Theoretical review of heavy-light spectroscopy

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EXCELENCIA SEVERO OCHOA

- M. Albaladejo, P. Fernández-Soler, F.-K. Guo and JN, PLB 767 (2017) 465
- M.-L.Du, M. Albaladejo, P. Fernández-Soler, F.-K. Guo, C. Hanhart, U.-G. Meissner, JN and D.-L. Yao, PRD 98 (2018) 094018
- M. Albaladejo, P. Fernández-Soler, JN and P.G. Ortega, EPJC78 (2018) 722
- M. Albaladejo, P. Fernández-Soler, JN and P.G. Ortega, EPJC77 (2017) 170
- JN and R. Pavao, arXiv: 1907.05747
- JN, R. Pavao and L. Tolos EPJC78 (2018) 114 AND

CERN

arXiv: 1812.07638

CERN-LPCC-2018-06
February 25, 2019

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

Thanks to all my collaborators!

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 ineslaticities
   - 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

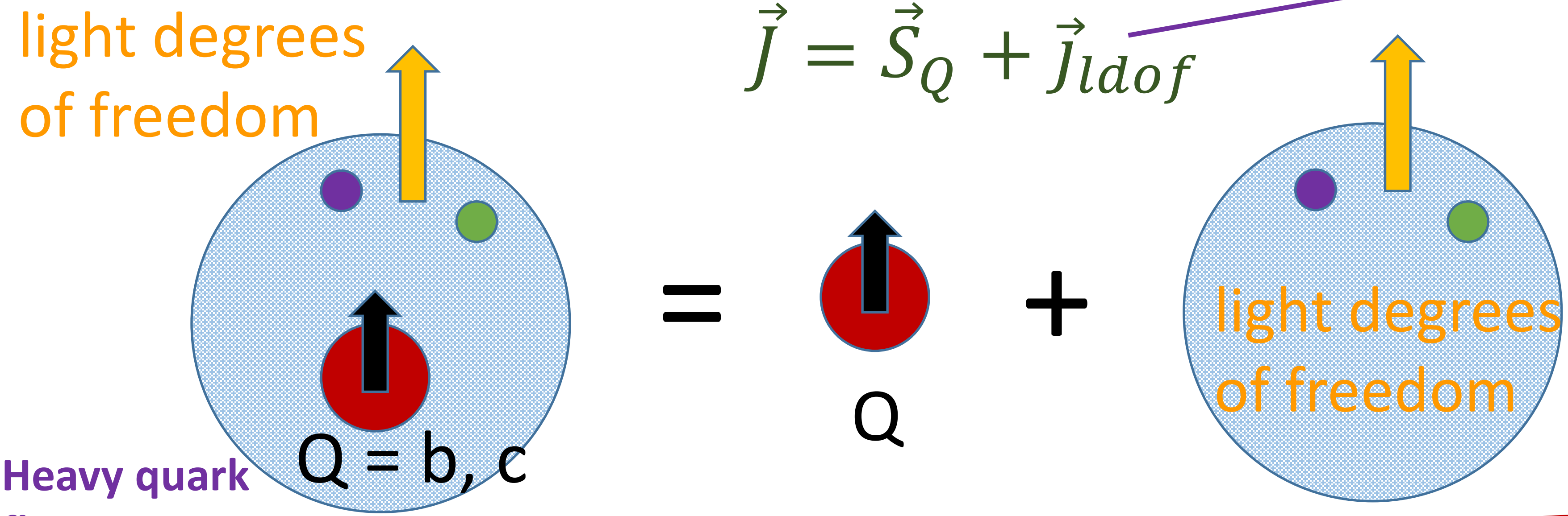
The light degrees of freedom in the hadron orbit around the heavy quark, which acts as a source of color moving with the hadrons's velocity. On average, this is also the velocity of the "brown muck".

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

$\vec{j}^{\,2}_{ldof}$ **is conserved!**

HQSS

***SU*$(2N_h)$ symmetry in the $m_Q \to \infty$ limit**



Heavy quark flavor symmetry HQFS

$$\mathcal{L}_{\rm eff} = \boxed{\bar{h}_v iv\cdot D h_v} + \frac{1}{2m_Q}\bar{h}_v (iD_\perp)^2 h_v + \frac{g_s}{4m_Q}\bar{h}_v \sigma_{\alpha\beta} G^{\alpha\beta} h_v + \mathcal{O}(1/m_Q^2)$$

$$D^\mu_{\alpha\beta} \equiv \delta_{\alpha\beta}\partial^\mu - i g_s T^a_{\alpha\beta} G^\mu_a$$

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 $\vec{j}_{ldof}$ of the brown muck, which is the subsystem of the hadron apart from the heavy quark, is conserved and hadrons with $J = j_{ldof} \pm \boxed{1/2}$ form a degenerate doublet. For instance, $m_{\bar{B}^*}(J^P = 1^-) - m_{\bar{B}}(J^P = 0^-) = 45.22 \pm 0.21 \text{ MeV} \sim \Lambda_{QCD}, m_d, m_u$ **doublet** for $j^P_{ldof} = 1/2^-$ $\quad S_Q$

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 $1/m_Q$, $\boldsymbol{M_H/m_Q \sim \left(1 + \frac{O(\Lambda_{QCD})}{M_Q}\right)}$

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

HQSFS $SU(2N_h)$ approximate symmetry seen in the hadron spectrum

Chiral symmetry $\Rightarrow$ 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 << Λ, while the heavier excitations with M >> Λ 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/Λ. 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 $(K, \pi, \eta, \overline{K})$ interactions with single heavy hadrons could be described using a perturbartive chiral $[SU(3)_L \times SU(3)_R]$ EFT consistent with the $1/m_Q$ expansion: **HMChPT**

PHYSICAL REVIEW D VOLUME 45, NUMBER 7 1 APRIL 1992

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 π, K, and η 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.

PACS number(s): 14.40.Jz, 11.30.Rd, 13.20.Fc, 13.20.Jf

hadron velocity

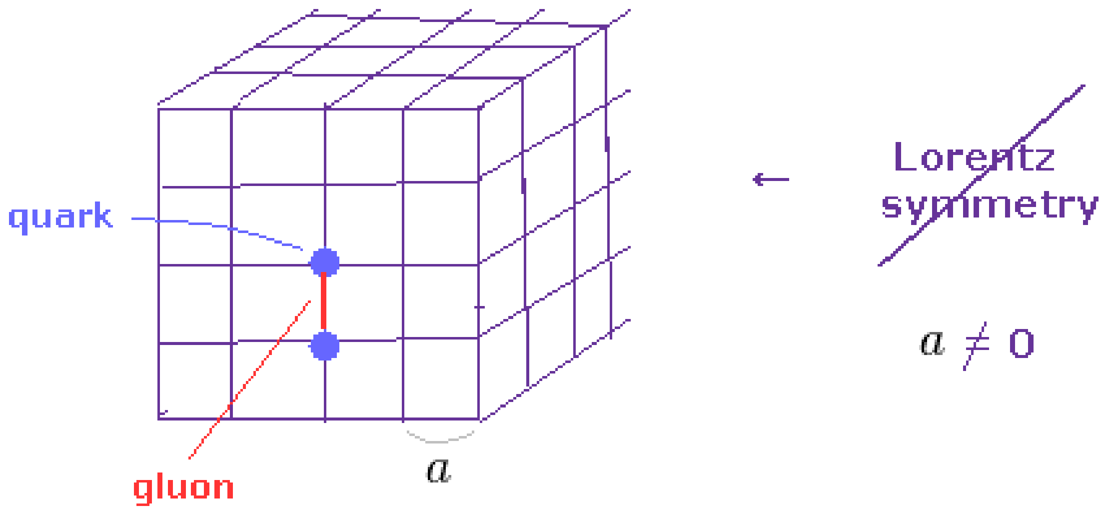
$$\mathcal{L} = -i\,\mathrm{Tr}\,\bar{H}_a v_\mu \partial^\mu H_a + \tfrac{1}{2} i\,\mathrm{Tr}\,\bar{H}_a H_b v^\mu (\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger)_{ba}$$

$$+ \tfrac{1}{2} ig\,\mathrm{Tr}\,\bar{H}_a H_b \gamma_\nu \gamma_5 (\xi^\dagger \partial^\nu \xi - \xi \partial^\nu \xi^\dagger)_{ba} + \cdots , \qquad (12)$$

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

Goldstone bosons

$$H_a = \frac{1+\not{v}}{2}\Big(\underbrace{P^*_{a\mu}\gamma^\mu}_{1^-} - \underbrace{P_a \gamma_5}_{0^-}\Big)$$



and Lattice QCD… (see talk by Jozef Dudek, 21/8)

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

Heavy light mesons

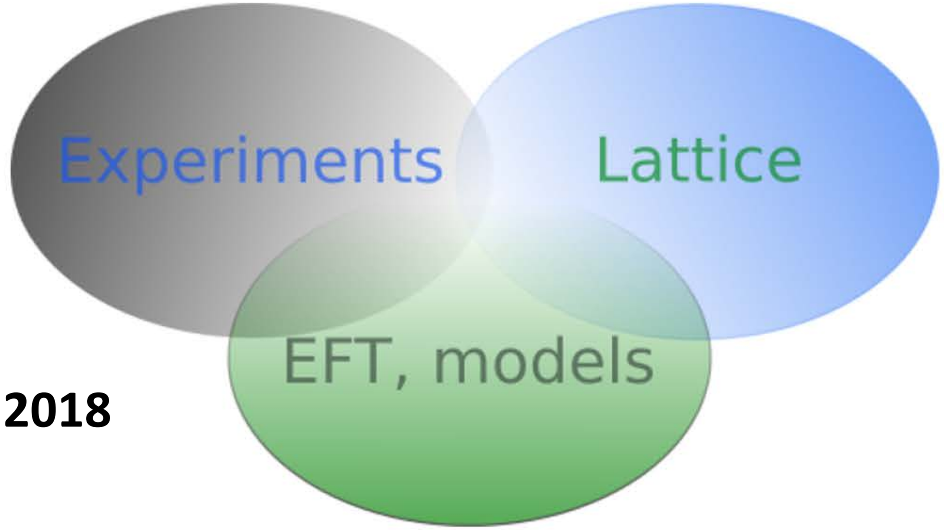
Juan Nieves, IFIC (CSIC & UV)

Even parity open heavy-flavor mesons

$D^{\pm}$
D^0
$D^*(2007)^0$
$D^*(2010)^{\pm}$
$D_0^*(2400)^0$
$D_0^*(2400)^{\pm}$
$D_1(2420)^0$
$D_1(2420)^{\pm}$
$D_1(2430)^0$
$D_2^*(2460)^0$
$D_2^*(2460)^{\pm}$
$D(2550)^0$
$D_J^*(2600)$ was $D(2600)$
$D^*(2640)^{\pm}$
$D(2740)^0$
$D(2750)$
$D(3000)^0$

RPP 2019 $D_0^*(2300)$

$D_s^{\pm}$
$D_s^{*\pm}$
$D_{s0}^*(2317)^{\pm}$
$D_{s1}(2460)^{\pm}$
$D_{s1}(2536)^{\pm}$
$D_{s2}^*(2573)$
$D_{s1}^*(2700)^{\pm}$
$D_{s1}^*(2860)^{\pm}$
$D_{s3}^*(2860)^{\pm}$
$D_{sJ}(3040)^{\pm}$



F.K. Guo @ CHARM 2018

$D_0^*(2400)$ interesting:

- ✓ Lightest scalar ($J^\pi = 0^+$) open charm states: $\begin{cases} D_{s0}^*(2317), & (S,I)=(1,0) \\ \boxed{D_0^*(2400), \ (S,I)=(0,1/2)} \end{cases}$
- ✓ **Lightest systems to test ChPT with heavy mesons,** besides $D^* \to D\pi$
- ✓ $D\pi$ 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:
  - o $D_{s0}^*(2317)$ is around 150 MeV below the predicted mass.

    Godfrey & Isgur, PRD 32 (1985) 189; Godfrey &Moats, PRD 93 (2016) 034035

    Lakhina, & Swanson, PLB 650 (2007) 159; Ortega et al., PRD94 (2016) 074037
  - o 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
  - o It determines the shape of the scalar form factor $f_0(q^2)$ in semileptonic $D \longrightarrow \pi$ decays.
  - o Relation to $|V_{cd}|$: $f_+(0) = f_0(0)$ and $d\Gamma \sim |V_{cd}\, f_+(q^2)|^2\, dq^2$
  - o Interesting also the relation of the bottom partner and $|V_{ub}|$

Introduction: Theoretical interpretations

$c\bar{q}$ states

Dai *et al*. Phys. Rev. D **68**, 114011 (2003)
Narison, Phys. Lett. B **605**, 319 (2005)
Bardeen *et al*., Phys. Rev. D **68**, 054024 (2003)
Lee *et al*., Eur. Phys. J. C **49**, 737 (2007)
Wang, Wan, Phys. Rev. D **73**, 094020 (2006)

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

Browder *et al*., Phys. Lett. B **578**, 365 (2004)
van Beveren, Rupp, Phys. Rev. Lett. **91**, 012003 (2003)

Pure tetraquarks

Cheng, Hou, Phys. Lett. B **566**, 193 (2003)
Terasaki, Phys. Rev. D **68**, 011501 (2003)
Chen, Li, Phys. Rev. Lett. **93**, 232001 (2004)
Maiani *et al*,, Phys. Rev. D **71**, 014028 (2005)
Bracco *et al*., Phys. Lett. B **624**, 217 (2005)
Wang, Wan, Nucl. Phys. A **778**, 22 (2006)

Heavy-light meson–meson molecules

Barnes *et al*., Phys. Rev. D **68**, 054006 (2003)
Szczepaniak, Phys. Lett. B **567**, 23 (2003)
Kolomeitsev, Lutz, Phys. Lett. B **582**, 39 (2004)
Hofmann, Lutz, Nucl. Phys. A **733**, 142 (2004)
Guo *et al*., Phys. Lett. B **641**, 278 (2006)
Gamermann *et al*., Phys. Rev. D **76**, 074016 (2007)
Faessler *et al*., Phys. Rev. D **76**, 014005 (2007)
Flynn, Nieves, Phys. Rev. D **75**, 074024 (2007)
Albaladejo *et al*., Eur. Phys. J. C **76**, 300 (2016)

M. Albaladejo @ PWA 9 & ATHOS 4

✓ $D_0^*(2400)$: Experimental situation [PDG avg: $\left(M, \frac{\Gamma}{2}\right) = (2300 \pm 19, 137 \pm 20)$ MeV neu

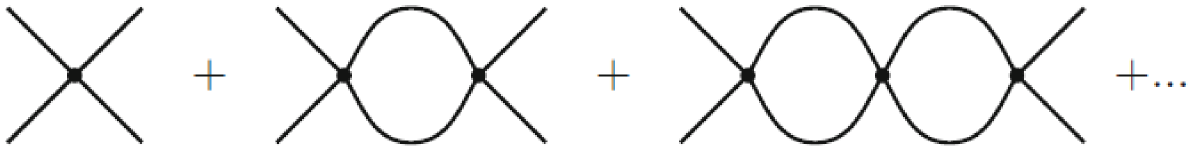
$= (2349 \pm \ \ 7, 110 \pm \ \ 9)$ MeV char]

	Collab.	M (MeV)	$\Gamma/2$ (MeV)	Ref.
Neu.	Belle	2308 ± 36	138 ± 33	Phys. Rev. D **69**, 112002 (2004)
	BaBar	2297 ± 22	137 ± 25	Phys. Rev. D **79**, 112004 (2009)
	FOCUS	2407 ± 41	120 ± 40	Phys. Lett. B **586**, 11 (2004)
Char.	LHCb	2360 ± 33	128 ± 29	Phys. Rev. D **92**, 012012 (2015)
	FOCUS	2403 ± 38	142 ± 21	Phys. Lett. B **586**, 11 (2004)

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

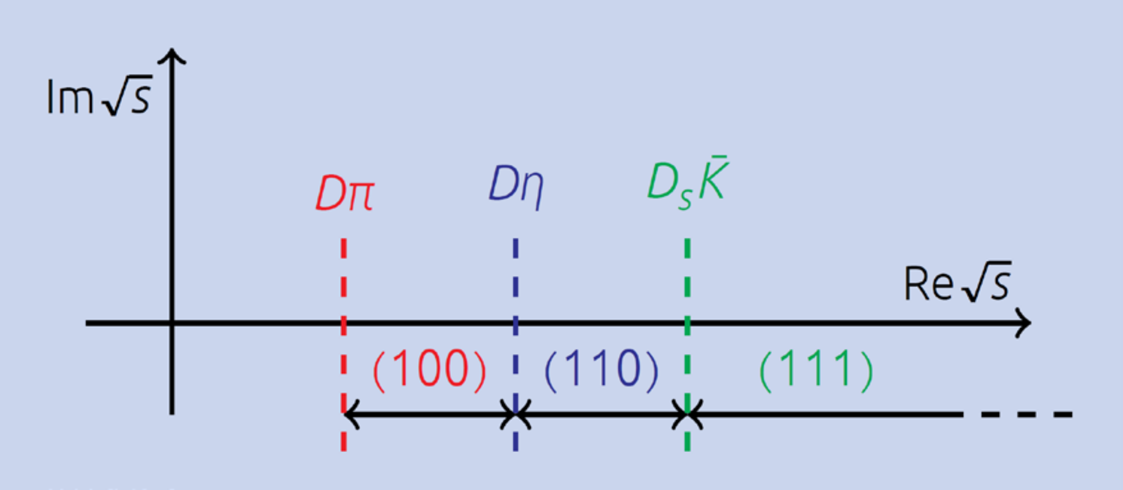
- Masses larger than the physical ones if using $c\bar{s}$ interpolators only [Bali, PRD68 (2003) 071501; UKQCD PLB569 (2003) 41]. Recent study including four quark operators [Bali et al., PRD96 (2017) 054501]
- Masses consistent with $D_0^*(2400)$ and $D_{s0}^*(2317)$ obtained when "meson-meson" interpolators 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 $D_0^*(2400)$

Theoretical Approach:
Infinite volume



- ✓ Coupled-channels T-matrix: $D\pi, D\eta, D_s\bar{K}$ S-wave scattering $\left[J^\pi = 0^+, (S,I) = \left(0,\frac{1}{2}\right)\right]$
- ✓ Unitarity: $T^{-1}(s) = V^{-1}(s) - \mathcal{G}(s)$
  - o Normalization: $-i\, p_{ii}(s) T_{ii}(s) = 4\pi\sqrt{s}\left(\eta_i(s) e^{2i\delta_{ii}(s)} - 1\right)$
  - o $\mathcal{G}_{ij}(s) = \delta_{ij}\, G(s, m_i, M_i)$, loop function regularized with a subtraction constant $a(\mu)$, $\mu = 1$ GeV
  - o Two particle irreducible amplitude $V(s)$ taken from $\mathcal{O}(p^2)$ HMChPT
- ✓ Analytical continuations: Riemann sheets (RS) denoted as $(\xi_1\xi_2\xi_3)$:

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



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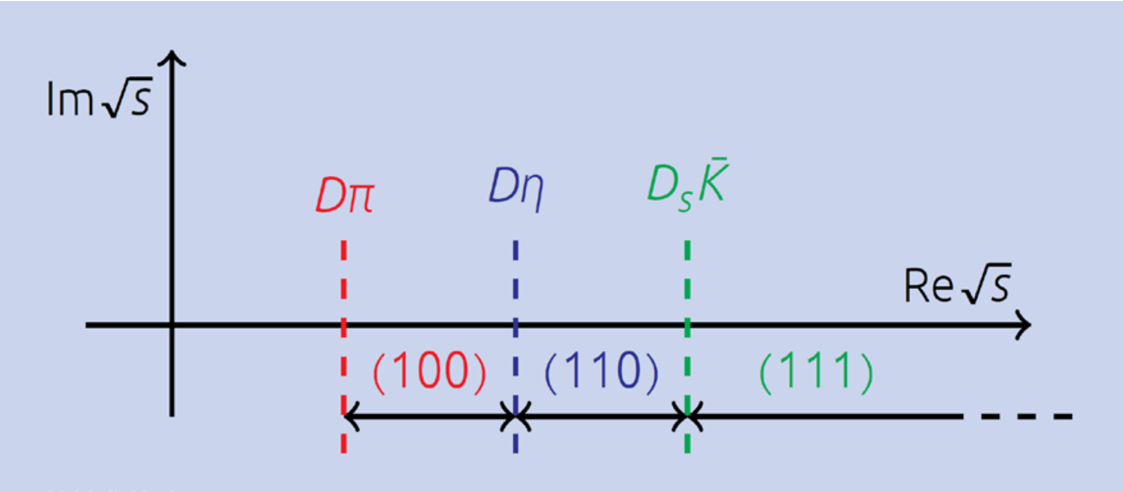


Chiral symmetry used to compute the $D\pi, D\eta, D_s\bar{K}$ coupled-channels potential $V(s)$

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

Guo et al., PLB666 (2008) 251

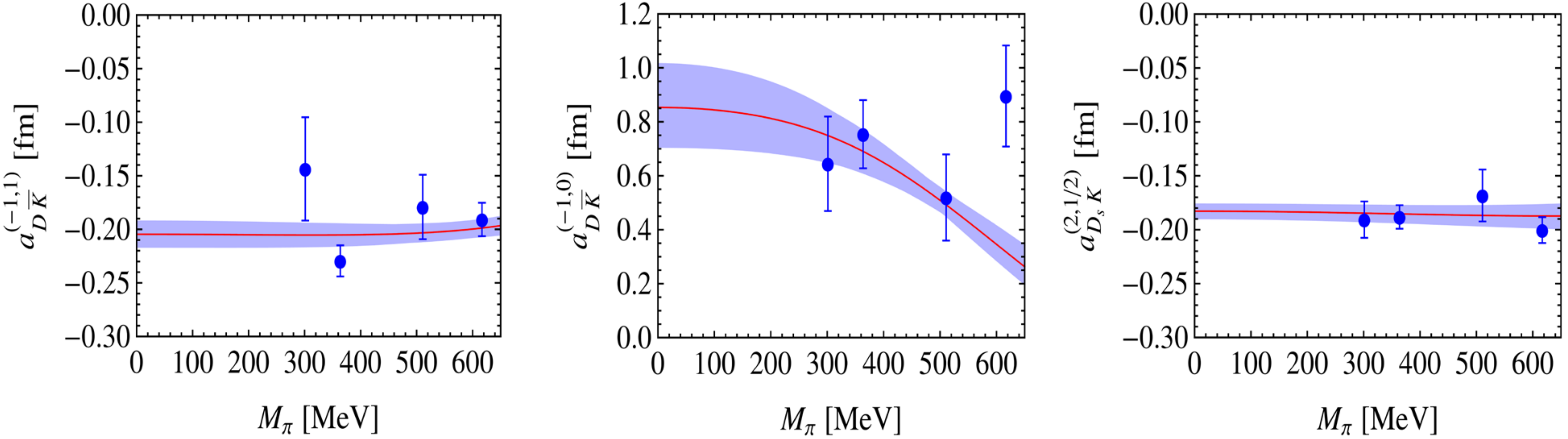
Liu et al., PRD87 (2013) 014508

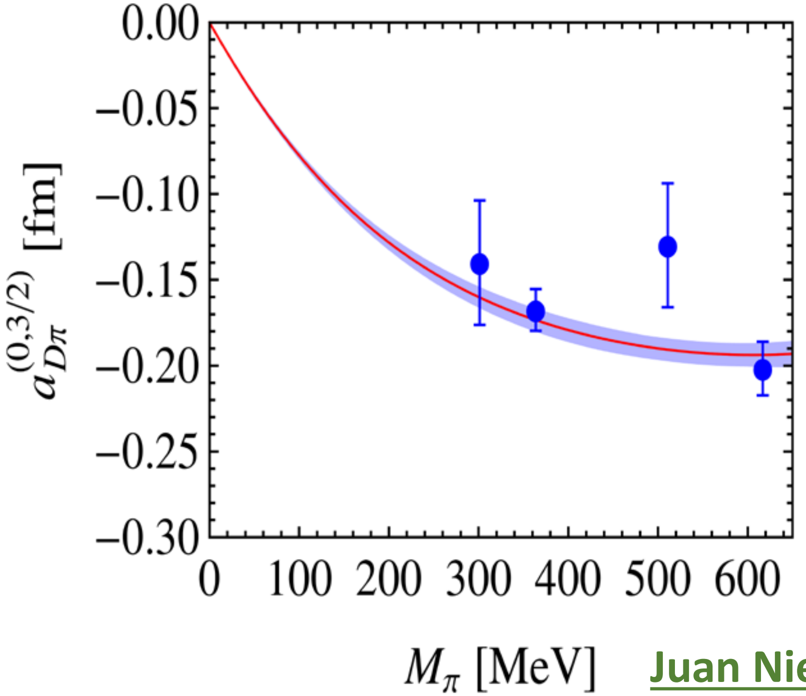
Lowest order: totally predicted by Chiral symmetry

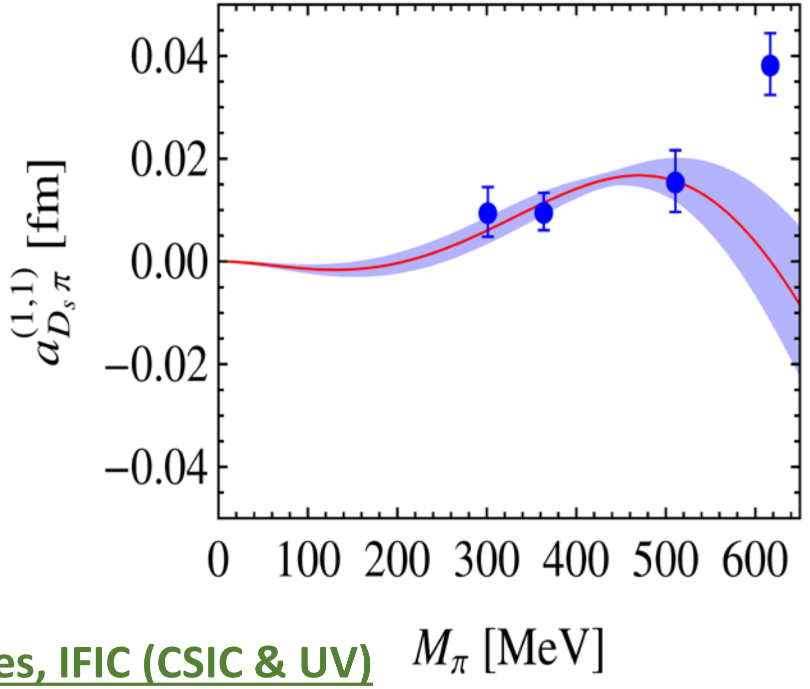
Next-to-leading LECs, together with the subtraction constant $a(\mu)$, have been <u>previously fitted</u> to reproduce scattering lengths obtained in a LQCD simulation

… and projection into S-wave

structures determined by chiral symmetry and its pattern of breaking







Scattering lengths as a function of the pion mass (300 -600 MeV)

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

$D\pi, D\eta, D_s\bar{K}$ energy levels in a **finite volume**

infinite volume	finite volume
$\vec{q} \in \mathbb{R}^3$	$\vec{q} = \frac{2\pi}{L}\vec{n}, \quad \vec{n} \in \mathbb{Z}^3$
$\int_{\mathbb{R}^3} \frac{d^3 q}{(2\pi)^3}$	$\frac{1}{L^3} \sum_{\vec{n}\in\mathbb{Z}^3}$

- ✓ Periodic boundary conditions imposes momentum quantization
- ✓ Lüscher formalism (C. Math. Phys. 105 (1986) 153 ; NPB 354 (1991) 531
- ✓ In practice, changes in the T−matrix: $T(s) \longrightarrow \widetilde{T}(s,L)$ [Döring et al., EPJA47 (2011) 139]

$$\mathcal{G}_{ii}(s) \longrightarrow \tilde{\mathcal{G}}_{ii}(s,L) = \mathcal{G}_{ii}(s) + \lim_{\Lambda\longrightarrow\infty}\left(\frac{1}{L^3}\sum_{\vec{n}}^{|\vec{q}|<\Lambda} I_i(\vec{q}) - \int_0^\Lambda \frac{q^2 d^3 q}{(2\pi)^3} I_i(\vec{q})\right)$$

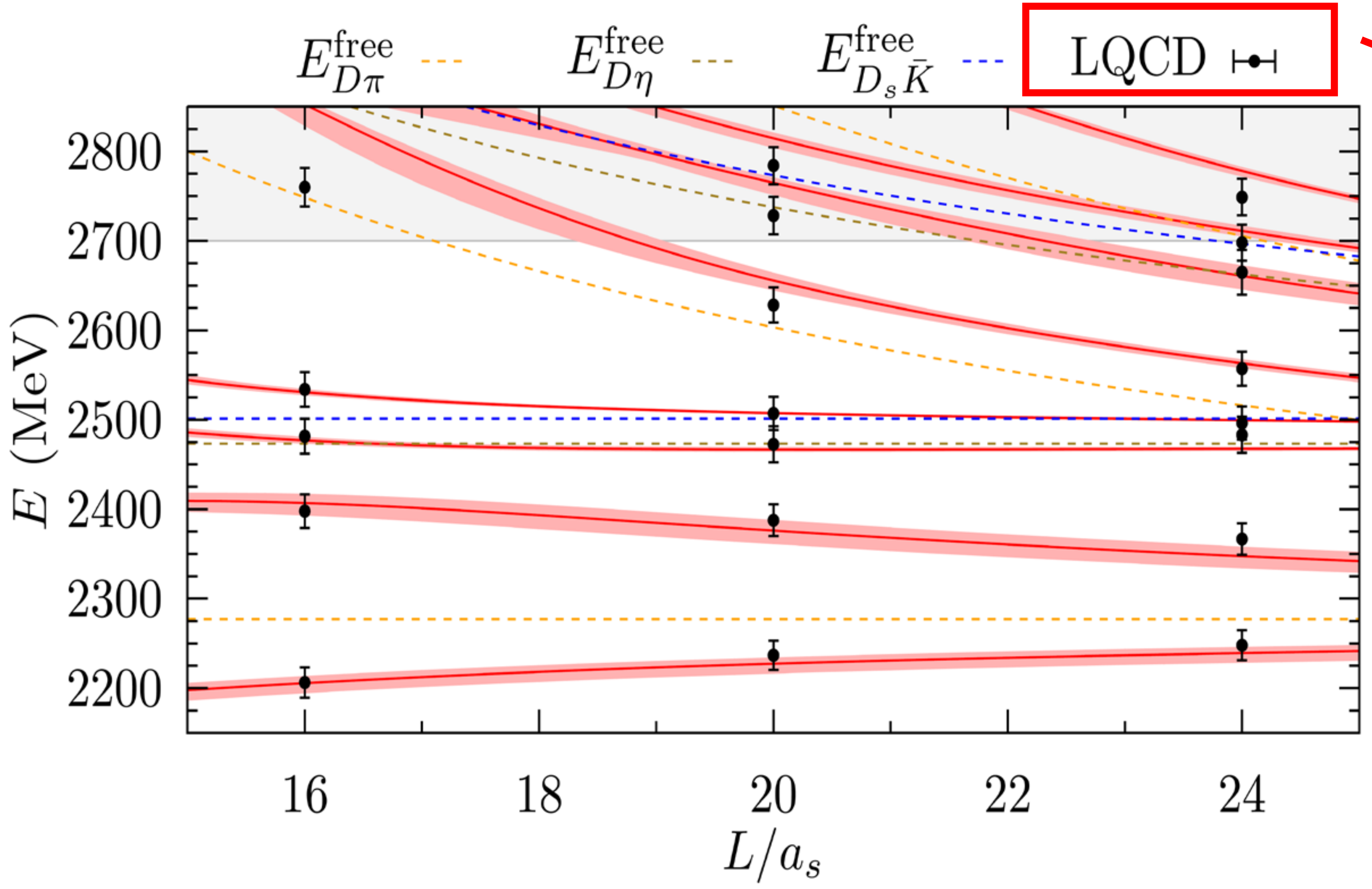
$$I_i(\vec{q}) = \frac{1}{2\omega_i(\vec{q})\omega_i'(\vec{q})}\frac{\omega_i(\vec{q})+\omega_i'(\vec{q})}{s-\left(\omega_i(\vec{q})+\omega_i'(\vec{q})\right)^2+i\epsilon}, \quad \omega_j(\vec{q}) = \sqrt{m_j^2+\vec{q}^2}, \quad \omega_j'(\vec{q}) = \sqrt{M_j^2+\vec{q}^2}$$

$$V(s) \longrightarrow \widetilde{V}(s,L) = V(s)$$

$$T^{-1}(s) \longrightarrow \widetilde{T}^{-1}(s,L) = V^{-1}(s) - \widetilde{\mathcal{G}}(s,L)$$

✓ Free energy levels: $E^i_{n,\mathrm{free}}(L) = \omega_i\left(\frac{2\pi}{L}\vec{n}\right) + \omega'_i\left(\frac{2\pi}{L}\vec{n}\right)$

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



LQCD: G. Moir et al., JHEP 1610 (2016) 011 (Hadron Spectrum Collaboration).
$D\pi, D\eta, D_s\overline{K}$ coupled-channels

M (MeV)	Latt.	Phys.
π	391	138
K	550	496
η	588	548
D	1886	1867
D_s	1952	1968

✓ Free energy levels: $E^{i}_{n,\mathrm{free}}(L) = \omega_i\left(\frac{2\pi}{L}\vec{n}\right) + \omega'_i\left(\frac{2\pi}{L}\vec{n}\right)$

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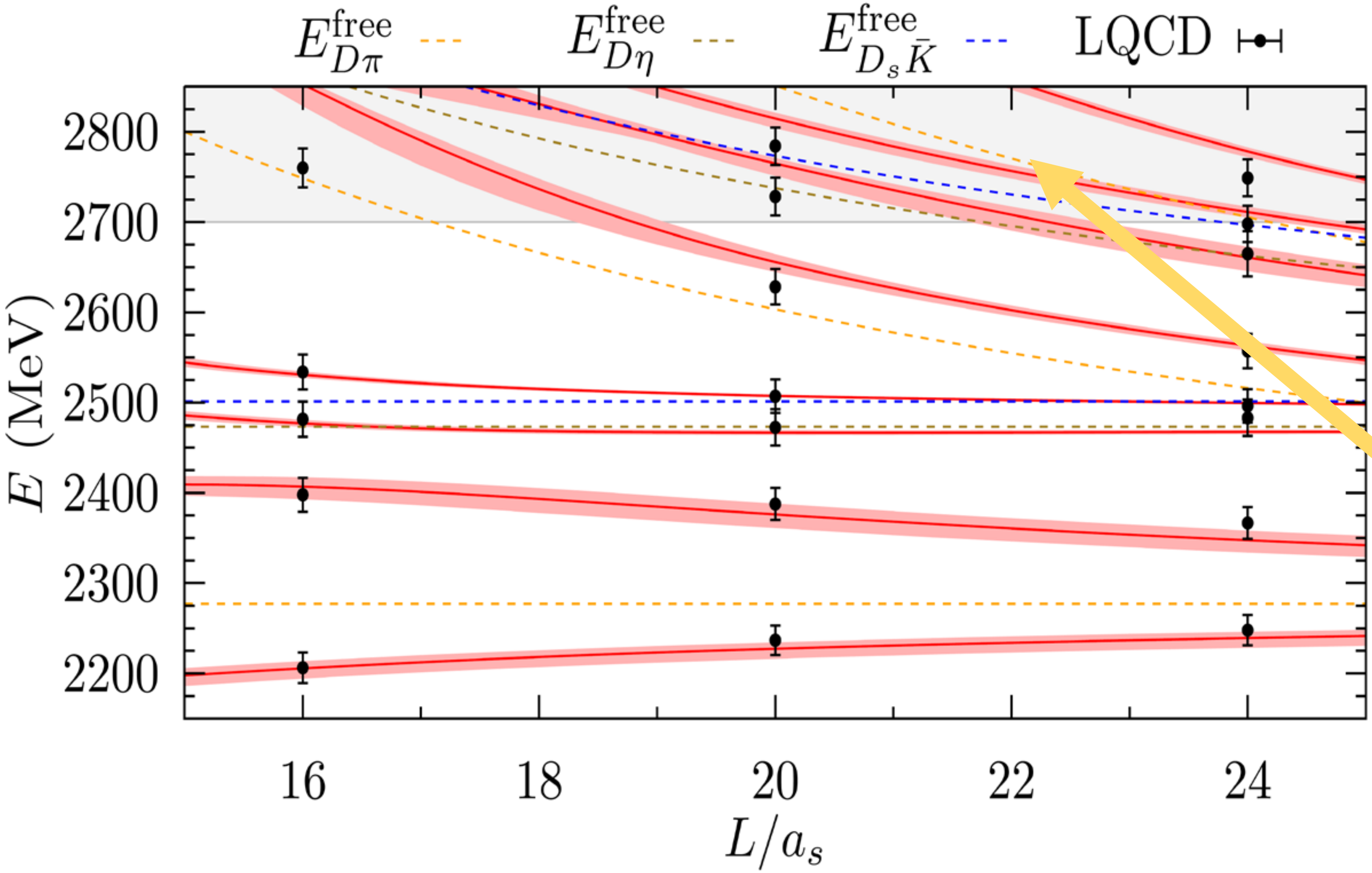

✓ We compute $E_n(L)$ and compare with the LQCD levels. **No fit is performed.**

✓ 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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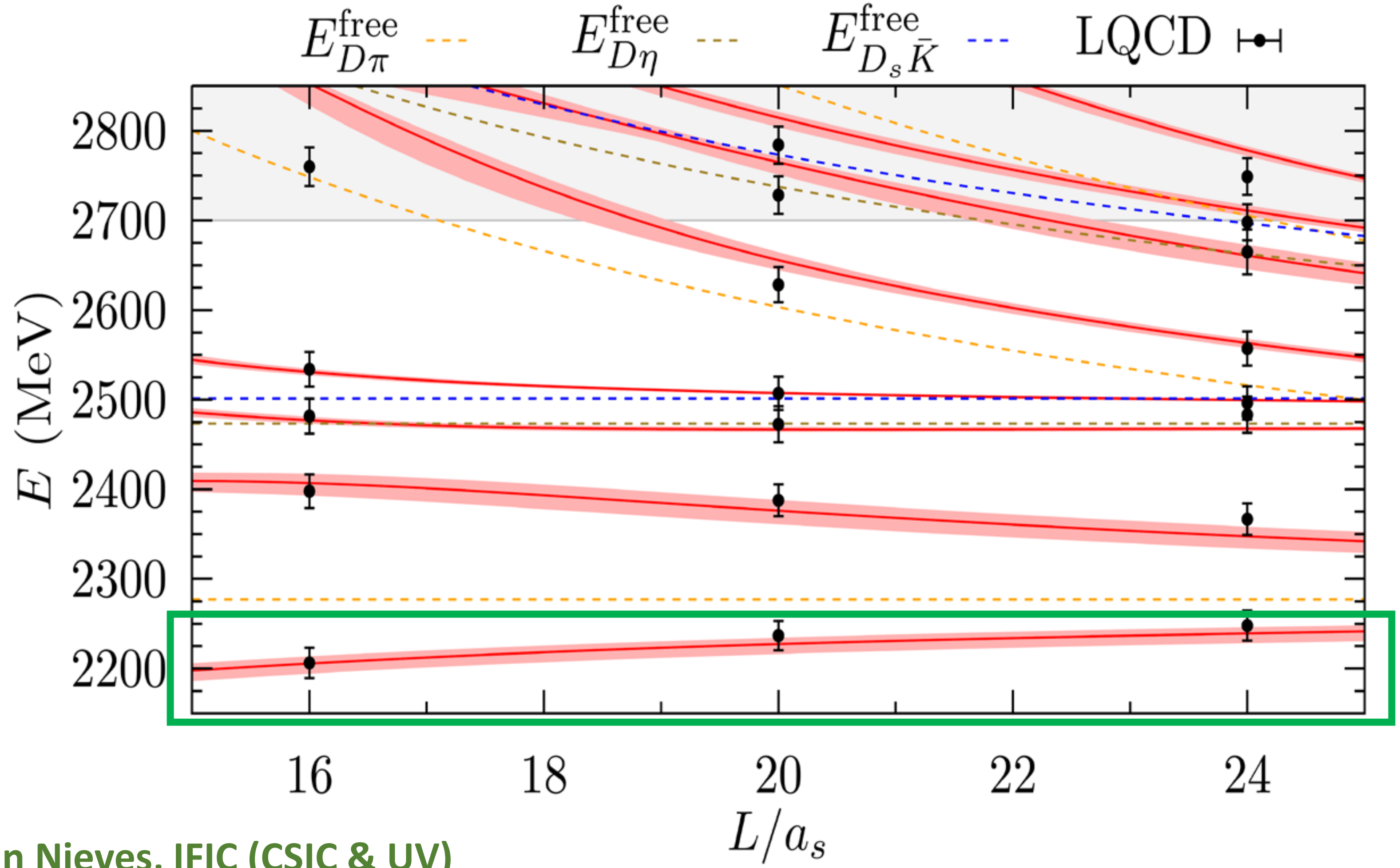

✓ **Level below threshold, associated with a bound state.**

✓ Free energy levels: $E^{i}_{n,\mathrm{free}}(L) = \omega_i\left(\frac{2\pi}{L}\vec{n}\right) + \omega'_i\left(\frac{2\pi}{L}\vec{n}\right)$

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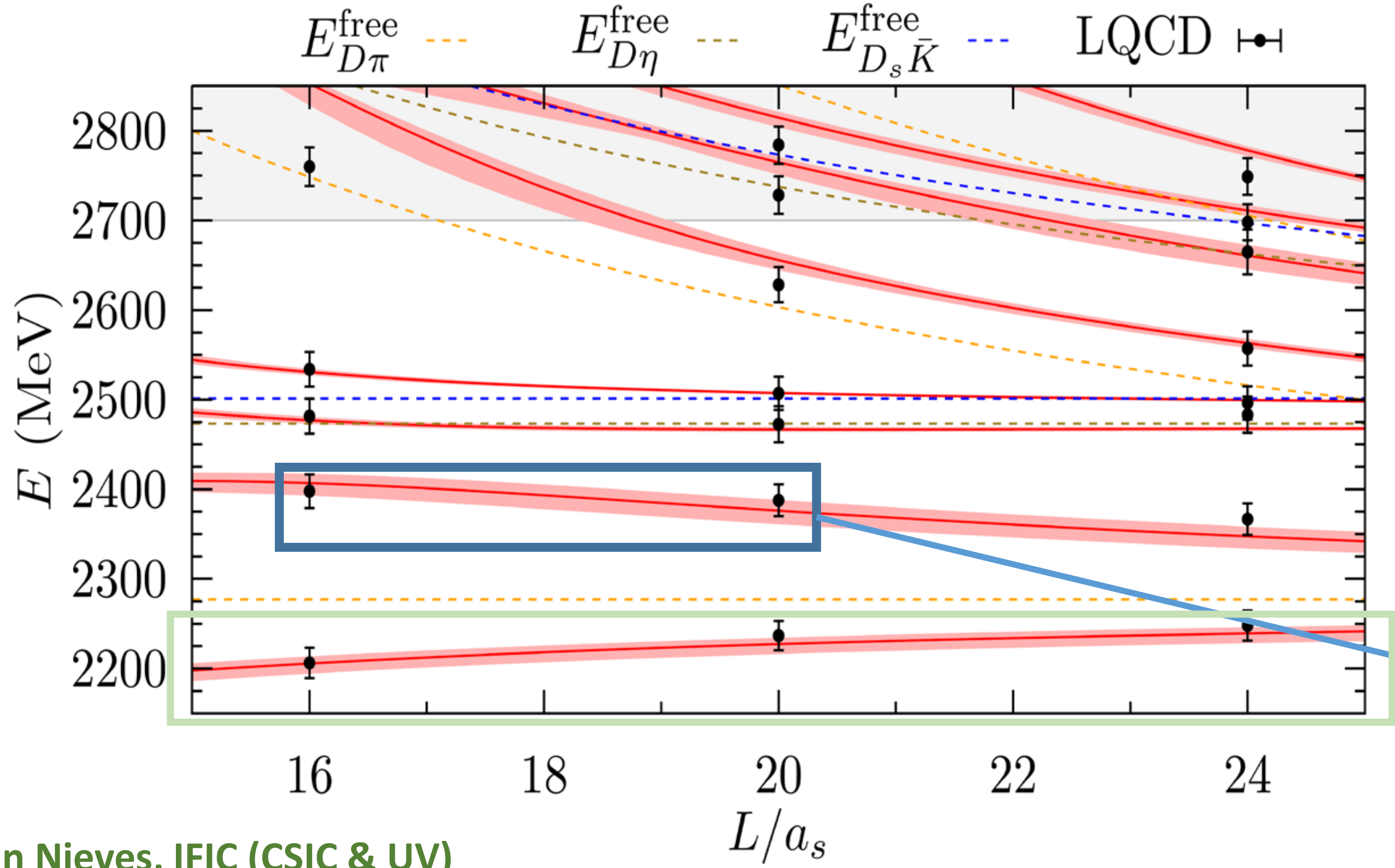
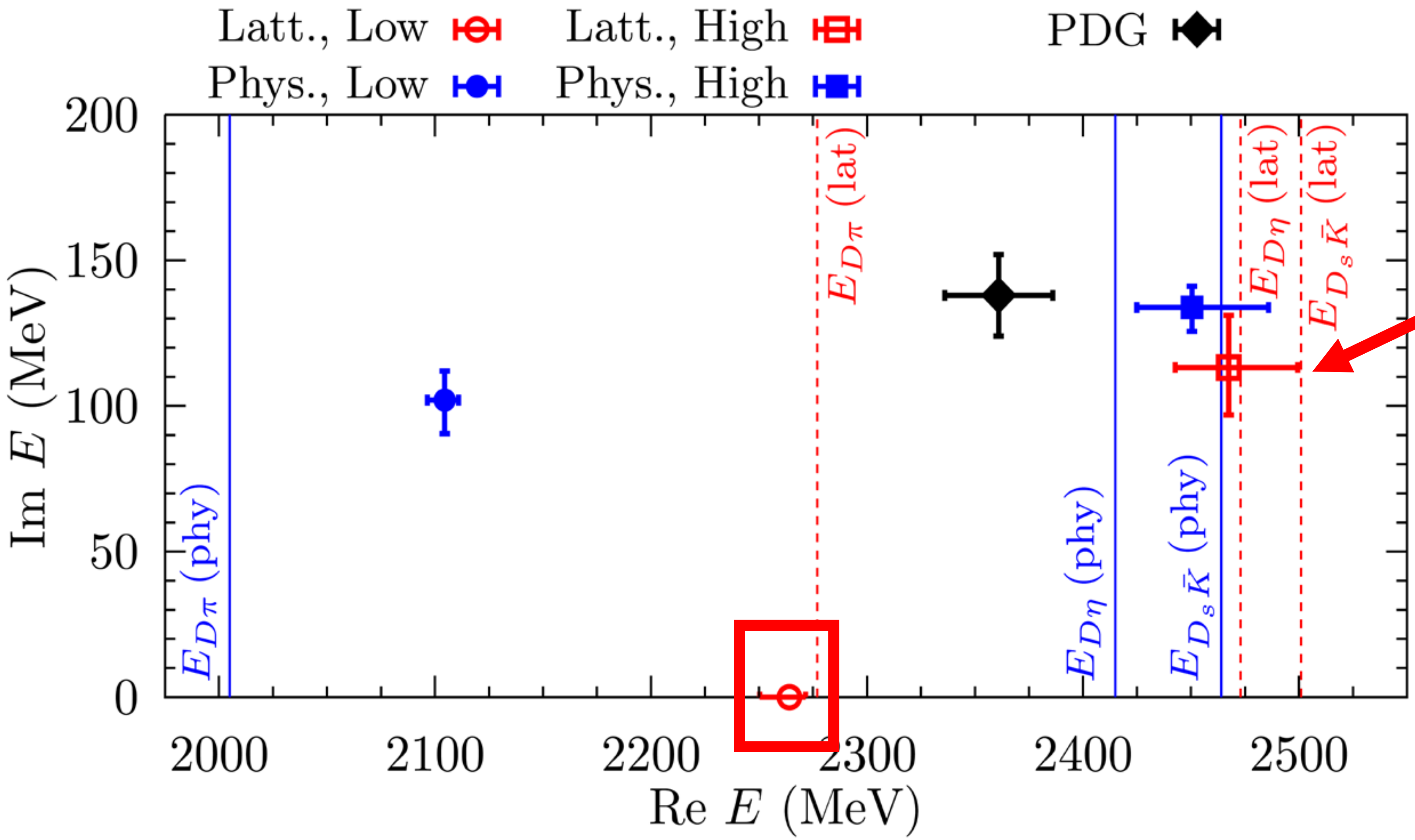


✓ **Level below threshold, associated with a bound state.**

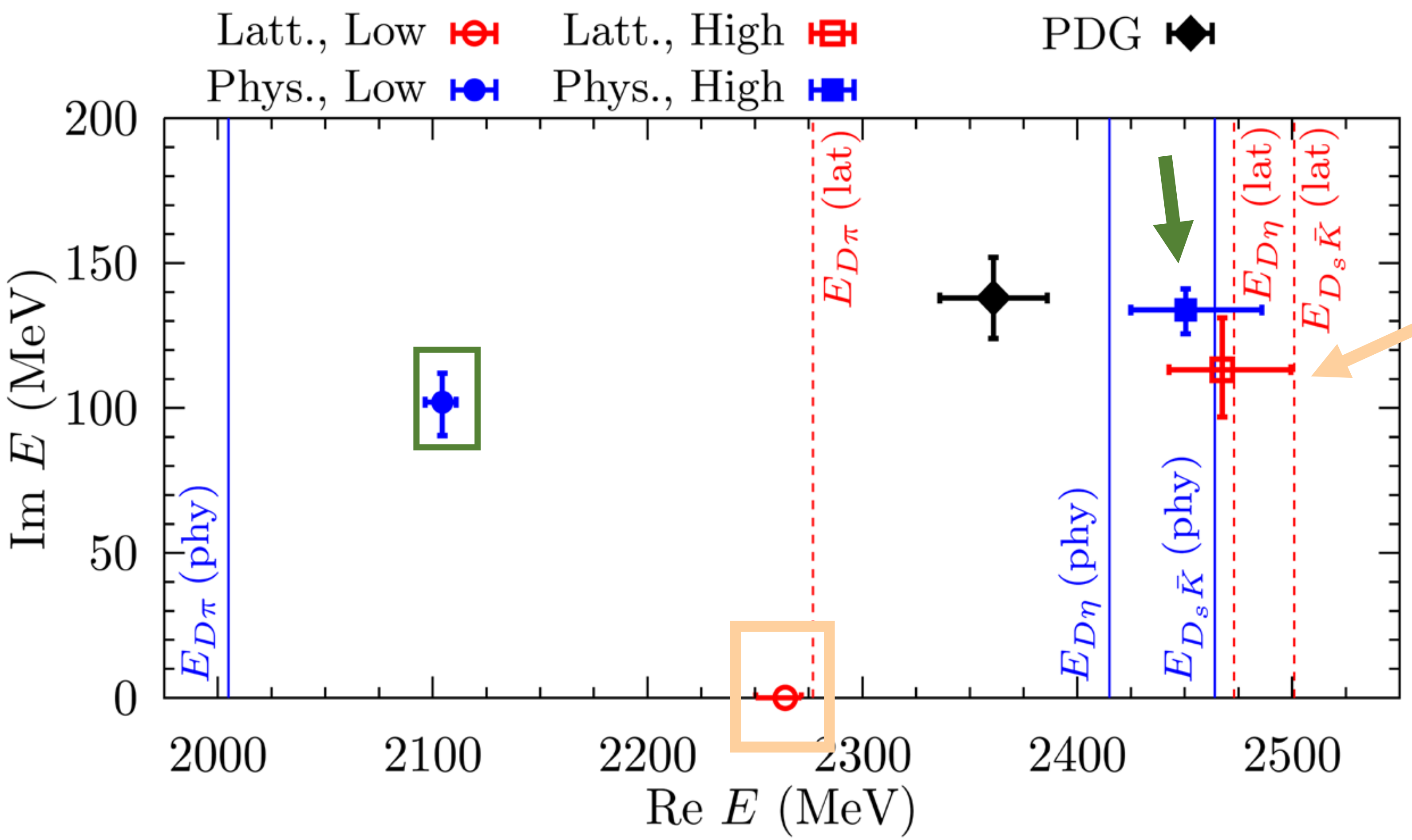
✓ Second level, lying between the $D\pi$ and $D\eta$ thresholds, is very shifted with respect to both of them, hinting at the presence of a **Resonance?**

Juan Nieves, IFIC (CSIC & UV)



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

Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
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)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$



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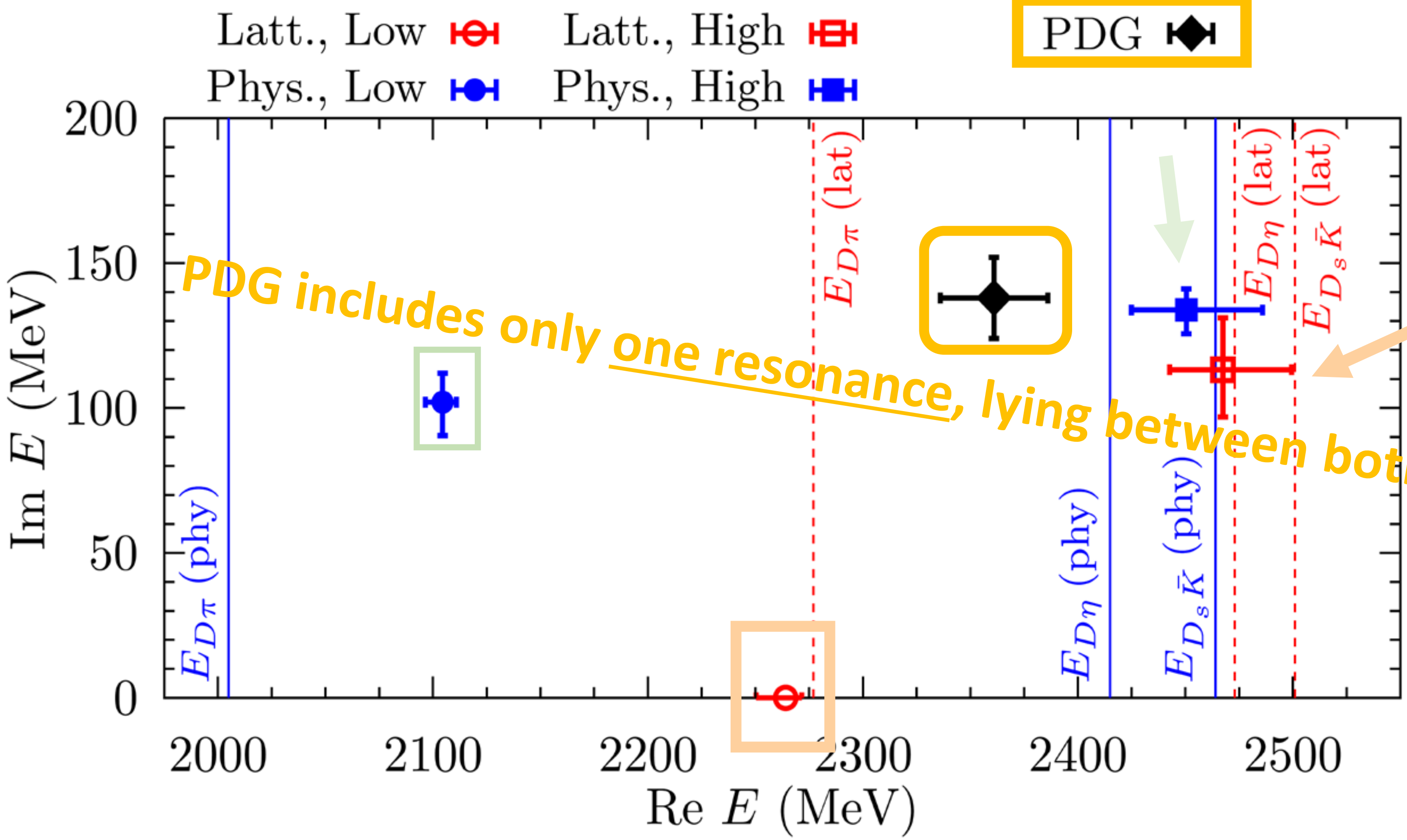
	2451^{+36}_{-26}	134^{+7}_{-8}	(110)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

- ✓ **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 *Dπ* threshold. The resonance varies very little, and is still a resonance (110). For both states, the coupling pattern is similar.**

Juan Nieves, IFIC (CSIC & UV)



PDG includes only one resonance, lying between both thresholds

Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
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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- ✓ For lattice masses, we find a bound state (000) and a resonance (110)
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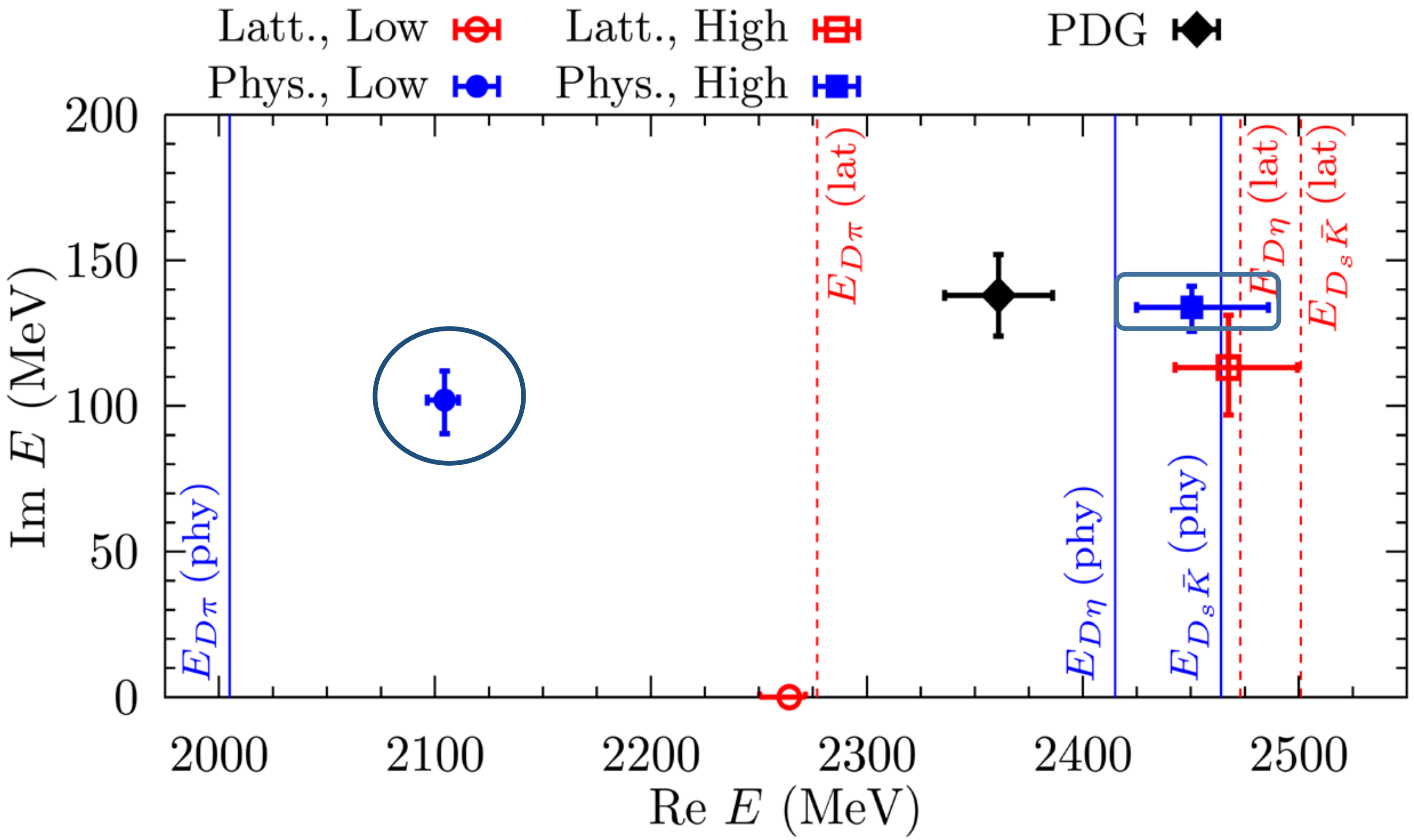

The $D_0^*(2400)$ structure is actually produced by two different states (poles), together with complicated interferences with thresholds. This two-pole structure was previously reported, and receives now a robust support

Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
lattice	2264^{+8}_{-14}	0	(000)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
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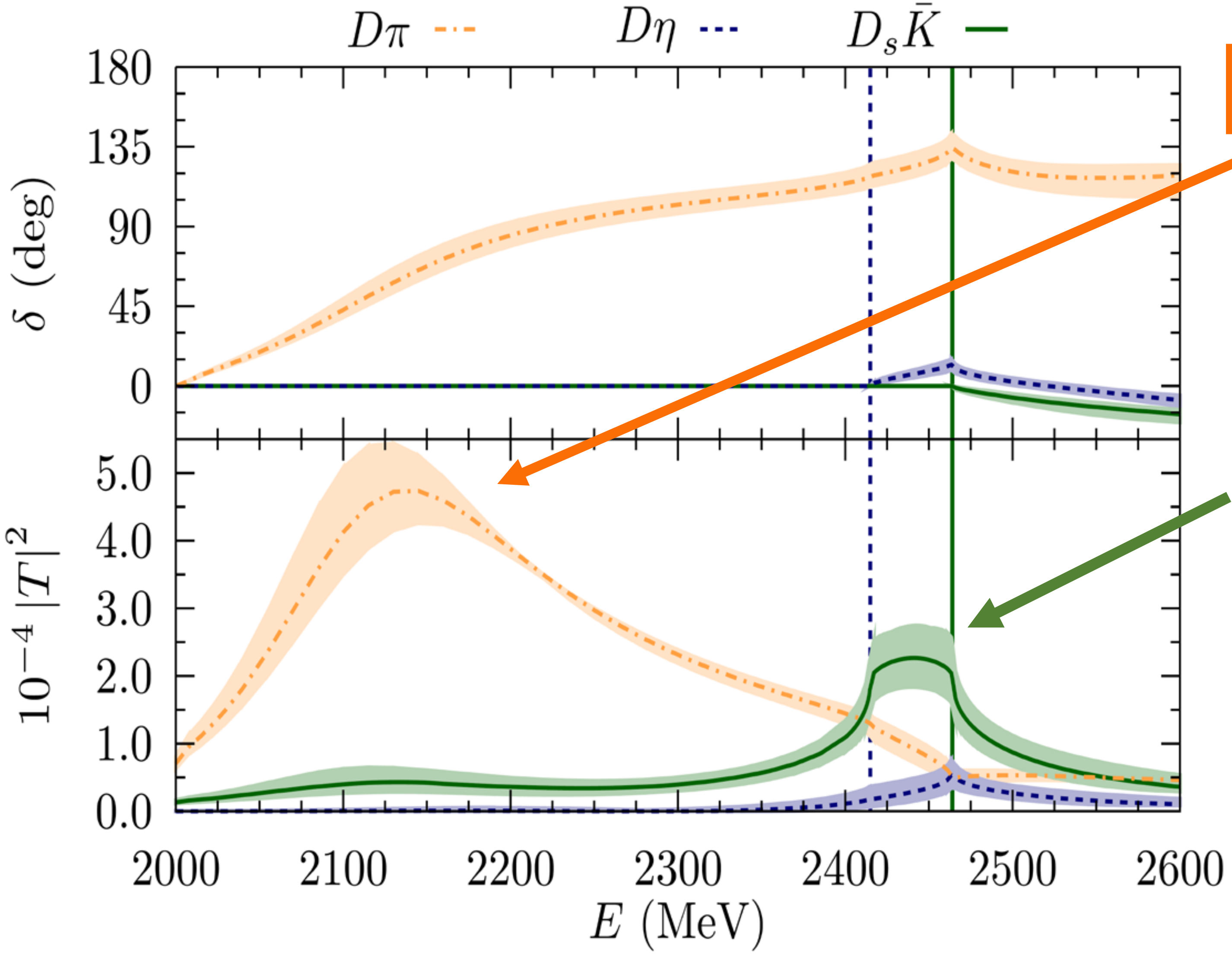
physical	2105^{+6}_{-8}	102^{+10}_{-12}	(100)	$9.4^{+0.2}_{-0.2}$	$1.8^{+0.7}_{-0.7}$	$4.4^{+0.5}_{-0.5}$
	2451^{+36}_{-26}	134^{+7}_{-8}	(110)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

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



Lower pole, $\sqrt{s} = (2.1 \; - i\; 0.1)$ GeV

- $|T_{11}(s)|^2$ **peaks at** $\sqrt{s} \sim 2.1$ **GeV**
- $\delta_{11}(s) = \pi/2$ **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** $B \longrightarrow D\phi\phi$ **decays**

Amplitudes

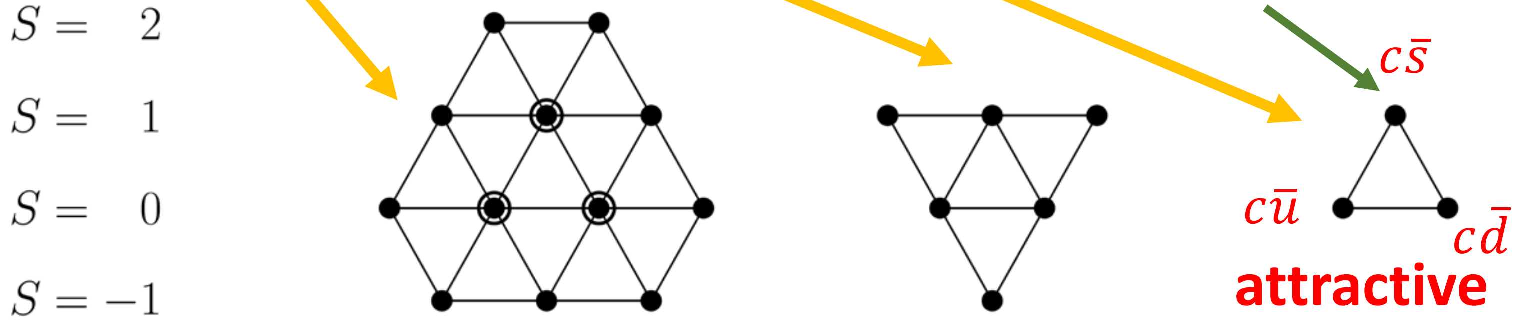
$$-i\, p_{ii}(s) T_{ii}(s) = 4\pi\sqrt{s}\left(\eta_i(s) e^{2i\delta_{ii}(s)} - 1\right)$$

SU(3) light flavor limit: $\bar{\mathbf{3}} \otimes \mathbf{8} = \overline{\mathbf{15}} \oplus \mathbf{6} \oplus \bar{\mathbf{3}}$

$D^+, D^0, D_s = c\bar{\ell}$

$\bar{K}, \pi, \eta, K$

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



repulsive | attractive | attractive

At LO: $V_A(s) = B(s)\ \mathrm{Diag}(1, -1, -3)$

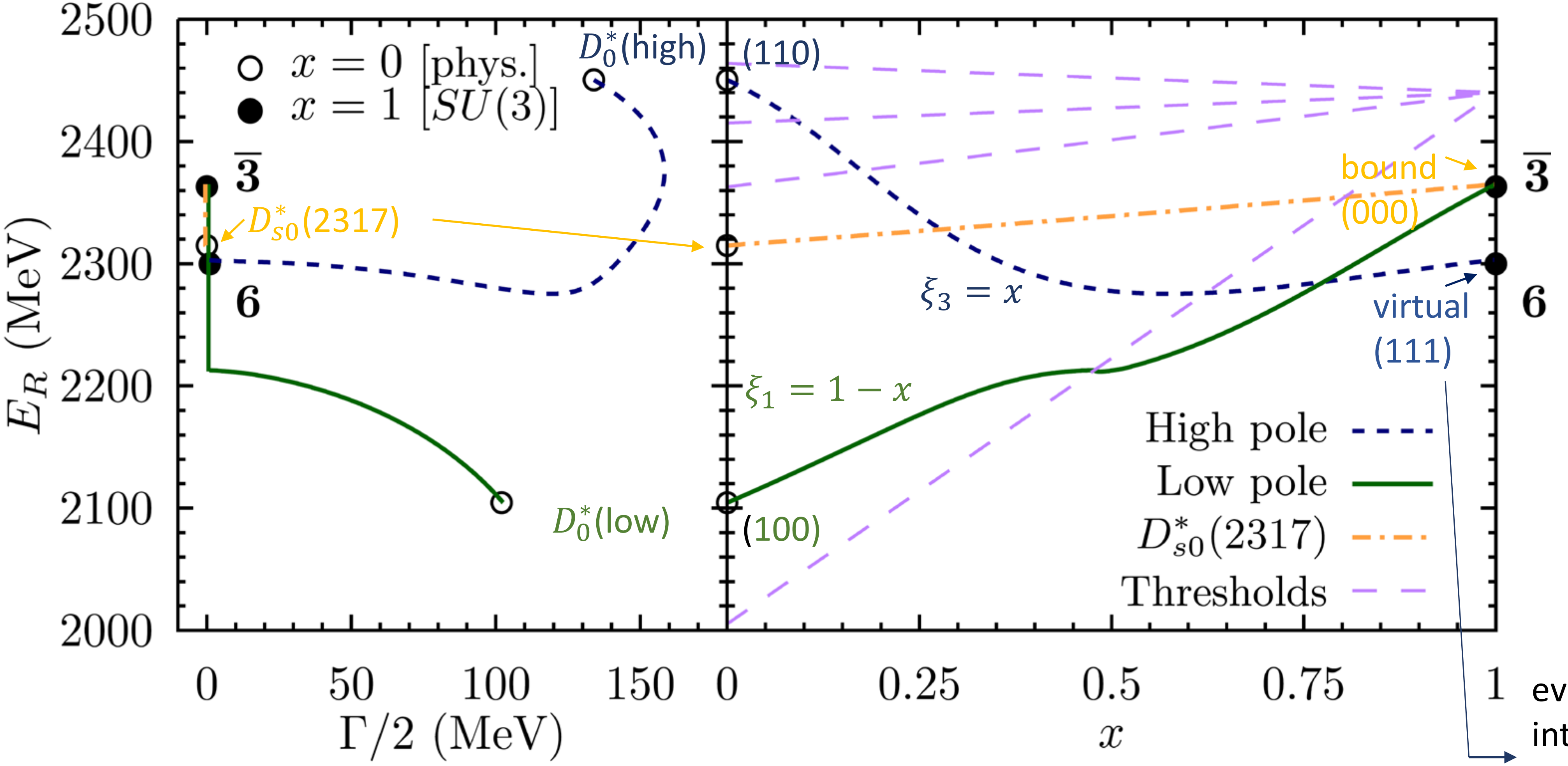
In this limit (all *D*-mesons and all Goldstone bosons have common masses *M* and *m*, respectively) , *T* and *V* can be diagonalized, while **$\mathcal{G}$ is already diagonal**,

diagonal!

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

State	Channels	(S, I)	$\overline{\mathbf{15}}$	$\mathbf{6}$	$\overline{\mathbf{3}}$
D_0^*	$D\pi, D\eta, D_s\bar{K}$	$\left(0, \frac{1}{2}\right)$	✓	✓	✓
$D_{s0}^*(2317)$	$DK, D_s\eta$	$(1, 0)$	✓	✗	✓

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 $D_{s0}^*(2317)$, $\boldsymbol{M = 2315^{+18}_{-28}}$ **MeV.**



Connecting physical (x = 0) & flavor SU(3) (x = 1) limits

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.

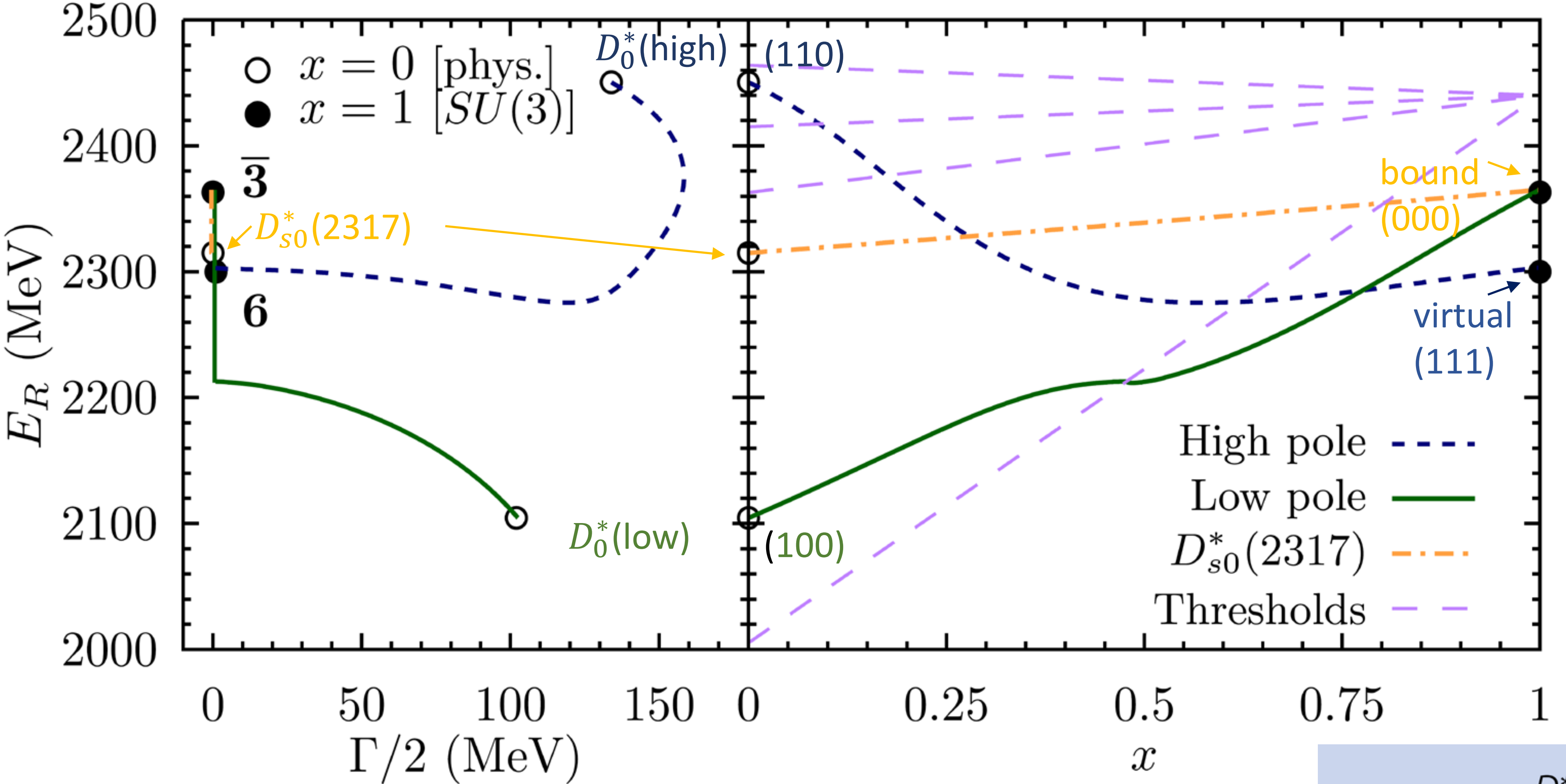
$$m_i = m_i^{\rm phys} + \boxed{x}(m - m_i^{\rm phys}),\ m = 0.49 \text{ GeV}$$
$$M_i = M_i^{\rm phys} + \boxed{x}(M - M_i^{\rm phys}),\ M = 1.95 \text{ GeV}$$

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, ξ_1 (for the lower pole) and ξ_3 (for the higher pole) depend on x

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

Juan Nieves, IFIC (CSIC & UV)



$m_i = m_i^{\rm phys} + x\,(m - m_i^{\rm phys})$

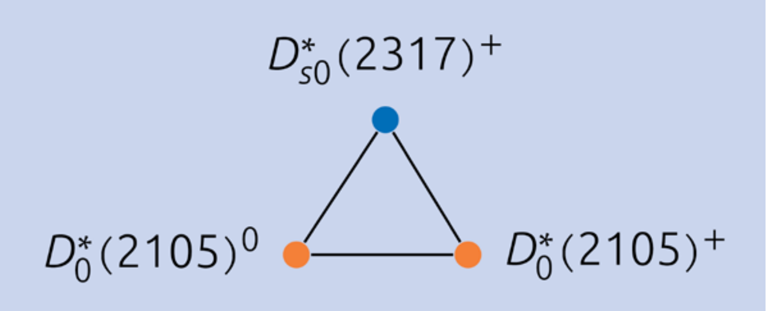
$M_i = M_i^{\rm phys} + x\,(M - M_i^{\rm phys})$

Juan Nieves, IFIC (CSIC & UV)

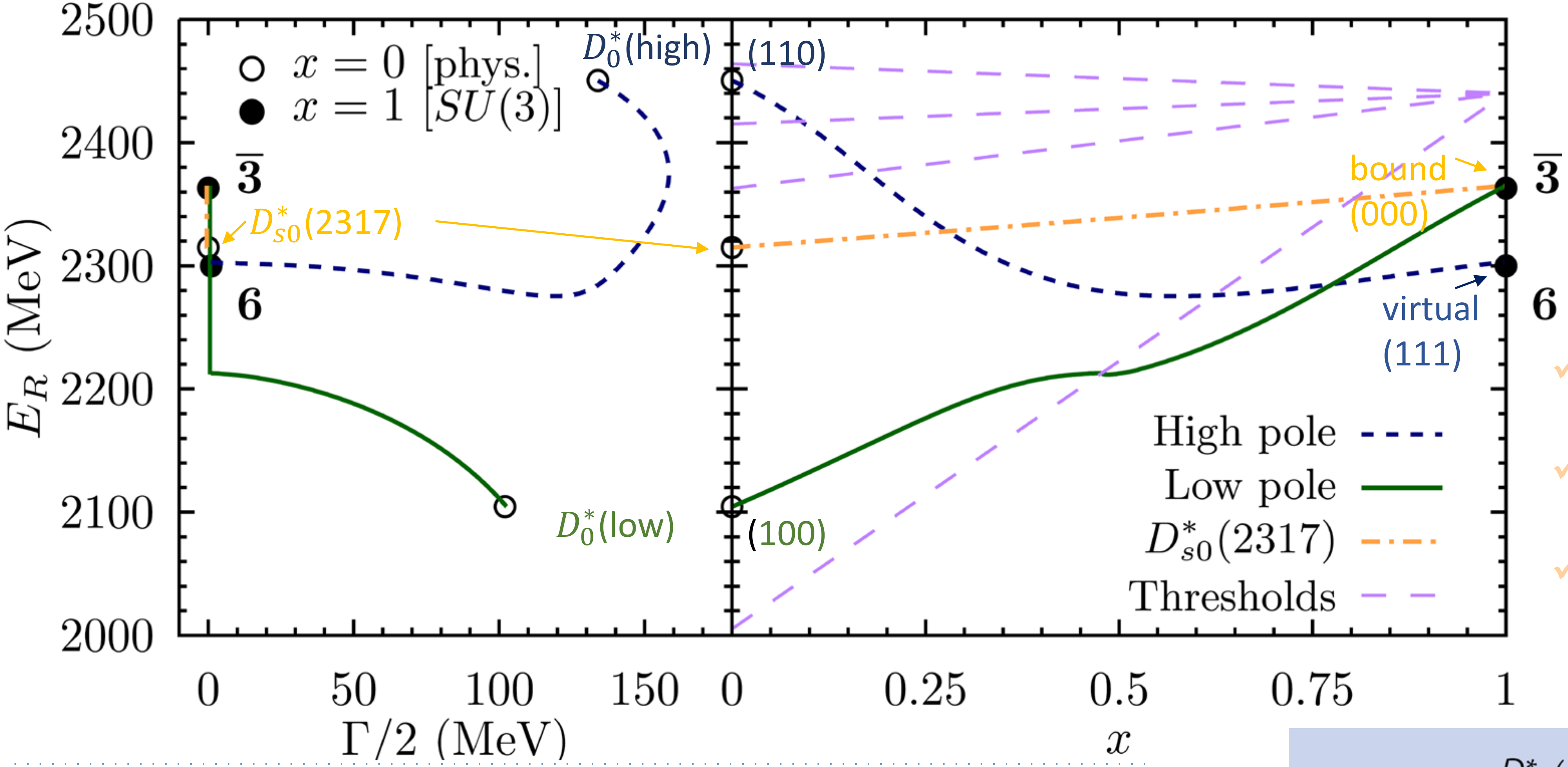
✓ **The high D_0^* connects with a 6 virtual state.**

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

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



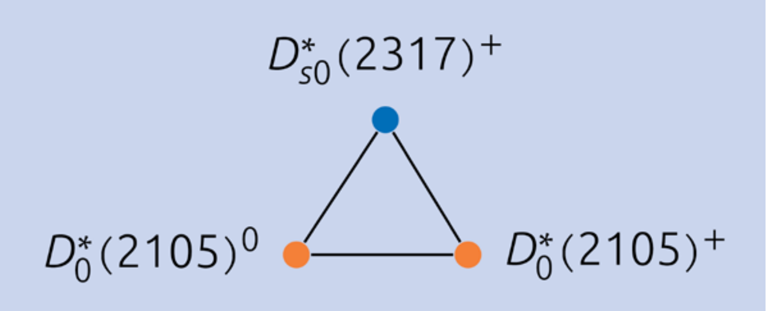
The low D_0^* and the $D_{s0}^*(2317)$ are SU(3) flavor partners



Juan Nieves, IFIC (CSIC & UV)

- ✓ 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

(S,I)	Channels	$\overline{15}$(R)	6(A)	$\overline{3}$ (A)	$J^P = 0^+$ (M ,Γ/2) [MeV]	$J^P = 1^+$ (M ,Γ/2) [MeV]
(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 $(2451^{+35}_{-26}, 134^{+7}_{-8})$	Lower pole $(2247^{+5}_{-6}, 107^{+11}_{-10})$ RPP $(2427 \pm 40, 192^{+65}_{-55})$ Higher pole $(2555^{+47}_{-30}, 203^{+8}_{-9})$
(1,0)	$D^{(*)}K, D_s^{(*)}\eta$	YES	NO	YES	2315^{+18}_{-28} (bound); RPP 2317.8±0.5	2456^{+15}_{-21} (bound); RPP 2459.5±0.6
(−1,0)	$D^{(*)}\bar{K}$	NO	YES	NO	2342^{+13}_{-41} (virtual)	the pole (virtual) moves deep in the complex plane
(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, $a^{D\bar{K}}_{(-1,0)} \sim 0.8$ fm. (Rest of scattering lengths are $|a| \sim 0.1$ fm.)

Predictions for other sectors: bottom

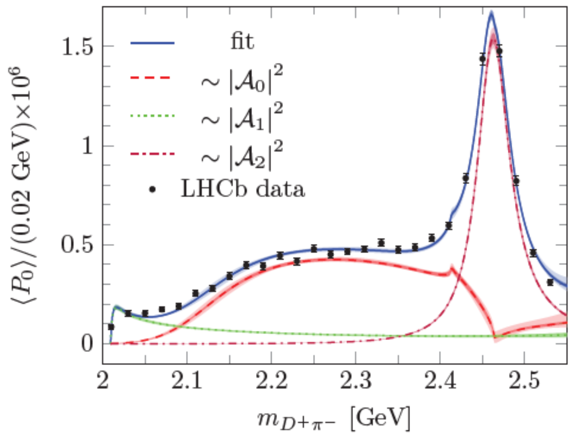
(S,I)	Channels	$\overline{15}$(R)	6(A)	$\bar{3}$ (A)	$J^P=0^+$ (M ,Γ/2) [MeV]	$J^P=1^+$ (M ,Γ/2) [MeV]
(0,1/2)	$\bar{B}^{(*)}\pi, \bar{B}^{(*)}\eta, \bar{B}_s^{(*)}\bar{K}$	YES	YES	YES	Lower pole $(5535^{+9}_{-11}, 113^{+15}_{-17})$ RPP — Higher pole $(5852^{+16}_{-19}, 36 \pm 5)$	Lower pole $(5584^{+9}_{-11}, 119^{+14}_{-17})$ RPP — Higher pole $(5912^{+15}_{-18}, 42^{+5}_{-4})$
(1,0)	$\bar{B}^{(*)}K, \bar{B}_s^{(*)}\eta$	YES	NO	YES	5720^{+16}_{-23} (bound); RPP —	5772^{+15}_{-21} (bound); RPP —
(−1,0)	$\bar{B}^{(*)}\bar{K}$	NO	YES	NO	(V-B) thr.	(V-B) thr.
(1,1)	$\bar{B}_s^{(*)}\pi, \bar{B}^{(*)}K$	YES	YES	NO	—	—

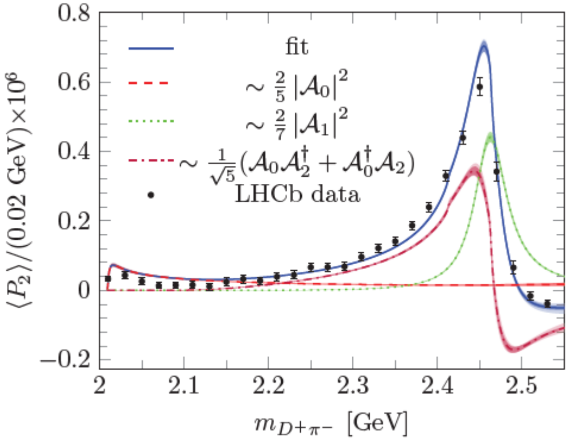
- ✓ Heavy flavour symmetry relates charm (*D)* and bottom ($\bar{B}$) sectors.
- ✓ (0, 1/2): $\bar{B}_0^*$, two-pole pattern also observed.
- ✓ (−1, 0): $[\bar{B}^{(*)}\bar{K}]$: very close to threshold. Relevant prediction. Can be either bound or virtual (6)
- ✓ (1, 1): $[\bar{B}_s\pi, \bar{B}K, 0^+]$, *X* (5568) channel. No state is found: 15 and 6. If it exists, it is not dynamically generated in $\bar{B}_s\pi$, $\bar{B}K$ interactions. [Albaladejo *et al.*, PL.B 757 (2016) 515; Guo *et al.*, Commun. Theor. Phys. 65 (2016) 593]
- ✓ (1, 0): Our results for $\bar{B}_{s0}^*$ and $\bar{B}_{s1}^*$ agree with other results from LQCD [Lang *et al.*, PLB 750 (2015) 17].

Chiral $D_{(s)}^{(*)}\phi$ molecular structure natural solution to three (experimental) puzzles:

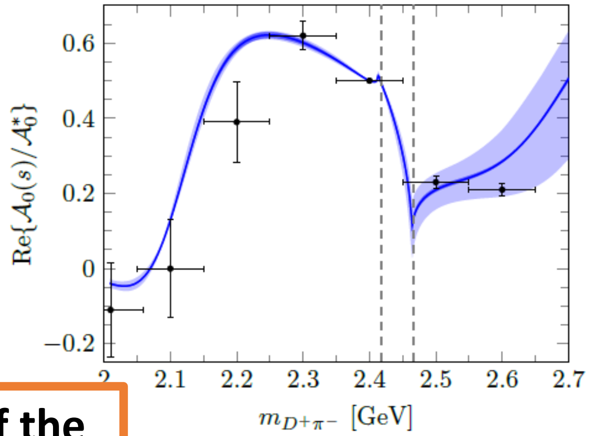
- ✓ Why are the $M_{D_{s0}^*(2317)}$ & $M_{D_{s1}(2460)}$ ≪ CQM $c\bar{s}$ 0^+ and 1^+ mass predictions
- ✓ Why $(M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)}) \sim (M_{D^*} - M_D)$ within 1 MeV.
- ✓ Why are the $D_0^*(2400)$ and $D_1(2430)$ masses almost equal to or even higher than their strange siblings despite of $\frac{m_s}{m_d} \sim 20$

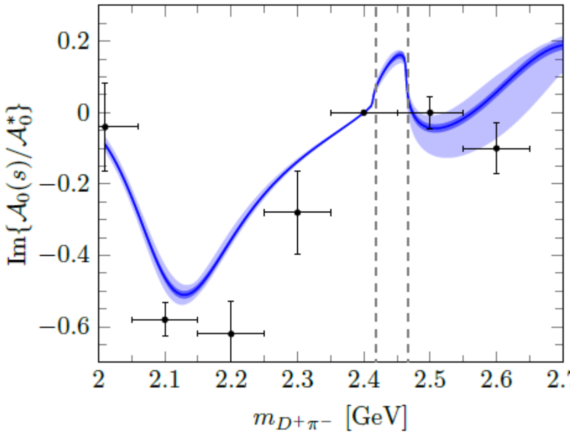
...confirmed by LHCb data for the $B^- \to D^+\pi^-\pi^-$ reaction





$\mathcal{A}_0$ (S-wave)

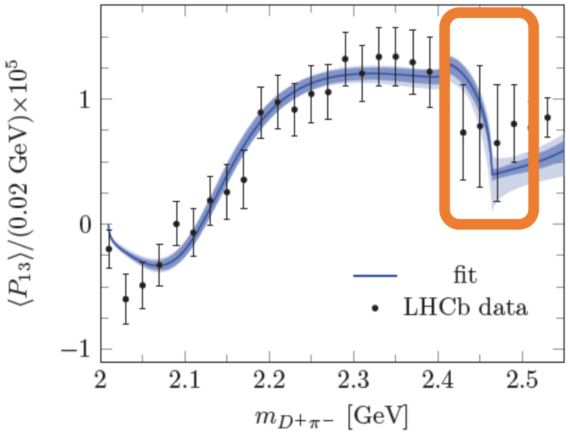




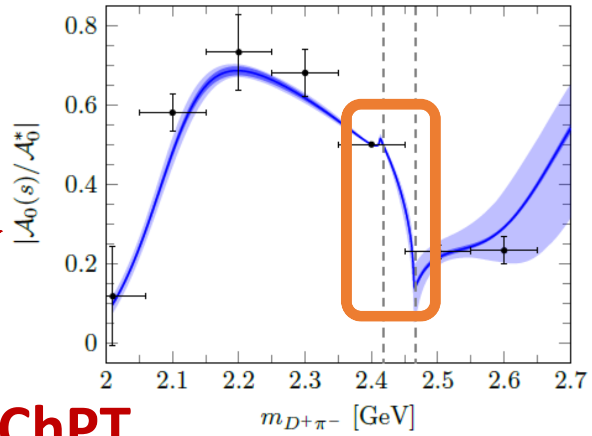
$< P_0 >$

$< P_2 >$

$< P_{13} >$



cusps: opening of the $D^0\eta$ and $D_s^+K^-$ thresholds enhanced by the higher D_0^*(2400) pole



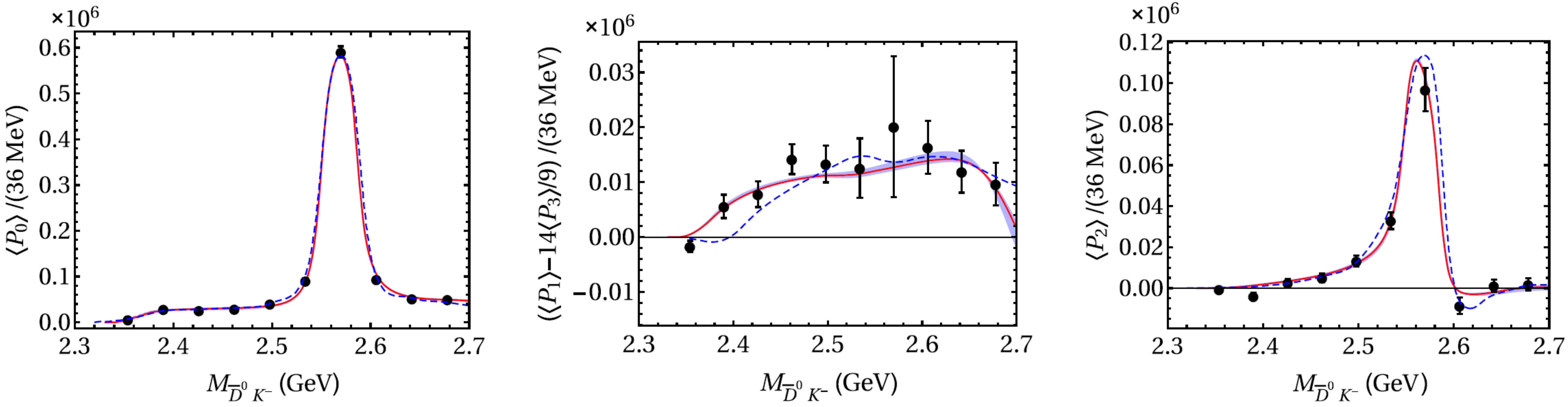
$$\langle P_0\rangle \propto \boxed{|\mathcal{A}_0|^2} + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2,$$

$$\langle P_2\rangle \propto \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}\boxed{|\mathcal{A}_0|}\mathcal{A}_2|\cos(\Delta\delta_2),$$

$$\langle P_{13}\rangle \equiv \langle P_1\rangle - \frac{14}{9}\langle P_3\rangle \propto \frac{2}{\sqrt{3}}\boxed{|\mathcal{A}_0|}\mathcal{A}_1|\cos(\Delta\delta_1),$$

$\mathcal{A}_0$ (S-wave) from UHMChPT

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



the LHCb data [R. Aaij et al. PRD 90 (2014) 072003] for the angular moments for $B_s^0 \longrightarrow \bar{D}^0 K^- \pi^+$ can be easily reproduced in the same framework with the untarized chiral $\bar{D}\bar{K}$ coupled-channels S-wave amplitude

… and two final remarks in this context

charm sector

(S,I)	Channels	$\overline{15}$(R)	6(A)	$\overline{3}$ (A)	$J^P=0^+$ (M ,Γ/2) [MeV]	$J^P=1^+$ (M ,Γ/2) [MeV]
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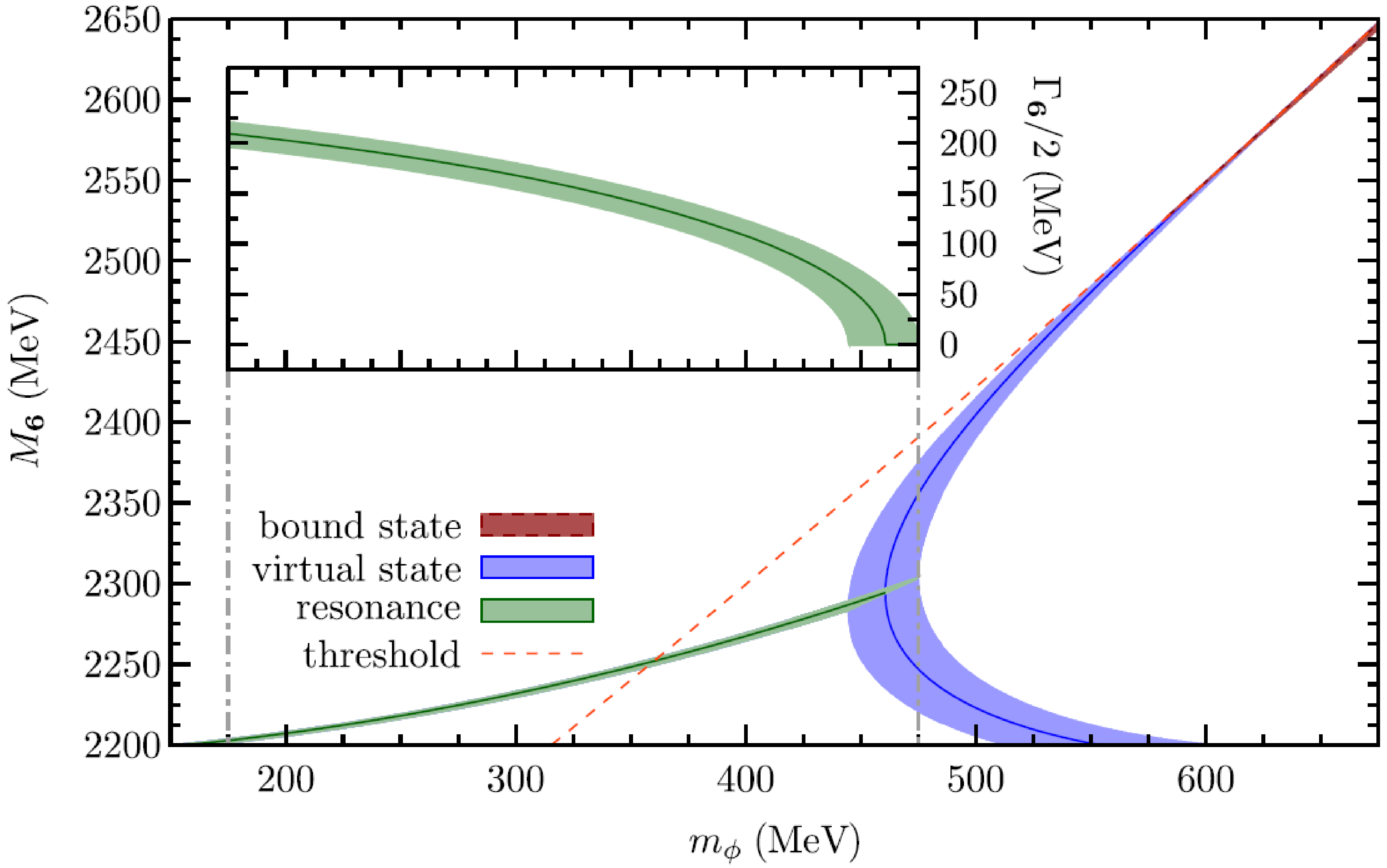
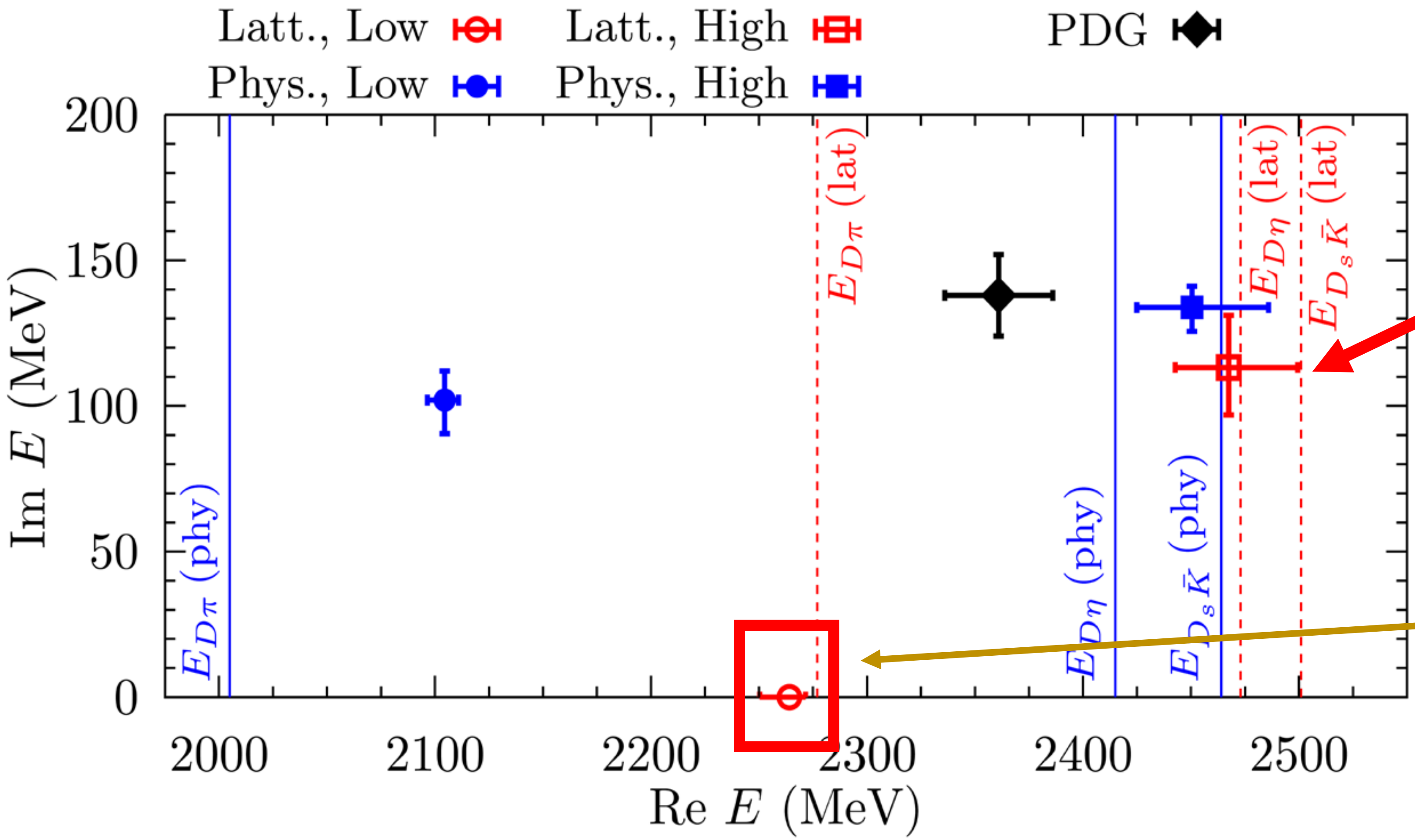
(−1,0)	$D^{(*)}\bar{K}$	NO	YES	NO	2342^{+13}_{-41} (virtual)	the pole (virtual) moves deep in the complex plane
(1,1)	$D_s^{(*)}\pi, D^{(*)}K$	YES	YES	NO	–	–

CQM: $c\bar{\ell}$ members of the flavor antitriplet—the presence of the **sextet is a nontrivial prediction** emerging from the meson-meson dynamics

Dynamics of the <u>sextet pole</u> in the SU(3) limit as a function of the Golstone boson mass. It can be tested in LQCD





Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
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✓ 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^+

$\boldsymbol{D^{(*)}}, \boldsymbol{D_s^{(*)}}$ **heavy light mesons**

undetermined LEC

Goldstone bosons

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

$$J_a = \frac{1+\not v}{2}\left(Y^*_{a\,\mu}\gamma_5\gamma^\mu + Y_a\right)$$ 0^+ and 1^+ **bare CQM $1\,^{2S+1}P_J c\bar{\ell}$** states

✓Chiral symmetry
✓HQSS
✓SU(3) flavor

coupling two-meson and CQM degrees of freedom

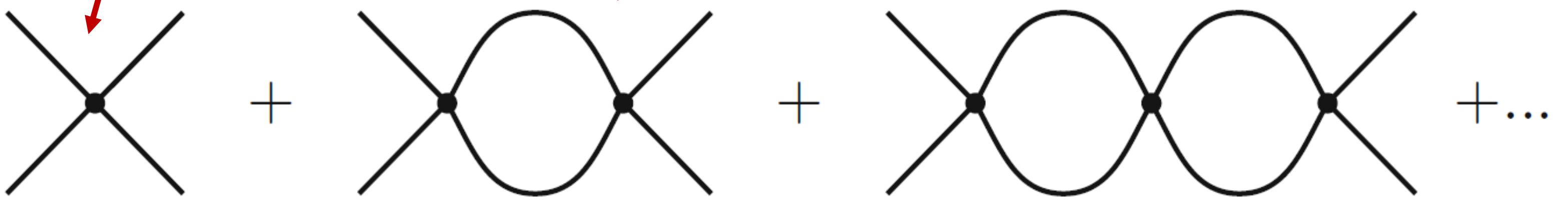
... also D.R. Entem's talk today

non-perturbative BSE re-summation

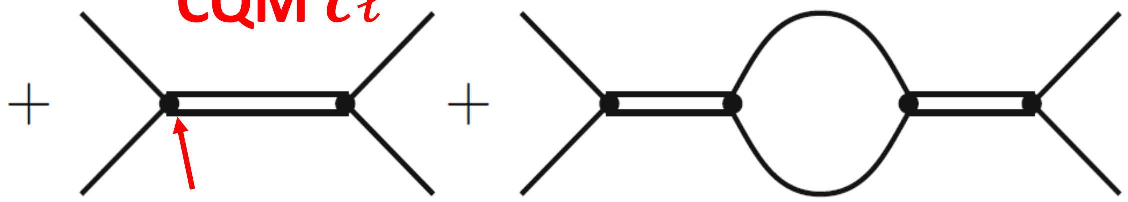
V. Baru, C. Hanhart, YuS Kalashnikova, A.E. Kudryavtsev, A.V. Nefediev, EPJA 44 (2010) 93.
E. Cincioglu JN, A. Ozpineci,
A. U. Yilmazer, EPJC 76 (2016) 576

LO HMChPT

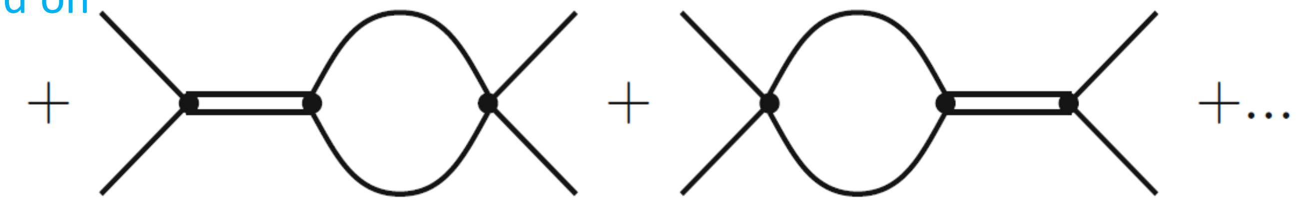
heavy light meson—Goldstone-boson loop (UV divergent)



CQM $c\bar{\ell}$



undetermined LEC (c): controls interplay between CQM and two-meson degrees of freedom



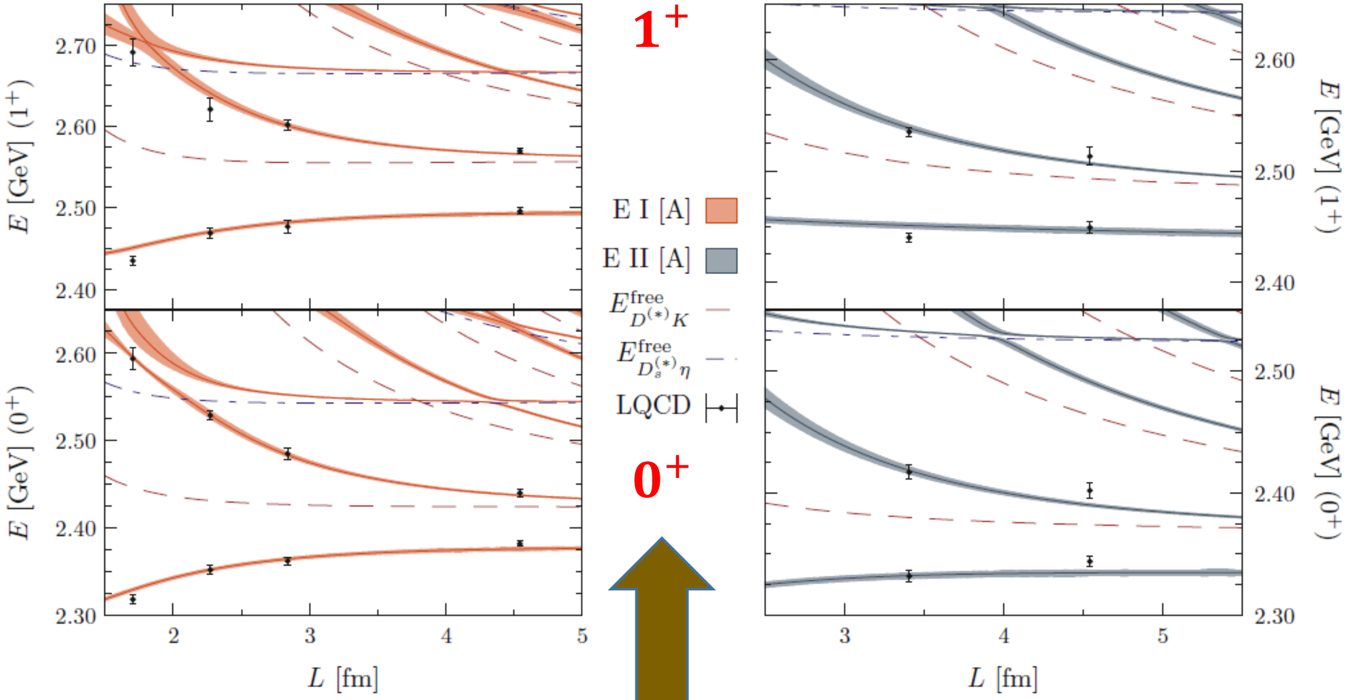
- ✓ LO HMChPT: avoid double-counting
- ✓ free parameters: UV regulator+LEC (c)
- ✓ bare CQM mass and LEC (c) depend on UV regulator

J^π	[Set A] $\mathring{m}_{c\bar{s}}$	[Set B] $\mathring{m}_{c\bar{s}}$	$(M_{D^{(*)}} + m_K)$	$(M_{D_s^{(*)}} + m_\eta)$
0^+	2510.7	2382.9	2362.8	2516.1
1^+	2593.1	2569.7	2504.2	2660.0
$1^+ - 0^+$	82.4	186.8		

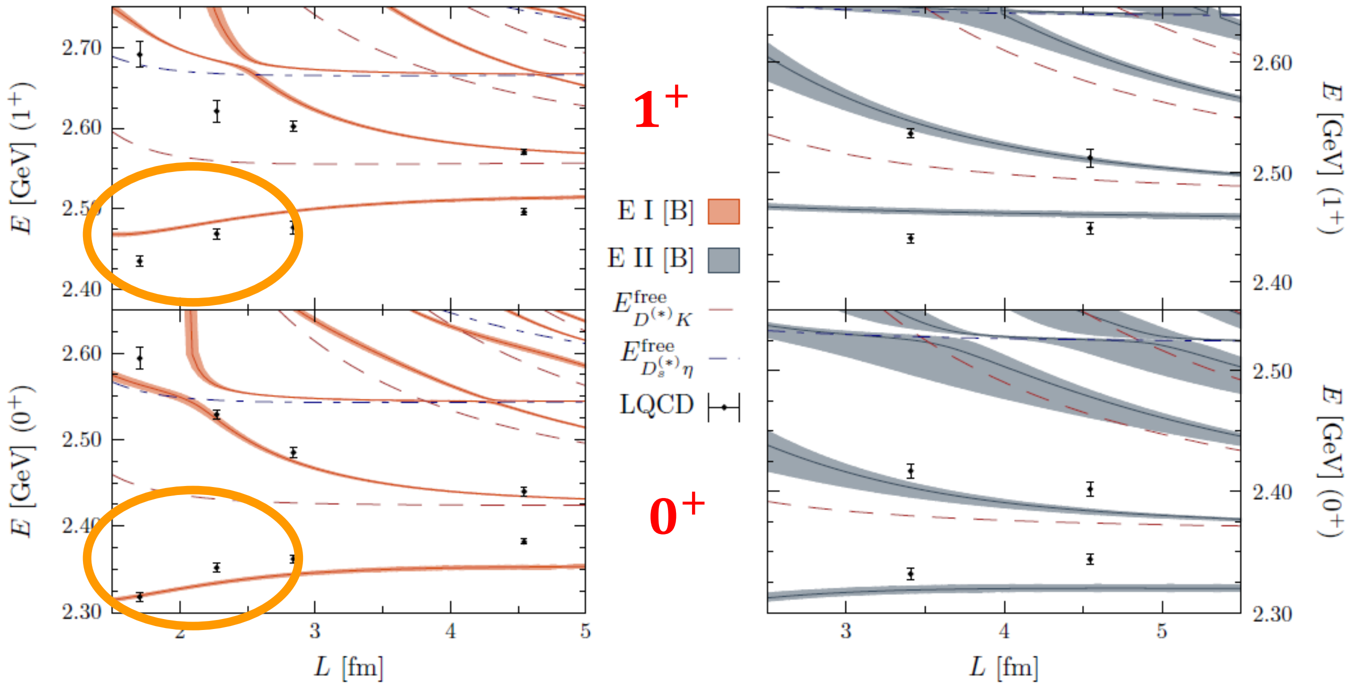
J. Segovia, C. Albertus, E. Hernandez, F. Fernandez, D.R. Entem, Phys. Rev. D **86**, 014010 (2012).

far from the mass of the physical state ~ 2460 MeV

contains OGE corrections [S.N. Gupta, J.M. Johnson, PRD 51 (1995) 168] that affect only the 0^+ state



CQM potential that includes OGE corrections <u>**does not describe well**</u> 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

<u>Juan Nieves, IFIC (CSIC & UV)</u>

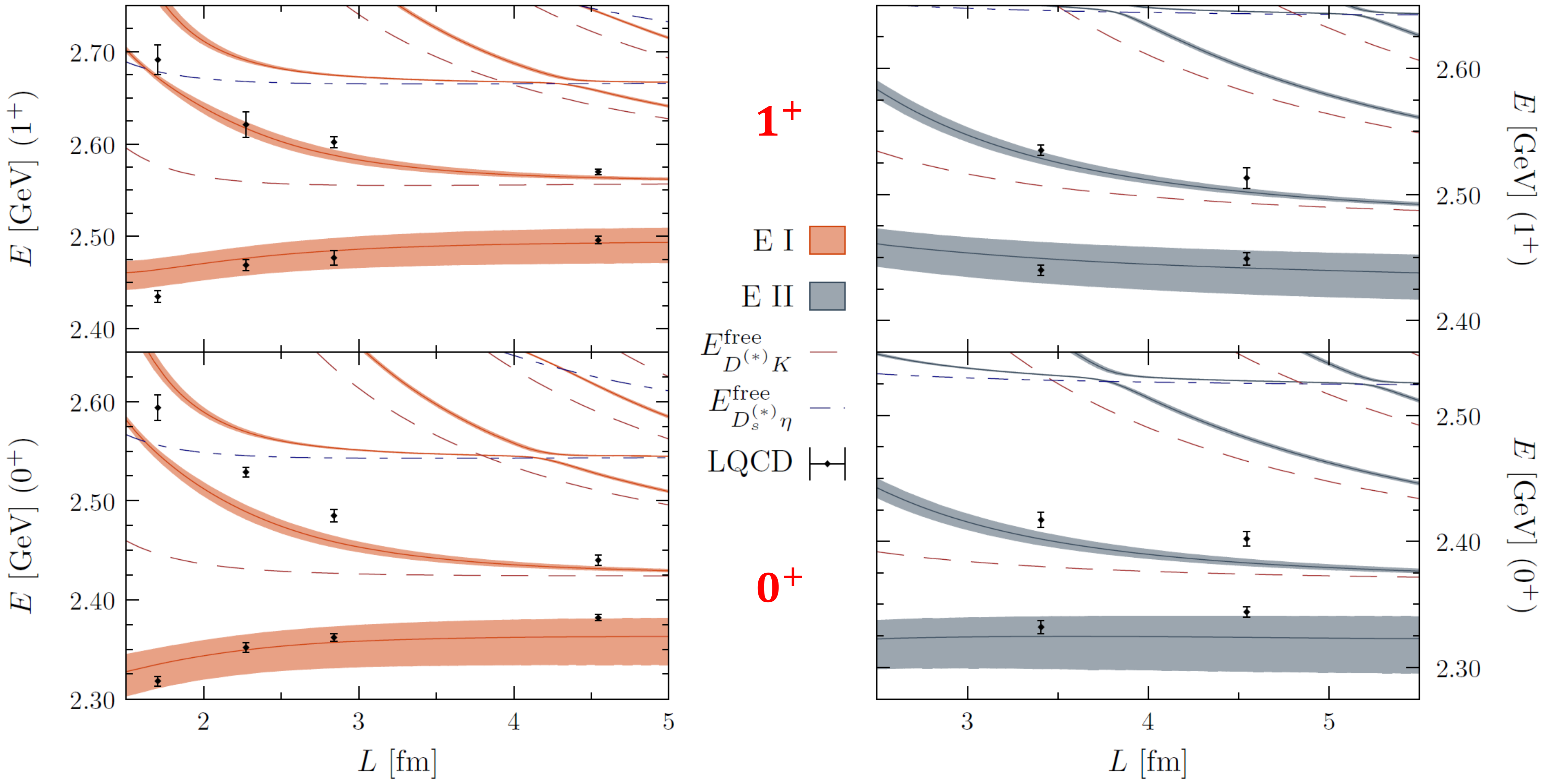
Table 3 Best fit LO+CQM parameters, together with infinite volume properties (masses, $D^{(*)}K$ and $D_s^{(*)}\eta$ molecular components and couplings) of the lowest-lying $j_{\bar q}^{\pi} = \frac{1}{2}^{+}$ D_s charm-strange meson doublet, determined from the fits to the lattice energy-levels obtained for each of the two lattice pion mass ensembles (I and II) calculated in Ref. [38], and using either Set A or B of bare CQM masses (see discussion in Sect. 2.3). S-wave isoscalar $D^{(*)}K$ scattering lengths (a) are also given, which are related to the amplitudes at threshold by $T[s=(M_{D^{(*)}}+m_K)^2] = -8\pi a(M_{D^{(*)}}+m_K)$, as in Ref. [38]. All these infinite volume quantities have been computed using physical meson masses. LQCD energy-levels and those determined in this work are shown in Figs. 1 and 2. Statistical 68%-CL errors on the best fit parameters and derived quantities are calculated from the distributions obtained after performing a sufficiently large number of fits to synthetic sets of LQCD data, as explained in the caption of Fig. 1. In addition, the $c-\Lambda$ correlation coefficients are −0.81, −0.93, 0.08 and −0.80 for fits AI, AII, BI and BII, respectively. Besides, in the Set C rows, we give the results obtained from a one-parameter (UV cutoff Λ)-fit that corresponds to an scheme where the LQCD energy-levels are described using finite-volume untarized LO HMChPT amplitudes. This is to say, the LEC c is fixed to zero, and therefore the contributions to the amplitudes of the exchange of even-parity charmed-strange CQM mesons are neglected. The volume dependence of the 0^+ and 1^+ energy-levels determined within this latter scheme are shown in Fig. 3 for the two lattice pion mass ensembles (I and II)

Parameters							Infinite volume predictions					
Set	Ensemble	J^π	$\mathring{m}_{c\bar s}$ [MeV]	c	Λ [MeV]	χ^2/dof	M_b [MeV]	$P_{D^{(*)}K}$ [%]	$P_{D_s^{(*)}\eta}$ [%]	$a_{D^{(*)}K}$ [fm]	$g_{D^{(*)}K}$ [GeV]	$g_{D_s^{(*)}\eta}$ [GeV]
A	I	0^+	2511	0.62 ± 0.04	663^{+23}_{-27}	1.8	2335 ± 2	67 ± 1	2.1 ± 0.2	$-1.41^{+0.05}_{-0.06}$	10.6 ± 0.2	5.43 ± 0.08
		1^+	2593				2465 ± 2	57 ± 1	1.9 ± 0.2	$-1.16^{+0.03}_{-0.04}$	$12.1^{+0.3}_{-0.2}$	5.83 ± 0.06
	II	0^+	2511	0.61 ± 0.09	710^{+70}_{-60}	3.1	2331 ± 3	64 ± 2	2.4 ± 0.4	$-1.29^{+0.07}_{-0.08}$	$10.9^{+0.4}_{-0.3}$	5.6 ± 0.1
		1^+	2593				2460 ± 3	55^{+2}_{-1}	$2.2^{+0.4}_{-0.3}$	$-1.07^{+0.05}_{-0.06}$	$12.2^{+0.5}_{-0.4}$	6.0 ± 0.1
B	I	0^+	2383	0.71 ± 0.01	426 ± 14	18.6	2330 ± 2	51 ± 1	0.51 ± 0.06	-1.36 ± 0.05	$11.8^{+0.1}_{-0.2}$	4.95 ± 0.1
		1^+	2570				2485 ± 2	67 ± 1	0.51 ± 0.07	-1.79 ± 0.09	$11.0^{+0.2}_{-0.3}$	4.9 ± 0.1
	II	0^+	2383	$0.57^{+0.07}_{-0.08}$	580^{+80}_{-50}	18.0	2320 ± 4	45^{+2}_{-1}	1.2			
		1^+	2570				2477 ± 4	60 ± 2	1.3			
C	I	0^+	–	0 fixed					5.6			
		1^+	–						5.6			
	II	0^+	–	0 fixed					5.6			
		1^+	–						5.6			

$$P_j = -g_j^2 \left.\frac{\partial G_j}{\partial s}\right|_{s=M_b^2}$$

lowest state: sizable molecular probabilities, obtained within a model that explicitly includes CQM degrees of freedom. **In addition, there appears a second pole: CQM state dressed by the meson loops**

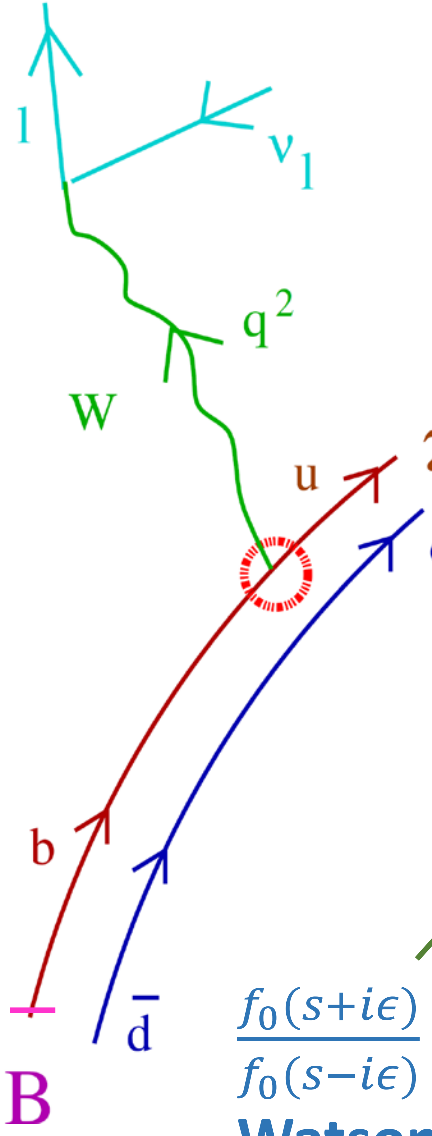
bottom sector: M. Albaladejo et al., EPJC77 (2017) 170



<u>Unitarized NLO HMChPT</u> [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, $\bar{B} \longrightarrow \pi\, l\, \bar{\nu}_l$

$$\langle \pi(p_\pi)|V^\mu|\bar{B}(p_B)\rangle = \left(p_B + p_\pi - q\frac{m_B^2 - m_\pi^2}{q^2}\right)^\mu f^+(q^2) + q^\mu \frac{m_B^2 - m_\pi^2}{q^2} \boxed{f^0(q^2)}$$

Omnès dispersive representation , generalized to coupled-channels

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

$$\frac{f_0(s+i\epsilon)}{f_0(s-i\epsilon)} = e^{2i\delta(s)}, s \in \mathrm{L},$$

Watson's theorem

$J^P = 0^+$,
$\pi\,\bar{B} \longrightarrow \pi\,\bar{B}$

It can be taken from the unitarized HMChPT amplitudes

Single heavy baryons

CHARMED BARYONS ($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

See related review:
Charmed Baryons

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		**
$\Xi_c(2970)$ was $\Xi_c(2980)$		***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***

Belle

LHCb

**** Existence is certain, and properties are at least fairly explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, $\Omega_b^- = ssb$

Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6227)$		***
Ω_b^-	$1/2^+$	***
b-baryon ADMIXTURE (Λ_b, Ξ_b, Σ_b, Ω_b)		

LHCb

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

Odd parity open heavy-flavor baryons

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".

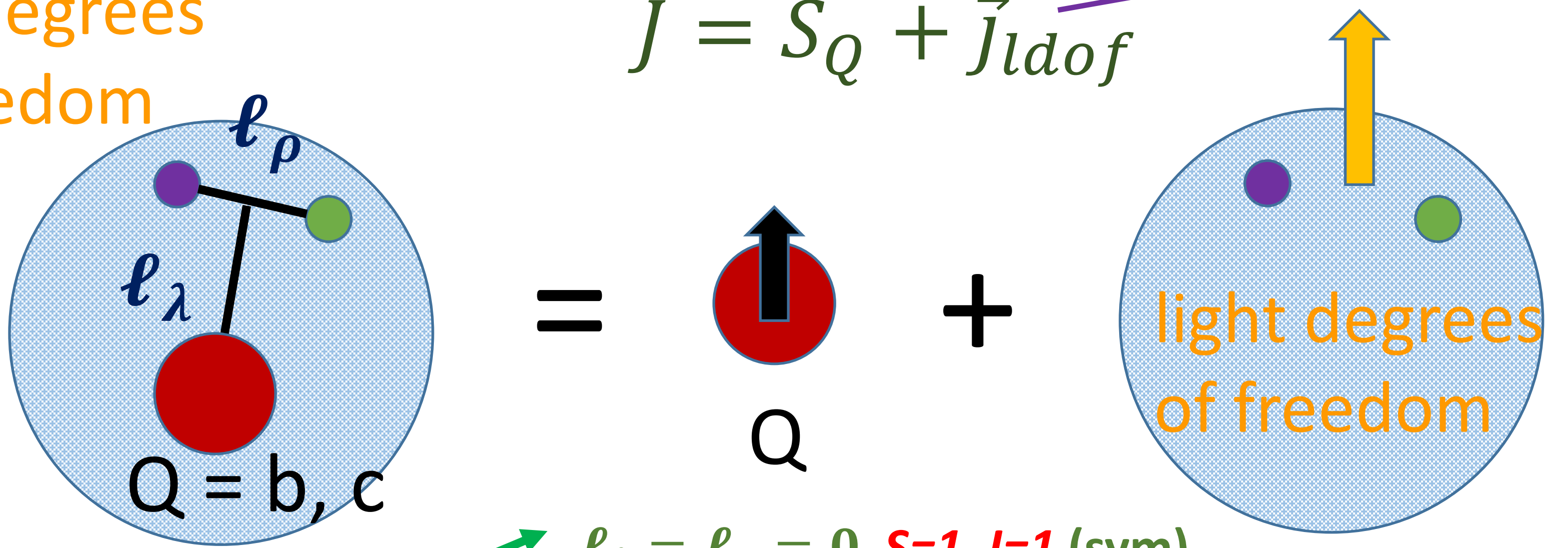
$$\vec{J} = \vec{S}_Q + \vec{j}_{ldof}$$

$\vec{j}^{\,2}_{ldof}$ **is conserved!**

HQSS

$\boldsymbol{SU(2N_h)}$ **symmetry in the $\boldsymbol{m_Q \to \infty}$ limit**

light degrees of freedom



$\ell_\lambda = \ell_\rho = 0$, ***S=0, I=0*** (sym)

$\ell_\lambda = \ell_\rho = 0$, ***S=1, I=1*** (sym)

$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{1^+}_{j_{ldof}^P} = \underbrace{1/2^+}_{\Sigma_c(2455)}\ ,\ \underbrace{3/2^+}_{\Sigma_c^*\,(2520)}$$

HQSS doublet

$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{0^+}_{j_{ldof}^P} = \boxed{\underbrace{1/2^+}_{\Lambda_c(2286)}}$$

HQSFS: odd parity excited states

CQM: T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, and K. Sadato, PRD92 (2015) 114029

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".

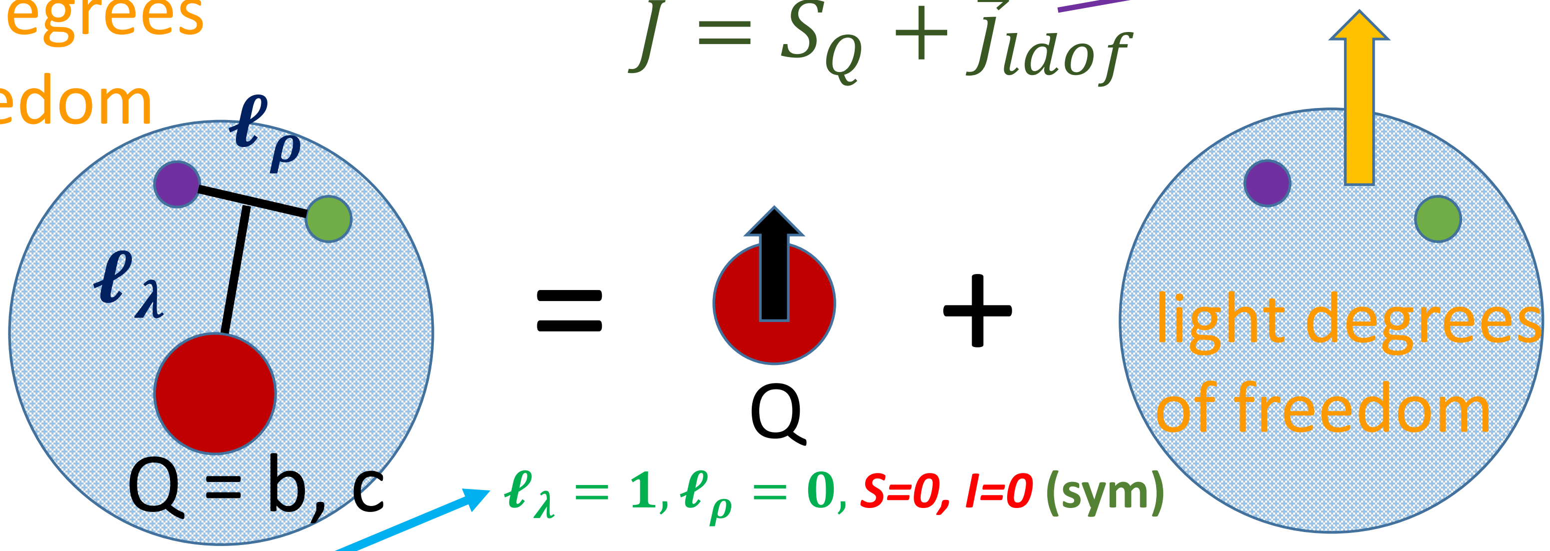
light degrees of freedom

$$\vec{J} = \vec{S}_Q + \vec{J}_{ldof}$$

$\vec{J}^2_{ldof}$ **is conserved!**

HQSS

***SU*(2*N*$_h$) symmetry in the $m_Q \to \infty$ limit**



$\ell_\rho = 0, \ell_\rho = 1$, $S=1$, $I=0$ (sym)

$\ell_\lambda = 1, \ell_\rho = 0$, $S=0$, $I=0$ (sym)

$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{1^-}_{j_{ldof}^P} = \underbrace{1/2^-}_{\Lambda_c(2595)}, \underbrace{3/2^-}_{\Lambda_c(2625)}$$

CQM states

$$\underbrace{1/2^+}_{S_Q^P} \otimes \underbrace{0^-, 1^-, 2^-}_{j_{ldof}^P} = \underbrace{1/2^-, \ldots}_{\Lambda_c^*}$$

λ –mode excitations

ρ –mode excitations

HQSFS: odd parity excited states

chiral molecules

Juan Nieves, IFIC (CSIC & UV)

$$\underbrace{\Sigma_c^{(*)}\pi}_{ldof:\,1^+\otimes\,0^-=1^-} \quad \Rightarrow \; J^P = 1/2^-, 3/2^-$$

NLO SU(3) ChPT: J.-X. Lu, Y. Zhou, H.-X. Chen, J.-J. Xie, and L.-S. Geng, PRD92 (2015) 014036

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

✓ CQM degrees of freedom

✓ Analogy $\Lambda(1520), \boldsymbol{\Lambda(1405)}$

$\Sigma^{(*)} \leftrightarrow \;\; \Sigma_c^{(*)}, \bar{K}^{(*)} \leftrightarrow \;\; D^{(*)}$

L. Tolos, J. Schaner-Bielich, and A. Mishra, PRC70 (2004) 025203

J. Hofmann and M. Lutz, NPA763 (2005) 90; 766 (2006) 7

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

existence of some relevant degrees of freedom (CQM states and/or $\boxed{ND^{(*)}}$ components) that are not properly accounted for ?

F.-K. Guo, U.-G. Meissner, and B.-S. Zou, Commun. Theor. Phys. 65 (2016) 5

M. Albaladejo, JN, E. Oset, Z.-F. Sun, and X. Liu, PLB757 (2016) 515

HQSFS: odd parity excited states hadron molecules

$$\underbrace{\Sigma_c^{(*)}\pi}_{}\quad \Rightarrow\; J^P = 1/2^-, 3/2^-$$

$$ldof: 1^+ \otimes 0^- = 1^-$$

$$\underbrace{ND^{(*)}}_{}\quad \Rightarrow\; J^P = 1/2^-, 3/2^-$$

$$ldof: 1/2^+ \otimes 1/2^- = \boxed{0^-}, 1^-$$

$\bar{\ell}$

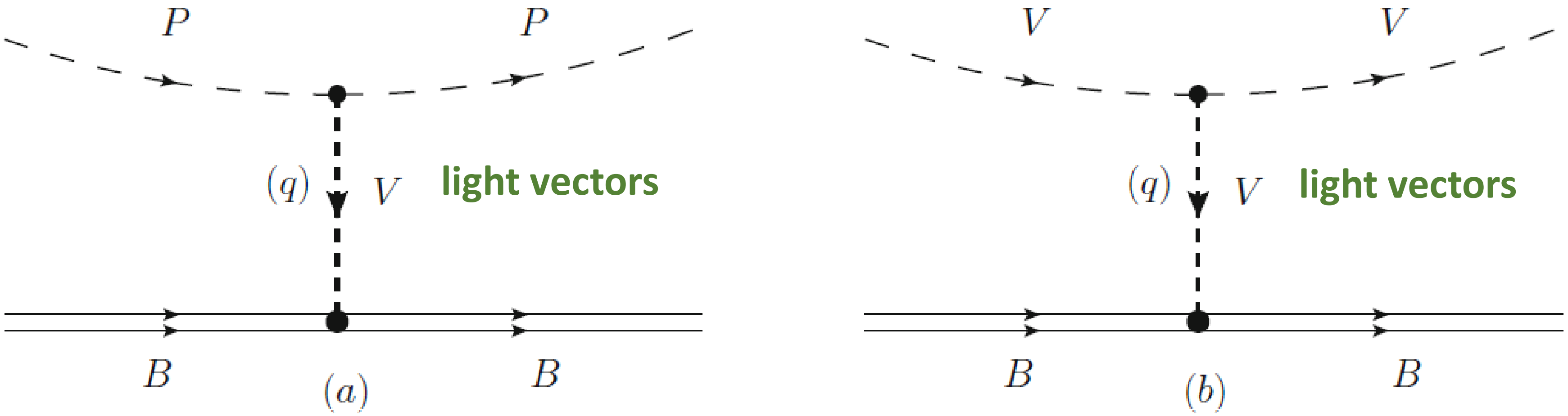
new configuration !

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

Σ_c and Σ_c^* or D and D^* are related by a charm quark spin rotation, which commutes with H_{QCD}, up to Λ_{QCD}/m_c corrections.

LO HQSS does not fix $ND^{(*)} \longrightarrow ND^{(*)}, \Sigma_c^{(*)}\pi$ 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....

Extended local hidden gauge (ELHG) model W. Liang, T. Uchino, C. Xiao, E. Oset, EPJ A**51** (2015) 16



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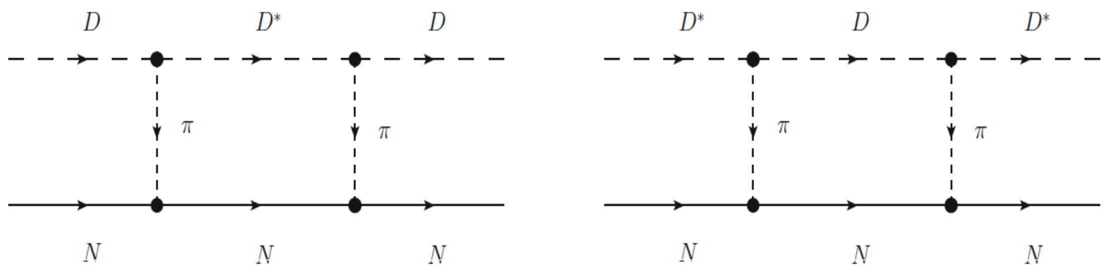

+....

$\Lambda_c(2625)$ $J^P = 3/2^-$

2628.35	D^*N	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
g_i	**10.11**	-0.55	0.49	-0.68
$g_i\,G_i^{II}$	**-29.10**	2.60	-2.78	2.50
$2990.43+i0.81$	D^*N	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
g_i	$0.06+i0.11$	**$5.44+i0.01$**	$0.03+i0.02$	$-0.04-i0.03$
$g_i\,G_i^{II}$	$-1.23-i0.79$	**$-44.53-i0.15$**	$-0.39-i0.25$	$0.25+i0.16$

- ✓ $\Lambda_c(2625)$ is mostly a bound ND^* state (no coupling to $\Sigma_c^*\pi$)
- ✓ $\Lambda_c(2595)$ generated by the $ND^{(*)} \longrightarrow ND^{(*)}$ coupled-channels interaction ($j^P_{ldof} = 0^-, 1^-$)
- ✓ $\Lambda_c(2595)$ 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.

$\Lambda_c(2595)$ $J^P = 1/2^-$

$2592.26+i0.56$	DN	$\pi\Sigma_c$	$\eta\Lambda_c$	
g_i	**$-8.18+i0.61$**	**$0.54+i0.00$**	$-0.40-i0.03$	
$g_i\,G_i^{II}$	**$13.88-i1.06$**	**$-10.30-i0.69$**	$1.76-i0.14$	
	D^*N	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
g_i	**$9.81+i0.77$**	$-0.45-i0.04$	$0.42+i0.03$	$-0.59-i0.05$
$g_i\,G_i^{II}$	**$-26.51-i2.10$**	$2.07+i0.17$	$-2.31-i0.19$	$2.10+i0.17$
$2611.06+i53.35$	DN	$\pi\Sigma_c$	$\eta\Lambda_c$	
g_i	$0.08-i1.81$	**$1.78+i1.40$**	$0.03-i0.09$	
$g_i\,G_i^{II}$	$-0.68+i3.13$	**$-55.22-i18.22$**	$-0.18+i0.39$	
	D^*N	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
g_i	$-1.56+i1.38$	$0.09-i0.05$	$-0.08+i0.05$	$0.11-i0.07$
$g_i\,G_i^{II}$	$4.66-i3.42$	$-0.44+i0.20$	$0.46-i0.25$	$-0.42+i0.24$
$2767.14+i0.98$	DN	$\pi\Sigma_c$	$\eta\Lambda_c$	
g_i	**$-3.70+i0.04$**	$0.02-i0.20$	$-0.52+i0.00$	
$g_i\,G_i^{II}$	**$14.78-i0.05$**	$3.54+i2.76$	$4.40+i0.02$	
	D^*N	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
g_i	**$-3.97+i0.05$**	$0.47-i0.00$	$-0.30+i0.00$	$0.43-i0.00$
$g_i\,G_i^{II}$	**$15.47-i0.16$**	$-2.62+i0.01$	$2.16-i0.02$	$-1.82+i0.02$
$2990.78+i0.60$	DN	$\pi\Sigma_c$	$\eta\Lambda_c$	
g_i	$0.01+i0.00$	$0.00+i0.00$	$-0.00-i0.01$	
$g_i\,G_i^{II}$	$0.09+i0.14$	$0.01+i0.03$	$0.16-i0.08$	
	D^*N	$\rho\Sigma_c$	$\omega\Lambda_c$	$\phi\Lambda_c$
g_i	$-0.09-i0.11$	**$-5.44-i0.02$**	$-0.04-i0.01$	$0.05+i0.02$
$g_i\,G_i^{II}$	$1.57+i0.59$	**$44.54+i0.20$**	$0.50+i0.19$	$-0.32-i0.12$

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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.

- ✓LHCb Ω_c^* states, W.-H. Liang, J.M. Dias, V.R. Debastiani, E. Oset, Nucl. Phys. B930 (2018) 524; **E.Oset's talk at session 3 (8.55h, 21/8).** See also results from a similar model (SU(4)-flavor t-channel exchange of vector mesons) in G. Montaña, A. Feijoo, A. Ramos, EPJ A54 (2018) 64.

- ✓Ξ_c and Ξ_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

- ✓ $\boldsymbol{\pi}$ −octet, $\boldsymbol{\rho}$ −nonet, $\boldsymbol{D_{(s)}^{(*)}, \bar{D}_{(s)}^{(*)}}$
- ✓ $\boldsymbol{N}$ −octet, $\boldsymbol{\Delta}$ −decuplet, $\boldsymbol{\Lambda_c, \Sigma_c^{(*)}, \Xi_c^{(*,\prime)}, \Omega_c^{(*)}}$

light spin-flavor (mesons and baryons)

L. Tolos talk at session 2 (14h, 20/8)

- $C = 1$, C. Garcia-Recio, V.K. Magas, T. Mizutani, JN, A. Ramos, L.L. Salcedo, L. Tolos, PRD79 (2009), 054004; O. Romanets, L. Tolos, C. Garcia-Recio, JN, L.L. Salcedo and R.G.E. Timmermans, PRD85 (2012) 114032.
- $C = -1$, D. Gamermann, C. Garcia-Recio, JN, L.L. Salcedo and L. Tolos, PRD81 (2010) 094016.
- beauty $\Lambda_b(5912)$ and $\Lambda_b(5920)$, C. Garcia-Recio, JN, O. Romanets, L.L. Salcedo and L. Tolos, PRD 87 (2013) 034032.
- LHCb Ω_c^* states, JN, R. Pavao and L. Tolos, EPJC78 (2018) 114.

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

$$T^J(s) = \frac{1}{1 - V^J(s) G^J(s)} V^J(s),$$

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

$$= \overline{G}_i(s) + G_i(s_{i+}) \qquad s_{i+} = (M_i + m_i)^2$$

finite UV divergent

different UV cutoffs for each meson-baryon channel

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

J. Hofmann and M. Lutz, NPA763 (2005) 90

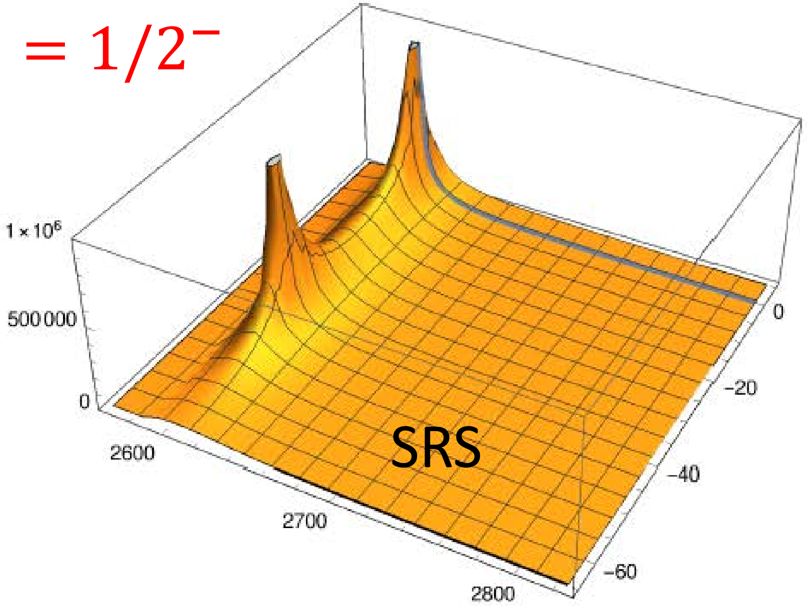
$$G_i^\mu(s_{i+}) = -\overline{G}_i(\mu^2)$$

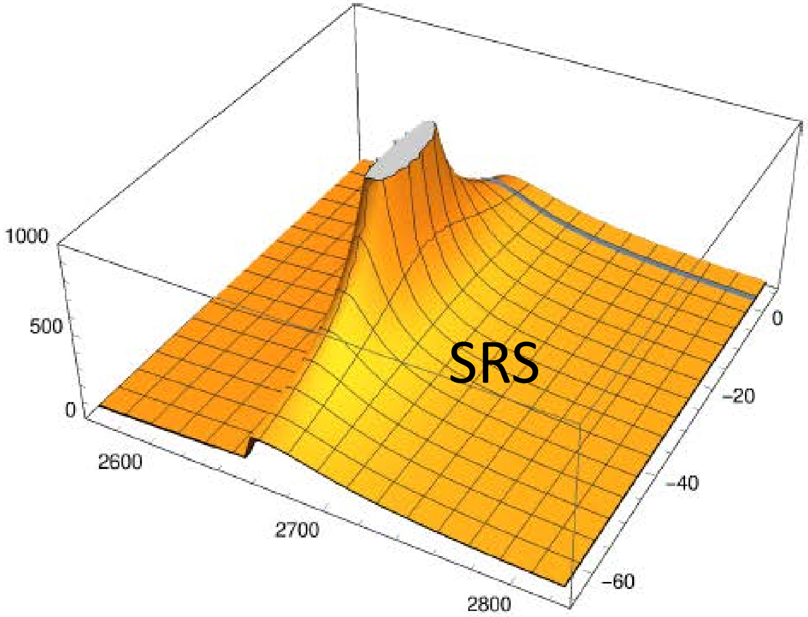
common UV cutoff
Λ =650 MeV

$$G_i^\Lambda(s_{i+}) = \frac{1}{4\pi^2} \frac{M_i}{m_i + M_i} \left(m_i \ln \frac{m_i}{\boxed{\Lambda} + \sqrt{\Lambda^2 + m_i^2}} + M_i \ln \frac{M_i}{\boxed{\Lambda} + \sqrt{\Lambda^2 + M_i^2}} \right)$$

Absolute value of the determinant of the T −matrix

$J^P = 1/2^-$



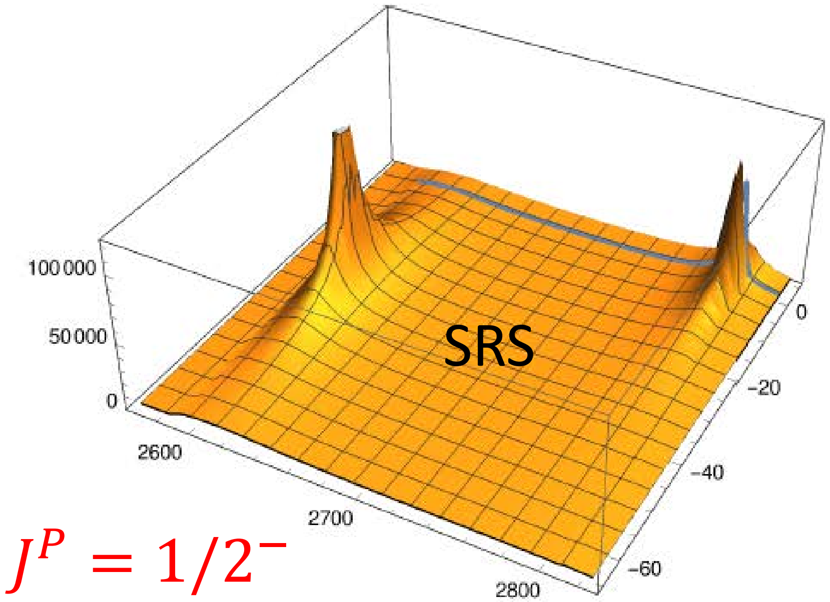


$J^P = 3/2^-$

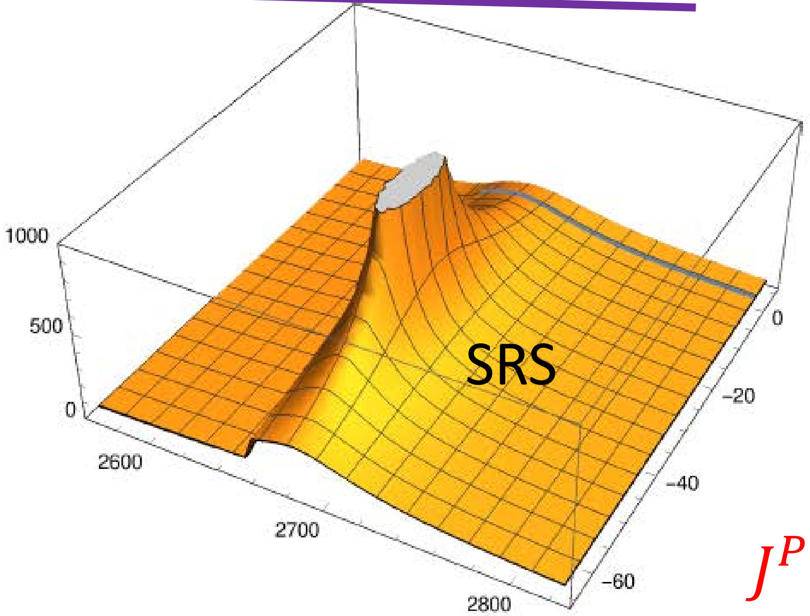
subtraction at a common scale **(no fit!)**

- ✓ main features of $3/2^-$ pole do not depend much on the RS: $M = 2660 - 2680$ MeV and $\Gamma = 55 - 65$ MeV: **difficult to assign it to the narrow $\Lambda_c(2625)$.**

- ✓ **spectrum in the $1/2^-$ sector depends strongly on the adopted RS**



$J^P = 1/2^-$



$J^P = 3/2^-$

common UV cutoff 650 MeV **(no fit!)**

$C = 1,\ ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels

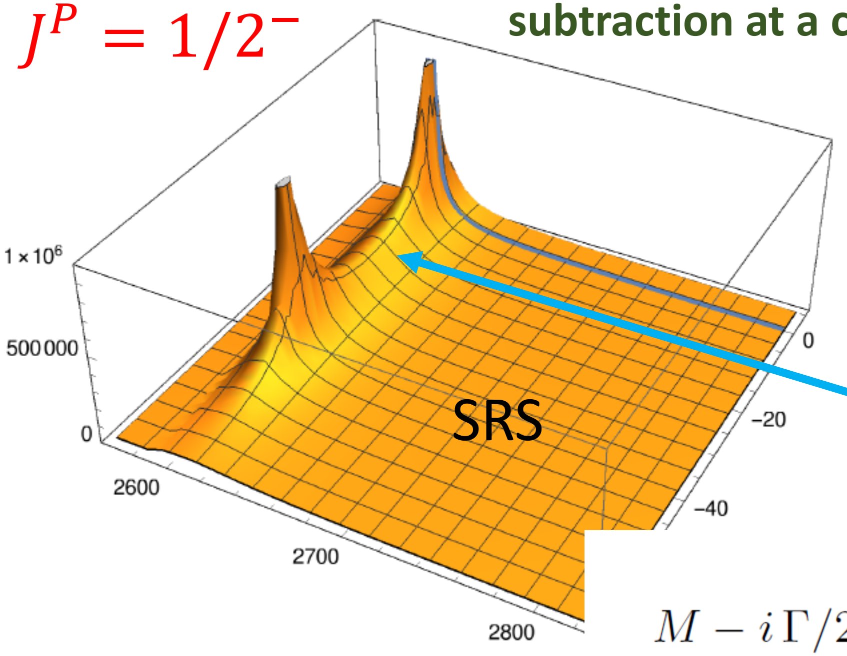
Juan Nieves, IFIC (CSIC & UV)

Absolute value of the determinant of the T −matrix

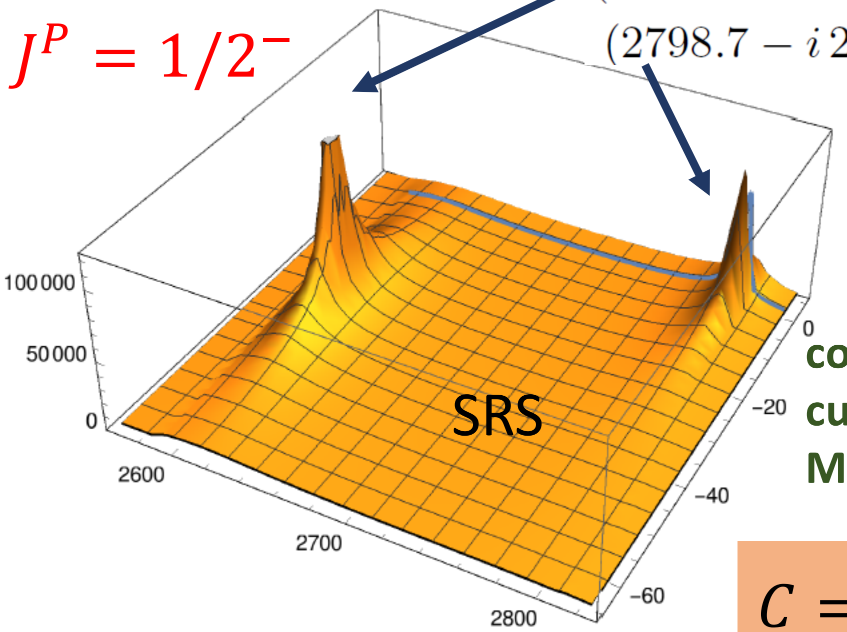
$J^P = 1/2^-$

subtraction at a common scale

(no fit!)



$J^P = 1/2^-$



(no fit!)

common UV cutoff 650 MeV

Two pole pattern , but

- ✓ **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.

$\Lambda = 650$ MeV					SCμ ($\alpha = 0.95$)				
$M - i\,\Gamma/2$	Type	$\lvert g_{\Sigma_c\pi}\rvert$	$\lvert g_{ND}\rvert$	$\lvert g_{ND^*}\rvert$	$M - i\,\Gamma/2$	Type	$\lvert g_{\Sigma_c\pi}\rvert$	$\lvert g_{ND}\rvert$	$\lvert g_{ND^*}\rvert$
$(2609.9 - i\,28.8)$	1^-	2.0	2.3	0.7	$(2608.9 - i\,38.6)$	1^-	2.3	2.0	1.9
$(2798.7 - i\,2.0)$	0^-	0.3	1.8	4.1	$(2610.2 - i\,1.2)$	0^-	0.5	3.9	6.2

- ✓ **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 $\Lambda_c(2595)$.

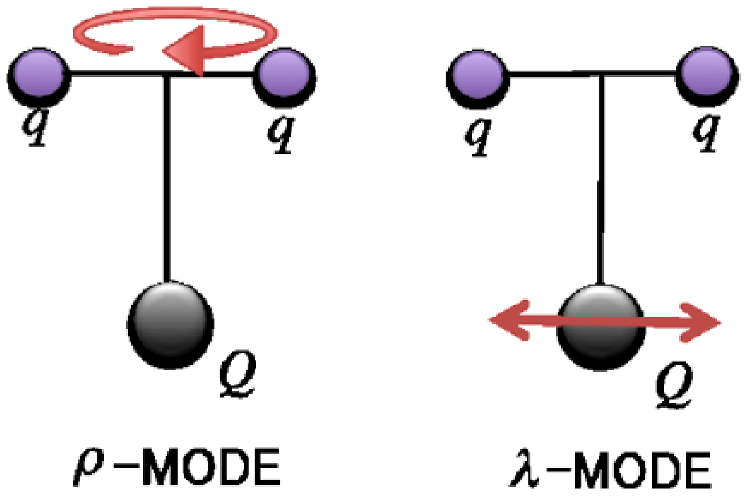
$C = 1,\ ND^{(*)}, \Sigma_c^{(*)}\pi$ coupled-channels

…and CQM predictions:

$\ell_\lambda = 1, \ell_\rho = 0$, *S=0, I=0* (sym)

λ –mode excitations

$$\underbrace{1/2^+}_{s_Q^P} \otimes \underbrace{1^-}_{j^P_{ldof}} = \underbrace{1/2^-}_{\Lambda_c(2595)} \;,\; \underbrace{3/2^-}_{\Lambda_c(2625)}$$



PHYSICAL REVIEW D **92,** 114029 (2015)

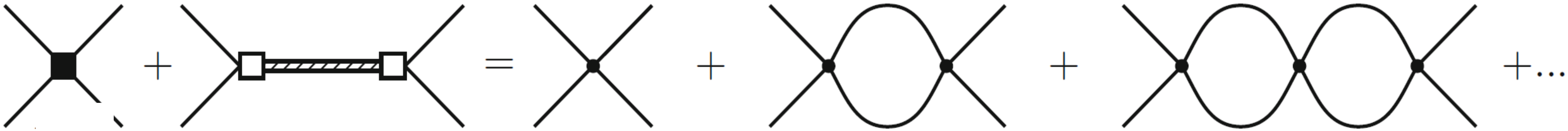
Spectrum of heavy baryons in the quark model

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

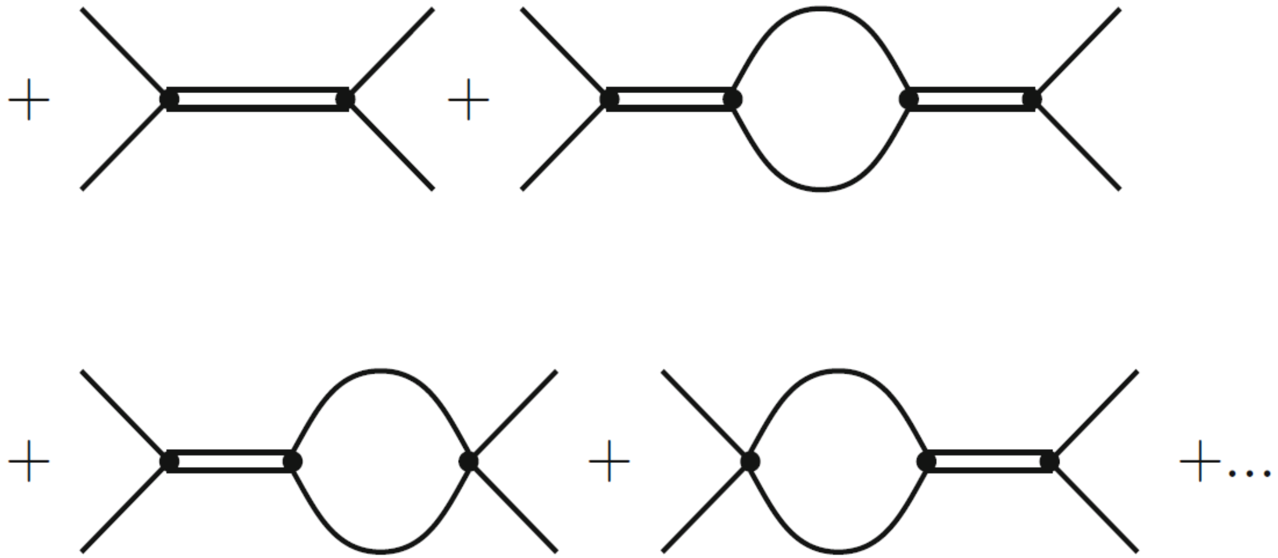
Λ_c		
J^P	Theory (MeV)	Experiment (MeV)
$\frac{1}{2}^+$	2285	2285
	2857	
	3123	
$\frac{3}{2}^+$	2920	
	3175	
	3191	
$\frac{5}{2}^+$	2922	2881
	3202	
	3230	
$\frac{1}{2}^-$	2628	2595
	2890	
	2933	

Λ_c		
J^P	Theory (MeV)	Experiment (MeV)
$\frac{3}{2}^-$	2630	2628
	2917	
	2956	
$\frac{5}{2}^-$	2960	
	3444	
	3491	

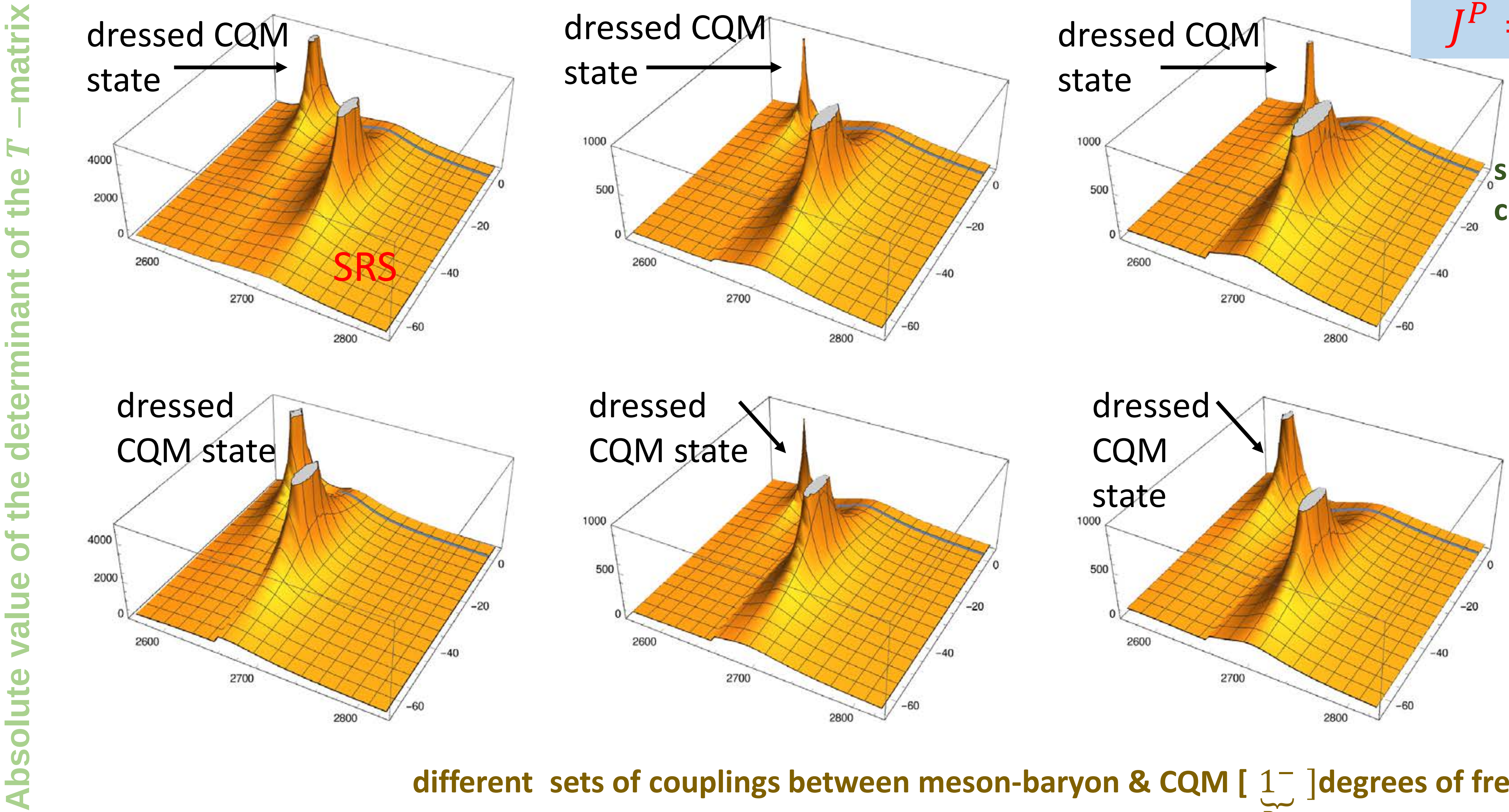
bare CQM state should be explicitly taken into account in the dynamics, in particular for the $\Lambda_c(2625)$ resonance: for these energies it produces a rapidly changing energy dependent interaction



... coupling meson-baryon and CQM degrees of freedom, taking into account HQSS constraints...



$J^P = 3/2^-$



subtraction at a common scale

common UV cutoff 650 MeV

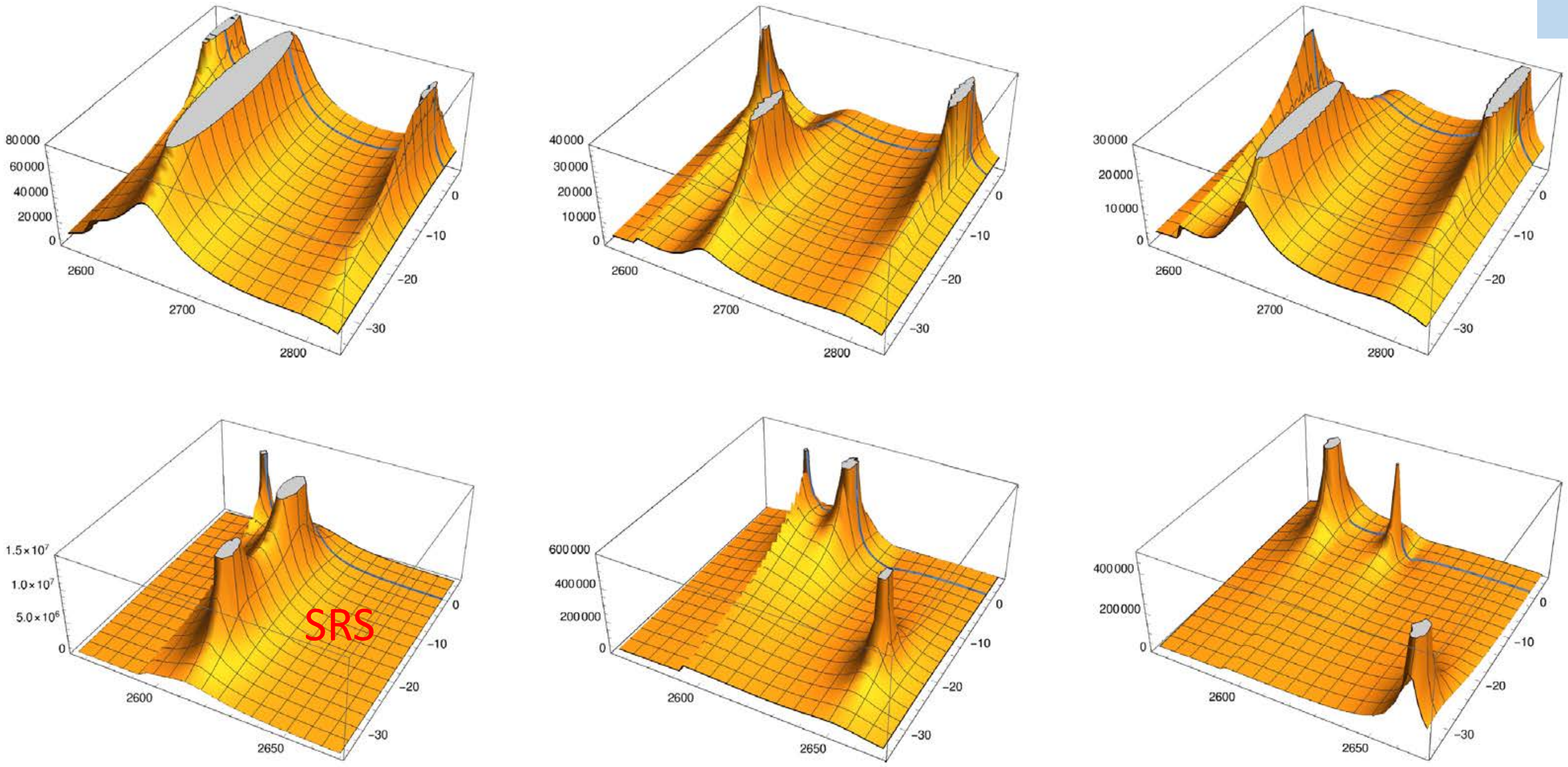
different sets of couplings between meson-baryon & CQM [$\underbrace{1^-}_{j^P_{ldof}}$]degrees of freedom

- ✓ In both RSs, the dressed CQM state describes fairly well de $\Lambda_c(2625)$ resonance. Moreover, the coupling to $\Sigma_c^*\pi$ is compatible with the existing measurements of the resonant contribution to $\Gamma[\Lambda_c(2625) \longrightarrow \Lambda\pi\pi]$
- ✓ In addition, a second broad pole is predicted in the region of 2.7 GeV.

Juan Nieves, IFIC (CSIC & UV)

$J^P = 1/2^-$

Absolute value of the determinant of the T −matrix



subtraction at a common scale

common UV cutoff 650 MeV

different sets of couplings between meson-baryon & CQM [$\underbrace{1^-}_{j^P_{ldof}}$]degrees of freedom

- ✓ $\left(j^P_{ldof} = 0^-\right)$ −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

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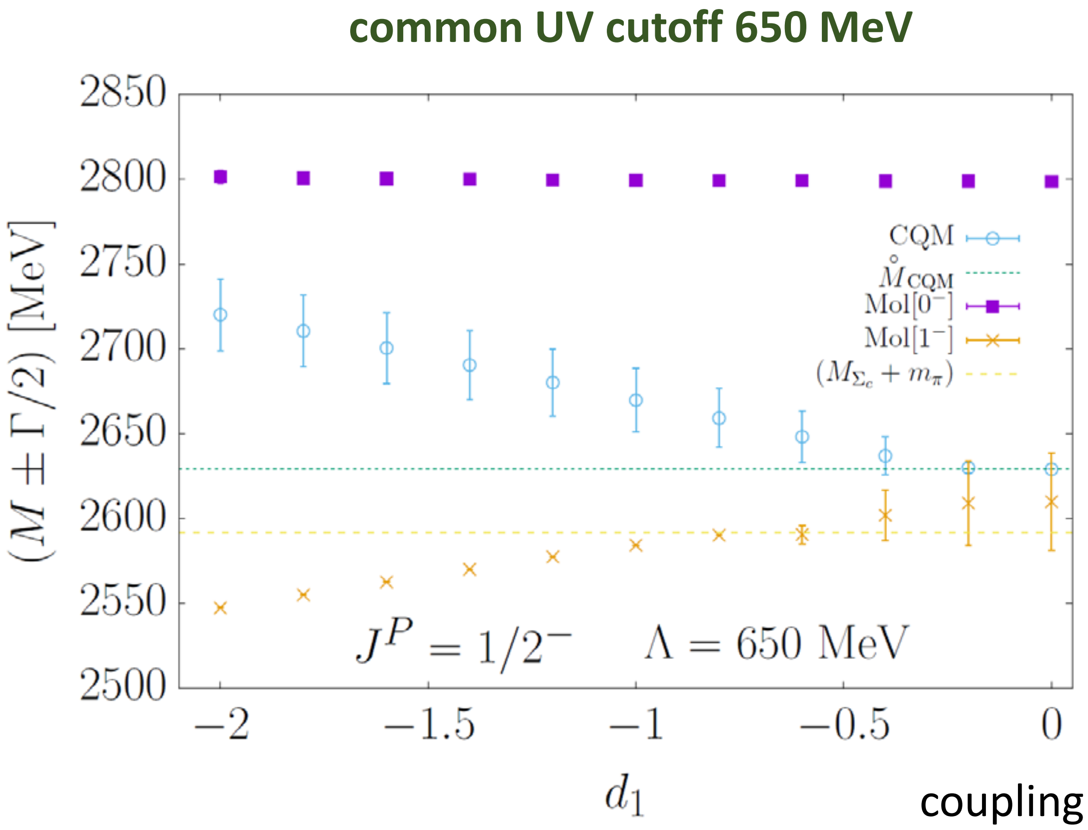
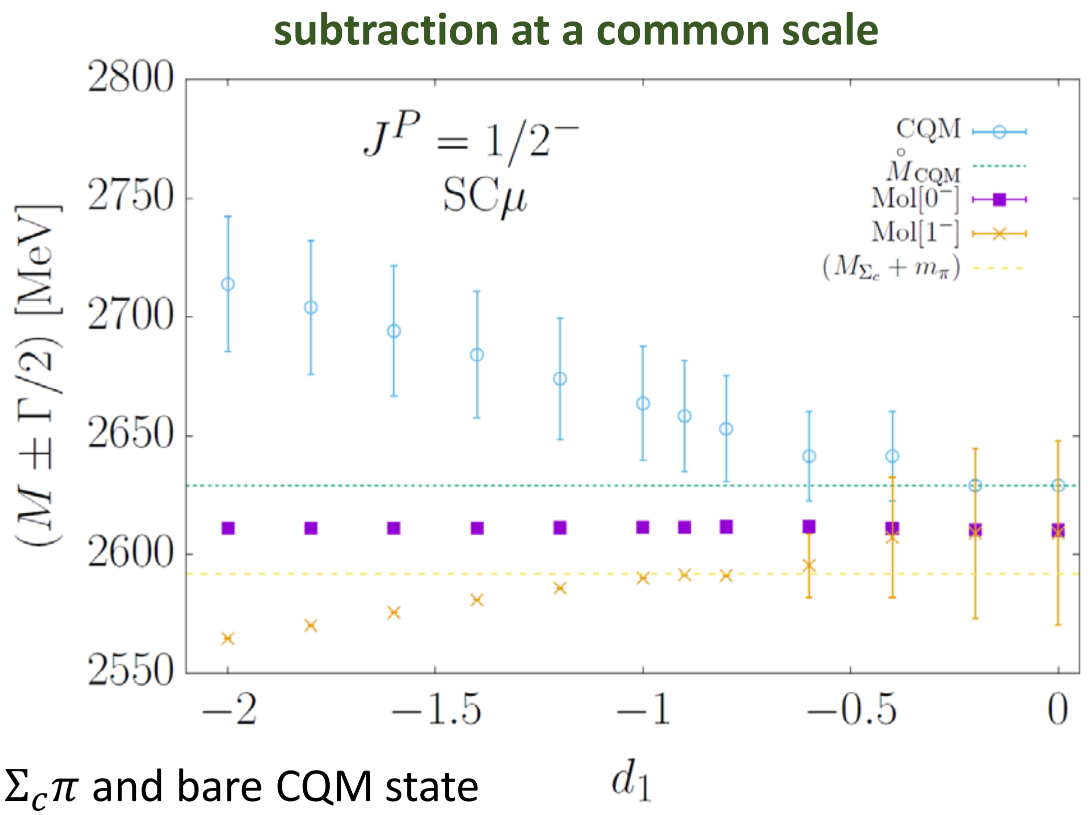




coupling between $\Sigma_c \pi$ and bare CQM state

- ✓ 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 $j^P_{ldof} = 0^-$ configuration of these states, since HQSS forbids their coupling to the $(j^P_{ldof} = 1^-)$ −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.

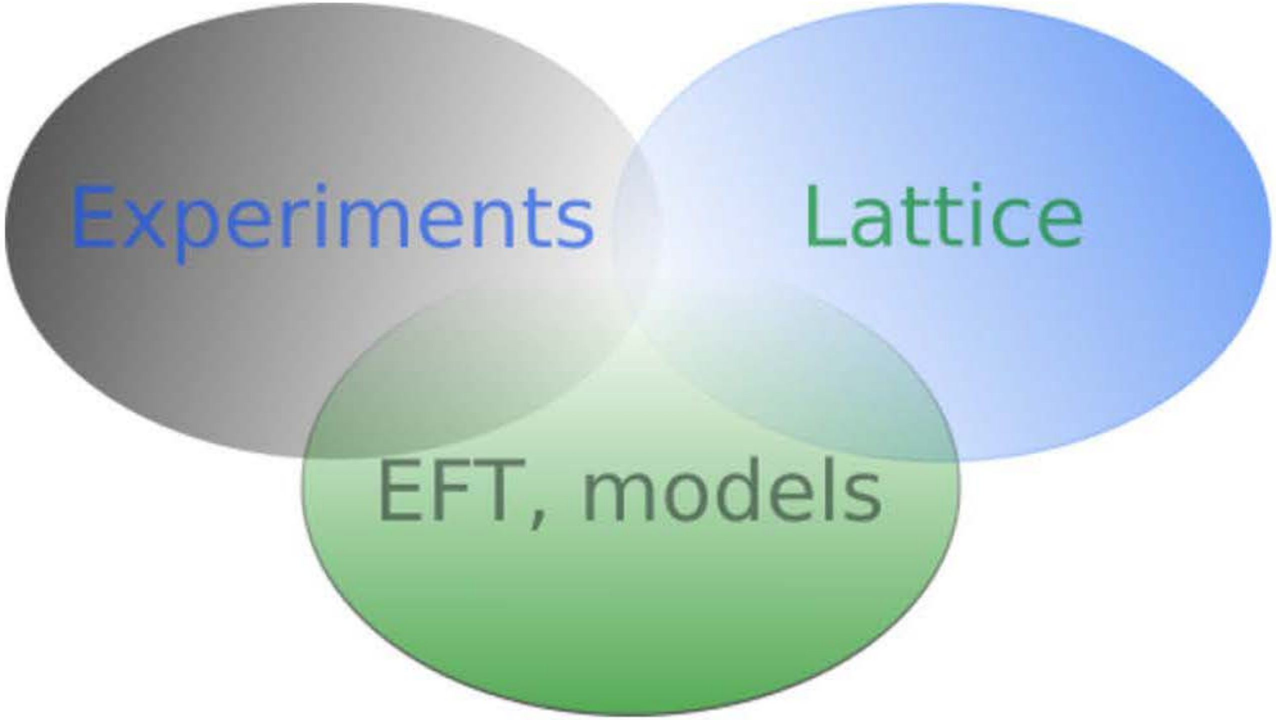
✓ The $\Lambda_c(2595)$ is predicted, however, to have a predominant molecular structure. This is because, it is either the result of the chiral $\Sigma_c\pi$ interaction [J.-X. Lu, Y. Zhou, H.-X. Chen, J.-J. Xie, and L.-S. Geng, PRD92 (2015) 014036; but this contradicts the conclusions of T. Hyodo in 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 $\Lambda_b[gs] \longrightarrow \Lambda_c(2595)$ and $\Lambda_b[gs] \longrightarrow \Lambda_c(2625)$ [W.-H. Liang, E. Oset, Z.-S. Xie, PRD95 (2017) 014015; JN, R. Pavao and S. Sakai, EPJC79 (2019) 417]

CONCLUSIONS

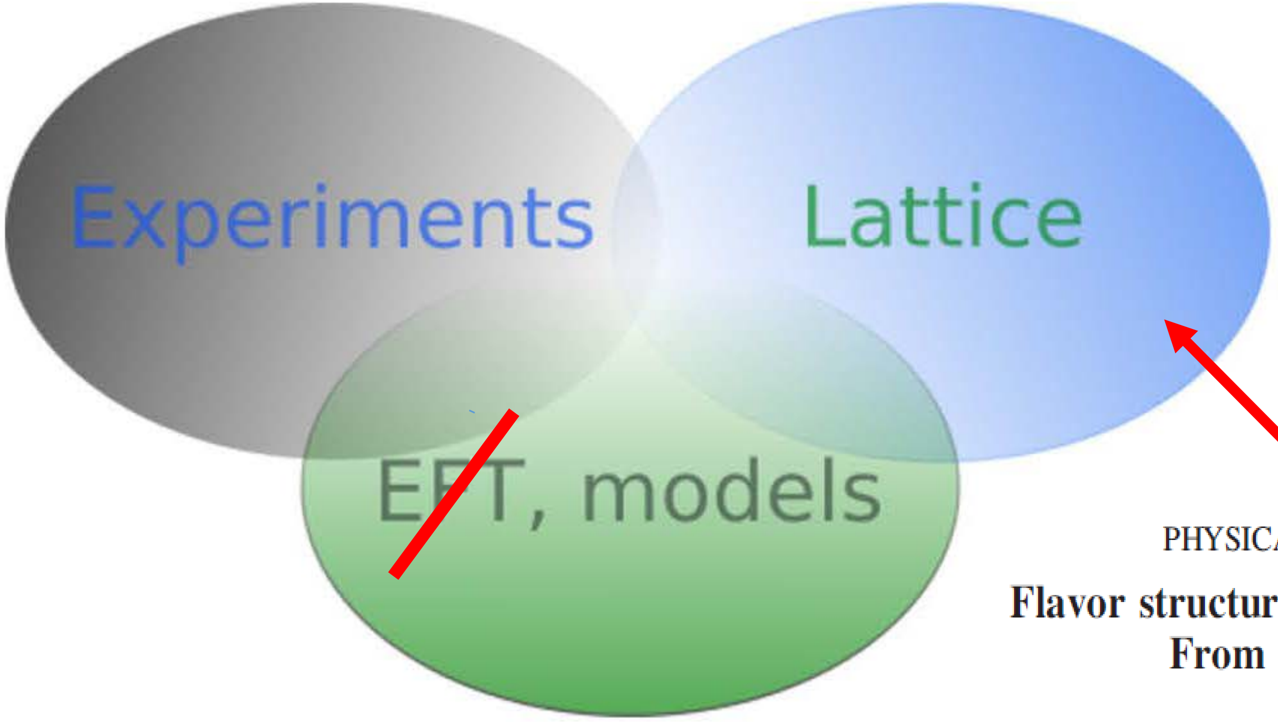
- ✓ We have studied $D\pi, D\eta, D_s\bar{K}$ coupled-channel scattering $[J^P = 0^+, (S,I) = (0, 1/2)]$: only one pole reported experimentally. We have presented a strong support for the existence of two $D_0^*(2400)$ poles [successful description of the energy levels obtained in LQCD simulation].
- ✓ 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
- ✓ This double pole structure is consequence of ChPT : similar to $\Lambda(1405)$ [Oller & Meißner, PLB 500 (2001) 263; Jido *et al.*, NPA 725 (2003) 181; García-Recio *et al.*, PLB 582 (2004) 49. Magas *et al.*, PRL 95 (2005) 052301] or $K_1(1270)$ [Roca *et al.*, PRD 72 (2005) 014002 (2005); Geng *et al.*, PRD 75 (2007) 014017; García-Recio *et al.*, PRD 83 (2011) 016007].
- ✓ Good description of the S-wave $P\phi$ amplitude extracted by LHCb from $B \longrightarrow P\phi\phi$ decays

✓ Muskhelishvili-Omnès representation of scalar form-factor using the HMChPT amplitudes+ HQSFS: results for scalar, $f_0(q^2)$, form factors for different $H \longrightarrow b\, l\, \bar{\nu}_l$ decays, $H = \bar{B}, \bar{B}_s, D, D_s$ and $b = \pi, \eta, K, \bar{K}$. Successful description of LQCD and LCSR results.



✓ Dynamics of the $\Lambda_c(2595)$ and the $\Lambda_c(2625)$ is more uncertain

- **Λ_c^* −puzzle y HQSS**
- **dependence on the RS**
- **role played by the CQM degrees of freedom**



PHYSICAL REVIEW D 94, 114518 (2016)

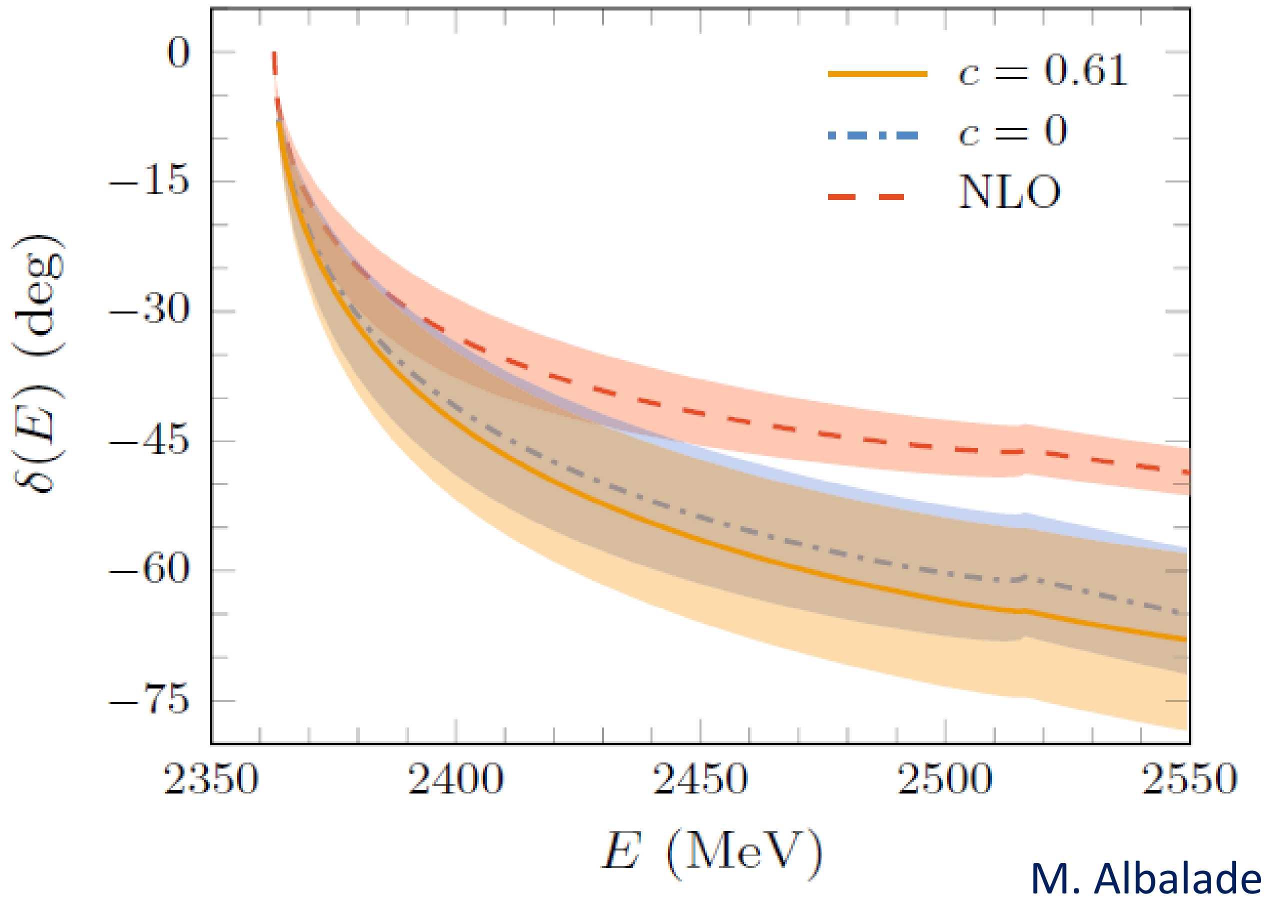
Flavor structure of Λ baryons from lattice QCD: From strange to charm quarks

Philipp Gubler,[1,*] Toru T. Takahashi,[2] and Makoto Oka[3,4]

… seems to support CQM findings!

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

Back up

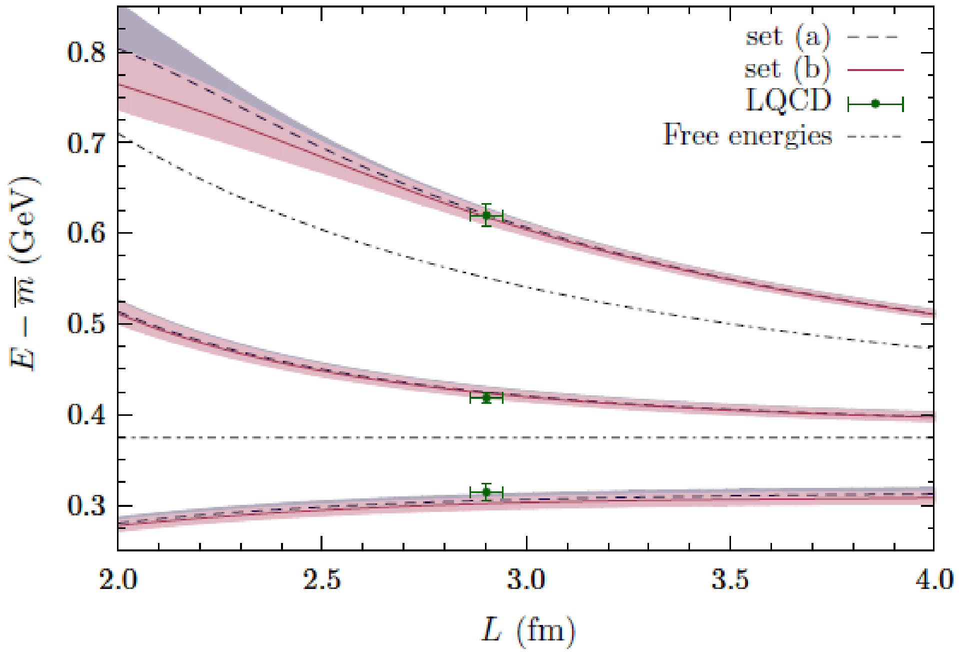


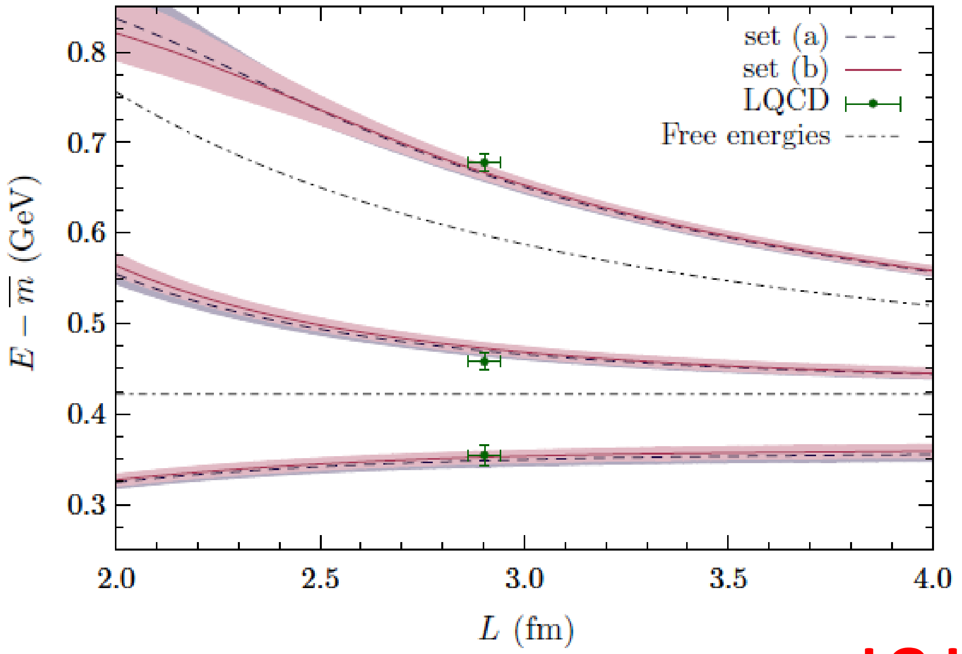
… differences appear at large energies

LO HMChPT+CQM & NLO HMChPT
0^+ D^*_{s0} sector

M. Albaladejo, P. Fernández-Soler, JN and P.G. Ortega, EPJC78 (2018) 722

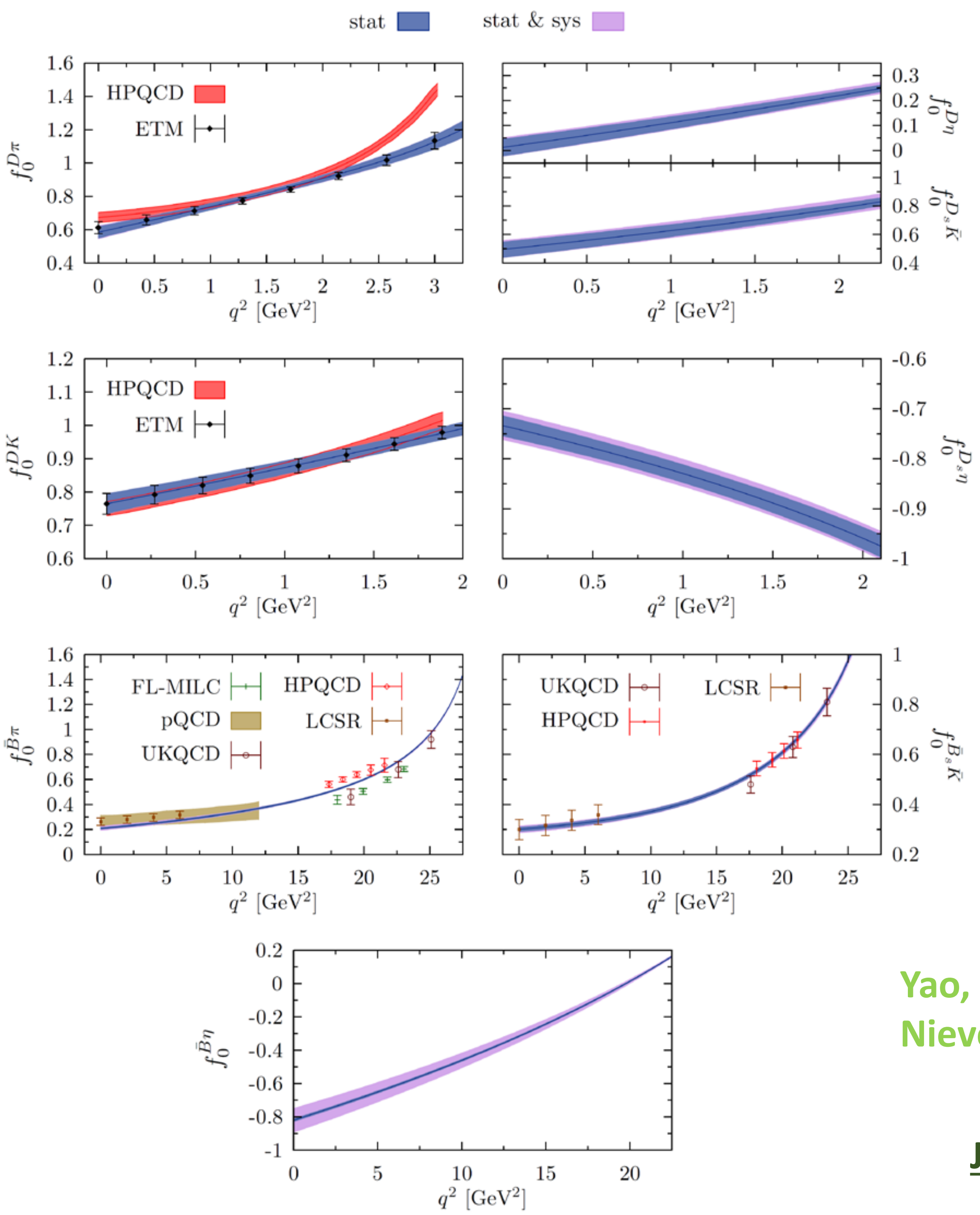
M. Albaladejo, P. Fernández-Soler, JN and P.G. Ortega, EPJC77 (2017) 170





LQCD: C.B. Lang, D. Mohler, S. Prelovsek, R.M. Woloshyn, PLB 750 (2015) 17.

LO HMChPT+CQM
0^+ & 1^+ $\bar{B}_s^*$sector



we obtain $|V_{cd}| = 0.244 \pm 0.022$, $|V_{cs}| = 0.945 \pm 0.041$ and $|V_{ub}| = (4.3 \pm 0.7) \times 10^{-3}$ for the involved Cabibbo–Kobayashi–Maskawa (CKM) matrix elements. In addition,

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