

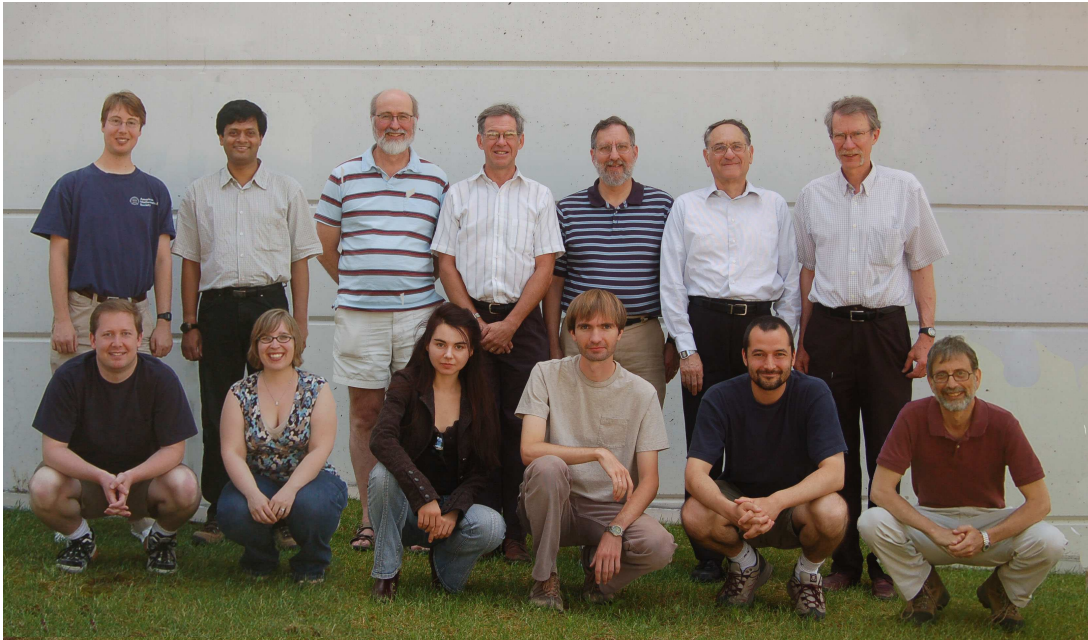
Future of Lattice Calculations with Staggered Sea Quarks

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Collaborators



MILC Collaboration (6/08):
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+ FNAL Collaboration (for
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R.T. Evans, E. D. Freeland,
E. Gamiz, **A.X. El-Khadra**, A.S. Kro-
nfeld, M. Di Pierro, P.B. Mackenzie,
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+ HPQCD & UKQCD Collabora-
tions (for scale, m_s , \hat{m} , m_s/\hat{m}):
C. Davies, E. Follana, A. Gray,
E. Gregory, J. Hein, G. P. Lepage,
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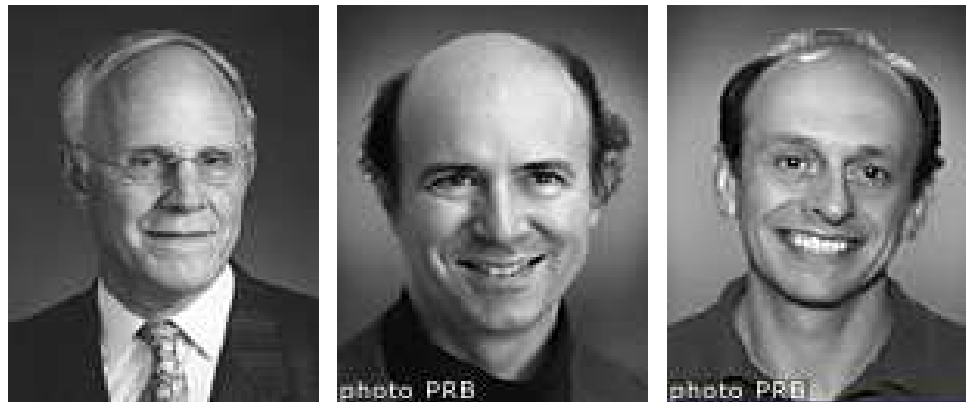
Outline

- 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., $D \rightarrow \pi l \nu$
 - 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 ≈ 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

$$\left(\begin{array}{ccc} \mathbf{V}_{ud} & \mathbf{V}_{us} & \mathbf{V}_{ub} \\ \pi \rightarrow l\nu & K \rightarrow \pi l\nu & B \rightarrow \pi l\nu \\ & K \rightarrow l\nu & \\ \mathbf{V}_{cd} & \mathbf{V}_{cs} & \mathbf{V}_{cb} \\ D \rightarrow \pi l\nu & D \rightarrow K l\nu & B \rightarrow D^{(*)} l\nu \\ D \rightarrow l\nu & D_s \rightarrow l\nu & \\ \mathbf{V}_{td} & \mathbf{V}_{ts} & \mathbf{V}_{tb} \\ \langle B_d | \bar{B}_d \rangle & \langle B_s | \bar{B}_s \rangle & \end{array} \right)$$

2008 Physics Nobel Prize



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

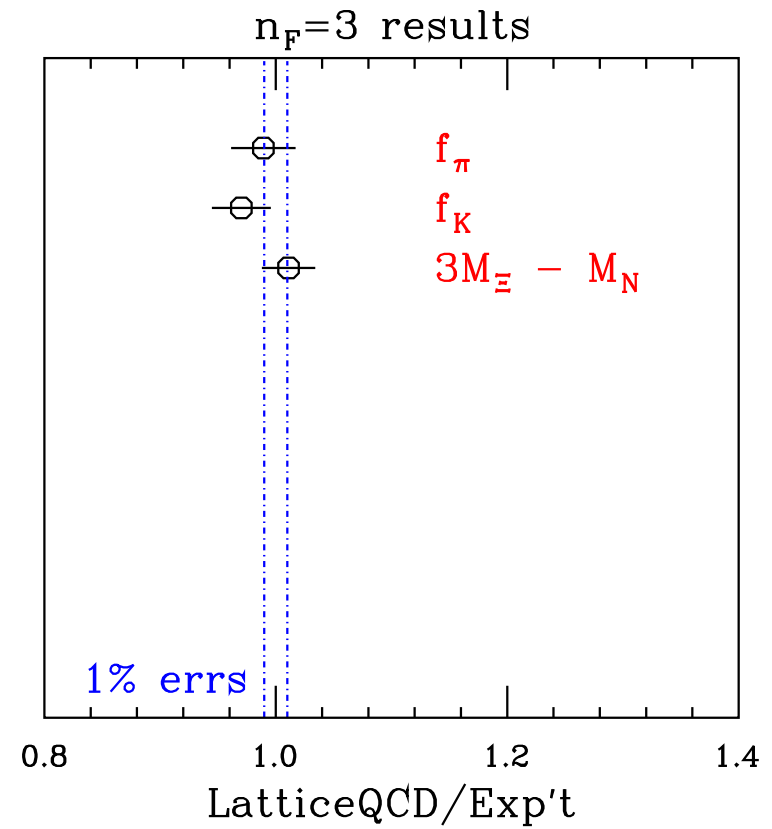
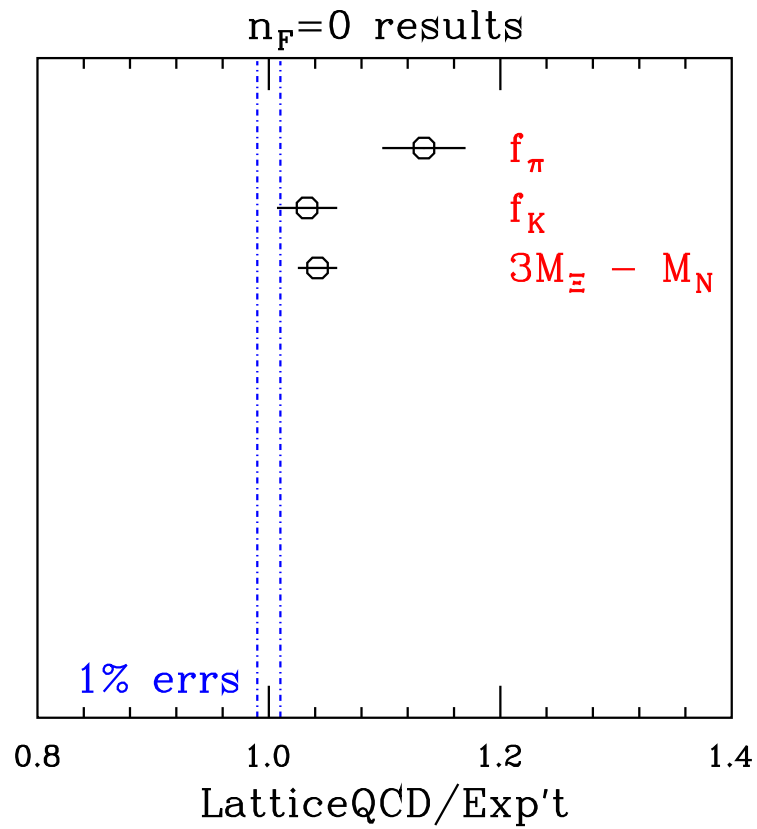
KEK photo from nobelprize.org

2008 Physics Nobel Prize

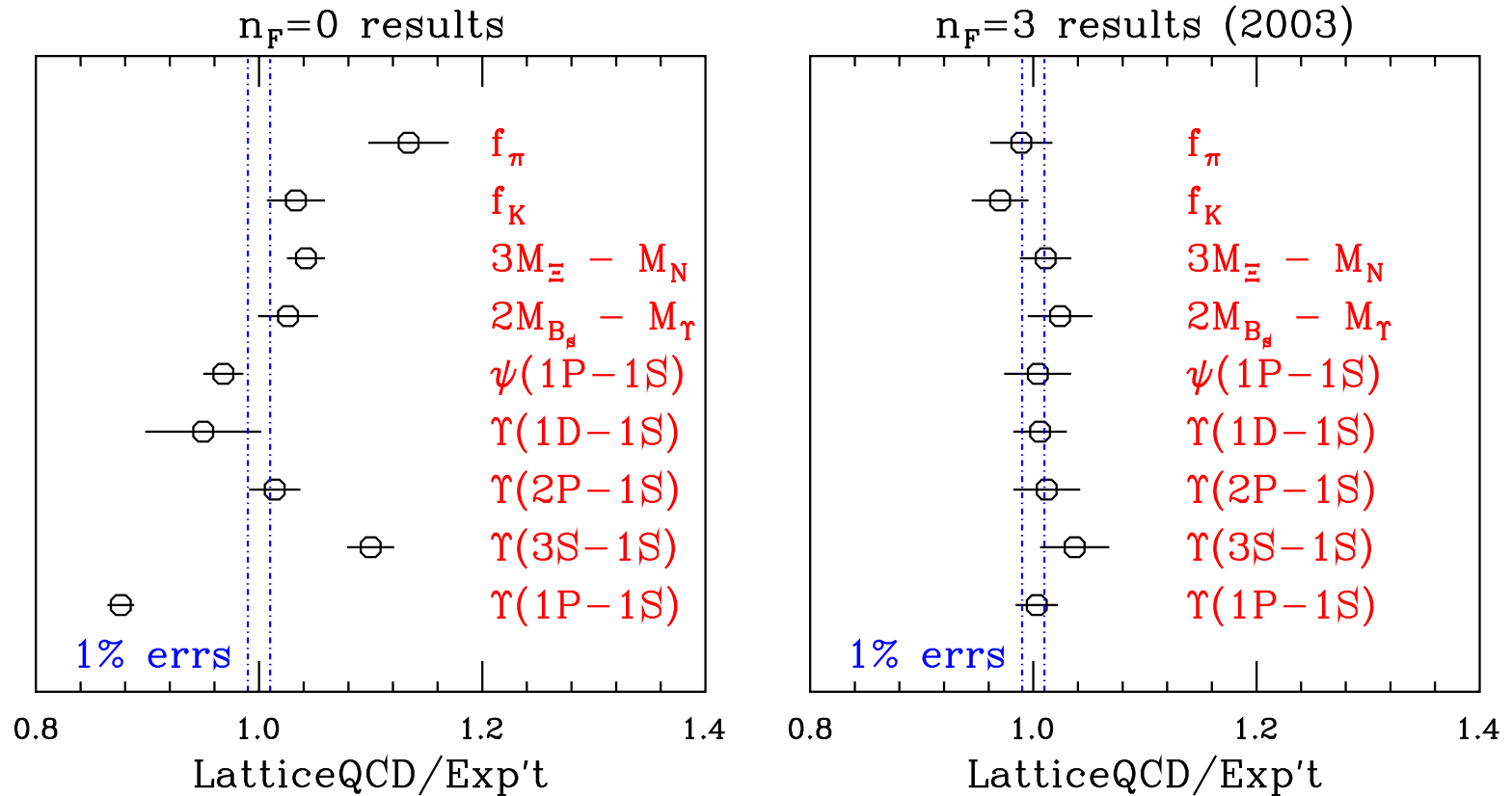


- Makoto Kobayashi (L) and Toshihide Maskawa (R). Is this after winning the prize? They don't look that much happier.

Ratio Plot



Ratio Plot

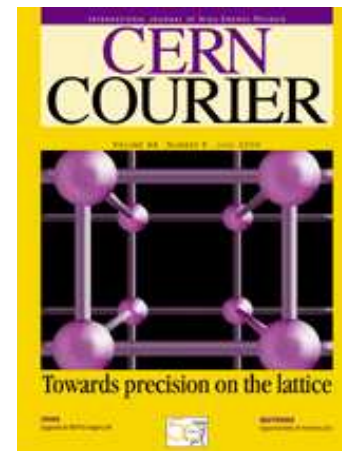


By sharing with FNAL, HPQCD and UKQCD [PRL 92, 0022001 (2004)]

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

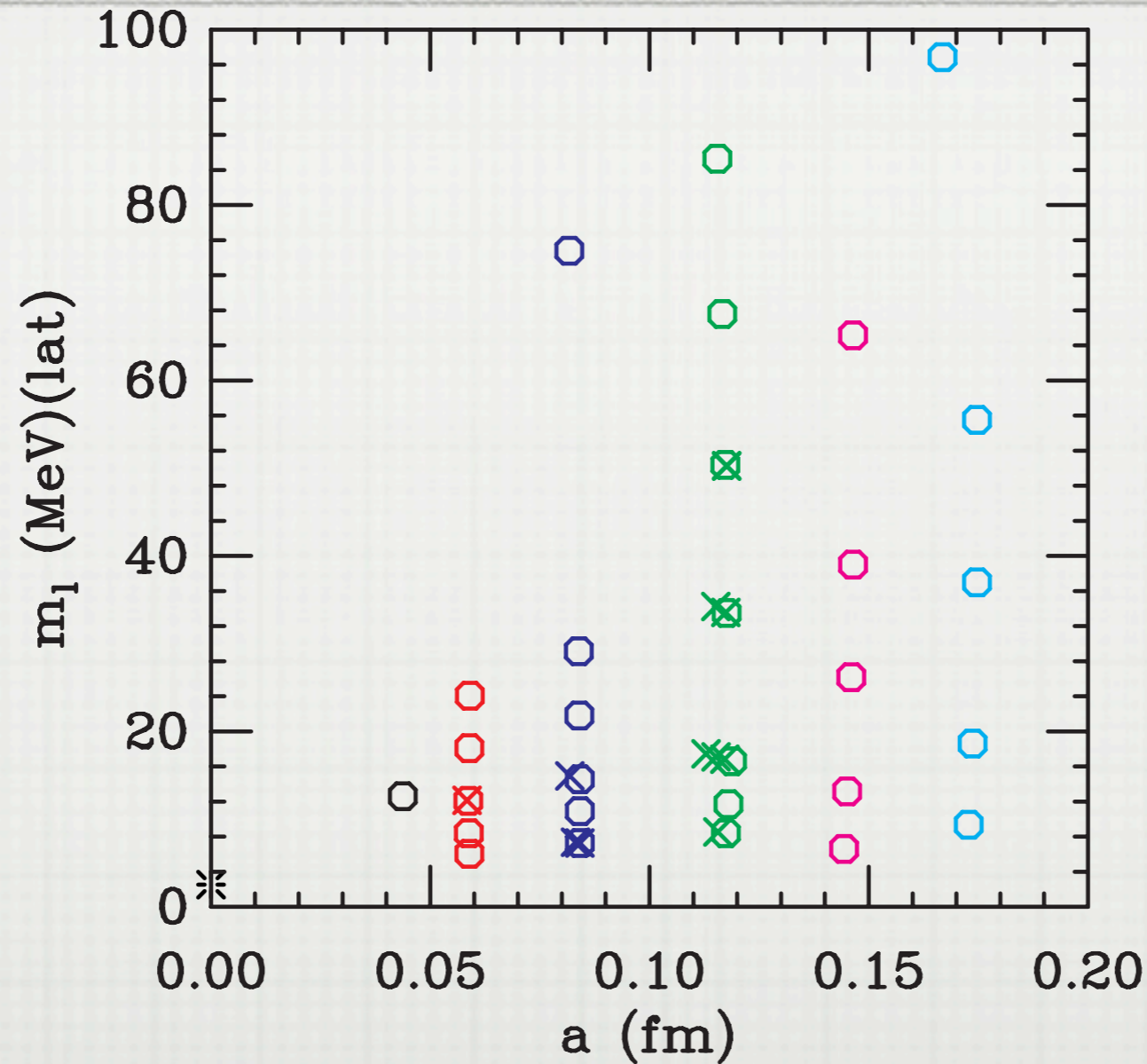
Control of Systematic Errors

- 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



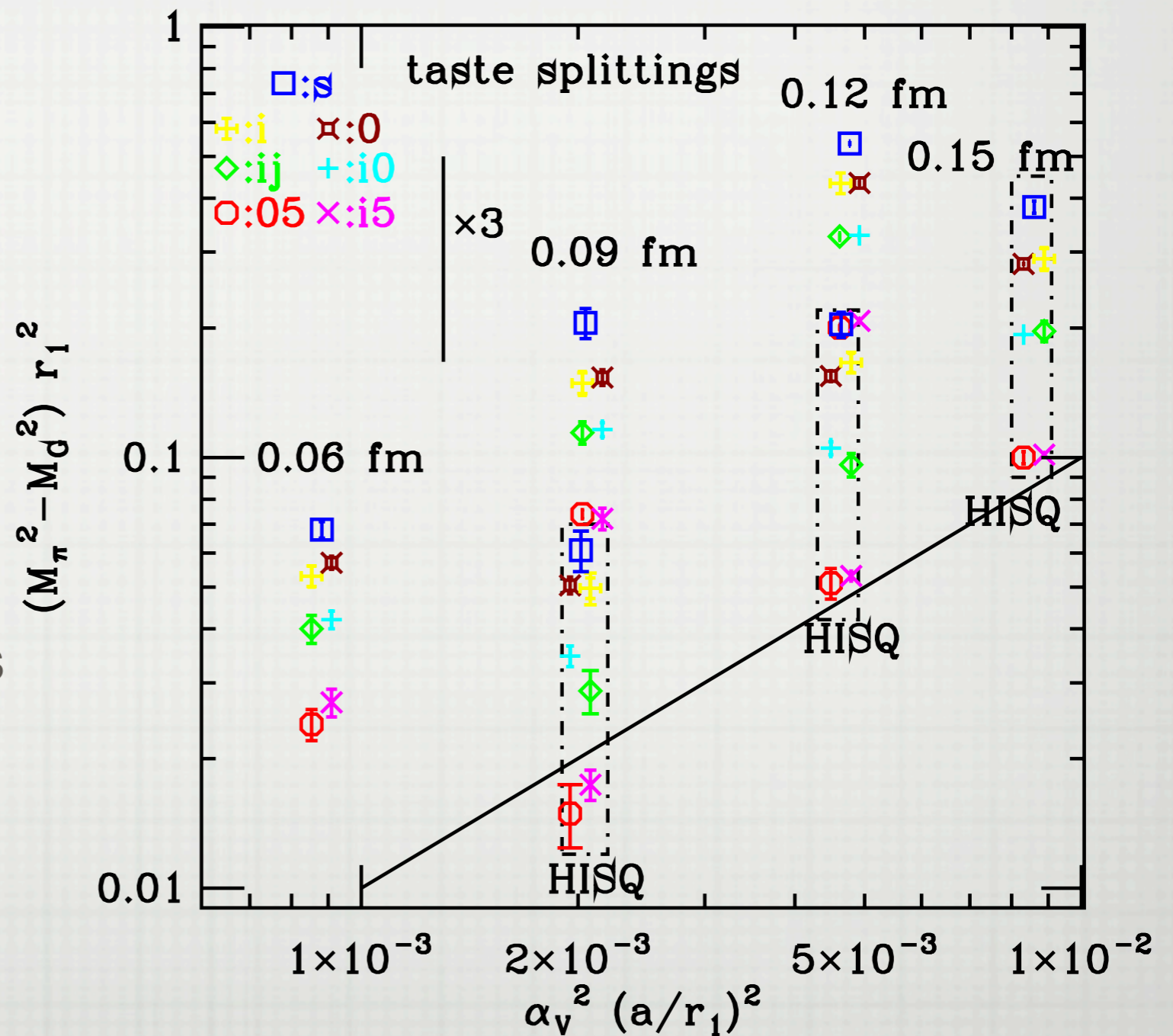
- octagons have physical strange quark mass, crosses lighter strange quark mass

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

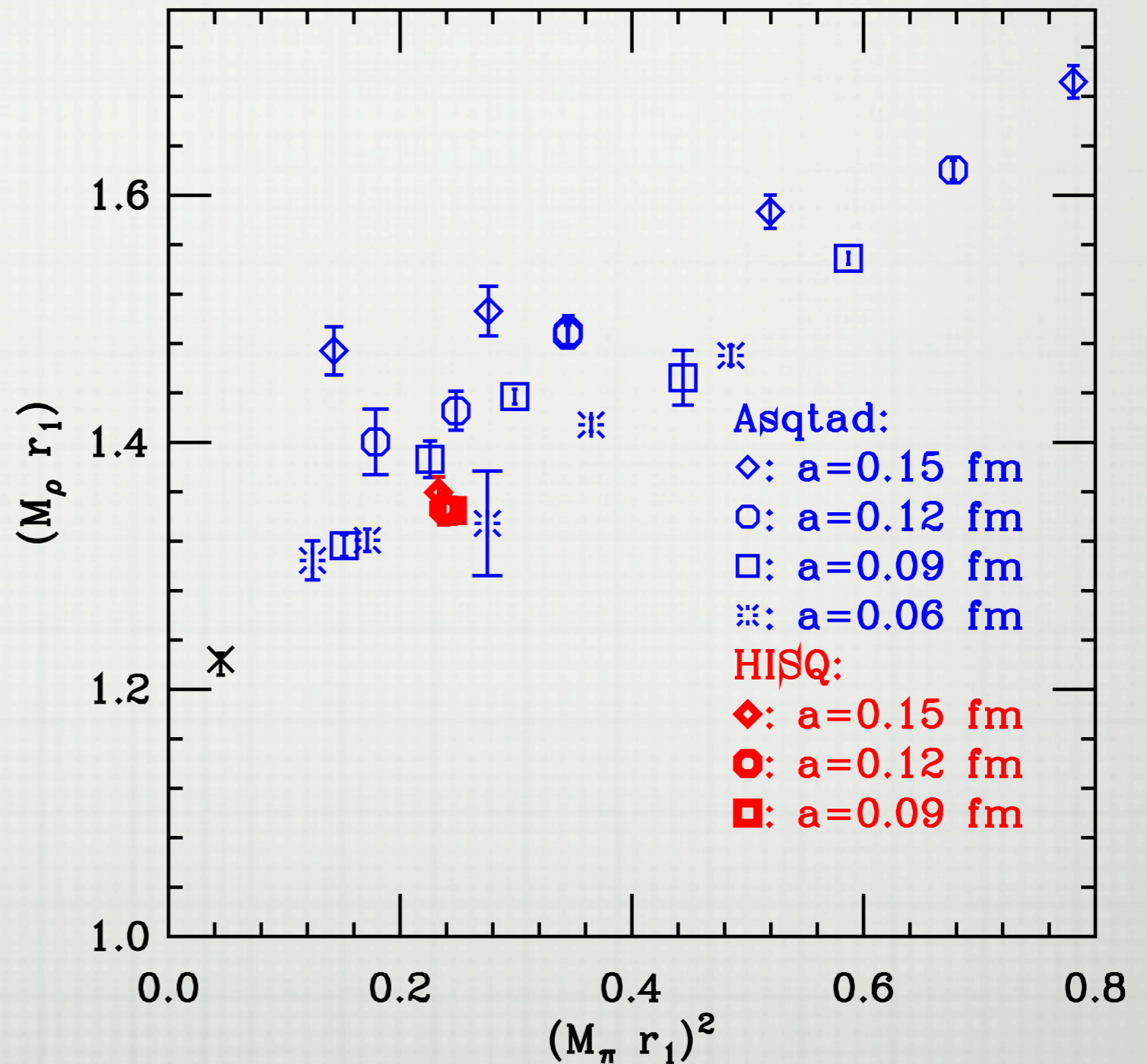
- To deal with fermion doubling problem on lattice, staggered quark calculations use rooting.
- With recent increase in precision, revival of concerns that rooting could lead to incorrect results, even in continuum limit.
- Theoretical work by Shamir, Bernard, Golterman, Sharpe; Adams
- Numerical work 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.

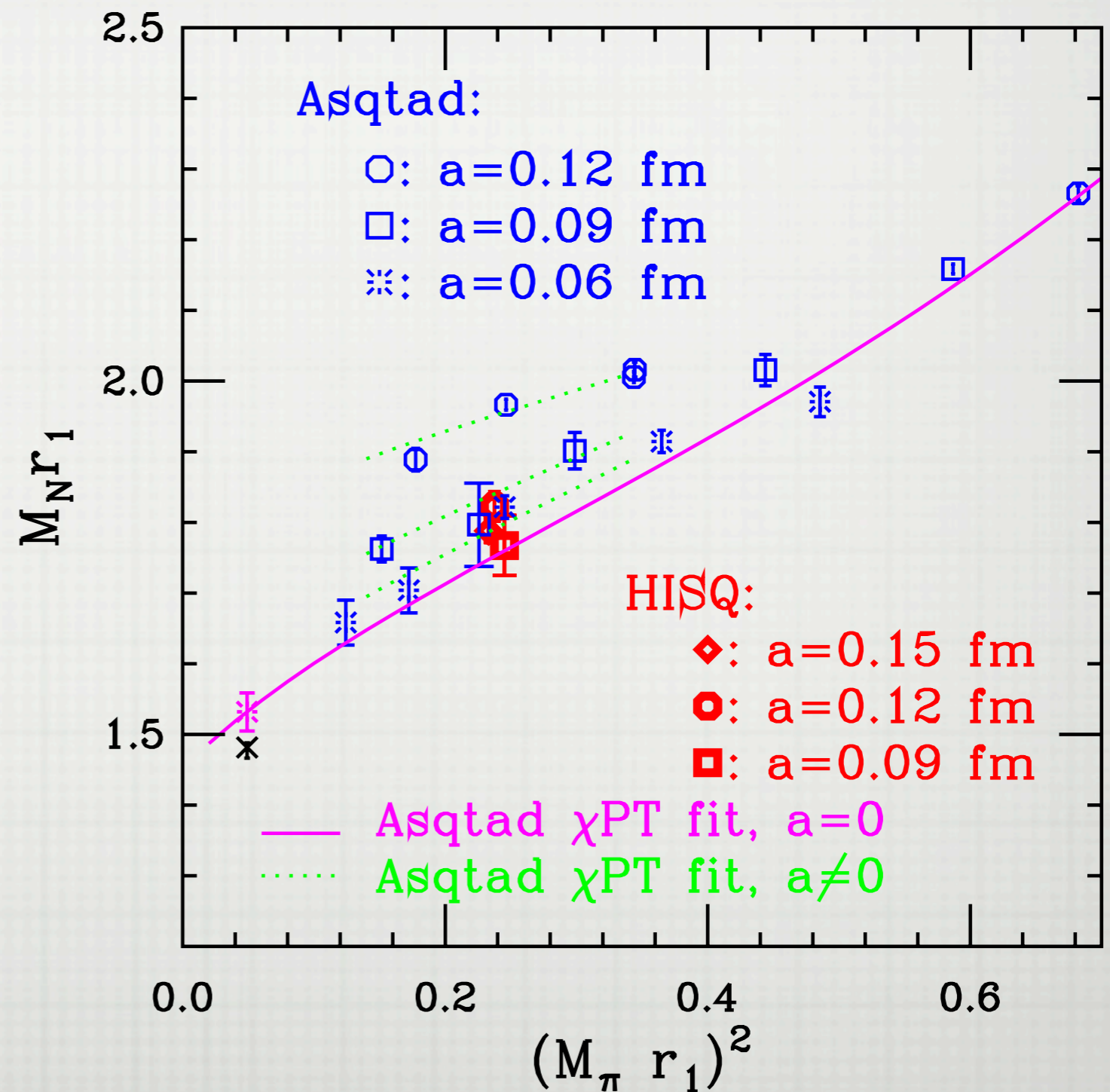
Rho Mass

- 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.



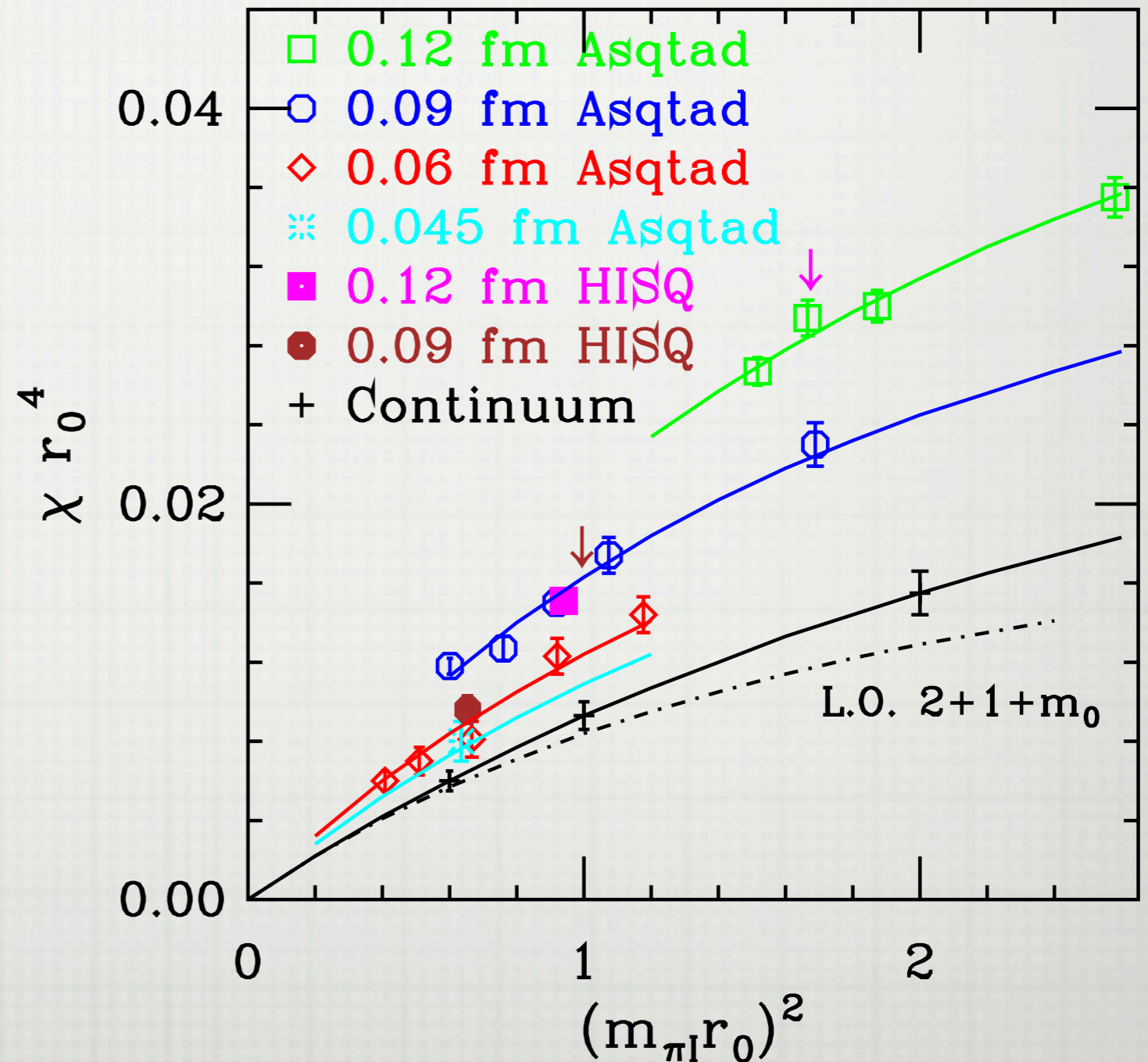
Nucleon Mass

- 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).



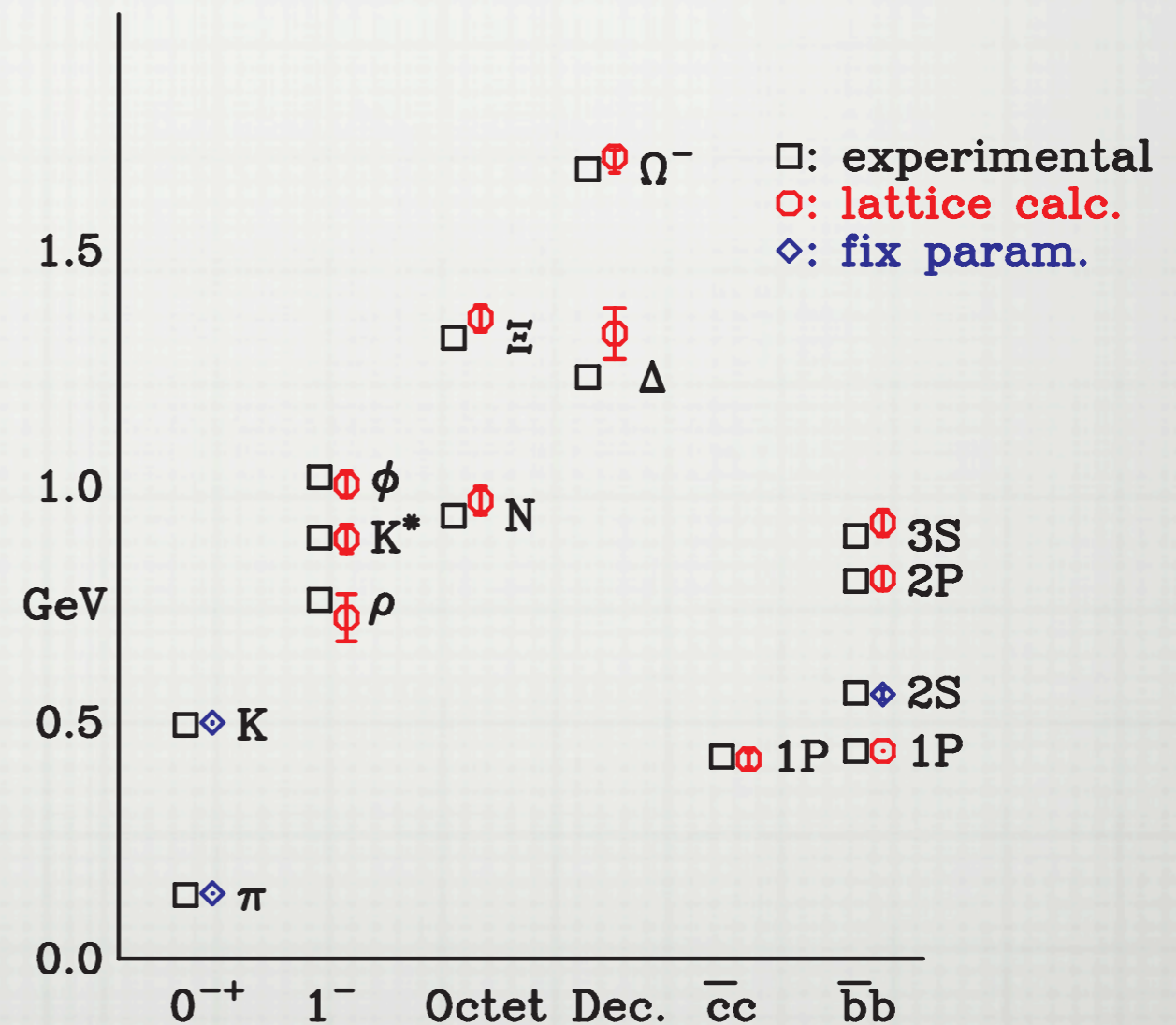
Topological Susceptibility

- 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



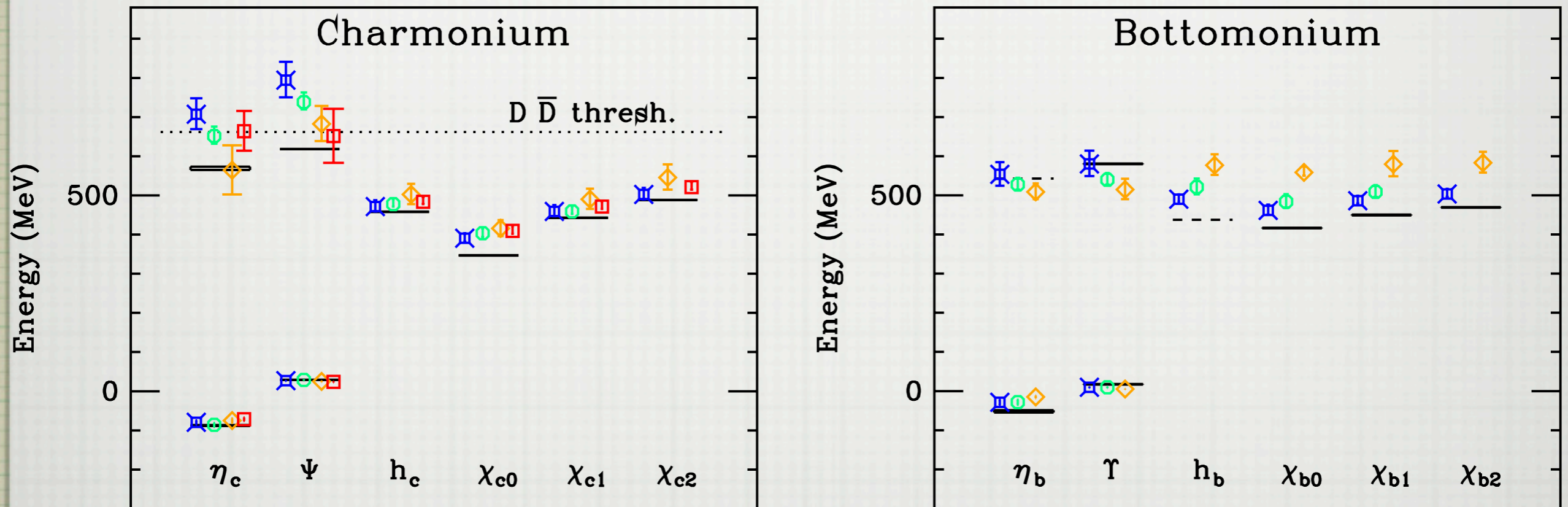
Summary of Hadron Spectrum

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



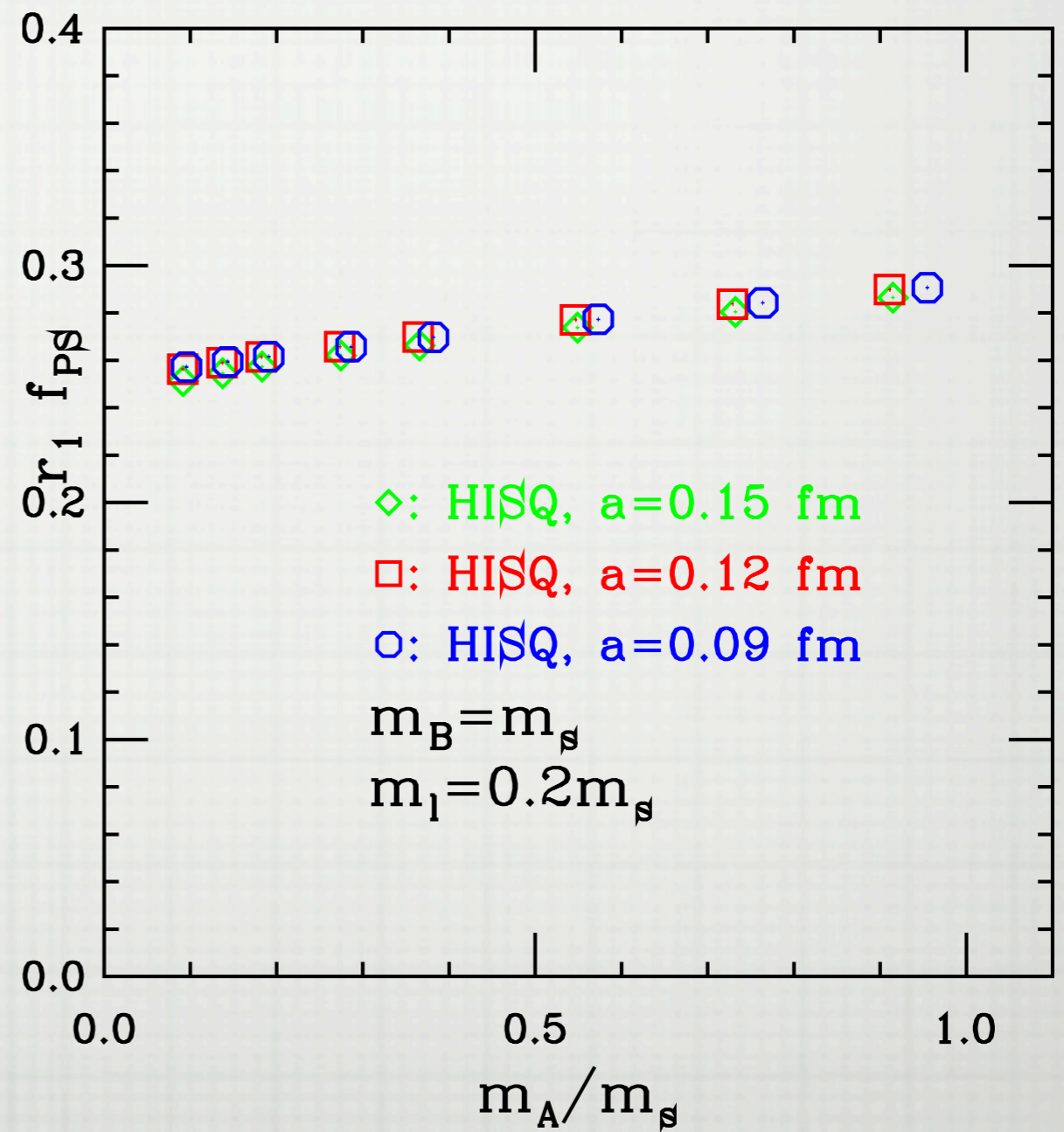
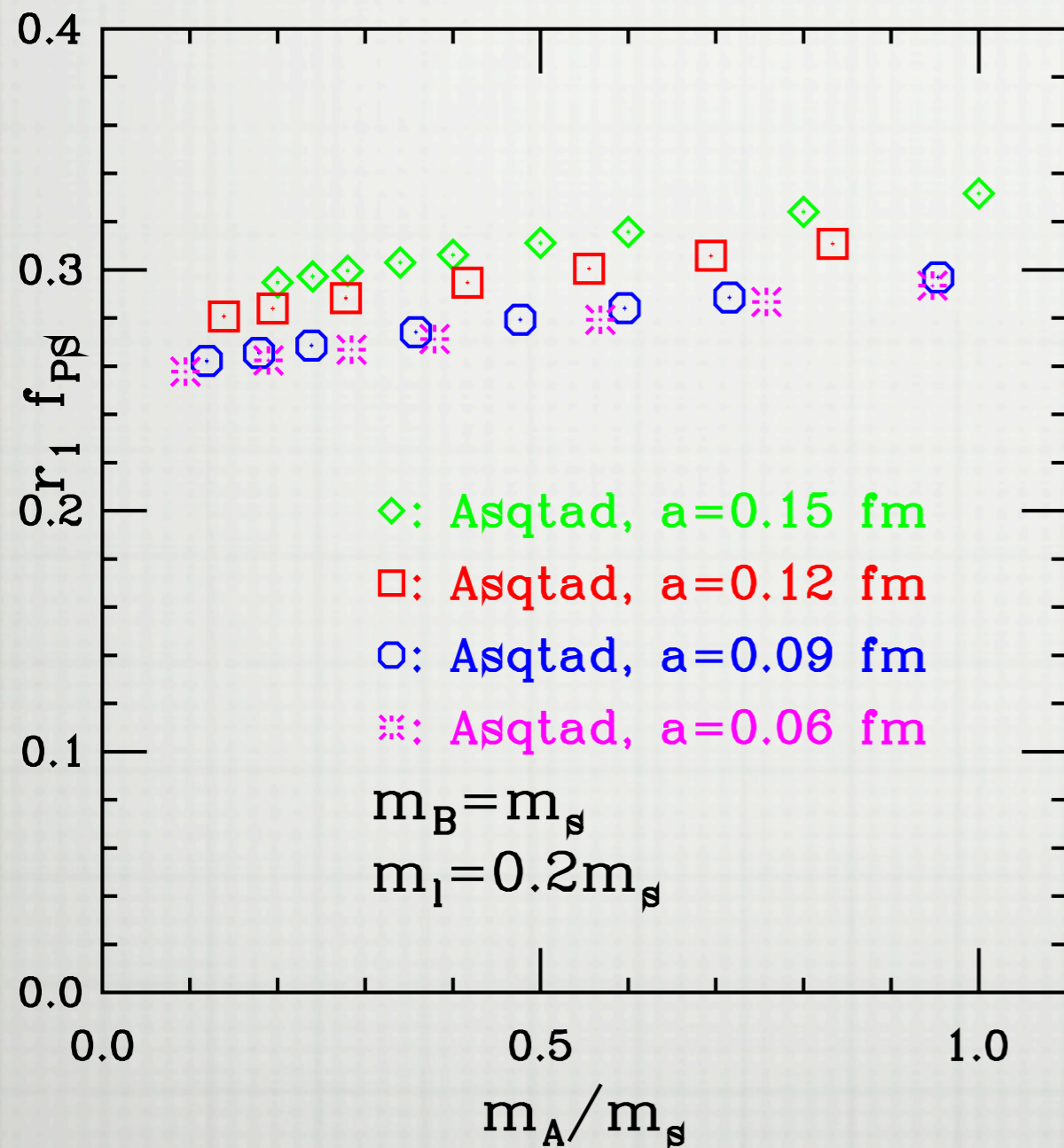
Onium Spectrum

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



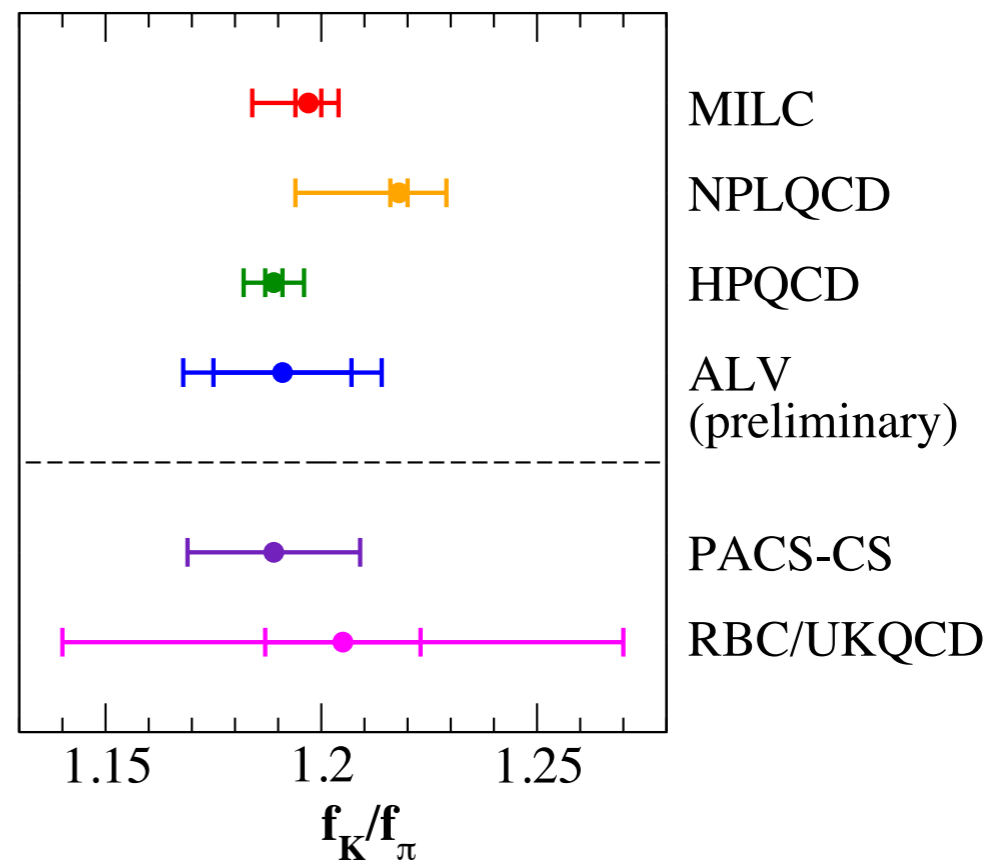
T. Burch *et al.*, PRD81, 034508, 2010

Kaon Decay Constant

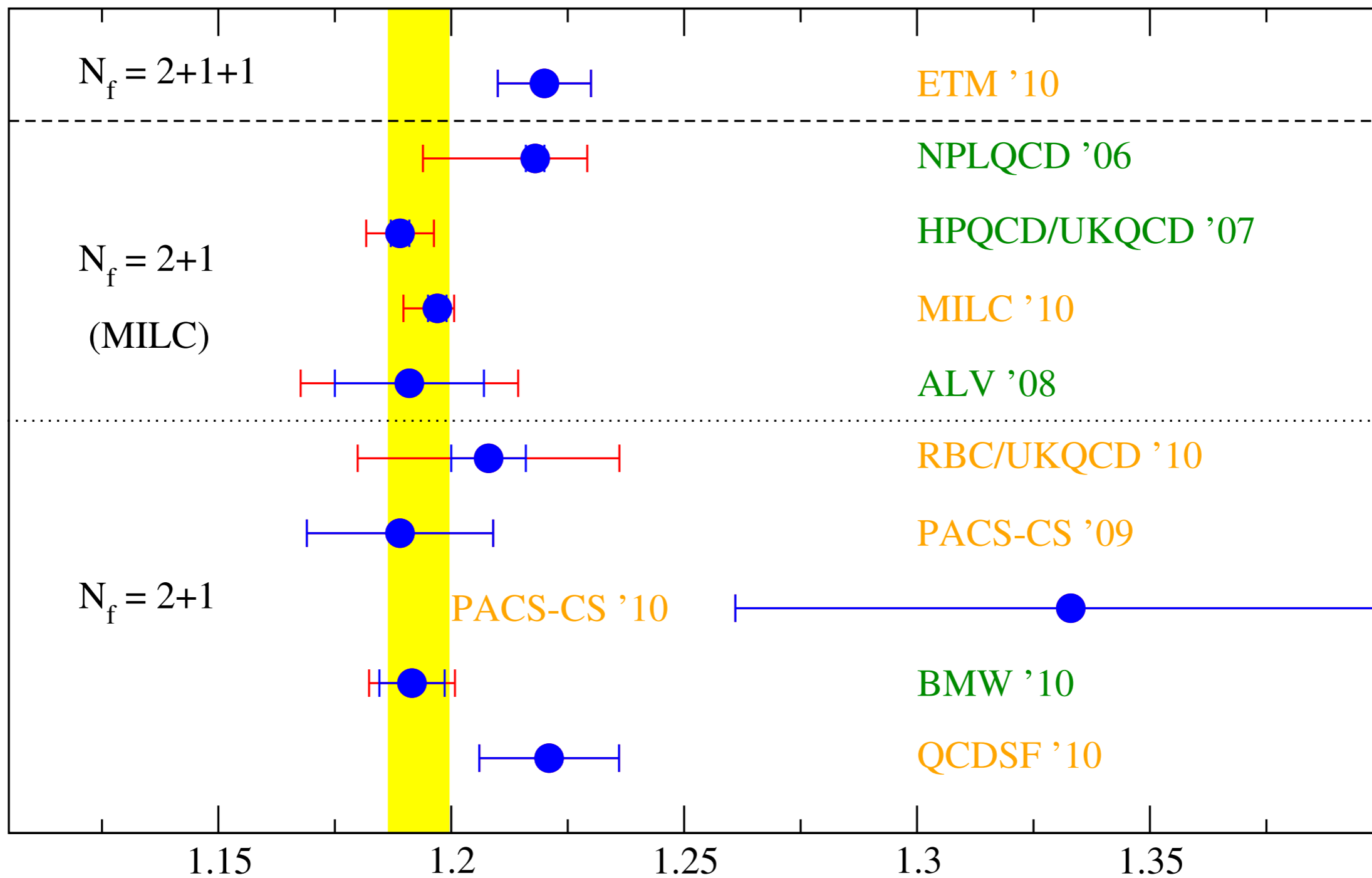


$$f_K / f_\pi$$

- 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

Quantity	% Errors		
	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.