DK scattering and the D_s spectrum

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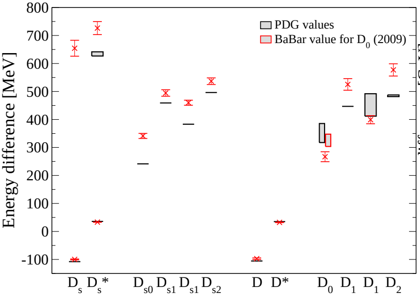
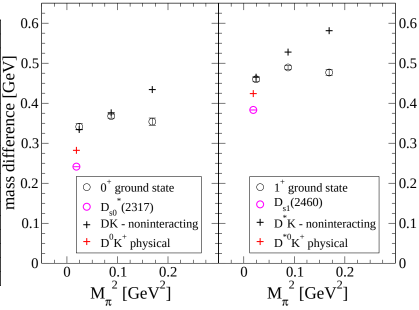
Motivation: Experimental D_s spectrum

- Established states:
  - D_s ($J^P = 0^-$) and D_s^* (1^-)
  - $D_{s0}^*(2317)$ (0^+), $D_{s1}(2460)$ (1^+), $D_{s1}(2536)$ (1^+), $D_{s2}^*(2573)$ (2^+)
- More recent discoveries:
  - $D_{s1}^*(2710)$ seen by BaBar, Belle (1^-)
  - $D_{sJ}^*(2860)$ seen by BaBar (3^-?,0^+?)
  - $D_{sJ}^*(3040)$ seen by BaBar (1^+?,2^-?)
  - $D_{sJ}^*(2632)$ seen by SELEX (1^-?)
- There is a zoo of phenomenological models and lattice results are getting dated
- Some models suggest a tetraquark/molecular interpretations for controversial states

Our previous attempt...



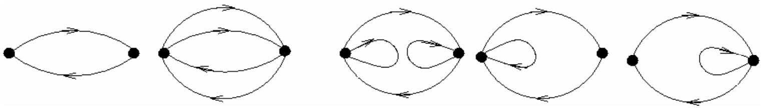


Mohler and Woloshyn, PRD 84 054503, 2011

- DK threshold turned out to be unphysical
- Even with light sea-quark masses the lowest states with $J^P = 0^+, 1^+$ remained unphysical
- Including the DK threshold explicitly might be vital

For our current efforts

- Work with a partially quenched strange quark
  - Use ϕ meson and η_s to set strange quark mass
  - We obtain $\kappa_s = 0.13666$
- Improve charm quark tuning used for Fermilab charm
  - Use Landau link for $c_{sw,c} = \frac{1}{u_0^3}$
  - Empirically this reduces discretization effects
- Explicitly include DK interpolators into the basis



Technicalities: The "Distillation" method

Peardon et al. PRD 80, 054506 (2009); Morningstar et al. PRD 83, 114505 (2011)

- Idea: Construct separable quark smearing operator using low modes of the 3D lattice Laplacian
  Spectral decomposition for an $N \times N$ matrix:

$$f(A) = \sum_{k=1}^{N} f(\lambda^{(k)})\; v^{(k)} v^{(k)\dagger}.$$

  With $f(\nabla^2) = \Theta(\sigma_s^2 + \nabla^2)$ (Laplacian-Heaviside (LapH) smearing):

$$q_s \equiv \sum_{k=1}^{N} \Theta(\sigma_s^2 + \lambda^{(k)}) v^{(k)} v^{(k)\dagger}\, q \;=\; \sum_{k=1}^{N_v} v^{(k)} v^{(k)\dagger}\, q\,.$$

- Advantages: momentum projection at source; large interpolator freedom, small storage
- Disadvantages: expensive; unfavorable volume scaling
- Stochastic approach improves bad volume scaling

Technicalities II: Lattices used

ID	$N_L^3 \times N_T$	N_f	a[fm]	L[fm]	#configs	m_π[MeV]	m_K[MeV]
(1)	$16^3 \times 32$	2	0.1239(13)	1.98	280/279	266(3)(3)	552(2)(6)
(2)	$32^3 \times 64$	2+1	0.0907(13)	2.90	196	156(7)(2)	504(1)(7)

- Ensemble (1) has 2 flavors of nHYP-smeared quarks

  `Gauge ensemble from Hasenfratz et al. PRD 78 054511 (2008)`

  `Hasenfratz et al. PRD 78 014515 (2008)`

- Ensemble (2) has 2+1 flavors of Wilson-Clover quarks

  `PACS-CS, Aoki et al. PRD 79 034503 (2009)`

- On the larger volume we use stochastic distillation

  `Morningstar et al. PRD 83, 114505 (2011)`

Technicalities III: Charm quark treatment

- We use the *Fermilab method* for the heavy (charm) quark

  El-Khadra et al., PRD 55, 3933 (1997)
- We tune κ so that the spin averaged kinetic mass $(M_{\eta_c} + 3M_{J/\Psi})/4$ assumes its physical value
- General form for the dispersion relation

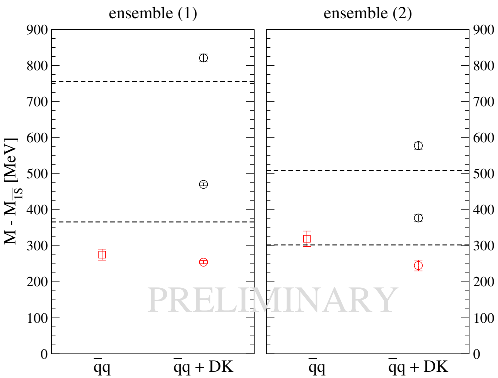
  Bernard et al. PRD 83,034503 (2011)

$$E(p) = M_1 + \frac{p^2}{2M_2} - \frac{a^3 W_4}{6} \sum_i p_i^4 - \frac{(p^2)^2}{8M_4^3} + \ldots$$

- We tried different strategies and neglect the term with W_4 for the final analysis
- For the DK we therefore use

$$E = \sqrt{m_K^2 + p^{*2}} + M_1 + \frac{p^{*2}}{2M_2} - \frac{p^{*4}}{8M_4^3} \,.$$

Energy levels for D_s with $J^P = 0^+$



- With the combined basis we obtain a much better quality of the ground state plateau
- The variational method yields two low-lying levels and fits are unambiguous

Possible interpretations

(1) A sub-threshold state stable under the strong interaction

- We call this “bound state scenario”
- This is irrespective of the nature of the state
- One expects a negative scattering length in this case

See `Sasaki and Yamazaki, PRD 74 114507 (2006)` for details.

See also `NPLQCD, arXiv 1301.5790` for an example.

(2) A resonance in a channel with attractive interaction

- The lowest state corresponds to the scattering level shifted below threshold in finite volume
- The additional level would indicate a QCD resonance
- One expects a positive scattering length in this case

This is the situation for the $D_0^*(2400)$ `DM, Prelovsek, Woloshyn PRD 87 034501 (2013).`

Using Lüscher's formula

- We can test the plausibility of these scenarios using Lüscher's formula and an effective range approximation

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

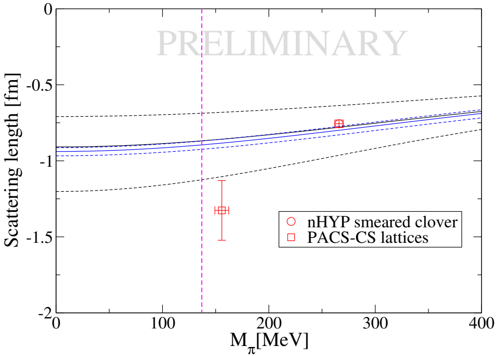
$$p \cot \delta(p) = \frac{2}{\sqrt{\pi} L} Z_{00}(1, p^2) \ , \\ \approx \frac{1}{a_0} + \frac{1}{2} r_0 p^2 \ ,$$

- Preliminary results for ensembles (1) and (2)

$$a_0 = -0.756 \pm 0.025 \mathrm{fm} \qquad r_0 = 0.056 \pm 0.031 \mathrm{fm} \qquad (1)$$

$$a_0 = -1.33 \pm 0.20 \mathrm{fm} \qquad r_0 = 0.27 \pm 0.17 \mathrm{fm} \qquad (2)$$

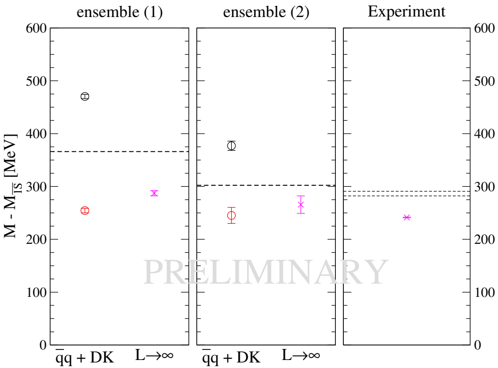
- We are still investigating the systematics



- We compare to the predictions from an indirect calculation
  Liu *et al.* PRD 87 014508 (2013).
- Our determination robustly leads to negative values.

Infinite volume bound states *vs.* experiment

- For a bound state we expect an S-matrix pole and $\cot\delta = i$
- Using our a_0 and r_0 we can determine the binding momentum and calculate the corresponding energy level



Conclusions

- We calculated energy levels in the D_s $J^P = 0^+$ channel with a combined basis of $\bar{q}q$ and DK interpolators
- We use partially quenched strange quarks, Fermilab c quarks and almost physical u/d quarks
- The DK interpolators are crucial to get reliable energy levels
- We observe an energy level compatible with the experimental $D_{s0}^*(2317)$
- The situation is similar but more messy for the $D_{s1}(2460)$...

For a similar situation see talk by `S. Prelovsek Thursday 17:30 in 8G`

Thank you!

Backup: Example energies