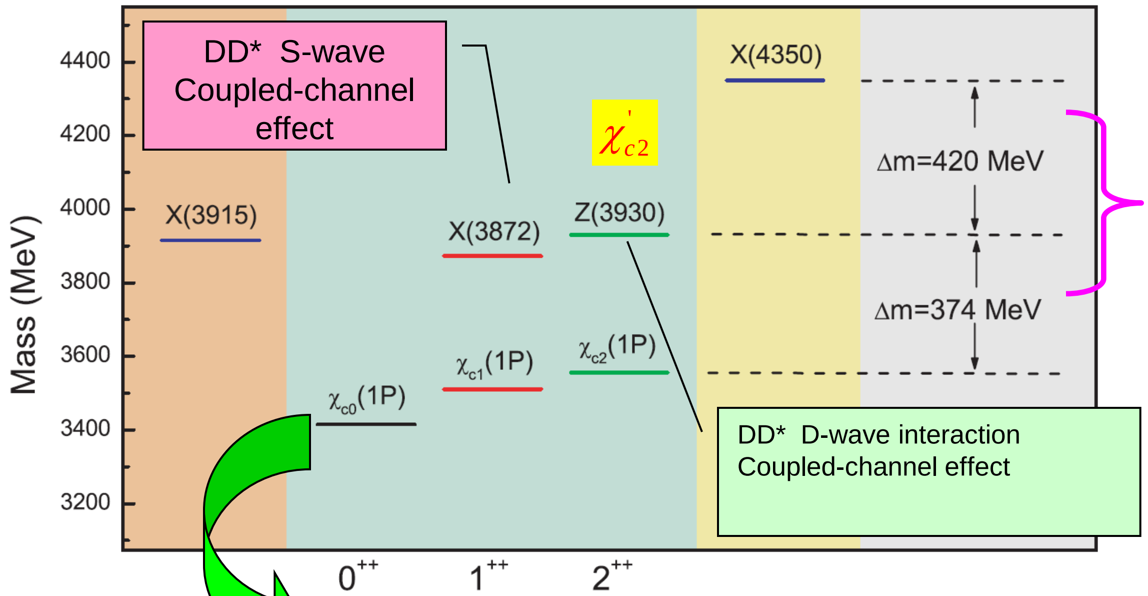
PDG average mass of $X(3872)$: 3872.2 ± 0.8 MeV

Abundant experimental information

Different mass values from different experiments

BaBar gave new result of the Spin-parity quantum

Mass spectrum analysis



$\chi_{c0}(3415)$ $\chi_{c0}(3510)$ $\chi_{c1}(3556)$

P-wave charmonium

X(4350)

Resonance spectrum expansion model

(van Beveren, Rupp)

M=4337 MeV Godfrey-Isgur relativized potential model

Spin-parity 0^{++} or 2^{++}

χ''_{c0} χ''_{c2}

X(3915)

$J^{PC} = 0^{++}$ or 2^{++} ⇒ Z(3930)

M=**3916** MeV Godfrey-Isgur relativized potential model

Barnes, Godfrey, Swanson PRD72, 054026

Close to the mass of Z(3930) small spin splitting

Blind to DD* channel → coupled-channel effect is small

Test P-wave charmonium assignment to X(3915) and X(4350)

Distinguish χ''_{c0} and χ''_{c2} assignment to X(4350)

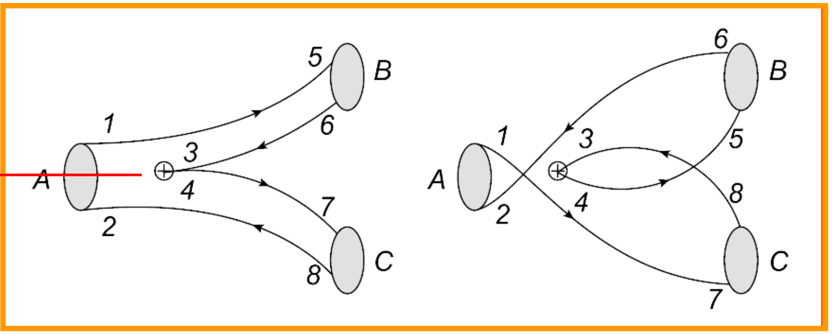
Predict the rest P-wave charmonium with the second radial excitation

Two-body strong decay

Quark pair creation model

L. Micu, Nucl. Phys. B **10**, 521 (1969)

$$\mathcal{T} = -3\gamma\sum_m \langle 1m; 1-m|00\rangle \int d\mathbf{k}_3 d\mathbf{k}_4 \delta^3(\mathbf{k}_3+\mathbf{k}_4) \times \mathcal{Y}_{1m}\left(\frac{\mathbf{k}_3-\mathbf{k}_4}{2}\right)\chi^{34}_{1,-m}\varphi^{34}_0\omega^{34}_0 d^\dagger_{3i}(\mathbf{k}_3)b^\dagger_{4j}(\mathbf{k}_4),$$



The expression of decay width in the QPC model is written as

$$\Gamma = \pi^2 \frac{|\mathbf{K}|}{M_A^2}\sum_{JL}\left|\mathcal{M}^{JL}\right|^2,$$

by the partial wave amplitude $\mathcal{M}^{JL}$, which is related to the helicity amplitude $\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}$ according to the Jacob-Wick formula [49]. The helicity amplitude $\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}$ is obtained by the transition amplitude

$$\langle BC|T|A\rangle = \delta^3(\mathbf{K}_B+\mathbf{K}_C-\mathbf{K}_A)\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}.$$

$$\mathcal{M}^{JL}(A\to BC) = \frac{\sqrt{2L+1}}{2J_A+1}\sum_{M_{J_B},M_{J_C}}\langle L0JM_{J_A}|J_AM_{J_A}\rangle \times\langle J_BM_{J_B}J_CM_{J_C}|JM_{J_A}\rangle\mathcal{M}^{M_{J_A}M_{J_B}M_{J_C}}(\mathbf{K}),$$

where $\mathbf{J}=\mathbf{J}_B+\mathbf{J}_C$ and $\mathbf{J}_A+\mathbf{J}_P=\mathbf{J}_B+\mathbf{J}_C+\mathbf{L}$.

Decay modes

TABLE I. The allowed open-charm strong decays of χ'_{c0} and χ''_{cJ} ($J = 0, 1, 2$). Here, we take 4350 MeV as the upper limit of the mass of χ''_{cJ}. $D_1(2420)$ is the 1^+ state in the $T = (1^+, 2^+)$ doublet while $D_1(2430)$ is the 1^+ state in the $S = (0^+, 1^+)$ doublet since as indicated in Ref. [15].

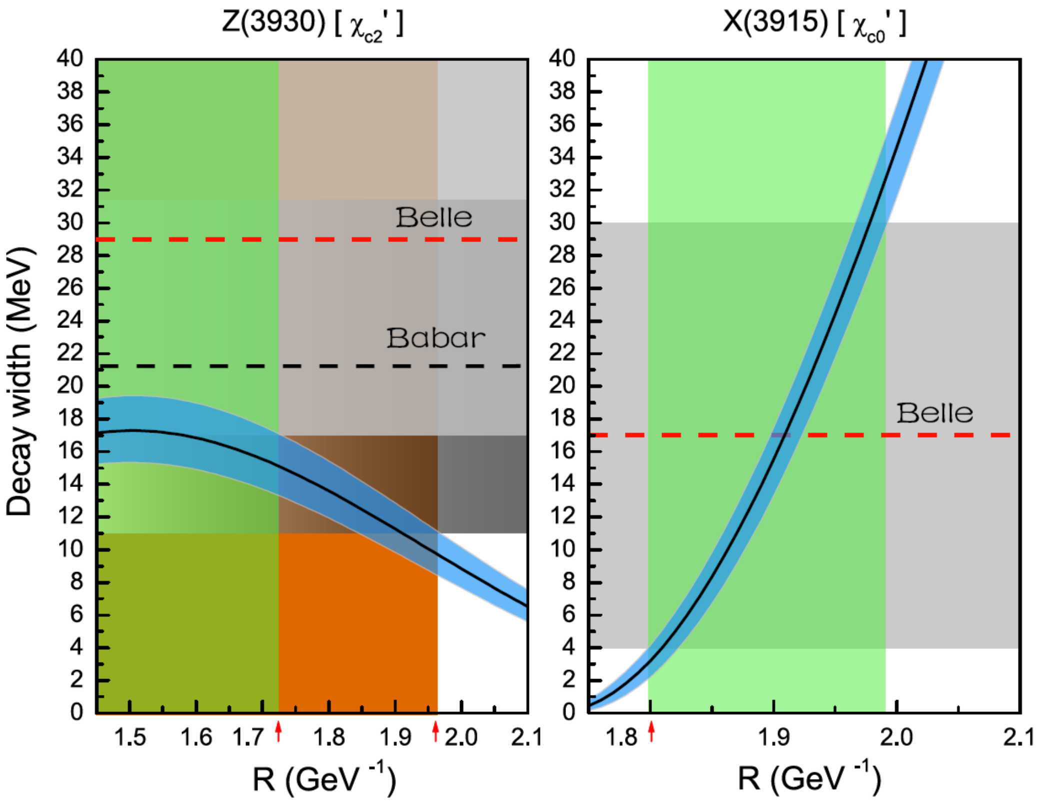
State	Modes	Decay channels
χ'_{c0}	$0^- + 0^-$	$D\bar{D}$
χ''_{c0}	$0^- + 0^-$	$D\bar{D}$, $D_s\bar{D}_s$
	$1^- + 1^-$	$D^*\bar{D}^*$, $D^*_s\bar{D}^*_s$
	$0^- + 1^+$	$D\bar{D}_1(2430)$ + H.c., $D\bar{D}_1(2420)$ + H.c.
χ''_{c1}	$0^- + 1^-$	$D\bar{D}^*$ + H.c., $D_s\bar{D}^*_s$ + H.c.
	$1^- + 1^-$	$D^*\bar{D}^*$, $D^*_s\bar{D}^*_s$
	$0^- + 0^+$	$D\bar{D}^*_0(2400)$ + H.c., $D_s\bar{D}_{s0}(2317)$ + H.c.
	$0^- + 1^+$	$D\bar{D}_1(2430)$ + H.c., $D\bar{D}_1(2420)$ + H.c.
χ''_{c2}	$0^- + 0^-$	$D\bar{D}$, $D_s\bar{D}_s$
	$0^- + 1^-$	$D\bar{D}^*$ + H.c., $D_s\bar{D}^*_s$ + H.c.
	$1^- + 1^-$	$D^*\bar{D}^*$, $D^*_s\bar{D}^*_s$
	$0^- + 1^+$	$D\bar{D}_1(2430)$ + H.c., $D\bar{D}_1(2420)$ + H.c.

Partial wave decay amplitude

TABLE II. The partial wave amplitude of the open-charm decay of χ'_{c0} and χ''_{cJ}. Here, two 1^+ charmed mesons in S and T doublets are the mixture of two basis 1^1P_1 and 1^3P_1, which indicates $|1^+(S)\rangle = \cos\theta|1^1P_1\rangle + \sin\theta|1^3P_1\rangle$ and $|1^+(T)\rangle = -\sin\theta|1^1P_1\rangle + \cos\theta|1^3P_1\rangle$ [15]. One takes $\mathcal{F} = 1/\sqrt{3}$ obtained from the calculation of the flavor matrix element. In heavy quark limit, one usually takes the mixing angle $\theta = -54.7°$. According to the partial wave amplitude, the partial decay width is expressed $\Gamma = \pi^2 \frac{|\mathbf{K}|}{M_A^2}\sum_{JL}|\mathcal{M}^{JL}|^2$ [12–14].

State	Modes	Partial wave amplitude
χ'_{c0}	0^-0^-	$\mathcal{M}^{00} = \mathcal{F}\frac{\sqrt{2}}{3}\sqrt{E_AE_BE_C}\gamma[2\mathcal{O}_{1,-1} - \mathcal{O}_{0,0}]$
χ''_{c0}	0^-0^-	$\mathcal{M}^{00} = \mathcal{F}\frac{\sqrt{2}}{3}\sqrt{E_AE_BE_C}\gamma[2\mathcal{Q}_{1,-1} - \mathcal{Q}_{0,0}]$
	1^-1^-	$\mathcal{M}^{00} = -\mathcal{F}\sqrt{\frac{2}{27}}\sqrt{E_AE_BE_C}\gamma[2\mathcal{Q}_{1,-1} - \mathcal{Q}_{0,0}]$
	$0^-1^+(S)$	$\mathcal{M}^{11} = \mathcal{F}\sqrt{E_AE_BE_C}\gamma\{-\frac{\sqrt{2}\cos\theta}{3}(2\mathcal{P}_{1,-1,0} - \mathcal{P}_{0,0,0}) - \frac{2\sin\theta}{3}(\mathcal{P}_{1,0,1} - \mathcal{P}_{0,1,1})\}$
	$0^-1^+(T)$	$\mathcal{M}^{11} = \mathcal{F}\sqrt{E_AE_BE_C}\gamma\{\frac{\sqrt{2}\sin\theta}{3}(2\mathcal{P}_{1,-1,0} - \mathcal{P}_{0,0,0}) - \frac{2\cos\theta}{3}(\mathcal{P}_{1,0,1} - \mathcal{P}_{0,1,1})\}$
χ''_{c1}	0^-1^-	$\mathcal{M}^{10} = -\mathcal{F}\frac{2}{3\sqrt{3}}\sqrt{E_AE_BE_C}\gamma[2\mathcal{Q}_{1,-1} - \mathcal{Q}_{0,0}]$
		$\mathcal{M}^{12} = \mathcal{F}\frac{2}{3\sqrt{6}}\sqrt{E_AE_BE_C}\gamma[\mathcal{Q}_{1,-1} + \mathcal{Q}_{0,0}]$
	1^-1^-	$\mathcal{M}^{22} = \mathcal{F}\frac{2}{3}\sqrt{E_AE_BE_C}\gamma[\mathcal{Q}_{1,-1} + \mathcal{Q}_{0,0}]$
	0^-0^+	$\mathcal{M}^{01} = \mathcal{F}\frac{2}{3\sqrt{3}}\sqrt{E_AE_BE_C}\gamma[\mathcal{P}_{1,-1,0} + \mathcal{P}_{1,0,1}]$
	$0^-1^+(S)$	$\mathcal{M}^{11} = \mathcal{F}\sqrt{E_AE_BE_C}\gamma\{\frac{\sqrt{2}\cos\theta}{3}[\mathcal{P}_{0,1,1} - \mathcal{P}_{1,0,1}] + \frac{\sin\theta}{3}[\mathcal{P}_{0,0,0} + \mathcal{P}_{0,1,1} - \mathcal{P}_{1,-1,0}]\}$
	$0^-1^+(T)$	$\mathcal{M}^{11} = \mathcal{F}\sqrt{E_AE_BE_C}\gamma\{-\frac{\sqrt{2}\sin\theta}{3}[\mathcal{P}_{0,1,1} - \mathcal{P}_{1,0,1}] + \frac{\cos\theta}{3}[\mathcal{P}_{0,0,0} + \mathcal{P}_{0,1,1} - \mathcal{P}_{1,-1,0}]\}$
χ''_{c2}	0^-0^-	$\mathcal{M}^{02} = \mathcal{F}\frac{2}{3\sqrt{5}}\sqrt{E_AE_BE_C}\gamma[\mathcal{Q}_{1,-1} + \mathcal{Q}_{0,0}]$
	0^-1^-	$\mathcal{M}^{12} = \mathcal{F}\frac{2}{\sqrt{30}}\sqrt{E_AE_BE_C}\gamma[\mathcal{Q}_{1,-1} + \mathcal{Q}_{0,0}]$
	1^-1^-	$\mathcal{M}^{20} = \mathcal{F}\frac{2}{3}\sqrt{\frac{2}{3}}\sqrt{E_AE_BE_C}\gamma[2\mathcal{Q}_{1,-1} - \mathcal{Q}_{0,0}]$
	$0^-1^+(S)$	$\mathcal{M}^{11} = \mathcal{F}\sqrt{E_AE_BE_C}\gamma\{\frac{\cos\theta}{15\sqrt{2}}[4\mathcal{P}_{0,0,0} + 6\mathcal{P}_{0,1,1} + 4\mathcal{P}_{1,-1,0} + 6\mathcal{P}_{1,0,1}] + \frac{\sin\theta}{30}[6\mathcal{P}_{0,0,0} + 14\mathcal{P}_{0,1,1} + 6\mathcal{P}_{1,-1,0} + 4\mathcal{P}_{1,0,1}]\}$
	$0^-1^+(T)$	$\mathcal{M}^{11} = \mathcal{F}\sqrt{E_AE_BE_C}\gamma\{-\frac{\sin\theta}{15\sqrt{2}}[4\mathcal{P}_{0,0,0} + 6\mathcal{P}_{0,1,1} + 4\mathcal{P}_{1,-1,0} + 6\mathcal{P}_{1,0,1}] + \frac{\cos\theta}{30}[6\mathcal{P}_{0,0,0} + 14\mathcal{P}_{0,1,1} + 6\mathcal{P}_{1,-1,0} + 4\mathcal{P}_{1,0,1}]\}$

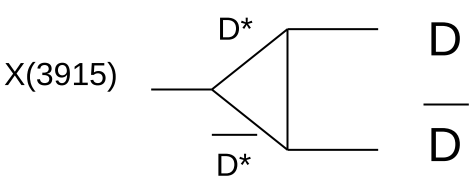
Numerical results



The node effect from the wave function of higher radial excited states results in the decay width calculated by the QPC model being dependent on the R value.

Using Z(3930) to test the reliability of R value applied to X(3915)

R. M. Albuquerque, J. M. Dias, and M. Nielsen, arXiv:1001.3092.
D*D* molecular state X(3915)



Hidden charm decay

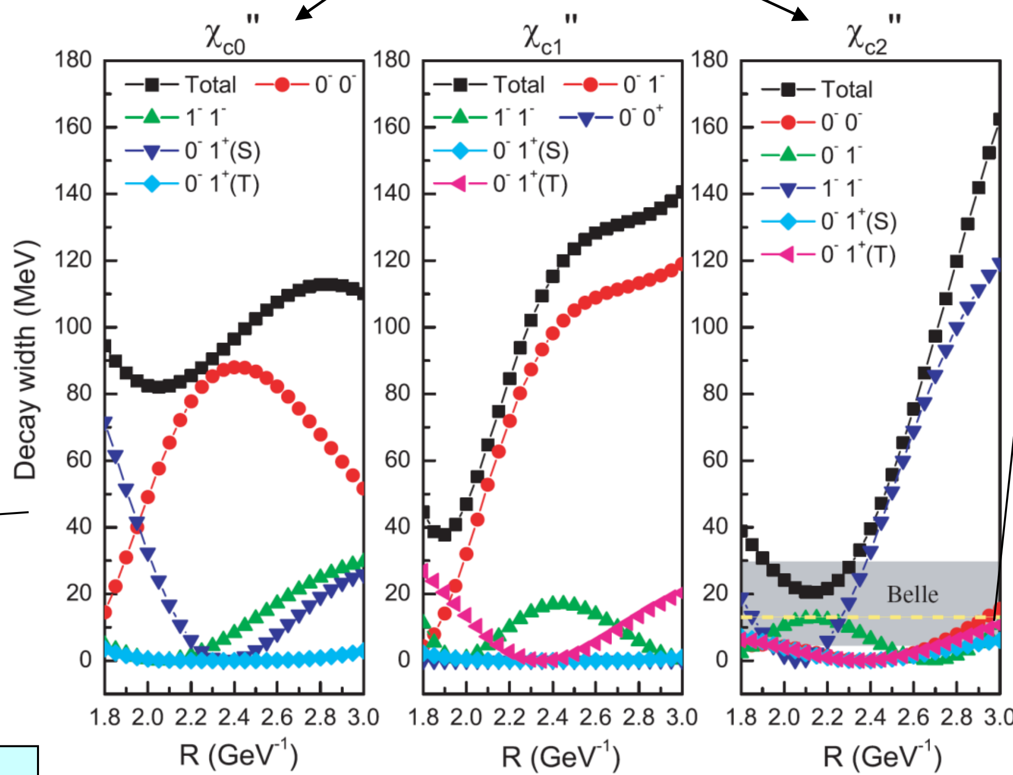
we propose the **experimental study of the open-charm decay DD** to be the **best way** to **distinguish** between the exotic and the conventional states for the controversial X(3915)

Thus, explaining X(3915) as a χ_{c0}' charmonium is tested through the open-charm decay of χ_{c0}'

$\gamma\gamma$ fusion $\Rightarrow$ X(4350) $J^{PC} = 0^{++}$ or 2^{++}

No

Yes



The total decay width can fit experimental data well.

We can fully exclude this assignment to X(4350)

The predicted properties of the remaining two P-wave charmonium states with the second radial excitation can serve as a guide in the experimental search

Xiang Liu， Z.G. Luo and Z.F. Sun, PRL 104, 122001 (2010)

Summary

✓ Explain newly observed X(3915) and X(4350) **P-wave charmonium**

✓ Decay behavior **supports** P-wave charmonium assignments to these two charmonium-like states

$$\chi_{c0}'\ (1^3P_0) \Rightarrow \mathrm{X(3915)} \qquad \chi_{c2}''\ (2^3P_2) \Rightarrow \mathrm{X(4350)}$$

✓ Predict the decay behaviors of the remaining two 2P charmonium states

Experimental search for these two state is encouraged

✓ X(3915) 0^{++}

X(4350) 2^{++}

Suggest to carry out angular distribution analysis in future experiment → Test P-wave charmonium explanation to X(3915) and X(4350)

Thank you for your attention!