Heavy Meson Molecules in Effective Field Theory

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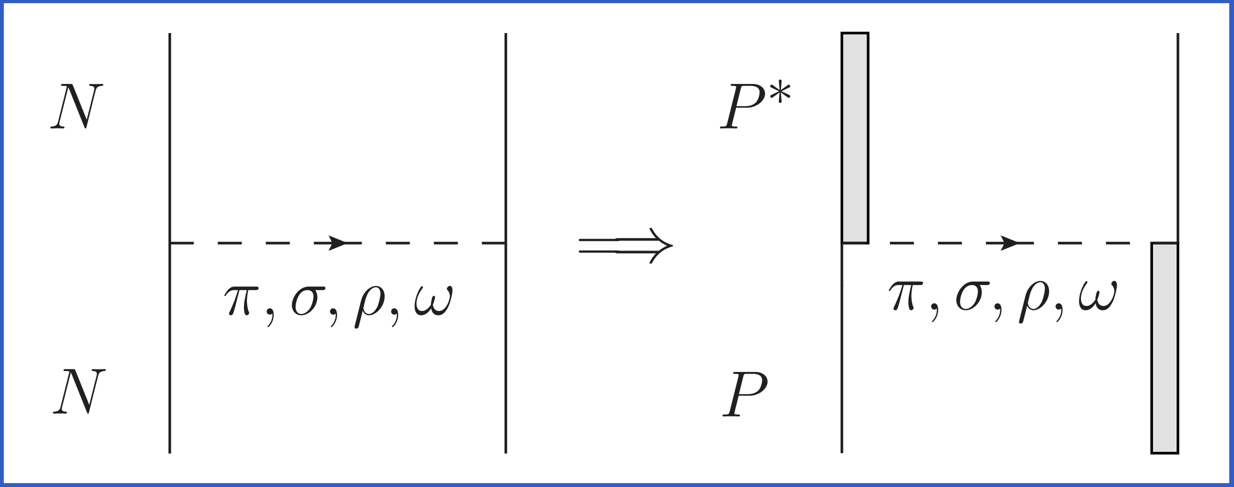
The Two Nucleon / Heavy Meson System

Observation: the force between two heavy mesons should be similar to the nuclear forces (Voloshin and Okun, 76).

- The nuclear force is mediated by meson exchange



  and the same thing happens between heavy mesons (provided they contain light quarks).

- Therefore, in analogy to the deuteron we should expect heavy meson bound (or "molecular") states

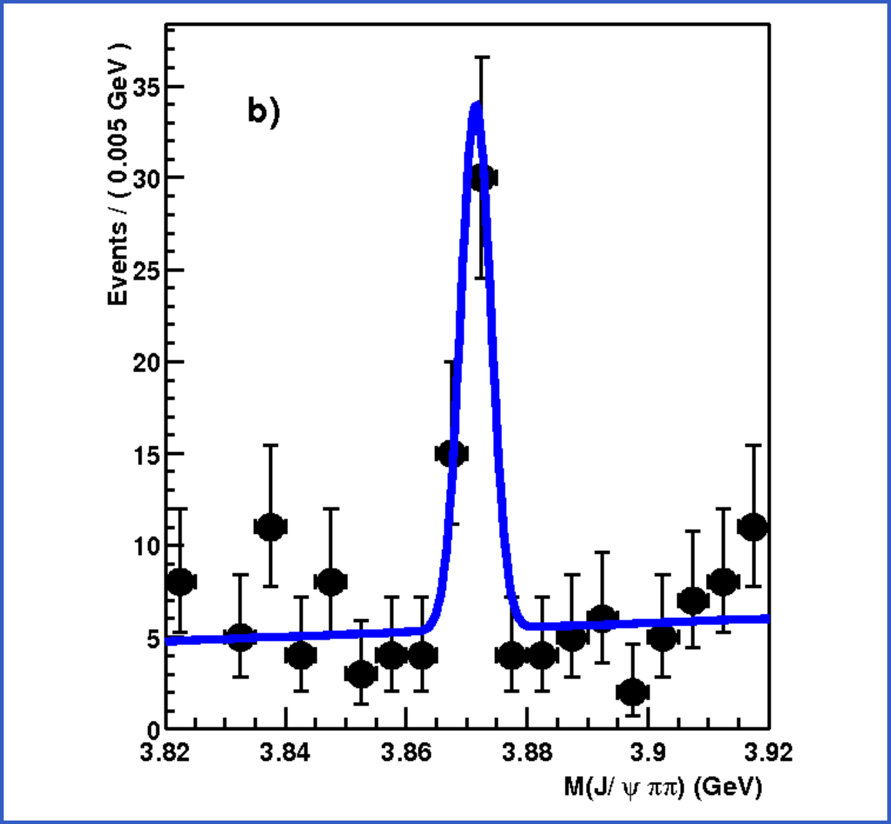
Heavy Meson Bound States

Early Speculations and Explorations:

- De Rújula, Georgi, Glashow (77): $\Psi(4040)$ as a $D^* \bar{D}^*$ resonance
- Jaffe (77): $f_0(980)$ and $a_0(980)$ as $K\bar{K}$ bound states.
- Weinstein, Isgur (82-83): apart from f_0 and a_0, molecular states are unlikely in the light quark sector.
- Törnqvist (93): OPE + monopolar form factor generate several possible molecular states in the charm and bottom sectors.
- Ericson, Karl (93): two body systems are more likely to bind if the reduced mass is increased; thus even weak central OPE may be eventually enough to form molecular states.

The X(3872) and the Charm Sector (I)

Discovered by the Belle collaboration in $B^{\pm} \to K^{\pm} J/\Psi \pi\pi$ (03):



... and later confirmed by D0 and CDF.

The X(3872) and the Charm Sector (II)

Properties: $M_X = 3871.56 \pm 0.22\,\mathrm{MeV}$, $I^G = 0^+$, $J^{PC} = 1^{++}/2^{-+}$.

- It's a hidden charm state ($X \to J/\Psi\pi\pi$)
- It's very close to the $D^0\bar{D}^{0*}$ threshold ($M_{\mathrm{th}} = 3871.79 \pm 0.21\,\mathrm{MeV}$)

The perfect candidate for a $D\bar{D}^*$ molecular state! (if $J^{PC} = 1^{++}$)

...and the perfect playground for theoreticians.

Molecular descriptions can be further subdivided into:

- Finite range theories: OBE + form factors (a la Törnqvist).
- Contact range theories: X bound by short range dynamics.

  Voloshin (03); Braaten, Kusunoki (03); X-EFT by Fleming et al. (04)

Alternative explanations (tetraquark, charmonium, etc.) also possible.

The X(3872) and the Charm Sector (III)

But there are many other X, Y and Z states *. Some may be molecular states too:

- $X(3915)$ as $D^{*+}D^{*-}$ and $Y(4140)$ as $D_s^*\bar{D}_s{}^*$

  (Liu, Zhu 09; Branz, Gutsche, Lyubovitskij 09; Ding 09)

- $Y(4660)$ / $X(4630)$ as $f_0(980)\psi'$

  (Guo, Hanhart, Meißner 08; Guo, Haidenbauer, Hanhart, Meißner 10)

- $Y(4260)$ as $J/\Psi K\bar{K}$ (three body structure)

  (Martinez Torres, Khemchandani, Gamermann, Oset 09)

- $X(3915)$, $Z(3930)$ and $X(4160)$ dynamically generated states

  (Molina, Oset 09)

- Plus many other proposals (the list is really long).

*: $X(3872/3915/3940/4160/4630/\ldots)$, $Y(3940/4008/4260/4350/4660/\ldots)$, $Z(3930/4050/4250/4430/\ldots)$

The Z_b's and the Bottom Sector

Belle collaboration:

$Z_b(10610)$, $Z_b(10650)$ at $M = 10608.4 \pm 2.0$, $M = 10653.2 \pm 1.5\,\mathrm{MeV}$

- $I^G = 1^+$, $J^{pc} = 1^{+-}$ (most probably).
- Close to $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds: 10604.4 and $10650.2\,\mathrm{MeV}$
  Strong candidate for molecular (not necessarily resonant) state
- Caveat: they are not necessarily above threshold.
  Cleven, Guo, Hanhart, Meißner (11)
- Unexpected: no OBE model seriously predicted isovector states
  Why? OPE is relatively weak in isovectors.

The Effective Field Theory Aproach (I)

The Nuclear / Heavy Meson EFT Approach:

- There is a separation of scales:
  - Long distances dominated by pion dynamics, while short distances unkown and phenomenological.
  - A low energy expansion (power counting) can be formulated.
- Nucleons / Heavy mesons are heavy: we can define a non-relativistic potential (ever heard of Weinberg counting?)
- There are symmetries:
  - Chiral symmetry constains pion exchanges.
  - For heavy mesons there is Heavy Quark Spin Symmetry.

The Effective Field Theory Approach (II)

- Power counting makes the EFT systematic:
  - In EFT we have a separation of scales:

$$\underbrace{|\vec{q}| \sim p \sim m_\pi \sim}_{\text{the known physics}} \quad Q \ll \Lambda_0 \quad \underbrace{\sim m_\rho \sim M_N \sim 4\pi f_\pi \ll m_Q}_{\text{the unknown physics}}$$

  - Power counting refers to the scaling with respect to Q:

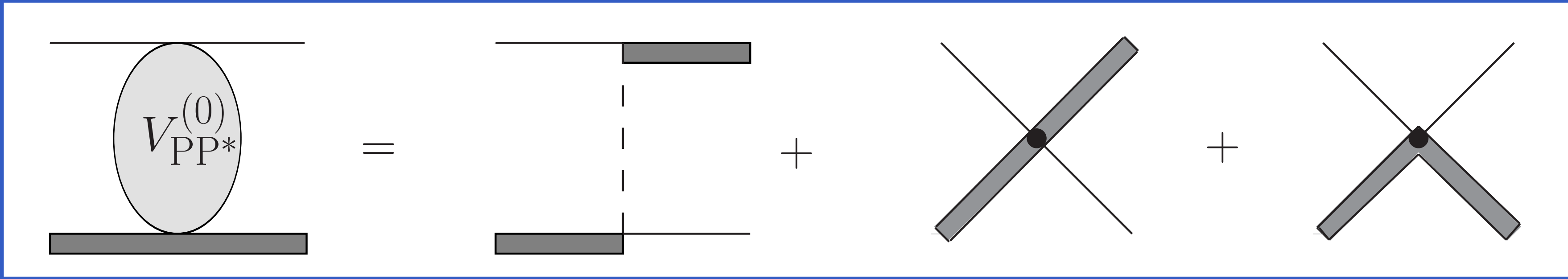
$$V^{(\nu)}(\lambda Q) = \lambda^\nu \, V^{(\nu)}(Q)$$

  - Taking $\lambda \to 0$ is equivalent to $Q/\Lambda_0 \to 0$: contributions of higher order are very small for large separation of scales. Thus we can write:

$$V_{\mathrm{EFT}} = V^{(-1)} + V^{(0)} + V^{(1)} + \mathcal{O}\left((\frac{Q}{\Lambda_0})^2 \right) .$$

The Leading Order Potential (I)

Leading order: one pion exchange and two contact interactions:



(the diagrams are particularized for the $\mathrm{P}\bar{\mathrm{P}}^*$ case)

- The naive scaling of OPE and contacts is Q^0.
- However, there are shallow bound states: the contacts get promoted to order Q^{-1}, defining a simpler leading order.
  Kaplan, Savage, Wise (98); Gegelia (98); van Kolck (98); Birse el al. (98).
- Particle channel transitions like $\mathrm{P}\bar{\mathrm{P}} \to \mathrm{P}^*\bar{\mathrm{P}}^*$ also suppressed.
- All other possible diagrams are higher order (Q^2 at least).

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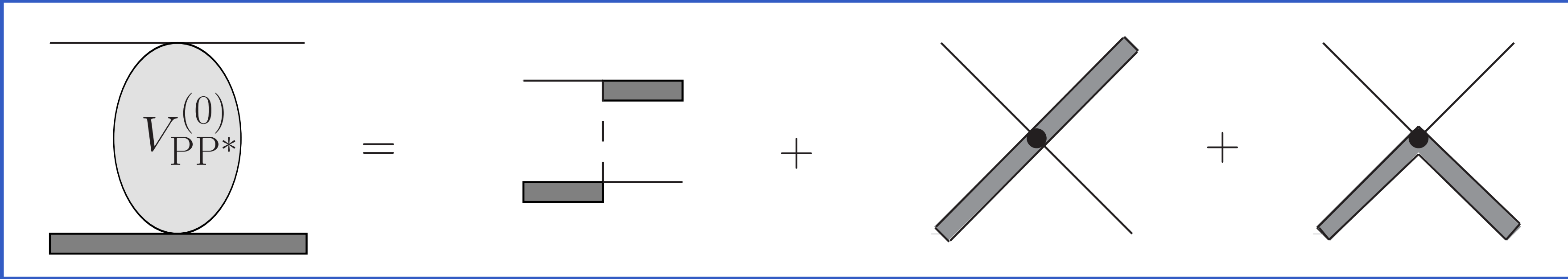

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The OPE Potential (I)

The one pion exchange potential is given by:

$$\tilde{V}_{\rm OPE}(\vec{q}) \quad = \quad -\eta \, \frac{g^2}{2 f_\pi^2} \, \vec{\tau}_2 \cdot \vec{\tau}_1 \, \frac{\vec{b}_2 \cdot \vec{q} \, \vec{a}_1 \cdot \vec{q}}{\vec{q}^{\,2} + \mu^2 + i\epsilon}$$

- Tensor force: mixes different angular momentum channels.
- From HQSS, OPE mixes the different $\mathrm{P}\bar{\mathrm{P}}$, $\mathrm{P}\bar{\mathrm{P}}^*$ / $\mathrm{P}^*\bar{\mathrm{P}}$ and $\mathrm{P}^*\bar{\mathrm{P}}$ particle channels.
- If we consider charmed mesons:
  - $g \simeq 0.6$ from $\Gamma(D^* \to D\pi)$ results in a very weak potential.
  - The $D\bar{D}^* \to D^*\bar{D}$ channel potential has $\mu^2 < 0$: small imaginary piece related to $DD^* \to DD\pi$.

    Baru, Filin, Hanhart, Kalashnikova, Kudryavtsev, Nefediev (11)
  - The static approximation also fails for $D\bar{D}/D\bar{D}^* \to D^*\bar{D}^*$.

The OPE Potential (II)

A closer look at the particle channel structure

$$V^{(0)}_{F,\mathrm{H}\bar{\mathrm{H}}}(\vec{q}) = \frac{g^2}{2f_\pi^2}\,\frac{\vec{\tau}_1\cdot\vec{\tau}_2}{\vec{q}^{\,2}+m_\pi^2}$$

$$\times\begin{pmatrix} 0 & 0 & 0 & -\vec{\epsilon_{1'}}^{\,*}\cdot\vec{q}\,\vec{\epsilon_{2'}}^{\,*}\cdot\vec{q} \\ 0 & 0 & -\vec{\epsilon_1}\cdot\vec{q}\,\vec{\epsilon_{2'}}^{\,*}\cdot\vec{q} & +\vec{S}_1\cdot\vec{q}\,\vec{\epsilon_{2'}}^{\,*}\cdot\vec{q} \\ 0 & -\vec{\epsilon_{1'}}^{\,*}\cdot\vec{q}\,\vec{\epsilon_2}\cdot\vec{q} & 0 & -\vec{\epsilon_{1'}}^{\,*}\cdot\vec{q}\,\vec{S}_2\cdot\vec{q} \\ -\vec{\epsilon_1}\cdot\vec{q}\,\vec{\epsilon_2}\cdot\vec{q} & +\vec{S}_1\cdot\vec{q}\,\vec{\epsilon_2}\cdot\vec{q} & -\vec{\epsilon_1}\cdot\vec{q}\,\vec{S}_2\cdot\vec{q} & +\vec{S}_1\cdot\vec{q}\,\vec{S}_2\cdot\vec{q} \end{pmatrix}$$

$$+\mathcal{O}\left(\frac{1}{m_Q}\right)$$

in the particle basis $\mathcal{B} = \{\mathrm{P}\bar{\mathrm{P}}, \mathrm{P}\bar{\mathrm{P}}^*, \mathrm{P}^*\bar{\mathrm{P}}, \mathrm{P}^*\bar{\mathrm{P}}^*\}$ indicates a quite rich (i.e. computationally difficult) coupled channel structure.

The Contact Operators

Alfiky, Gabbiani, Petrov (06): HQSS implies the existence of two contact operators at the lowest order

$$
\begin{aligned}
\mathcal{L} &= C_{0a}\,\mathrm{Tr}\left[\bar{H}^{(Q)} H^{(Q)} \gamma_\mu\right] \mathrm{Tr}\left[H^{(\bar{Q})} \bar{H}^{(\bar{Q})} \gamma_\mu\right] \\
&+ C_{0b}\,\mathrm{Tr}\left[\bar{H}^{(Q)} H^{(Q)} \gamma_\mu \gamma_5\right] \mathrm{Tr}\left[H^{(\bar{Q})} \bar{H}^{(\bar{Q})} \gamma_\mu \gamma_5\right]
\end{aligned}
$$

- C_{0a} gives the same contribution for PP, PP^* and $\mathrm{P}^*\mathrm{P}^*$
- C_{0b} mixes the different PP, PP^* and $\mathrm{P}^*\mathrm{P}^*$ channels and its effect changes depending on the C-parity.

HQSS reduces the possible number of counterterms from six to two!

Simplifications in the Power Counting

OPE mixes angular momentum and particle channels: quite involved!

However, there are important simplifications:

- For shallow bound states, such as the $X(3872)$, the contact interactions are enhanced with respect to OPE:

$$C_0 \sim \frac{1}{m_Q \gamma}$$

  with $\gamma \sim m_\pi \sim Q$. They are not Q^0 but Q^{-1}!!

  Kaplan, Savage, Wise (98); Gegelia (98); van Kolck (98); Birse el al. (98).

- Coupled channels effects are also suppressed: transition such as $\mathrm{P\bar{P}} \to \mathrm{P^*\bar{P}^*}$ are suppressed by an additional factor of Q^2.

The outcome: tremendous simplifications at lowest order (now Q^{-1}).

The (New) Leading Order Potential:

We have the following Q^{-1} contact range interactions:

$$
\begin{aligned}
V^{(-1)}_{P\bar{P}}(\vec{q}, 0^{++}) &= C_{0a} \, , \\
V^{(-1)}_{P^*\bar{P}/P\bar{P}^*}(\vec{q}, 1^{+-}) &= C_{0a} - C_{0b} \, , \\
V^{(-1)}_{P^*\bar{P}/P\bar{P}^*}(\vec{q}, 1^{++}) &= C_{0a} + C_{0b} \, , \\
V^{(-1)}_{P^*\bar{P}^*}(\vec{q}, 0^{++}) &= C_{0a} - 2\, C_{0b} \, , \\
V^{(-1)}_{P^*\bar{P}^*}(\vec{q}, 1^{+-}) &= C_{0a} - C_{0b} \, , \\
V^{(-1)}_{P^*\bar{P}^*}(\vec{q}, 2^{++}) &= C_{0a} + C_{0b} \, .
\end{aligned}
$$

where we can appreciate certain patterns, for example:

- $V^{(-1)}(1^{+-})$: similar binding for $Z_b(10610)$ and $Z_b(10650)$.
  Cleven et al. (11); Voloshin (11); Mehen and Powell (11).

HQSS, the $X(3872)$ and the $X(4012)$

There is another pair of quantum numbers with identical LO potentials:

- $V^{(-1)}_{\mathrm{P^*\bar{P}/P\bar{P}^*}}(1^{++}) = V^{(-1)}_{\mathrm{P^*\bar{P}^*}}(2^{++})$

which implies the following:

If the $X(3872)$ is a $D\bar{D}^*/D^*\bar{D}$ molecule with $J^{PC} = 1^{++}$, then there should be a $X(4012)$ $D^*\bar{D}^*$ molecule with $J^{PC} = 2^{++}$.

Comments:

- Isospin symmetric limit: the $X(3872)$ is a $D\bar{D}^*/D^*\bar{D}$ molecular state with binding $B_X \simeq 4\,\mathrm{MeV}$.
- HQSS violations ($\sim \frac{\Lambda_{\mathrm{QCD}}}{m_c}$): $M = 4012^{+4}_{-9}\,\mathrm{MeV}$.
- OPE effects (without particle mixing) are small: $\Delta M = 2 - 3\,\mathrm{MeV}$.

Bottomline: the $X(4012)$ prediction looks quite solid.

HQSS: Predicting Further States (I)

There are two counteterms at LO: C_{0a} and C_{0b}:

- The $X(3872)$ can fix a linear combination ($C_{0a} + C_{0b}$) and thus predict one HQSS partner, the $X(4012)$.
- We need to assume the molecular nature of another state to fix C_{0b} and predict the full spectrum of $D^{(*)}\bar{D}^{(*)}$ molecules.

Candidates:

- $X(3915)$ compatible with a $D^*\bar{D}^*$ 0^{++} molecule (Liu, Zhu 09; Branz, Gutsche, Lyubovitskij 09; Ding 09)
- $X(3940)$ could also be $D^*\bar{D}^*$ molecule. However:
  - Decays mostly to $D\bar{D}^*$: compatible with $J^{PC} = 1^{+-}$.
  - The most probable production mechanism, $e^+e^- \to \gamma^* \to J/\Psi X(3940)$, suggests $C = +1$ instead.

HQSS: Predicting Further States (II)

Then, we assume the $X(3915)$ to be a $D^*\bar{D}^*\ 0^{++}$ molecule:

J^{PC}	$\mathrm{H\bar{H}}$	E ($\Lambda = 0.5$ GeV)	E ($\Lambda = 1$ GeV)	Exp (PDG)
0^{++}	$D\bar{D}$	3706 ± 10	3712^{+13}_{-17}	$-$
1^{++}	$D^*\bar{D}$	Input	Input	3872
1^{+-}	$D^*\bar{D}$	3814 ± 17	3819^{+24}_{-27}	$-$
0^{++}	$D^*\bar{D}^*$	Input	Input	3917
1^{+-}	$D^*\bar{D}^*$	3953 ± 17	3956^{+25}_{-28}	3942
2^{++}	$D^*\bar{D}^*$	4012 ± 3	4012^{+4}_{-9}	$-$

We predict a total of six states! (Curiously there is a state in the region of the $X(3940)$, maybe resuggesting $C = -1$ after all)

But how Robust are the Predictions?

Well, there are three effects that can potentially change the spectrum:

- HQSS violations: up to $\pm 25\,\mathrm{MeV}$ for $J^{PC} = 1^{+-}$.
- OPE exchange: up to $\pm 10\,\mathrm{MeV}$ (a surprisingly mild effect).
- Coupled channel dynamics (only in the 0^{++} and 1^{+-} states):
  - The LO potential actually mixes particle channels with identical quantum numbers, but the effect is suppressed.
  - The 0^{++} (1^{+-}) states move by about $20-25$ (35) MeV.
  - Consistent with a Q^2-suppressed effect, but quite dependent on regularization conditions. More effort required.

Conclusion: the exact positions are subjected to uncertainties of up to $40\,\mathrm{MeV}$ in the more bound cases, but the spectrum is robust.

Comparison with Other Works

With the exception of the $X(4012)$, all the previous states have also been predicted in previous works:

- The 0^{++} $\mathrm{D\bar{D}}$ $X(3710)$ states is also to be found in Maiani et al. 04 (quark model, predicts also six states, but usually much more bound) and Gamermann et al. 07 (hidden gauge).
- The 1^{+-} $\mathrm{D\bar{D}^*}$ $X(3820)$ also predicted in Gamermann, Oset 07.
- The 1^{+-} $\mathrm{D\bar{D}^*}$ $X(3955)$ in Molina, Oset 09.
- Finally, the molecular nature of the $X(3915)$ we use as input have been proposed in many works, as already mentioned.

  (Liu, Zhu 09; Branz, Gutsche, Lyubovitskij 09; Ding 09; Molina, Oset 09)

Quite probably there are other works with similar predictions.

Conclusions

- EFT formalism of heavy meson molecules:
  - Contact interactions dominate the low energy description
  - The OPE potential has a much smaller effect than expected.
  - Coupled channel dynamics from HQSS is a subleading (but nonetheless important) contribution.
- HQSS allows the prediction of new molecular states from previously known ones:
  - The $X(3872)$ implies the existence of a 2^{++} $X(4012)$
  - If the $X(3915)$ is molecular, then we have three new partners, the 0^{++} $X(3710)$ and the 1^{+-} $X(3820)$ and $X(3955)$.
- We have estimated the size of subleading corrections: results are theoretically robust.