Update on current status and future plans for MILC and MILC/FNAL projects

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Collaborators

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

$+$ 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

Outline

- Outline of MILC Projects
- Ensemble 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

Ensemble 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 ($m_{u,d}, m_s$)

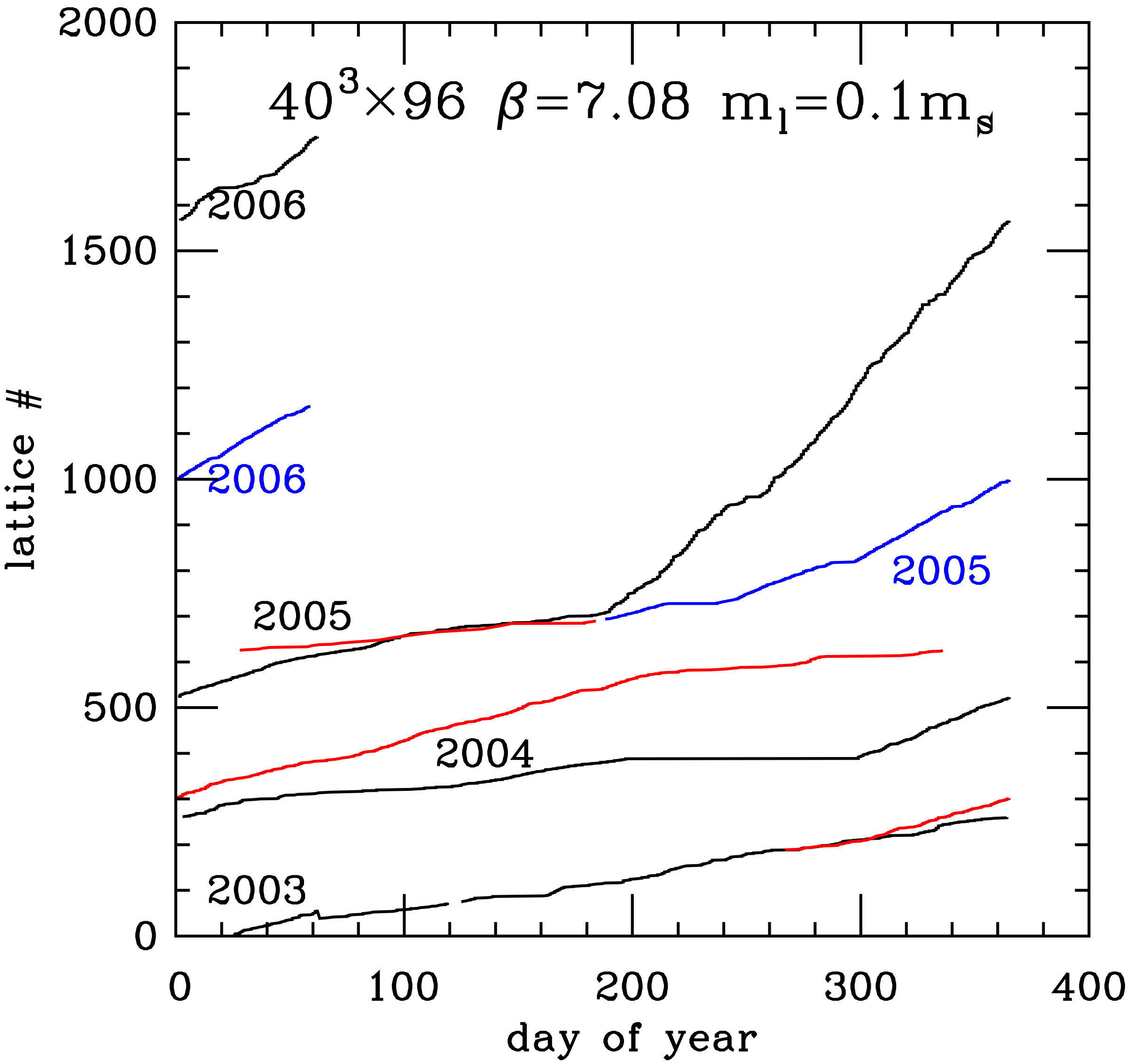
To control systematic error we must

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

MILC has been generating three flavor configurations to allow control of these errors. Many configurations are available to others through NERSC Gauge Connection. Some new configurations generated via SciDAC program.

$a = 0.09$ fm; $28^3 \times 96$		
$am_{u,d}$ / am_s	$10/g^2$	# config.
0.031 / 0.031	7.18	496
0.0124 / 0.031	7.11	527
0.0062 / 0.031	7.09	592
$a = 0.09$ fm; $40^3 \times 96$		
0.0031 / 0.031	7.08	≈ 420 (100)

Value in blue is ensemble size at time of ILFT 1 in Izu.



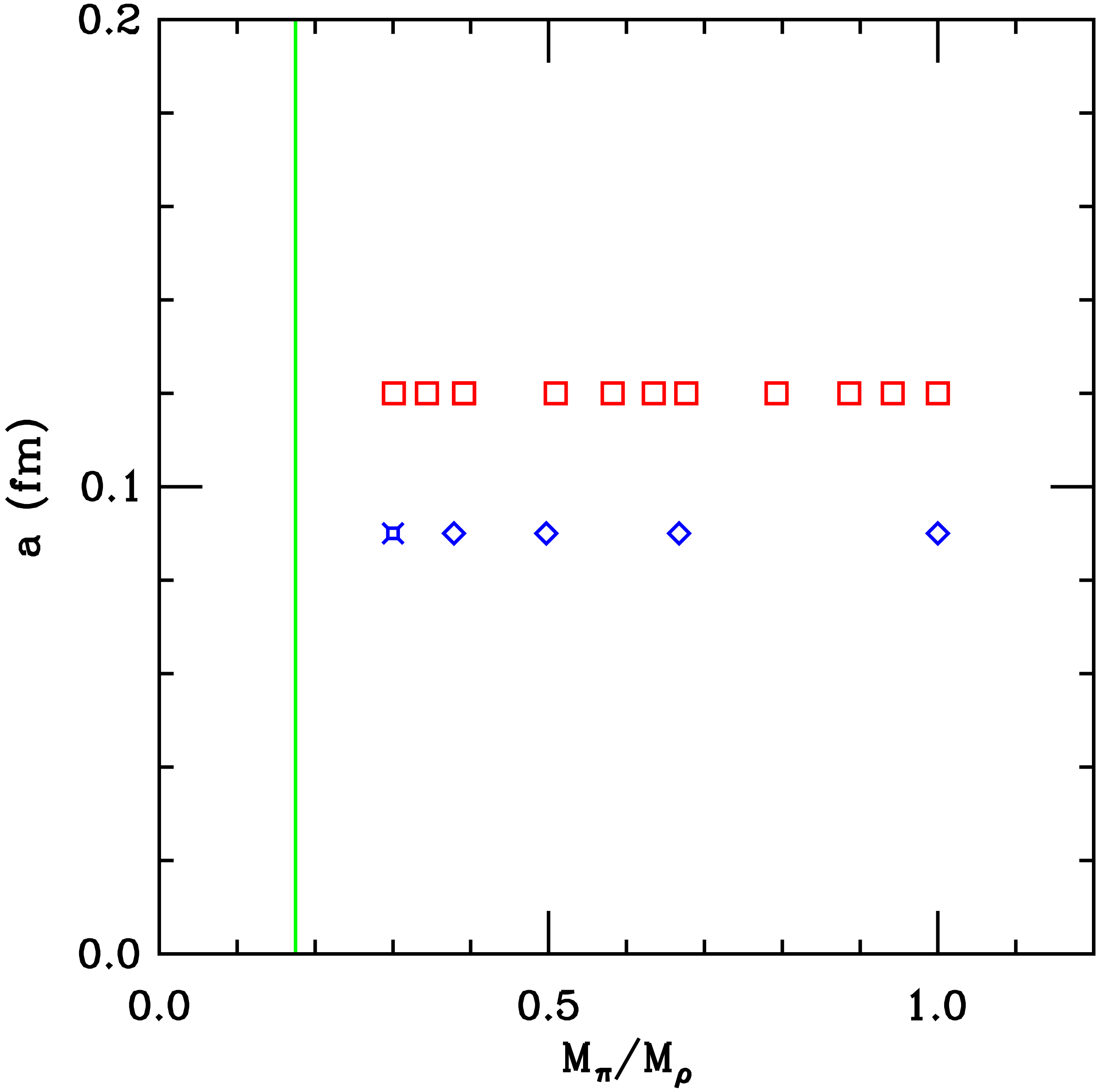
$40^3\times96$ $\beta=7.08$ $m_l=0.1m_s$
2006
2006
2005
2005
2004
2003
lattice #
day of year
0
500
1000
1500
2000
0
100
200
300
400

$a = 0.12$ fm; $20^3 \times 64$		
$am_{u,d}$ / am_s	$10/g^2$	# config.
0.40 /0.40	7.35	332
0.20 /0.20	7.15	341
0.10 /0.10	6.96	339
0.05 /0.05	6.85	425
0.04 /0.05	6.83	351
0.03 /0.05	6.81	564
0.02 /0.05	6.79	484
0.01 /0.05	6.76	658
0.007/0.05	6.76	493
0.03 /0.03	6.75	350
0.01 /0.03	6.75	350
$a = 0.12$ fm; $24^3 \times 64$		
0.005/0.05	6.76	500 (375)

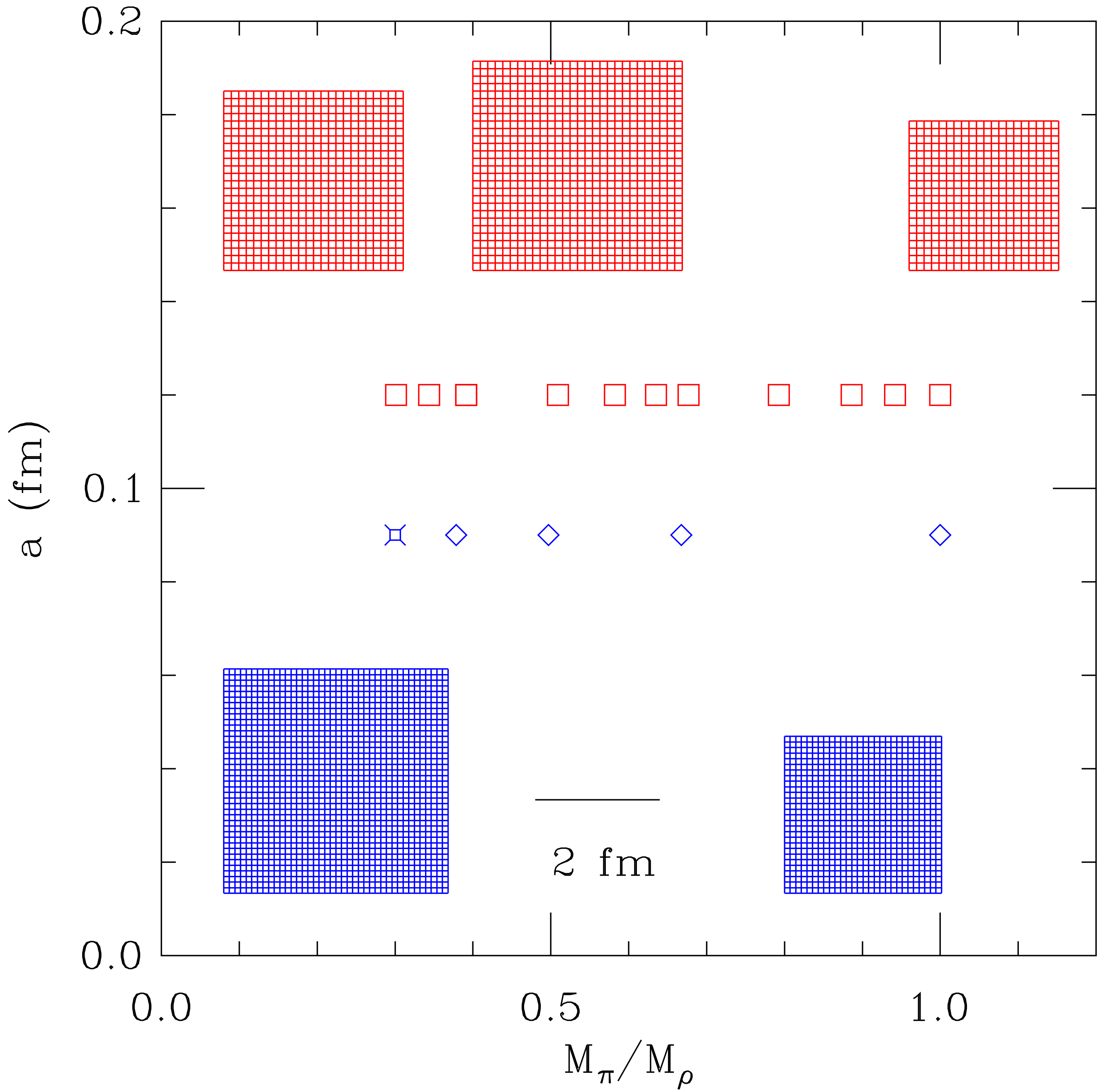
Additional Ensembles

- These two tables correspond to “fine” and “coarse” lattice spacings.
- To better control continuum limit, we have:
  - Extra coarse: $a \approx 0.18$ fm
  - Medium coarse: $a \approx 0.15$ fm
  - Extra fine: $a \approx 0.06$ fm. This is a challenging project and will require more than a year to “complete.” Currently have about 850 time units with $m_l = 0.4 m_s$. For $m_l = 0.2 m_s$ just equilibrating.
- The best way to control the continuum limit is to use smaller lattice spacing, but it is very expensive. By doing the much less demanding larger lattice spacings we hope better control the limit, or at least better estimate our systematic error.

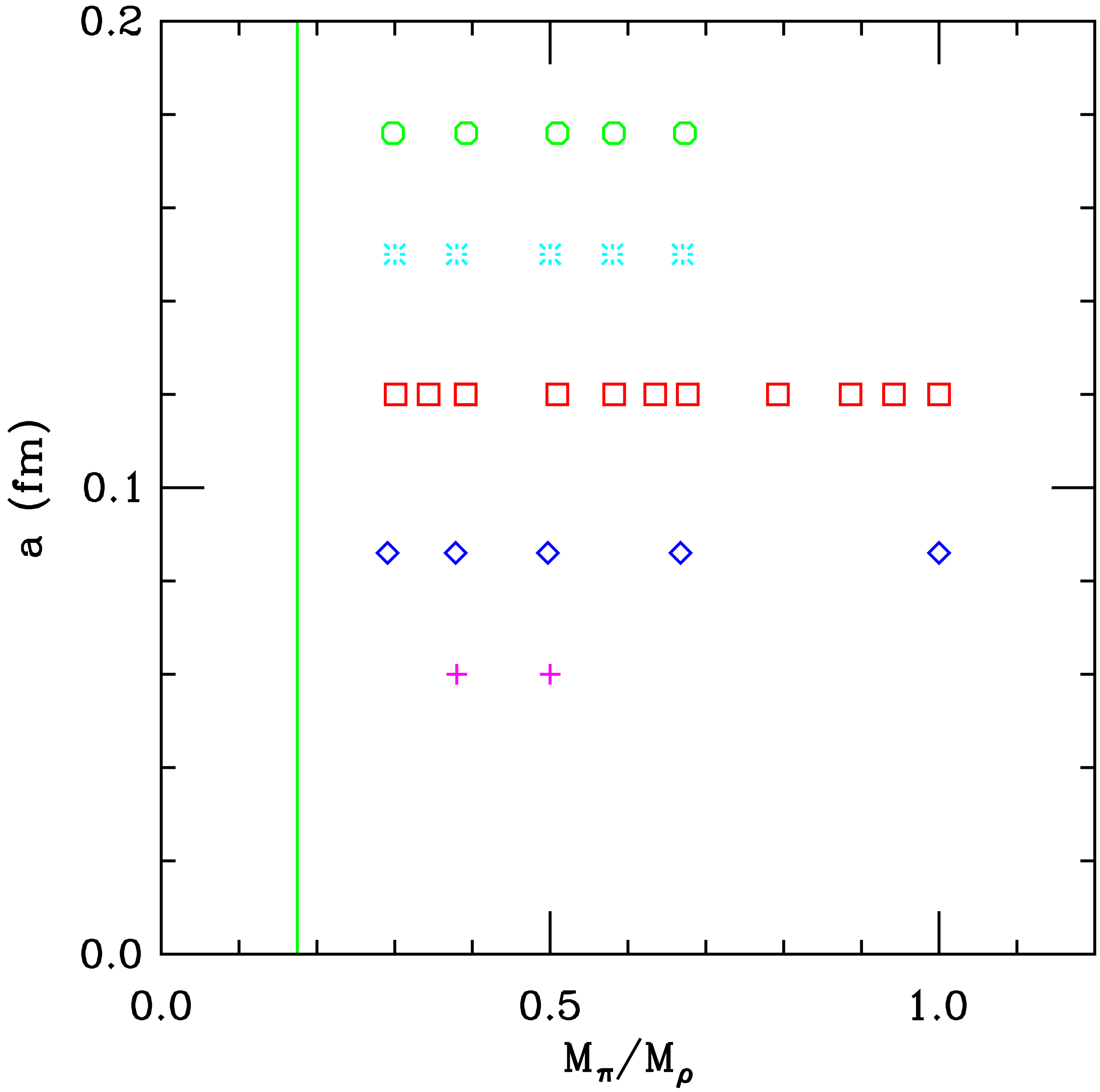
MILC Ensembles



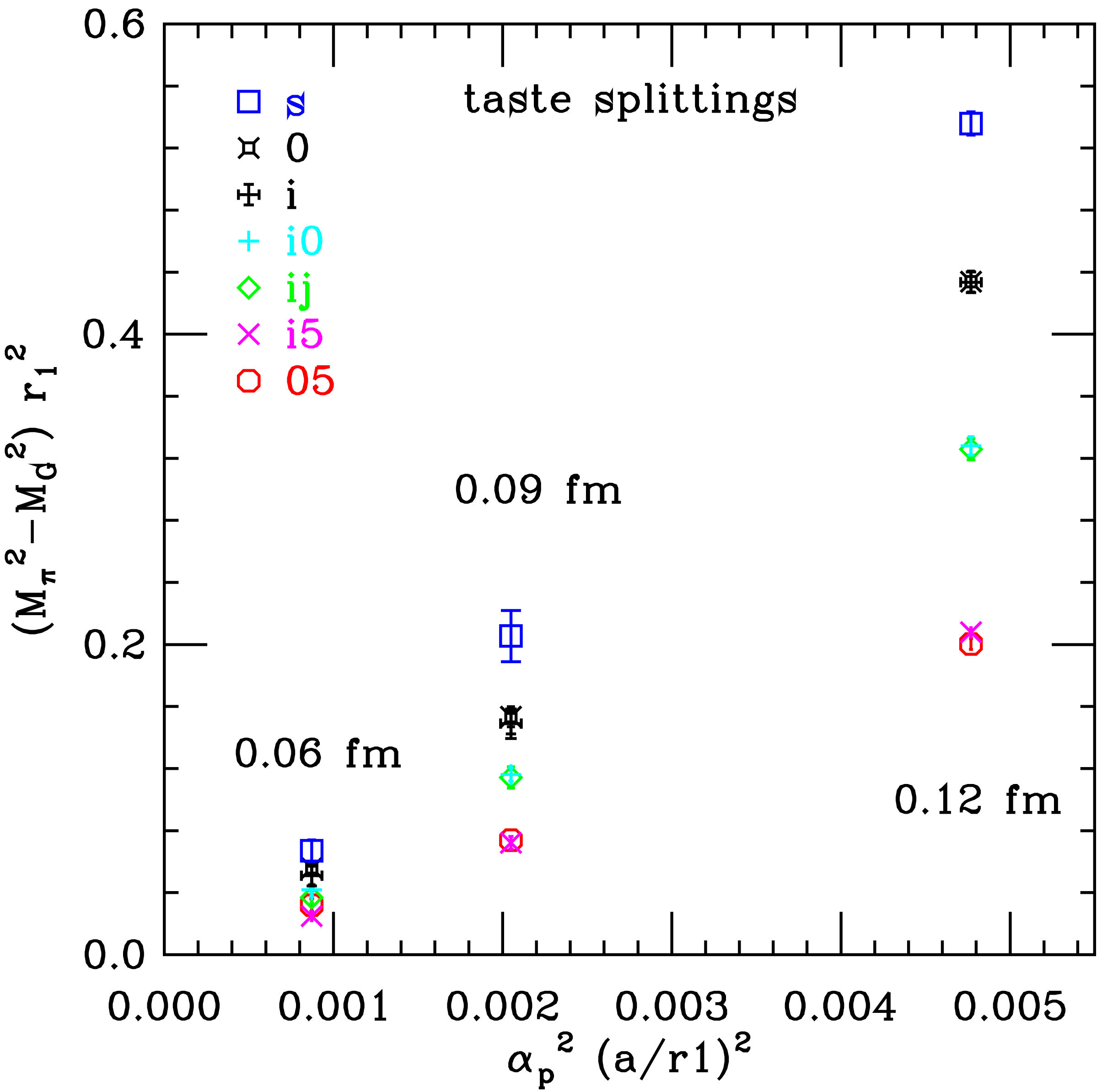
MILC Ensembles



MILC Ensembles

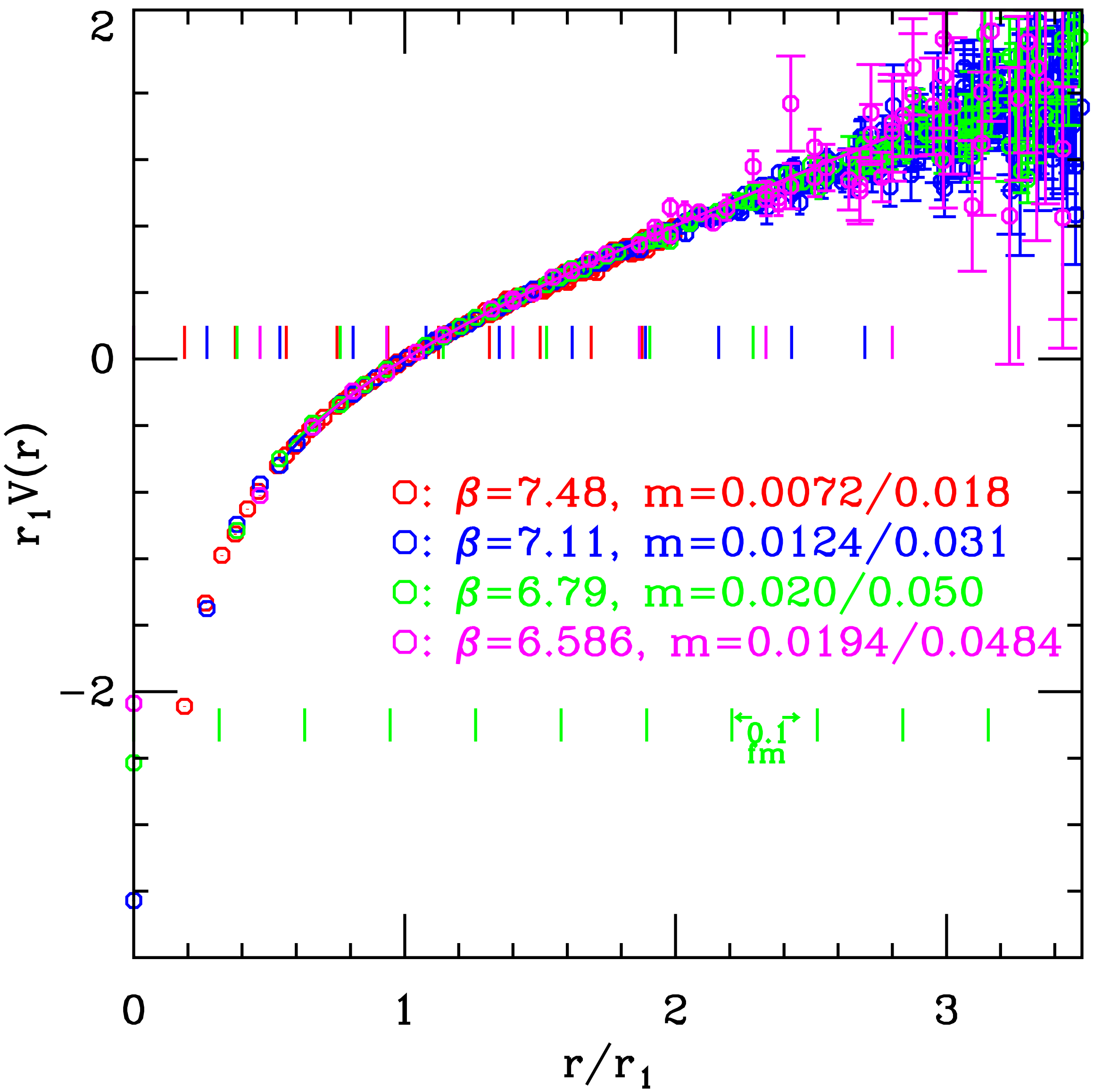


Taste symmetry restoration



$$m_{\pi_S}^2 - m_{\pi_G}^2 = (435\mathrm{MeV})^2[a = 0.12], (152\mathrm{MeV})^2[a = 0.06]$$

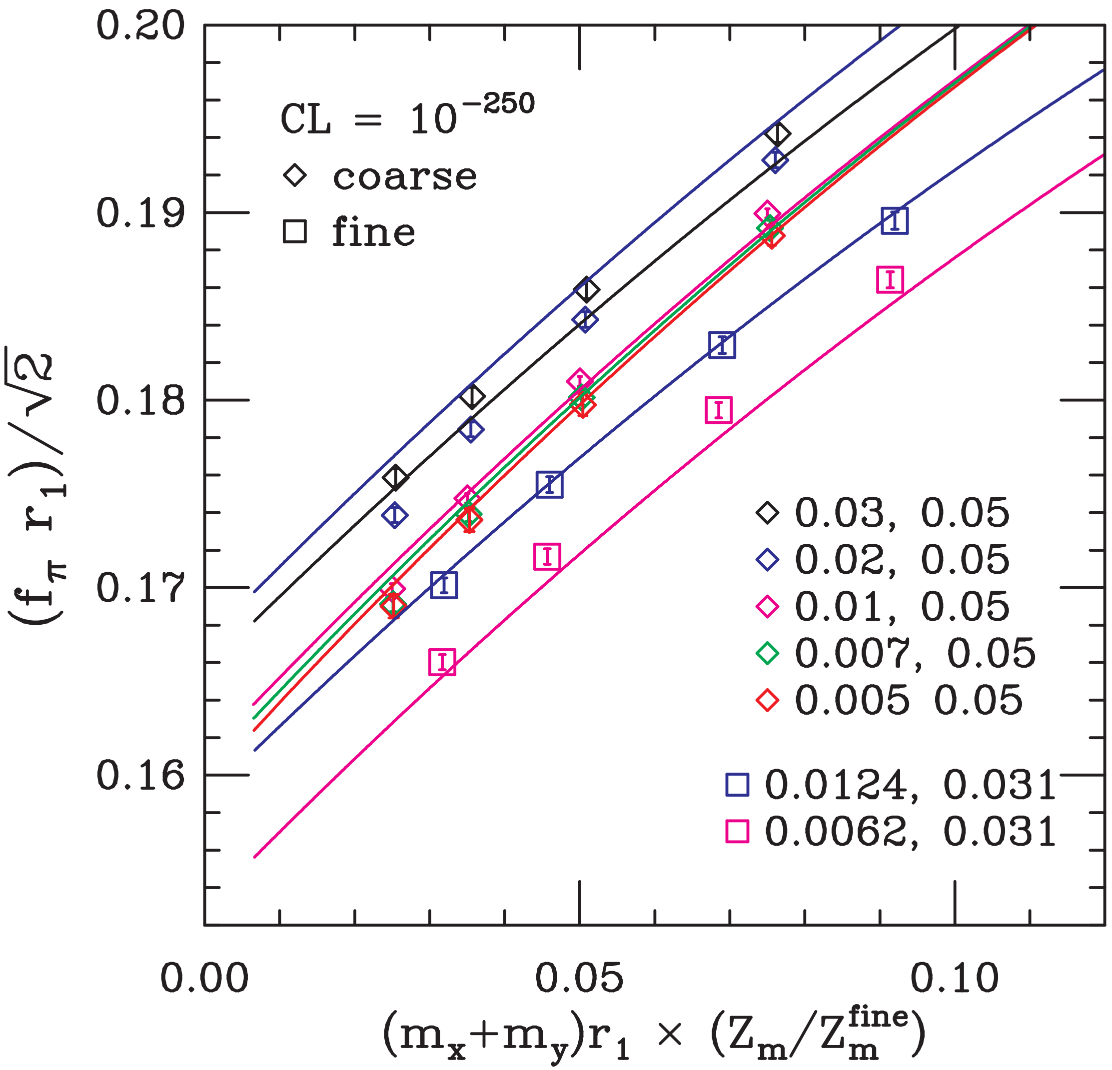
Static Quark Potential



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

π, K decay constants

continuum χPT fit to both f_π and m_π fails badly

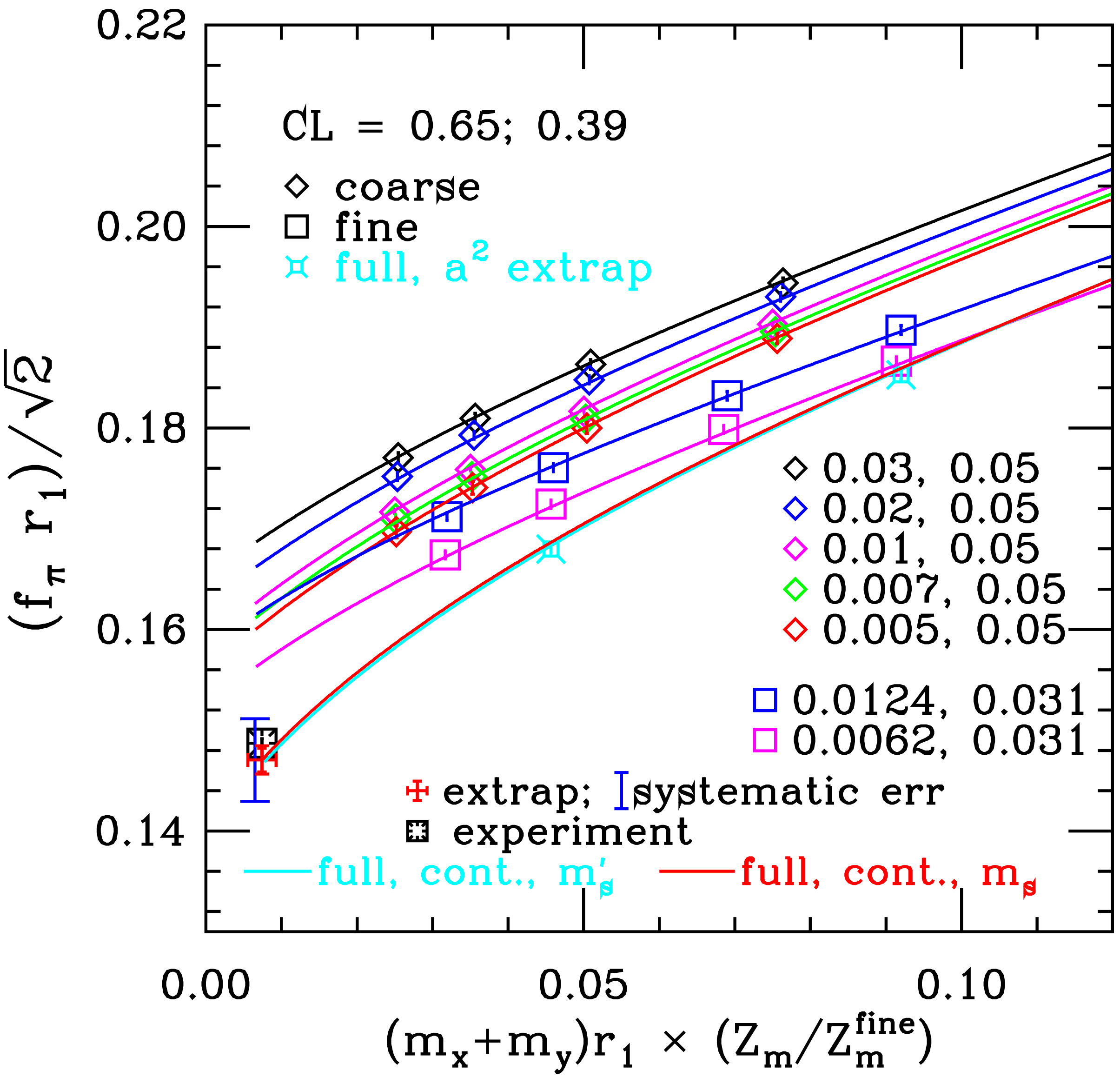


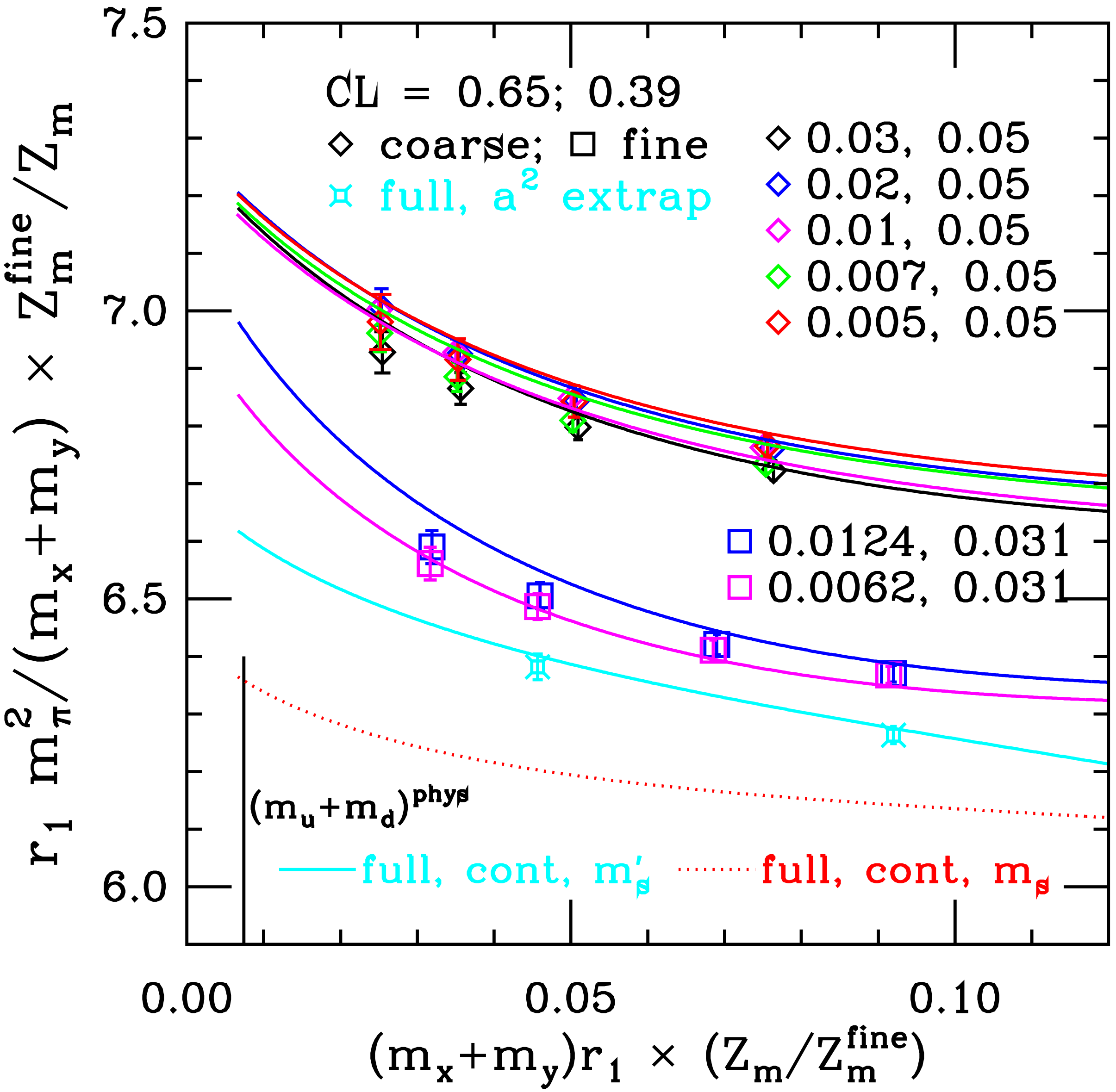
Next two slides show improved fit:

- 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

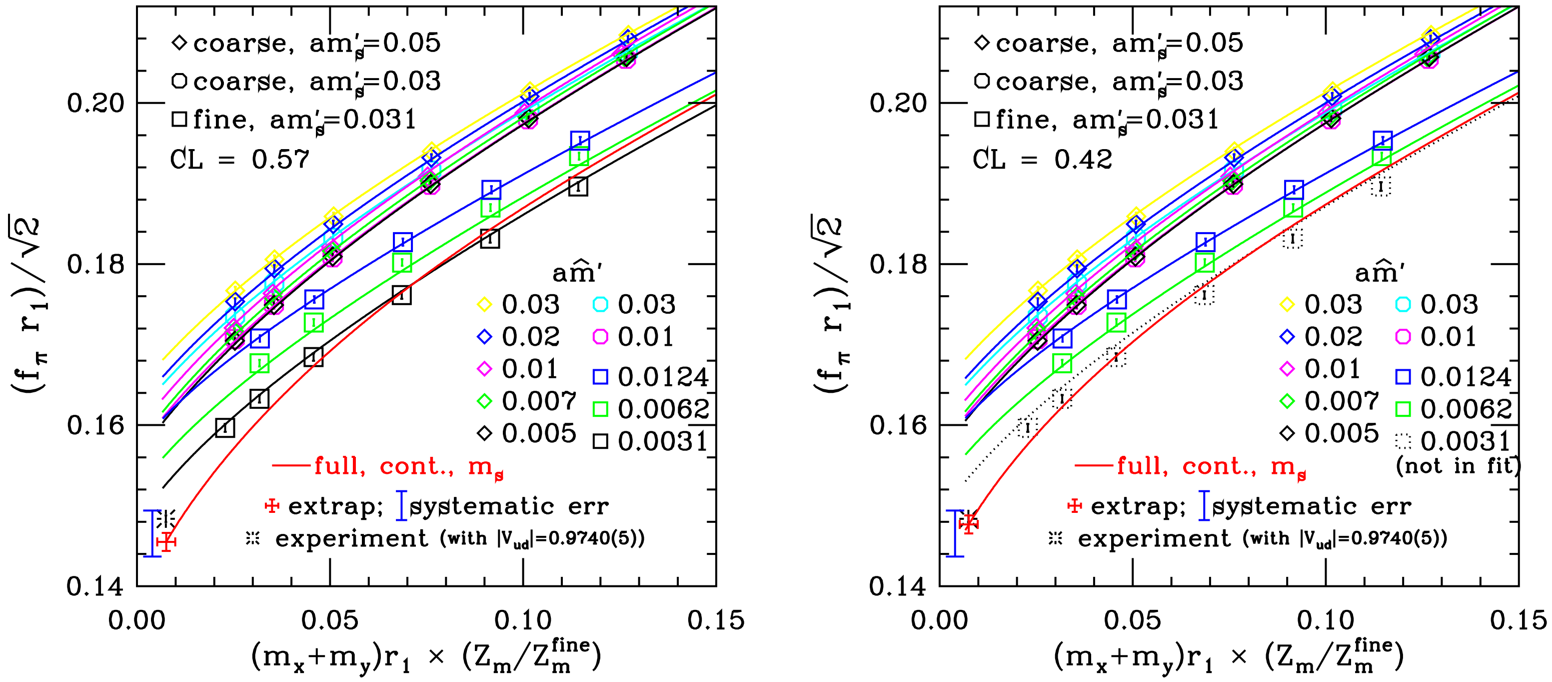
After fit, we:

- 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
(fπ r1)/√2
0.22
0.20
0.18
0.16
0.14
0.00
0.05
0.10
(mx+my)r1 × (Zm/Zm^fine)


CL = 0.65; 0.39
◇ coarse; □ fine
full, a^2 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
$(m_u+m_d)^{phys}$
full, cont, m_s'
full, cont, m_s
7.5
7.0
6.5
6.0
0.00
0.05
0.10
$r_1\ m_\pi^2/(m_x+m_y) \times Z_m^{fine}/Z_m$
$(m_x+m_y)r_1 \times (Z_m/Z_m^{fine})$

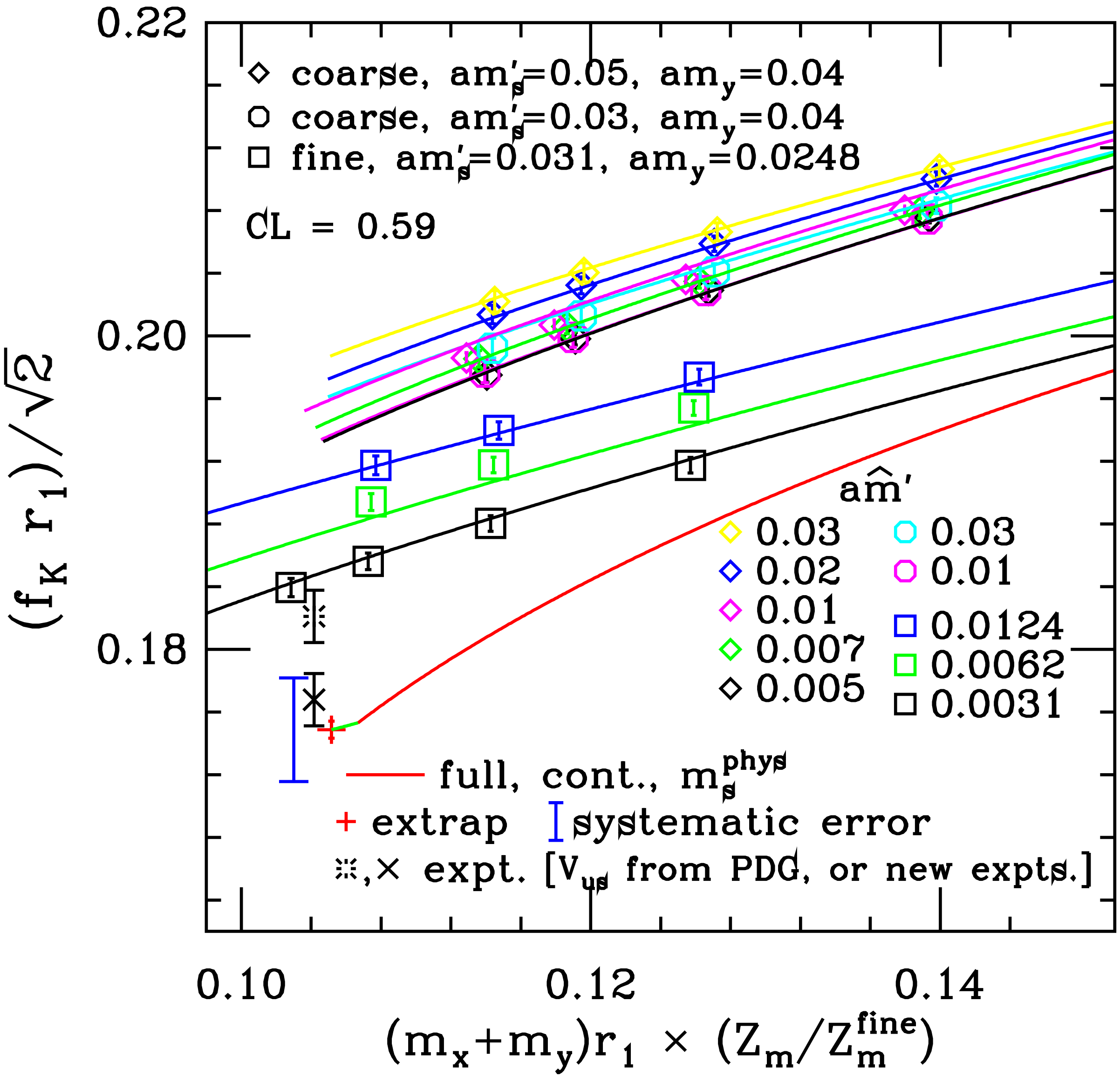
Preliminary Results with New Configs



Two fits have 556 and 488 dof. The 0.0031/0.031 fine run is pulling the results down. This run was only 1/3 done when analysis done. Statistical fluctuation? Variation included in systematic error. (PoS(Lattice05) 025)

Extend range to include K

Preliminary



Results for light decay constants

$$\begin{aligned} f_\pi &= 128.6 \pm 0.6 \pm 2.5\ \mathrm{MeV} (129.5 \pm 0.9 \pm 3.5) \\ f_K &= 154.3 \pm 0.6 \pm 3.0\ \mathrm{MeV} (156.6 \pm 1.0 \pm 3.6) \\ f_K/f_\pi &= 1.198(3)(^{+16}_{-5})(1.210(4)(13)) \end{aligned}$$

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

- Large error in f_K from error in V_{us}
- Using our $f_K/f_\pi \Rightarrow V_{us} = 0.2242^{+11}_{-31} 0.2219(26)$
- PDG value = 0.2196(26)
- Recent expt. average = 0.2262(23) [KTEV, KLOE, NA48, E. Blucher, CKM2005]
- Our error comparable to PDG, with a reduced error, lattice could be best method to determine V_{us}

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 $m_u = m_d = \hat{m}$:
  $m_{\hat{\pi}}$, $m_{\hat{K}}$

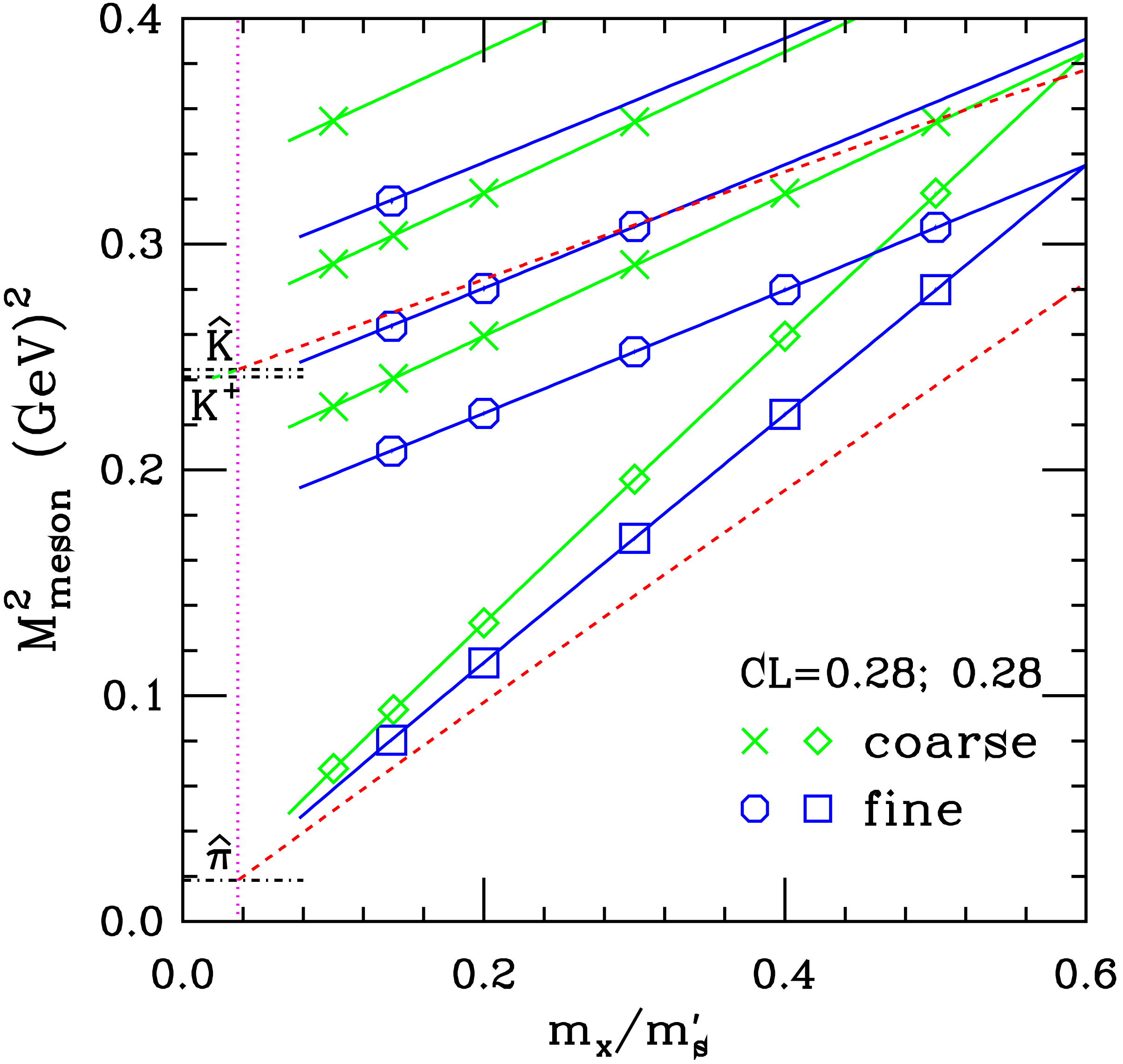
EM & Isospin Violation

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

- $\Delta_E = 0$ 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.
In collaboration with the HPQCD and UKQCD groups, we find [hep-lat/0405022 $=$ PRD70, 031504(2004)]:

$$\begin{aligned} m_s^{\overline{\mathsf{MS}}} &= 76(0)(3)(7)(0)\ \mathrm{MeV}, 87(0)(4)(4)(0) \\ m_{u,d}^{\overline{\mathsf{MS}}} &= 2.8(0)(1)(3)(0)\ \mathrm{MeV}, 3.2(0)(2)(2)(0) \\ m_s/m_{u,d} &= 27.4(1)(4)(0)(1) \end{aligned}$$

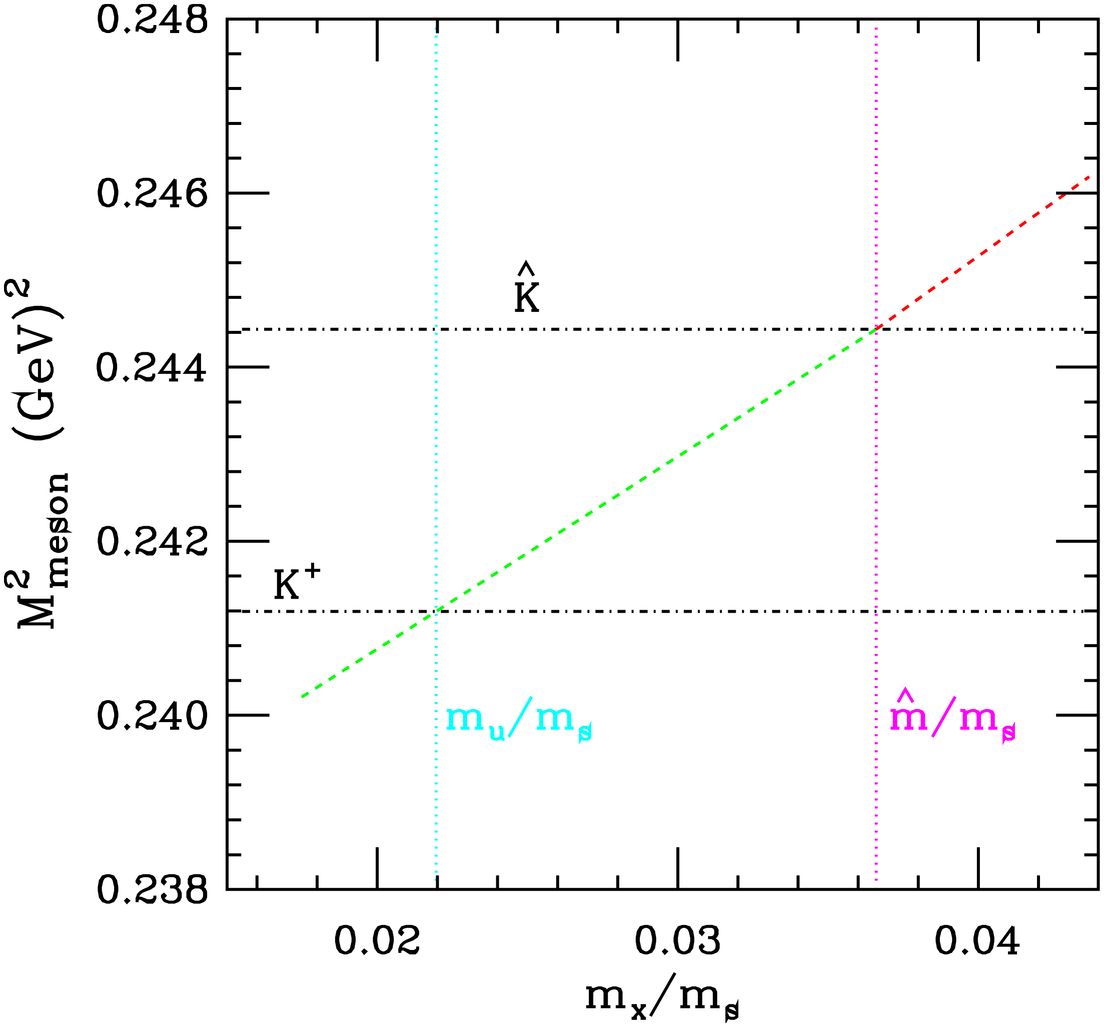
where the errors are from statistics, simulation, perturbation theory, and electromagnetic effects, respectively. The renormalization scale of the masses is $2\,\mathrm{GeV}$. Values in blue from 2-loop perturbation theory by HPQCD. (hep-ph/0511160)

PDG Comparison

$$\begin{aligned}
m_s^{\overline{\mathsf{MS}}} &= 76(0)(3)(7)(0)\ \mathrm{MeV}\ , \\
PDGLat &= 105(25)\ \mathrm{MeV}\ , \\
PDGLat(N_f = 2) &= 90(7)\ \mathrm{MeV}\ , \\
Continuum & \quad 80\ \mathrm{MeV} \leq m_s \leq 155\ \mathrm{MeV}\ , \\
m_{u,d}^{\overline{\mathsf{MS}}} &= 2.8(0)(1)(3)(0)\ \mathrm{MeV}\ , \\
PDGLat &= 4.2(1.0)\ \mathrm{MeV}\ , \\
Continuum & \quad 3.2 \leq m_{u,d} \leq 7\ \mathrm{MeV}\ , \\
m_s/m_{u,d} &= 27.4(1)(4)(0)(1) \\
PDG\ \chi PT &= 25.8
\end{aligned}$$

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

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

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

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

PDG Comparison II

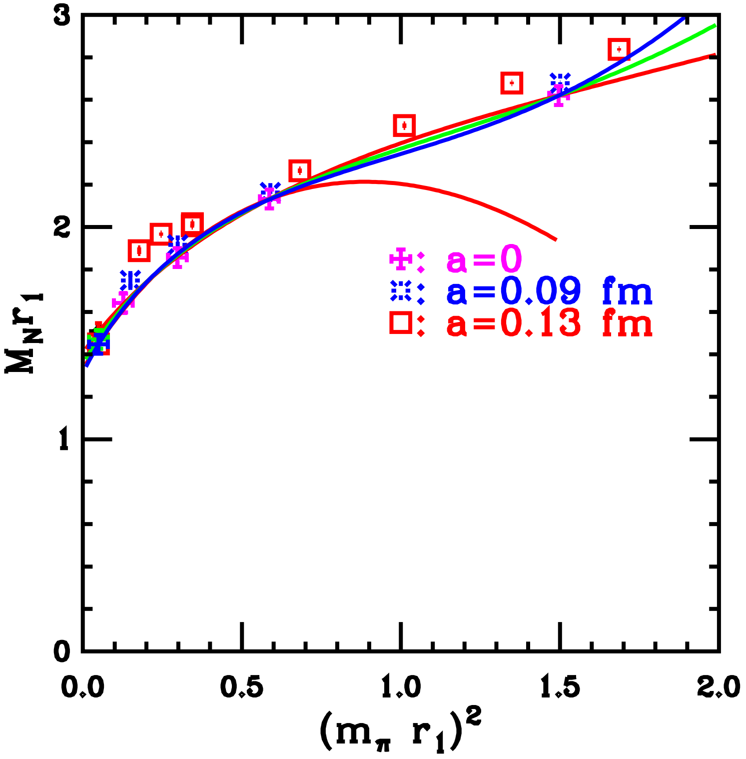
$$
\begin{aligned}
m_u/m_d &= 0.44(0)(1)(2)\ , \\
PDG\ \chi PT &= 0.56\ , \\
PDG \quad & 0.3 \le m_u/m_d \le 0.71\ , \\
m_u^{\overline{\mathrm{MS}}} &= 1.7(0)(1)(2)(2)\ \mathrm{MeV}\ , \\
PDG\ Continuum \quad & 1.5\ \mathrm{MeV} \le m_u \le 5\ \mathrm{MeV}, \\
m_d^{\overline{\mathrm{MS}}} &= 3.9(0)(1)(4)(2)\ \mathrm{MeV}\ . \\
PDG\ Continuum \quad & 5\ \mathrm{MeV} \le m_d \le 7\ \mathrm{MeV},
\end{aligned}
$$

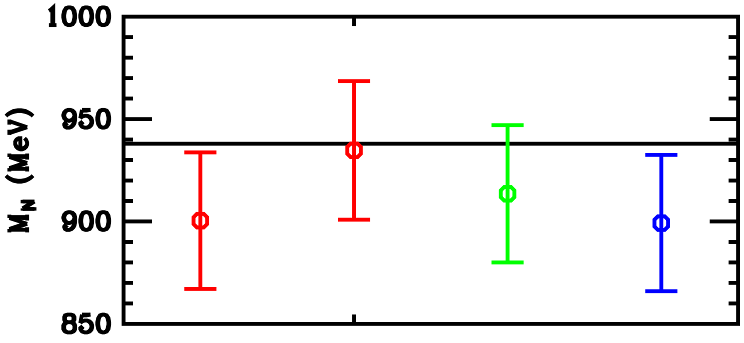
No previous lattice result for m_u or m_d.

Nucleon continuum chiral extrapolation

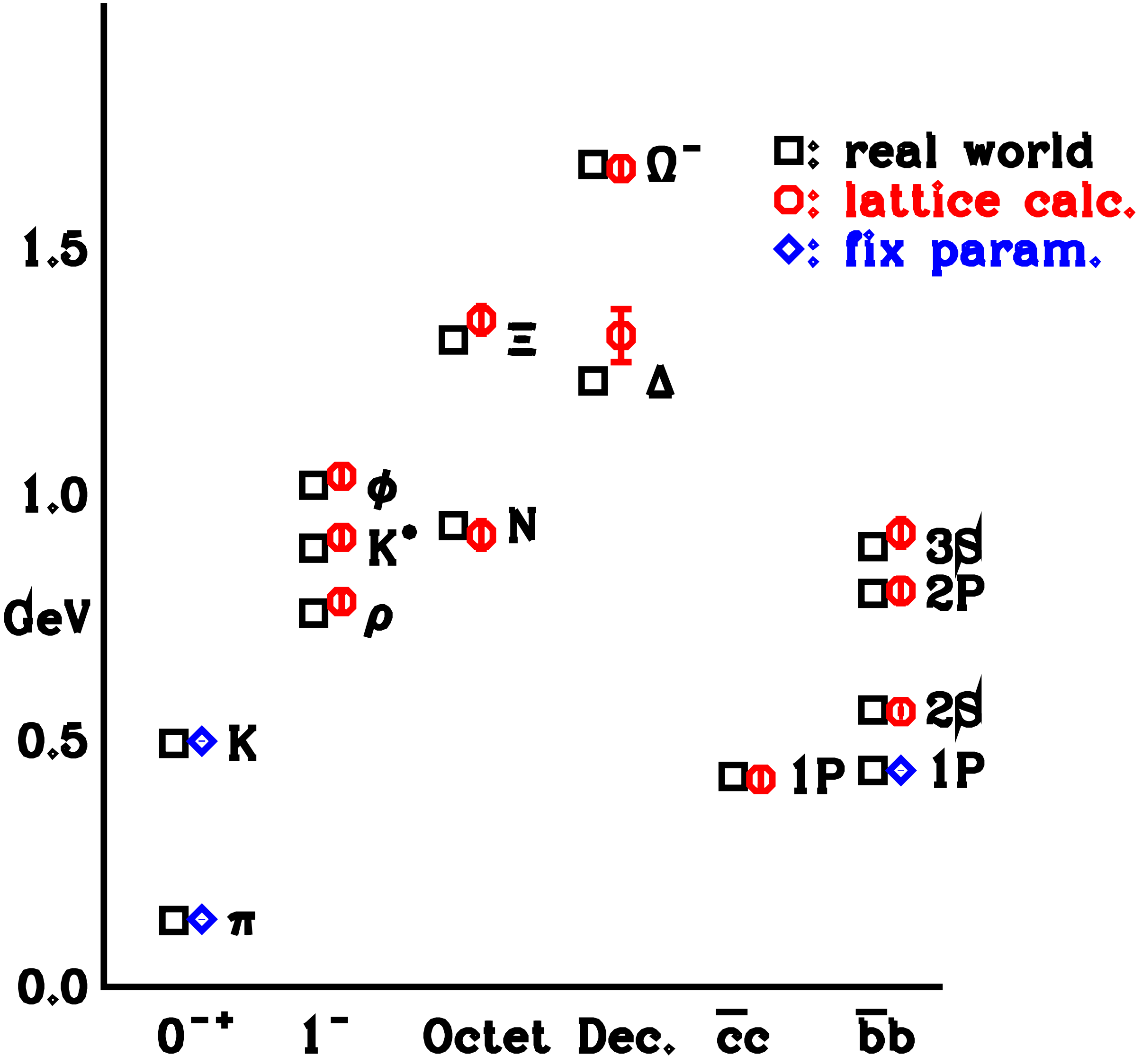
hep-lat/0402030 = PRD70, 094505 (2004)

These graphs updated from that publication





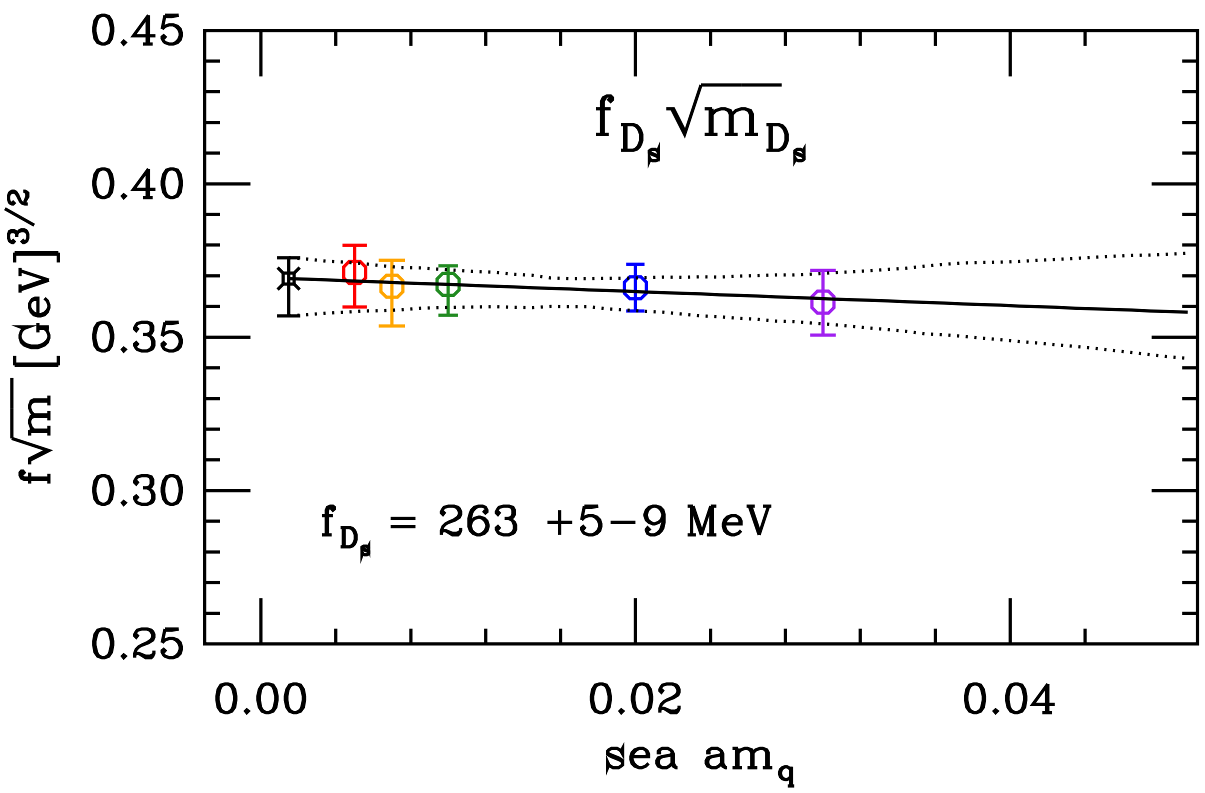
Big Picture


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

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

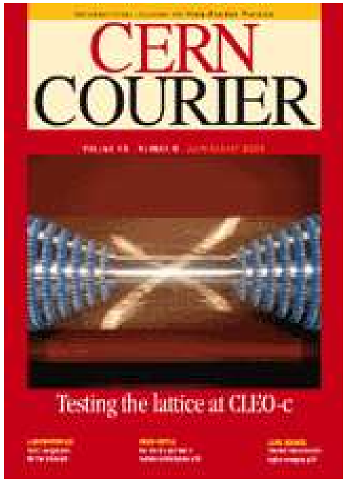
$$\begin{aligned} f_{D_s} &= 249 \pm 3 \pm 16 \text{ MeV} \ , \\ f_{D^+} &= 201 \pm 3 \pm 17 \text{ MeV} \ , \\ & . \end{aligned}$$

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±8 D^+ decays observed. Latter by

CLEO-c

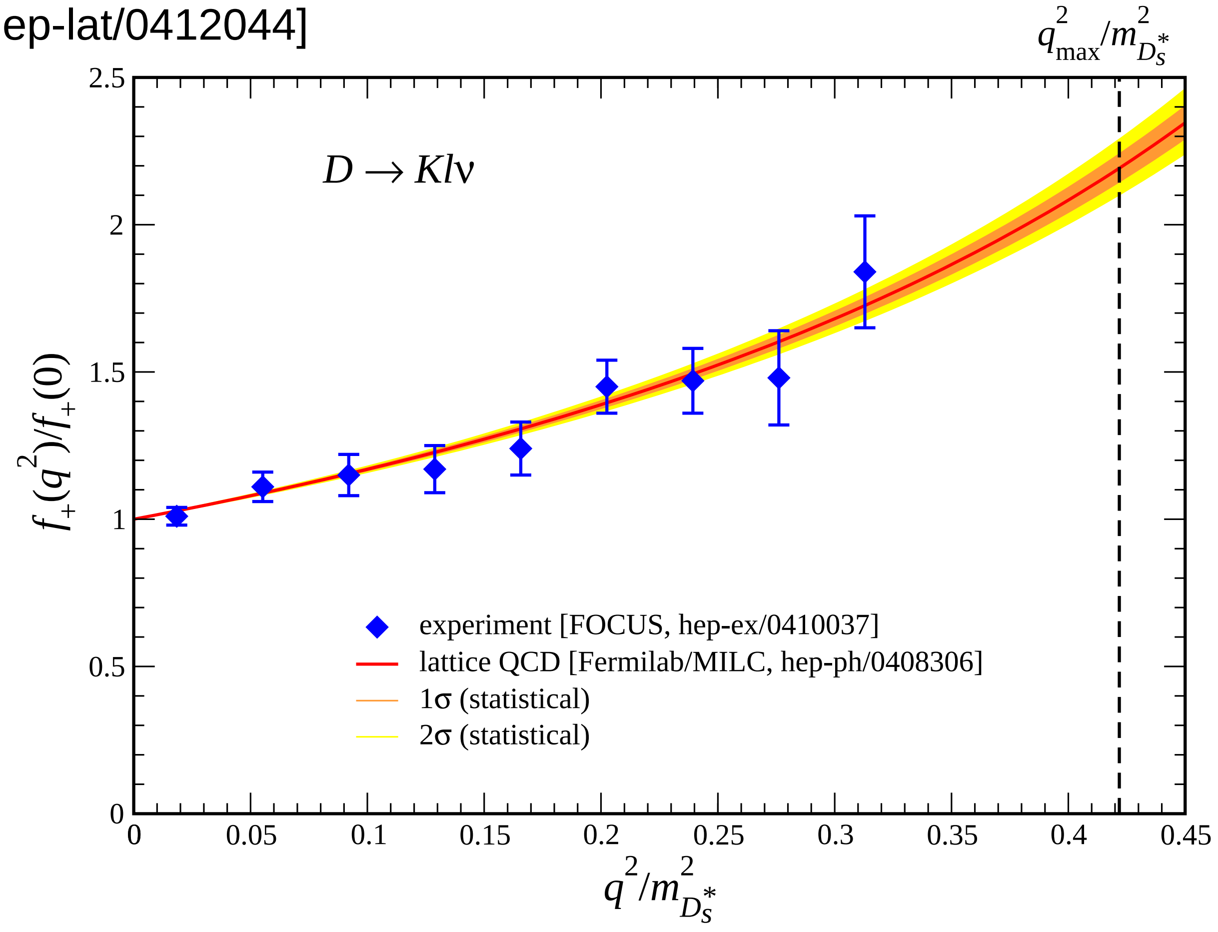
$$\begin{aligned} f_{D_s^+} &= 267 \pm 33 \text{ MeV} \\ f_{D^+} &= 223 \pm 17 \pm 3 \text{ MeV} \end{aligned}$$



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]



$D \to Kl\nu$ 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

- At Izu, I showed how we determined the transition temperature.
- Recently, we have been calculating the equation of state for $N_t = 4$ and 6.
- Use the integral method:

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

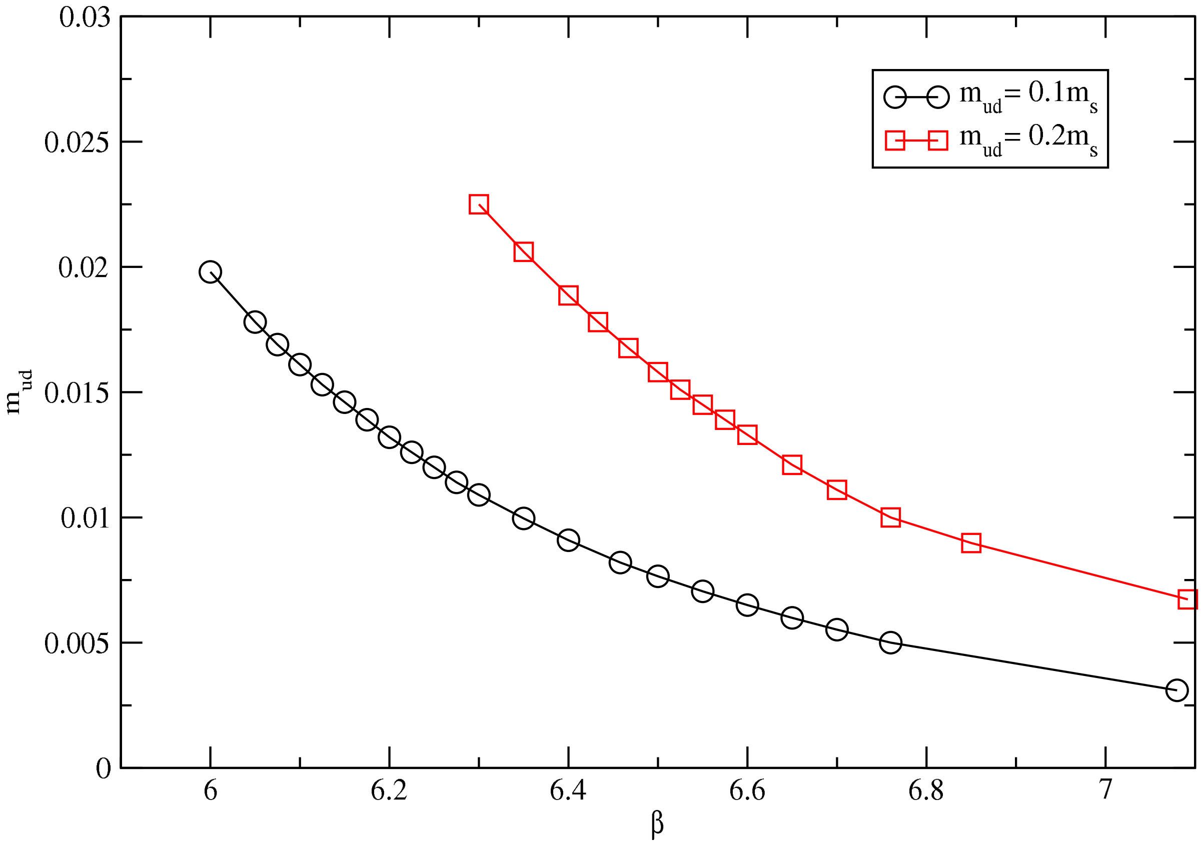
$$I = \varepsilon - 3p = - \frac{T}{V} \frac{d \ln Z}{d \ln a},$$

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

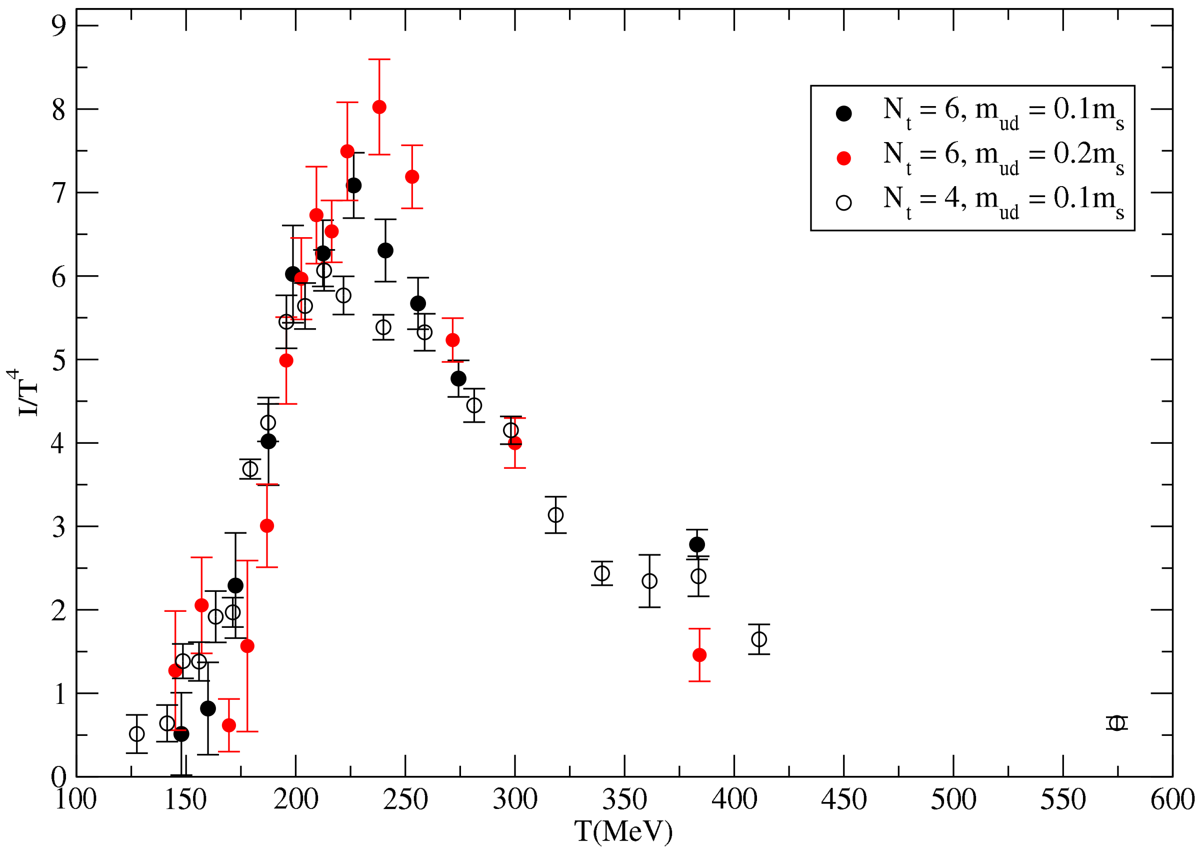
$$
\begin{aligned}
Ia^4 &= -6\frac{d\beta}{d\ln a}\Delta\langle P\rangle - 12\frac{d\beta_{\mathrm{rt}}}{d\ln a}\Delta\langle R\rangle - 16\frac{d\beta_{\mathrm{ch}}}{d\ln a}\Delta\langle C\rangle \\
&\quad -\sum_f \frac{n_f}{4}\left[\frac{d(m_f a)}{d\ln a}\Delta\left\langle\bar\psi\psi\right\rangle_f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

See Proceedings of Science, Lattice 2005, 156.

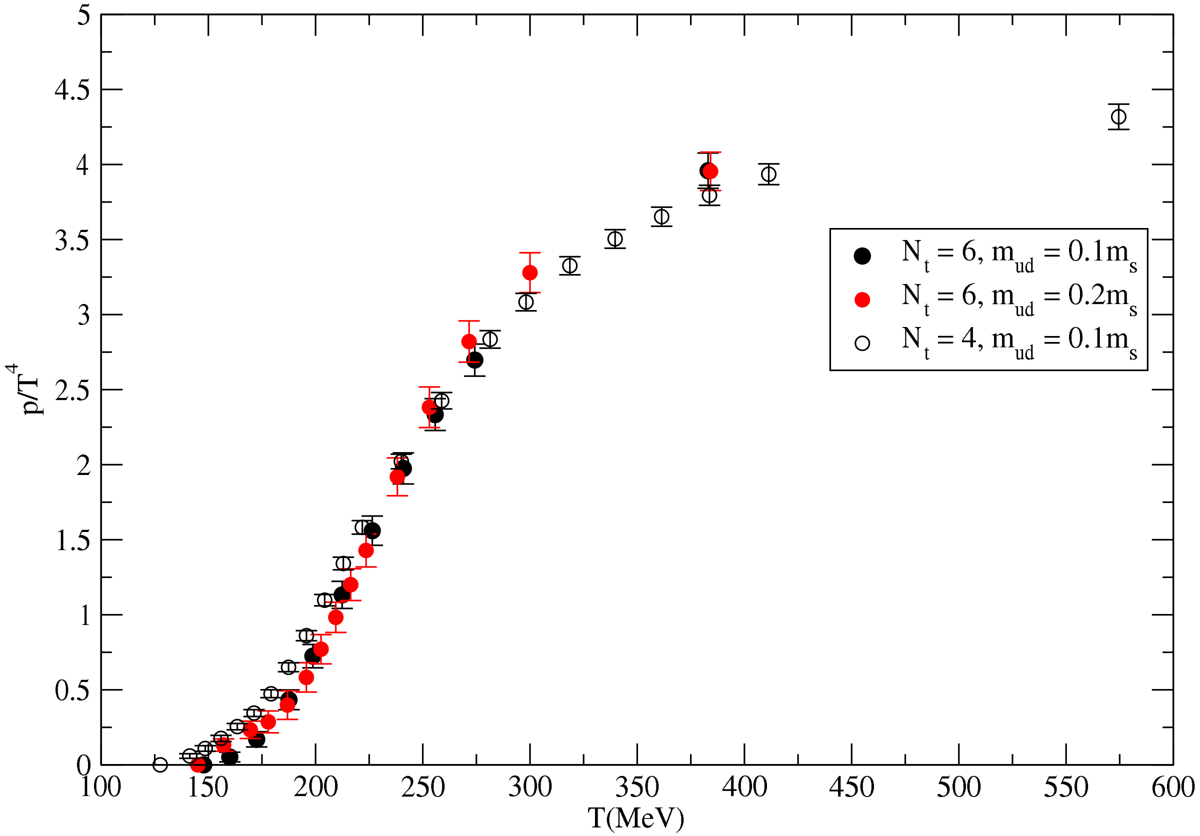
Trajectories of Constant Physics



Interaction Measure



Pressure



p/T^4
T(MeV)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
100
150
200
250
300
350
400
450
500
550
600
● N_t = 6, m_ud = 0.1m_s
● N_t = 6, m_ud = 0.2m_s
○ N_t = 4, m_ud = 0.1m_s

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 will generate new ensembles with a smaller lattice spacing 0.06 fm.
  - The first $48^3 \times 144$ $m_l = 0.4 m_s$ run with $a = 0.06$ fm should be completed in the coming year.
  - We have just started the $48^3 \times 144$ $m_l = 0.2 m_s$ run. The run requires > 1 TF-yr of computing. Further refinements require 2–8–50 Tf-yr.
  - We plan to explore the RHMC algorithm.

- We will complete analysis of B meson decays on the available ensembles and compare with NRQCD results.
- We may undertake a study of EOS with $N_t = 8$ using BlueGene/L computers.
- Alternative methods, such as overlap, domain wall and twisted mass, should contribute to reducing systematic uncertainties. We look forward to comparing results.

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- Alternative methods, such as overlap, domain wall and twisted mass, should contribute to reducing systematic uncertainties. We look forward to comparing results.
- We look forward to getting together again with colleagues and friends in such lovely settings to discuss exciting developments.
- Thanks to all the organizers: Sinya, Shoji, Yusuke and safe journeys home to all!