Charmonium spectroscopy from $N_f = 2 + 1$ dynamical anisotropic lattices

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Plan

- Introduction: charmonium; the challenges.
- Lattices.
- Techniques:
  - Particle identification and spin on the lattice.
  - Operator construction (up to 2 derivatives in this work).
  - Distillation: a new definition of smearing and determination of all elements of the quark propagator. [M. Peardon, tomorrow].
  - Variational analysis (not yet incorporated).
- Results.
- Conclusions.

More sophisticated, complete analyses of the low-lying light meson and baryon spectra presented by C. Thomas on Monday & S. Wallace on Tuesday.
Also, J. Foley, C.K. Wong and K.J. Juge presented new results using distillation technology yesterday.

Introduction: why now for Charmonium?

- New experimental results for Charmonium are motivating lattice studies.
  - ~ 10 new resonances in 5 years.
  - many at variance with nonrelativistic quark model predictions (eg $X(3872)$).
  - can we understand the structure of these states: $c\bar{c}$ à la quark model, hybrid states, tetraquark or molecular states.
  - the lightest hybrid charmonium state is expected at > 4.3GeV, the $D\bar{D}$ threshold is above 3.7GeV $\Rightarrow$ threshold effects are important.
- In principle lattice QCD can help to shed light on the nature of the excited spectrum of $c\bar{c}$ states.

Simulation Details

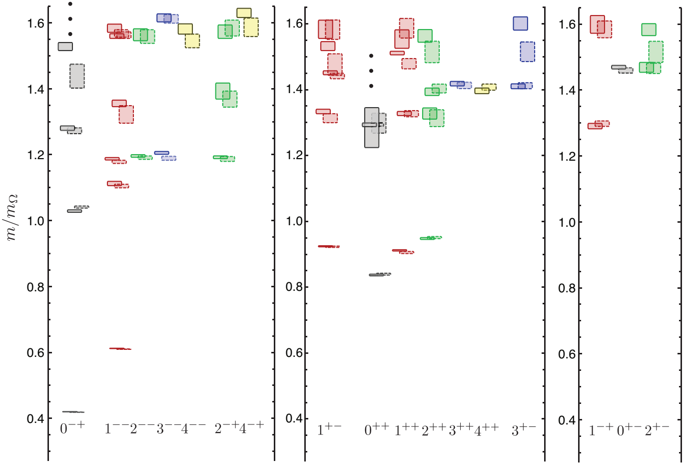
PRD 74 014505,2006 and PRD 79 034502,2009

- Quark field dynamics included in the importance sampling
- 3, 2+1 dynamical flavours
- Anisotropic lattice to enhance temporal resolution. Non-perturbatively tuned to $a_s/a_t = 3.5$.
- Tree-level Symanzik-improved gauge action
- Sheikholeslami-Wohlert quark action
- Spatial stout-link background for quark propagation

Status	N_f	Volume	m_π	$a^{-1}_{(m_\Omega)}$
Exploratory	3	$12^3 \times 96$	702MeV	4.76 GeV
Preliminary	2+1	$16^3 \times 128$	392MeV	5.67 GeV

Light meson spectrum

arXiv:1004.4930



Spin assignment from lattice states

- Continuum spin assignment: form the representations of O_h subduced from $O(3)$. Multiplicities:

J	0	1	2	3	4
A_1, dim 1	1	0	0	0	1
A_2, dim 1	0	0	0	1	0
E, dim 2	0	0	1	0	1
T_1, dim 3	0	1	0	1	1
T_2, dim 3	0	0	1	1	1

- Degeneracies across lattice irreps as continuum is approached.
- Difficulty for charmonium: small HFS, near-degeneracy of many states with different spin assignments.
- A pathological example: hard to distinguish near-degenerate triplet of spin 0,1,2 from spin 4. Both: $A_1 \oplus T_1 \oplus E \oplus T_2$. Can a radial excitation of P-wave $\bar{c}c$ be distinguished from 4^{++} F-wave?

Distillation I: Smearing redefined

Phys.Rev.D80:054506,2009; and M. Peardon talk tomorrow

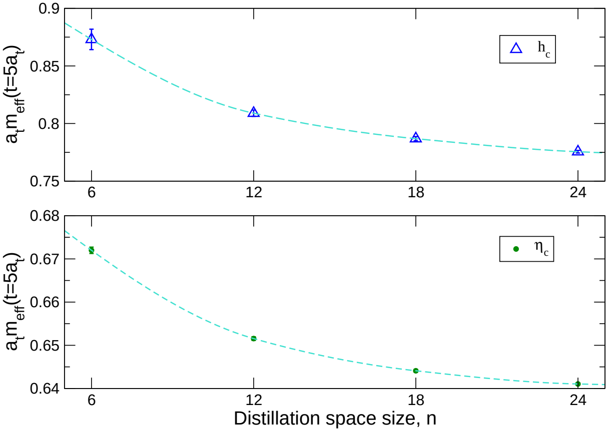
- Redefine smearing to be a projection operator onto a low-dimensional space of fields:

$$\square = \sum_{k=1}^{M} v^{(k)} \otimes v^{(k)*}$$

- This is distillation.
- How to choose v? the lowest M eigenvectors of Δ^2, the lattice Laplacian. Not unique.

Very useful for excited states, disconnected diagrams and multi-hadron states.

How big should the distillation space be?



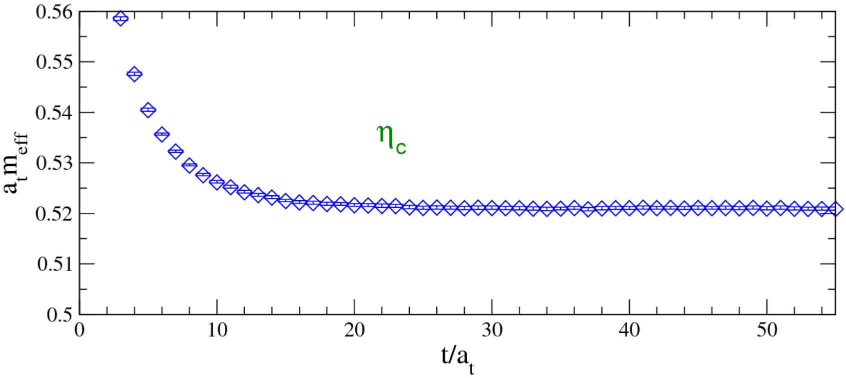
- $12^3 \times 96$. S-wave (η_c) and P-wave (h_c) still falling as n increased.
- The space is large but feasible.
- This work: $n = 32$ on $16^3 \times 128$ lattices. Volume scaling $\Rightarrow$ use $n = 56$. Running $n = 64$.

The spectrum analysis

- m_c tuned from the η_c mass.
- $12^3 \times 96$ lattices used for testing. Preliminary results on $16^3 \times 128$ lattices.
- Results on 100 configurations with perambulators on 4 timeslices for $12^3 \times 96$; 32 configurations and perambulators on all timeslices for $16^3 \times 128$ lattices.
- Only single exponential fits to single correlators presented here.
- Chi-by-eye, no sliding window analysis in effective mass fits.
- A full variational analysis is planned.

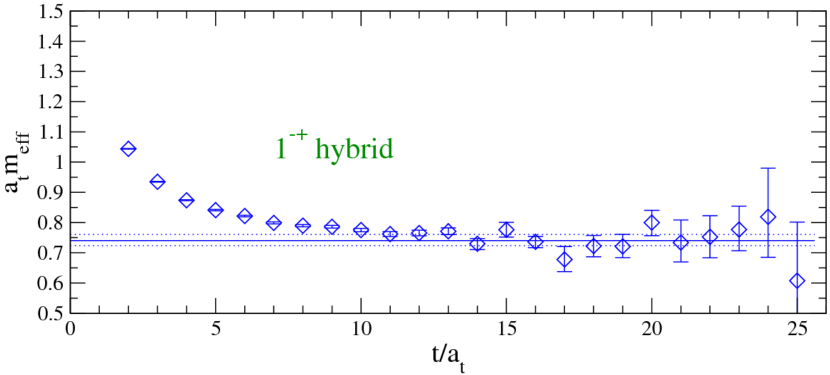
The spectrum: preliminary η_c

- Effective mass of the η_c
- $16^3 \times 128$ lattice, 32 configurations, perambulators on all t.
- Errors $< 1\%, < 1\mathrm{MeV}$ on fitted mass.



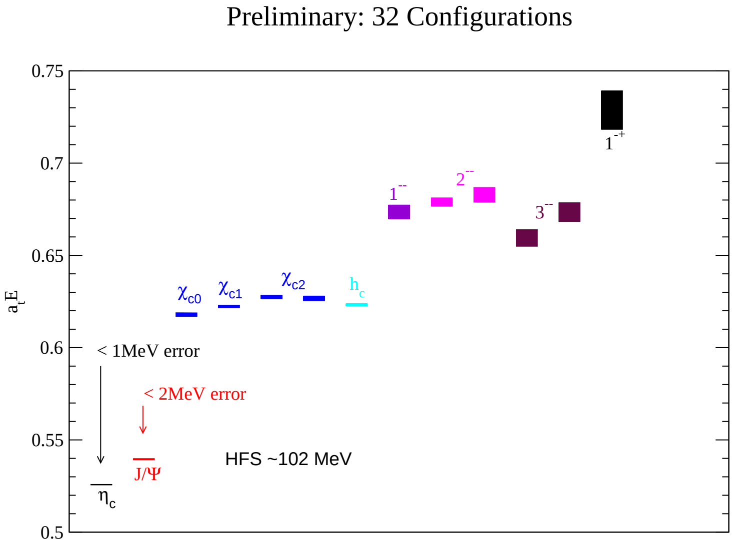
The spectrum: preliminary 1^{-+} hybrid

- Effective mass of the $1^{-+}\mathrm{hybrid}$
- $16^3 \times 128$ lattice, 32 configurations, perambulators on all t.
- Errors $< 2\%, \sim 60\mathrm{MeV}$ on fitted mass.



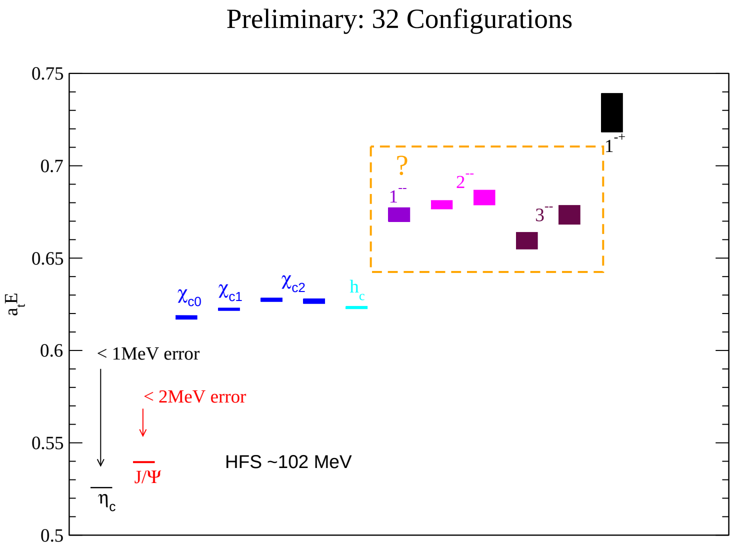
The spectrum: preliminary

assuming a quark-model spin identification ...



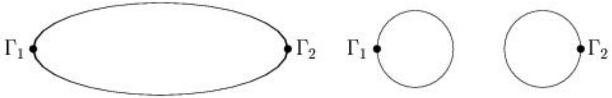
The spectrum: preliminary

assuming a quark-model spin identification ...



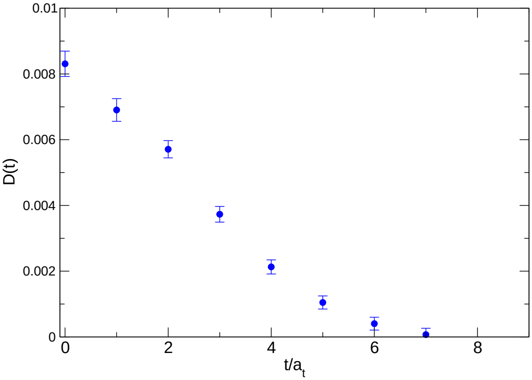
Including disconnected diagrams (1)

$c\bar{c}$ interpolating operators are singlet ($\bar{c}\Gamma c$) $\rightarrow$ bubble diagrams in Wick contractions.



OZI suppressed $\Rightarrow$ small. Unless other nonperturbative effects play a role.
Handled easily with distillation.

Including disconnected diagrams (2)

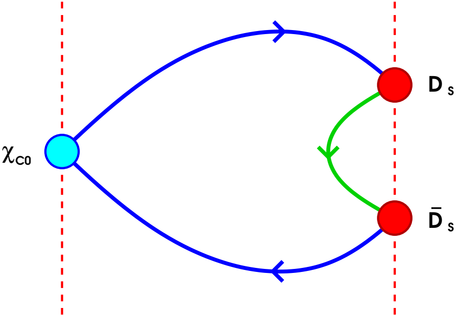


The disconnected contribution to η_c ($12^3 \times 96$).

- Fit $(1 - D/C)$ to resolve the $m_{\eta_c(C-D)} - m_{\eta_c(C)}$ difference.
- Needs a variational analysis of connected correlator to fit $(1 - D/C)$ at small time, $t < 6$.
- All very preliminary yet - a full analysis is underway on $16^3 \times 128$.

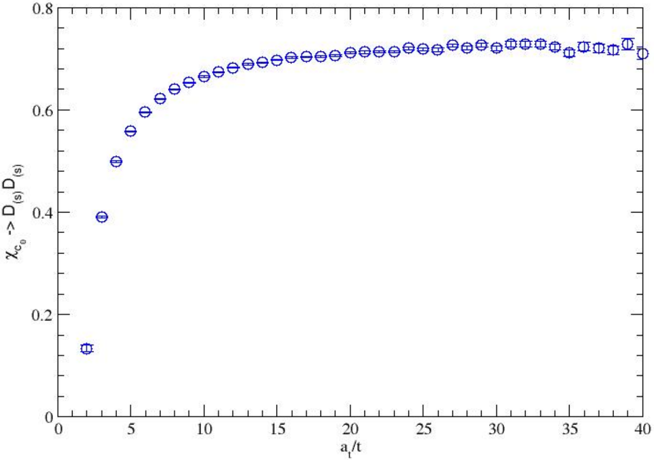
Including threshold effects: a start

Calculating threshold effects is (relatively) straightforward with distillation. Eg. one needs to determine the S-wave mixing



The effective mass for $\chi_{c_0} \to D_s \bar{D}_s$

On $12^3 \times 96$



Conclusions

- This is a first application of distillation to charmonium. Very promising already on just 32 configs. $n = 64$ data should improve again.
- The Hadron Spectrum Collab. is continuing to generate perambulators on all timeslices.
- The combination of anisotropic lattices, distillation and variational fitting techniques mean the orbital, radial and gluonic excitations of Charmonia can be resolved.
- Additional operators will give a definitive spin identification of calculated excited states. In progress.
- A similar analysis is in progress for the heavy-light ($D_{(s)}$) system
- Simulations at lighter sea quark masses, larger volumes etc are planned.
- Distillation allows us to investigate threshold and disconnected effects.
- GPU implementation is proving very efficient for charmonium.