Recent progress in lattice calculations of properties of open-charm mesons

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Fermilab

Outline

1. Introduction
2. Single hadron spectra
   - D and D_s spectra
   - Gluonic excitations
3. Charmed mesons and scattering
   - $D\pi$ scattering
   - DK scattering
4. Calculations of $g_{DD^*\pi}$ and $g_{DD\rho}$, $g_{D^*D^*\rho}$
5. Searches for exotic charmed states
   - Charmed tetraquarks

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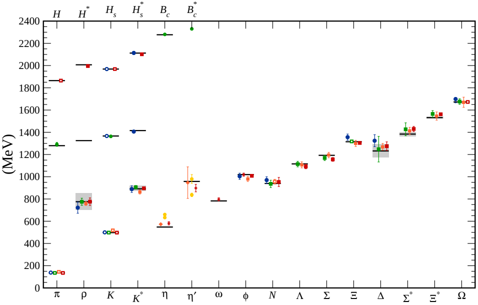
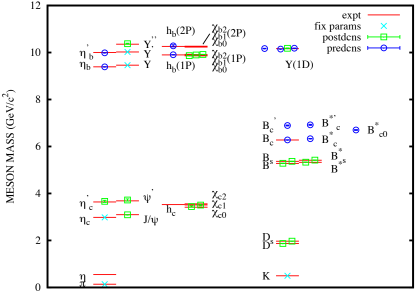
Ground state masses

Low lying hadrons



From A Kronfeld
Ann.Rev.Nucl.Part.Sci. 62 (2012)

Heavy mesons

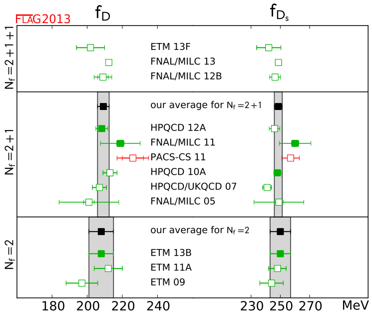


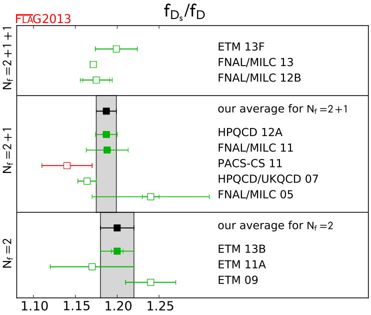
From HPQCD
Dowdall et al. PRD 86 094510 (2012)

- Ground states charmed mesons have been calculated with full control of systematic uncertainties
- This can be done for various (ground state) observables

Precision flavor physics: FLAG review

- Aims to answer: “What is currently the best lattice value for a particular quantity?”
- Uses symbols derived from rigorous quality criteria and covers precision results
- Can be found at http://itpwiki.unibe.ch/flag/
- For lattice flavor physics see talk by E. Gamiz





Two kinds of progress...

precision results $\leftrightarrow$ exploratory studies

- Ground state properties with full systematic uncertainties
- Properties of excitations are much more challenging conceptually and computationally
  Looking at Euclidean correlators:

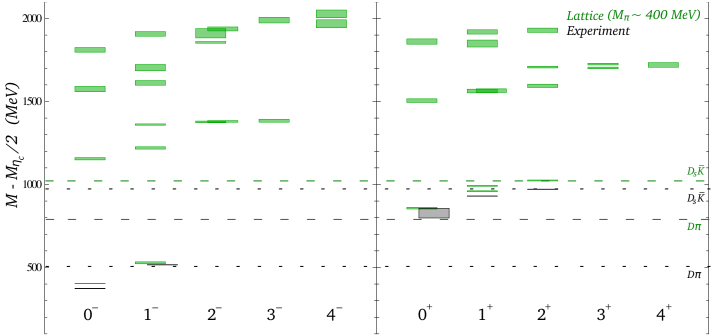
$$\left\langle \hat{O}_2(t)\hat{O}_1(0)\right\rangle_T \propto \sum_n e^{-tE_n} < 0|\hat{O}_2|n >< n|\hat{O}_1|0 >$$

- Lüscher's finite volume method to extract hadron resonances and bound states
- I will report on exploratory calculations with regard to charmed mesons
- There will be preliminary data - use with caution

Outline

Energy level from $\bar{q}q$ operators at $m_\pi = 400MeV$

D meson spectrum:

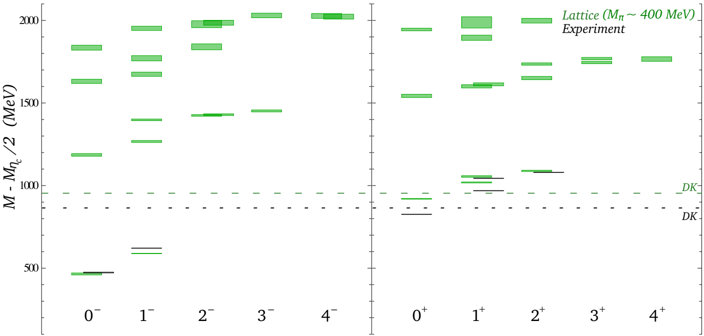


HSC, Moir et al. JHEP 1305 (2013) 021

- Energy levels related to high spin states can be identified
- Relation of energy levels to resonances not straight forward

Energy level from $\bar{q}q$ operators at $m_\pi = 400MeV$

D_s meson spectrum:



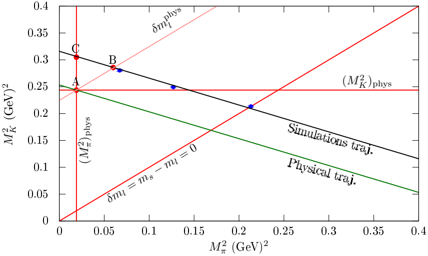
HSC, Moir et al. JHEP 1305 (2013) 021

- Energy levels related to high spin states can be identified
- Relation of energy levels to resonances not straight forward

Charmed mesons from QCDSF: Setup

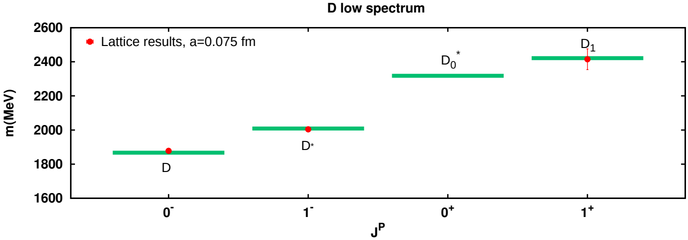
Perez-Rubio, Collins, Bali arXiv:1503.0844

- QCDSF ensembles with 2+1 flavors, 2 volumes, 3 pion masses with $259 \leq m_\pi \leq 460$
- Study geared mainly at charmed baryons
  $\rightarrow$ talk by Padmanath
- Results for D and D_s mesons extrapolated to the chiral limit in a single volume
- All results from quark-antiquark interpolating fields



Charmed mesons from QCDSF: Results

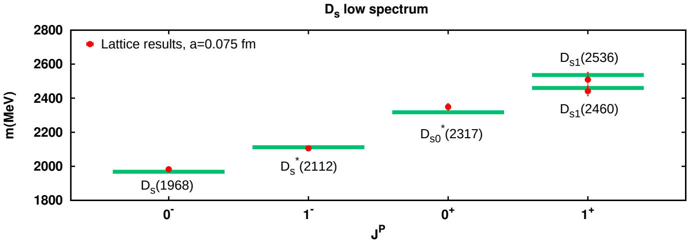
Perez-Rubio, Collins, Bali arXiv:1503.0844



- Ground state $D\pi$ observed (not shown) for $J^P = 0^+$
- Ground state $D^*\pi$ observed (not shown) for $J^P = 1^+$
- Basis not large enough to obtain second D_1

Charmed mesons from QCDSF: Results

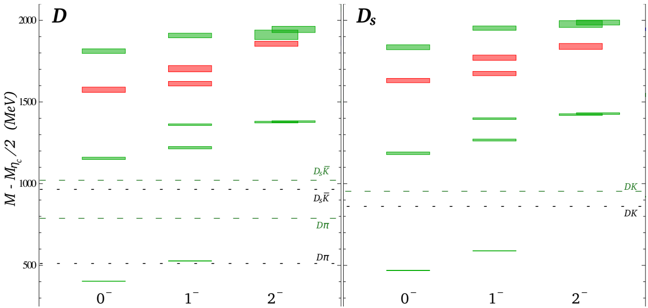
Perez-Rubio, Collins, Bali arXiv:1503.0844



- Authors comment that $D_{s1}(2536)$ might be D^*K
- Analysis for D^*_{s0} uses a single interpolator
- QCDSF is working on a more comprehensive analysis

Gluonic excitations

HSC, Moir et al. JHEP 1305 (2013) 021



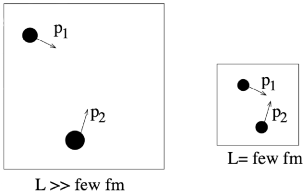
- Red energy level show the hybrid meson candidates with $P = -$
- Hybrid state candidates seen for various quantum numbers
- Same pattern than charmonium and light meson hybrids

Outline

The Lüscher method

M. Lüscher Commun. Math. Phys. 105 (1986) 153; Nucl. Phys. B 354 (1991) 531; Nucl. Phys. B 364 (1991) 237.

$$E = E(p_1) + E(p_2)$$



$$E = E(p_1) + E(p_2) + \Delta_E$$

$$E_n(L) \quad \xrightarrow{(2)} \quad \delta_l \quad \xrightarrow{(3)} \quad m_R; \quad \Gamma_R \text{ or coupling } g$$

(1) Extract energy levels $E_n(L)$ in a finite box

(2) Lüscher formula → phase shift of the continuum scattering amplitude

(3) Extract resonance parameters (similar to experiment)

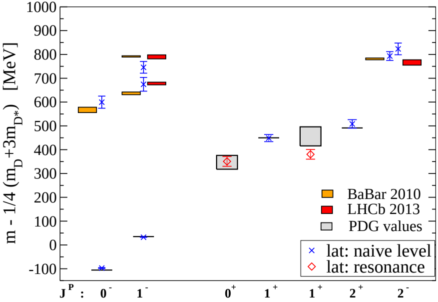
- 2-hadron scattering and transitions well understood; progress for 3 (or more) hadrons but difficult

See LATTICE2014 plenary by Raúl A. Briceño, arXiv:1411.6944

Resonances in $D\pi$ and $D^\star\pi$ scattering

DM, Prelovsek, Woloshyn, PRD 87 034501 (2013)

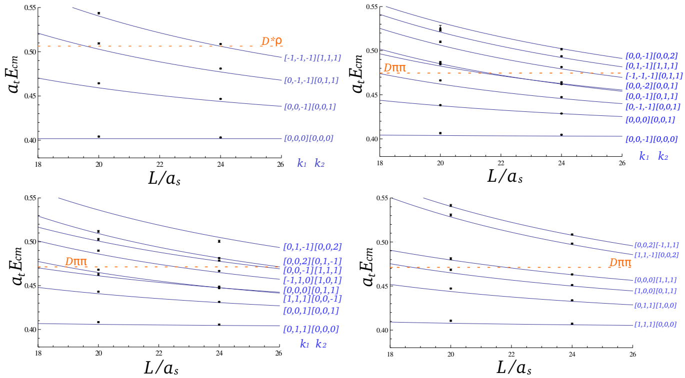
- For resonances determine coupling g rather than $\Gamma = g^2 \frac{p^*}{s}$ (for s-wave)
- Data at $m_\pi = 266 MeV$ on a single volume / lattice spacing



	$D_0^*(2400)$	$D_1(2430)$
g^{lat} [GeV]	2.55 ± 0.21	2.01 ± 0.15
g^{exp} [GeV]	1.92 ± 0.14	2.50 ± 0.40

$D\pi$ scattering with Isospin $\frac{3}{2}$: Energy levels

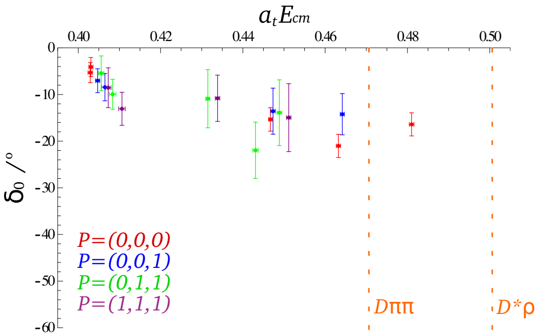
Preliminary results from the Hadron spectrum collaboration



- Multiple momentum frames lead to many energy levels

$D\pi$ S-wave scattering with Isospin $\frac{3}{2}$: Phase Shift

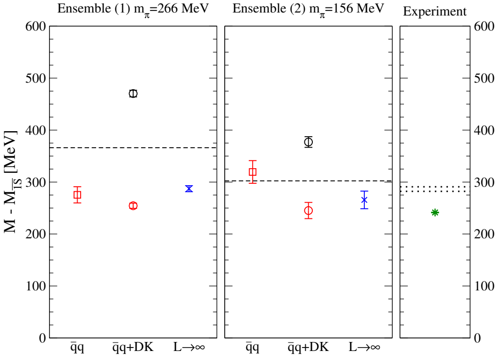
Preliminary results from the Hadron spectrum collaboration



- Preliminary results consider only the lowest partial wave
- Dense coverage of interesting energy region

$D_{s0}^*(2317)$ including D meson - Kaon

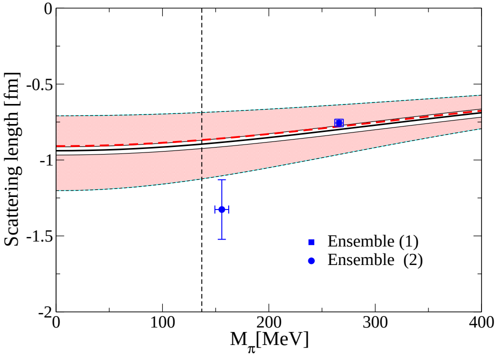
DM, Lang, Leskovec, Prelovsek, Woloshyn, PRL 111 222001 (2013)



- Much better quality of the ground state plateau with combined basis
- $D_{s0}^*(2317)$ as a QCD bound state
- Suggests that including multi-hadron levels is vital

Results for the scattering length a_0

DM, Lang, Leskovec, Prelovsek, Woloshyn, PRL 111 222001 (2013)



- We compare to the predictions from an indirect calculation

  Liu et al. PRD 87 014508 (2013).

- Our determination robustly leads to negative values.

Analysis using an auxiliary potential

Martinez-Torres et al. arXiv:1412.1706

$$V = \alpha + \beta(s - s_{th}) \qquad \tilde{T} = \frac{1}{V^{-1} - \tilde{G}}$$

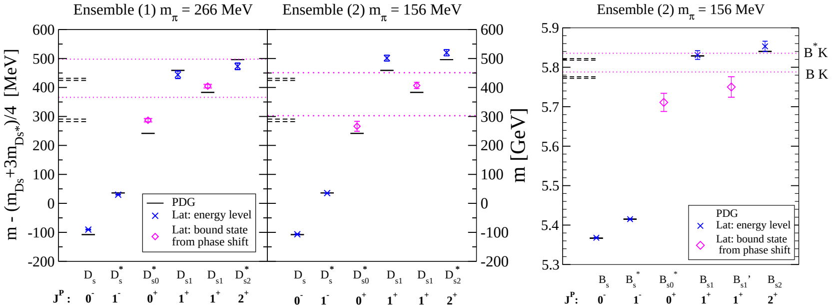
$$\tilde{G} = G + \lim_{q_{max}\to\infty}\left(\frac{1}{L^3}\sum_{q_i}^{q_{max}} I(\vec{q}_i - \int_{q<q_{max}} \frac{d^3q}{(2\pi)^3} I(\vec{q}))\right)$$

- The parameters of V are extracted from the lattice energies
- A generalization of Weinberg's compositeness condition yields

$$P(KD) = 0.72(12) \quad \text{for the} \quad D^*_{s0}(2317)$$
$$P(KD^*) = 0.63(16) \quad \text{for the} \quad D_{s1}(2460)$$

- Authors suggest a study with increased precision, inclusion of $D^{(*)}\eta$
- A word of caution: Discretization effects are important!

Resulting D_s and B_s P-wave spectrum



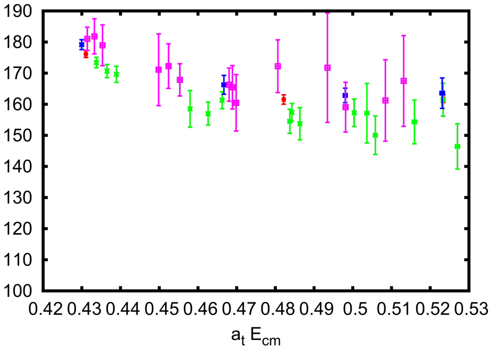
Results from Lang et al. PRD 90 034510 (2014)

- Remaining differences of the size of discretization uncertainties
- Many improvements possible for the D_s states
- Predicted corresponding B_s states with full uncertainty estimate

C. B. Lang, DM, S. Prelovsek, R. M. Woloshyn arXiv:1501.01646

DK S-wave scattering with Isospin 1: Phase shift

Preliminary results from the Hadron spectrum collaboration



- Preliminary results consider only the lowest partial wave
- Results for channels with resonances announced

Outline

Recent dynamical calculations of $g_{DD^*\pi}$

(1) Can et al. PLB 719 103-109 (2013)
(2) Becirevic and Sanfilippo, PLB 721 94-100 (2013)

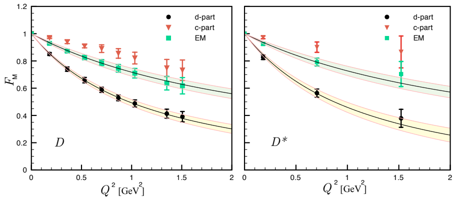
- Computed via (transition) matrix element

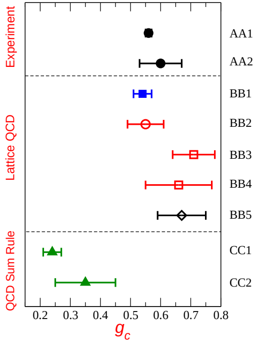
$$< D(p')|A_\mu(q)|D^*(p,s) > \quad \text{with} \quad A_\mu = \bar{u}\gamma_5\gamma_i d$$
$$< D(p')|V_\mu(q)|D(p) > \quad \text{with} \quad V_\mu = \frac{2}{3}\bar{c}\gamma_\mu c + \frac{2}{3}\bar{u}\gamma_\mu u - \frac{1}{3}\bar{d}\gamma_\mu d$$

- (1) uses 2+1 flavor gauge configurations with $a = 0.0907(13)$ and $m_\pi \in (300, 410, 570, 700)$ to extract $g_{DD^*\pi}$, $g_{DD\rho}$, $g_{D^*D^*\rho}$, the electromagnetic form factors and charge radii of D, D^*
- (2) uses 2 flavor gauge configurations at 4 lattice spacings with $m_\pi \in (280, 500)$ to determine $g_{DD^*\pi}$ at the physical point
- (2) uses nonperturbative renormalization and assesses the systematic uncertainties in the chiral and continuum extrapolations

(1) PLB 719 103-109 (2013)

(2) PLB 721 94-100 (2013)





- Uses VMD with

$$F_V(Q^2) = \left[1 - \frac{Q^2}{m_\rho^2 + Q^2}\frac{g_{D^{(*)}D^{(*)}\pi}}{g_\rho}\right]$$

- Disconnected part neglected

$$g_{DD\rho} = 4.84(34)$$
$$g_{D^*D^*\rho} = 5.94(56)$$

$$g_{DD^*\pi} = \frac{2\sqrt{m_D m_{D^*}}}{f_\pi} g_c$$

- Leads to $\Gamma(D^{*+} \to \bar{D}^0\pi^+) = 50 \pm 5 \pm 6\text{keV}$

Outline

Recent simulations of charm or beauty tetraquarks

- Searches for charmed tetraquarks
  - Doubly charmed and charmed-strange tetraquarks with the HALQCD method

    `Ikeda et al. PLB 729 85-90 (2014)`
  - Search for doubly charmed tetraquarks on CLS lattices (preliminary)

    `Guerrieri et al. arXiv:1411.2247`
- HHLL systems with static heavy quarks
  - Tetraquark bound states in heavy-light heavy-light systems

    `Brown and Orginos PRD 86 114506 (2012)`
  - Lattice QCD results for a bottom-bottom tetraquark

    `Bicudo and Wagner PRD 87 114511 (2013)`
  - Search for $ud\bar{b}\bar{b}$ $ss\bar{b}\bar{b}$ and $cc\bar{b}\bar{b}$ tetraquarks

    `Bicudo et al. arXiv:1505.00613`

Search for charmed tetraquarks by HALQCD

Ikeda et al. PLB 729 85-90 (2014)

- Search for bound states or resonances in DD, $\bar{K}D$, DD^* and $\bar{K}D^*$ interactions with flavor structure $cc\bar{u}\bar{d}$ and $cs\bar{u}\bar{d}$
- These contain no quark line diagrams with quark annihilation
- Uses 2+1 flavor gauge configurations with $a = 0.907(13)$ and $m_\pi = 410, 570, 700$
- HALQCD method

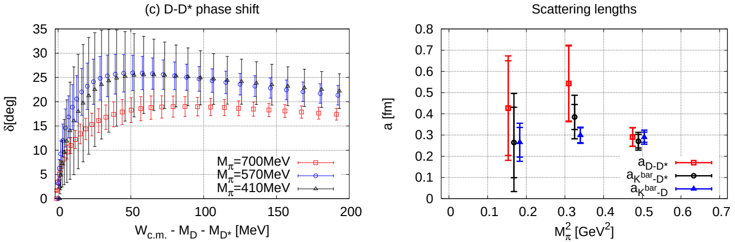
  Ishii et al. PLB 712, 437 (2012)

  - Calculate a potential as a function of distance r
  - Solve Schrödinger equation with given $V(r)$ and determine scattering phase shifts
- Uses variant of the Fermilab method (relativistic heavy quark action)

Tetraquarks with the HALQCD method: Results

Ikeda et al. PLB 729 85-90 (2014)

- Repulsive interaction in all $I = 1$ channels considered
- Attractive interaction in all $I = 0$ channels considered

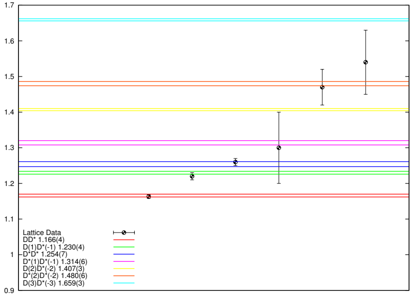


- No bound states or resonances at simulated m_π
- Attraction becomes more prominent at light pion masses
- Authors have some indication that BB^* with $IJ^P = 01^+$ is bound

Search for doubly charmed tetraquarks (preliminary)

Guerrieri et al. arXiv:1411.2247

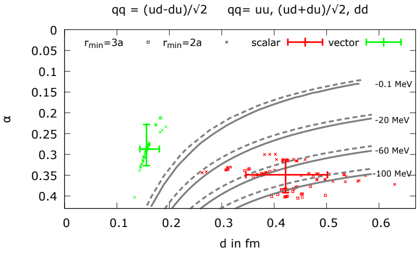
- 2 flavor simulation with $a = 0.075$fm and $m_\pi = 490$MeV and lighter than physical m_{charm}
- Considers $[cc][\bar{u}\bar{d}]$ tetraquarks with $IJ^P = 01^+, 11^+$
- Basis of tetraquark and meson-meson interpolators (also smeared)
- No additional low-lying energy level observed (just meson-meson states)

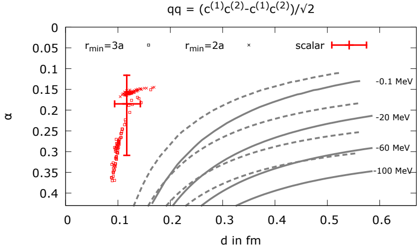


Search for $ud\bar{b}\bar{b}$ $ss\bar{b}\bar{b}$ and $cc\bar{b}\bar{b}$ tetraquarks

- Study of potentials of two static antiquarks in the presence of two finite mass quarks
- Search for bound states (rather than resonances)
- Two different lattices with $a = 0.079, a = 0.042$ fm and $m_\pi \approx 350$
- Fit function used for the lattice QCD potentials

$$V(r) = -\frac{\alpha}{r} \exp\left(-\left(\frac{r}{d}\right)^p\right) + V_0$$





Conclusions & Outlook

- Masses of $D_{(s)}^{(*)}$ ground states well determined, simulations focus on properties
- A large number of energy levels can be extracted, evidence for gluonic excitations
- Very few simulations that study close to threshold bound states and resonances
  New promising preliminary results from the Hadron Spectrum Collaboration
- Multiple simulations of flavored tetraquark states
- Most excited state studies use a single lattice spacing
  $\rightarrow$ Need for simulations at multiple lattice spacings to make stronger statements

Thank you!

... also to my collaborators Christian Lang, Luka Leskovec, Sasa Prelovsek and Richard Woloshyn

... to Uktu Can, Graham Moir, Paula Perez-Rubio, Sasa Prelovsek for providing me material