The non-perturbative unquenched quark model

XIIth Quark Confinement and the Hadron Spectrum

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Introduction

- The naive quark model has been very successful classifying the particle spectra
- However higher Fock components should be included (already considered in the Cornell model)
- Unquenching the quark model includes these effects in a similar way as lattice unquenched calculations using dynamical quarks
- The higher Fock components became more relevant in 2003 with the $X(3872)$ an other XYZ states
- The $X(3872) \to J/\Psi\pi\pi$ decay is a clear indication that it can not be a pure $c\bar{c}$ state and can be naturally explained if a DD^* component is present.
- Excited states can be close to a hadron-hadron threshold and the multiquark component can be enhanced
- One expects ground states (usually far from thresholds) to have small multiquark components

Introduction

- Different approaches
  - Mass shift and mixing (as Phys. Rev. D17, 3090)
  - Systems of one or more $q\bar{q}$ coupled with close two meson channels (as Phys. Rev. D21, 772)
  - Unitarized quark models including two meson loops (as Phys. Rev. D29, 110)
- Models usually study the influence of two-meson loops on the $c\bar{c}$ states
  - E. Eichten et al., Phys. Rev. D21 203
  - E. van Beveren and G. Rupp, hep-ph/0304105
  - J. Ferreti et al., Phys. Rev. D90 054010
- A slightly different point of view P.G. Ortega et al., PRD 81, 054023
- The influence on the dynamics of two meson channels of $q\bar{q}$ states is studied
- This allows to study the shifts in mass and width of naive quark model states but also generates new states.
- The $q\bar{q}$ components are always expanded as an expansion on the Eigenstates of the $q\bar{q}$ Hamiltonian.
- Naive quark model states have to be chosen a priori
- In this contribution we propose a new method to include all states leaving the $q\bar{q}$ wave function as an unknown, in order to check the convergence of the expansion on Eigenstates.

The Cornell Model

E. Eichten et al., Phys. Rev. D 17, 3090

The Hamiltonian is

$$H_I = \frac{1}{2}\int d^3x d^3y : \rho_a(\vec{x})\frac{3}{4}V(\vec{x}-\vec{y})\rho_a(\vec{y}) :$$

$$\rho_a(\vec{x}) = \sum_{\text{flavors}} \psi^\dagger(\vec{x})\frac{1}{2}\lambda_a\psi(\vec{x})$$

$$\Omega_{nm}(z)=\sum_{\tau}\int d^3p_1 d^3p_2 \times \frac{\langle n|U|\tau\vec{p}_1\vec{p}_2\rangle\langle m|U|\tau\vec{p}_1\vec{p}_2\rangle^*}{z-E_1-E_2}. \quad (3.23)$$

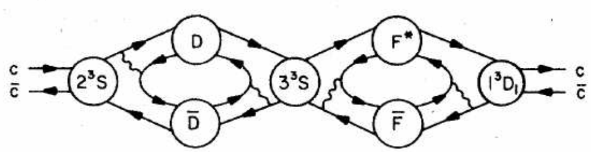
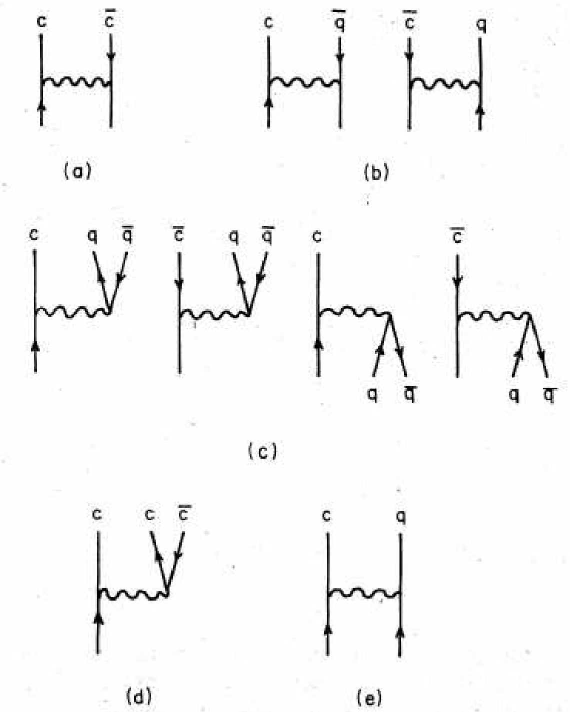


FIG. 8. The propagation of a $c\bar{c}$ pair in the presence of open and closed decay channels as described in the Green's function $\mathcal{G}$.



$$\text{Det}\left|(z-\epsilon_n)\delta_{nm}-\Omega_{nm}(z)\right|=0. \quad (3.28)$$

Framework

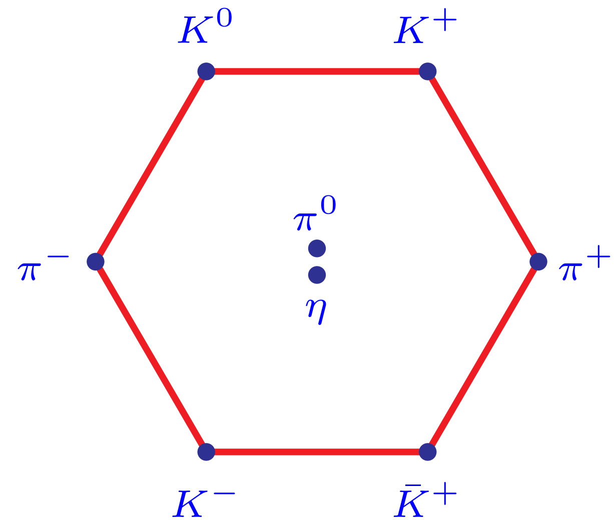
The needed pieces are

- The interaction between quarks: the Chiral Quark Model
- The interaction between mesons: obtained from the quark interactions using the RGM
- Coupling between one meson and two meson states: the $^3P_0$ model
- Solve the coupled system: Different approaches
  - Perturbatively: Mass shifts, widths and mixing
  - Study the two meson dynamics including coupling coupling with the one meson sector
  - Solving the coupled equations allows to obtain states above threshold

The Chiral Quark Model

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

- **Spontaneous Chiral Symmetry Breaking** $\rightarrow$
  $\rightarrow$ **Goldstone 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**:

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

The RGM

The hadron wave function

$$\psi_H \quad = \quad \phi_H(\vec{p}_{\xi_H})\chi_{SF}\xi_c$$

The two hadron wave function

$$\begin{aligned} \psi_{H_1H_2} &= \mathcal{A}\left[\chi(\vec{P})\psi^{SF}_{H_1H_2}\right] \\ &= \mathcal{A}\left[\phi_{H_1}(\vec{p}_{\xi_{H_1}})\phi_{H_2}(\vec{p}_{\xi_{H_2}})\chi(\vec{P})\chi^{SF}_{H_1H_2}\xi_c\right] \end{aligned}$$

Rayleigh-Ritz variational principle (Resonating Group Method)

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

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

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

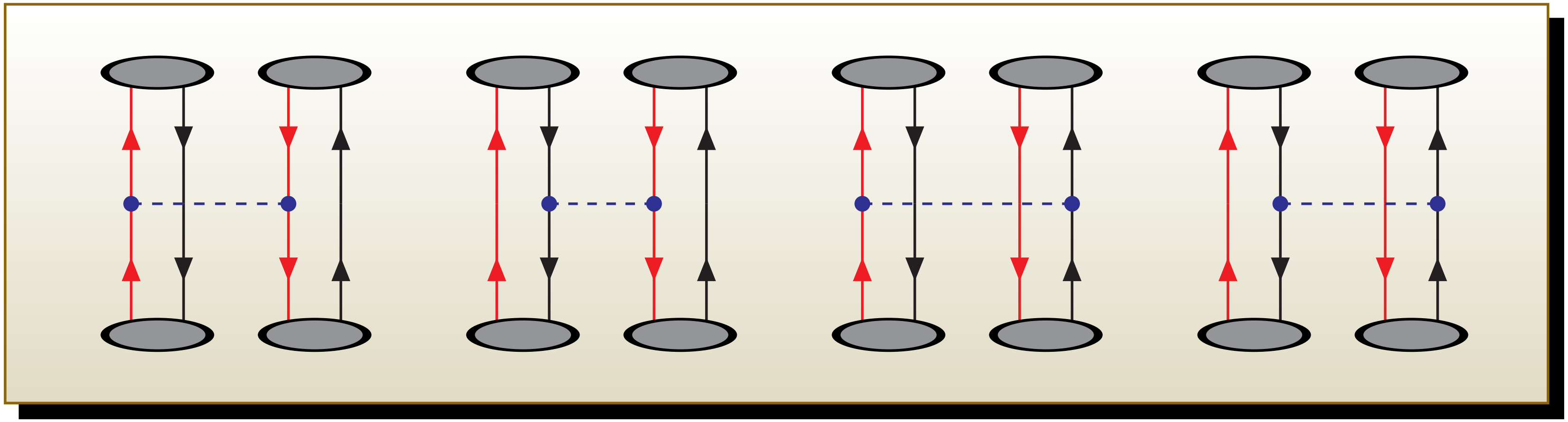
Lippmann-Schwinger Equation

The $M_1 M_2$ system

- **Quark interactions** $\rightarrow$ **Cluster interaction.**
- **For the DD^* 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_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}
$$

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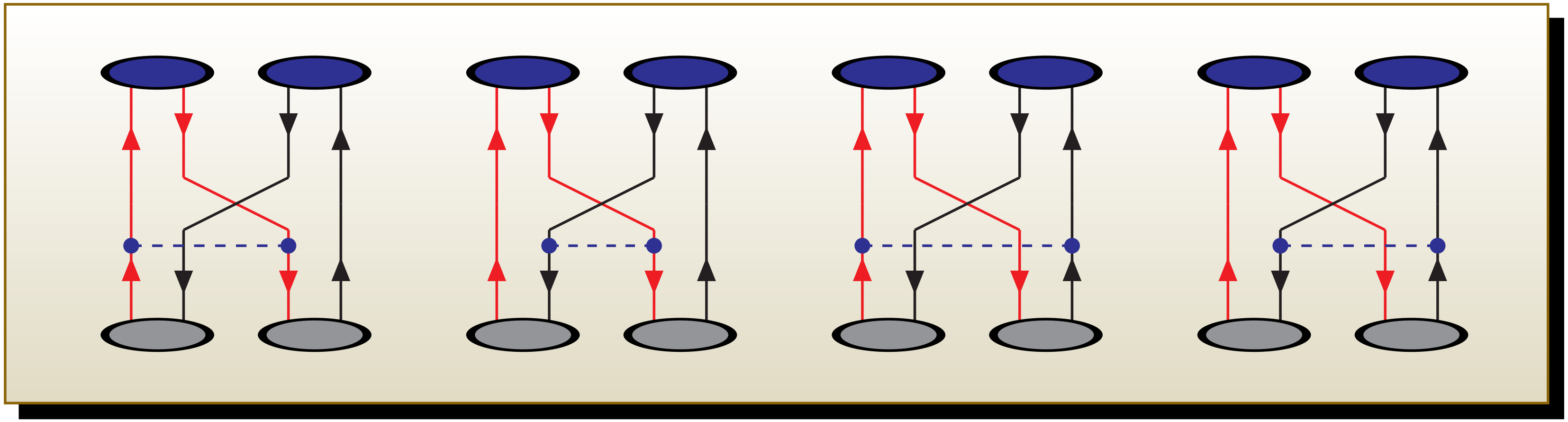
Rearrangement processes (like $DD^* \rightarrow J/\psi\omega$)



$^3P_0$ model

- **Pair creation Hamiltonian:**

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

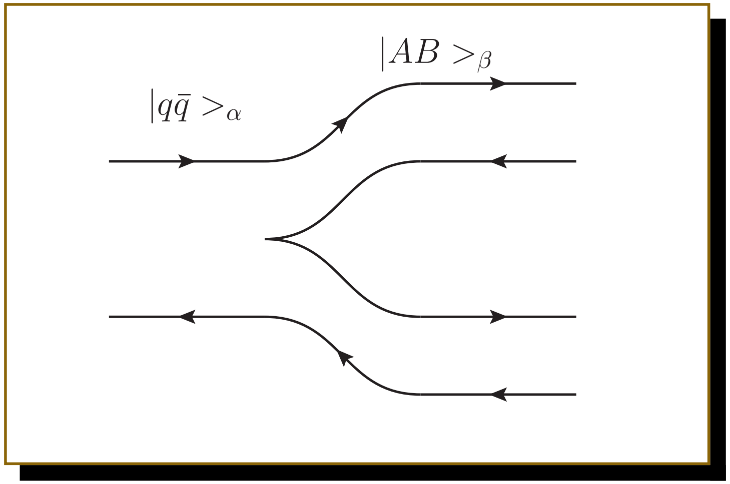
- **Non relativistic reduction:**

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

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

- **Transition potential:**

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



$^3P_0$ model

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

Running coupling

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

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

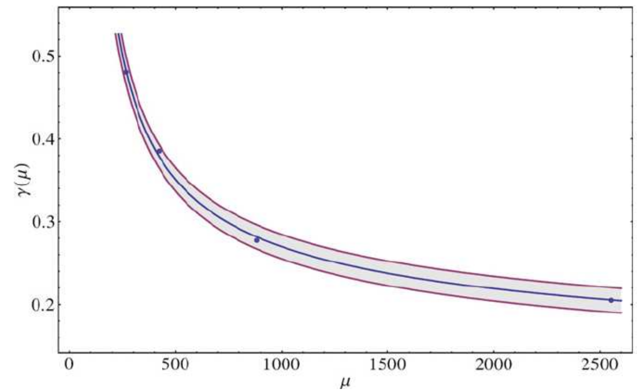


Table 1
Meson decay widths which have been taken into account in the fit of the scale-dependent strength, γ. Some properties of these mesons are also shown.

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

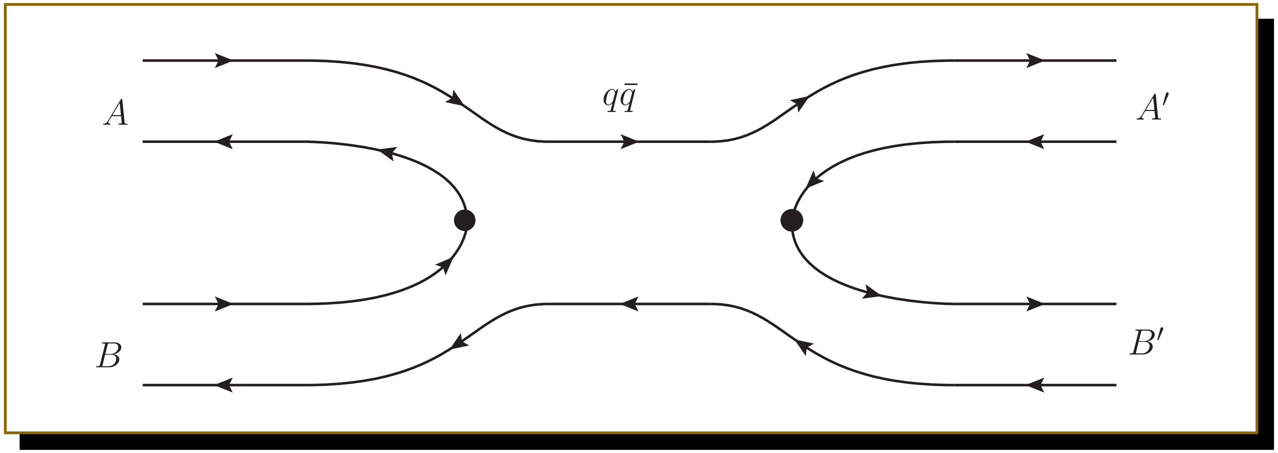
Coupling $q\bar{q}$ and $q\bar{q}\bar{q}q$ sectors

- **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

Lippmann-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))

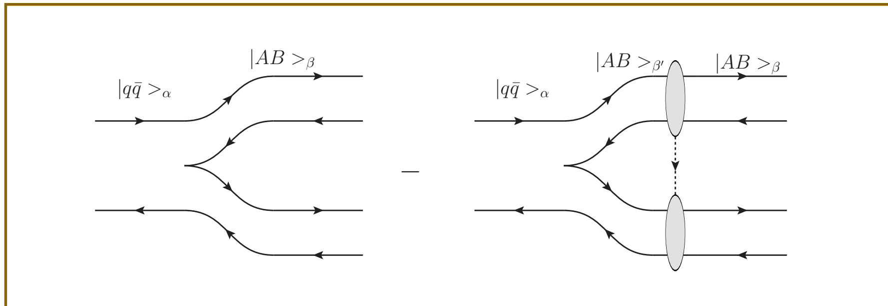
$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'}\phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

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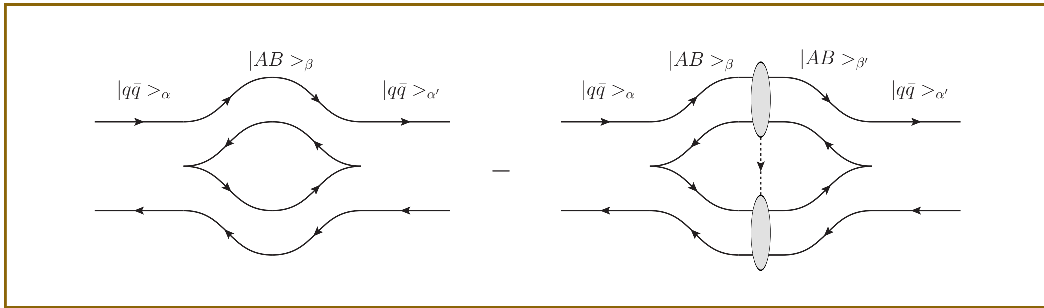
- **Non resonant contribution**
- **Resonant contribution**

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



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**

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

- **Normalization**

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

Non-perturbative version

- **Hadronic state:** $|\Psi\rangle = \sum_\alpha \mathcal{N}_\alpha \, |\psi_\alpha\rangle + \sum_\beta \chi_\beta(P) \, |\phi_{M1}\phi_{M2}\beta\rangle$
- **Here α doesn't mean a bare $c\bar{c}$ state but a $c\bar{c}$ partial wave (for example $^3P_1$ or $^3P_2$ and $^3F_2$ for a coupled case)**
- **We don't make an expansion of the $c\bar{c}$ component in Eigenstates of the $c\bar{c}$ Hamiltonian but in a basis (the GEM basis):**

$$|\psi_\alpha\rangle = \sum_{n=1}^{n_{\max}} c_n^\alpha \phi_{nl}^G(r)|ljm\rangle|\xi_c\rangle$$

- **We follow the same procedure but now the vertex function is**

$$h_{\beta\alpha}(P) = \sum_{n=1}^{n_{\max}} c_n^\alpha h_{\beta\alpha}^n(P)$$

- **And the Equations become**

$$\begin{aligned} \sum_{\alpha,n} \left[\mathcal{H}_{n'n}^{\alpha'\alpha} - \mathcal{G}_{n'n}^{0\,\alpha'\alpha}(E)\right] c_n^\alpha &= E N_{n'n}^{\alpha'} c_n^{\alpha'} \\ \sum_\beta \int H_{\beta'\beta}(P',P)\chi_\beta(P)P^2 dP + \sum_\alpha h_{\beta'\alpha}(P') &= E\chi_{\beta'}(P') \end{aligned}$$

with

$$\mathcal{G}_{n'n}^{0\,\alpha'\alpha}(E) = -\delta^{\alpha'\alpha}\delta_{n'n}\sum_\beta \int h_{\alpha'\beta}^{n'}(P)\chi_\beta(P)P^2 dP$$

Non-perturbative version

- Again we use the solution T_V

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

- Now

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

and so

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

- We end up with an Schrödinger like equation

$$\sum_{\alpha,n}\left[\mathcal{H}^{\alpha'\alpha}_{n'n} - \mathcal{G}^{\alpha'\alpha}_{n'n}(E)\right]c^{\alpha}_{n} \quad = \quad E N^{\alpha'}_{n'n} c^{\alpha'}_{n}$$

with the energy-dependent complete mass-shift matrix

$$\mathcal{G}^{\alpha'\alpha}_{n'n}(E) = \sum_{\beta}\int dq q^2 \frac{\phi^{n'}_{\alpha'\beta}(q,E)h^n_{\beta\alpha}(q)}{q^2/2\mu - E - i0^+}$$

Non-perturbative version

- **Molecular wave function**

$$\chi_{\beta'}(P') = -2\mu_{\beta'} \sum_{\alpha,n=1}^{n_{\max}} \frac{\phi_{\beta'\alpha}(E;P')c_n^\alpha}{P'^2 - k_{\beta'}^2 - i0^+}$$

- **Normalization**

$$\sum_{\alpha',\alpha} \sum_{n',n=1}^{n_{\max}} c_{n'}^{\alpha' *} N_{n'n}^{\alpha'\alpha} c_n^\alpha + \sum_\beta < \chi_\beta | \chi_\beta >= 1$$

The 1^{++} sector

Charge symmetry breaking is included with the right threshold positions of charged states

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

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

Lower states in the 1^{++} channel

$\gamma^{3}P_{0}$	$M(MeV)$	$c\bar{c}$	$D^{0}D^{*0}$	$D^{\pm}D^{*\pm}$	**I=0**	**I=1**
	3949	56,71 %	22,47 %	20,82 %	43,10 %	0,25 %
0.260	3867	30,22 %	51,37 %	18,40 %	64,72 %	5,06 %
	3468	95,70 %	2,18 %	2,12 %	4,30 %	0,0 %
	3944	56,82 %	22,10 %	21,07 %	42,89 %	0,51 %
0.218	3871	3,94 %	93,46 %	2,61 %	55,79 %	38,90 %
	3481	97,10 %	1,47 %	1,43 %	2,9 %	0,0 %

In order to obtain the correct binding energy of the $X(3872)$ we fine tune γ

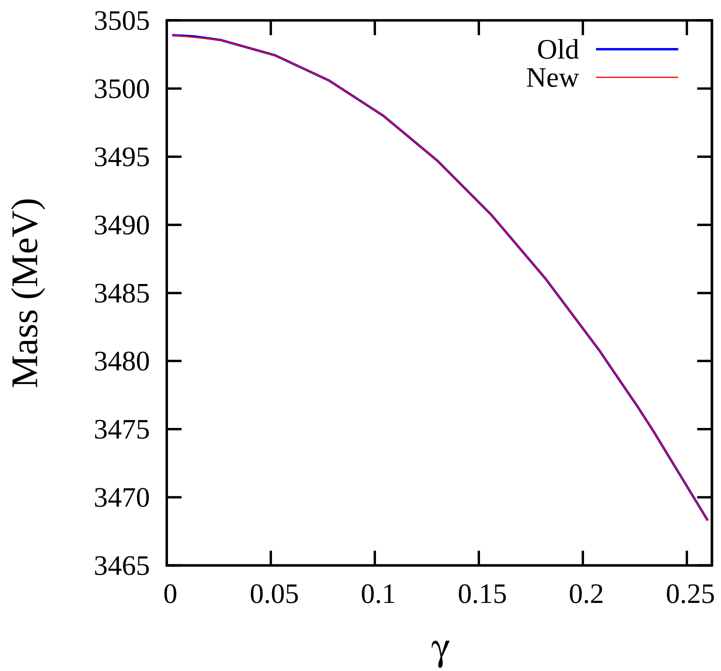
The 1^{++} sector

We can project on the naive quark model basis

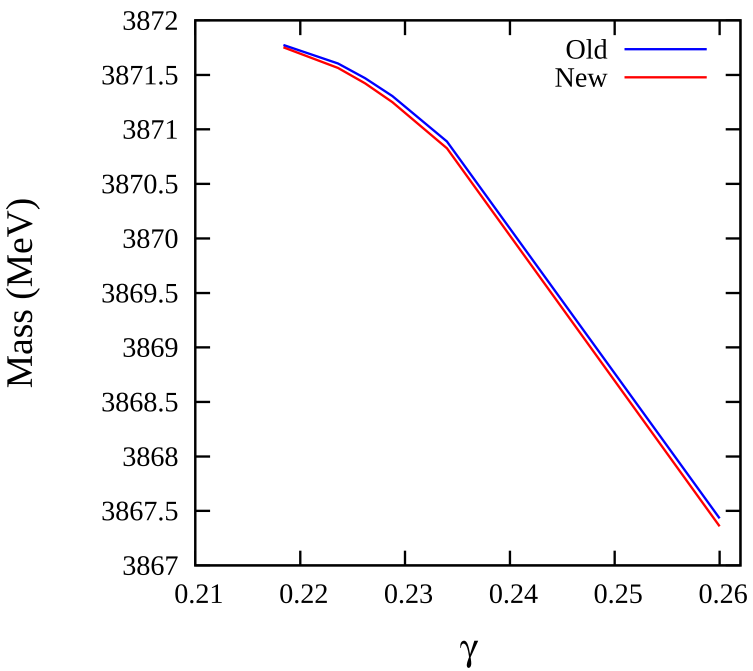
γ^3P_0	$M(MeV)$	$c\bar{c}$	1^3P_1	2^3P_1	3^3P_1	4^3P_1
	3949	56,71 %	1,61 %	96,33 %	1,28 %	0,78 %
0.260	3867	30,22 %	1,80 %	98,14 %	0,06 %	0,0 %
	3468	95,70 %	99,99 %	0,01 %	0,0 %	0,0 %
	3944	56,82 %	0,61 %	99,01 %	0,38 %	0,0 %
0.218	3871	3,94 %	2,11 %	97,75 %	0,14 %	0,0 %
	3481	97,10 %	100,0 %	0,0 %	0,0 %	0,0 %

The 1^{++} sector

$\chi_{c1}(1P)$



$X(3872)$

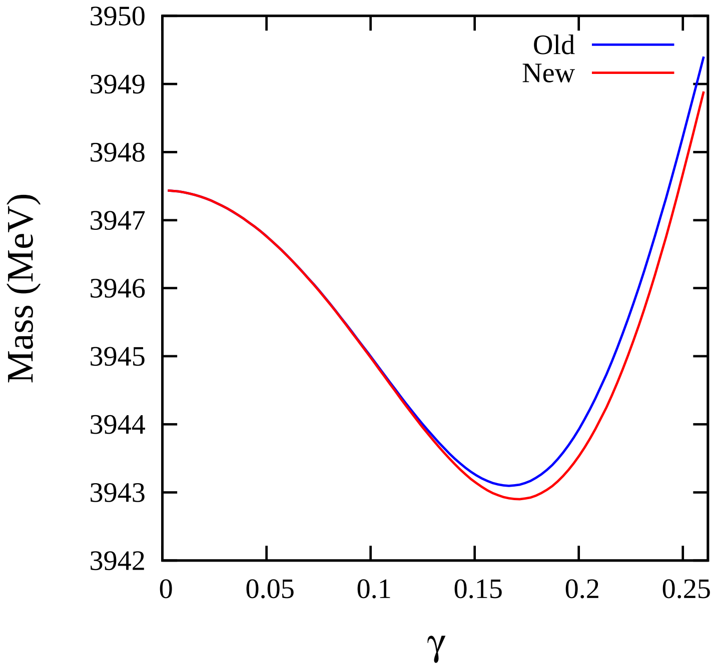


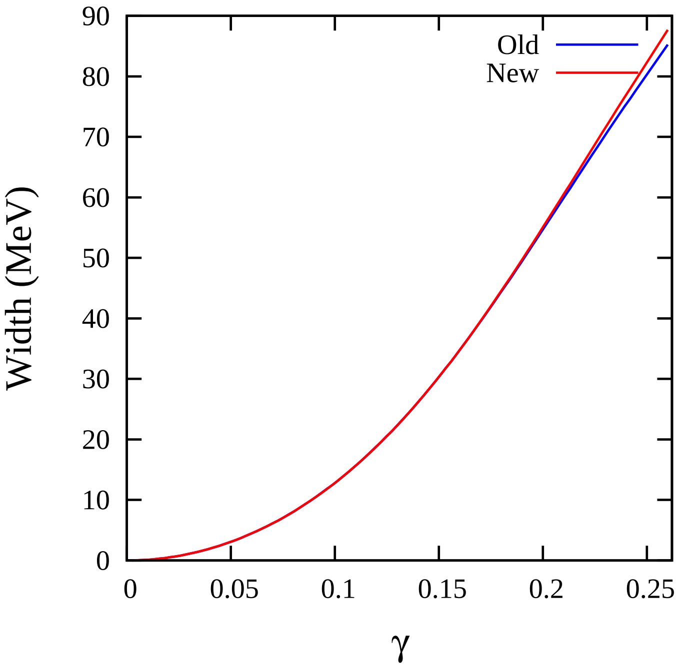
Coupling only with $1P$ and $2P$ bare states in the old approach

Coupling with all states in the new approach

The 1^{++} sector

$X(3940)$





Coupling only with $1P$ and $2P$ bare states in the old approach

Coupling with all states in the new approach

Summary

- The unquenched quark model is a useful tool to study the XYZ states
- In the unquenched quark model we include
  - The $q\bar{q}$ interaction to obtain naive quark model states.
  - The interaction between meson derived from the same quark interaction through the RGM.
  - The coupling between one meson and two meson states using the $^3P_0$ model.
- We have developed the framework to include all states of the bare Hamiltonian on the $q\bar{q}$ content of physical states
- On the small coupling limit the two approaches agree
- In the charmonium sector the coupling is small an only small variations on previous results are found.
- We will study lighter sectors where the coupling is bigger