X(3872) and Its Production

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2nd workshop on the XYZ particles

11月21日，安徽黄山

Outline

- Experimental information on X(3872) before BESIII
- Molecular model: a critical review
  - Production rate
  - Decay pattern
- X as a mixing state of χ'_{c1} and $D^0\overline{D}^{*0} + c.c.$
  - Spectrum
  - Scattering amplitudes v.s. line shapes
- Production of X
  - Production in B decays
  - Production in $p\bar{p}/pp$ collision
  - Production in e^+e^- annihilation
  - Production in the E1 transitions of higher chamonia
- Summary

Experimental information

- 1st observed by Belle Collaboration in

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

- Mass, width and quantum numbers:

- $m_X = 3871.68 \pm 0.17\ \mathrm{MeV}$ PDG'12

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

- $\Gamma < 1.2\ \mathrm{MeV} \quad \mathrm{CL} = 90\%$ PDG'12

- $J^{PC} = 1^{++}$ or 2^{-+}

✓ $J^{PC} = 2^{-+}$ is favored by the $\omega \to \pi^+\pi^-\pi^0$ mass spectrum in $B \to X(3872)K \to J/\psi\omega(\pi^+\pi^-\pi^0)K$ [BaBar'10], but is excluded by the recent analysis on the angular correlations in $B \to X(3872)K \to J/\psi\rho(\pi^+\pi^-)K$ by LHCb [LHCb'13]

Experimental information

- ➢ Decay pattern:
- Well-established decay modes:

$J/\psi\rho(\pi^+\pi^-), J/\psi\omega(\pi^+\pi^-\pi^0), D^0\bar{D}^{*0}/\bar{D}^0D^{*0}/D\bar{D}\pi, J/\psi\gamma$

Relative ratios of these 4 modes: $1:1:10:0.3$ PDG'12

✓ Large isospin violations

$$\mathrm{R}_{\rho/\omega} = \mathrm{Br}(X \to J/\psi\rho)/\mathrm{Br}(X \to J/\psi\omega) \approx 1$$

✓ $\mathrm{Br}(X \to J/\psi\rho) = \mathrm{Br}(X \to J/\psi\pi^+\pi^-) \equiv \mathrm{Br}_0 < 9\%$

- ➢ B-production:

$1 \times 10^{-4} < \mathrm{Br}(B \to X(3872)K) < 3.2 \times 10^{-4}$ BaBar'05

$\mathrm{Br}(B \to X(3872)K)\mathrm{Br}_0 = (8.6 \pm 0.8) \times 10^{-6}$ PDG'12

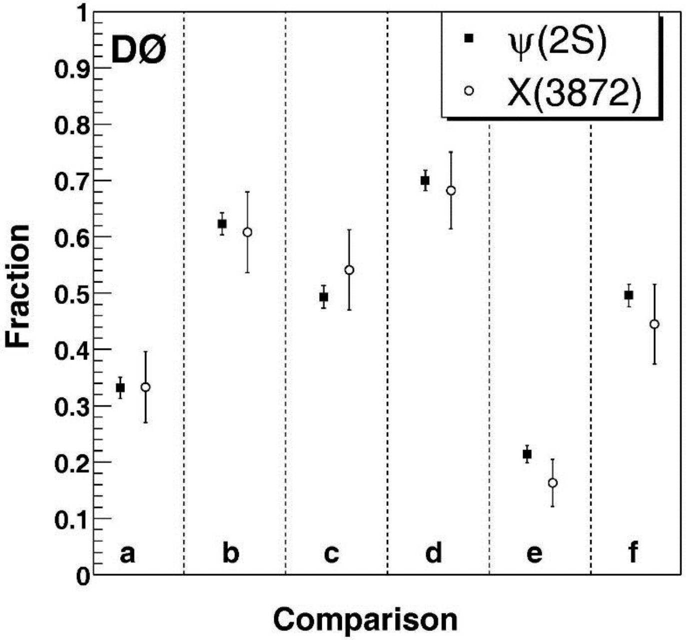
$$2.6\% < \mathrm{Br}_0 < 9\%$$

Experimental informations

- Hadro-production
- Large production rate: $\frac{\sigma(p\bar{p}\to X)\mathrm{Br}_0}{\sigma(p\bar{p}\to\psi\prime)}\frac{\epsilon_{\psi\prime}}{\epsilon_X} = (4.8 \pm 0.8)\%$ CDF’04
- Similar behaviors to ψ' production in p_T distribution and …

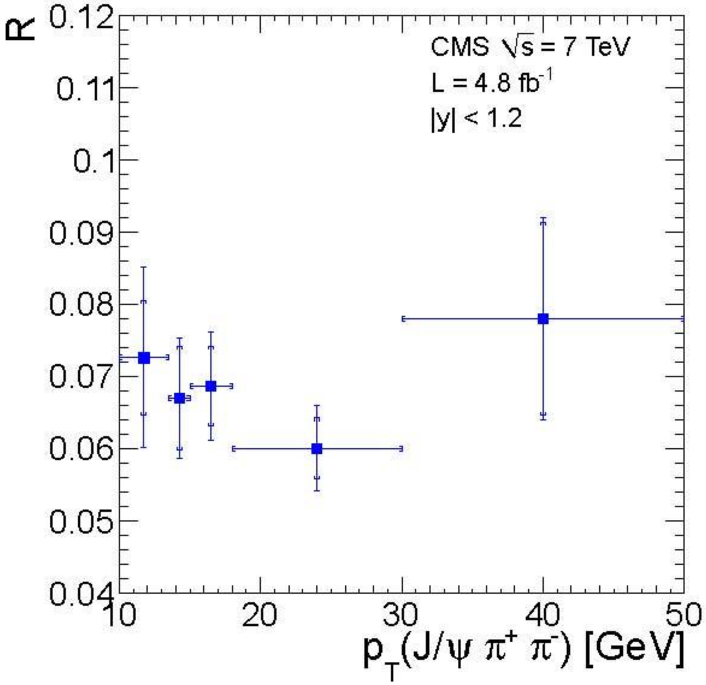
D0 PRL’04

a. $p_T > 15\ \mathrm{GeV}$ b. …



CMS arXiv:1302.3968

Ratio to ψ' is not depend on p_T



Molecule models

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

- X(3872) is a loosely bound state of $D^0\bar{D}^{*0}/\bar{D}^0D^{*0}$
- The mass, J^{PC} and $R_{\rho/\omega}$ …… can be understood naturally.
- The large production rate seems to be questionable

✓ Naively, $\sigma(X) \sim k_0^3,\ k_0 = \sqrt{2\mu_{DD^*}|E_b|} < 40$ 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]

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

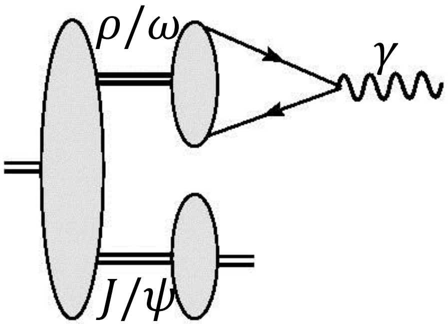
Molecule models

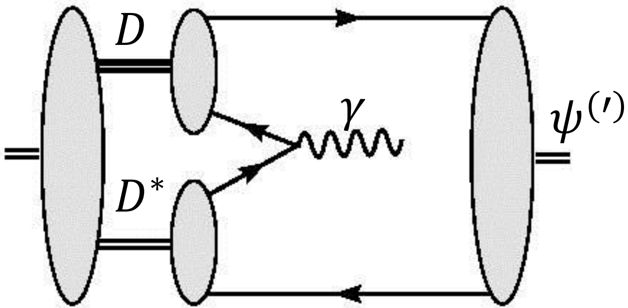
- Decay pattern

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

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

- Radiative decays: [Swanson’04]





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

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

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

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

$\chi_{c1}' - D^0\overline{D}^{*0}$ mixing model

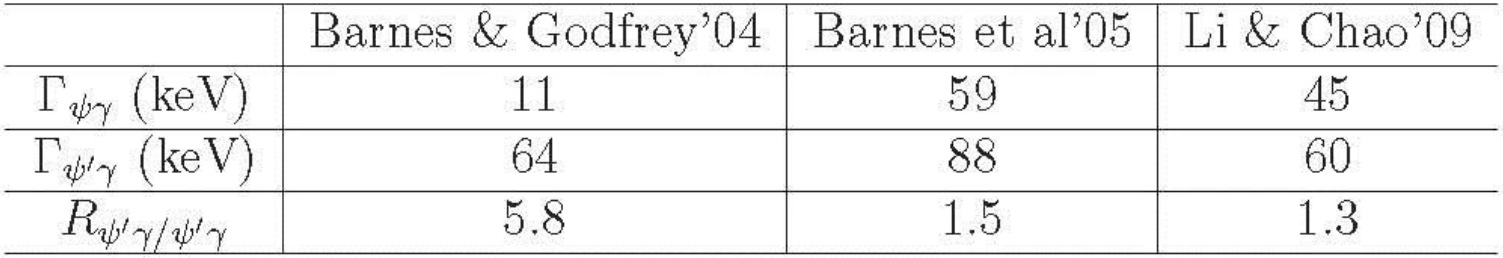
Meng, Gao and Chao, PRD_87_074025 (2013) [hep-ph/0506222]

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

1. The short distance (the b- and $hadro$-) production and the quark annihilation decays of $X(3872)$ proceed dominantly through the χ_{c1}' component.
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 χ_{c1}' in $X(3872)$.

Mixing state: Decay pattern

- χ'_{c1} induced decay modes
  - Radiative decay modes



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

  - Others

$\Gamma(\chi'_{c1} \to LHs) \sim \Gamma(\chi_{c1} \to LHs) \sim$ 1 MeV

$\Gamma(\chi'_{c1} \to \chi_{c1}\pi^+\pi^-) \simeq 1.5$ keV Dubynskiy & Voloshin, PRD'08

be relavant to Chengping's talk

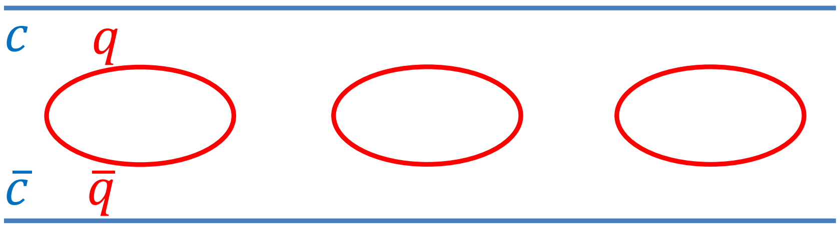
- DD^* induced decay modes

$\Gamma(D^0\bar{D}^0\pi) \sim 0.5\text{-}1\ \mathrm{MeV}$ $\Gamma(J/\psi\rho(\omega)) \sim 50\text{-}100\ \mathrm{keV}$ Meng & Chao'07

Which could not be separated from the LD evolution amplitude, but can be incorporated in fitting the experimental line shapes.

Specrum: Charmonium

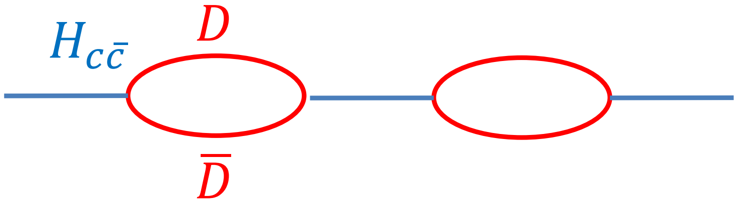
- Quark-level picture



Quark-pairs creation ⇒ Screening the linear potential

⇒ Screened (unquenched) potential model [Chao & Ding & Qin’92]

- Hadron-level picture

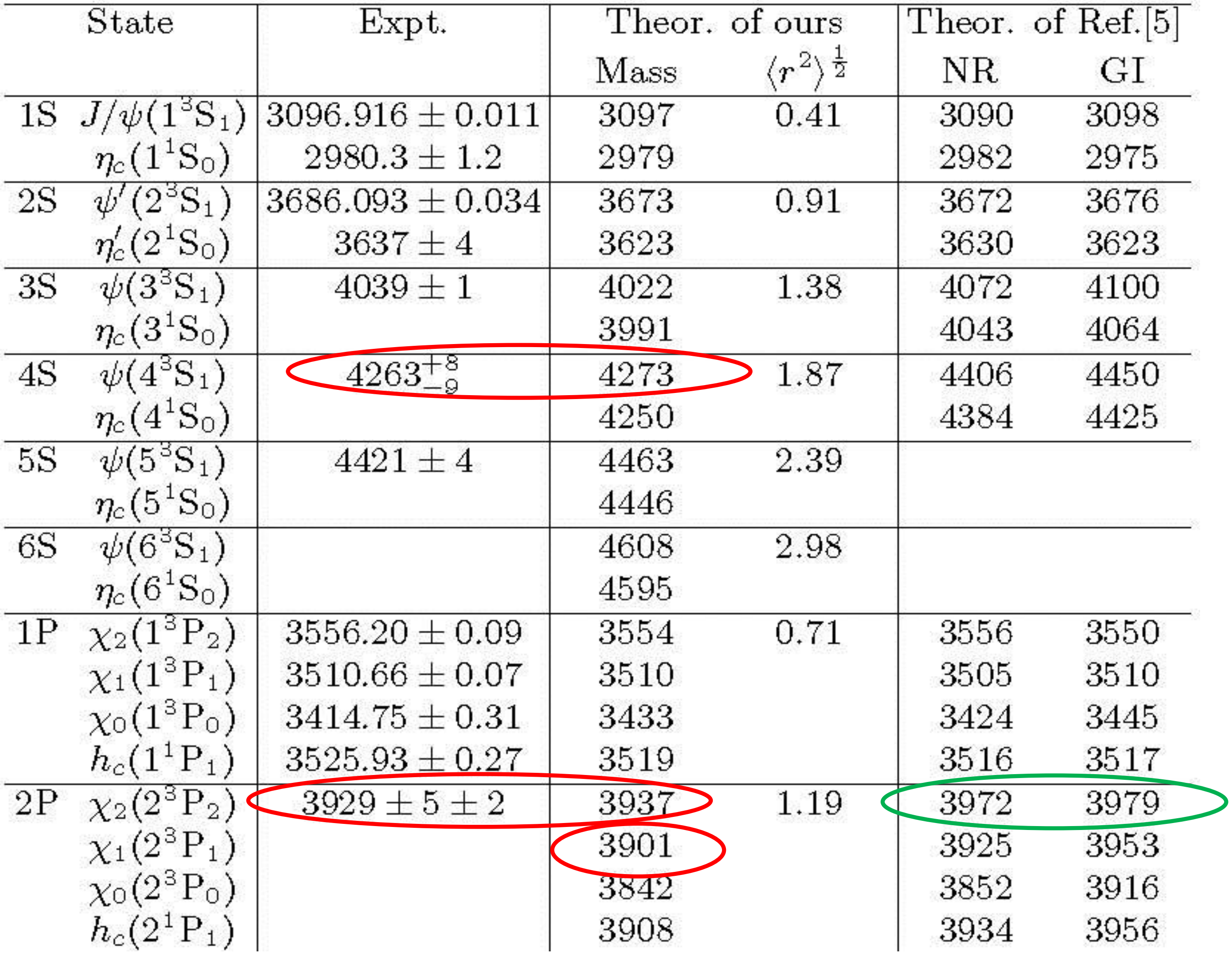


Coupled-Channel models ⇒ mixing between $H_{c\bar{c}}$ and $D\bar{D}$

Which have been considered even in the Cornell model [E. Eichten et al’78].

Specrum: Screened potential model

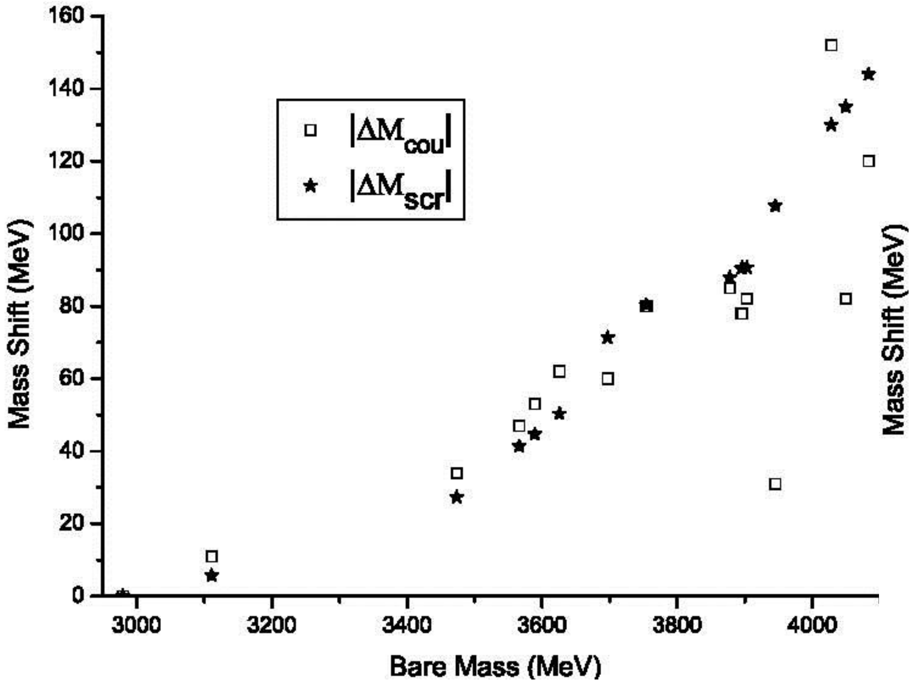
Li & Chao, PRD_79_094004 (2009)

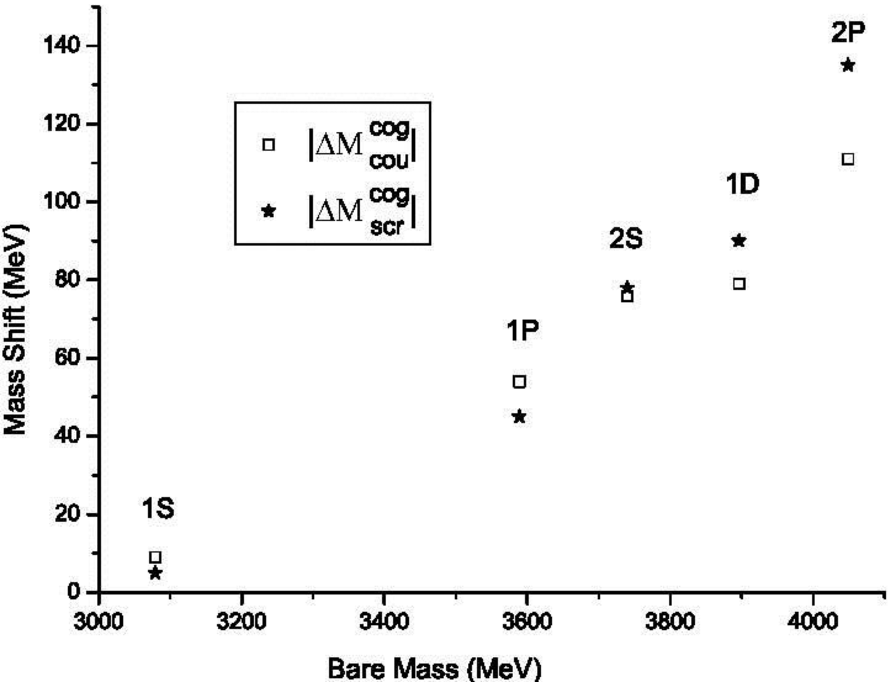


State		Expt.	Theor. of ours		Theor. of Ref.[5]	
			Mass	$\langle r^2\rangle^{\frac{1}{2}}$	NR	GI
1S	$J/\psi(1^3S_1)$	3096.916 ± 0.011	3097	0.41	3090	3098
	$\eta_c(1^1S_0)$	2980.3 ± 1.2	2979		2982	2975
2S	$\psi'(2^3S_1)$	3686.093 ± 0.034	3673	0.91	3672	3676
	$\eta_c'(2^1S_0)$	3637 ± 4	3623		3630	3623
3S	$\psi(3^3S_1)$	4039 ± 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 ± 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 ± 0.09	3554	0.71	3556	3550
	$\chi_1(1^3P_1)$	3510.66 ± 0.07	3510		3505	3510
	$\chi_0(1^3P_0)$	3414.75 ± 0.31	3433		3424	3445
	$h_c(1^1P_1)$	3525.93 ± 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)





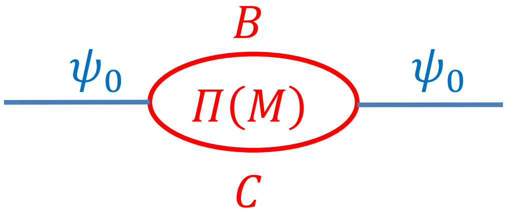
- SPM ≈ CCM in the global features.
- CCM is more adept in investigating the open-charmed threshold effects.

Specrum: S-wave threshold v.s. X(3872)

Li & Meng & Chao, PRD_80_014012 (2009)

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

$$\left|\langle BC, \vec{p}|H_{QPC}|\psi_0\rangle\right|^2 \sim \Gamma(\psi \to BC)$$
$$\sim (M - M_B - M_C)^{\frac{2L+1}{2}}$$

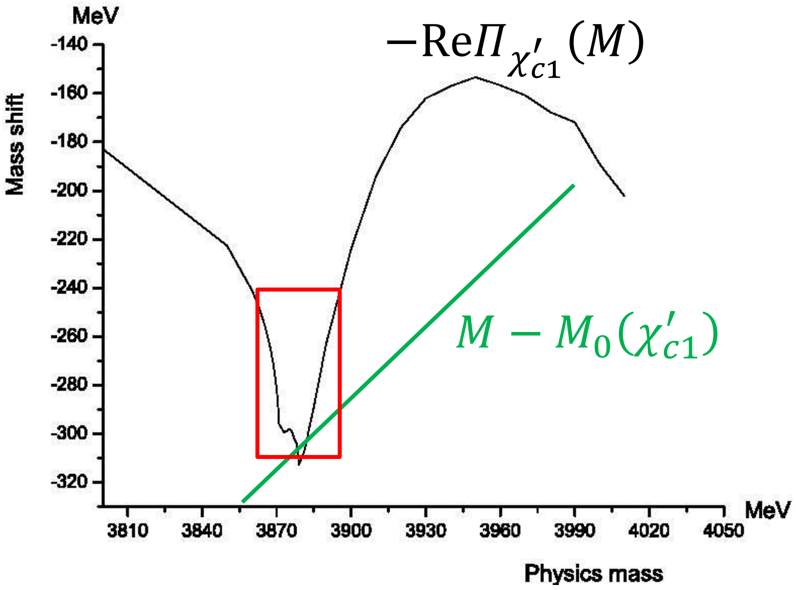


- ➢ S-wave threshold effect: $L = 0 \qquad E = M - M_B - M_C \Rightarrow 0$

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

$\Rightarrow$ S-wave cusp

$\Rightarrow$ “attracting” the mass of the bare state to the threshold



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

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

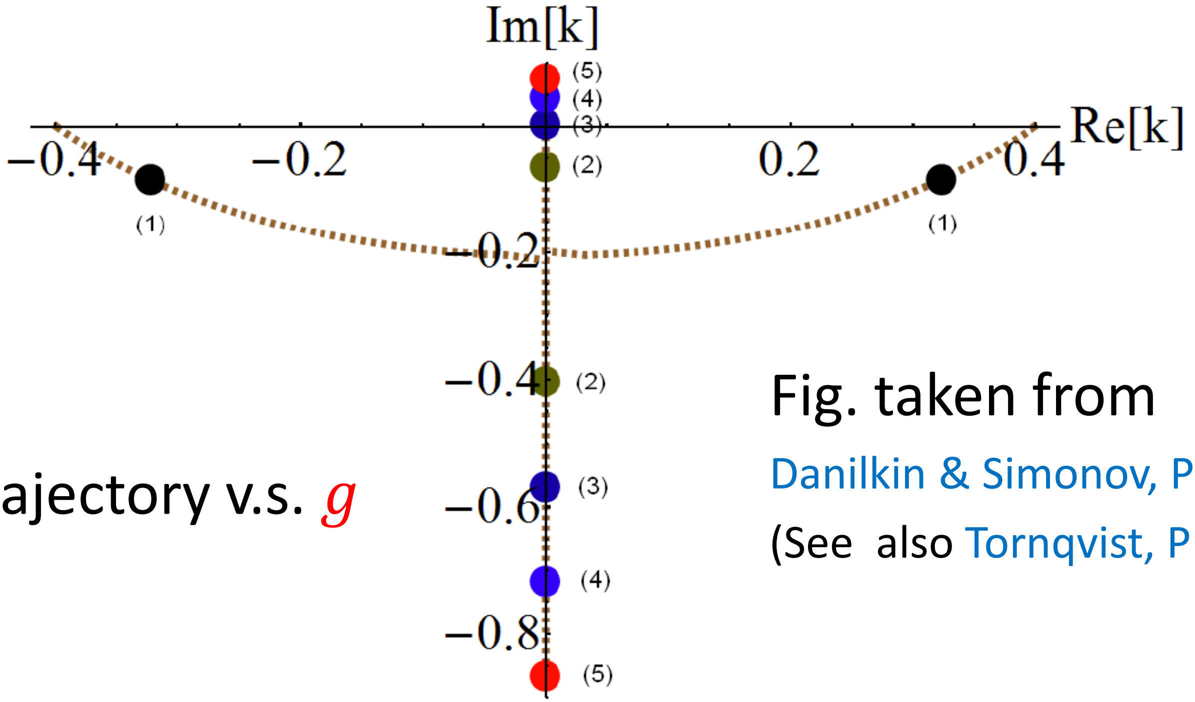
X(3872) in the CCM: Pole Trajectory

- Near-threshold expansion

$$\Pi(E) \approx \Pi(0) + igk(E)/2, \quad k(E) = \sqrt{2\mu E + i0^+}$$

Solving $$E - E_0 + \Pi(0) + igk(E)/2 = 0$$

$$k_\pm = -\frac{ig}{2}\mu \pm \sqrt{-\frac{g^2}{4}\mu^2 - 2\mu(\Pi(0) - E_0 + i0^+)}$$



Pole trajectory v.s. g

Fig. taken from

Danilkin & Simonov, PRL’10

(See also Tornqvist, PRD’95)

X(3872) in the CCM: Pole Trajectory

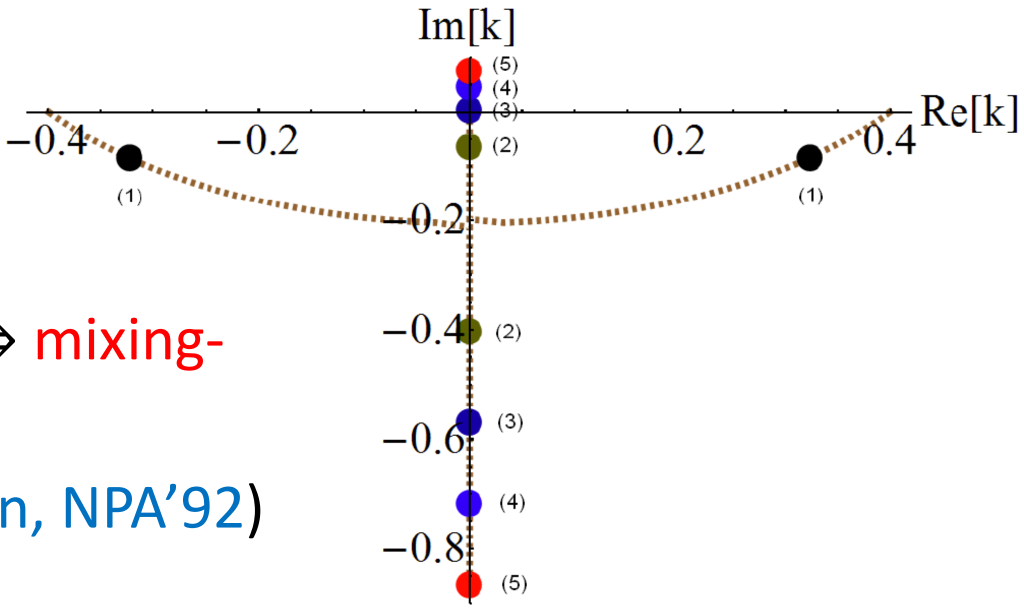
- ➢ Pole trajectory v.s. g
- $g = 0$: bare BW state
- g is fine tuned:

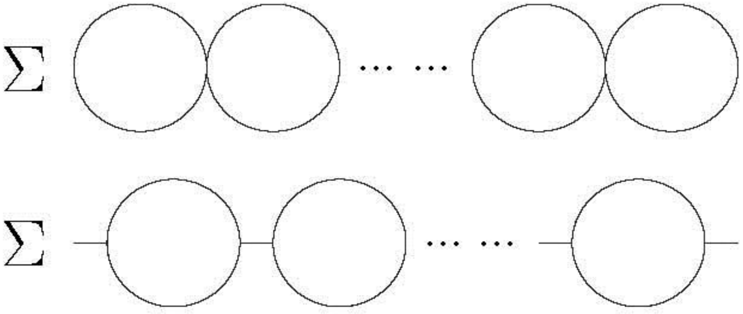
Two near threshold poles ⇔ mixing-induced virtual state

(Pole counting rule   Morgan, NPA'92)

- g is sufficient large:

Bound state ⇔ molecule?





$$\sum \cdots\cdots = \frac{1}{1-L(E)},\ L(E)\sim\sqrt{E}$$

$$\Pi(E) = -g\cdot L(E)$$

$$\sum \cdots\cdots = \frac{1}{E-E_0-g\cdot L(E)}$$

Size of χ'_{c1} in the X(3872)

- For the bound state [Weinberg'65, Baru et al'04]

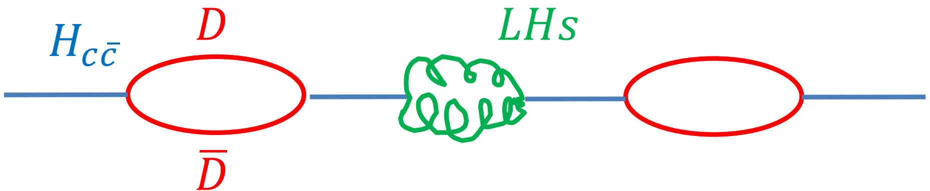
$$Z = \frac{\partial \Pi(E)}{\partial E}\Big|_{E=-\epsilon} \approx \frac{1}{1+\frac{g}{2\sqrt{2}}\sqrt{\mu/\epsilon}} \xrightarrow{\epsilon\to 0} 0!$$

$$g_R = Z \cdot g = 2\sqrt{2}\sqrt{\epsilon/\mu}\,(1-z)$$ see Fengkun's and Qian's talks

spectrum density: $w(E) = \frac{gk/2\pi}{|E-E_0+\Pi(E)|^2}$

spectrum sum rule: $Z + \int_0^\infty w(E)dE = 1$ [Baru et al'10]

- Inelastic decay modes:



$$\Gamma_0 \sim 1MeV \sim \epsilon$$

- Generalized spectrum density:

$$w(E) = \frac{(gk+\Gamma_0)/2\pi}{|E-E_0+\Pi(E)+i\Gamma_0/2|^2}, \quad Z = \int_{-\Delta E}^{+\Delta E} w(E)dE$$

Γ_0 may make the X spending more time in the short distant $\bar{c}c$ configuration [Li & Meng & Chao, in progress]

Scattering amplitude

- Coupled-channel amplitude

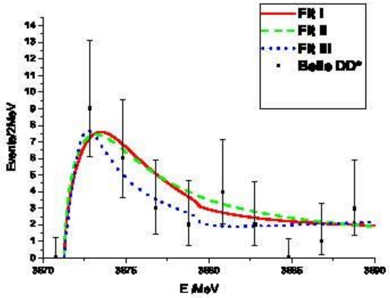
$$F(E) = \frac{g/2}{E - E_0 + \Pi(0) + igk(E)/2 + i\Gamma(E)/2 + i\Gamma_0/2}$$

- Fitting the experimental line-shapes:
  - Vitual state poles are favored [Hanhart et al'07]
  - With nonzero Γ_0, two near threshold poles are favored [Zhang & Meng & Zheng'09]
  - With $\Gamma_0 = 1 \sim 2$ MeV [Kalashnikova & Nefediev'09]

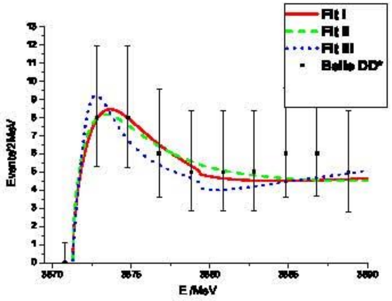
$$Z = \int_{-10\ \mathrm{MeV}}^{+10\ \mathrm{Me}V} w(E)dE = 0.3 \sim 0.5$$

Scattering amplitude v.s. line shape

Meng & Sanz-Cillero & Shi & Yao & Zheng, in preparation



(a)



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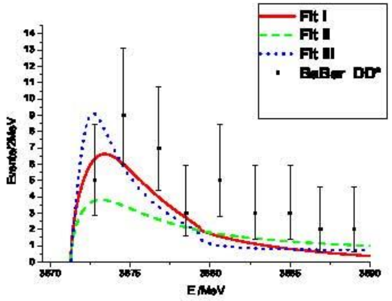

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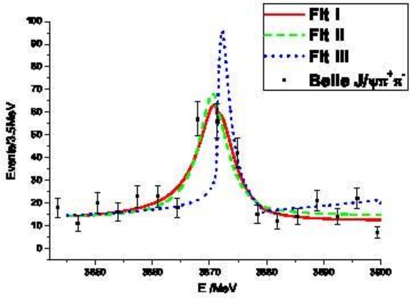

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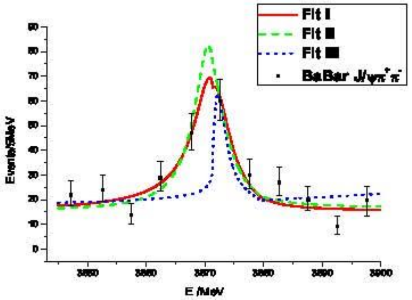


(e)

	Fit I	Fit II	Fit III
Amplitudes	C.C. + B.C.	Coupled-channel	Bubble chain
$\chi^2/d.o.f.$	44.1/42	49.7/43	83.3/46

Production of X(3872)

General factorization formula

- Energy scales:

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

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

- Factorization I:

$$\sigma\big(X(J/\psi\pi^+\pi^-)\big) = \sigma(\chi'_{c1}) \cdot k, \qquad k = Z_{c\bar{c}}\mathrm{Br}_0$$

- Factorization II: NRQCD Bodwin & Braaten & Lepage'95

$$d\sigma(\chi'_{c1}) = \sum_n d\hat{\sigma}\big((c\bar{c})_n\big) \frac{\left\langle O_n^{\chi'_{c1}} \right\rangle}{m_c^{2L_n}}$$

$n = {}^3P_1^{[1]}$ & ${}^3S_1^{[8]}$ at leading order in v for χ'_{c1} production

Production in B decays

- Theory: [Meng, Gao and Chao, PRD_87_074025 (2013) [hep-ph/0506222]]

  Input: $|R'_{2P}(0)|^2 = |R'_{1P}(0)|^2 = 0.075\ \mathrm{GeV}^5$

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

$$\mathrm{Br}(B \to \chi'_{c1} K) = (2 \sim 4) \times 10^{-4}$$

- Fits: [Kalashnikova & Nefediev PRD'09]

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

- Experimental data:

$$\mathrm{Br}(B \to X(J/\psi \pi^+ \pi^-) K) = \mathrm{Br}(B \to \chi'_{c1} K) \cdot k$$

$$= (8.6 \pm 0.8) \times 10^{-6}$$ PDG'12

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

✓ With a modest value $\mathrm{Br}_0 = 5\%$ $\in (2.6\%\text{–}9\%)$

$$Z_{c\bar{c}} = 28\%\text{–}44 \qquad (Z^{\mathrm{fit}} = 0.3 \sim 0.5$$ Kalashnikova'09)

Production in B decays

- Comparing with exparamental data:

Input:$\mathrm{Br}(B \to \chi'_{c1} K) = \mathrm{Br}_{\mathrm{PDG}}(B \to \chi_{c1} K), \quad k = 0.18$

$\mathrm{Br_i} \cdot \mathrm{Br_0} \cdot 10^6$ $i =$	**Predictions**	**data**	
$B^+ \to XK^+$	8.6 ± 0.4	8.6 ± 0.8	PDG'12
$B^0 \to XK^0$	7.1 ± 0.5	4.4 ± 1.3	PDG'12
$B^+ \to XK^{*+}$	5.4 ± 1.0		
$B^0 \to XK^+\pi^-$	6.8 ± 0.7	8.5 ± 1.3	Chenping's talk
$B^0 \to XK^{*0}$	4.0 ± 0.7	3.7 ± 1.0 $Br(K^{*0} \to K^+\pi^-) = 2/3$	Chenping's talk

Production at hadron collider

- NRQCD Factorization: [Bodwin & Braaten & Lepage'95]

$$d\sigma(pp \to \chi'_{c1}) = \sum_n d\hat{\sigma}\left((c\bar{c})_n\right) \frac{\left\langle O_n^{\chi'_{c1}} \right\rangle}{m_c^{2L_n}}$$

$$= \sum_{i,j,n} \int dx_1 dx_2 G_{i/p} G_{j/p}\, d\hat{\sigma}(ij \to (c\bar{c})_n) \left\langle O_n^{\chi'_{c1}} \right\rangle$$

$n = {}^3P_1^{[1]}$ & ${}^3S_1^{[8]}$ at leading order in v for χ'_{c1} production

➢ Molecule model : Artoisenet & Braaten, PRD'09

$$d\sigma(pp \to X_{D^0\bar{D}^{*0}}) = d\hat{\sigma}\left(c\bar{c}\left[{}^3S_1^{[8]}\right]\right) \left\langle O_{{}^3S_1^{[8]}}^{D^0\bar{D}^{*0}} \right\rangle$$

✓ Different long distant matrix elements

✓ Different combination of the $c\bar{c}$ channels

✓ One can compare the two models with the help of the CMS data on the pT distribution!

Production at hadron collider

Meng & Han & Chao, arXiv:1304.6710

- NLO calculations:

- Inputs: Ma & Wang & Chao'11 (MWC'11)

$$\mu_r = \mu_f = m_T = \sqrt{p_T^2 + 4m_c^2}, \qquad \mu_{NR} = m_c = 1.5 \pm 0.1 \text{ GeV}$$

$$|R'_{2P}(0)|^2 = |R'_{1P}(0)|^2 = 0.075 \text{ GeV}^5$$

- To compare our following results with the available ones for χ_{c1} production [MWC'11], we parameterize the matrix elements as

$$r = m_c^2 \left\langle O^{\chi'_{c1}}_{{}^3S_1^{[8]}} \right\rangle / \left\langle O^{\chi'_{c1}}_{{}^3P_1^{[1]}} \right\rangle \qquad (r_{1P} = 0.27 \pm 0.06, \text{ MWC'11})$$

- The cross section in the χ'_{c1} production mechanism is a simple function of r, k and p_T

Fit to the CMS p_T distribution

Meng & Han & Chao, arXiv:1304.6710

- χ'_{c1} production mechanism:

$$r = 0.26 \pm 0.07, \qquad k = 0.014 \pm 0.006$$

- The central values correspond $\chi^2/2 = 0.26$
- The value of r_{2P} for χ'_{c1} is almost the same as that for $\chi_{c1}(1P)$:

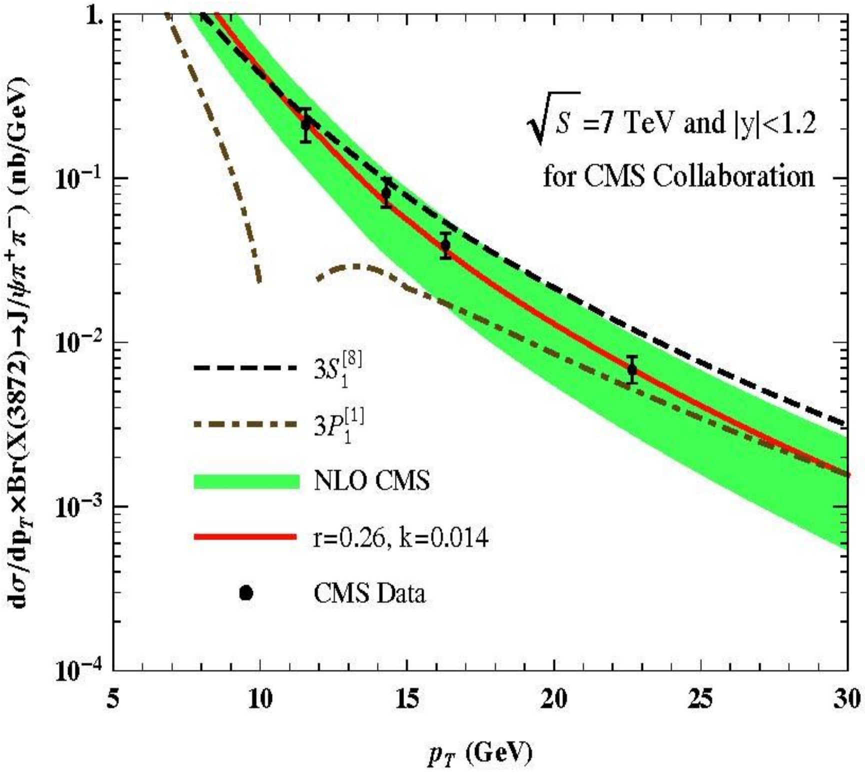
$$r_{1P} = 0.27 \pm 0.06 \text{ [MWC'11]}$$

which strongly suggests that X(3872) be produced through its χ'_{c1} component at short distance

- Molecule production mechanism:

$$\left\langle O^{D^0\bar{D}^{*0}}_{^3S_1^{[8]}} \right\rangle \mathrm{Br}_0 = (6.0 \pm 0.6)10^{-5}\ \mathrm{GeV}^3$$

$$\chi^2/3 = 1.03$$



Predictions v.s. CDF/LHCb data

Meng & Han & Chao, arXiv:1304.6710

Inputs: $r = 0.26,\ k = 0.014;\ \left\langle O_{^3S_1^{[8]}}^{D^0\bar{D}^{*0}} \right\rangle \mathrm{Br}_0 = 6.0 \times 10^{-5}\ \mathrm{GeV}^3$

	Data	χ'_{c1} mechanism	molecule
σ_{CMS}/nb	1.06 ± 0.19	$1.09^{+0.08}_{-0.12}$	0.89 ± 0.09
σ_{CDF}/nb	3.1 ± 0.7	2.5 ± 0.7	1.1 ± 0.4
σ_{LHCb}/nb	$(5.4 \pm 1.4) \cdot 0.8$	9.4 ± 2.2	4.0 ± 1.3

- CMS + CDF data favor the χ'_{c1} production mechanism
  - Same forward rapidity region
  - Almost same gluon energy: $\sqrt{s} = \sqrt{x_1 x_2 S} \sim 2P_T$
  - ✓ Test the universality and the evolution of the gluon PDF
- CMS + LHCb data favor the molecule production mechanism
  - less meaningful since the predicted pT distribution at CMS is almost inconsistent with the data.

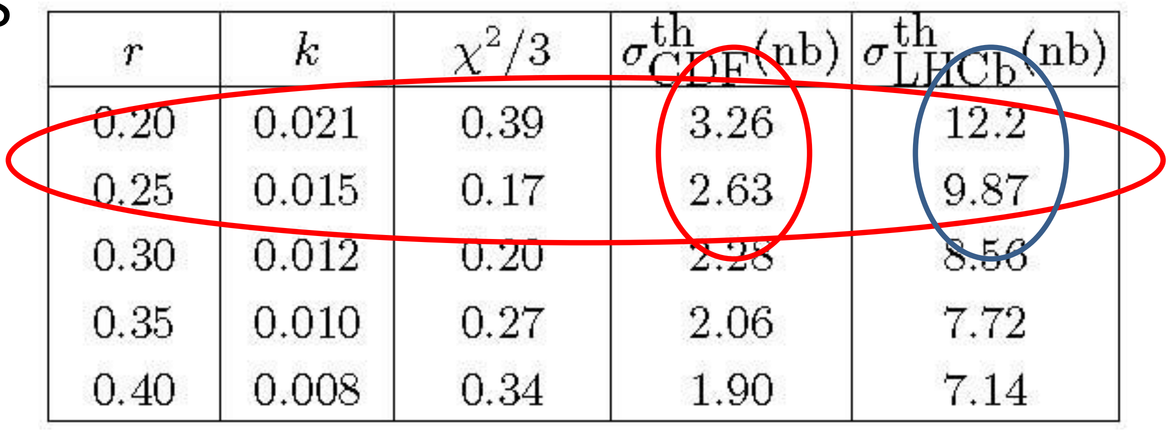
Single parameter fit

- Fitting k to the CMS data with fixed r

  $(3.1 \pm 0.7\ \mathrm{nb})^{\mathrm{ex}}_{\mathrm{CDF}}$

  $(5.4 \pm 1.4\ \mathrm{nb})^{\mathrm{ex}}_{\mathrm{LHCb}} \cdot 80\%$
- Fitting k to B decay data

Kalashnikova & Nefediev PRD'09



r	k	$\chi^2/3$	$\sigma^{\mathrm{th}}_{\mathrm{CDF}}(\mathrm{nb})$	$\sigma^{\mathrm{th}}_{\mathrm{LHCb}}(\mathrm{nb})$
0.20	0.021	0.39	3.26	12.2
0.25	0.015	0.17	2.63	9.87
0.30	0.012	0.20	2.28	8.56
0.35	0.010	0.27	2.06	7.72
0.40	0.008	0.34	1.90	7.14

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

- ✓ Window in the table: $r = 0.20\text{-}0.26$
- ✓ The consistency of the CDF data with our prediction is better, but that for the LHCb data is worse.
- Similar results were obtained in [Butenschoen & He & Kniehl, arXiv: 1303.6524v2]

Production in e^+e^- annihilation

- $e^+e^- \to \gamma X \ (X = \eta_c, \chi_{cJ} \dots\dots)$
- NLO at $\sqrt{S} = 10.6$ GeV: Li & He & Chao'09

$$\sigma(e^+e^- \to \gamma\chi'_{c1}) = 18\ \text{fb}$$

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

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

- NLO at $\sqrt{S} = 4 - 5$ GeV: $\sigma \sim 1/S^2$

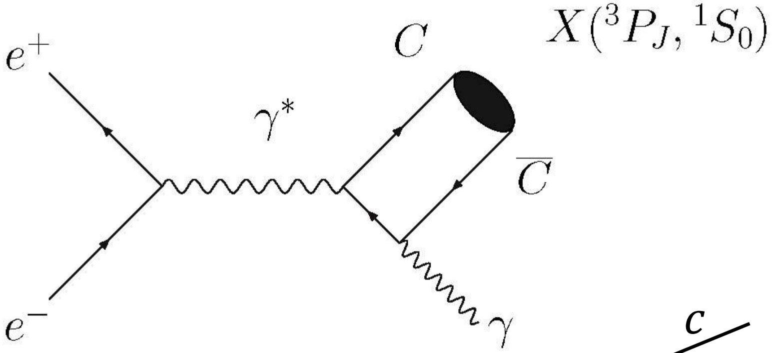
✍ Chao & He & Li & Meng, arXiv: 1310.8597

  - $m_c = 1.5\ \text{GeV}$

✍ Li & Xu &Liu & Zhang, arXiv: 1310.0374 (see Guangzhi's talk)

  - $m_c = M_X/2$
  - Relativistic corrections are included

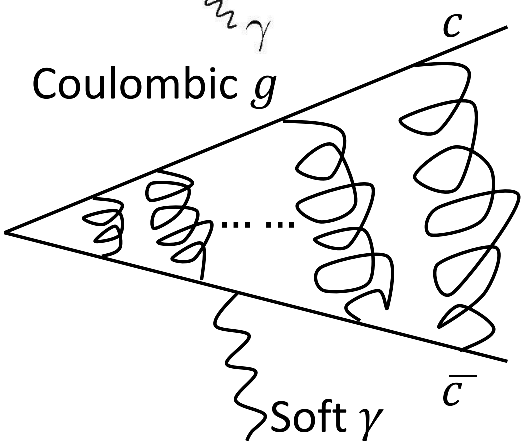
Production in e^+e^- annihilation



- LO (pure QED process)

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

$\Rightarrow$ near-threshold singularity



- QCD pollution in the near-threshold region

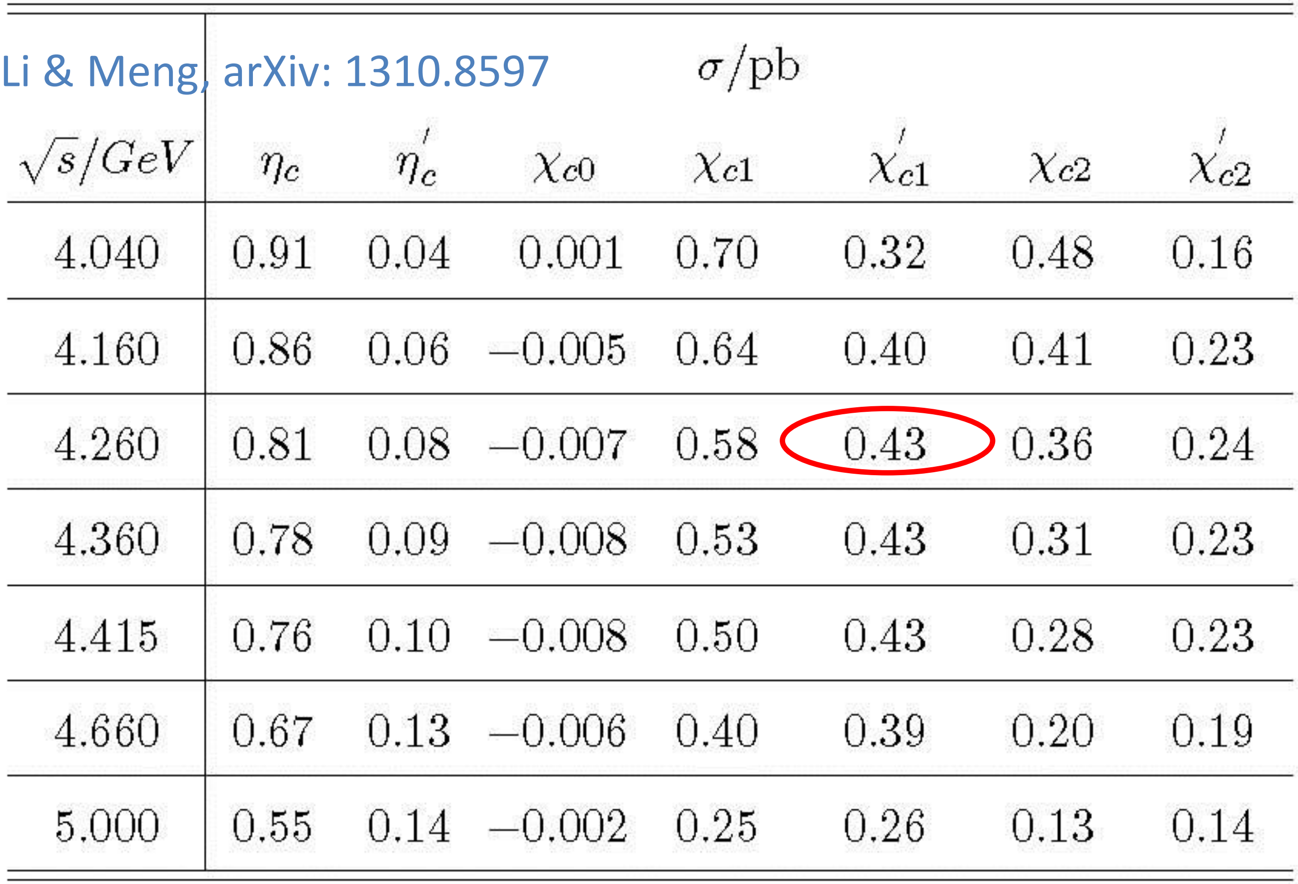
The Coulombic gluons need to be resummed

$\Rightarrow$ E1 transitions of resonances

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

Production in e^+e^- annihilation

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

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

Resonance contributions should be dominant!

E1 transitions of higher chamonia

Li & Meng & Chao, arXiv: 1201.4155

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

- 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

$\Gamma(\mathbf{keV})$	$\psi_{3S}(4040)$	$\psi_{2D}(4160)$	$\psi_{4S}(4260)$
$\chi'_{c2}(3930)$	56	9.2	15
$\chi'_{c1}(3872)$	88	189	88

- $\mathrm{Br}(\psi_{4S} \to \gamma X[J/\psi\pi\pi]) \sim \mathrm{Br}(\psi_{4S} \to \gamma\chi'_{c1}) \cdot k \sim 1.6 \times 10^{-5}$

$$\frac{Br(Y\to\gamma X[J/\psi\pi\pi])}{Br(Y\to J/\psi\pi\pi)} \sim 5.7 \times 10^{-3}$$

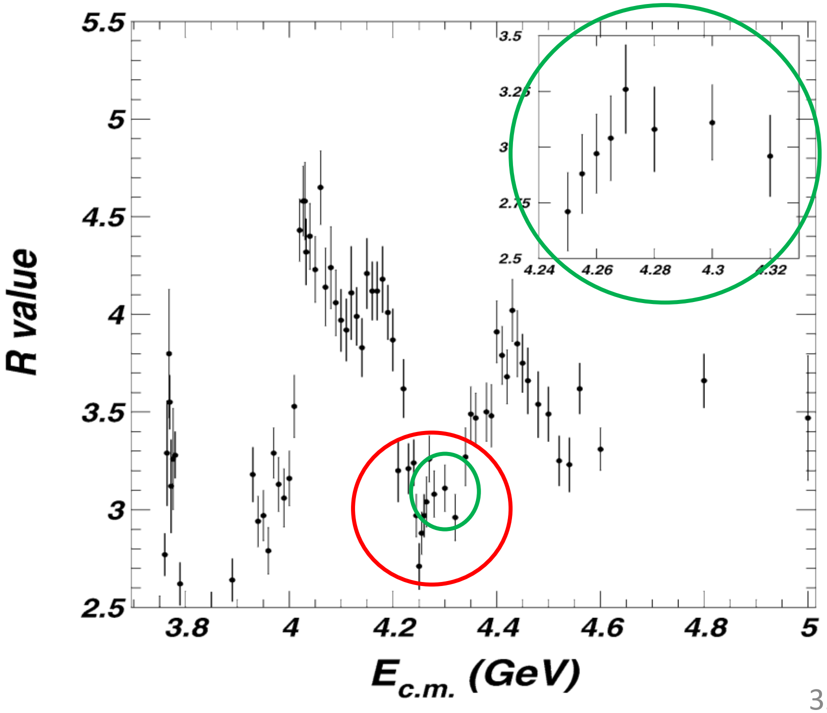
see Zhiqing's talk

$$\Gamma_{\mathrm{ee}} \cdot Br(Y \to J/\psi\pi\pi) \sim 6\ \mathrm{eV} \quad \Rightarrow \quad \text{Need } \Gamma_{\mathrm{ee}} \sim 2\ \mathrm{keV!}$$

- Same value is also needed for the molecule model. see Fengkun's talk

$\Gamma_{\mathrm{ee}}(4260)$

- ψ_{4S}: 970 eV [Li & Chao, PRD'09]
- Hybrid: 25(20) eV   See Ying's talk
- Fitting the line-shape ($e^+e^- \to Y(4260) \to J/\psi\pi^+\pi^-$):
  1. Dai & Shi & Tang & Zheng'12: 211 eV (without Γ_0)
  2. Cleven et al'13 (see Qian's talk): several tens eV (private communication)
- Fitting R-value: Mo et al'06
  - $\Gamma_{\mathrm{ee}} < 580$ eV
  - Ignoring the dip structure
  - Relative phases between different resonances are important!



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

Li & Meng & Chao, in preparation

- Amplitude

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

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

$$\sigma(e^+e^- \to \gamma X(3872)[J/\psi\,\pi\pi]) = k\cdot|A|^2$$

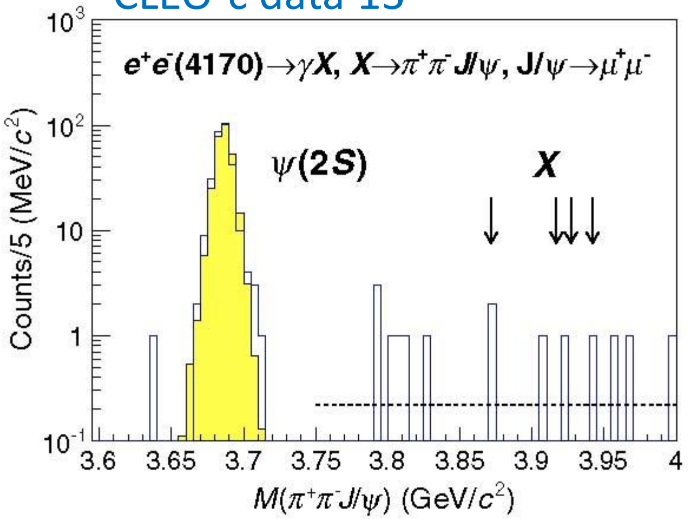
- Inputs:

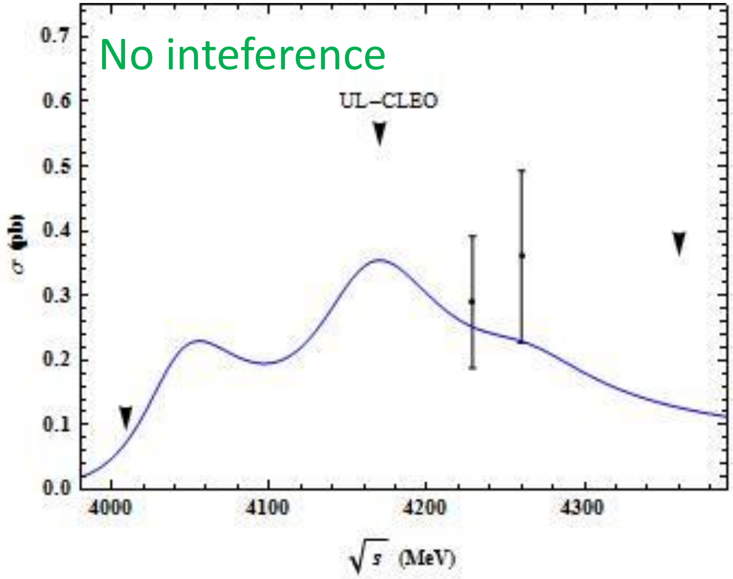
i	m_i/MeV	Γ^i_{tot}/MeV	Γ^i_{ee}/keV
1	4260	100	0.5
2	4160	100	0.83
3	4040	80	0.86

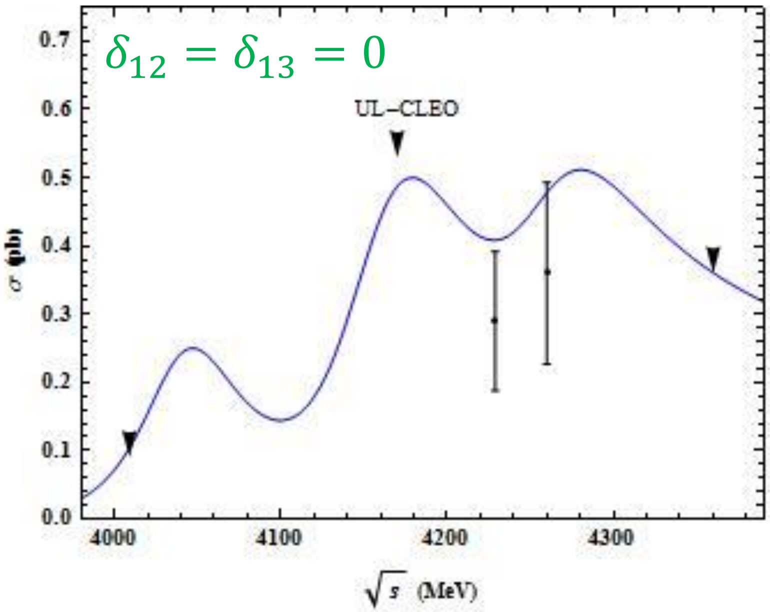
$e^+e^- \to \psi^n \to \gamma X(3872)$

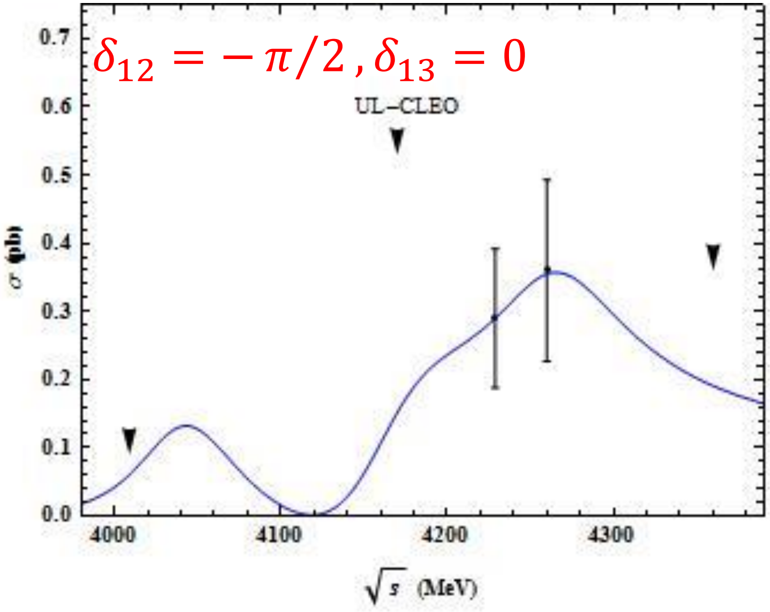
Li & Meng & Chao, in preparation

CLEO-c data'13




No inteference


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


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

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

Li & Meng & Chao, in preparation

- What are indicated?
  - $\sigma > 0.15\ \mathrm{pb}\ @\ 4170\ \mathrm{MeV}$
  - $\sigma(e^+e^- \to \gamma Z(3930)) \sim 50\ \mathrm{pb}\ @\ 4060\ \mathrm{MeV}$
  - Contributions from the DD^* component may also be important especially at 4260 MeV[see Fengkun'talk]

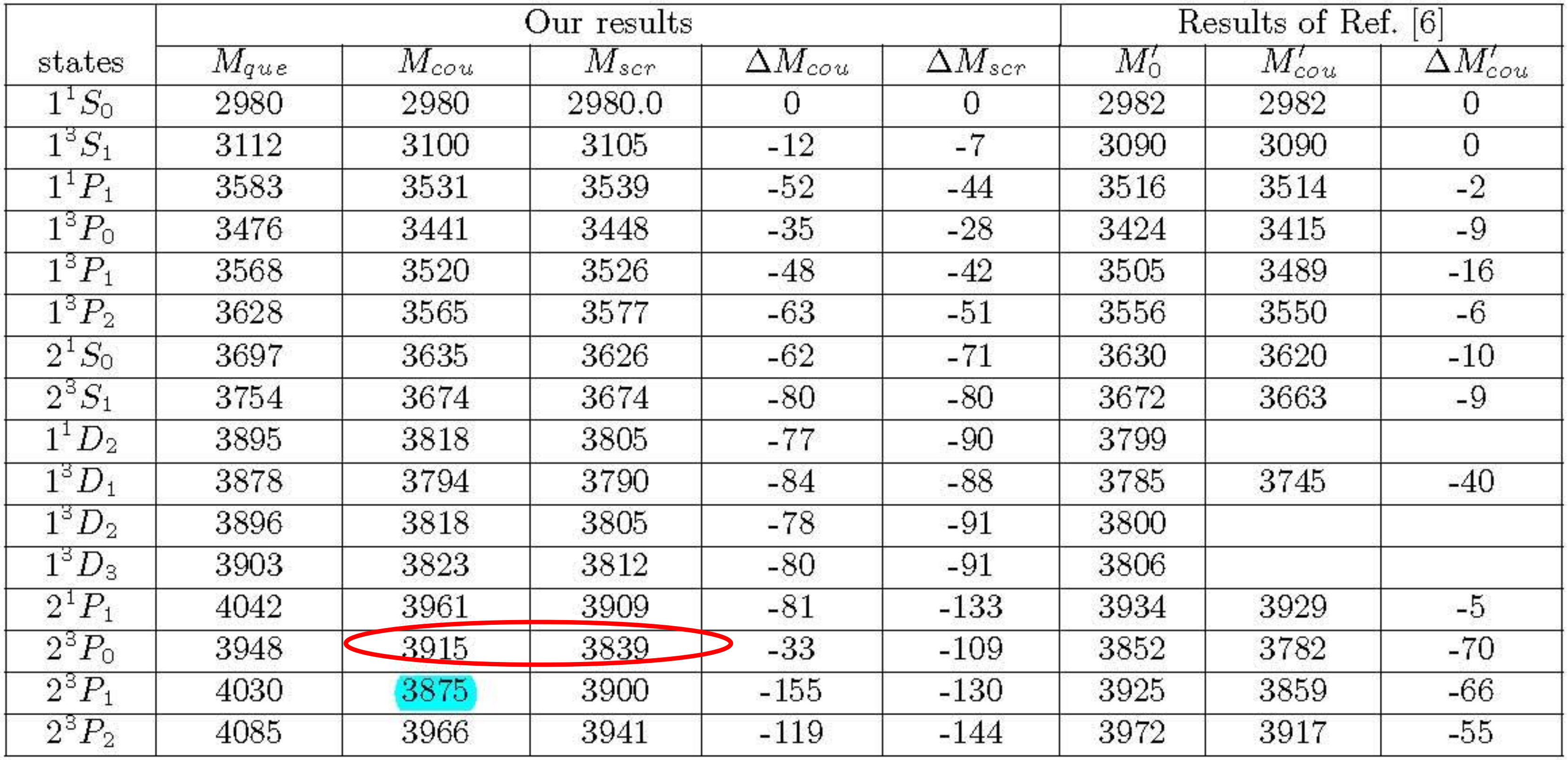
Summary

- With $Z_{c\bar{c}} = 0.3\text{-}0.5$, X(3872) could be understood in the mixing model:
  - Decay pattern ($X \to \gamma\psi'$ need to be confirmed)
  - Closeness to the threshold (S-wave threshold effect).
  - Experimental line-shapes
  - Large production rate
    - ✓ B-production
    - ✓ Hadro-production
    - ✓ E1 production (hadron-loop contributions need to be clarified)
- More efforts (th. & ex.) are needed to study X and YZ @ BESIII.
  - Resonance parameters and relative phases
  - Line-shapes scanning
  - Continue $DD, DD\pi, \pi Z_c$, … …

BackUp

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 3850 MeV

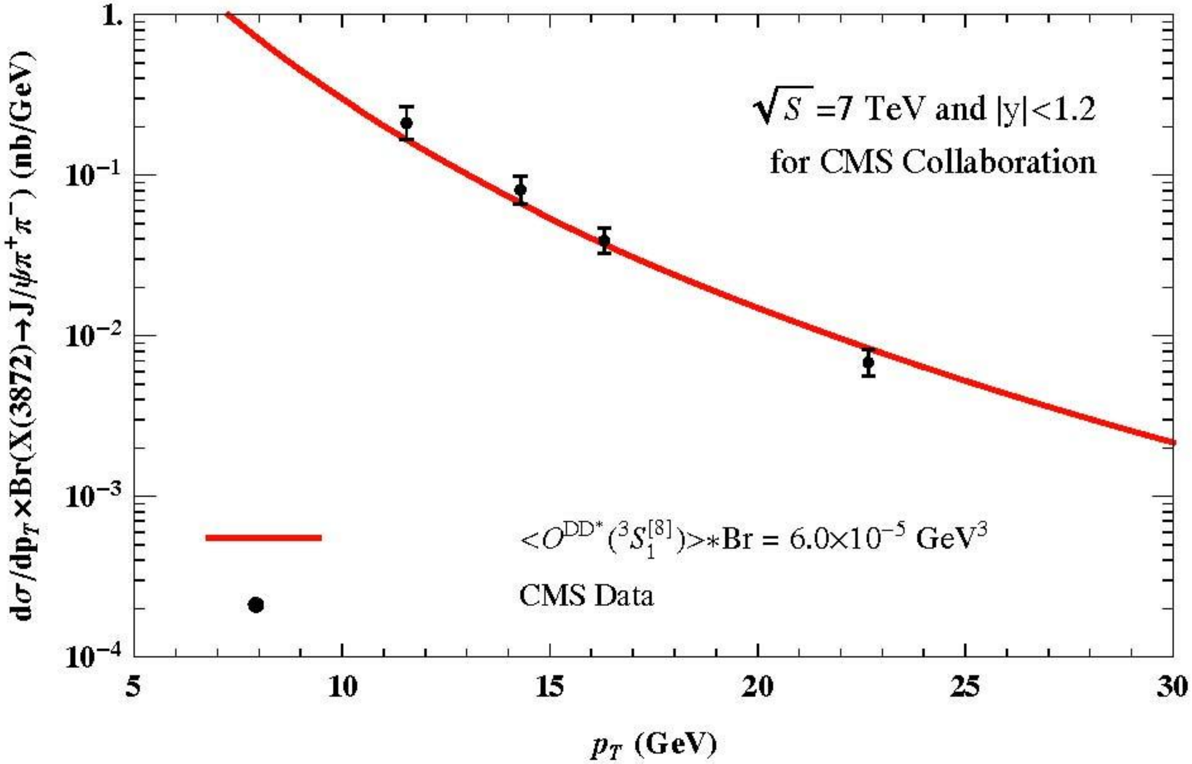
Fit to the CMS p_T data

$$\sqrt{S} = 7\ \text{TeV}, \qquad |y| < 1.2, \qquad 10\ \text{GeV} < p_T < 30\ \text{GeV}$$

- Molecule production mechanism:

$$\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[8]}} \right\rangle \text{Br}_0 = (6.0 \pm 0.6)10^{-5}\ \text{GeV}^3$$

$$\chi^2/3 = 1.03$$



Predictions v.s. CDF data

$\sqrt{S} = 1.96\ \mathrm{TeV}, \qquad |y| < 0.6, \qquad p_{\mathrm{T}} > 5\ \mathrm{GeV}$

- χ'_{c1} production mechanism:

  Inputs: $r = 0.26,\ k = 0.014$

  $\sigma^{\mathrm{th}}_{\mathrm{CDF}}\left(p\bar{p} \to X(J/\psi\pi^+\pi^-)\right) = 2.5 \pm 0.7\ \mathrm{nb} \quad (v.s.\ (3.1 \pm 0.7\ \mathrm{nb})_{\mathrm{ex}})$

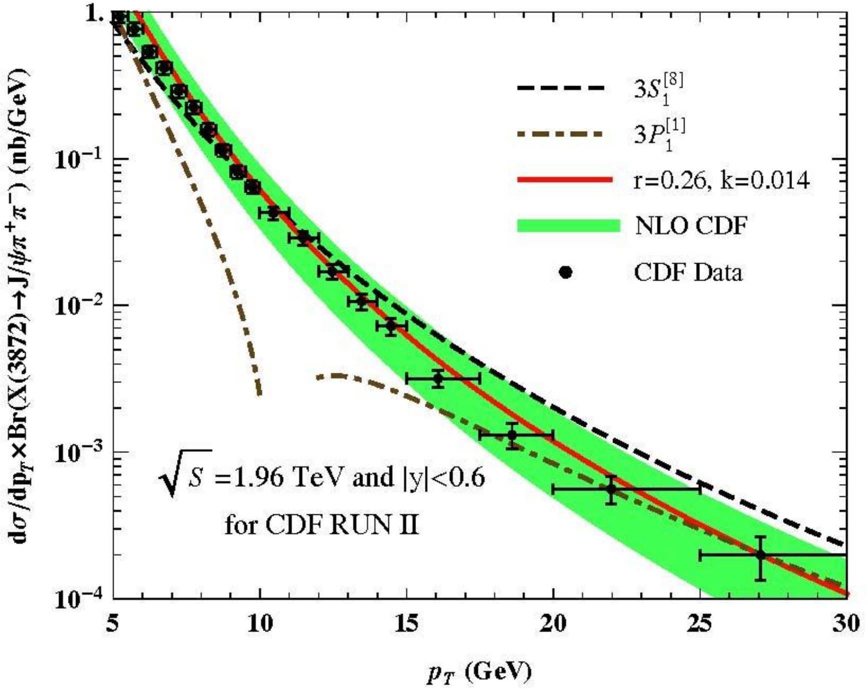
  The predicted p_T distribution of $X(3872)$ is compared with that of ψ' [CDF, PRD'09] (see the diagram)

- Molecule production mechanism:

  $\sigma^{\mathrm{molecule}}_{\mathrm{CDF}} = 1.1 \pm 0.4\ \mathrm{nb}$

  $2.6\ \sigma$ deviation from data

- Both the CMS and the CDF data favor the χ'_{c1} production mechanism, but a little bit disfavor the molecule production mechanism.

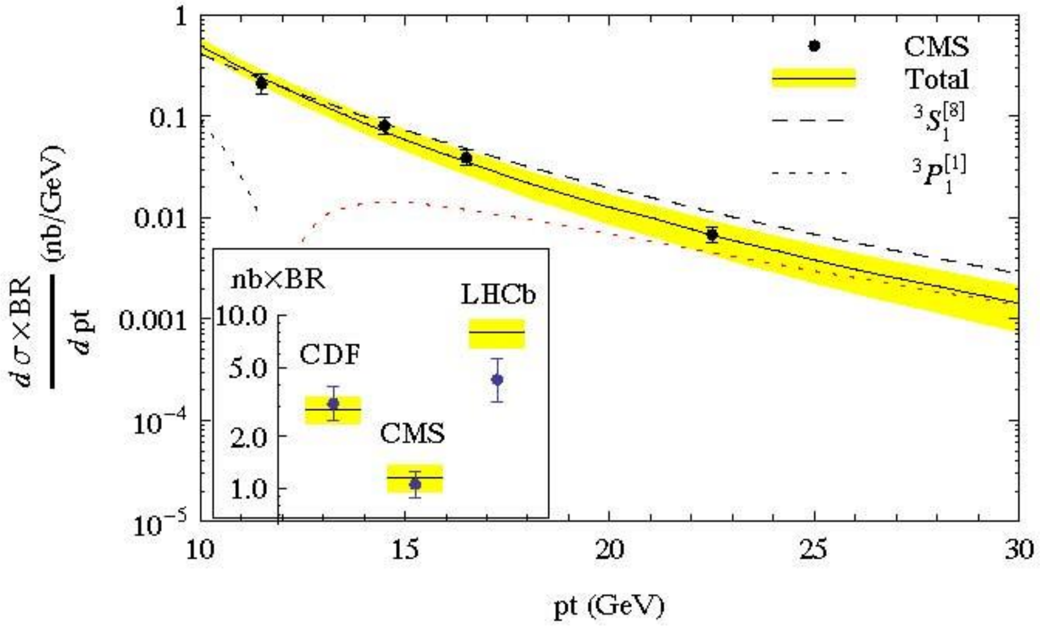


Comparison with arXiv: 1303.6524

- Butenschoen & He & Kniehl, arXiv: 1303.6524v1:

  Set IV: fit two matrix elements to both the CMS and CDF data

	Input	**Fit values**		**Predictions**	
	$\vert R'_{2P}(0)\vert^2/\mathrm{GeV}^5$	$r \times 10^2$	$k \times 10^3$	$\sigma^{\mathrm{th}}_{\mathrm{CDF}}/\mathrm{nb}$	$\sigma^{\mathrm{th}}_{\mathrm{LHCb}}/\mathrm{nb}$
BHK/set IV	0.102	24 ± 4	11 ± 5	2.9 ± 0.5	8.0 ± 1.5
Ours	0.075	26 ± 4	14 ± 6	2.5 ± 0.7	9.4 ± 2.5



Only stress that the X(3872) could not be a pure χ'_{c1} state