Unquenching the quark model: baryon and mesons

E. Santopinto (INFN Genoa)
Quark Models

• Many versions of QM’s
  Isgur-Karl, Capstick-Isgur, Goldstone BE, U(7), hQM, Godfrey-Isgur, …

• Share the main features:
  Effective degrees of freedom $\rightarrow$ 3 quarks (quark-antiquark)
  confining potential

• Good description of static observables
  spectrum, magnetic moments
Considering also CQMs for mesons, CQMs able to reproduce the overall trend of hundred of data

• … but they show very similar deviations for dynamical observables such as elastic e.m. form factors

• photocouplings

• helicity amplitudes …

• Pair creation effects (continuum coupling effects) are neglected
• the medium $Q^2$ behaviour is fairly well reproduced
• there is lack of strength at low $Q^2$ (outer region) in the e.m. transitions

• emerging picture:
  quark core plus (meson or sea-quark) cloud
Continuum Coupling Effects

- **Continuum coupling** (pair creation) effects neglected in QM’s

  Coupling to meson-baryon (meson-meson) channels

- **Properties of resonances influenced by nearby channels**

  for ex. we will see the $X(3872)$ influenced by $D\bar{D}^*$ channel

Above threshold $\rightarrow$ Strong decays
Below threshold $\rightarrow$ virtual $qqq$-$qq\bar{q}$ ($qq\bar{q}$-$qq\bar{q}$) components in meson WF’s
There are two possibilities:

- phenomenological parametrization
- microscopic explicit quark description
quark-antiquark pair effects
(meson cloud)
dressing baryon states

CQM states have zero width

consistent inclusion of meson cloud implies
• coupling to the continuum
• effects on the spectrum
• realistic description of strong decays

- clue: $\pi$ cloud
- qqq - meson states
- qqq + selection of some higher Fock components
- unquenching the CQM (loops of virtual baryon-meson states described at the quark level)
How to introduce dressing

**hadronic approach:** mesons and baryons (nucleon + resonances)
(equations for amplitudes, coupled channel calculations, lagrangians, …)

**hybrid models**

![Diagrams](image)

at the quark level
inclusion of higher Fock components in the baryon state

\[ |\Psi\rangle = \Psi_{3q} |qqq\rangle + \Psi_{3q \bar{q}q} |3q \bar{q}q\rangle \]

**unquenching the quark model**
Geiger-Isgur
Capstick, BRAG 2007
Santopinto-Bijker, Nstar2007, PR C 2009
Problems

1) find a quark pair creation mechanism QCD inspired

2) implementation of this mechanism at the quark level but in such a way to do not destroy the good QMs results
Pair-creation Mechanism

• Mechanism → creation of $q\bar{q}$ pairs

• Pair-creation operator $^3P_0$

• $^3P_0$ model reproduces hundreds of data for strong hadronic decays

• A → BC strong decay : initial quarks spectators, creation of a $^3P_0$ pair, so with

• vacuum quantum numbers → $J^{PC} = 0^{++}$: $(L=1, S=1) \; J=0$ ; $SU(3)_f$ singlet; $SU(3)_c$ singlet.
Unquenched QM (UQM) for Baryons

E.S. ,R. Bijker, Few Body Syst. 44, 95 (2008); PRC80, 065210 (2009); PRC82, 062202 (2010); Bijker, Ferretti , E.S, PRC85, 035204 (2012).

• Higher Fock components in hadron wave functions

\[ \psi_A \rightarrow N \left[ |A\rangle + \sum_{BC\ell J} \int d^3q \left| BC\bar{q}\ell J\right\rangle \frac{\left\langle BC\bar{q}\ell J\middle|h_{q\bar{q}}A\right\rangle}{E_A - E_B - E_C} \right] \]

valence component
higher Fock components

\[ h_{q\bar{q}} = {}^3P_0 \text{ quark-pair creation operator} \]

B/C = intermediate baryon/meson states (meson/meson)

• Extended to the meson sector in Refs.:
  Ferretti, Galatà, Santopinto and Vassallo, PRC86, 015204 (2012); Ferretti, Galatà and Santopinto, PRC88, 015207 (2013); Ferretti and Santopinto, arXiv:1306.2874.
Unquenched QM (UQM)

• $^{3}P_{0}$ operator:

$$h_{q\bar{q}} = -3\gamma_0^{\text{eff}} \int d^3p_3 d^3p_4 \delta(\vec{p}_3 + \vec{p}_4) C_{34} F_{34} e^{-r_q^2(\vec{p}_3 - \vec{p}_4)^2/6} \left[ \chi_{34} \times Y_1(\vec{p}_3 - \vec{p}_4) \right]^{(0)}_0 b^+_3(\vec{p}_3) d^+_4(\vec{p}_4)$$

• Gaussian factor, smears out pair-creation point since Constituent quarks have effective size
The good magnetic moment results of the CQM are preserved by the UCQM


FIG. 3. (Color online) Magnetic moments of octet baryons: experimental values from the Particle Data Group [34] (circles), CQM (squares), and unquenched quark model (triangles).
Flavor Asymmetry

Gottfried sum rule

\[ S_G = \int_0^1 dx \frac{F_{2p}(x) - F_{2n}(x)}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 dx \left[ \bar{d}(x) - \bar{u}(x) \right] \]

\[ S_G \neq \frac{1}{3} \Rightarrow N_{\bar{d}} \neq N_{\bar{u}} \]

\[ S_G = 0.2281 \pm 0.0065 \]

\[ \int_0^1 dx \left[ \bar{d}(x) - \bar{u}(x) \right] = 0.16 \pm 0.01 \]
Proton Flavor asymmetry
Santopinto, Bijker, PRC 82,062202(R) (2010)
Flavor asymmetry of the octect baryons in the UCQM

Santopinto, Bijker, PRC 82,062202(R) (2010)

![Flavor asymmetry of octet baryons](image)

**Figure 1.** Flavor asymmetry of octet baryons

Pauli blocking (Field & Feynman, 1977) too small
Pion dressing of the nucleon (Thomas et al., 1983)
Meson cloud models
Flavor asymmetries of octect baryons

Santopinto, Bijker, PRC 82,062202(R) (2010)

<table>
<thead>
<tr>
<th>Model</th>
<th>$A(\Sigma^+)/A(p)$</th>
<th>$A(\Xi^0)/A(p)$</th>
<th>Ref.</th>
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<tr>
<td>Unquenched CQM</td>
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<td>−0.005</td>
<td>present</td>
</tr>
<tr>
<td>Chiral QM</td>
<td>2</td>
<td>1</td>
<td>Eichen</td>
</tr>
<tr>
<td>Balance model</td>
<td>3.083</td>
<td>2.075</td>
<td>Y.-J Zhang</td>
</tr>
<tr>
<td>Octet couplings</td>
<td>0.353</td>
<td>−0.647</td>
<td>Alberg</td>
</tr>
</tbody>
</table>

$\Sigma^\pm p \rightarrow \ell^+\ell^- + X$ (e.g., at CERN).
3. Proton Spin Crisis

1980’s

Naive parton model
3 valence quarks

\[
\frac{1}{2} = \frac{1}{2} (\Delta u + \Delta d)
\]

\[
\begin{align*}
\Delta u &= 0.842 \\
\Delta d &= -0.427 \\
\Delta s &= -0.085
\end{align*}
\]

1990’s

QCD: contributions from sea quarks and gluons

\[
\frac{1}{2} = \frac{1}{2} \frac{(\Delta u + \Delta d + \Delta s)}{\Delta \Sigma} + \Delta G + \Delta L
\]

\[
\Delta \Sigma = 0.330 \pm 0.039
\]

2000’s

.. and orbital angular momentum

HERMES, PRD 75, 012007 (2007)
COMPASS, PLB 647, 8 (2007)
Proton Spin

- COMPASS@CERN: Gluon contribution is small (sign undetermined)
- Unquenched quark model

\[
\begin{array}{|c|c|c|c|}
\hline
 & CQM & \text{Unquenched QM} & \text{QM} \\
\hline
 & \Delta \Sigma & 1 & 0.378 & 0.298 & 0.676 \\
\hline
 & 2 \Delta L & 0 & 0.000 & 0.324 & 0.324 \\
\hline
 & 2 \Delta J & 1 & 0.378 & 0.622 & 1.000 \\
\hline
\end{array}
\]

- More than half of the proton spin from the sea, but seen from an explicit calculation
- Orbital angular momentum Dominated by N\pi channel

See Myhrer & Thomas, 2008
4. Strangeness in the Proton

• The strange (anti)quarks come uniquely from the sea: there is no contamination from up or down valence quarks

• The strangeness distribution is a very sensitive probe of the nucleon’s properties

• Flavor content of form factors

• New data from Parity Violating Electron Scattering experiments: SAMPLE, HAPPEX, PVA4 and GO Collaborations
Quark Form Factors

• Charge symmetry

\[ G_{u,p}^u = G_{d,n}^d \equiv G_{u}^u \]
\[ G_{d,p}^d = G_{u,n}^u \equiv G_{d}^d \]
\[ G_{s,p}^s = G_{s,n}^s \equiv G_{s}^s \]

• Quark form factors

\[ G_{u}^u = \left( 3 - 4 \sin^2 \Theta_W \right) G_{\gamma,p}^\gamma - G_{Z,p}^Z \]
\[ G_{d}^d = \left( 2 - 4 \sin^2 \Theta_W \right) G_{\gamma,p}^\gamma + G_{\gamma,n}^\gamma - G_{Z,p}^Z \]
\[ G_{s}^s = \left( 1 - 4 \sin^2 \Theta_W \right) G_{\gamma,p}^\gamma - G_{\gamma,n}^\gamma - G_{Z,p}^Z \]

Kaplan & Manohar, NPB 310, 527 (1988)

Genova 2012
Static Properties

\[ G_E(0) = e \quad \text{Electric charge} \]

\[ G_M(0) = \mu \quad \text{Magnetic moment} \]

\[ \langle r^2 \rangle_E = -6 \frac{dG_E}{dQ^2} \bigg|_{Q^2=0} \quad \text{Charge radius} \]

\[ \langle r^2 \rangle_M = -6 \frac{\mu}{\mu} \frac{dG_M}{dQ^2} \bigg|_{Q^2=0} \quad \text{Magnetic radius} \]
Strange Magnetic Moment

\[ \mu_s = \sum_i \mu_{i,s} \left[ 2\bar{s}(q_i) + \bar{\ell}(q_i) - 2\bar{s}(\bar{q}_i) - \bar{\ell}(\bar{q}_i) \right] \]

Strange Radius

\[ R_s^2 = \sum_{i=1}^{5} e_{i,s} (\vec{r}_i - \vec{R}_{CM})^2 \]

Unquenched QM(UQM) for Mesons

Ferretti, Galatà, E.S., Vassallo, PRC86, 015204 (2012); Ferretti, Galatà, E.S.
PRC88, 015207 (2013); Ferretti, E.S., arXiv:1306.2874.

• $^3P_0$-type operator:

$$h_{q\bar{q}} = -3\gamma_0^{\text{eff}} \int d^3p_3 d^3p_4 \delta(\vec{p}_3 + \vec{p}_4) C_{34} F_{34} \Gamma_{q\bar{f}} (\vec{p}_3, \vec{p}_4)$$

$$\left[ \chi_{34} \times Y_1 (\vec{p}_3 - \vec{p}_4) \right]^{(0)}_0 b^+_3 (\vec{p}_3) d^+_4 (\vec{p}_4)$$

• Effective pair creation strength

$$\gamma_0^{\text{eff}} = \gamma_0 \frac{m_u}{m_i}$$

• Introduced to suppress unphysical heavy $qq\bar{q}$ pair creation

Kalashnikova, PRD72, 034010 (2005).

• Gaussian factor $\Gamma_{q\bar{f}} (\vec{p}_3, \vec{p}_4)$ smears out pair-creation point Constituent quarks have effective size
**Open charm strong decays**

Ferretti, Galatà, E.S., PRC88, 015207 (2013)

- Used to set the values of the $^3P_0$ Model parameters
- Used in the UQM

\[
\Gamma_{A \rightarrow BC} = \Phi_{A \rightarrow BC}(q_0) \sum_{\ell,J} |\langle BCq_0 \ell J | T^\dagger | A \rangle|^2
\]

\[
\Phi_{A \rightarrow BC} = 2\pi q_0 \frac{E_b(q_0) E_c(q_0)}{M_a}
\]

\[
E_b = \sqrt{M_b^2 + q_0^2}
\]

\[
E_c = \sqrt{M_c^2 + q_0^2}
\]

<table>
<thead>
<tr>
<th>State</th>
<th>Mass [GeV]</th>
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<td>$D$</td>
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<td>$D^*(2007)$</td>
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<td>$D_s$</td>
<td>1.969</td>
</tr>
<tr>
<td>$D_s^*$</td>
<td>2.112</td>
</tr>
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</table>

Strong decay widths in the $^3P_0$ Model

Masses of open charm mesons used
Open charm strong decays. Results

Ferretti, Galatà ,E.S., PRC88, 015207 (2013)

<table>
<thead>
<tr>
<th>State</th>
<th>DD</th>
<th>DD*</th>
<th>D* D*</th>
<th>D_s D_s</th>
<th>D_s D_s*</th>
<th>D_s* D_s*</th>
<th>Total</th>
<th>Exp.</th>
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<tbody>
<tr>
<td>( \eta_c(3^1S_0) )</td>
<td>–</td>
<td>38.8</td>
<td>52.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>91.1</td>
<td>–</td>
</tr>
<tr>
<td>( \Psi(4040)(3^3S_1) )</td>
<td>0.2</td>
<td>37.2</td>
<td>39.6</td>
<td>3.3</td>
<td>–</td>
<td>–</td>
<td>80.3</td>
<td>80 ± 10</td>
</tr>
<tr>
<td>( h_c(2^1 P_1) )</td>
<td>–</td>
<td>64.6</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>64.6</td>
<td>–</td>
</tr>
<tr>
<td>( \chi_0(2^3 P_0) )</td>
<td>97.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>97.7</td>
<td>–</td>
</tr>
<tr>
<td>( \chi_2(2^3 P_2) )</td>
<td>27.2</td>
<td>9.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>37.0</td>
<td>–</td>
</tr>
<tr>
<td>( \Psi(3770)(1^3 D_1) )</td>
<td>27.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>27.7</td>
<td>27.2 ± 1.0</td>
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<tr>
<td>( c\bar{c}(1^3 D_3) )</td>
<td>1.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.7</td>
<td>–</td>
</tr>
<tr>
<td>( c\bar{c}(2^1 D_2) )</td>
<td>–</td>
<td>62.7</td>
<td>46.4</td>
<td>–</td>
<td>8.8</td>
<td>–</td>
<td>117.9</td>
<td>–</td>
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<tr>
<td>( \Psi(4160)(2^3 D_1) )</td>
<td>11.2</td>
<td>0.4</td>
<td>39.4</td>
<td>2.1</td>
<td>5.6</td>
<td>–</td>
<td>58.7</td>
<td>103 ± 8</td>
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<tr>
<td>( c\bar{c}(2^3 D_2) )</td>
<td>–</td>
<td>43.5</td>
<td>49.3</td>
<td>–</td>
<td>11.3</td>
<td>–</td>
<td>104.1</td>
<td>–</td>
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<tr>
<td>( c\bar{c}(2^3 D_3) )</td>
<td>17.2</td>
<td>58.3</td>
<td>48.1</td>
<td>3.6</td>
<td>2.6</td>
<td>–</td>
<td>129.8</td>
<td>–</td>
</tr>
</tbody>
</table>

Charmonium strong decay widths in open charm mesons [MeV]

Parameters of the \( ^3P_0 \) model: fitted to the strong decays

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>( \gamma_0 )</td>
<td>0.510</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.500 GeV</td>
</tr>
<tr>
<td>( r_q )</td>
<td>0.335 fm</td>
</tr>
<tr>
<td>( m_n )</td>
<td>0.330 GeV</td>
</tr>
<tr>
<td>( m_s )</td>
<td>0.550 GeV</td>
</tr>
<tr>
<td>( m_c )</td>
<td>1.50 GeV</td>
</tr>
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</table>
Self-energies (1)

The Hamiltonian we consider, \( H = H_0 + V \), is the sum of an "unperturbed" part \( H_0 \), acting only in the bare meson space, and of a second part, \( V \), which can couple a meson state to a continuum made up of meson-meson intermediate states.

- The dispersive equation can be written as

\[
\Sigma(E_a) = \sum_{BC} \int_0^\infty q^2 dq \frac{|V_{a,bc}(q)|^2}{E_a - E_{bc}}
\]

where the bare energy \( E_a \) satisfies

\[
M_a = E_a + \Sigma(E_a)
\]

where \( \Sigma(E_a) \) is the self-energy.
Self-energies (2)

- one has to take the contributions from various channels BC into account. A channel BC is a meson-meson intermediate state.

- The matrix element $V_{a,bc}$ results from the coupling, due to the operator $V$, between the intermediate state BC and the unperturbed quark-antiquark wave function of the meson A.

- one has to choose a precise form for the transition operator, $V$, responsible for the creation of qq pairs: our choice is that of the unquenched quark model (UQM).
Godfrey and Isgur relativized QM

• The relativized QM by Godfrey and Isgur is a potential model for qq meson spectroscopy. This model assumes a relativistic kinetic energy, a QCD-motivated running coupling constant, a flavor dependent potential smearing parameter, and replaces factors of quark mass with quark kinetic energy.
Godfrey and Isgur relativized QM

- The Godfrey and Isgur Hamiltonian is

\[
H = \sqrt{q^2 + m_1^2} + \sqrt{q^2 + m_2^2} + V_{\text{conf}} + V_{\text{hyp}} + V_{\text{so}}
\]

\[
V_{\text{conf}} = -\left(\frac{3}{4} c + \frac{3}{4} br - \frac{\alpha_s(r)}{r}\right) \vec{F}_1 \cdot \vec{F}_2
\]

\[
V_{\text{hyp}} = -\frac{\alpha_s(r)}{m_1 m_2} \left[ \frac{8\pi}{3} \vec{S}_1 \cdot \vec{S}_2 \delta^3(\vec{r}) + \frac{1}{r^3} \left(\frac{3}{r^2} \frac{\vec{S}_1 \cdot \vec{r}}{r} \vec{S}_2 \cdot \vec{r} - \vec{S}_1 \cdot \vec{S}_2 \right) \right] \vec{F}_i \cdot \vec{F}_j
\]

\[
V_{\text{so}} = V_{\text{so,cm}} + V_{\text{so,tp}}
\]

\[
V_{\text{so,cm}} = -\frac{\alpha_s(r)}{r^3} \left(\frac{1}{m_i} + \frac{1}{m_j}\right) \left(\frac{\vec{S}_i}{m_i} + \frac{\vec{S}_j}{m_j}\right) \cdot \vec{L} \vec{F}_i \cdot \vec{F}_j
\]

\[
V_{\text{so,tp}} = -\frac{1}{2r} \frac{\partial H_{ij}^{\text{conf}}}{\partial r} \left(\frac{\vec{S}_i}{m_i^2} + \frac{\vec{S}_j}{m_j^2}\right) \cdot \vec{L}
\]
### Charmonium spectrum with Self En. corrections

**Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)**

<table>
<thead>
<tr>
<th>State</th>
<th>$J^{PC}$</th>
<th>$D \bar{D}$</th>
<th>$\bar{D} D^*$</th>
<th>$\bar{D}^* D^*$</th>
<th>$D_s \bar{D}_s$</th>
<th>$D_s \bar{D}_s^*$</th>
<th>$D_s^* \bar{D}_s^*$</th>
<th>$\eta_c \eta_c$</th>
<th>$\eta_c J/\Psi$</th>
<th>$J/\Psi J/\Psi$</th>
<th>$\Sigma(E_a)$</th>
<th>$E_a$</th>
<th>$M_a$</th>
<th>$M_{exp.}$ [MeV]</th>
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<tr>
<td>$\eta_c(1^1S_0)$</td>
<td>$0^{--}$</td>
<td>-34</td>
<td>-31</td>
<td>-8</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>-2</td>
<td>-83</td>
<td>3062</td>
<td>2979</td>
</tr>
<tr>
<td>$J/\Psi(1^3S_1)$</td>
<td>$1^{--}$</td>
<td>-8</td>
<td>-27</td>
<td>-2</td>
<td>-6</td>
<td>-10</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>0</td>
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<td>-41</td>
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<td>-8</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
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<td>0</td>
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<td>$\Psi(2^3S_1)$</td>
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<td>-42</td>
<td>-54</td>
<td>-7</td>
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<td>-134</td>
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<td>$h_c(1^1P_1)$</td>
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<td>-48</td>
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<td>0</td>
<td>0</td>
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<td>3501</td>
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<td>-1</td>
<td>-1</td>
<td>-3</td>
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<tr>
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<td>-53</td>
<td>-9</td>
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<td>-40</td>
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\[
\Sigma(E_a) = \sum_{BC\ell J} \int_0^\infty q^2 dq \left| \langle BCq\ell J | T^+ | A \rangle \right|^2 \frac{E_a - E_b - E_c}{E_a - E_b - E_c}
\]
Charmonium spectrum with SE corrections

Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)
The X(3872) puzzle

- The nature of the recently discovered X(3872) resonance has not been understood yet.

- The quark structure of the X(3872) resonance, observed for the first time by the Belle Collaboration and then confirmed by CDF, D0 and BABAR, still remains an open puzzle. We only know thanks to LHCb that it is $1^{++}$.
The X(3872) puzzle

- The nature of the recently discovered X(3872) resonance has not been understood yet.
- At the moment there are two possible interpretations for this meson.
  1) A weakly-bound $1^{++}$ DD* molecule
  2) A cc state with $1^{++}$
X(3872) as a $c\bar{c}$ state

- In this case, the resonance would correspond to a $1^1D_2$ ($J^{PC} = 2^{-+}$) state or to a $2^3P_1$ one [$\chi_{c1}(2P), J^{PC} = 1^{++}$]
- The Godfrey and Isur QM predicts these states to be at energies of
  - $1^1D_2$ ($J^{PC} = 2^{-+}$) at 3.84 GeV
  - $2^3P_1$ one [$\chi_{c1}(2P), J^{PC} = 1^{++}$] 3.95 GeV
- both too high
- Moreover, from LHCb we know that the X(3872) has $1^{++}$ quantum numbers
Charmonium spectrum with Self Energy corrections, solution of X(3872) puzzle?

Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)
**X(3872). Our work**
Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)

- Loop effects lower the mass of the X(3872) to 3908 MeV
- X(3872) is a $\chi_{c1}(2P)$ state [$J^{PC} = 1^{++}$]
- In our picture, the X(3872) is a $c\bar{c}$ core plus extra components due to coupling to meson-meson continuum
- Difference with the experimental mass has to do with the intrinsic error of a QM (see figure with $c\bar{c}$ spectrum)
- Necessary to analyse other properties of the X(3872) (various type of decays) to draw a definitive conclusion
X(3872). Comparison with other works
Ferretti, Galatà, Santopinto, PRC88, 015207 (2013)

• Calculations of charmonium spectrum including continuum coupling effects (loop effects)

<table>
<thead>
<tr>
<th>$\chi_c(2P)$ mass [MeV]</th>
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<tbody>
<tr>
<td>3908</td>
<td>Ferretti et al.</td>
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<td>4007.5</td>
<td>Eichten et al. (2004)</td>
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<td>3990</td>
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<td>Eichten et al. (2006)</td>
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<td>3896</td>
<td>Pennington and Wilson</td>
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References
Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)
Eichten et al., PRD69, 094019 (2004)
Kalashnikova, PRD72, 034010 (2005)
Eichten et al., PRD73, 014014 (2006)
Pennington and Wilson, PRD76, 077502 (2007)
\textbf{X(3872). Charmonium interpretation}

- Ratio between $X(3872) \to J/\Psi \, \rho$ and $X(3872) \to J/\Psi \, \omega$ decays

and also the $X(3872) \to D^0 \bar{D}^0 \pi^0$

favor a charmonium interpretation

Meng and Chao, PRD75, 114002 (2007)

$X(3872) \to \psi(2S) \gamma$ dominant with respect to $X(3872) \to J/\psi \gamma$

$B(B^\pm \to K^\pm \, X \, )B(X \to \psi(2S)\gamma \, ) = (9.9 \pm 2.9 \pm 0.9) \times 10^{-6}$

$B(B^\pm \to K^\pm \, X \, )B(X \to J/\psi\gamma \, ) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$
X(3872). Molecule interpretation

- Is the $X(3872)$ a meson-meson molecule?

- The $D\bar{D}^*$ system can be found by $\pi$-exchange and forms a meson-meson molecule.
  Törnqvist, PRL67, 556 (1991)

- Prompt production incompatible with molecule interpretation
  Molecule of a few fm, with intrinsic fragility can be promptly produced?!?
  Bignamini et al., PRL103, 162001 (2009)
Bottomonium spectrum with SE corrections
Ferretti and Santopinto, arXiv:1306.2874
• \(\chi_b(3P)\) system discovered by ATLAS Collaboration
  Aad et al., PRL108, 152001 (2012)
  \(M = 10.530 \pm 0.005\) (stat.) \(\pm 0.009\) (syst.) GeV  (mass barycenter for the \(\chi_b(3P)\) signal)

• Confirmed by D0 Collaboration
  Abazov et al., PRD86, 031103 (2012)
  \(M = 10.551 \pm 0.014\) (stat.) \(\pm 0.017\) (syst.) GeV  (mass barycenter for the \(\chi_b(3P)\) signal)

  “Further analysis is underway to determine whether this structure is due to the \(\chi_b(3P)\) system or some exotic bottom quark state”

• \(\chi_b(3P)\) states lie close to \(B\bar{B}, B\bar{B}^*\) and \(B^*\bar{B}^*\) decay thresholds

• Continuum coupling effects are important?
χ_b(3P) system. Mass barycenter
Ferretti and Santopinto, arXiv:1306.2874

- **ATLAS Collaboration:**  
  \[ M = 10.530 \pm 0.005 \text{ (stat.)} \pm 0.009 \text{ (syst.) GeV} \]
  Aad et al., PRL108, 152001 (2012)

- **D0 Collaboration:**  
  \[ M = 10.551 \pm 0.014 \text{ (stat.)} \pm 0.017 \text{ (syst.) GeV} \]
  Abazov et al., PRD86, 031103 (2012)

- **Our work:**  
  \[ M = 10.551 \text{ GeV} \]
Continuum coupling (pair creation) effects

- **Mass shifts** because of pair creation effects (self energy terms)

  Already shown by several authors in baryon and meson sectors


- **Importance of orbital angular momentum in proton spin**

  Bijker, E.S., PRC80, 065210 (2009); E.S., Bijker, Few Body Syst. 44, 95 (2008).

- **Flavor Asymmetry of the proton**

  E.S and Bijker, PRC82, 062202 (2010).

- **Strangeness content of the proton**

  Bijker, Ferretti, E.S., PRC85, 035204 (2012).

- **Interpretation of the X(3872) as a charmonium state plus an extra component due to the coupling to meson-meson continuum**

  Ferretti, Galatà and E.S, PRC88, 015207 (2013).