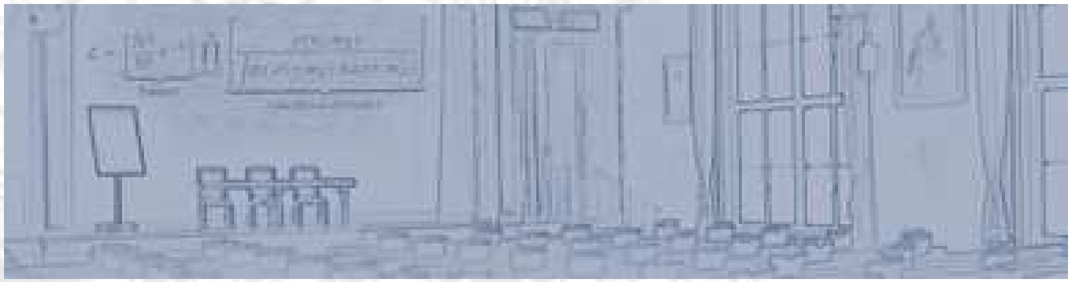
Molecular effects in Charmonium Spectrum



Hadron 2011

Munich, June 2011

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Measured Properties of $X(3872)$

- **Quantum Numbers compatible with** $J^{PC} = 1^{++}$ **(strongly preferred by the data) and** $J^{PC} = 2^{-+}$**.**
- **Width :** $\Gamma < 2{,}3 MeV$
- **Mass :** $M_X = 3871{,}61 \pm 0{,}16 \pm 0{,}19\ MeV/c^2$ $\rightarrow$ **below** $D^0 D^{*0}$ **mass threshold of** $3871{,}80 \pm 0{,}35\ MeV/c^2$
- $\frac{\mathcal{B}(X \to J/\psi \pi^+ \pi^- \pi^0)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 1{,}0 \pm 0{,}5,$
- $\frac{\mathcal{B}(X \to J/\psi \gamma)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 0{,}33 \pm 0{,}12,$ $\frac{\mathcal{B}(X \to \psi(2S) \gamma)}{\mathcal{B}(X \to J/\psi \gamma)} < 2{,}1$
- $\frac{\mathcal{B}(X \to \psi(2S) \gamma)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 1{,}1 \pm 0{,}4.$

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Charmonium - Too heavy for a 1D charmonium state and too light for a 2P one.

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Other - Tetraquarks, glueballs, diquark clusters, hybrids,... are other possible explanations.

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Molecule - Most popular explanation, but troubles to explain the radiative decay rates.

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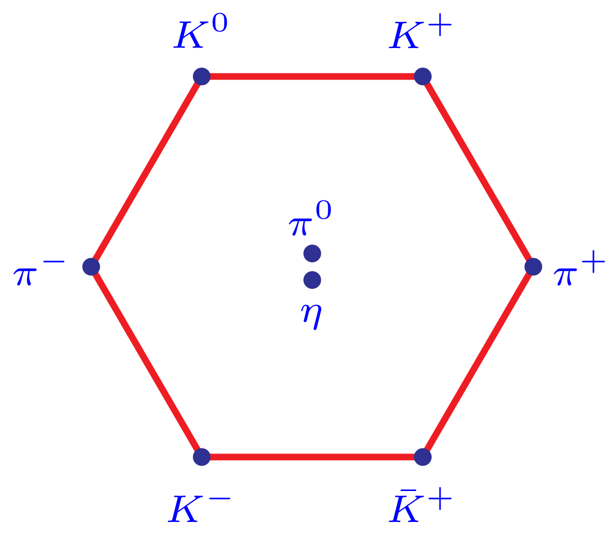
Experimental data suggest a weakly-bound DD^* molecule coupled to a $2P$ $c\bar{c}$ state.

The Constituent Quark Model

- Spontaneous Chiral Symmetry Breaking $\longrightarrow$
  - $\longrightarrow$ Constituent quark mass
  - $\longrightarrow$ Golstone bosons



$$\mathcal{M} = \bar{\Psi}(i\gamma^{\mu}\partial_{\mu} - MU^{\gamma_5})\Psi$$

$$U^{\gamma_5} = e^{i\pi^a\lambda^a\gamma_5/f_\pi} \sim 1 + \frac{1}{f_\pi}\gamma_5\lambda^a\pi^a - \frac{1}{2f_\pi^2}\pi^a\pi^a$$

  - $\longrightarrow$ Goldstone bosons exchange
  - $\longrightarrow$ σ and κ exchanges
- Gluon coupling

$$\mathcal{L}_{gqq} = i\sqrt{4\pi\alpha_s}\bar{\Psi}\gamma_\mu G_c^\mu \lambda^c \Psi$$

  - $\longrightarrow$ One gluon exchange
- Confinement
- Interactions:

$$V_{q_iq_j} = \begin{cases} q_iq_j = nn \Rightarrow V_{CON} + V_{OGE} + V_\pi + V_\sigma + V_\eta \\ q_iq_j = nQ \Rightarrow V_{CON} + V_{OGE} \\ q_iq_j = QQ \Rightarrow V_{CON} + V_{OGE} \end{cases}$$

Model Results for 1^{--} sector.

(nL)	States	QM	Exp.
(1S)	J/ψ	3096	$3096{,}916 \pm 0{,}011$
(2S)	$\psi(2S)$	3703	$3686{,}09 \pm 0{,}04$
(1D)	$\psi(3770)$	3796	$3772 \pm 1{,}1$
(3S)	$\psi(4040)$	4097	4039 ± 1
(2D)	$\psi(4160)$	4153	4153 ± 3
(4S)	$Y(4360)$	4389	4361 ± 9
(3D)	$\psi(4415)$	4426	4421 ± 4
(5S)	$X(4630)$	4614	4634^{+9}_{-11}
(4D)	$Y(4660)$	4641	4664 ± 12

Masses in MeV of $J^{PC} = 1^{--}$ $c\bar{c}$ mesons (nL) refers to the dominant partial wave and QM denotes the results of the model.

XYZ Mesons

N.Brambila et al. Eur. Phys. J. C 71, 1534 (2011)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), BABAR [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), BABAR [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), BABAR [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), BABAR [97, 98] (3.6)		
				$B \to K(\gamma \psi(2S))$	BABAR [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), BABAR [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	BABAR [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!

XYZ Mesons

N.Brambila et al. Eur. Phys. J. C 71, 1534 (2011)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

XYZ Mesons

Meson	Mass (Exp)	Candidate?	J^{PC}	Mass (Th)
$Y(4360)$	4353 ± 11	$\psi(4S)$	1^{--}	4389
$X(4630)$	4634^{+9}_{-11}	$\psi(5S)$	1^{--}	4614
$Y(4660)$	4664 ± 12	$\psi(4D)$	1^{--}	4641
$X(4160)$	4156 ± 15	η_{c2}	2^{-+}	4166

Candidates for some XYZ mesons in our CQM $c\bar{c}$ spectrum.

No $c\bar{c}$ candidates for $X(3872)$, $X(3915)$, $X(3940)$, $G(3900)$, $Y(4008)$, $Y(4140)$, $Y(4260)$, $Y(4274)$, $X(4350)$,

$^3P_0$ model

- **Pair creation Hamiltonian:**

$$\mathcal{H} = g \int d^3x \bar{\psi}(x)\psi(x)$$

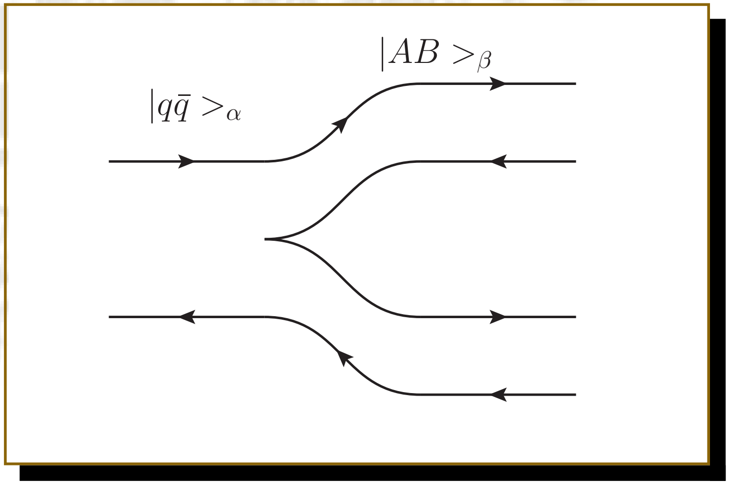
- **Non relativistic reduction:**

$$T = -3\sqrt{2}\gamma' \sum_{\mu} \int d^3p d^3p' \, \delta^{(3)}(p+p') \left[\mathcal{Y}_1 \left(\frac{p-p'}{2} \right) b^{\dagger}_{\mu}(p) d^{\dagger}_{\nu}(p') \right]^{C=1,I=0,S=1,J=0}$$

with $\gamma' = 2^{5/2}\pi^{1/2}\gamma$, $\gamma = \frac{g}{2m}$ **(in the light quark sector)**

- **Transition potential:**

$$\langle \phi_{M_1}\phi_{M_2}\beta | T | \psi_\alpha \rangle = P h_{\beta\alpha}(P)\delta^{(3)}(\vec{P}_{cm})$$



${}^3P_0$ results for $c\bar{c}$ strong decays

γ **parameter fitted to** $\psi(3770) \to DD$ **Phys. Rev. D 78, 114033 (2008).**

Meson	Dominant Mode	Γ_{QM} (MeV)	Γ_{exp} (MeV)
$\psi(3770)$	DD	22,2	$22{,}4 \pm 2{,}5$
	D^+D^-	9,5	$9{,}5 \pm 1{,}4$
	$D^0\bar{D}^0$	12,7	$12{,}8 \pm 1{,}8$
$\psi(4040)$	D^*D^*	92,9	80 ± 10
$\psi(4160)$	D^*D^*	96,8	103 ± 8
$\psi(4360)$	DD_1	89,8	103 ± 11
$\psi(4415)$	DD_1	113,1	$119 \pm 16(^*)$
$\psi(4660)$	D^*D^*	107,9	42 ± 6

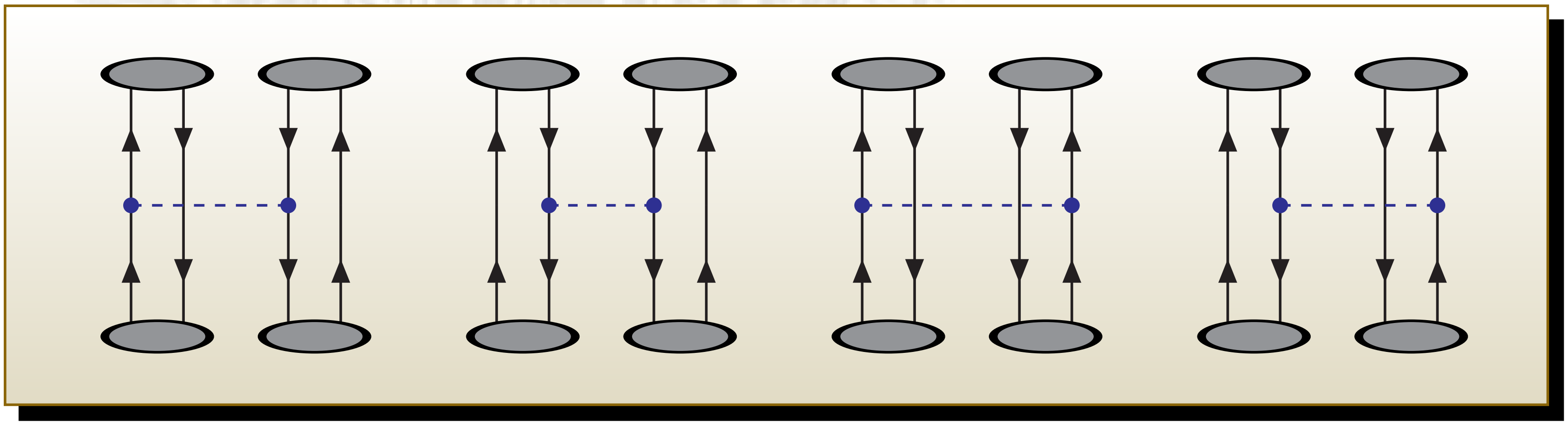
Ratio	Experimental value	${}^3P_0$
$\frac{\mathcal{B}(\psi(4040)\to D\bar{D})}{\mathcal{B}(\psi(4040)\to D\bar{D}^*)}$	$0{,}24 \pm 0{,}05 \pm 0{,}12$	0,21
$\frac{\mathcal{B}(\psi(4040)\to D^*\bar{D}^*)}{\mathcal{B}(\psi(4040)\to D\bar{D}^*)}$	$0{,}18 \pm 0{,}14 \pm 0{,}03$	3,7
$\frac{\mathcal{B}(\psi(4160)\to D\bar{D})}{\mathcal{B}(\psi(4160)\to D^*\bar{D}^*)}$	$0{,}02 \pm 0{,}03 \pm 0{,}02$	0,27
$\frac{\mathcal{B}(\psi(4160)\to D\bar{D}^*)}{\mathcal{B}(\psi(4160)\to D^*\bar{D}^*)}$	$0{,}34 \pm 0{,}14 \pm 0{,}05$	0,027

The $M_1 M_2$ system

- **Quark interactions** $\rightarrow$ **Cluster interaction.**
- **For the $D\bar{D}$ system only direct RGM Potential:**

$$
\begin{aligned}
{}^{RGM}V_D(\vec{P}',\vec{P}_i) \;=\; & \sum_{i\in A,j\in B}\int d\vec{p}_{\xi'_A}\, d\vec{p}_{\xi'_B}\, d\vec{p}_{\xi_A}\, d\vec{p}_{\xi_B} \\
& \phi_A^*(\vec{p}_{\xi'_A})\phi_B^*(\vec{p}_{\xi'_B})V_{ij}(\vec{P}',\vec{P}_i)\phi_A(\vec{p}_{\xi_A})\phi_B(\vec{p}_{\xi_B})
\end{aligned}
$$

- **$\phi_C(\vec{p}_C)$ is the wave function for cluster C solution of Schrödinger's equation using Gaussian Expansion Method.**



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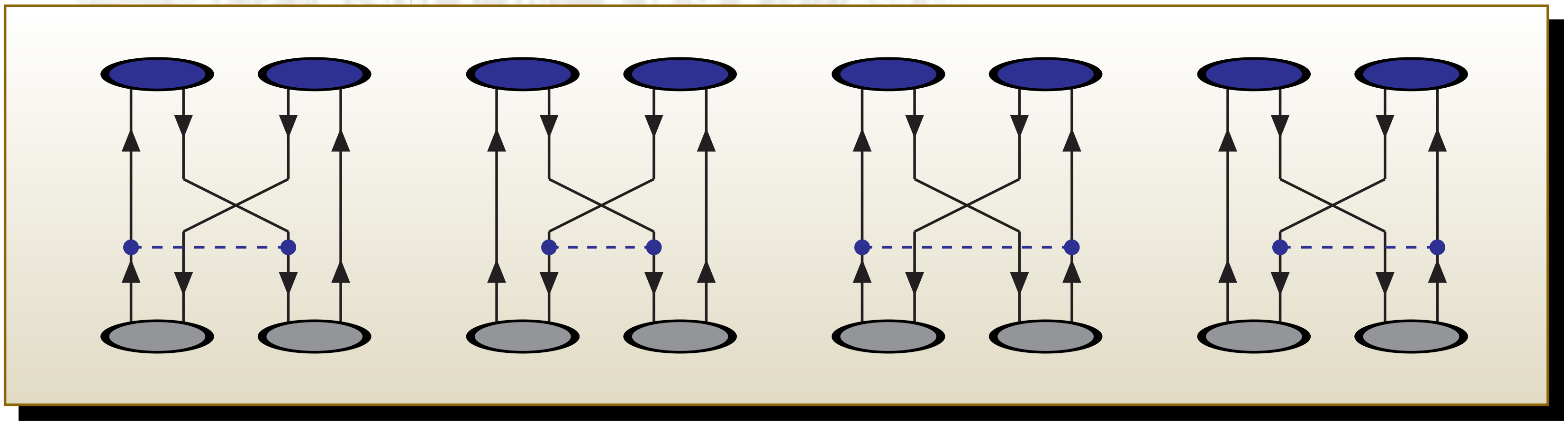
$$

- $\phi_C(\vec{p}_C)$ **is the wave function for cluster C solution of Schrödinger's equation using Gaussian Expansion Method.**

Rearrangement processes (like $D\bar{D} \rightarrow J/\psi\omega$)



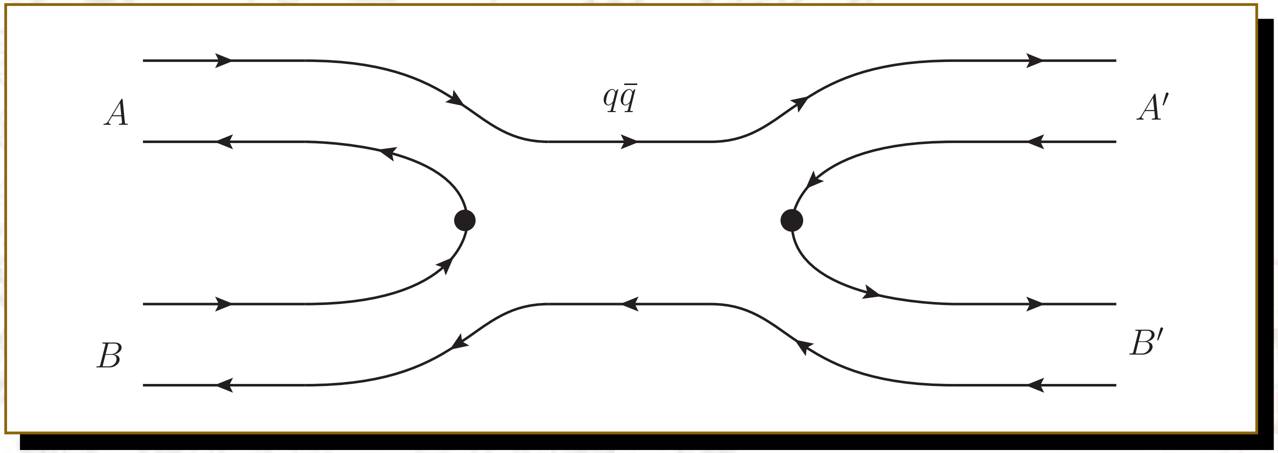
Coupling $q\bar{q}$ and $q\bar{q}\bar{q}q$ sectors

- **Hadronic state:** $|\Psi\rangle = \sum_\alpha c_\alpha |\psi\rangle + \sum_\beta \chi_\beta(P) |\phi_{M1}\phi_{M2}\beta\rangle$
- **Solving the coupling with $c\bar{c}$ states** → **Schrödinger type equation:**

$$\sum_\beta \int \left(H^{M_1 M_2}_{\beta'\beta}(P',P) + V^{eff}_{\beta'\beta}(P',P) \right) \chi_\beta(P) P^2 dP = E\chi_{\beta'}(P')$$

with

$$V^{eff}_{\beta'\beta}(P',P) = \sum_\alpha \frac{h_{\beta'\alpha}(P') h_{\alpha\beta}(P)}{E - M_\alpha}$$



- **The $c\bar{c}$ amplitudes are given by,**

$$c_\alpha = \frac{1}{E - M_\alpha} \sum_\beta \int h_{\alpha\beta}(P) \chi_\beta(P) P^2 dP$$

First results

- ${}^3S_1$ **and** ${}^3D_1$ DD^* **partial waves included.**
- **Coupling to** 1^{++} **ground and first excited** $c\bar{c}$ **states with bare masses within the model:**

$$c\bar{c}(1^3P_1) \rightarrow \; M = 3503{,}9 \; MeV$$
$$c\bar{c}(2^3P_1) \rightarrow \; M = 3947{,}4 \; MeV.$$

First results:

$M\ (MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$	**Assignment**
3936	$0\,\%$	$79\,\%$	$10{,}5\,\%$	$10{,}5\,\%$	$\rightarrow X(3940)$
3865	$1\,\%$	$32\,\%$	$33{,}5\,\%$	$33{,}5\,\%$	$\rightarrow X(3872)$
3467	$95\,\%$	$0\,\%$	$2{,}5\,\%$	$2{,}5\,\%$	$\rightarrow \chi_{c1}(3510)$

Parameter free calculation.

Isospin breaking

Charge basis $\longrightarrow$ Isospin breaking:

$$|D^{\pm} D^{*\mp}\rangle = \frac{1}{\sqrt{2}}\left(|DD^* I=0\rangle - |DD^* I=1\rangle\right)$$

$$|D^{0} D^{*0}\rangle = \frac{1}{\sqrt{2}}\left(|DD^* I=0\rangle + |DD^* I=1\rangle\right)$$

$M\ (MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	$D^0 D^{*0}$	$D^{\pm} D^{*\mp}$	**Assignment**
3937	$0\,\%$	$79\,\%$	$7\,\%$	$14\,\%$	$\rightarrow X(3940)$
3863	$1\,\%$	$30\,\%$	$46\,\%$	$23\,\%$	$\rightarrow X(3872)$
3467	$95\,\%$	$0\,\%$	$2{,}5\,\%$	$2{,}5\,\%$	$\rightarrow \chi_{c1}(3510)$

Isospin probabilities:

- $I=0 \longrightarrow \mathcal{P} = 66\,\%$,
- $I=1 \longrightarrow \mathcal{P} = 3\,\%$.

Final results

γ **a** $25\,\%$ **smaller** $\rightarrow E_{bind} = -0{,}6\ MeV$.

$M\ (MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	$D^0 D^{*0}$	$D^{\pm} D^{*\mp}$	**Assignment**
3942	$0\,\%$	$88\,\%$	$4\,\%$	$8\,\%$	$\rightarrow X(3940)$
3871	$0\,\%$	$7\,\%$	$83\,\%$	$10\,\%$	$\rightarrow X(3872)$
3484	$97\,\%$	$0\,\%$	$1{,}5\,\%$	$1{,}5\,\%$	$\rightarrow \chi_{c1}(3510)$

Isospin probabilities:

- $I = 0 \rightarrow \mathcal{P} = 70\,\%$,
- $I = 1 \rightarrow \mathcal{P} = 23\,\%$.

Comparison with data

Flatte parametrization

Following V. Baru *et al.* Phys. Lett. B 586, 53 (2004)

$$F^{\beta}_{DD*}(P,P;E) = -\pi\mu \sum_{\alpha} \frac{h^2_{\beta\alpha}(P)}{E - M_\alpha + g^{\alpha}_{DD*}(E)}$$

$$g^{\alpha}_{DD*}(E) = \sum_{\beta} \int \frac{h^2_{\beta\alpha}(P)}{\frac{P^2}{2\mu} - E - i0^+} P^2\, dP \sim \bar{E}^{\alpha}_{DD*} + \frac{i}{2}\Gamma^{\alpha}_{DD*} + \mathcal{O}(4\mu^2\epsilon/\Lambda^2)$$

for small binding energies

$$\frac{dBr(B \to KD^0D^{*0})}{dE} = \mathcal{B}\frac{1}{2\pi}\frac{\Gamma_{D^0D^{*0}}(E)}{|D(E)|^2}$$

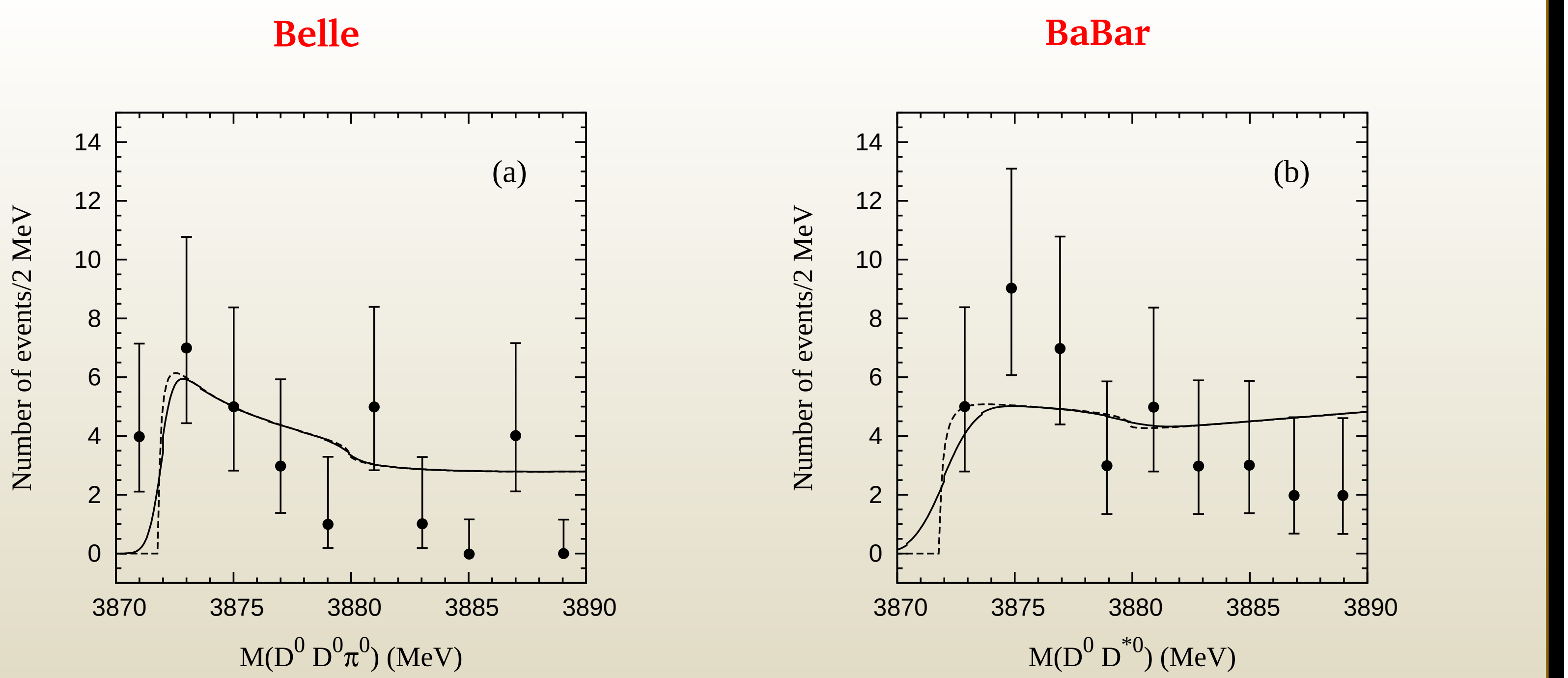
$$\frac{dBr(B \to K\pi^+\pi^- J/\Psi)}{dE} = \mathcal{B}\frac{1}{2\pi}\frac{\Gamma_{\pi^+\pi^- J/\Psi}(E)}{|D(E)|^2}.$$

$$D(E) = E - E_f + \frac{i}{2}(\Gamma_{D^0D^{*0}} + \Gamma_{D^+D^{*-}} + \Gamma(E)) + \mathcal{O}(4\mu^2\epsilon/\Lambda^2)$$

We calculate

$$\Gamma_{\pi^+\pi^- J/\Psi} = \sum_{JL} \int_0^{k_{max}} dk \frac{\Gamma_\rho}{(M_X - E_\rho - E_{J/\Psi})^2 + \frac{\Gamma_\rho^2}{4}} \left|\mathcal{M}^{JL}_{X\to\rho J/\Psi}(k)\right|^2.$$

Belle and BaBar data



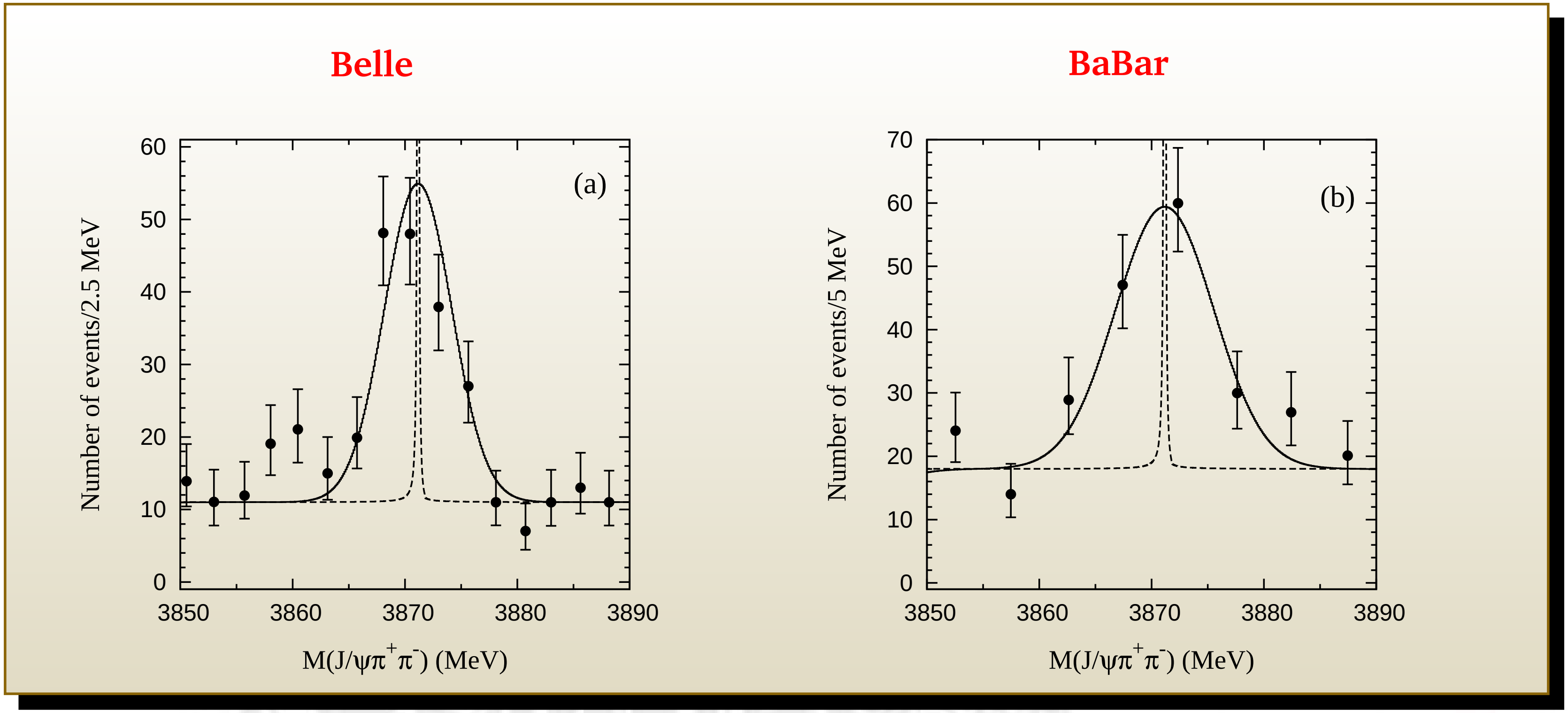
$B \to K D^0 \bar{D}^0 \pi^0$ **data**

solid (dashed) line with (without) resolution function

$$N^{D^0 \bar{D}^0 \pi^0}_{Belle}(E) = 2{,}0[\textbf{MeV}] \left(\frac{48{,}3}{0{,}73\, 10^{-4}} \right) \frac{dBr(B \to K D^0 \bar{D}^0 \pi^0)}{dE}$$

$$N^{D^0 D^{*0}}_{BaBar}(E) = 2{,}0[\textbf{MeV}] \left(\frac{33{,}1}{1{,}67\, 10^{-4}} \right) \frac{dBr(B \to K D^0 \bar{D}^{*0})}{dE}$$

Belle and BaBar data



$B \to K\pi^+\pi^- J/\Psi$ **data**

solid (dashed) line with (without) resolution function

$$N^{\pi\pi J/\Psi}_{Belle}(E) = 2{,}5\,[\mathbf{MeV}] \left(\frac{131}{8{,}3\,10^{-6}}\right) \frac{dBr(B \to K\pi^+\pi^- J/\Psi)}{dE}$$

$$N^{\pi\pi J/\Psi}_{BaBar}(E) = 5\,[\mathbf{MeV}] \left(\frac{93{,}4}{8{,}4\,10^{-6}}\right) \frac{dBr(B \to K\pi^+\pi^- J/\Psi)}{dE}$$

Resonance states

Lippman-Schwinger equation

$$T^{\beta'\beta}(E;P',P) = V_T^{\beta'\beta}(P',P) + \sum_{\beta''}\int dP'' P''^2 V_T^{\beta'\beta''}(P',P'')\frac{1}{E-E_{\beta''}(P'')}T^{\beta''\beta}(E;P'',P)$$

with $V_T^{\beta'\beta}(P',P) = V^{\beta'\beta}(P',P) + V_{eff}^{\beta'\beta}(P',P)$, $V_{\beta'\beta}^{eff}(P',P) = \sum_\alpha \frac{h_{\beta'\alpha}(P')h_{\alpha\beta}(P)}{E-M_\alpha}$

Resonance states

Lippman-Schwinger equation

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Solution (Baru et al. Eur. Phys. Jour. A 44, 93 (2010))

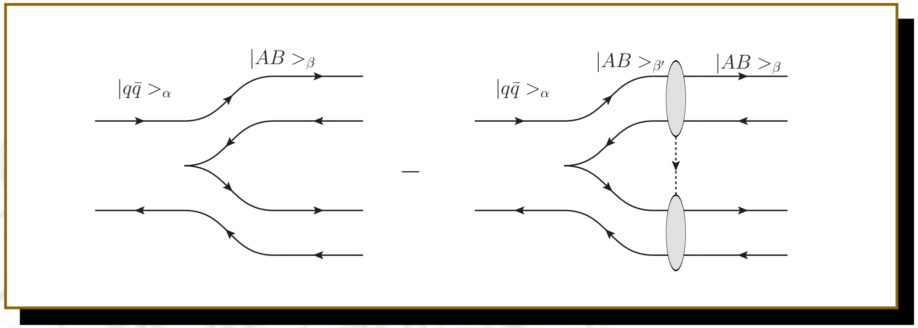
$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'}\phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

- **Non resonant contribution**
- **Resonant contribution**

with

$$T_V^{\beta'\beta}(E;P',P) = V^{\beta'\beta}(P',P) + \sum_{\beta''}\int dP'' P''^2 V^{\beta'\beta''}(P',P'')\frac{1}{z-E_{\beta''}(P'')}T_V^{\beta''\beta}(E;P'',P)$$

Resonance states



Solution (Baru et al. Eur. Phys. Jour. A 44, 93 (2010))

$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'} \phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

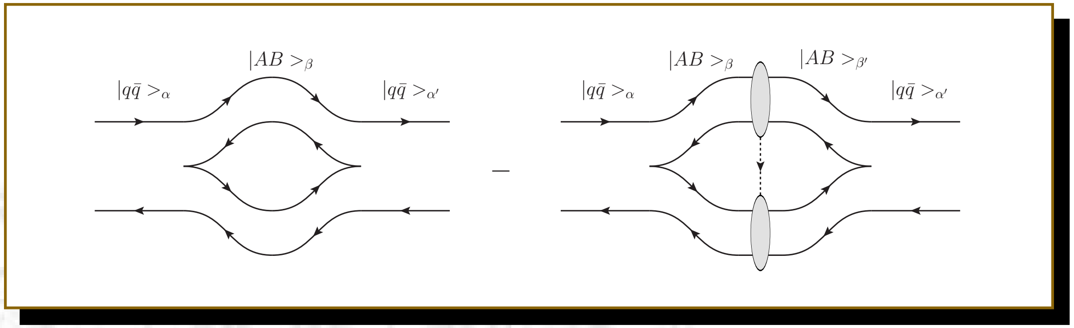
- **Non resonant contribution**
- **Resonant contribution**

with

$$\phi^{\alpha\beta'}(E;P) = h_{\alpha\beta'}(P) - \sum_\beta \int \frac{T_V^{\beta'\beta}(E;P,q)h_{\alpha\beta}(q)}{q^2/2\mu - E} q^2\,dq,$$

$$\bar{\phi}^{\alpha\beta}(E;P) = h_{\alpha\beta}(P) - \sum_{\beta'} \int \frac{h_{\alpha\beta'}(q)T_V^{\beta'\beta}(E;q,P)}{q^2/2\mu - E} q^2\,dq$$

Resonance states



Solution (Baru et al. Eur. Phys. Jour. A 44, 93 (2010))

$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'} \phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

- **Non resonant contribution**
- **Resonant contribution**

with

$$\Delta^{\alpha'\alpha}(E) = \left\{(E - M_\alpha)\delta^{\alpha'\alpha} + \mathcal{G}^{\alpha'\alpha}(E)\right\}$$

$$\mathcal{G}^{\alpha'\alpha}(E) = \sum_\beta \int dq q^2 \frac{\phi^{\alpha\beta}(q,E)h_{\beta\alpha'}(q)}{q^2/2\mu - E}$$

Resonance states

- **Resonance mass** (**pole position in the second Riemann sheet**)

$$\left|\Delta^{\alpha'\alpha}(\bar{E})\right| = \left|(\bar{E} - M_\alpha)\delta^{\alpha'\alpha} + \mathcal{G}^{\alpha'\alpha}(\bar{E})\right| = 0$$

- **Bare $c\bar{c}$ probabilities**

$$\left\{M_\alpha \delta^{\alpha\alpha'} - \mathcal{G}^{\alpha'\alpha}(\bar{E})\right\} c_{\alpha'}(\bar{E}) = \bar{E}\, c_\alpha(\bar{E})$$

- **Molecular wave function**

$$\chi_{\beta'}(P') \quad = \quad -2\mu_{\beta'} \sum_\alpha \frac{\phi_{\beta'\alpha}(E;P')c_\alpha}{P'^2 - k^2_{\beta'}}$$

- **Normalization**

$$\sum_\alpha |c_\alpha|^2 + \sum_\beta < \chi_\beta|\chi_\beta >= 1$$

Partial widths

The scattering matrix is

$$S^{\beta'\beta}(E) = -i2\pi\delta^4(p_f - p_i)\sum_{\alpha,\alpha'}\phi^{\beta'\alpha'}(k,E)\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(k,E) + S^{\beta'\beta}_{bg}(E)$$

with

- $\Delta_{\alpha'\alpha}(E) \sim (E-\bar{E})\left[\delta_{\alpha'\alpha} + \mathcal{G}'_{\alpha'\alpha}(\bar{E})\right] = (E-\bar{E})\mathcal{Z}_{\alpha'\alpha}(\bar{E})$
- $\mathcal{G}'_{\alpha'\alpha}(\bar{E}) = \text{lím}_{E\to\bar{E}}\dfrac{\mathcal{G}_{\alpha'\alpha}(E) - \mathcal{G}_{\alpha'\alpha}(\bar{E})}{E-\bar{E}}$

and then

$$S^{\beta'\beta}(E) \sim -i2\pi\delta^4(p_f - p_i)\sum_{\alpha,\alpha',\lambda}\frac{\left[\phi^{\beta'\alpha'}(\bar{k},\bar{E})\mathcal{Z}^{-1/2}_{\alpha'\lambda}(\bar{E})\right]\left[\mathcal{Z}^{-1/2}_{\lambda\alpha}(E)\bar{\phi}^{\alpha\beta}(\bar{k},\bar{E})\right]}{E-\bar{E}} + S^{\beta'\beta}_{bg}(E)$$

So

$$S(X_c \to f)^{\beta\alpha} = \sum_{\lambda}\phi^{\beta\lambda}(\bar{k},\bar{E})\mathcal{Z}^{-1/2}_{\lambda\alpha}(\bar{E})$$

We define the partial width

$$\hat{\Gamma}_\beta = 2\pi\frac{E_A E_B}{E_R}k_{o\beta}\sum_{\alpha,\lambda,\lambda'}\phi^{*\,\beta\lambda'}(\bar{k})\left(\mathcal{Z}(\bar{E})^{-1/2}\right)^*_{\lambda'\alpha}\mathcal{Z}(\bar{E})^{-1/2}_{\lambda\alpha}\phi^{\beta\lambda}(\bar{k}) \quad \mathcal{B}_\beta = \frac{\hat{\Gamma}_\beta}{\sum_\beta\hat{\Gamma}_\beta} \quad \Gamma_\beta = \mathcal{B}_\beta\Gamma$$

The 0^{++} sector

Bare $c\bar{c}\ 2^3P_0$ (3909)

Meson channels: $DD + J/\psi\omega + D_sD_s + J/\psi\phi$

Mass(MeV)	2^3P_0	DD	$J/\psi\omega$	D_sD_s	$J/\psi\phi$	Γ_{DD}	$\Gamma_{J/\psi\omega}$	$\Gamma_{D_sD_s}$
$3896{,}05 - i2{,}10$	34,22	46,67	9,41	9,67	0,03	3,37	0,83	–
$3970{,}07 - i94{,}67$	57,27	35,32	0,15	5,72	1,54	38,69	2,89	147,76
	E.J. Eichten et al. Phys. Rev. D 73 014014 (2005) (C^3)							
$3881{,}4 - i\,30{,}75$	49	34,22	–	4,41	–			

$X(3945)$ **and** $Y(3940) \rightarrow X(3915)$

Uehara et al. PRL 104, 092001 $M = 3915 \pm 3 \pm 2\ \Gamma = 17 \pm 10 \pm 3\ e^+e^- \rightarrow e^+e^-\omega J/\psi$

Choi et al. PRL 94, 182002 $M = 3943 \pm 11 \pm 13\ \Gamma = 87 \pm 22 \pm 26\ B \rightarrow \omega J/\psi K$

The 1^{--} sector

Bare $c\bar{c}$ 3^3S_1 (4097) and 2^3D_1 (4153)

Meson channels: $DD + DD^* + D^*D^* + D_sD_s + D_sD_s^* + D_s^*D_s^*$

$M\ (MeV)$	3^3S_1	2^3D_1	DD	DD^*	D^*D^*	D_sD_s	$D_sD_s^*$	$D_s^*D_s^*$
$3994{,}6 - i\,11{,}60$	31,56	3,00	2,49	36,44	17,75	7,53	0,52	0,71
$4048{,}4 - i\,7{,}54$	0,92	36,15	2,99	23,49	25,81	8,86	0,92	0,85
$4123{,}9 - i\,71{,}11$	59,01	0,98	2,13	6,84	19,19	0,75	3,37	7,73
	E.J. Eichten et al. Phys. Rev. D 73 014014 (2005) (C^3)							
$4038 - i\,37$	44,89	0,16	2,87	20,36	23,10	0,98	1,58	1,08
$(4160) - i\,24{,}6$	0,09	47,61	8,37	4,24	8,87	0,55	0,96	1,31

M	Γ	$\Gamma(DD)$	$\Gamma(DD^*)$	$\Gamma(D^*D^*)$	$\Gamma(D_sD_s)$	$\Gamma(D_sD_s^*)$
3994,6	23,37	0,12	19,09	–	4,16	–
4048,4	15,09	0,51	7,24	4,42	2,92	–
4123,9	142,23	4,73	7,51	100,03	3,82	26,15

The 1^{--} sector

Ratio	Experimental value	$q\bar{q}$ with $^3P_0$	Coupled channel
$\frac{\mathcal{B}(\psi(4040)\to D\bar{D})}{\mathcal{B}(\psi(4040)\to D\bar{D}^*)}$	$0{,}24 \pm 0{,}05 \pm 0{,}12$	0,21	0,07
$\frac{\mathcal{B}(\psi(4040)\to D^*\bar{D}^*)}{\mathcal{B}(\psi(4040)\to D\bar{D}^*)}$	$0{,}18 \pm 0{,}14 \pm 0{,}03$	3,7	0,61
$\frac{\mathcal{B}(\psi(4160)\to D\bar{D})}{\mathcal{B}(\psi(4160)\to D^*\bar{D}^*)}$	$0{,}02 \pm 0{,}03 \pm 0{,}02$	0,27	0,05
$\frac{\mathcal{B}(\psi(4160)\to D\bar{D}^*)}{\mathcal{B}(\psi(4160)\to D^*\bar{D}^*)}$	$0{,}34 \pm 0{,}14 \pm 0{,}05$	0,027	0,08

Summary

- We have performed a **couple channel calculation in a phenomenological chiral constituent quark model including $q\bar{q}$ and $q\bar{q}\bar{q}q$ configurations**
- The **coupling between DD^* and $c\bar{c}$ states in the 1^{++} sector** generates a **new bound state** that we assigned to the $X(3872)$
- We have analyzed the **Belle and BaBar data for the decays $B \to K D^0 \bar{D}^0 \pi^0$ and $B \to K \pi^+ \pi^- J/\Psi$ finding a good agreement**.
- We find a candidate for $X(3940)$ **as a $\chi_{c1}(2P)$ state with a sizable DD^* component**
- In the 0^{++} sector we find **two states in the 3900 MeV energy range**
- In the 1^{--} sector we find a new state that could be the $G(3900)$ or the $Y(4008)$
- In the 1^{--} sector the original $3S$ and $2D$ states **get mixed and they change the order**
- The coupled channel calculation is in less disagreement with the experimental branchings than the original naive quark model result

The $X(3872)$ branching ratios

γ	E_{bind}	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$
0,231	−0,60	12,40	79,24	7,46	0,49	0,40
0,226	−0,25	8,00	86,61	4,58	0,53	0,29

The $X(3872)$ branching ratios

E_{bind} (MeV)	$\Gamma_{\pi^+\pi^- J/\psi}$	$\Gamma_{\pi^+\pi^-\pi^0 J/\psi}$	R_1
$-0{,}60$	$27{,}61$	$14{,}40$	$0{,}52$
$-0{,}25$	$24{,}18$	$10{,}64$	$0{,}44$

$$R_1 = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 1{,}0 \pm 0{,}4 \pm 0{,}3$$

The $X(3872)$ branching ratios

E_{bind} **(MeV)**	$\Gamma^{VMD}_{J/\psi\gamma}$	$\Gamma^{ANN}_{J/\psi\gamma}$	R_2^M	$\Gamma^{c\bar{c}}_{J/\psi\gamma}$	$R_2^{c\bar{c}}$	R_2
$-0{,}60$	0,014	0,056	0,0025	8,15	0,29	0,30
$-0{,}25$	0,011	0,045	0,0023	5,25	0,22	0,22

$$R_1 = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 1{,}0 \pm 0{,}4 \pm 0{,}3$$

$$R_2 = \frac{\Gamma(X(3872) \to \gamma J/\psi)}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 0{,}14 \pm 0{,}05 \quad 0{,}33 \pm 0{,}12$$

The $X(3872)$ branching ratios

E_{bind} **(MeV)**	$\Gamma^{ANN}_{\Psi(2S)\gamma}$	R_3^M	$\Gamma^{c\bar{c}}_{\Psi(2S)\gamma}$	$R_3^{c\bar{c}}$	R_3
$-0{,}60$	0,134	0,0048	9,80	0,35	0,34
$-0{,}25$	0,101	0,0042	6,31	0,26	0,26

$$R_1 = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 1{,}0 \pm 0{,}4 \pm 0{,}3$$

$$R_2 = \frac{\Gamma(X(3872) \to \gamma J/\psi)}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 0{,}14 \pm 0{,}05 \quad 0{,}33 \pm 0{,}12$$

$$R_3 = \frac{\Gamma(X(3872) \to \gamma \psi(2S))}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 1{,}1 \pm 0{,}4$$

The $X(3872)$ branching ratios

E_{bind} **(MeV)**	R_3/R_2
$-0{,}60$	$1{,}13$
$-0{,}25$	$1{,}18$

$$R_1 = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 1{,}0 \pm 0{,}4 \pm 0{,}3$$

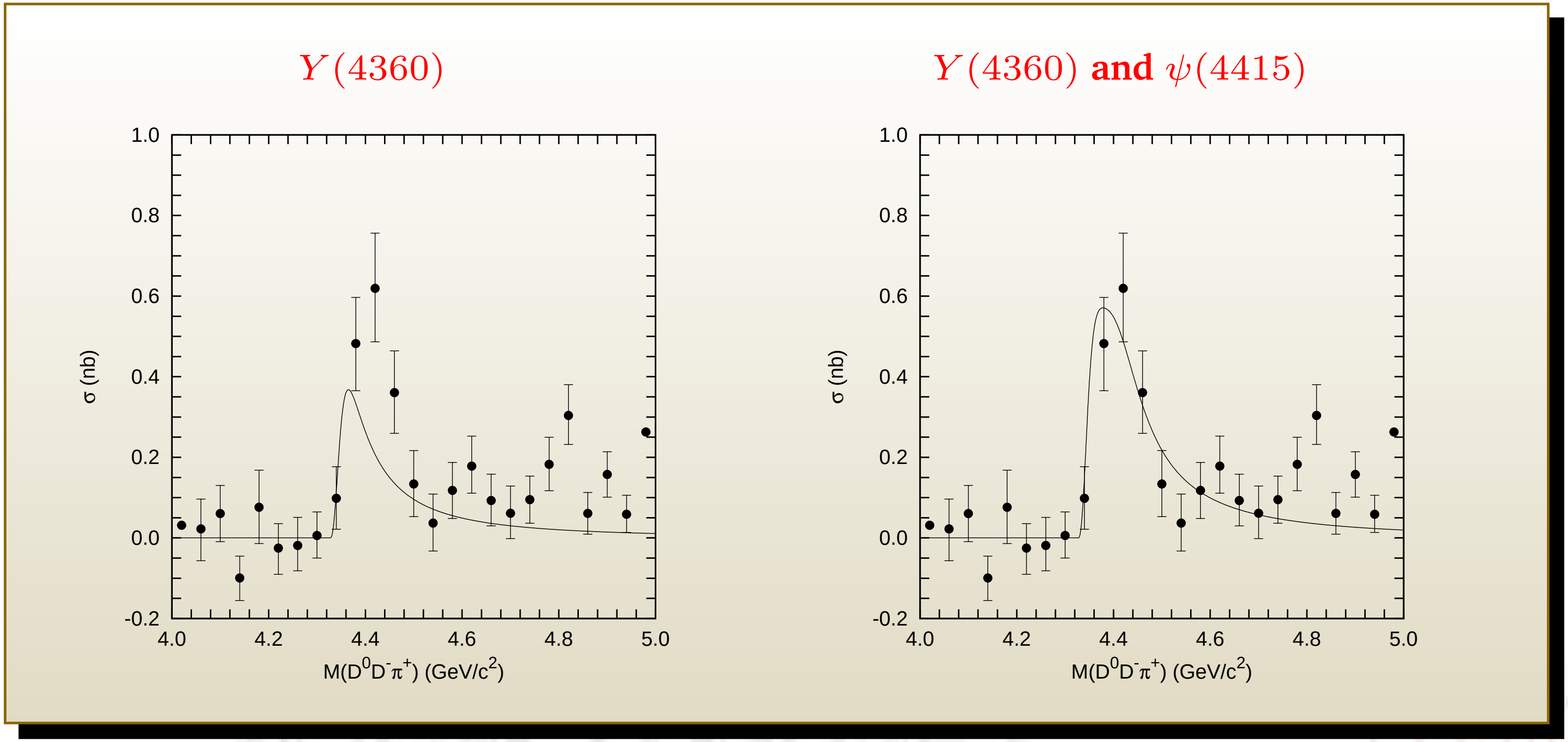
$$R_2 = \frac{\Gamma(X(3872) \to \gamma J/\psi)}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 0{,}14 \pm 0{,}05 \quad 0{,}33 \pm 0{,}12$$

$$R_3 = \frac{\Gamma(X(3872) \to \gamma \psi(2S))}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 1{,}1 \pm 0{,}4$$

$$\frac{R_3}{R_2} = \frac{\mathcal{B}(X \to \psi(2S)\gamma)}{\mathcal{B}(X \to J/\psi\gamma)} < 2{,}1$$

The $Y(4360)$

$e^+e^- \to D^0 D^- \pi^+$ **(through** $DD_2^*(2460)$**)**

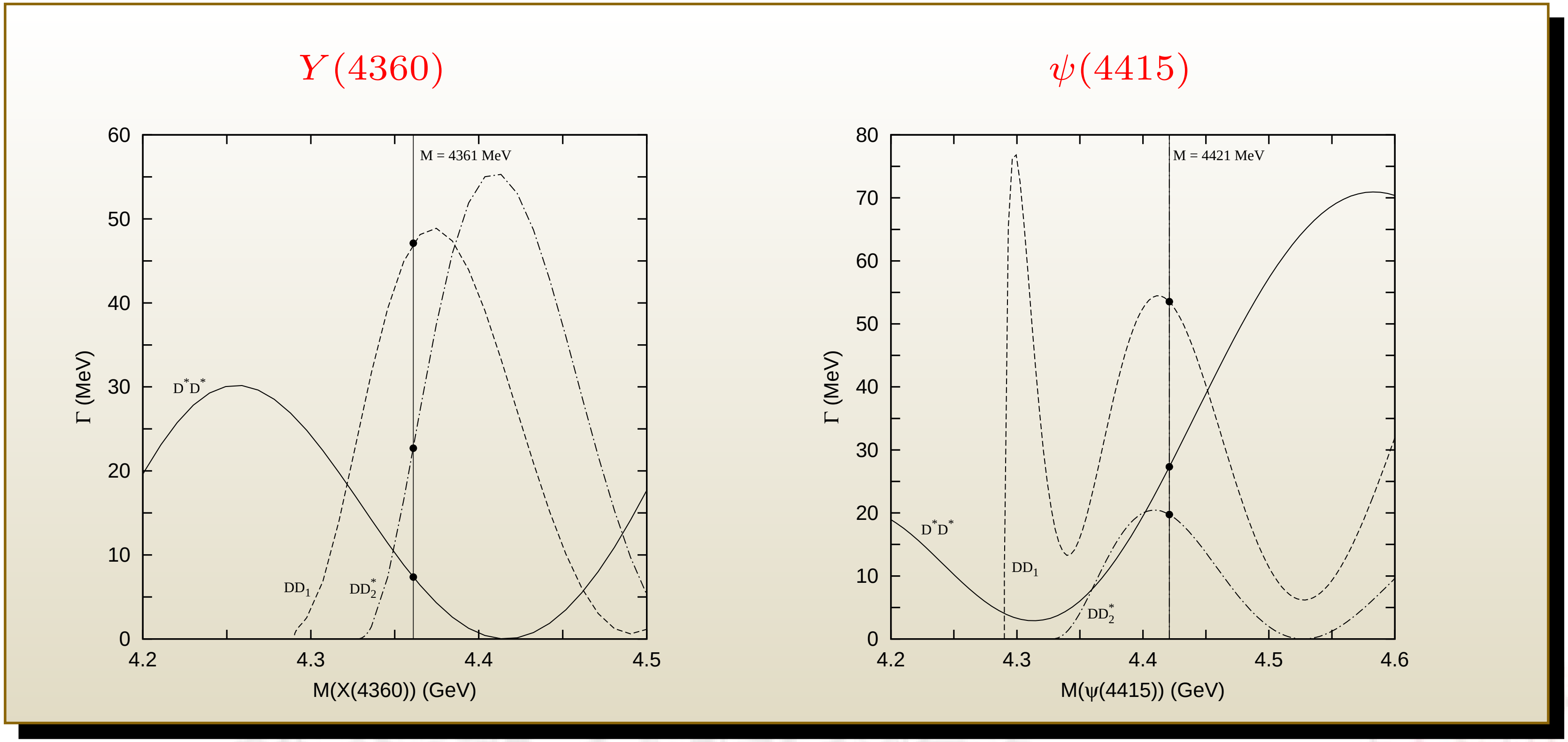


J. Segovia et al., accepted for publication in Phys. Rev. D

PDG data $\mathcal{B}(X \to D^0 D^{*-} \pi^+)/\mathcal{B}(X \to \pi^+\pi^-\psi(2S)) < 8$

The $Y(4360)$

$e^+e^- \to D^0 D^- \pi^+$ **(through** $DD_2^*(2460)$**)**



J. Segovia et al., accepted for publication in Phys. Rev. D

PDG data $\mathcal{B}(X \to D^0 D^{*-}\pi^+)/\mathcal{B}(X \to \pi^+\pi^-\psi(2S)) < 8$

Model $\Gamma(D^0 D^{*-}\pi^+) = \Gamma(X(4360) \to D^{*+}D^{*-})\mathcal{B}(D^{*+} \to D^0\pi^+) = 2{,}5$ **MeV**

So $\Gamma(X(4360) \to \psi(2S)\pi^+\pi^-) \sim 300$ **keV**