$e^+e^- \to \gamma\chi_c(1P, 2P)$ @ $4.0 - 4.3$ GeV

孟 策　　北京大学

4th XYZ, 2016

11月24日，北京·北航

Outline

- Motivations
- $e^+e^- \to \gamma\chi_c$: continuum contribution
- $e^+e^- \to \gamma\chi_c$: resonance contribution
- Summary

Motivations

$\chi_{cJ}(2P)$ as XYZ states

- $\chi_{c2}(2P)$ as $X(3930)$:
  - $\gamma\gamma \to X(3930) \to D\bar{D}$ Belle, PRL'06

    $m = 3927.2 \pm 2.6$ MeV $\Gamma = 24 \pm 6$ MeV PDG'14
  - ✓ $J^{PC} = 2^{++}$ $\Gamma_{\gamma\gamma} Br_{D\bar{D}} = 0.18 \pm 0.05$ keV Belle, PRL'06
- Consistent with the Screened Potential Model (SPM):
  - $m(\chi'_{c2}) = 3937$ MeV in SPM Li & Chao, PRD'09

    30-40 MeV lower than the older results Barnes et al, PRD'05
  - $\Gamma_{\gamma\gamma} = 0.23$ keV Li & Chao, PRD'09
  - $\Gamma(\chi'_{c2}(3972)) \approx \Gamma_{DD} + \Gamma_{DD^*} = 42 + 37 = 79$ MeV Barnes'05

    $\Rightarrow \Gamma(\chi'_{c2}(3927)) \approx 25 + 8 = 33$ MeV $Br_{D\bar{D}} \approx 76\%$

$\chi_{cJ}(2P)$ as XYZ states

- $\chi_{c0}(2P)$ as $X(3915)$: X. Liu et. al., PRL'10
  - $B \to X(3915)K \to J/\psi\omega K$ Belle, PRL'05 BaBar, PRL'08
  - $\gamma\gamma \to X(3915) \to J/\psi\omega$ Belle, PRL'10
  - ✓ $J^{PC} = 0^{++}$ BaBar PRD'12
  - ✗ Different suggestions: Guo & Meissner, PRD'12; Olsen, PRD'15; Zhou & Xiao, PRL'15
- $\chi_{c0}(2P)$ as $X(3840)$: Guo & Meissner; Olsen
  - $\gamma\gamma \to X(3840) \to D\overline{D}$ Belle, PRL'06
  - Consistent with Screened Potential Model (SPM):

    $m(\chi'_{c0}) = 3842\ \mathrm{MeV}$ Li & Chao, PRD'09
  - Too broad to be observed ($\Gamma \sim 200$ MeV)

$\chi_{cJ}(2P)$ as XYZ states

- $X(3872)$ as a mixing state of $\chi_{c1}(2P)$ and DD^* :

  Meng & Gao & Chao, arXiv: hep-ph/0506222 (PRD'13)

  - Large production rates

    $B \to XK, \quad X \to J/\psi\pi\pi, J/\psi\gamma, \psi'\gamma, DD^*(DD\pi)$ Belle/BaBar

    $pp(p\bar{p}) \to X + \text{anyth.}, \quad X \to J/\psi\pi\pi, \psi'\gamma$ CDF/D0/CMS/LHCb

  ✓ Short distance pro. is dominant by the $\chi_{c1}(2P)$ component

$$\sigma\big(X(J/\psi\pi\pi)\big) = \sigma(\chi'_{c1}) \cdot k, \qquad k = Z_{cc} \cdot Br(X \to J/\psi\pi\pi)$$

$$k \sim 0.018 \pm 0.004$$

$$\text{both in} \begin{cases} pp \text{ collision} & \text{Meng \& Han \& Chao'13} \\ B \text{ decays} & \text{Meng \& Chao, in preparation} \end{cases}$$

X(3872) production in B decays

Meng and Chao, in preparation

$$\mathrm{Br}(B \to X(J/\psi\pi^+\pi^-)\ldots) = \mathrm{Br}^{ex}(B \to \chi_{c1}\ldots) \cdot k$$

$$k = 0.018 \pm 0.002$$

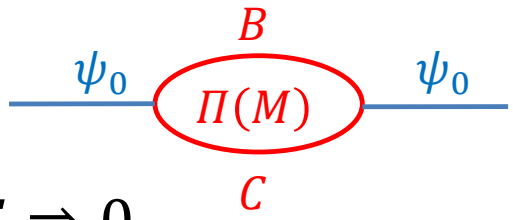
$X(J/\psi\pi^+\pi^-)$	Br $\times 10^6$/predictions	Br $\times 10^6$/data
$B^0 \to XK^0$	7.1 ± 0.9	4.3 ± 1.3 PDG'14
$B^+ \to XK^+$	8.6 ± 0.8	8.6 ± 0.8 PDG'14
$B^0 \to XK^+\pi^-$	6.8 ± 1.0	7.9 ± 1.4 Belle'15
$B^+ \to XK^0\pi^+$	9.9 ± 1.2	10.6 ± 3.1 Belle'15
$B^0 \to XK^{*0}$	4.4 ± 0.6	4.0 ± 1.5 Belle'15
$B^+ \to XK^{*+}$	5.4 ± 1.2	
$B_s \to X\phi$	3.6 ± 0.6	

X(3872) as a mixing state in the CCM

Li & Meng & Chao, PRD_80_014012 (2009)

$M - M_0 + \Pi(M) = 0$ $\quad \Pi = \sum_{BC} \int d^3p \frac{\left|\left\langle BC, \vec{p}\right| H_{QPC} \left|\psi_0\right\rangle\right|^2}{E_{BC}(\vec{p}) - M - i\epsilon}$

$$\mathrm{Im}\Pi(E) \sim \Gamma(\psi \to BC) \sim E^{\frac{2L+1}{2}}$$
$$E = M - M_B - M_C$$

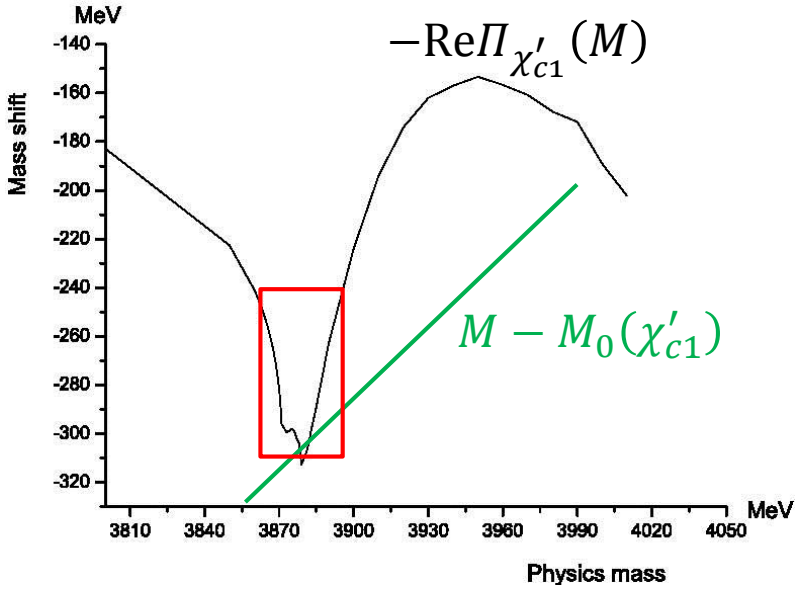


- S-wave threshold effect: $L = 0$ $\quad E \Rightarrow 0$

$\Pi(E) \sim \sqrt{E},\ \mathrm{d}\Pi(E)/\mathrm{d}E \sim 1/\sqrt{E}$

⇒ S-wave cusp

⇒ "attracting" the mass of the bare state to the threshold



- $M_{\chi'_{c1}} \sim th_{DD^*}$:

$\Delta M \sim 15$ MeV $\Leftrightarrow \Delta \mathrm{Re}\Pi \sim 70$ MeV

$\Leftrightarrow \Delta M_0 \sim 85$ MeV

Evidence for $e^+e^- \to \gamma\chi_{c1,2}$

BESIII, Chin. Phys. C'15

- Totally, 3.0 σ for $\gamma\chi_{c1}$ & 3.4 σ for $\gamma\chi_{c2}$

$\sqrt{s}$(GeV)		Sign.(σ)	σ^{B}(pb)	σ^{UP}(pb)
4.009	χ_{c1}	2.2	2.4 ± 1.4	5.3
	χ_{c2}	1.5	4.7 ± 4.4	18
4.230	χ_{c1}	1.9	0.7 ± 0.5	1.7
	χ_{c2}	2.9	2.7 ± 1.1	5.0
4.260	χ_{c1}	1.1	0.4 ± 0.4	1.1
	χ_{c2}	2.3	2.0 ± 1.1	4.2
4.360	χ_{c1}	2.4	1.4 ± 1.3	2.9
	χ_{c2}	2.0	2.3 ± 2.3	5.0

$$\sigma(\gamma\chi_{c1,2}) \sim 0.5 - 3 \text{ pb} \qquad \sigma^{\text{UP}}_{4.26}(\gamma\chi_{c0}) \sim 20 \text{ pb}$$

$$e^+e^- \to \gamma\chi_c$$

continuum contribution

$e^+e^- \to \gamma\chi_c$ @ NLO in PQCD

- $\sqrt{s} = 10.6$ GeV: Li & He & Chao, PRD'09; Sang & Chen PRD'10

  $\sigma(e^+e^- \to \gamma\chi_{c1}) \sim 13$ fb $\sigma(e^+e^- \to \gamma\chi'_{c1}) \sim 18$ fb

  Search X(3872) at Belle (711 fb^{-1} data sample)

  $$N(\gamma X \to \gamma\mu^+\mu^-\pi^+\pi^-) \sim 10$$

- $\sqrt{s} = 4 - 5$ GeV: $\left(\frac{10.6}{\sqrt{s}}\right)^4 \sim 20 - 50$

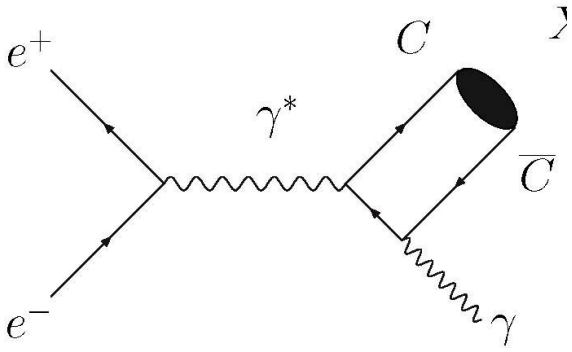
  - Chao & He & Li & Meng, arXiv: 1310.8597
    - $m_c = 1.5$ GeV
  - Li & Xu &Liu & Zhang, JHEP'14
    - $m_c = M_X/2$
    - Relativistic corrections are included

$e^+e^- \to \gamma\chi_c$ @ NLO in PQCD

- LO (pure QED process)

$$\sigma(\chi_c) \sim \frac{1}{1-r}, r = (2m_c)^2/s$$

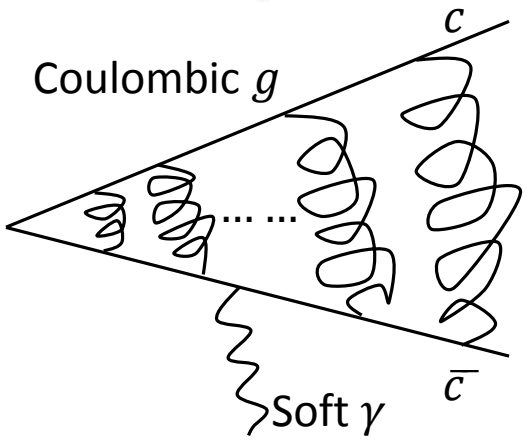
⇒ near-threshold singularity



- QCD pollution in the near-threshold region

The Coulombic gluons need to be resummed

⇒ E1 transitions of resonances



⇒ $\sigma(m_c = 1.5\text{GeV})$ might be viewed as the lower limit of the continuum contribution (without resonance contribution)

$$r = (3/4)^2 \sim 0.5 \ @ \ \sqrt{s} = 4 \text{ GeV}$$

$e^+e^- \to \gamma\chi_c$ @ NLO in PQCD

$\sqrt{s}$(GeV)		σ^{ours}(pb)	σ^{LXLZ}(pb)	$\sigma^{\text{B,ex}}$(pb)	$\sigma^{\text{UP,ex}}$(pb)
4.230	χ_{c1}	0.60	3.6	0.7 ± 0.5	1.7
	χ_{c2}	0.38	5.0	2.7 ± 1.1	5.0
4.260	χ_{c1}	0.58	3.3	0.4 ± 0.4	1.1
	χ_{c2}	0.36	4.2	2.0 ± 1.1	4.2

$$\sigma^{\text{ours}}(\gamma\chi_{c1,2}) \sim 0.5 \text{ pb} \leq \sigma^{\text{ex}}$$

Resonance contributions may be significant for $\sigma(\gamma\chi_{c2})$!

$$\sigma^{\text{ours}}(\gamma\chi'_{c1,2}) \sim 0.2 - 0.4 \text{ pb}$$

$$\sigma(\gamma X[J/\psi\pi^+\pi^-]) = \sigma(\gamma\chi'_{c1}) \cdot k(= 0.018) \sim 0.01 \text{ pb}$$

$$\ll \sigma^{ex} \sim 0.3 \text{ pb} \ @ \sqrt{s} = 4.26 \text{ GeV} \quad \text{BESIII'13}$$

Resonance contributions may be dominant!

$$e^+e^- \to \gamma\chi_c$$

resonance contribution

E1 transitions of higher charmonia

Li & Meng & Chao, arXiv: 1201.4155

$$\Gamma\left(\psi^n \to \gamma\chi_{cJ}^m\right) = \frac{4}{3} C_{mn} e_c^2 \alpha \left|\left\langle \chi_{cJ}^m \middle| r \middle| \psi^n \right\rangle\right|^2 E_\gamma^3$$

- Three potential models are used and they are consistent with each other quite well. (see below for results of SPM)
- Relativistic corrections are included in the wave functions

$\Gamma(\mathbf{keV})$	$\psi_{3S}(4040)$	$\psi_{2D}(4160)$	$\psi_{4S}(4260)^a$
χ_{c0}	54	372	3.9
χ_{c1}	11	63	0.3
χ_{c2}	4.1	0.6	16
$\chi'_{c0}(3915)$	7.9	89	59
$\chi'_{c0}(3840)$	32	193	101
$\chi'_{c1}(3872)$	88	189	88
$\chi'_{c2}(3930)$	56	9.2	15

[a] $m(\psi_{4S} = 4273\ \mathrm{MeV})$ in the SPM Li & Chao, PRD'09

$e^+e^- \to \psi^n \to \gamma\chi_c(1P)$

- Cross section at the resonance peaks: $\sqrt{s} = m_i$

$$\sigma^{\text{peak}} = 12\pi \frac{\Gamma^i_{ee} \cdot \Gamma^i_{\gamma X}(S)}{\left(m_i \cdot \Gamma^i_{tot}\right)^2}$$

- Inputs:

i	m_i/MeV	Γ^i_{tot}/MeV	Γ^i_{ee}/keV
1	4260	100	0.5
2	4160	100	0.83
3	4040	80	0.86

$e^+e^- \to \psi^n \to \gamma\chi_c(1P)$

$\sigma^{\mathrm{peak}}(\mathrm{pb})$	$\psi_{3S}(4040)$	$\psi_{2D}(4160)$	$\psi_{4S}(4260)$
χ_{c0}	6.5	26(3.9[a])	0.16
χ_{c1}	1.3	4.4(2.0[a])	0.01
χ_{c2}	0.50	0.04	0.64

[a] Without relativistic corrections

$\sqrt{s}(\mathrm{GeV})$		$\sigma^{\mathrm{non-res}}(\mathrm{pb})$	$\sigma^{\mathrm{res}}(\mathrm{pb})$	$\sigma^{\mathrm{B,ex}}(\mathrm{pb})$
4.230	χ_{c1}	0.60		0.7 ± 0.5
	χ_{c2}	0.38		2.7 ± 1.1
4.260	χ_{c1}	0.58	0.01	0.4 ± 0.4
	χ_{c2}	0.36	0.64	2.0 ± 1.1

- Checks: search $e^+e^- \to \gamma\chi_{c1}$ around $\sqrt{s} \sim 4.16(4.18)$ GeV

$e^+e^- \to \psi^n \to \gamma\chi_c(2P)$

$\sigma^{\text{peak}}(\text{pb})$	$\psi_{3S}(4040)$	$\psi_{2D}(4160)$	$\psi_{4S}(4260)$
$\chi'_{c0}(3915)$	0.95	6.3	2.4
$\chi'_{c0}(3840)$	3.9	14	4.1
$\chi'_{c1}(3872)$	11	13	3.6
$\chi'_{c2}(3930)$	6.8	0.65	0.61

- $\sigma(\gamma X[J/\psi\pi^+\pi^-]) = \sigma(\gamma\chi'_{c1}) \cdot k \sim 0.065$ pb

  $\ll \sigma^{ex} \sim 0.3$ pb @ $\sqrt{s} = 4.26$ GeV BESIII'13

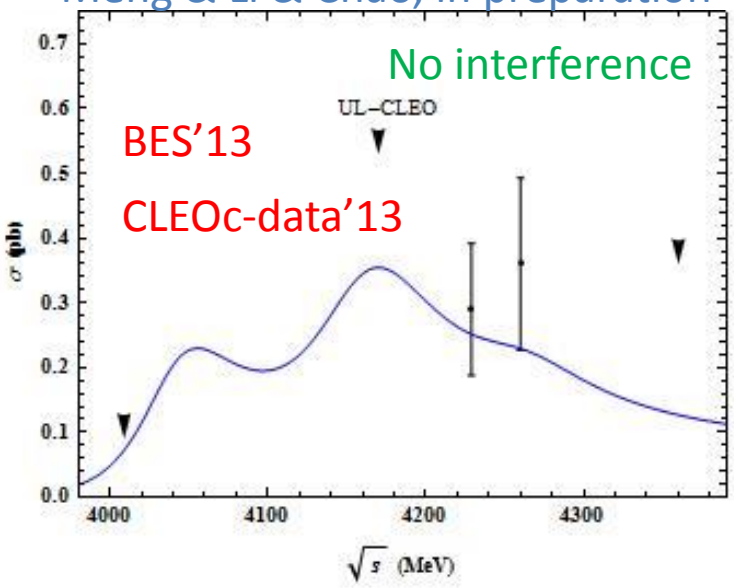
- Interference:

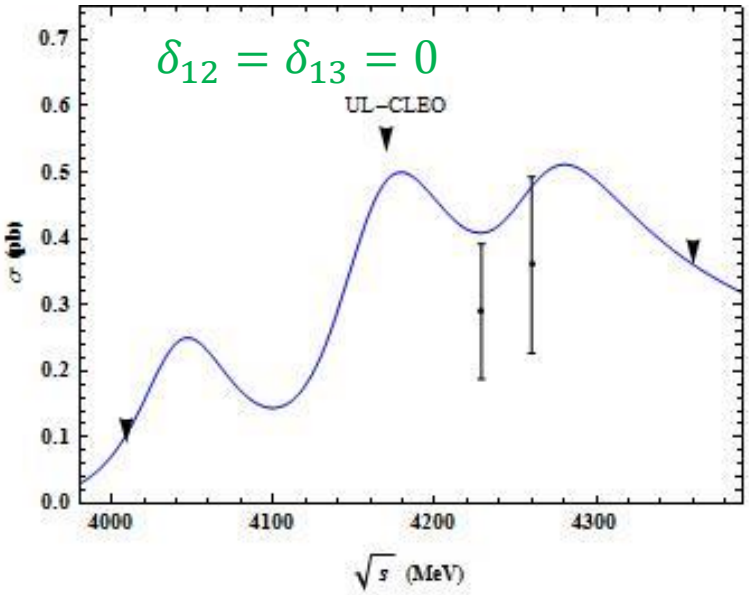
$$A = BM_1 + BW_2 * e^{i\delta_{12}} + BW_3 * e^{i\delta_{13}}$$

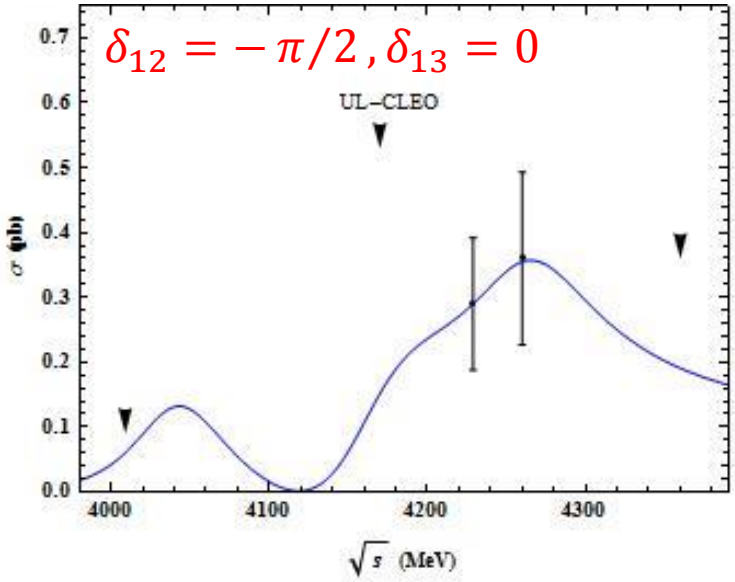
$$BM_i(s) = \frac{\sqrt{12\pi\Gamma^i_{ee}\cdot\Gamma^i_{\gamma X}(S)}}{S - m_i^2 + im_i\cdot\Gamma^i_{tot}} \qquad \Gamma^i_{\gamma X}(S) = \Gamma^i_{\gamma X}(m^2_{i0})\left(\frac{1-\frac{m_X^2}{S}}{1-\frac{m_X^2}{m^2_{i0}}}\right)^{3/2}$$

$e^+e^- \to \psi^n \to \gamma X(3872)$

Meng & Li & Chao, in preparation



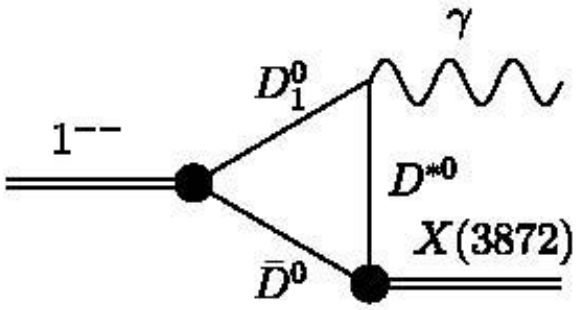




$\sigma \geq 0.2$ pb

$@\ \sqrt{s} = 4.18$ GeV

$e^+e^- \to \psi^n \to \gamma X(3872)$



From Guo et al, PLB'13

- Molecule models: Guo et al, PLB'13
- Enhancement for

  $DD_1(4260) \to \gamma[DD^*(3872)]$

  $\Gamma \sim 10 - 50\ \mathrm{keV} < \Gamma_{E1} = 88\ \mathrm{keV}$

- $\sigma(\gamma X[J/\psi\pi^+\pi^-]) \leq 0.1\mathrm{pb}$ for $\Gamma_{e^+e^-}^{Y(4260)} = 0.5\ \mathrm{keV}$
- Single peak around $Y(4260)$
- $\Gamma(\psi_{3S} \to \gamma[DD^*(3872)]) < 0.23\ \mathrm{keV}$

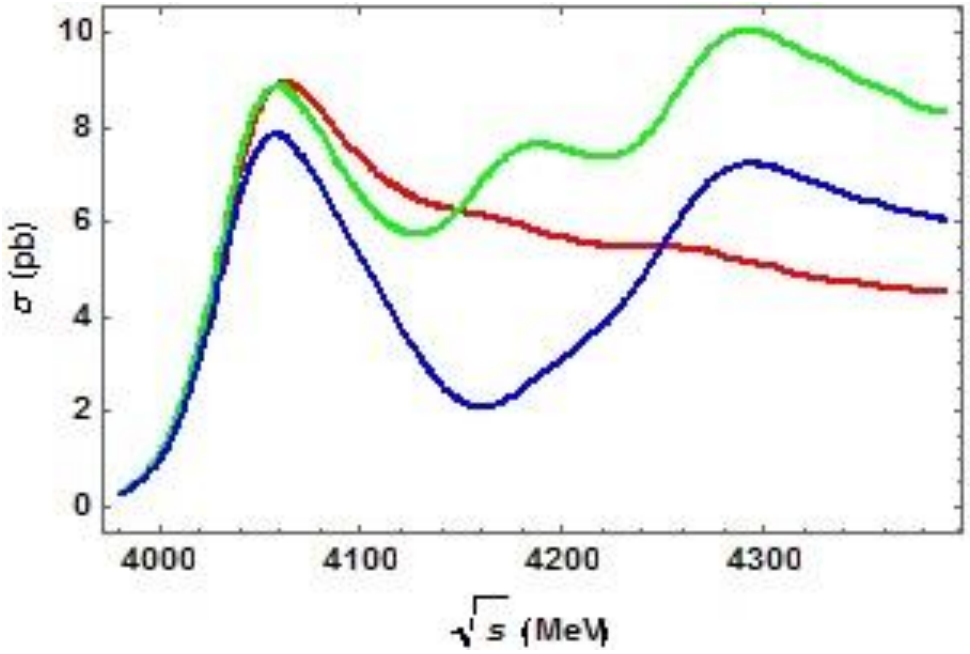
  $\Gamma(\psi_{2D} \to \gamma[DD^*(3872)]) \sim 3\ \mathrm{keV}$

  Can be neglected compared with our predictions.

$e^+e^- \to \psi^n \to \gamma\chi'_{c2}(3930)$

Meng & Li & Chao, in preparation

$\sigma^{\text{peak}}(\text{pb})$	$\psi_{3S}(4040)$	$\psi_{2D}(4160)$	$\psi_{4S}(4260)$
$\chi'_{c2}(3930)$	6.8	0.65	0.61



No interference

$\delta_{12} = \delta_{13} = 0$

$\delta_{12} = -\pi/2\,, \delta_{13} = 0$

$\sigma \sim 5$ pb @ $\sqrt{s} = 4.18 - 4.26$ GeV

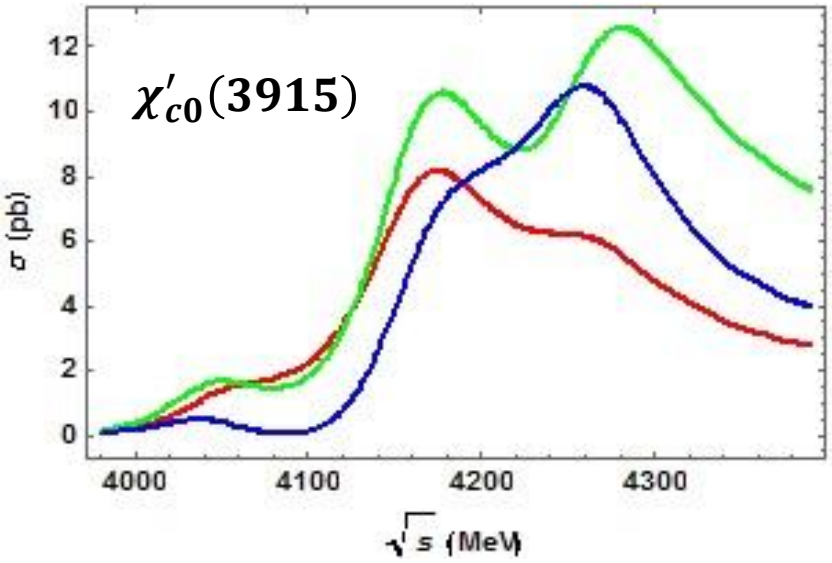
$\sigma^{\text{non-res}} \sim 0.2$ pb

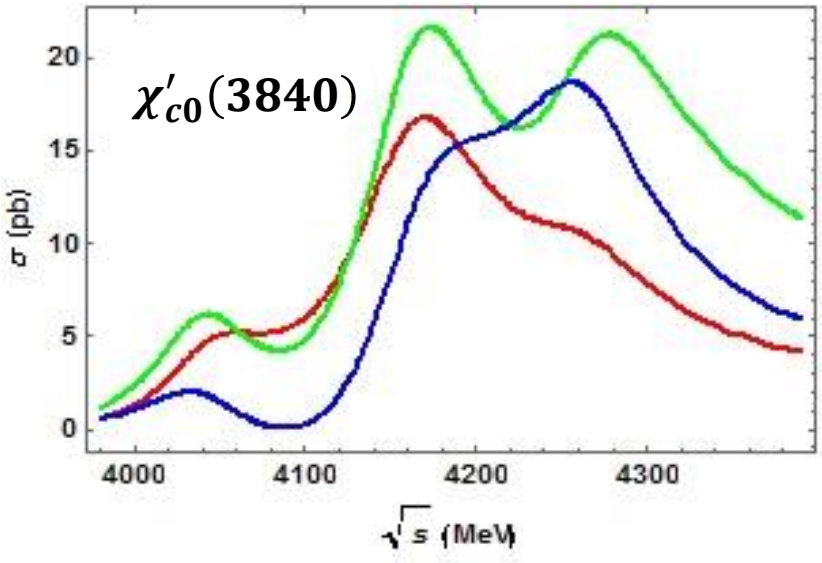
Chao & He & Li & Meng, arXiv: 1310.8597

$e^+e^- \to \psi^n \to \gamma\chi'_{c0}$

Meng & Li & Chao, in preparation

$\sigma^{\text{peak}}(\text{pb})$	$\psi_{3S}(4040)$	$\psi_{2D}(4160)$	$\psi_{4S}(4260)$
$\chi'_{c0}(3915)$	0.95	6.3	2.4
$\chi'_{c0}(3840)$	3.9	14	4.1





$\sigma^{\text{non-res}} \sim 0.0$ pb

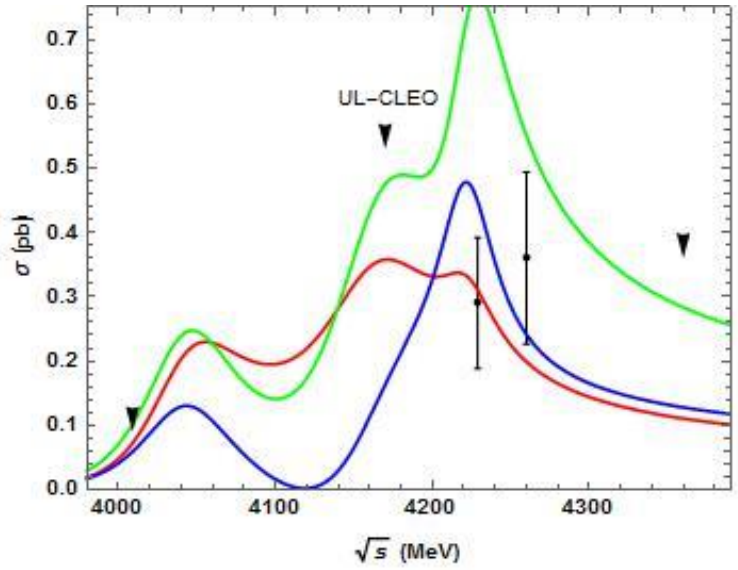
Chao & He & Li & Meng, arXiv: 1310.8597

$e^+e^- \to \psi^n \to \gamma X(3872)$

i	m_i/MeV	Γ^i_{tot}/MeV	Γ^i_{ee}/keV
1	4221	44	0.2

$$\sigma^{\text{peak}} = 12\pi \frac{\Gamma^i_{ee} \cdot \Gamma^i_{\gamma X}(S)}{\left(m_i \cdot \Gamma^i_{tot}\right)^2} \cdot k$$

σ^{peak}(pb)	$\psi_{3S}(4040)$	$\psi_{2D}(4160)$	$\psi_{4S}(4221)$
$X(J/\psi\pi^+\pi^-)$	0.19	0.26	0.10



No interference

$\delta_{12} = \delta_{13} = 0$

$\delta_{12} = -\pi/2\,, \delta_{13} = 0$

Summary

- $e^+e^- \to \gamma\chi_c(1P)$:
  - $e^+e^- \to \gamma\chi_{c1,2}$: $\sigma^{\text{non-res}} \sim 0.5$ pb, $\sigma^{\text{res}} \sim 1$ pb
    $\sigma^{\text{res}}(\gamma\chi_{c1}) > 1$ pb @ $\sqrt{s} = 4.18$ GeV
  - $e^+e^- \to \gamma\chi_{c0}$: $\sigma^{\text{res}} \geq 4$ pb @ $\sqrt{s} = 4.18$ GeV.
- $e^+e^- \to \gamma\chi_c(2P)$:
  - $\sigma^{\text{non-res}}$ can be neglected!
  - $e^+e^- \to \gamma X(3872) \to \gamma J/\psi\pi\pi$: $\sigma > 0.2$ pb @ $\sqrt{s} = 4.18$ GeV
  - $e^+e^- \to \gamma\chi'_{c2}(3930)$: $\sigma \sim 5$ pb @ $\sqrt{s} = 4.18 - 4.26$ GeV
  - $e^+e^- \to \gamma\chi'_{c0}(3915/3840)$: $\sigma \sim 10$ pb @ $\sqrt{s} = 4.18$ GeV

BackUp

$\chi_{cJ}(2P)$ as XYZ states

- $N_{\rm sig}$ with $\sigma = 1$ pb & $\int L = 1\ fb^{-1}$(without ϵ corr.):
  - $\chi_{c0}(2P) = X(3915)$ in $J/\psi(l^+l^-)\omega\left(\pi^+\pi^-\pi^0(\gamma\gamma)\right)$

$$N = 3.1\ \frac{Br(\chi'_{c0} \to J/\psi\omega)}{3\%}$$

$\Gamma_{\gamma\gamma} = 1.7$ keV Li & Chao, PRD'09; $\Gamma_{\gamma\gamma} \cdot Br_{J/\psi\omega} \sim 60$ eV Belle, PRL'10

  - $\chi_{c2}(2P) = X(3930)$ in $D^0(K^-\pi^+)\bar{D}^0$ (single-tag?)

$$N = 15\ \frac{Br(\chi'_{c2} \to D^0\bar{D}^0)}{75\% * 0.5}$$

  - $\chi_{c2}(2P)$ as component of $X(3872)$ in $J/\psi(l^+l^-)\pi^+\pi^-$

$$N = 2.1\ \frac{k}{0.018}$$

$e^+e^- \to \gamma\chi_c$ @ NLO in PQCD

Chao & He & Li & Meng, arXiv: 1310.8597

	σ/pb						
$\sqrt{s}/GeV$	η_c	$\eta_c^{'}$	χ_{c0}	χ_{c1}	$\chi_{c1}^{'}$	χ_{c2}	$\chi_{c2}^{'}$
4.040	0.91	0.04	0.001	0.70	0.32	0.48	0.16
4.160	0.86	0.06	−0.005	0.64	0.40	0.41	0.23
4.260	0.81	0.08	−0.007	0.58	0.43	0.36	0.24
4.360	0.78	0.09	−0.008	0.53	0.43	0.31	0.23
4.415	0.76	0.10	−0.008	0.50	0.43	0.28	0.23
4.660	0.67	0.13	−0.006	0.40	0.39	0.20	0.19
5.000	0.55	0.14	−0.002	0.25	0.26	0.13	0.14

$$\sigma(\gamma\chi_{c1,2}) \sim 0.5\ \text{pb} \leq \sigma^{\text{ex}} \sim 1-3\ \text{pb}$$

$$\sigma(\gamma X[J/\psi\pi^+\pi^-]) = \sigma(\gamma\chi_{c1}') \cdot k \sim 0.01\ \text{pb} \ll \sigma^{ex} \sim 0.3\ \text{pb}$$

Resonance contributions may be significant/dominant!

E1 transitions of higher charmonia

Li & Meng & Chao, arXiv: 1201.4155

$$\Gamma\left(\psi^n \to \gamma\chi_{cJ}^m\right) = \frac{4}{3} C_{mn} e_c^2 \alpha \left|\left\langle \chi_{cJ}^m \middle| r \middle| \psi^n \right\rangle\right|^2 E_\gamma^3$$

$\Gamma(\mathrm{keV})/\sigma(\mathrm{pb})$	$\psi_{3S}(4040)$	$\psi_{2D}(4160)$	$\psi_{4S}(4260)$
χ_{c0}	54 / 6.5	372/26	3.9 / 0.16
χ_{c1}	11 / 1.3	63/4.4	0.3 / 0.01
χ_{c2}	4.1 / 0.50	0.6/0.04	16 / 0.64
$\chi'_{c0}(3915)$	7.9 / 0.95	89 / 6.3	59 / 2.4
$\chi'_{c0}(3840)$	32/3.9	193/14	101/4.1
$\chi'_{c1}(3872)$	88 / 11	189 / 13	88 / 3.6
$\chi'_{c2}(3930)$	56 / 6.8	9.2 / 0.65	15 / 0.61

Specrum: SPM v.s. CCM

Li & Meng & Chao, PRD_80_014012 (2009)

states	Our results					Results of Ref. [6]		
	M_{que}	M_{cou}	M_{scr}	ΔM_{cou}	ΔM_{scr}	M'_0	M'_{cou}	$\Delta M'_{cou}$
1^1S_0	2980	2980	2980.0	0	0	2982	2982	0
1^3S_1	3112	3100	3105	-12	-7	3090	3090	0
1^1P_1	3583	3531	3539	-52	-44	3516	3514	-2
1^3P_0	3476	3441	3448	-35	-28	3424	3415	-9
1^3P_1	3568	3520	3526	-48	-42	3505	3489	-16
1^3P_2	3628	3565	3577	-63	-51	3556	3550	-6
2^1S_0	3697	3635	3626	-62	-71	3630	3620	-10
2^3S_1	3754	3674	3674	-80	-80	3672	3663	-9
1^1D_2	3895	3818	3805	-77	-90	3799		
1^3D_1	3878	3794	3790	-84	-88	3785	3745	-40
1^3D_2	3896	3818	3805	-78	-91	3800		
1^3D_3	3903	3823	3812	-80	-91	3806		
2^1P_1	4042	3961	3909	-81	-133	3934	3929	-5
2^3P_0	3948	3915	3839	-33	-109	3852	3782	-70
2^3P_1	4030	3875	3900	-155	-130	3925	3859	-66
2^3P_2	4085	3966	3941	-119	-144	3972	3917	-55

- Two faces of χ'_{c0}: [X. Liu et al, PRL'10, EPJC'12; F.K. Guo et al, PRD'12]
  - Narrow peak ($\Gamma \sim 1$ MeV) at 3915 MeV
  - Broad structure ($\Gamma > 100$ MeV) around 3840 MeV