Charmonium spectroscopy on N_f=2+1 isotropic lattices

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Introduction

I am going to give an overview of the lattice QCD calculations done by our group that include the charm quark.

- Ratio of masses of the charm and strange quarks.
- Masses of mesons that include the charm quark (η_c, D_s, D_{s0}, ..)
- One graph with charmed exotics.
- One example of a charmed baryon.

This is a joint project between Wuppertal and Regensburg and their collaborations (BMW-c and QCDSF). Slightly more details in write up for the lattice 2011 conference (arXiv:1108.6147). All the results are preliminary.

Brief introduction to lattice QCD

$$c_{ij}(t) = \frac{1}{Z} \int du \int d\psi \overline{d\psi} O(t)_i O(0)_j^\dagger e^{-S_F - S_G}$$

- The path integral is regulated by the introduction of a space-time lattice. Lattice calculations are now being done at several lattice spacings and volumes.
- The multi-dimensional integral is computed in Euclidean space using Monte Carlo techniques on the computer.
- The dynamics of the gluon and quarks is in the Dirac action (S_F) and gauge action (S_G).

$$c_{ij}(t) \sim a_{ij} e^{-m_a t} + b_{ij} e^{-m_b t} + \ldots$$

Key issue

How physical are the parameters (quark mass, lattice spacing..) ?

Details of lattice calculations

The QCDSF collaboration have recently developed a fermion action called SLiNC This is a clover action with stout links in the Wilson term only. Tree level Symanzik gauge action used. Tuning to physical light quark masses via SU3 limit.

n_f	a fm	Vol	M_π MeV
3	0.0795(3)	24^3 48	442
2+1	0.0795(3)	32^3 64	348

Calculations with the 2 hex clover action

The BMW-c collaboration use the 2 hex smeared clover action with the tree level Symanzik improved gauge action. Wide range of light masses and 5 different lattice spacings. Precision calculation of light quark masses (arXiv:1011.2711), and B_k kaon bag parameter (arXiv:1106.3230).

Summary of 2 hex clover ensembles

β	a m_q	a m_s	Volume	a fm	$M_\pi L$	M_π GeV
3.5	-0.041	-0.006	$24^3 \times 48$	0.091	4.61	415
3.5	-0.0437	-0.006	$24^3 \times 64$	0.091	4.13	371
3.5	-0.049	-0.006	$32^3 \times 64$	0.091	3.90	260
3.5	-0.049	-0.012	$32^3 \times 64$	0.091	3.76	256
3.5	-0.05294	-0.006	$64^3 \times 64$	0.091	3.92	131
3.61	-0.0280	0.0045	$32^3 \times 48$	0.075	4.75	390
3.61	-0.0330	0.0045	$48^3 \times 48$	0.075	4.93	265
3.61	-0.0365	-0.003	$64^3 \times 72$	0.075	3.0	120
3.7	-0.0208	-0.005	$32^3 \times 64$	0.064	4.0	390
3.7	-0.0254	-0.005	$48^3 \times 64$	0.064	3.87	250
3.7	-0.0254	0.0	$48^3 \times 64$	0.064	3.94	248
3.7	-0.027	0.0	$64^3 \times 64$	0.064	3.86	187
3.8	-0.014	0.0	$32^3 \times 64$	0.054	4.0	454
3.8	-0.019	0.0	$48^3 \times 64$	0.054	4.01	317
3.8	-0.021	0.0	$64^3 \times 144$	0.054	3.83	220

Lattice QCD and charm physics

- Take the light quark masses and lattice spacing from light quark spectroscopy (m_π, m_k, m_Ω).
- Only valence charm quarks included.
- Charm quark mass from η_c mass. (later also use the D_s meson).

Additional complications with lattice QCD calculations that include the charm quark.

- "Main problem" is the mass of the charm quark is $m_c \sim 1.2$ GeV, so in lattice units (am_c) varies between 0.6 to 0.29 for the 2 hex clover action.
- The leading lattice spacing errors are: $O((am_c)^2)$ or $O(\alpha_s am_c)$ for clover actions.

Extracting the mass of the charm quark

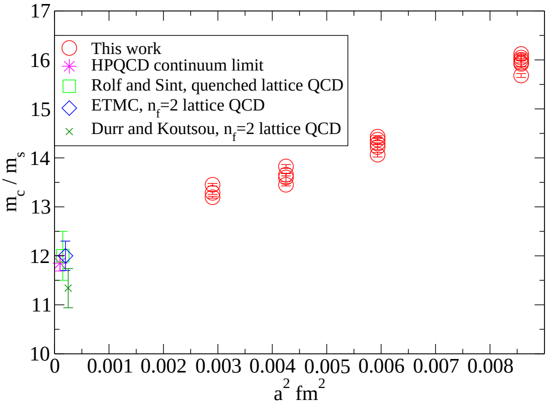
- The calculations are done with 3 heavy quarks close to the charm mass.
- An estimate of the mass of the bare charm quark is made by interpolating to get the mass of heavy hadron correct.
- Use the quark mass defined from the PCAC relation.
- The quark mass needs to be renormalized. Study the ratio of the strange to charm quark masses.

Absolute value of charm mass can be obtained from the mass of the strange quark determined with non-perturbative renormalization (BMW-c collaboration, arXiv:1011.2711).

$$m_s(2 \text{ GeV}) = 95.5(1.1)(1.5)\text{MeV}$$

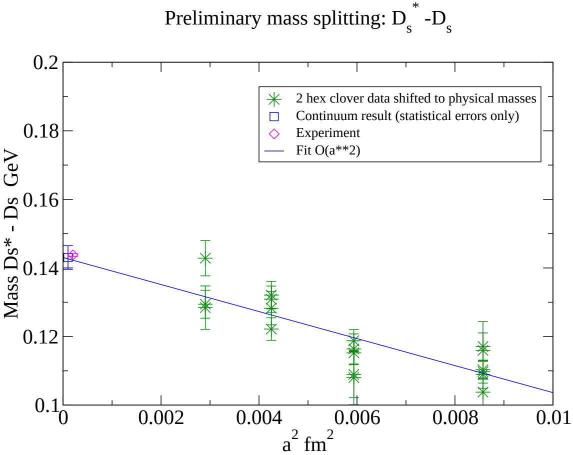
Ratio of masses of the charm and strange quarks

Preliminary analysis. Large lattice spacing errors similar to those seen by the ALPHA collaboration in quenched QCD.



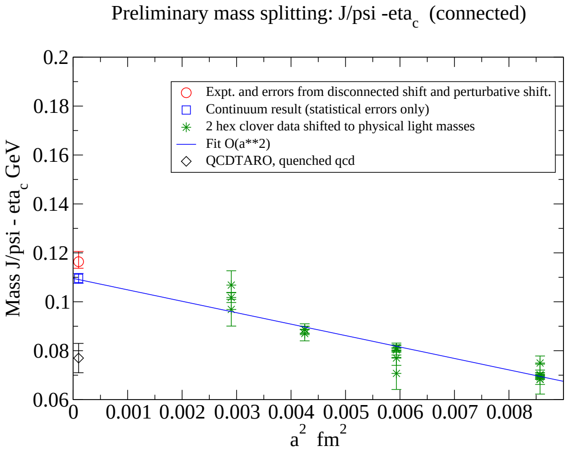
Mass splitting between $D_s^\star$ and D_s mesons.

Results from using the 2 hex clover action

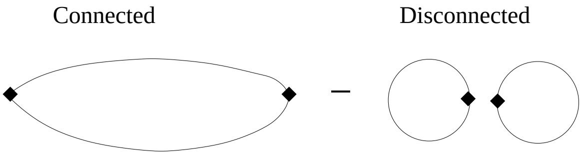


Mass splitting between J/ψ and η_c mesons.

Preliminary results from using the 2 hex clover action.



Comments on charmonium hyperfine splitting



- η_c has a big width (28.6 ± 2.2 MeV) relative to hyperfine splitting
- Disconnected diagrams were not included in this calculation – these are difficult to estimate.
- Levkova and DeTar (arXiv:1012.1837) compute the disconnected diagrams and estimate the effect of them to be upto $+4$ MeV.
- The HPQCD collaboration (hep-lat/0610092) estimate -2.4 MeV from perturbation theory.

$D_{s0}(2317)$

- $D_{s0}(2317)$ discovered in 2003 by BaBar.
- 0^+ state potentially made from strange and charm quark
- The experimental mass was unexpected by groups using potentials and quantum mechanics.
- Is it a molecule/tetraquark? What does the question mean?
- Similar questions for other states: X(3872),Y,Z ..

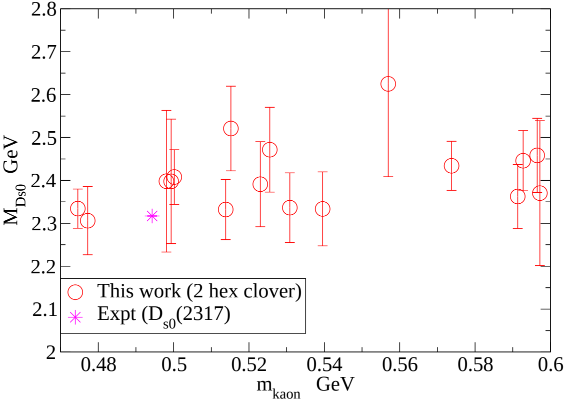
Cleven, Guo, Hanhart, Meissner (1009.3804) suggest studying the mass dependence. They argue that the mass dependence (M_{mol}) of a molecular state should be linear in the kaon mass (M_K)

$$M_{mol} = M_K + M_h - \epsilon$$

where ϵ is the binding energy. For a resonance they claim the mass dependence should be quadratic in the kaon mass.

Mass of 0+ charm-strange state ($D_{s0}(2317)$)

0.5 % errors on mass of 0+ charm-strange from variational method.



Masses of excited states from the lattice

The calculations with SLiNC action used the variational method. A correlation matrix using 3 basis states is computed

$$C_{ij}(t) = \langle O_i(t) O_j^\dagger(0) \rangle$$

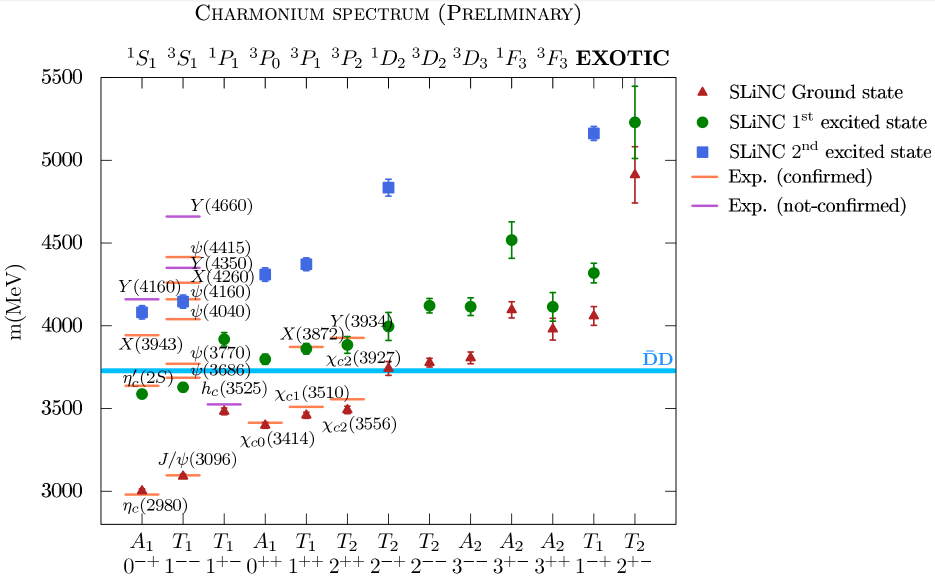
The quarks are smeared with gauge invariant Gaussians with different sizes. The masses of the excited states come essentially from diagonalisation.

$$C^{-1/2}(t_0) C(t) C^{-1/2}(t_0) \sim e^{-E(t-t_0)}$$

Calculations with the 2 hex clover action

The calculations with the 2 hex clover action used a single Gaussian and local sources. The same methods as used for light quark spectroscopy (arXiv:1011.2711). Not designed for excited states, but still useful.

(SLiNC, 24×48, a=0.08 fm, $M_\pi = 442$ MeV)



Triple charmed baryon

- Spin $\frac{3}{2}$ baryon made out of three charm quarks.
- Motivated by Meinel's recent paper (arXiv:1008.3154) on the bbb baryon using NRQCD lattice QCD.
- It is of theoretical interest, eg. three body forces.
- Until recently it wasn't clear whether Ω_{ccc} would be found experimentally. In 1985 Bjorken said "it would be difficult to find, but not unthinkable."

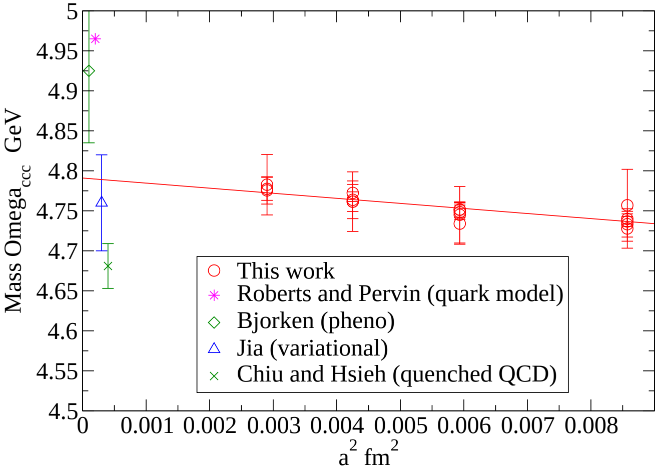
However, recent work by Yu-Qi Chen and Su-Zhi Wu (arXiv:1106.0193)

> $10^4 - 10^5$ *events of triply heavy baryons can be accumulated for 10* fb^{-1} *integrated luminosity*

Prospects are good for experimental detection of Ω_{ccc}.

Preliminary results for Ω_{ccc} baryon

Similar range of predictions for Ω_{bbb} baryon (see Meinel, arXiv:1008.3154)



Conclusions

- On two of the 2 hex clover ensembles there are pion masses close to physical pion masses!!!
- The variational method will be used with the 2 hex clover action.
- As well as checks against experiment there will be cross-checks between two fermion actions.
- Include 2 meson operators in variational basis (Gunnar Bali and Ehmann, arXiv:0911.1238)
- There may be a way to compute wave function at the origin for heavy baryons (eg. arXiv:0902.3087).
- I hope that the LHC experiments will look for triple charmed baryons [1]

Goals

The spectroscopy of heavy hadrons (including exotic mesons) from unquenched lattice QCD should be ready well before the start of the PANDA experiment in 2018.

[1] probably more fun than not finding SUSY, large extra dimensions.