Lattice results on Charmonium and Open Charm

Daniel Mohler

Giessen,
March 19, 2015

Fermilab

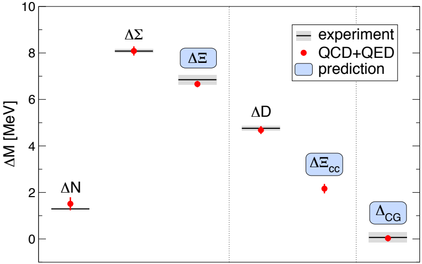
Outline

Outline

Recent progress in lattice QCD

"... there is every reason to expect that progress in LQCD will continue in the future, to the extent that precise LQCD predictions will be available when the PANDA experiment starts." – Physics Performance Report for: $\bar{P}$ANDA, 2009

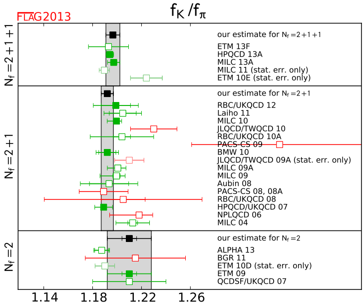
- Dynamical simulations with 2+1(+1) quark flavors
- Simulations at physical pion masses
- Isospin splitting and QCD+QED simulations



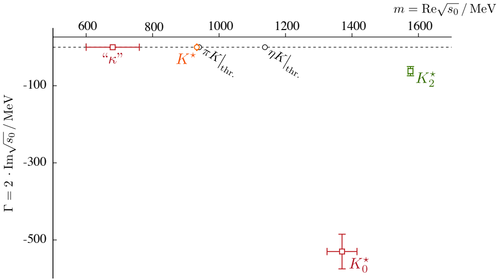
BMW Collaboration, Borsanyi et al. arXiv:1406.4088

Two kinds of progress...

Precision results:



Exploratory studies:



Example: FLAG review

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

Example: πK-ηK-scattering

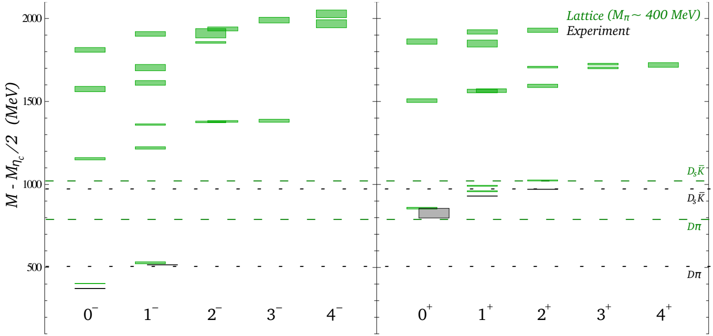
`Dudek et al. PRL 113 182001 (2014)`

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

Outline

Energy level from $\bar{q}q$ operators at $m_\pi = 400MeV$

D meson spectrum:

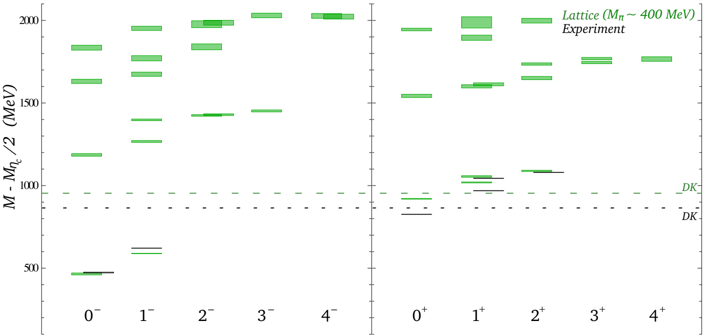


HSC, Moir et al. JHEP 1305 (2013) 021

- Energy levels related to high spin states can be identified
- Relation of energy levels to resonances not straight forward

Energy level from $\bar{q}q$ operators at $m_\pi = 400 MeV$

D_s meson spectrum:



HSC, Moir et al. JHEP 1305 (2013) 021

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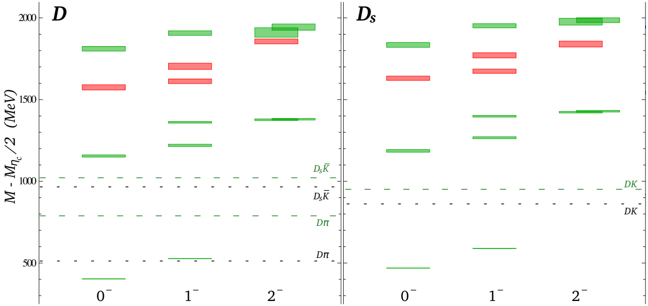
Gluonic excitations

HSC, Moir et al. JHEP 1305 (2013) 021



- Red energy level show the hybrid meson candidates with $P = -$
- Hybrid state candidates seen for various quantum numbers

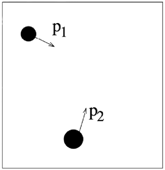
Experimental D_s spectrum

- 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:
  - $D_{s1}^*(2700)$ seen by BaBar, Belle, LHCb (1^-)
  - $D_{sJ}^*(2860)$ seen by BaBar
    LHCb overlapping 1^- and 3^- states
  - $D_{sJ}^*(3040)$ seen by BaBar (1^+?,2^-?)
- $j = \frac{1}{2}$ doublet almost mass-degenerate with non-strange states
- Some models suggest a tetraquark/molecular interpretations for controversial states
- (Most) lattice studies using single hadron ($c\bar{s}$) operators get too large or badly determined masses
- Large m_π: $D_{s0}^*(2317)$ below DK threshold;
  Small m_π: $D_{s0}^*(2317) \approx DK$ threshold

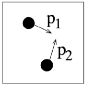
The Lüscher method

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

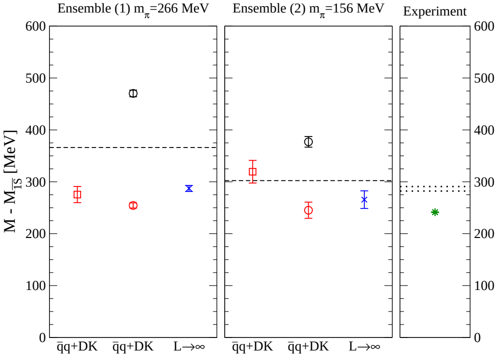
(3) Extract resonance parameters (similar to experiment)

- 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

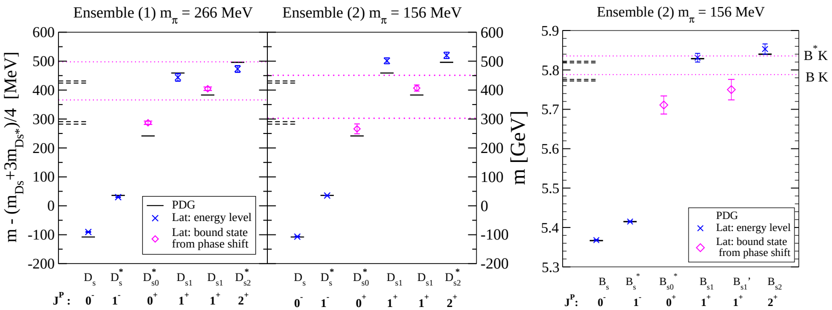
$D_{s0}^*(2317)$ including D meson - Kaon

DM, Lang, Leskovec, Prelovsek, Woloshyn, PRL 111 222001 (2013)



- Much better quality of the ground state plateau with combined basis
- $D_{s0}^*(2317)$ as a QCD bound state
- Suggests that including multi-hadron levels is vital

Resulting D_s and B_s P-wave spectrum



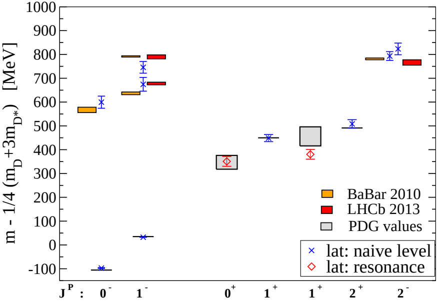
- Remaining differences of the size of discretization uncertainties
- Many improvements possible for the D_s states
- Predicted corresponding B_s states with full uncertainty estimate

C. B. Lang, DM, S. Prelovsek, R. M. Woloshyn arXiv:1501.01646

Resonances in $D\pi$ and $D^\star\pi$ scattering

DM, Prelovsek, Woloshyn, PRD 87 034501 (2013)

- For resonances determine coupling g rather than $\Gamma = g^2 \frac{p^*}{s}$ (for s-wave)
- Data at $m_\pi = 266 MeV$ on a single volume / lattice spacing



	$D_0^*(2400)$	$D_1(2430)$
g^{lat} [GeV]	2.55 ± 0.21	2.01 ± 0.15
g^{exp} [GeV]	1.92 ± 0.14	2.50 ± 0.40

Outline

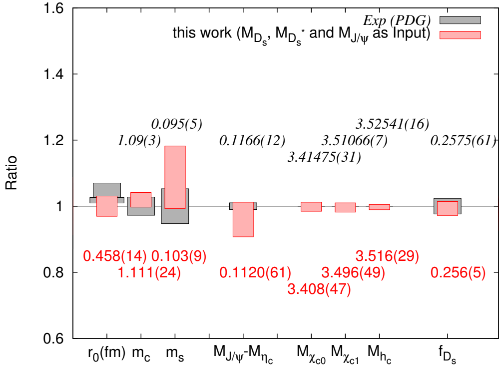
Low-lying charmonium: A precision benchmark

- Well understood from potential models
- Well determined in experiment
- 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

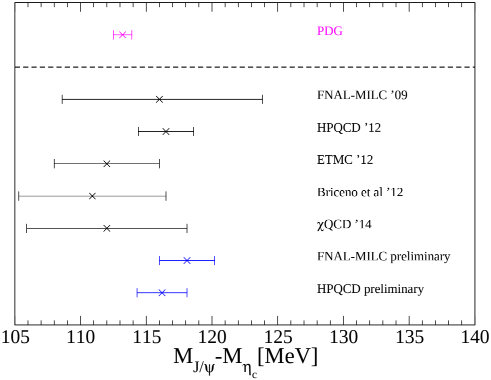
Results from the χQCD Collaboration

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

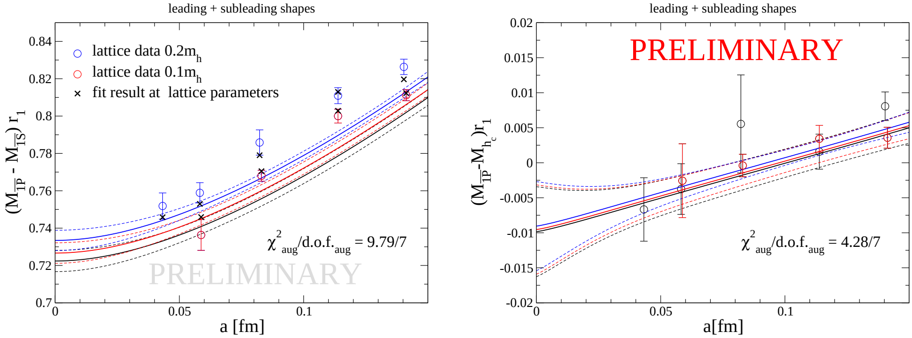
A comparison of hyperfine splittings



- 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`

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



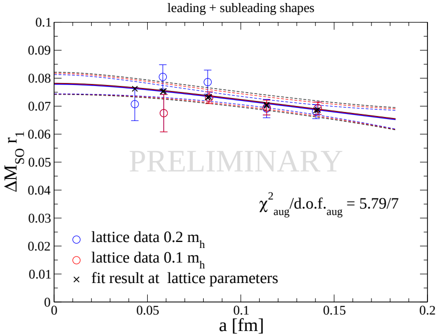
- Not yet included: Scale-setting uncertainty

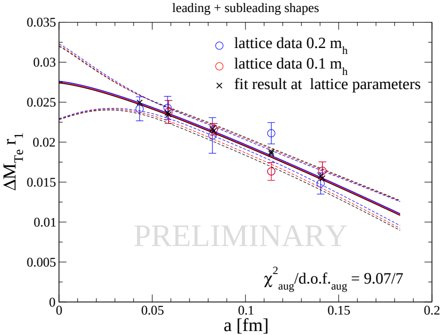
Mass difference	This analysis [MeV]	Experiment [MeV]
1P1S	457.3 ± 3.6	457.5 ± 0.3
1P hyperfine	-6.2 ± 4.1	-0.10 ± 0.22

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

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

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

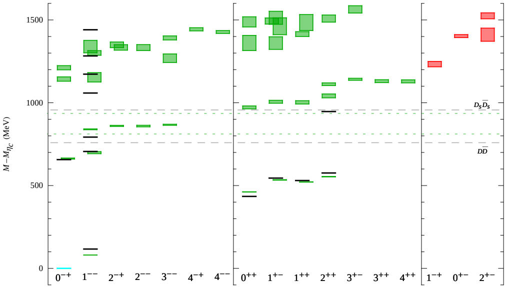




Mass difference	This analysis [MeV]	Experiment [MeV]
1P spin-orbit	49.5 ± 2.5	46.6 ± 0.1
1P tensor	17.3 ± 2.9	16.25 ± 0.07

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

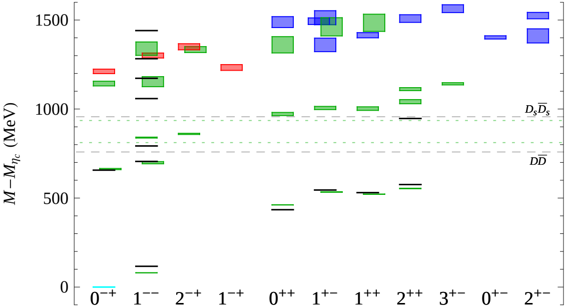
HSC, L. Liu et al. JHEP 1207 126 (2012)



- 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)

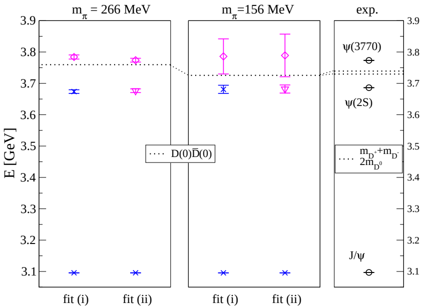


- Hybrid mesons with both regular and spin-exotic quantum numbers
- Relation of energy levels to resonances not straight forward

Outline

$\Psi(3770)$ resonance from Lattice QCD

Lang, Leskovec, DM, Prelovsek, in preparation



	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

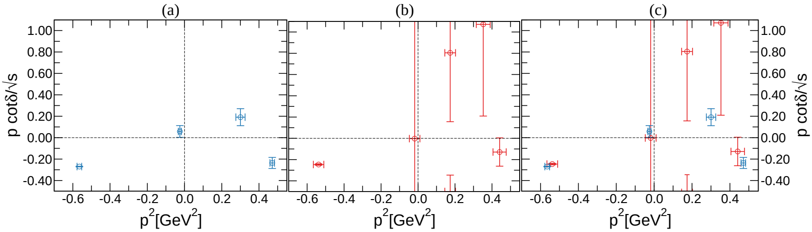
  - No evidence for fall-apart mode $X(3915) \to \bar{D}D$
  - Spin splitting $m_{\chi_{c2}(2P)} - m_{\chi_{c0}(2P)}$ to small
  - Large OZI suppressed $X(3915) \to \omega J/\psi$
  - Width should be significantly larger than $\Gamma_{\chi_{c2}(2P)}$
- Investigate $\bar{D}D$ scattering in S-wave on the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

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

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

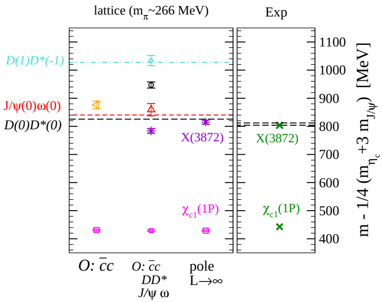
χ'_{c0}: Exploratory lattice calculation

Lang, Leskovec, DM, Prelovsek, in preparation

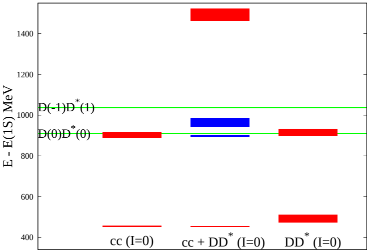


- Assumes only $\bar{D}D$ is relevant
- Lattice data suggests a fairly narrow resonance with $3.9\text{GeV} < M < 4.0\text{GeV}$ and $\Gamma < 100\text{MeV}$
- Future experiment and lattice QCD results needed to clarify the situation

An $X(3872)$ candidate from Lattice QCD



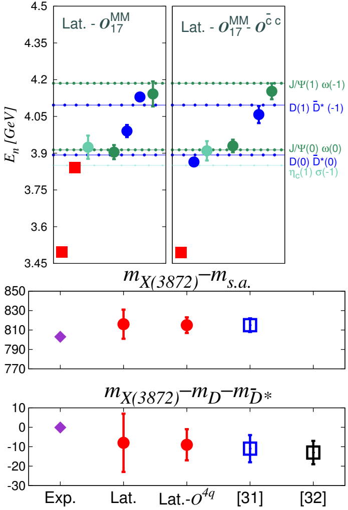
Prelovsek, Leskovec, PRL 111 192001 (2013)



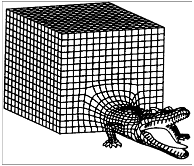
Lee, DeTar, DM, Na, arXiv:1411.1389

- 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)

Padmanath, Lang, Prelovsek, arXiv:1503.03257

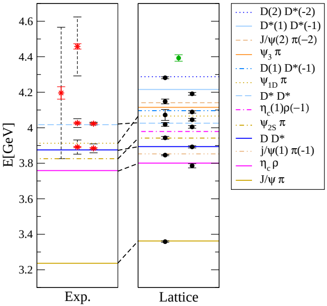


- Without $\bar{q}q$ interpolators signal vanishes
- Simulations still unphysical in many ways!
- Discretization and finite volume effects sizable!



- Makes interpretation as pure molecule or pure tetraquark unlikely

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

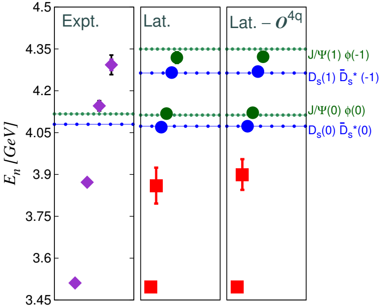


Prelovsek, Lang, Leskovec, DM, Phys.Rev. D91 014504 (2015)

- 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 $J^{PC} = 1^{++}$

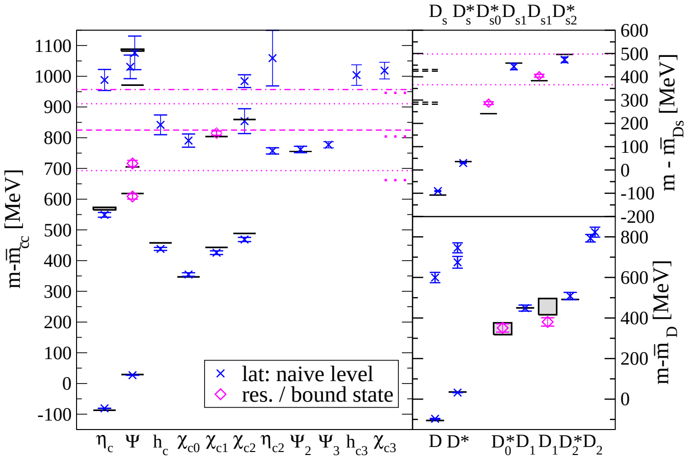
Padmanath, Lang, Prelovsek, arXiv:1503.03257



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

Outline

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



- 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)
- Progress with regard to hybrids and higher spin states
- Simulations of p-wave D and D_s states are now possible
    - $D_s(2317)$ and $D_s(2460)$ as QCD bound states
    - D meson states as resonances
- 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)
- Still a lot of progress to be made to fulfil the Physics Performance Report expectations

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

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

- We compare results from three different fit strategies
- Energy splittings are expected to be close to physical
- For MeV values of masses

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

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);`

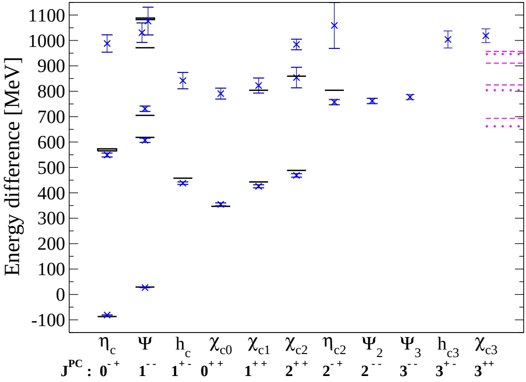
  `Morningstar et al. PRD 83, 114505 (2011)`

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

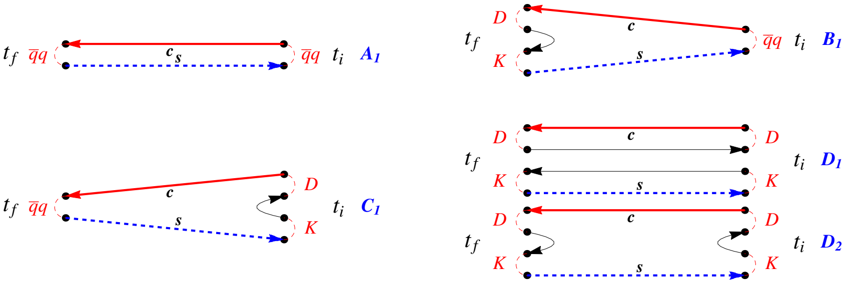
Low-lying charmonium spectrum



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)`

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.

(2) A resonance in a channel with attractive interaction

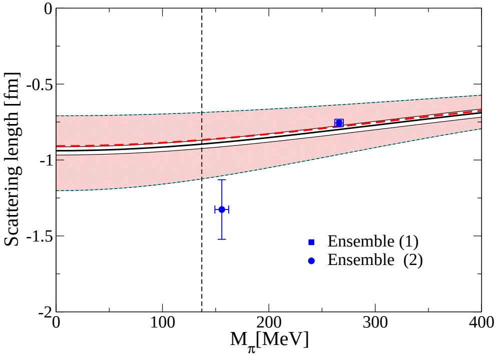
- The lowest state corresponds to the scattering level shifted below threshold in finite volume
- The additional level would indicate a QCD resonance
- One expects a positive scattering length in this case

This is the situation for the $D_0^*(2400)$

`DM, Prelovsek, Woloshyn, PRD 87 034501 (2013).`

Results for the scattering length a_0

DM, Lang, Leskovec, Prelovsek, Woloshyn, PRL 111 222001 (2013)

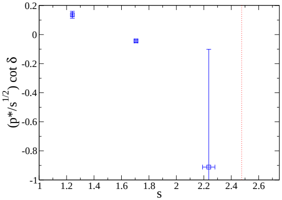


- We compare to the predictions from an indirect calculation
  `Liu et al. PRD 87 014508 (2013).`
- Our determination robustly leads to negative values.

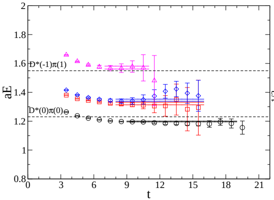
$D\pi$ and $D^{\star}\pi$ scattering

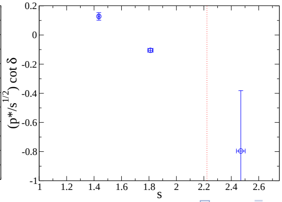
DM, Prelovsek, Woloshyn, PRD 87 034501 (2013)

- In the $J^P = 0^+$ $D_0^{\star}$ channel we extract three levels



- For the $J^P = 1^+$ channel there are two resonances $D_1(2420)$ and $D_1(2430)$



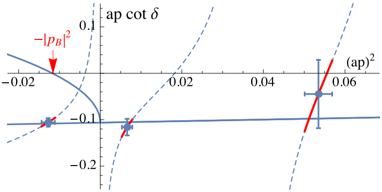


Testing our tuning: charm and beauty

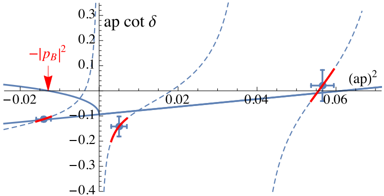
	Ensemble (1)	Ensemble (2)	Experiment
$m_{J/\Psi} - m_{\eta_c}$	107.9(0.3)(1.1)	107.1(0.2)(1.5)	113.2(0.7)
$m_{D_s^*} - m_{D_s}$	120.4(0.6)(1.3)	142.1(0.7)(2.0)	143.8(0.4)
$m_{D^*} - m_D$	129.4(1.8)(1.4)	148.4(5.2)(2.1)	140.66(10)
$2m_{\overline{D}} - m_{\overline{c}c}$	890.9(3.3)(9.3)	882.0(6.5)(12.6)	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)
$m_{B^*} - m_B$	-	46.8(7.0)(0.7)	45.78(35)
$m_{B_{s^*}} - m_{B_s}$	-	47.1(1.5)(0.7)	$48.7^{+2.3}_{-2.1}$
$m_{B_s} - m_B$	-	81.5(4.1)(1.2)	87.35(23)
$m_\Upsilon - m_{\eta_b}$	-	44.2(0.3)(0.6)	62.3(3.2)
$2m_{\overline{B}} - m_{\overline{b}b}$	-	1190(11)(17)	1182.7(1.0)
$2m_{\overline{B_s}} - m_{\overline{b}b}$	-	1353(2)(19)	1361.7(3.4)
$2m_{B_c} - m_{\eta_b} - m_{\eta_c}$	-	169.4(0.4)(2.4)	167.3(4.9)

- Errors statistical and scale setting only
- Bottom quark slightly to light

B_{so}^* and B_{s1}: Results



$$a_0^{BK} = -0.85(10)\,\mathrm{fm}$$
$$r_0^{BK} = 0.03(15)\,\mathrm{fm}$$
$$M_{B_{s0}} = 5.711(13)\,\mathrm{GeV}$$



$$a_0^{B^*K} = -0.97(16)\,\mathrm{fm}$$
$$r_0^{B^*K} = 0.28(15)\,\mathrm{fm}$$
$$M_{B_{s0}} = 5.750(17)\,\mathrm{GeV}$$

- Energy from the difference to the $B^{(*)}K$ threshold

B_{so}^* and B_{s1}: Systematic uncertainties

source of uncertainty	expected size [MeV]
heavy-quark discretization	12
finite volume effects	8
unphysical Kaon, isospin & EM	11
b-quark tuning	3
dispersion relation	2
spin-average (experiment)	2
scale uncertainty	1
3 pt vs. 2 pt linear fit	2
total	19

- discretiation effects from HQET power counting also considering mass mismatches

  `Oktay, Kronfeld Phys.Rev. D78 014504 (2008)`

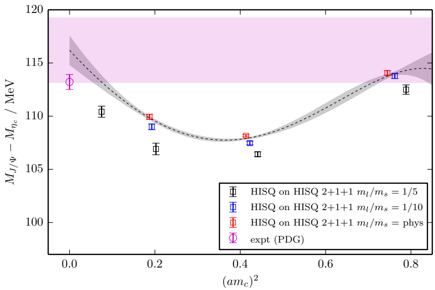
- Finite volume from difference between the energy level and the pole

Comparing to models

	0^+	1^+
Covariant (U)ChPT	5726(28)	5778(26)
NLO UHMChPT	5696(20)(30)	5742(20)(30)
LO UChPT	5725(39)	5778(7)
LO χ-SU(3)	5643	5690
Bardeen, Eichten, Hill	5718(35)	5765(35)
rel. quark model	5804	5842
rel. quark model	5833	5865
rel. quark model	5830	5858
HPQCD 2010	5752(16)(5)(25)	5806(15)(5)(25)
this work	5713(11)(19)	5750(17)(19)

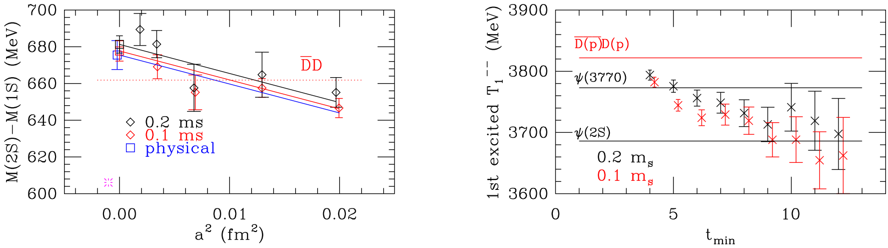
Preliminary results from the HPQCD Collaboration

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



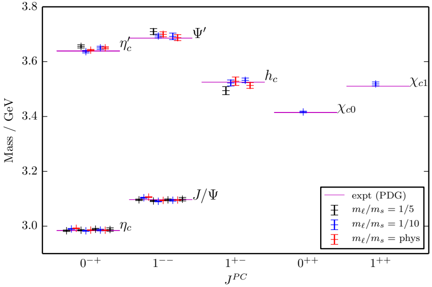
- Uses MILC 2+1+1 flavor HISQ (Highly Improved Staggered Quarks) ensembles

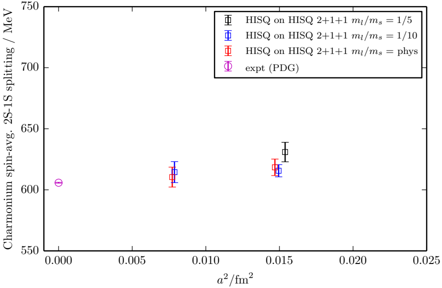
Fermilab/MILC, DeTar *et al.* arXiv:1410.3343



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

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
- Systematics on 1S hyperfine dominated by estimate of annihilation effects