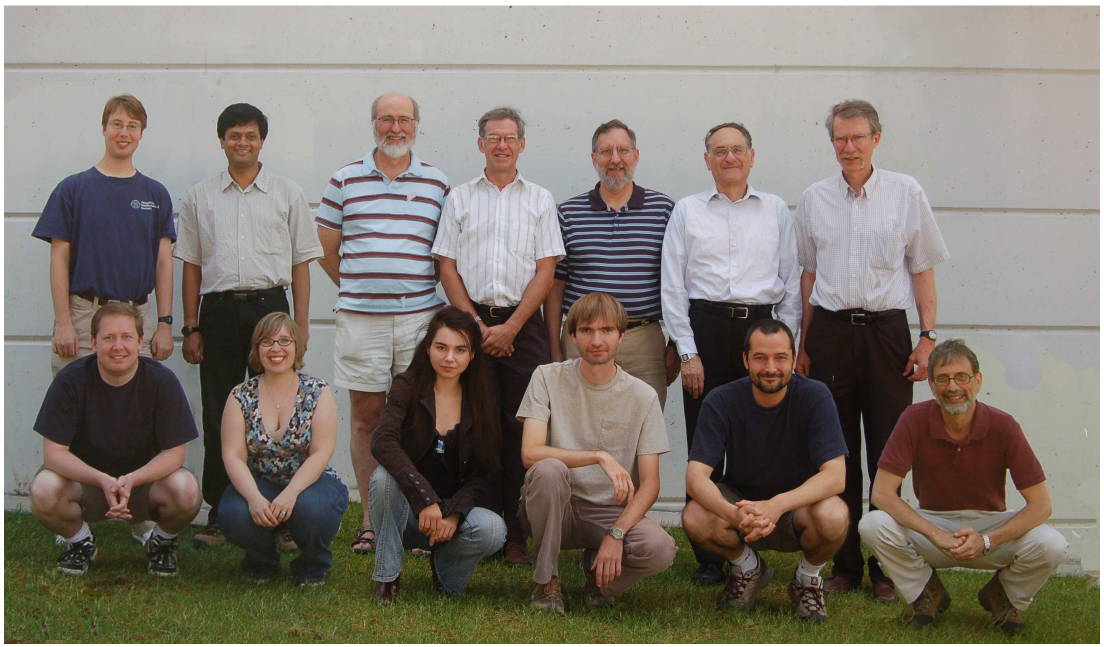
Future of Lattice Calculations with Staggered Sea Quarks

Steven Gottlieb

Indiana University

sg at iub.edu

Collaborators



MILC Collaboration (6/08): J. Laiho*, S. Basak, U. Heller, D. Toussaint, S. G., R. Sugar, C. DeTar, J. Osborn, R. Van de Water*, L. Levkova, A. Basavov, T. Burch, C. Bernard, (not pictured) C. Aubin, J. Hetrick

$+$ FNAL Collaboration (for heavy-light decays): J.A. Bailey, R.T. Evans, E. D. Freeland, E. Gamiz, A.X. El-Khadra, A.S. Kronfeld, M. Di Pierro, P.B. Mackenzie, D. Menscher, M. Okamoto, M.B. Oktay*, J. Simone

$+$ HPQCD & UKQCD Collaborations (for scale, m_s, $\hat{m}$, $m_s/\hat{m}$): C. Davies, E. Follana, A. Gray, E. Gregory, J. Hein, G. P. Lepage, Q. Mason, M. Nobes, J. Shigemitsu, H. Trottier, M. Wingate

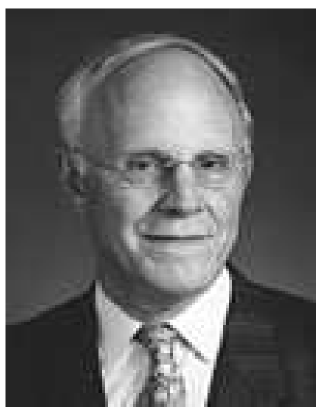
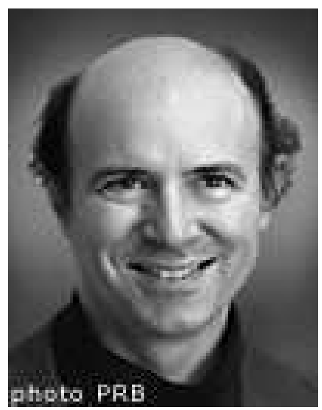
Outline

- Background
- Ratio Plot
- High Precision Results
- Leptonic Decay Constants

Background

- Perturbative QED $\alpha = 1/137$

- Perturbative QCD (asymptotic freedom) $\alpha_s \approx 1/8$

Photos from nobelprize.org

Beyond Perturbation Theory

- Many phenomena of QCD require nonperturbative prowess
  - Confinement
  - Meson and Baryon Masses
  - Decay constants: f_π, f_K, f_D, etc.
  - Semileptonic form factors, *e.g.*, $D \to \pi l \nu$
  - Extraction of CKM matrix elements
  - Nucleon structure functions
  - Quark-gluon plasma
- Distinguishing new physics from SM physics
- Theories such as technicolor and other approaches to dynamical symmetry breaking
- Recently there has been considerable progress

QCD and Standard Model Parameters

- 11 of the $\approx$ 18 parameters of the standard model are related to quarks
- Six quark masses: u, d, s, c, b, t
- Strong coupling constant: α_s
- Four parameters describe CKM matrix: λ, A, ρ and η

$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to l\nu & K \to \pi l\nu & B \to \pi l\nu \\ & K \to l\nu & \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \pi l\nu & D \to K l\nu & B \to D^{(*)} l\nu \\ D \to l\nu & D_s \to l\nu & \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ \langle B_d | \overline{B}_d \rangle & \langle B_s | \overline{B}_s \rangle & \end{pmatrix}$$

2008 Physics Nobel Prize

- Makoto Kobayashi (L) and Toshihide Maskawa (R) on September 26, 2001.

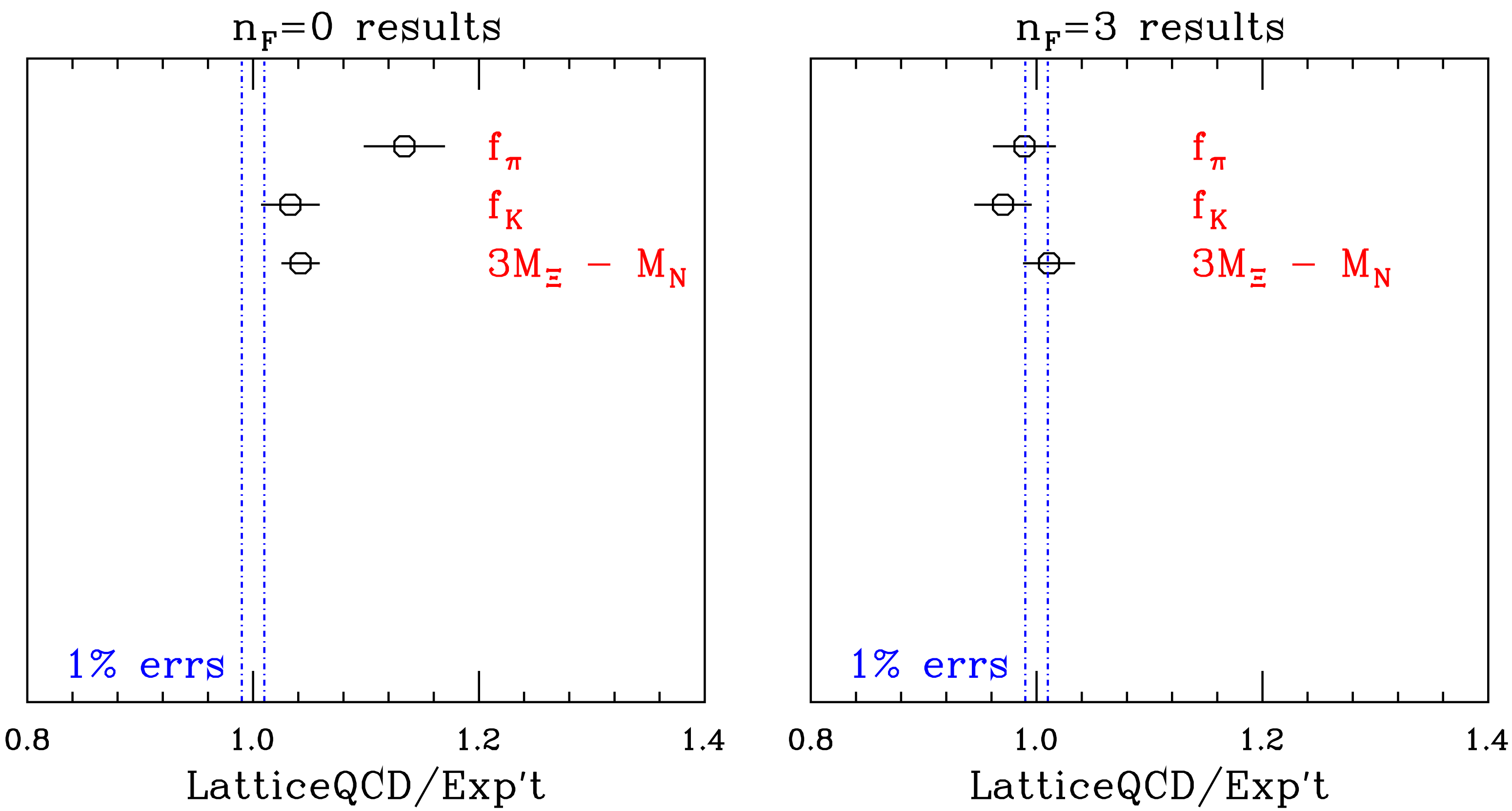
KEK photo from nobelprize.org

2008 Physics Nobel Prize

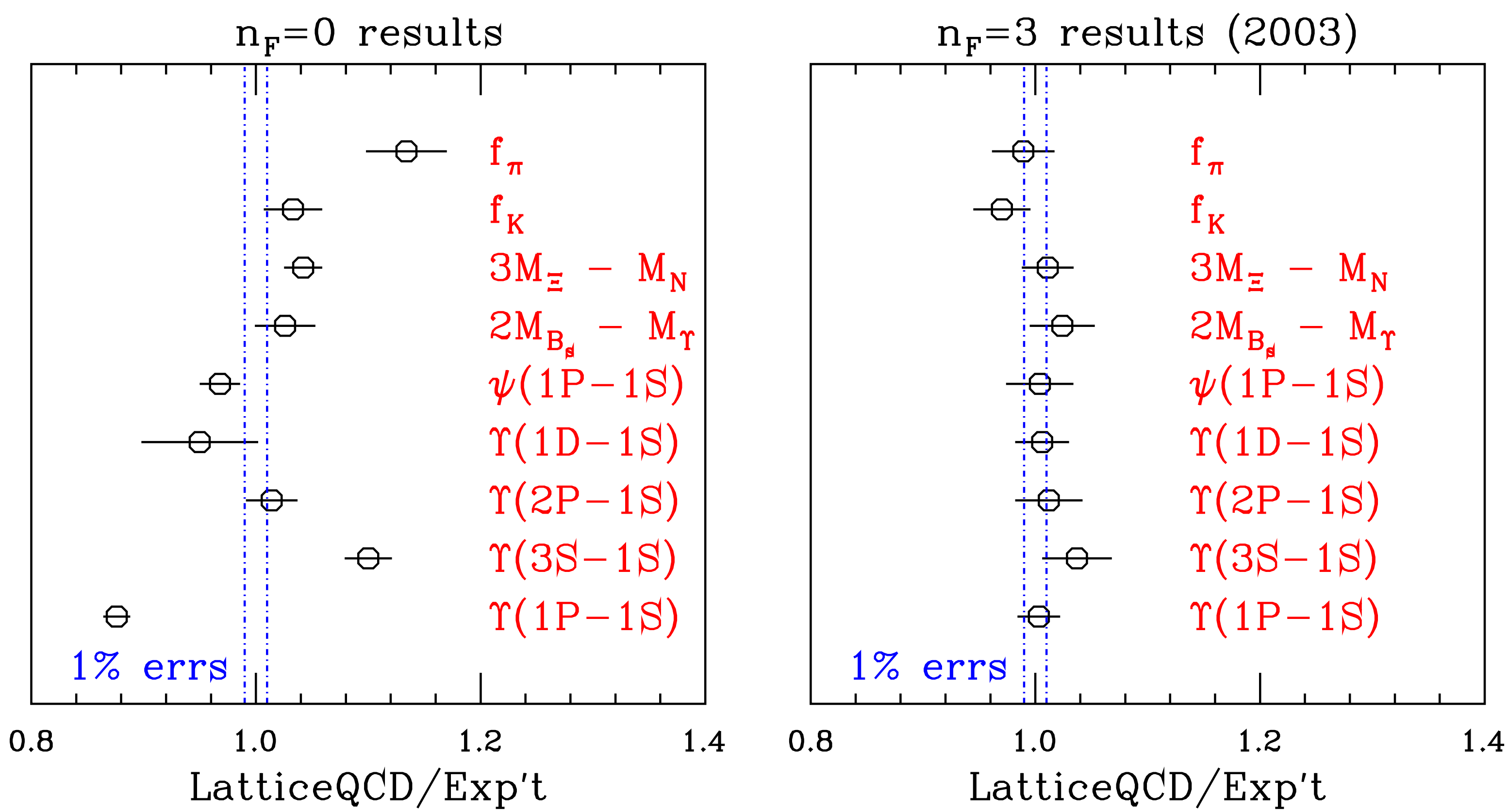
- Makoto Kobayashi (L) and Toshihide Maskawa (R). Is this after winning the prize? They don’t look that much happier.

KEK photo from nobelprize.org

Ratio Plot


n_F=0 results
n_F=3 results
f_π
f_K
$3M_\Xi - M_N$
1% errs
0.8
1.0
1.2
1.4
LatticeQCD/Exp't

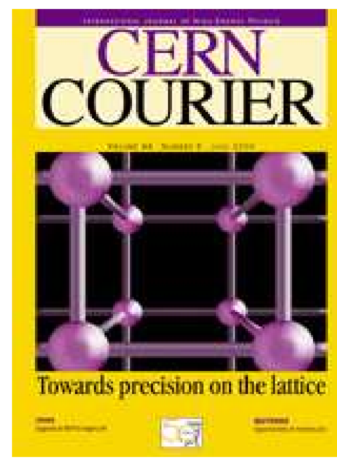
Ratio Plot



By sharing with FNAL, HPQCD and UKQCD [PRL 92, 0022001 (2004)]

High Precision Results (2004)

- MILC dynamical configurations have allowed a major breakthrough in high precision lattice calculations
- With FNAL, HPQCD and UKQCD calculations we calculated 9 quantities to 1–3% accuracy
- The PRL describing this work has resulted in significant publicity:
    - CERN Courier
    - Fermilab Today
    - Nature
    - Physics Today
    - Science



- See physics.indiana.edu/~sg/milc.html

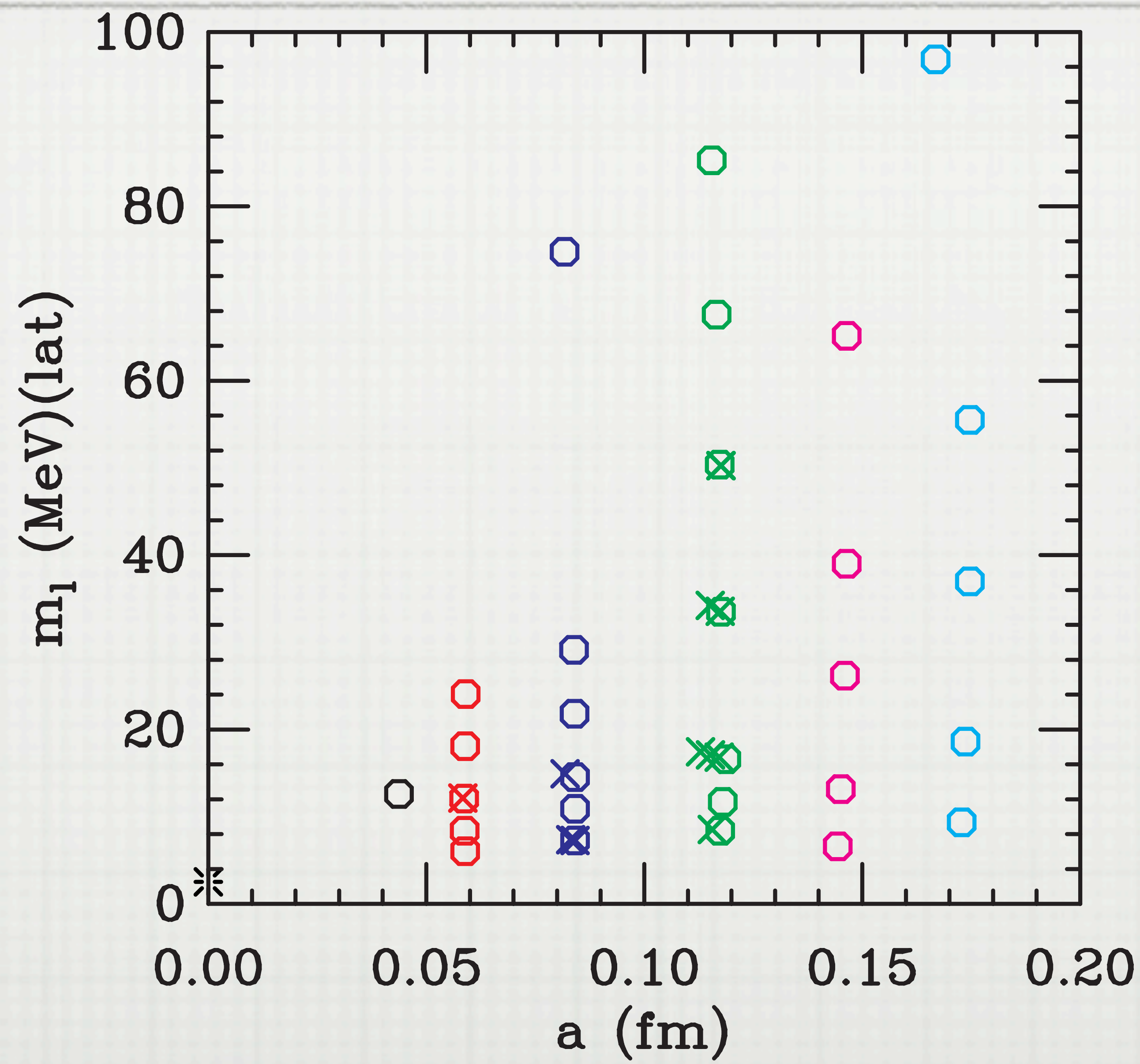
Control of Systematic Errors

- To carry out a simulation we must select certain physical parameters:
  - lattice spacing (a) or gauge coupling (β)
  - grid size ($N_s^3 \times N_t$)
  - sea quark masses ($m_{u,d}$, m_s , m_c)
- To control systematic error we must:
  - take continuum limit
  - take infinite volume limit
  - extrapolate in light quark mass; can use physical s quark mass

Asqtad Program

- Since 1999, MILC has been generating ensembles of configurations with three flavors (up, down, strange) of dynamical staggered quarks.
  - Six lattice spacings: 0.18, 0.15, 0.12, 0.09, 0.06, 0.045 fm
  - Strange quark mass approximately at physical value
  - Degenerate *u* and *d* down to 0.1 or 0.05 strange mass
- Many results summarized in RMP **82**, 1349 (2010).
- About 25,000 configurations publicly available (>40 ensembles)

Map of Ensembles



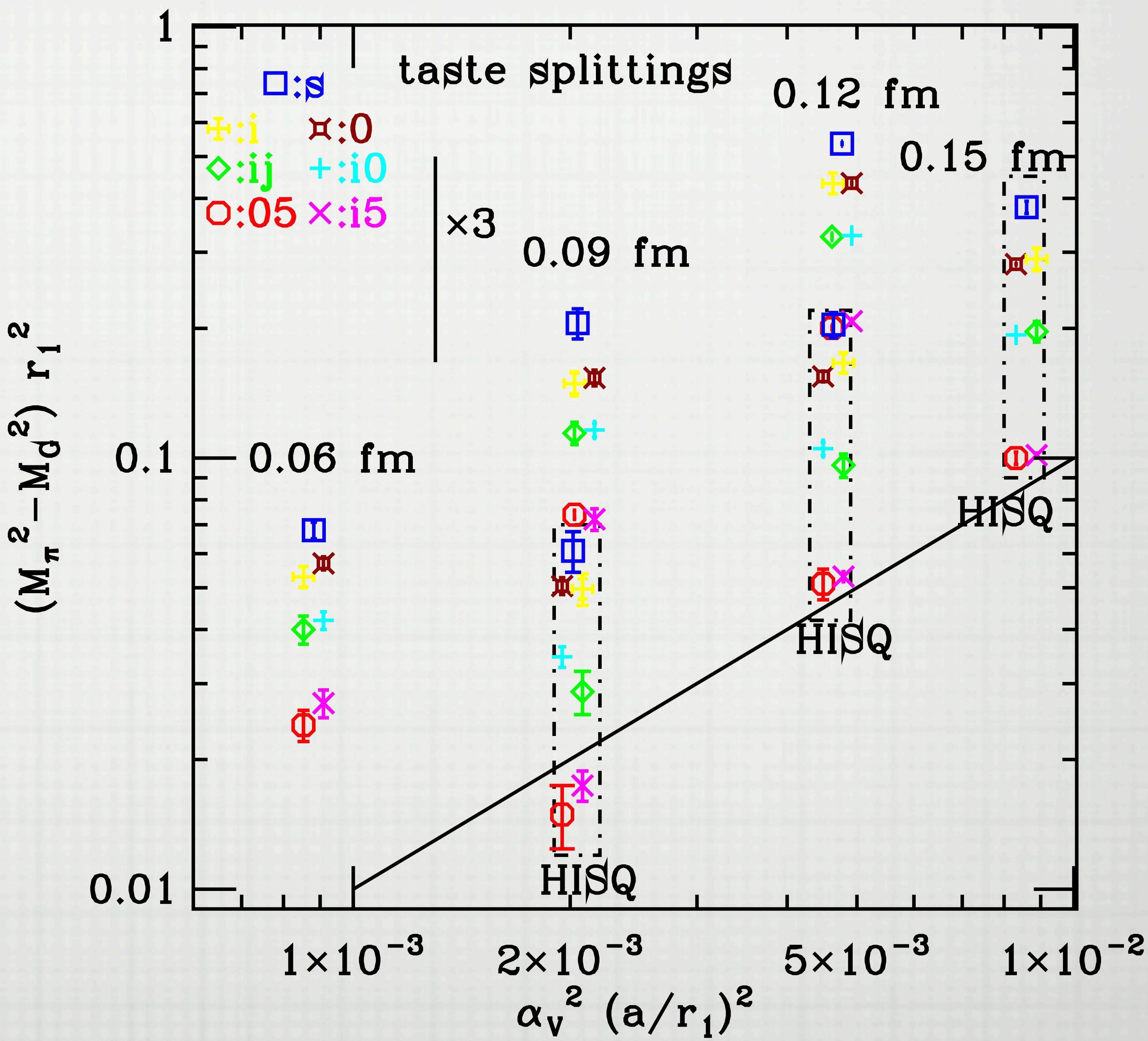
- octagons have physical strange quark mass, crosses lighter strange quark mass

HISQ Program

- Highly Improved Staggered Quark (HISQ) action developed by HPQCD/UKQCD (Follana *et al.*, PRD **75**, 054502)
  - Two levels of smearing reduce taste symmetry breaking
  - We now include a dynamical charm quark
  - Quark loop effects in gauge action known to 1-loop order
  - We are using larger volumes than with asqtad
  - We do a better job of tuning strange quark mass
  - Eventually plan to run at physical up and down quark masses
- arXiv:1004.0342 for initial HISQ scaling study

Taste Symmetry Breaking

- Pion taste splittings with asqtad or HISQ (boxed) dynamical quarks.
- $m_l = 0.2\ m_s$
- splittings about 3 times smaller with HISQ
- line shows expected slope



Rooting

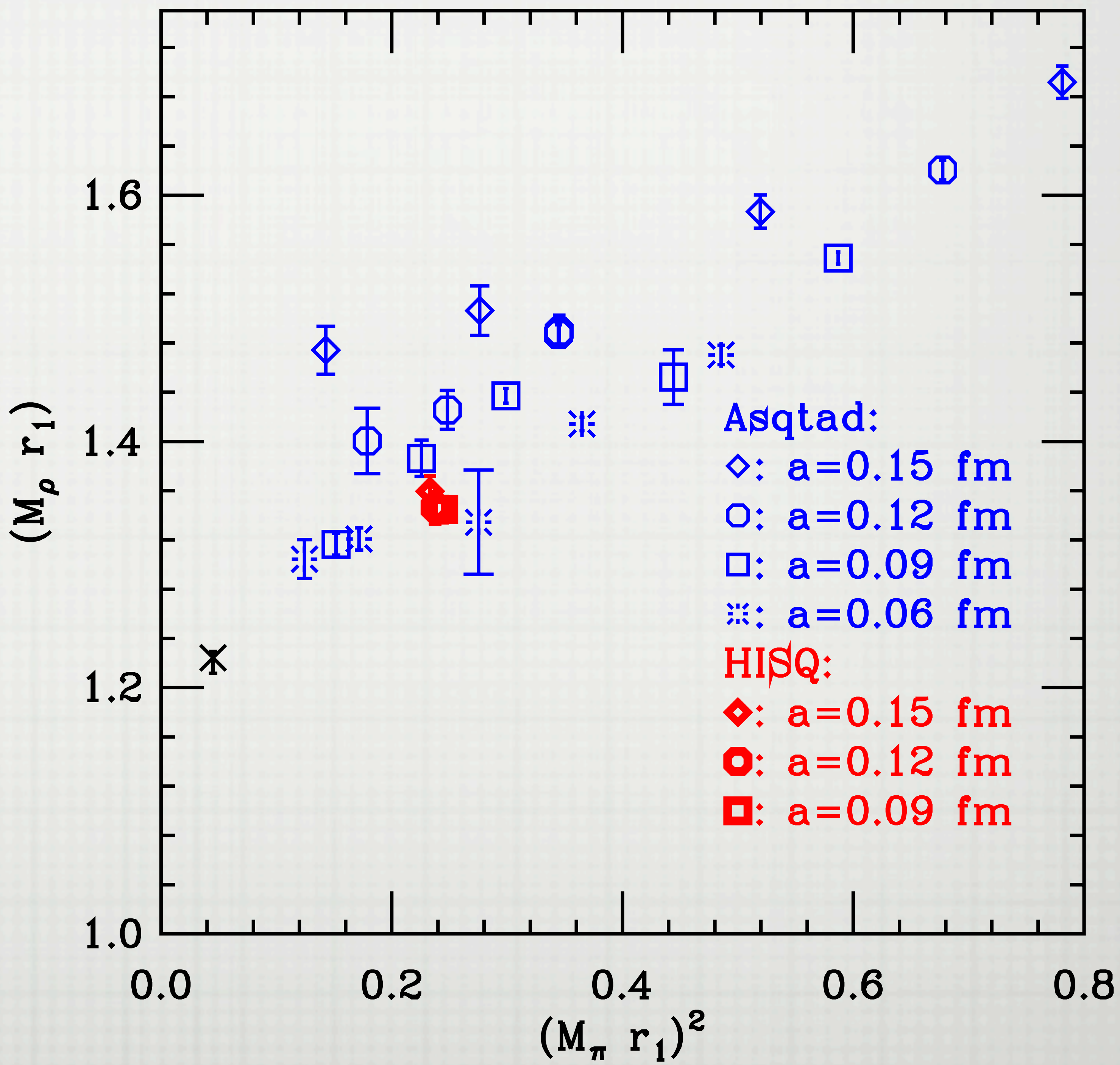
- To deal with fermion doubling problem on lattice, staggered quark calculations use rooting.
- With recent increase in precision, revival of concerns that rooting could lead to incorrect results, even in continuum limit.
- Theoretical work by Shamir, Bernard, Golterman, Sharpe; Adams
- Numerical work by Durr, Hoelbling, Wegner; Follana, Hart, Davies
- Support the conclusion that rooting is a valid procedure.
- Reviews: Sharpe (LAT’06), Kronfeld (LAT’07), Goltermann (QCHS’08)
- Also RMP **82**, 1349 (2010). [χ_{top} , n_r =0.28(2)(3)]

Results

- MILC Collaboration has studied a number of properties of light quark hadrons
    - spectrum
    - decay constants
    - topology
    - quark masses
- Fermilab Lattice/MILC Collaborations have done heavy-light studies
    - decay constants
    - semileptonic decay form factors
    - heavy hadron spectrum
- Other groups have done additional studies on asqtad configs.
- See RMP **82**, 1349 (2010) for results and references.

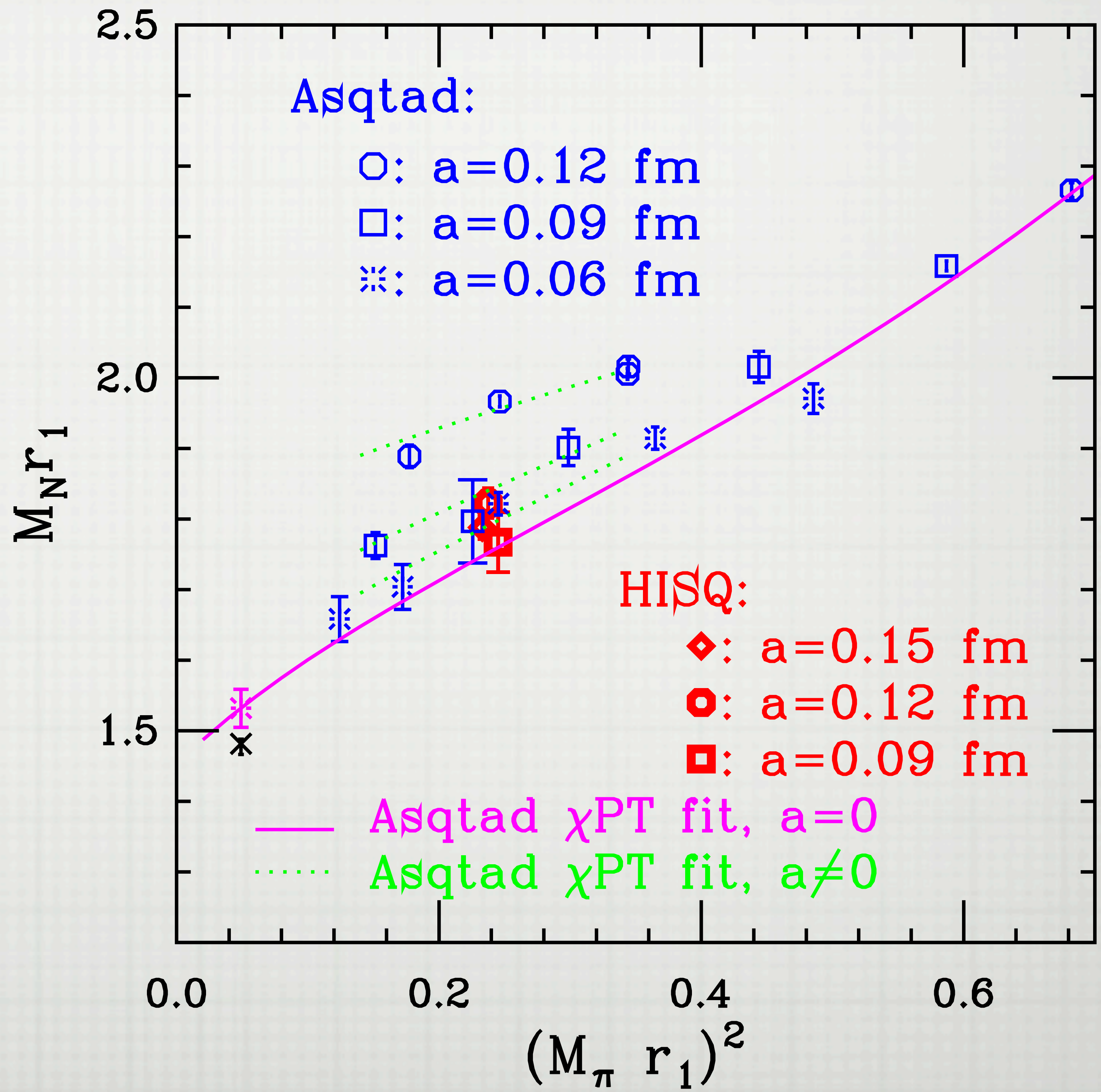
Rho Mass

- Using r_1 from static quark potential to set the scale, we see that the rho mass has much smaller *a* dependence with HISQ than with asqtad.



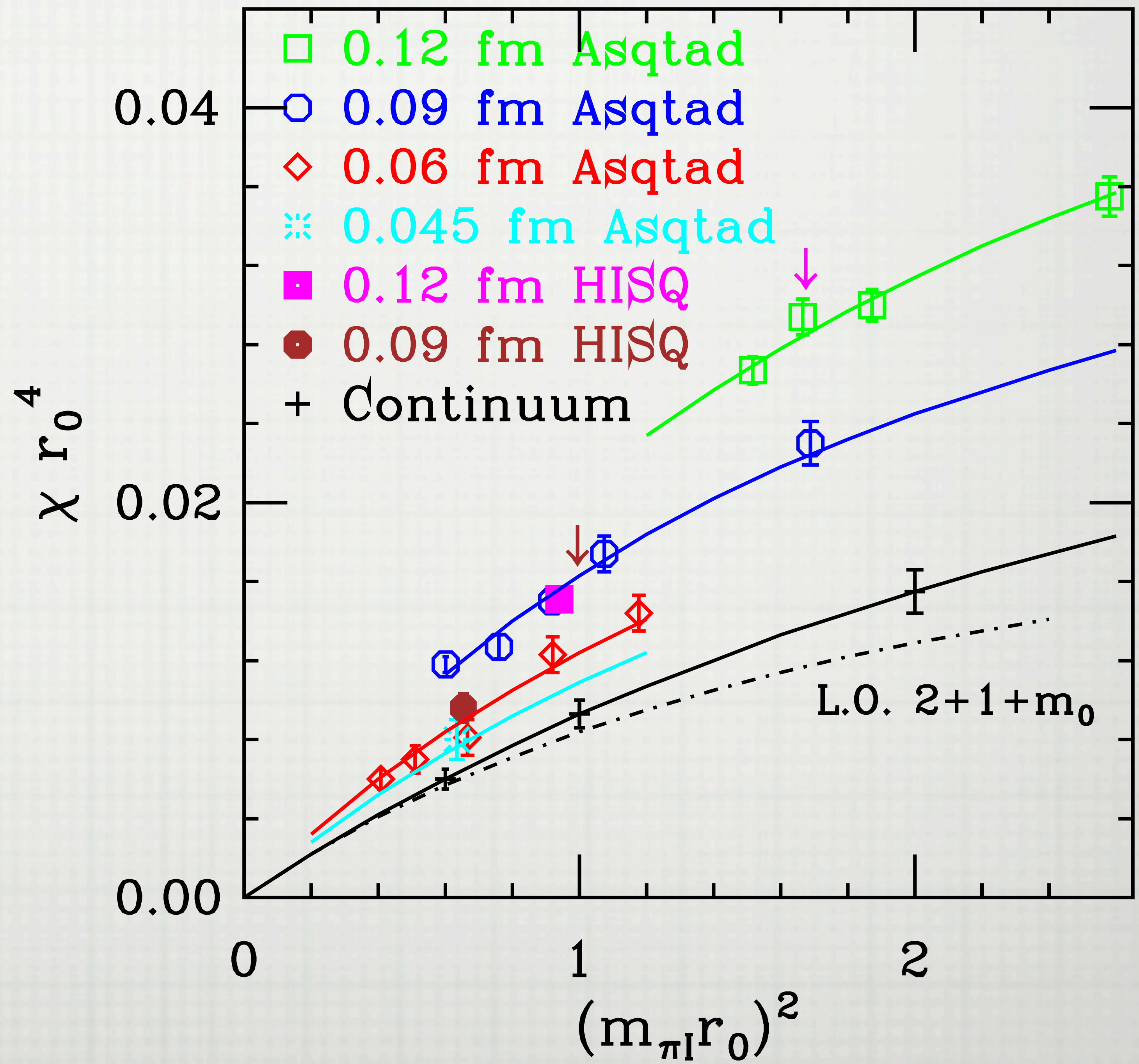
Nucleon Mass

- Similar effect is observed for nucleon.
- The long purple curve shows the continuum limit of asqtad data.
- Based on formulae of Jenkins ('92); Bernard, Kaiser & Meissner ('93).



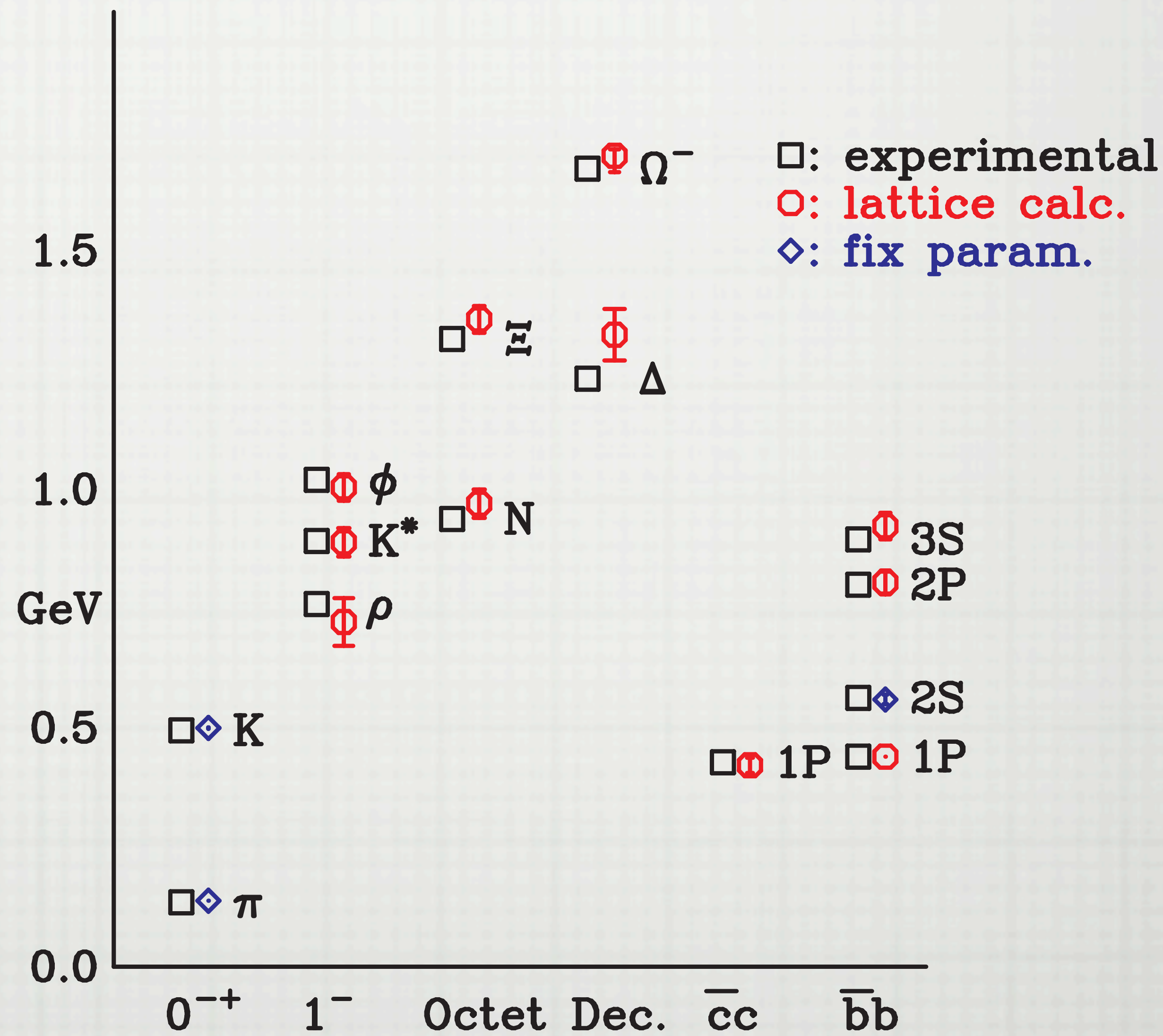
Topological Susceptibility

- Its value depends on taste singlet pion mass.
- HISQ both reduces taste breaking and susceptibility, moving point left and down.
- Continuum topological susceptibility depends on sea quark content.
- arXiv:1003:5695,1004.0342



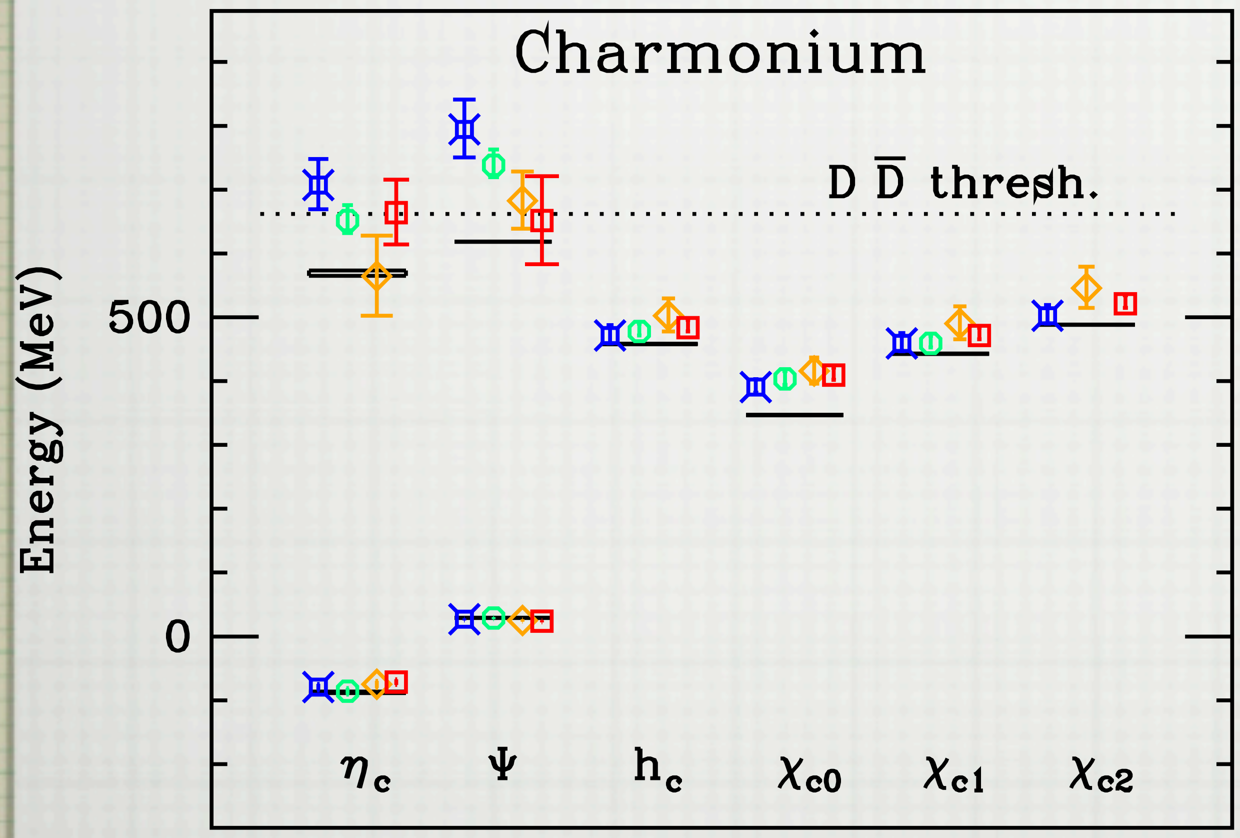
Summary of Hadron Spectrum

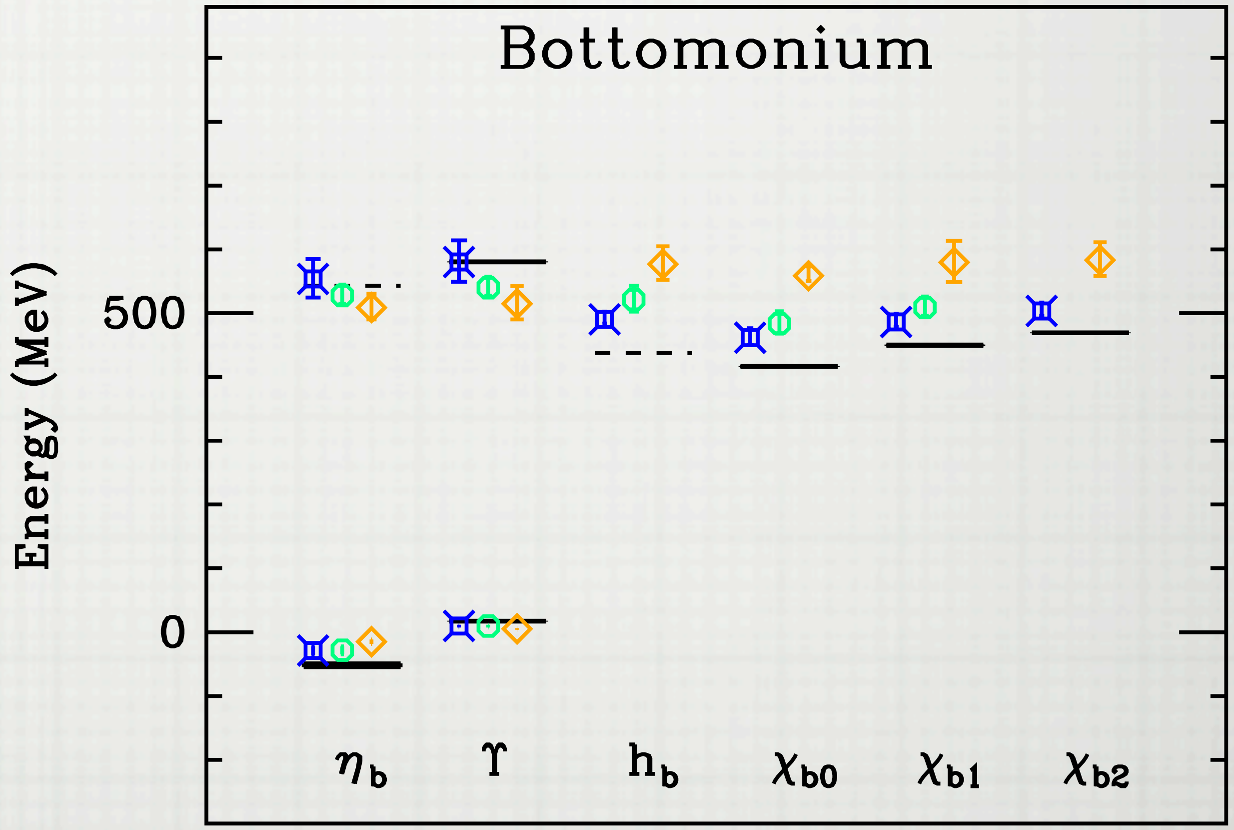
- Summary of continuum limit of asqtad spectrum results.
- States marked with diamond used to set quark mass or lattice spacing.
- For onium plot difference from spin averaged 1S mass.
- Details in RMP (2010), PDG (2008)



Onium Spectrum

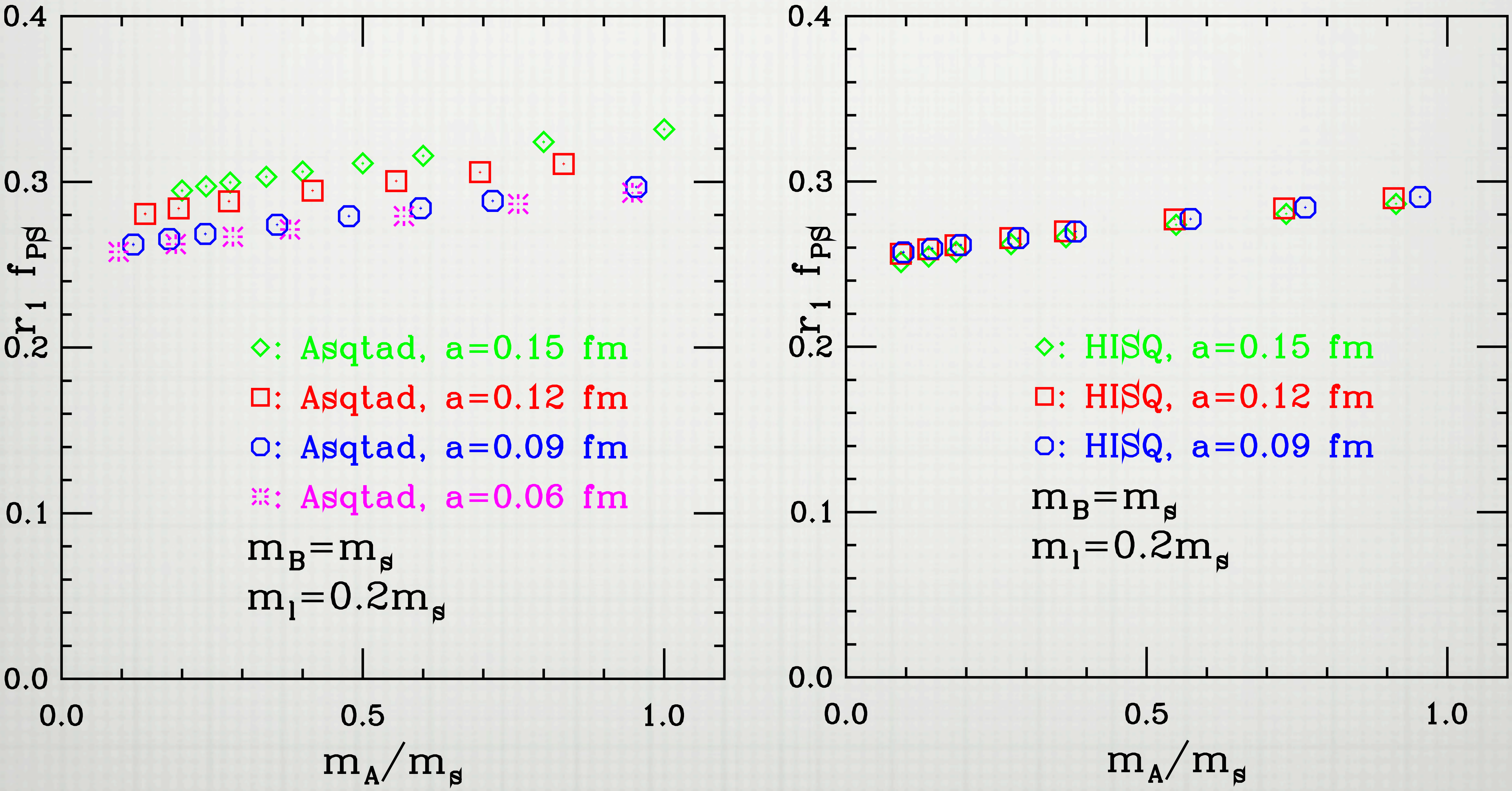
asqtad: blue=0.09fm; green=0.12fm; orange=0.15 fm; red=0.18fm





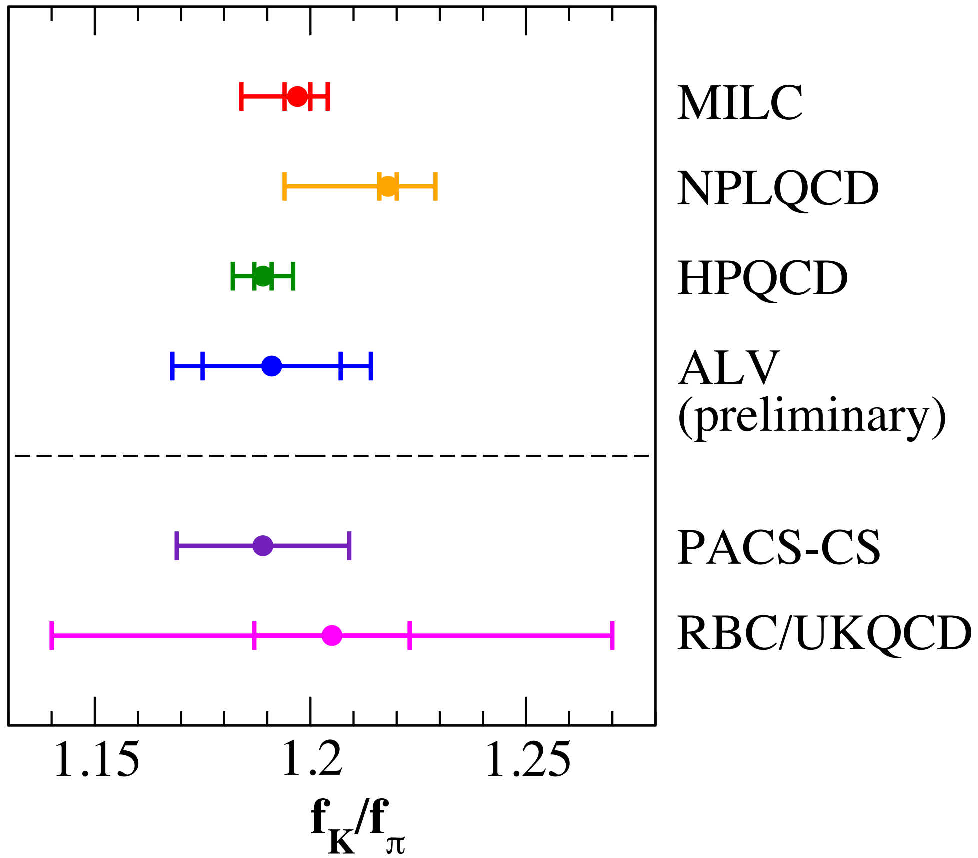
T. Burch *et al.*, PRD81, 034508, 2010

Kaon Decay Constant

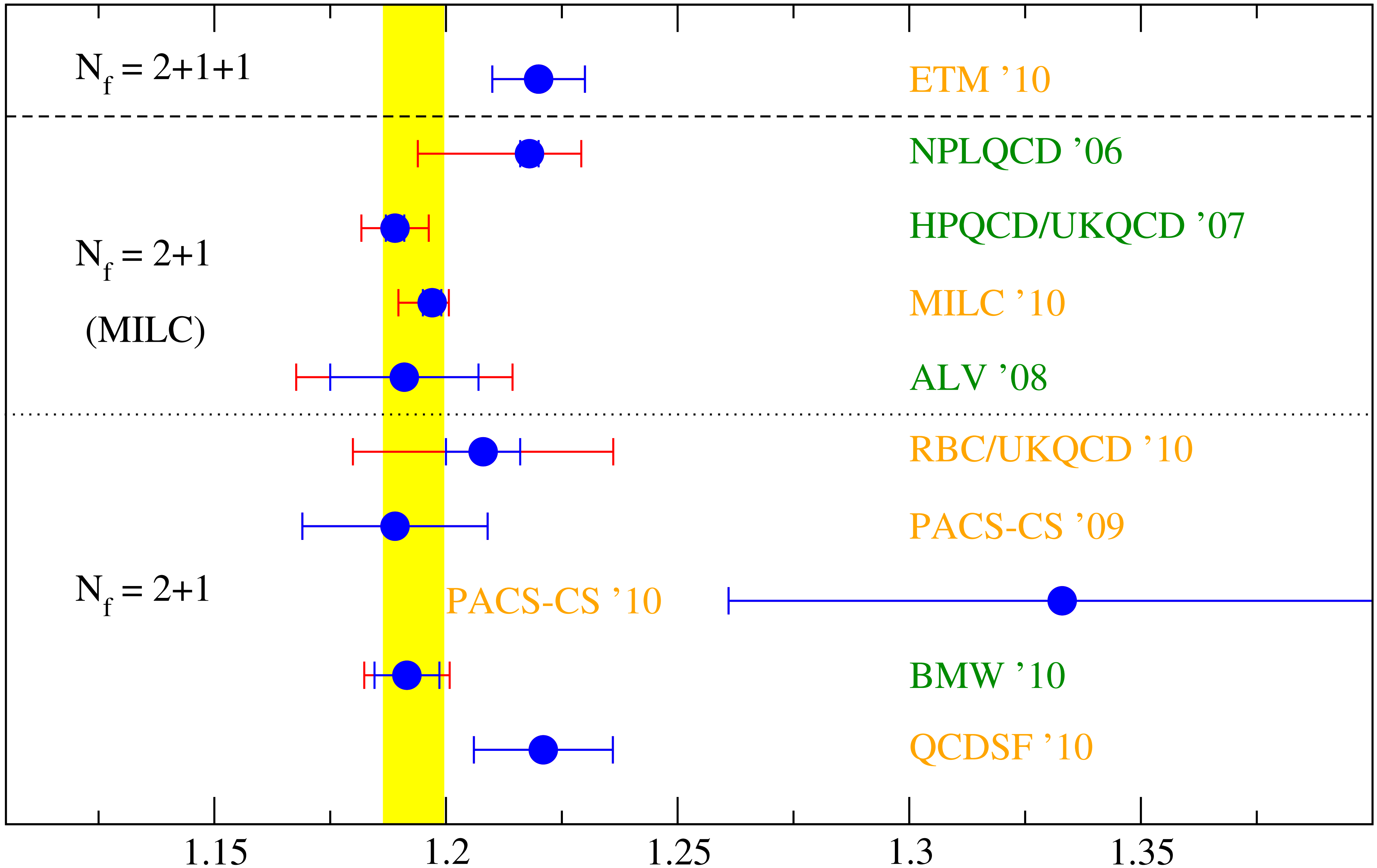


f_K / f_π

- From the RMP article.
- See Hoelbling Lattice'10 review for update that includes new BMW, ETMC (2+1+1), PACS-CS, RBC/UKQCD, etc. (next slide).



F_K / F_π Summary



Future

Short Term

- The asqtad ensembles have enabled many physics studies.
- The Fermilab Lattice/MILC Collaborations have quite a few configurations yet to be analyzed for multiple projects.
- Completion of this work will take another 1-2 years.
- We are also adding electromagnetic effects (quenched U(1)).
- At the same time, we will be generating new HISQ ensembles and gearing up for analysis of them as initial scaling study is very promising.

Longer Term

- We plan HISQ ensembles with a=0.15, 0.12, 0.09, 0.06 and 0.045 fm.
- We will not cover as wide a range of light quark mass as before:
  - m_l = 0.2 m_s, 0.1 m_s, and 0.04 m_s (physical value)
- Expect 1000 configurations per ensemble.
- This program will require sustained petascale resources such as NCSA's Blue Waters (Power 7) and ALCF's Mira (BG/Q).

Taste Symmetry Expectations

- Anticipated pion spectrum in MeV for future ensembles.
- Leftmost ensemble is in production now.
- Taste breaking can be reduced to a 10-20% effect.

	0.06 fm, $m_s/10$	0.06 fm, $m_s/27$	0.045fm, $m_s/27$
π_5	220	135	135
π_{05}, π_{i5}	225	143	139
π_{ij}, π_{0j}	231	152	144
π_0, π_i	235	159	147
π_S	239	164	149

Decay Constant Outlook

	% Errors		
Quantity	Now	~1 year	~3-5 yrs.
f_{D_s}	3.5	1.8	0.6
f_D	4.3	2.2	0.7
f_{D_s}/f_D	1.7	0.9	0.2
f_{B_s}	3.1	1.7	0.9
f_B	4.0	2.0	1.0
f_{B_s}/f_B	1.8	0.9	0.3

HISQ valence & sea

Fermilab valence b; HISQ sea & light valence

Concluding Remarks

- Based on success of the asqtad program and the initial scaling results with HISQ, I would say that the future of calculations with dynamical staggered quarks is bright.
- New, more powerful computers will play a large role.
- We hope that some algorithmic improvements will also play a role.
- For heavy-light work, the OK action (Oktay & Kronfeld) may be important for *b*-quark calculations.
- We will continue to make configurations available.