D and D_s meson spectroscopy from lattice QCD

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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

Gauge ensembles used

- We use 2+1 flavor Clover-Wilson ensembles of size $32^3 \times 64$ generated by the PACS-CS collaboration
- (Sea) Pion masses range from 156MeV to 702MeV
- We use the lattice spacing as determined by PACS-CS ($a = 0.0907(13)\mathrm{fm}$)

Ensemble	$c_{sw}^{(h)}$	$\kappa_{u/d}$	κ_s	#configs D/D_s
1	1.52617	0.13700	0.13640	200/200
2	1.52493	0.13727	0.13640	-/200
3	1.52381	0.13754	0.13640	200/200
4	1.52327	0.13754	0.13660	-/200
5	1.52326	0.13770	0.13640	200/348
6	1.52264	0.13781	0.13640	198/198

Charm quark treatment I

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

  `El-Khadra et al., PRD 55, 3933`

- We tune κ for the spin averaged kinetic mass $(M_{D_s} + 3M_{D_s^*})/4$ to assume its physical value
- General form for the dispersion relation

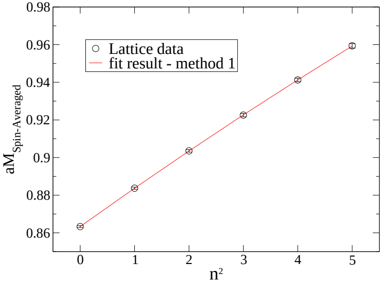
  `Bernard et al.  PRD83:034503,2011`

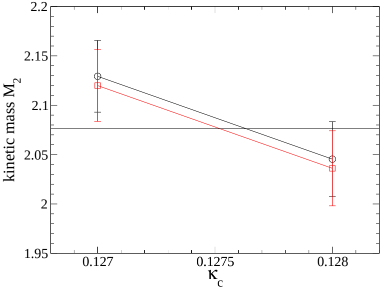
$$E(p) = M_1 + \frac{p^2}{2M_2} - \frac{a^3 W_4}{6} \sum_i p_i^4 - \frac{(p^2)^2}{8M_4^3} + \dots$$

- We compare results from two different fits:
  1. Neglect the term with coefficient W_4
  2. Fit $E^2(p)$ and neglect $(p^2)^2$ term from mismatch of M_1, M_2 and M_4

$$E^2(p) \approx M_1^2 + \frac{M_1}{M_2} p^2 - \frac{M_1 a^3 W_4}{3} \sum_i (p_i)^4 \qquad (1)$$

Charm quark treatment II





Method 1:

	$\kappa_c = 0.128$	$\kappa_c = 0.127$
M_1	0.86334(50)	0.89314(51)
M_2	0.9337(73)	0.9716(76)
M_4	0.8638(274)	0.8855(284)
$\frac{M_2}{M_1}$	1.0815(86)	1.0878(88)
$M_2[GeV]$	2.0315(158)(291)	2.1137(166)(303)

Method 2:

	$\kappa_c = 0.128$	$\kappa_c = 0.127$
M_1	0.86342(50)	0.89322(51)
$\frac{M_2}{M_1}$	1.0889(116)	1.0955(118)
$M_2[GeV]$	2.0454(215)(293)	2.1293(227)(305)

Variational method for hadron masses

Variational method (`Michael; Lüscher and Wolff; Blossier et al.`)

- Matrix of correlators projected to fixed momentum

$$C(t)_{ij} = \sum_n \mathrm{e}^{-tE_n} \langle 0|O_i|n\rangle \left\langle n|O_j^\dagger|0\right\rangle$$

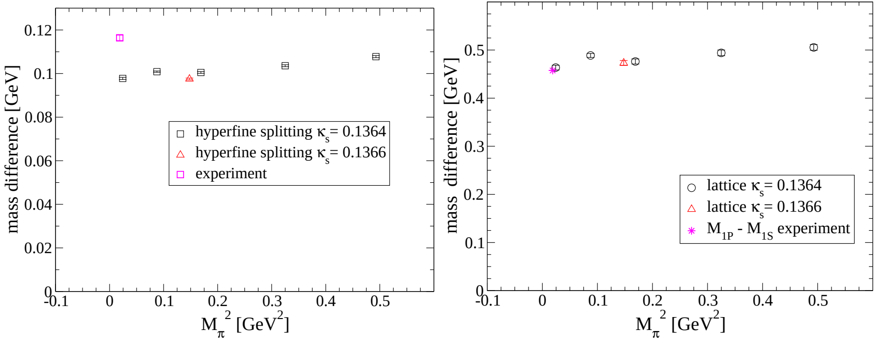
- Solve the generalized eigenvalue problem:

$$C(t)\vec{\psi}^{(k)} = \lambda^{(k)}(t)C(t_0)\vec{\psi}^{(k)}$$
$$\lambda^{(k)}(t) \propto \mathrm{e}^{-tE_k}\left(1+\mathcal{O}\left(\mathrm{e}^{-t\Delta E_k}\right)\right)$$

- At large time separation: only a single mass in each eigenvalue.
- Eigenvectors can serve as a fingerprint.

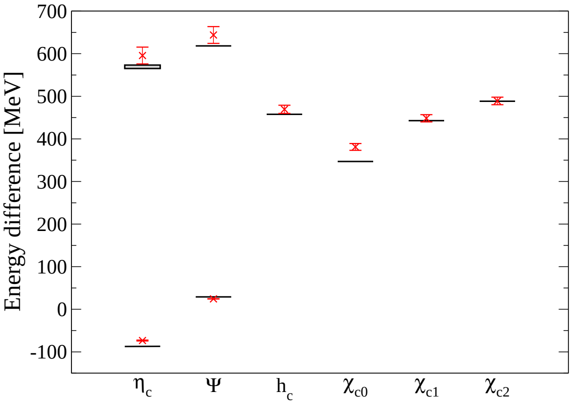
Charmonium results I

- We use the low-lying Charmonium spectrum as a benchmark



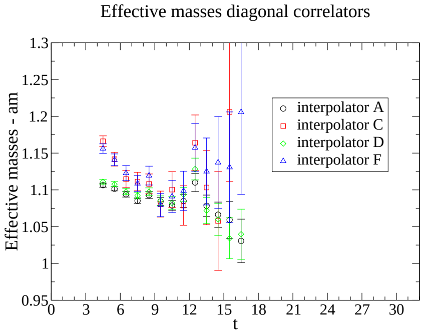
- Noticeable discretization effects expected for Spin-dependent quantities
- Spin-averaged quantities agree nicely with experiment

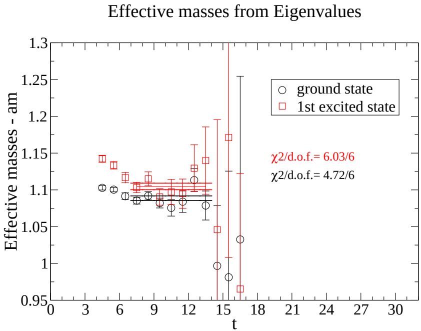
Charmonium results II



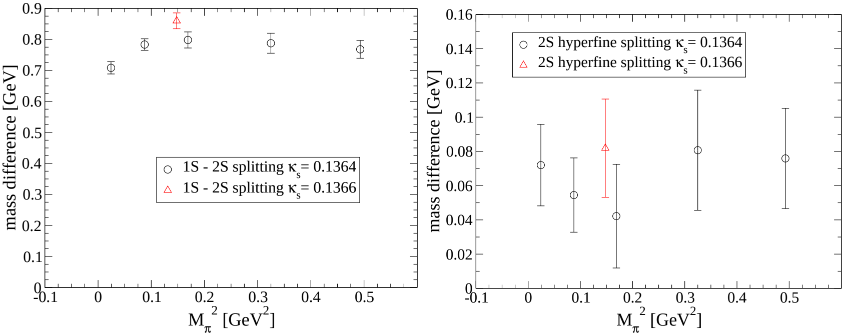
Mass difference	Our results [MeV]	Experiment [MeV]
1S hyperfine	$97.8 \pm 0.5 \pm 1.4$	116.6 ± 1.2
1P spin-orbit	$37.5 \pm 2.4 \pm 0.5$	46.6 ± 0.1
1P tensor	$10.44 \pm 1.13 \pm 0.15$	16.25 ± 0.07
2S hyperfine	$48 \pm 18 \pm 1$	49 ± 4

- In the 1^+ channel we consider mixing between interpolating fields that correspond to positive and negative charge conjugation in the mass-degenerate limit
- Neglecting the mixing leads to mass splitting much smaller than in experiment

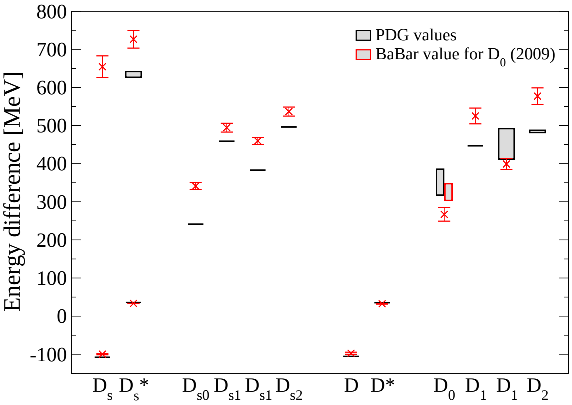




- For D_s mesons we also determine the 2S states
- We obtain a reasonable hyperfine splitting (within somewhat large errors)

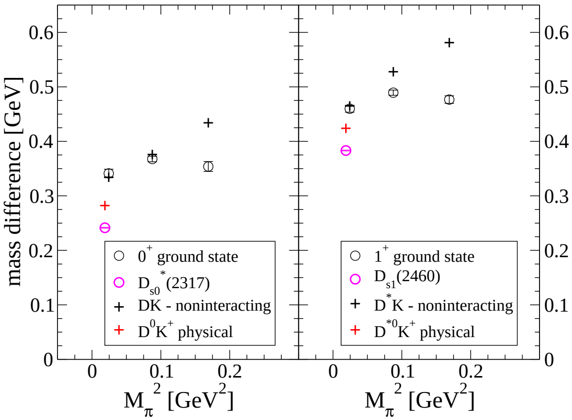


Charmed and charmed strange mesons



- Results for the D_{s0} and D_{s1} ground states differs significantly from experiment
- The results from D and D_s mesons differ significantly

The role of scattering states



- Energy levels are very close to non-interacting scattering states
- The energy of DK and $D^\star K$ states is slightly unphysical
- Future studies will have to include these states in the variational basis

Conclusions

- We determined the spectrum of low-lying charmonium and heavy-light states on configurations with 2+1 flavors of dynamical quarks.
- The charmonium spectrum below the $D\bar{D}$ threshold can be extracted with small discretization effects and agrees favorably with experiment.
- In some cases excited states can also be extracted.
- For P-wave charmed and charmed-strange mesons substantial differences with regard to experiment remain.
- In future studies effects of nearby scattering thresholds and/or the lattice discretization will have to be investigated

Thanks to ...

The PACS-CS collaboration for their gauge configurations

Martin Lüscher for making his DD-HMC code available