# TOWARDS A NEW PARADIGM FOR HEAVY-LIGHT MESON SPECTROSCOPY

## from combining results from Lattice QCD, EFTs and Experiment

August 27, 2018 | Christoph Hanhart | IKP/IAS Forschungszentrum Jülich

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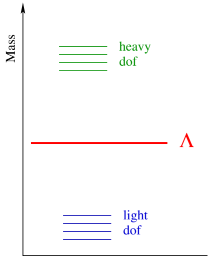
# EFFECTIVE FIELD THEORIES

Weinberg 1979

- Precondition: separation of scales
  low vs. high energy dynamics
  - low-energy dynamics in terms of relevant dof's: $E \sim p \sim Q$
  - symmetries build in
  - high-energy dynamics not resolved
    $\rightarrow$ contact interactions




- Small parameter(s) & power counting
  - Standard QFT: trees + loops $\rightarrow$ renormalization
  - Expansion in powers of $Q$ over the large scale

    $M = \sum_\nu (Q/\Lambda)^\nu f(Q/\mu, C_i)$

    $\mu$: regularization scale; $C_i$: low–energy constants
    $\nu$ bounded from below $\rightarrow$ controlled expansion

# LIMITING CASES OF QCD

$$\mathcal{L}_{\mathrm{QCD}} = \sum_f \bar{q}_f \left(\gamma_\mu D^\mu - m_f\right) q_f - \frac{1}{4}\left(F_a^{\mu\nu} F_{\mu\nu}^a\right)$$

Limit of massless Quarks

Weinberg/ Gasser, Leutwyler

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}_L \left\{ i\partial\!\!\!/ + g A\!\!\!/^a t^a \right\} q_L + \bar{q}_R \left\{ i\partial\!\!\!/ + g A\!\!\!/^a t^a \right\} q_R + \mathcal{O}(m_f/\Lambda_{\mathrm{QCD}})$$

L and R Quarks decouple + spontaneous symmetry breaking

$\rightarrow$ Chiral Perturbation Theory (ChPT)

with naturally energy–dependent vertices

Limit of infinitely Heavy Quarks

Isgur, Wise, Manohar, Caswell/Lepage

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}_f \left\{ i v \cdot \partial + g v \cdot A^a t^a \right\} q_f + \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_f)$$

Independent of Heavy Quark Spin and Flavour

$\rightarrow$ Heavy Quark Effective Field Theory (HQEFT)

# UNITARIZATION

Unitarity relation: $\text{Im}(t) = \sigma|t|^2$ with $\sigma = \sqrt{1 - 4m_\pi^2/s}$

- Perturbative expansion consistent only to given order
- $s$–dependent terms quickly hit unitarity bound

Solution: Unitarization $\rightarrow$ can produce poles

Truong, Dorado, Pelaez, Kaiser, Weise, Oller, Oset, Lutz, Kolomeitsev, Guo, Meißner, C.H., ...

Different methods used (dep. needs to be clarified);

$\rightarrow$ universal picture emerges in many channels!

Example: Unitarized Chiral Perturbation Theory

Idea: write unitarity as

$$\text{Im}(t^{-1}) = -\sigma \quad \longrightarrow t = \frac{1}{\text{Re}(t^{-1}) - i\sigma}$$

use ChPT+HQEFT to fix $\text{Re}(t^{-1})$ to the accuracy needed for analysis

# HADRONIC MOLECULES

- are few-hadron states, bound by the strong force
- do exist: light nuclei.
  e.g. deuteron as *pn* & hypertriton as $\Lambda d$ bound state
- are located typically close to relevant continuum threshold;
  e.g., for $E_B = m_1 + m_2 - M$ and $\gamma = \sqrt{2\mu E_B}$
  - $E_B^{\text{deuteron}} = 2.22$ MeV ($\gamma = 45$ MeV)
  - $E_B^{\text{hypertriton}} = (0.13 \pm 0.05)$ MeV (to $\Lambda d$) ($\gamma = 13$ MeV)
- can be identified in observables (Weinberg compositeness):

$$\frac{g_{\text{eff}}^2}{4\pi} = \frac{4M^2\gamma}{\mu}(1-\lambda^2) \;\rightarrow\; a = -2\left(\frac{1-\lambda^2}{2-\lambda^2}\right)\frac{1}{\gamma}\;; \quad r = -\left(\frac{\lambda^2}{1-\lambda^2}\right)\frac{1}{\gamma}$$

where $(1-\lambda^2)$=probability to find molecular component in bound state wave function

Are there mesonic molecules?



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# DISCLAIMERS

- The method presented is 'diagnostic' — especially,
  - it does not allow for conclusions on the binding force
  - it allows one only to study individual states.

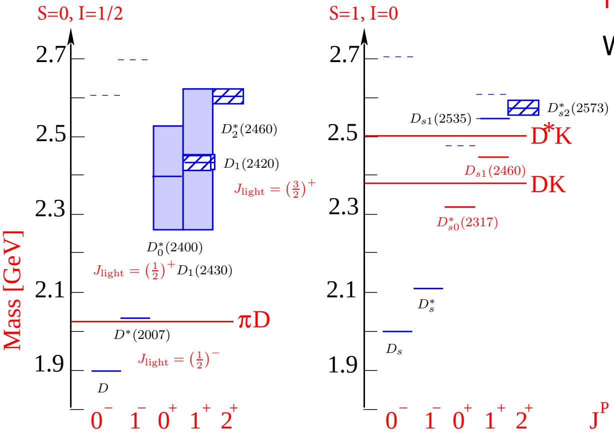
  To go beyond we here use unitarized ChPT+HQEFT

- Quantitative interpretation gets lost when states get bound too deeply ('uncertainty' $\sim R\gamma$) or become resonances; we propose to stick to

  'the larger the coupling the more molecular the state'

  There are striking phenomenological implications from large couplings for they lead to
  - relations between seemingly unrelated reactions
  - rather specific, unusual line shapes.

# CHARMED STATES




Quark Modell: M. Di Pierro and E. Eichten, PRD 64 (2001) 114004

Puzzles:

Why are/is

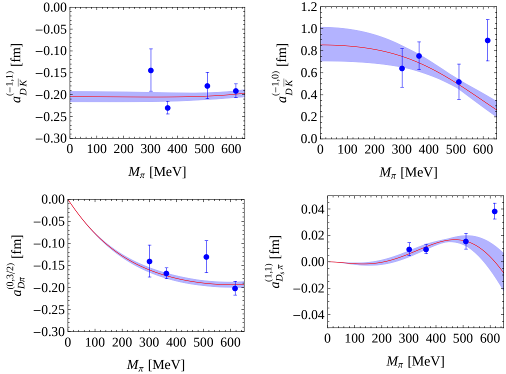
1. $M(D_{s1})\&M(D_{s0}^*)$ so light?
2. $M(D_{s1})-M(D_{s0}^*) \simeq M(D^*)-M(D)$?
3. $M(D_0^*) > M(D_{s0}^*)$? $M(D_1) \simeq M(D_{s1})$?

These will be solved by combining unitarized EFTs and Lattice input.
Strong support for the findings is provided from experiment.

# HEAVY LIGHT SYSTEMS

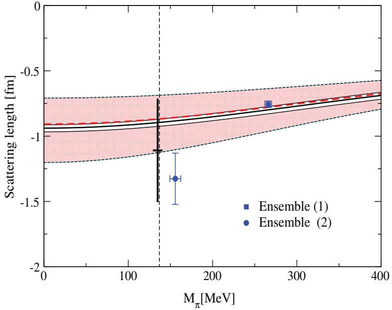
- $\pi/K/\eta$–$D/D_s$ scattering in ChPT to NLO unitarized (6 Parameter)
- controlled quark mass dependence
- fit LECs to lattice data for $a^{(S,I)}_{D_x\phi}$ in selected channels

Liu et al. PRD87(2013)014508




- $D^*_{s0}(2317)$ emerges as a pole with $M_{D^*_{s0}} = 2315^{+18}_{-28}$ MeV.

# INTERPRETATION




shaded band (dashed line):
full result (best fit)

white band (solid line):
$D^*_{s0}(2317)$ mass fixed to physical value

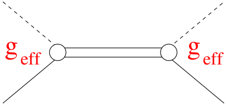
Liu et al. PRD87(2013)014508
Lattice: Mohler et al., PRL 11(2013)222001

most recent: for $m_\pi = 150$ MeV

$a = -1.49^{+0.1}_{-0.3}$ fm; corr.: $-1.16^{+0.1}_{-0.3}$ fm

Bali et al., PRD96(2017)074501

$D^*_{s0}(2317)$: $a =$




$+\mathcal{O}(1/\beta) \simeq \left(\frac{2(1-\lambda^2)}{2+\lambda^2}\right) \frac{-1}{\sqrt{2m_K E_B}}$

$a = -(1.05 \pm 0.36)\ \mathrm{fm}$ for molecule $(\lambda^2 = 0)$; smaller otherwise

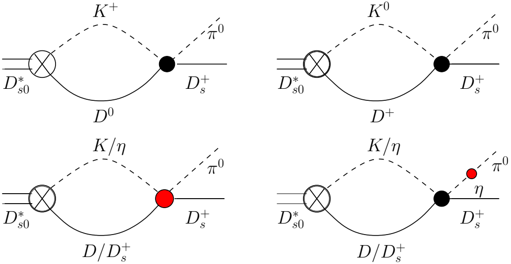
# EXP. TEST: HADRONIC DECAYS

Faessler et al. PRD76(2007)014005; Lutz, Soyeur NPA813(2008)14; Guo et al., PLB666 (2008)251

Isospin breaking (drives decay) via quark masses and charges

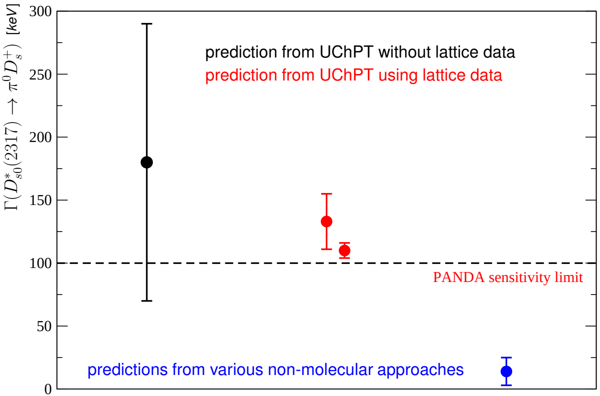
The same effective operators lead to

- mass differences, e.g.
  - $m_{D^+} - m_{D^0} = \Delta m^{\mathrm{q}} + \Delta m^{\mathrm{e.m.}} = ((2.5 \pm 0.2) + (2.3 \pm 0.6))$ MeV
  - $\pi^0 - \eta$ mixing $\longrightarrow$ parameters fixed
- Isospin breaking scattering amplitude
  - e.g. $KD \to \pi^0 D_s$ predicted




Specific for molecules!

# HADRONIC WIDTH



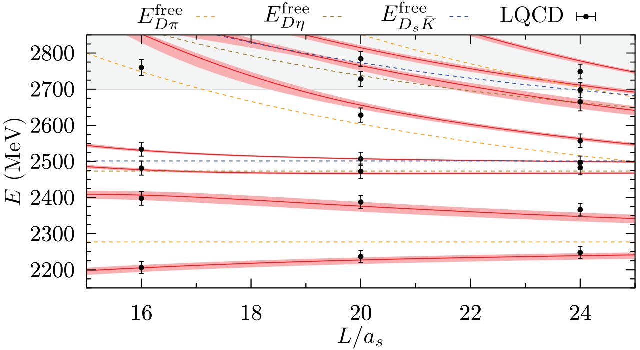

F.K. Guo et al., PLB666(2008)251; L. Liu et al. PRD87(2013)014508; X.Y. Guo et al., PRD98(2018)014510
and, e.g., P. Colangelo and F. De Fazio, PLB570(2003)180

Measurement of width is decisive, if $D^*_{s0}$ is molecular or not

Experiment needs very high resolution $\to$ PANDA

# ... AND IN THE S = 0 SECTOR

Keeping parameters fixed one gets:




Albaladejo et al., PLB767(2017)465; Lattice: Moir et al. [Had.Spec.Coll.] JHEP1610(2016)011

Poles for

- $m_\pi \simeq 391$ MeV: (2264, 0) MeV [000] & (2468, 113) MeV [110]
- $m_\pi = 139$ MeV: (2105, 102) MeV [100] & (2451, 134) MeV [110]

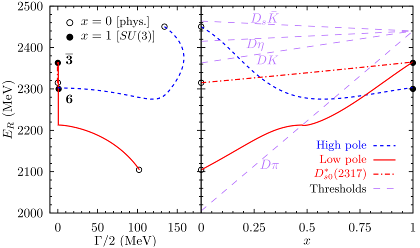
Questions $c\bar{q}$ nature of lowest lying $0^+$ $D$ state, $D_0^*(2400)$

# SU(3) STRUCTURE

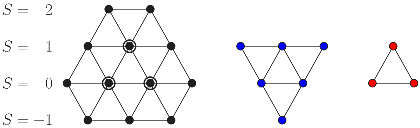
$m(x) = m^{\rm phy} + x(m - m^{\rm phy})$

Albaladejo et al., PLB767(2017)465

$m_\phi = 0.49$ GeV; $M_D = 1.95$ GeV




Multiplets: $[\bar{3}] \otimes [8] = [\overline{15}] \oplus [6] \oplus [\bar{3}]$




with $[\overline{15}]$ repulsive
and $[\bar{3}]$ most attractive

- 3 poles give observable effect with SU(3)-breaking on
- At $SU(3)$ symmetric point $m_\phi \simeq 490$ MeV: 3 bound and 6 virtual states
- For $m_\phi \simeq 600$ MeV (SU(3) sym.): even [6]-states get bound
- Quark Model: $[\bar{3}] \otimes [1] = [\bar{3}]$ — the [6] is absent

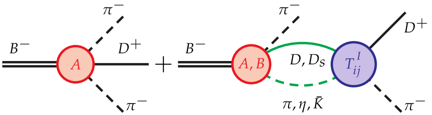
Lattice simulation should allow one to distinguish the scenarios

started in coll. with E. Berkowitz, F.-K. Guo and T. Luu

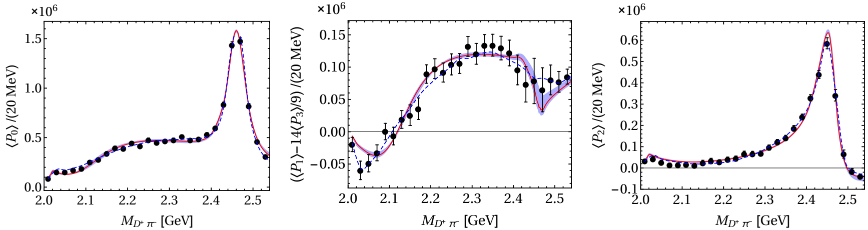
# OBSERVABLE: $B^- \to D^+\pi^-\pi^-$

With the $\phi D$ amplitude fixed we can calc. production reactions:

Du et al., arXiv:1712.07957 [hep-ph]




for the *S*-wave (two free para.);
other partial waves from BW-fit

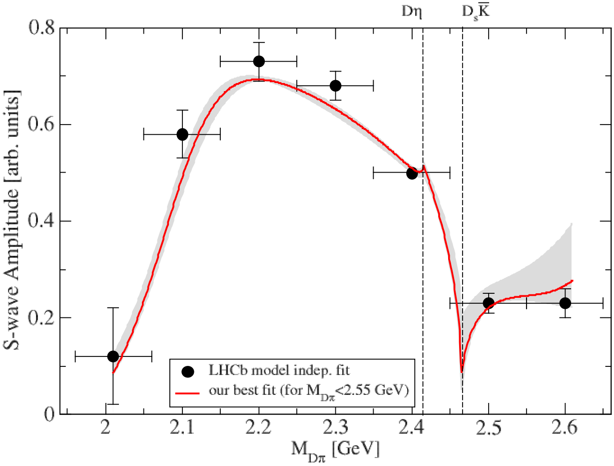



LHCb, PRD94(2016)072001

$$\langle P_0\rangle \propto |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2, \quad \langle P_2\rangle \propto \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}|\mathcal{A}_0||\mathcal{A}_2|\cos(\delta_2 - \delta_0)$$

$$\langle P_{13}\rangle \equiv \langle P_1\rangle - \frac{14}{9}\langle P_3\rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_1 - \delta_0)$$

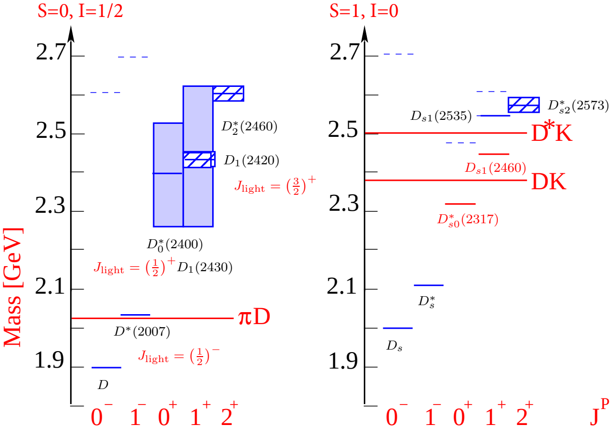
# $D\pi$ S-WAVE FROM $B^- \to D^+\pi^-\pi^-$




Effect of thresholds enhanced, by pole at $\sqrt{s_p} \sim (2451 - i134)$ MeV

on nearby unphysical sheet

# CHARMED STATES



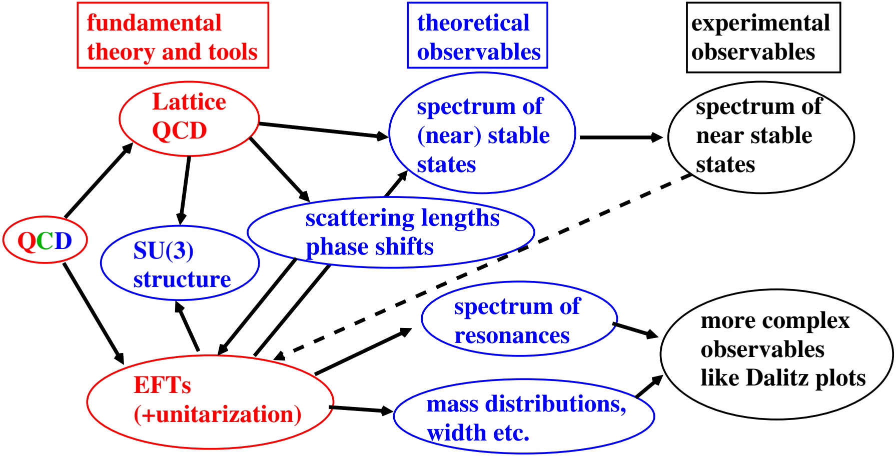

Quark Modell: M. Di Pierro and E. Eichten, PRD 64 (2001) 114004

Puzzles solved:

1. $M(D_{s1})$&$M(D_{s0}^*)$ are $DK$ and $D^*K$ bound states
2. $M(D_{s1})-M(D_{s0}^*) \simeq M(D^*)-M(D)$, since spin symmetry gives equal binding
3. States with strangeness heavier
   $M(D_0^*) = 2100$ MeV
   $M(D_{s0}^*) = 2317$ MeV
   $M(D_1) = 2247$ MeV
   $M(D_{s1}) = 2460$ MeV

... with strong support from experiment

# ROADMAP FOR FUTURE STUDIES



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