Collaborative research center CRC 110

"Symmetries and the emergence of structure in QCD"

Status of Project A.5

Quark mass dependence of hadronic observables

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NSFC National Natural Science Foundation of China

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Results I: Goldstone boson scattering off D-mesons

M. Du, F.-K. Guo, UGM, D. Yao, arXiv:1703.10836

- Already many studies of ϕ-D scattering to elucidate the structure of the light charm-strange mesons

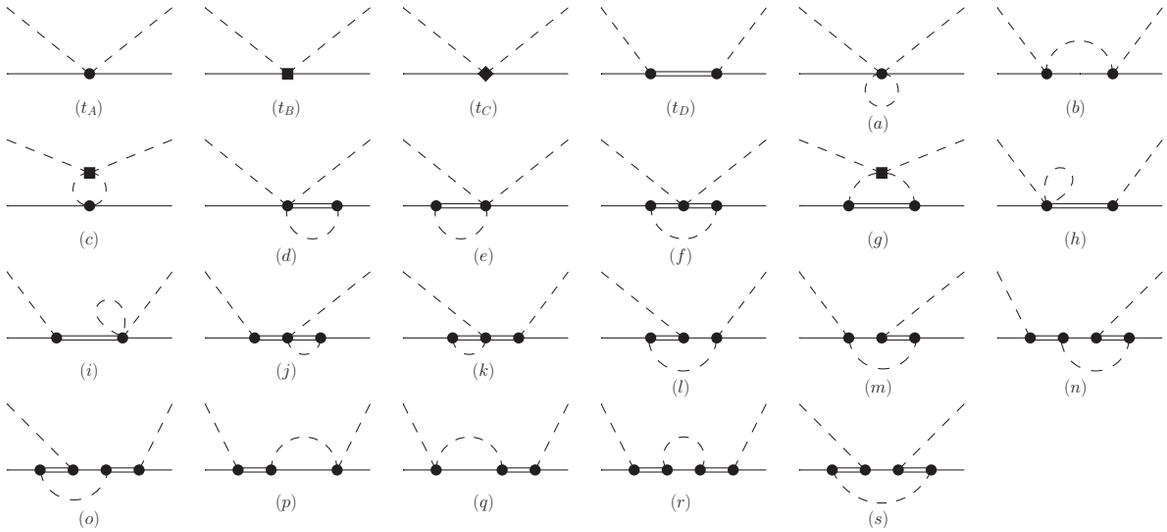
- Most elaborate calculation so far:
  - ⋆ covariant formulation to NNLO (EOMS scheme)
  - ⋆ explicit inclusion of D^* mesons (heavy quark symmetry) → slide

- Results (LECs determined from a fit to existing LQCD data):
  - ⋆ Effects of D^*-mesons in the threshold region very small
  - ⋆ LQCD data can be described, but no improvement to NLO → slide
    ↪ large kaon loop contributions in the crossed channel
  - ⋆ interesting pion mass dependences:
    ↪ $D^*_{s0}(2317)$ stays below the DK threshold → slide
    ↪ Pole in $(S, I) = (0, 1/2)$ similar to the $f_0(500)$ → slide

Hanhart, Pelaez, Rios, Phys. Rev. Lett. **100** (2008) 152001

Results I: Goldstone boson scattering . . . cont'd

- Pertinent diagrams for $\phi D \to \phi D$ [10 channels]



$D^0 K^- \to D^0 K^-, D^+ K^+ \to D^+ K^+$

$D^+ \pi^+ \to D^+ \pi^+, D^+ \eta \to D^+ \eta$

$D_s^+ K^+ \to D_s^+ K^+, D_s^+ \eta \to D^+ \eta$

$D_s^+ \pi^0 \to D_s^+ \pi^{+0}, D^0 \eta \to D^0 \eta$

$D_s^+ K^+ \to D^0 \pi^0, D_s^+ K^- \to D^0 \eta$

- Pertinent amplitudes: $\mathcal{V}_{\mathrm{LO}}^{(\mathrm{WT})}(s,t) = \mathcal{C}_{\mathrm{LO}} \frac{s-u}{4F_0^2}$

$$\mathcal{V}_{\mathrm{EX}}^{(\mathrm{WT})}(s,t) = \mathcal{C}_S \frac{g_0^2}{F_0^2} \mathcal{F}_S(s,t) + \mathcal{C}_U \frac{g_0^2}{F_0^2} \mathcal{F}_U(s,t)$$

$$\mathcal{V}_{\mathrm{NLO}}^{(\mathrm{CT})}(s,t) = \frac{1}{F_0^2} \left[-4h_0 \mathcal{C}_0^{(2)} + 2h_1 \mathcal{C}_1^{(2)} - 2\mathcal{C}_{24}^{(2)} \mathcal{H}_{24}(s,t) + 2\mathcal{C}_{35}^{(2)} \mathcal{H}_{35}(s,t) \right]$$

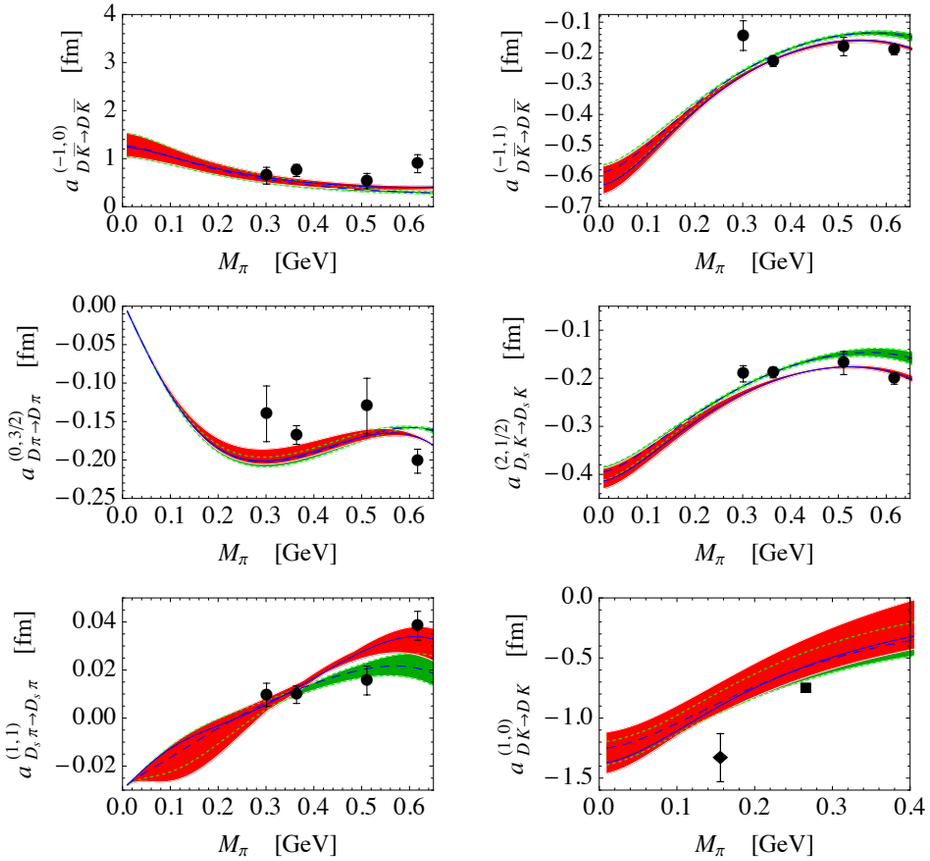
$$\mathcal{V}_{\mathrm{NNLO}}^{(\mathrm{CT})}(s,t) = \frac{4g_1}{F_0^2} \left[\mathcal{C}_{1a}^{(3)} (p_1+p_3)\cdot(p_2+p_4) + \mathcal{C}_{1b}^{(3)} (p_1+p_3)\cdot p_2 \right] + \frac{4\mathcal{C}_{23}^{(3)} \mathcal{G}_{23}(s,t)}{F_0^2}$$

Note: loop expressions too lengthy, esp. with D^*, LECs $h_{0,1,2,3,4,5}$ and $g_{1,2,3}$

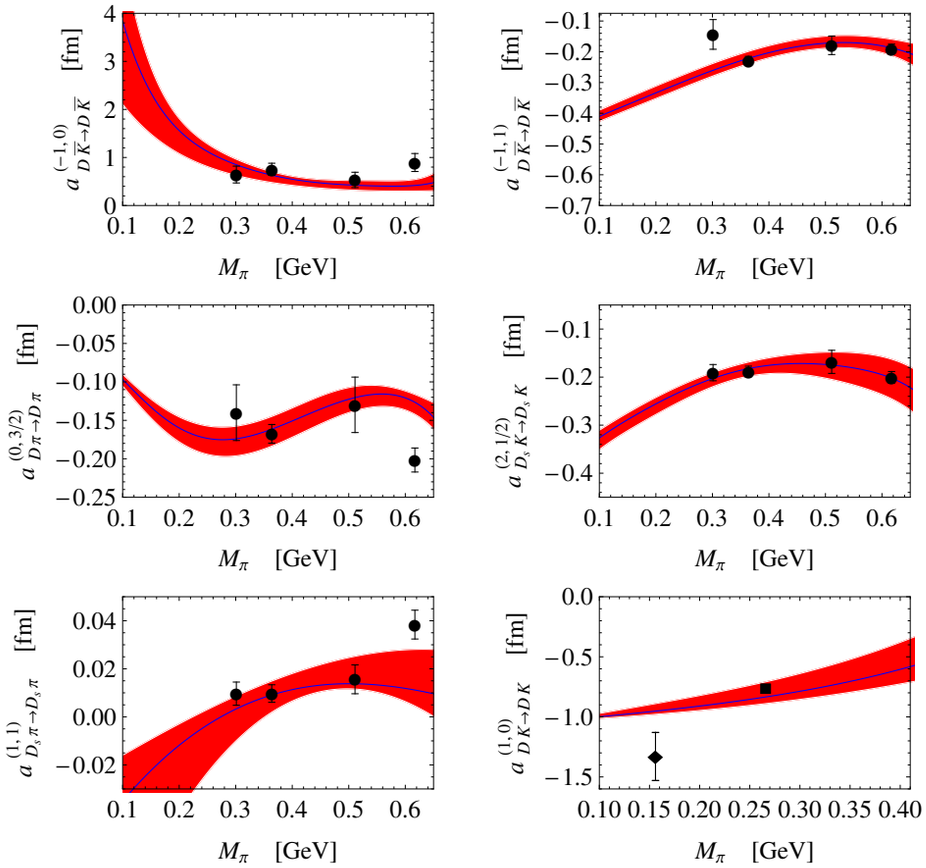
Results I: Goldstone boson scattering . . . cont'd

M.-L. Du, F.-K. Guo, UGM, D.-L. Yao, arXiv:1703.10836

- A typical NLO fit



- A typical NNLO fit



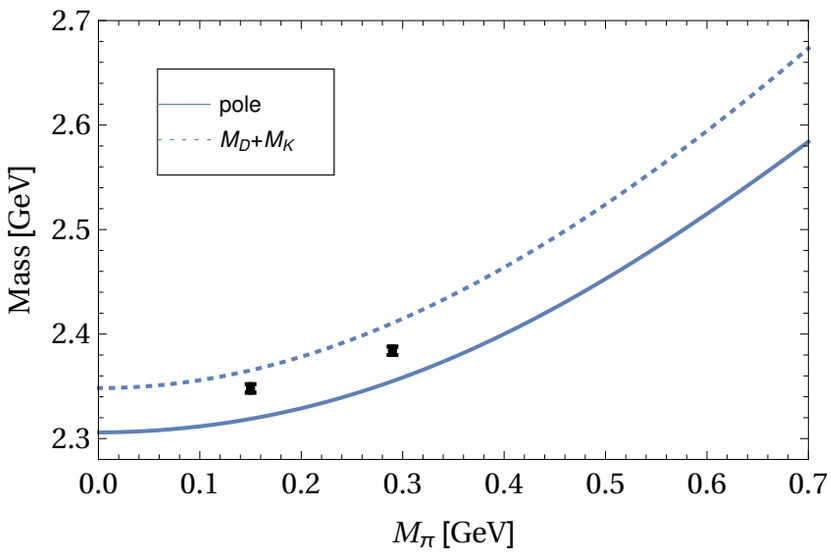
D.-L.Yao, M.-L.Du, F.-K.Guo, UGM, JHEP **1511** (2015) 058

Results I: Goldstone boson scattering . . . cont'd

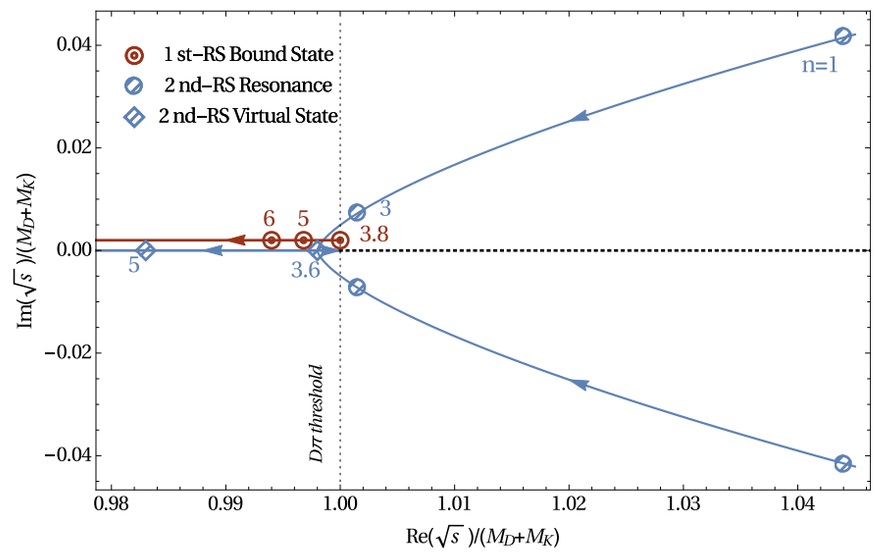
M.-L. Du, F.-K. Guo, UGM, D.-L. Yao, arXiv:1703.10836

- Pion mass dependence

⋆ $D_{s0}^*(2317)$ trajectory



⋆ Trajectory of the pole at 2.1 GeV



- recent LCQD at $M_\pi = 150, 290$ MeV

G.S. Bali et al., arXiv:1706.01247

- typical behaviour for a scalar meson

Hanhart, Pelaez, Rios, PRL **100** (2008) 152001

↪ prediction: $M_{D_{s0}^*}(290\ \mathrm{MeV}) - M_{D_{s0}^*}(150\ \mathrm{MeV}) = 36$ MeV

↪ lattice: $M_{D_{s0}^*}(290\ \mathrm{MeV}) = 2384(3)$ MeV, $M_{D_{s0}^*}(150\ \mathrm{MeV}) = 2348(4)$ MeV

Results I: Goldstone boson scattering . . . cont'd

M. Albaladejo, P. Fernandez-Soler, F.-K. Guo, J. Nieves, Phys. Lett. B **767** (2017) 465

- Coupled-channels $D\pi$-$D\eta$, D_sK $(I = 1/2)$

- use UCHPT in a finite volume

- LECs from earlier NLO analysis of D-ϕ scattering

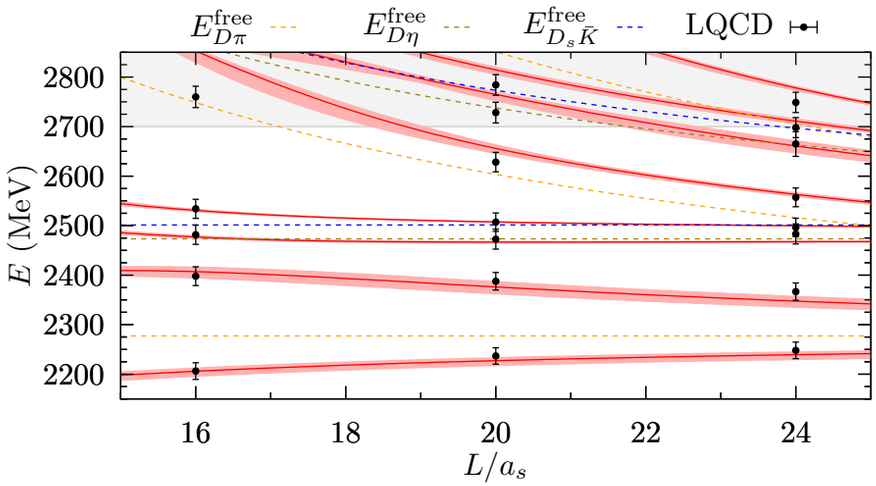
  L. Liu et al., Phys. Rev. D**87** (2013) 014508

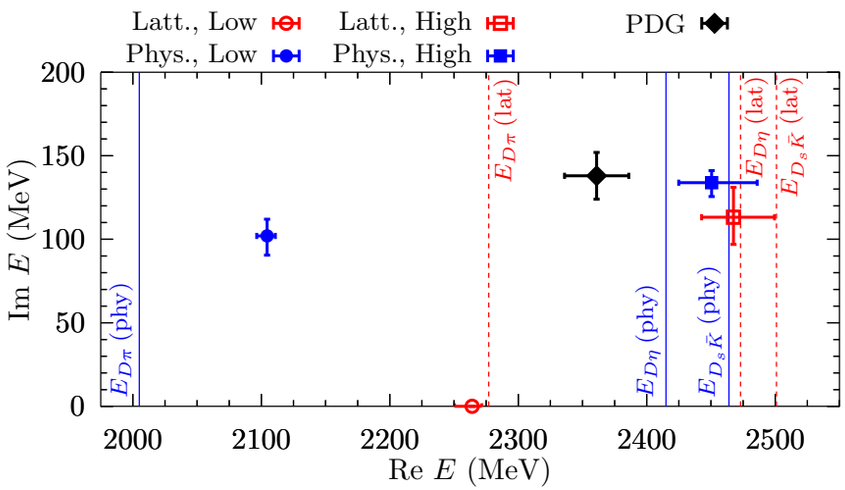
- excellent description of the energy levels from the Hadron Spectum Collaboration

  G. Moir et al., JHEP **1610** (2016) 011

$\hookrightarrow$ while HadSpecColl finds only one pole, the UCHPT analysis reveals a two-pole (state) structure of the $D_0^*(2400)$ similar to the famous $\Lambda(1405)$

J.A. Oller, UGM, Phys. Lett. B **500** (2001) 263





Results II: $\pi\eta$ scattering and the $a_0(980)$

Z.-H. Guo, L. Liu, UGM, J.A. Oller, A. Rusetsky, Phys. Rev. D **95** (2017) 054004

- Combined analysis of scattering data (finite volume, unphysical pion mass) from the HadSpec Coll. & the $\gamma\gamma \to \eta\pi$ XS data from Belle

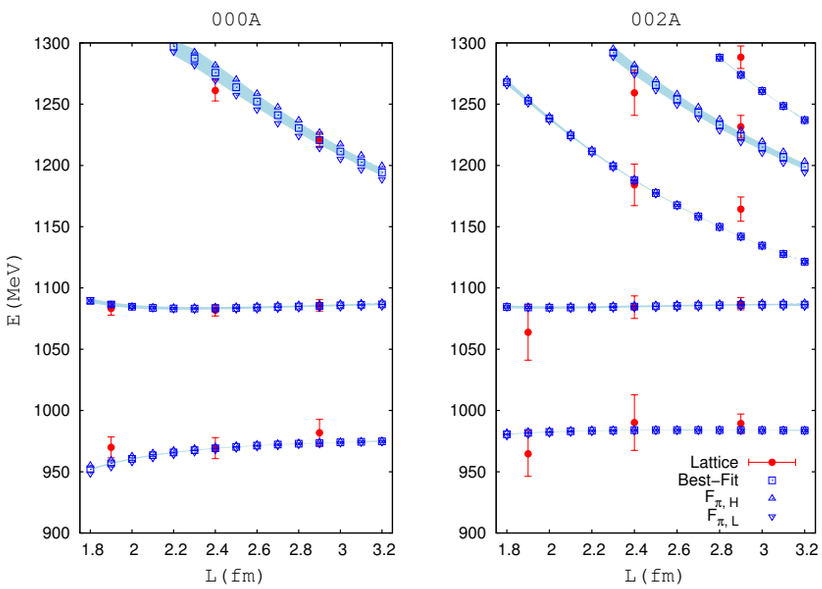
- combines two recently developed methods:
  - ⋆ coupled-channel finite volume formalism from Bonn (first FP + TR 16)
  - ⋆ coupled-channel U(3) UCHPT approach from Murcia (Oller et al.)

- Results:
  - ⋆ LO and NLO approaches describe all data/energy levels well → slide
  - ⋆ Extrapolation to the physical π, K, η and η' masses
    ↪ different results, mostly due to the bare $a_0(1450)$ pole at NLO → slide
  - ⋆ Pole structure at heavy and physical pion masses
    ↪ at the heavy pion mass, results agree within errors for $a_0(980)$
    ↪ at the phys. pion mass, same $a_0(980)$ pole plus $a_0(1450)$ pole

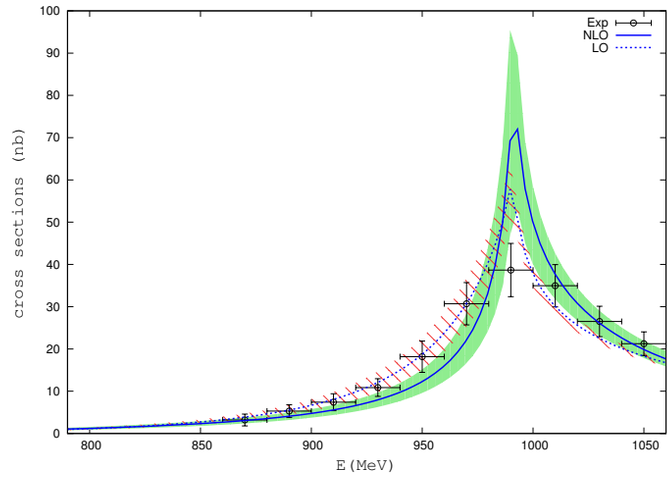
Results II: $\pi\eta$ scattering and the $a_0(980)$ cont'd

Z.-H. Guo, L. Liu, UGM, J.A. Oller, A. Rusetsky, Phys. Rev. D **95** (2017) 054004

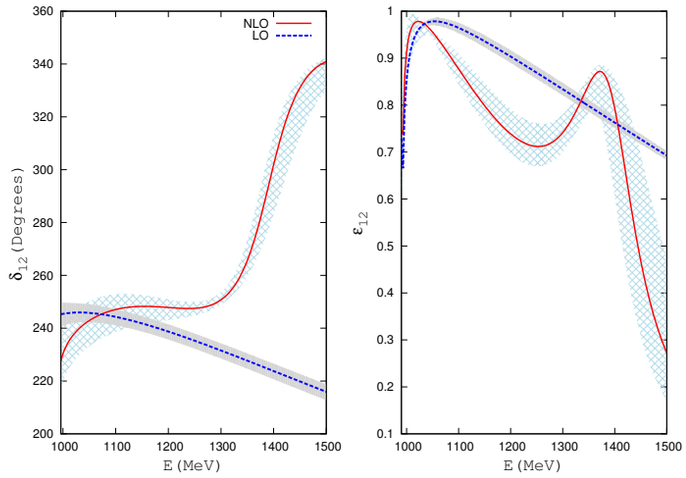
- A typical NLO fit (HadSpec Coll.) [$M_\pi = 391$ MeV, m_s physical]



- $\gamma\gamma \to \pi\eta$ XS from Belle [phys.]



- $\pi\eta \to \bar{K}K$ above 1 GeV [phys.]



Belle:
S. Uehara et al. [Belle Collaboration], Phys. Rev. D **80** (2009) 032001

Hadron Spectrum Coll.:
J. J. Dudek et al. [Hadron Spectrum Collaboration], Phys. Rev. D **93** (2016) 094506

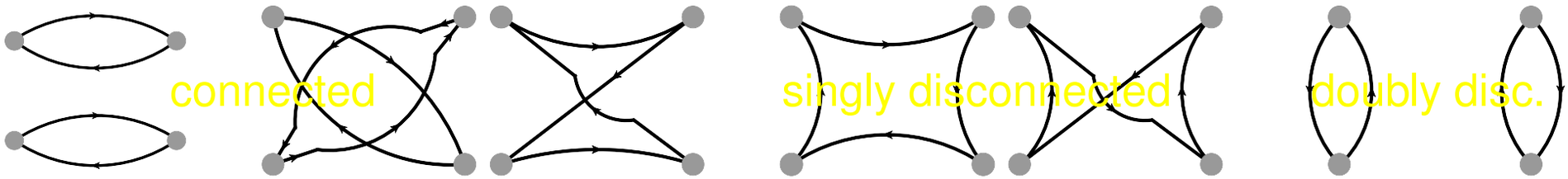
Results III: Contractions in pion-pion scattering

N.R. Acharya, F.-K. Guo, UGM, C.-Y. Seng, Nucl. Phys. B **922** (2017) 480 [arXiv:1704.06754]

- So-called disconnected diagrams pose severe problems to LQCD practitioners

$\hookrightarrow$ analyze various contributions using two-flavor PQCHPT SU(4|2) (deg. masses)
$\rightarrow$ slide

- consider pion-pion scattering, one amplitude: $T(s,t,u)$



D C R V

$$T^{I=0}(s,t,u) = T_D^{I=0}(s,t,u) + T_C^{I=0}(s,t,u) + T_R^{I=0}(s,t,u) + T_V^{I=0}(s,t,u)$$
$$T^{I=1}(s,t,u) = T_D^{I=0}(s,t,u) + T_R^{I=0}(s,t,u)$$
$$T^{I=2}(s,t,u) = T_D^{I=0}(s,t,u) + T_C^{I=0}(s,t,u)$$

$\hookrightarrow$ well-known hierarchy (connected/singly-disconnected/doubly-disconnected)

$\hookrightarrow$ provide analytical results

Digression: Partially Quenched QCD

- PQQCD for two flavors, equal masses: e.g. Sharpe, hep-lat/0607016

$$Q = (\underbrace{j\,k}_{\text{valence}}\ \underbrace{u\,d}_{\text{sea}}\,|\,\underbrace{\tilde{j}\,\tilde{k}}_{\text{ghost}})^T$$

- Invariance under $Q_{L/R} \to U_{L/R} Q_{L/R}$, with $U_{L/R} \in \mathrm{SU}(4|2)_{L/R}$
  where $\mathrm{SU}(4|2)_{L/R}$ is a special unitary graded symmetry group

- $(a|b)$-graded matrix: $A = \begin{pmatrix} A_1 & A_2 \\ A_3 & A_4 \end{pmatrix} = \begin{pmatrix} a \times a & a \times b \\ b \times a & b \times b \end{pmatrix}, \ A_{nm} \in \mathbb{C}$

$\hookrightarrow$ requires the the supertrace: $\mathrm{Str}[A] \equiv \sum_{i=1}^{a} A_{ii} - \sum_{i=a+1}^{a+b} A_{ii}$

- Corresponding EFT: PQCHPT $\mathrm{SU}(4|2)_L \times \mathrm{SU}(4|2)_R \to \mathrm{SU}(4|2)_V$

$\hookrightarrow 6^2 - 1 = 35$ Goldstone bosons, collected in $U = \exp\left\{\frac{2i}{F_0}\sum_{a=1}^{35} \phi^a T^a\right\}$

Results III: Contractions in . . . cont'd

N.R. Acharya, F.-K. Guo, UGM, C.-Y. Seng, Nucl. Phys. B **922** (2017) 480 [arXiv:1704.06754]

- Calculate scattering lengths for various contractions: $a_X^{IJ} = \lim_{q^2 \to 0} \frac{Re T_X^{IJ}(4M_\pi^2 + 4q^2)}{(q^2)^J}$

	$10^2 a_X^{00}$	$10^2 a_X^{20}$	$10^2 M_\pi^2 a_X^{11}$	$10^4 M_\pi^4 a_X^{02}$	$10^4 M_\pi^4 a_X^{22}$
D	0.35 ± 0.24	0.35 ± 0.24	0.02 ± 0.26	3.5 ± 2.0	3.5 ± 2.0
C	2.41 ± 0.12	-4.81 ± 0.23	0	0.95 ± 0.96	-1.9 ± 1.9
R	14.8 ± 0.7	0	3.59 ± 0.26	6.7 ± 7.8	0
V	2.48 ± 0.38	0	0	0.8 ± 7.3	0
Total	20.0 ± 0.2	-4.46 ± 0.07	3.61 ± 0.04	11.9 ± 0.8	1.54 ± 0.71

with the LECs $\bar{\ell}_i$ from Bijnens/Ecker (2016) and $L_i^{PQ,r}$ from Boyle et al. (2016)

- find combinations least dependent on new PQ LECs such as:

$$a_V^{00} - \tfrac{3}{2} a_D^{00} = \frac{M_\pi^4}{\pi F_\pi^4} \left[\frac{3\bar{\ell}_4}{64\pi^2} - 3L_5^{PQ,r} + \frac{9}{512\pi^2} + \frac{3F_\pi^2}{4M_\pi^2}\mu_\pi \right]$$

$\hookrightarrow$ if scatt. lengths for various contractions can be extracted from LQCD data (t.b.p.) then use this framework to extract noisy LECs from less noisy combinations

Milestones

2016/2

- Calculating the connected, singly-disconnected and doubly-disconnected contributions separately to the isoscalar $\pi\pi$ scattering amplitude

  $\rightarrow$ fully achieved $\surd$

2017

- Analysis of the pion mass dependence for the $Z_c(3900)$ including the $DD\pi$ three-body system in a finite volume

  $\rightarrow$ in the works (with Bonn/Jülich/Bochum/ITP/ITEP Moscow people)

- Extension of the Wick contraction calculation to the scattering processes involving kaons and the eta meson

  $\rightarrow$ first proof for two-flavor case (extraction from LQCD)

  $\rightarrow$ next application: weak pion-nucleon coupling h_π

  $\rightarrow$ then SU(3) extension

Publications

- V. Baru, E. Epelbaum, A. A. Filin, C. Hanhart, U.-G. Meißner and A. V. Nefediev, "Heavy-quark spin symmetry partners of the X (3872) revisited," Phys. Lett. B **763** (2016) 20 [arXiv:1605.09649 [hep-ph]].
- M. L. Du, F. K. Guo and U.-G. Meißner, "One-loop renormalization of the chiral Lagrangian for spinless matter fields in the SU(N) fundamental representation," J. Phys. G **44** (2017) 014001 [arXiv:1607.00822 [hep-ph]].
- M. L. Du, F. K. Guo and U.-G. Meißner, "Subtraction of power counting breaking terms in chiral perturbation theory: spinless matter fields," JHEP **1610** (2016) 122 [arXiv:1609.06134 [hep-ph]].
- M. L. Du, F.-K. Guo, U. G. Meißner and D. L. Yao, "Aspects of the low-energy constants in the chiral Lagrangian for charmed mesons," Phys. Rev. D **94** (2016) no.9, 094037 [arXiv:1610.02963 [hep-ph]].
- M. L. Du, F. K. Guo, U.-G. Meißner and D. L. Yao, "Study of open-charm 0^+ states in unitarized chiral effective theory with one-loop potentials," arXiv:1703.10836 [hep-ph] (submitted for publication).
- M. Albaladejo, P. Fernandez-Soler, F.-K. Guo and J. Nieves, "Two-pole structure of the $D_0^*(2400)$," Phys. Lett. B **767** (2017) 46 [arXiv:1610.06727 [hep-ph]].
- N. R. Acharya, F. K. Guo, U.-G. Meißner and C. Y. Seng, "Connected and Disconnected Contractions in Pion-Pion Scattering," Nucl. Phys. B **922** (2017) 480 [arXiv:1704.06754 [hep-lat]].
- X. G. Wang, C. R. Ji, W. Melnitchouk, Y. Salamu, A. W. Thomas and P. Wang, "Strange quark asymmetry in the proton in chiral effective theory," Phys. Rev. D **94** (2016) no.9, 094035 [arXiv:1610.03333 [hep-ph]].
- H. Li and P. Wang, "Chiral extrapolation of nucleon axial charge g_A in effective field theory," Chin. Phys. C **40** (2016) no.12, 123106 [arXiv:1608.03111 [hep-ph]].
- F.-K. Guo, C. Hanhart, U.-G. G. Meißner, Q. Wang, Q. Zhao, B.-S. Zuo, "Hadronic Molecules," arXiv:1705.00141 [hep-ph] (submitted for publication to *Rev. Mod. Phys.*)

Summary & outlook

- Project **A.5** is on a good track
- Fruitful collaborations with other projects:

  B.3, **B.4** – on-going

  A.2, **B.5** – starting
- stay tuned . . .