Physics Results with Three Flavors of Asqtad Quarks on MILC Ensembles

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Abstract

For some time, the MILC Collaboration has been generating ensembles of gauge configurations containing the effects of three flavors of dynamical quarks. Generally, these ensembles have degenerate up and down quarks with a mass as small as one-tenth the strange quark mass. A range of lattice spacing from 0.06 to 0.18 fm is available. The ensembles use the improved staggered quark action known as Asqtad. These configurations have been shared with the international lattice field theory community and used for a variety of physics studies. This talk will concentrate on work by the MILC, Fermilab and HPCQCD collaborations on spectrum, light and heavy-light pseudoscalar decay constants, quark masses, semileptonic decay constants, and QCD equation of state. Future prospects will be mentioned.

Collaborators

MILC Collaboration: C. Aubin, C. Bernard, B. Billeter, T. Burch, C. DeTar, E. Gregory, U. Heller, J. Hetrick, L. Levkova, F. Maresca, J. Osborn, D. Renner, D. Toussaint, R. Sugar

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

$+$ FNAL Collaboration (for heavy-light decays):
A.S. Kronfeld, M. Di Pierro, E. D. Freeland, A.X. El-Khadra, P.B. Mackenzie, D. Menscher, M. Nobes, M. Okamoto, M.B. Oktay, J. Simone, E. Freeland, J. Laiho, R. Van de Water

Outline

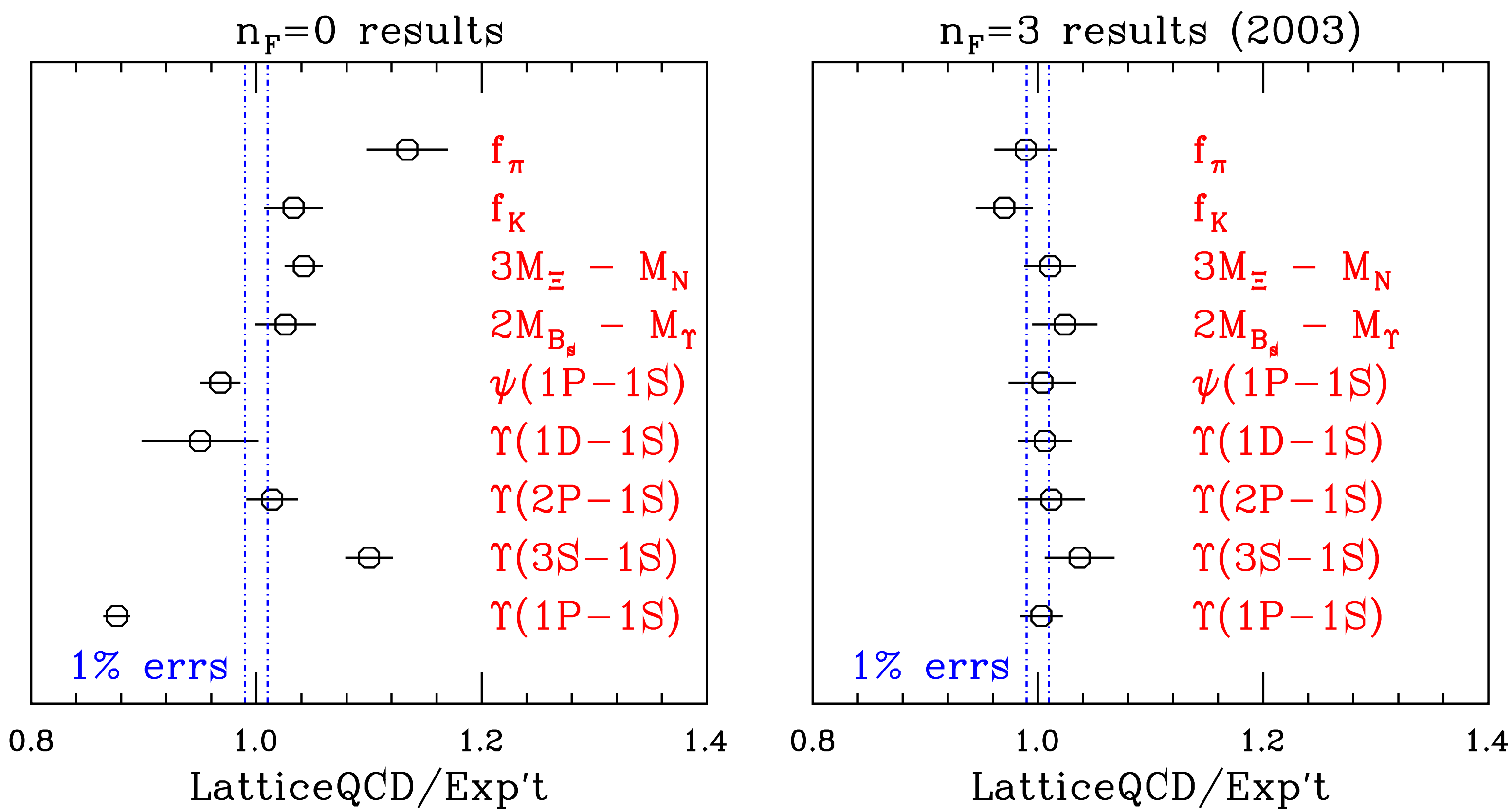
- Outline of MILC Projects
- Ensembles of Configurations
- Recent Results
- Future Plans

Outline of MILC Projects

MILC's physics interests are varied:

- Light quarks
  - π, K decay constants
  - quark masses
  - spectrum, including exotics
- Heavy quarks
  - leptonic decay constants
  - semi-leptonic decay form factors
- Topology
- High temperature QCD

C.T.H. Davies *et al.*, [FNAL, HPQCD, MILC, UKQCD Collaborations], PRL 92 (2004) 022001



Ensembles of Configurations

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)

To control systematic error we must

- take continuum limit
- take infinite volume limit
- extrapolate to light quark mass; can work at physical s quark mass

Existing Ensembles: $\mathbf{a = 0.18, 0.15}$ fm

- Ensembles have been generated with lattice spacing $\mathbf{a = 0.18}$ and $\mathbf{0.15}$ fm for $\mathbf{0.1 \leq m_l/m_s \leq 1.0}$.
- These ensembles are quite coarse. They have been used to set the scale for thermodynamics calculations, and to estimate systematic errors due to finite lattice spacing artifacts.

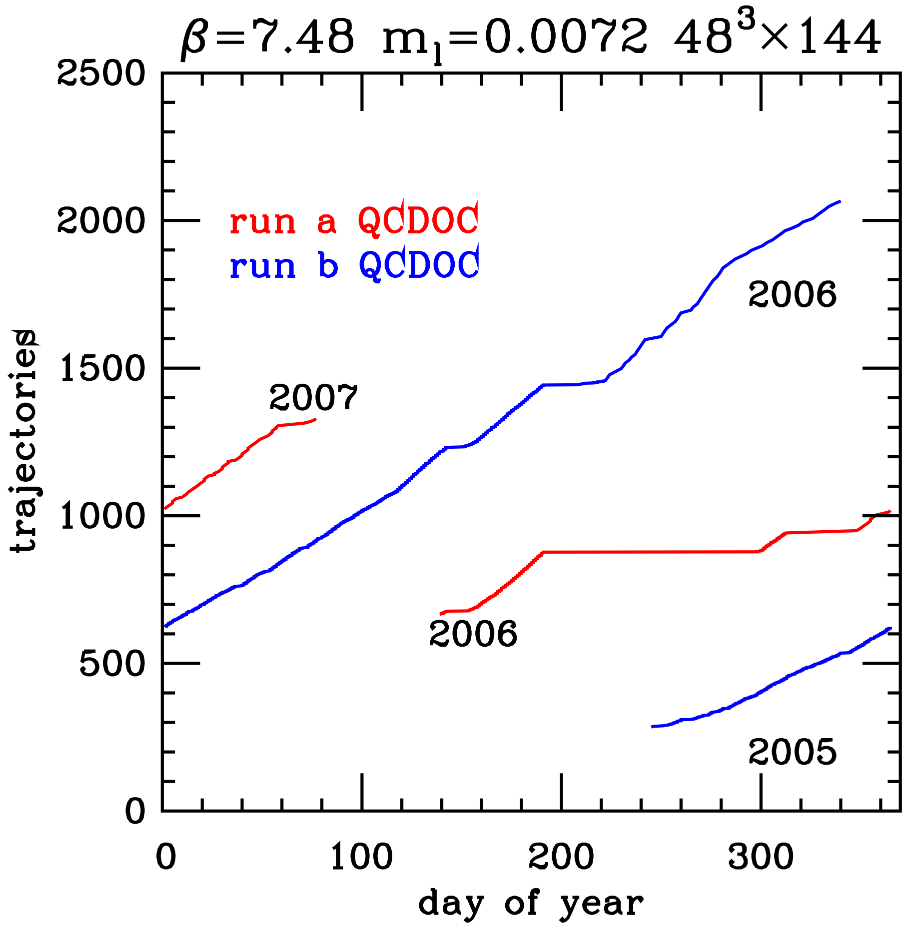
Existing Ensembles: $\mathbf{a = 0.12\ fm}$

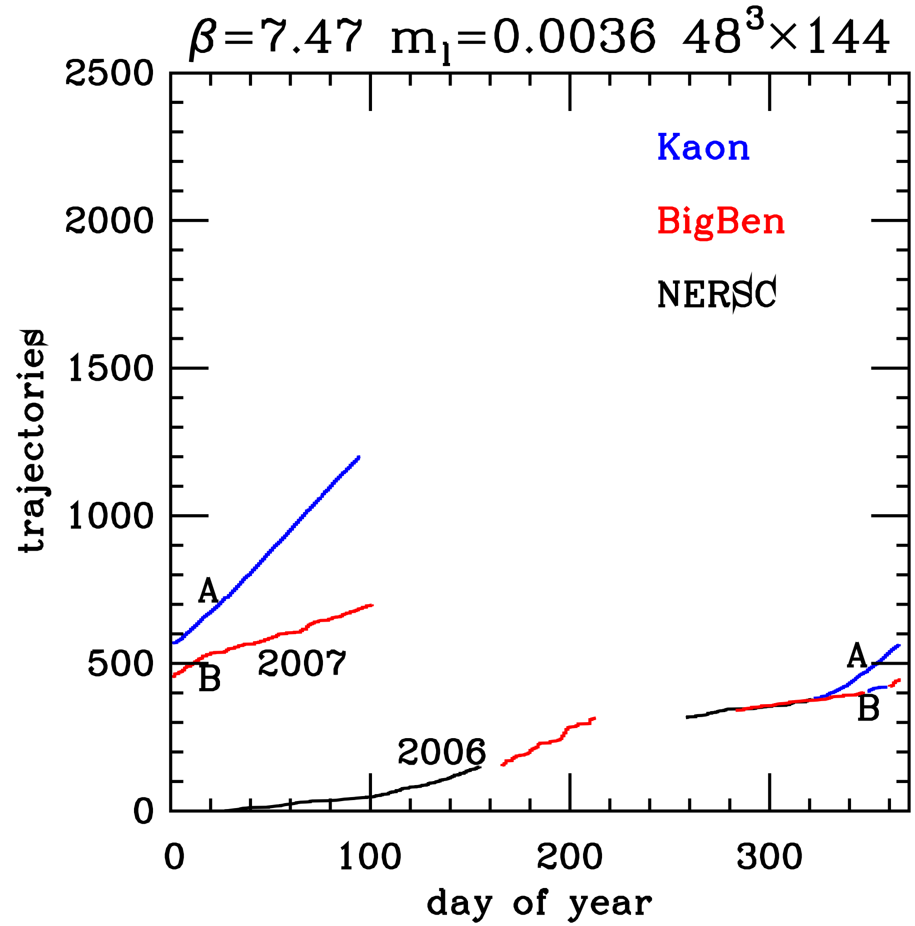
$\mathbf{am_l}$ / $\mathbf{am_s}$	$\mathbf{m_\pi L}$	Lattice	# Lats
0.05 / 0.05	9.7	$\mathbf{20^3 \times 64}$	425
0.04 / 0.05	8.7	$\mathbf{20^3 \times 64}$	351
0.03 / 0.05	7.6	$\mathbf{20^3 \times 64}$	564
0.02 / 0.05	6.2	$\mathbf{20^3 \times 64}$	484
0.01 / 0.05	4.5	$\mathbf{20^3 \times 64}$	658
0.01 / 0.05	6.3	$\mathbf{28^3 \times 64}$	241
0.007 / 0.05	3.8	$\mathbf{20^3 \times 64}$	493
0.005 / 0.05	3.8	$\mathbf{24^3 \times 64}$	527
0.03 / 0.03	7.6	$\mathbf{20^3 \times 64}$	359
0.01 / 0.03	4.5	$\mathbf{20^3 \times 64}$	346

Existing Ensembles: $a = 0.09, 0.06$ fm

am_l / am_s	$m_\pi L$	Lattice	# Lats
$a = 0.09$ fm			
0.0124 / 0.031	5.8	$28^3 \times 96$	527
0.0062 / 0.031	4.1	$28^3 \times 96$	592
0.0031 / 0.031	4.2	$40^3 \times 96$	500
$a = 0.06$ fm			
0.0072 / 0.018	6.3	$48^3 \times 144$	441R
0.0036 / 0.018	4.5	$48^3 \times 144$	340R

Progress on Running Ensembles

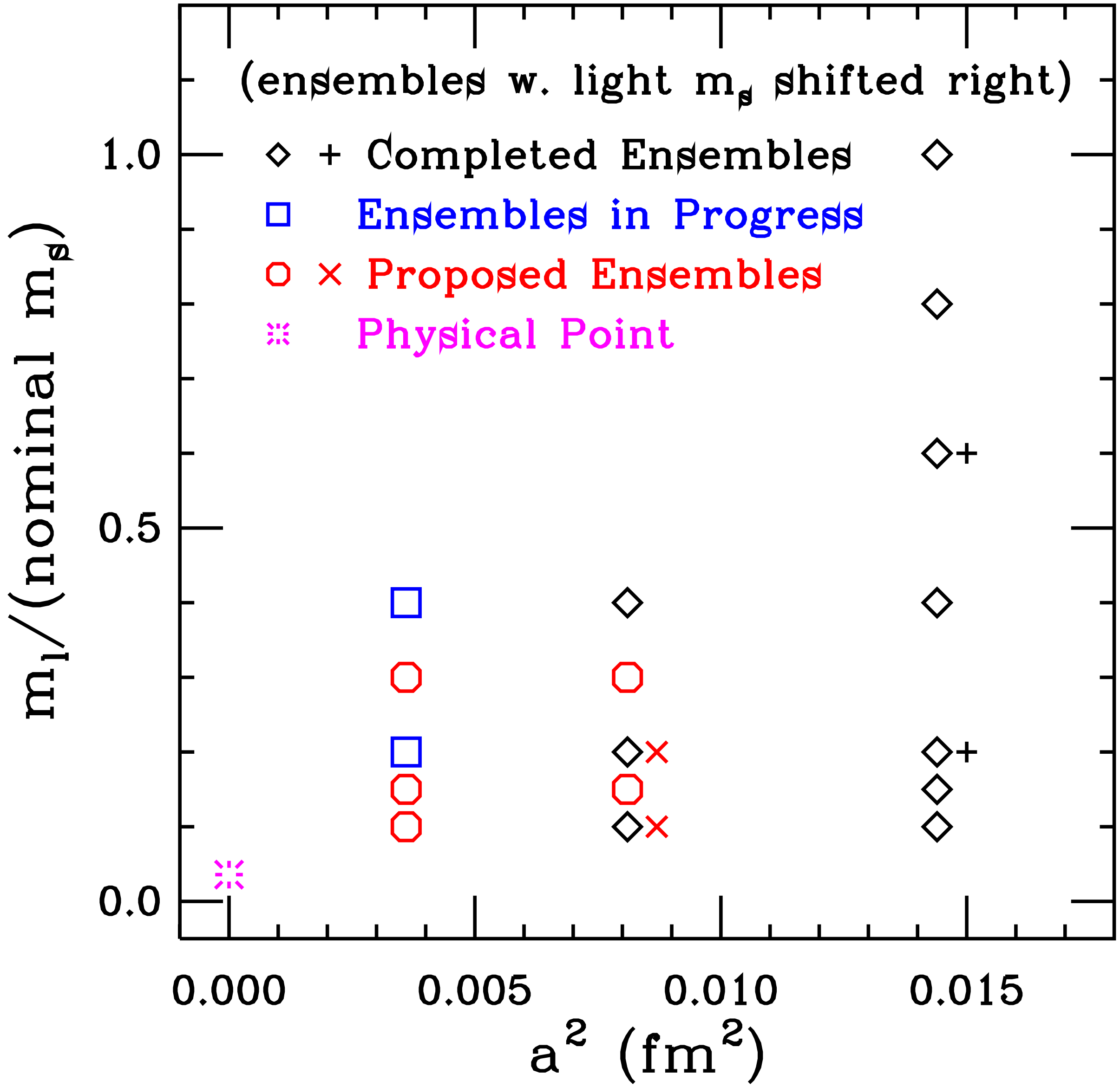




Summary of Ensembles

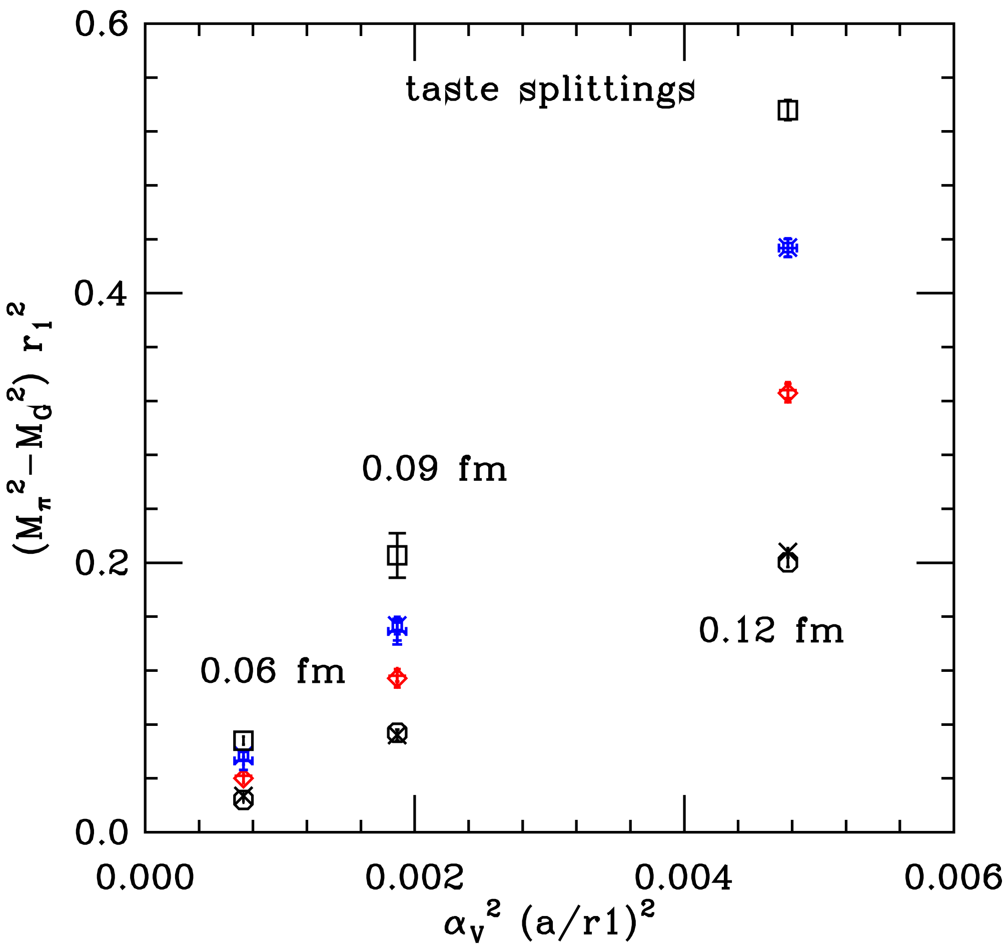
Need a range of quark mass and lattice spacing to control the chiral and continuum limits.

Must have a large volume to control finite size effects, particularly at small quark mass.

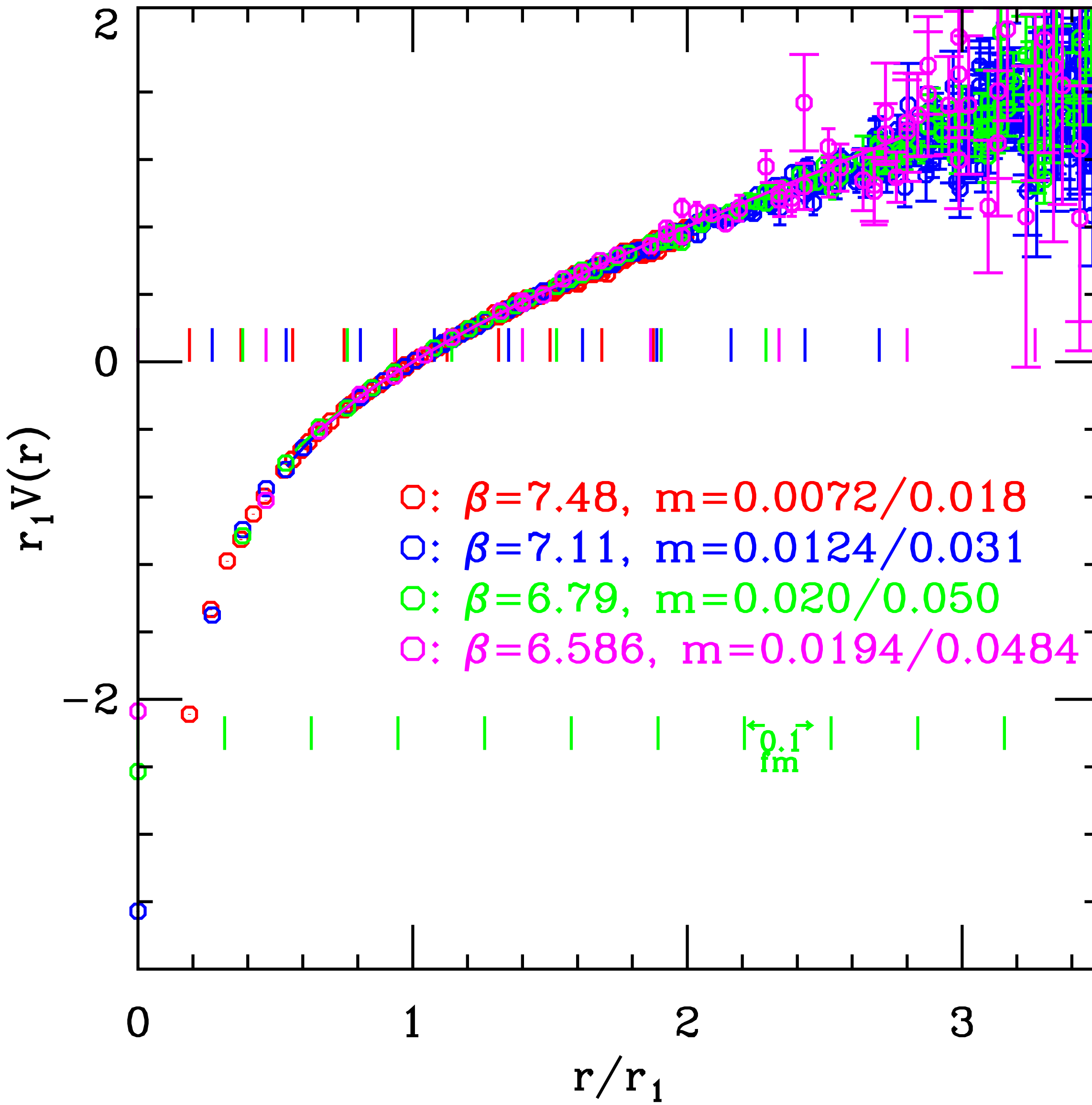


Restoration of Taste Symmetry

- The decrease in the splitting as the lattice spacing is reduced is consistent with $a^2\alpha_S^2$, as predicted.



Static Quark Potential



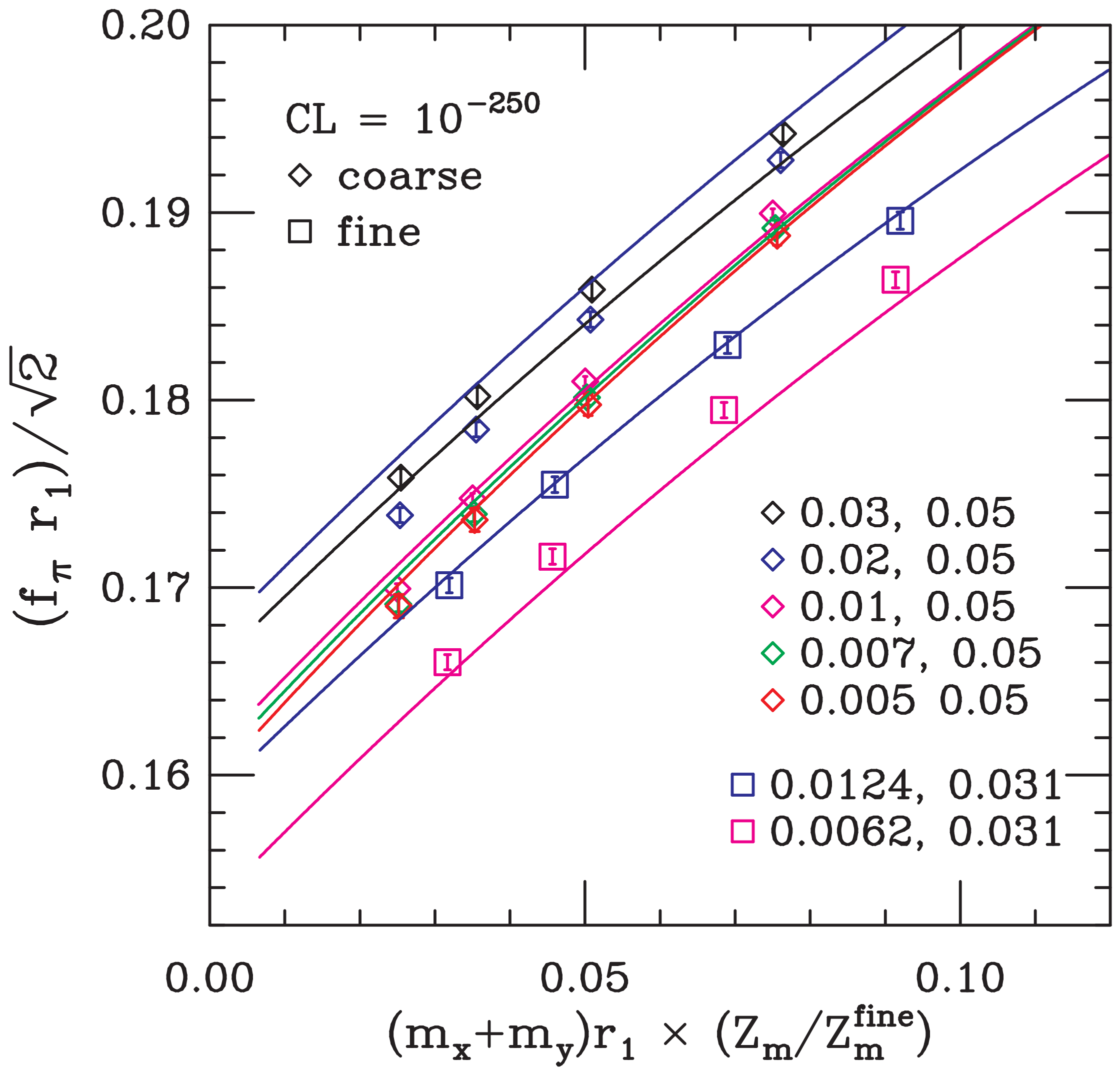
Potential looks very similar at different lattice spacings after rescaling according to the lattice spacing.

π, K decay constants

- We have very precise data for pion and kaon decay constants and masses.
- We have results for many different valence masses for each dynamical ensemble, so we have many hundreds of values to fit to chiral perturbation theory.
- It is important to use Staggered Chiral Perturbation Theory to fit our results.

The MILC Collaboration, C. Aubin, *et al.*, Phys. Rev. D **70**, 114501 (2004); Nucl. Phys. B (Proc. Suppl.) **140**, 231 (2005); Proceedings of Science (Lattice 2005) 025 (2005); Proceedings of Science (Lattice 2006) 163 (2006).

continuum χPT fit to both f_π and m_π fails badly

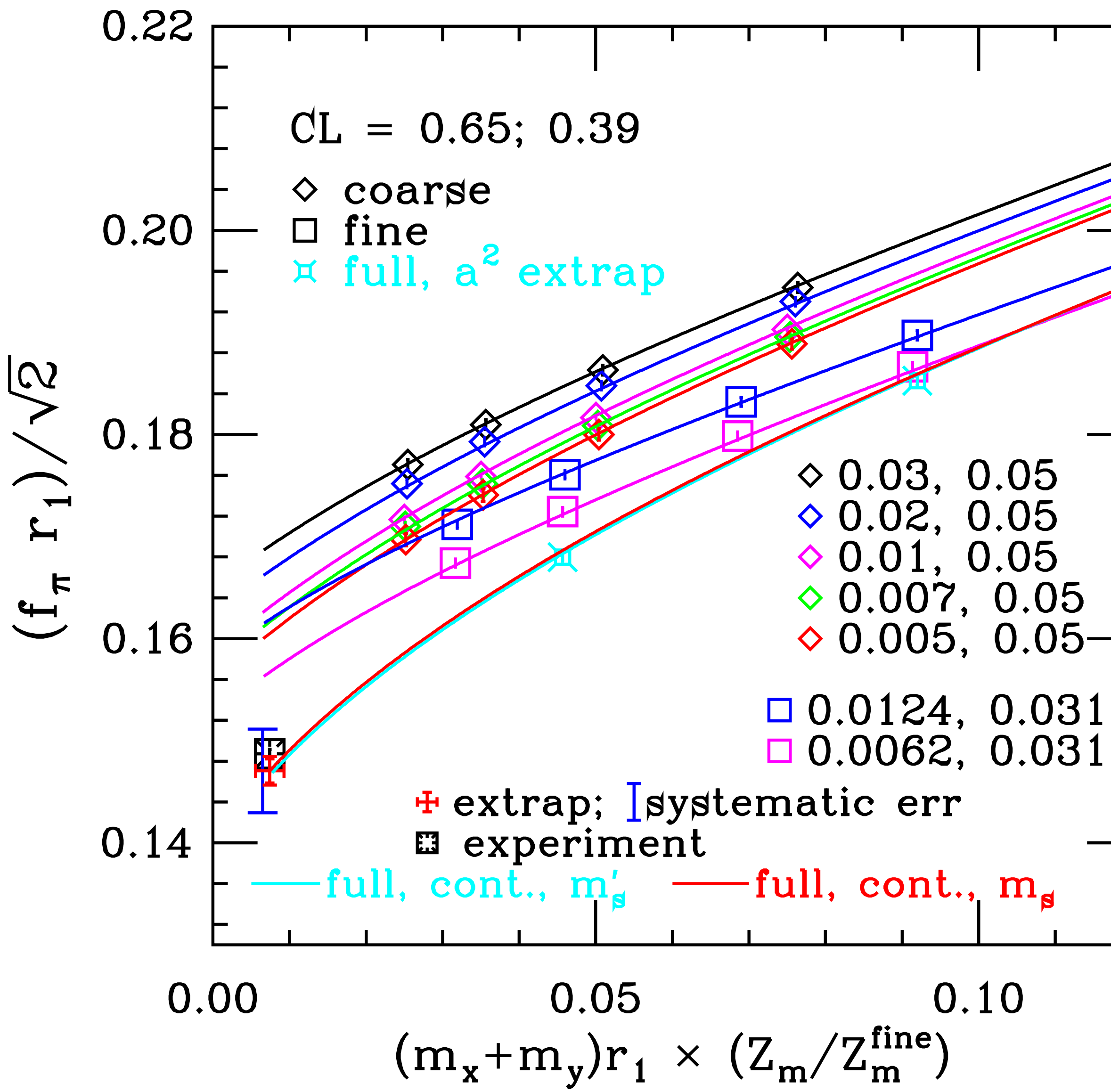


Next two slides show improved fit:

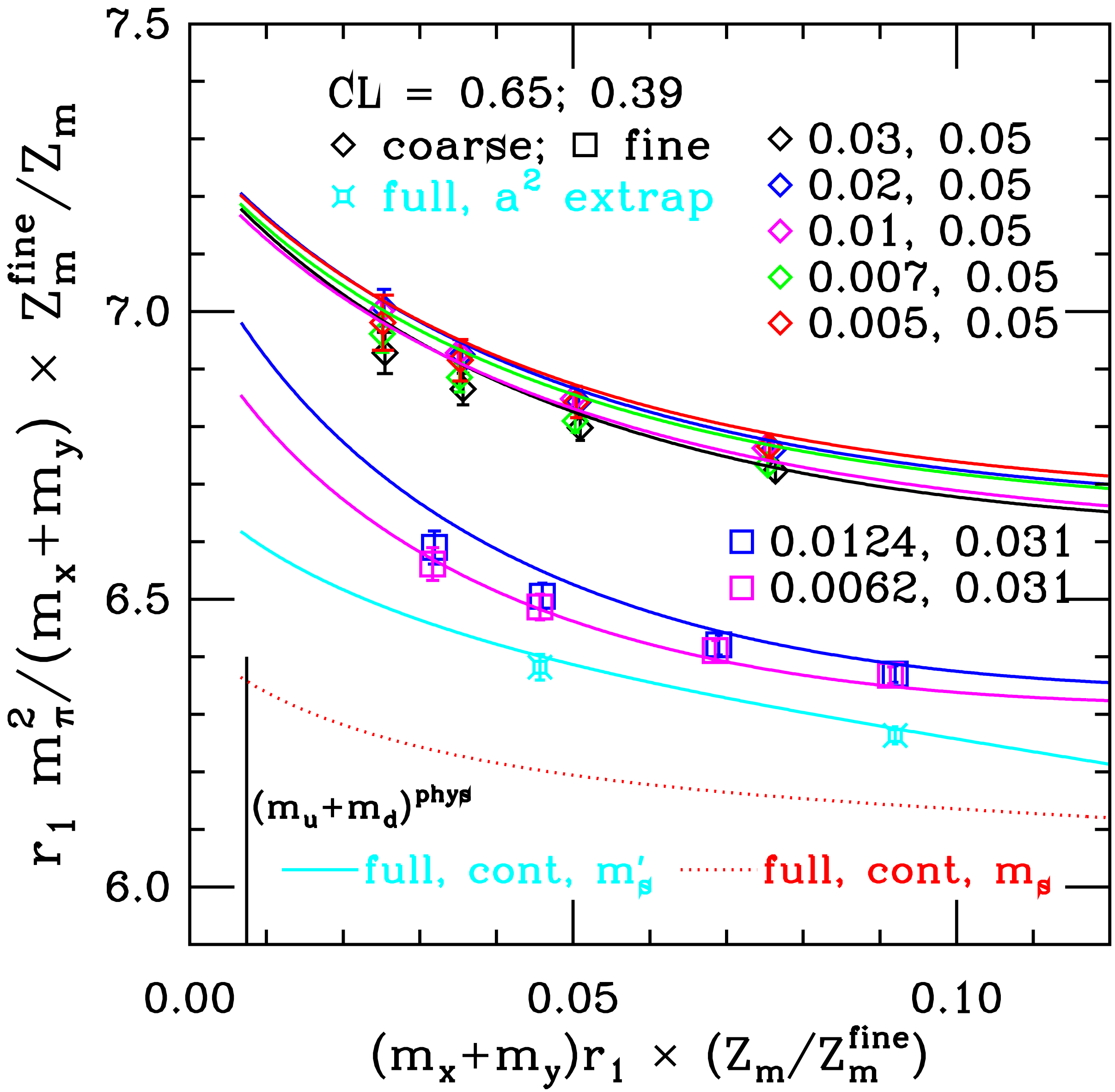
- Use SχPT(Aubin & Bernard), *i.e.* including taste breaking plus NNLO corrections
- Points plotted after finite volume correction
- Partially quenched data used, so not all points plotted

After fit, we:

- Extrapolate fit parameters to continuum
- Show difference between m_s' (simulation strange mass) and m_s (correct value)
- Details in hep-lat/0407028 $=$ PRD70, 114501 (2004)



CL = 0.65; 0.39
coarse
fine
full, a² extrap
0.03, 0.05
0.02, 0.05
0.01, 0.05
0.007, 0.05
0.005, 0.05
0.0124, 0.031
0.0062, 0.031
extrap; systematic err
experiment
full, cont., m′s
full, cont., ms
0.22
0.20
0.18
0.16
0.14
0.00
0.05
0.10
(fπ r1)/√2
(mx+my)r1 × (Zm/Zm^fine)


CL = 0.65; 0.39
coarse; fine
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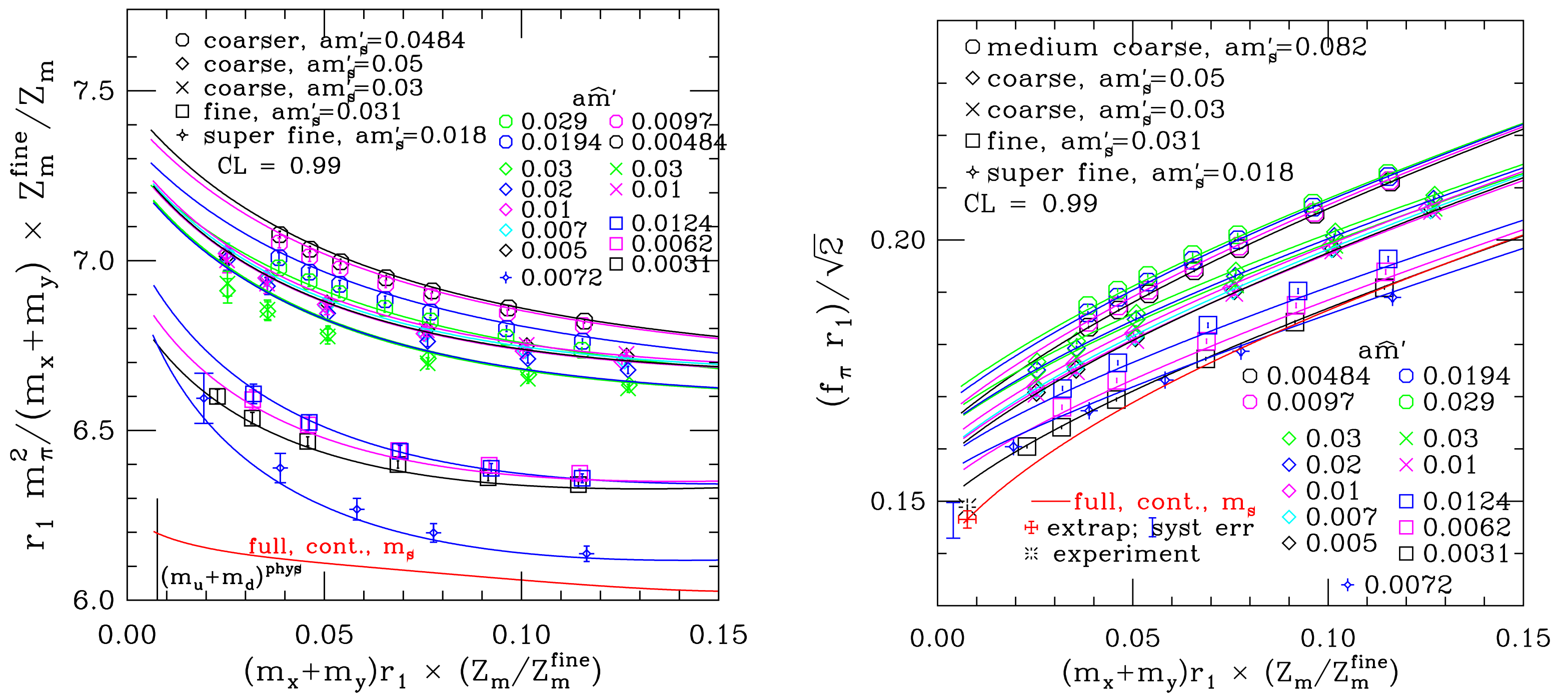
0.0124, 0.031
0.0062, 0.031
(mu+md)phys
full, cont, m's
full, cont, ms
7.5
7.0
6.5
6.0
0.00
0.05
0.10
r1 m2π/(mx+my) × Zfinem/Zm
(mx+my)r1 × (Zm/Zfinem)

Preliminary Results with New Configs

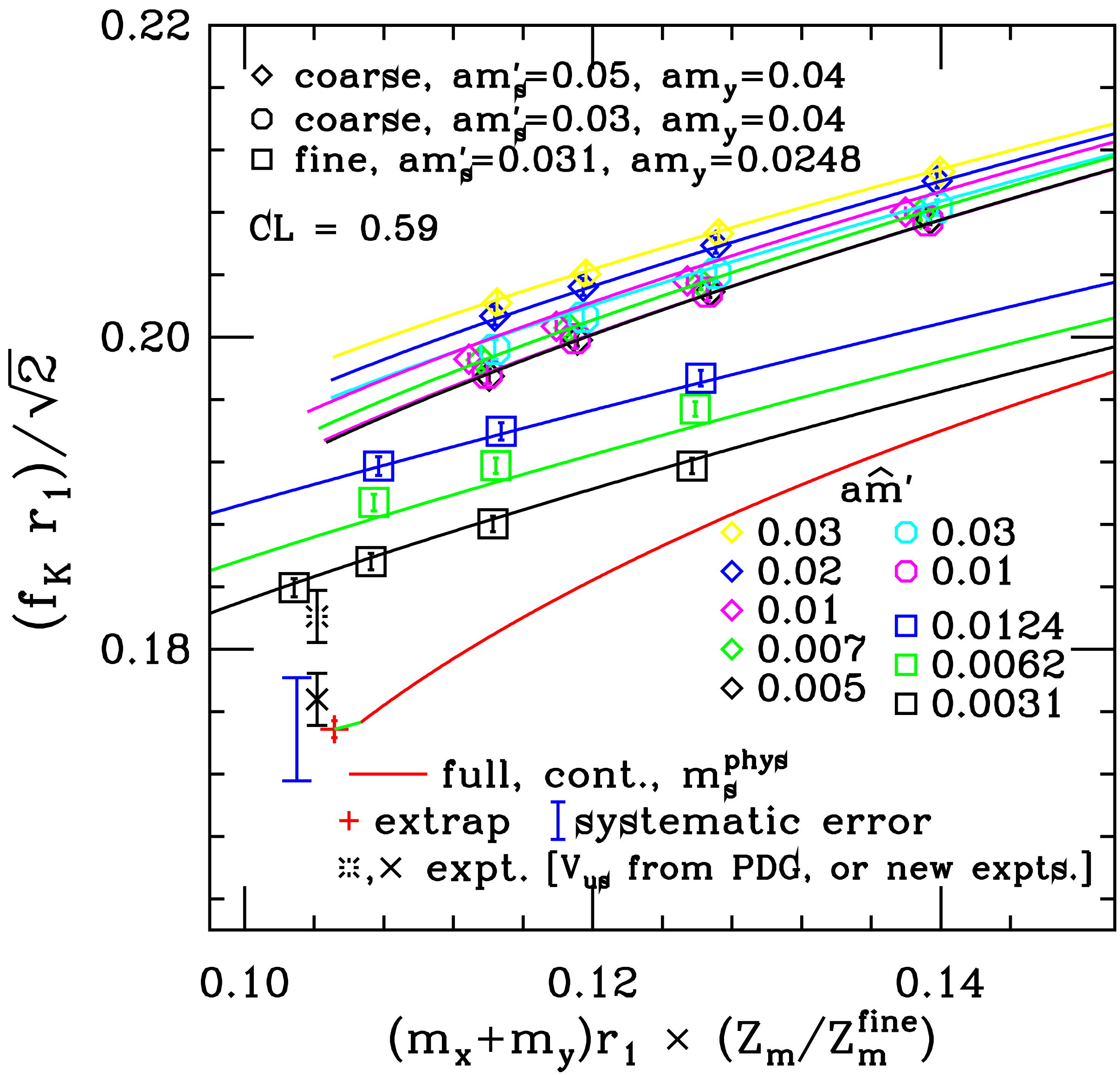


This includes results on coarser ($a = 0.18$ fm) and super-fine ($a = 0.06$ fm) ensembles.

(PoS(Lattice06) 163)

Extend range to include K

Preliminary



Results for light decay constants

$$f_\pi = 128.6 \pm 0.4 \pm 3.0 \text{ MeV} (129.5 \pm 0.9 \pm 3.5)$$
$$f_K = 155.3 \pm 0.4 \pm 3.1 \text{ MeV} (156.6 \pm 1.0 \pm 3.6)$$
$$f_K/f_\pi = 1.208(2)(^{+7}_{-14})(1.210(4)(13))$$

Experiments find:
$f_\pi = 130.7 \pm 0.4\,\text{MeV}$, $f_K = 159.8 \pm 1.5\,\text{MeV}$,
$f_K/f_\pi = 1.223(12)$.

- Large error in f_K from error in V_{us}
- Using our $f_K/f_\pi \Rightarrow V_{us} = 0.2223^{+26}_{-14} 0.2219(26)$
- 2004 PDG value = 0.2196(26) (based on semileptonic decays)
- Recent expt. average = 0.2262(23) [KTEV, KLOE, NA48, E. Blucher, CKM2005]
- 2006 PDG value = 0.2257(21)

Light Quark Masses

To find quark masses, must extrapolate to the physical meson masses

Electromagnetic and isospin-violating effects are important

- Experimental masses:
  $m_{\pi^0}^{\mathrm{expt}}$, $m_{\pi^+}^{\mathrm{expt}}$, $m_{K^0}^{\mathrm{expt}}$, $m_{K^+}^{\mathrm{expt}}$
- Masses with EM effects turned off:
  $m_{\pi^0}^{\mathrm{QCD}}$, $m_{\pi^+}^{\mathrm{QCD}}$, $m_{K^0}^{\mathrm{QCD}}$, $m_{K^+}^{\mathrm{QCD}}$
- Masses with EM effects turned off and $m_u = m_d = \hat{m}$:
  $m_{\hat{\pi}}$, $m_{\hat{K}}$

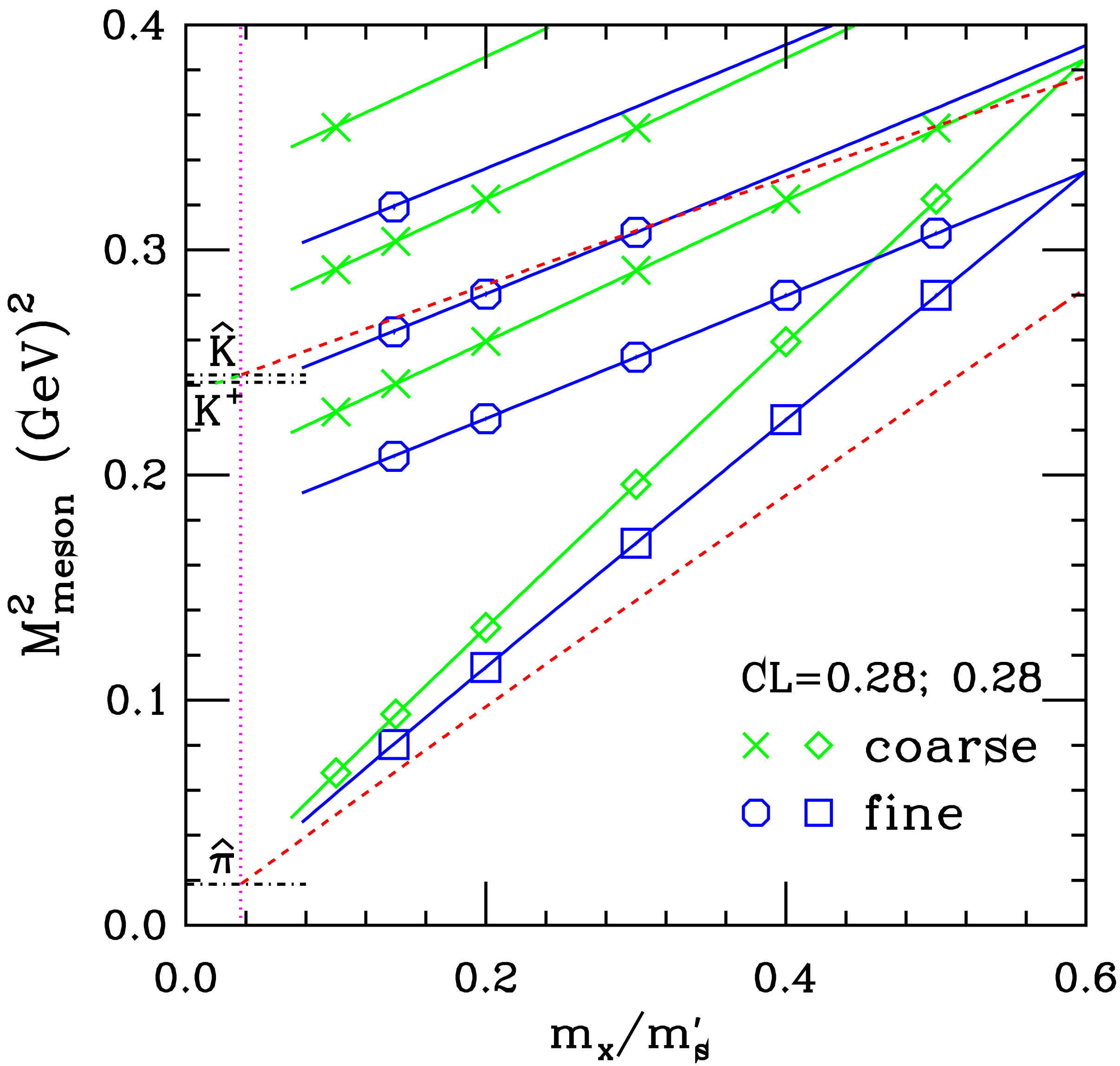
EM & Isospin Violation

$$
\begin{aligned}
m^2_{\hat{\pi}} &\approx (m^{\rm QCD}_{\pi^0})^2 \approx (m^{\rm expt}_{\pi^0})^2 \\
m^2_{\hat{K}} &\approx \frac{(m^{\rm QCD}_{K^0})^2 + (m^{\rm QCD}_{K^+})^2}{2} \\
(m^{\rm QCD}_{K^0})^2 &\approx (m^{\rm expt}_{K^0})^2 \\
(m^{\rm QCD}_{K^+})^2 &\approx (m^{\rm expt}_{K^+})^2 - (1+\Delta_E)\left((m^{\rm expt}_{\pi^+})^2 - (m^{\rm expt}_{\pi^0})^2\right)
\end{aligned}
$$

- $\Delta_E = 0$ is “Dashen’s theorem.”
- Continuum suggests: $\Delta_E \approx 1$.
- We use $0 < \Delta_E < 2$

Fit for $\hat{m}$, m_s

Red lines are continuum extrapolated full QCD fits with m_s adjusted so that both $\hat{\pi}$ and $\hat{K}$ are fit



Quark Masses: $m_{u,d}$, m_s

Using a perturbative evaluation of the mass renormalization constant allows us to obtain absolute values of quark masses.
Latest results from [PoS(2006) 163, hep-lat/0611024], based on prior collaboration with the HPQCD and UKQCD groups, [PRD70, 031504(2004)], and HPQCD 2-loop perturbation theory [hep-ph/0511160]:

$$\begin{aligned} m_s^{\overline{\mathrm{MS}}} &= 90(0)(5)(4)(0)\ \mathrm{MeV} \\ m_{u,d}^{\overline{\mathrm{MS}}} &= 3.3(0)(2)(2)(0)\ \mathrm{MeV} \\ m_s/m_{u,d} &= 27.2(0)(4)(0)(0) \end{aligned}$$

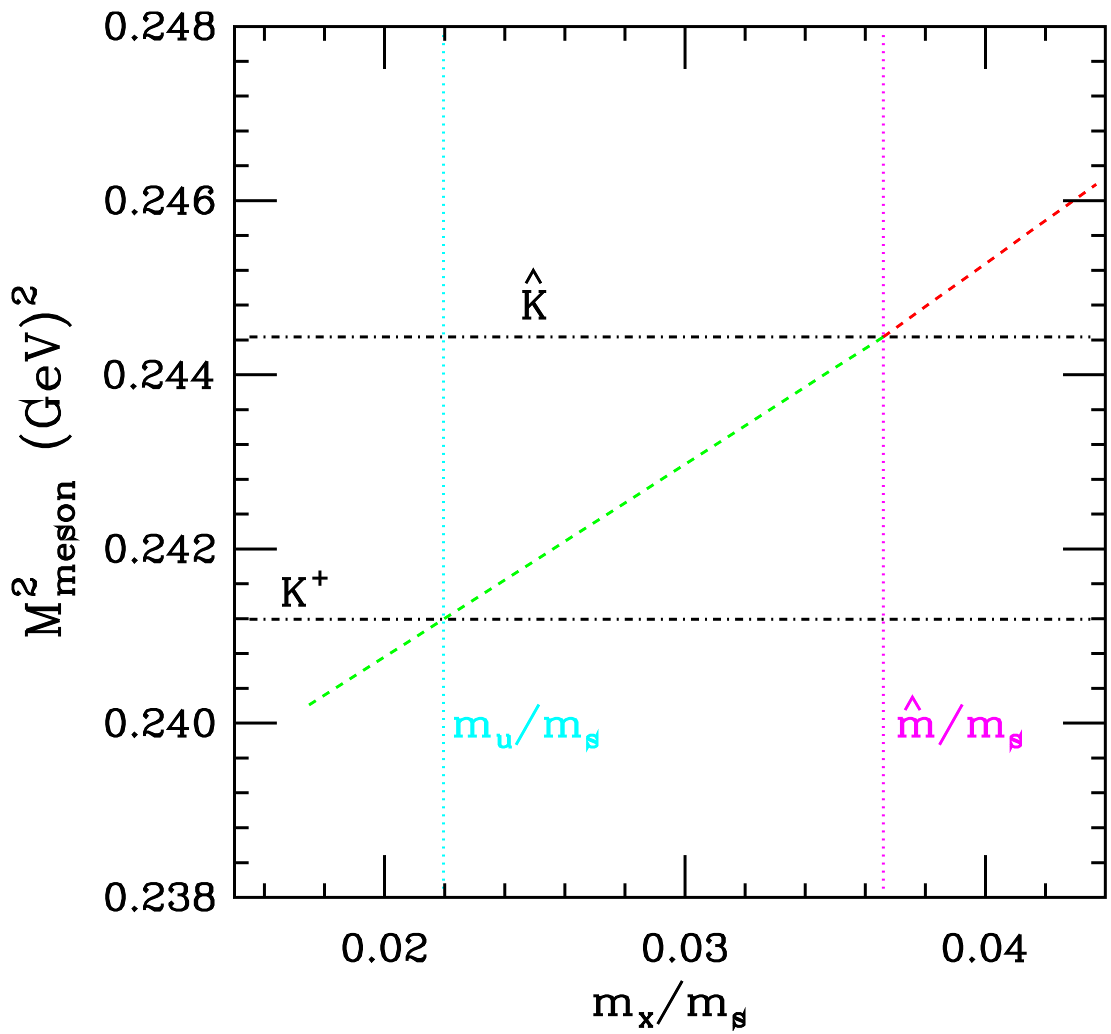
where the errors are from statistics, simulation, perturbation theory, and electromagnetic effects, respectively. The renormalization scale of the masses is $2\,\mathrm{GeV}$.

PDG Comparison

$$
\begin{aligned}
m_s^{\overline{\mathrm{MS}}} &= 90(0)(5)(4)(0)\ \mathrm{MeV}\ , \\
PDGLat &= 105(25)\ \mathrm{MeV}\ , \\
PDGLat(N_f = 2) &= 90(7)\ \mathrm{MeV}\ , \\
Continuum & \quad 80\ \mathrm{MeV} \le m_s \le 155\ \mathrm{MeV}\ , \\
CP - PACS/JLQCD &= 91.1^{+14.6}_{-6.2}\ \mathrm{MeV}\ , \\
m_{u,d}^{\overline{\mathrm{MS}}} &= 3.3(0)(2)(2)(0)\ \mathrm{MeV}\ , \\
PDGLat &= 4.2(1.0)\ \mathrm{MeV}\ , \\
Continuum & \quad 3.2 \le m_{u,d} \le 7\ \mathrm{MeV}\ , \\
CP - PACS/JLQCD &= 3.54^{+0.64}_{-0.35}\ \mathrm{MeV}\ , \\
m_s/m_{u,d} &= 27.2(0)(4)(0)(0) \\
PDG\ \chi PT &= 25.8
\end{aligned}
$$

Next estimate m_u by extrapolating in quark mass to K^+ mass.

Below $\hat{m}$ only valence mass changes. There is a small isospin violation because $m_u = m_d = \hat{m}$.



Quark Masses: m_u, m_d

In 2004, we found [PRD 70 (2004) 114501]:

$$m_u/m_d = 0.43(0)(2)(8)\ ,$$

where the errors are statistical (rounded down to 0), lattice systematics, and a conservative estimate of the effects of electromagnetism, which have not been included in the simulation.
Using instead a phenomenological evaluation of the electromagnetic effects from Bijnens and Prades [NPB 490, 239 (1997)] $\Delta_E = 0.84 \pm 0.25$ we would obtain

$$\begin{aligned} m_u/m_d &= 0.44(0)(1)(2)\ , \\ m_u^{\overline{\mathrm{MS}}} &= 1.7(0)(1)(2)(2)\ \mathrm{MeV}\ , \\ m_d^{\overline{\mathrm{MS}}} &= 3.9(0)(1)(4)(2)\ \mathrm{MeV}\ . \end{aligned}$$

PDG Comparison II

Latest, preliminary results from Lattice 2006:

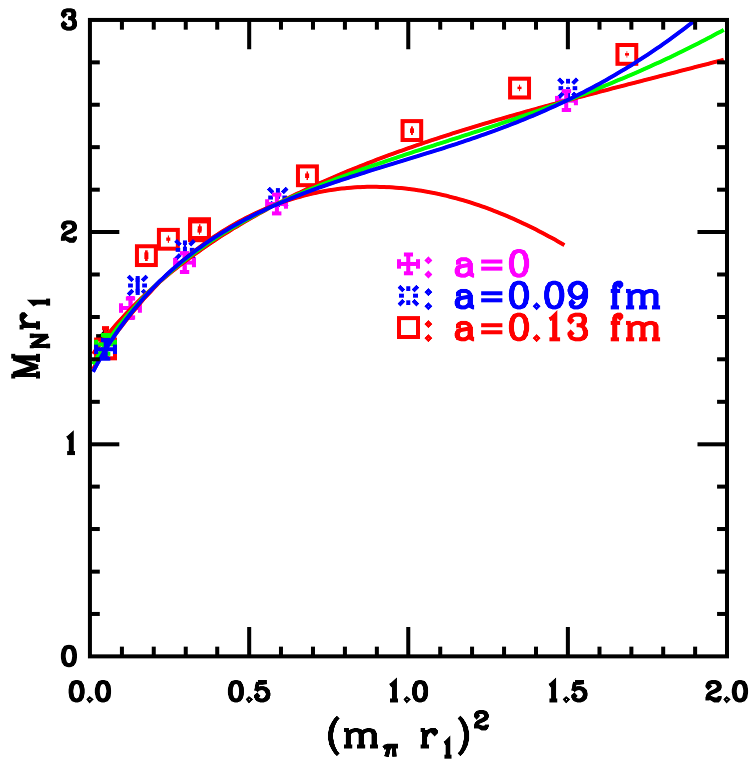
$$
\begin{aligned}
m_u/m_d &= 0.42(0)(1)(0)(4)\ , \\
PDG\ \chi PT &= 0.56\ , \\
PDG & \quad 0.3 \leq m_u/m_d \leq 0.71\ , \\
m_u^{\overline{\text{MS}}} &= 2.0(0)(1)(2)(1)\ \text{MeV}\ , \\
PDG\ Continuum & \quad 1.5\ \text{MeV} \leq m_u \leq 5\ \text{MeV}, \\
m_d^{\overline{\text{MS}}} &= 4.6(0)(1)(2)(1)\ \text{MeV}\ . \\
PDG\ Continuum & \quad 5\ \text{MeV} \leq m_d \leq 7\ \text{MeV},
\end{aligned}
$$

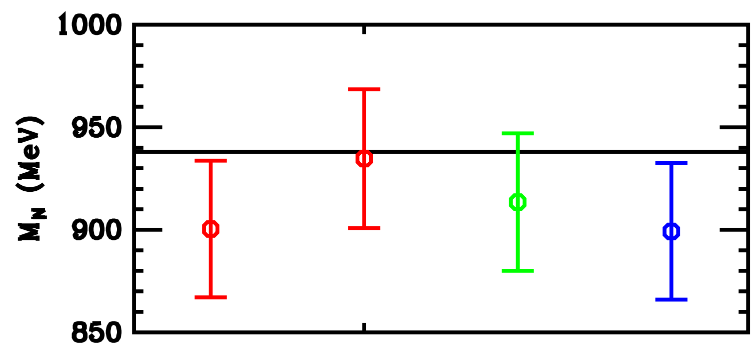
No previous lattice result for m_u or m_d.

Nucleon continuum chiral extrapolation

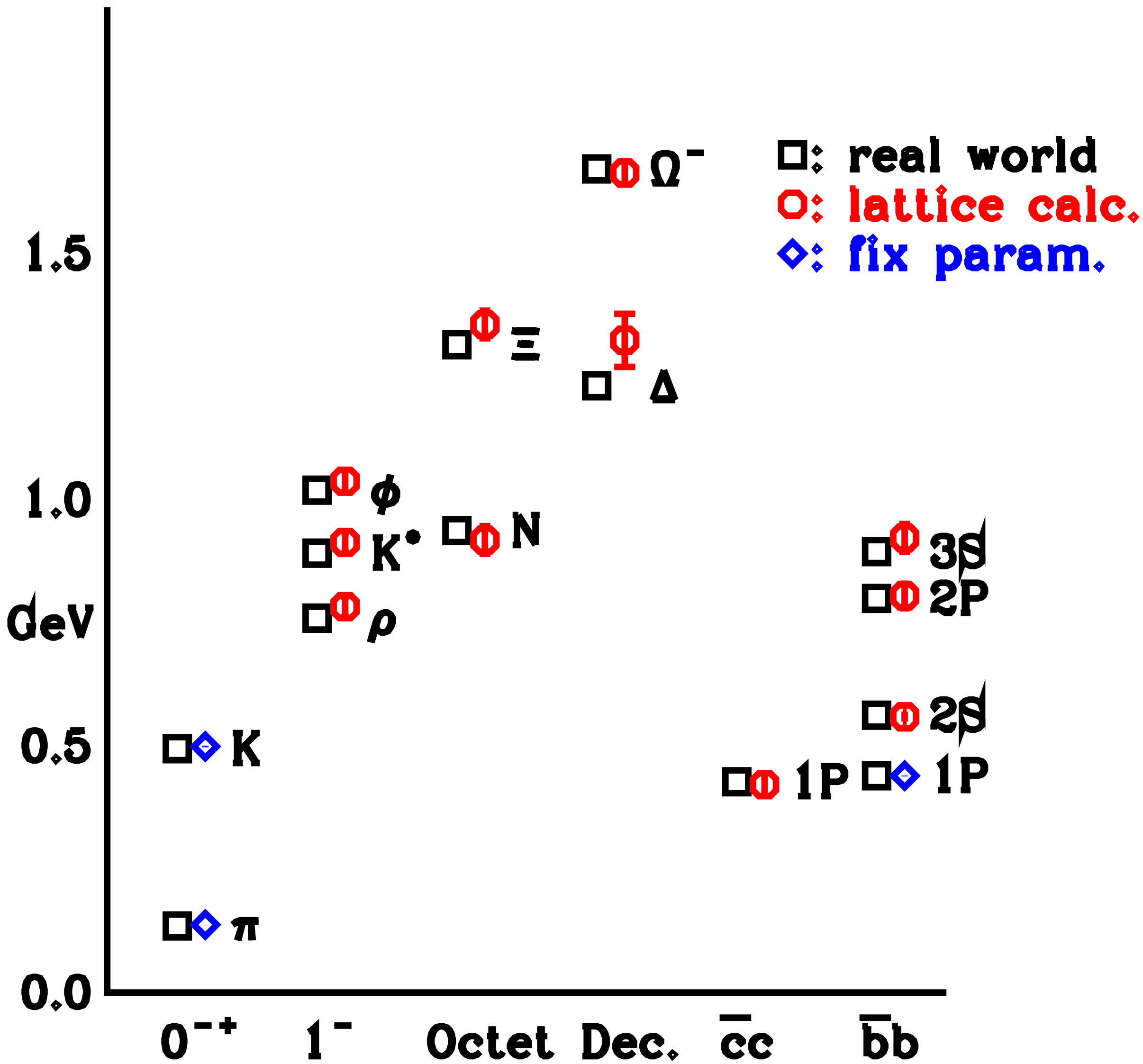
hep-lat/0402030 = PRD70, 094505 (2004)

These graphs updated from that publication





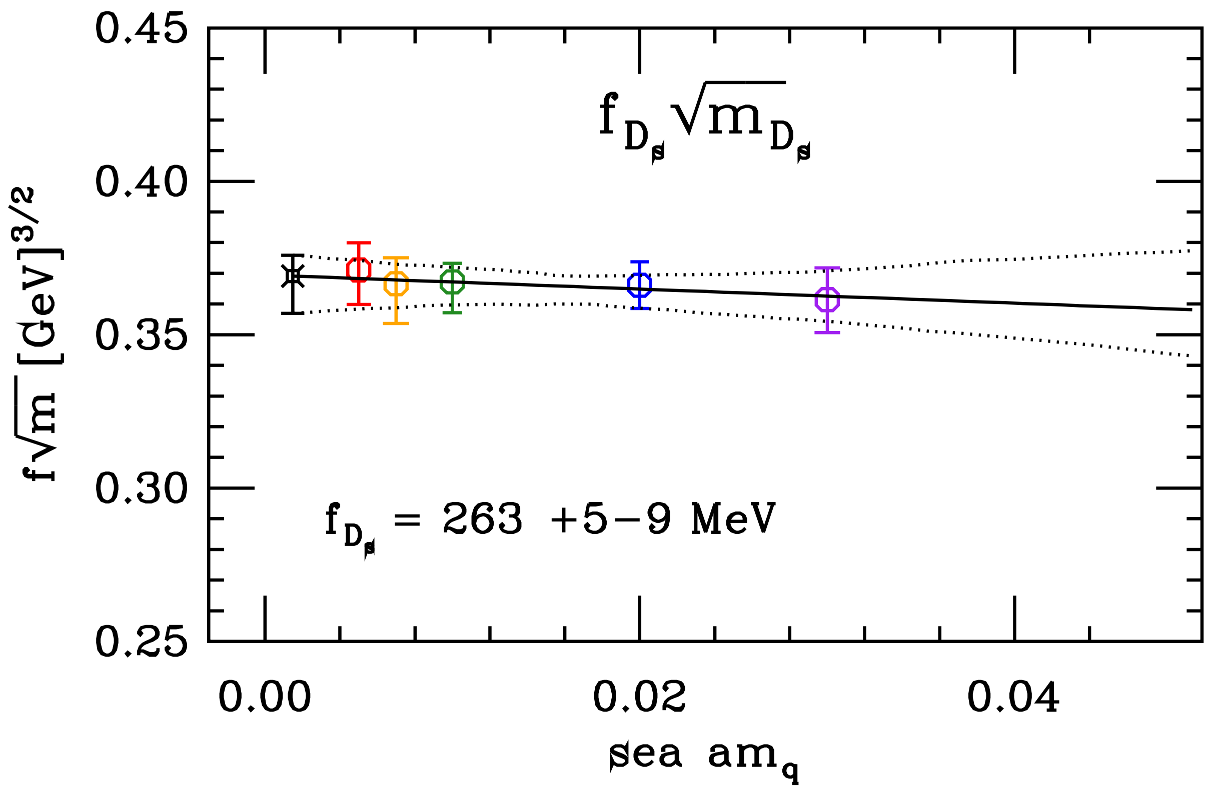
Big Picture


□: real world
○: lattice calc.
◇: fix param.
GeV
0.0
0.5
1.0
1.5
π
K
ρ
K*
φ
N
Ξ
Δ
Ω⁻
1P
2S
2P
3S
0⁻⁺
1⁻
Octet
Dec.
c̄c
b̄b

Heavy quarks

- MILC has been doing Clover-light, Clover-heavy calculations for some time using $N_f = 2+1$ ensembles to study decay constants and form factors
- Using same ensembles, now using Asqtad light quarks in collaboration with Fermilab group
  - This allows better control of chiral extrapolation (D, B)
  - Techniques may be comparable for D_s and B_s
  - Very active experimental programs at CLEO-c, BaBar, Belle, D0, CDF

Leptonic Decays



J. Simone *et al.*, [Fermilab/MILC] arXiv:hep-lat/0410030; C. Aubin *et al.*, PRL 95 (2005) 122002 = arXiv:hep-lat/0506030

FNAL/MILC Results

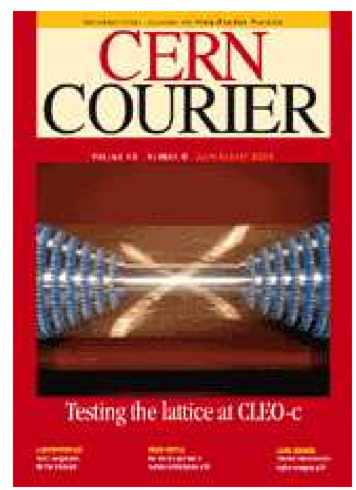
$$
\begin{aligned}
f_{D_s} &= 249 \pm 3 \pm 16 \text{ MeV} \ , \\
f_{D^+} &= 201 \pm 3 \pm 17 \text{ MeV} \ , \\
&.
\end{aligned}
$$

Results for B mesons will follow. We were rushing because of CLEO-c schedule. Our results were announced just before the experiment (hep-ex/0508057).

Currently, one D_s and 47$\pm$8 D^+ decays observed. Latter by

CLEO-c

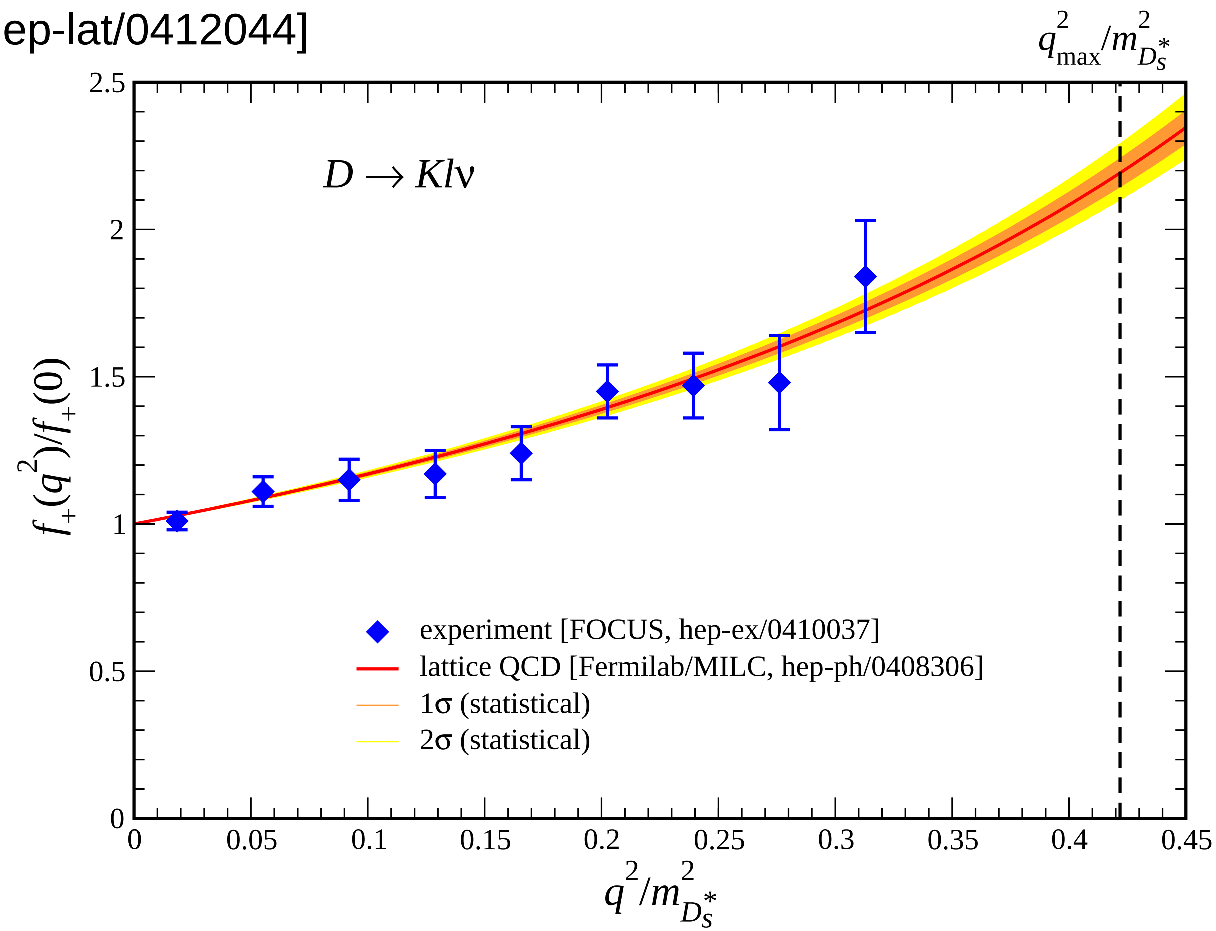
$$
\begin{aligned}
f_{D_s^+} &= 267 \pm 33 \text{ MeV} \\
f_{D^+} &= 223 \pm 17 \pm 3 \text{ MeV}
\end{aligned}
$$



Semileptonic Decays

MILC (see slide 2) + FNAL + HPQCD (M. Di Pierro, A. El-Khadra, A.S. Kronfeld, P.B. Mackenzie, D. Menscher, M. Nobes, M. Okamoto, M.B. Oktay, J. Osborn, J. Simone, and H.D. Trottier), [hep-ph/0408306 $=$ PRL94, 011601 (2005)]

M. Okamoto [hep-lat/0412044]



$D \to K l \nu$ and $D \to \pi l \nu$ also, B meson decays allow extraction of several CKM matrix elements

$$|V_{cd}| = 0.239(10)(24)(20)$$

$$|V_{cs}| = 0.969(39)(94)(24)$$

$$|V_{ub}| = 3.48(29)(38)(47) \times 10^{-3}$$

$$|V_{cb}| = 3.91(07)(06)(34) \times 10^{-2}$$

$$|V_{us}| = 0.2250(14)(20)(12)$$

High Temperature QCD

- We have been calculating the equation of state for $N_t = 4$ and 6.
- Use the integral method:

$$\varepsilon V = -\left.\frac{\partial \ln Z}{\partial(1/T)}\right|_V, \qquad \frac{p}{T} = \left.\frac{\partial \ln Z}{\partial V}\right|_T \approx \frac{\ln Z}{V},$$

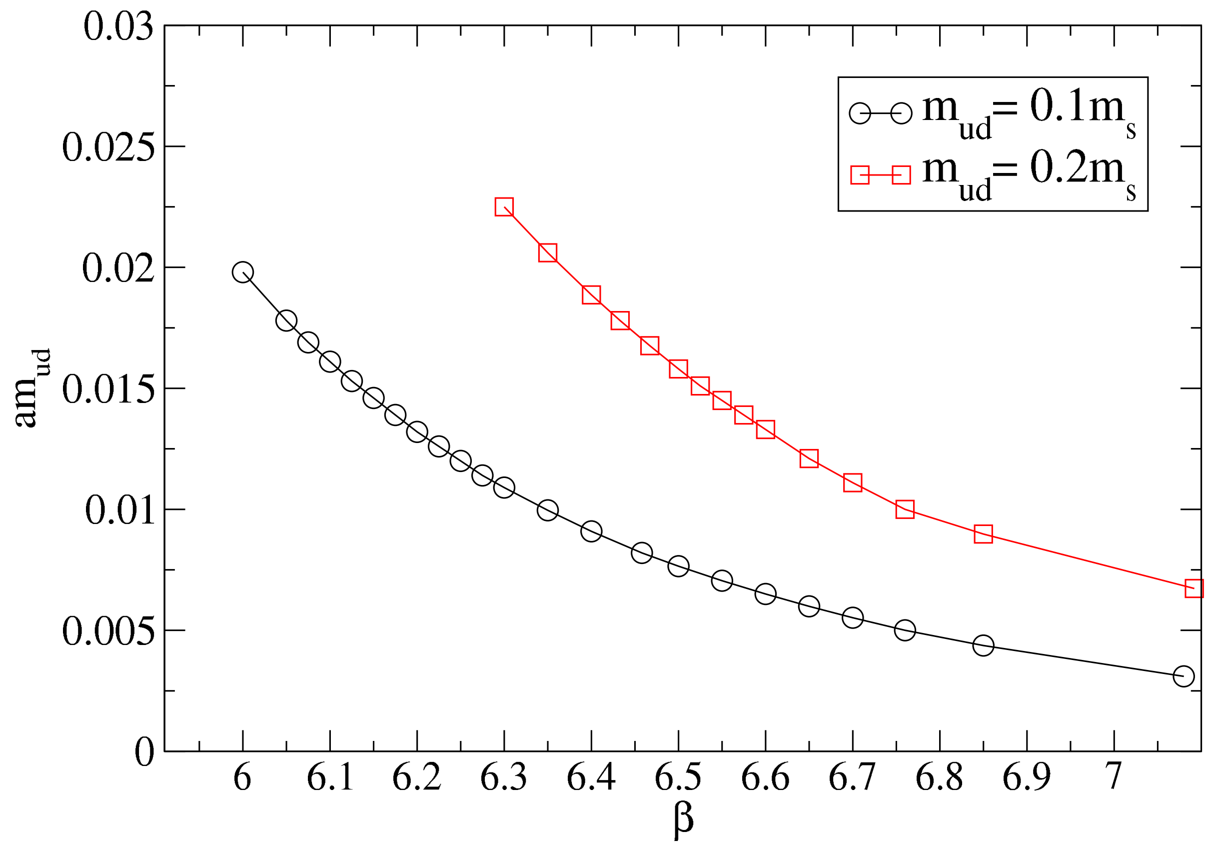
$$I = \varepsilon - 3p = -\frac{T}{V}\frac{d \ln Z}{d \ln a},$$

where ε is the energy density, p is the pressure and I is the interaction measure.

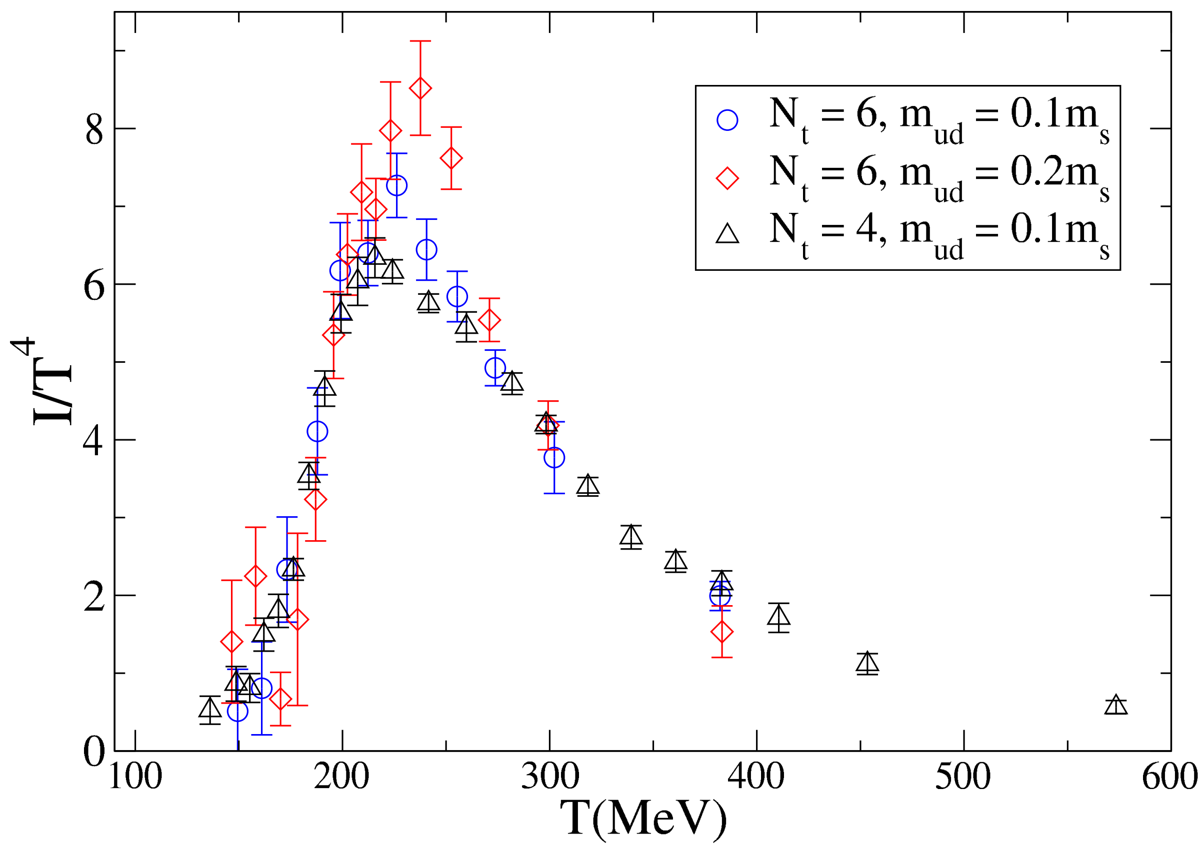
$$
\begin{aligned}
Ia^4 &= -6\frac{d\beta}{d\ln a}\Delta\langle P\rangle - 12\frac{d\beta_{\rm rt}}{d\ln a}\Delta\langle R\rangle - 16\frac{d\beta_{\rm ch}}{d\ln a}\Delta\langle C\rangle \\
&\quad -\sum_f \frac{n_f}{4}\left[\frac{d(m_f a)}{d\ln a}\Delta\left\langle\bar\psi\psi\right\rangle_f + \frac{du_0}{d\ln a}\Delta\left\langle\bar\psi\,\frac{dM}{du_0}\,\psi\right\rangle_f\right], \\
pa^4 &= \int_{\ln a_0}^{\ln a}(-Ia'^4)d\ln a' \\
&= \int_{\ln a_0}^{\ln a}\left\{6\frac{d\beta}{d\ln a}\Delta\langle P\rangle + 12\frac{d\beta_{\rm rt}}{d\ln a}\Delta\langle R\rangle + 16\frac{d\beta_{\rm ch}}{d\ln a}\Delta\langle C\rangle\right. \\
&\quad + \left.\sum_f \frac{n_f}{4}\left[\frac{d(m_f a)}{d\ln a}\Delta\left\langle\bar\psi\psi\right\rangle_f + \frac{du_0}{d\ln a}\Delta\left\langle\bar\psi\,\frac{dM}{du_0}\,\psi\right\rangle_f\right]\right\} d\ln a'
\end{aligned}
$$

See hep-lat/0611031

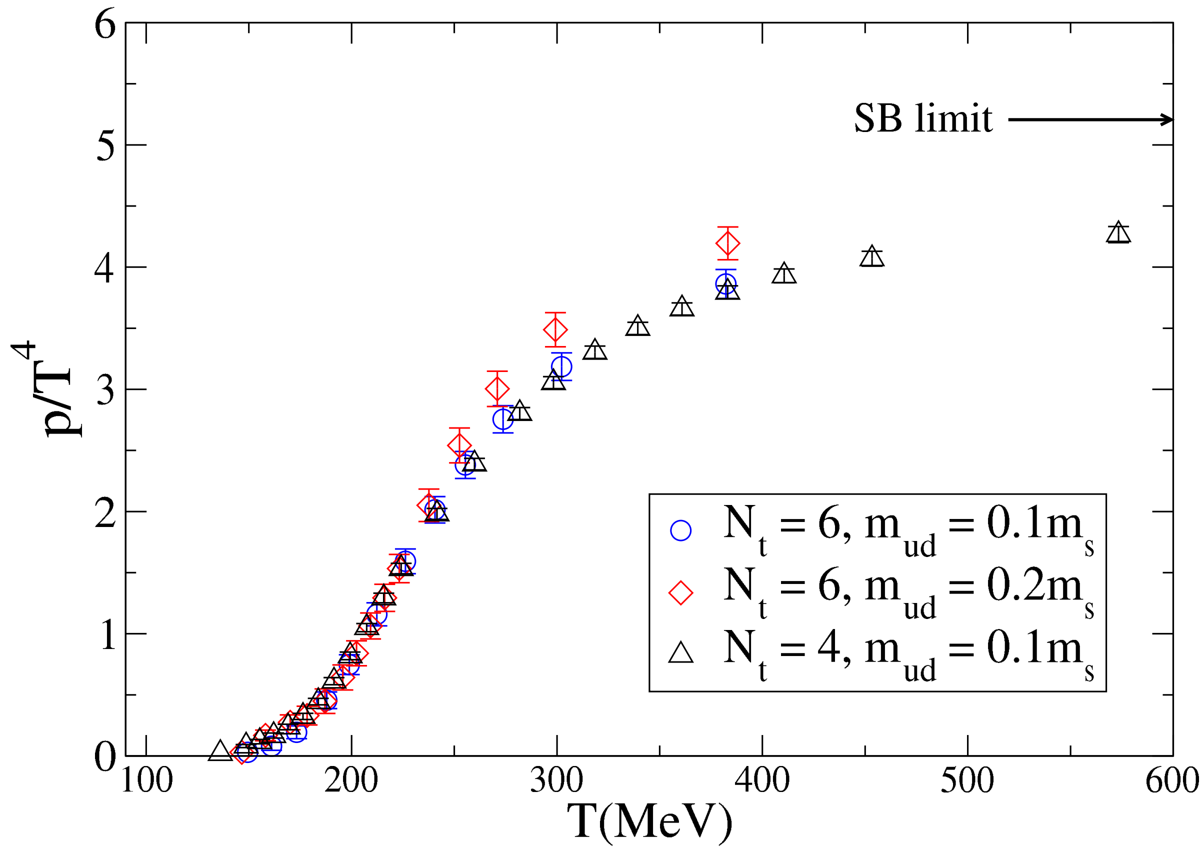
Trajectories of Constant Physics



Interaction Measure



Pressure



6
5
4
3
2
1
0
100
200
300
400
500
600
T(MeV)
p/T4
SB limit
Nt = 6, mud = 0.1ms
Nt = 6, mud = 0.2ms
Nt = 4, mud = 0.1ms

Future Plans

- MILC and FNAL/MILC plan to continue increasing precision on a number of calculations, including masses, decay constants and semileptonic form factors.
- It is important to increase our precision to keep pace with upcoming experimental advances.
- To further reduce systematic errors, we are generating new ensembles with a smaller lattice spacing 0.06 fm.
  - A $48^3 \times 144\ m_l = 0.2 m_s$ run with $a = 0.06$ fm is about half done.
  - We have just started the $64^3 \times 144\ m_l = 0.1 m_s$ run. The run requires 2.4 TF-yr of computing.
  - We we soon be doing some additional ensembles with $a = 0.09$ fm to better control chiral extrapolation.
  - We are using the RHMD algorithm for the newest runs.

- We will complete analysis of B meson decays on the available ensembles and compare with NRQCD results.
- EOS with $N_t = 8$ using BlueGene/L computers at LLNL is now being done by HotQCD collaboration.
- Alternative methods, such as overlap, domain wall and twisted mass, should contribute to reducing systematic uncertainties. We look forward to comparing results.
- MILC and HPQCD will be exploring use of HISQ quarks before deciding whether to reduce the lattice spacing to 0.045 fm.

- We will complete analysis of B meson decays on the available ensembles and compare with NRQCD results.
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- Thanks to Terry and Al for all their work organizing this symposium.