Heavy meson molecules and HQSS breaking

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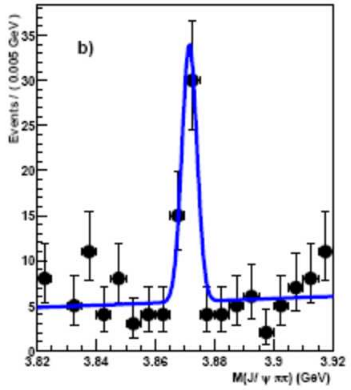
Outline

- The $X(3872)$ and its partners
- The Chiral Quark Model
- Coupling two meson and one meson states: the ${}^3P_0$ model
- Heavy Quark Spin Symmetry relations
- Predictions of the Chiral Quark model in the charmonium and bottomonium sectors
- Summary

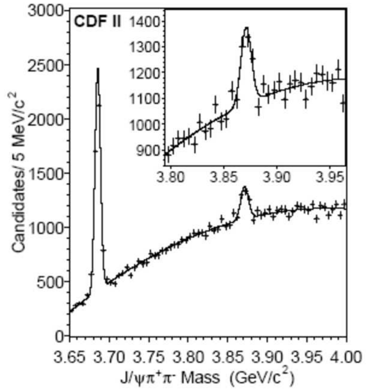
The $X(3872)$

Narrow state seen in B decays and $p\bar{p}$ collision decaying to $\pi\pi J/\psi$, $\pi\pi\pi J/\psi$, $\gamma J/\psi$ and $D^0\bar{D}^0\pi^0$.



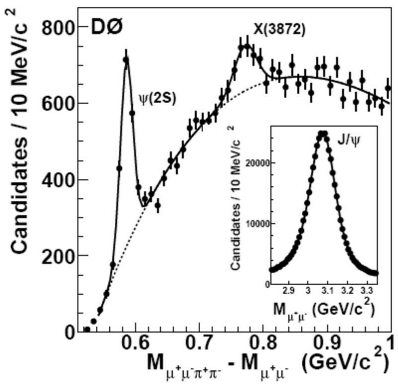
Belle 2003

$B^{\pm} \to K^{\pm}\pi^+\pi^- J/\Psi$



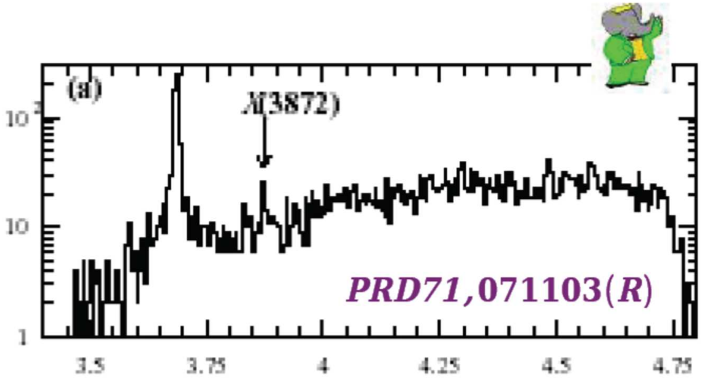
CDFII 2004

$\pi\pi J/\Psi$ **in** $p\bar{p}$ **collisions**



D0 2004

$\pi\pi J/\Psi$ **in** $p\bar{p}$ **collisions**

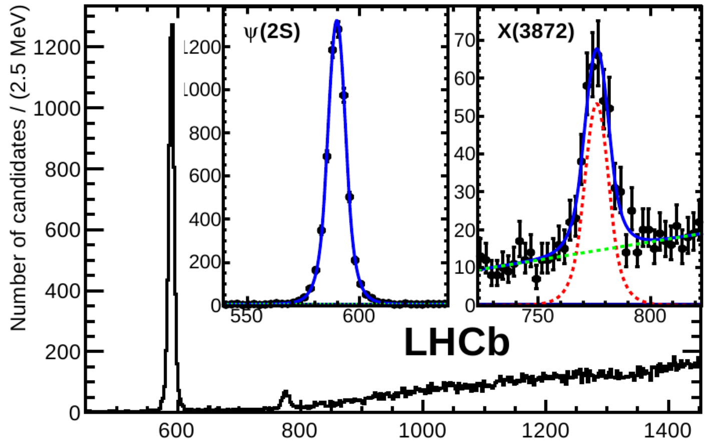


BaBar 2005

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

The $X(3872)$

LHCb determines $J^{PC} = 1^{++}$ in 2014



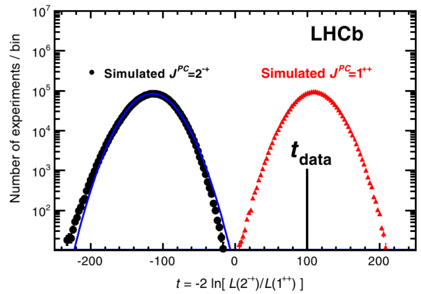


FIG. 2 (color online). Distribution of the test statistic t for the simulated experiments with $J^{PC} = 2^{-+}$ and $\alpha = \hat{\alpha}$ (black circles on the left) and with $J^{PC} = 1^{++}$ (red triangles on the right). A Gaussian fit to the 2^{-+} distribution is overlaid (blue solid line). The value of the test statistic for the data t_{data} is shown by the solid vertical line.

$X(3872)$ partners

Experimental search of the X_b: bottom partner in the 1^{++} sector

- **Phys. Lett. B 727, 57 (2013). CMS didn't find it in the $\Upsilon(1S)\pi^+\pi^-$ decay channel in pp collisions**
- **Phys. Lett. B 740, 199 (2015). ATLAS also didn't find it in the same decay channel**
- **Phys. Rev. Lett. 113, 142001 (2014). Belle didn't find it in $\omega\Upsilon(1S)$ in e^+e^- collisions between 10.55 and 10.65 GeV**

$X(3872)$ partners

HQSS expectation: Charm sector

J. Nieves and M. Pavón-Valderrama, Phys. Rev. D 86, 056004

- **HQSS implies the existence of a 2^{++} D^*D^* partner $X(4012)$**
- **Assuming the $X(3915)$ to be the 0^{++} partner a total of six-molecular states.**
  - **Spin independent (C_{0a}) and spin dependent (C_{0b}) terms.**
  - **Small coupled channel effects.**
  - **No coupling with $c\bar{c}$ states.**

HQSS and HFS expectations: Charm and Bottom sector relations

Feng-Kun Guo et al., Phys. Rev. D 88, 054007

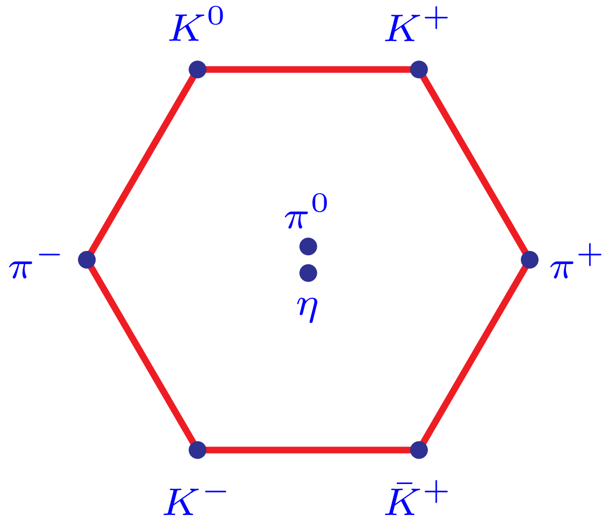
- **A 1^{++} isoscalar BB^* state at 10.58 GeV $V^{LO}_{DD^*}(1^{++}) = V^{LO}_{BB^*}(1^{++})$**
- **Isovector partners of Z_b in the chamonium sectors are predicted**

The Chiral Quark Model

J. Vijande *et al.*, J. Phys. G 31

- Spontaneous Chiral Symmetry Breaking $\longrightarrow$
  $\longrightarrow$ 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
  $\longrightarrow$ Scalar boson exchanges
- Gluon coupling

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

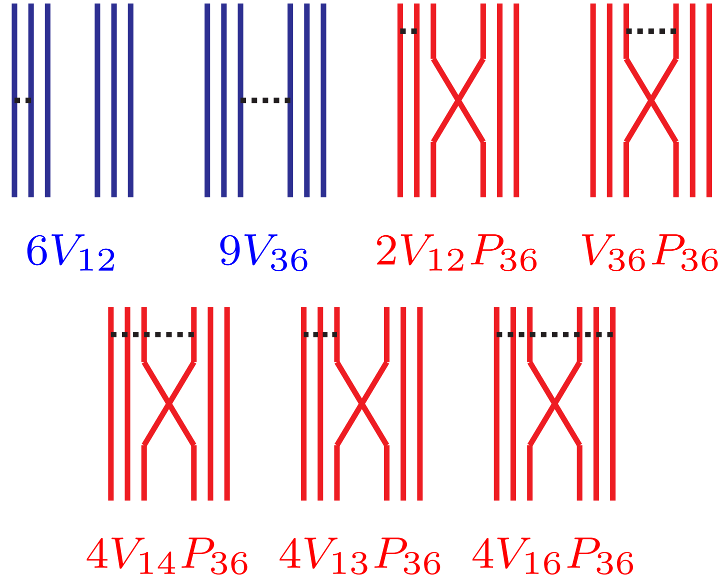
  $\longrightarrow$ One gluon exchange
- Confinement
- Interactions:

$$\boxed{V_{q_iq_j} = \begin{cases} q_iq_j = nn \Rightarrow V_{CON} + V_{OGE} + V_{GBE} + V_{SBE} \\ q_iq_j = nQ \Rightarrow V_{CON} + V_{OGE} \\ q_iq_j = QQ \Rightarrow V_{CON} + V_{OGE} \end{cases}}$$

The $B_1 B_2$ interaction

$$\psi_B = \phi_B(\vec{p}_{\xi_1}, \vec{p}_{\xi_2})\chi_B \xi_c[1^3]$$

$$\phi_B(\vec{p}_{\xi_1}, \vec{p}_{\xi_2}) = \left[\frac{2b^2}{\pi}\right]^{\frac{3}{4}} e^{-b^2 p_{\xi_1}^2} \left[\frac{3b^2}{2\pi}\right]^{\frac{3}{4}} e^{-\frac{3b^2}{4} p_{\xi_2}^2}$$



$$\psi_{B_1 B_2} = \mathcal{A}\left[\chi(\vec{P})\psi^{ST}_{B_1 B_2}\right]$$
$$= \mathcal{A}\left[\phi_{B_1}(\vec{p}_{\xi_{B_1}})\phi_{B_2}(\vec{p}_{\xi_{B_2}})\chi(\vec{P})\chi^{ST}_{B_1 B_2}\xi_c[2^3]\right]$$

Rayleigh-Ritz variational principle (Resonating Group Method)

$$(\mathcal{H} - E_T)\,|\,\psi\,\rangle = 0 \quad \Rightarrow \quad \langle\,\delta\psi\,|\,(\mathcal{H} - E_T)\,|\,\psi\,\rangle = 0$$

$$\left(\frac{\vec{P}'^{\,2}}{2\mu} - E\right)\chi(\vec{P}') + \int \left({}^{\rm RGM}V_D(\vec{P}', \vec{P}_i) + {}^{\rm RGM}K(\vec{P}', \vec{P}_i)\right)\chi(\vec{P}_i)d\vec{P}_i = 0$$

$$T_\alpha^{\alpha'}(z; p', p) = V_\alpha^{\alpha'}(p', p) + \sum_{\alpha''}\int dp''\, p''^2\, V_{\alpha''}^{\alpha'}(p', p'')\frac{1}{z - E_{\alpha''}(p'')}T_\alpha^{\alpha''}(z; p'', p)$$

Lippmann-Schwinger Equation

NN System

	Quark	χN^{3}LO	CD-Bonn	Exp.
E_D (MeV)	2.2246	2.224575	2.224575	2.224575(9)
r_m (fm)	1.985	1.978	1.970	1.97535(85)
A_S (fm$^{-1/2}$)	0.8941	0.8843	0.8846	0.8846(9)
η	0.0250	0.0256	0.0256	0.0256(4)

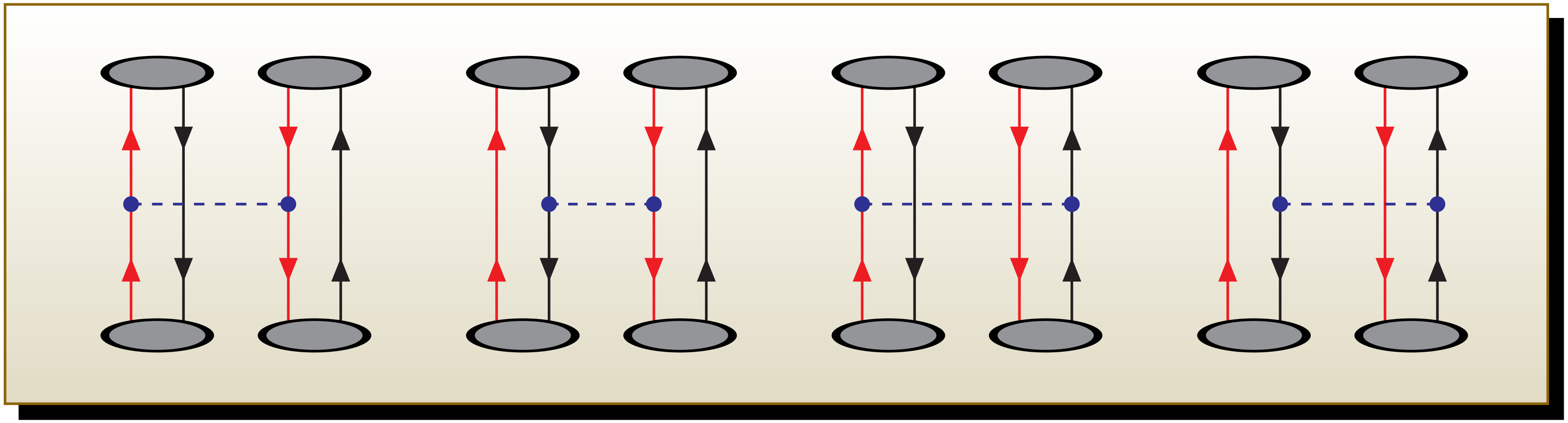
- **Constituent quark model,** *Phys. Rev C 62, 034002 (2000)*
- **Antisymmetry is not present in $D^{(*)}\bar{D}^{(*)}$.**
- **One bound state in NN, what happens in $D^{(*)}\bar{D}^{(*)}$**

The $M_1 M_2$ system

- **Quark interactions** $\longrightarrow$ **Cluster interaction.**
- **For the DD^* system only direct RGM Potential:**

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

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



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& \phi_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})
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$$

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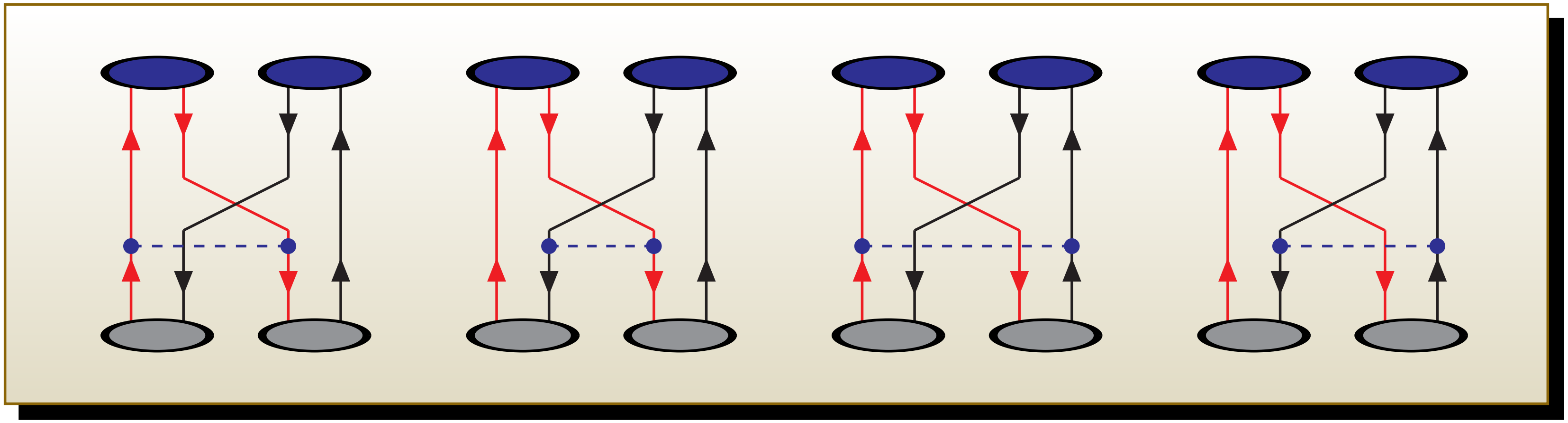
Rearrangement processes (like $DD^* \to J/\psi\omega$)



$^3P_0$ model

- **Pair creation Hamiltonian:**

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

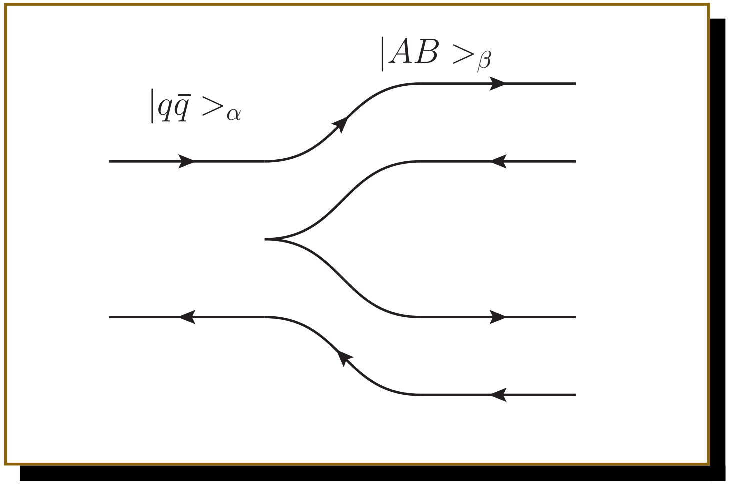
- **Non relativistic reduction:**

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

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

- **Transition potential:**

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



$^3P_0$ model

J. Segovia, DRE, F. Fernández, Phys. Lett. B 715, 322 (2012)

Running coupling

$$\gamma(\mu) \quad = \quad \frac{\gamma_0}{\log(\frac{\mu}{\mu_0})}$$

$\gamma_0 = 0{,}81 \pm 0{,}02$
$\mu_0 = (49{,}84 \pm 2{,}58)$ **MeV**

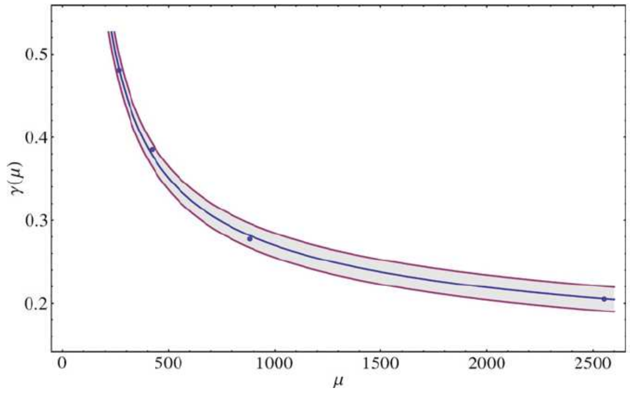


Table 1
Meson decay widths which have been taken into account in the fit of the scale-dependent strength, γ. Some properties of these mesons are also shown.

Meson	I	J	P	C	Mass (MeV)	$\Gamma_{\text{Exp.}}$ (MeV)	
$D_1(2420)^{\pm}$	1/2	1	+1	–	2423.4 ± 3.1	25 ± 6	[21]
$D_2^*(2460)^{\pm}$	1/2	2	+1	–	2464.4 ± 1.9	37 ± 6	[21]
$D_{s1}(2536)^{\pm}$	0	1	+1	–	2535.12 ± 0.25	1.03 ± 0.13	[22]
$D_{s2}^*(2575)^{\pm}$	0	2	+1	–	2571.9 ± 0.8	17 ± 4	[21]
$\psi(3770)$	0	1	−1	−1	3778.1 ± 1.2	27.5 ± 0.9	[21]
$\Upsilon(4S)$	0	1	−1	−1	10579.4 ± 1.2	20.5 ± 2.5	[21]

$^3P_0$ model

Table 3
Strong total decay widths calculated through the $^3P_0$ model of the mesons which belong to charmed, charmed-strange, hidden charm and hidden bottom sectors. The value of the parameter γ in every sector is given by Eq. (10).

Meson	I	J	P	C	n	Mass (MeV)	$\Gamma_{\text{Exp.}}$ (MeV)	[21]	$\Gamma_{\text{The.}}$ (MeV)
$D^*(2010)^{\pm}$	0.5	1	-1	–	1	2010.28 ± 0.13	$0.096 \pm 0.004 \pm 0.022$		0.036
$D_0^*(2400)^{\pm}$	0.5	0	$+1$	–	1	$2403 \pm 14 \pm 35$	$283 \pm 24 \pm 34$		212.01
$D_1(2420)^{\pm}$	0.5	1	$+1$	–	1	2423.4 ± 3.1	25 ± 6		25.27
$D_1(2430)^0$	0.5	1	$+1$	–	2	$2427 \pm 26 \pm 25$	$384^{+107}_{-75} \pm 74$		229.12
$D_2^*(2460)^{\pm}$	0.5	2	$+1$	–	1	2464.4 ± 1.9	37 ± 6		64.07
$D(2550)^0$	0.5	0	-1	–	2	$2539.4 \pm 4.5 \pm 6.8$	$130 \pm 12 \pm 13$	[29]	132.07
$D^*(2600)^0$	0.5	1	-1	–	2	$2608.7 \pm 2.4 \pm 2.5$	$93 \pm 6 \pm 13$	[29]	96.91
$D_J(2750)^0$	0.5	$\begin{bmatrix} 2 \\ 3 \end{bmatrix}$	-1	–	1	$2752.4 \pm 1.7 \pm 2.7$	$71 \pm 6 \pm 11$	[29]	$\begin{bmatrix} 229.86 \\ 107.64 \end{bmatrix}$
$D_J^*(2760)^0$	0.5	1	-1	–	3	$2763.3 \pm 2.3 \pm 2.3$	$60.9 \pm 5.1 \pm 3.6$	[29]	338.63
$D_{s1}(2536)^{\pm}$	0	1	$+1$	–	1	2535.12 ± 0.25	1.03 ± 0.13	[22]	0.99
$D_{s2}^*(2575)^{\pm}$	0	2	$+1$	–	1	2571.9 ± 0.8	17 ± 4		18.67
$D_{s1}^*(2710)^{\pm}$	0	1	-1	–	2	$2710 \pm 2^{+12}_{-7}$	$149 \pm 7^{+39}_{-52}$	[30]	170.76
$D_{sJ}^*(2860)^{\pm}$	0	$\begin{bmatrix} 1 \\ 3 \end{bmatrix}$	-1	–	$\begin{bmatrix} 3 \\ 1 \end{bmatrix}$	$2862 \pm 2^{+5}_{-2}$	$48 \pm 3 \pm 6$	[30]	$\begin{bmatrix} 153.19 \\ 85.12 \end{bmatrix}$
$D_{sJ}(3040)^{\pm}$	0	1	$+1$	–	$\begin{bmatrix} 3 \\ 4 \end{bmatrix}$	$3044 \pm 8^{+30}_{-5}$	$239 \pm 35^{+46}_{-42}$	[30]	$\begin{bmatrix} 301.52 \\ 432.54 \end{bmatrix}$
$\psi(3770)$	0	1	-1	-1	3	3778.1 ± 1.2	27.5 ± 0.9		26.47
$\psi(4040)$	0	1	-1	-1	4	4039 ± 1	80 ± 10		111.27
$\psi(4160)$	0	1	-1	-1	5	4153 ± 3	103 ± 8		115.95
$X(4360)$	0	1	-1	-1	6	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$	[31]	113.92
$\psi(4415)$	0	1	-1	-1	7	4421 ± 4	62 ± 20		159.02
$X(4640)$	0	1	-1	-1	8	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}	[32]	206.37
$X(4660)$	0	1	-1	-1	9	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$	[31]	135.06
$\Upsilon(4S)$	0	1	-1	-1	6	10579.4 ± 1.2	20.5 ± 2.5		20.59
$\Upsilon(10860)$	0	1	-1	-1	8	10876 ± 11	55 ± 28		27.89
$\Upsilon(11020)$	0	1	-1	-1	10	11019 ± 8	79 ± 16		79.16

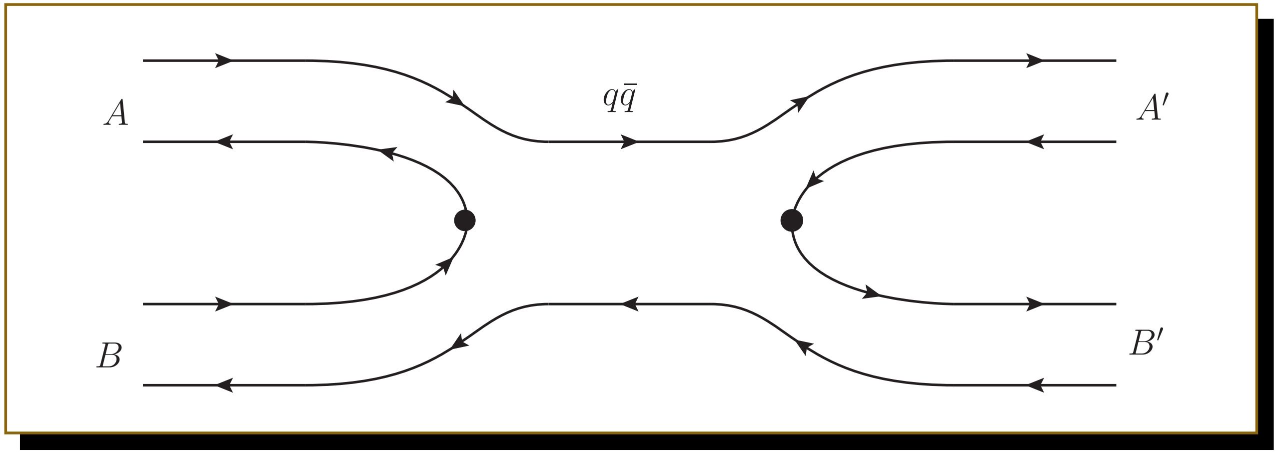
Coupling $q\bar{q}$ and $q\bar{q}\bar{q}q$ sectors

- **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 $\rightarrow$ 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,**

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

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

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

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

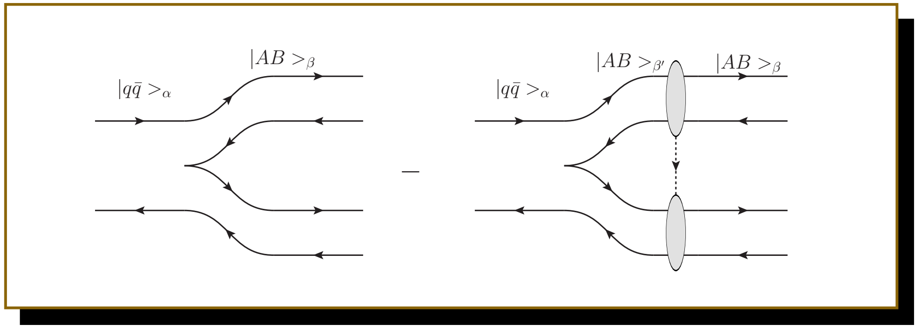
$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'} \phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

- **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



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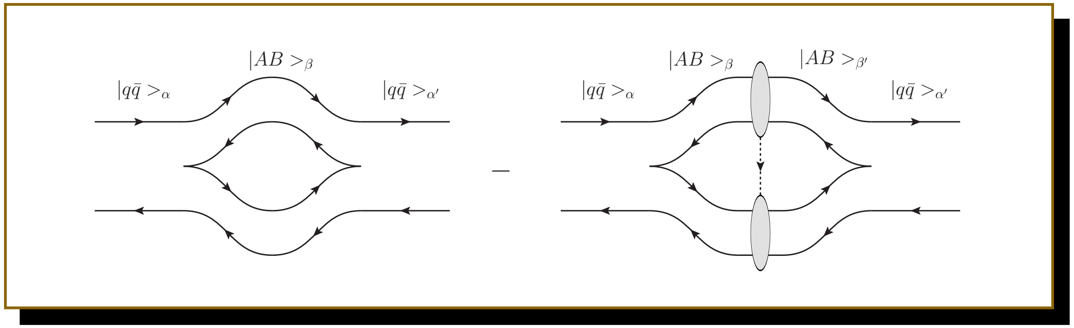
- **Non resonant contribution**
- **Resonant contribution**

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



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- **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)**

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

- **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**

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

HQSS

- **Our convention is that meson and antimeson are $q\bar{q}$ states so $C(D) = \bar{D}$ and $C(D^*) = -\bar{D}^*$.**
- **So**

$$C|AB; J_T M_T S_{AB} L\rangle = (-1)^{J_{AB}-J_A-J_B+L}|C(B)C(A); J_T M_T S_{BA} L\rangle$$

- **Our C-parity states are**

$$\begin{aligned}
C|D\bar{D}; J_T M_T 0L\rangle &= (-1)^L|D\bar{D}; J_T M_T 0L\rangle \\
|\Psi^{\pm}_{D\bar{D}^*}\rangle &= \frac{1}{\sqrt{2}}(|D\bar{D}^*; J_T M_T 1L\rangle \mp |D^*\bar{D}; J_T M_T 1L\rangle) \\
C|\Psi^{\pm}_{D\bar{D}^*}\rangle &= \pm(-1)^L|\Psi^{\pm}_{D\bar{D}^*}\rangle \\
C|D^*\bar{D}^*; J_T M_T S_{AB} L\rangle &= (-1)^{S_{AB}+L}|D^*\bar{D}^*; J_T M_T S_{BA} L\rangle
\end{aligned}$$

- **HQSS implies that (S waves)**

$$\begin{aligned}
H_{S_{23}} &= \delta_{S'_T S_T}\delta_{S'_{23} S_{23}}\delta_{S'_{14} S_{14}} \\
&\langle(\frac{1}{2}_{\bar{n}}, \frac{1}{2}_{n})S'_{23}(\frac{1}{2}_{\bar{c}}, \frac{1}{2}_{c})S'_{14}; S'_T|H|(\frac{1}{2}_{\bar{n}}, \frac{1}{2}_{n})S_{23}(\frac{1}{2}_{\bar{c}}, \frac{1}{2}_{c})S_{14}; S_T\rangle
\end{aligned}$$

HQSS

If we consider only S-waves for $D^{(*)}D^{(*)}$ states so we have

- **We only have H_0 and H_1**
- 0^{++} **sector**

$$
\begin{aligned}
|DD(0^{++})\rangle &= \frac{1}{2}|(\frac{1}{2}\,\frac{1}{2})0(\frac{1}{2},\frac{1}{2})0;0\rangle + \frac{\sqrt{3}}{2}|(\frac{1}{2}\,\frac{1}{2})1(\frac{1}{2},\frac{1}{2})1;0\rangle \\
|D^*D^*(0^{++})\rangle &= -\frac{\sqrt{3}}{2}|(\frac{1}{2}\,\frac{1}{2})0(\frac{1}{2},\frac{1}{2})0;0\rangle + \frac{1}{2}|(\frac{1}{2}\,\frac{1}{2})1(\frac{1}{2},\frac{1}{2})1;0\rangle
\end{aligned}
$$

So

$$
\begin{aligned}
\langle DD(0^{++})|H|DD(0^{++})\rangle &= \frac{1}{4}H_0 + \frac{3}{4}H_1 \qquad (C_{0a}) \\
\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle &= \frac{3}{4}H_0 + \frac{1}{4}H_1 \\
\langle DD(0^{++})|H|D^*D^*(0^{++})\rangle &= \langle D^*D^*(0^{++})|H|DD(0^{++})\rangle \\
&= \frac{\sqrt{3}}{4}(H_1 - H_0) \qquad (\sqrt{3}C_{0b})
\end{aligned}
$$

HQSS

We consider only S-waves for $D^{(*)}D^{(*)}$ states so we have

- 1^{+-} **sector**

$$
\begin{aligned}
|DD^*(1^{+-})\rangle &= \frac{1}{\sqrt{2}}\left[|(\frac{1}{2}\,\frac{1}{2})0(\frac{1}{2},\frac{1}{2})1;1\rangle - |(\frac{1}{2}\,\frac{1}{2})1(\frac{1}{2},\frac{1}{2})0;1\rangle\right] \\
\langle DD^*(1^{+-})|H|DD^*(1^{+-})\rangle &= \frac{1}{2}(H_0 + H_1)
\end{aligned}
$$

- 1^{++} **sector**

$$
\begin{aligned}
|DD^*(1^{++})\rangle &= |(\frac{1}{2}\,\frac{1}{2})1(\frac{1}{2},\frac{1}{2})1;2\rangle \\
\langle DD^*(1^{++})|H|DD^*(1^{++})\rangle &= H_1
\end{aligned}
$$

- 2^{++} **sector**

$$
\begin{aligned}
|D^*D^*(2^{++})\rangle &= -|(\frac{1}{2}\,\frac{1}{2})1(\frac{1}{2},\frac{1}{2})1;2\rangle \\
\langle D^*D^*(2^{++})|H|D^*D^*(2^{++})\rangle &= H_1
\end{aligned}
$$

HQSS

We find the relations

$$
\begin{aligned}
\frac{2}{\sqrt{3}}\langle D^*D^*(0^{++})|H|DD(0^{++})\rangle &= \langle DD(0^{++})|H|DD(0^{++})\rangle \\
&\quad -\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle \\
2\langle DD^*(1^{+-})|H|DD^*(1^{+-})\rangle &= \langle DD(0^{++})|H|DD(0^{++})\rangle \\
&\quad +\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle \\
\langle DD^*(1^{++})|H|DD^*(1^{++})\rangle &= \langle D^*D^*(2^{++})|H|D^*D^*(2^{++})\rangle \\
&= \frac{3}{2}\Big[\langle DD(0^{++})|H|DD(0^{++})\rangle \\
&\quad -\frac{1}{3}\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle\Big]
\end{aligned}
$$

HQSS

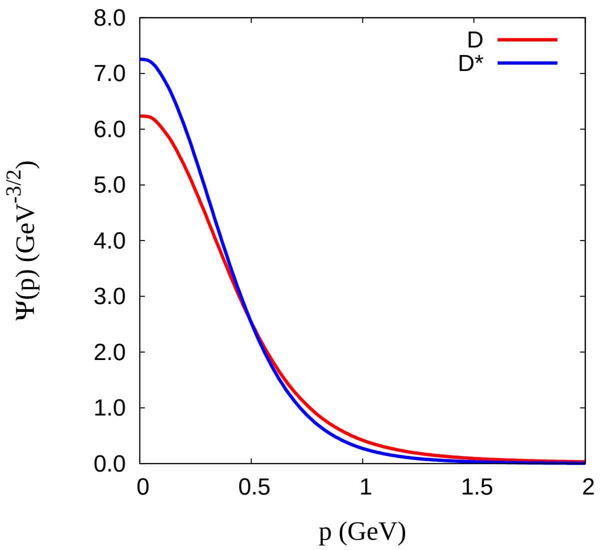
HQSS Breaking

- **Mass**

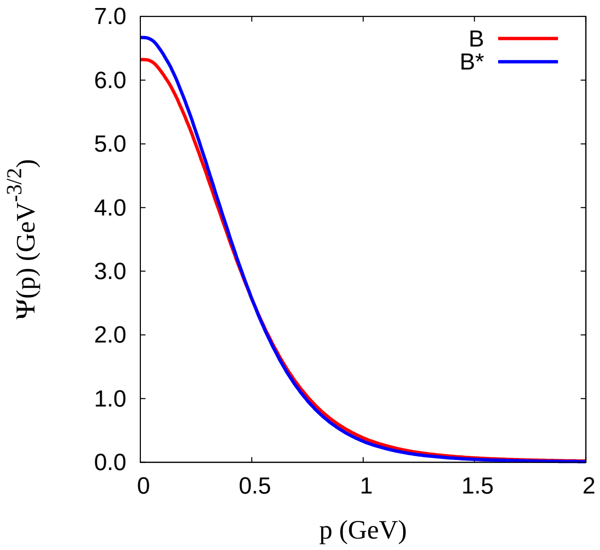
	Teo.(MeV)	**Exp.(MeV)**
D	**1896**	**1867**
D^*	**2017**	**2009**
B	**5275**	**5279**
B^*	**5315**	**5325**

- **Wave function**

Charm sector



Bottom sector

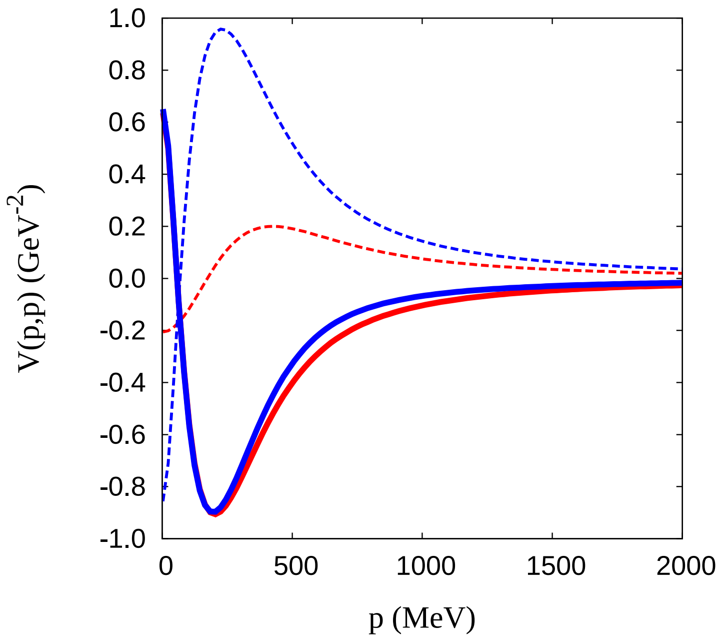


HQSS

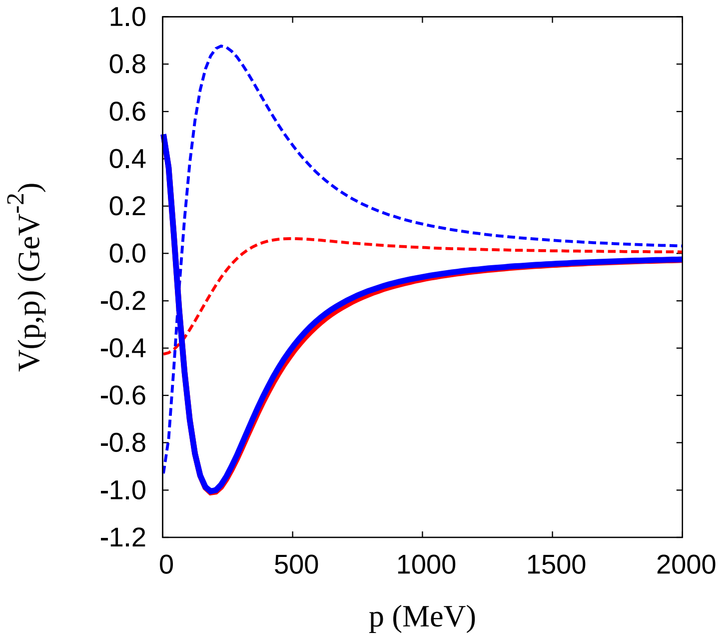
We find the relations

$$\frac{2}{\sqrt{3}}\langle D^* D^*(0^{++})|H|DD(0^{++})\rangle \quad = \quad \langle DD(0^{++})|H|DD(0^{++})\rangle - \langle D^* D^*(0^{++})|H|D^* D^*(0^{++})\rangle$$

Charm sector



Bottom sector



$\langle DD(0^{++})|H|DD(0^{++})\rangle$

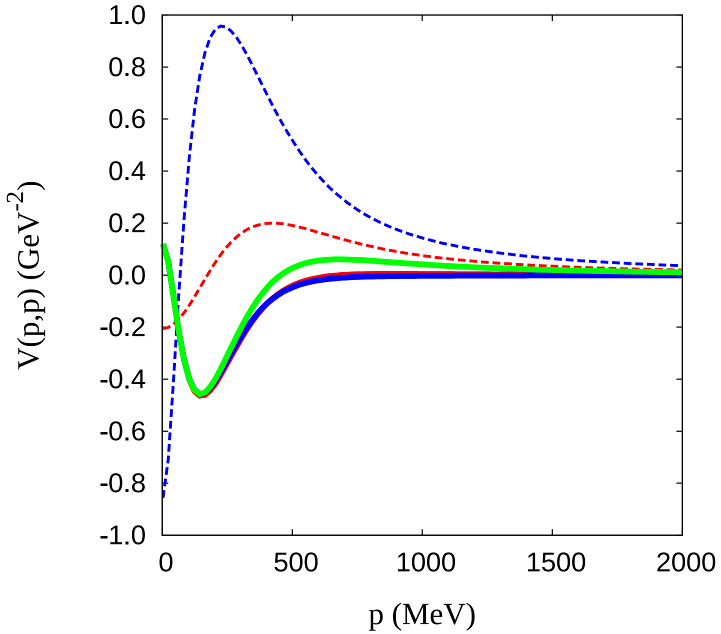
$\langle D^* D^*(0^{++})|H|D^* D^*(0^{++})\rangle$

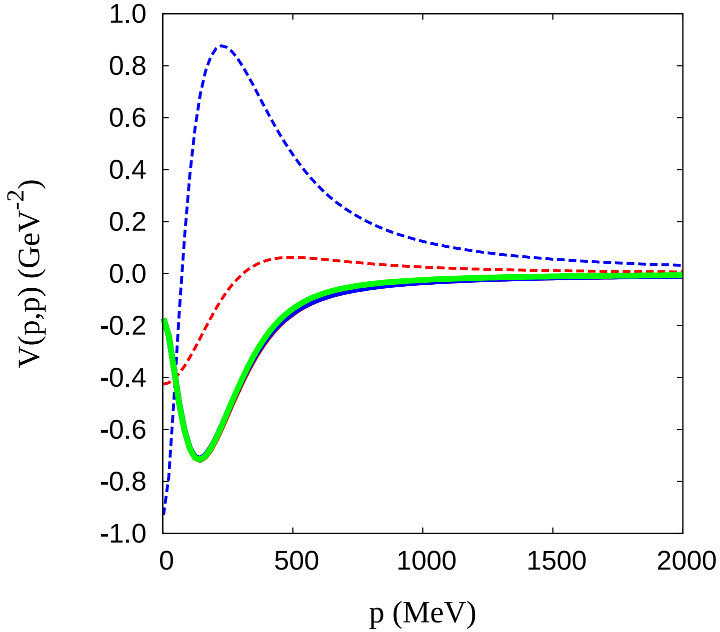
HQSS

We find the relations

$$\langle DD^*(1^{++})|H|DD^*(1^{++})\rangle = \langle D^*D^*(2^{++})|H|D^*D^*(2^{++})\rangle$$
$$= \frac{3}{2}\left[\langle DD(0^{++})|H|DD(0^{++})\rangle - \frac{1}{3}\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle\right]$$

Charm sector **Bottom sector**



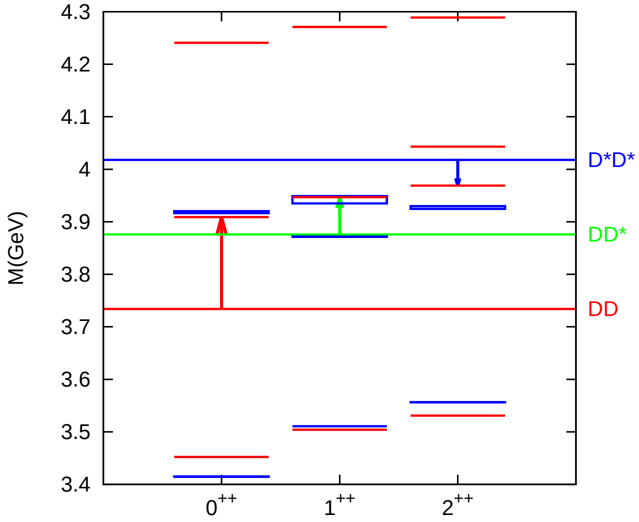


$\langle DD(0^{++})|H|DD(0^{++})\rangle$

$\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle$

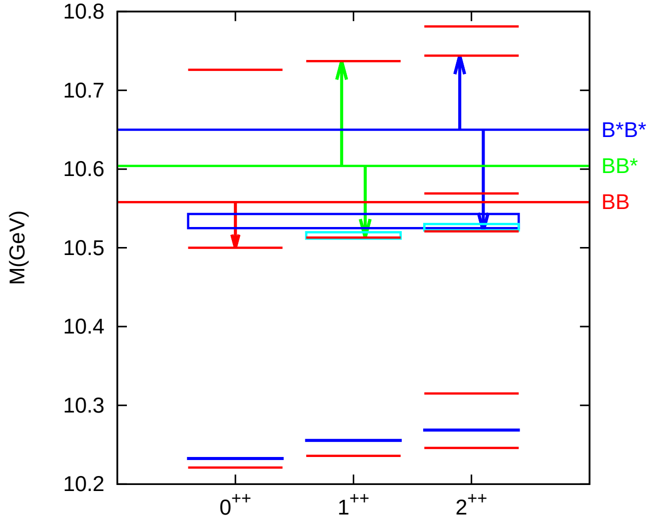
HQSS

Charmonium



0^{++}	1^{++}	2^{++}
3452	**3504**	**3531**
3909	**3947**	**3969**
		4043
4241	**4271**	**4289**

Bottomonium



0^{++}	1^{++}	2^{++}
9855	**9874**	**9886**
10221	**10236**	**10246**
		10315
10500	**10513**	**10521**
		10569
10726	**10737**	**10744**
		10781

The $X(3872)$

- ${}^3S_1$ **and** ${}^3D_1$ DD^* **partial waves included.**
- **Coupling to** 1^{++} **ground and first excited** $c\bar{c}$ **states with bare masses within the model:** $c\bar{c}(1^3P_1) \to \ M = 3503{,}9\ MeV$ $c\bar{c}(2^3P_1) \to \ M = 3947{,}4\ MeV$ **and**
- **Isospin breaking** $M_{D^\pm} + M_{D^{*\pm}} \neq M_{D^0} + M_{D^{*0}}$

Parameter free calculation.

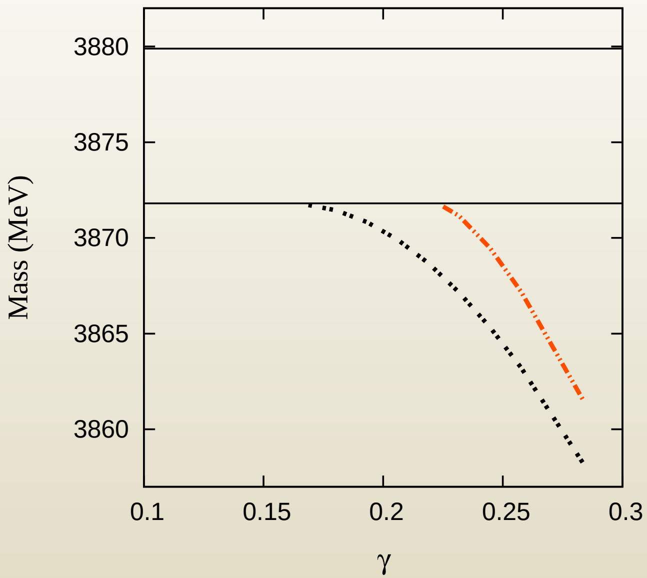
$M\,(MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^\pm D^{*\mp}$	**Assignment**
3937	$0\,\%$	$79\,\%$	$7\,\%$	$14\,\%$	
3863	$1\,\%$	$30\,\%$	$46\,\%$	$23\,\%$	$\to X(3872)$
3467	$95\,\%$	$0\,\%$	$2{,}5\,\%$	$2{,}5\,\%$	

- **Isospin probabilities:** $\mathcal{P}_{I=0} = 66\,\%$, $\mathcal{P}_{I=1} = 3\,\%$, $\mathcal{P}_{c\bar{c}} = 30\,\%$.
- **Fine tune** ${}^3P_0$ γ **strength parameter to** E_{bind}. $\mathcal{P}_{I=0} \sim 70\,\%$, $\mathcal{P}_{I=1} \sim 23\,\%$, $\mathcal{P}_{c\bar{c}} \sim 7\,\%$
- **P.G. Ortega, J. Segovia, DRE, F. Fernández, Phys. Rev. D 81 (2010)**
- **P.G. Ortega, DRE, F. Fernández, J. Phys. G 40 (2013)**
- **M. Takizawa, S. Takeuchi, PTEP 9 (2013) at hadron level**

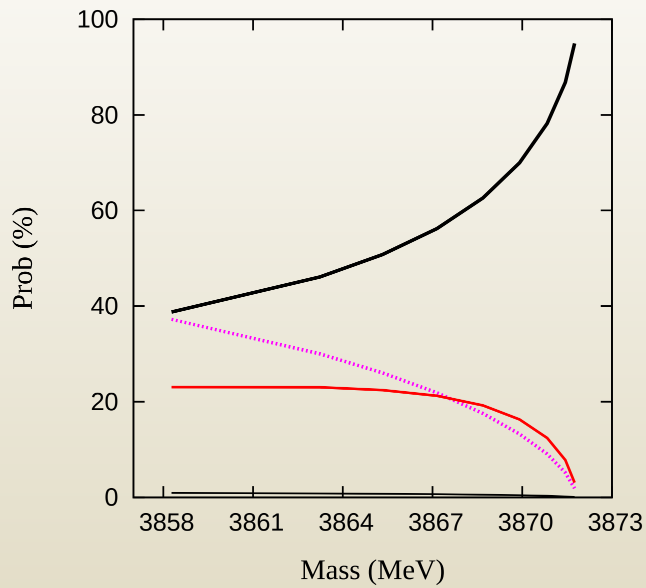
Dependence on γ

No $X(3872)$ without coupling to $c\bar{c}$ states

$X(3872)$ Mass vs. γ



Probabilities for different channels vs. $X(3872)$ Mass



No DD^* interaction included.
DD^* interaction included.

$D^0\bar{D}^{*0}$ component
D^+D^{*-} component
$c\bar{c}(2P)$ component
$c\bar{c}(1P)$ component

The 2^{++} charmonium sector

- **We couple the** $c\bar{c}(2\,^3P_2)$, $c\bar{c}(1\,^3F_2)$, $DD(^1D_2)$, $DD^*(^3D_2)$, $D_sD_s(^1D_2)$, $D^*D^*(^5S_2)$, $D^*D^*(^1D_2)$, $D^*D^*(^5D_2)$
- **No new state appears, we only find the original $c\bar{c}$ states dressed**

M(MeV)	$c\bar{c}(2\,^3P_2)$	$c\bar{c}(1\,^3F_2)$	$DD(^1D_2)$	$DD^*(^3D_2)$
3887	38.0	0.2	47.8	10.0
4012	0.9	52.1	21.6	21.0

M(MeV)	$D_sD_s(^1D_2)$	$D^*D^*(^5S_2)$	$D^*D^*(^1D_2)$	$D^*D^*(^5D_2)$
3887	0.2	2.4	0.2	1.1
4012	2.6	0.5	0.7	0.6

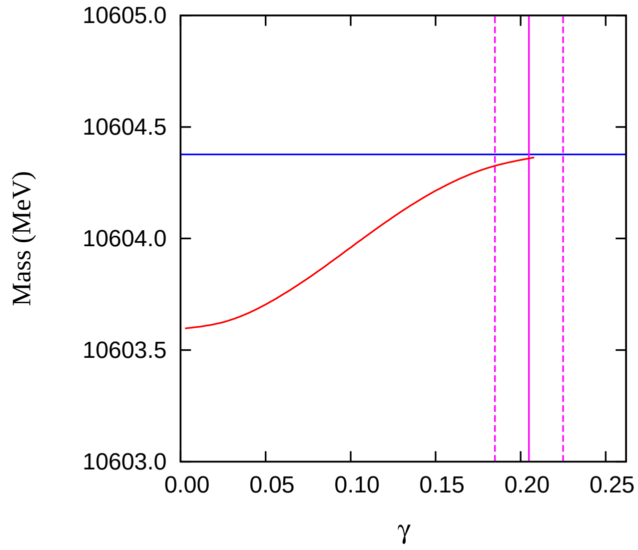
M(MeV)	Γ_{DD} (MeV)	Γ_{DD^*} (MeV)	$\Gamma_{D_sD_s}$ (MeV)
3887	12.3	21.6	-
4012	0.6	49.5	1.6

The $X_b\ 1^{++}$ state

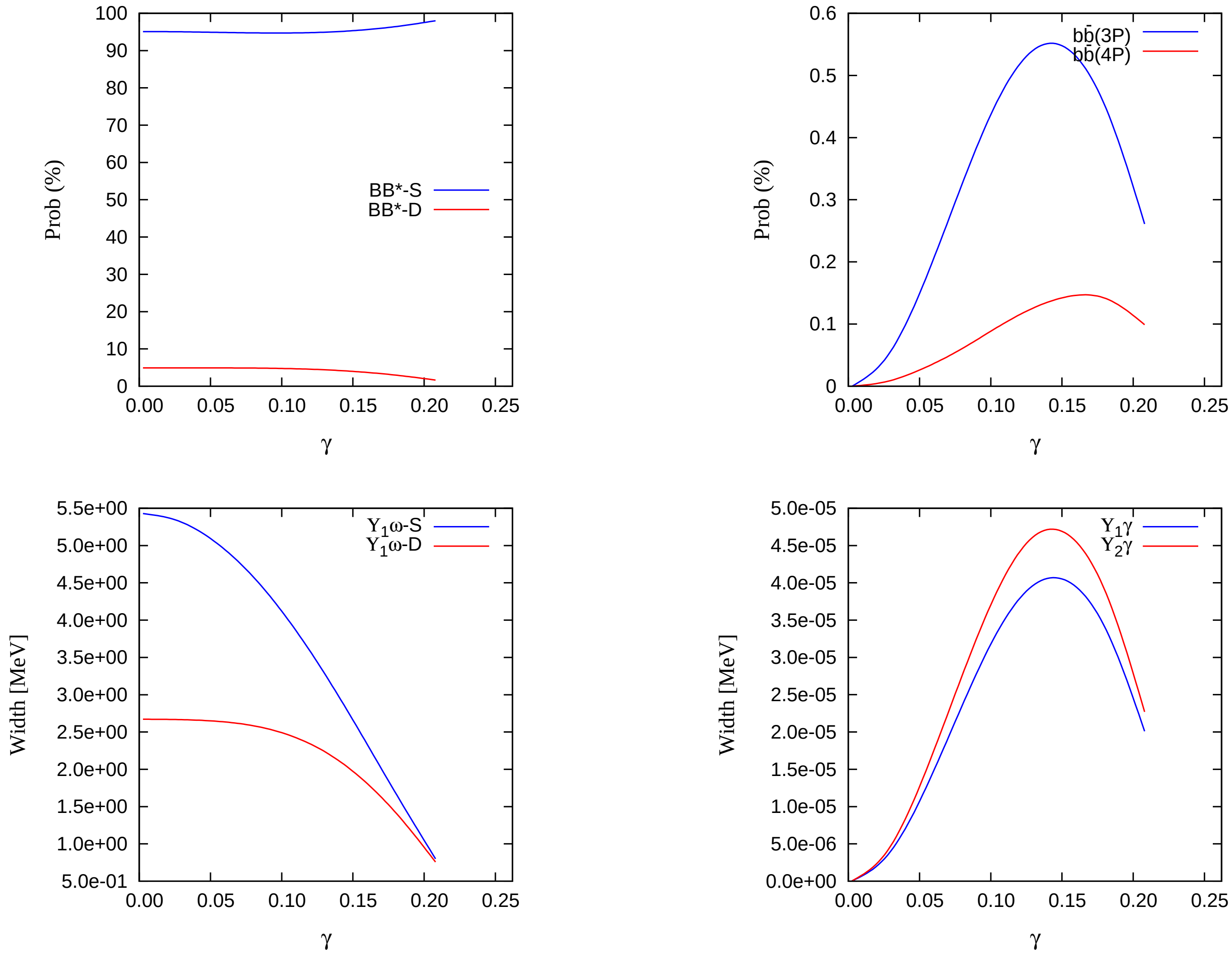
- **Channels:** $b\bar{b}(3\,^3P_1)$, $b\bar{b}(4\,^3P_1)$, $B\bar{B}^*(\,^3S_1)$, $B\bar{B}^*(\,^3D_1)$.
- **The** $b\bar{b}(3\,^3P_1)$ **has been measured by LHCb, JHEP 10, 088 (2014)**

$$\begin{aligned} M(3\,^3P_1) &= 10515{,}7^{+2{,}2+1{,}5}_{-3{,}9-2{,}1}\,MeV \\ M(3\,^3P_2)-M(3\,^3P_1) &= 10{,}5\,MeV \end{aligned}$$

- **Very shallow bound state with** $E_{bind}=-0{,}016$ **MeV and** $\Gamma=1{,}7$ **MeV**
- **No definite conclusions can be obtained about its existence**

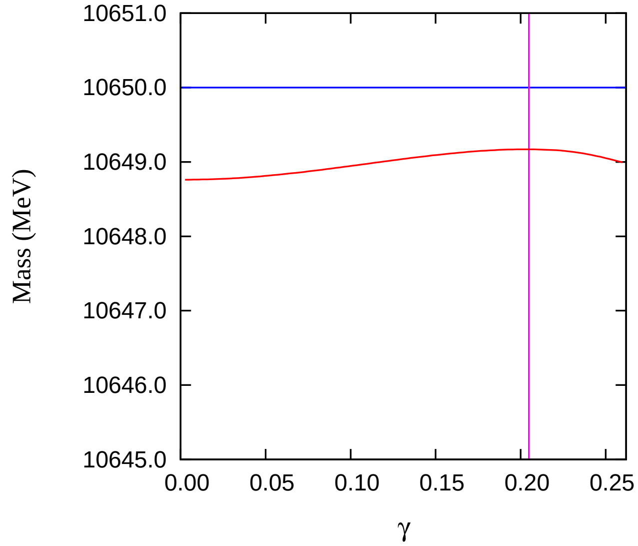


X_b properties



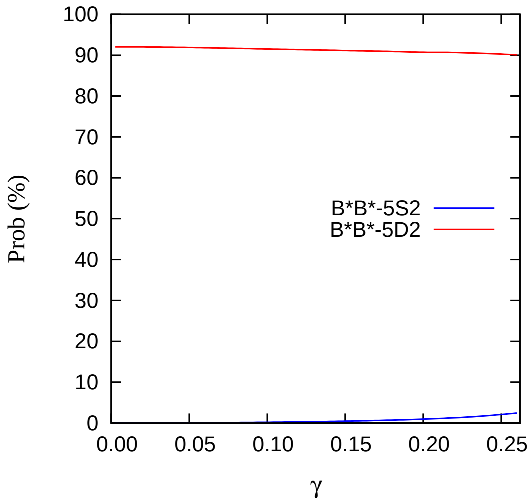
The $X_b\, 2^{++}$ state

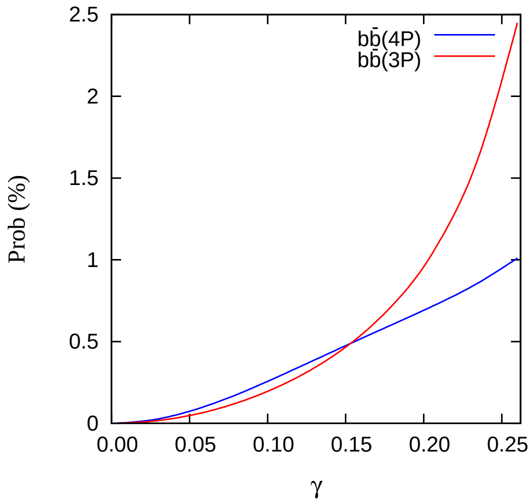
- **Channels:** $b\bar{b}(3\,^3P_2)$, $b\bar{b}(4\,^3P_2)$, $b\bar{b}(2\,^3F_2)$, $B^*\bar{B}^*(\,^5S_2)$, $B^*\bar{B}^*(\,^5D_2)$, $B^*\bar{B}^*(\,^1D_2)$.

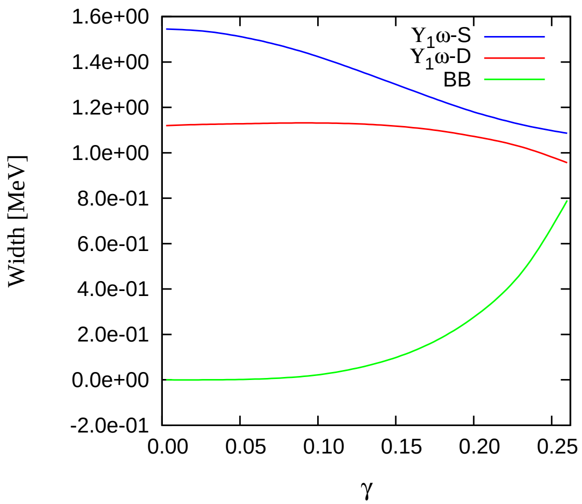


M **(MeV)**	$b\bar{b}(3\,^3P_2)$	$b\bar{b}(4\,^3P_2)$	$B^*\bar{B}^*(\,^5S_2)$	$B^*\bar{B}^*(\,^5D_2)$	$B^*\bar{B}^*(\,^1D_2)$
10469.2	**0.71**	**1.03**	**90.7**	**7.4**	**0.01**

X_b properties







Summary

- We have studied the partners of the $X(3872)$ using a Chiral Quark model
- HQSS relations are almost fulfilled by the interaction Hamiltonian
- HQSS breaking effects are mostly due to threshold effects
- The coupling to $c\bar{c}$ and $b\bar{b}$ states produces discrepancies from HQSS expectations
- The 1^{++} state in the charmonium sector is bound due to the coupling with the $2P$ $c\bar{c}$ state
- In the 2^{++} charmonium sector we don't have a new state, however we have a dressed $c\bar{c}$ state with a mass of 4012 MeV.
- In the bottom sector the 1^{++} state have a strong repulsion due to the coupling with the $3P$ state and no definite conclusions about its existence can be obtained
- In the bottom sector the 2^{++} state is bounded with and without coupling to $b\bar{b}$ states