Partners of the $X(3872)$ 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

$X(3872)$ and its partners

The $X(3872)$ was discovered by Belle in 2003 and very soon confirmed by CDFII, D0 and BaBar

The Quantum numbers have been measured by LHCb in 2014 to be $J^{PC} = 1^{++}$

The mass is very close to the DD^* threshold so it is a well accepted candidate for a DD^* molecule

One would expect partners with other quantum numbers in the charmonium and bottomonium sectors.

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

- Heavy Quark Spin Symmetry (HQSS), independence of the heavy quark spin
- Heavy Flavour Symmetry (HFS), independece on the c or b flavours

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 $V^{LO}_{DD^*}(1^{++}) = V^{LO}_{BB^*}(1^{++})$
- A 2^{++} isoscalar B^*B^* state at 10.6 GeV $V^{LO}_{DD^*}(2^{++}) = V^{LO}_{BB^*}(2^{++})$
- Isovector partners of Z_b in the chamonium sectors are predicted

The Chiral Quark Model

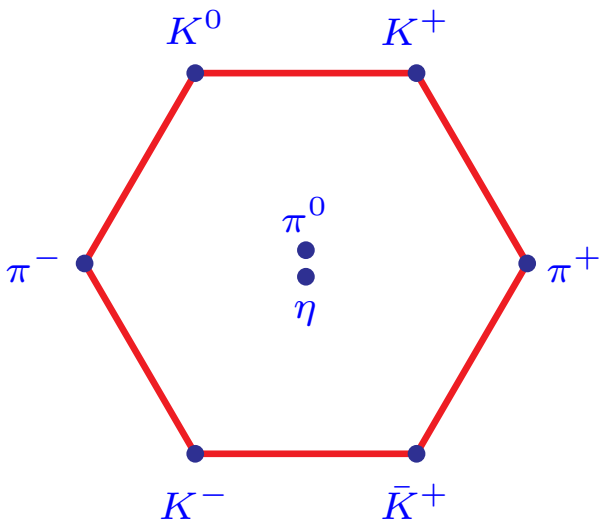
F. Fernández *et al.*, **J. Phys. G 19 (1993), J. Vijande** *et al.*, **J. Phys. G 31 (2005)**

- **Spontaneous Chiral Symmetry Breaking** $\rightarrow$
  $\rightarrow$ **Golstone bosons**

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

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

  $\rightarrow$ **Goldstone bosons exchange**
  $\rightarrow$ **Scalar boson exchanges**



- **Gluon coupling**

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

  $\rightarrow$ **One gluon exchange**

- **Confinement**
- **Interactions**:

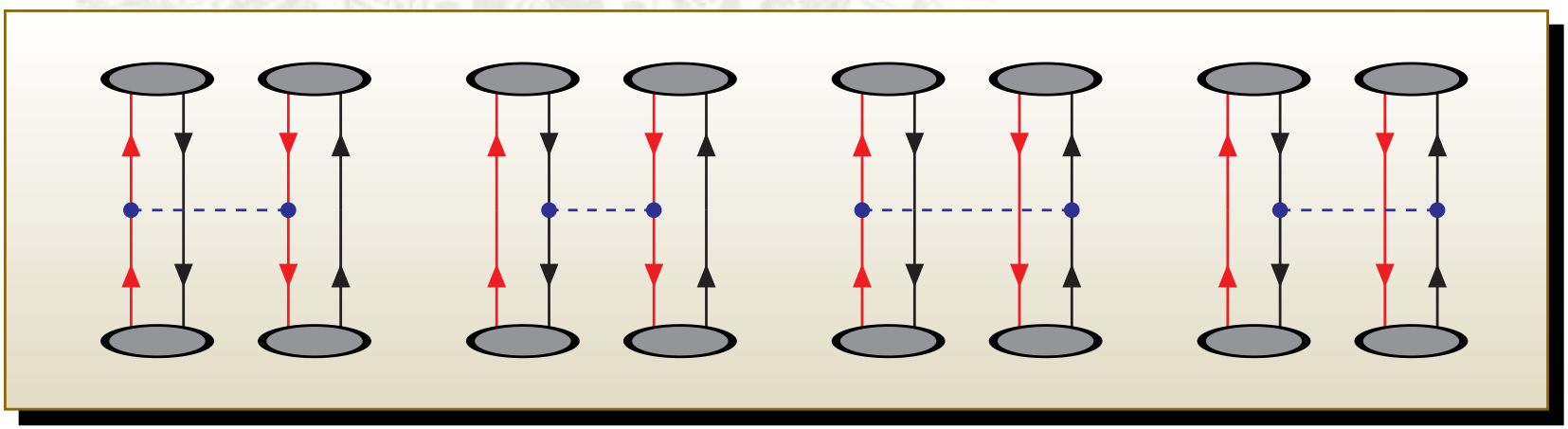
$$V_{q_iq_j} = \begin{cases} q_iq_j = nn \Rightarrow V_{CON} + V_{OGE} + V_{GBE} + V_{SBE} \\ q_iq_j = nQ \Rightarrow V_{CON} + V_{OGE} \\ q_iq_j = QQ \Rightarrow V_{CON} + V_{OGE} \end{cases}$$

The $M_1 M_2$ system

- **Quark interactions** $\rightarrow$ **Cluster interaction** **(Resonanting Group Method)**
- **For the** DD^* **system only direct RGM Potential:**

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

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



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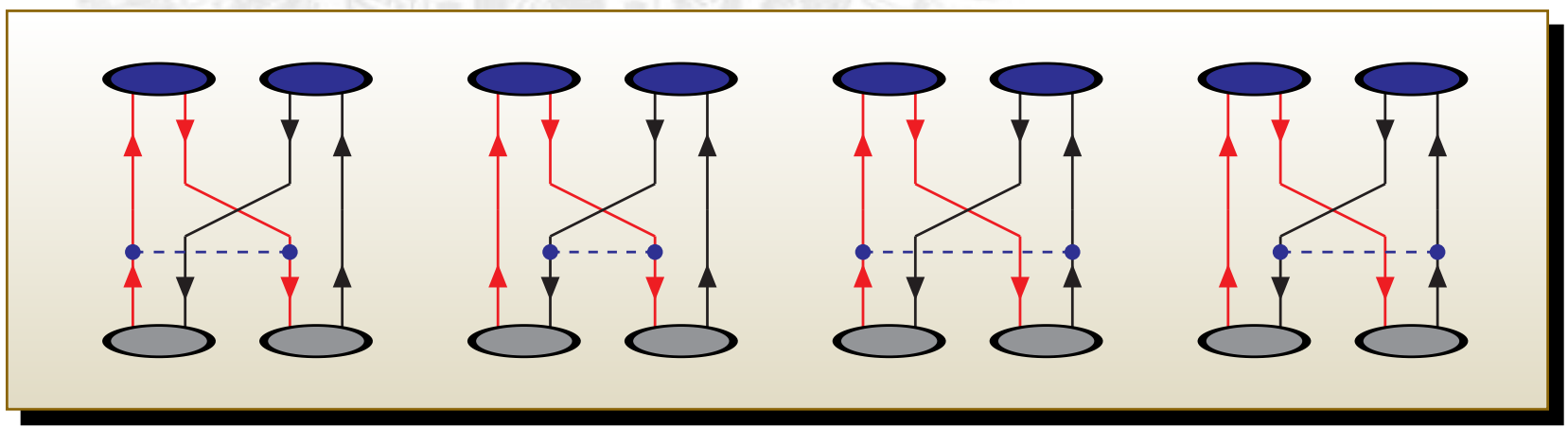
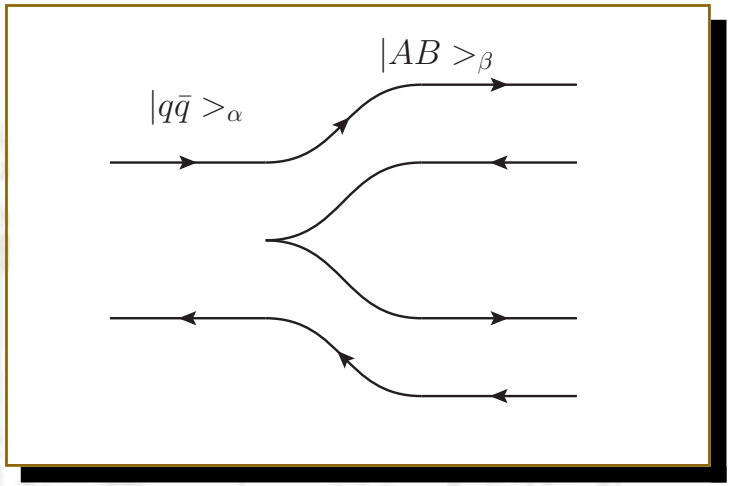
& \phi^*_A(\vec{p}_{\xi'_A})\phi^*_B(\vec{p}_{\xi'_B})V_{ij}(\vec{P}', \vec{P}_i)\phi_A(\vec{p}_{\xi_A})\phi_B(\vec{p}_{\xi_B})
\end{aligned}
$$

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

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



$^3P_0$ model

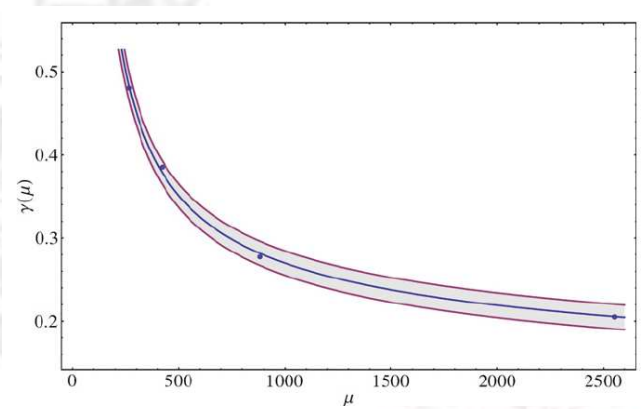


J. Segovia, DRE, F. Fernández, Phys. Lett. B 715, 322 (2012)

Running coupling

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

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



- **Fitted to 6 states in the $c\bar{n}$, $c\bar{s}$, $c\bar{c}$ and $b\bar{b}$ sectors.**
- **Overall good description of the widths of other states in these sectors.**
- **Good description of the $b\bar{n}$ sector not included in the fit.**

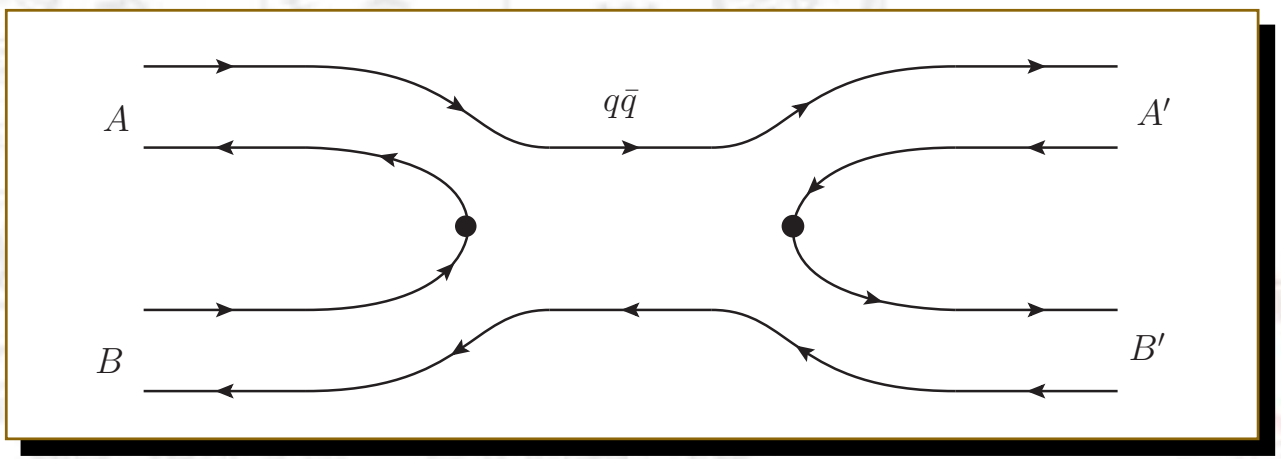
Coupling $q\bar{q}$ and $q\bar{q}q\bar{q}$ sectors

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

Resonance states

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

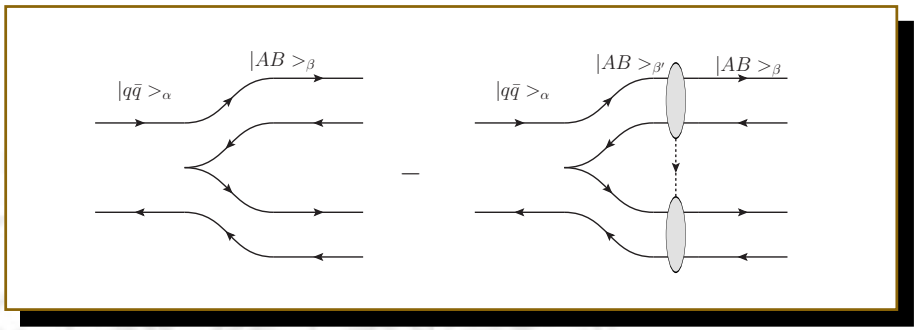
$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'}\phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

- **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



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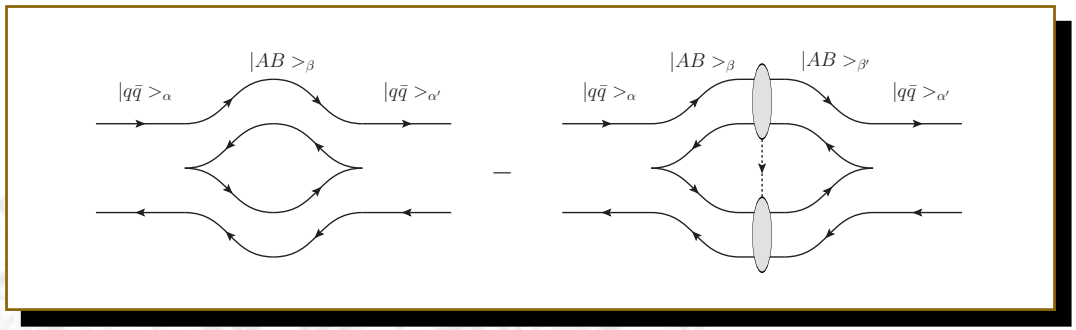
- **Non resonant contribution**
- **Resonant contribution**

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



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

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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

HQSS implies the relations (S waves)

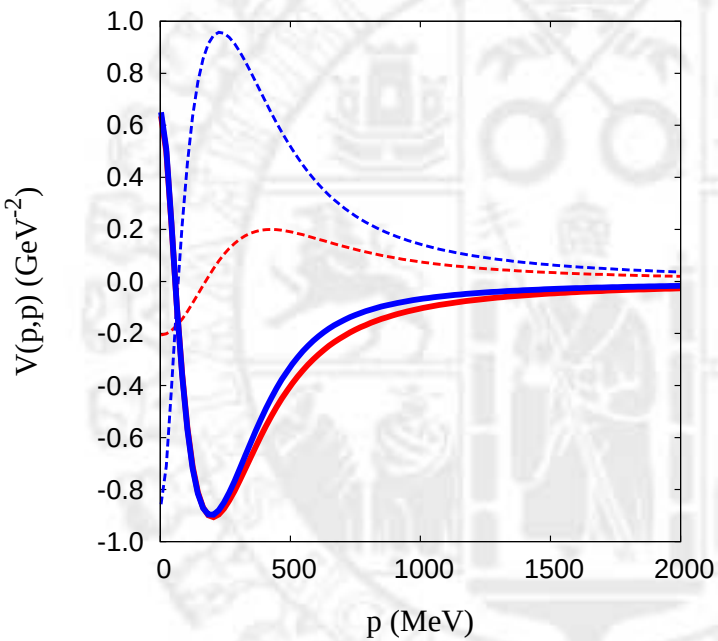
$$
\begin{aligned}
\frac{2}{\sqrt{3}}\langle D^*D^*(0^{++})|H|DD(0^{++})\rangle &= \langle DD(0^{++})|H|DD(0^{++})\rangle \\
&\quad -\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle \\
2\langle DD^*(1^{+-})|H|DD^*(1^{+-})\rangle &= \langle DD(0^{++})|H|DD(0^{++})\rangle \\
&\quad +\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle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

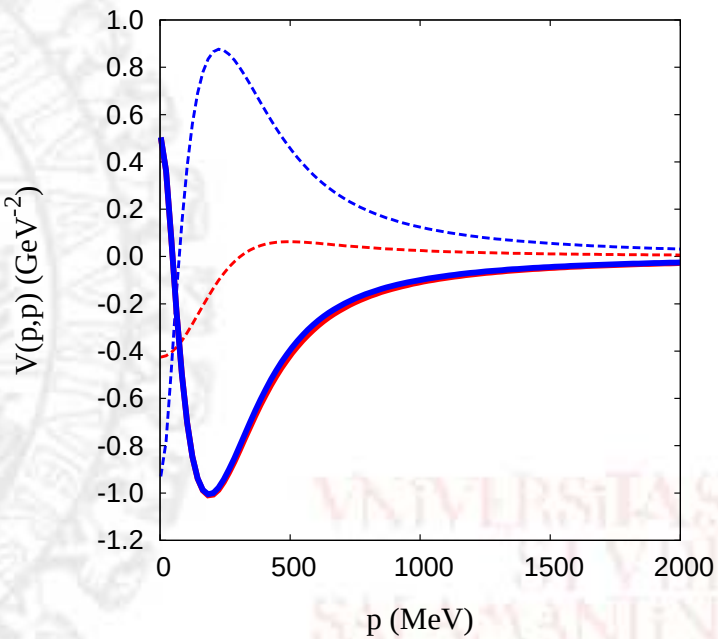
HQSS

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**





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

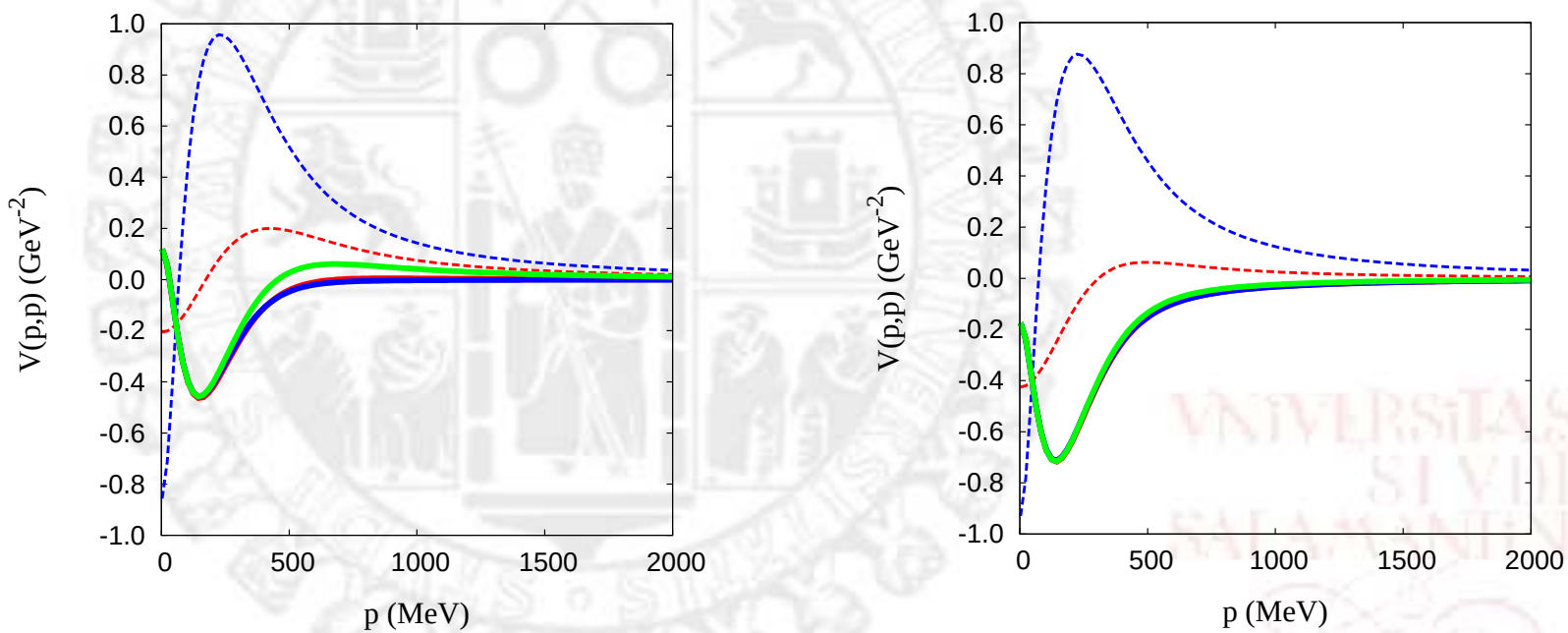
$\langle D^*D^*(0^{++})|H|D^*D^*(0^{++})\rangle$

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 breaking

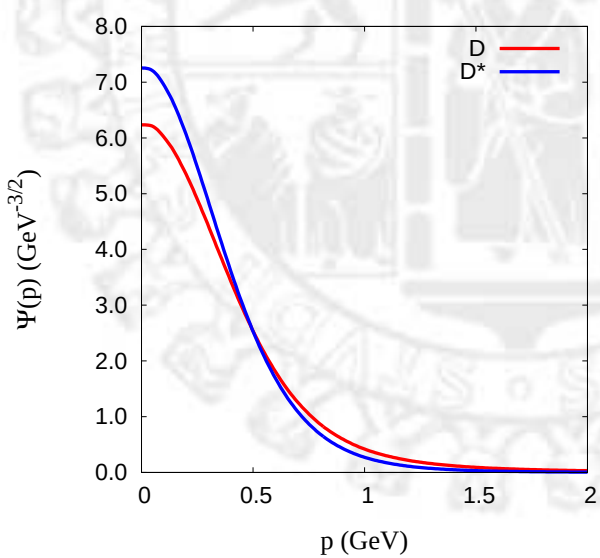
HQSS slightly broken

- **Mass**

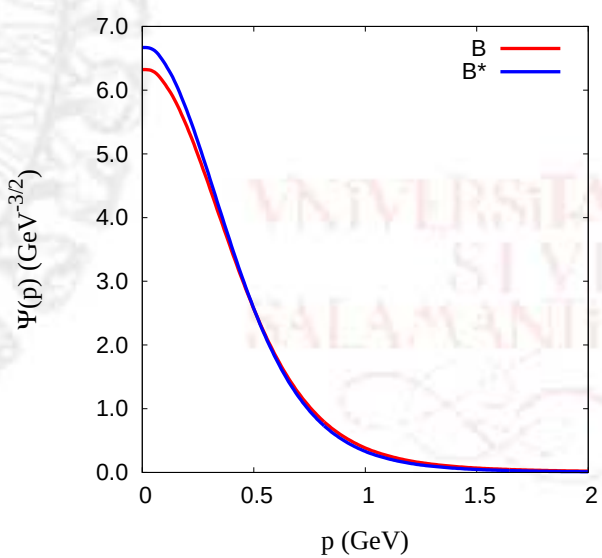
	Theo.(MeV)	Exp.(MeV)
D	1896	1867
D^*	2017	2009
B	5275	5279
B^*	5315	5325

- **Wave function**

$D^{(*)}$



$B^{(*)}$



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: $c\bar{c}(1^3P_1) \rightarrow\ M = 3503{,}9\ MeV$ $c\bar{c}(2^3P_1) \rightarrow\ M = 3947{,}4\ MeV$ and
- Isospin breaking $M_{D^\pm} + M_{D^{*\pm}} \neq M_{D^0} + M_{D^{*0}}$

Parameter free calculation.

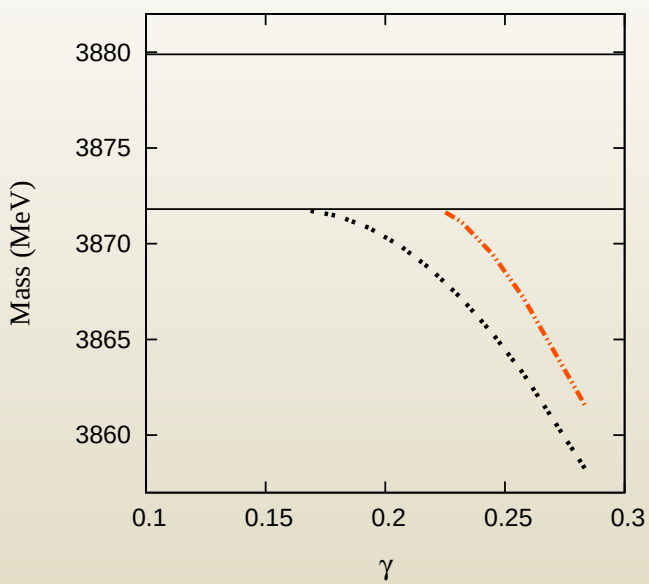
$M\ (MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^\pm D^{*\mp}$	Assignment
3937	0 %	79 %	7 %	14 %	
3863	1 %	30 %	46 %	23 %	$\rightarrow X(3872)$
3467	95 %	0 %	2,5 %	2,5 %	

- 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

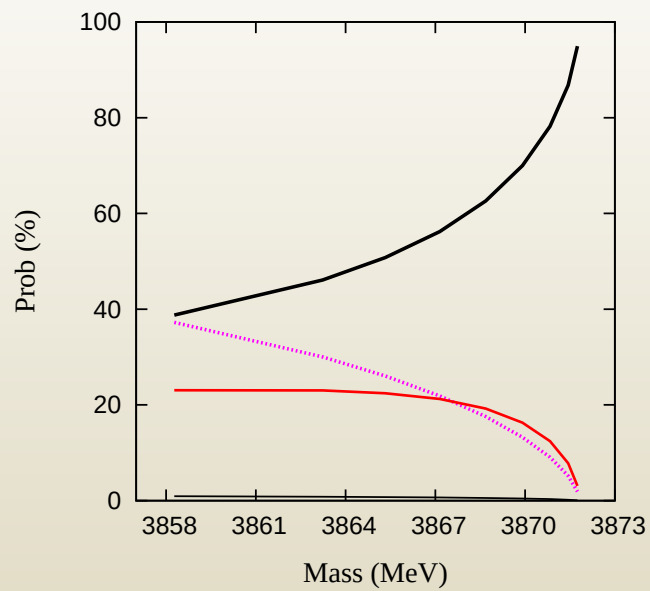
Dependence on γ

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**

HQSS and HFS breaking

- We investigate the deviation on HQSS and HFS expections induced by the coupling to $Q\bar{Q}$ states
- Our prescription is to include the states above and below the relevant threshold.
- We only include thresholds where an S wave is present
- In the 0^{++} sector we include DD (BB) and D^*D^* (B^*B^*) ${}^1S_0$ waves
- In the 1^{++} sector we include DD^* (BB^*) ${}^3S_1$ and ${}^3D_1$ waves
- In the 1^{+-} sector we include DD^* (BB^*) and D^*D^* (B^*B^*) ${}^3S_1$ and ${}^3D_1$ waves
- In the 2^{++} sector we include D^*D^* (B^*B^*) ${}^5S_2$, ${}^1D_2$ and ${}^5D_2$ waves

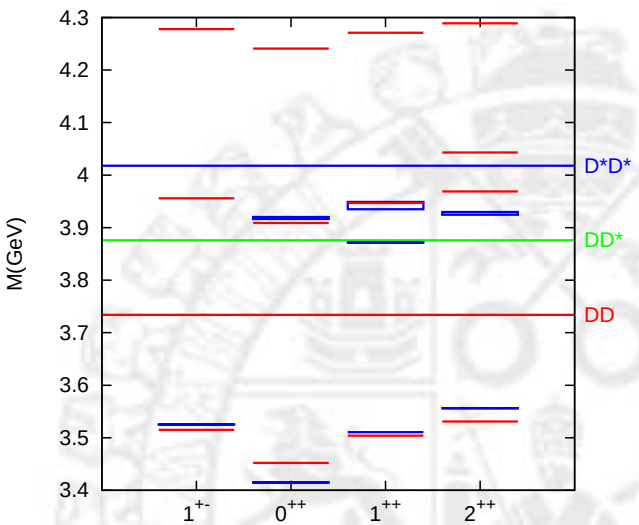
Additional states to naive quark model results

Charmonium	1^{+-}	0^{++}	1^{++}	2^{++}
HQSS and HFS	3815/3955	3710/Input	Input	4012
coupling $Q\bar{Q}$	No	No	$X(3872)$	No

Bottomonium	1^{+-}	0^{++}	1^{++}	2^{++}
HQSS and HFS			10580	10600
coupling $Q\bar{Q}$	No	10621	?	10648

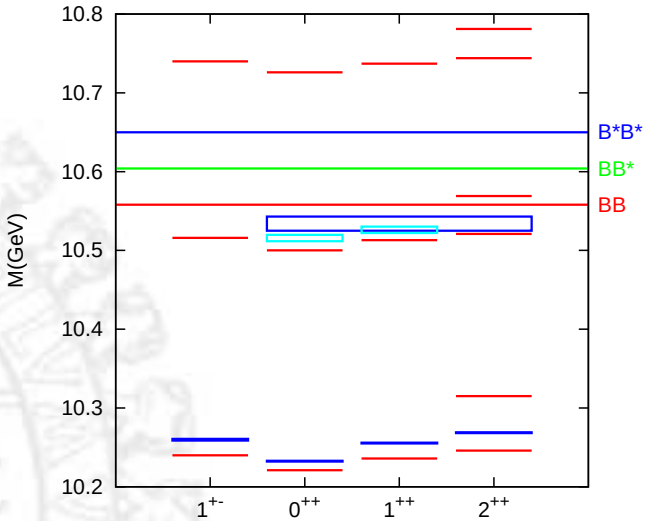
Spectrum

Charmonium



1^{+-}	0^{++}	1^{++}	2^{++}
3515	3452	3504	3531
3956	3909	3947	3969
			4043
4278	4241	4271	4289

Bottomonium



1^{+-}	0^{++}	1^{++}	2^{++}
9879	9855	9874	9886
10240	10221	10236	10246
			10315
10516	10500	10513	10521
			10569
10740	10726	10737	10744
			10781

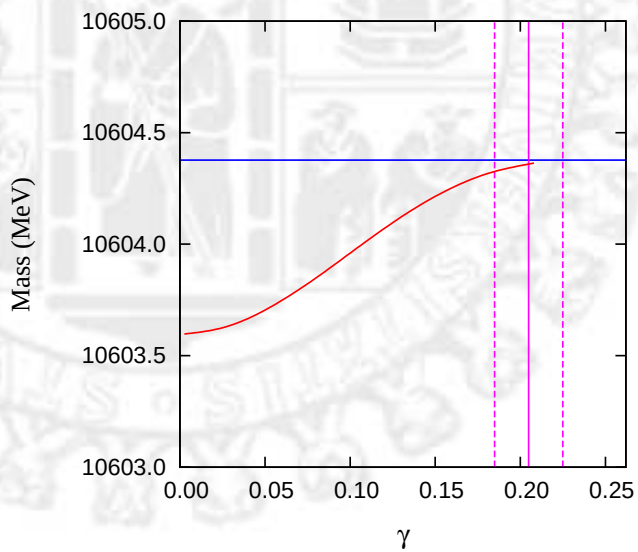
- Small breaking in $c\bar{c}$ and $b\bar{b}$
- Sronger breaking in meson-meson thresholds

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)**

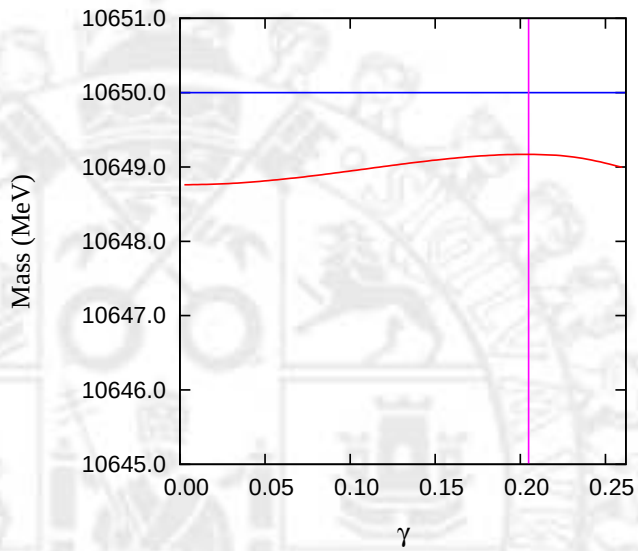
$$M(3\,^3P_1) = 10515{,}7^{+2{,}2+1{,}5}_{-3{,}9-2{,}1}\ MeV$$
$$M(3\,^3P_2) - M(3\,^3P_1) = 10{,}5\ MeV$$

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



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**

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 close to the D^*D^* threshold.
- 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
- In the 0^{++} and 1^{+-} channels only a new state appears in the 0^{++} botomonium spectrum.
- Coupling with $Q\bar{Q}$ states can induced discrepancies from $HQSS$ and HFS expectations