New Frontiers in Lattice Gauge Theory

Can the sextet gauge model hide the Higgs impostor ?

Lattice Higgs Collaboration (LHC)

with Zoltan Fodor, Kieran Holland, Daniel Nogradi, Chris Schroeder, Chik Him Wong

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New Frontiers in Lattice Gauge Theory
Galileo Institute, Florence, September 17, 2012

Outline

Two necessary conditions to hide the Higgs impostor
focus on SU(3) sextet fermion representation with two flavors

Dilaton as Higgs impostor? (broken scale invariance)

Chiral and conformal tests of the sextet model

Running (walking) coupling

Summary and outlook

for more details of the discussions:

arXiv:1209.0391 [pdf, other]

Can the nearly conformal sextet gauge model hide the Higgs impostor?

Zoltán Fodor, Kieran Holland, Julius Kuti, Dániel Nógrádi, Chris Schroeder, Chik Him Wong

Comments: 10 pages, 8 figures

Subjects: **High Energy Physics - Lattice (hep-lat)**; High Energy Physics - Phenomenology (hep-ph)

focus of talk

arXiv:1208.1051 [pdf, ps, other]

The Yang-Mills gradient flow in finite volume

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong

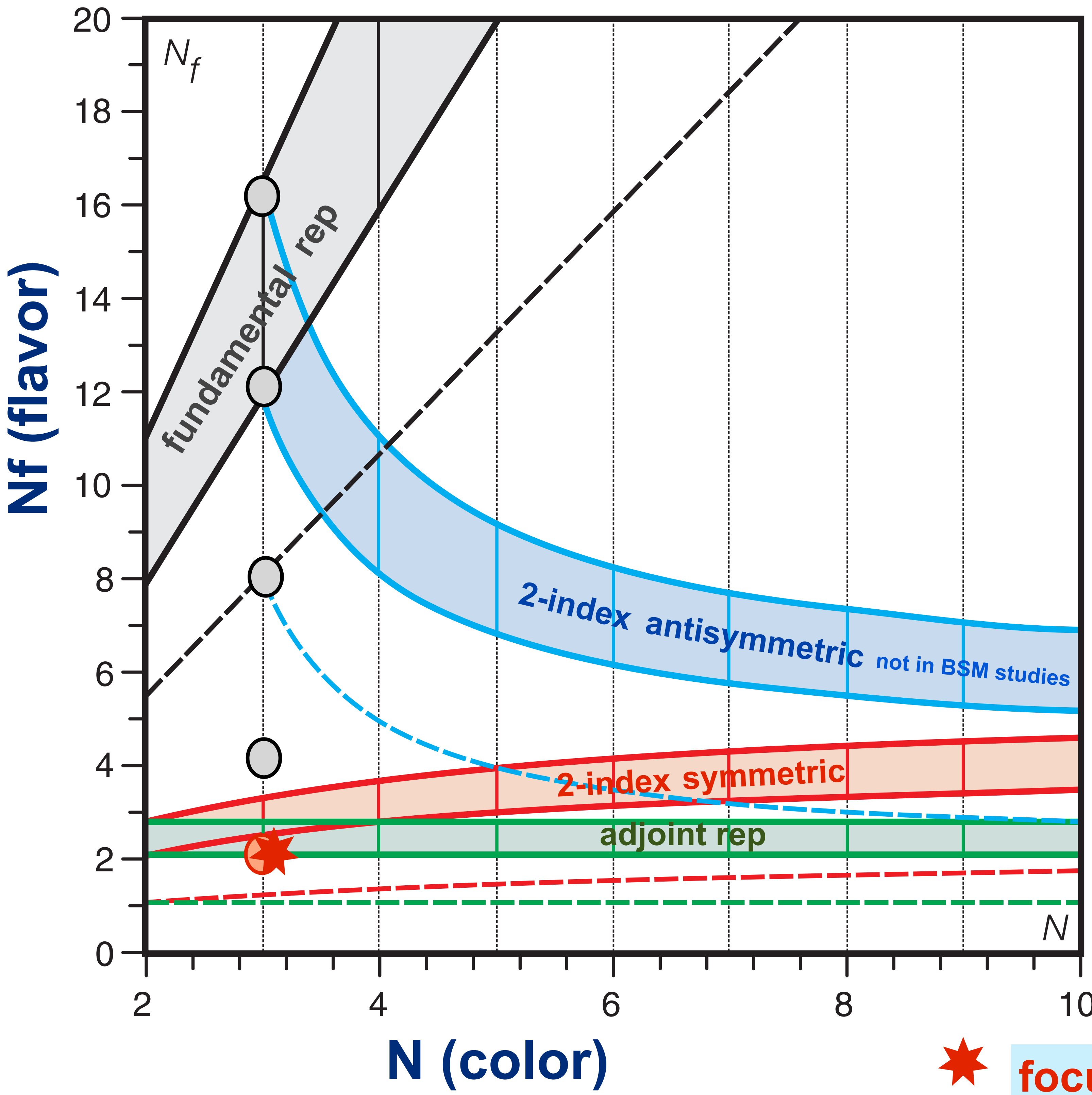
Comments: 16 pages, 8 figures, minor corrections, references added

Subjects: **High Energy Physics - Lattice (hep-lat)**

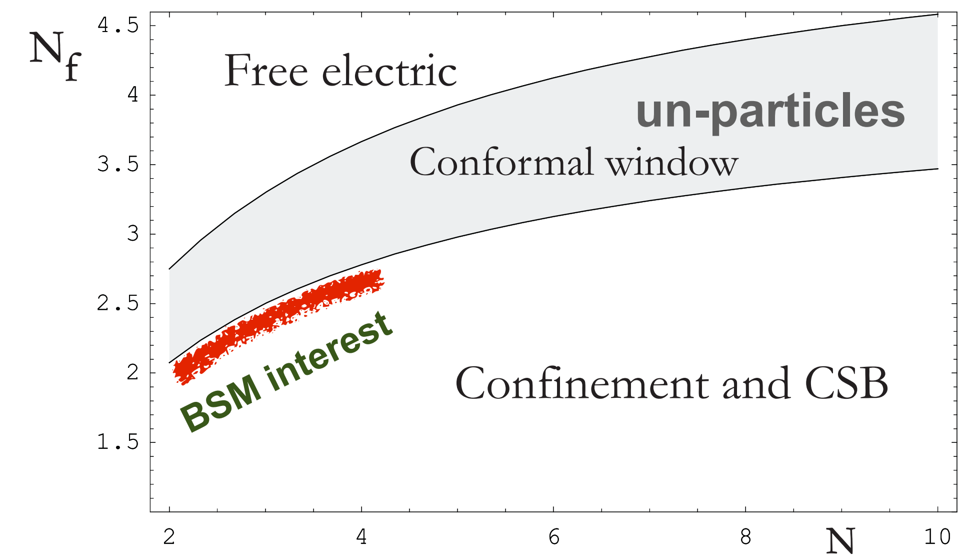
running coupling

why the sextet model?

theory space and conformal window
color, flavor, and massless fermion representation



for each rep BSM interest is below conformal window but close to it:



earlier:
arXiv:1205.1878 [hep-lat]

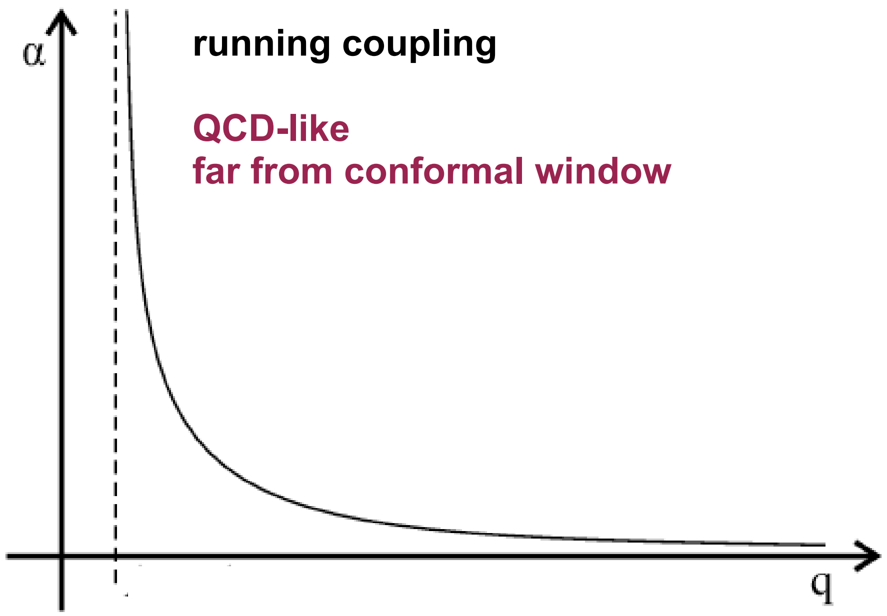
N_f=12 fundamental rep tests

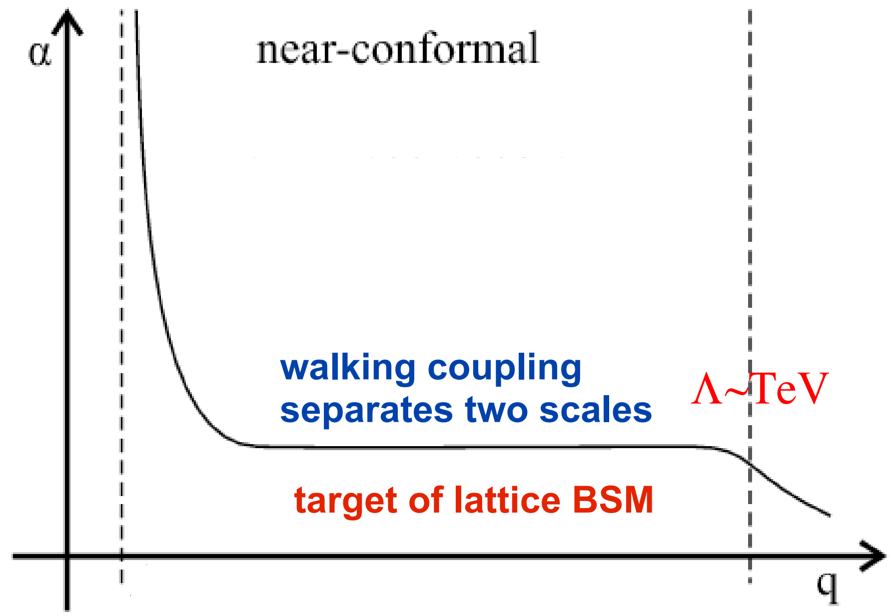
physics prospect of sextet?

★ focus of talk

New extended data set and analysis

simple realization of composite Higgs: Nf=2 SU(3) sextet representation





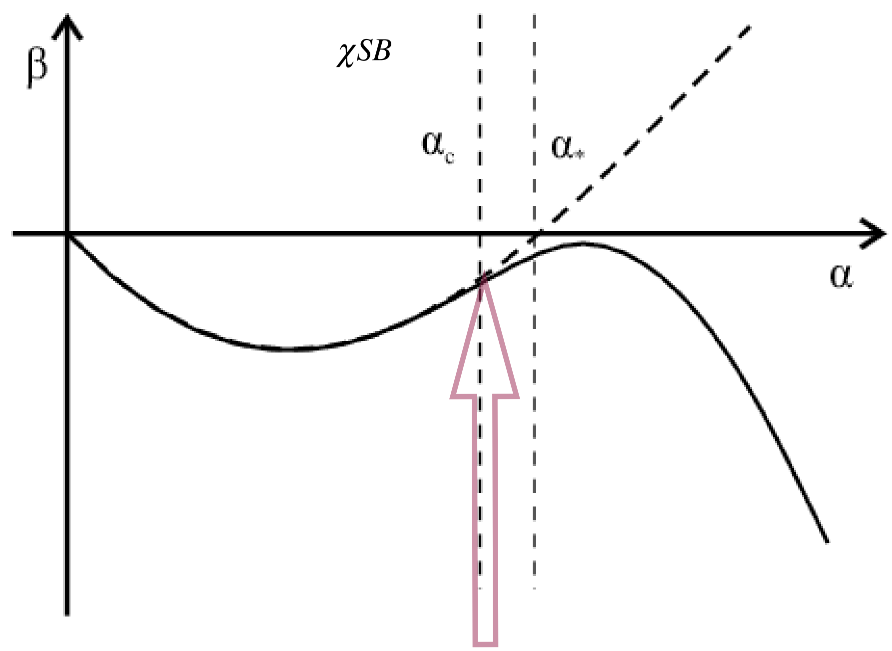
original Technicolor paradigm replaced with sextet SU(3) color rep:

one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$
χSB on Λ~TeV scale

three Goldstone pions
become longitudinal
components of weak bosons

composite Higgs mechanism
scale of Higgs condensate ~ F=250 GeV

conflicts with EW precision constraints?



when chiral symmetry breaking
turns conformal FP into walking

sextet model with two critical requirements:
(1) χSB
(2) walking gauge coupling?

χSB on Λ~TeV scale

walking gauge coupling

fermion mass generation not addressed

what composite Higgs mechanism ?

broken scale invariance (dilaton)
and/or light non-SM composite Higgs particle?

Early work using sextet rep:

Marciano (QCD paradigm, 1980)

Kogut,Shigemitsu,Sinclair
(quenched, 1984)

recent work:

DeGrand,Shamir,Svetitsky
IRFP or walking gauge coupling

Lattice Higgs Collaboration
χSB

Kogut,Sinclair
finite temperature

role of the third fermion flavor?

dilaton as Higgs impostor?

The dilaton: pseudo-Goldstone particle of broken scale invariance

RG invariant

$$\partial_\mu \mathcal{D}^\mu = \Theta^\mu_\mu = \frac{\beta(\alpha)}{4\alpha} G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{D}^\mu = \Theta^{\mu\nu} x_\nu$$

Dilatation current
symmetric energy-momentum tensor

$$\langle 0|\Theta^{\mu\nu}(x)|\sigma(p)\rangle = \frac{f_\sigma}{3}(p^\mu p^\nu - g^{\mu\nu} p^2) e^{-ipx}$$

Looking for PCDC relation among three unknowns:

1. dilaton mass m_σ
2. dilaton decay constant f_σ
3. non-perturbative gluon condensate

$$\langle 0|\partial_\mu \mathcal{D}^\mu(x)|\sigma(p)\rangle = f_\sigma m_\sigma^2 e^{-ipx}$$

$$\left[\Theta^\mu_\mu\right]_{NP} = \frac{\beta(\alpha)}{4\alpha}\left[G^a_{\mu\nu} G^{a\mu\nu}\right]_{NP}$$

long history of PCDC relation
only non-perturbative part kept in derivation

recently:
Bai and Appelquist Phys.Rev. D82 (2010) 071701
Matsuzaki and Yamawaki arXiv:1206.6703[hep-ph]

$$\left[\Theta^\mu_\mu\right]_{NP} = \frac{\beta(\alpha)}{4\alpha} G^a_{\mu\nu} G^{a\mu\nu} - \langle 0|\frac{\beta(\alpha)}{4\alpha} G^a_{\mu\nu} G^{a\mu\nu}|0\rangle_{PT}$$

$$m_\sigma^2 \simeq -\frac{4}{f_\sigma^2}\langle 0|\left[\Theta_\mu^\mu(0)\right]_{NP}|0\rangle$$

Partially Conserved Dilatation Current (PCDC)

there are two different expectations on limit of right-hand side ratio when conformal window is approached:

1. dilaton mass parametrically vanishes when CW approached $m_\sigma^2 \simeq (N_f^c - N_f)\cdot\Lambda^2$ **Bai and Appelquist**

$g(\mu=\Lambda)=g_c$ **where ChiSB is triggered** $\frac{m_\sigma}{f_\sigma}\to 0$

2. dilaton mass remains finite in the limit as measured in $f_\sigma \simeq \Lambda$ **units** **Yamawaki et al.** $\frac{m_\sigma}{f_\sigma}\to const$

Realistic BSM models have not been built with parametric tuning close to the conformal window. For example, the sextet model is at some intrinsically determined position near the conformal window and only non-perturbative lattice calculations can explore the physical properties of the scalar particle.

important role of $\frac{f_\pi}{f_\sigma}$ in electroweak phenomenology

both scenarios expect light Higgs-like dilaton

$$\lim_{a\to 0}\left(\frac{1}{a^4}\langle 1-\frac{1}{3}\,\mathrm{tr}\,U_P\rangle\right)=\frac{\pi^2}{36}\langle\frac{\alpha}{\pi}GG\rangle_{\mathrm{lattice}}$$

non-perturbative lattice gluon condensate?

from current correlators?

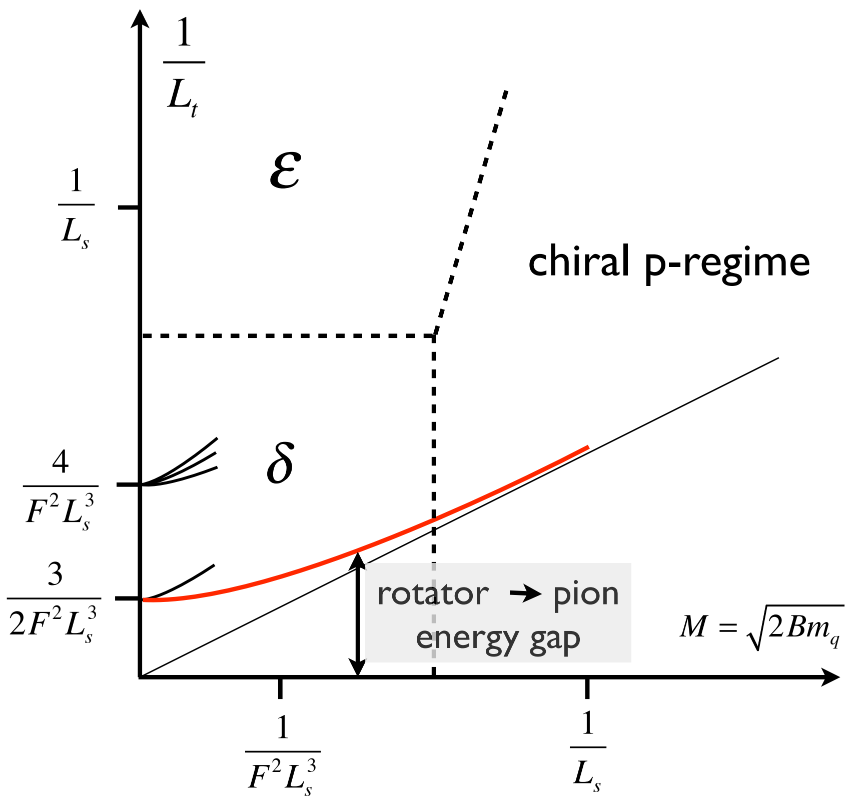
$$\left\langle 1-\frac{1}{3}\,\mathrm{tr}\,U_P\right\rangle=\sum_n c_n\cdot g_0^{2n}+a^4\,\frac{\pi^2}{36}\left(\frac{b_0}{\beta(g_0)}\right)\left\langle\frac{\alpha}{\pi}GG\right\rangle_{\mathrm{lattice}}+O(a^6)$$

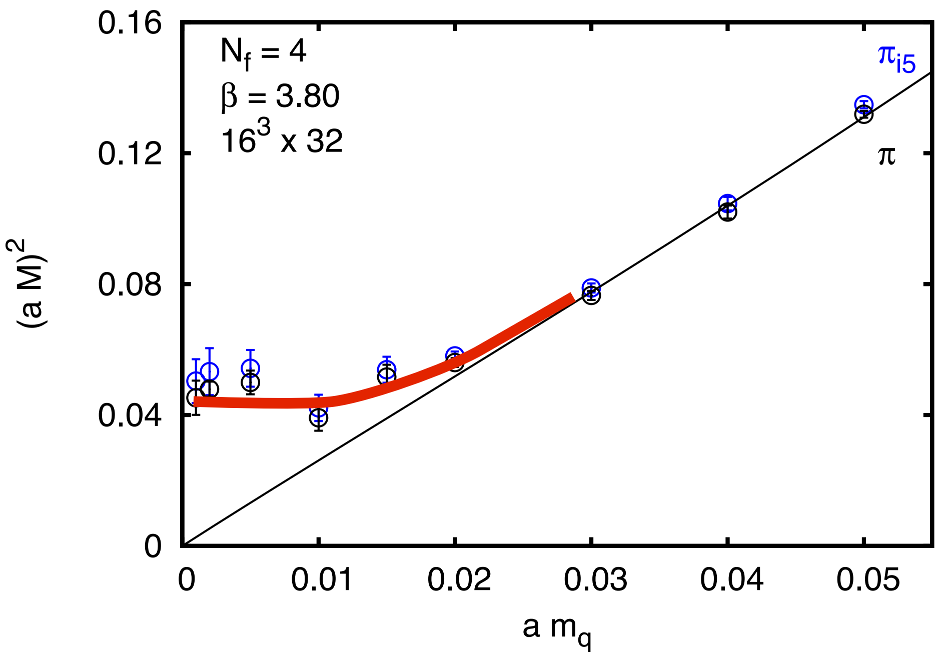
from gradient flow of GG composite operator?

is this separation meaningful?

chiral symmetry breaking in the sextet model

mass deformed chiral SB in finite volume below conformal window:





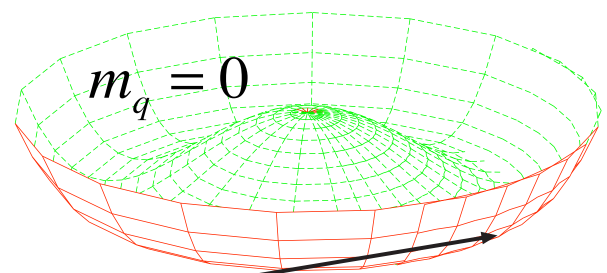
Goldstone dynamics is different in each regime

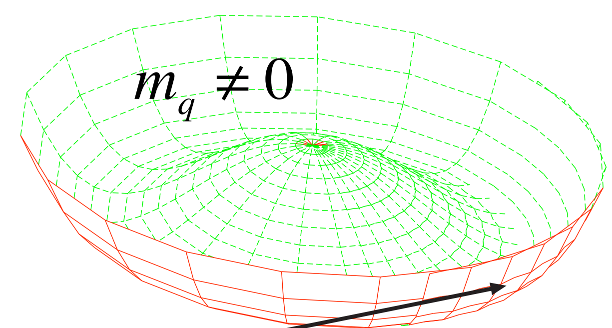
We study δ and ε-regimes (RMT)

and p-regime (probing chiral loops)

complement each other

interpretation of rotator levels in $m_q \to 0$ limit:

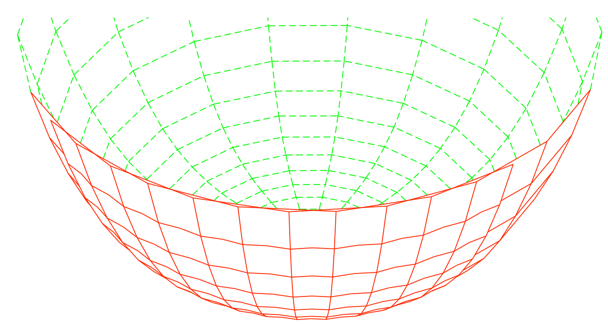




Veff: chiral condensate in flavor space

arbitrary orientation of condensate

tilted condensate



Not to misidentify rotator gaps as evidence of chirally symmetric phase !

Our sextet simulations are in the p-regime β=3.2 and β=3.25

simulation details:

tree level improved Symanzik gauge action; $\beta=6/g^2$ normalization

smearing in staggered fermions: 2 stout steps

rooting with two flavors (follow-up work without rooting if model will pass first tests)

RHMC

multiple time scales and Omelyan integrator

$\beta=3.20$ m=0.003-0.010 mass range 24^3x48, 28^3x56, 32^3x64, 48^3x96 lattices

$\beta=3.25$ m=0.004-0.008 mass range 24^3x48, 28^3x56, 32^3x64 lattices

error analysis: mass fits with double Jackknife procedure on covariance matrices

Nf=2 sextet bulk phase structure ?

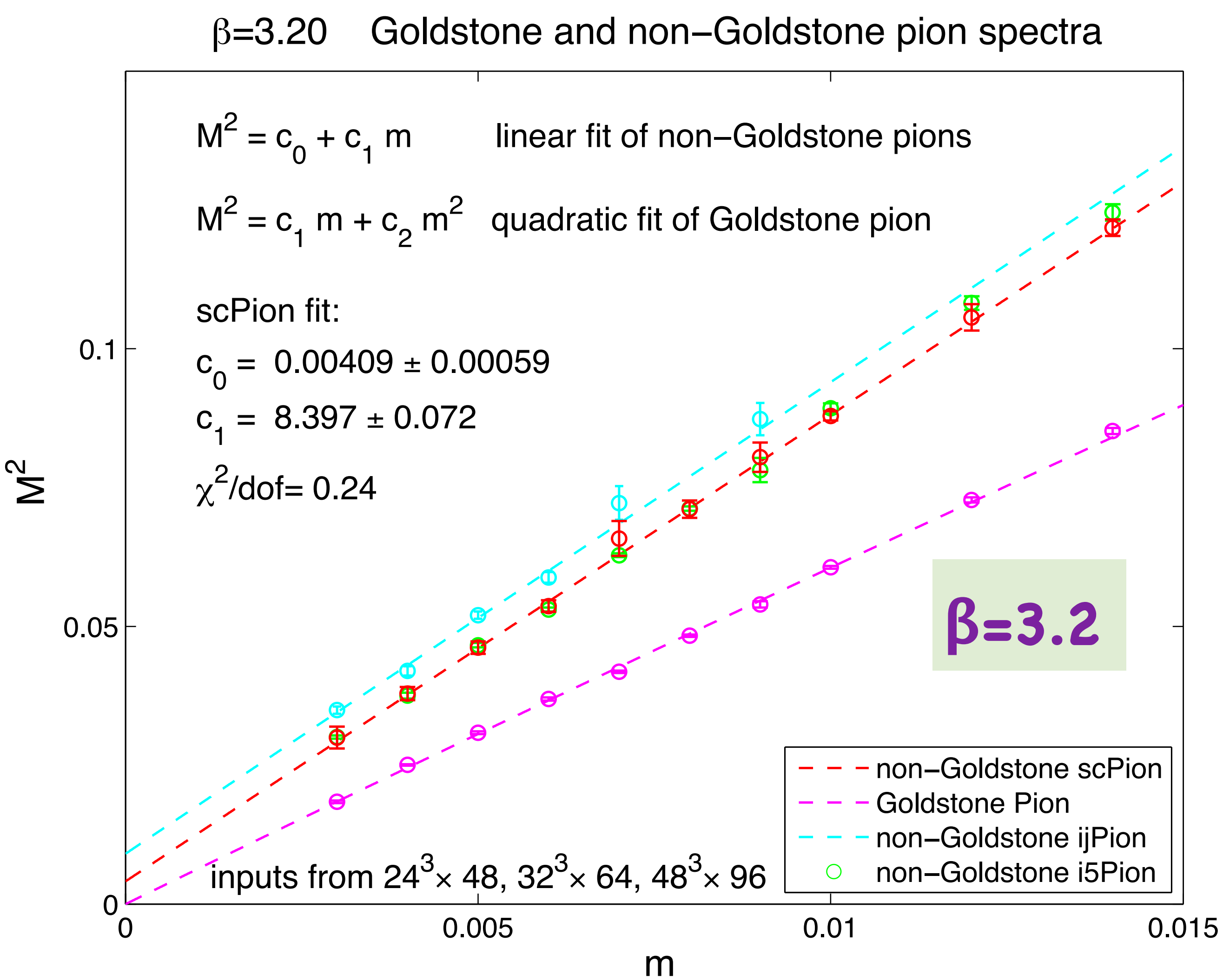
are we sitting in the weak coupling phase at β=3.2 ?

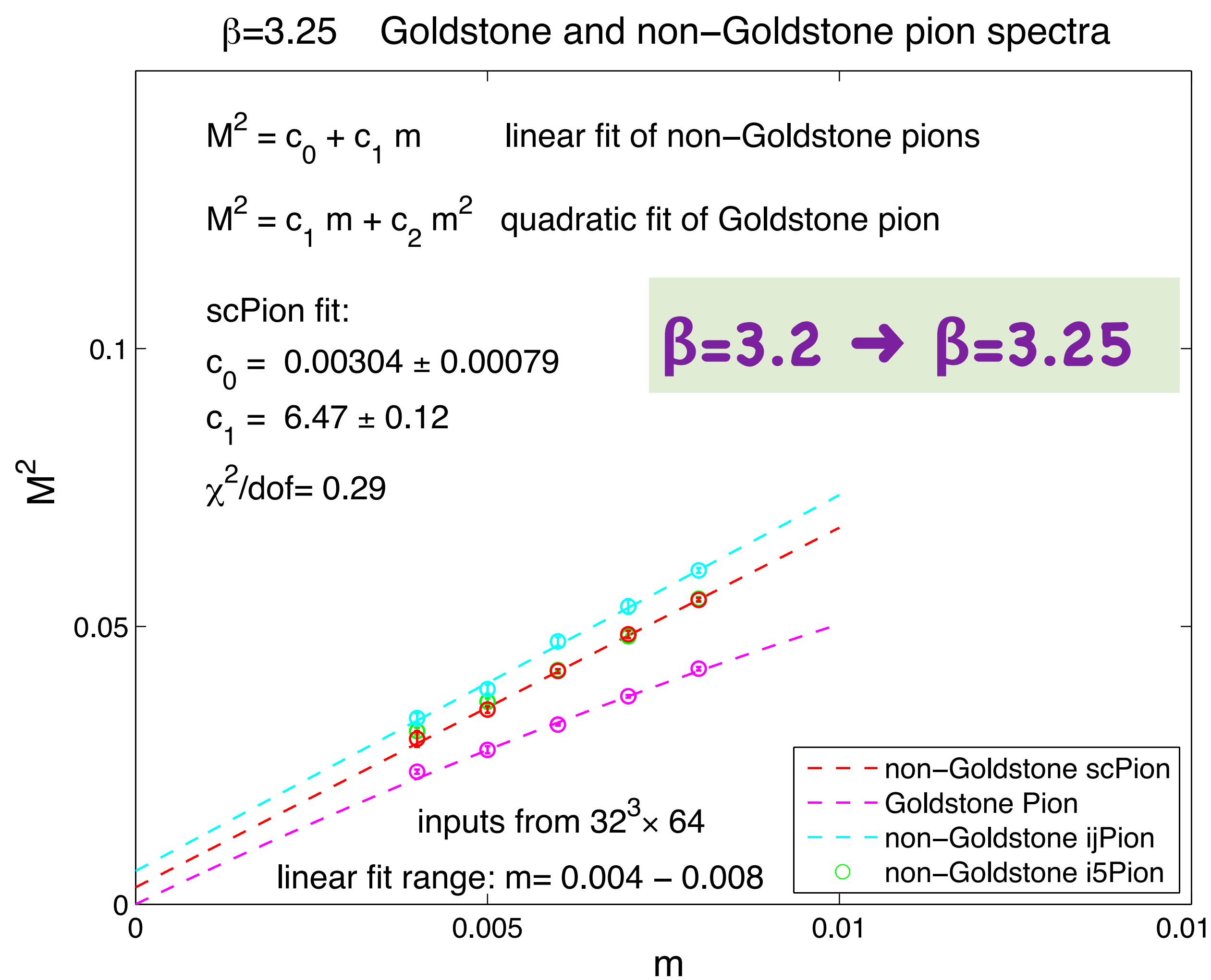
(most of the results)

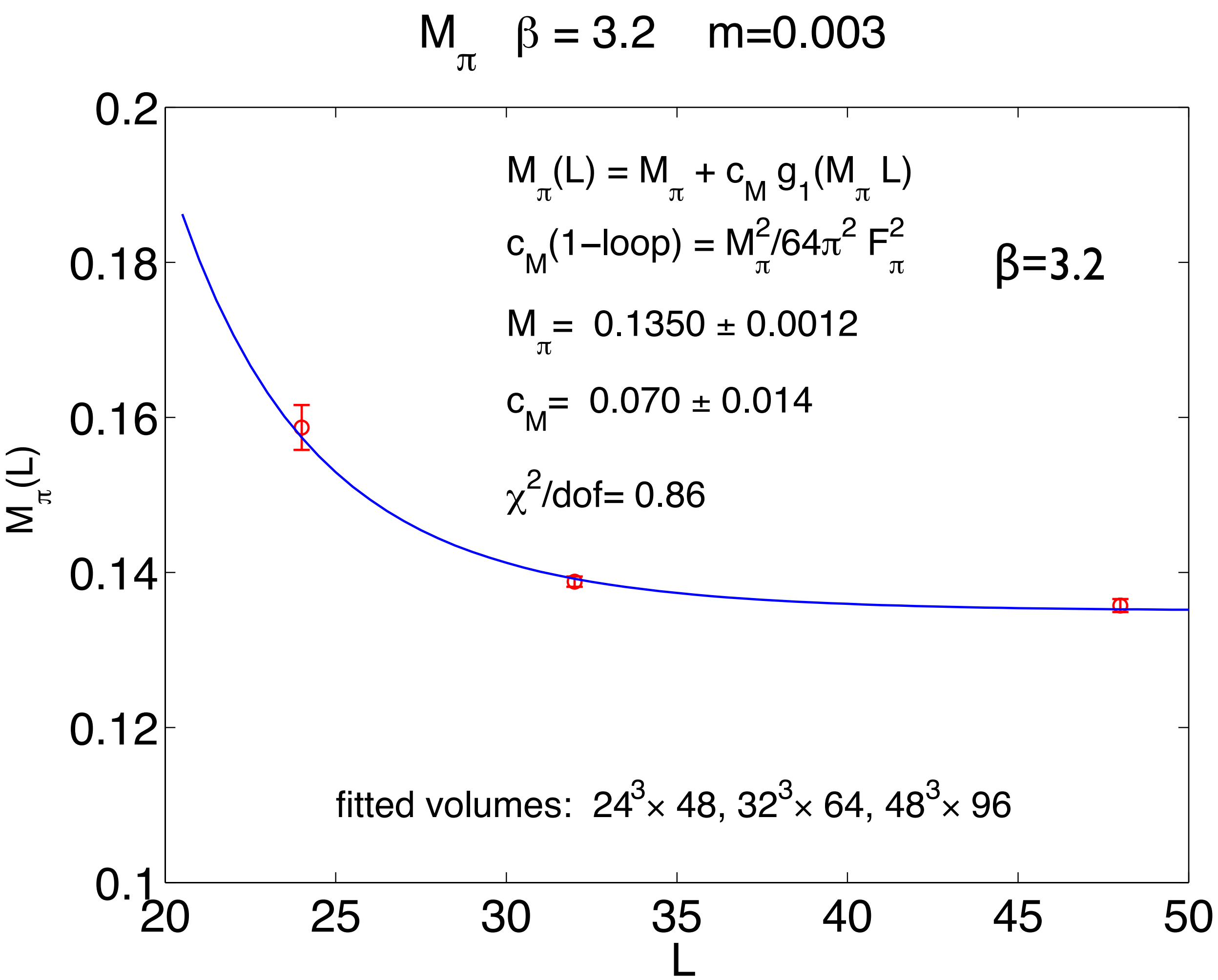
new data: β=3.2 ➜ β=3.25

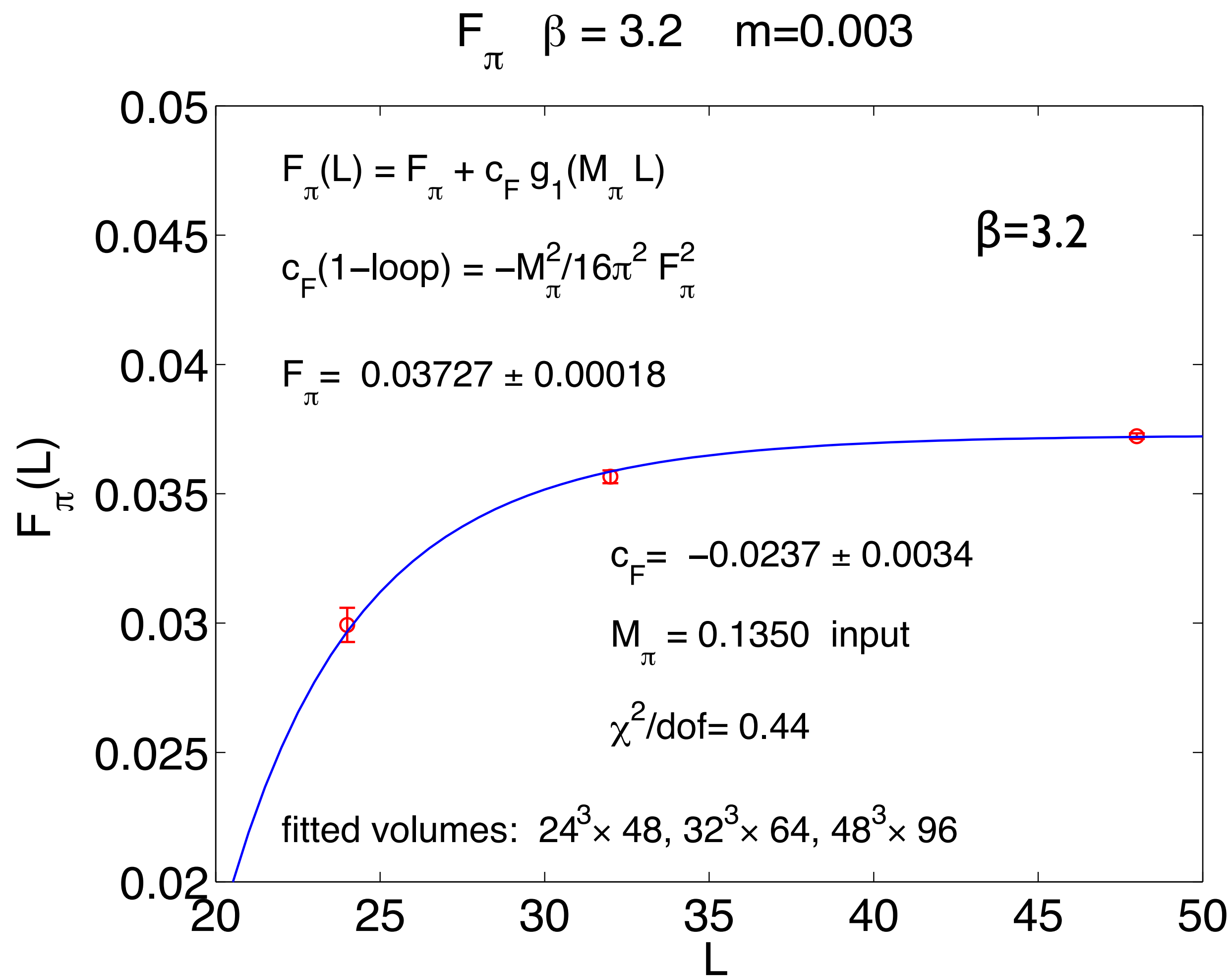
(non)Goldstone splittings and spectroscopy respond like in weak coupling QCD

full scan of bulk phase to reconfirm chiSB phase









strategy: $L \to \infty$ extrapolation first

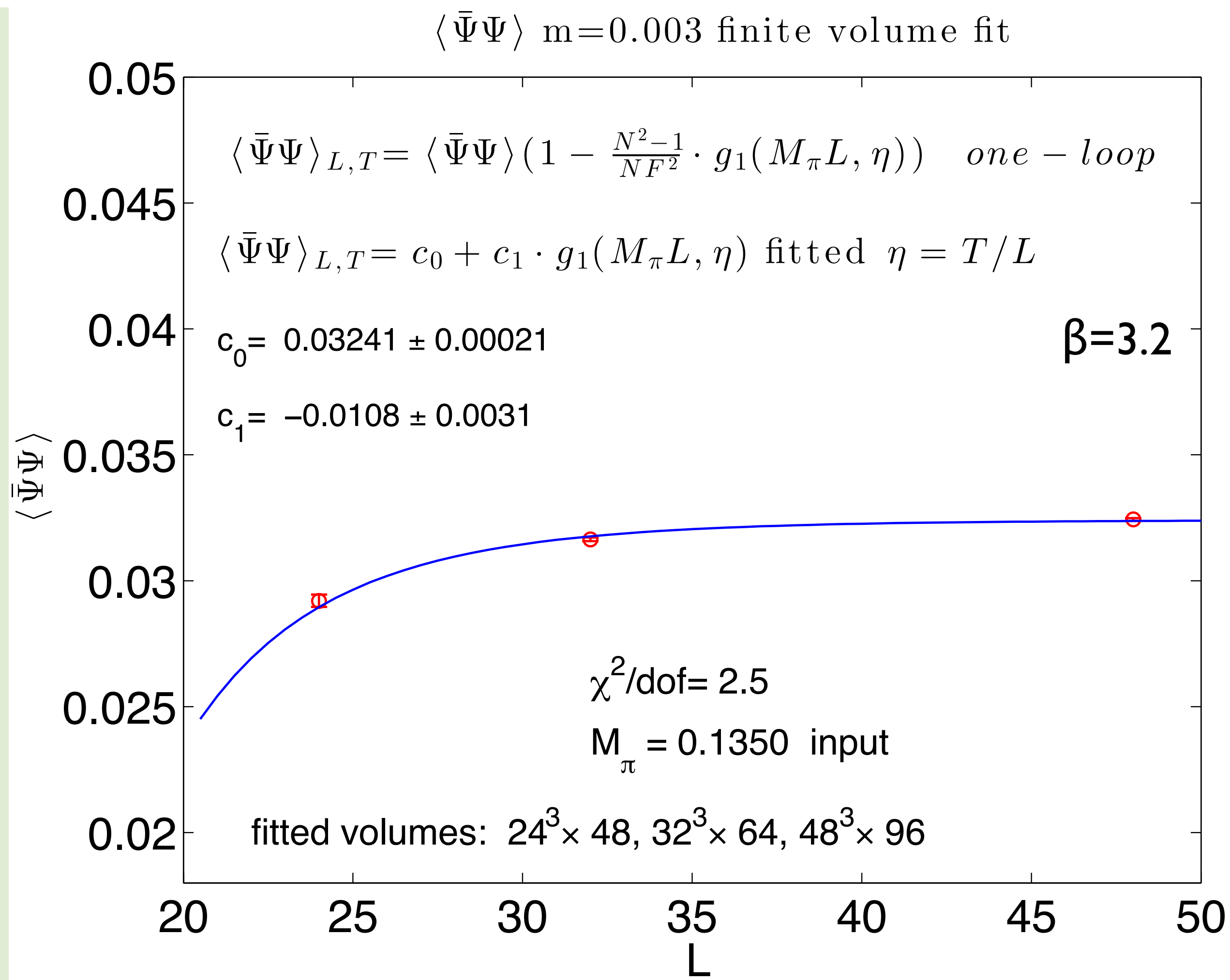
mass-deformed theory

close to m=0 critical surface

$L \to \infty$ extrapolated chiral and conformal scaling tests in sextet model

for $L \cdot M_\pi > 5$ less than one percent L correction left

C_M and C_F signs correct, numerically off



Strategy I: L=∞ extrapolation first and then scaling tests in m

Chiral hypothesis (in)complete analysis on both sides **Conformal hypothesis**

chiral logs not resolved yet for N_f=8, or N_f=12 !
N_f=2 sextet easier to reach chiral log regime

$$(M_\pi^2)_{NLO} = (M_\pi^2)_{LO} + (\delta M_\pi^2)_{1-loop} + (\delta M_\pi^2)_{m^2} + (\delta M_\pi^2)_{a^2 m} + (\delta M_\pi^2)_{a^4}$$

$\sim m^2$ kept; $\sim a^2 m$ cutoff term in B; $\sim a^4$ see LO a^2 term

$$(M_\pi^2)_{LO} = 2B \cdot m + a^2 \Delta_B$$

would require more data

$$(\delta M_\pi^2)_{1-loop} = [(M_\pi^2)_{LO} + a^2]^2 \ln(M_\pi^2)_{LO}$$

$$\boxed{M_\pi^2 = c_1 m + c_2 m^2 \ + \text{logs}}$$

fitted function for all Goldstones

$$\boxed{M_{nuc} = c_0 + c_1 m \ + \ \text{logs}}$$

nucleon states, rho, a1, higgs, ...

$$(F_\pi)_{LO} = F, \quad (\delta F_\pi)_{1-loop} = [(M_\pi^2)_{LO} + a^2]\ln(M_\pi^2)_{LO}$$

chiral log regime was not reached in fermion mass range

$$(\delta F_\pi)_{m^2} \sim m, \quad (\delta F_\pi)_{a^2 m} = a^2$$

kept cutoff term in F

$$\boxed{F_\pi = F + c_1 m + \text{logs}}$$

fitted function

$$\boxed{\langle \bar\psi\psi \rangle = \langle \bar\psi\psi \rangle_0 + c_1 m + c_2 m^2 + \text{logs}}$$

chiral condensate

$$\boxed{M_\pi = c_\pi \cdot m^{1/y_m}, \qquad y_m = 1 + \gamma}$$

leading conformal scaling
functional form for all hadron masses

$$\boxed{F_\pi = c_F \cdot m^{1/y_m}, \qquad y_m = 1 + \gamma}$$

same critical exponent

$$\boxed{\langle \bar\psi\psi \rangle = c_\gamma \cdot m^{(3-\gamma)/y_m} + c_1 m}$$

Del Debbio and Zwicky

recent improvements (Patella) from Dirac spectrum

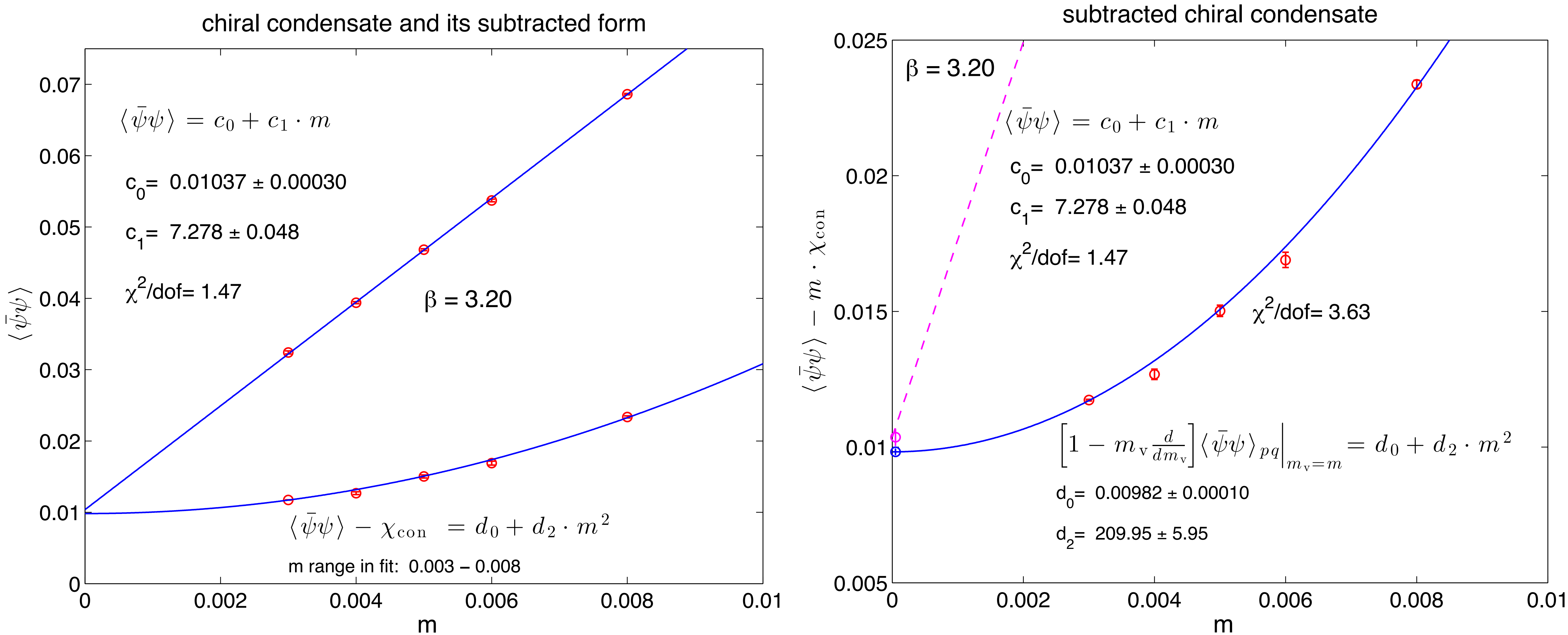
Asymptotic infinite volume limit has not been reached yet in important candidate models for conformal window

infinite volume conformal scaling violation analysis ?

conformal finite size scaling analysis and its scaling violations ?

related criticisms did not change our conclusions

Nf=2 SU(3) sextet chiral condensate



two independent determinations of the chiral condensate

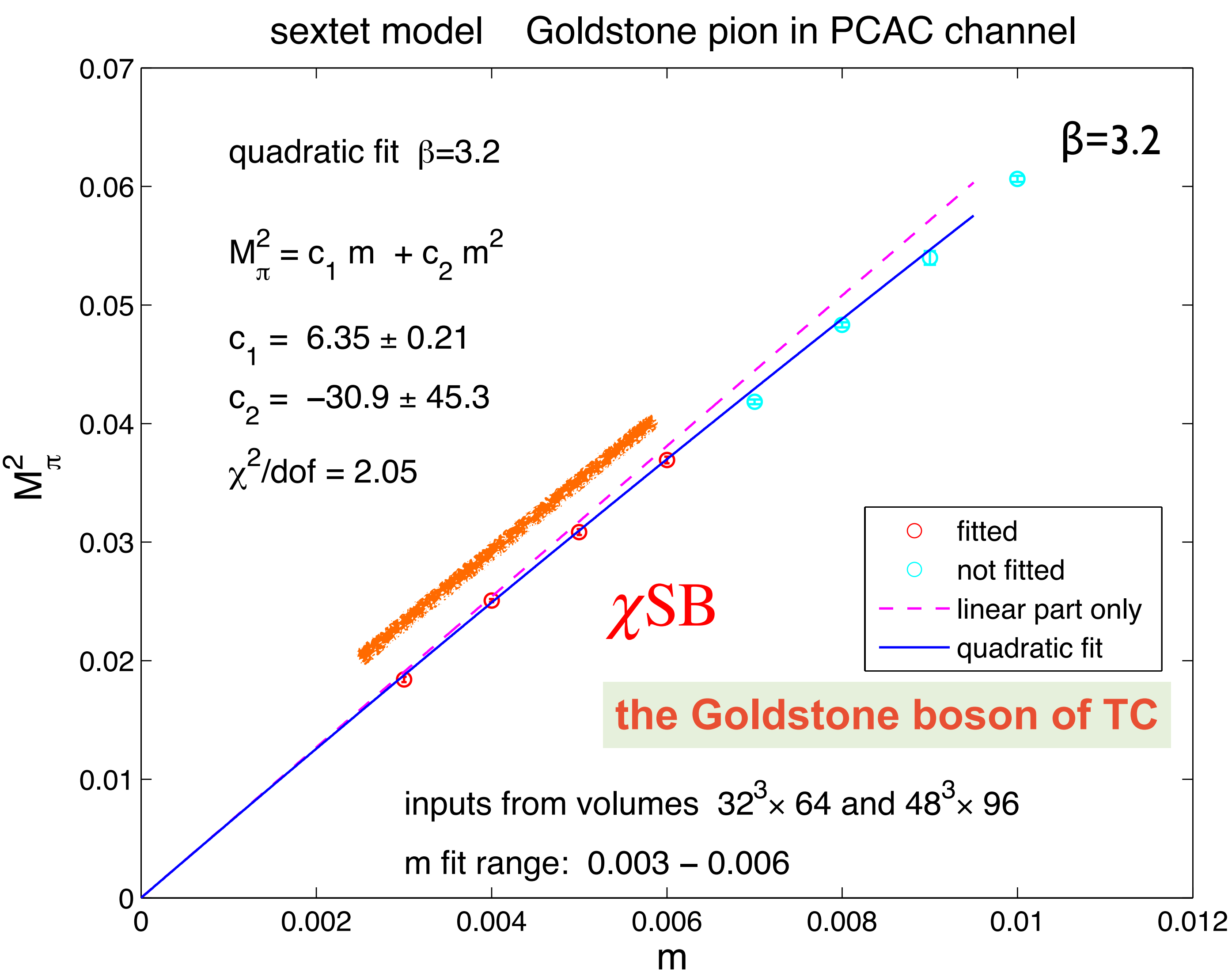
consistently non-vanishing in chiral limit

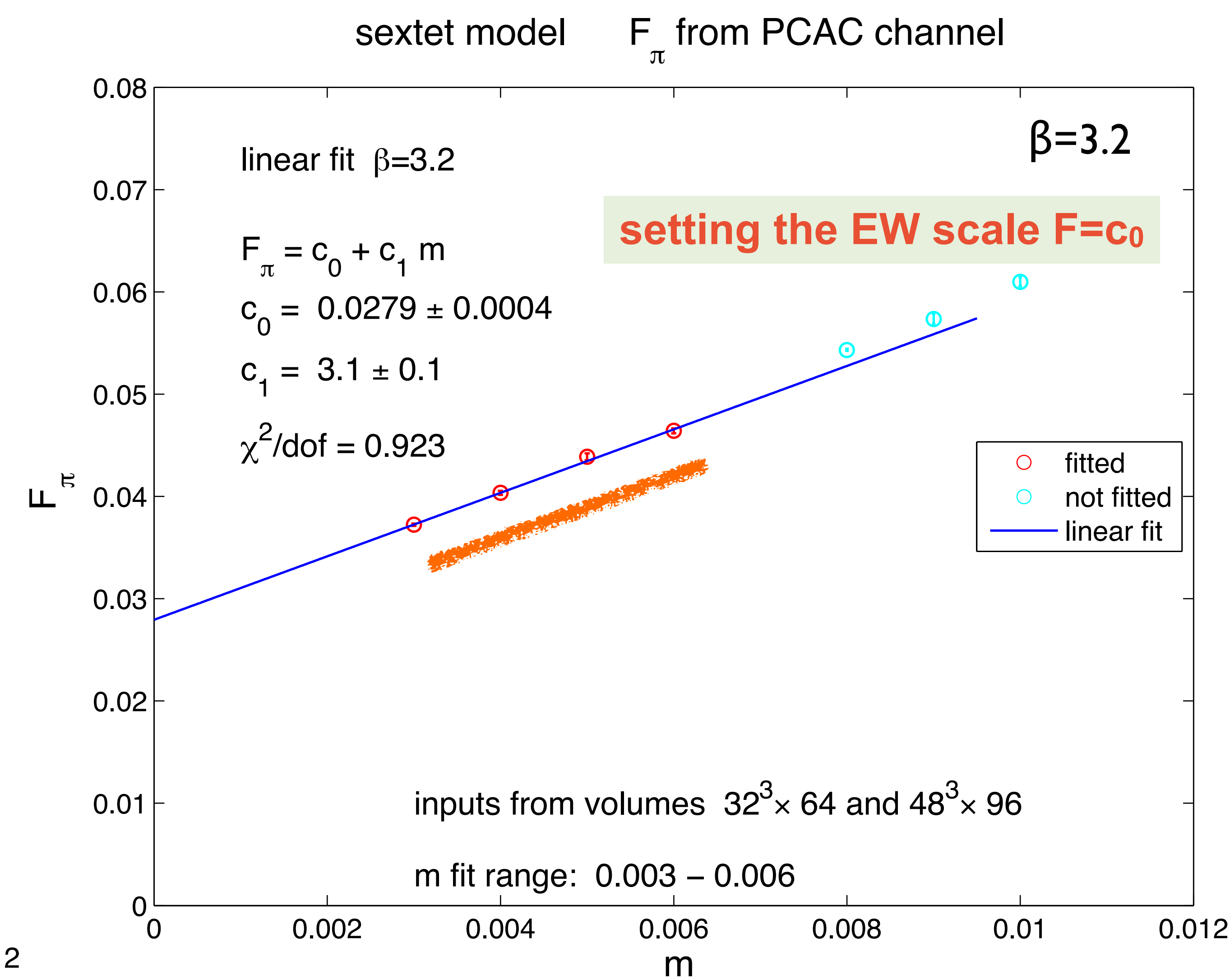
all sextet results are treated as inf volume (only m=0.003 is truly extrapolated)

new run set will have full finite volume analysis without relying on L·Mπ > 5 less than one percent L correction

spectral density analysis in the works (Giusti and Luscher)

Nf=2 SU(3) sextet chiral fits of M_π and F_π



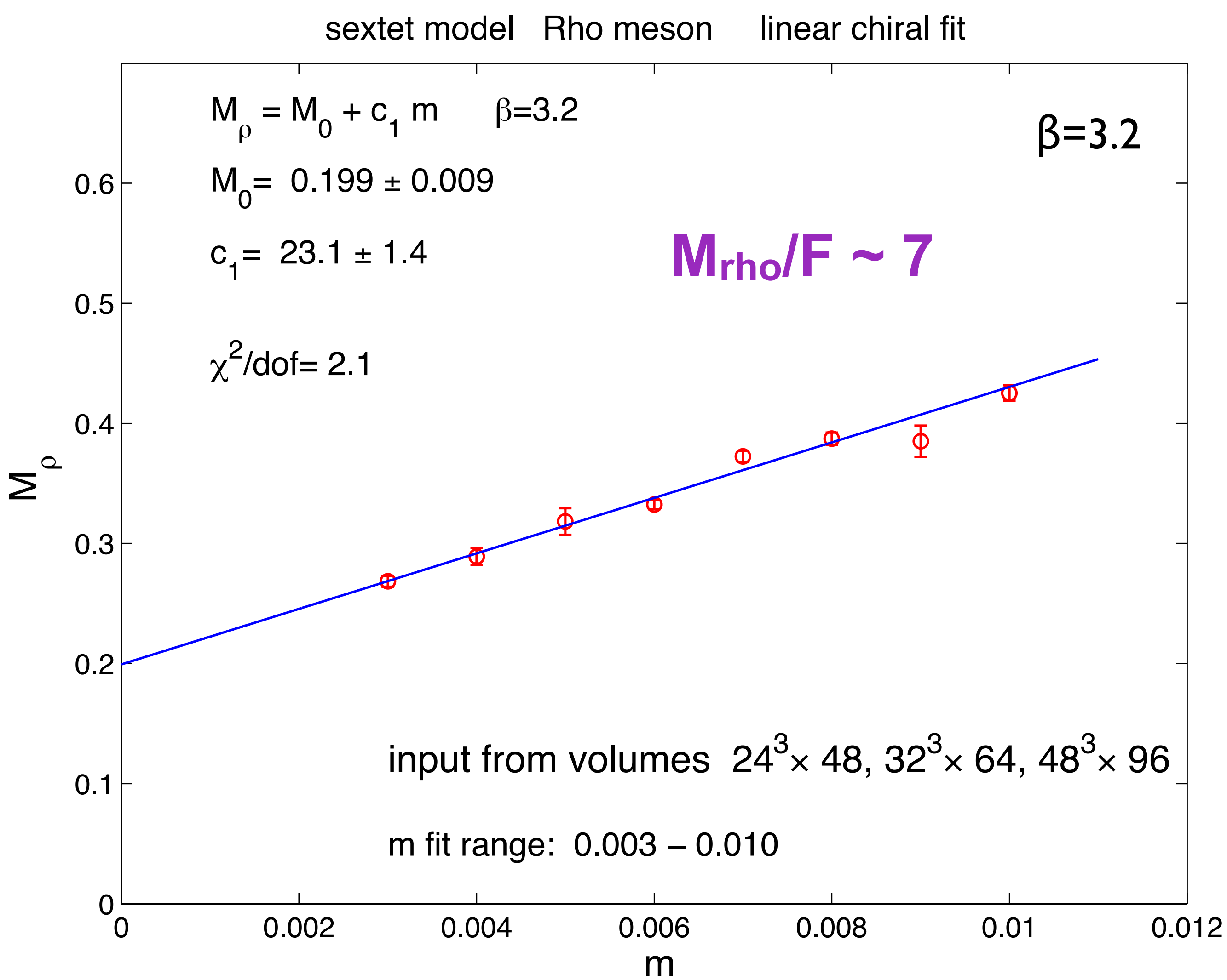


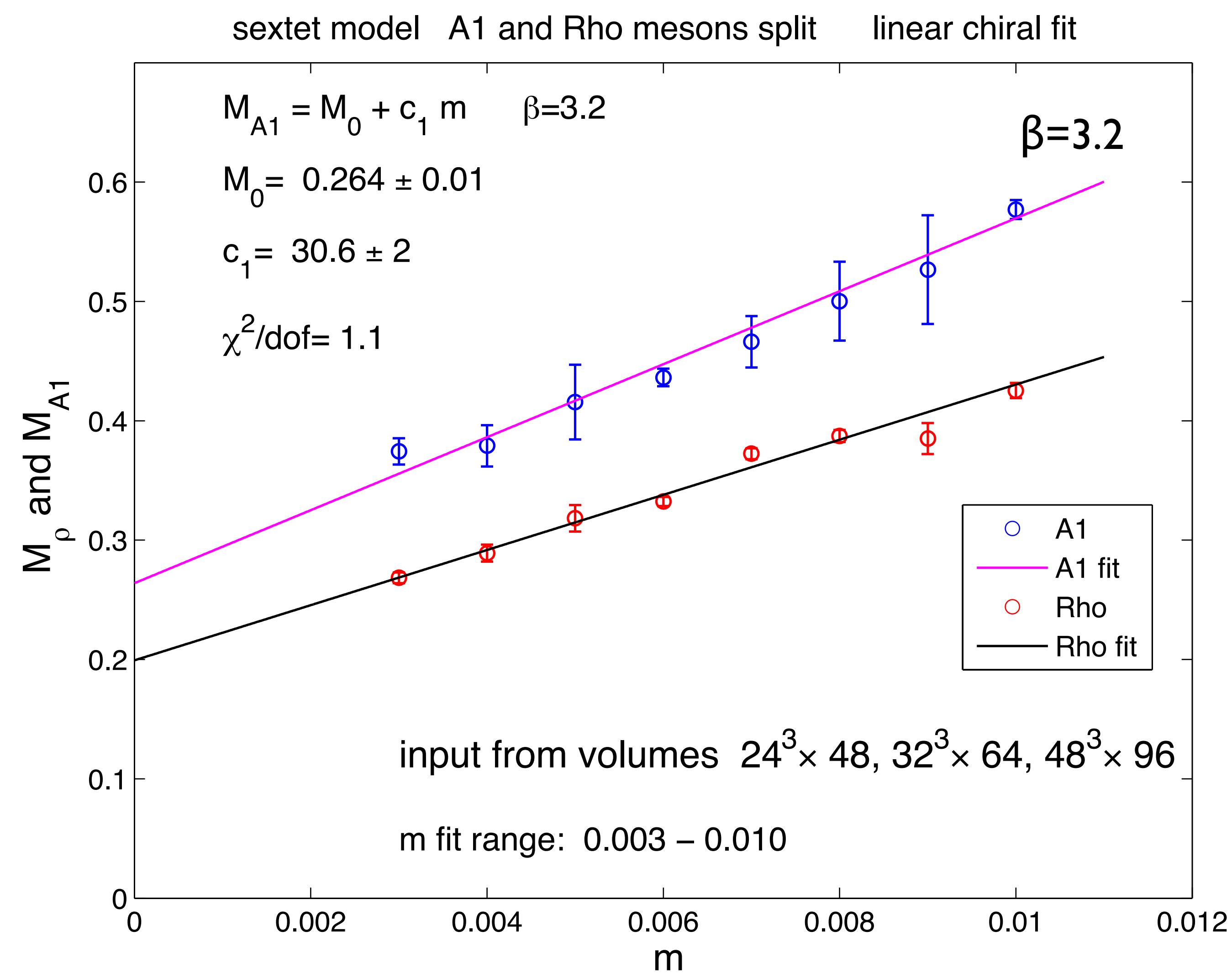
m=0.003-0.006 range close to chiral log regime? Nf=2 helps, more QCD-like

log detection will require even more precise data

consistency with partially quenched staggered chiral perturbation theory?

Nf=2 SU(3) sextet chiral fits M_ρ and $M(A_1)$

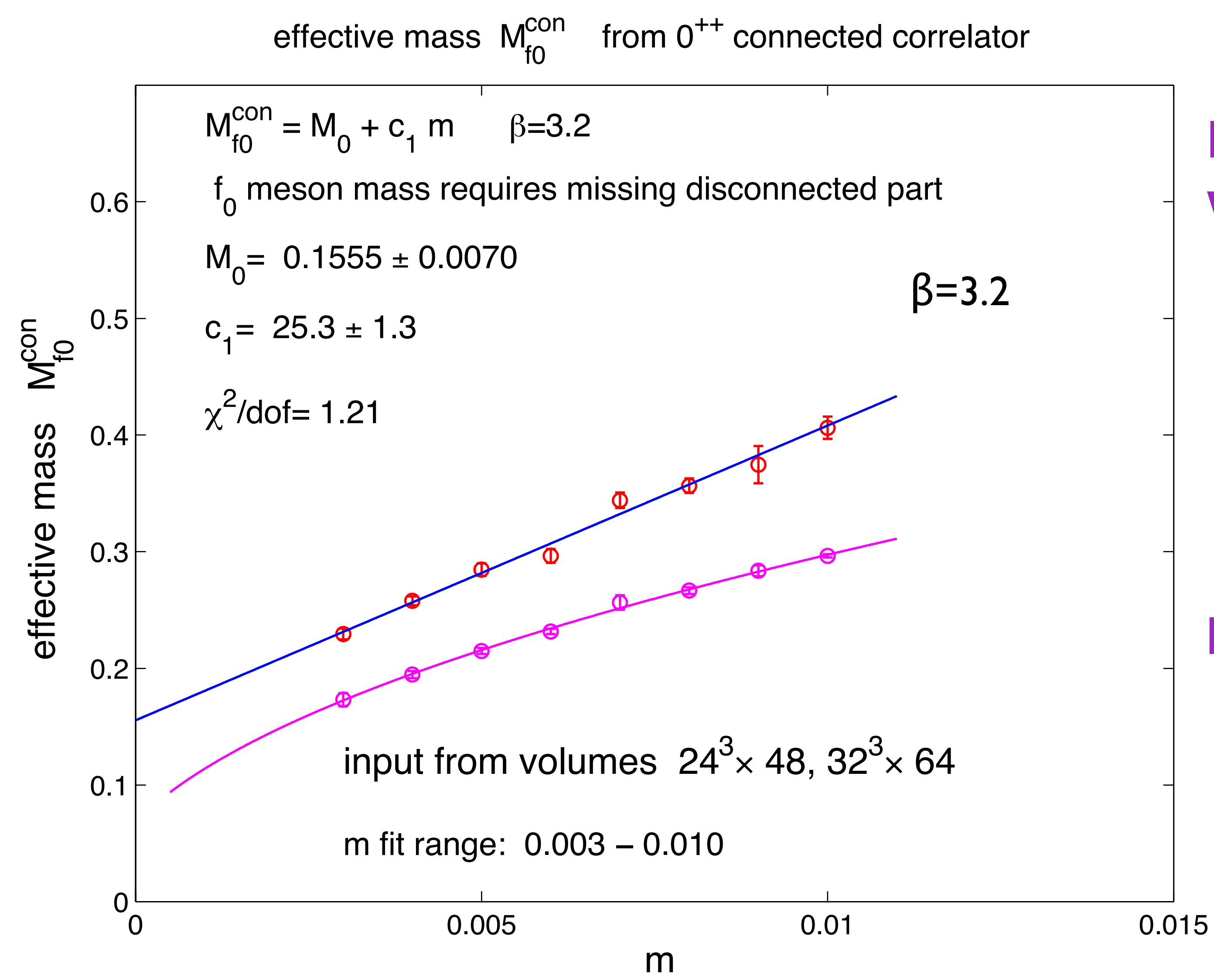




M_ρ remains heavy in massless fermion limit

parity partners remain split in massless fermion limit

Nf=2 SU(3) sextet chiral fits: f_0 state with 0^{++} quantum numbers:



M(f_0)/F ~ 6
without disconnected diagram

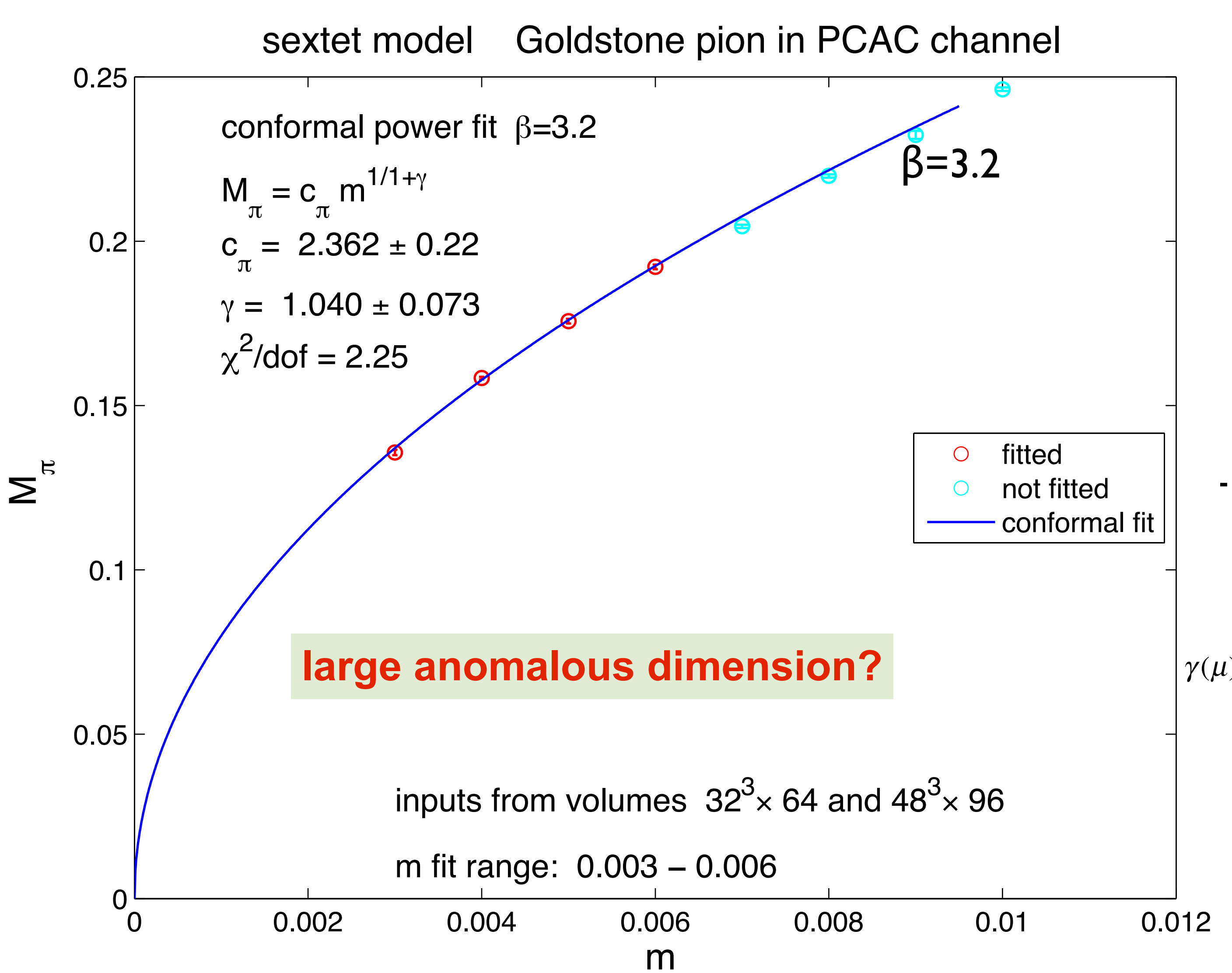
Higgs impostor in this channel?

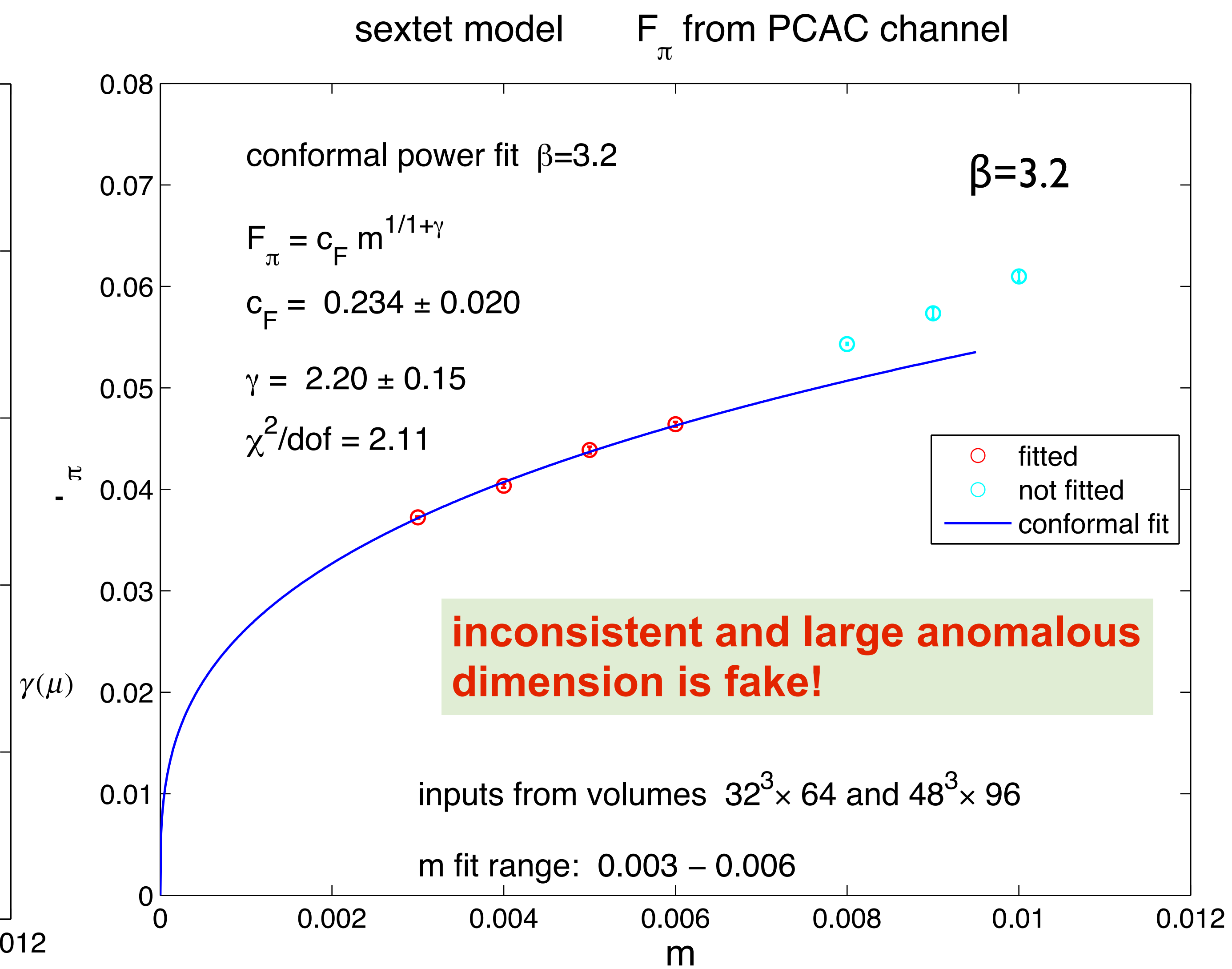
to include disconnected diagram with good signal/noise: major undertaking

staggered fermions with rooting presents further complication Bernard et al.

mixed action is being considered

conformal hypothesis breaks down in global fits:

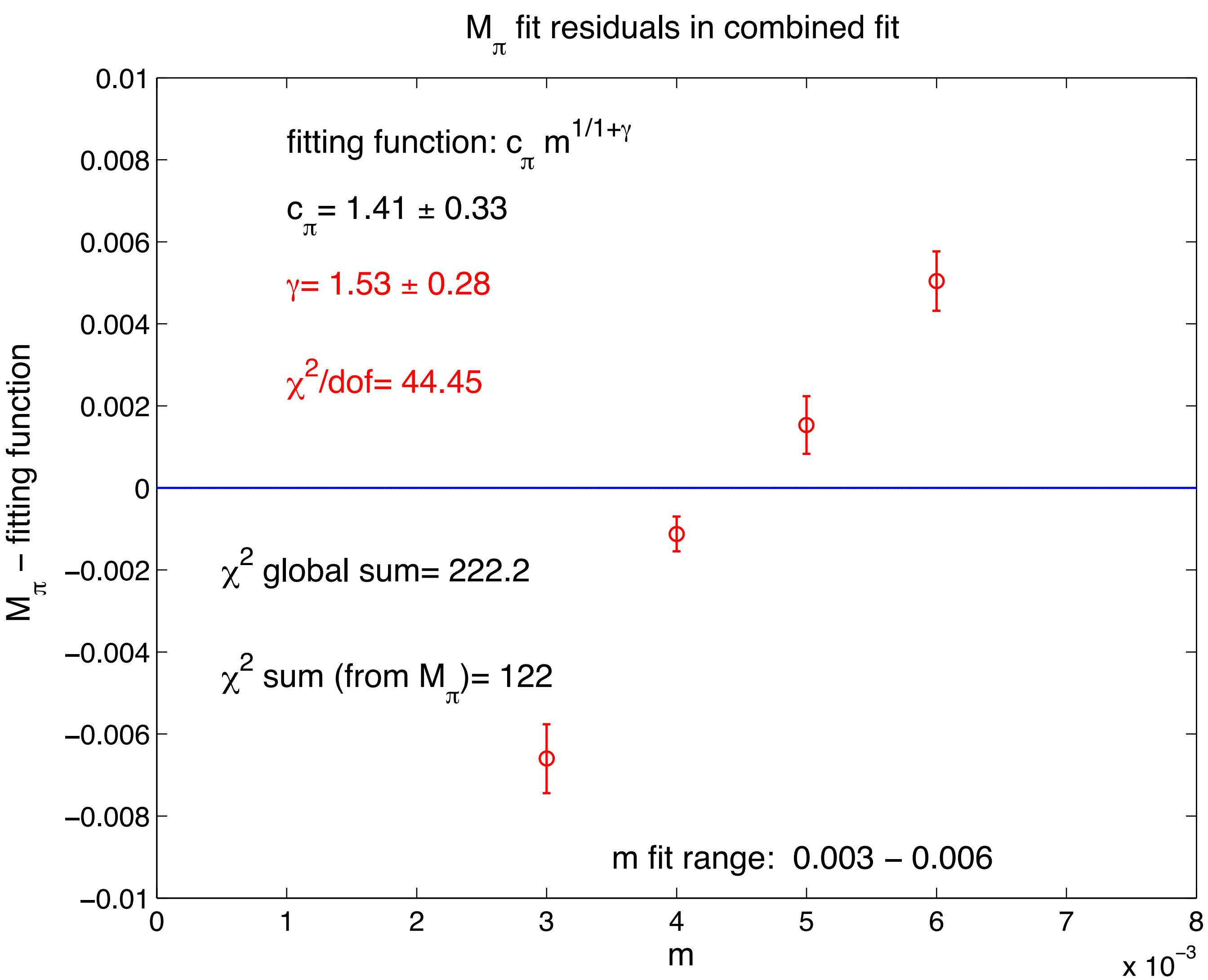


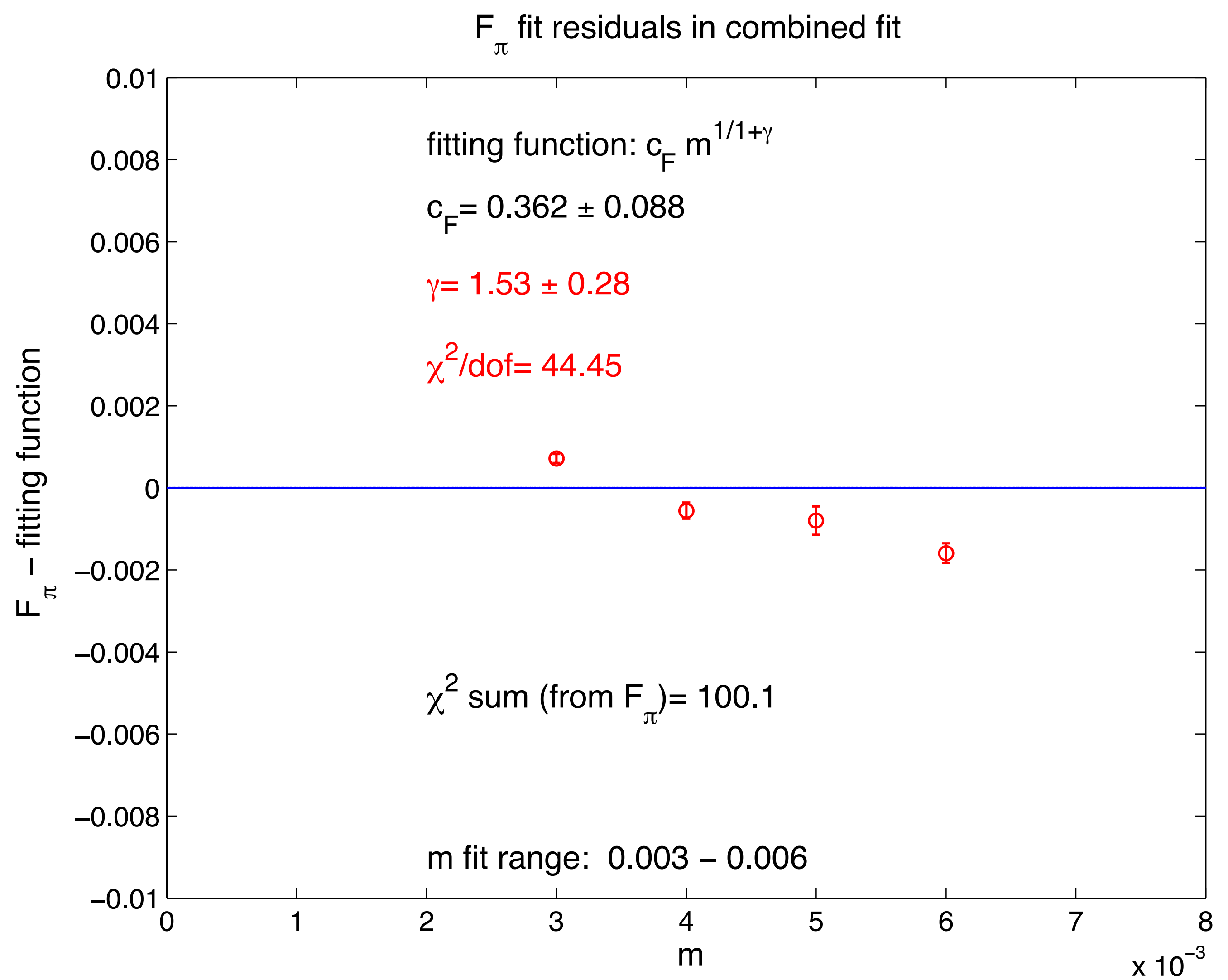


inconsistent large critical exponents γ forced by chiral behavior in far infrared

it is not the running $\gamma(\mu)$ at scale μ!

conformal hypothesis breaks down in global fits:





large and inconsistent critical exponents γ

are we close enough to the critical surface?

fix with scaling violation terms? don't think so

further Nf=2 SU(3) sextet model tests ?

$L=\infty$ conformal scaling tests ✓

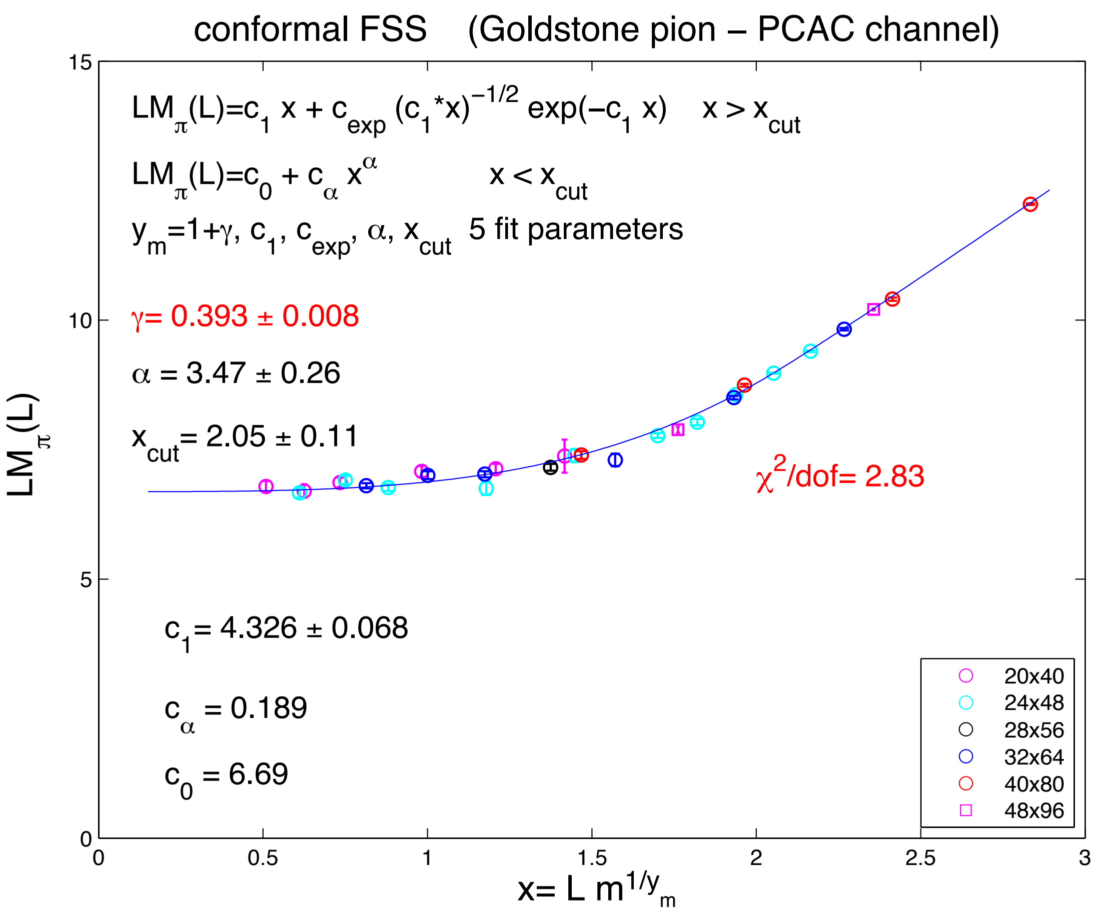
conformal FSS tests — illustrated by Nf=12 model

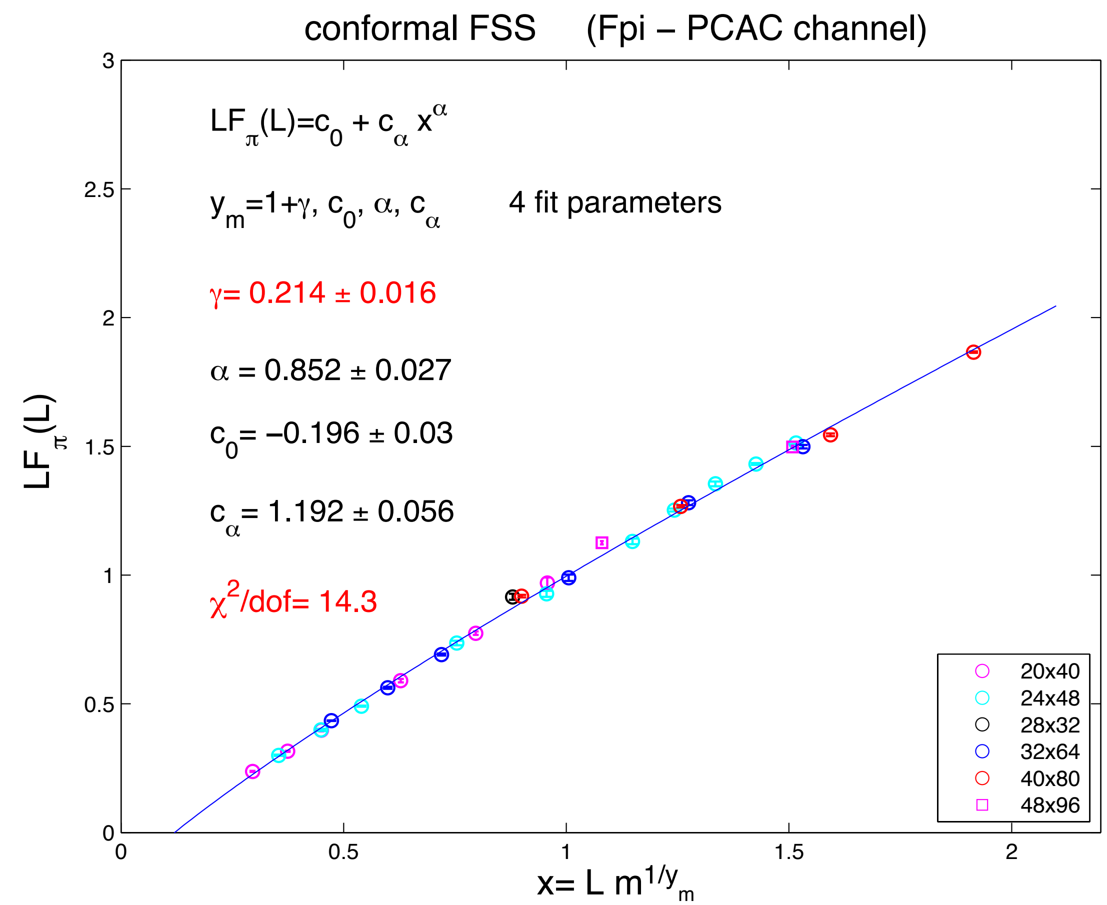
confining force in chiral limit ? — Kieran Holland's talk next week

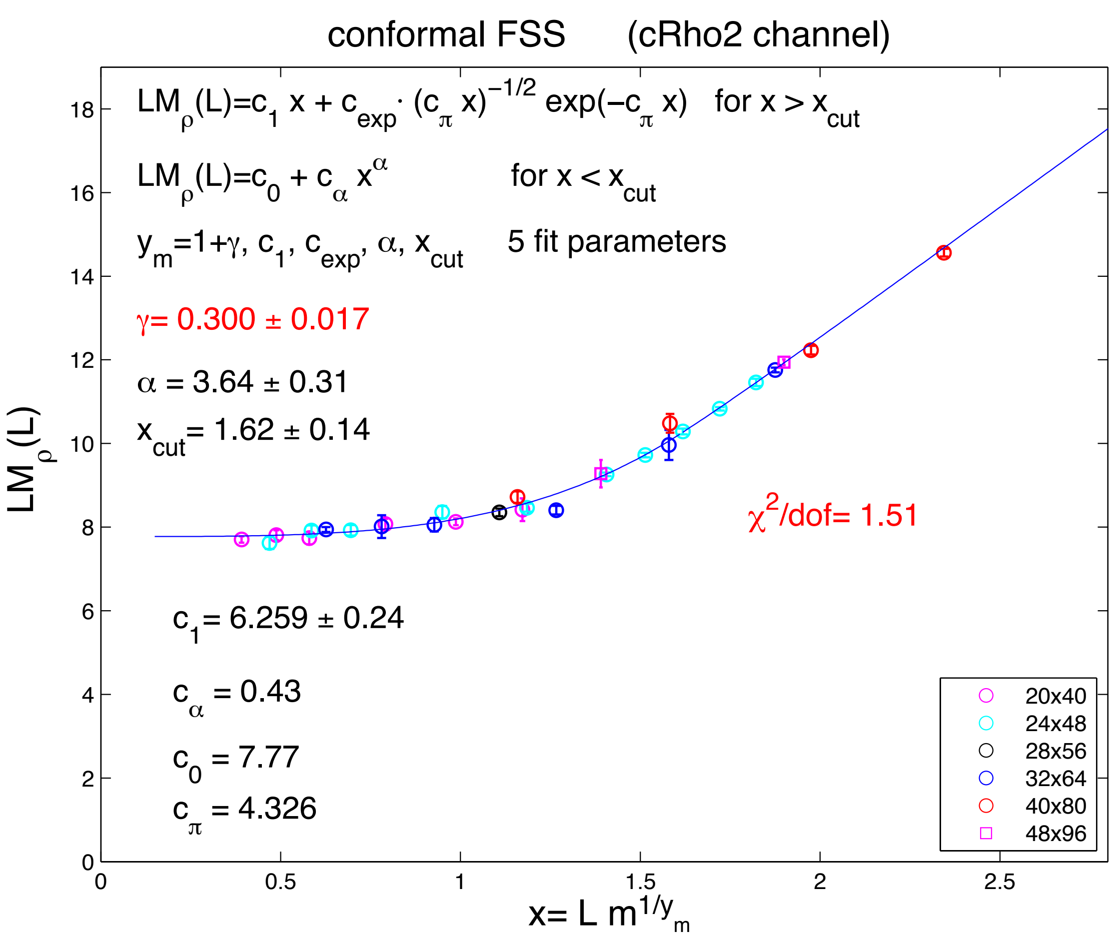
Electroweak phase transition (and dark matter from third flavor)

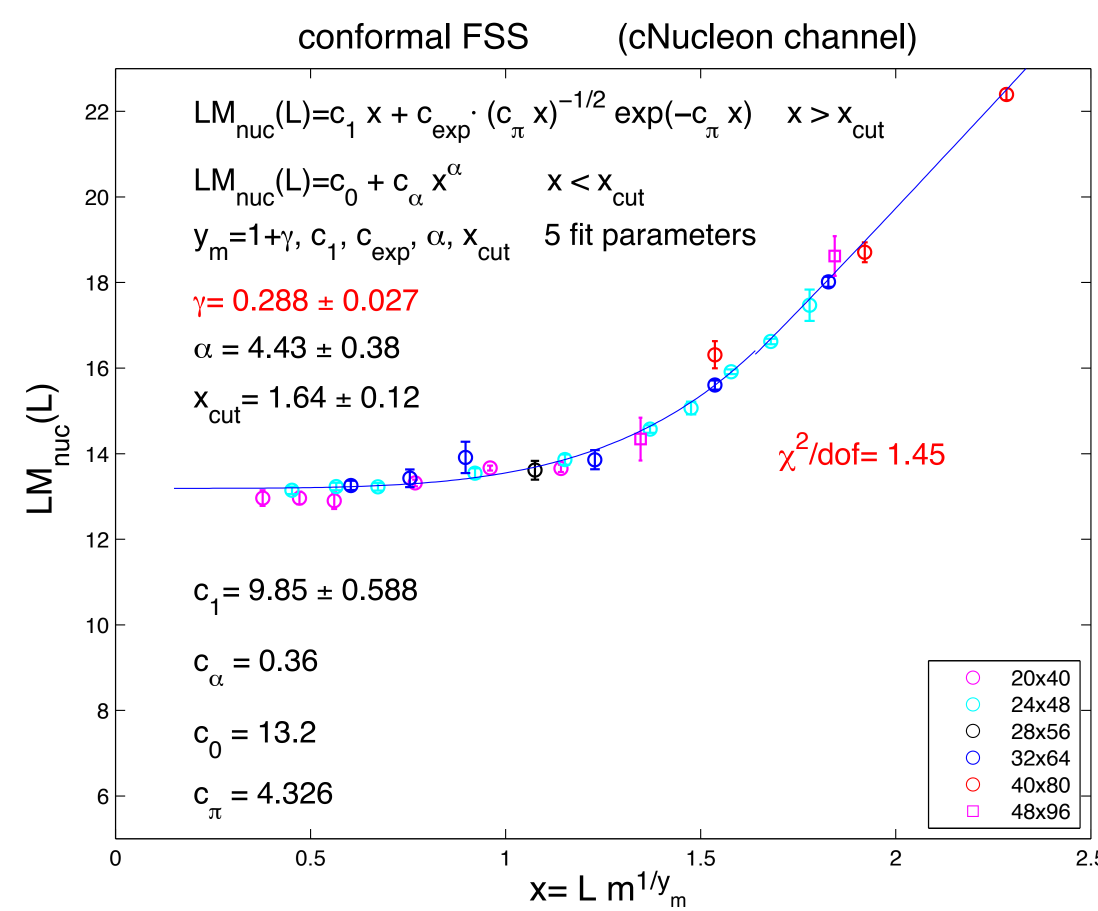
running (walking?) gauge coupling

conformal scaling test with FSS - physical model fit (spline fit similar)









further Nf=2 SU(3) sextet model tests ?

L=∞ conformal scaling tests ✓

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Electroweak phase transition (and dark matter from third flavor)

running (walking?) gauge coupling

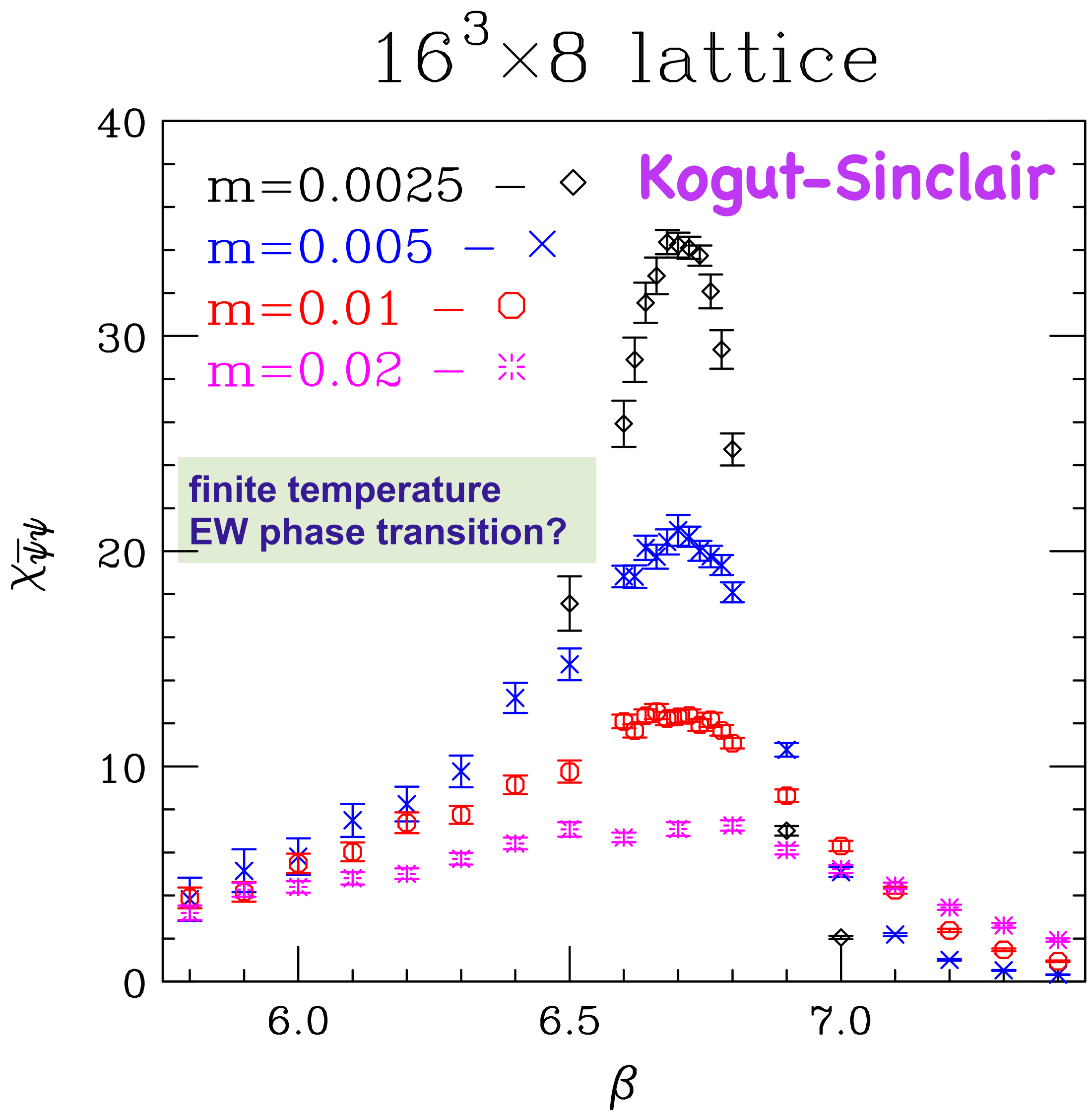
EW phase transition in sextet model - early universe

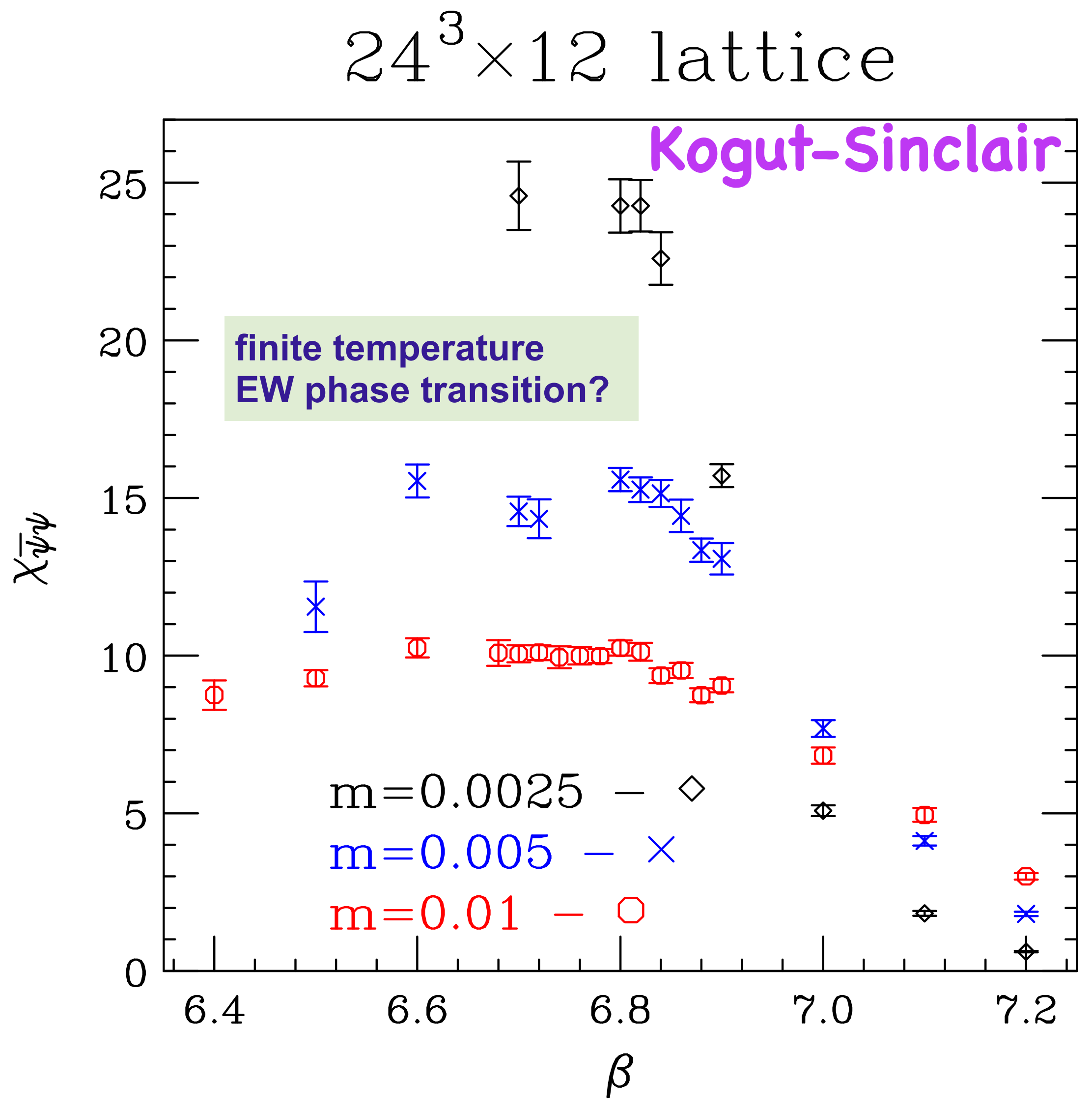
Kogut-Sinclair consistent with χSB phase at T=0

relevance in early cosmology

We are planning to run sextet thermodynamics

Third massive fermion flavor (electroweak singlet) dark matter?



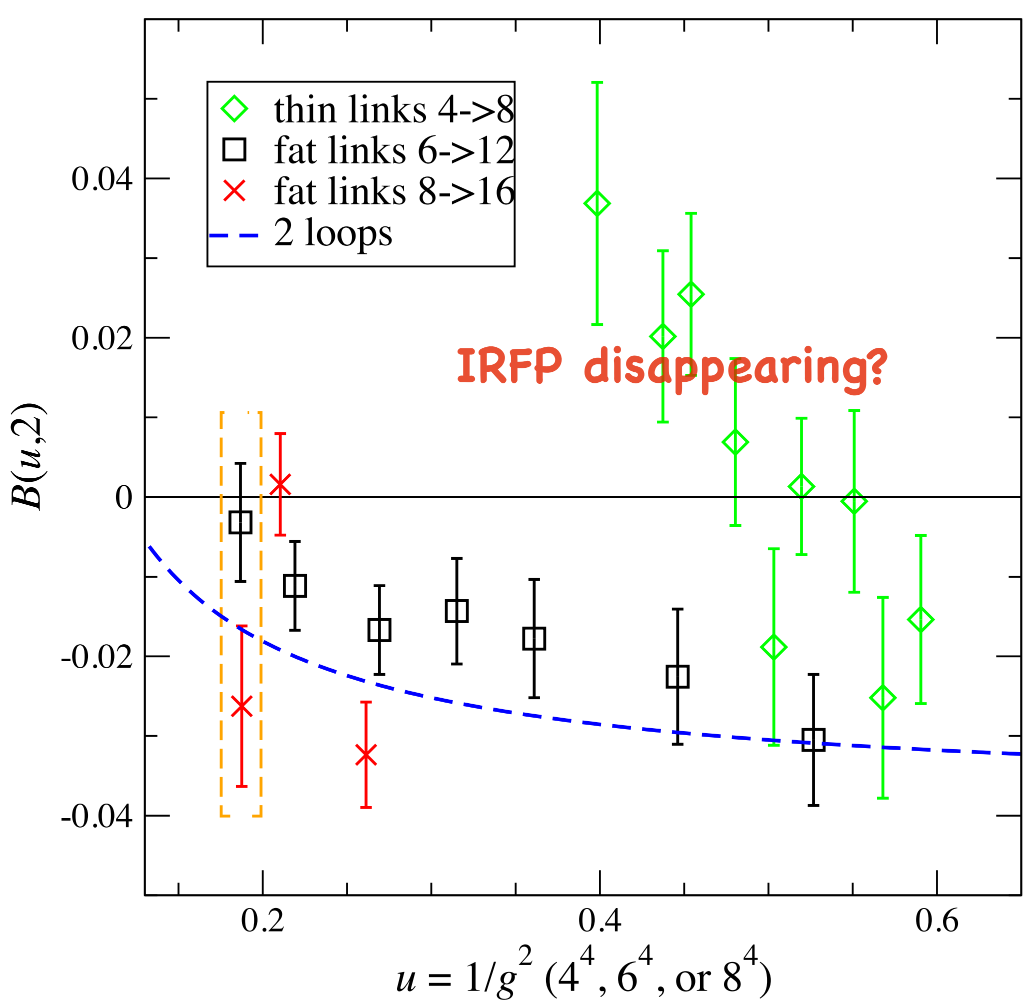


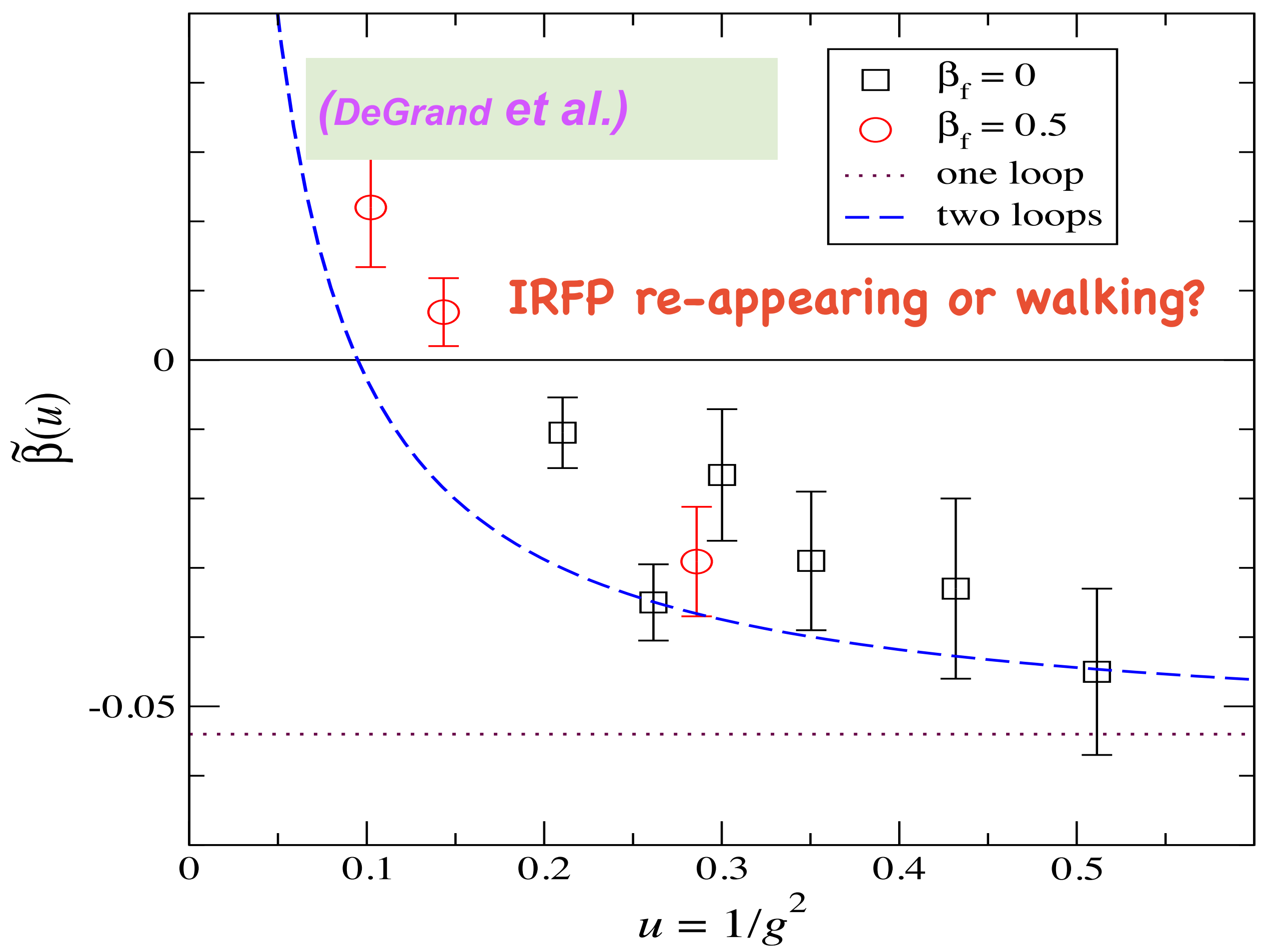
running (walking?) gauge coupling

DeGrand et al. find: Nf=2 sextet beta function may have an IRFP zero or walks?

model has small anomalous dimension ?

$\gamma(\mu) < 0.45$ controversy, if conformal; if χSB what is $\gamma(\mu)$?





Running coupling definition from gauge field gradient flow

$$\langle E(t)\rangle = \frac{3}{4\pi t^2}\alpha(q)\{1 + k_1\alpha(q) + O(\alpha^2)\}, \quad q = \frac{1}{\sqrt{8t}}, \quad k_1 = 1.0978 + 0.0075 \times N_f$$

t is the gradient flow time

Running coupling definition (range is $(8t)^{1/2}$) :

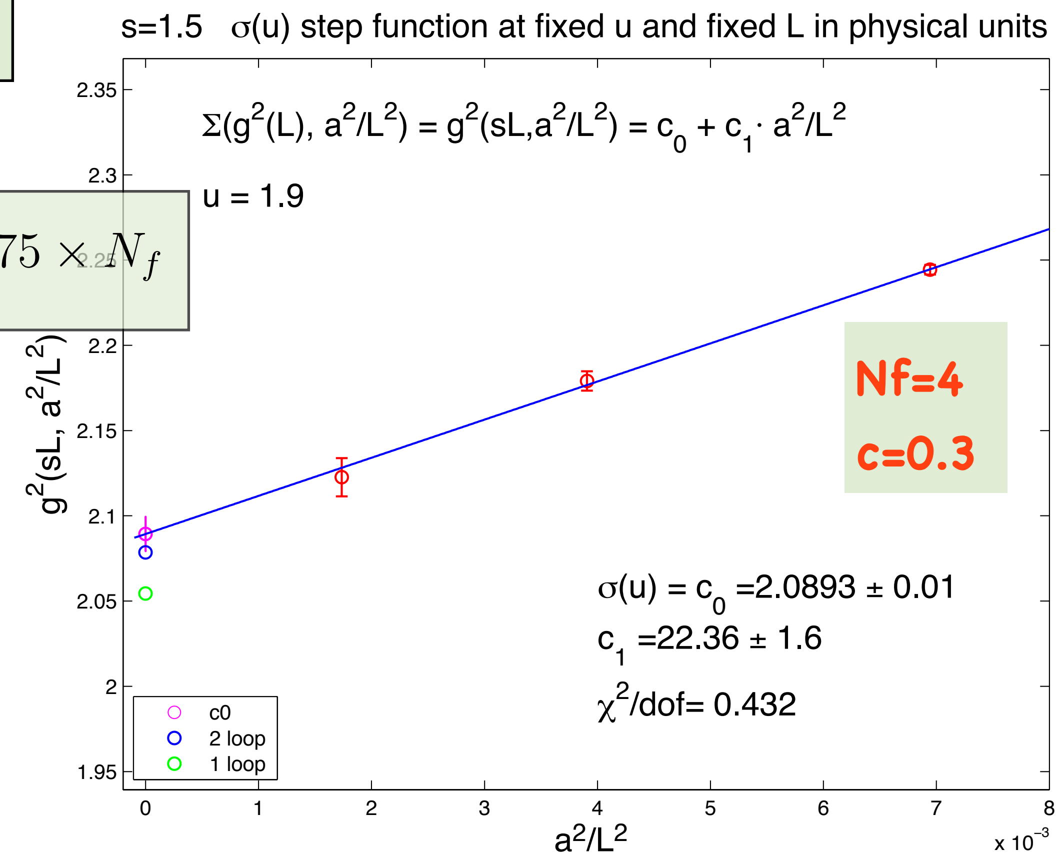
while holding $c = (8t)^{1/2}/L$ fixed: $\alpha_c(L) = \frac{4\pi}{3}\frac{\langle t^2 E(t)\rangle}{1+\delta(c)}$

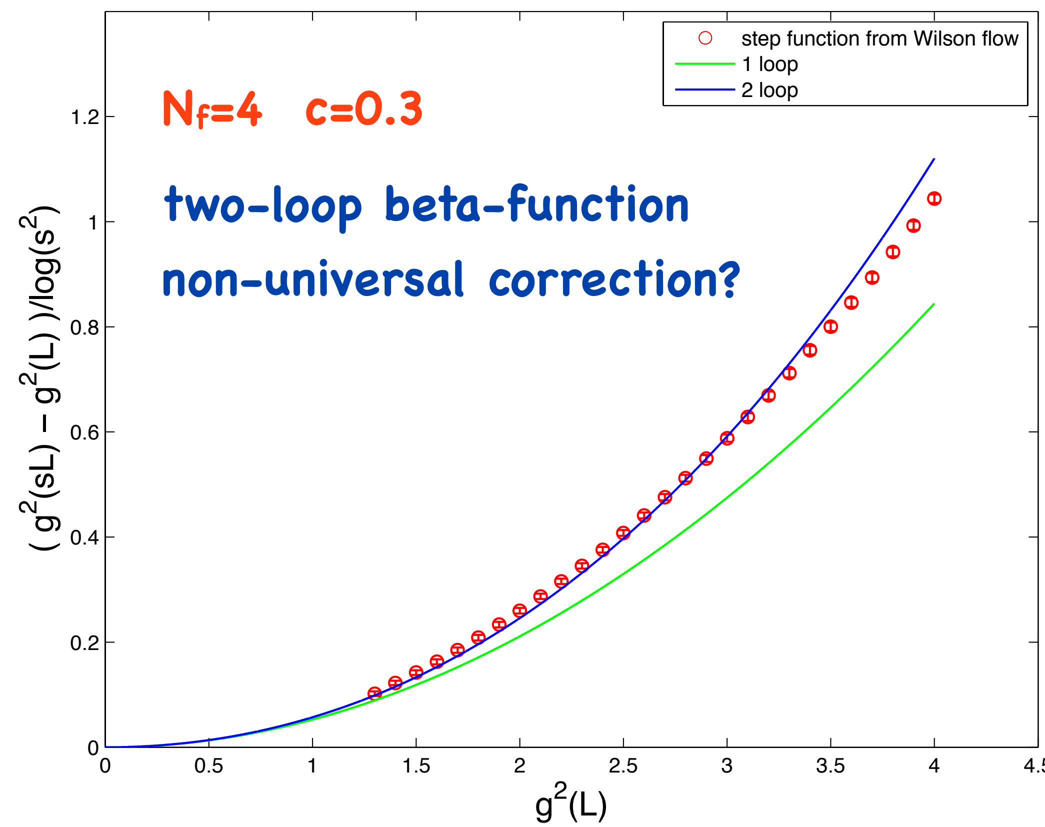
$$\delta(c) = \vartheta_3^4(e^{-1/c^2}) - 1 - \frac{c^4\pi^2}{3}$$

3rd Jacobi function

massless fermions; antiperiodic all directions s=1.5 step

N_f=4 staggered fermions; 4-stout; L=12-18; 16-24; 24-36





run production now in sextet model

Summary and Outlook

Consistency with χSB in Nf=2 SU(3) sextet model

Inconsistency with conformal symmetry and IRFP in all L=∞ like tests

Results of DeGrand et al. reconciled if walking coupling

Scalar spectrum from disconnected correlator is highest priority

S-parameter and size of anomalous dimension remain unresolved
("effective" γ in 1-2 range)

Electroweak phase transition?