Plans for meson spectroscopy

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In May I will start a five year position as leader of a junior research group (Emmy Noether Programme) at Humboldt University Berlin.

The position is associated with two scientific projects:

- **Project 1: computation of the spectrum of \( s \) and \( c \) mesons.**
  
  * Goal: Compute the \( s \) and \( c \) meson spectrum (kaons, \( D \) mesons, \( D_s \) mesons, charmonium) as fully as possible with \( N_f = 2 + 1 + 1 \) ETMC gauge field configurations.

- **Project 2: (mixed) action simulations at fixed topology.**

Project 1 requires investigation, implementation and understanding of certain lattice techniques, which might be of general interest for members of ETMC:

- I would like to let you know, what we plan to do in the next months/years such that you can possibly profit from our experience.

- If some of you are interested, any form of active collaboration will be very welcome.
Physical goals, $s/c$ meson spectrum (1)

- Compute the $s$ and $c$ meson spectrum as fully as possible:
  - Consider all mesons, which have at least one $s$ or $c$ quark, i.e.
    * kaons (strange-light mesons), [light = up or down]
    * $D$ mesons (charm-light mesons), [light = up or down]
    * $D_s$ mesons (charm-strange mesons),
    * charmonium (charm-charm mesons),
    * possibly strangeonium (strange-strange mesons).
  - Consider parity $\pm$, charge conjugation $\pm$, radial and orbital excitations.
  - Lattice setup:
    * $N_f = 2 + 1 + 1$ flavor ETMC gauge field configurations.
    * $s/c$ quarks via an Osterwalder-Seiler mixed action setup (no flavor breaking, only parity is explicitly broken).
Experimental status (Particle Data Group): 73 known states.
Physical goals, s/c meson spectrum (3)

- Why is a lattice computation of the s and c meson spectrum important?
  - Some mesons, e.g. $D_s$, $\eta_c$, $J/\psi$, have been measured experimentally with high precision and can also be computed on the lattice very accurately → ideal candidates to test QCD by means of lattice QCD.
  - Some mesons are only poorly understood → lattice QCD is the perfect tool to clarify the situation:
    * 31 meson states labeled with “ omitted from summary table” (states colored red), i.e. vague experimental signals, experimental contradictions, states not well established.
    * Example $X(3872)$ (cc state): mass not as expected from quark models; could be a $D^0-\bar{D}^*(2007)^0$ molecule, a bound diquark-antidiquark, ... or models could yield wrong answers.
    * Example $D_{s0}^*(2317)$, $D_{s1}(2460)$: masses significantly lower than expected from quark models, almost equal or even lower than the corresponding $D$ mesons; could be $D$-$K$ molecules, tetraquarks, ...
Physical goals, $s/c$ meson spectrum (4)

- Why is a lattice computation of the $s$ and $c$ meson spectrum important?
  - Lattice QCD predictions of meson masses give valuable input for future experiments.
  - Comprehensive new information expected from existing and new facilities (BABAR, Belle, CEBAF, CLEO, upgraded BES, CDF, D0, FAIR (PANDA), LHC, ...) ... i.e. a “hot topic”.
  - Lattice results for the $s$ and $c$ meson spectrum exist, but no comprehensive picture available at the moment (different discretizations, scale setting methods, numbers of quark flavors, sometimes rather coarse lattice spacings, unphysically heavy $u/d$ quarks, no extrapolations).
Technical aspects, overview

- Construction and selection of suitable meson creation operators, application of the “generalized eigenvalue problem”.

- Efficient computation of quark propagators and correlation functions (stochastic sources, one-end-trick, distillation).

- How to deal with multiparticle states?
Construction/selection of operators (1)

- Construction of suitable meson creation operators:
  - Goal: construct a set of operators, which almost exclusively excites the states you want to compute; then the masses of these states can be extracted from the corresponding correlation functions/matrices at rather small temporal separation, where statistical errors are also small.
  - General form of a meson creation operator in a continuum-like notation:
    \[
    \mathcal{O}(x) = \left( \bar{Q} (S^{(Q)})^\dagger \right)(x) \int d\hat{n} \Gamma(\hat{n}) U(x; x + d\hat{n}) \left( S^{(q)} q \right)(x + d\hat{n}).
    \]
  - Degrees of freedom:
    * Spin structure, parity ($\gamma$ matrices).
    * Angular momentum structure (displacement of valence quarks, lattice versions of spherical harmonics).
    * Width of the operator (smearing techniques).
    * Nodes in the generated wavefunctions (application of derivatives).
Selection of suitable meson creation operators:

- Optimize operators by minimizing effective masses at small temporal separations.
- Choose a small set of operators, which are sufficiently different:
  - What are suitable criteria? Can this selection be automated in an effective way?
  - The HS Collaboration recommends minimizing the condition number of “normalized” correlation submatrices at small temporal separation (condition number = largest eigenvalue/smallest eigenvalue).

Construction/selection of operators (3)

- Application of the “generalized eigenvalue problem”:

\[ C(t)v_n(t, t_0) = \lambda_n(t, t_0)C(t_0)v_n(t, t_0), \]

\[ E_n = \lim_{t \to \infty} E_{\text{eff}}^n(t), \quad E_{\text{eff}}^n(t) = \ln \left( \frac{\lambda_n(t, t_0)}{\lambda_n(t + 1, t_0)} \right), \quad n = 1, \ldots, N. \]

- Is it advisable to determine ground states from correlation matrices solving a generalized eigenvalue problem or is the effective mass of a single optimized correlation function sufficient?

- My current experience with static-light mesons, static-light baryons, the static potential (Wilson loops), ... indicates that there are no practical benefits in using correlation matrices.

- However B. Blossier et al. showed that the difference between the mass \( E_n \) and the effective mass \( E_{\text{eff}}^n(t) \) is proportional to \( e^{-(E_{N+1} - E_n)t} \), i.e. decreases exponentially with respect to \( t \), where \( E_{N+1} \) is the mass of the first state “out of the basis”.

[B. Blossier, M. Della Morte, G. von Hippel, T. Mendes and R. Sommer, JHEP 0904, 094 (2009)]
Computation of all-to-all quark propagators would be ideal, is, however, computationally prohibitively expensive.
Efficient computation of propagators (2)

- Strategies to maximize efficiency:
  - Unbiased stochastic estimation of all-to-all quark propagators (stochastic sources, possibly diluted).
  - One-end-trick:
    (+) Eliminates statistical noise on “one end” of the correlation function.
    (−) Requires spin diluted sources.
    (−) Requires separate inversions for each operator.
  - Distillation:
    (+) A specific type of smearing recently proposed by the HS Collaboration.
    (−) Computationally very expensive (requires low lying eigenmodes of the lattice Laplacian).

[M. Peardon et al. [HSC], Phys. Rev. D 80, 054506 (2009)]

- Implement and compare these approaches with respect to efficiency.
How to deal with multiparticle states? (1)

- At (close to) realistic pion masses ($m_{PS} \lesssim 300$ MeV) most excited states have the same quantum numbers as lighter multiparticle states (e.g. ground state + pion(s)), i.e. are resonances.
How to deal with multiparticle states? (2)

- How to deal with contamination by such multiparticle states?
  - Usually multiparticle states are just ignored (one assumes e.g. that a state created by a two-quark meson operator has negligible overlap to multiparticle states) ... easy, but questionable/dangerous.
  - Lüscher’s method to extract resonances from the volume dependence of the spectrum ... theoretically sound, but computationally very demanding/not applicable in practice.
  - Compute the overlap of e.g. a two-quark meson operator and a four-quark multiparticle operator to demonstrate that the effect of this particular multiparticle state is indeed negligible.
  - Further approaches/ideas?