Plans for meson spectroscopy

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Introduction

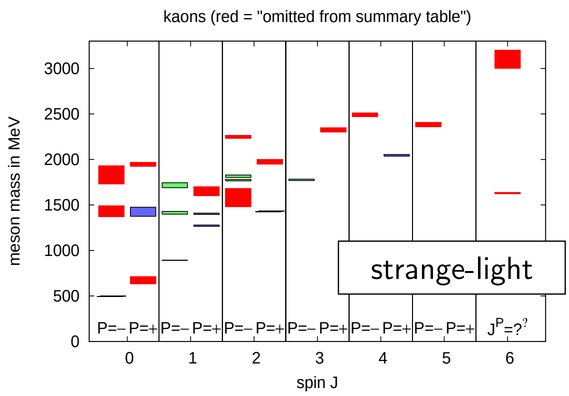
- In May I will start a five year position as leader of a junior research group (Emmy Noether Programme) at Humboldt University Berlin.
- The position is associated with two scientific projects:
  - **Project 1: computation of the spectrum of s and c mesons.**
    - Goal: Compute the s and c meson spectrum (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.

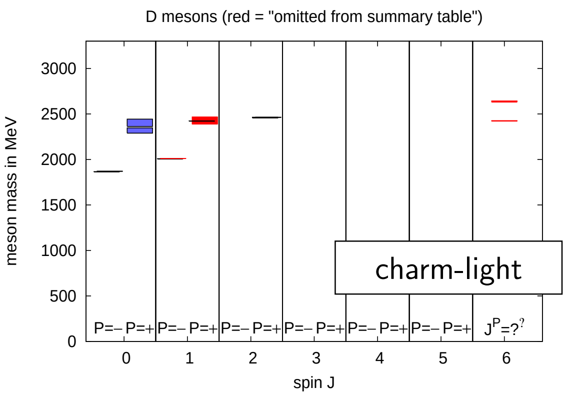
Physical goals, s/c meson spectrum (1)

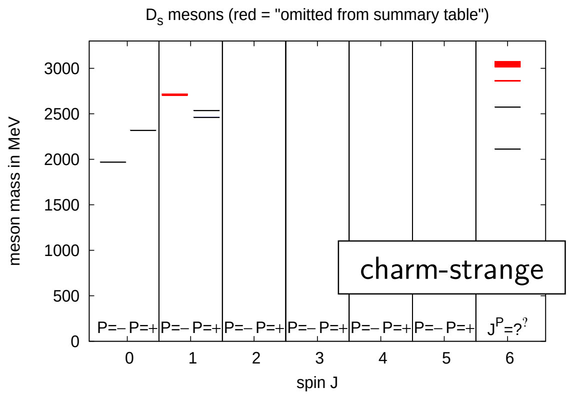
- Compute the s and c meson spectrum as fully as possible:
  - Consider all mesons, which have at least one s or c quark, i.e.
    - kaons (strange-light mesons), [light $=$ up or down]
    - D mesons (charm-light mesons), [light $=$ up or down]
    - D_s mesons (charm-strange mesons),
    - charmonium (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 explicitely broken).

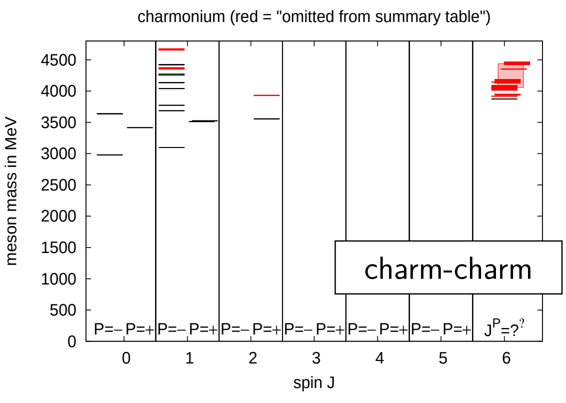
Physical goals, s/c meson spectrum (2)

- Experimental status (Particle Data Group): 73 known states.


kaons (red = "omitted from summary table")


D mesons (red = "omitted from summary table")


D_s mesons (red = "omitted from summary table")


charmonium (red = "omitted from summary table")

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, η_c, J/ψ, have been measured experimentally with high precision and can also be computed on the lattice very accurately $\longrightarrow$ ideal candidates to test QCD by means of lattice QCD.
  - Some mesons are only poorly understood
    $\longrightarrow$ 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 $X(3872)$ ($\bar{c}c$ 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

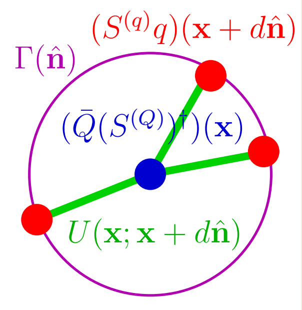
- Construction and selection of suitable meson creation operators, application of the "generalized eigenvalue problem".
- Efficient computation of quark propagators and correlation functions (stochastic sources, one-end-trick, distillation).
- How to deal with multiparticle states?

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:

$$\mathcal{O}(\mathbf{x}) \quad = \quad \Big(\bar{Q}(S^{(Q)})^\dagger\Big)(\mathbf{x}) \int d\hat{\mathbf{n}}\,\Gamma(\hat{\mathbf{n}}) U(\mathbf{x};\mathbf{x}+d\hat{\mathbf{n}}) \Big(S^{(q)} q\Big)(\mathbf{x}+d\hat{\mathbf{n}}).$$

  - Degrees of freedom:
    - ∗ Spin structure, parity (γ 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).



Construction/selection of operators (2)

- 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).

      [C. Morningstar, PoS **LATTICE2008**, 009 (2008)]

Construction/selection of operators (3)

- Application of the "generalized eigenvalue problem":

$$C(t) v_n(t,t_0) \quad = \quad \lambda_n(t,t_0) C(t_0) v_n(t,t_0) \quad ,$$

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

  - 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 $E_n^{\mathrm{eff}}(t)$ 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)]

Efficient computation of propagators (1)

- 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 ($m_{\mathrm{PS}} \lesssim 300\,$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.

    [M. Lüscher, Nucl. Phys. B **364**, 237 (1991)]
  - 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.

    [C. McNeile and C. Michael [UKQCDC], Phys. Rev. D **63**, 114503 (2001)]

    [C. McNeile, C. Michael and P. Pennanen [UKQCDC], Phys. Rev. D **65**, 094505 (2002)]

    [C. McNeile, C. Michael and G. Thompson [UKQCDC], Phys. Rev. D **70**, 054501 (2004)]
  - Further approaches/ideas?