Simulations with dynamical HISQ quarks

A. Bazavov, C. Bernard, C. DeTar, W. Freeman, S. Gottlieb, U.M. Heller, J. Hetrick, J. Laiho, L. Levkova, M. Oktay, J. Osborn, R.L. Sugar, D. Toussaint, R. Van de Water

June 16, 2010

Background: a^2_{tad} (asqtad) lattices

- Started in 1999
- 2+1 dynamical flavors
- Lattice artifacts much smaller than naive staggered
- Lattice spacings 0.18, 0.15, 0.12, 0.09, 0.06 and 0.045 fm
- Light quark masses 0.1 m_s to m_s (and one at $0.05m_s$)
- Spatial sizes 2.5 – 5.8 fm
- Controlled continuum and chiral extrapolations
- Around 25,000 equilibrated lattices generated
- All these lattices are publicly available (NERSC,ILDG,informal)

Next generation: "HISQ lattices"

HISQ action developed by UKQCD/HPQCD

Actually, this generation is better in several ways:

- Two-level fermion link smearing (HISQ). Taste violations about one-third of a^2_{tad}, generic lattice artifacts about one-half.
- Inclusion of dynamical charm. Mass dependent Naik term (HISQ) makes this accurate up to $am_c \approx 1$.
- Larger spatial sizes, about 20% larger than similar a^2_{tad} ensembles
- Quark loop effects in gauge action coefficients (not available when a^2_{tad} started)
- Better tuning of quark masses (within ≈2%, *c.f.* as bad as 20% for a^2_{tad})

Physics motivation

What will, or could be, done with these lattices?

- Static quark potential (tuning)
- Local hadron spectrum (tuning)
- f_π, f_K, f_D, f_{D_s}.
- f_B, f_{B_s} with Fermilab/NRQCD/HISQ b
- Charmonium spectroscopy
- Heavy-light semileptonic form factors
- B_K
- Strange and light quark condensates, (dark matter)
- Nucleon structure and interactions
- ...

HISQ lattice generation

General outline of the program:

- Runs at $m_l = 0.2 m_s$, $0.1 m_s$ and $\approx 0.04 m_s$
- Lattice spacings: (0.045), 0.06, 0.09, 0.12, 0.15, (0.18, 0.20) fm
- Spatial volumes $<\approx$ 5.6 fm
- Size of ensembles $\approx$ 1000 lattices
- "mass independent" – lines of constant $10/g^2$ and u_0
- Determine lattice spacing from r_1 and/or f_{ss}
- Tune m_s from $2M_K^2 - M_\pi^2$
- Tune m_c from $\frac{3}{4}M_\Psi + \frac{1}{4}M_{\eta_c}$.

Completed:

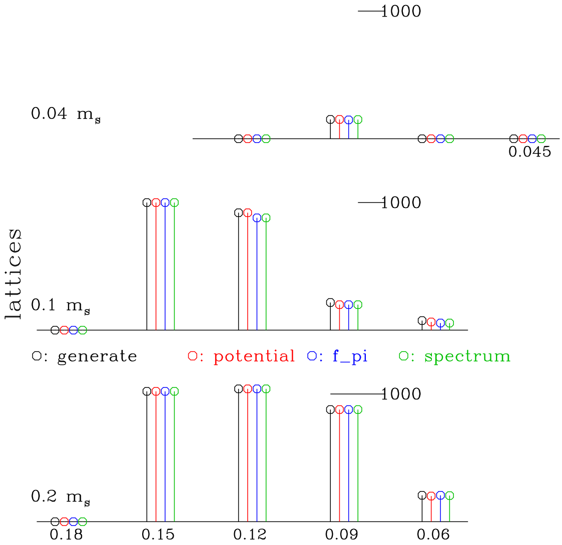
- Test scaling at fixed quark mass
- Series of ensembles with $m_l = 0.2 m_s$
- Lattice spacings 0.15, 0.12 and 0.09 fm
- Extend tests of scaling (lattice artifacts) to dynamical HISQ and things other than taste violation.
- arXiv:1004.0342, and next three slides

HISQ, June 2010

β	am_l	am_s	am_c	size	u_0	N_{lats}	s	len.	ϵ	acc.	r_1/a	a (fm)	$m_\pi L$	m_π
5.80	0.013	0.065	0.838	$16^3 \times 48$	0.85535	1021	5	1.0	0.033	0.73	2.041(10)	$0.1527(^{+10}_{-17})$	3.78	306
5.80	0.0064	0.064	0.828	$24^3 \times 48$	0.85535	1000	5	1.0	0.020	0.73	2.062(5)	$0.1512(^{+7}_{-16})$	3.99	217
6.00	0.0102	0.0509	0.635	$24^3 \times 64$	0.86372	1040	5	1.0	0.036	0.66	2.574(5)	$0.1211(^{+6}_{-12})$	4.54	309
6.00	0.00507	0.0507	0.628	$32^3 \times 64$	0.86372	920	5	1.0	0.025	0.64	2.618(17)	$0.1190(^{+9}_{-14})$	4.29	221
6.30	0.0074	0.037	0.440	$32^3 \times 96$	0.874164	878	6	1.5	0.031	0.68	3.520(7)	$0.0886(^{+4}_{-9})$	4.50	314
6.30	0.00363	0.0363	0.430	$48^3 \times 96$	0.874164	217	6	1.5	0.0197	0.66	3.552(15)	$0.0878(^{5}_{-10})$	4.71	221
6.30	0.0012	0.0363	0.432	$64^3 \times 96$	0.874164	151	6	1.5	0.0123	0.64	3.594(12)	$0.0867(^{+5}_{-9})$	3.66	130
6.72	0.0048	0.024	0.286	$48^3 \times 144$	0.885773	206	6	2.0	0.0217	0.61	5.312(16)	$0.0587(^{+3}_{-6})$	4.51	315
6.72	0.0024	0.024	0.286	$64^3 \times 144$	0.885773	75	6	2.0	0.0143	0.67	5.410(15)	$0.0576(^{+3}_{-6})$	4.25	227

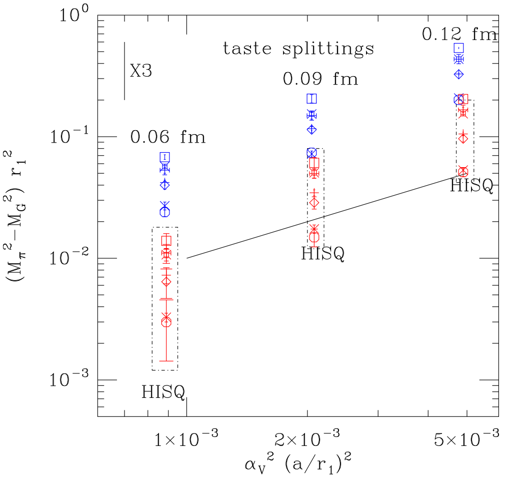
Parameters of the HISQ runs. N_{lats} is the number of equilibrated lattices. "s" is the separation of the lattices in simulation time, "len" is the length of a trajectory in simulation time, "ϵ" is the molecular dynamics step size, and "acc." is the fraction of trajectories accepted. Our definition of the step size is such that there is one evaluation of the fermion force per step, so a complete cycle of the Omelyan integration algorithm includes two fermion action steps and six gauge action steps. The physical lattice spacing given in this table uses the determination of $r1 = 0.3117(6)(^{+12}_{-31})$ fm made using f_π to set the scale on the Asqtad ensembles.

HISQ program, summary



- ○ = done
- Goal: Complete all these, ≈ 1000 lattices

Taste symmetry



- arXiv:1004.0342
- At $m_l = 0.2 m_s$
- Done earlier by UKQCD/HPQCD on quenched and asqtad sea
- Works as expected with dynamical HISQ

Taste symmetry, expected

where we will be in three years

Pion spectrum at $a \approx 0.06$ and 0.045 fm (MeV)

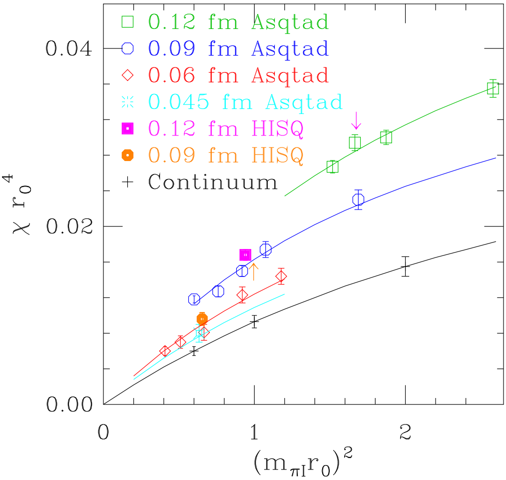
Splittings scaled from $0.09 fm$ masses

Tastes good: $\log(m_\pi^2 + a^2\Delta^2) \approx \log(m_\pi^2) + a^2\Delta^2/m_\pi^2$

	0.06fm	0.06fm	0.045 fm
taste	$m_s/10$	$m_s/27$	$m_s/27$
π_5	220	135	135
π_{05}, π_{i5}	225	143	139
π_{ij}, π_{i0}	231	152	144
π_i, π_0	236	159	147
π_s	239	164	149

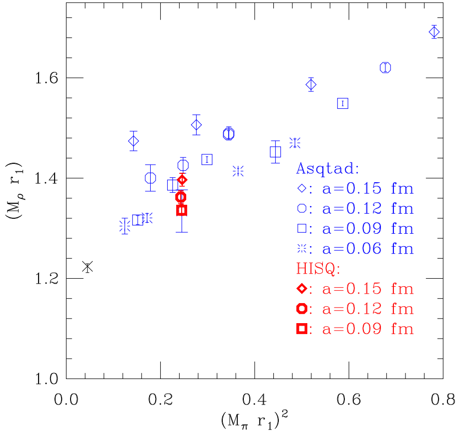
The $m_s/10$ run is in progress, the $m_s/27$ runs are for later years.

Topology



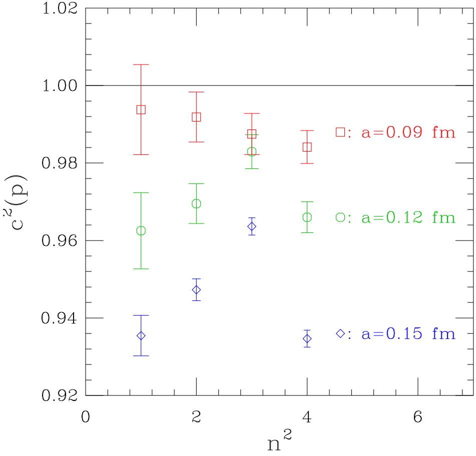
- arXiv:1003.5695, 1004.0342
- Really does improve the gauge configurations!!
- (Other tests involve valence quarks)

Masses



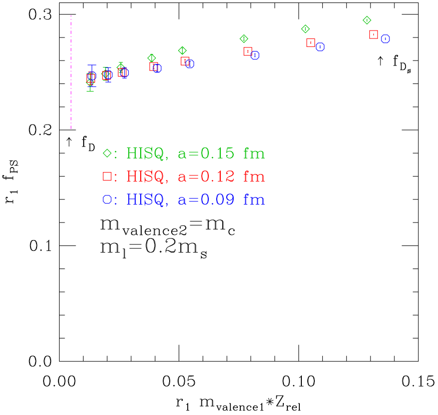
- Improvement in masses and decay constants
- But much of this depends on choice of length scale

Charmonium dispersion relation



- $m_l = 0.2 m_s$
- "Speed of light" for η_c
- $\vec{p}^2 = \left(\frac{2\pi}{L}\right)^2 \vec{n}^2$
- Similar to UKQCD/HPQCD on a^2_{tad} sea
- This is with dynamical HISQ

m_{pseudo} and f_{pseudo}



- charm-light f_{PS}
- $m_l = 0.2 m_s$
- Eventually, find f_D, f_{D_s} and f_{D_s}/f_D

Scale setting: conventional, r_1

- Use $r_1 = \mathrm{root}\left(r^2 F(r) = 1\right)$ to set scale
- Not a physical quantity, but a convenient interpolating quantity
- Declare that r_1 is independent of lattice spacing and sea quark masses
- Find value for r_1 by matching some physical quantity in continuum and chiral limit.
- From f_π, $r_1 = 0.311$ fm.

Scale setting: alternative, f_{η_s}

- HPQCD: arXiv:0910.1229
- Use $f_{ss} = f_{PS}$ at $m_{val} = \mathrm{root}\left(\frac{M_{PS}(m_{val})}{f_{PS}(m_{val})} = 0.2647\right)$
- Not a physical quantity, but a convenient interpolating quantity
- Declare that f_{ss} is independent of lattice spacing and sea quark masses
- Find value for f_{ss} by matching some physical quantity in continuum and chiral limit.
- From f_π, f_{ss} =???
- Working estimate from χPT: $f_{ss} = 181.5$ MeV.

Scale setting: alternative, f_{η_s}

- Actually, can use any reference mass
- We are experimenting with $m_{valence} = 0.4 m_s$
- Tradeoff: heavy enough to get small statistical error
- Tradeoff: light enough for reliable χPT

Scale setting from f_{ss}

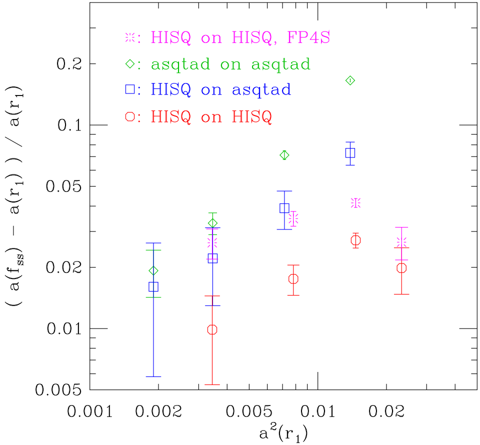
- GOOD: Can get very high accuracy
- GOOD: Better understood systematic errors than r_1 (fit ranges, etc.)
- GOOD: For decay constant projects, produces a self contained project
- BAD: Takes longer than static potential (unless you were going to do f_{PS} anyway)
- BAD: Depends on fermion formulation: Asqtad and HISQ valence quarks give different lattice spacings for same ensemble.

Finding the lattice spacing

Action	$10/g^2$	am_l	am_s	am_c	$a(r_1)$	$a(f_{ss,\mathrm{asq}})$	$a(f_{ss,\mathrm{HISQ}})$
asqtad	6.76	0.01	0.05	–	0.1178(2)	0.1373(2)	0.1264 (11)
asqtad	7.09	0.0062	0.031	–	0.0845(1)	0.0905(3)	0.0878(7)
asqtad	7.46	0.0036	0.018	–	0.0588(2)	0.0607(1)	0.0601(5)
asqtad	7.81	0.0028	0.014	–	0.0436(2)	0.0444(1)	0.0443(4)
HISQ	5.80	0.013	0.065	0.838	0.1527(7)	na	0.1558(3)
HISQ	6.00	0.0102	0.0509	0.635	0.1211(2)	na	0.1244(2)
HISQ	6.30	0.0074	0.037	0.440	0.0884(2)	na	0.0900(1)

Lattice spacing in fermi from $r_1 = 0.3117$ fm (us),
f_{ss} with Asqtad sea (us),
f_{ss} with HISQ sea (from HPQCD for Asqtad sea ensembles).
Errors on $a(r_1)$ are statistical only - they do not include the errors in $r_1 = 0.3108(15)(^{+26}_{-79})$ fm.
Errors on HISQ/Asqtad $a(HISQ)$ are from HPQCD.
Errors on HISQ/HISQ $a(HISQ)$ are statistical, no autocorrelations.
Errors on Asq/Asq $a(Asq)$ are statistical, no autocorrelations.
$Z \approx 1.4$

Finding the lattice spacing



- fractional differences in *a* determinations
- All agree as $a \to 0$

Summary

- The HISQ action reduces lattice artifacts relative to the Asqtad action
- Cost for lattice generation is around twice as large (depending on quark mass)
- Four ensembles completed, five more in production
- Main motivation is high precision QCD
- We expect the lattices will be useful for a wide range of QCD studies

Extra Slides

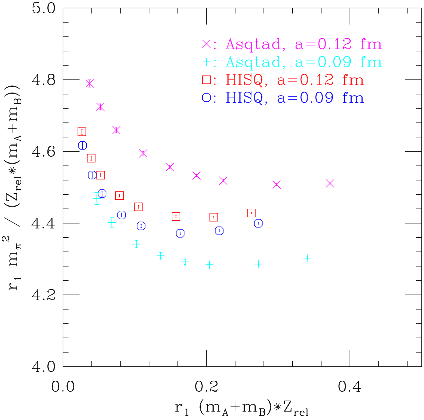
Is $r_1 = 0.3117$ fm?

- We have four dynamical quark flavors
- $\frac{1}{m_c r_1} \approx 0.65$, so charm quark might matter.
- At $m_l \approx 0.2 m_s$ four flavor HISQ r_0/r_1 is about 0.01 larger that three flavor Asqtad
- Can't tell if this is from different n_f or different action. (Asqtad r_0/r_1 increases as a decreases).
- Eventually, matching f_π or $b\bar{b}$ spectrum will sort this out.

m_{pseudo} and f_{pseudo}

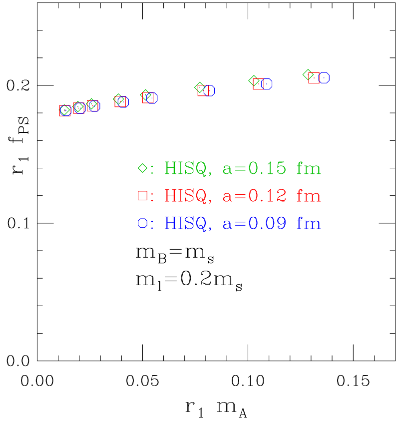
- First approximation - just plug into current analysis with smaller taste violation parameters.
- What issues arise in extending analysis up to charm quark mass?
- Need to include adjustments for mistuned quark masses, as always.

m_{pseudo} and f_{pseudo}



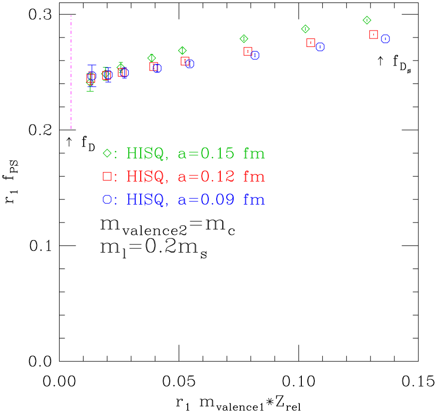
- $M_{PS}^2/(m_A+m_B)$
- $m_l = 0.2m_s$

m_{pseudo} and f_{pseudo}



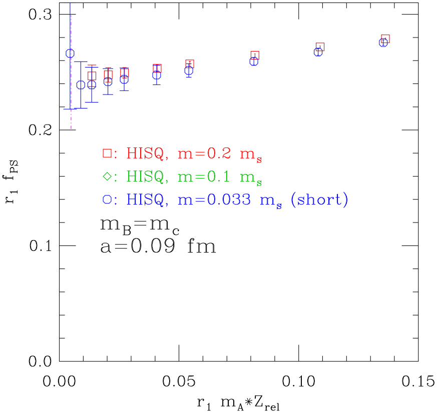
- f_{PS} with $m_A = m_B$
- $m_l = 0.2 m_s$

m_{pseudo} and f_{pseudo}



- charm-light f_{PS}
- $m_l = 0.2m_s$
- Find f_{D_s}/f_D?

m_{pseudo} and f_{pseudo}

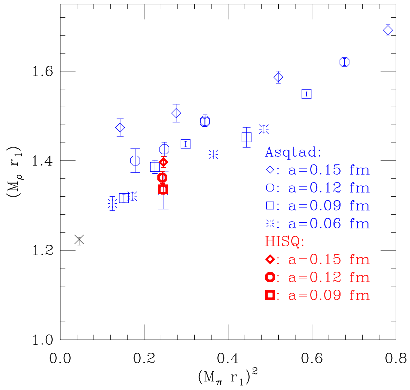


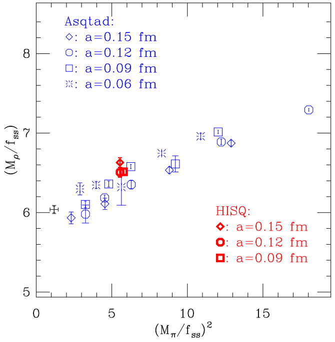
- charm-light f_{PS}
- $a = 0.09$ fm
- Find f_{D_s}/f_D?

Scale setting from f_{ss}

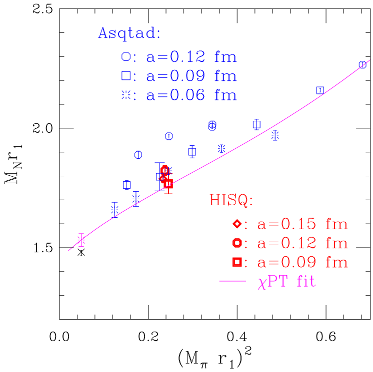
Ensemble	$a(r_1)$	$a(Asq)$	$a(HISQ)$
b6572m0097m04845	0.1453(9)	0.1771(?)(linear)	0.1583(13)
b6586m0194m04845	0.1473(8)	0.1769(?)(linear)	0.1595(14)
b676m005m050	0.1175 (2)	0.1360 (?)(linear)	0.1247 (10)
b676m010m050	0.1178 (2)	0.1397 (2?)(linear)	0.1264 (11)
b679m020m050	0.1175(2)	0.1368(?)(linear)	0.1263(11)
b709m0062m031	0.0845(1)	0.09080(27)(linear)	0.0878(7)
b709m0062m031	0.0845(1)	0.08732(21)(quad)	0.0878(7)
b711m0124m031	0.0842(2)	0.09146(28)(linear)	0.0884(7)
b746m0036m018	0.0588(2)	0.06057(11)(linear)	0.0601(5)
b746m0036m018	0.0588(2)	0.06074(13)(quad)	0.0601(5)
b781m0028m014	0.0436(2)	0.04455(08)(linear)	0.0443(4)
b781m0028m014	0.0436(2)	0.04444(09)(quad)	0.0443(4)
b580m013m065m838	0.1524(3)	na	0.15444(22)
b580m013m065m838	0.1524(3)	na	0.15581(31)
b600m0102m0509m635	0.1208(2)	na	0.12358(12)
b600m0102m0509m635	0.1208(2)	na	0.12434(16)

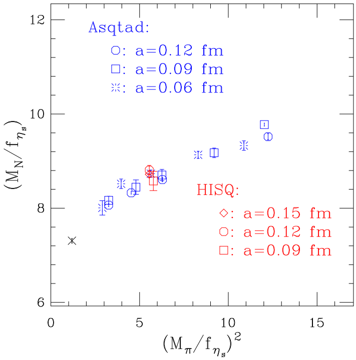
Scaling


1.6
1.4
1.2
1.0
0.0
0.2
0.4
0.6
0.8
$(M_\rho\ r_1)$
$(M_\pi\ r_1)^2$
Asqtad:
◇: a=0.15 fm
○: a=0.12 fm
□: a=0.09 fm
⋇: a=0.06 fm
HISQ:
◇: a=0.15 fm
○: a=0.12 fm
□: a=0.09 fm


8
7
6
5
0
5
10
15
(M_ρ/f_{ss})
$(M_\pi/f_{ss})^2$
Asqtad:
◇: a=0.15 fm
○: a=0.12 fm
□: a=0.09 fm
⋇: a=0.06 fm
HISQ:
◇: a=0.15 fm
○: a=0.12 fm
□: a=0.09 fm

Scaling


Asqtad:
○: a=0.12 fm
□: a=0.09 fm
⁂: a=0.06 fm
HISQ:
◇: a=0.15 fm
○: a=0.12 fm
□: a=0.09 fm
χPT fit
$M_N r_1$
$(M_\pi r_1)^2$
2.5
2.0
1.5
0.0
0.2
0.4
0.6


Asqtad:
○: a=0.12 fm
□: a=0.09 fm
⁂: a=0.06 fm
HISQ:
◇: a=0.15 fm
○: a=0.12 fm
□: a=0.09 fm
(M_N/f_{η_s})
$(M_\pi/f_{\eta_s})^2$
12
10
8
6
0
5
10
15

Time distribution

How much time is used in generating/measuring?

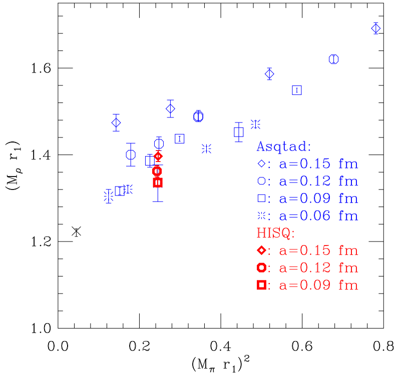
- It depends (on masses, precision, algorithm, ...
- Focus on the largest current lattice: $a = 0.06$ fm, $m_l = m_s/10$

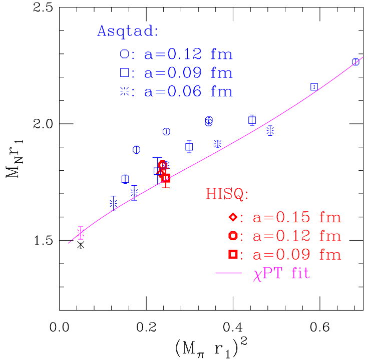
Timings for the $64^3 \times 144$ mass 0.0024/0.024/0.286 run.
Lattices are saved every six time units (three trajectories)

operation	J/psi core-hours/lattice
generate(RHMC)	30K
generate(RHMD)(est)	15K
static potential	0.5K
point spectrum (8×3 sources)	5K
pseudoscalars (4×6 sources)	11K

The pseudoscalar measurement is expensive because it includes valence quarks down to $m_s/20$. Largest uncertainties are in generation, since step size still being adjusted and RHMD trials underway.

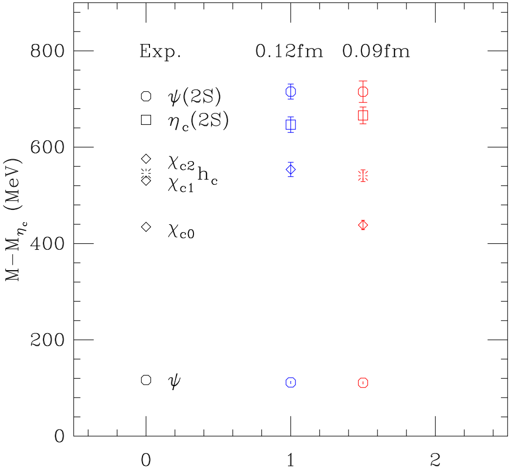
Scaling





- As we know, HISQ scales better than Asqtad.
- HOWEVER, maybe r_1 is not an optimal quantity for setting the scale, we need fair comparison.

Charmonium spectroscopy



- $m_l = 0.2 m_s$
- wall source/point sink
- Just ran the old "point meson" code
- no χ_{c2} operator

Charmonium spectroscopy

- Need 2S and higher source
- Need nonrelativistic P-wave source
- What physics are we trying to address?