Theoretical review of heavy-light spectroscopy

Juan M Nieves (IFIC, CSIC & U. Valencia)
- M. Albaladejo, P. Fernández-Soler, JN and P.G. Ortega, EPJC77 (2017) 170
- JN, R. Pavao and L. Tolos EPJC78 (2018) 114 AND

arXiv: 1812.07638

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Opportunities in Flavour Physics
at the HL-LHC and HE-LHC

Thanks to all my collaborators!

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Outline

1. Heavy quark and chiral symmetries
2. Heavy light mesons: even parity open heavy-flavor states
   - HMChpT & infinite volume
   - Lüscher & finite volume
   - Spectroscopy
   - Phase shifts and inelasticities
   - SU(3) limit
   - Predictions for other states: charm & bottom sectors
   - LHCb S-wave $P\phi$ amplitudes
   - Interplay between CQM & two-meson degrees of freedom
   - Muskhelishvili-Omnès representation of the scalar $f_0(q^2)$ form factor
3. Single heavy baryons: odd parity $\Lambda_c(2595)$ and $\Lambda_c(2625)$ puzzle and dependence on the renormalization scheme.
4. Conclusions
Heavy quark spin-flavor symmetry

The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons’s velocity. On average, this is also the velocity of the “brown muck”.

\[ \mathbf{J} = \mathbf{S}_Q + \mathbf{j}_{l dof} \]

\[ \mathbf{J}_{l dof} \text{ is conserved!} \]

\[ SU(2N_h) \text{ symmetry in the } m_Q \to \infty \text{ limit} \]

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HQSS predicts that all types of spin interactions vanish for infinitely massive quarks: the dynamics is unchanged under arbitrary transformations in the spin of the heavy quark \( Q \). The spin-dependent interactions are proportional to the chromomagnetic moment of the heavy quark, hence are of the order of \( 1/m_Q \).

The total angular momentum \( \vec{J}_{\text{idof}} \) of the brown muck, which is the subsystem of the hadron apart from the heavy quark, is conserved and hadrons with \( J = j_{\text{idof}} \pm \frac{1}{2} \) form a degenerate doublet. For instance, \( m_{B^*}(J^P = 1^-) - m_B(J^P = 0^-) = 45.22 \pm 0.21 \text{ MeV} \sim \Lambda_{QCD}, m_d, m_u \) doublet for \( j_{\text{idof}} = 1/2^- \).

HQFS predicts that, besides de mass of the heavy quark, the single-heavy hadron mass is independent of the flavor of the heavy quark \( Q \). The flavor-dependent interactions are proportional to \( 1/m_Q \), \( M_H/m_Q \sim (1 + \frac{O(\Lambda_{QCD})}{M_Q}) \).

\[
[m_{B^*}(J^P = 1^-) - m_B(J^P = 0^-)] \sim [m_{D^*}(J^P = 1^-) - m_D(J^P = 0^-)] \sim \Lambda_{QCD}, m_d, m_u
\]

HQSFS \( SU(2N_h) \) approximate symmetry seen in the hadron spectrum.
Chiral symmetry $\iff$ EFT: Chiral perturbation theory

effective field theory constructed with a Lagrangian consistent with the (approximate) chiral symmetry of quantum chromodynamics (QCD), as well as the other symmetries of parity and charge conjugation.

ChPT is a theory which allows one to study the low-energy dynamics of QCD: take explicitly into account the relevant degrees of freedom, i.e. those states with $m \ll \Lambda$, while the heavier excitations with $M \gg \Lambda$ are integrated out from the action. One gets in this way a string of non-renormalizable interactions among the light states, which can be organized as an expansion in powers of energy/$\Lambda$. The information on the heavier degrees of freedom is then contained in the couplings of the resulting low-energy Lagrangian. Although EFTs contain an infinite number of terms, renormalizability is not an issue since, at a given order in the energy expansion, the low-energy theory is specified by a finite number of couplings; this allows for an order-by-order renormalization.

Goldstone boson ($K, \pi, \eta, \bar{K}$) interactions with single heavy hadrons could be described using a perturbative chiral $[SU(3)_L \times SU(3)_R]$ EFT consistent with the $1/m_Q$ expansion: **HMChPT**

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Chiral perturbation theory for hadrons containing a heavy quark

Mark B. Wise
California Institute of Technology, Pasadena, California 91125
(Received 10 January 1992)

An effective Lagrangian that describes the low-momentum interactions of mesons containing a heavy quark with the pseudo Goldstone bosons $\pi, K,$ and $\eta$ is constructed. It is invariant under both heavy-quark spin symmetry and chiral SU(3)$_L \times$SU(3)$_R$ symmetry. Implications for semileptonic $B$ and $D$ decays are discussed.


\[
\mathcal{L} = -i \text{Tr} \bar{H}_a \gamma_\mu \partial^\mu H_a + \frac{1}{2} i \text{Tr} \bar{H}_a H_b \gamma_\mu \left( \xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger \right)_{ba} \\
+ \frac{1}{2} i g \text{Tr} \bar{H}_a H_b \gamma_\nu \gamma_5 \left( \xi^\dagger \partial_\nu \xi - \xi \partial_\nu \xi^\dagger \right)_{ba} + \cdots , \tag{12}
\]

Goldstone bosons

hadron velocity

For instance, for heavy mesons: super-field including the $j^P_{1dof} = 1/2^-$ doublet

\[
H_a = \frac{1 + \gamma'}{2} (P^*_a \gamma^\mu - P_a \gamma_5) \\
\begin{array}{c}
1^- \\
0^- 
\end{array}
\]

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strategy: combining effective field theory methods with LQCD results to describe data!

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Heavy light mesons
<table>
<thead>
<tr>
<th>$D^\pm$</th>
<th>$D_s^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$D_s^0$</td>
</tr>
<tr>
<td>$D^*(2007)^0$</td>
<td>$D_s^*(2317)^\pm$</td>
</tr>
<tr>
<td>$D^*(2010)^\pm$</td>
<td>$D_{s0}(2317)^\pm$</td>
</tr>
<tr>
<td>$D_0^*(2400)^0$</td>
<td>$D_{s1}(2460)^\pm$</td>
</tr>
<tr>
<td>$D_0^*(2400)^\pm$</td>
<td>$D_{s1}(2536)^\pm$</td>
</tr>
<tr>
<td>$D_1(2420)^0$</td>
<td>$D_{s2}(2573)$</td>
</tr>
<tr>
<td>$D_1(2420)^\pm$</td>
<td>$D_{s1}(2700)^\pm$</td>
</tr>
<tr>
<td>$D_1(2430)^0$</td>
<td>$D_{s1}(2860)^\pm$</td>
</tr>
<tr>
<td>$D_2^*(2460)^0$</td>
<td>$D_{s3}(2860)^\pm$</td>
</tr>
<tr>
<td>$D_2^*(2460)^\pm$</td>
<td>$D_{sJ}(3040)^\pm$</td>
</tr>
</tbody>
</table>

Even parity open heavy-flavor mesons

---

RPP 2019 $D_0^*(2300)$

| $D_J(2600)$ was $D(2600)$ |
| $D^*(2640)^\pm$ |
| $D(2740)^0$ |
| $D(2750)$ |
| $D(3000)^0$ |

F.K. Guo @ CHARM 2018

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**$D_0^*(2400)$ interesting:**

- Lightest scalar ($J^\pi = 0^+$) open charm states:
  \[
  \begin{cases}
    D_{s0}^*(2317), & (S,I) = (1,0) \\
    D_0^*(2400), & (S,I) = (0,1/2)
  \end{cases}
  \]

- Lightest systems to test ChPT with heavy mesons, besides $D^* \rightarrow D\pi$

- $D\pi$ interactions are relevant, since $D\pi$ appears as a final state in many reactions where exotic states are discovered (f.i. $Z_c(3900)$ & $\bar{D}^*D\pi$)

- Difficult to describe within Constituent Quark Model schemes:
  - $D_{s0}^*(2317)$ is around 150 MeV below the predicted mass.
    - Lakhina, & Swanson, PLB 650 (2007) 159; Ortega et al., PRD94 (2016) 074037
  - One would expect $D_{s0}^*(\sim c\bar{s})$ to be heavier than $D_0^*(\sim c\bar{n})$.

- $D_0^*(2400)$ might be important in weak interactions and CKM parameters
  - Yao, Fernández-Soler, Albaladejo, Guo, Nieves EPJC 70 (2018) 310
    - It determines the shape of the scalar form factor $f_0(q^2)$ in semileptonic $D \rightarrow \pi$ decays.
    - Relation to $|V_{cd}|$: $f_+(0) = f_0(0)$ and $d\Gamma \sim |V_{cd} f_+(q^2)|^2 dq^2$
    - Interesting also the relation of the bottom partner and $|V_{ub}|$
# Introduction: Theoretical interpretations

## $c\bar{q}$ states

## $c\bar{q}+\text{tetraquarks or meson–meson}$

## Pure tetraquarks

## Heavy-light meson–meson molecules
**$D_0^*(2400)$: Experimental situation** [PDG avg: $(M, \Gamma/2) = (2300 \pm 19, 137 \pm 20)$ MeV neu = $(2349 \pm 7, 110 \pm 9)$ MeV char ]

<table>
<thead>
<tr>
<th>Collab.</th>
<th>$M$ (MeV)</th>
<th>$\Gamma/2$ (MeV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neu.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Char.</strong></td>
<td></td>
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</tr>
</tbody>
</table>

**$D_0^*(2400)$ & $D_{s0}^*(2317)$ Lattice QCD**

- **Masses larger than the physical ones if using $c\bar{s}$ interpolators only** [Bali, PRD68 (2003) 071501; UKQCD PLB569 (2003) 41]. **Recent study including four quark operators** [Bali et al., PRD96 (2017) 054501]

- **Masses consistent with $D_0^*(2400)$ and $D_{s0}^*(2317)$ obtained when “meson-meson” interpolators are employed** [Mohler, Prelovsek, Woloshyn, PRD 87 (2013) 034501; Mohler et al., PRL111 (2013) 222001]

- **Hadron Spectrum Collab., JHEP 1610, 011 (2016):** $D\pi, D\eta, D_s\bar{K}$ coupled-channels and a bound state with large coupling to $D\pi$ is identified with the $D_0^*(2400)$

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Theoretical Approach: Infinite volume

✓ Coupled-channels $T$-matrix: $D\pi, D\eta, D_s\bar{K}$ S-wave scattering $[J^\pi = 0^+, (S,I) = (0,\frac{1}{2})]$

✓ Unitarity: $T^{-1}(s) = V^{-1}(s) - \mathcal{G}(s)$
  - Normalization: $-i \, p_{ii}(s) T_{ii}(s) = 4\pi \sqrt{s} \, (\eta_i(s)e^{2i\delta_{ii}(s)} - 1)$
  - $\mathcal{G}_{ij}(s) = \delta_{ij} \, G(s, m_i, M_i)$, loop function regularized with a subtraction constant $a(\mu), \mu = 1 \text{ GeV}$
  - Two particle irreducible amplitude $V(s)$ taken from $\mathcal{O}(p^2)$ HMChPT

✓ Analytical continuations: Riemann sheets (RS) denoted as $(\xi_1, \xi_2, \xi_3)$:

$$\mathcal{G}_{ii}(s) \rightarrow \mathcal{G}_{ii}(s) + i \frac{p_i(s)}{4\pi \sqrt{s}} \xi_i$$

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Theoretical Approach: Infinite volume

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- Analytical continuations: Riemann sheets (RS) denoted as $(\xi_1, \xi_2, \xi_3)$:

\[
G_{ii}(s) \rightarrow G_{ii}(s) + i \frac{p_i(s)}{4\pi\sqrt{s}} \ \xi_i
\]
Chiral symmetry used to compute the $D\pi, D\eta, D_s\bar{K}$ coupled-channels potential $V(s)$

At $\mathcal{O}(p^2)$ \( \to \) $f^2 V_{ij}(s, t, u) = C_{ij}^{LO} \frac{s-u}{4} + \sum_{k=0}^{5} h_a C_{ij}^a(s, t, u)$

Lowest order: totally predicted by Chiral symmetry

Next-to-leading LECs, together with the subtraction constant $a(\mu)$, have been previously fitted to reproduce scattering lengths obtained in a LQCD simulation

\[ \text{structures determined by chiral symmetry and its pattern of breaking} \]

Guo et al., PLB666 (2008) 251
Liu et al., PRD87 (2013) 014508

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Liu et al., PRD87 (2013) 014508

the subtraction constant is taken to be the same for the different channels, its pion mass dependence is neglected.

$h_1$ is fixed from the SU(3) mass splitting of the charmed mesons
$D\pi, D\eta, D_s\overline{K}$ energy levels in a **finite volume**

- Periodic boundary conditions imposes momentum quantization
- In practice, changes in the $T$–matrix: $T(s) \rightarrow \overline{T}(s, L)$ [Döring et al., EPJA47 (2011) 139]

\[
\begin{align*}
\mathcal{G}_{ii}(s) &\rightarrow \tilde{\mathcal{G}}_{ii}(s, L) = \mathcal{G}_{ii}(s) + \lim_{\Lambda \to \infty} \left( \frac{1}{L^3} \sum_{\mathbf{n}} I_i(\mathbf{q}) - \int_0^\Lambda \frac{q^2 d^3 q}{(2\pi)^3} I_i(\mathbf{q}) \right) \\
I_i(\mathbf{q}) &= \frac{1}{2\omega_i(\mathbf{q})\omega'_i(\mathbf{q})} \frac{\omega_i(\mathbf{q}) + \omega'(\mathbf{q})}{s - (\omega_i(\mathbf{q}) + \omega'_i(\mathbf{q}))^2 + i\epsilon}, \quad \omega(\mathbf{q}) = \sqrt{m_j^2 + \mathbf{q}^2}, \quad \omega'(\mathbf{q}) = \sqrt{M_j^2 + \mathbf{q}^2}
\end{align*}
\]

\[
V(s) \rightarrow \overline{V}(s, L) = V(s)
\]

\[
T^{-1}(s) \rightarrow \overline{T}^{-1}(s, L) = V^{-1}(s) - \overline{\mathcal{G}}(s, L)
\]

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✓ Free energy levels: \( E_{n,\text{free}}^i(L) = \omega_i \left( \frac{2\pi}{L} \vec{n} \right) + \omega_i' \left( \frac{2\pi}{L} \vec{n} \right) \)

✓ Interacting energy levels \( E_n(L) \) such that: \( \mathcal{T}^{-1}(E_n^2(L), L) = 0 \) [poles of the \( \mathcal{T} \) matrix]


\( D\pi, D\eta, D_s\bar{K} \) coupled-channels

\[
\begin{array}{c|c|c}
  M (\text{MeV}) & \text{Latt.} & \text{Phys.} \\
  \hline
  \pi & 391 & 138 \\
  K & 550 & 496 \\
  \eta & 588 & 548 \\
  D & 1886 & 1867 \\
  D_s & 1952 & 1968 \\
\end{array}
\]
Free energy levels: \( E_{n,\text{free}}^i(L) = \omega_i \left( \frac{2\pi}{L} n \right) + \omega'_i \left( \frac{2\pi}{L} n \right) \)

Interacting energy levels \( E_n(L) \) such that: \( \bar{T}^{-1}(E_n^2(L), L) = 0 \) [poles of the \( \bar{T} \) matrix]

We compute \( E_n(L) \) and compare with the LQCD levels. No fit is performed.

68% CL bands inherited from the errors on the LECs.

\( E > 2.7 \) GeV is probably beyond the range of validity for the HMChPT \( T \) -matrix.

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Free energy levels: \( E_{n,\text{free}}^i(L) = \omega_i \left( \frac{2\pi}{L} \bar{n} \right) + \omega'_{i} \left( \frac{2\pi}{L} \bar{n} \right) \)

Interacting energy levels \( E_n(L) \) such that: \( \mathcal{T}^{-1}(E^2_n(L), L) = 0 \) [poles of the \( \mathcal{T} \) matrix]

Level below threshold, associated with a bound state.
✓ Free energy levels: \( E_{n,\text{free}}^i(L) = \omega_i \left( \frac{2\pi}{L} \vec{n} \right) + \omega'_i \left( \frac{2\pi}{L} \vec{n}' \right) \)

✓ Interacting energy levels \( E_n(L) \) such that: \( \overline{T}^{-1}(E_n^2(L), L) = 0 \)

[ poles of the \( \tilde{T} \) matrix]

✓ Level below threshold, associated with a bound state.

✓ Second level, lying between the \( D\pi \) and \( D\eta \) thresholds, is very shifted with respect to both of them, hinting at the presence of a Resonance?

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For lattice masses, we find a bound state \((000)\) and a resonance \((110)\).
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For physical masses: The bound state evolves into a resonance \((100)\) above \(D\pi\) threshold. The resonance varies very little, and is still a resonance \((110)\). For both states, the coupling pattern is similar.

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For lattice masses, we find a bound state (000) and a resonance (110).

For physical masses:
The bound state evolves into a resonance (100) above $D\pi$ threshold. The resonance varies very little, and is still a resonance (110).

For both states, the coupling pattern is similar.

| Masses | $M$ (MeV) | $\Gamma/2$ (MeV) | RS | $|g_{D\pi}|$ | $|g_{D\eta}|$ | $|g_{Ds\bar{K}}|$ |
|--------|-----------|-----------------|----|------------|------------|--------------|
| lattice | $2264^{+8}_{-14}$ | 0 | (000) | $7.7^{+1.2}_{-1.1}$ | $0.3^{+0.5}_{-0.3}$ | $4.2^{+1.1}_{-1.0}$ |
|         | $2468^{+32}_{-25}$ | $113^{+18}_{-16}$ | (110) | $5.2^{+0.6}_{-0.4}$ | $6.7^{+0.6}_{-0.4}$ | $13.2^{+0.6}_{-0.5}$ |
| physical | $2105^{+6}_{-8}$ | $102^{+10}_{-12}$ | (100) | $9.4^{+0.2}_{-0.2}$ | $1.8^{+0.7}_{-0.7}$ | $4.4^{+0.5}_{-0.5}$ |
|         | $2451^{+36}_{-26}$ | $134^{+7}_{-8}$ | (110) | $5.0^{+0.7}_{-0.4}$ | $6.3^{+0.8}_{-0.5}$ | $12.8^{+0.8}_{-0.6}$ |
The $D_0^*$ (2400) structure is actually produced by two different states (poles), together with complicated interferences with thresholds. This two-pole structure was previously reported, and receives now a robust support.

Kolomeitsev, & Lutz, PLB 582 (2004) 39
Guo et al., PLB 641 (2006) 278; Guo et al., EPJA 40 (2009) 171

| Masses  | $M$ (MeV) | $\Gamma/2$ (MeV) | RS  | \( |g_{D\pi}| \)  | \( |g_{D\eta}| \)  | \( |g_{D_{s\bar{K}}}| \) |
|---------|-----------|------------------|-----|----------------|----------------|----------------|
| lattice | 2264\(^{+8}_{-14}\) | 0 | (000) | 7.7\(^{+1.2}_{-1.1}\) | 0.3\(^{+0.5}_{-0.3}\) | 4.2\(^{+1.1}_{-1.0}\) |
|         | 2468\(^{+32}_{-25}\) | 113\(^{+18}_{-16}\) | (110) | 5.2\(^{+0.6}_{-0.4}\) | 6.7\(^{+0.6}_{-0.4}\) | 13.2\(^{+0.6}_{-0.5}\) |
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|         | 2451\(^{+36}_{-26}\) | 134\(^{+7}_{-8}\)  | (110) | 5.0\(^{+0.7}_{-0.4}\) | 6.3\(^{+0.8}_{-0.5}\) | 12.8\(^{+0.8}_{-0.6}\) |
\[ -i \rho_{ii}(s) T_{ii}(s) = 4\pi \sqrt{s} \left( \eta(s) e^{2i\delta_{ii}(s)} - 1 \right). \]

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Lower pole, \( \sqrt{s} = (2.1 - i 0.1) \) GeV
- \( |T_{11}(s)|^2 \) peaks at \( \sqrt{s} \sim 2.1 \) GeV
- \( \delta_{11}(s) = \frac{\pi}{2} \) at \( \sqrt{s} \sim 2.2 \) GeV

Higher pole, \( \sqrt{s} = (2.45 - i 0.13) \) GeV
- Small enhancement in \( |T_{11}(s)| \)
- Clear peak in the \( D_s\bar{K} \) amplitude.
- Narrow, non-conventional shape, stretched between thresholds cusps.
- Possible tests in \( B \rightarrow D\phi\phi \) decays
SU(3) light flavor limit: \[
\bar{3} \otimes 8 = 15 \oplus 6 \oplus \bar{3}
\]

\[D^+, D^0, D_s = c\bar{c}\]

\[\bar{K}, \pi, \eta, K\]

\begin{align*}
S &= 2 \\
S &= 1 \\
S &= 0 \\
S &= -1
\end{align*}

the most attractive irrep admits a \(c\bar{n}\) interpretation

\[c\bar{s}, c\bar{u}, c\bar{d}\]

\[\text{repulsive}, \text{attractive}\]

At LO: \[V_A(s) = B(s) \text{ Diag}(1, -1, -3)\]

In this limit (all \(D\)-mesons and all Goldstone bosons have common masses \(M\) and \(m\), respectively), \(T\) and \(V\) can be diagonalized, while \(G\) is already diagonal,

\[T_A^{-1}(s) = V_A^{-1}(s) - G(s, m, M), \ A = 15, 6, \bar{3}\]

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<table>
<thead>
<tr>
<th>State</th>
<th>Channels</th>
<th>$(S, I)$</th>
<th>15</th>
<th>6</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_0^*$</td>
<td>$D \pi, D \eta, D_s \bar{K}$</td>
<td>$(0, \frac{1}{2})$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$D_{s0}^*(2317)$</td>
<td>$DK, D_s \eta$</td>
<td>$(1, 0)$</td>
<td>✔️</td>
<td>X</td>
<td>✔️</td>
</tr>
</tbody>
</table>

Note that the LECs fitted in Liu et al., PRD87 (2013) 014508 leads to a pole in the $DK, D_s \eta$ coupled-channels $T$-matrix than can naturally be identified with the $D_{s0}^*(2317)$, $M = 2315^{+18}_{-28}$ MeV.
Connecting physical \((x = 0)\) & flavor SU(3) \((x = 1)\) limits

\[
m_i = m_i^{\text{phys}} + x (m - m_i^{\text{phys}}), \quad m = 0.49 \text{ GeV}
\]

\[
M_i = M_i^{\text{phys}} + x (M - M_i^{\text{phys}}), \quad M = 1.95 \text{ GeV}
\]

The purple long dashed lines stand for the \(D\pi, D\bar{K}, D\eta,\) and \(D_s K\) thresholds (from bottom to top). Even in the SU(3) limit the interaction is not strong enough to produce a bound state.

Riemann sheets (RS) denoted as \((\xi_1, \xi_2, \xi_3)\) in the SU(3) limit, there are only 2 RS's: \((000)\) and \((111)\).

In the \(D_0^*(2400)\) pole trajectories, \(\xi_1\) (for the lower pole) and \(\xi_3\) (for the higher pole) depend on \(x\).

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\[ m_i = m_{\text{phys}} + x (m - m_{\text{phys}}) \]

- The high \( D_0^* \) connects with a 6 virtual state.
- The low \( D_0^* \) connects with a \( \bar{3} \) bound state.
- The \( D_{0s}^*(2317) \) also connects with the \( \bar{3} \) bound state.

The low \( D_0^* \) and the \( D_{s0}^*(2317) \) are SU(3) flavor partners.
The high $D_0^*$ connects with a 6 virtual state.

The low $D_0^*$ connects with a $\bar{3}$ bound state.

The $D_{0s}^*(2317)$ also connects with the $\bar{3}$ bound state

This solves the “puzzle” of $D_{s0}^*(2317)$ being lighter than $D_0^*(2400)$: it is not, the lower $D_0^*(2400)$ pole ($M = 2105$ MeV) is lighter!

The low $D_0^*$ and the $D_{s0}^*(2317)$ are SU(3) flavor partners
Predictions for other sectors: charm

\[ J^P = 0^+ \]

<table>
<thead>
<tr>
<th>( (S, I) )</th>
<th>Channels</th>
<th>( 15(R) )</th>
<th>( 6(A) )</th>
<th>( 3 ) (A)</th>
<th>( (M, \Gamma/2) ) [MeV]</th>
</tr>
</thead>
</table>
| (0,1/2)     | \( D^{(*)}\pi, D^{(*)}\eta, D_s^{(*)}\bar{K} \) | YES | YES | YES | Lower pole \( (2105^{+6}_{-8}, 102^{+10}_{-11}) \)  
RPP \( (2300 \pm 19, 137 \pm 20) \)  
Higher pole \( (2451^{+35}_{-26}, 134^{+7}_{-8}) \) |
| (1,0)       | \( D^{(*)}K, D_s^{(*)}\eta \) | YES | NO | YES | 2315^{+18}_{-28} (bound); RPP 2317.8\pm0.5 |
| (−1,0)      | \( D^{(*)}\bar{K} \) | NO | YES | NO | 2342^{+13}_{-41} (virtual) |
| (1,1)       | \( D_s^{(*)}\pi, D^{(*)}K \) | YES | YES | NO | – |

\[ J^P = 1^+ \]

<table>
<thead>
<tr>
<th>( (S, I) )</th>
<th>Channels</th>
<th>( 15(R) )</th>
<th>( 6(A) )</th>
<th>( 3 ) (A)</th>
<th>( (M, \Gamma/2) ) [MeV]</th>
</tr>
</thead>
</table>
| (0,1/2)     | \( D^{(*)}\pi, D^{(*)}\eta, D_s^{(*)}\bar{K} \) | YES | YES | YES | Lower pole \( (2247^{+5}_{-6}, 107^{+11}_{-10}) \)  
RPP \( (2427 \pm 40, 192^{+6}_{-55}) \)  
Higher pole \( (2555^{+47}_{-30}, 203^{+8}_{-9}) \) |
| (1,0)       | \( D^{(*)}K, D_s^{(*)}\eta \) | YES | NO | YES | 2456^{+15}_{-21} (bound); RPP 2459.5\pm0.6 |
| (−1,0)      | \( D^{(*)}\bar{K} \) | NO | YES | NO | – |
| (1,1)       | \( D_s^{(*)}\pi, D^{(*)}K \) | YES | YES | NO | – |

- HQSS relates \( 0^+ (D_{(S)}P) \) and \( 1^+ (D_{(S)}^*P) \) sectors: similar resonance pattern.
- Two pole structure: higher \( D_1 \) pole probably affected by \( D^{(*)}\rho \) channels.
- \( D\bar{K} [0^+, (-1, 0)] \): this virtual state (from 6) has a large impact on the scattering length, \( a_{D\bar{K}}^{(−1,0)} \sim 0.8 \text{ fm.} \) (Rest of scattering lengths are \( |a| \sim 0.1 \text{ fm.} \))
### Predictions for other sectors: bottom

<table>
<thead>
<tr>
<th>((S, I))</th>
<th>Channels</th>
<th>(\overline{15}(R))</th>
<th>(\overline{3}(A))</th>
<th>((M,\Gamma/2)) [MeV]</th>
<th>((M,\Gamma/2)) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 1/2)</td>
<td>(\overline{B}^{(<em>)}\pi, \overline{B}^{(</em>)}\eta, \overline{B}^{(*)}_S\overline{K})</td>
<td>YES</td>
<td>YES</td>
<td>Lower pole ((5535^{+9}<em>{-11}, 113^{+15}</em>{-17}))</td>
<td>Lower pole ((5584^{+9}<em>{-11}, 119^{+14}</em>{-17}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RPP –</td>
<td>RPP –</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Higher pole ((5852^{+16}_{-19}, 36 \pm 5))</td>
<td>Higher pole ((5912^{+15}<em>{-18}, 42^{+5}</em>{-4}))</td>
</tr>
<tr>
<td>(1, 0)</td>
<td>(\overline{B}^{(<em>)}K, \overline{B}^{(</em>)}_S\eta)</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5720^{+16}_{-23} (bound); RPP –</td>
<td>5772^{+15}_{-21} (bound); RPP –</td>
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<tr>
<td>(−1, 0)</td>
<td>(\overline{B}^{(*)}\overline{K})</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>(V-B) thr.</td>
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<tr>
<td>(1, 1)</td>
<td>(\overline{B}^{(<em>)}_S\pi, \overline{B}^{(</em>)}K)</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>–</td>
</tr>
</tbody>
</table>

- Heavy flavour symmetry relates charm \((D)\) and bottom \((\overline{B})\) sectors.
- \((0, 1/2)\): \(\overline{B}^{(*)}_0\), two-pole pattern also observed.
- \((-1, 0)\): \([\overline{B}^{(*)}\overline{K}]\): very close to threshold. Relevant prediction. Can be either bound or virtual (6).
- \((1, 1)\): \([\overline{B}^{(*)}_S\pi, \overline{B}^{(*)}K, 0^+]\), \(X\) (5568) channel. No state is found: 15 and 6. If it exists, it is not dynamically generated in \(\overline{B}^{(*)}_S\pi, \overline{B}^{(*)}K\) interactions. [Albaladejo et al., PLB 757 (2016) 515; Guo et al., Commun. Theor. Phys. 65 (2016) 593]
- \((1, 0)\): Our results for \(\overline{B}^{(*)}_S\) and \(\overline{B}^{(*)}_1\) agree with other results from LQCD [Lang et al., PLB 750 (2015) 17].

Juan Nieves, IFIC (CSIC & UV)
Chiral $D_{(s)}^{(*)}\phi$ molecular structure natural solution to three (experimental) puzzles:

- Why are the $M_{D^*_{s0}(2317)}$ & $M_{D_{s1}(2460)} \ll$ CQM $c\bar{s}$ 0$^+$ and 1$^+$ mass predictions

- Why $(M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)}) \sim (M_{D^*} - M_D)$ within 1 MeV.

- Why are the $D_0^*(2400)$ and $D_1(2430)$ masses almost equal to or even higher than their strange siblings despite of $\frac{m_s}{m_d} \sim 20$

...confirmed by LHCb data for the $B^- \rightarrow D^+\pi^-\pi^-$ reaction

Juan Nieves, IFIC (CSIC & UV)


\[ \mathcal{A}_0 (S\text{-wave}) \]

\[ \langle P_0 \rangle \propto |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2, \]
\[ \langle P_2 \rangle \propto \frac{2}{5} |\mathcal{A}_1|^2 + \frac{2}{7} |\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}} |\mathcal{A}_0| |\mathcal{A}_2| \cos(\Delta \delta_2), \]
\[ \langle P_{13} \rangle \equiv \langle P_1 \rangle - \frac{14}{9} \langle P_3 \rangle \propto \frac{2}{\sqrt{3}} |\mathcal{A}_0| |\mathcal{A}_1| \cos(\Delta \delta_1), \]

...confirmed by LHCb data [R. Aaij et al. (LHCb Collaboration) PRD 94 (2016) 072001] for the \( B^- \to D^+ \pi^- \pi^- \) reaction

\[ \mathcal{A}_0 (S\text{-wave}) \text{ from UHMChPT} \]

\[ \text{cusps: opening of the } D^0 \eta \text{ and } D_s^+ K^- \text{ thresholds enhanced by the higher } D_0^* (2400) \text{ pole} \]
the LHCb data [R. Aaij et al. PRD 90 (2014) 072003] for the angular moments for $B_{s}^{0} \rightarrow \bar{D}^{0}K^{-}\pi^{+}$ can be easily reproduced in the same framework with the untarized chiral $\bar{D}K$ coupled-channels S-wave amplitude... and two final remarks in this context

Juan Nieves, IFIC (CSIC & UV)
### charm sector

<table>
<thead>
<tr>
<th>((S,I))</th>
<th>Channels</th>
<th>(15(R))</th>
<th>(6(A))</th>
<th>(\bar{3}(A))</th>
<th>((M,\Gamma/2)) [MeV]</th>
<th>((M,\Gamma/2)) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>((0,1/2))</td>
<td>(D^{(<em>)}\pi, D^{(</em>)}\eta, D_s^{(*)}\bar{K})</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>Lower pole ((2105_{-8}^{+6}, 102_{-11}^{+10}))</td>
<td>Lower pole ((2247_{-6}^{+5}, 107_{-10}^{+11}))</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RPP ((2300 \pm 19, 137 \pm 20))</td>
<td>RPP ((2427 \pm 40, 192_{-55}^{+65}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Higher pole ((2451_{-26}^{+35}, 134_{-7}^{+7}))</td>
<td>Higher pole ((2555_{-30}^{+47}, 203_{-8}^{+8}))</td>
</tr>
<tr>
<td>((1,0))</td>
<td>(D^{(<em>)}\eta, D_s^{(</em>)}\eta)</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>2315_{-28}^{+18} (bound); RPP 2317.8 \pm 0.5</td>
<td>2456_{-21}^{+15} (bound); RPP 2459.5 \pm 0.6</td>
</tr>
<tr>
<td>((-1,0))</td>
<td>(D^{(*)}\bar{K})</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>2342_{-41}^{+13} (virtual)</td>
<td>the pole (virtual) moves deep in the complex plane</td>
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<tr>
<td>((1,1))</td>
<td>(D_s^{(<em>)}\pi, D^{(</em>)}\pi)</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

CQM: \(c\bar{c}\) members of the flavor antitriplet—the presence of the \textbf{sextet is a nontrivial prediction} emerging from the meson-meson dynamics.
Dynamics of the sextet pole in the SU(3) limit as a function of the Golstone boson mass. It can be tested in LQCD.
For lattice masses, we find a bound state (000) and a resonance (110).

LQCD: G. Moir et al., JHEP 1610 (2016) 011 (Hadron Spectrum Collaboration) reported only one pole. No further pole is found in the HadSpec analysis. With the quark masses used there, the predicted sextet pole is located deep in the complex plane and thus it is not captured easily. Importance of using NLO HMChPT amplitudes: combined LQCD & ChPT analysis.
... and CQM states? molecular probabilities?

Let us focus on the $D^{*}_{s0}(2317)$ and $D_{s1}(2460)$ resonances. Flavor content $c\bar{s}$ and $j^P = 0^+$ and $1^+$

$D^{(*)}, D^{(*)}_s$ heavy light mesons

Goldstone bosons

undetermined LEC

\[
\mathcal{L} = \frac{ic}{2} \text{Tr} \left( \bar{H}^a J_b \gamma^\mu \gamma_5 \left[ \xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger \right]^b \right) + h.c.,
\]

$J_a = \frac{1 + \psi}{2} (Y^*_a \gamma_5 \gamma^\mu \gamma^a + Y_a)$ $0^+$ and $1^+$ bare CQM $1^{2S+1}P_J c\bar{c}$ states

✓ Chiral symmetry
✓ HQSS
✓ SU(3) flavor

Juan Nieves, IFIC (CSIC & UV)
non-perturbative BSE re-summation


- LO HMChPT: avoid double-counting
- free parameters: UV regulator+LEC (c)
- bare CQM mass and LEC (c) depend on UV regulator

CQM $c\bar{c}$

undetermined LEC (c): controls interplay between CQM and two-meson degrees of freedom
<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$[\text{Set A}]$</th>
<th>$[\text{Set B}]$</th>
<th>$(M_{D^*} + m_K)$</th>
<th>$(M_{D_{s}^*} + m_\eta)$</th>
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</thead>
<tbody>
<tr>
<td>0$^+$</td>
<td>2510.7</td>
<td>2382.9</td>
<td>2362.8</td>
<td>2516.1</td>
</tr>
<tr>
<td>1$^+$</td>
<td>2593.1</td>
<td>2569.7</td>
<td>2504.2</td>
<td>2660.0</td>
</tr>
<tr>
<td>1$^+$ − 0$^+$</td>
<td>82.4</td>
<td>186.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


far from the mass of the physical state $\sim$ 2460 MeV
CQM potential that includes OGE corrections does not describe well the LQCD energy-levels

CQM model A + LO HMChPT describe de LQCD results

LQCD energy-levels [G.S. Bali, S. Collins, A. Cox, A. Schfer, PRD 96 (2017) 074501] for $m_\pi \sim 290$ MeV and $m_\pi \sim 150$ MeV

Juan Nieves, IFIC (CSIC & UV)
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Set</th>
<th>Ensemble</th>
<th>$J^P$</th>
<th>$m_{c\bar{s}}$ [MeV]</th>
<th>$c$</th>
<th>$\Lambda$ [MeV]</th>
<th>$\chi^2$/dof</th>
<th>$P_{D^{(*)}K}$ [%]</th>
<th>$P_{D^{(*)}\eta}$ [%]</th>
<th>$a_{D^{(*)}K}$ [fm]</th>
<th>$g_{D^{(*)}K}$ [GeV]</th>
<th>$g_{D^{(*)}\eta}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>I</td>
<td>0⁺</td>
<td>2511</td>
<td>0.62 ± 0.04</td>
<td>663^{+23}_{-27}</td>
<td>1.8</td>
<td></td>
<td>2335 ± 2</td>
<td>67 ± 1</td>
<td>2.1 ± 0.2</td>
<td>−1.41^{+0.05}_{−0.06}</td>
<td>10.6 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1⁺</td>
<td>2593</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2465 ± 2</td>
<td>57 ± 1</td>
<td>1.9 ± 0.2</td>
<td>−1.16^{+0.03}_{−0.04}</td>
<td>12.1^{+0.3}_{−0.2}</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>0⁺</td>
<td>2511</td>
<td>0.61 ± 0.09</td>
<td>710^{+70}_{−60}</td>
<td>3.1</td>
<td></td>
<td>2331 ± 3</td>
<td>64 ± 2</td>
<td>2.4 ± 0.4</td>
<td>−1.29^{+0.07}_{−0.08}</td>
<td>10.9^{+0.4}_{−0.3}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1⁺</td>
<td>2593</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2460 ± 3</td>
<td>55^{+2}_{−1}</td>
<td>2.2^{+0.4}_{−0.3}</td>
<td>−1.07^{+0.05}_{−0.06}</td>
<td>12.2^{+0.5}_{−0.4}</td>
</tr>
<tr>
<td>B</td>
<td>I</td>
<td>0⁺</td>
<td>2383</td>
<td>0.71 ± 0.01</td>
<td>426 ± 14</td>
<td>18.6</td>
<td></td>
<td>2330 ± 2</td>
<td>51 ± 1</td>
<td>0.51 ± 0.06</td>
<td>−1.36 ± 0.05</td>
<td>11.8^{+0.1}_{−0.2}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1⁺</td>
<td>2570</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2485 ± 2</td>
<td>67 ± 1</td>
<td>0.51 ± 0.07</td>
<td>−1.79 ± 0.09</td>
<td>11.0^{+0.2}_{−0.3}</td>
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<td>II</td>
<td>0⁺</td>
<td>2383</td>
<td>0.57^{+0.07}_{−0.08}</td>
<td>580^{+80}_{−50}</td>
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<td>2320 ± 4</td>
<td>45^{+2}_{−1}</td>
<td>1.23 ± 0.04</td>
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<td>1⁺</td>
<td>2570</td>
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<td></td>
<td>2477 ± 4</td>
<td>60 ± 2</td>
<td>1.33 ± 0.04</td>
<td>−1.07^{+0.05}_{−0.06}</td>
<td>12.2^{+0.5}_{−0.4}</td>
</tr>
</tbody>
</table>
Unitarized NLO HMChPT [LECs from Liu et al., PRD87 (2013) 014508; same scheme that in the study of $D^*_0(2400)$] describes (no fit) the LQCD energy-levels!
S-wave $B\pi$, $B_s\bar{K}$, $D\pi$ and $D\bar{K}$ scattering and Lattice calculations of Scalar Form Factors in Semileptonic Decays: Muskhelishvili-Omnès representation of form factors

Yao, Fernández-Soler, Albaladejo, Guo, Nieves EPJC 70 (2018) 310

For instance, $\bar{B} \rightarrow \pi l \bar{v}_l$

$$\langle \pi(p_\pi)|V^\mu|\bar{B}(p_B)\rangle = (p_B + p_\pi - q \frac{m_B^2 - m_\pi^2}{q^2})^\mu f^+(q^2)$$

$$+ q^\mu \frac{m_B^2 - m_\pi^2}{q^2} f^0(q^2)$$

Omnès dispersive representation, generalized to coupled-channels

$$f^0(q^2) = f^0(s_0) e^{\frac{s-s_0}{\pi}} \int_{s_{th}}^{+\infty} \frac{dx}{x-s_0} \delta(x) , q^2 \notin L$$

It can be taken from the unitarized HMChPT amplitudes

$$J^P = 0^+,$$

$$\pi \bar{B} \rightarrow \pi \bar{B}$$

Juan Nieves, IFIC (CSIC & UV)
Single heavy baryons
## CHARMED BARYONS ($C = +1$)

$A_c^+ = udc$, $\Sigma_c^{1+} = uuc$, $\Sigma_c^0 = udc$, $\Sigma_c^+ = ddc$, $\Xi_c^0 = ucc$, $\Xi_c^+ = dsc$, $\Omega_c^0 = scc$

See related review: Charged Baryons

<table>
<thead>
<tr>
<th>Particle</th>
<th>Quantum Numbers</th>
<th>Status</th>
</tr>
</thead>
<tbody>
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</tr>
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<tr>
<td>$\Sigma_c(2455)$</td>
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<td>$\Xi_c(2800)$</td>
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<td>$\Xi_c(3123)$</td>
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<td>$\Xi_c(3120)$</td>
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</tbody>
</table>

## BOTTOM BARYONS ($B = -1$)

$A_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dss$, $\Omega_b^- = ssb$

<table>
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<th>Quantum Numbers</th>
<th>Status</th>
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<td>$A_b(5912)$</td>
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<td>$A_b(5920)$</td>
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<td>***</td>
</tr>
<tr>
<td>$\Sigma_b$</td>
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</tr>
<tr>
<td>$\Sigma_b^-$</td>
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<td>$\Xi_b(5945)^-$</td>
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<td>$\Xi_b(6227)^-$</td>
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<td>$\Omega_b^-$</td>
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</tr>
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</table>

### b-baryon ADMIXTURE ($A_b$, $\Xi_b$, $\Sigma_b$, $\Omega_b$)

### Odd parity open heavy-flavor baryons

---

Juan Nieves, IFIC (CSIC & UV)
HQSFS: ground states

The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons’s velocity. On average, this is also the velocity of the “brown muck”.

\[ \vec{J} = \vec{S}_Q + \vec{j}_{ldof} \]

light degrees of freedom

\[ \ell_\lambda = \ell_\rho = 0, S=1, I=1 \text{ (sym)} \]

HQSS doublet

\[ \frac{1}{2}^+ \]

\[ \otimes \]

\[ \frac{1}{2}^+ \]

\[ \Sigma_c(2455) \]

\[ \Sigma_c^*(2520) \]

\[ \frac{1}{2}^+ \]

\[ \otimes \]

\[ 0^+ \]

\[ \Lambda_c(2286) \]

Juan Nieves, IFIC (CSIC & UV)
**HQSFS: odd parity excited states**

The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons’s velocity. On average, this is also the velocity of the “brown muck”.

\[
\vec{J} = \vec{S}_Q + \vec{j}_{ldof}
\]

\[\ell_\lambda = 1, \ell_\rho = 0, S=0, I=0 \text{ (sym)}\]

\[
\frac{1}{2}^+ \bigotimes \frac{1^-}{j_{ldof}} = \underbrace{\frac{1}{2}^-}_{\Lambda_c(2595)} , \underbrace{\frac{3}{2}^-}_{\Lambda_c(2625)}
\]

**CQM states**

\[
\begin{align*}
\frac{1}{2}^+_{S_Q} & \bigotimes 0^-_{j_{ldof}} = \frac{1}{2}^-_{\Lambda_c^*} \\
\frac{1}{2}^+_{S_Q} & \bigotimes 1^-_{j_{ldof}} = \frac{1}{2}^-_{\Lambda_c^*} \\
\frac{1}{2}^+_{S_Q} & \bigotimes 2^-_{j_{ldof}} = \frac{1}{2}^-_{\Lambda_c^*} \
\end{align*}
\]

\[\lambda - \text{mode excitations}\]

\[\rho - \text{mode excitations}\]

HQSFS: odd parity excited states  chiral molecules

\[ \Sigma_c^{(*)} \pi \quad \Rightarrow \quad J^P = 1/2^-, 3/2^- \]

ldof: \( 1^+ \otimes 0^- = 1^- \)


• obtains the \( \Lambda_c(2625) \) \( [J^P = \frac{3^-}{2} \] using a moderately large UV cutoff \( \sim 2.1 \) GeV

✓ CQM degrees of freedom
✓ Analogy \( \Lambda(1520), \Lambda(1405) \)
\( \Sigma^{(*)} \leftrightarrow \Sigma_c^{(*)}, \bar{K}^{(*)} \leftrightarrow D^{(*)} \)

T. Mizutani and A. Ramos, PRC74 (2006) 065201

existence of some relevant degrees of freedom (CQM states and/or \( N\bar{D}(*) \) components) that are not properly accounted for?

M. Albaladejo, JN, E. Oset, Z.-F. Sun, and X. Liu, PLB757 (2016) 515
**HQSFS:** odd parity excited states \[ \text{hadron molecules} \]

\[
\Sigma_c^{(*)} \pi \quad \Rightarrow \quad J^P = 1/2^-, 3/2^-
\]

\[
N D^{(*)} \quad \Rightarrow \quad J^P = 1/2^-, 3/2^-
\]

**key issue:** \[ ND^{(*)} \rightarrow ND^{(*)}, \Sigma_c^{(*)} \pi \] coupled-channels interaction consistent with HQSS and its breaking pattern. In addition renormalization of BSE amplitudes & short distance (UV) physics

\[ \Sigma_c \text{ and } \Sigma_c^* \text{ or } D \text{ and } D^* \text{ are related by a charm quark spin rotation, which commutes with } H_{QCD}, \text{ up to } \Lambda_{QCD}/m_c \text{ corrections.} \]
LO HQSS does not fix $\Lambda^D(*) \rightarrow \Lambda^D(*)$, $\Sigma_c^(*) \pi$ coupled-channels interaction; There exist several models in the literature consistent with LO HQSS constraints. Moreover, renormalization parameters can be fine tuned to reproduce the position of the $\Lambda_c(2595)$ and $\Lambda_c(2625)$ resonances.

\( \Lambda_c(2595) \) 

\[ J^P = 1/2^- \]

\[ \begin{array}{|c|c|c|c|}
\hline
2592.26 + i0.56 & D^* N & \pi \Sigma_c & \eta \Lambda_c \\
\hline
-8.18 + i0.61 & 0.54 + i0.00 & 0.40 - i0.03 \\
\hline
13.88 - i1.06 & -10.30 - i0.69 & 1.76 - i0.14 \\
\hline
\end{array} \]

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\hline
\end{array} \]

\( \Lambda_c(2625) \) 

\[ J^P = 3/2^- \]

\[ \begin{array}{|c|c|c|c|}
\hline
2628.35 & D^* N & \rho \Sigma_c & \omega \Lambda_c \\
\hline
10.11 & -0.55 & 0.49 & -0.68 \\
\hline
-29.10 & 2.60 & -2.78 & 2.50 \\
\hline
\end{array} \]

\[ \begin{array}{|c|c|c|c|}
\hline
2628.35 & D^* N & \rho \Sigma_c & \omega \Lambda_c \\
\hline
10.11 & -0.55 & 0.49 & -0.68 \\
\hline
-29.10 & 2.60 & -2.78 & 2.50 \\
\hline
\end{array} \]

\( \Lambda_c(2625) \) is mostly a bound ND* state (no coupling to \( \Sigma_c^* \pi \))

\( \Lambda_c(2595) \) generated by the ND(\( ^(*) \)) \( \rightarrow \) ND(\( ^(*) \)) coupled-channels interaction (\( J_{idof}^{P} = 0^{-}, 1^{-} \))

\( \Lambda_c(2595) \) narrow because it has a very small \( \Sigma_c \pi \) coupling.

Second \( \Lambda_c(2595) \) pole [similar to \( \Lambda(1405) \)], broad because it has a large \( \Sigma_c \pi \) coupling.
more predictions from ELHG model:

✓ beauty $\Lambda_b(5912)$ and $\Lambda_b(5920)$ states [heavy flavor partners of the $\Lambda_c(2595)$ and $\Lambda_c(2625)$], W.H. Liang, C.W. Xiao, E. Oset, PRD 89 (2014) 054023.


✓ $\Xi_c$ and $\Xi_b$ odd parity excited states, Q. X. Yu, R. Pavao, V. R. Debastiani, E. Oset2 EPJ C79 (2019) 167; R. Pavao’s talk at session 3 (17.50h, 17/8).
A different approach: $SU(6)_{lsf} \times SU(2)_{HQSS}$ extension of the Weinberg-Tomozawa $N\pi$ interaction

- $\pi$ – octet, $\rho$ – nonet, $D_{(s)}^{(*)}, \bar{D}_{(s)}^{(*)}$
- $N$ – octet, $\Delta$ – decuplet, $\Lambda_c, \Sigma_c^{(*)}, \Xi_{c}^{(s,*)}, \Omega_{c}^{(*)}$


- beauty $\Lambda_b(5912)$ and $\Lambda_b(5920)$, C. Garcia-Recio, JN, O. Romanets, L.L. Salcedo and L. Tolos, PRD 87 (2013) 034032.


- consistent with HQSS and chiral symmetry
- dependence of renormalization scheme

Juan Nieves, IFIC (CSIC & UV)
\[ T^J(s) = \frac{1}{1 - V^J(s) G^J(s)} V^J(s), \]

\[ G_i(s) = i2M_i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_i^2 + i\epsilon} \frac{1}{(P - q)^2 - M_i^2 + i\epsilon} \]

finite \hspace{1cm} \text{UV divergent} \hspace{1cm} \text{different UV cutoffs for each meson-baryon channel}

**subtraction at a common scale** \( \mu \sim \sqrt{m_\pi^2 + M_{\Sigma_c}^2} : \)

\[ G_i^{\mu}(s_{i+}) = -\overline{G}_i(\mu^2) \]

common UV cutoff \( \Lambda = 650 \text{ MeV} \)

Juan Nieves, IFIC (CSIC & UV)
\[ J^P = 1/2^- \]

\[ J^P = 3/2^- \]

Subtraction at a common scale (no fit!)

- Main features of 3/2^- pole do not depend much on the RS: \( M = 2660 - 2680 \text{ MeV} \) and \( \Gamma = 55 - 65 \text{ MeV} \):
- Difficult to assign it to the narrow \( \Lambda_c(2625) \).

- Spectrum in the 1/2^- sector depends strongly on the adopted RS.

Common UV cutoff 650 MeV (no fit!)

\[ C = 1, \ ND^*(\cdot), \Sigma_c^*(\cdot)\pi \text{ coupled-channels} \]

Juan Nieves, IFIC (CSIC & UV)
Absolute value of the determinant of the T-matrix

\[ J^P = 1/2^- \]

subtraction at a common scale

(no fit!)

Two pole pattern, but

\( \checkmark \) narrow resonance has a small coupling to \( \Sigma_c \pi \), since it has dominant \( 0^- \) configuration for the light degrees of freedom. Moreover its position depends strongly on the RS, since it might appear close to the \( ND \) or \( \Sigma_c \pi \) thresholds (~200 MeV of difference!). In the latter case (subtraction at a common scale), it could be identified with the \( \Lambda_c(2595) \). In both RS’s the narrow resonance has large \( ND \) and \( ND^* \) components.

\[ \Lambda = 650 \text{ MeV} \]

\[
\begin{array}{c|c|c|c}
M - i \Gamma/2 & Type & |g_{\Sigma_c \pi}| & |g_{ND}| & |g_{ND^*}| \\
\hline
(2609.9 - i 28.8) & 1^- & 2.0 & 2.3 & 0.7 \\
(2798.7 - i 2.0) & 0^- & 0.3 & 1.8 & 4.1 \\
\end{array}
\]

\[ SC_{\mu} (\alpha = 0.95) \]

\[
\begin{array}{c|c|c|c|c}
M - i \Gamma/2 & Type & |g_{\Sigma_c \pi}| & |g_{ND}| & |g_{ND^*}| \\
\hline
(2608.9 - i 38.6) & 1^- & 2.3 & 2.0 & 1.9 \\
(2610.2 - i 1.2) & 0^- & 0.5 & 3.9 & 6.2 \\
\end{array}
\]

\( J^P = 1/2^- \)

(broad resonance) has a large coupling to \( \Sigma_c \pi \), and hence has a dominant \( 1^- \) configuration for the light degrees of freedom. It is located around 2610 MeV and with a width of 60-80 MeV. In the subtraction at a common scale RS, this state will be completely shadowed by the narrow \( \Lambda_c(2595) \) state. When a common UV cutoff is used, it is difficult to assign this pole to the \( \Lambda_c(2595) \).

\[ C = 1, \ ND^*, \Sigma_c^* \pi \text{ coupled-channels} \]

Juan Nieves, IFIC (CSIC & UV)
...and CQM predictions:

\[
\left\{ \frac{1}{2}^+ \right\}_Q^{S_Q^P} \times \left\{ \frac{1}{2}^- \right\}_{I_{l_{dof}}}^P = \frac{1}{2}^- , \quad \frac{3}{2}^- \lambda_c(2595), \quad \lambda_c(2625) \]

\[\ell_\lambda = 1, \ell_\rho = 0, S=0, I=0 \text{ (sym)}\]

\[
\mathbf{\ell} = 0, \mathbf{l} = 0, S = 0, I = 0, \text{ (sym)}
\]

PHYSICAL REVIEW D 92, 114029 (2015)

Spectrum of heavy baryons in the quark model

T. Yoshida,1,* E. Hiyama,2,1,3 A. Hosaka,4,3 M. Oka,1,3 and K. Sadato4,†

<table>
<thead>
<tr>
<th>(J^P)</th>
<th>Theory (MeV)</th>
<th>Experiment (MeV)</th>
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<tbody>
<tr>
<td>(1/2^+)</td>
<td>2285</td>
<td>2285</td>
</tr>
<tr>
<td>(3/2^+)</td>
<td>2857</td>
<td>2857</td>
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<tr>
<td>(5/2^+)</td>
<td>3123</td>
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<tr>
<td>(1/2^-)</td>
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<tr>
<td>(3/2^-)</td>
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<tr>
<td>(5/2^-)</td>
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<td>3191</td>
</tr>
<tr>
<td>(3/2^)</td>
<td>2922</td>
<td>2881</td>
</tr>
<tr>
<td>(5/2^)</td>
<td>3202</td>
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<tr>
<td>(1/2^-)</td>
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<td>3230</td>
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<tr>
<td>(3/2^-)</td>
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</tr>
<tr>
<td>(3/2^-)</td>
<td>2933</td>
<td>2933</td>
</tr>
</tbody>
</table>

\[
\rho \text{-MODE}
\]

\[
\lambda \text{-MODE}
\]

Juan Nieves, IFIC (CSIC & UV)

bare CQM state should be explicitly taken into account in the dynamics, in particular for the \(\Lambda_c(2625)\) resonance: for these energies it produces a rapidly changing energy dependent interaction.
... coupling meson-baryon and CQM degrees of freedom, taking into account HQSS constraints...
In both RSs, the dressed CQM state describes fairly well the $\Lambda_c(2625)$ resonance. Moreover, the coupling to $\Sigma_c^*\pi$ is compatible with the existing measurements of the resonant contribution to $\Gamma[\Lambda_c(2625) \rightarrow \Lambda\pi\pi]$. In addition, a second broad pole is predicted in the region of 2.7 GeV.

Juan Nieves, IFIC (CSIC & UV)
Absolute value of the determinant of the $T$-matrix

$$J^P = 1/2^-$$

subtraction at a common scale

common UV cutoff 650 MeV

different sets of couplings between meson-baryon & CQM $[\frac{1^-}{j_{dof}}]$ degrees of freedom

- $j_{dof}^P = 0^-$ — components are not affected by the consideration of the CQM degrees of freedom
- There are appear three poles, but their characteristics and interpretations depend on the RS and the interplay between CQM and meson-baryon degrees of freedom

Juan Nieves, IFIC (CSIC & UV)
The mass and the width of the narrow state at 2800 MeV (common UV cutoff 650 MeV) or 2610 MeV (subtraction at a common scale) are practically unaltered by the coupling between meson-baryon and CQM degrees of freedom. This is a trivial consequence of the largely dominant $j_{l=0}^P = 0^-$ configuration of these states, since HQSS forbids their coupling to the $(j_{l=1}^P = 1^-) -$CQM bare state.

In both renormalization schemes we obtain the dressed CQM pole at masses around 2640-2660 MeV and with a width of the order of 30-50 MeV, depending on the chosen regulator and on the details of coupling meson-baryon and CQM degrees of freedom.
The $\Lambda_c(2595)$ and the $\Lambda_c(2625)$ might not be HQSS partners. ($\Lambda_c^*-$puzzle)

The $J^P = 3/2^-$ resonance should be viewed mostly as a quark-model state naturally predicted to lie very close to its nominal mass. In addition, there will exist a molecular baryon, moderately broad, with a mass of about 2.7 GeV and sizable couplings to both $\Sigma_c^*\pi$ and $ND^*$ that will fit into the expectations of being $\Sigma_c^*\pi$ molecule generated by the chiral interaction of this pair.

The $\Lambda_c(2595)$ is predicted, however, to have a predominant molecular structure. This is because, it is either the result of the chiral $\Sigma_c\pi$ interaction [J.-X. Lu, Y. Zhou, H.-X. Chen, J.-J. Xie, and L.-S. Geng, PRD92 (2015) 014036; but this contradicts the conclusions of T. Hyodo in PRL 111 (2013) 132002], which threshold is located much more closer than the mass of the bare three-quark state, or because the $ldof$ in its inner structure are coupled to the unnatural $0^-$ quantum-numbers, depending on the RS. In the latter case, the resonance would have dominant $ND^{(*)}$ components.

The relative importance of $0^-$ and $1^-$ components in the $\Lambda_c(2595)$ can be extracted from the ratio between the widths of the semileptonic decays $\Lambda_b[gs] \rightarrow \Lambda_c(2595)$ and $\Lambda_b[gs] \rightarrow \Lambda_c(2625)$ [W.-H. Liang, E. Oset, Z.-S. Xie, PRD95 (2017) 014015; JN, R. Pavao and S. Sakai, EPJC79 (2019) 417]
CONCLUSIONS

✓ We have studied $D\pi$, $D\eta$, $D_s\bar{K}$ coupled-channel scattering [$J^P = 0^+$, $(S,I) = (0,1/2)$]: only one pole reported experimentally. We have presented a strong support for the existence of two $D_0^*(2400)$ poles [successful description of the energy levels obtained in LQCD simulation].

✓ Chiral dynamics: Incorporates the SU(3) light-flavor structure and determines the strength of the interaction. A SU(3) study shows that $D_{s0}^*(2317)$ and the lower $D_0^*(2400)$ are flavour partners: they complete a 3 multiple, with large molecular probabilities.

✓ The lower pole ($M = 2105^{+6}_{-8}$ MeV, $\Gamma = 204^{+20}_{-24}$ MeV) is lighter than $D_{s0}^*(2317)$, solving this apparent contradiction.

✓ Predictions for other sectors (heavy vectors, bottom sector) have been also given. We find a natural explanation to why $(M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)}) \sim (M_{D^*} - M_D)$ within 1 MeV


✓ Good description of the S-wave $P\phi$ amplitude extracted by LHCb from $B \rightarrow P\phi\phi$ decays

Juan Nieves, IFIC (CSIC & UV)
Muskhelishvili-Omnès representation of scalar form-factor using the HMChPT amplitudes+ HQSFS: results for scalar, $f_0(q^2)$, form factors for different $H \to b l \bar{\nu}_l$ decays, $H = \bar{B}, \bar{B}_s, D, D_s$ and $b = \pi, \eta, K, \bar{K}$. Successful description of LQCD and LCSR results.
○ $\Lambda_c^*$ — puzzle y HQSS
○ dependence on the RS
○ role played by the CQM degrees of freedom

LO HQSS does not fix $ND^{(*)} \rightarrow ND^{(*)}, \Sigma_c^{(*)} \pi$
coupled-channels interaction

Juan Nieves, IFIC (CSIC & UV)
Back up
... differences appear at large energies

LO HMChPT+CQM & NLO HMChPT
$0^+ \ D_{s0}^*$ sector

M. Albaladejo, P. Fernández-Soler, JN and P.G. Ortega, EPJC77 (2017) 170

LO HMChPT+CQM
$0^+ \& 1^+ B_s^*$ sector

We obtain $|V_{ub}| = (4.3 \pm 0.7) \times 10^{-3}$ for the involved Cabibbo-Kobayashi-Maskawa (CKM) matrix elements. In addition, $|V_{cd}| = 0.244 \pm 0.022$. 

Yao, Fernández-Soler, Albaladejo, Guo, Nieves EPJC 70 (2018) 310