Charmonium spectroscopy from Lattice QCD

Daniel Mohler

Baltimore,
April 9, 2015

Fermilab

Outline

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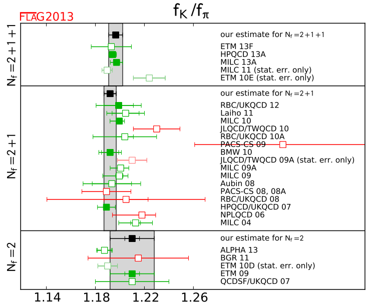
1. Introduction
2. Charmonia from single-hadron operators
   - Low lying charmonia
   - New results on the 1S hyperfine splitting
   - New results on charmonium 1P states and 2S states
   - Exited state energy levels from $\bar{q}q$
   - Gluonic excitations
3. Charmonia including meson-meson states
   - The $\psi(2S)$ and $\Psi(3770)$
   - χ'_{c0} and $X/Y(3915)$
   - Lattice results for the $X(3872)$
   - Searches for Z_c and $Y(4140)$
4. Conclusions and Outlook

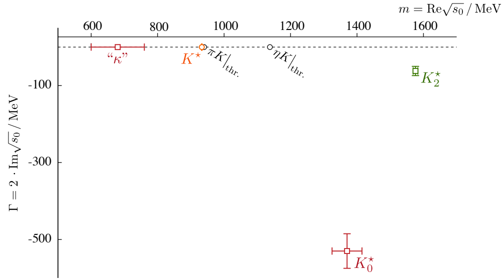
Precision results:



Example: FLAG review

See http://itpwiki.unibe.ch/flag/

Exploratory studies:



Example: πK-ηK-scattering

`Dudek et al. PRL 113 182001 (2014)`

See talk by David Wilson Fri

- I will report on both kind of progress with regard to charmonium
- There will be preliminary data - use with caution

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Low-lying charmonium: A precision benchmark

- Well understood from potential models
- Well determined in experiment
- Well separated from open-charm threshold(s)
- Spin-dependent mass splittings extremely sensitive to the charm-quark mass and heavy-quark discretization

meson	mass	width
η_c	2983.7(7)	32.0(9) MeV
J/Ψ	3096.916(11)	92.9(2.8) keV
χ_{c0}	3414.75(31)	10.3(6) MeV
χ_{c1}	3510.66(3)	0.86(5) MeV
χ_{c2}	3556.20(9)	1.97(11) MeV
h_c	3525.38(11)	0.7(4) MeV
$\eta_c(2S)$	3639.4(1.3)	$11.3^{(+3.2)}_{(-2.9)}$ MeV
$\Psi(2S)$	$3686.109^{(+12)}_{(-14)}$	299(8) keV

Preliminary results from Fermilab-MILC

`Fermilab Lattice and MILC collaborations - to be published`

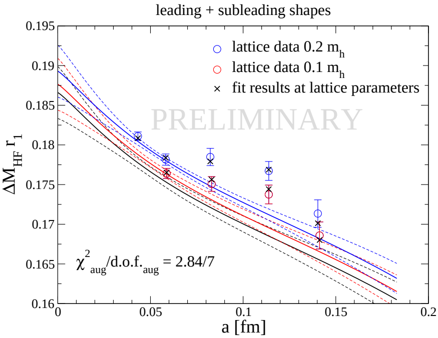
We use the *Fermilab method* for the charm quark

`El-Khadra et al., PRD 55, 3933 (1997)`

- m_c tuned by demanding the D_s meson kinetic mass to be physical
- We quote splittings among charmonium states
- 5 lattice spacings with two different light sea-quark masses
  $\rightarrow$ Controlled extrapolation to the chiral-continuum limit
- 2+1 flavor simulation with high statistics
- Follows previous efforts

  `T. Burch et al. PRD 81 034508, 2010`
- Charm annihilation contributions are omitted

Fermilab-MILC results for the 1S hyperfine splitting

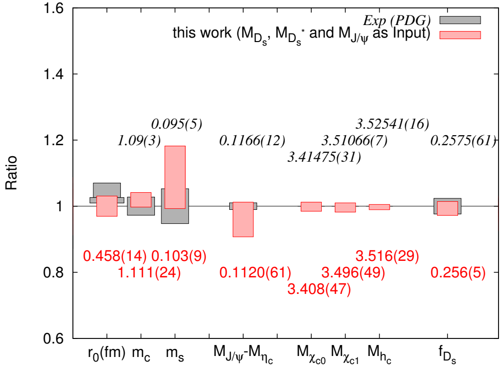


- Curves for physical (black), $0.1m_s$, and $0.2m_s$ light-quark masses
- This corresponds to $M_{J/\Psi} - M_{\eta_c} = 118.1(2.1)\binom{-1.5}{-4.0}$
- Errors include statistics, chiral and continuum extrapolations
- Contribution from disconnected diagrams expected $\binom{-1.5}{-4.0}$

Levkova and DeTar, PRD 83 074504, 2011

Results from the χQCD Collaboration

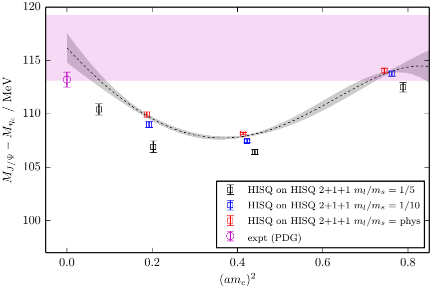
χQCD Collaboration, Yang *et al.* arXiv:1410.3343



- Results from Overlap fermions on 2+1 flavor domain wall gauge configurations
- Uncertainty do not include charm-quark annihilation effects

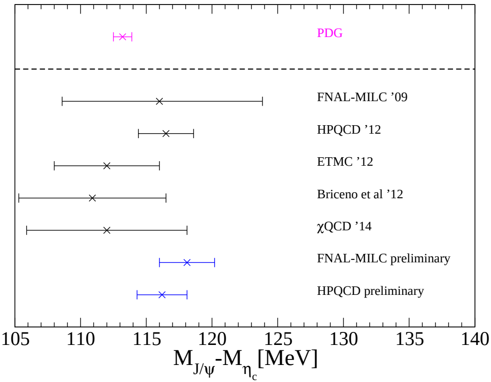
Preliminary results from the HPQCD Collaboration

`HPQCD, Galloway et al. PoS LATTICE2014 (2014) 092`



- Uses MILC 2+1+1 flavor HISQ (Highly Improved Staggered Quarks) ensembles
- Systematics on 1S hyperfine dominated by estimate of annihilation effects

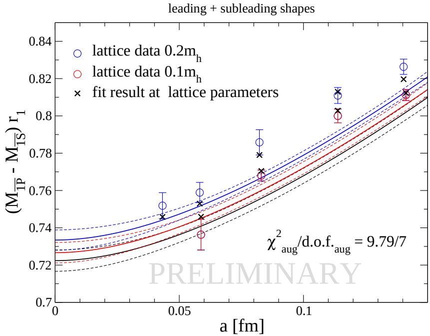
A comparison of hyperfine splittings

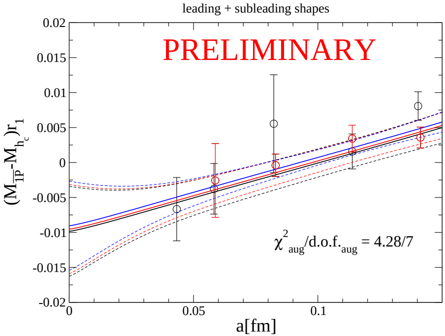


- All results at physical quark masses and in the continuum limit
- Lattice numbers exclude (now dominant?) annihilation effects
- Estimate from data expects a shift of -1.5..-4.5 MeV

Levkova and DeTar, PRD 83 074504, 2011

Fermilab-MILC 1P-1S and 1P hyperfine splittings





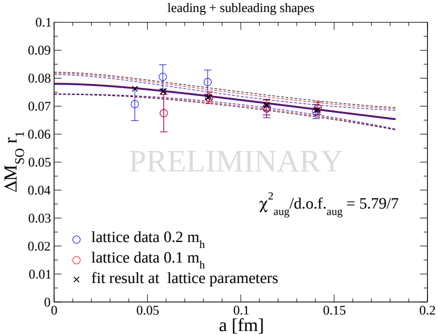
- Not yet included: Scale-setting uncertainty

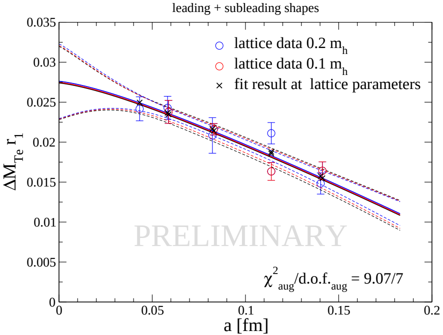
Mass difference	This analysis [MeV]	Experiment [MeV]
1P1S	457.3 ± 3.6	457.5 ± 0.3
1P hyperfine	-6.2 ± 4.1	-0.10 ± 0.22

Fermilab-MILC P-wave spin-orbit and tensor splittings

$$\Delta M_{\text{Spin-Orbit}} = (5M_{\chi_{c2}} - 3M_{\chi_{c1}} - 2M_{\chi_{c0}})/9$$

$$\Delta M_{\text{Tensor}} = (3M_{\chi_{c1}} - M_{\chi_{c2}} - 2M_{\chi_{c0}})/9$$

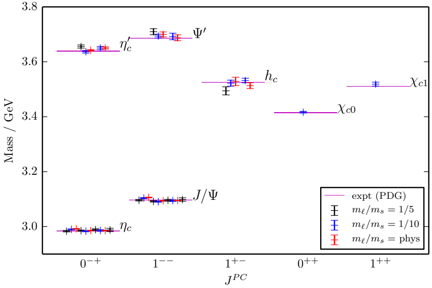


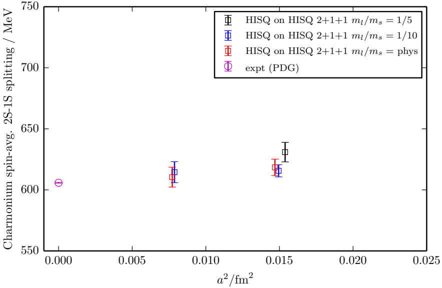


Mass difference	This analysis [MeV]	Experiment [MeV]
1P spin-orbit	49.5 ± 2.5	46.6 ± 0.1
1P tensor	17.3 ± 2.9	16.25 ± 0.07

Preliminary results from the HPQCD Collaboration

HPQCD, Galloway *et al.* PoS LATTICE2014 (2014) 092

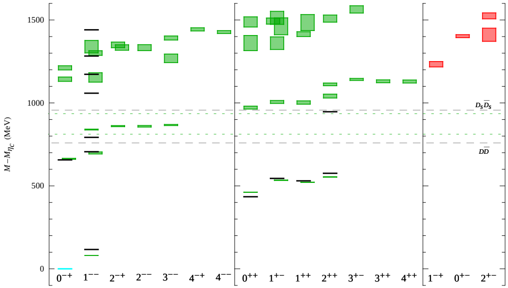




- Uses MILC 2+1+1 flavor HISQ (Highly Improved Staggered Quarks) ensembles
- Shaded region shows the systematic uncertainty

Exited state energy levels from $\bar{q}q$ operators

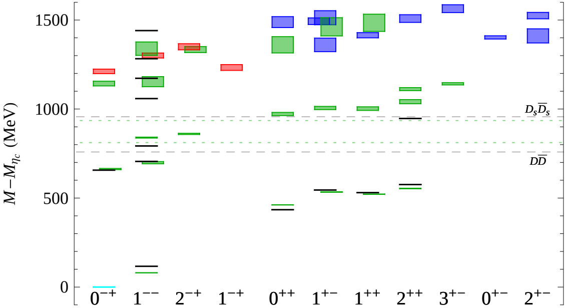
HSC, L. Liu et al. JHEP 1207 126 (2012)



- A large number of energy levels including higher spin states can be identified
- Mesons with spin-exotic quantum numbers!
- Relation of energy levels to resonances not straight forward

Gluonic excitations

HSC, L. Liu et al. JHEP 1207 126 (2012)



- Hybrid mesons with both regular and spin-exotic quantum numbers
- Relation of energy levels to resonances not straight forward

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Single hadron interpolators: what do we see?

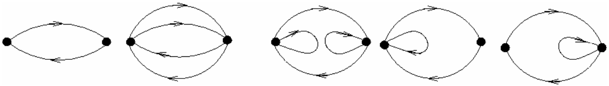
- In practical calculations $\bar{q}q$ and qqq interpolators couple very weakly to multi-hadron states

  McNeile & Michael, Phys. Lett. B 556, 177 (2003); Engel et al. PRD 82, 034505 (2010); Bulava et al. PRD 82, 014507(2010); Dudek et al. PRD 82, 034508(2010);

- This is not unlike observations in QCD string-breaking studies

  Pennanen & Michael hep-lat/0001015;Bernard et al. PRD 64 074509 2001;

- Necessitates the inclusion of hadron-hadron interpolators

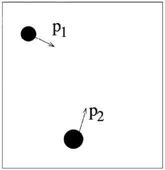


- We know: Energy levels $\neq$ resonance masses
  Naïve expectation: Correct up to $\mathscr{O}(\Gamma_R(m_\pi))$
- Was good enough for heavy pion masses where one would deal with bound states or very narrow resonances.

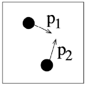
The Lüscher method

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

$$E = E(p_1) + E(p_2)$$



L >> few fm



L= few fm

$$E = E(p_1) + E(p_2) + \Delta_E$$

$$E_n(L) \quad \xrightarrow{(2)} \quad \delta_l \quad \xrightarrow{(3)} \quad m_R; \quad \Gamma_R \text{ or coupling } g$$

(1) Extract energy levels $E_n(L)$ in a finite box

(2) Lüscher formula $\rightarrow$ phase shift of the continuum scattering amplitude

(3) Extract resonance parameters (similar to experiment)

- 2-hadron scattering and transitions well understood; progress for 3 (or more) hadrons but difficult

See LATTICE2014 plenary by Raúl A. Briceño, arXiv:1411.6944

Technicalities: 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)`

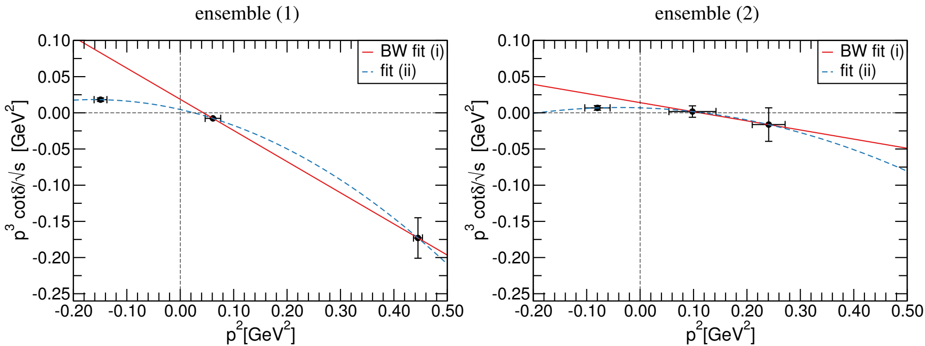
- On the small volume we use distillation
  On the larger volume we use stochastic distillation

  `Peardon et al. PRD 80, 054506 (2009);`

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

Ψ(3770) resonance from Lattice QCD

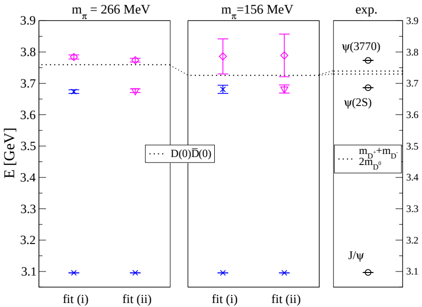
Lang, Leskovec, DM, Prelovsek, arXiv:1503.05363



- Proof of principle - many improvements possible

Ψ(3770) resonance: Results

Lang, Leskovec, DM, Prelovsek, arXiv:1503.05363



	Mass [MeV]	$g_{\Psi(3770)DD}$
Ensemble(1)	3784(7)(8)	13.2 (1.2)
Ensemble(2)	3786(56)(10)	24(19)
Experiment	3773.15(33)	18.7(1.4)

- First resonance determination of a charmonium state
- Proof of principle - many improvements possible

χ'_{c0} and $X/Y(3915)$

- PDG is identifying the $X(3915)$ with the χ'_{c0}
- Based on BaBar determination of its quantum numbers
- Some of the reasons to doubt this assignment:

Guo, Meissner Phys. Rev. **D**86, 091501 (2012)

Olsen, arxiv 1410.6534

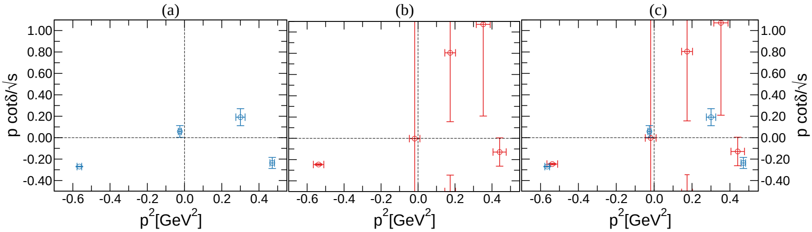
  - No evidence for fall-apart mode $X(3915) \to \bar{D}D$
  - Spin splitting $m_{\chi_{c2}(2P)} - m_{\chi_{c0}(2P)}$ to small
  - Large OZI suppressed $X(3915) \to \omega J/\psi$
  - Width should be significantly larger than $\Gamma_{\chi_{c2}(2P)}$
- Investigate $\bar{D}D$ scattering in S-wave on the lattice!
- Candidates:

$$m = 3837.6 \pm 11.5 \text{ MeV}, \qquad \Gamma = 221 \pm 19 \text{ MeV} \qquad \text{Guo\&Meissner}$$

$$m = 3878 \pm 48 \text{ MeV}, \qquad \Gamma = 347 \begin{array}{c} +316 \\ -143 \end{array} \text{ MeV} \qquad \text{Olsen}$$

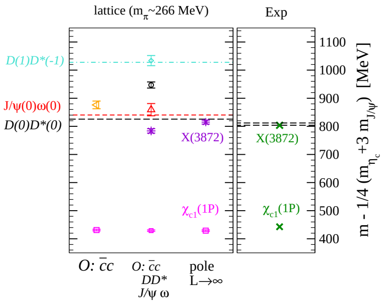
χ'_{c0}: Exploratory lattice calculation

Lang, Leskovec, DM, Prelovsek, arXiv:1503.05363

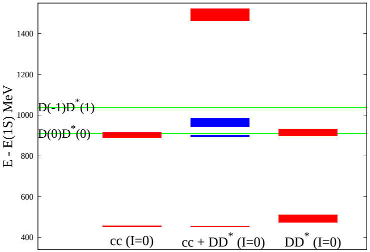


- Assumes only $\bar{D}D$ is relevant
- Lattice data suggests a fairly narrow resonance with $3.9\text{GeV} < M < 4.0\text{GeV}$ and $\Gamma < 100\text{MeV}$
- Future experiment and lattice QCD results needed to clarify the situation

An $X(3872)$ candidate from Lattice QCD



Prelovsek, Leskovec, PRL 111 192001 (2013)

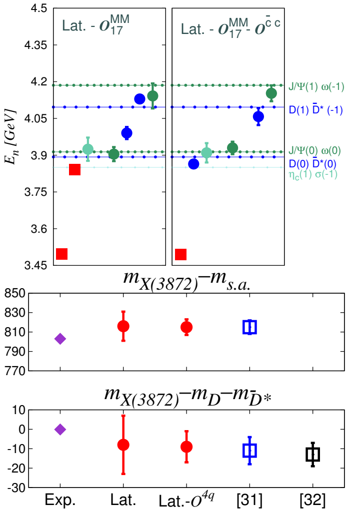


Lee, DeTar, DM, Na, arXiv:1411.1389

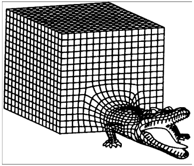
- Neglects charm annihilation and $J/\psi\omega$
- Seen only when $\bar{q}q$ and $\bar{D}^*D$ are used
- The two simulations have vastly different systematics (yet results are similar)

An $X(3872)$ candidate from Lattice QCD II

Padmanath, Lang, Prelovsek, arXiv:1503.03257

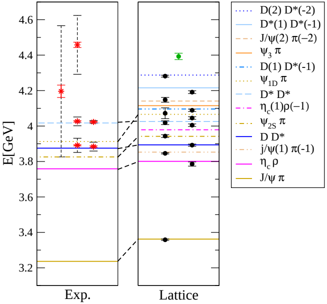


- Without $\bar{q}q$ interpolators signal vanishes
- Simulations still unphysical in many ways
- Discretization and finite volume effects sizable!



- Makes interpretation as pure molecule or pure tetraquark unlikely

Search for Z_c^+ with $I^G J^{PC} = 1^+ 1^{+-}$

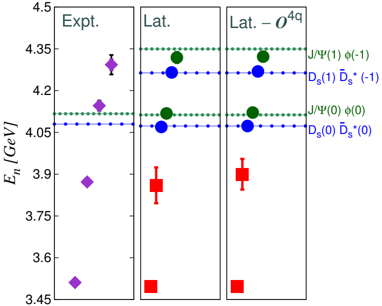


Prelovsek, Lang, Leskovec, DM, Phys.Rev. D91 014504 (2015)

- Simple level counting approach
- We find 13 two meson states as expected
- We find no extra energy level that could point to a Z_c candidate

Search for $Y(4140)$ with $J^{PC} = 1^{++}$

Padmanath, Lang, Prelovsek, arXiv:1503.03257



- Considered only $J/\psi\phi$ and $D_s\bar{D}_s^*$
- No additional energy level seen
- Further simulations necessary

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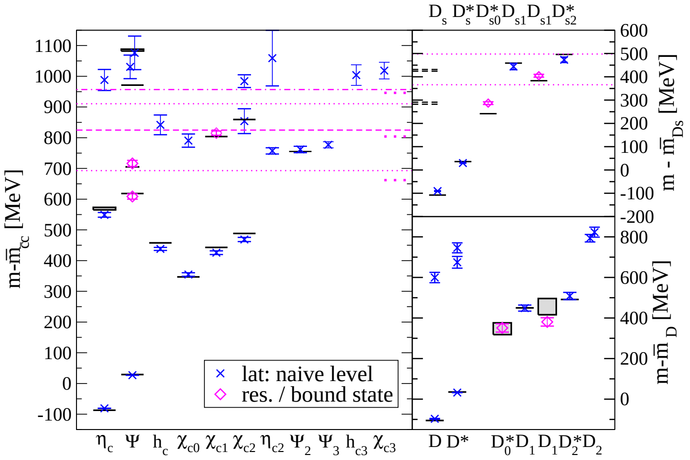
Snapshot of spectrum calculations at $m_\pi = 266 MeV$



- First principles determination of resonances and bound states just starting
- Program will have to be done with a number of lattice spacings/volumes

Conclusions & Outlook

- Most current charmonium and charmed meson results are of an exploratory nature
- Low-lying charmonium states are under good control (full error budgets)
- New ideas might be needed for charm-annihilation contributions
- Progress with regard to hybrids and higher spin states
- Bound states and resonances close to $D\bar{D}$, $D\bar{D}^*$ and $D^*\bar{D}^*$ can be investigated
- No signal yet for manifestly exotic four quark states
- For states well established on the lattice: calculation of radiative transitions, etc. possible (and will be done)
- A lot of progress but still much to do for excited charmonium

Thank you!

... also to my collaborators Carleton DeTar, Andreas Kronfeld, Christian Lang, Song-Haeng Lee, Luka Leskovec, Ludmila Levkova, Sasa Prelovsek and Jim Simone

Backup slides

• • •

Heavy quarks using the *Fermilab method*

El-Khadra et al., PRD 55,3933

- We tune κ for the spin averaged kinetic mass $(M_{\eta_c} + 3M_{J/\Psi})/4$ 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 three different fit strategies
- Energy splittings are expected to be close to physical
- For MeV values of masses

$$M = \Delta M + M_{sa,phys}$$

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- On the small volume we use distillation
  On the larger volume we use stochastic distillation

  `Peardon et al. PRD 80, 054506 (2009);`

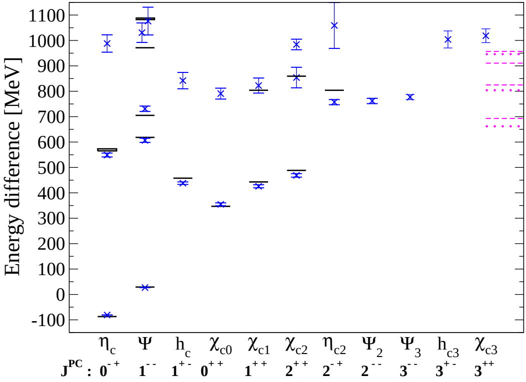
  `Morningstar et al. PRD 83, 114505 (2011)`

Testing our tuning: charm and light

	Ensemble (1)	Ensemble (2)	Experiment
m_π	266(3)(3)	156(7)(2)	139.5702(4)
m_K	552(1)(6)	504(1)(7)	493.677(16)
m_ϕ	1015.8(1.8)(10.7)	1018.4(2.8)(14.6)	1019.455(20)
m_{η_s}	732.3(0.9)(7.7)	692.9(0.5)(9.9)	688.5(2.2)*
$m_{J/\Psi} - m_{\eta_c}$	107.9(0.3)(1.1)	107.1(0.2)(1.5)	113.2(0.7)
$m_{D_s^*} - m_{D_s}$	120.4(0.6)(1.3)	142.1(0.7)(2.0)	143.8(0.4)
$m_{D^*} - m_D$	129.4(1.8)(1.4)	148.4(5.2)(2.1)	140.66(10)
$2m_{\overline{D}} - m_{\overline{c}c}$	890.9(3.3)(9.3)	882.0(6.5)(12.6)	882.4(0.3)
$2M_{\overline{D_s}} - m_{\overline{c}c}$	1065.5(1.4)(11.2)	1060.7(1.1)(15.2)	1084.8(0.6)
$m_{D_s} - m_D$	96.6(0.9)(1.0)	94.0(4.6)(1.3)	98.87(29)

- A single ensemble: Discrepancies due to discretization and unphysical light-quark masses expected

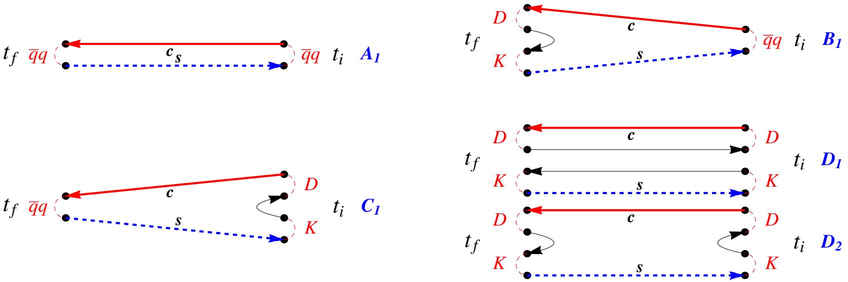
Low-lying charmonium spectrum



DM, S. Prelovsek, R. M. Woloshyn, PRD 87 034501 (2013);

- Serves as further confirmation of our heavy-quark approach
- Data from 1 ensemble; Errors statistical + scale setting

Contractions

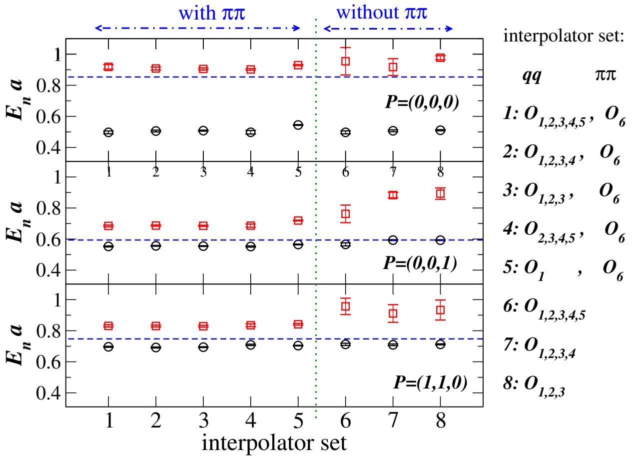


- Handled efficiently within the distillation method

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

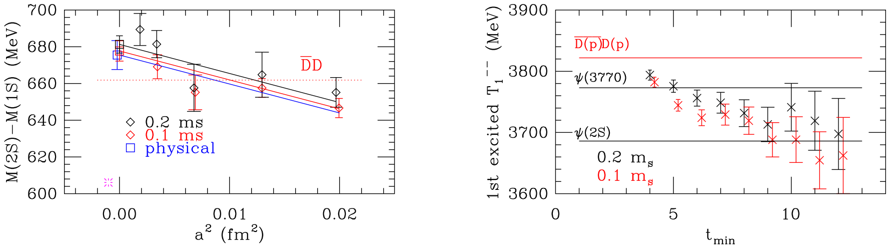
An example: Different rho momentum frames

Lang, DM, Prelovsek, Vidmar, PRD 84 054503 (2011) & erratum ibid



2S states

Fermilab/MILC, DeTar *et al.* arXiv:1410.3343



- Simple analysis of 2S states lead to splittings much larger than in experiment
- Strong dependence on fit range and very noisy data