Lattice Studies of the Nearly Conformal Composite Higgs Mechanism

Julius Kuti

Jefferson Lab seminar

April19, 2010

With Lattice Higgs Collaboration members:

Z. Fodor, K. Holland, D. Nogradi, C. Schroeder

Video Games in Technicolor

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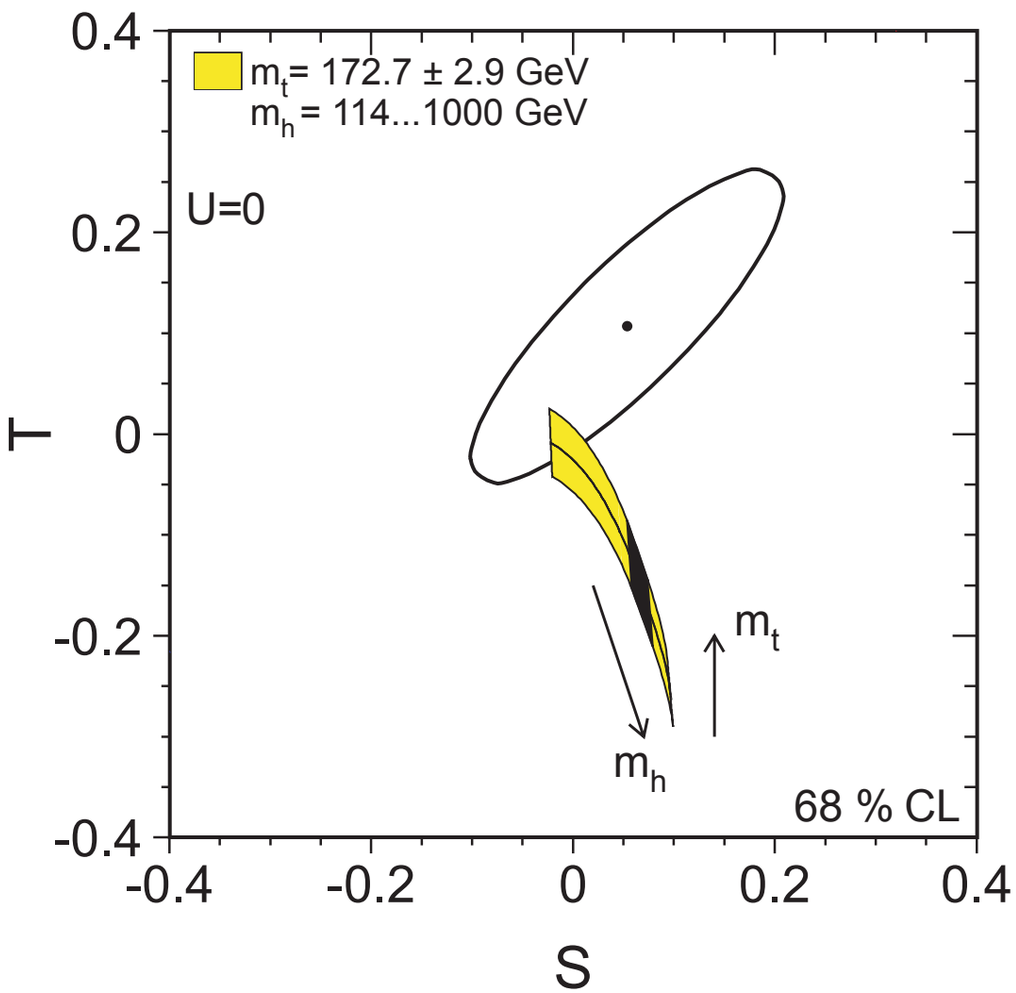
The New York Times

Friday, April 1, 2011 Last Update: 11:17 AM ET

Physicists at CERN in Geneva find the Higgs particle with unexpected characteristics

By Jane Ellis

The properties of the newly found Higgs particle shook the foundations of modern particle physics. Although its decay properties are very similar to what was expected, the mass at 507 GeV is far too heavy and the width far too narrow to accommodate what is know to be the Standard Model of modern particle physics. Physicists are turning now to lattice gauge theorists who are trying to explain with nearly conformal gauge theories the experiments at the Large Hadron Collider. *Continued on page 11 ...*



How to pull out the heavy Higgs particle to 507 GeV from the allowed oval region without violating EW precision data?

Nearly conformal gauge theories might work?

Requires unusual nonperturbative properties which can be studied on the lattice with extreme computing resources

Can the lattice be transformational when we do not know the answer?

Outline

1. Overview of three coordinated projects in our program
   - SU(3) color, fundamental rep, staggered Nf=4-20
   - sextet representation with SU(3) color
   - Running coupling (new ideas, first results)
2. Chiral symmetry breaking
   - Finite volume p-regime, delta-regime, epsilon-regime
   - Goldstone spectra and staggered CHPT
   - New results at Nf=4,8,9,12 will be presented
3. Inside and above the conformal window
   - Zero momentum dynamics at Nf=16,20
4. Conclusions and Outlook
   - Prospects towards model building ?
   - Can lattice studies be transformational ?
   - Is peta-scale to exa scale power needed for definitive phenomenology ?

Talk is based on published results last year:

1. **Topology and higher dimensional representations.**
   Published in **JHEP 0908:084,2009**.
   e-Print: **arXiv:0905.3586** [hep-lat]

2. **Nearly conformal gauge theories in finite volume.**
   Phys.Lett.B681:353-361,2009.
   e-Print: **arXiv:0907.4562** [hep-lat]

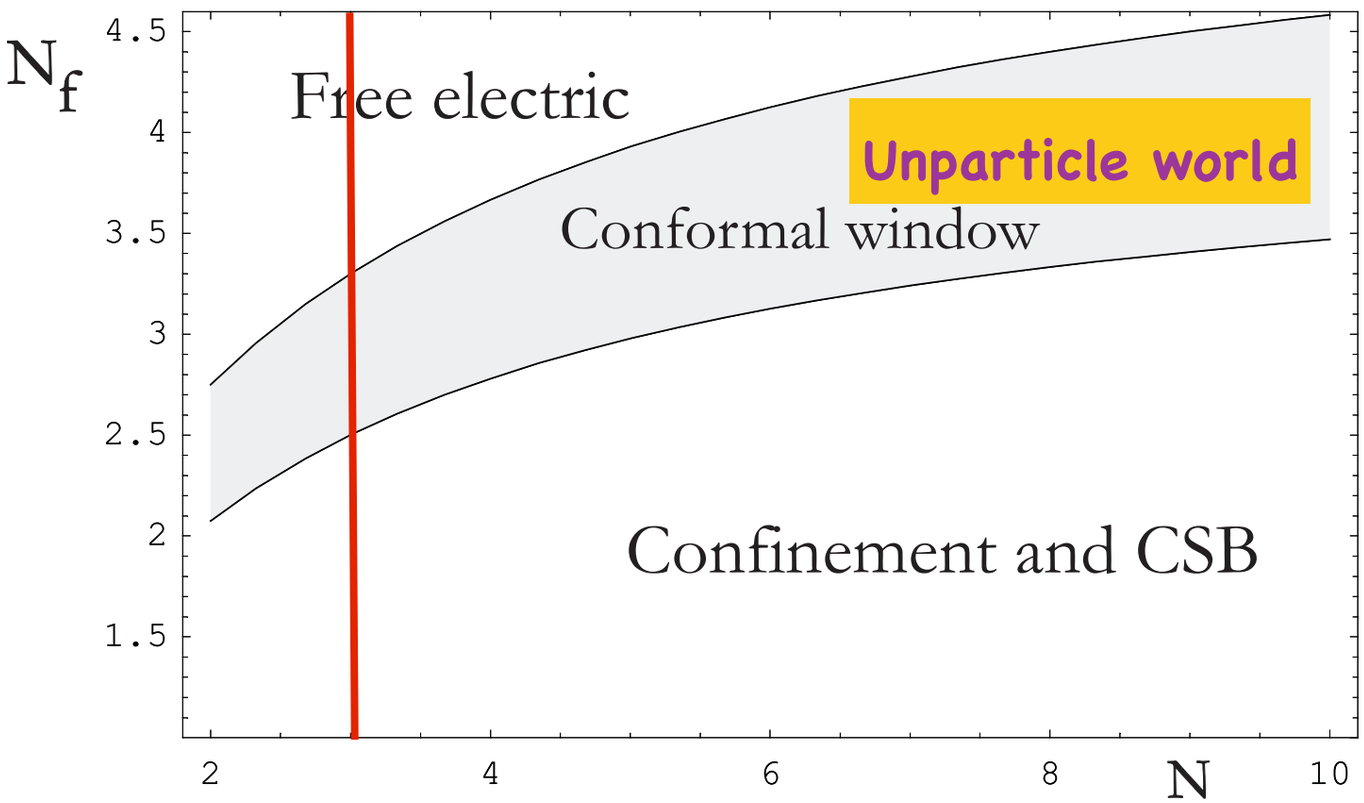
3. **Chiral properties of SU(3) sextet fermions**
   e-Print: **arXiv:0908.2466** [hep-lat]

4. **Chiral symmetry breaking in nearly conformal gauge theories**
   e-Print: **arXiv:0911.2463** [hep-lat] **posted**

5. **Calculating the running coupling in strong electroweak models**
   e-Print: **arXiv:0911.2934** [hep-lat]

and some unpublished new analysis

Phase diagram of TWO projects as nearly conformal gauge theories in flavor-color space ?



Phenomenology goal: nearly conformal gauge theory with minimal realization of the composite Higgs mechanism

Consistent with ElectroWeak Precision Data ?

They are fun lattice field theories anyway!

Project 1:

Fundamental rep Nf=4,8-12,14,16,20 flavors and three colors with staggered fermions.

Project 2:

2-index symmetric rep with Nf=2 flavors and three colors with overlap chiral fermions → staggered

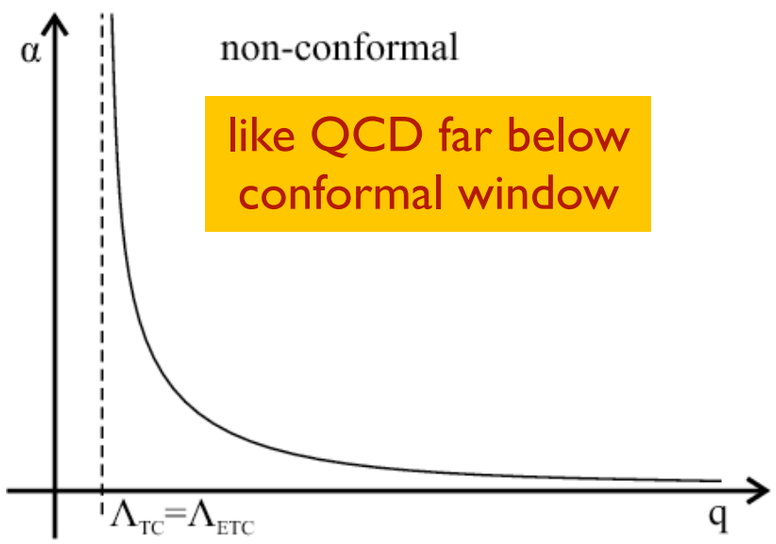
(will be briefly discussed here, but quenched results with interesting topology are published and full dynamical simulations are running)

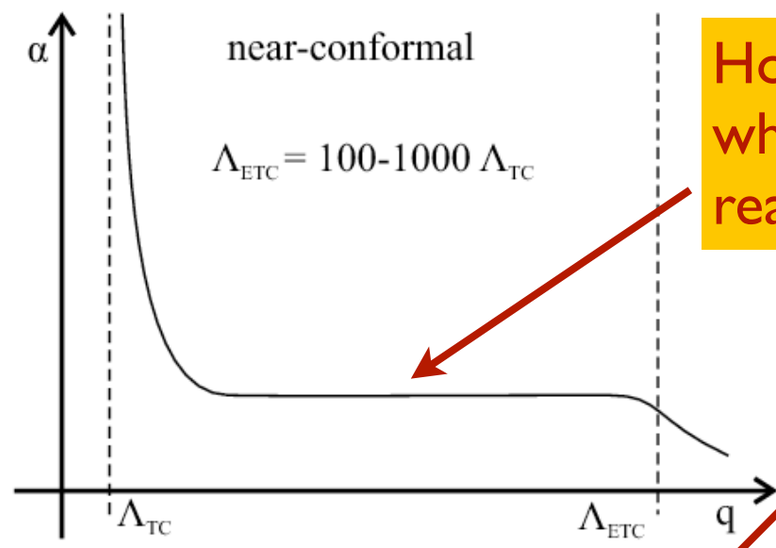
Unified GPU/MPI code

near the conformal window (walking):

Higgs phenomenology with nearly vanishing beta function

Project 3: Important to complement the test of chirality with running coupling and beta function





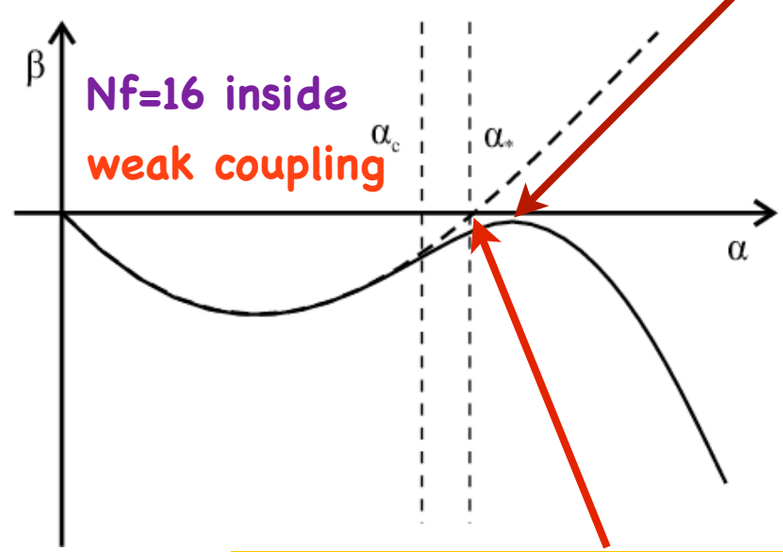
How to reach walking scale which is wanted for several reasons in BSM?

Is 2-index symmetric rep nearly conformal?

Fundamental rep with Nf=4,8,9 should be similar

Nf=10,11,12,14,16,20 under continued study

Nf=12 controversial



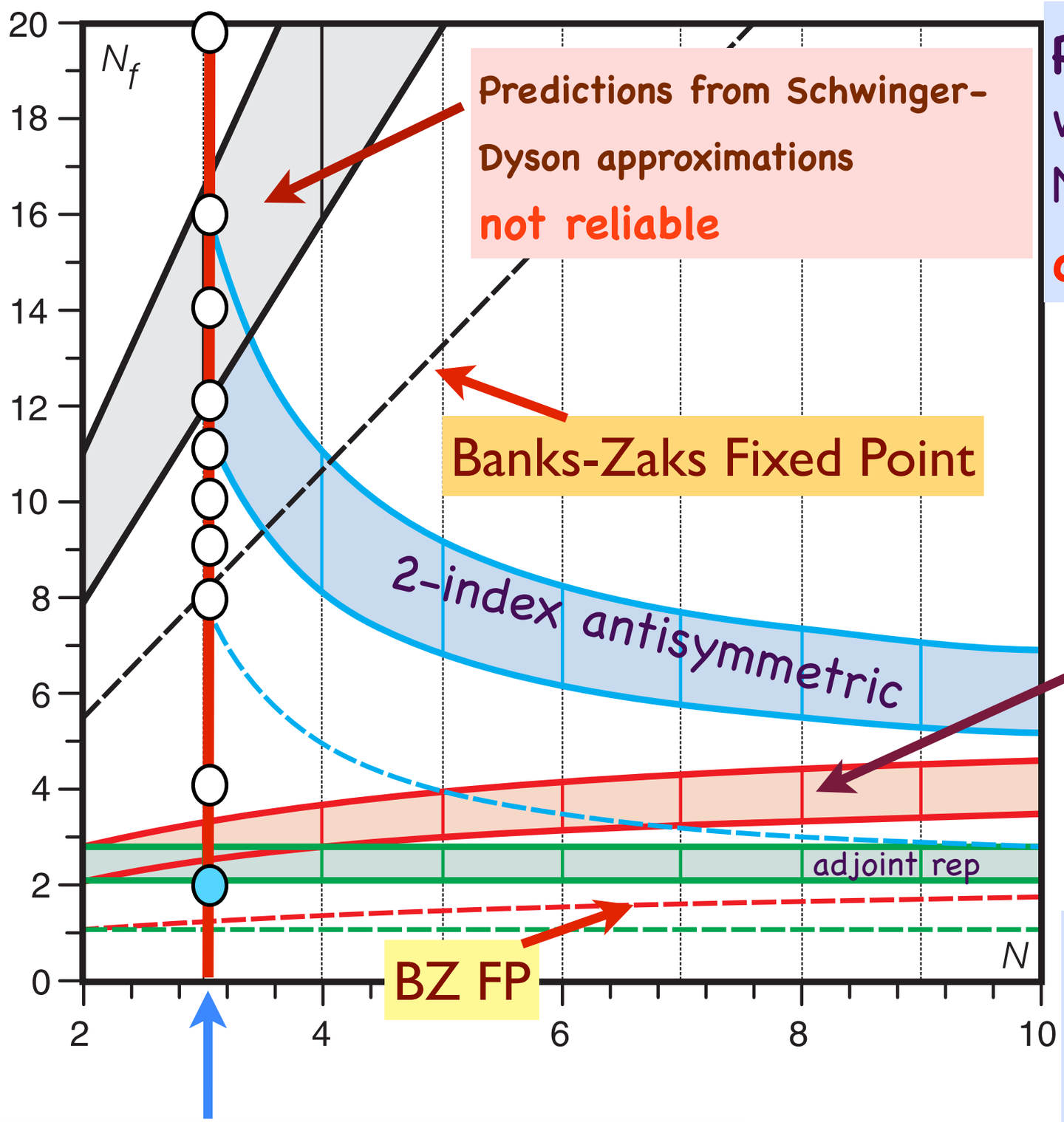
would be Banks-Zaks FP

DeGrand et al. (conformal?)

our staggered simulations disagree with conformal phase

important in model building

Theory space and conformal windows



Project 1: in fundamental rep with N=3 colors with Nf=4,8,9,10,11,12,14,16,20 flavors

dynamical staggered

Project 2: 2-index symmetric rep (sextet)

N=3 colors and Nf=2 flavors

dynamical overlap

We only run with N=3 colors

Running on CPU clusters and GPU clusters

Very demanding

Unified code

We are supported by the Wuppertal hardware/software infrastructure

We built on Wuppertal software library:
Fodor, Szabo, Katz

Very limited use of Wuppertal hardware

We are USQCD !!

GPU Hardware

CUDA code:
Kalman Szabo
Sandor Katz
Chris Schroeder
Daniel Nogradi

GTX 280
Flops: single 1 Tflop, double 80 Gflops
Memory 1GB, Bandwidth 141 GBs^{-1}
230 Watts, $350

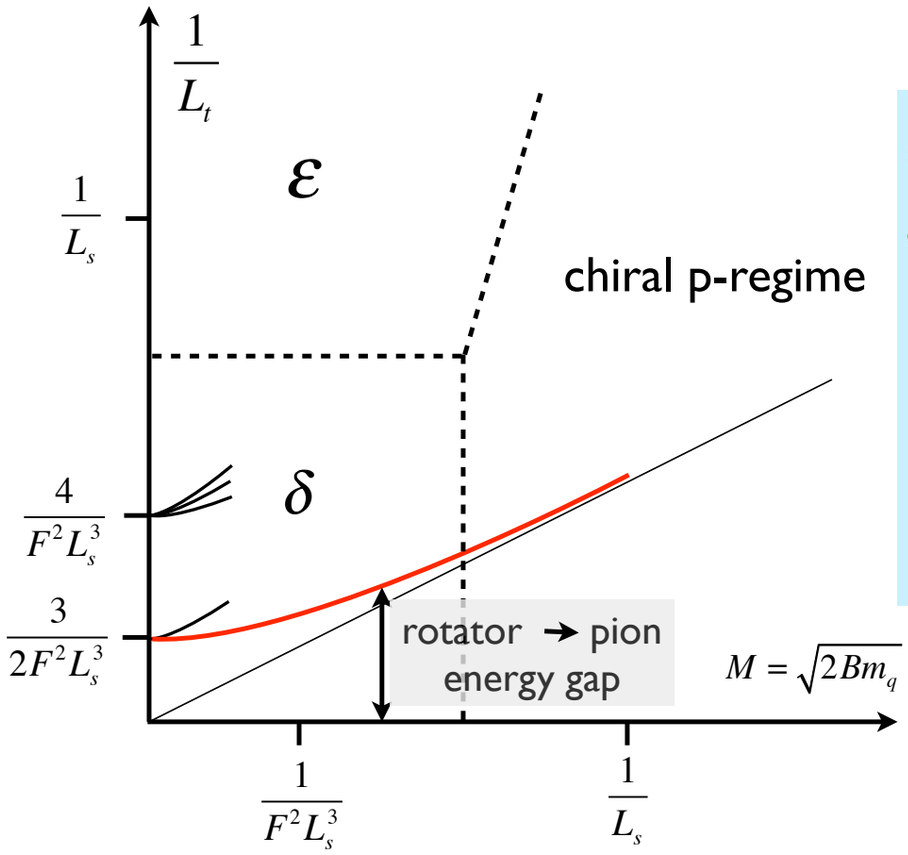
Our new DYNQCD software mostly by Szabo, Nogradi, Schroeder

For code development:
Small UCSD Tesla cluster
ARRA funded by DOE
waiting for Fermi cards

Tesla 1060
Flops: single 1 Tflop, double 80 Gflops
Memory 4GB, Bandwidth 102 GBs^{-1}
230 Watts, $1200

Tesla 1070
Flops: single 4 Tflops, double 320 Gflops
Memory 16GB, Bandwidth 408 GBs^{-1}
900 Watts, $8000

Chiral regimes to identify in theory space:



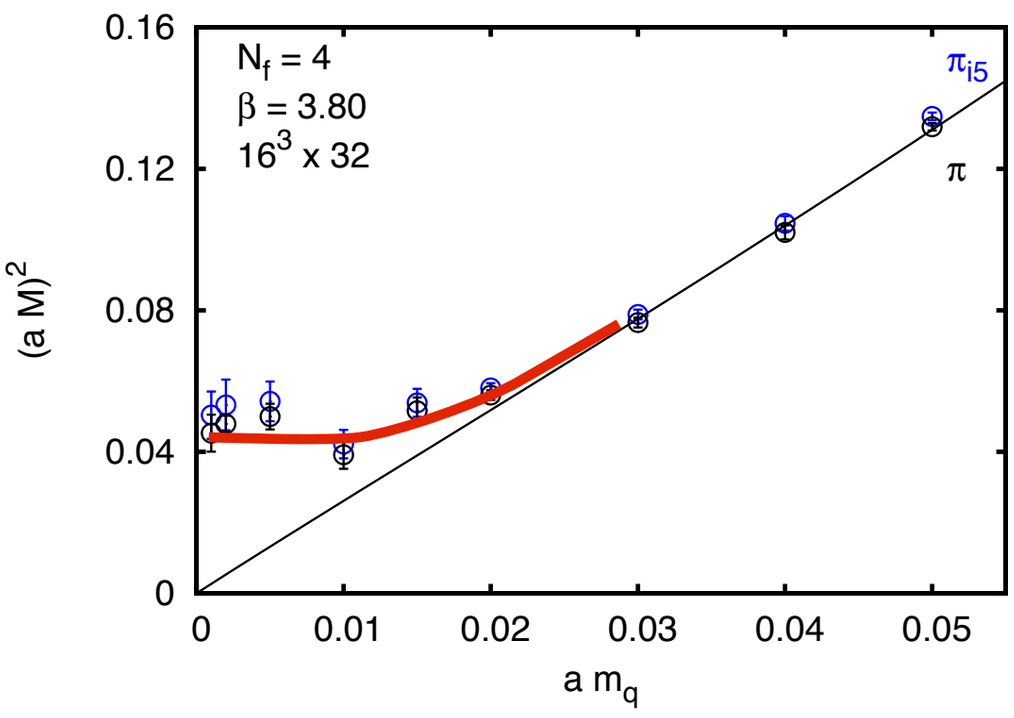
Goldstone dynamics is different in each regime

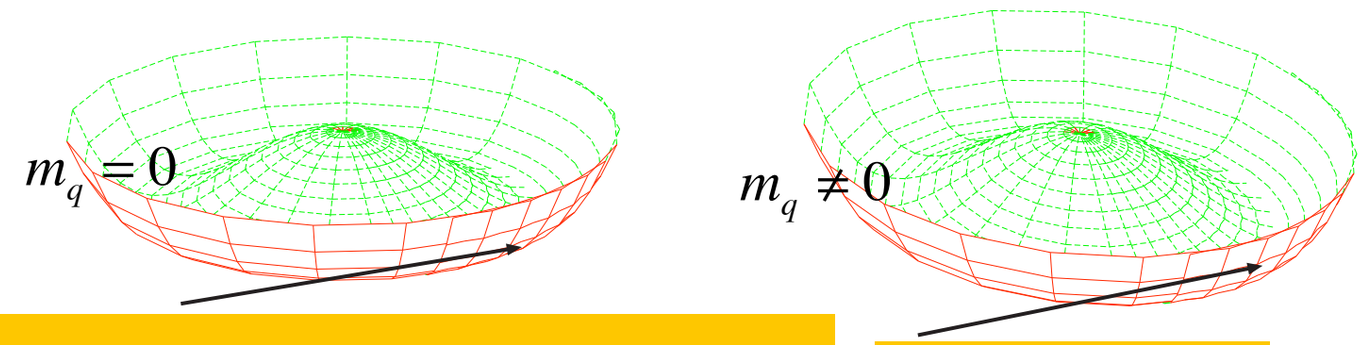
We study δ and ε -regimes (RMT)

and p-regime (probing chiral loops)

complement each other

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

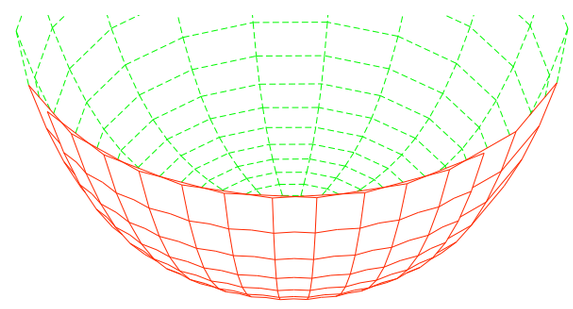




Veff: chiral condensate in flavor space

arbitrary orientation of condensate

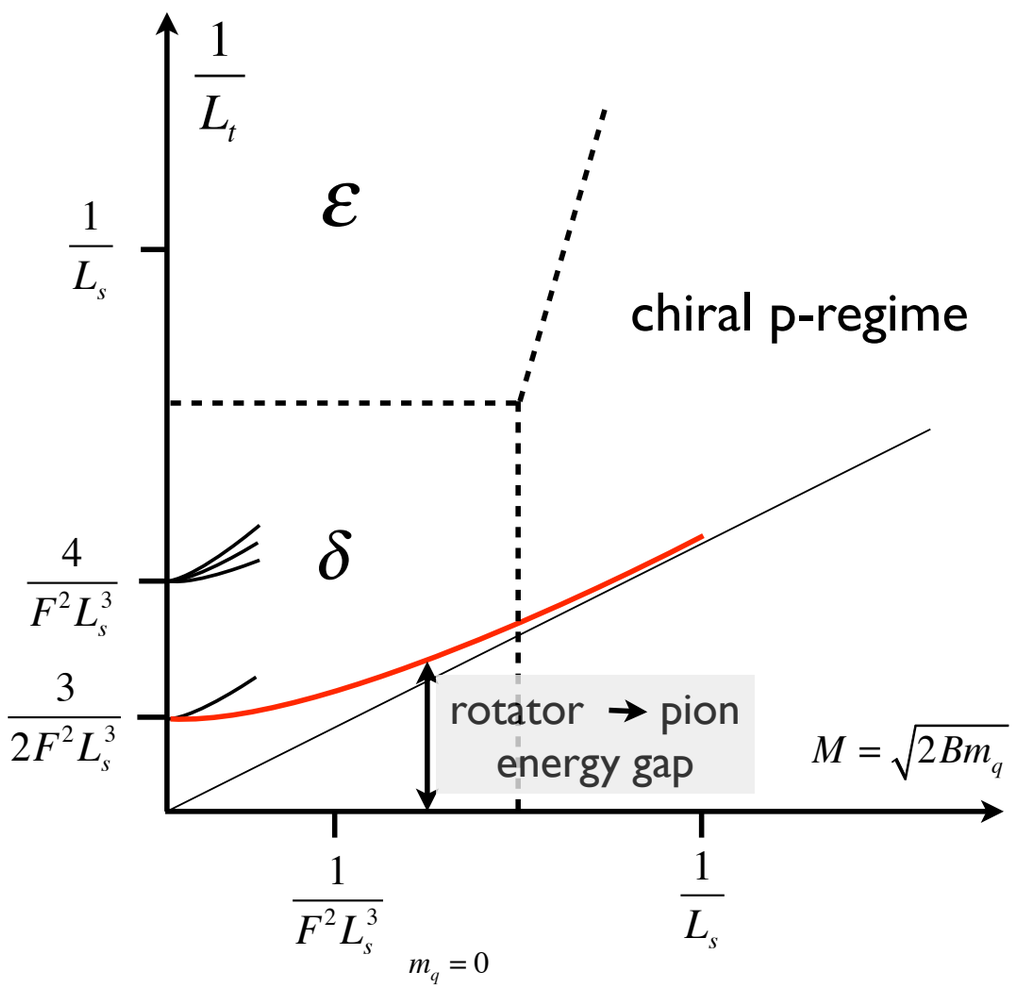
tilted condensate



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

One-loop expansion in our analysis of p-regime:

Leutwyer, Gasser, P. Hasenfratz,
Niedermayer, Hansen, Neuberger, ...



$$M_\pi^2 = M^2\left[1 - \frac{M^2}{8\pi^2 N_f F^2} ln\left(\frac{\Lambda_3}{M}\right)\right],$$

$$F_\pi = F\left[1 + \frac{N_f M^2}{16\pi^2 F^2} ln\left(\frac{\Lambda_4}{M}\right)\right],$$

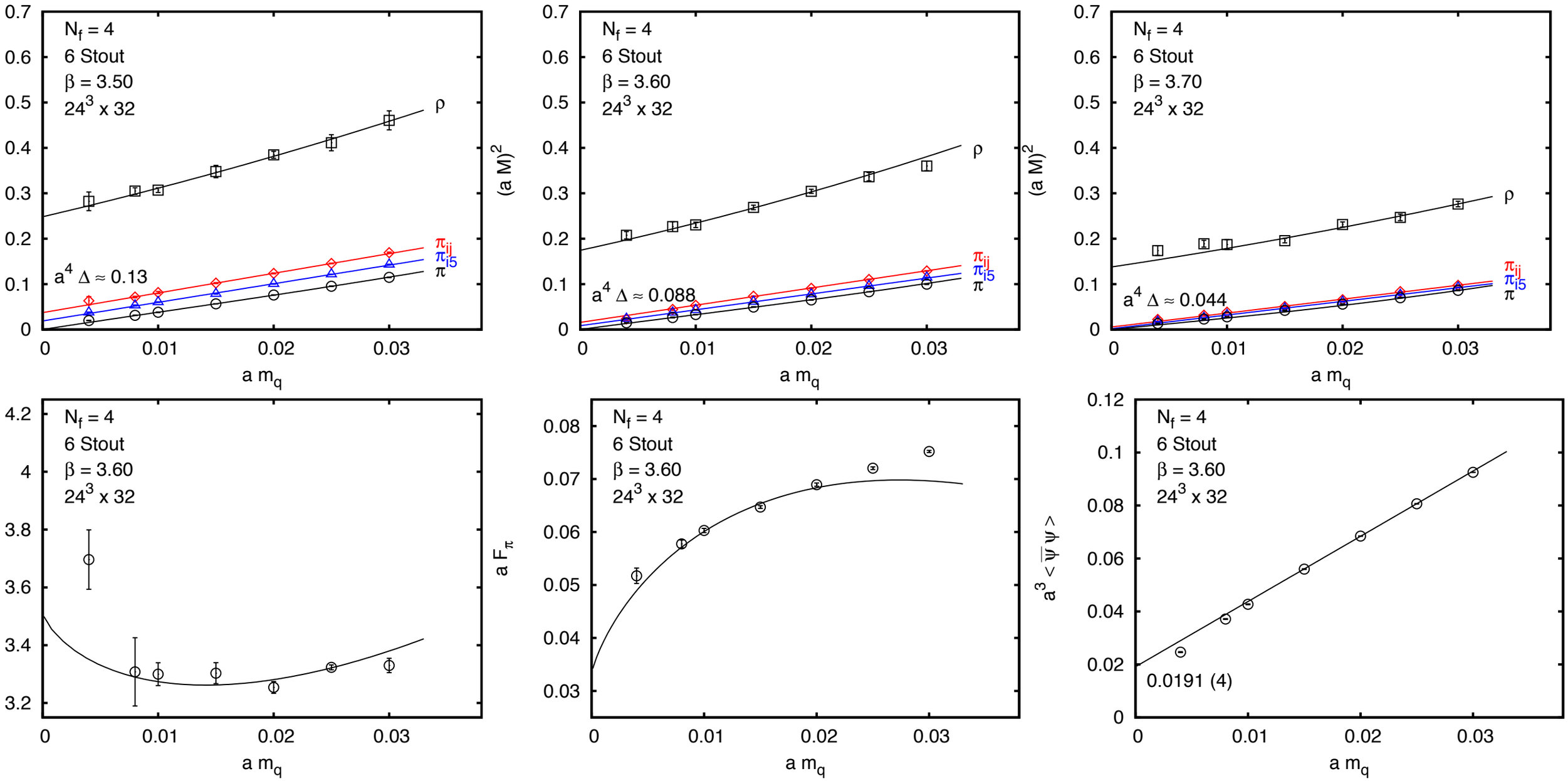
Note Nf scaling of pion mass!
warning: 2-loop ~Nf^2 (Bijnens)

$$M_\pi(L_s,\eta) = M_\pi\left[1 + \frac{1}{2N_f}\frac{M^2}{16\pi^2 F^2}\cdot \widetilde{g}_1(\lambda,\eta)\right], \quad \lambda = ML_s$$

$$F_\pi(L_s,\eta) = F_\pi\left[1 - \frac{N_f}{2}\frac{M^2}{16\pi^2 F^2}\cdot \widetilde{g}_1(\lambda,\eta)\right],$$

We use staggered action with stout smearing
Taste breaking included in staggered perturbation theory!
structure changing as Nf grows

Nf=4 NLO chiral analysis in p-regime:

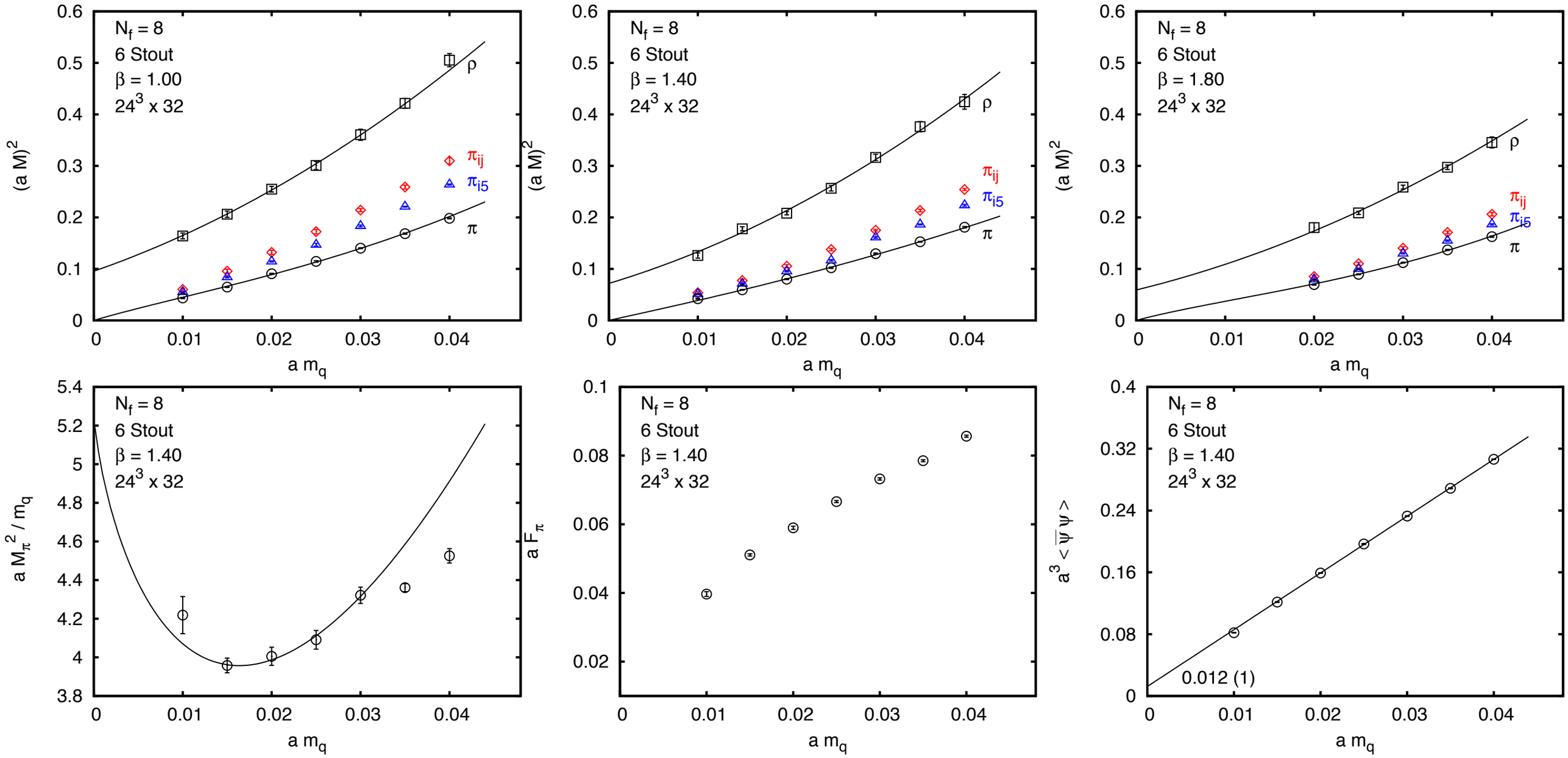


$$\mathcal{L}_\chi^{(4)} = \frac{F^2}{4}\mathrm{Tr}(\partial_\mu\Sigma\partial_\mu\Sigma^\dagger) - \frac{1}{2}B\,m_q\,F^2\mathrm{Tr}(\Sigma + \Sigma^\dagger) \;+V_\chi^{(6)}$$

$$M_\pi(T_a)^2 = 2Bm_q + a^2\Delta(T_a) + O(a^2 m_q) + O(a^4)$$

$$\begin{aligned}
\Delta(\xi_5) &= 0\,, \\
\Delta(\xi_\mu) &= \frac{8}{F^2}(C_1 + C_2 + C_3 + 3C_4 + C_5 + 3C_6)\,, \\
\Delta(\xi_{\mu 5}) &= \frac{8}{F^2}(C_1 + C_2 + 3C_3 + C_4 - C_5 + 3C_6)\,, \\
\Delta(\xi_{\mu\nu}) &= \frac{8}{F^2}(2C_3 + 2C_4 + 4C_6)\,.
\end{aligned}$$

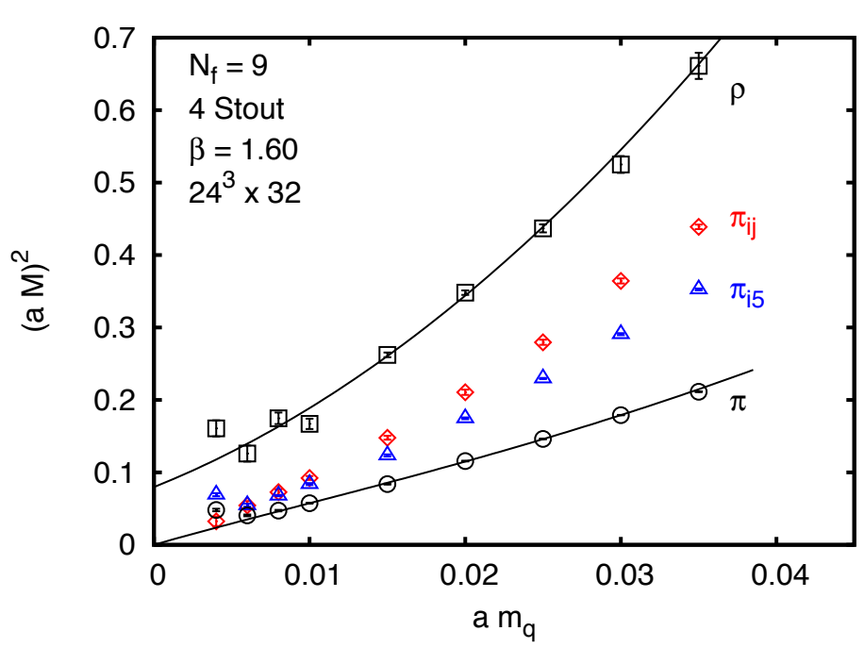
Nf=8 NLO chiral analysis in p-regime:

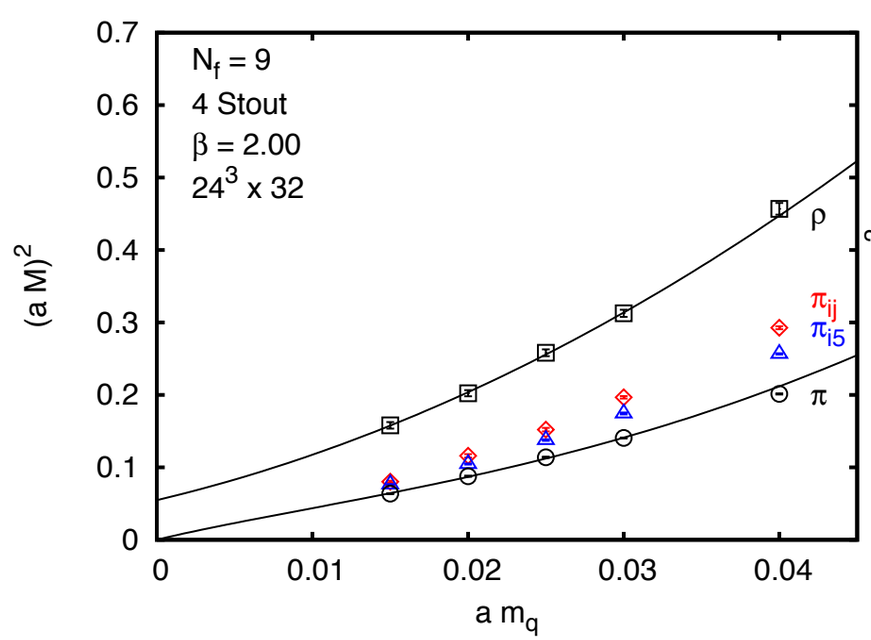


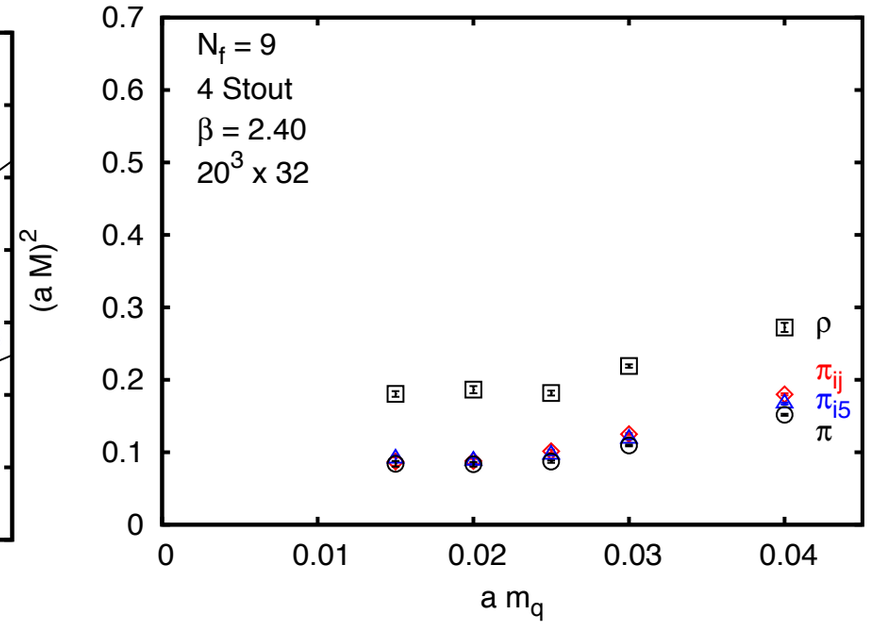
$$\frac{(m_{\pi_5^+}^{1-\mathrm{loop}})^2}{2m} = \mu\Bigg\{1 + \frac{1}{16\pi^2 f^2}\Bigg(\frac{2}{N_F}\Big[\ell(m^2_{\eta'_V}) - \ell(m^2_{\pi_V})\Big] + \frac{2}{N_F}\Big[\ell(m^2_{\eta'_A}) - \ell(m^2_{\pi_A})\Big] + \frac{1}{2N_F}\ell(m^2_{\pi_I})\Bigg) + \frac{16\mu}{f^2}\,(2L_8 - L_5)\,(2m) + \frac{32\mu}{f^2}\,(2L_6 - L_4)\,(4N_F m) + a^2 C\Bigg\}$$

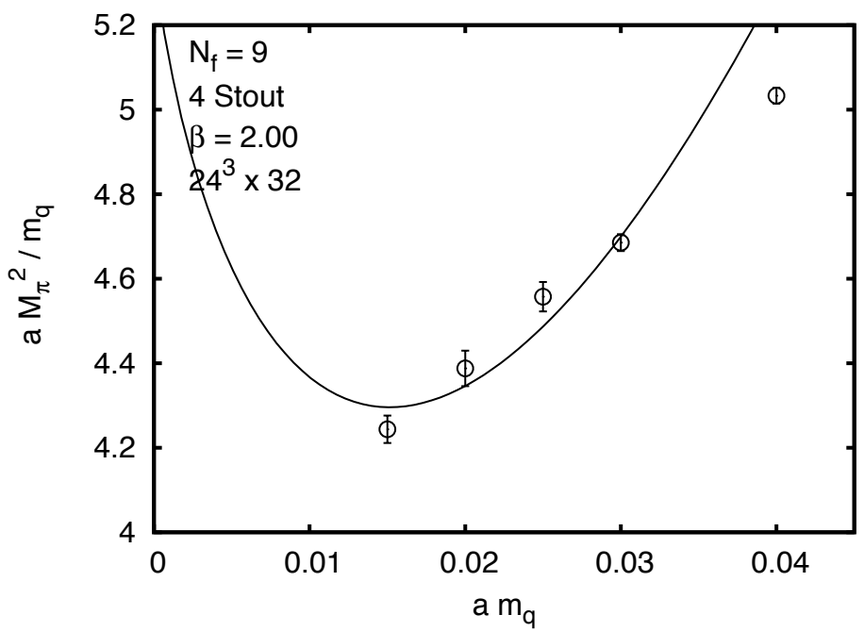
Nf=8 staggered NLO

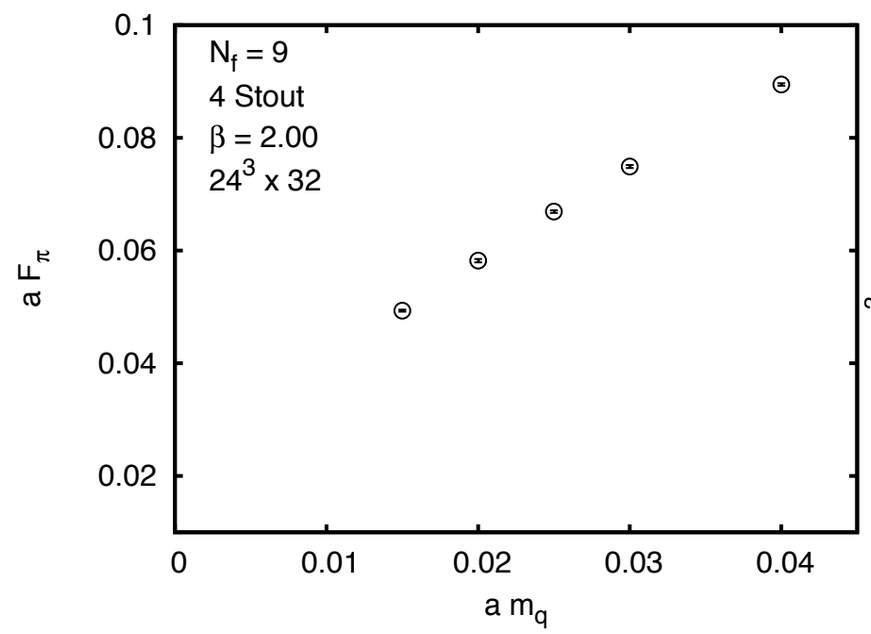
Nf=9 NLO chiral analysis in p-regime:

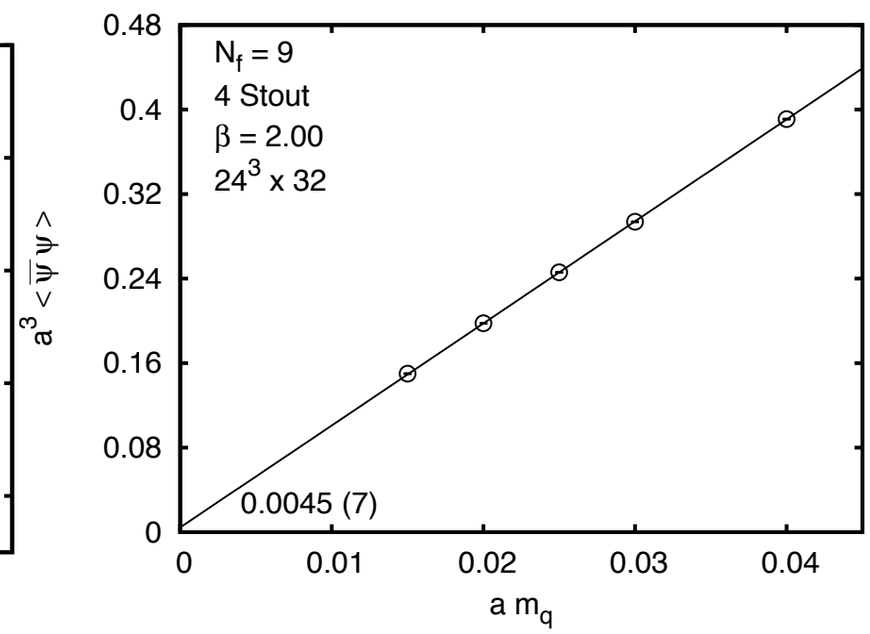










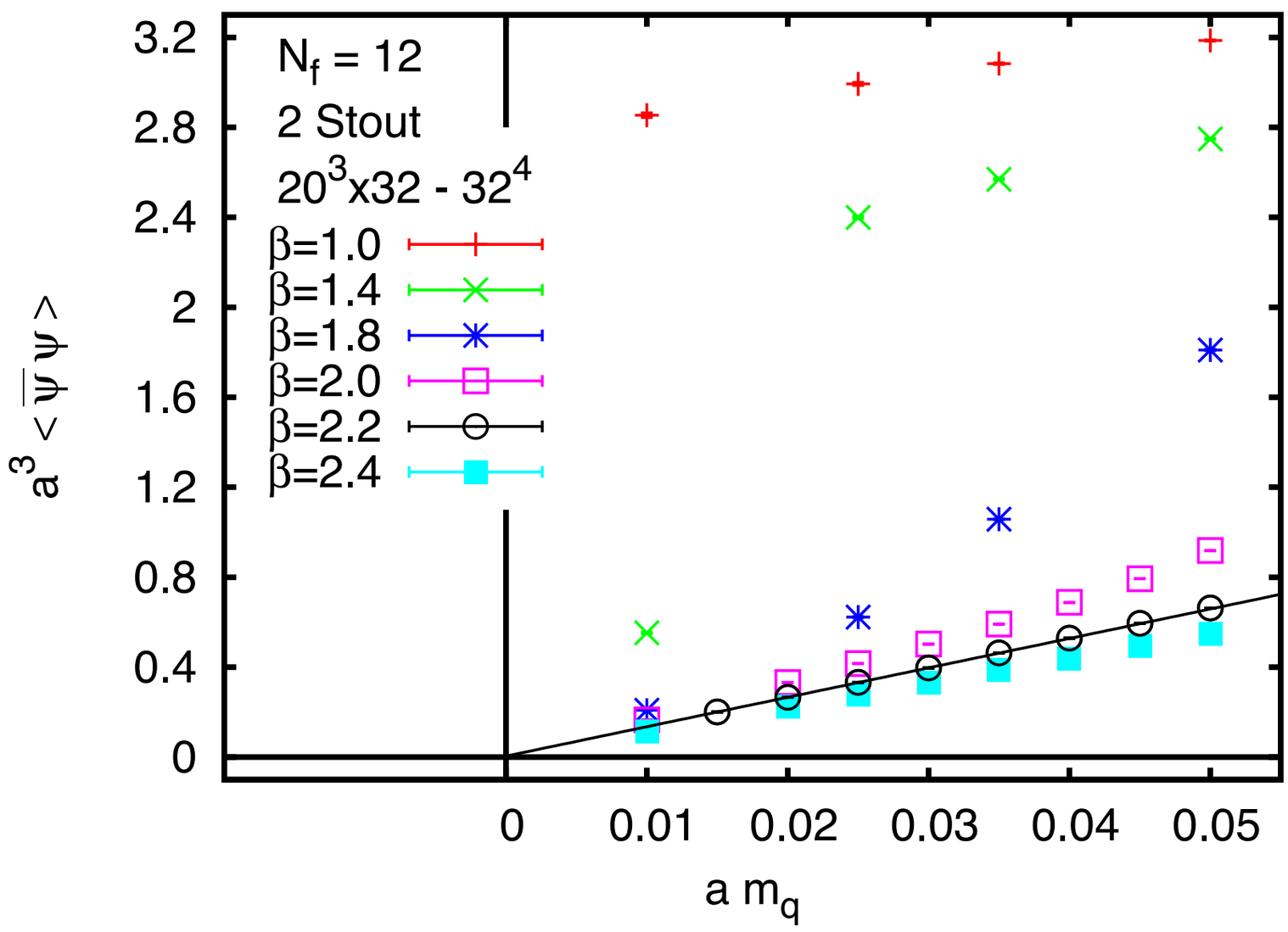


Testing rooting (nothing unusual happens)

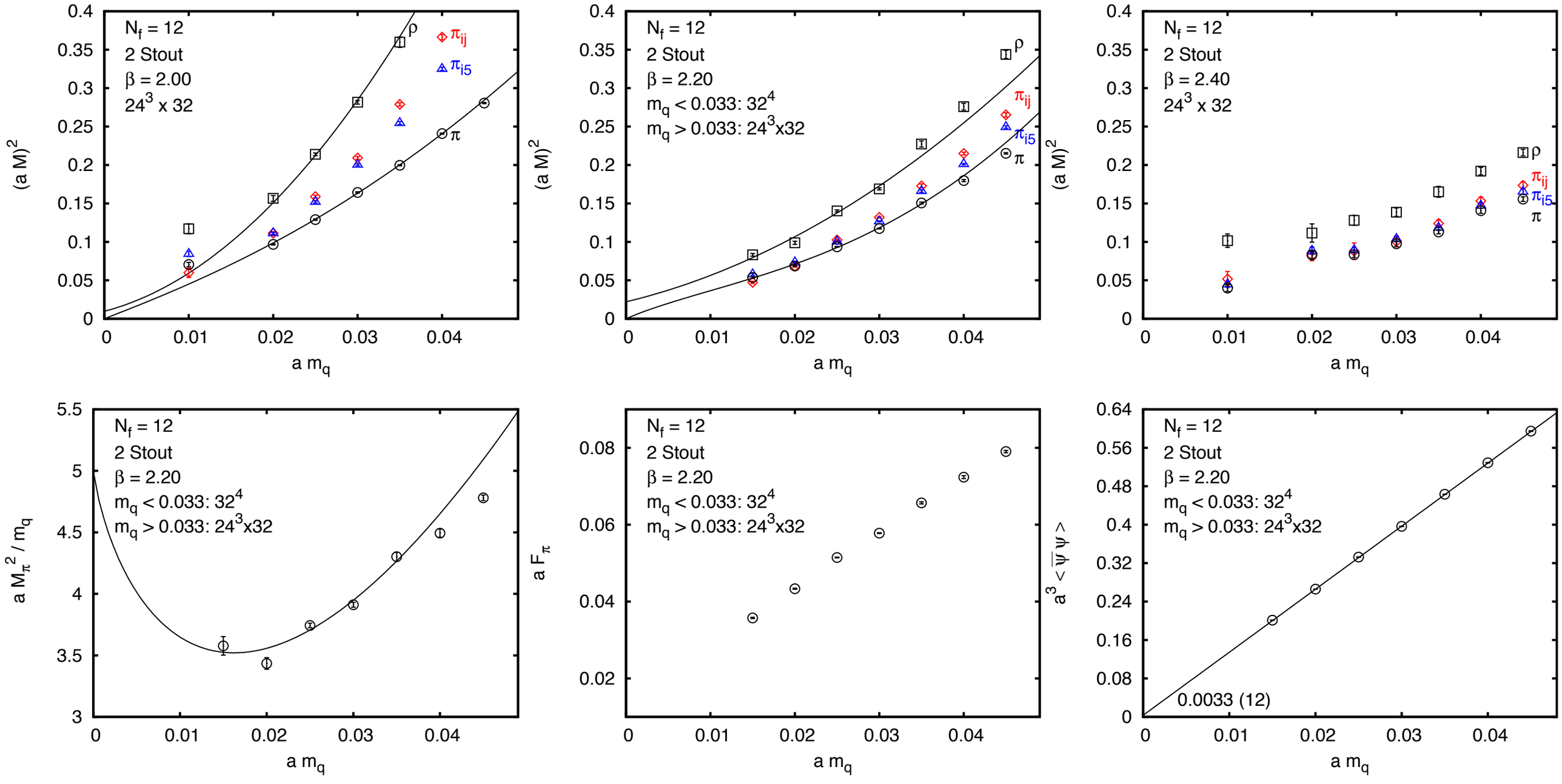
(useful for rooted sextet code, complete and running with Nf=2)

Provides additional independent info on chiral condensate trend

Nf=12 runs are far away from crossover region



Nf=12 NLO chiral analysis in p-regime:



Similar pattern to Nf=9 case!

All features exhibit chiral symmetry breaking

more work is needed

Some features of Nf=4,8,9,12 runs:

Nearly degenerate Goldstone spectra

stout action performs very well

Chiral condensate measured in F unit is enhanced as Nf increases

$$\sim \frac{<\bar{\psi}\psi>^{1/3}}{F}$$

renormalization scale is not set

Nf=4 B/F = 53(6)

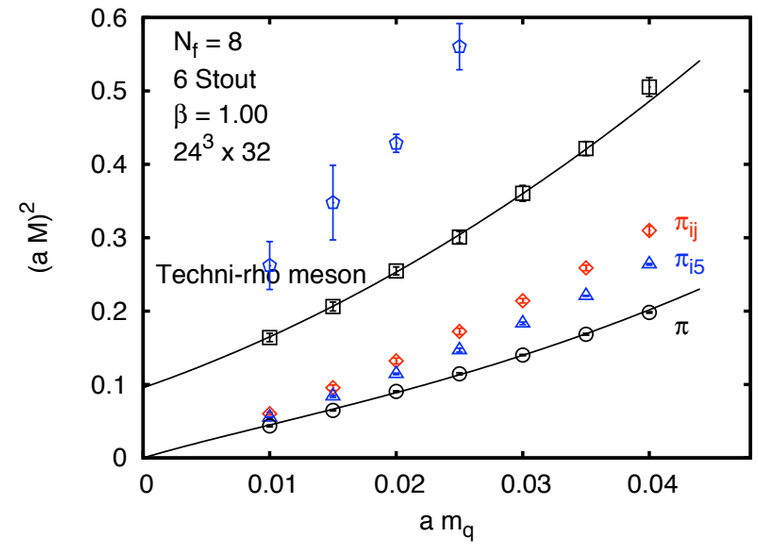
Nf=8 B/F = 157(17)

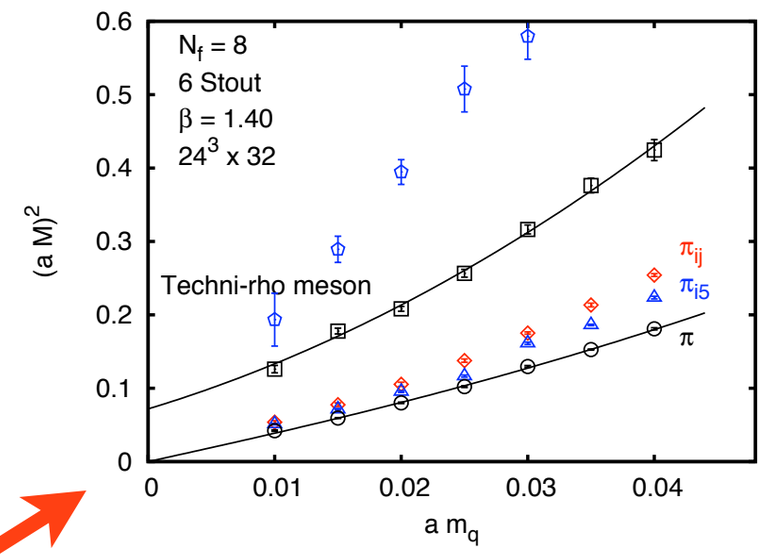
Nf=9 B/F = 125(19)

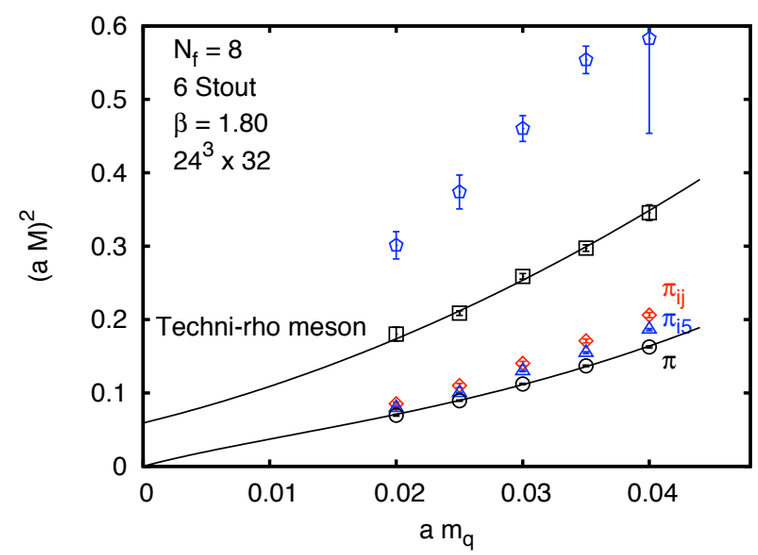
Nf=12 B/F = 209(64)

large errors, preliminary, limited to Ls=32!

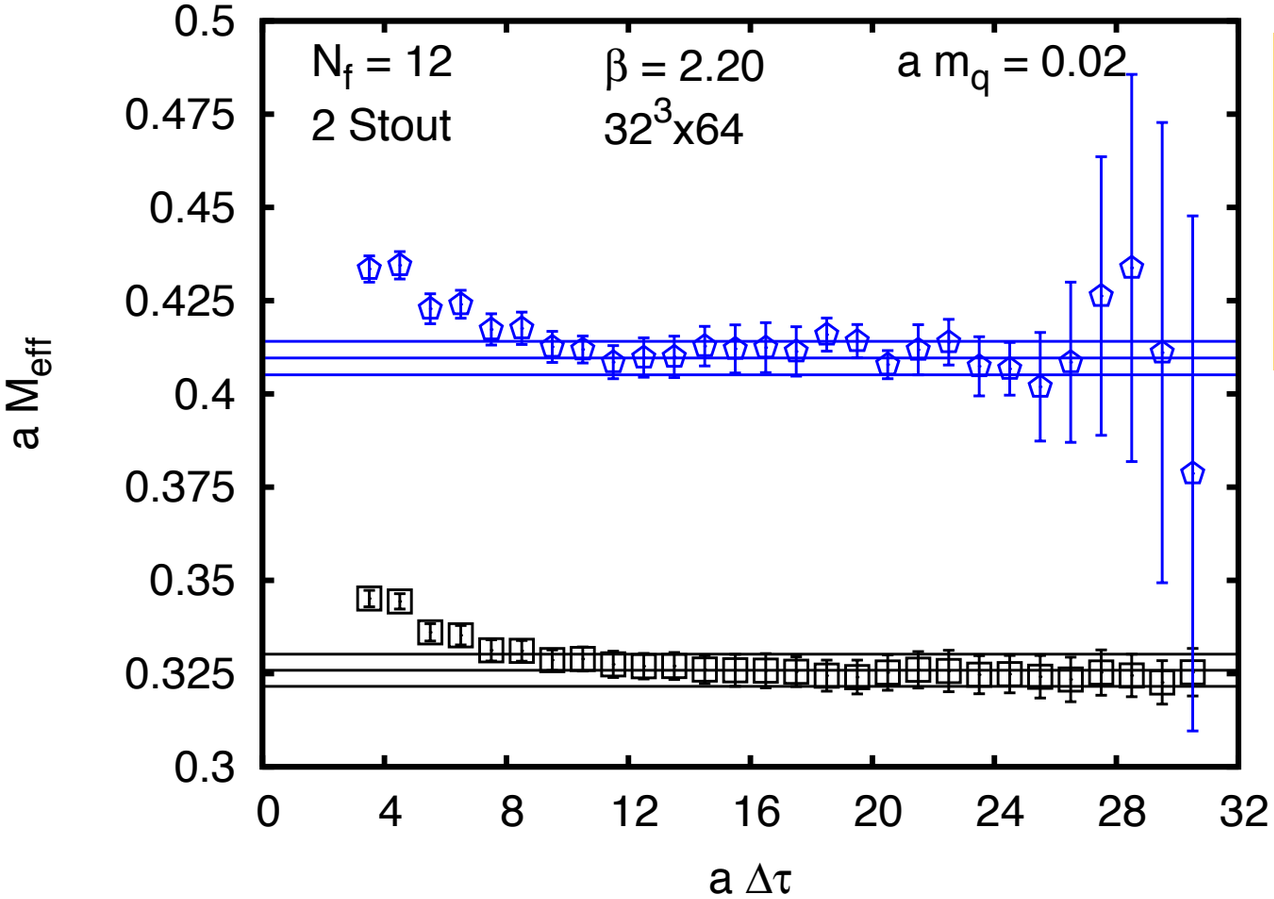
rho - A1 splitting



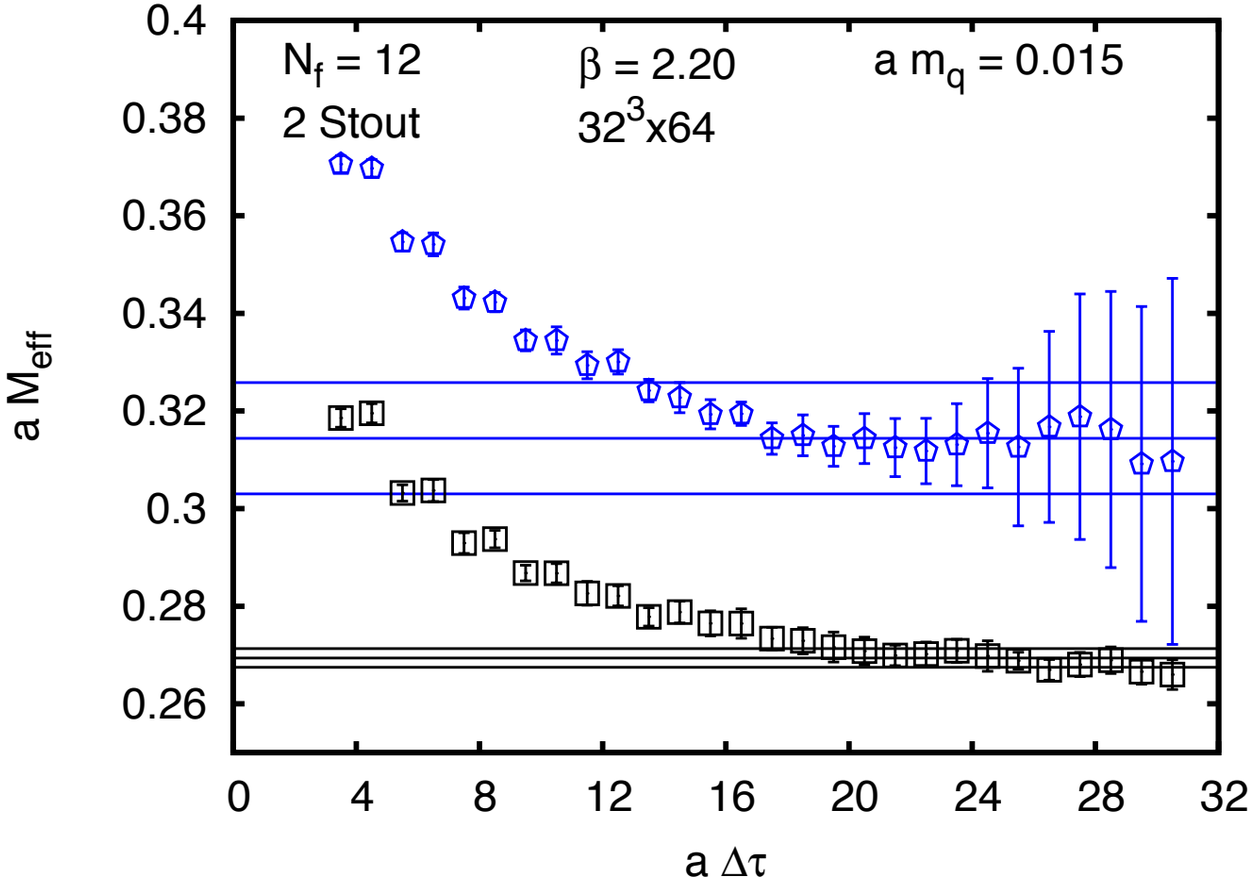




Better separtaion of rho and Goldstones at Nf=12 would require bigger runs at smaller fermion masses

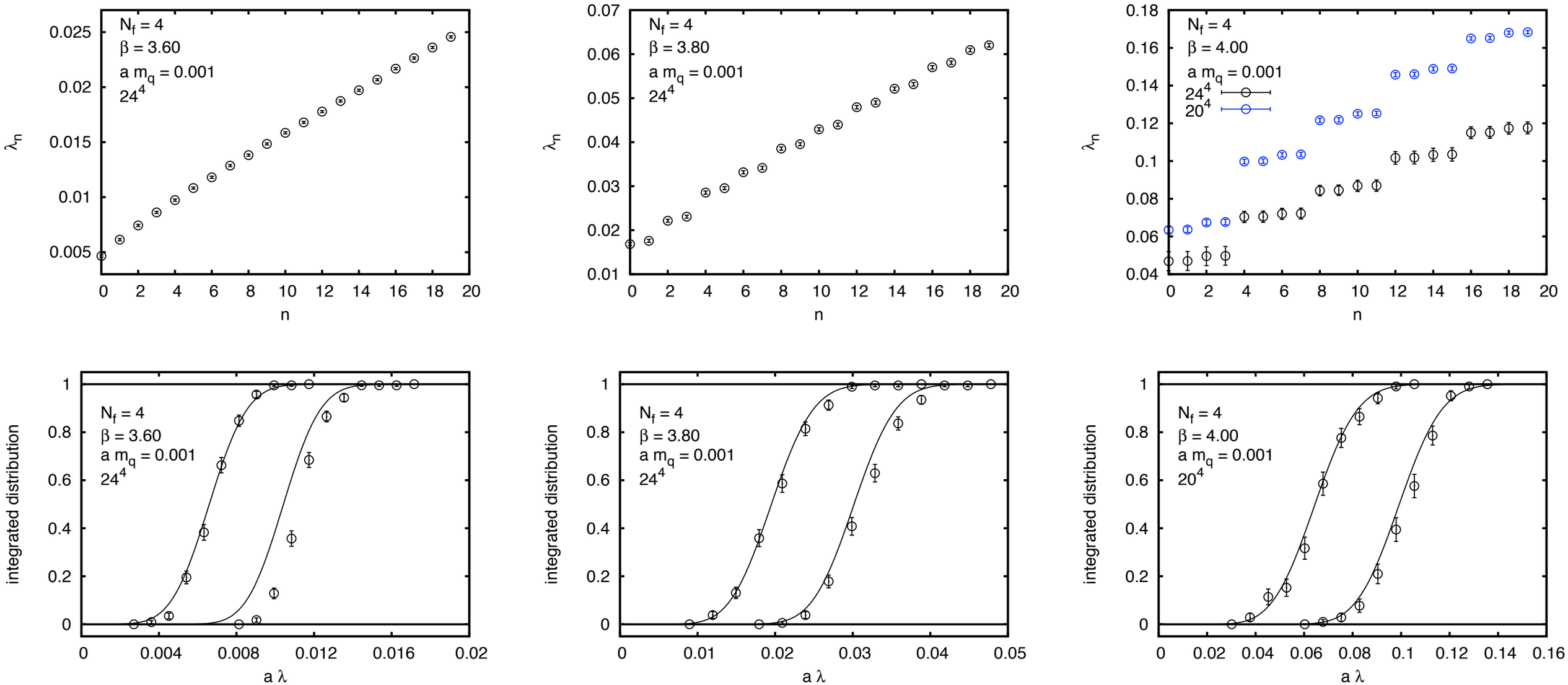


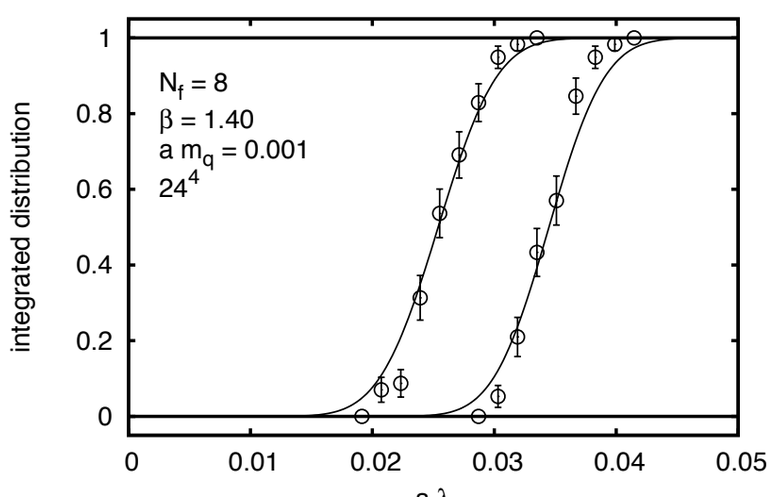
Nf=12 mq=0.02 rho-A1 splitting pulled out from single correlator with two parity partners



Nf=12 mq=0.015 rho-A1 splitting pulled out from single correlator with two parity partners

Random Matrix Theory tests in epsilon regime:





Dirac spectrum

Integrated eigenvalue distrubutions of RMT

--> quartet degeneracy

--> RMT

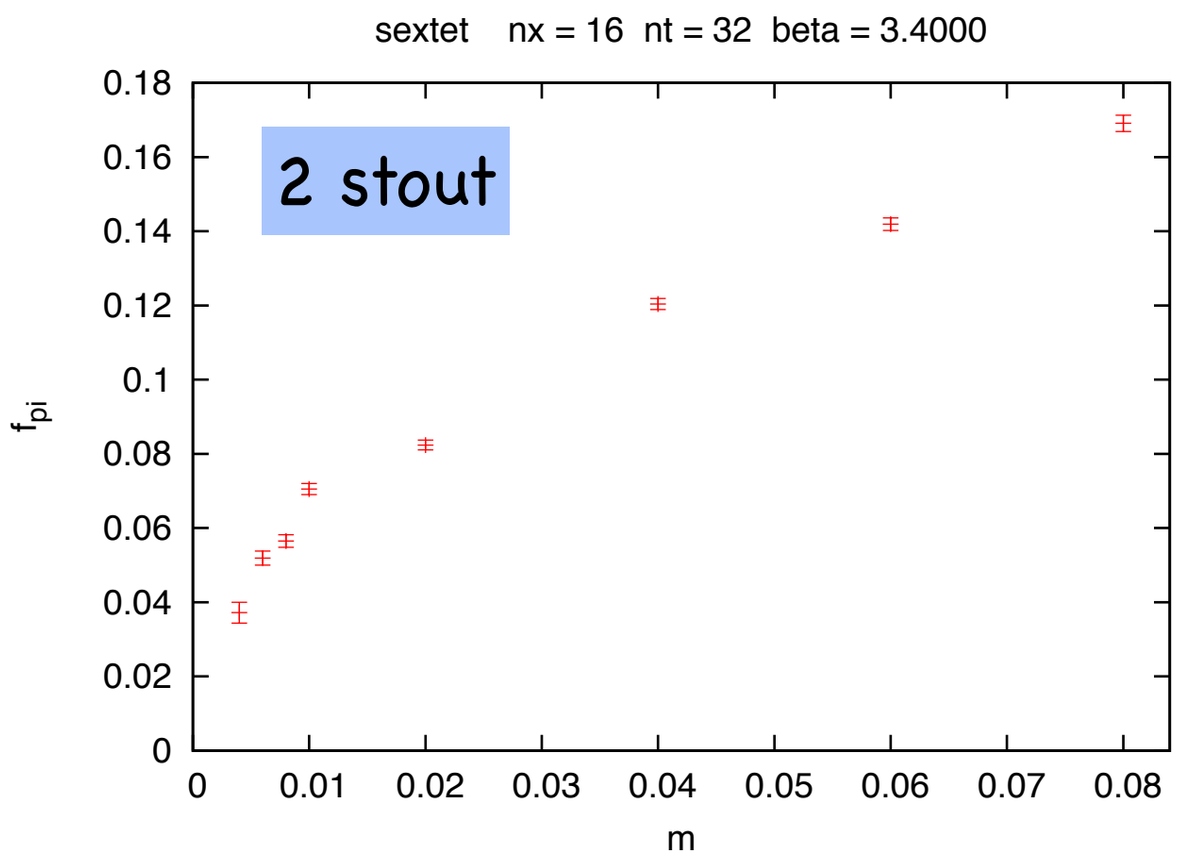
First conclusions on our Nf sequence:

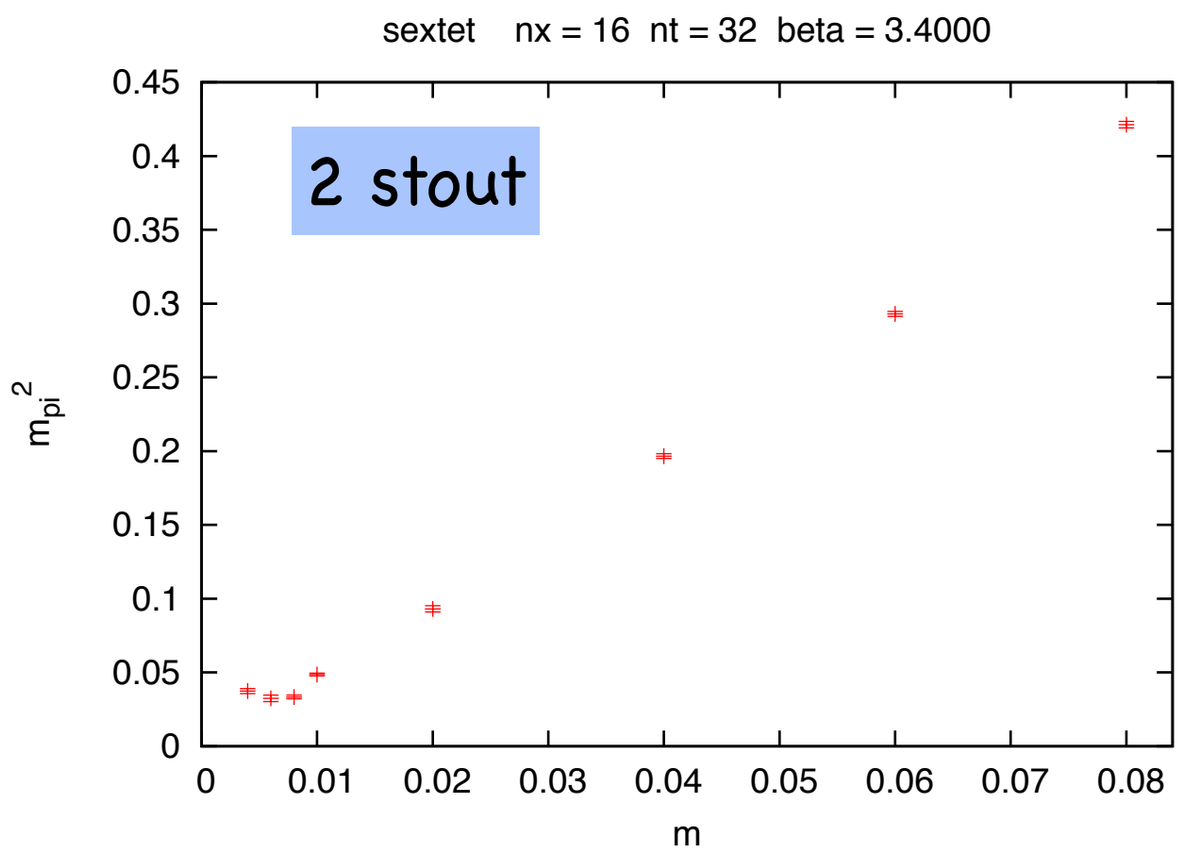
Nf=4,8,9,12 all appear to be in chirally broken phase according to several tests:

1. chiral Goldstone dynamics
2. nonvanishing condensate in chiral limit
3. rho-A1 parity doublet splitting close to chiral limit
4. epsilon regime and RMT
5. string tension and running coupling from potential/force ?

Important warning is appropriate related to the size of F*L

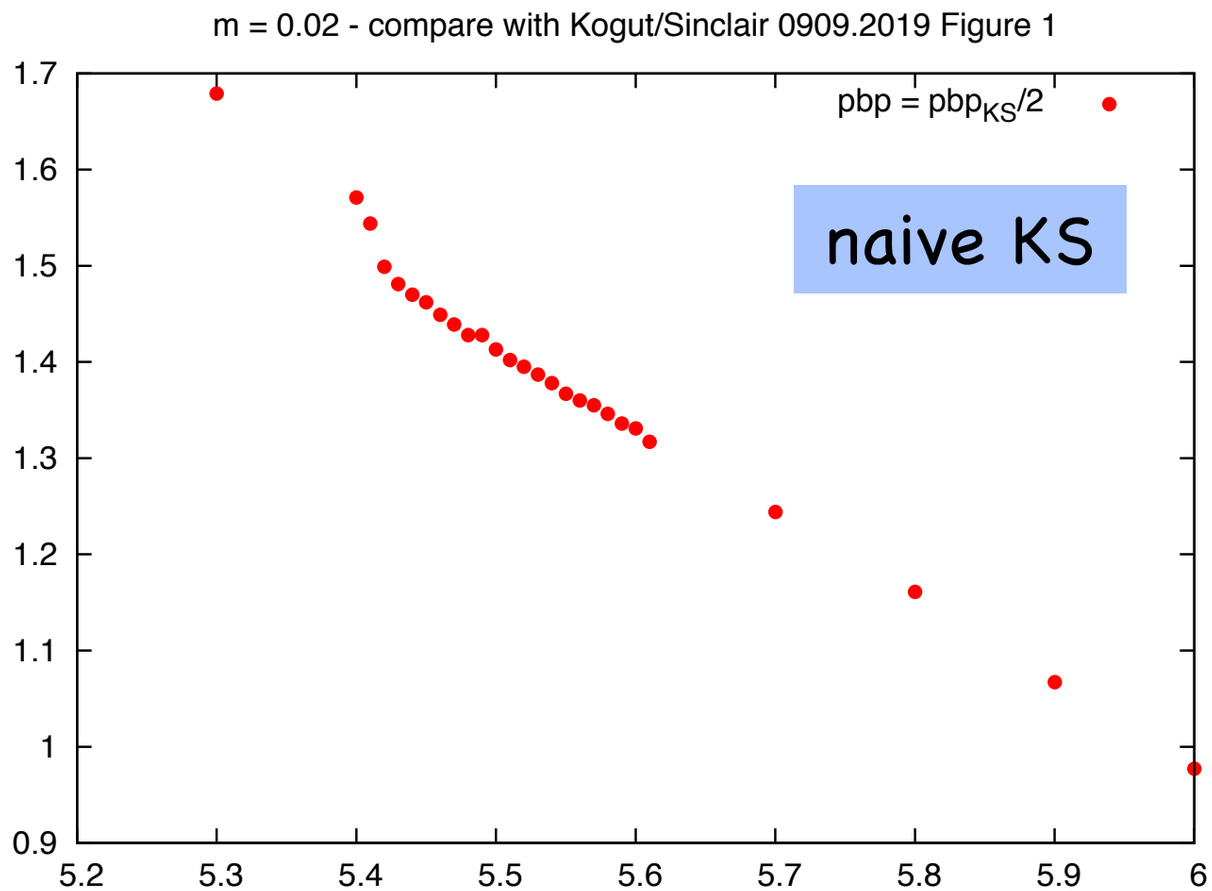
Sextet representation with Nf=2

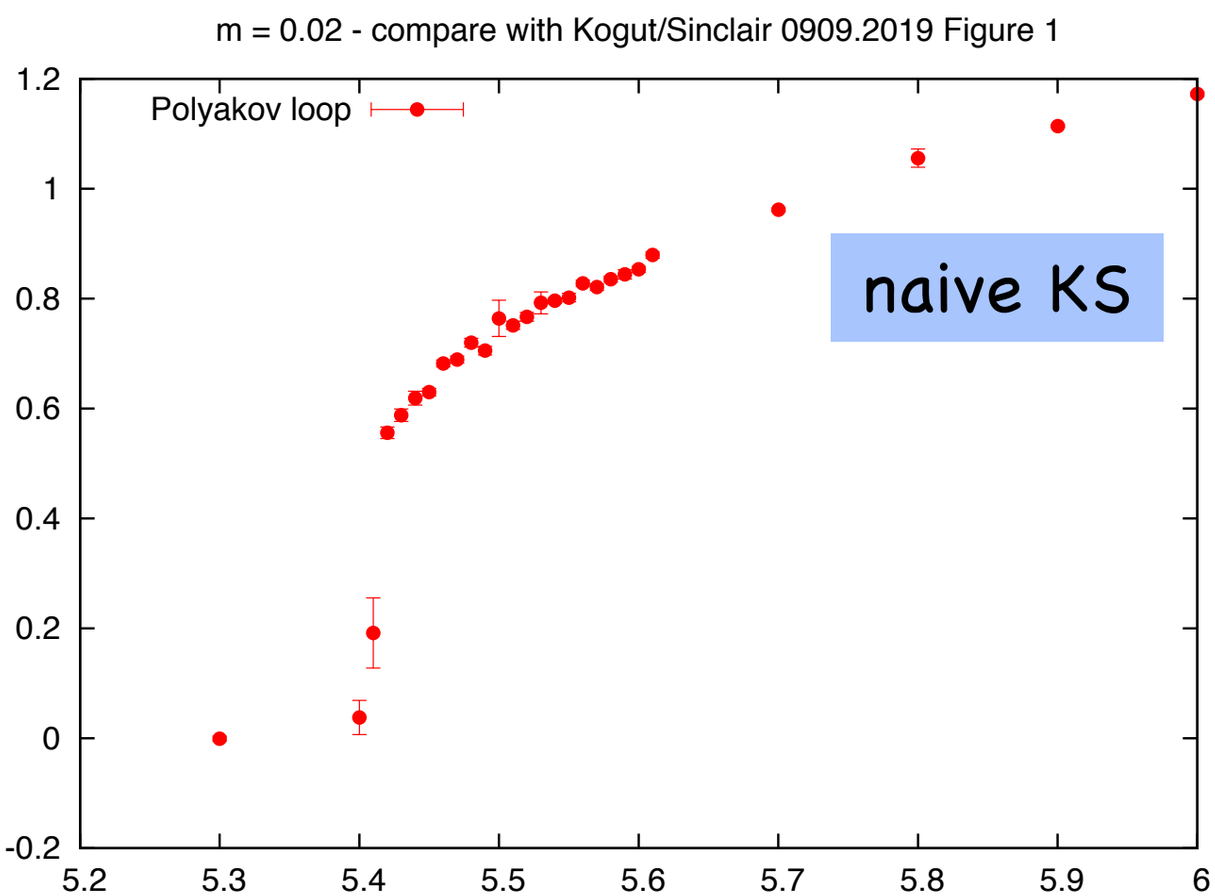




Goldstone spectrum and Fpi-> chirally broken

Will be easy 2 flavor analysis





Code reproduces Kogut-Sinclair results with the 2 stout steps disabled

Preliminary indications on our Nf=2 sextet model:

It appears to be in chirally broken phase according to several tests like the ones discussed earlier:

1. chiral Goldstone dynamics
2. nonvanishing condensate in chiral limit
3. rho-A1 parity doublet splitting close to chiral limit ?
4. epsilon regime and RMT ?
5. string tension and running coupling from potential/force ?

More favorable to reach large enough F*L values

When is F*L large enough?

This can be quantified

(epsilon, delta and p regimes are all connected)

$E_l = \frac{1}{2\theta} l(l+2)$ with $l = 0,1,2,...$ rotator spectrum for SU(2)

with $\theta = F^2 L_s^3 (1 + \frac{C(N_f = 2)}{F^2 L_s^2} + O(1/F^4 L_s^4))$ (P. Hasenfratz and F. Niedermayer)

there is overall factor $\frac{N_f^2 - 1}{N_f}$ for arbitrary N_f

$C(N_f = 2) = 0.45$ expected to grow with N_f

At $FL_s = 0.8$ the correction is 70% and grows with N_f

When expansion collapses in $\delta -$ regime, the p-regime analysis needs more scrutiny

Cross checks from several running coupling schemes is important

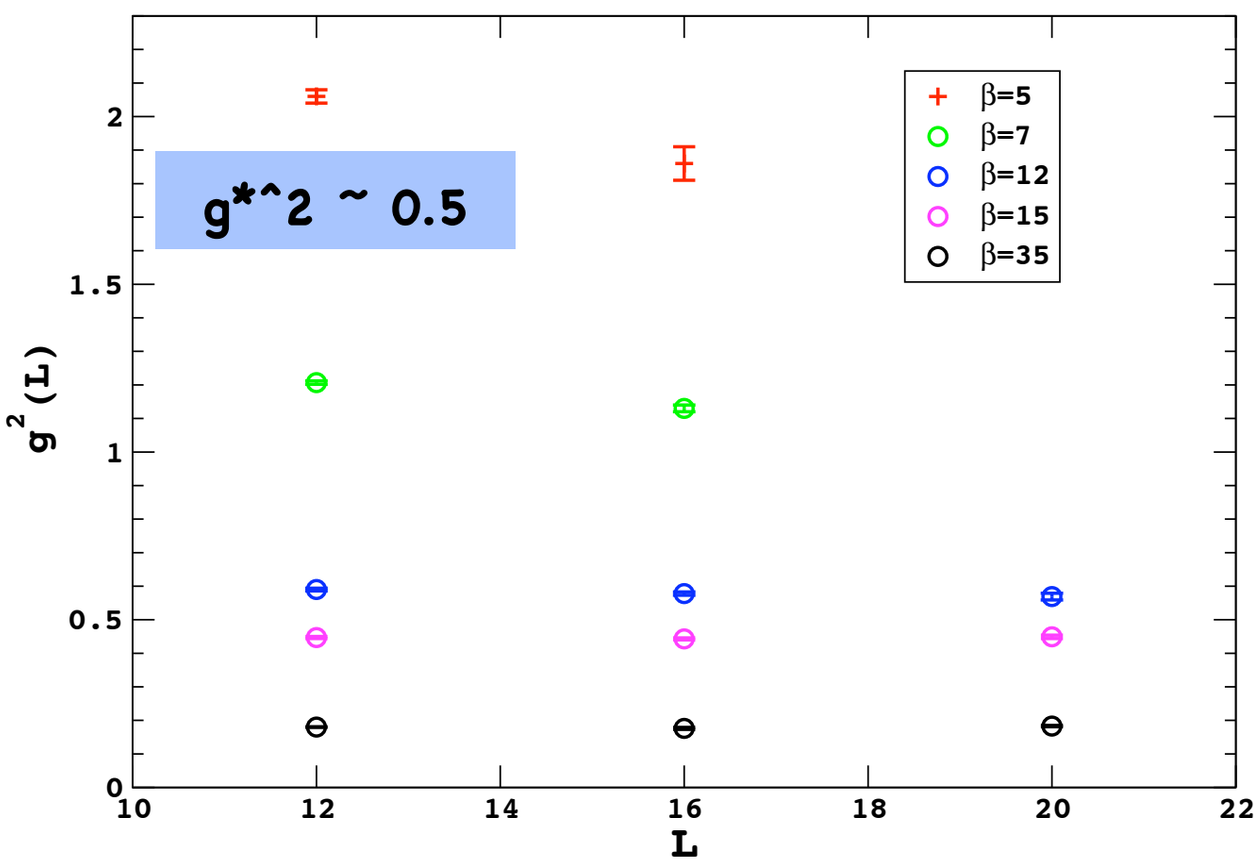
Our running coupling methods (important to have 3 methods)

SF, MCRG, Wilson loops (including $\alpha_W(R)$, V(R), F(R))

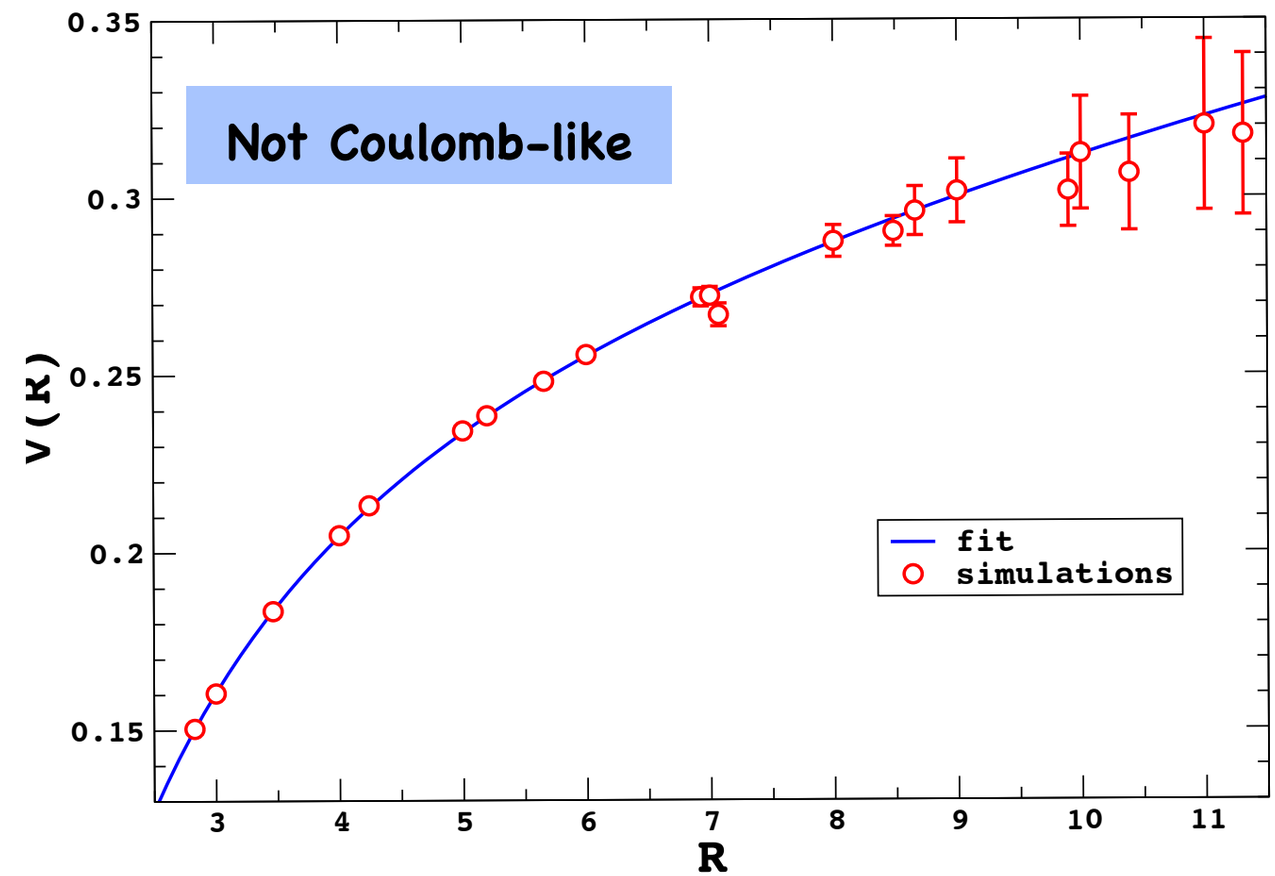
We use Wilson loop ratios, V(r) potential, and F(r) force to get the running coupling g(R) in several schemes Looks promising

We are running with R, or with L when R/L fixed (different schemes)

Nf=16 Creutz coupling running



N_f=12, 2-stout 32^3x64, β=2.2, m=0.015

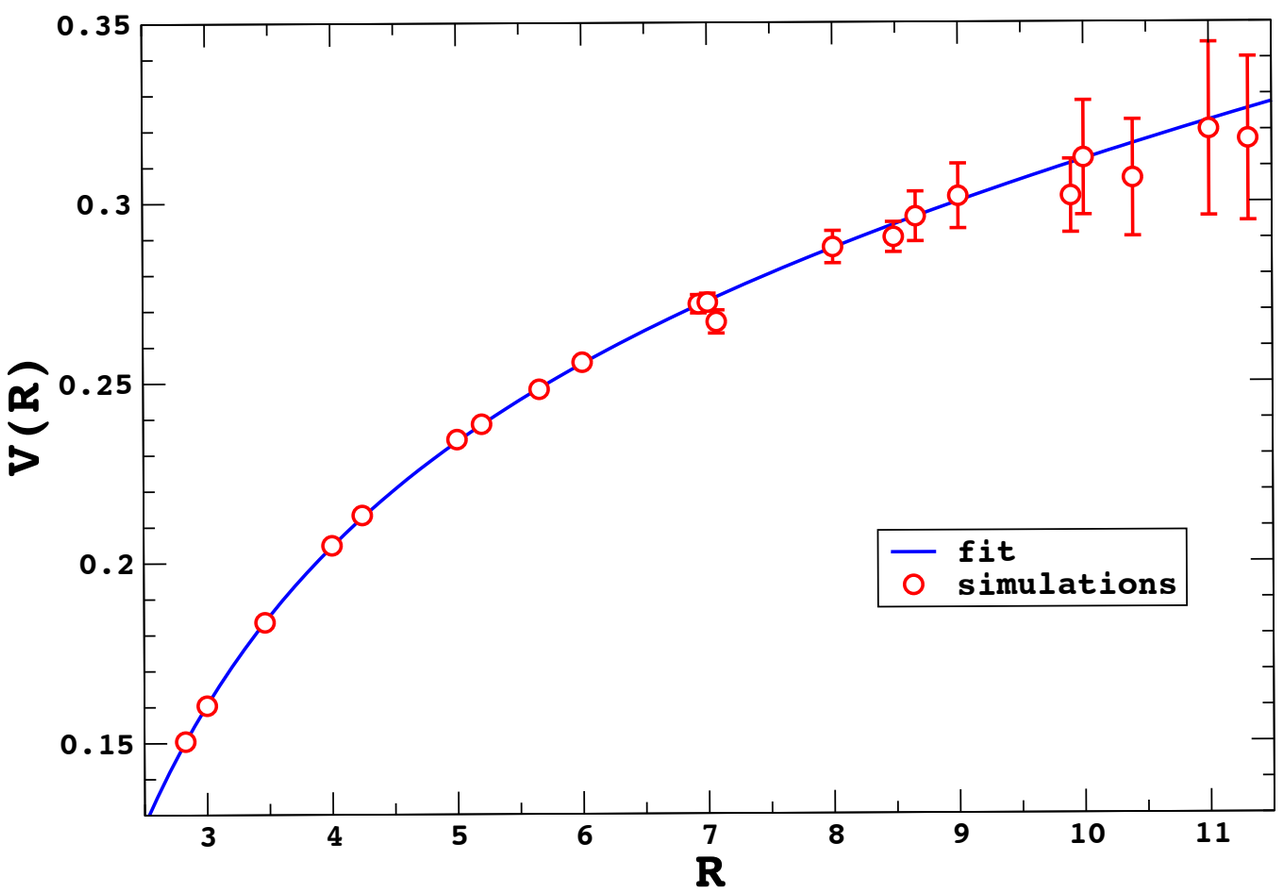


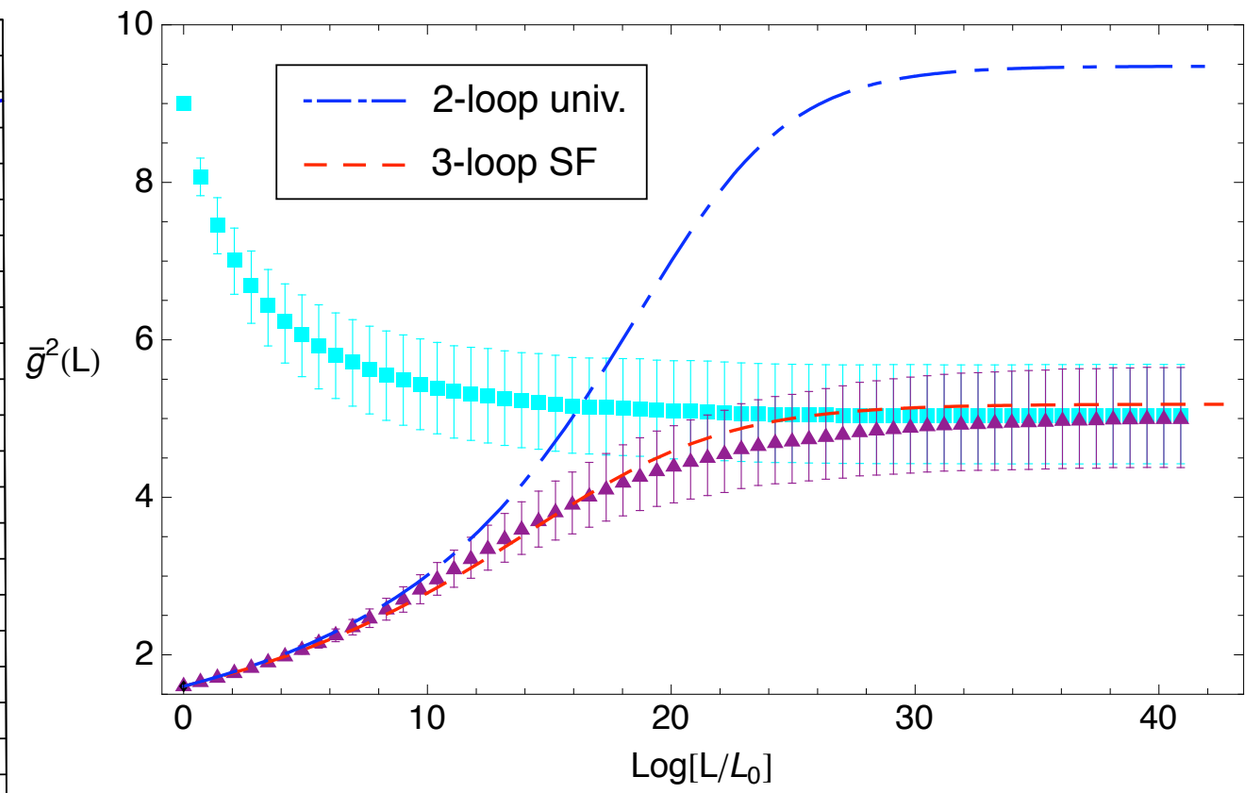
Our new calculation:

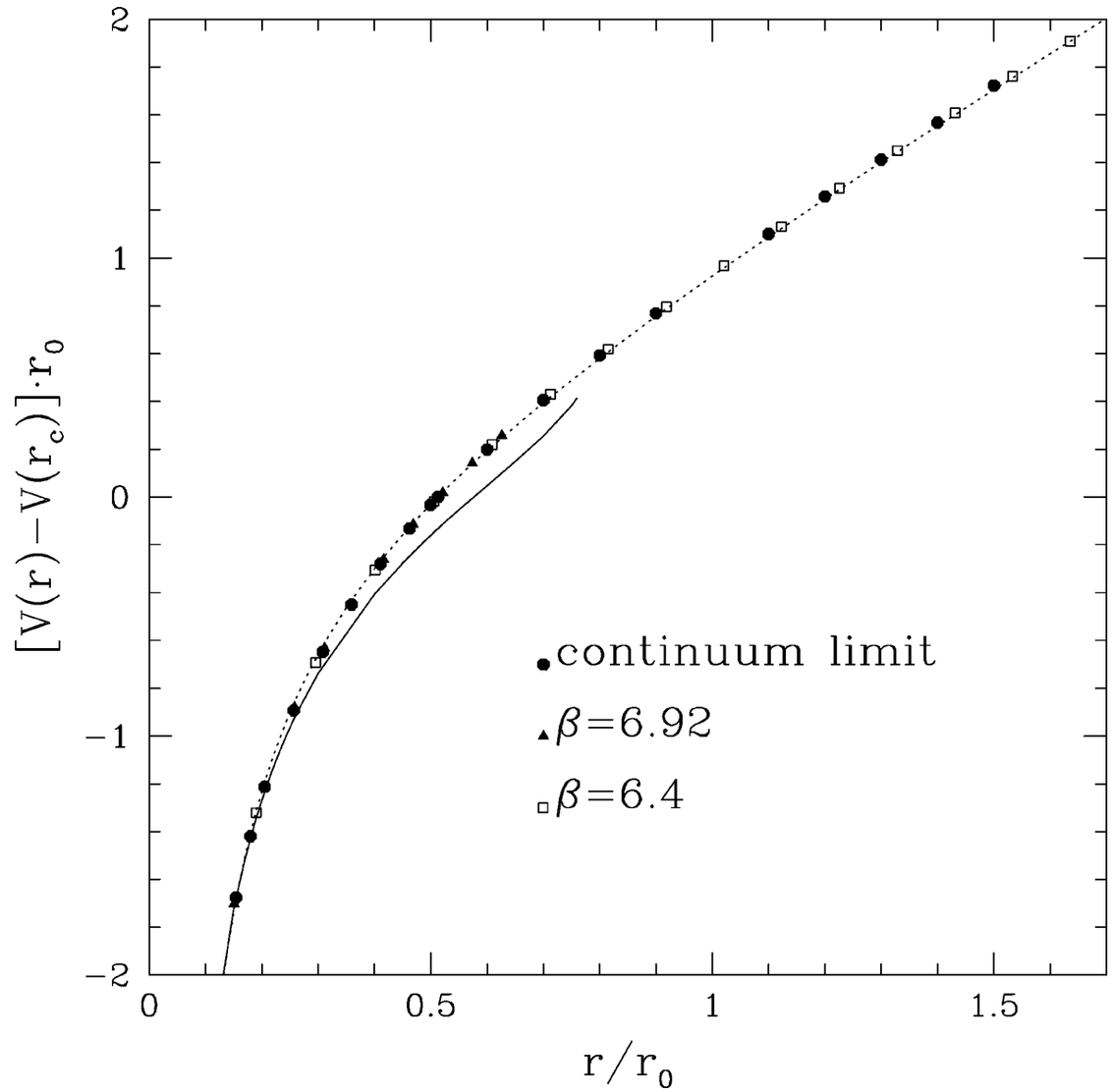
use V(r) potential and F(r) force to get traditional running g(r) in several schemes just like in QCD

Looks very promising

N_f=12, 2-stout 32^3x64, β=2.2, m=0.015







Quenched test works Necco-Sommer

$$F(r) = \frac{C_F \bar{g}^2_{qq}(r)}{4\pi r^2}, \qquad C_F = \frac{4}{3},$$

$$-r\frac{d}{dr}\bar{g}_{qq} = \beta(\bar{g}_{qq}) = -\sum_{\nu=0}^{2} b_\nu \bar{g}_{qq}^{2\nu+3}, \qquad b_0 = \frac{11}{16\pi^2}, \qquad b_1 = \frac{102}{(16\pi^2)^2},$$

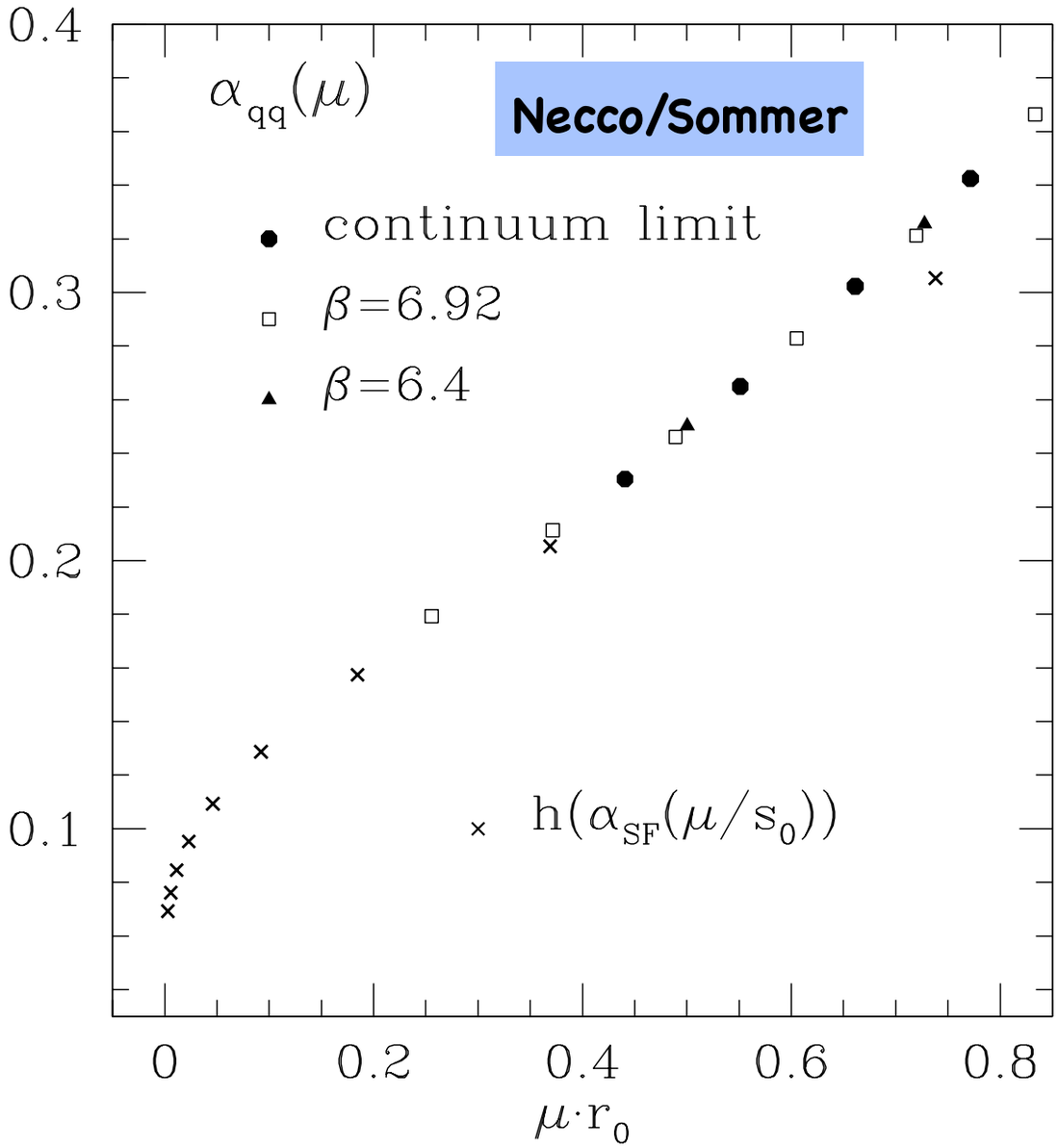
$$b_2 = \frac{1}{(4\pi)^6}\left(-3470 + 2519\frac{\pi^2}{3} - 99\frac{\pi^4}{4} + 726\zeta(3)\right).$$

$$F(r) = \sigma + \frac{\pi}{12r^2}, \qquad \sigma r_0^2 = 1.65 - \frac{\pi}{12}$$

Infinite volume, continuum extrapolated

limited r/ro range between 0.15 and 0.3

we try to run with the volume!

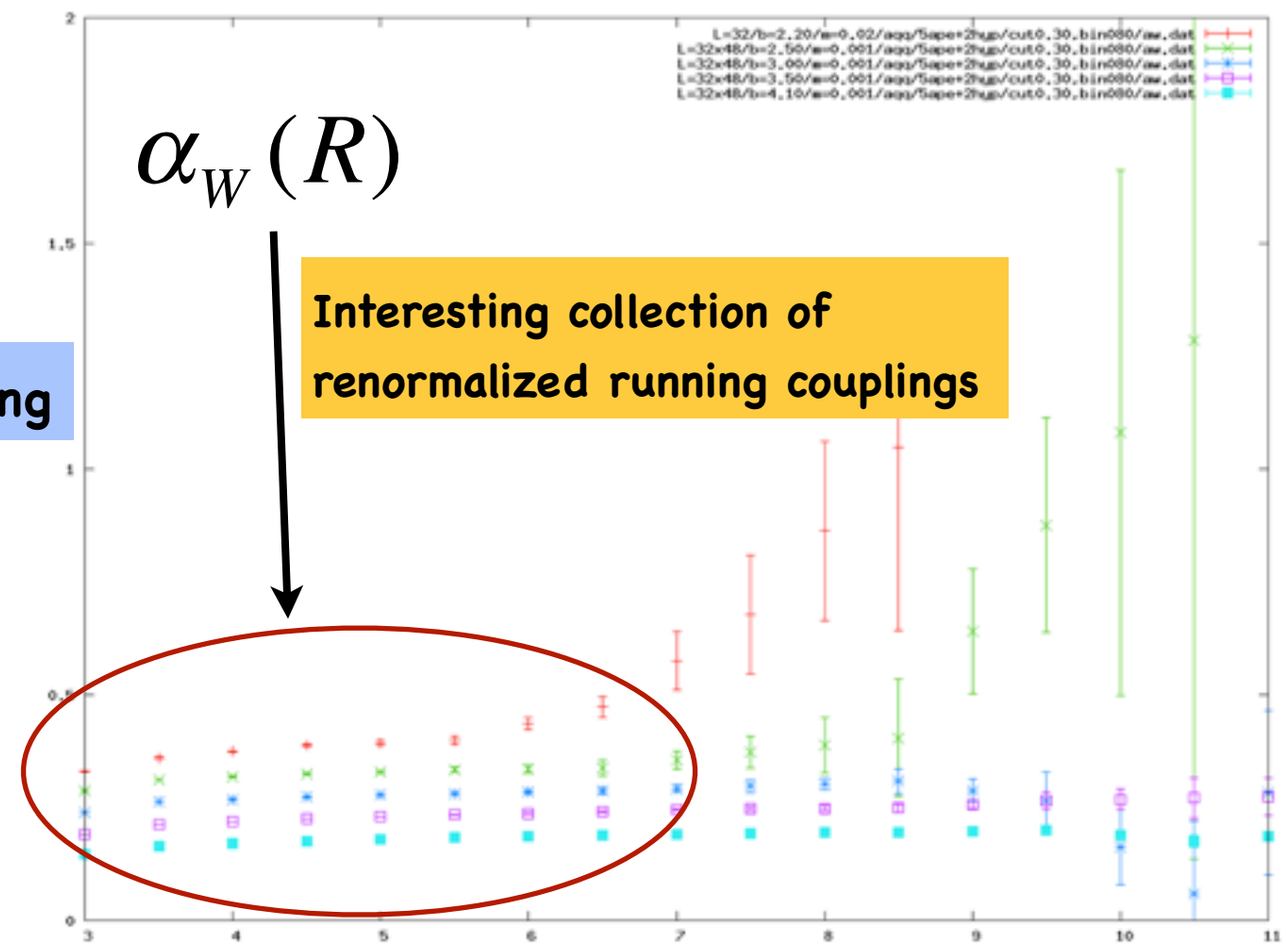


Very difficult to resolve fixed point from walking

Running coupling from force and SF running nicely match for Nf=0 and Nf=2

We have difficulties to match data from the Force/Creutz running coupling and the Yale SF running at Nf=12 in the relevant coupling range

Will requires further careful studies

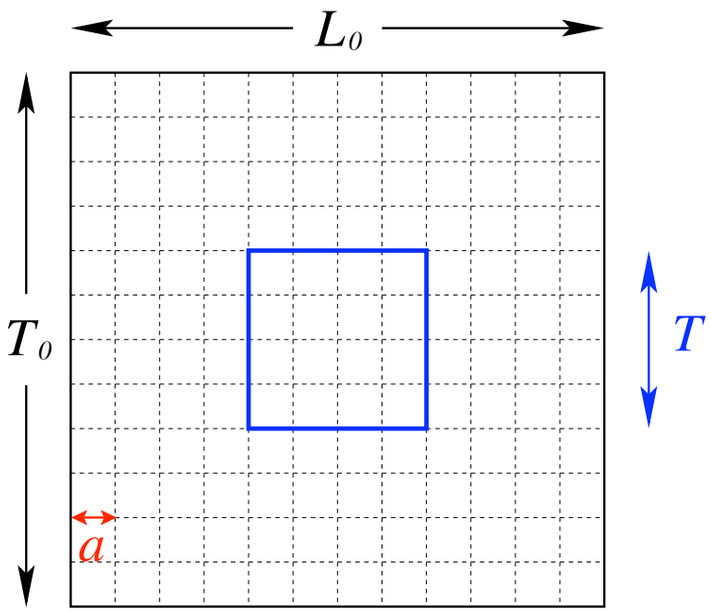


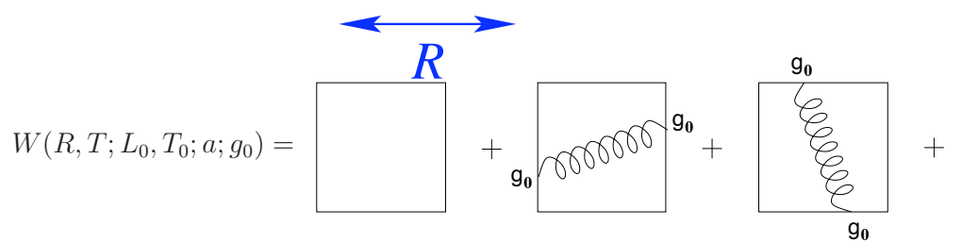
Running gauge coupling from RG on large Wilson loops

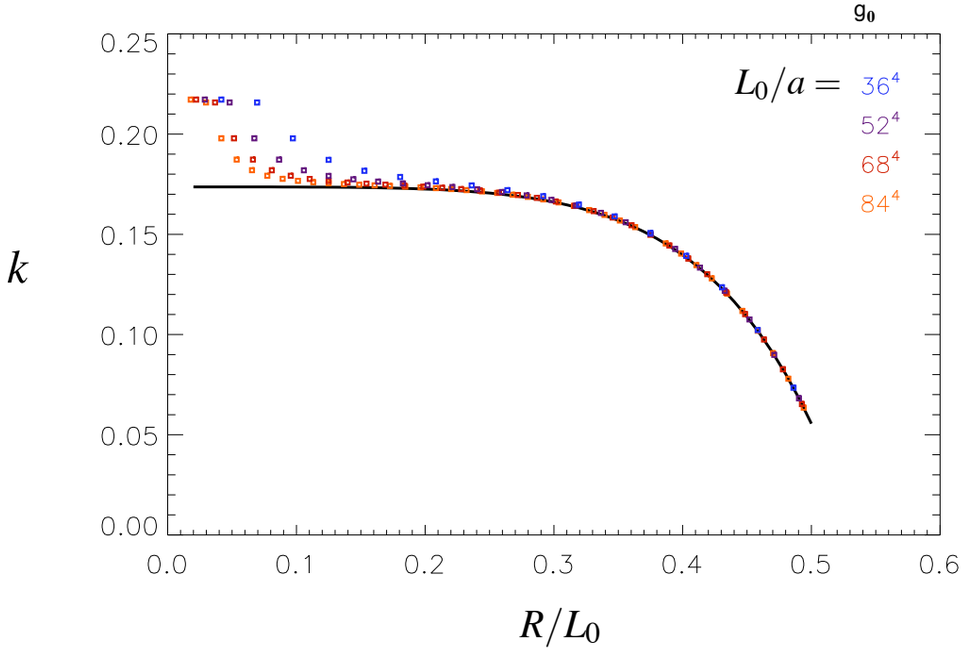
two groups: our group and Bilgici et al. (generalization from earlier work)

problem with Bilgici et al: implementation was not independent of Schrodinger functional method (corrected now)

Important that our implementation is







define renormalized coupling from second derivative of Wilson loops running with L if R/L is kept fixed:

$$k \cdot g_R^2(L_0, \tfrac{R}{L_0}) = -R^2 \frac{\partial^2}{\partial R \partial T} \ln \langle W(R,T;L_0,T_0) \rangle \Big|_{T=R}$$

k is geometric factor (cutoff dependent on lattice) defined from tree level relation with the bare coupling g_0

$$-R^2 \frac{\partial^2}{\partial R \partial T} \ln \langle W(R,T;L_0) \rangle^{\text{tree}} \Big|_{T=R} = k g_0^2$$

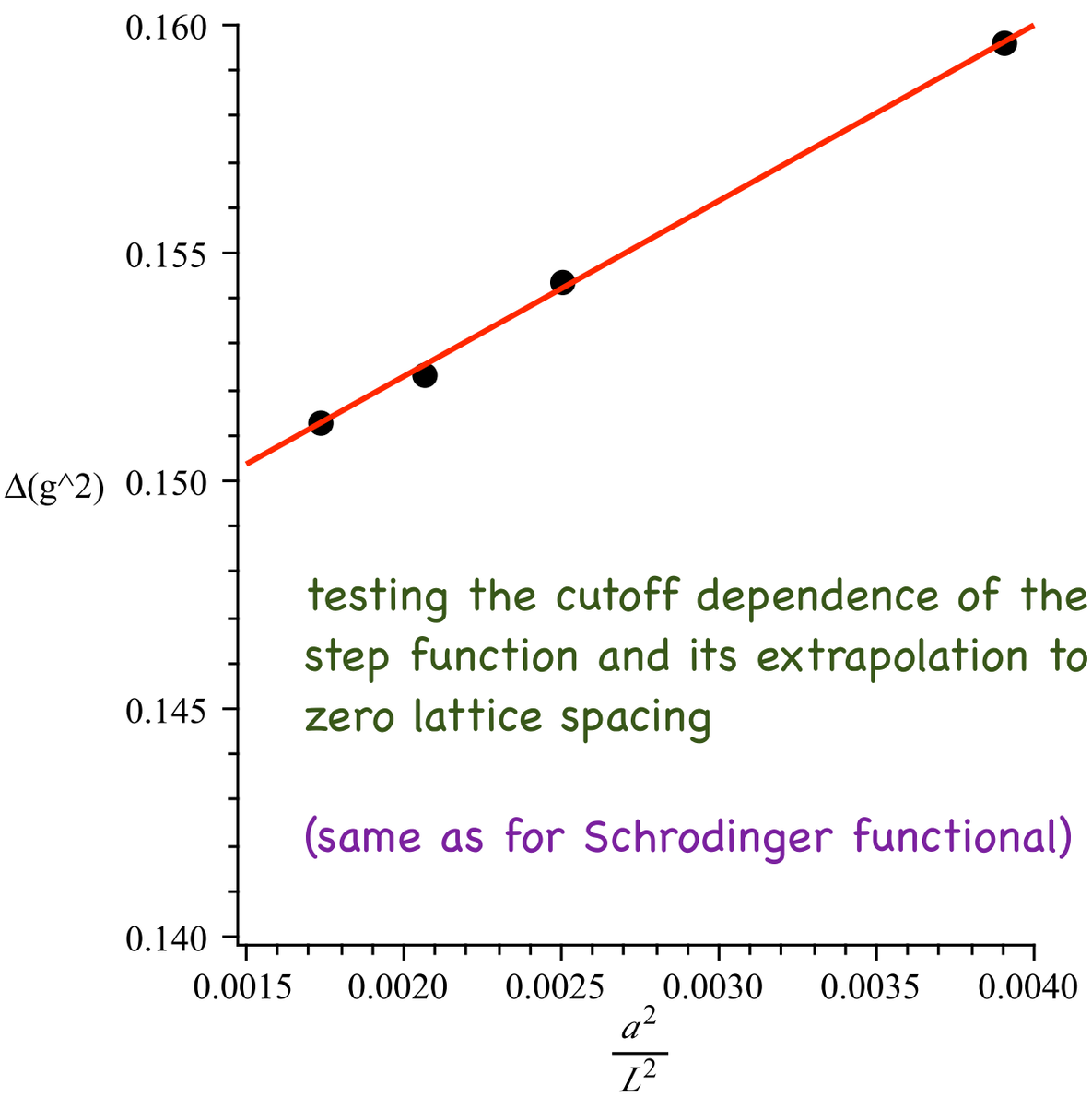
Lattice implementation requires the study of the step function together with its cutoff dependence

Useful alternative to Schrodinger functional?

Wilson loops could be replaced by Polyakov loop correlators

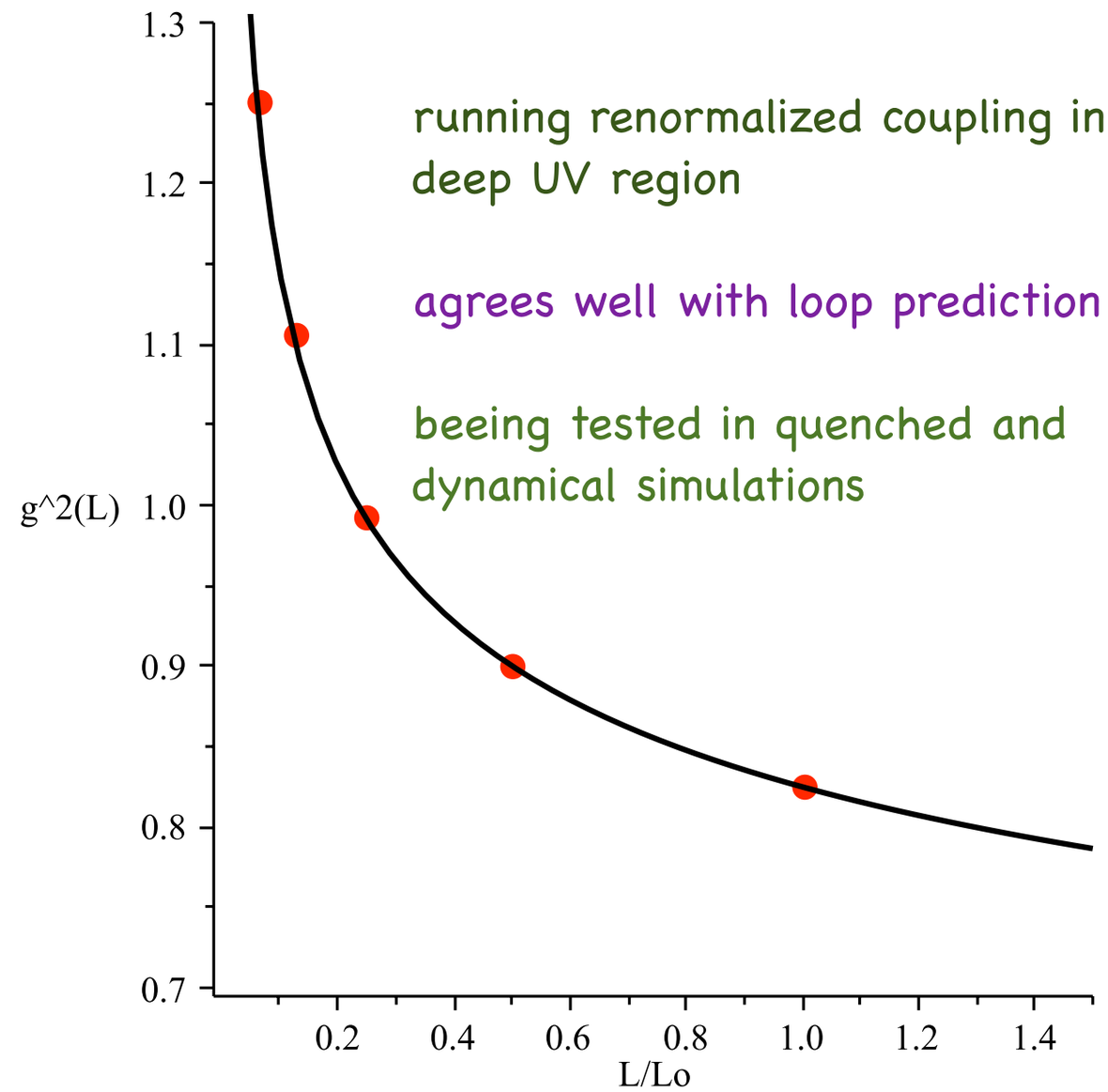
We first tested the method at weak coupling for large Wilson loops. Rather than simulating Wilson loops with Monte Carlo, we calculated (simulated) them analytically using the boosted coupling procedure of Lepage and McKenzie which reproduces even large Wilson loops accurately

The finite volume dependence was obtained from Urs Heller's code who calculated the Wilson loops in bare perturbation theory
(thanks to Urs Heller and Paul Mackenzie for the help they provided)



testing the cutoff dependence of the step function and its extrapolation to zero lattice spacing

(same as for Schrodinger functional)



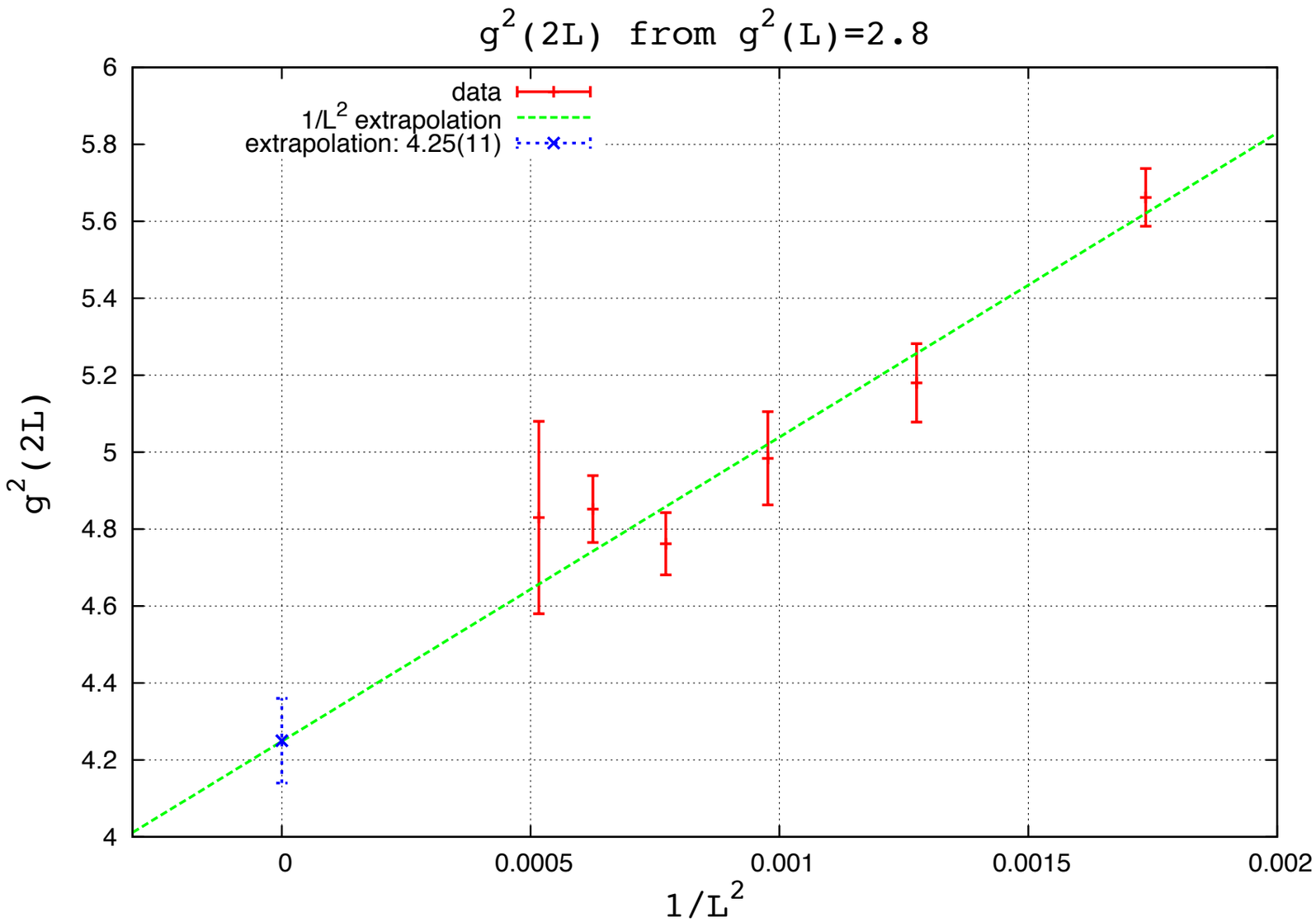
running renormalized coupling in the deep UV region

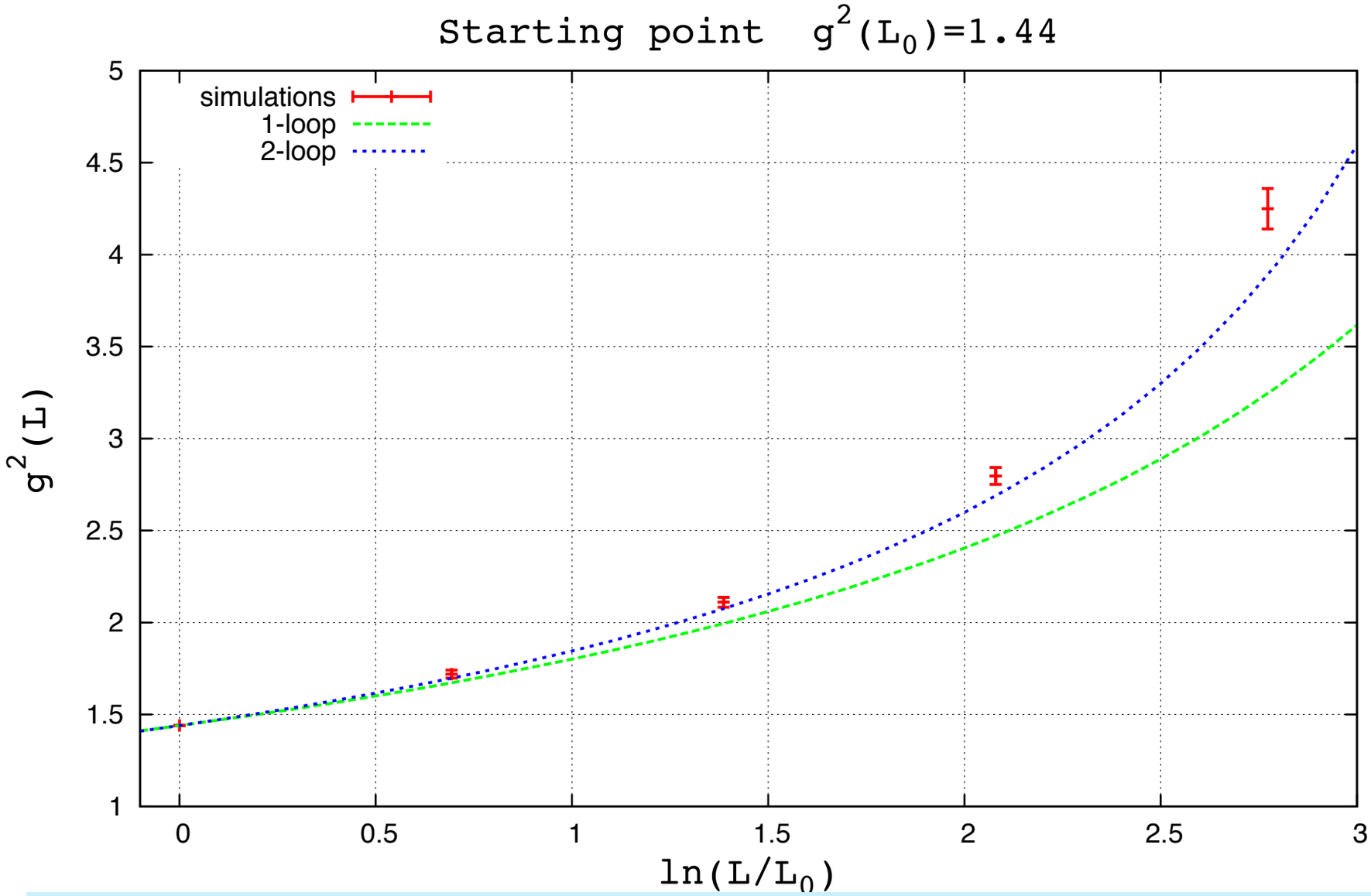
agrees well with loop prediction

beeing tested in quenched and dynamical simulations

Onto Monte Carlo now -->

Quenched SU(3) simulation extrapolating the step function renormalized coupling to zero cutoff at fixed finite physical box size:





The running coupling of our Wilson-Creutz scheme

In quenched SU(3) simulation renormalized coupling is running with physical box size L without lattice cutoff effects

Onto dynamical fermions: fairly strong cutoff effects but no sign of Nf=12 conformal fixed point

Conclusions and Outlook

- Our focus shifted to Nf=10-16 range (and beyond?)
  Nf=12 chiral symmetry breaking and running coupling
  from V(r) and F(r) and Wilson loops

- Nf=12 might be close enough to realize walking technicolor but
  otherwise (like the S-parameter) we do not know how it will perform

- What is the fate of the Nf=2 sextet model? Next
  controversy is brewing? Walking Nf=2 sextet would be a
  favorite candidate for composite Higgs (mass generation?)

- Zero mode dynamics important at weak coupling inside
  conformal window

- Reliable EW precision quantities (S/T/U) will be important to
  get accurately once we settle on the candidate model(s)