# Higher charmonium states

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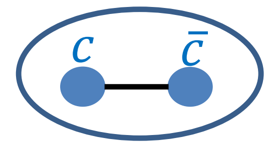
# Charmonium & Higher Charmonium

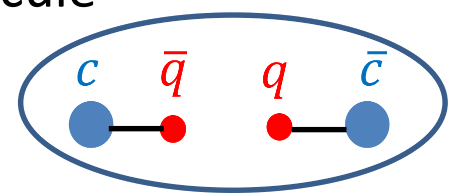
- Many Higher charmonium states have been discovered since 2003:

  $X(3872), \chi'_{c0}(3915), \chi'_{c2}(3930), X(4260), \ldots$ PDG'14

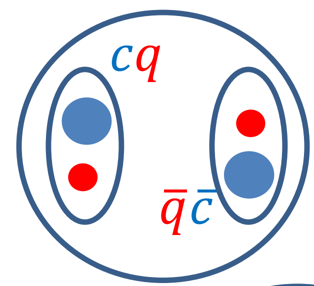
- Coventional charmonium = $c\bar{c}$ bound state



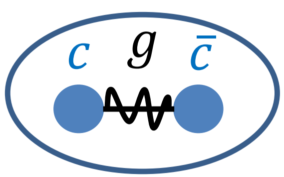

- Higher charmonium or … …
  - Molecule



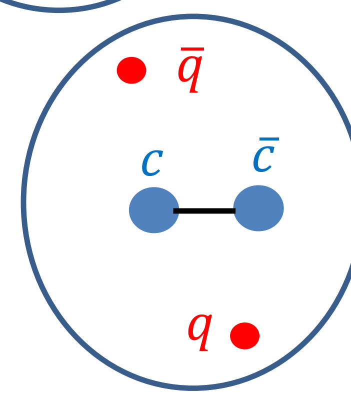

  - Diquark onium




  - Hybrid




  - Hadro-charmonium



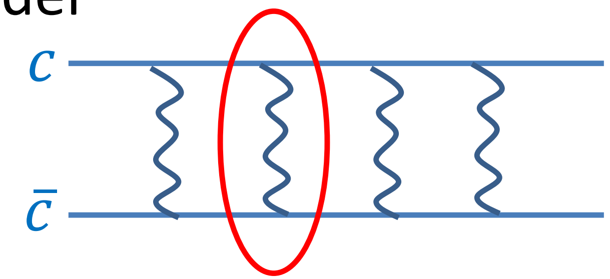
# Charmonium & Higher Charmonium

- How to incorporate the QCD dynamics into the constituent quark/gloun model pictures?
- Lattice QCD will play a major role see Chen, Ying's talk
- Phenomenological models:

  Molecule models, tetraquark models, hadron loop, EFT……
- Conventional charmonium potential model + mixing effects …
  - ✓ Charmonium potential model is successful in description of the properties of lower charmonium states
  - ✓ Most of $XYZ$ states have similar quantum numbers to usual charmonia

# Charmonium & Higher Charmonium

- ➢ Quenched potential model
- Short distance effects




Single-gluon-exchange approximation

- Long distance confinement


Color flux tube

- Cornell type potential

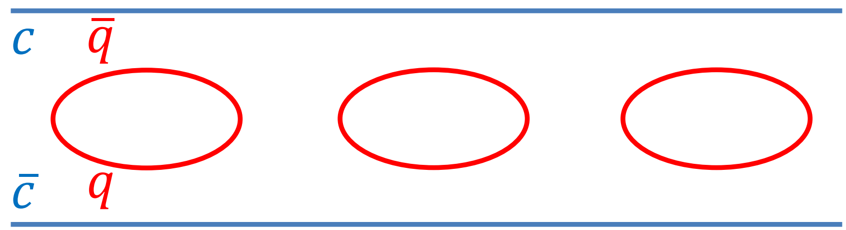
Eichten et al'78

$$V(r) = -\frac{4}{3}\frac{\alpha_c}{r} + \lambda r$$

$$\alpha_c \sim \alpha_s(m_c v) \sim v \sim 0.5, \qquad \lambda \sim 0.2\ \text{GeV}^2$$

# charmonium & Higher Charmonium

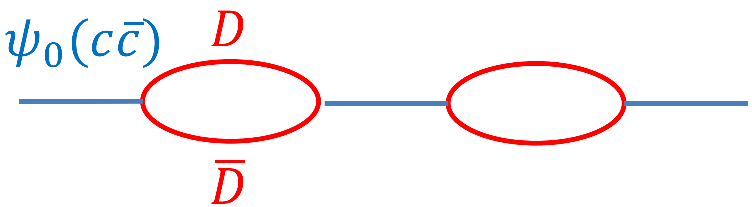
- Unquenched effects
- Quark-level picture




String breaking at scale $\mu \sim 100\ \mathrm{MeV}\ (\mu^{-1} \sim 2\ \mathrm{fm})$

$\Rightarrow$ Screened potential model (SPM) [Chao & Ding & Qin'92]

- Hadron-level picture




Coupled-Channel model (CCM) $\Rightarrow$ mixing between $\psi_0(c\bar{c})$ and $D\bar{D}$

Have been considered even in the Cornell model [E. Eichten et al'78].

# SPM v.s. CCM

- Screened potential model (SPM)
  - 👍 Simple parameterization: $\alpha_c, \lambda, \mu$
  - 👎 Can hardly incorporate the threshold dynamics
- Coupled-channel model (CCM)
  - 👍 Including the dynamics of open-charm threshold
  - 👎 Pollutions from multi-channels:

    The mass, width, WFs of $D$ meson … …

Are these two models consistent with each other?

Especially, the compression of the spectrum of higher charmonium comparing with that in the quenched PM

# SPM v.s. CCM

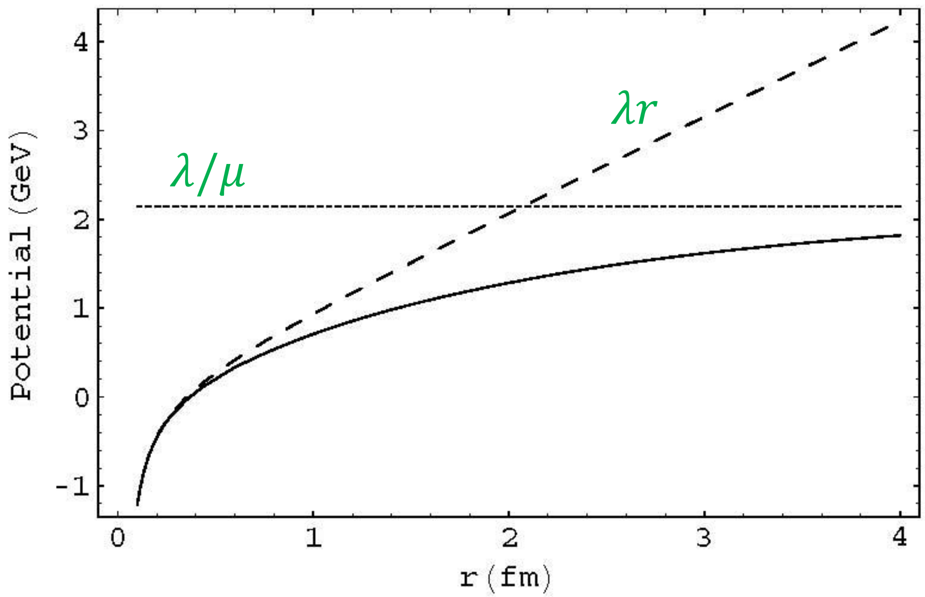
Li & Meng & Chao, PRD_80_014012 (2009)

- Set-ups:
- Bare spectrum $M_0$:

$$V_0(r) = -\frac{4}{3}\frac{\alpha_c}{r} + \lambda r$$

- Screened potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_c}{r} + \lambda r\,\frac{1-e^{-\mu r}}{\mu r}$$




- Coupled-channel dynamics:

$^{3}P_0$ quark-pair creation model  Le Yaouanc et al'73

Solving multi-channel Schrodinger eq.: $H = H_0 + H_{D\bar{D}} + H_{QPC}$

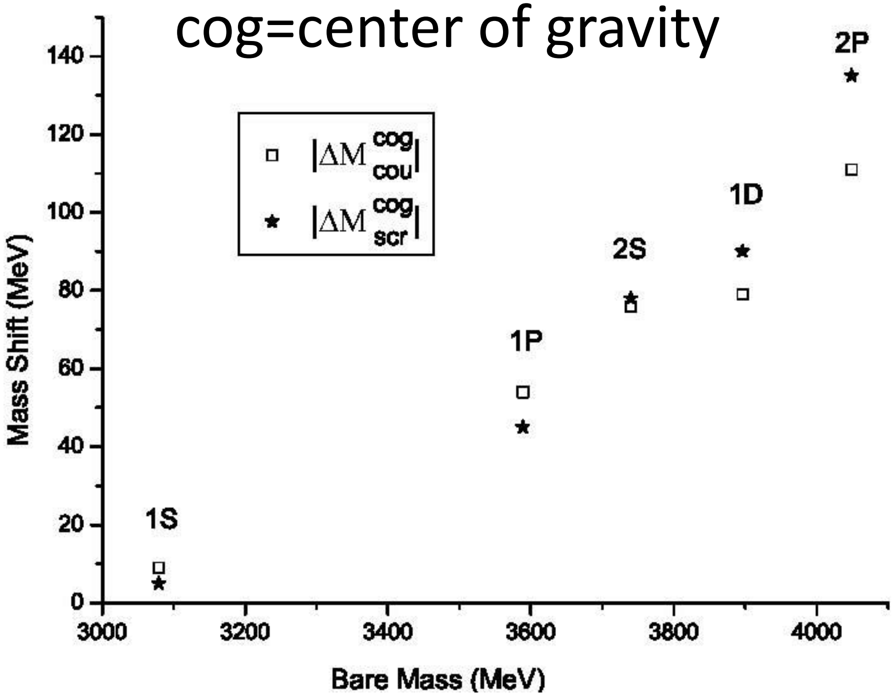
✓ Comparing mass shift $\Delta M = M_{phy} - M_0 < 0$

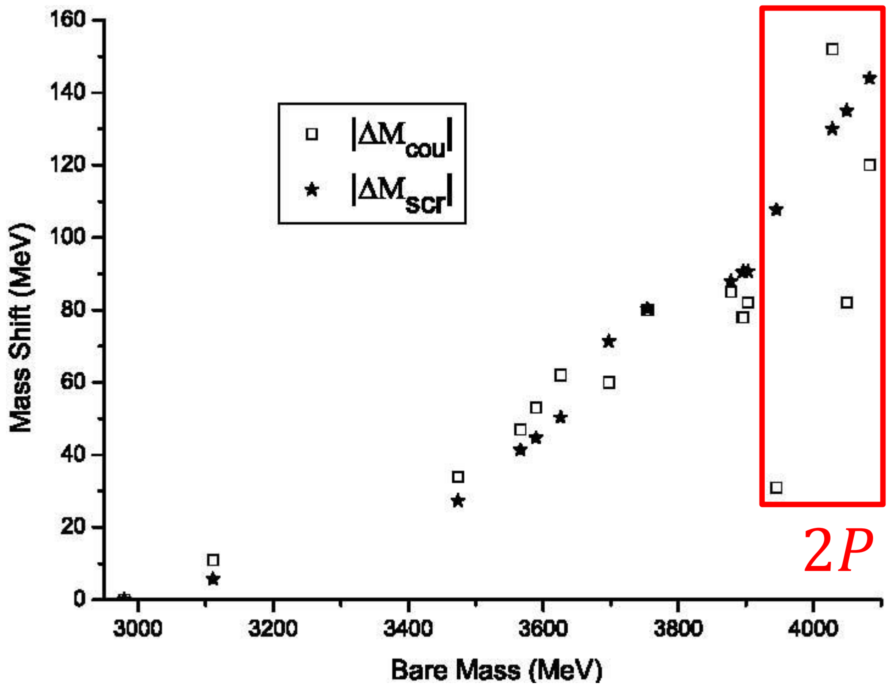
$M_{phy} < 4$ GeV: only $D\,\&\,D^*$ are relevant dynamically

# SPM v.s. CCM

Li & Meng & Chao, PRD_80_014012 (2009)

cog=center of gravity




- SPM ≈ CCM in the global features.
- CCM is more adapt in descriping the open-charmed threshold effects. (Especially for the 2P states)

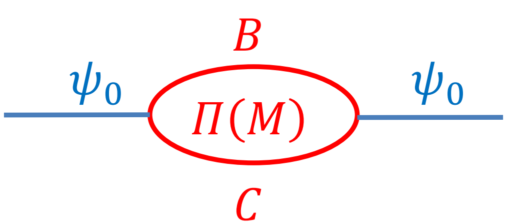
# CCM: 2P charmonium states

Li & Meng & Chao, PRD_80_014012 (2009)

The relative importance of the S-wave coupling

| | $DD$ | $DD^*$ | $D^*D^*$ |
|---|---|---|---|
| $\chi'_{c0}$ | 3/4 | | 1/4 |
| $\chi'_{c1}$ | | 1 | |
| $\chi'_{c2}$ | | | 1 |

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




$$\left|\langle BC, \vec{p} | H_{QPC} | \psi_0 \rangle\right|^2 \sim \Gamma_\psi^{BC} \sim E^{(2L+1)/2}$$

- S-wave cusp: $\quad L = 0 \qquad E = M - M_B - M_C \Rightarrow 0$

$$\Pi(E) = const + \sqrt{E} + \cdots, \quad \Pi'(E) \sim 1/\sqrt{E} \xrightarrow{E \to 0} \infty$$

# CCM: $\chi'_{c1}$

Li & Meng & Chao, PRD_80_014012 (2009)

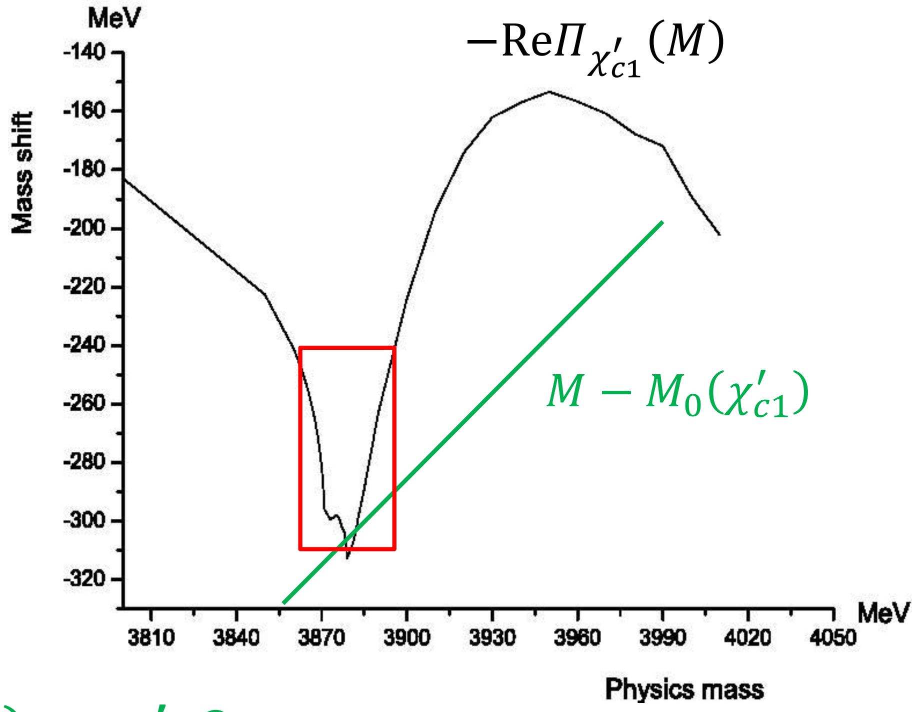
Solving the Breit-Wigner mass:

$$M - M_0 = -\mathrm{Re}\Pi(M) \qquad \mathrm{Re}\Pi'(E) \sim 1/\sqrt{E}$$

The S-wave cusp "attracts" physical mass $M_{\chi'_{c1}}$ to the threshold

✓ $M_{\chi'_{c1}} \approx m_D + m_{D^*}$:

$$\delta M \sim 15\ \mathrm{MeV}$$
$$\Leftrightarrow \delta\mathrm{Re}\Pi \sim 70\ \mathrm{MeV}$$
$$\Leftrightarrow \delta M_0 \sim 85\ \mathrm{MeV}$$




$$X(3872) = \chi'_{c1}?$$

# CCM: $\chi'_{c0}$

Li & Meng & Chao, PRD_80_014012 (2009)

- $M_{\chi'_{c0}} \approx 3915\ \mathrm{MeV}\ \left(> M_{\chi'_{c1}}\right)$
  - $\left|\Delta M_{\chi'_{c0}}\right| \ll \left|\Delta M_{\chi'_{c1}}\right|$

  Far away from threshold of $D\bar{D}$ (3735 MeV) or $D^*\bar{D}^*$ (4010)
- $\Gamma(\chi'_{c0} \to D\bar{D}) < 5\ \mathrm{MeV}$ B.Q. Li, PHD Thesis, PKU'07

  $\left|\langle D\bar{D}|H_{QPC}|\psi_0\rangle\right|^2(M) \approx 0$ at $M = 3910$ MeV

  Due to the node structure of the 2P WF's

✓ Consistent with the PDG assignment:

$$\chi'_{c0} = X(3915)$$

PDG'14

# CCM: $\chi'_{c2}$

Li & Meng & Chao, PRD_80_014012 (2009)

- $M_{\chi'_{c2}} \approx 3966\ \mathrm{GeV}$

- Not very close to the threshold of $D^*\bar{D}^*$ (4010)

  modest mass-shift $\left|\Delta M_{\chi'_{c2}}\right| < \left|\Delta M_{\chi'_{c1}}\right|$

  ✓ Tend to enlarge the splitting $M_{\chi'_{c2}} - M_{\chi'_{c1}}$

- Roughly consistent with the PDG assignment

$$\chi'_{c2} = X(3930)$$

PDG'14

- No strong threshold-attraction: sensitive to the model details

# Summary I

- SPM and CCM are consistent with each other
  - Unquenched effects result in the screened spectrum and/or the mixing of charmonium with $D\bar{D}$
- Threshold effects are important for understanding 2P states
  - $\chi'_{c0} = X(3915)$
  - $\chi'_{c2} = X(3930)$
  - ✓ $M_{\chi'_{c1}} \approx m_D + m_{D^*} = 3872\ \mathrm{MeV}$

    The closeness is not sensitive to model details

$$|X(3872)\rangle = \alpha|\chi'_{c1}\rangle + \beta|DD^*\rangle$$

# $X(3872)$: $\chi'_{c1}$-$D^0\overline{D}^{*0}$ mixing model

Meng, Gao and Chao, PRD_87_074035 (2013) [hep-ph/0506222]

- $X(3872)$ is a mixing state of $\chi'_{c1}$ and $D^0\overline{D}^{*0}/\overline{D}^0 D^{*0}$
- Both the two components are substantial, and they may play different roles in the dynamics of $X(3872)$.

1. The $\chi'_{c1}$ component is dominant in the short distance processes: the B- and hadro- production and the quark annihilation decays (into LHs, $\psi^{(\prime)}\gamma$ )
2. The $D^0\overline{D}^{*0}$ component is mainly in charge of the hadronic decays of $X(3872)$ into $DD\pi/DD\gamma$ as well as $J/\psi\rho$ and $J/\psi\omega$.
3. The long distance coupled-channel effects between the two components could renormalize the short distance dynamics by a product factor $Z_{c\bar{c}}$, the equivalent probability of $\chi'_{c1}$ in $X(3872)$.

# $X(3872)$ as a mixing state : Decay pattern

- $\chi'_{c1}$ induced decay modes
  - Radiative decay modes $E_\gamma^3(\psi')/E_\gamma^3(J/\psi) \approx 0.02$

| | Barnes & Godfry'04 | Barnes et al'05 | Li & Chao'09 |
|---|---|---|---|
| $\Gamma_{\psi\gamma}$/keV | 11 | 59 | 45 |
| $\Gamma_{\psi'\gamma}$/keV | 64 | 88 | 60 |
| $\Gamma_{\psi'\gamma}/\Gamma_{\psi\gamma}$ | 5.8 | 1.5 | 1.3 |

$\chi'_{c1} \to \gamma\psi'$ node-allowed; $\chi'_{c1} \to \gamma J/\psi$ node-surppressed

✓Consistent with data

$\Gamma_{\psi'\gamma}/\Gamma_{\psi\gamma}$: $3.4 \pm 1.1$ (BaBar'09) & $2.5 \pm 1.7$ (LHCb'14)

  - Light hadron decay mode

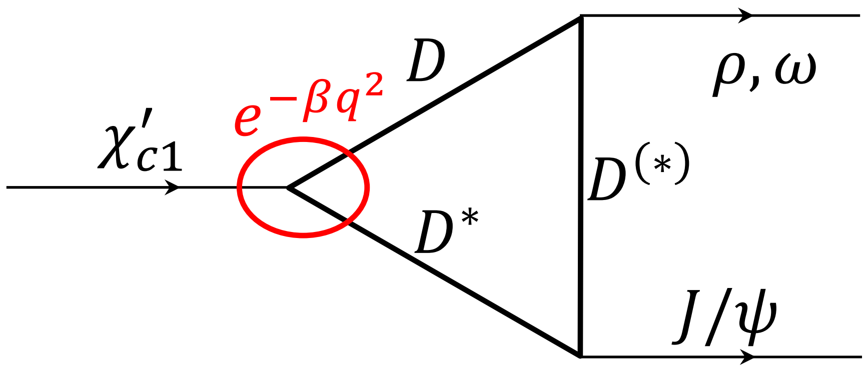
$$\Gamma(\chi'_{c1} \to LHs) \sim \Gamma(\chi_{c1} \to LHs) \sim 0.6\ \text{MeV}$$

# $X(3872)$ as a mixing state : Decay pattern

- $DD^*$ induced decay modes  Meng & Chao, PRD'07

$$\Gamma(D^0\bar{D}^0\pi) \sim 0.5\text{-}1\ \mathrm{MeV}$$

$$\Gamma(J/\psi\rho) \approx \Gamma(J/\psi\omega) \sim 50\text{-}100\ \mathrm{keV}$$




- Isospin violation

✓ The difference between $D^0\bar{D}^{*0}$ and $D^{\pm}\bar{D}^{*\mp}$ can be "seen"

✓ Suppression of the PS of $J/\psi\omega$

- Totally,

$$\mathrm{Br}_0 \equiv \mathrm{Br}(X \to J/\psi\pi^+\pi^-) \sim 0.05$$

Consistent with the experimental decay pattern  PDG'14

# $X(3872)$ as a mixing state : Production

- General factorization formula:

$$d\sigma(X(J/\psi\pi^+\pi^-)) = \sum_n d\hat{\sigma}((c\bar{c})_n) \cdot \langle O_n^{\chi'_{c1}} \rangle \cdot k, \qquad k = Z_{c\bar{c}}\mathrm{Br}_0$$

$$p_T, m_b, m_c \gg m_c v, m_c v^2, \Lambda_{QCD} \gg \epsilon, \Gamma_X \sim 1\ \mathrm{MeV}$$

$c\bar{c}$ production $\quad \chi'_{c1}$ production $\quad$ Binding & Decay(LD)

$$\mathrm{Br}_0 = \mathrm{Br}(X \to J/\psi\pi^+\pi^-)$$

✓ Hard production of $\chi'_{c1}$ is very similar to that of $\chi_{c1}(1P)$

- $\sigma(\chi'_{c1}) \sim R'_{2P}(0)$ $\quad R'_{2P}(0) \approx R'_{1P}(0)$ $\quad$ Eichten & Quigg'95
- For the $b\bar{b}$ sector: $pp \to \chi_b$ @ LHC

$$\sigma_{\chi_b}(1P) \sim \sigma_{\chi_b}(2P) \sim \sigma_{\chi_b}(3P)$$

LHCb'14 v.s. Han & Ma & Meng & Shao & Zhang & Chao'14

# $X(3872)$ as a mixing state : B-Production

- Factorization assumption: [Meng, Gao and Chao, PRD_87_074035 (2013) [hep-ph/0506222]]

$$\mathrm{Br}(B \to \chi'_{c1} K)/\mathrm{Br}(B \to \chi_{c1} K) = 0.75 \sim 1$$

$$\mathrm{Br}_{\mathrm{PDG}}(B \to \chi_{c1} K) = (4-5) \times 10^{-4}$$

- Consistent with the fitting result: [Kalashnikova & Nefediev PRD'09]

$$\mathrm{Br}^{\mathrm{fit}}(B \to \chi'_{c1} K) = (3.7\text{–}5.7) \times 10^{-4}$$

$$\mathrm{Br}(B \to X(J/\psi \pi^+ \pi^-) K) = (8.6 \pm 0.8) \times 10^{-6}$$ PDG'14

$$\therefore k = Z_{c\bar{c}} \mathrm{Br}_0 = 0.018 \pm 0.004$$

($Z_{c\bar{c}} = 28\%\text{–}44\%$ for $\mathrm{Br}_0 = 5\%$)

# $X(3872)$ as a mixing state : B-Production

- B-production rates in $J/\psi\pi^+\pi^-$ mode:

Inputs: $\mathrm{Br}(B \to \chi'_{c1} \ldots) = \mathrm{Br}_{\mathrm{PDG}}(B \to \chi_{c1} \ldots)$, $k = 0.018$

| $\mathrm{Br_i} \cdot \mathrm{Br_0} \cdot 10^6$ $i =$ | Predictions | data | |
|---|---|---|---|
| $B^+ \to XK^+$ | $8.6 \pm 0.4$ | $8.6 \pm 0.8$ | PDG'14 |
| $B^0 \to XK^0$ | $7.1 \pm 0.5$ | $4.3 \pm 1.3$ | |
| $B^+ \to XK^{*+}$ | $5.4 \pm 1.0$ | | |
| $B^0 \to XK^+\pi^-$ | $6.8 \pm 0.7$ | $8.5 \pm 1.5$ | Belle's Preliminary [1] |
| $B^0 \to XK^{*0}$ | $4.0 \pm 0.7$ | $3.7 \pm 1.2$ | |

[1] Shen, Chengping's talk given in the 2nd workshop on XYZ particles, 20-21 Nov, 2013, Huangshan, China

# $X(3872)$ as a mixing state : Production at $pp(p\bar{p})$ collider

Meng & Han & Chao, arXiv:1304.6710

- Hadro-procution:

- Similar to that of $\chi_{c1}(1P)$

  $d\sigma(\chi'_{c1}) \approx d\sigma(\chi_{c1})$[MWC'11]

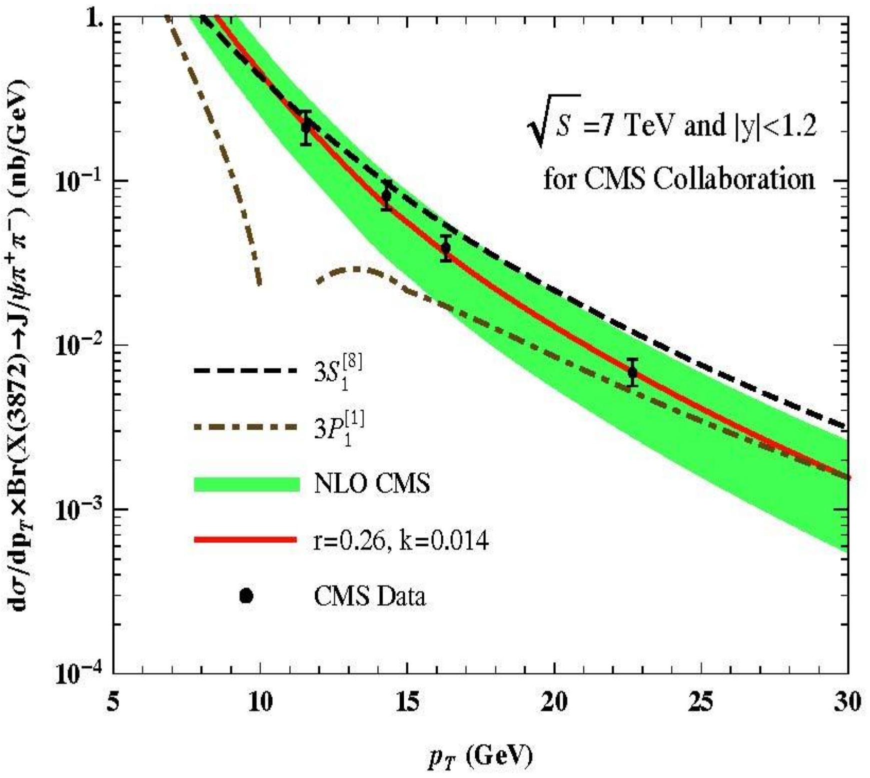
- Consistent with B-production

  $$k = 0.014 \pm 0.007$$

  $$(0.018 \pm 0.004)_{\text{B-pro}}$$

- Consistent with the $P_T$ spectrum [CMS'13]

  $$\chi^2/3 = 0.17$$



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

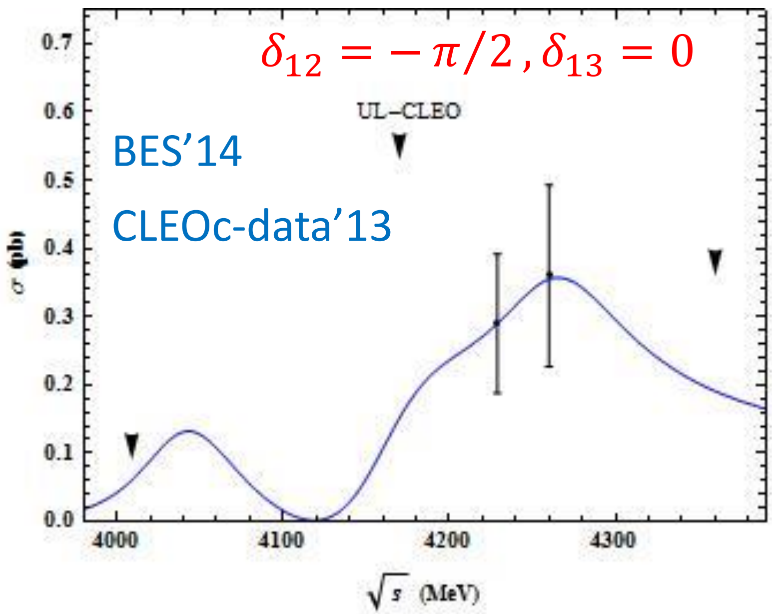
$$e^+e^- \to \psi^n \to \gamma\chi'_{cJ}$$

Li & Meng & Chao, arXiv: 1201.4155

- 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

| $\Gamma(\mathrm{keV})$ | $\psi_{3S}(4040)$ | $\psi_{2D}(4160)$ | $\psi_{4S}(4260)$ |
|---|---|---|---|
| $\chi'_{c2}(3930)$ | 56 | 9.2 | 15 |
| $\chi'_{c1}(3872)$ | 88 | 189 | 88 |
| $\chi'_{c0}(3915)$ | 7.9 | 89 | 59 |

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




Meng & Li & Chao, in preparation

| $m_i$/MeV | $\Gamma^i_{tot}$/MeV | $\Gamma^i_{ee}$/keV |
|---|---|---|
| 4260 [1] | 100 | 0.5 |
| 4160 | 100 | 0.83 |
| 4040 | 80 | 0.86 |

[1] $Y(4260) = \psi(4S)$ Li & Chao'09

Molecule models: $DD_1(4260) \to \gamma[DD^*(3872)]$. Guo et al, PLB'13

$$\mathrm{Br}(Y \to \gamma X[J/\psi\pi\pi]) \sim \frac{50\ \mathrm{keV}}{100\ \mathrm{MeV}} \mathrm{Br}_0 \sim 2.5 \times 10^{-5}$$

$$\frac{\mathrm{Br}(Y \to \gamma X[J/\psi\pi\pi])}{\mathrm{Br}(Y \to J/\psi\pi\pi)} \sim 5 \times 10^{-3}$$ BES'13

$$\Gamma_{\mathrm{ee}} \cdot \mathrm{Br}(Y \to J/\psi\pi\pi) \sim 6\ \mathrm{eV} \Rightarrow \text{Need } \Gamma_{\mathrm{ee}} \sim 1\ \mathrm{keV!}$$

# $e^+e^- \to \psi^n \to \gamma\chi_{cJ}(2P)$

Meng & Li & Chao, in preparation

- $\sigma\left(e^+e^- \to \gamma\chi'_{c2}(3930)\right) \sim \mathcal{O}(10)\ \mathrm{pb}$

  $\mathrm{Br}(\chi'_{c2} \to D\bar{D}) \sim 70\%$

- $\sigma\left(e^+e^- \to \gamma\chi'_{c0}(3915)\right) \sim \mathcal{O}(10)\ \mathrm{pb}$

  Assuming $\Gamma_{tot}(\chi'_{c0}) = 10\ \mathrm{MeV}$

  $\mathrm{Br}(\chi'_{c2} \to \gamma\psi') \sim 1\%$

- Hopeful to be studied at BEPC II/Super $\tau$-$c$/Super-B

# Summary & Perspectives

- SPM and CCM are confirmed and supplied by each other
  - The $q\bar{q}$ creation in flux tube induces screened spectrum and/or the mixing between charmonium and $D\bar{D}$
  - The threshold effects are important for 2P states:

$$\chi'_{c2}(3930), \chi'_{c1}(3872), \chi'_{c0}(3915)$$

  - The transition $e^+e^- \to \psi^n \to \gamma\chi_{cJ}(2P)$ processes are apt to study both 2P and higher vector charmonium states.
- Have all unquenched effects been incorporated in the simple picture of the mixing of $c\bar{c}$ with $D\bar{D}$?

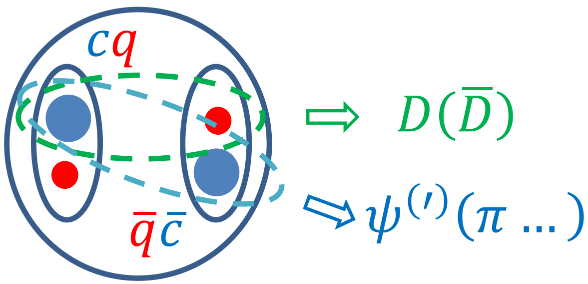
  Generally not!

  Especially when going to higher mass … …

# Summary & Perspectives

- Diquark onium

Esposito et al'14, Brodsky & Hwang & Lebed'14



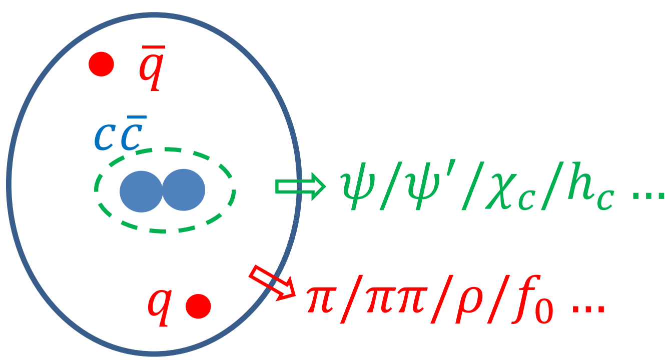

✓ Suppression of hadronization rate

✓ Suppression of $D\bar{D}$ rate

✓ Suppression of $\psi(1S)/\psi(2S)$

- Hadro-charmonium

Voloshin'08




✓ Specific final states

Di-excitation is suppressed

✓ Suppression of $D\bar{D}$ rate

… …

# Summary & Perspectives

- All the above configurations could be mixed together in the same state:

  Is this similar to the case where the SPM can roughly describe the effects caused by the mixing of $c\bar{c}$ and $D\bar{D}$?

  Can the mixing be described by effective potential which may have different faces at different separation $r$'s of $c\bar{c}$ ?

  - Lattice QCD
  - Born-Oppenheimer potentials    Braaten et al'14

High Intensity Collider @ 2-7GeV is sincerely welcome!

Thank you for your patience!

# Back Ups

# $X(3872)$: experimental information

- 1st observed by Belle Collaboration in

  $B \to J/\psi\pi^+\pi^- K$ $\quad \pi^+\pi^- \approx \rho$ Belle'03

- Mass, width and quantum numbers:

- $m_X = 3871.68 \pm 0.17$ MeV PDG'14

  $m_X - m_{D^0 D^{*0}} = -0.142 \pm 0.220$ MeV Tomaradze *et al.*'12

- $\Gamma < 1.2$ MeV $\quad$ CL $= 90\%$ PDG'14

- $J^{PC} = 1^{++}$ LHCb'13

- Decay pattern:

  $J/\psi\rho, J/\psi\omega, D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}/D\bar{D}\pi, J/\psi\gamma, \psi'\gamma$

  Relative ratios of these 5 modes: $1:1:10:0.3:1$ PDG'14

  $\mathrm{Br}_0 \equiv \mathrm{Br}(X \to J/\psi\pi^+\pi^-) < 8\%$

# $X(3872)$: experimental information

- B-production:

$$1\times10^{-4} < \mathrm{Br}(B\to X(3872)K) < 3.2\times10^{-4}$$ BaBar'05

$$\mathrm{Br}(B\to X(3872)K)\mathrm{Br}_0 = (8.6\pm0.8)\times10^{-6}$$ PDG'14

$$2.6\% < \mathrm{Br}_0 \equiv \mathrm{Br}(X\to J/\psi\pi^+\pi^-) < 8\%$$

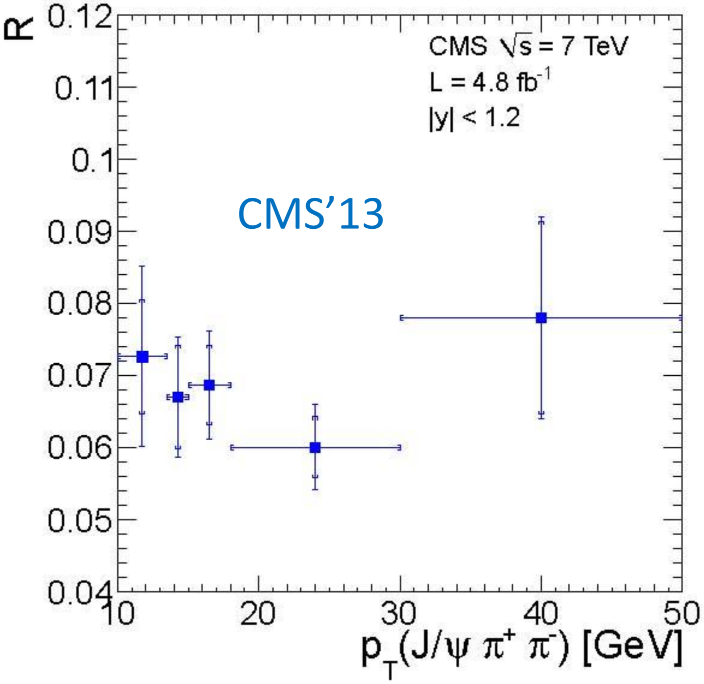
- Hadro-production

- Large production rate:

$$\frac{\sigma(p\bar{p}\to X)\mathrm{Br}_0}{\sigma(p\bar{p}\to\psi\prime)}\frac{\epsilon_{\psi\prime}}{\epsilon_X} = (4.8\pm0.8)\%$$ CDF'04

- Similar behaviors to $\psi'$ production

$$R = d\sigma(\psi')/d\sigma(X) \sim P_T$$



# $X(3872)$: $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}$ Molecule models

[Tornqvist'04, Voloshin'04, Swanson'04, Braaten'04, …]

- The mass, $J^{PC}$ and $R_{\rho/\omega}$ …… can be understood naturally.
- The large production rate seems to be questionable

- Naively, $\sigma(X) \sim R(0) \sim k_0^3,\ k_0 = \sqrt{2\mu_{DD^*}|E_b|} < 40$ MeV
- Explicit calculations [Bignamini *et al*, PRL'09]:

$$\sigma_{\mathrm{CDF}}^{\mathrm{th}}(X) < 0.085\ \mathrm{nb} \quad v.s. \quad \sigma_{\mathrm{CDF}}^{\mathrm{ex}}(X)\mathrm{Br}_0 = 3.1 \pm 0.7\ \mathrm{nb}$$

✓ Artoisenet and Braaten [PRD'10] proposed that the rescattering effects of $D^0\bar{D}^{*0}$ may enhance the rate to values consistent with the CDF data if the upper bound of the relative momentum of $D^0\bar{D}^{*0}$ in the rescattering is as large as $3m_\pi \approx 400$ MeV

- Similarly, small B-production rate [Braaten, Lu, Kusunoki'05-06]

$$\mathrm{Br}\big(B^+ \to K^+ X(3872)\big) = (0.07 - 1) \times 10^{-4} \quad \text{for } k_0 \sim 40\ \mathrm{MeV}$$

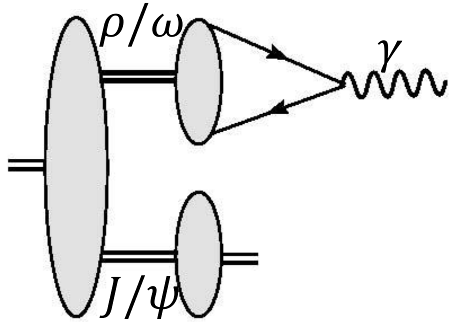
# Molecule models

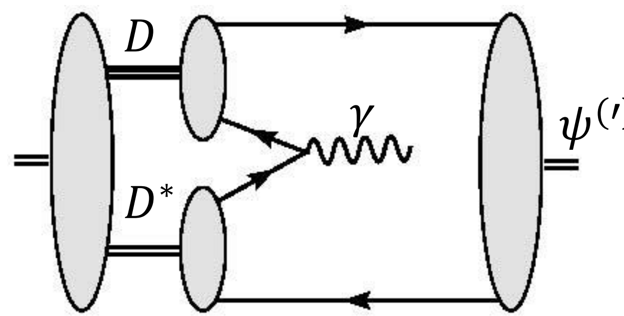
➢ Decay pattern

- $DD\pi$ decay mode [Swanson; Voloshin; Fleming, mehen, ……]

$$\Gamma(X \to D^0\bar{D}^0\pi) \sim 2\Gamma\left(D^{*0} \to D^0\pi\right) \sim 100 \text{ keV}$$

- Radiative decays: [Swanson’04]




$\Gamma(X \to J/\psi\gamma) \approx 8 \text{ keV}$ $\quad$ $\Gamma(X \to \psi'\gamma) \approx 0.03 \text{ keV}$

$$\frac{\Gamma(X\to\psi'\gamma)}{\Gamma(X\to D^0\bar{D}^0\pi)} \sim 10^{-4} \quad v.s. \quad (10^{-1})_{ex}$$ [BaBar’08]

- $J/\psi\rho(\omega)$ decay mode [Swanson’04]

$$\Gamma(X \to J/\psi\rho(\omega)) \sim 1\text{-}2 \text{ MeV}$$

# Specrum: Screened potential model

B.Q. Li & K.T. Chao, PRD_79_094004 (2009)

| State | | Expt. | Theor. of ours | | Theor. of Ref.[5] | |
|---|---|---|---|---|---|---|
| | | | Mass | $\langle r^2 \rangle^{\frac{1}{2}}$ | NR | GI |
| 1S | $J/\psi(1^3S_1)$ | $3096.916 \pm 0.011$ | 3097 | 0.41 | 3090 | 3098 |
| | $\eta_c(1^1S_0)$ | $2980.3 \pm 1.2$ | 2979 | | 2982 | 2975 |
| 2S | $\psi'(2^3S_1)$ | $3686.093 \pm 0.034$ | 3673 | 0.91 | 3672 | 3676 |
| | $\eta_c'(2^1S_0)$ | $3637 \pm 4$ | 3623 | | 3630 | 3623 |
| 3S | $\psi(3^3S_1)$ | $4039 \pm 1$ | 4022 | 1.38 | 4072 | 4100 |
| | $\eta_c(3^1S_0)$ | | 3991 | | 4043 | 4064 |
| 4S | $\psi(4^3S_1)$ | $4263^{+8}_{-9}$ | 4273 | 1.87 | 4406 | 4450 |
| | $\eta_c(4^1S_0)$ | | 4250 | | 4384 | 4425 |
| 5S | $\psi(5^3S_1)$ | $4421 \pm 4$ | 4463 | 2.39 | | |
| | $\eta_c(5^1S_0)$ | | 4446 | | | |
| 6S | $\psi(6^3S_1)$ | | 4608 | 2.98 | | |
| | $\eta_c(6^1S_0)$ | | 4595 | | | |
| 1P | $\chi_2(1^3P_2)$ | $3556.20 \pm 0.09$ | 3554 | 0.71 | 3556 | 3550 |
| | $\chi_1(1^3P_1)$ | $3510.66 \pm 0.07$ | 3510 | | 3505 | 3510 |
| | $\chi_0(1^3P_0)$ | $3414.75 \pm 0.31$ | 3433 | | 3424 | 3445 |
| | $h_c(1^1P_1)$ | $3525.93 \pm 0.27$ | 3519 | | 3516 | 3517 |
| 2P | $\chi_2(2^3P_2)$ | $3929 \pm 5 \pm 2$ | 3937 | 1.19 | 3972 | 3979 |
| | $\chi_1(2^3P_1)$ | | 3901 | | 3925 | 3953 |
| | $\chi_0(2^3P_0)$ | | 3842 | | 3852 | 3916 |
| | $h_c(2^1P_1)$ | | 3908 | | 3934 | 3956 |

# Specrum: SPM v.s. CCM

Li & Meng & Chao, PRD_80_014012 (2009)

| states | Our results | | | | | Results of Ref. [6] | | |
|---|---|---|---|---|---|---|---|---|
| | $M_{que}$ | $M_{cou}$ | $M_{scr}$ | $\Delta M_{cou}$ | $\Delta M_{scr}$ | $M'_0$ | $M'_{cou}$ | $\Delta M'_{cou}$ |
| $1^1S_0$ | 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 $\chi'_{c0}$: [X. Liu et al, PRL'10, EPJC'12; F.K. Guo et al, PRD'12]
  - Narrow peak ($\Gamma < 10$ MeV) at 3915 MeV
  - Broad structure ($\Gamma > 100$ MeV) around 3850 MeV

# $X(4260)$ v.s. $\psi(4S)$

- $X(4260)$ was first observed in $e^+e^- \to J/\psi\pi^+\pi^-$ BaBar'05

$$\Gamma_{tot} \sim 100 \text{ MeV}$$ PDG'14

$$\Gamma_{ee}\text{Br}(X \to J/\psi\pi^+\pi^-) \sim 10 \text{ eV}$$ Belle'07

- $\psi_{4S}$: $\Gamma_{ee} = 970$ eV [Li & Chao, PRD'09]
- Fitting $R$-value: Mo et al'06
  - $\Gamma_{\text{ee}} < 580$ eV
  - Ignoring the dip structure
  - Relative phases between different resonances are important!