Near-conformal BSM theories on the lattice

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in collaboration with Julius Kuti, Zoltan Fodor, Daniel Nogradi, Chris Schroeder, Chik Him Wong

summary

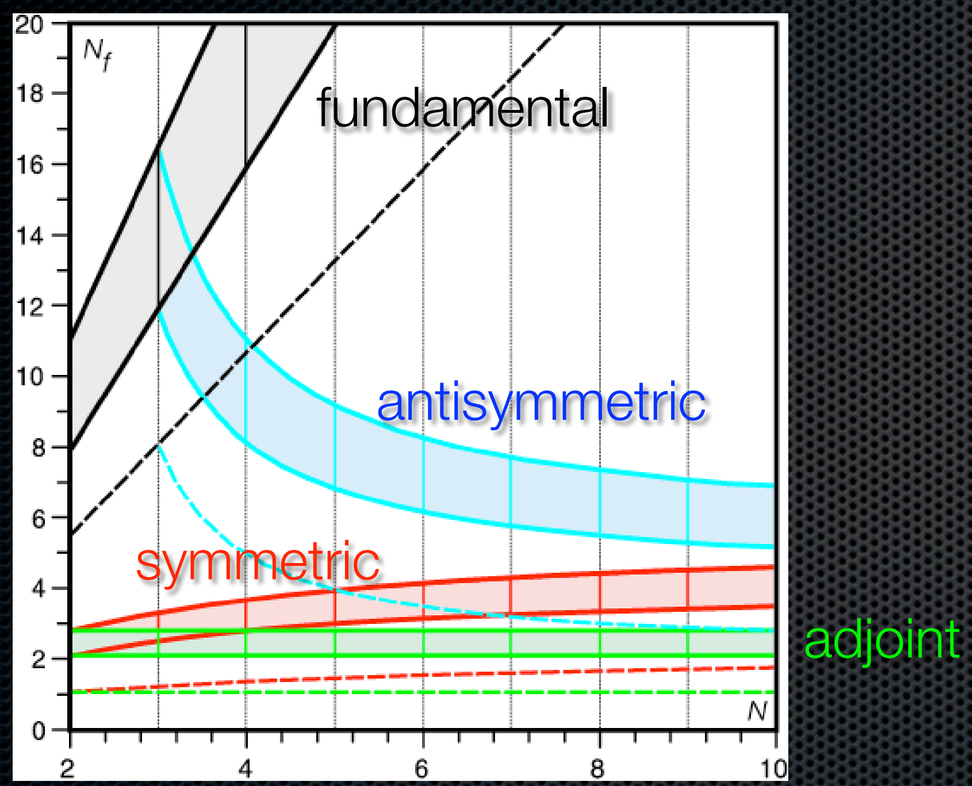
- lattice role for BSM
- what can you do on the lattice?
- limitations of simulations
- latest SU(3) results
- future focus

lattice role for BSM

- strong dynamics for EWSB: fix naturalness, triviality
- near-conformal ("walking"): fix FCNC/mass generation tension?
- new vista: reps beyond SU(3) fundamental, less tension with expt
- interesting models likely non-perturbative: lattice
- can lattice show if any given gauge theory conformal or not?
- would be sad if we (lattice) were not exploring possibility of new strong gauge theories in Nature

conformal window

N_f Dietrich,Sannino,Tuominen



N_c

each TC fermion rep has window in flavor-color space where theory conformal

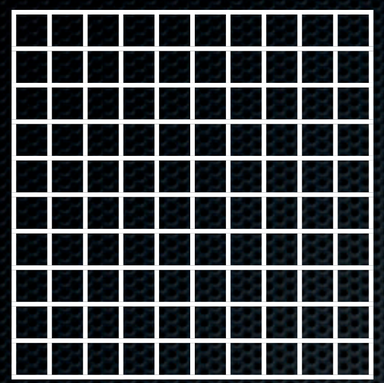
perturbative: find IR fixed point of beta-fn

amend: strong IRFP could break chiral symmetry

near-conformal just below window

lattice task: where exactly are the windows?

lattice



discretize space-time: regulator, lattice spacing a

fundamental Lagrangian e.g. QCD: quarks, gluons

fermions on sites, gauge fields on links U

gauge-invariance exact

can fix

lose symmetry: translation, rotation, chirality

recovered in continuum limit (zero spacing)

observable $\langle B \rangle = \int DU \{\mathrm{Det}(D[U])\}^{N_f} \exp(-S_g[U])\ B[U]$

non-perturbative

no expansion

Monte Carlo simulation $\int DU \to \sum_{\text{typical } U}$

limitations of simulations

1. generation of U configurations: numerical algorithm
slow due to non-local fermion determinant

2. discrete lattice action - artifacts, difference from continuum
improve lattice action: reduce artifacts (good) reduce speed (bad)

3. always simulate at finite volume, typically at finite mass
control: continuum limit at fixed large physical volume,
then take chiral limit - always saturate available computers

4. larger Nf or unusual representation - even harder than QCD!

cost

- USQCD: central US allocation of hep-lat computational resources
- BSM efforts: tens of millions of computer core-hours per year
- 1 core-year approx. 8,000 core hours
- similar resources as large-scale QCD efforts (MILC/HPQCD)
- since 2007, many lattice groups worldwide work on BSM
- lattice community not trying to do BSM on the cheap!

lattice observables

- particle spectrum
- chiral condensate, Dirac operator eigenvalues
- running of renormalized gauge coupling (various schemes)
- detection of finite-temperature phase transitions
- S parameter
- RG flow in bare coupling space

which theories

my talk:

(a) 2-flavor SU(3) 2-index symmetric rep (sextet/NMWT)

(b) 12-flavor SU(3) fundamental rep

why?

(a) sextet attractive for BSM: 3 Goldstones match W&Z, few d.o.f.

(b) much work on fundamental rep for various number flavors

next talk: Francis Bursa on SU(2) reps

particle spectrum

expectations:

if chirally broken

$$M_\pi^2 = a_1 m + a_2 m^2$$

$$F_\pi = F + b_1 m$$

$$M_{\rm nuc} = M_{\rm nuc,0} + c_1 m$$

$$\langle \bar{\Psi}\Psi \rangle = d_0 + d_1 m + d_2 m^2$$

polynomials chiPT motivated

but not sensitive to logs

+ large Nf issues in chiPT

if conformal

$$M_{\rm hadron} = c_{\rm hadron} m^{1/(1+\gamma)}$$

$$\langle \bar{\Psi}\Psi \rangle = c_{\rm cond} m^{(3-\gamma)/(1+\gamma)} + c_1 m$$

universal critical exponent

no mass gap in chiral limit

notation $y_m = 1 + \gamma$ anomalous dimension

2-flavor SU(3) sextet

Fodor et al. arXiv:1205.1878

simulation details:
staggered fermion discretization - fast, remnant chiral symmetry
but flavor symmetry broken
partial fix - improved fermion and gauge lattice action

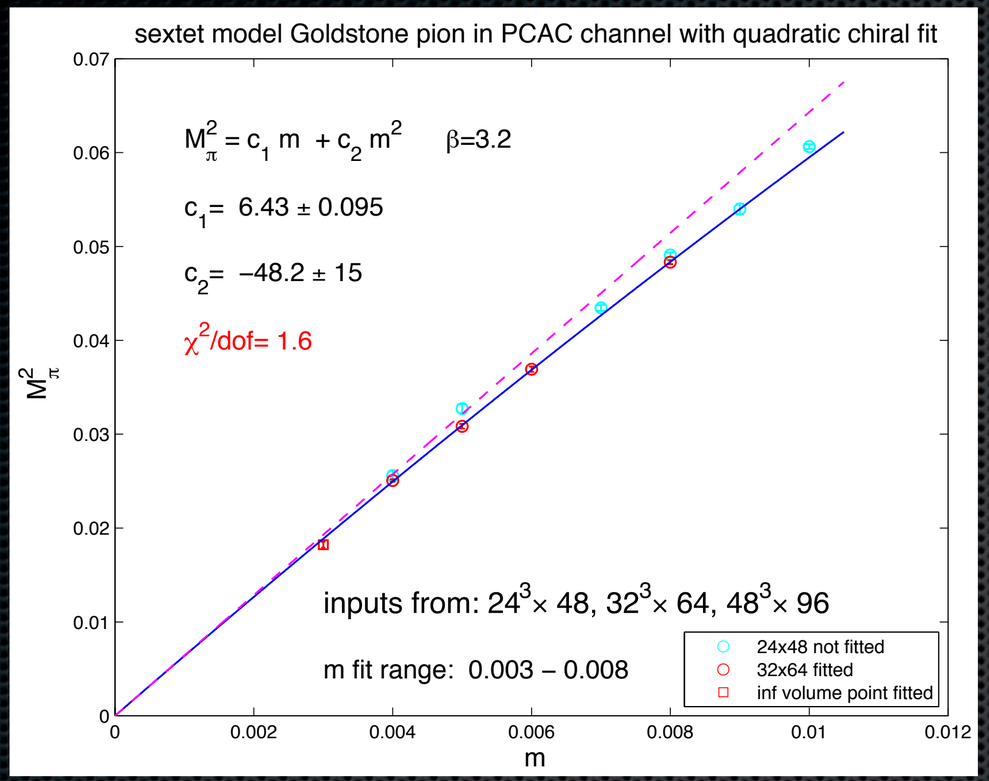
bare parameter choice: set fermion mass and lattice spacing

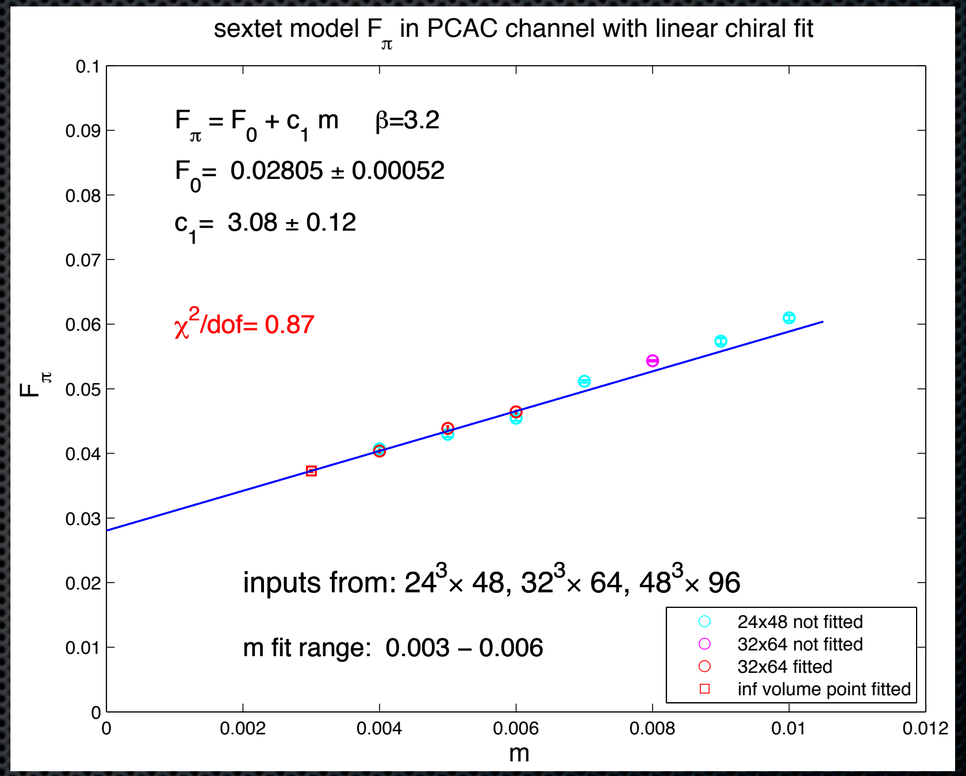
largest lattice size $48^3 \times 96$ lightest fermion mass $1/(m_\pi a) \approx 7$

several lattice volumes, fermion masses, 2 lattice spacings

each simulation: 1-2 thousand gauge configurations - expensive

results: spectrum



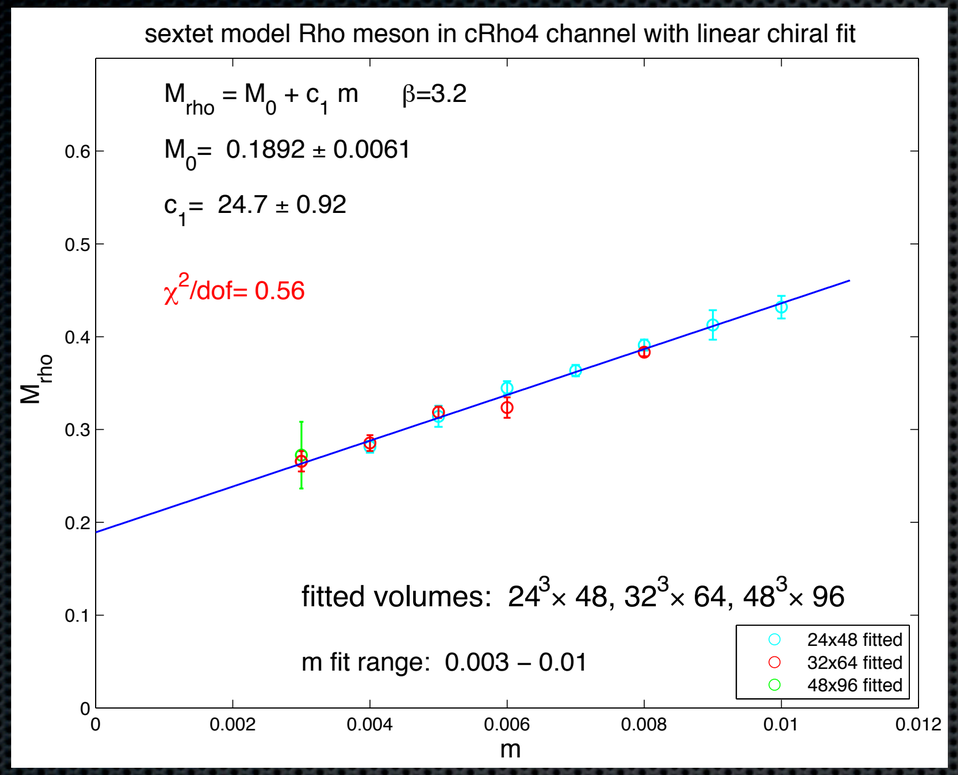


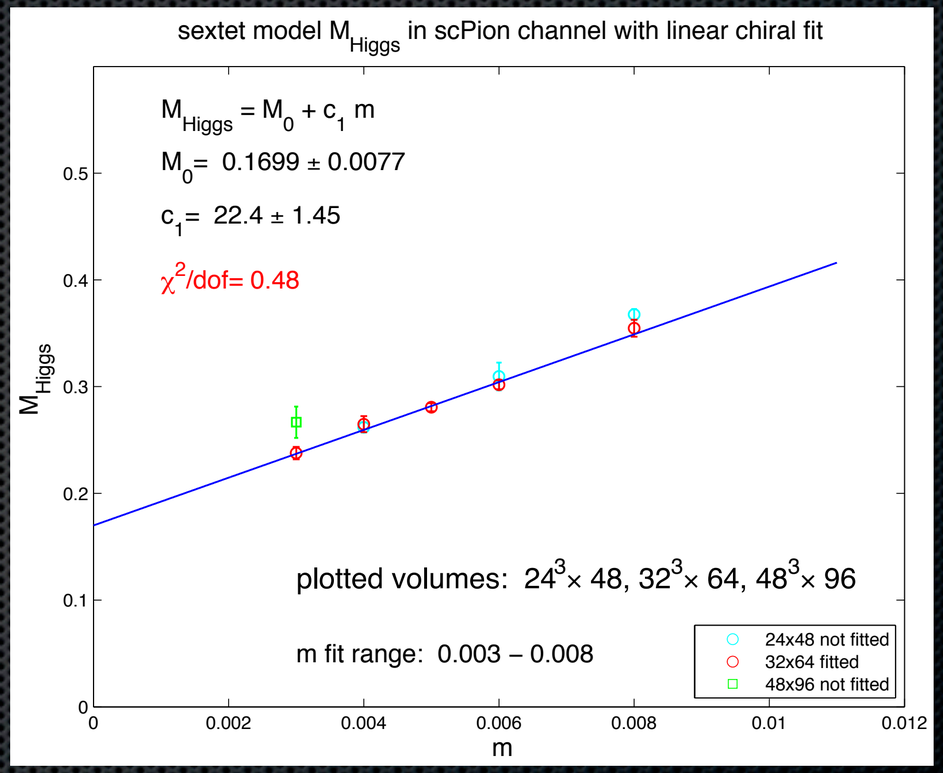
chiPT-like fit good description of data

chiral limit of pion decay constant non-zero $aF_0 = 0.0281(5)$

sets physical scale of theory

results: spectrum



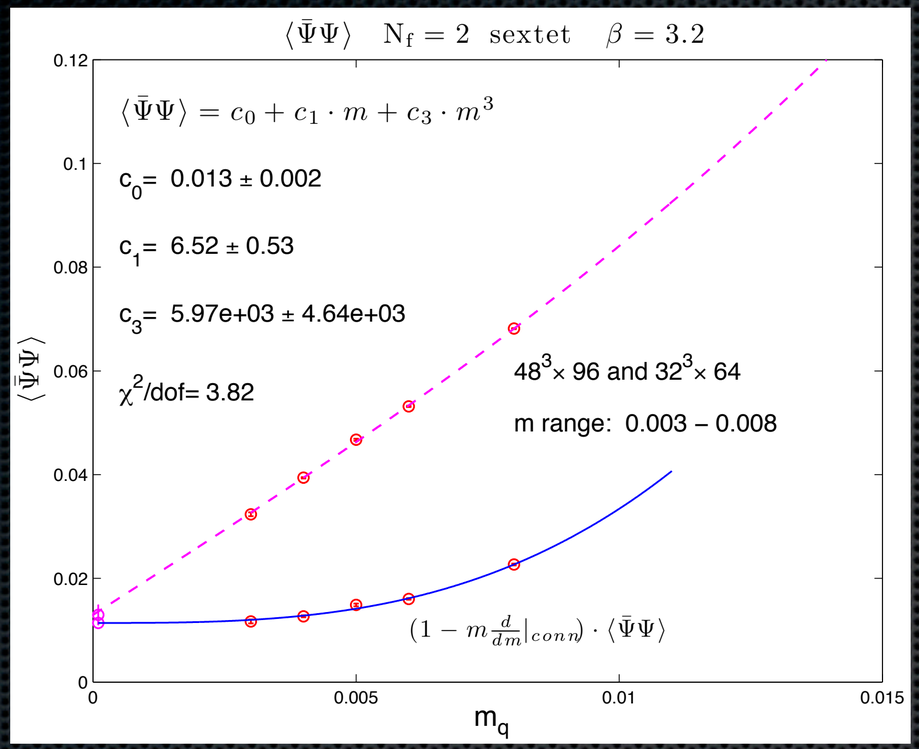


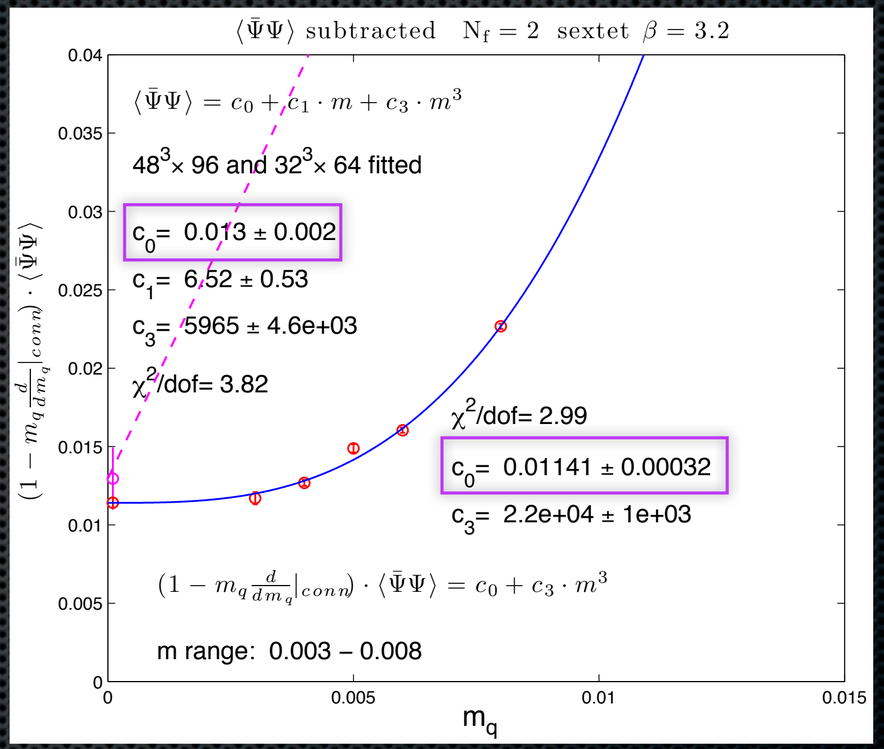
again, chiPT-like fits to data are good

non-zero mass gaps in chiral limit

ratios $\frac{M_\rho}{F_0} \sim 7, \ \frac{M_{\rm higgs}}{F_0} \sim 6$

results: chiral condensate



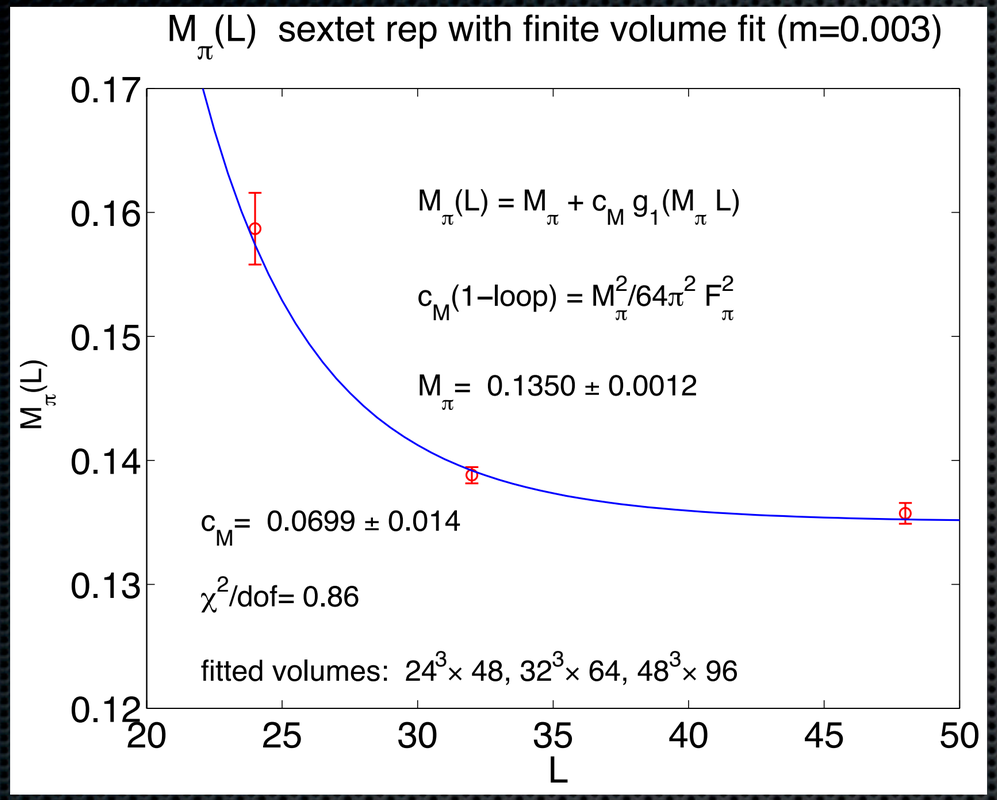


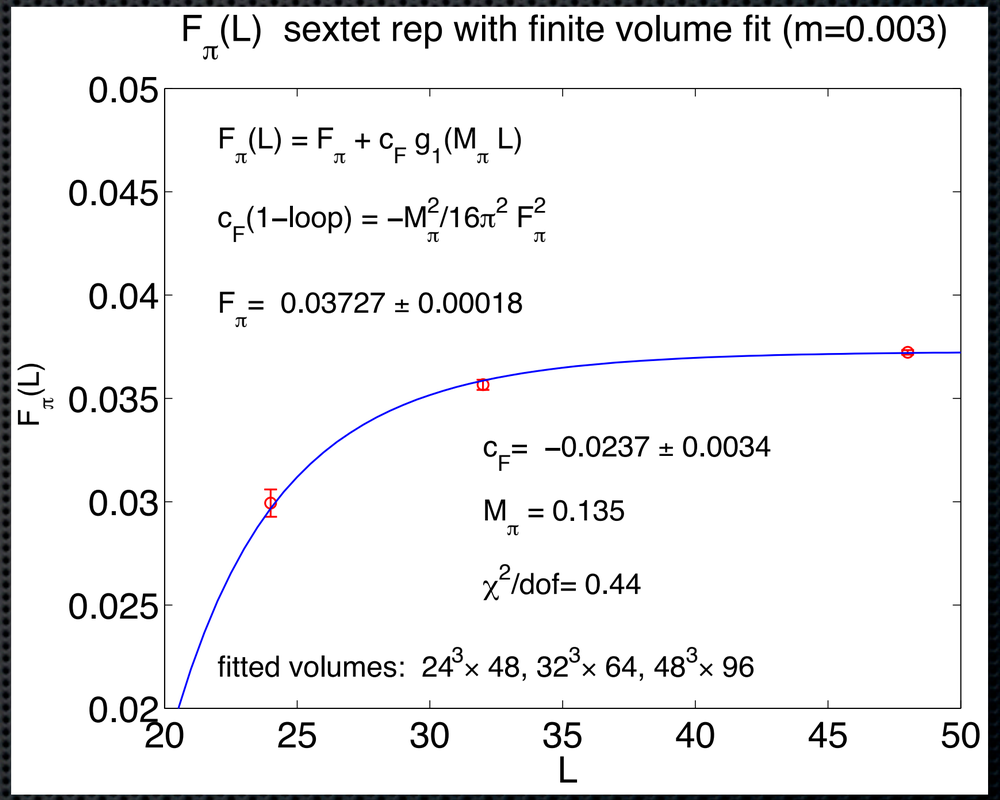
chiral condensate also fit reasonably, with non-zero chiral limit

2nd independent measurement of subtracted condensate

two methods have consistent values in chiral limit - very good

volume-dependence

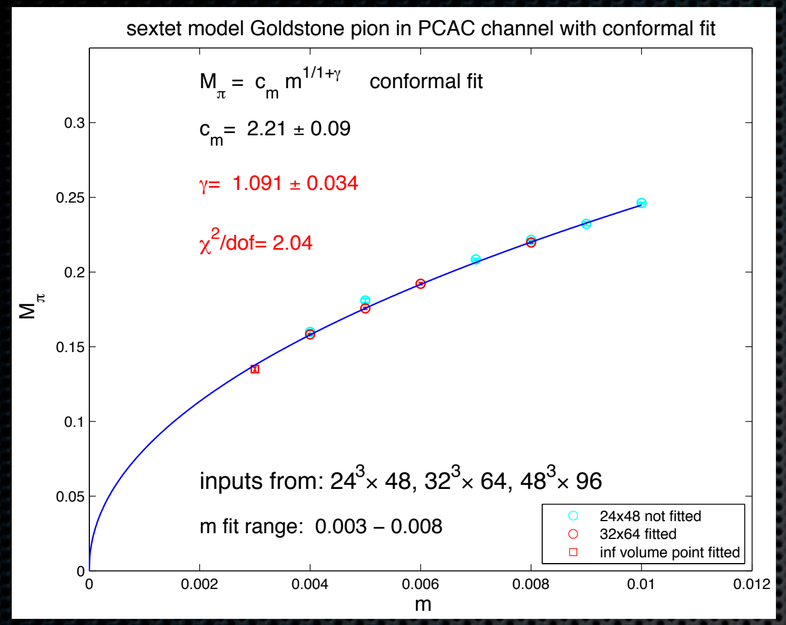


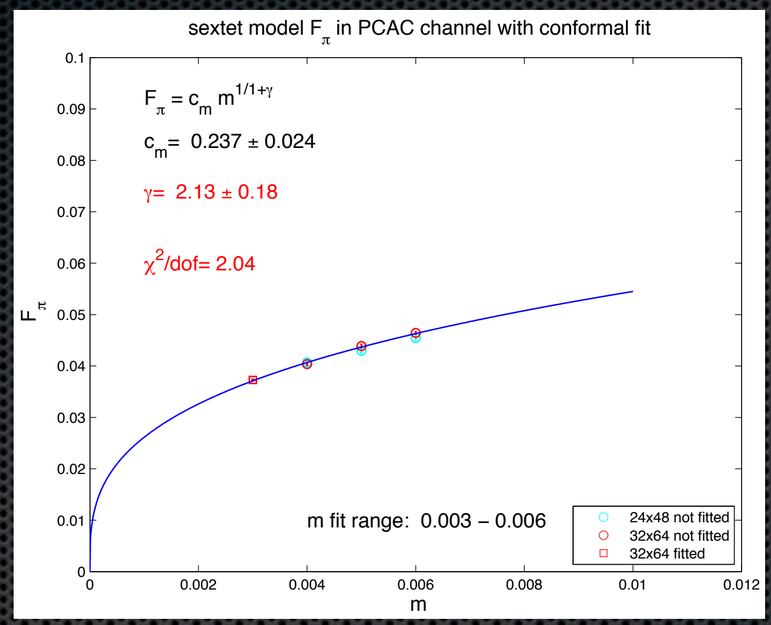


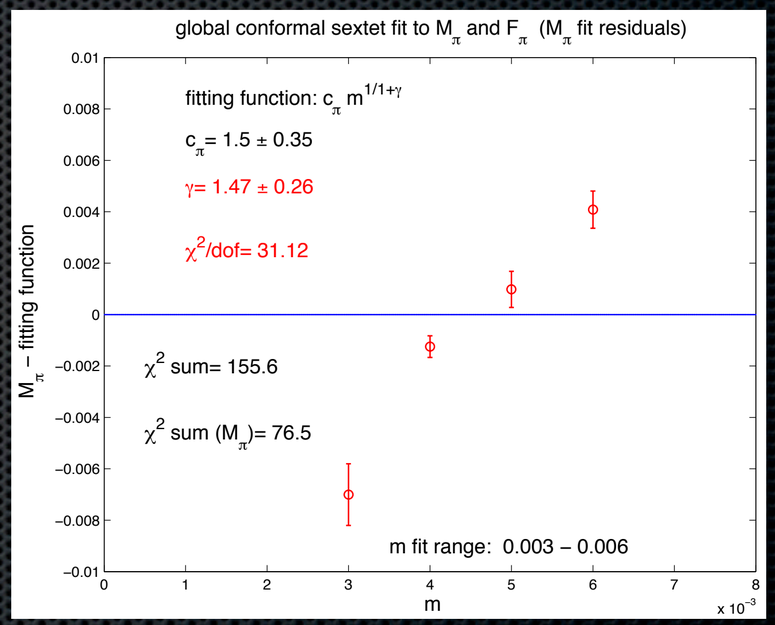
volume-dependence of spectrum significant

$M_\pi L > 5$ to be within 1% of infinite-volume value

alternative:conformal?







$\gamma = 1.091 \pm 0.0034$

$\gamma = 2.13 \pm 0.18$

fit states together: bad

$\gamma = 1.47 \pm 0.26$

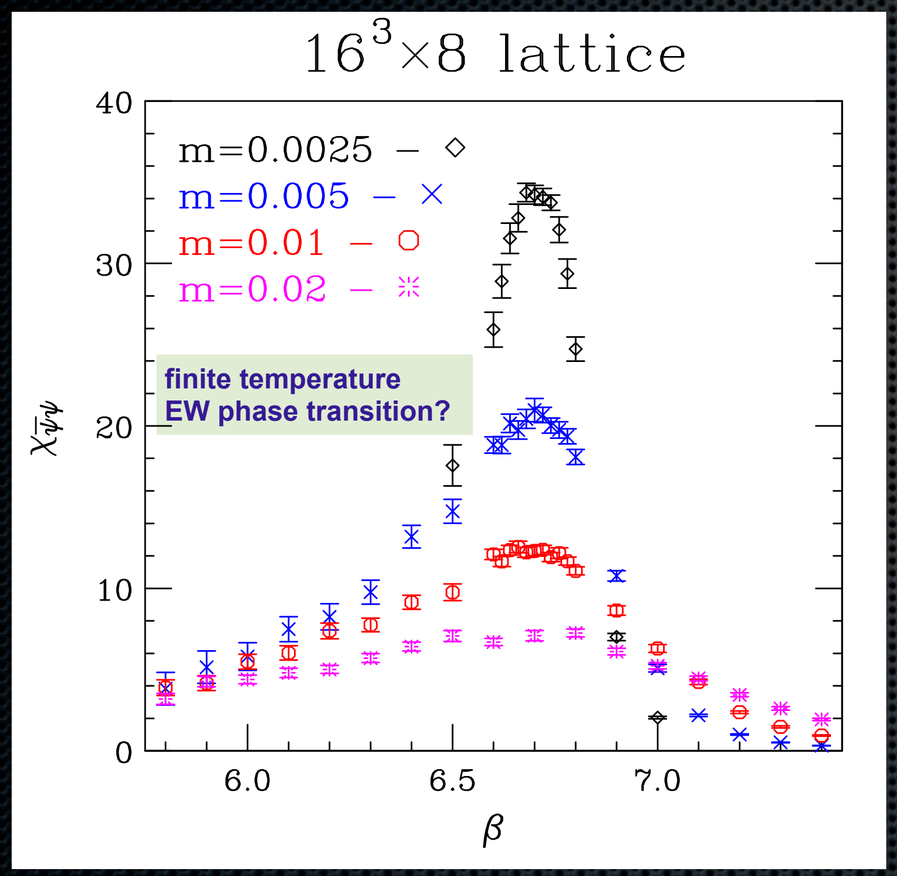
fit data to power-like conformal behavior

$M_{\rm had} = c_{\rm had} m^{1/1+\gamma}$ anomalous dimension γ large

individual fits reasonable; combined fit unacceptable

other 2-flavor sextet work

Kogut & Sinclair, arXiv:1111.2319



finite-temperature chiral phase transition

vary physical size of (periodic) time direction via lattice spacing (bare coupling)

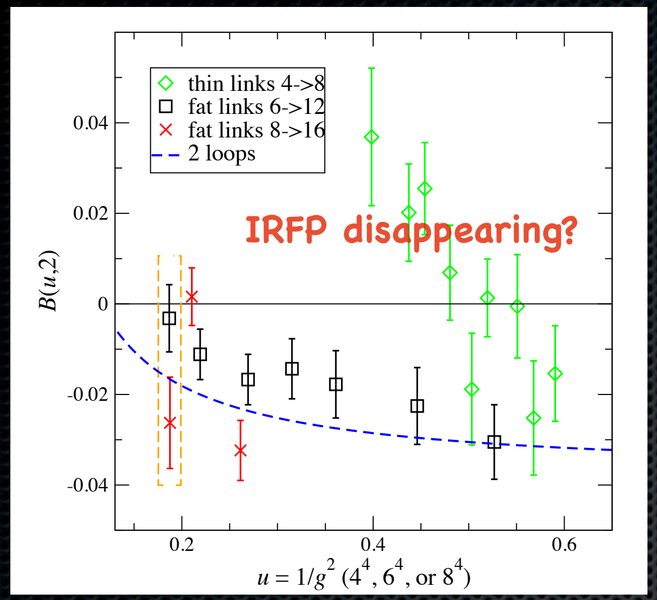
chiral susceptibility develops peak at critical temperature

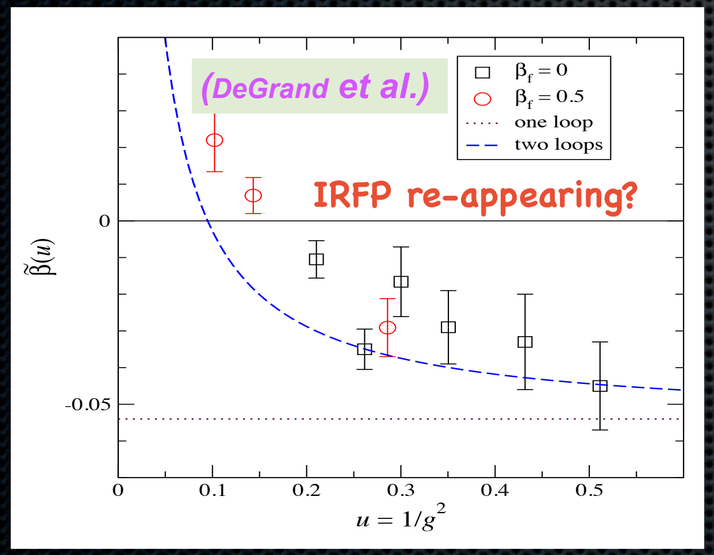
peak more pronounced at lighter mass

consistent with chiSB at zero temperature

want to repeat closer to continuum limit

other 2-flavor sextet work





DeGrand et al.,arXiv:1201.0935,1006.0707

define renormalized coupling $g^2(L)$ at scale L

particular scheme: Schrodinger Functional

change lattice size e.g. L to 2L
discrete beta function

vary lattice action and operator

IR fixed point existence varies with method

also find small value $\gamma < 0.45$

12-flavor SU(3) fund

Fodor et al. arXiv:1205.1878,1104.3124

simulation details:
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partial fix - improved fermion and gauge lattice action

bare parameter choice: set fermion mass and lattice spacing

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several lattice volumes, fermion masses, 1 lattice spacing

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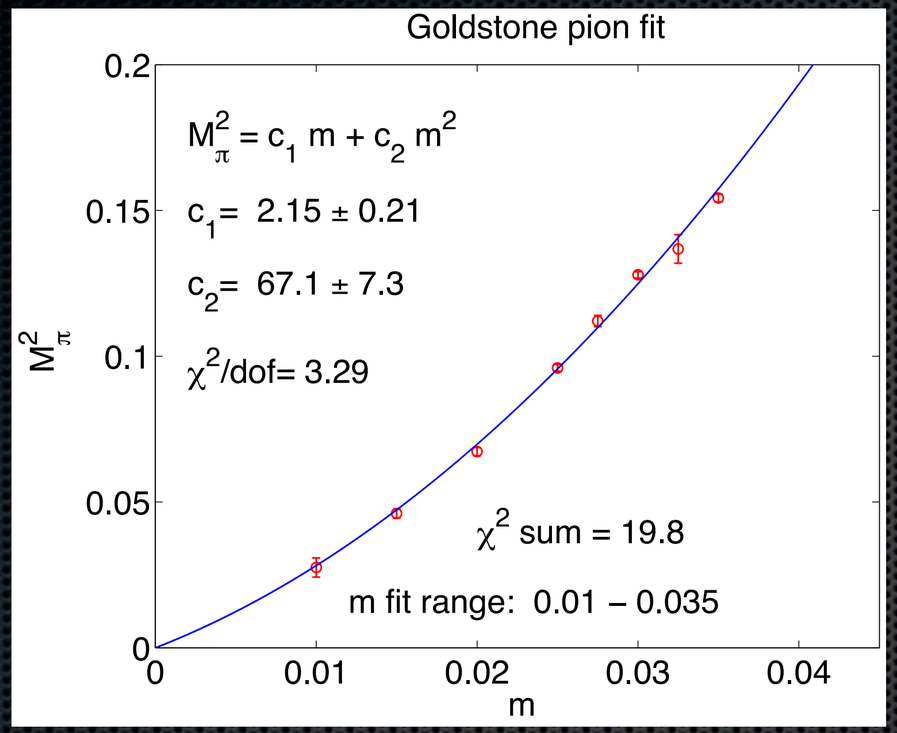
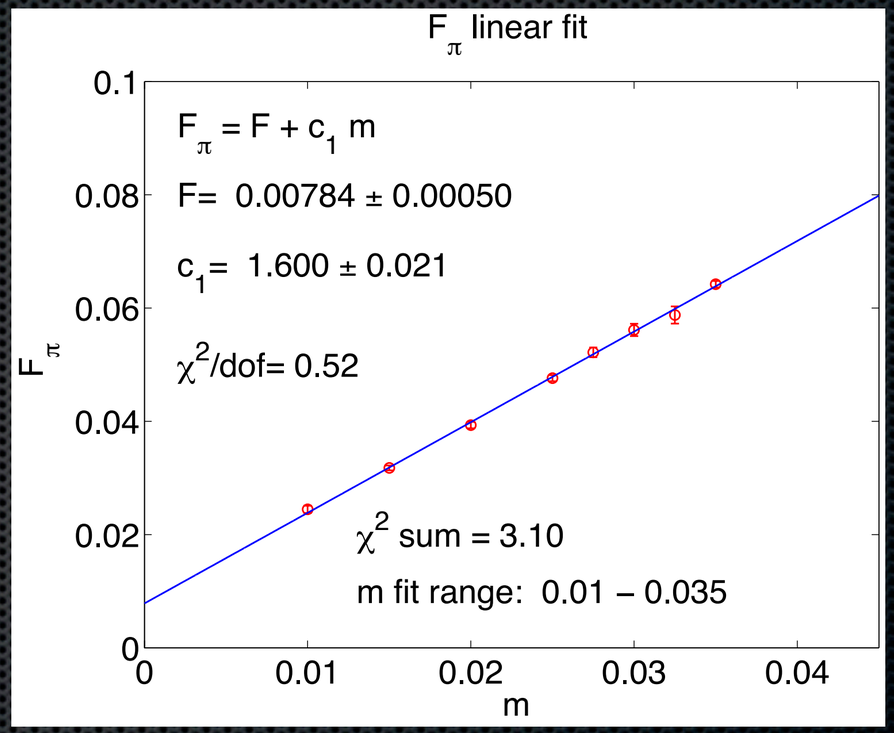
spectrum





chiPT-like fits of data reasonable

Fpi steep variation with mass

already expected due to large Nf

to actually reach chiPT regime (small corrections) very hard

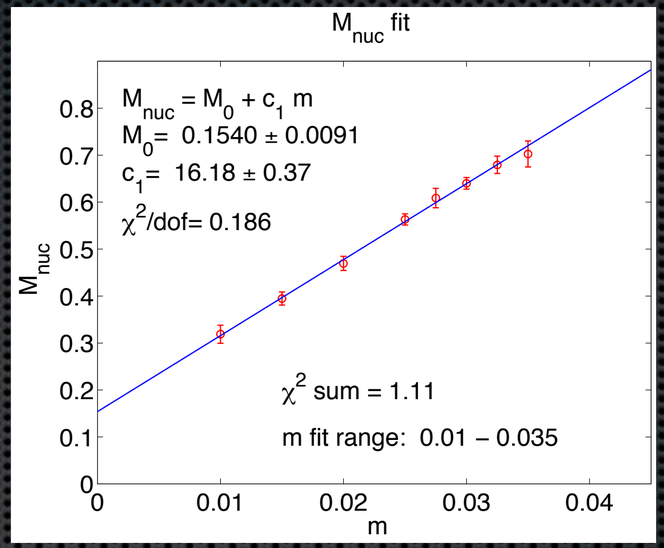
spectrum

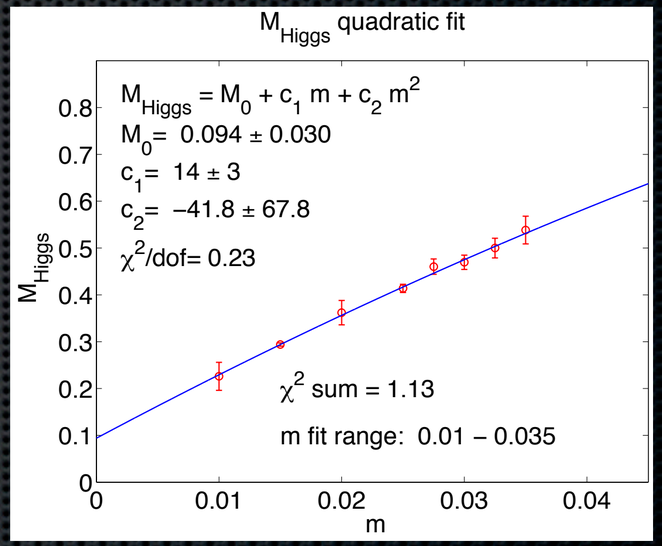
rest of spectrum appears to have mass gap in chiral limit

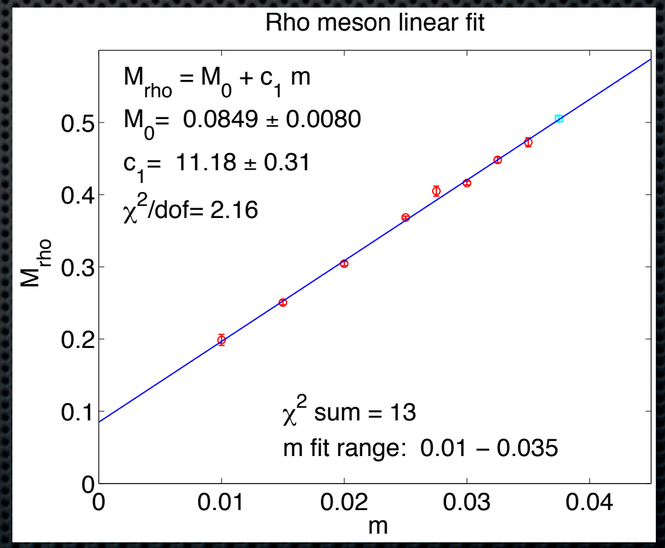
again polynomial fits good

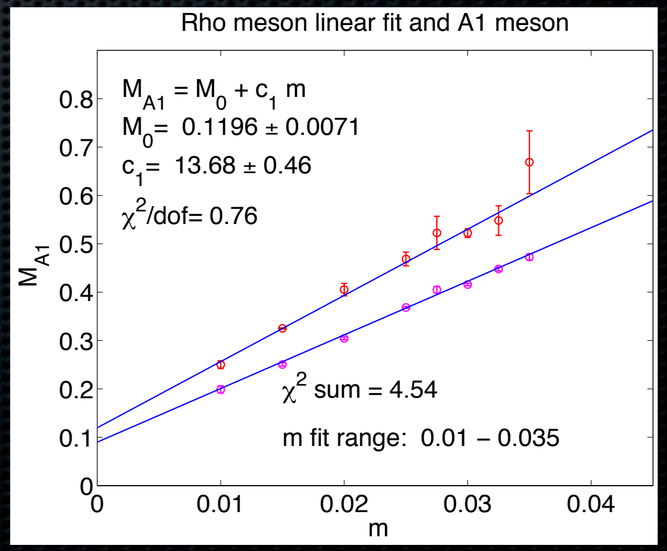
ratios

$$\frac{M_\rho}{F_0} \sim 11, \quad \frac{M_{\rm higgs}}{F_0} \sim 12$$

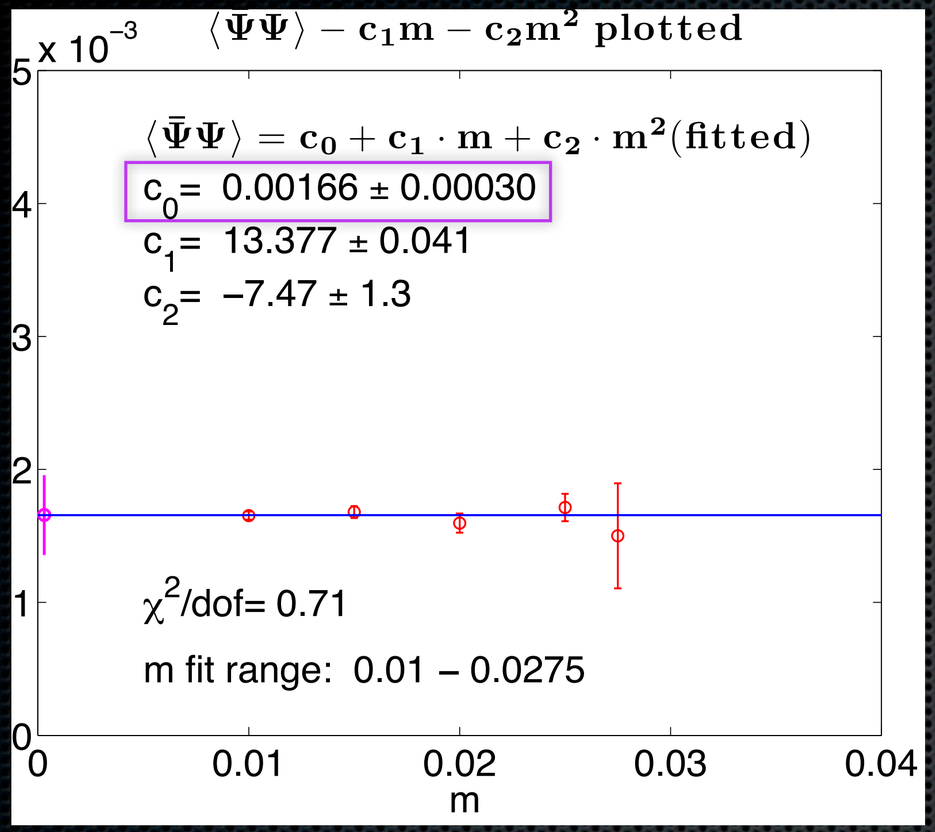








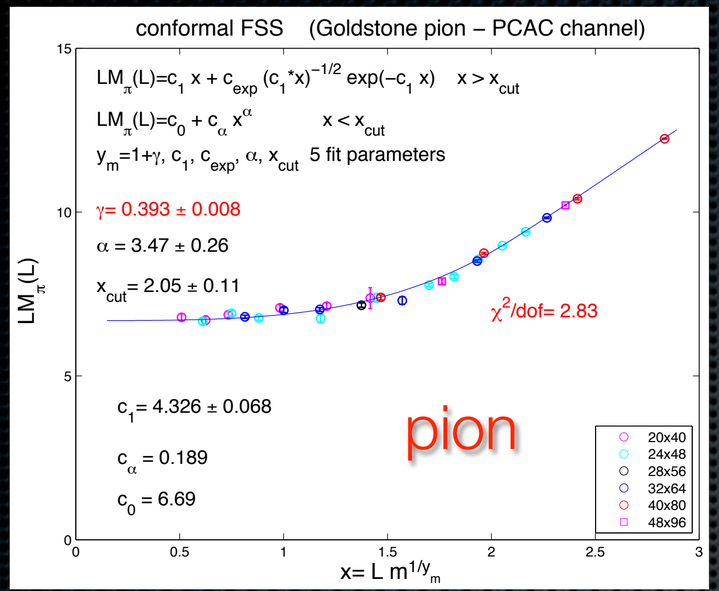
chiral condensate

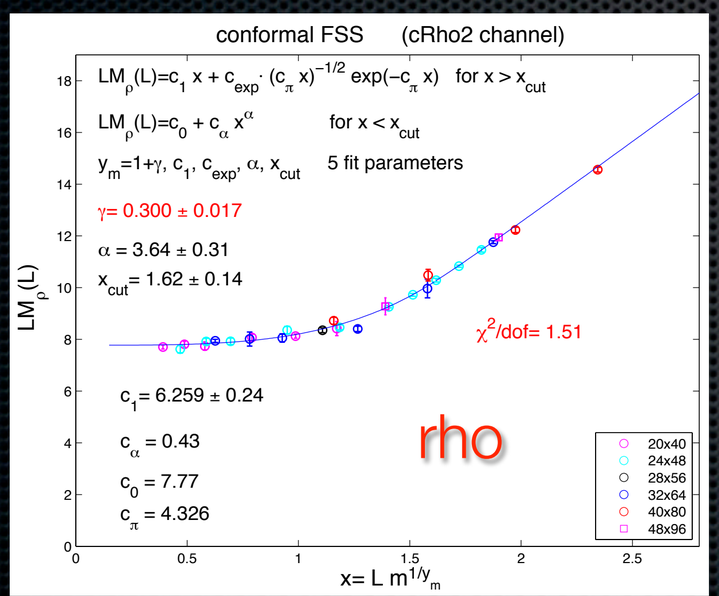


value of condensate in chiral limit O(100) smaller than signal at finite quark mass

dangerous to make this sole criterion to decide if theory conformal or not

alternative: conformal?





universal behavior: $LM_\pi(L) = f(x), \quad x = Lm^{1/y_m}$

L: lattice size, m: fermion mass

function f(x) can be different for each state

limits: $f(x) = c_1 x \quad \text{large } x \qquad \text{i.e.} \quad M_\pi = c_1 m^{1/y_m}$

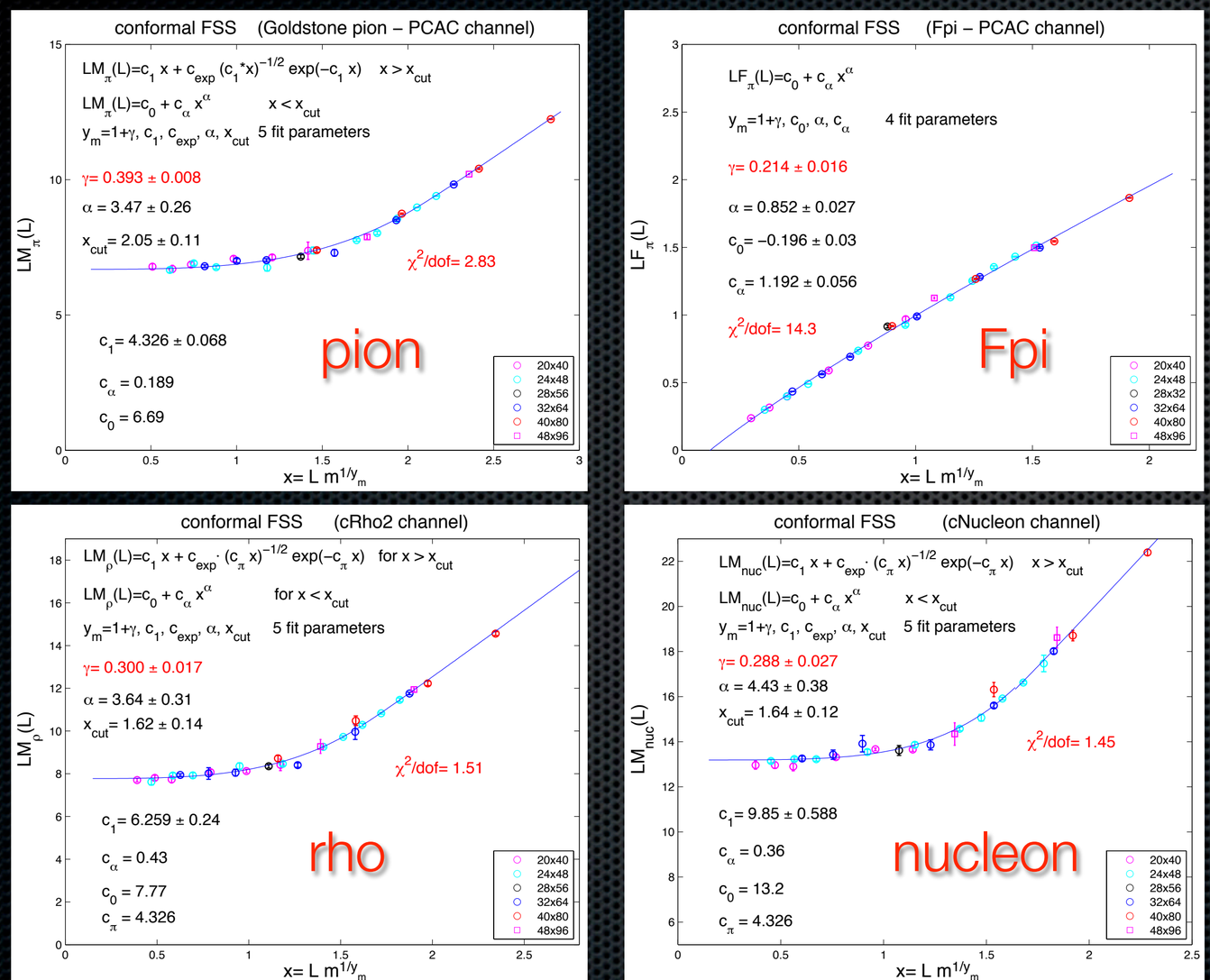
$$f(x) = c_0 \neq 0 \qquad \text{as } x \to 0$$

each fit individually reasonable

but exponent values do not agree

pion: 0.393(8) rho: 0.300(17)

alternative: conformal?



add more states: situation worse

data appears not to allow universal value of exponent

conformal description of data appears worse than chiSB form

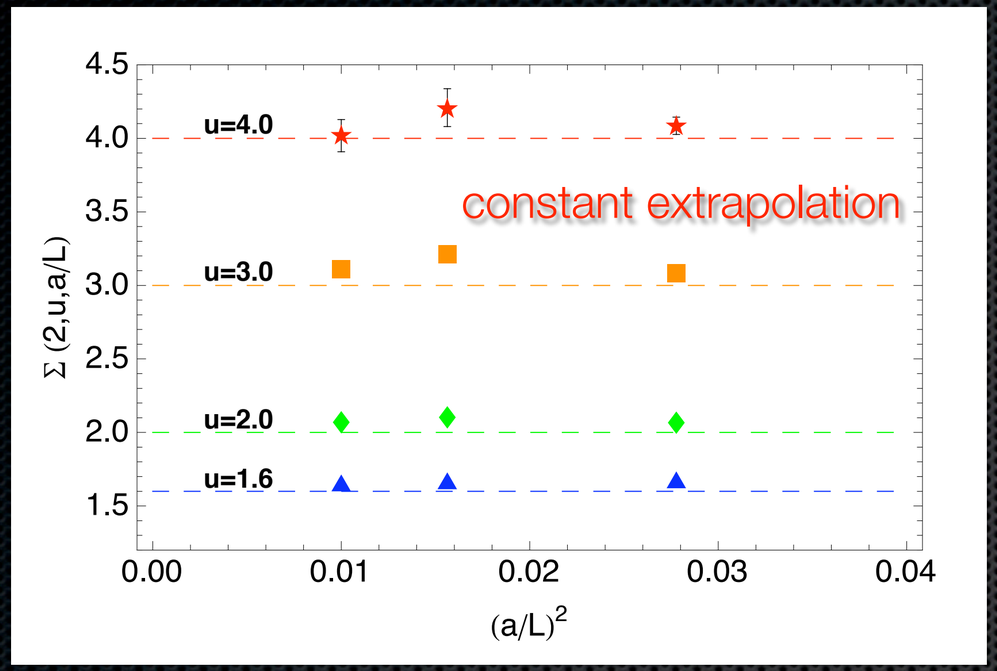
need accurate data to test this

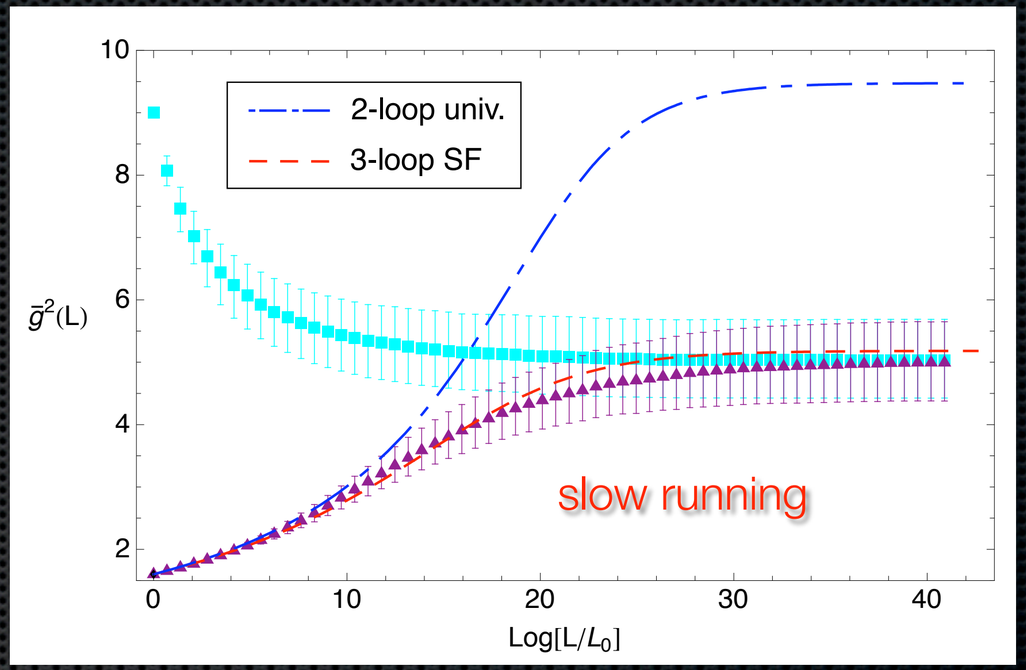
lattice activity SU(3) 12-flavor

- Fodor et al.
- Appelquist et al., Lattice Strong Dynamics
- Pallante, Lombardo, Deuzeman
- Lin et al.
- Yamawaki et al.
- Jin & Mawhinney
- Hasenfratz et al.

running coupling

Appelquist,Fleming,Neil,arXiv:0901.3766





renormalized coupling as function of lattice size L $g^2(L)$

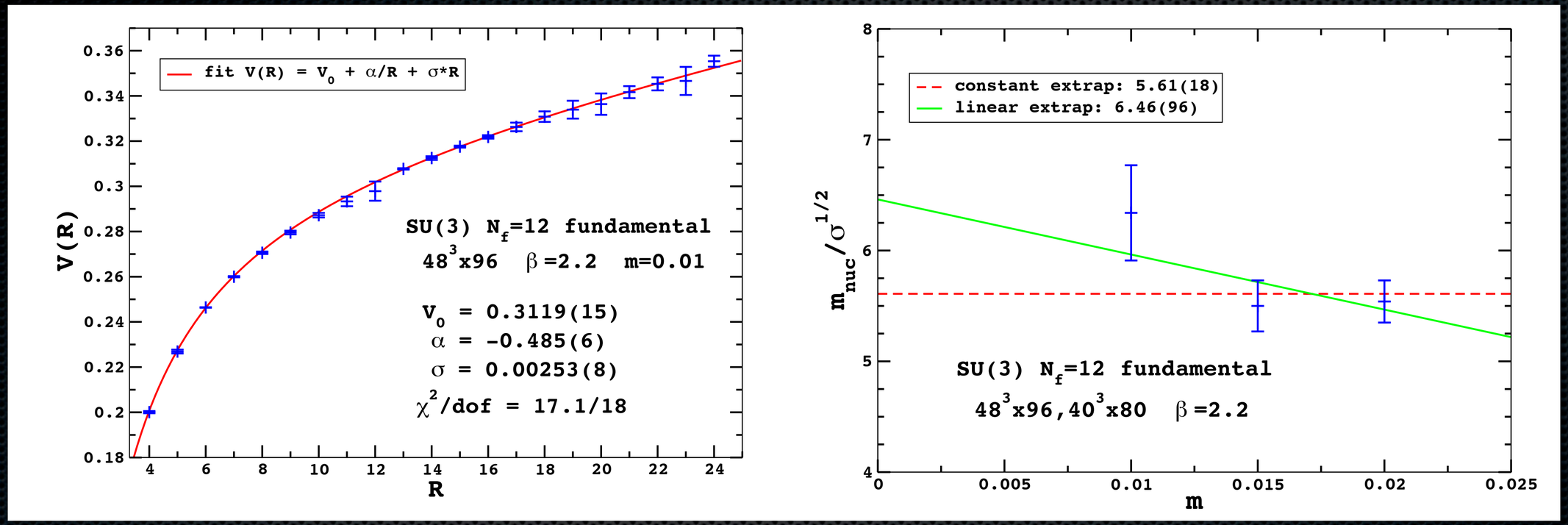
run coupling by varying lattice size e.g. L to 2L

repeat at various lattice spacings, find continuum limit $a/L \to 0$

coupling flows to IR fixed point - conformal

static quark potential

Fodor et al. arXiv:1104.3124



measure quark potential on same simulations for particle spectrum

potential has confining linear behavior at intermediate separation

$M_{\rm nucleon}/\sqrt{\sigma}$ appears non-zero in chiral limit, as does nucleon mass

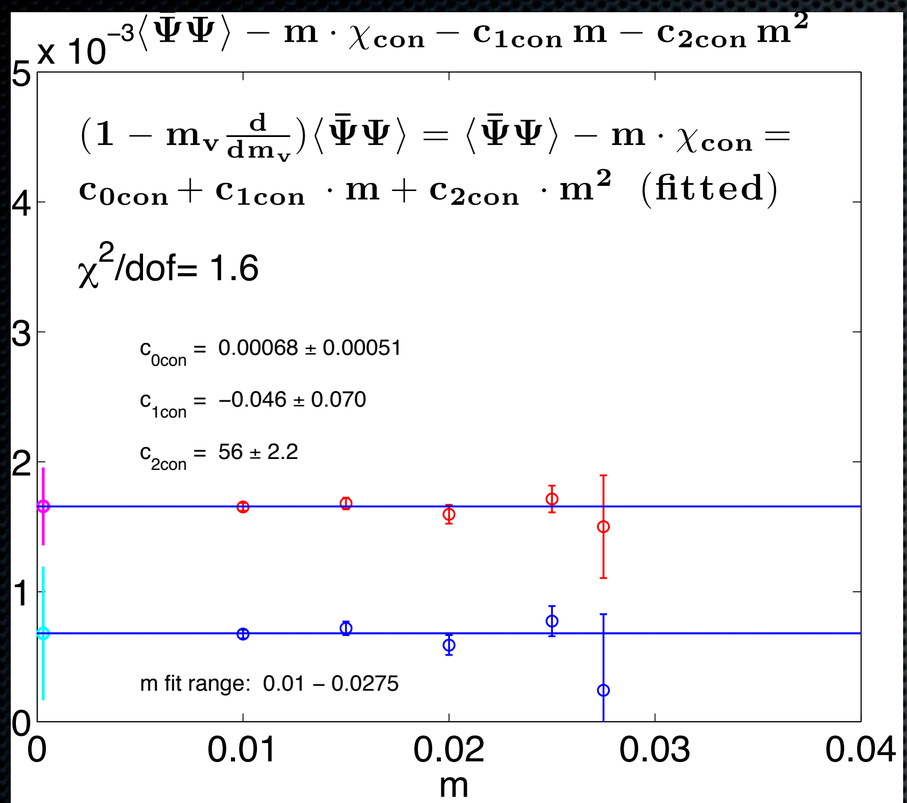
consistent with chiSB in spectrum, inconsistent with IRFP

the story so far

- lattice methods and machines can be applied to new models
- very important to have many signals,discretizations,people
- 2-flavor sextet theory looks non-conformal, but remaining issues
- 12-flavor fundamental is difficult - many puzzles
- many more studies done on fundamental rep - learning phase
- given high cost, may wish to focus resources on sextet model

extra slides

12-flavor chiral condensate

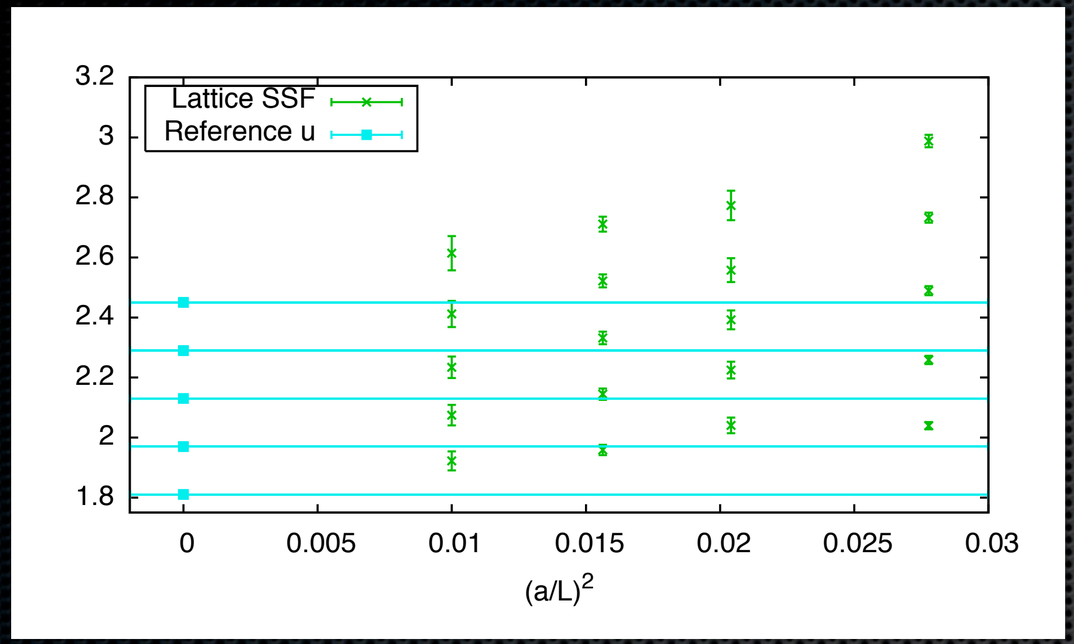


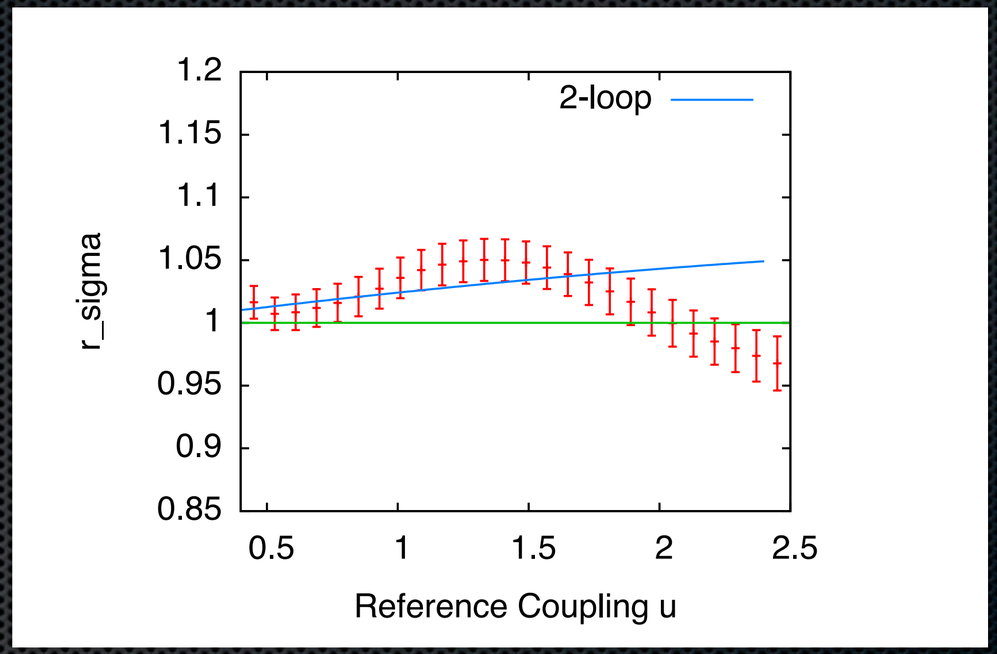
2 independent observables give consistent condensate in chiral limit

but not as clear as sextet case

running coupling

Lin et al.,arXiv:1205.6076





Polyakov loop correlator scheme $g^2(L)$

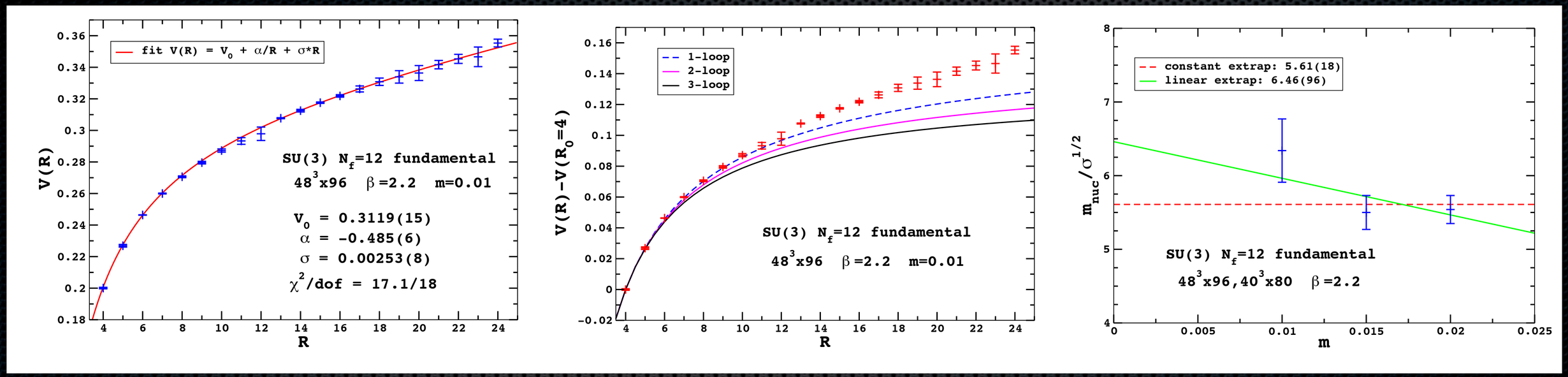
again, run coupling by varying lattice size e.g. L to 2L

lattice artifacts require continuum limit $a/L \to 0$

indication of IR fixed point, systematics issues

static quark potential

Fodor et al. arXiv:1104.3124



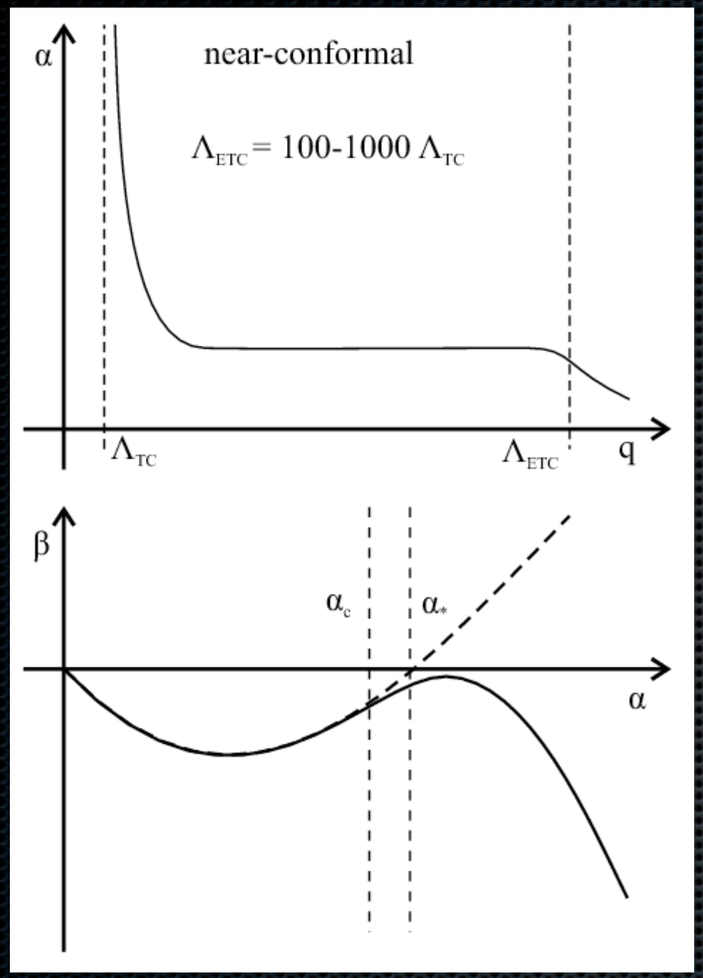
quark potential runs faster than perturbation theory

inconsistent with existence of IR fixed point

$$V(R) - V(R_0) = C_F \int_{R_0}^{R} \frac{\alpha_{qq}(R')}{R'^2} dR'$$

predict RHS with n-loop pert thy

near-conformal TC



near-zero of beta function

gauge coupling walks, not runs

separate scales - useful phenomenology