Toward the Nearly Conformal Composite Higgs Mechanism

Julius Kuti

Lattice 2010

June 14-19, 2010

With Lattice Higgs Collaboration members:

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

Outline

1. Nf=12

- detailed chiral analysis with estimates of serious limitations

2. Nf=2 sextet chiral symmetry breaking

- first steps toward complete chiral analysis (preliminary)
- this model can be settled!

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]

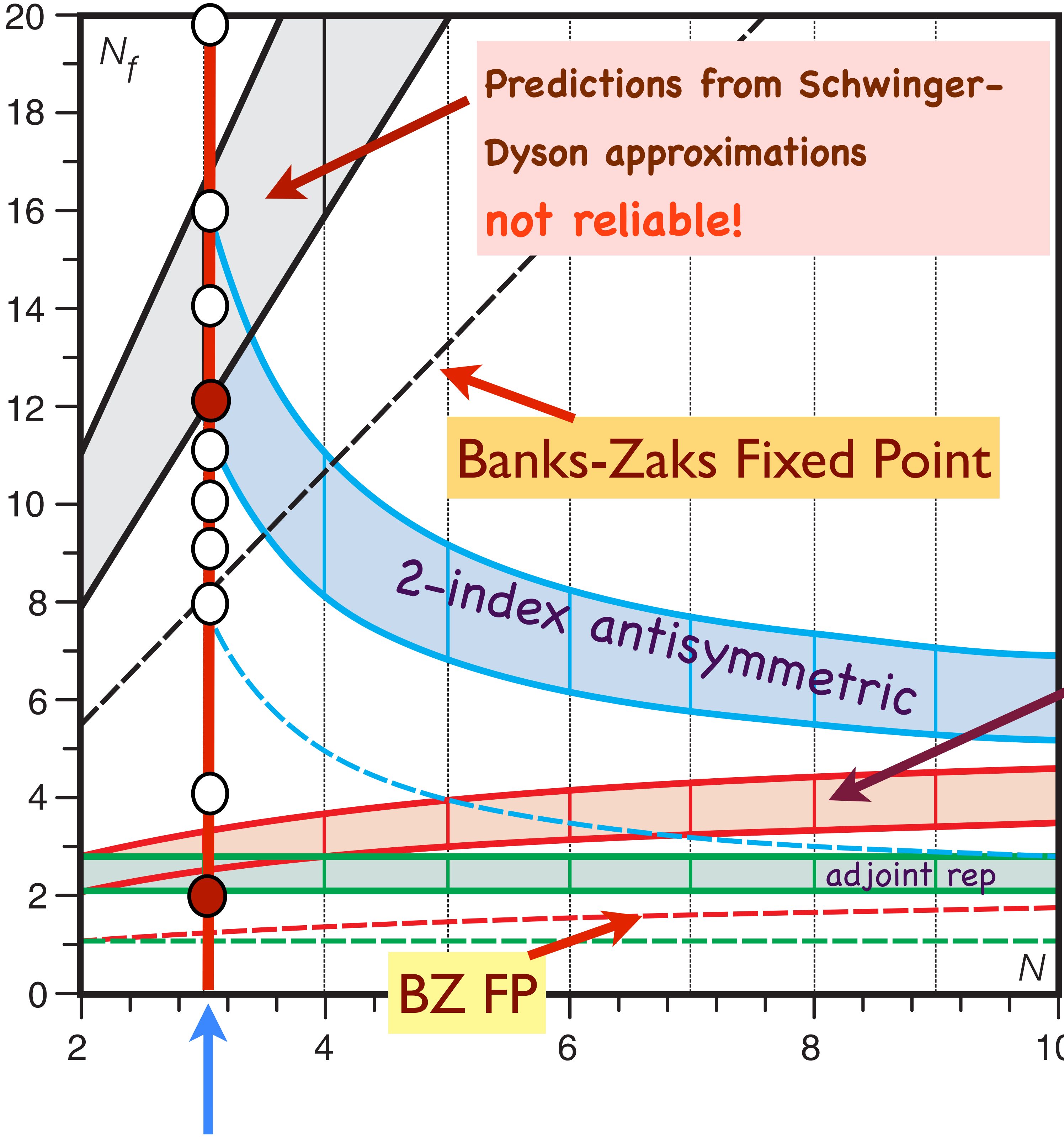
3. **Chiral properties of SU(3) sextet fermions**
   e-Print: **arXiv:0908.2466** [hep-lat]

4. **Chiral symmetry breaking in nearly conformal gauge theories**
   e-Print: **arXiv:0911.2463** [hep-lat] **PoS Lattice 2009**

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

and unpublished new sextet analysis soon to be published

Conformal windows in theory space



Chris Schroeder **and** **Daniel Nogradi** **are twin engines of two projects:**

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

Project 2: 2-index symmetric rep (sextet)
N=3 colors and Nf=2 flavors

both projects use 2-stout dynamical staggered fermions
tree-level Symanzik gauge action

We only run with N=3 colors

We are supported by the Wuppertal hardware/software infrastructure

Zoltan Fodor
Kalman Szabo
Sandor Katz

GPU Hardware

CUDA code:
Kalman Szabo
Sandor Katz

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

USQCD and Teragrid support

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

Evolution of nearly conformal gauge model with volume

What is the finite volume spectrum?

How does the running coupling $g^2(L)$ evolve with L?

At small $g^2(L)$ the zero momentum components of the gauge field dominate the dynamics: Born-Oppenheimer approximation

Originally it was applied to pure-gauge system: Luscher, van Baal

SU(3) pure-gauge model: 27 inequivalent vacua

Low excitations of Hamiltonian (Transfer Matrix) scale with $\sim g^{2/3}(L)/L$
will evolve into glueball states for large L

Three scales of dynamics:
(1) WF is localized on one vacuum (perturbation theory)
(2) tunneling accross vacua on second scale (nonperturbative, calculable)
(3) over the barrier: confinement scale (nonperturbative, not calculable)

third stage is either broken chiral symmetry or conformal

Quantum vacuum is at minimum of Veff(C) when massless fermions are turned on

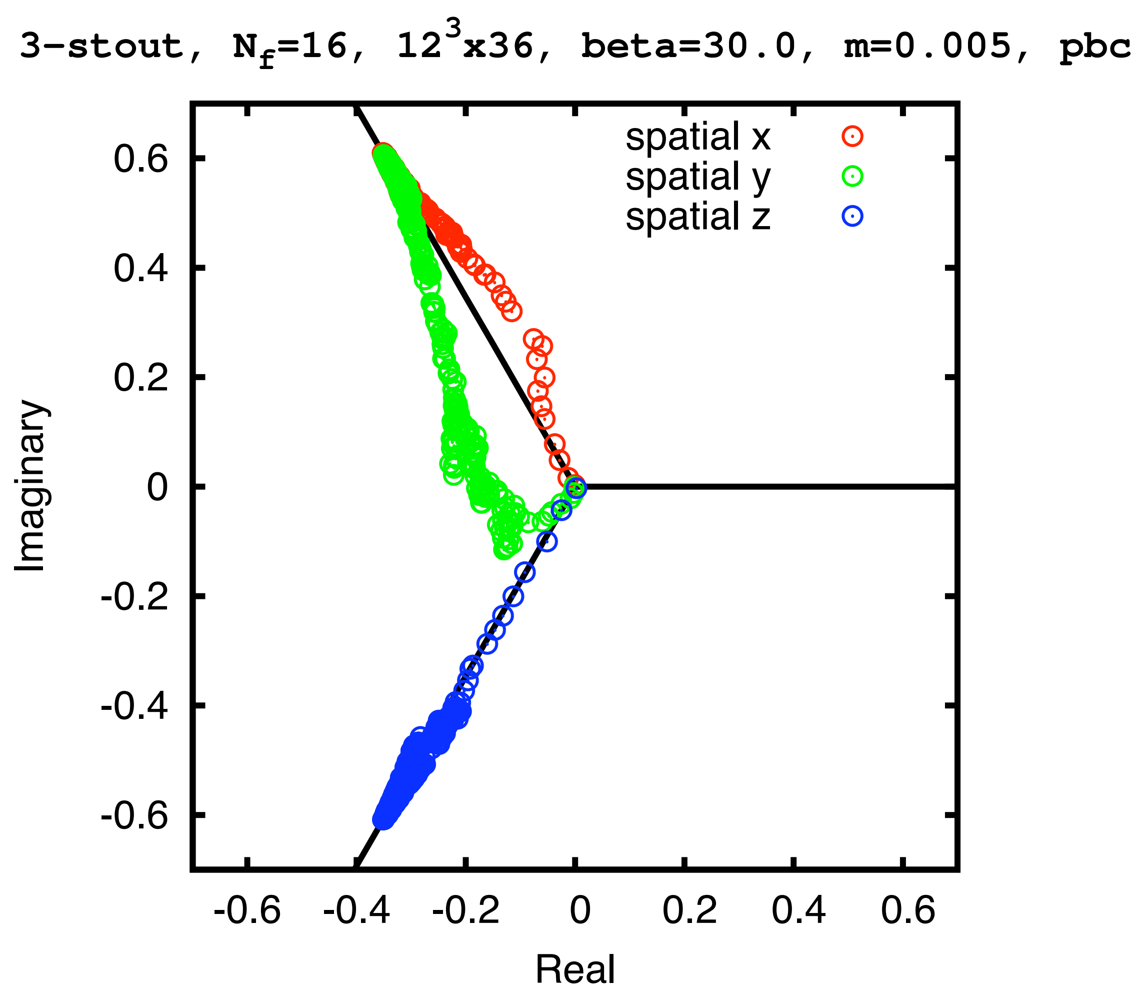
early work by van Baal, Kripfganz and Michael

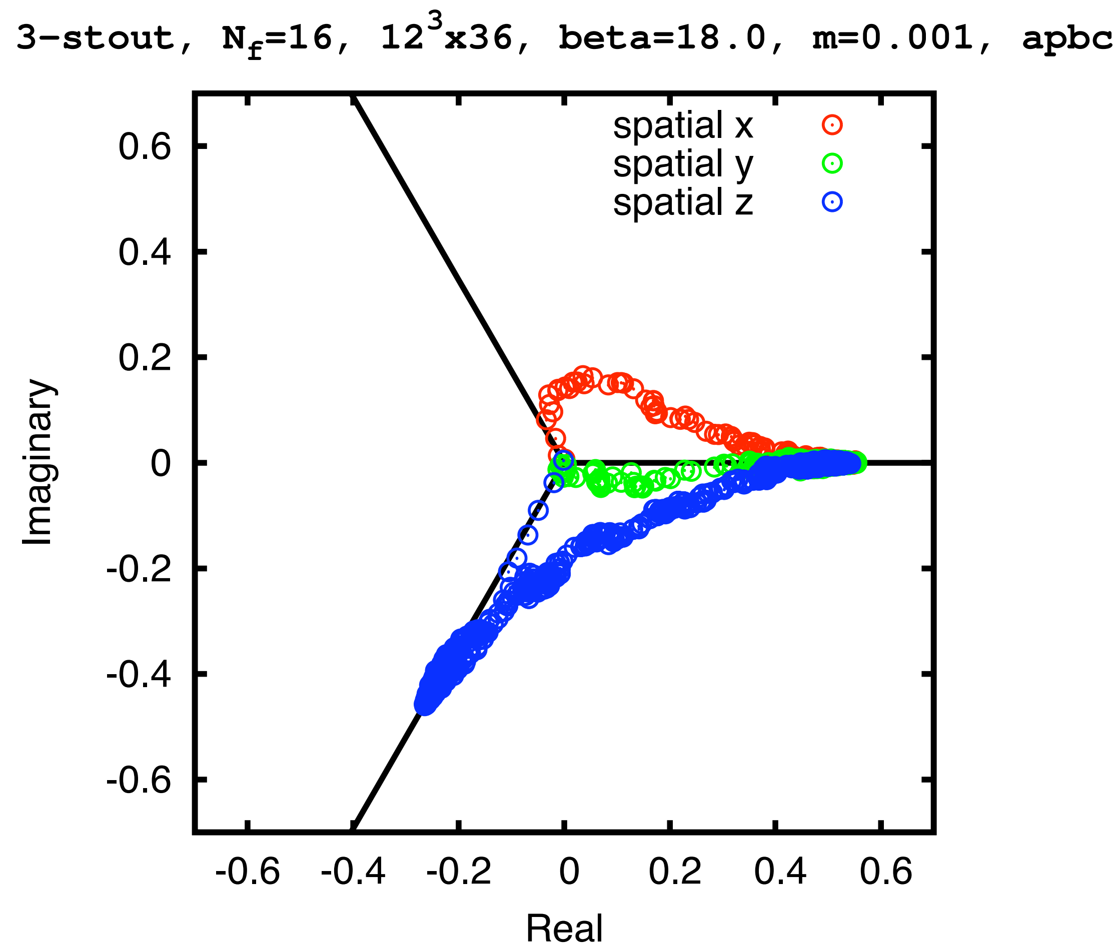
Fermions develop a gap $\sim \pi/L$ in the spectrum

k=(1,1,1) antiperiodic minimal when l=0 (mod 2π) A=0 $A = 0 \; (P_j = 1)$

k=(0,0,0) periodic minimal when $\vec{l} \neq 0$ nontrivial vacua $P_j = \exp(\pm 2\pi i/3)$

Polyakov loop distributions probe the vacua





Check first that simulation reached stage 3 where testing begins in ernest

Nf=12 fundamental representation

(1) Chiral symmetry breaking hypothesis

(2) First crude asymptotic tests include

(a) Goldstone spectrum, parity partner? tantalizing

(b) $M_\pi \sim \sqrt{2Bm_q}$ asymptotics difficult

(c) NLO expansion in p regime has question marks

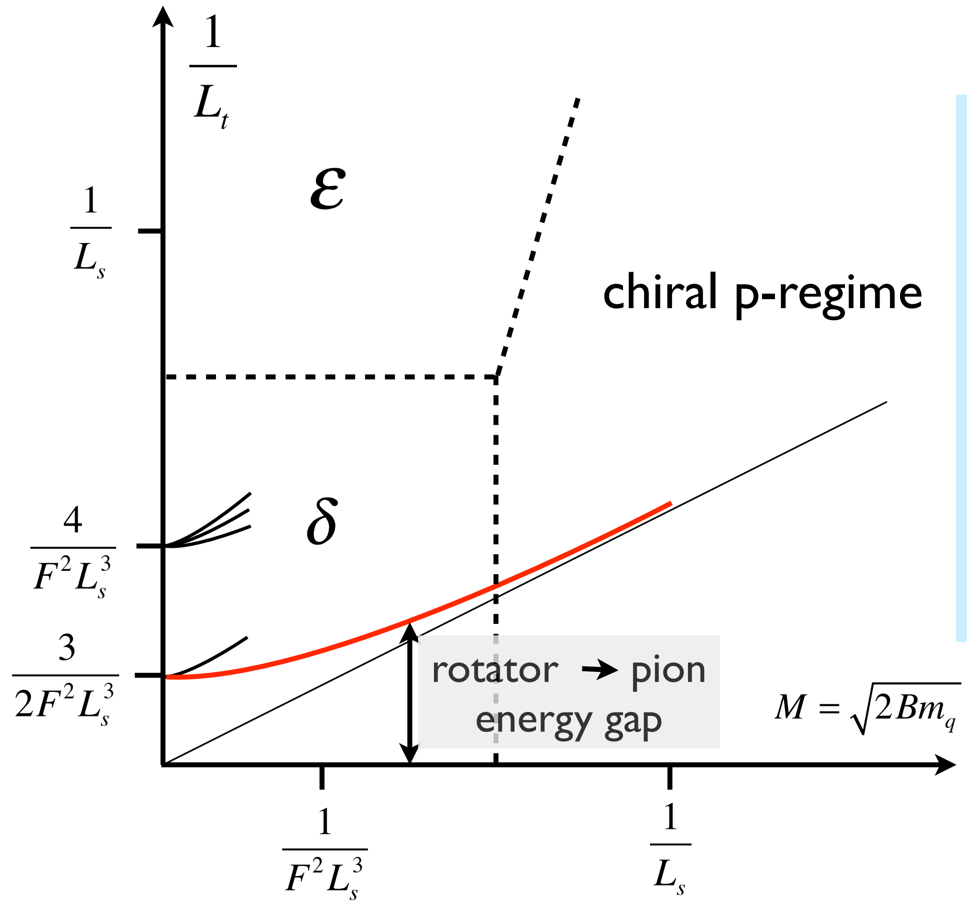
(d) Is F*L large enough? not at Nf=12

(e) Can RMT help? only if F*L is large enough

(3) Use running coupling tests to complement chiral analysis (Kieran Holland's talk)

(4) Check whether conformal picture provides alternative what is it?
has to be better then simple power fits of "anomalous dimensions"

Chiral regimes to identify in theory space:



Goldstone dynamics is different in each regime

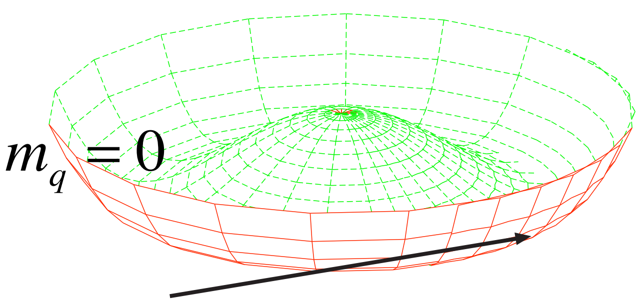
We study δ and ε -regimes (RMT)

and p-regime (probing chiral loops)

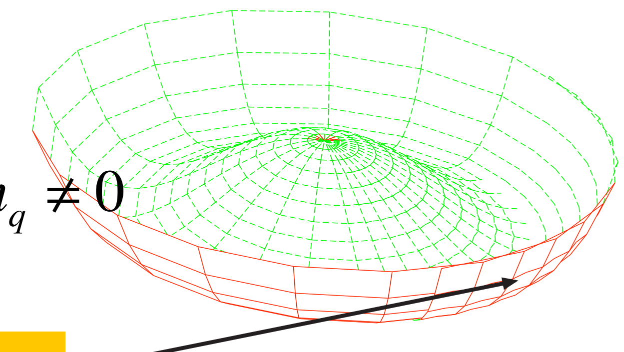
complement each other

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

$m_q = 0$



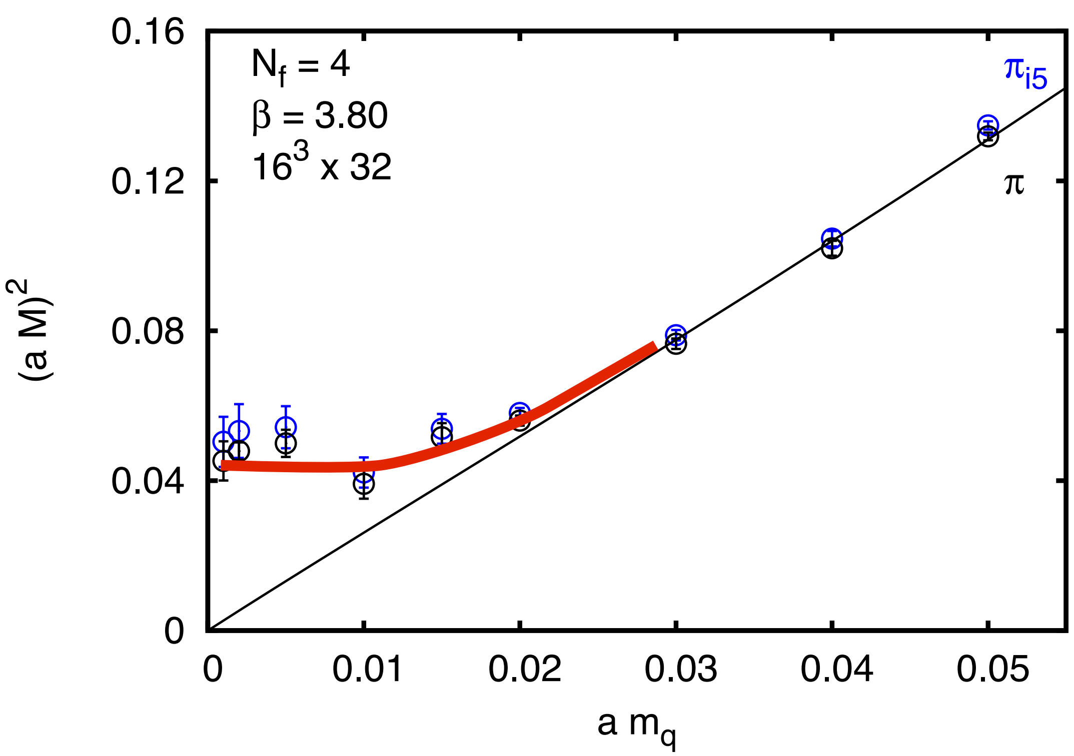
$m_q \neq 0$

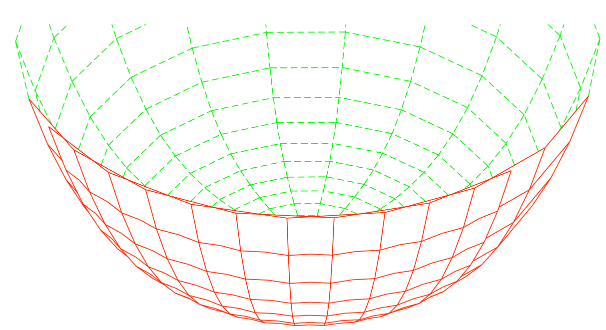


Veff: chiral condensate in flavor space

arbitrary orientation of condensate

tilted condensate



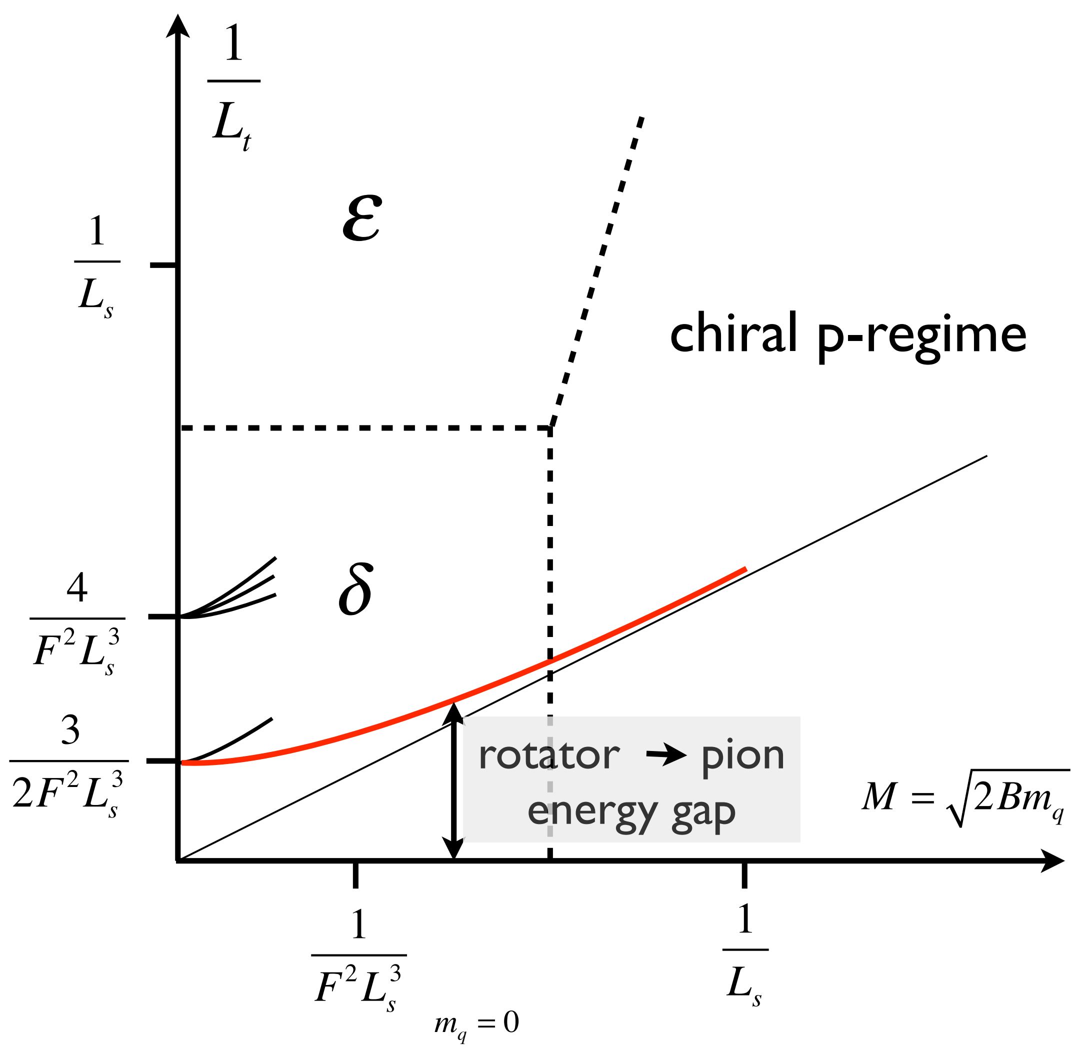


Not to misidentify rotator gaps as evidence of chirally symmetric phase !!

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)

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

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

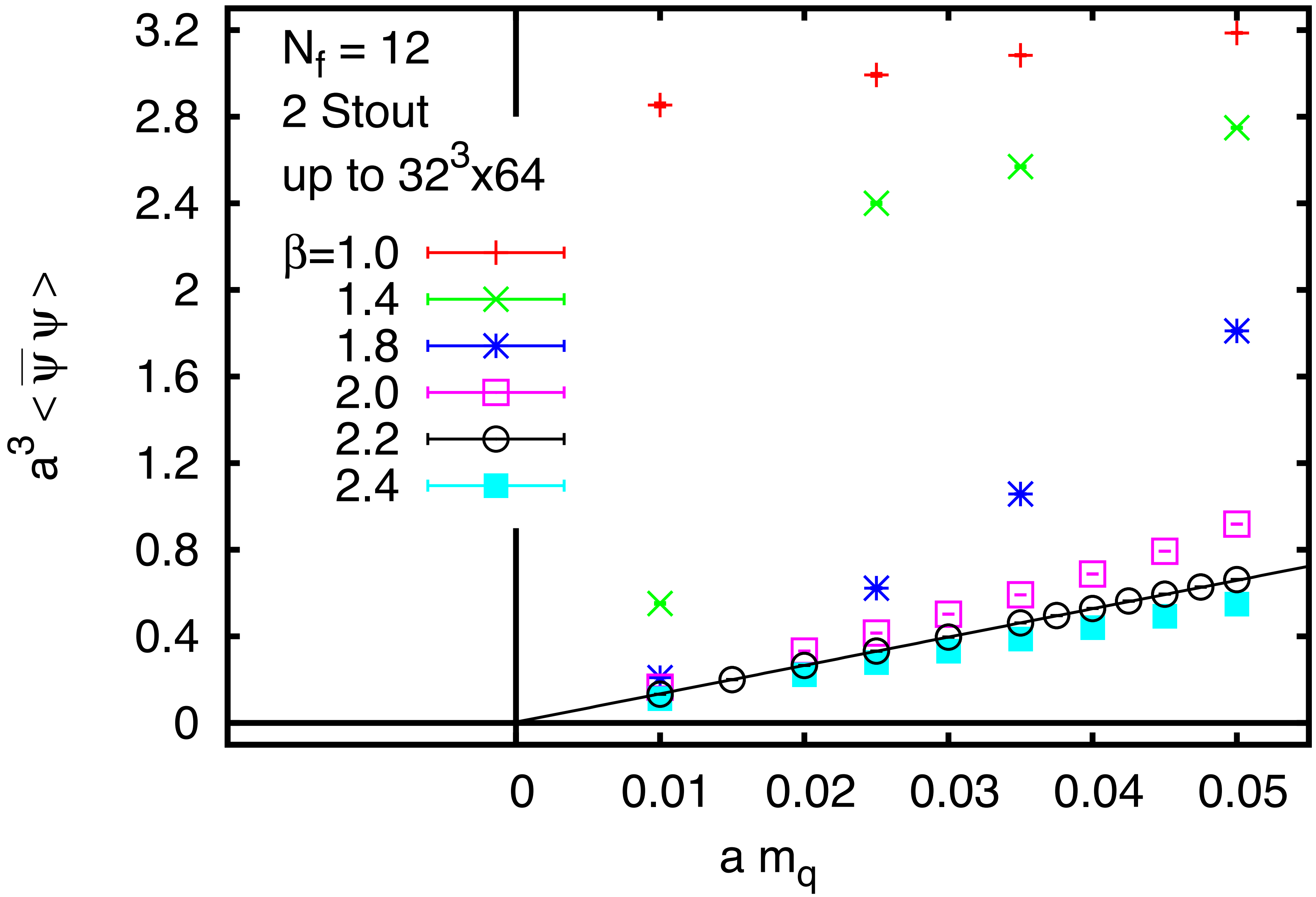
We use staggered action with stout smearing

Taste breaking can be included in staggered perturbation theory!

structure changing as Nf grows

If F*L is not large enough, everything is beginning to break

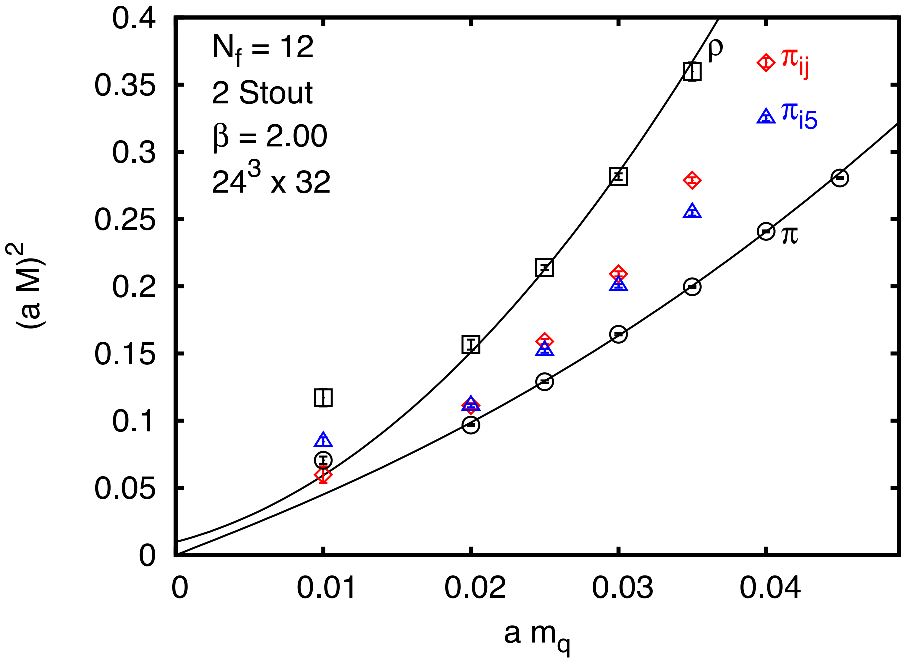
Nf=12 runs are away from crossover region !

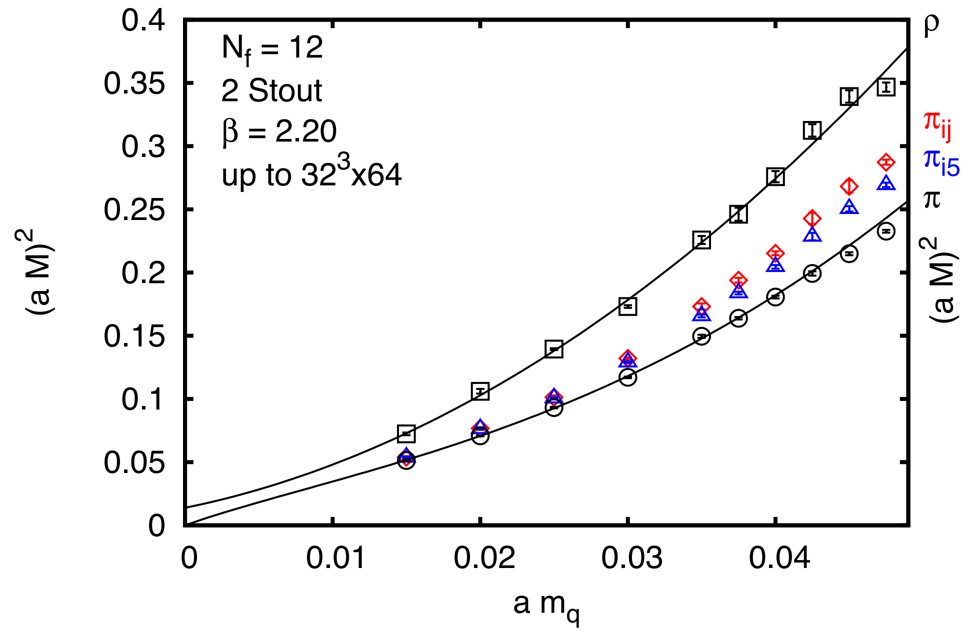


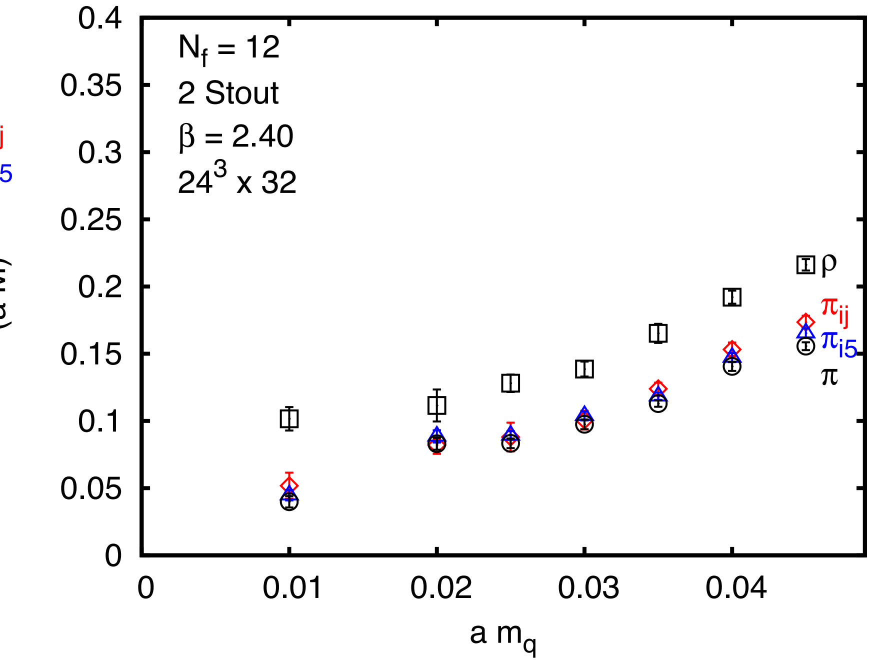
$GMOR \;\; Nf \cdot B \cdot F^2 = 0.0039(9)$

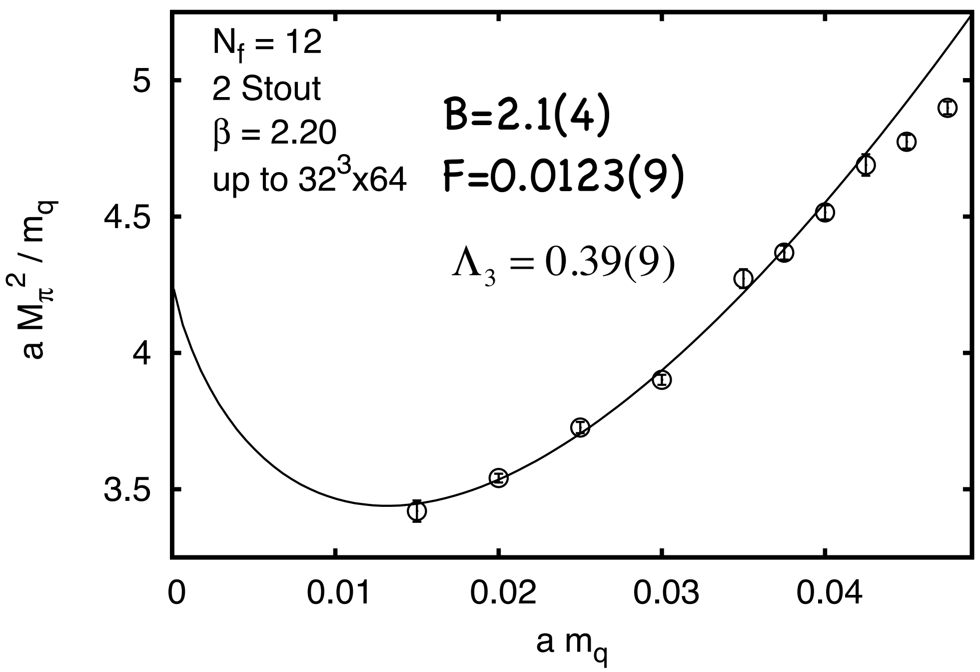
$\langle \bar{\psi}\psi \rangle = 0.0014(2)$

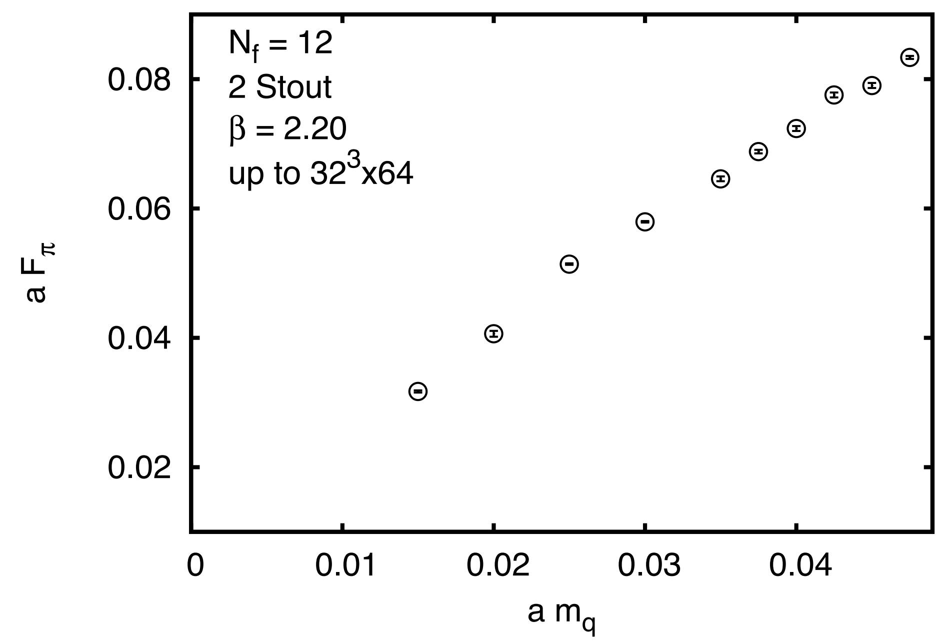
Nf=12 new NLO beta=2.2 chiral analysis in p-regime:





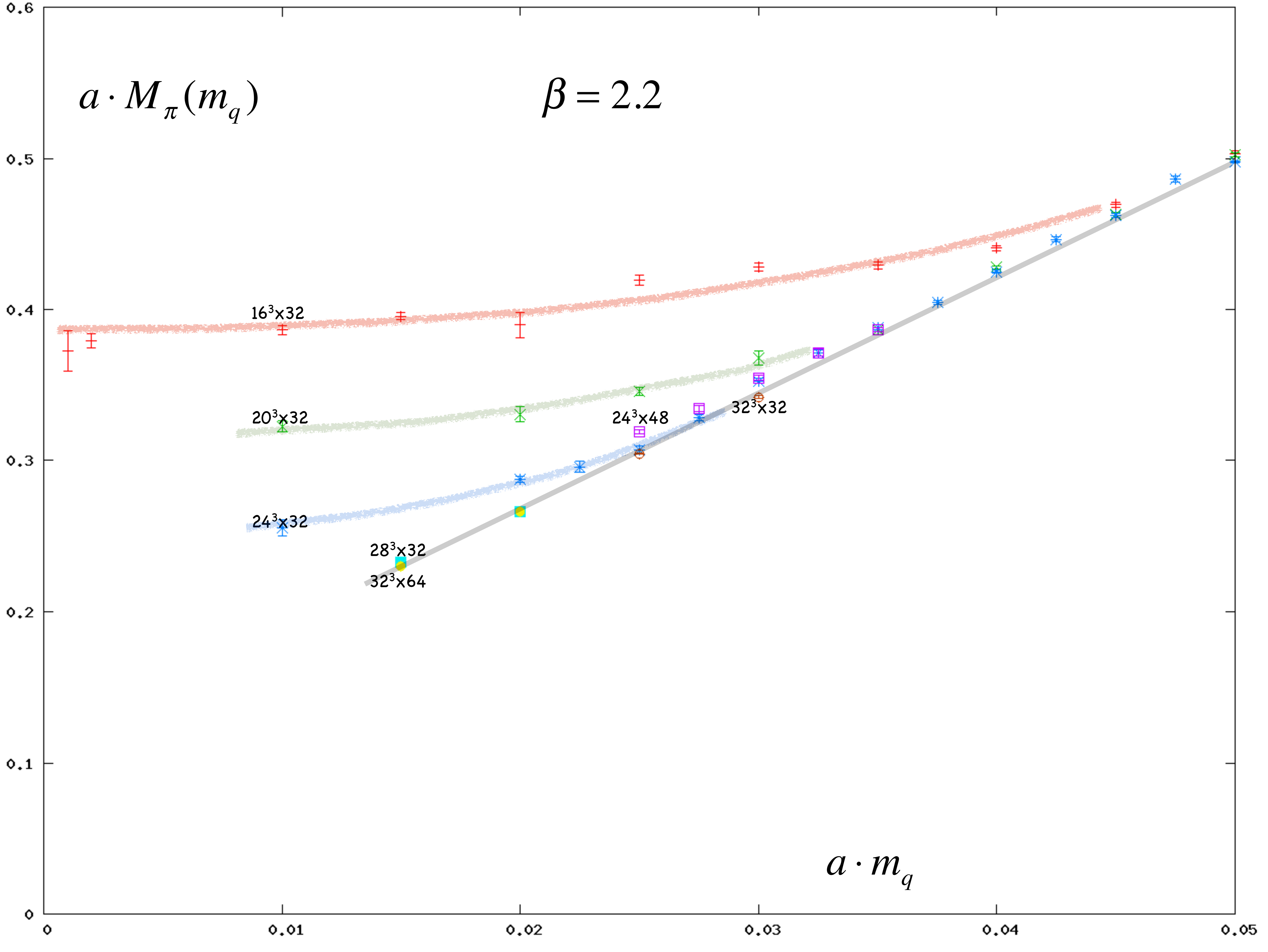




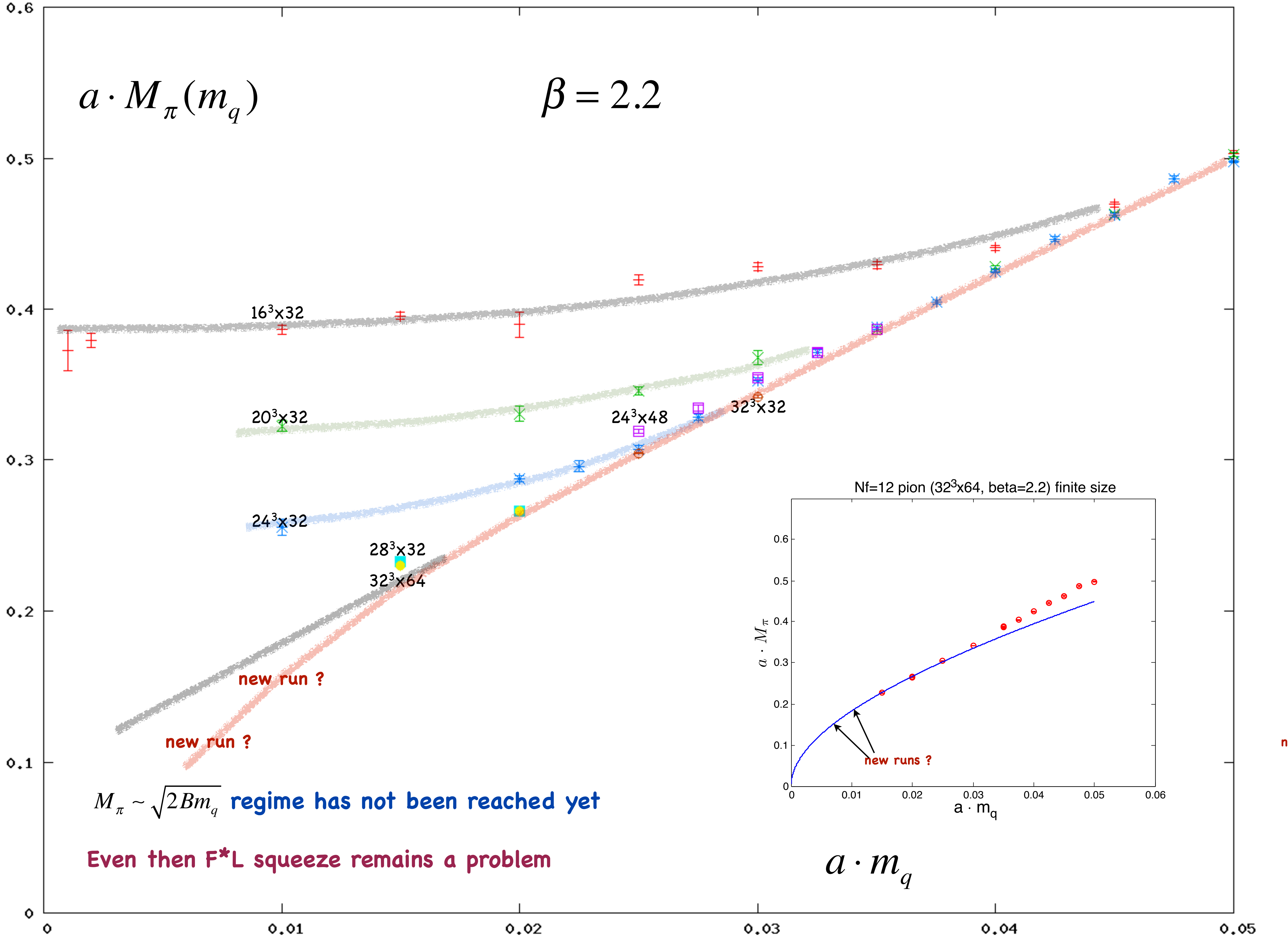


$$\frac{M_\rho}{F} = 10.2(1.1)$$

- Pattern similar to Nf=8 case!
- Consistent with chiral symmetry breaking
- Can this be improved? Hard ...
- What would be the conformal phase analysis?



$a \cdot M_\pi(m_q)$
$\beta = 2.2$
16^3x32
20^3x32
24^3x32
24^3x48
32^3x32
28^3x32
32^3x64
$a \cdot m_q$
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.01
0.02
0.03
0.04
0.05



$a \cdot M_\pi(m_q)$
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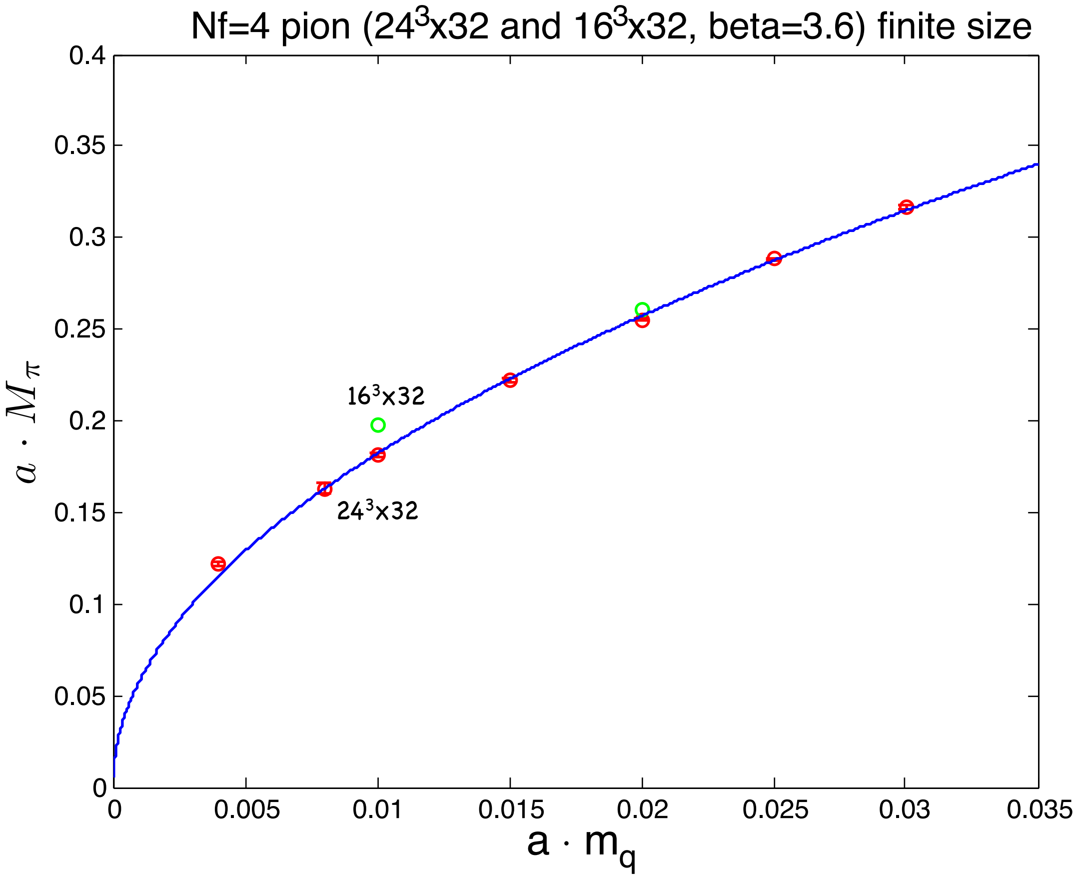
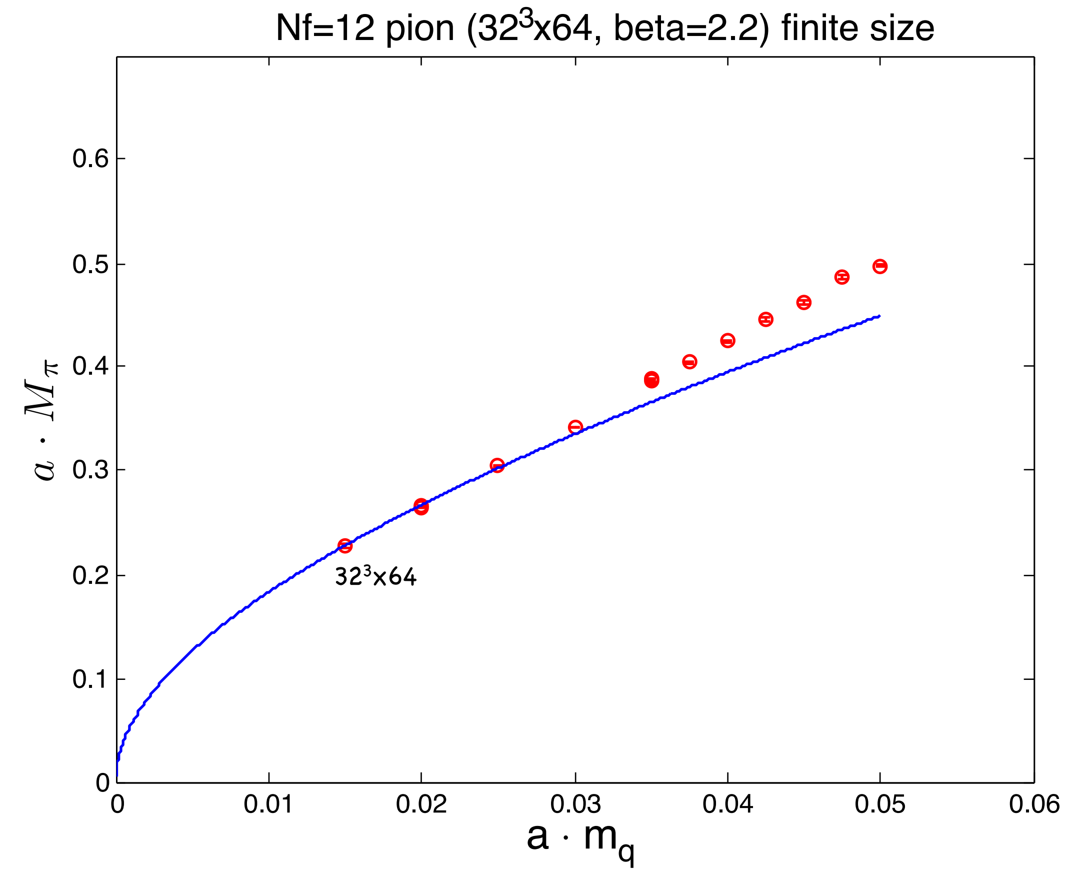
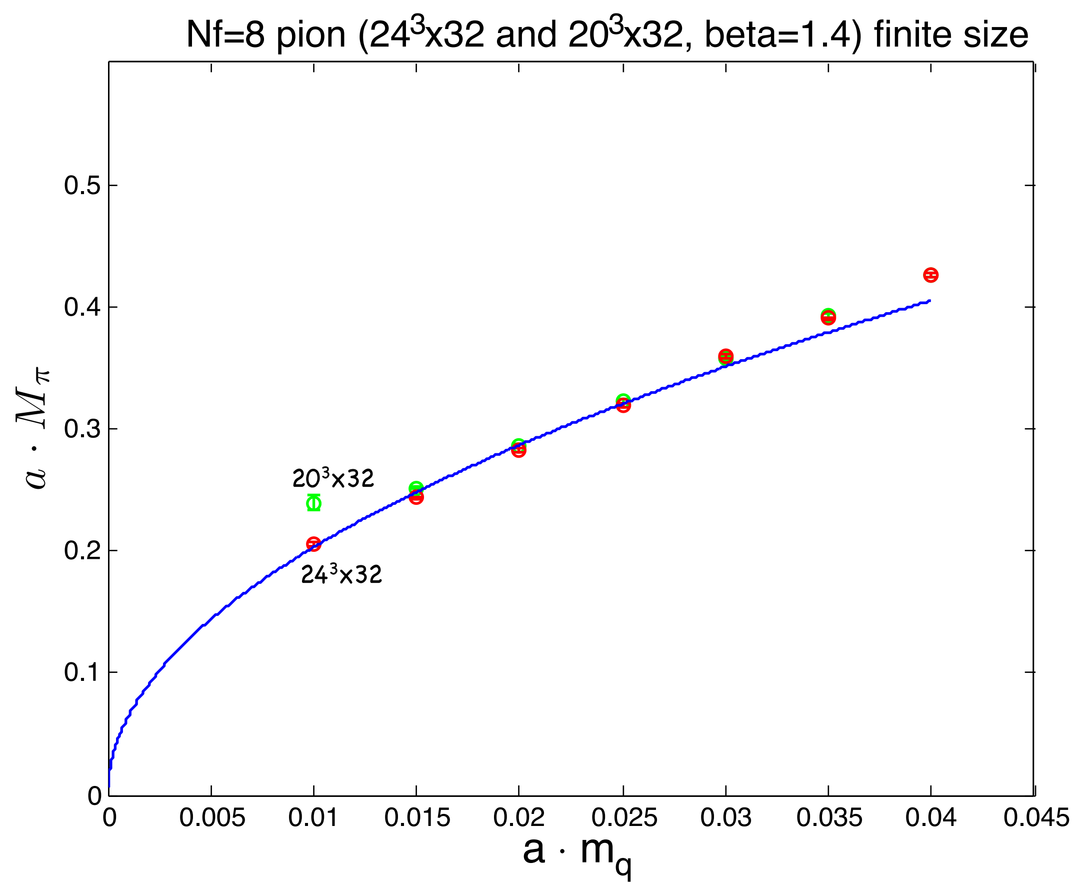
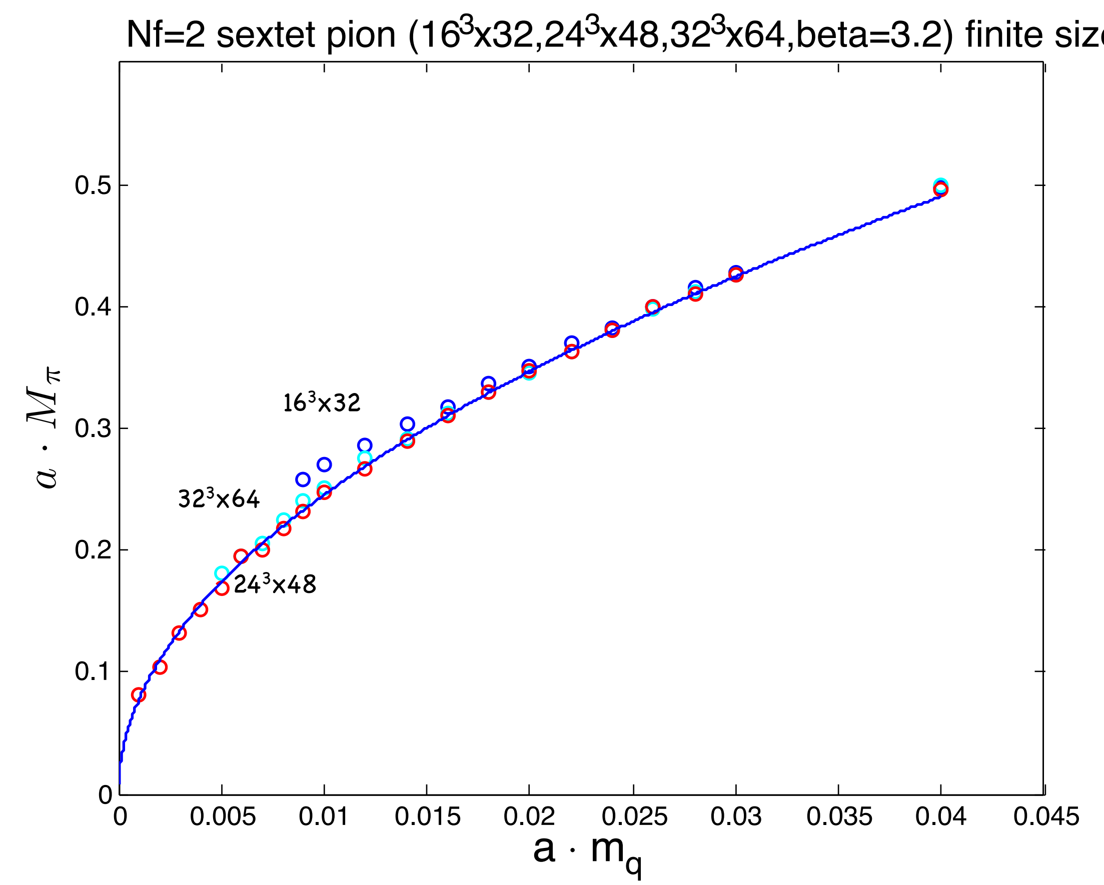
0.05
16^3x32
20^3x32
24^3x32
24^3x48
32^3x32
28^3x32
32^3x64
new run ?
new run ?
Nf=12 pion (32^3x64, beta=2.2) finite size
$a \cdot M_\pi$
$a \cdot m_q$
new runs ?
$M_\pi \sim \sqrt{2Bm_q}$ regime has not been reached yet
Even then F*L squeeze remains a problem
$a \cdot m_q$

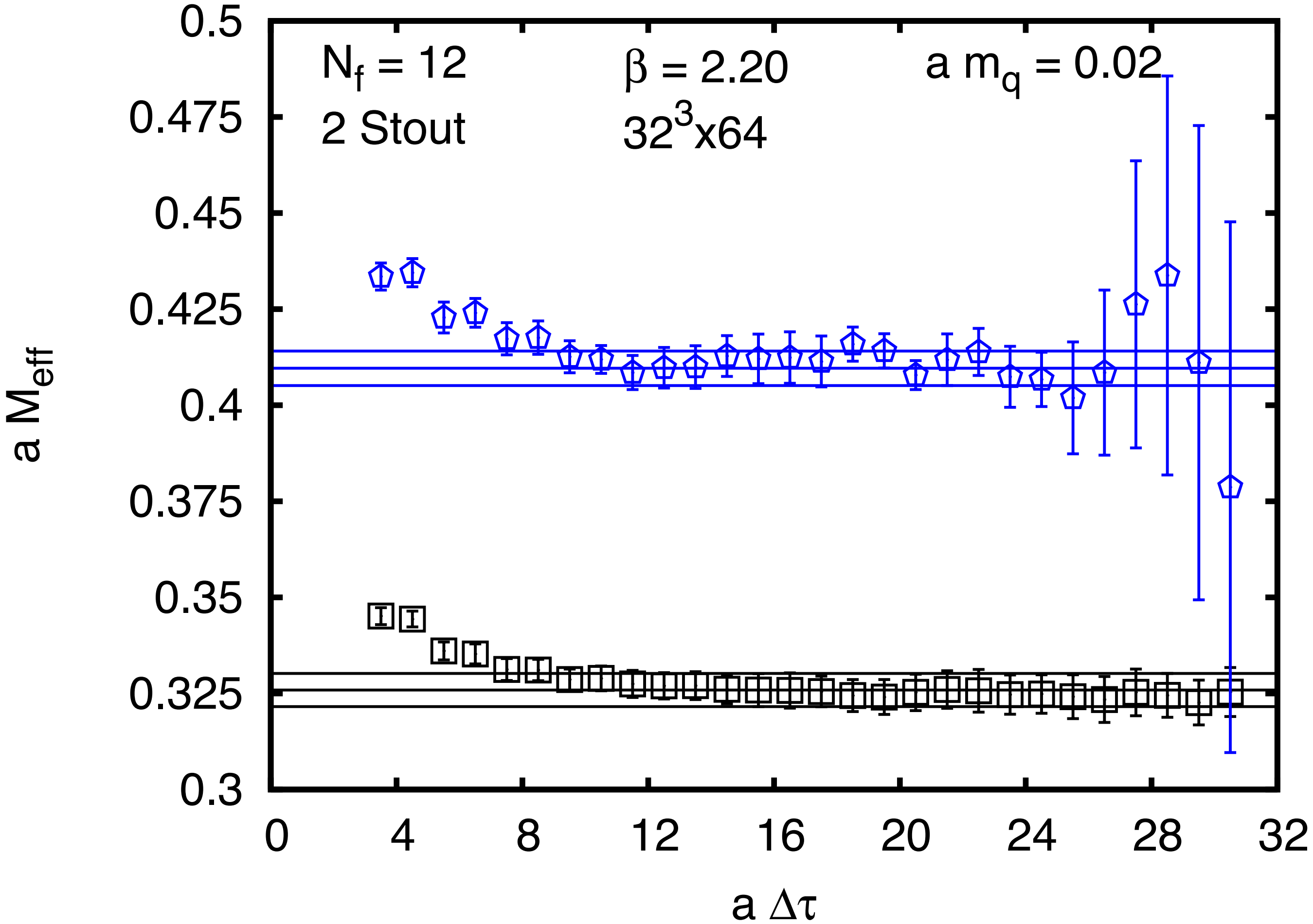
Slow emergence of asymptotic $M_\pi \sim \sqrt{2Bm_q}$ behavior







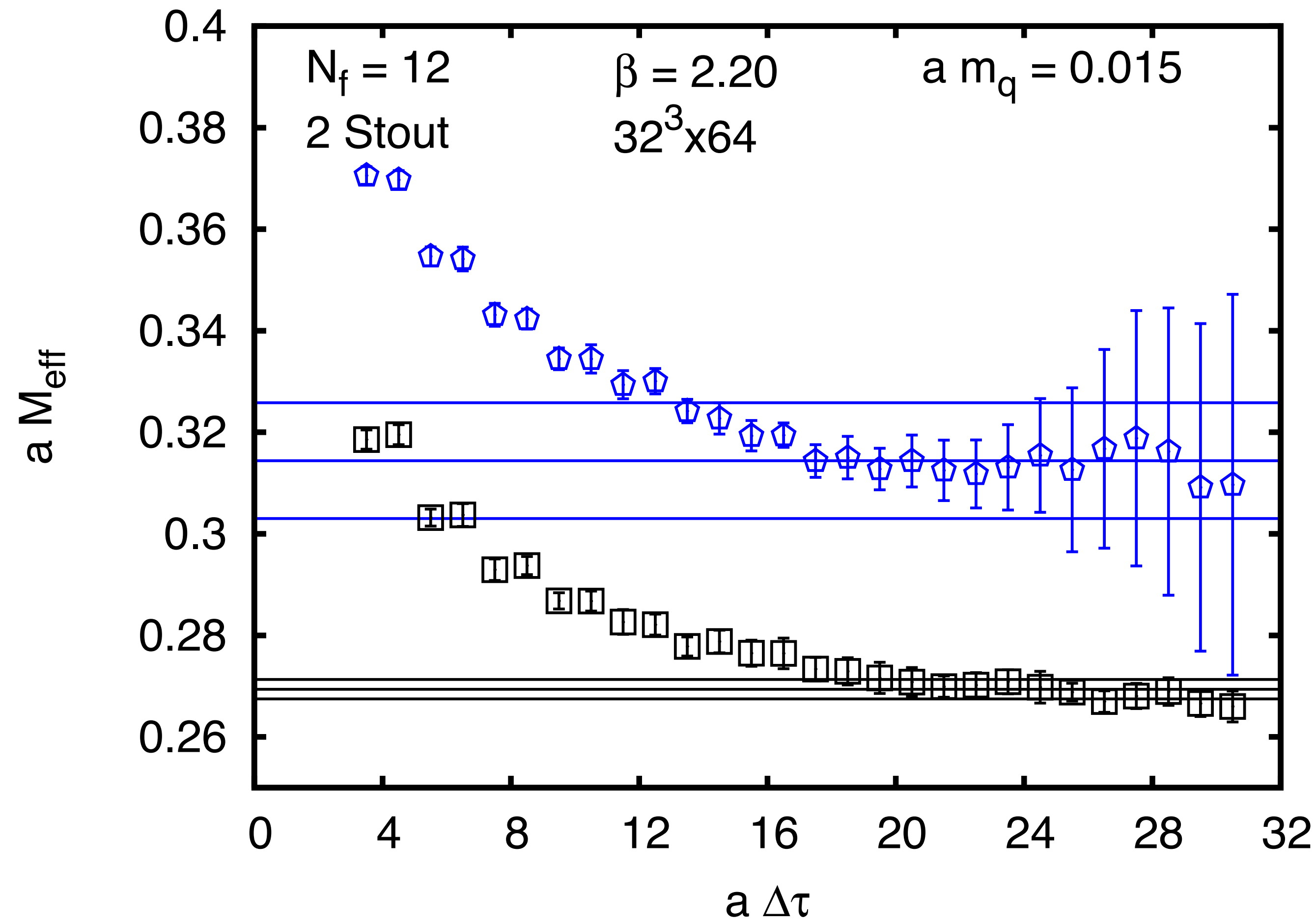




Nf=12 mq=0.02 rho-A1 splitting

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

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

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

per fermion flavor

renormalization scale is not set

Nf=4 B/F = 53(6)

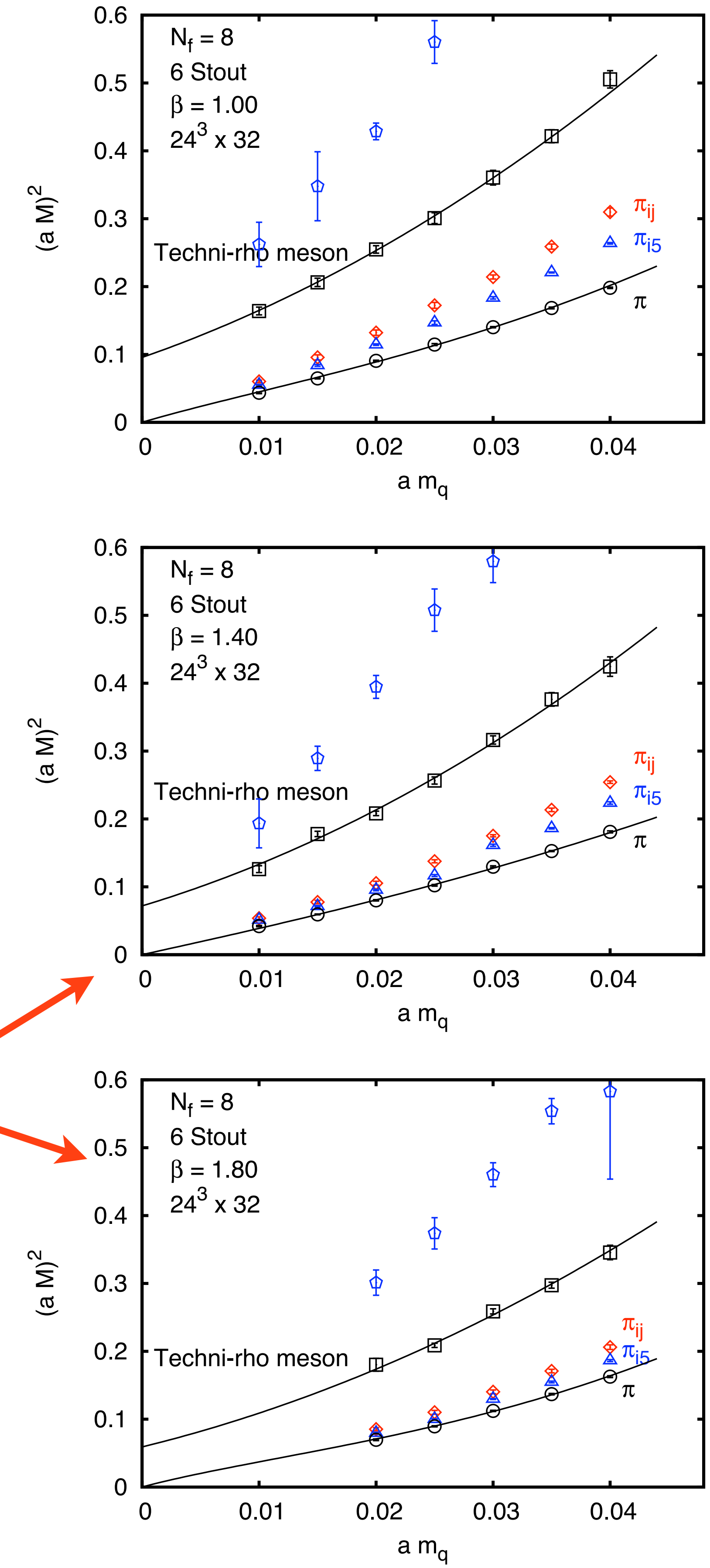
Nf=8 B/F = 157(17)

Nf=12 B/F = 173(32)

large errors, preliminary, limited to Ls=32!

rho - A1 splitting resolution in chiral limit requires lower m_q

Better separation of rho and Goldstones toward chiral limit at Nf=12 would require bigger runs at smaller fermion masses



The F*L squeeze

(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

expansion in $1/F^2L^2$

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

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

When expansion collapses in δ – regime, the p-regime analysis needs more scrutiny

Cross checks from several running coupling schemes is important

The Nf=2 sextet model simulations

(1) Similar check list and warnings as Nf=12 case

(2) However, Nf=2 makes it easier

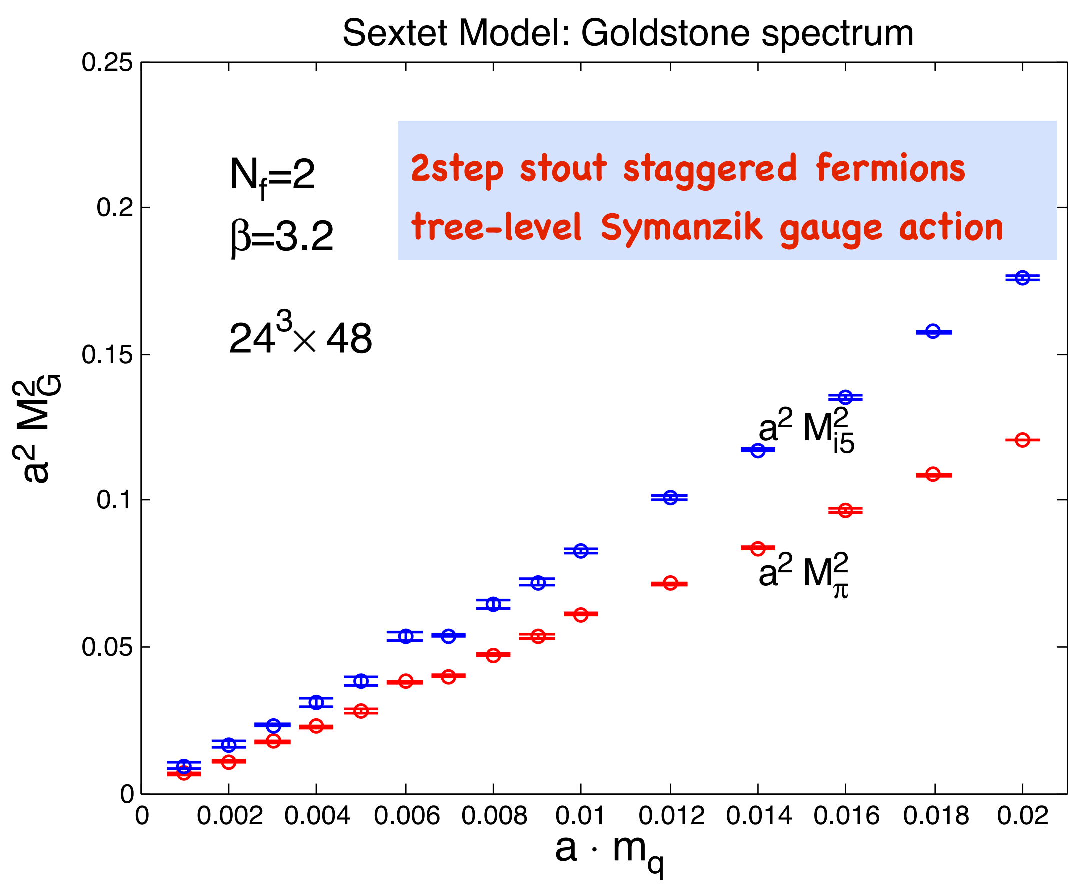
(3) Analysis is preliminary!

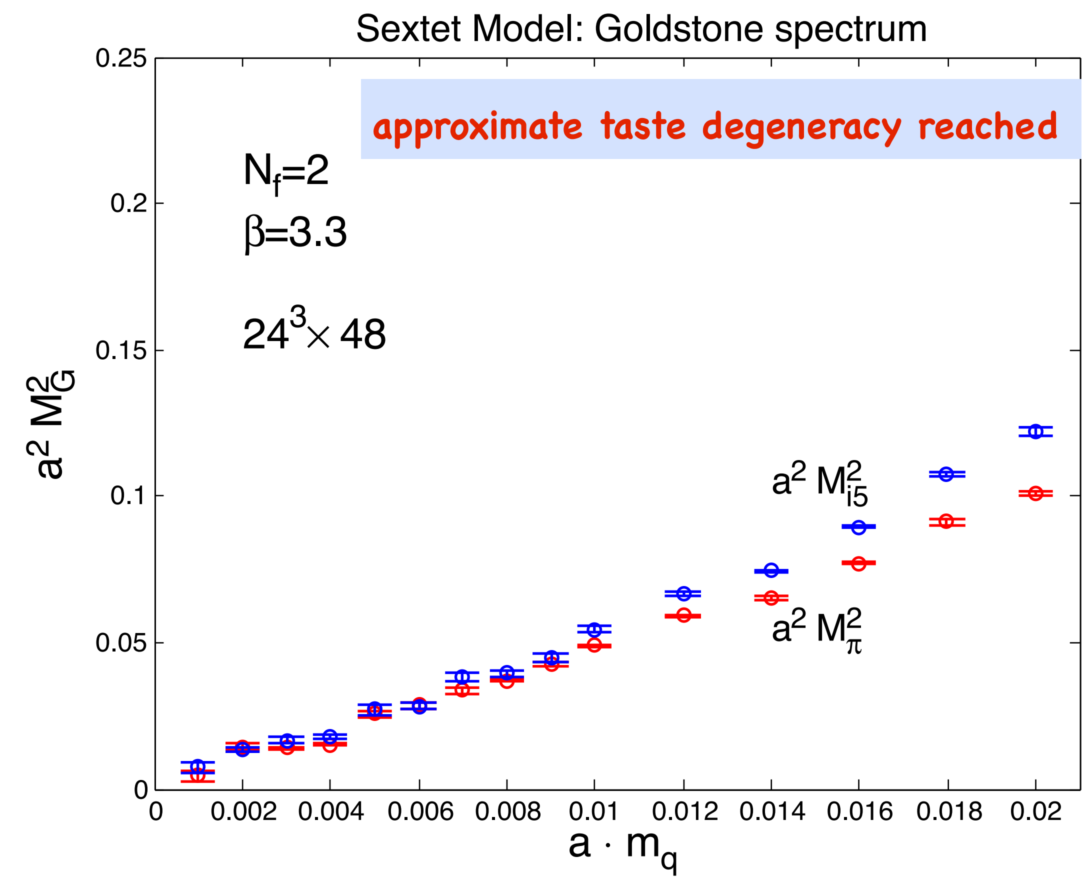
(4) So far quite consistent with chiral symmetry breaking

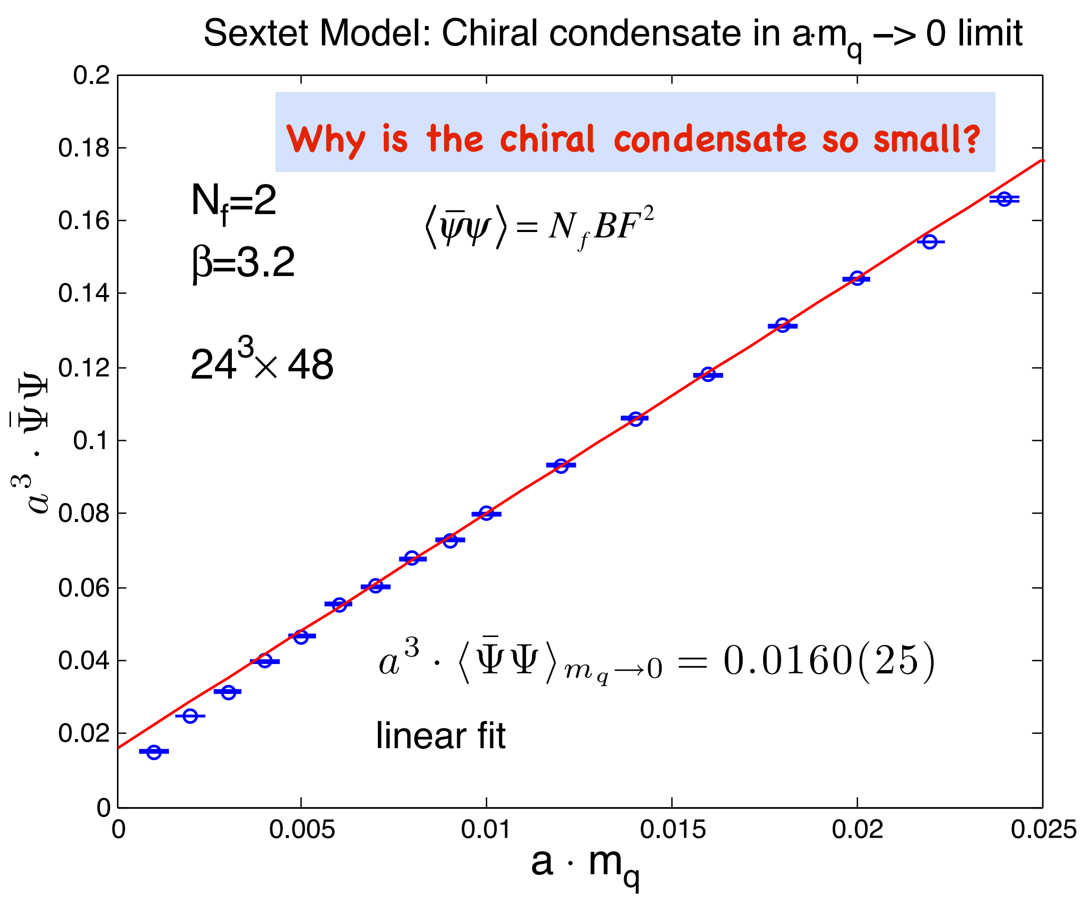
(5) Unlike Nf=12 case, no intrinsic barriers with
NNLO convergence, F*L squeeze, ...

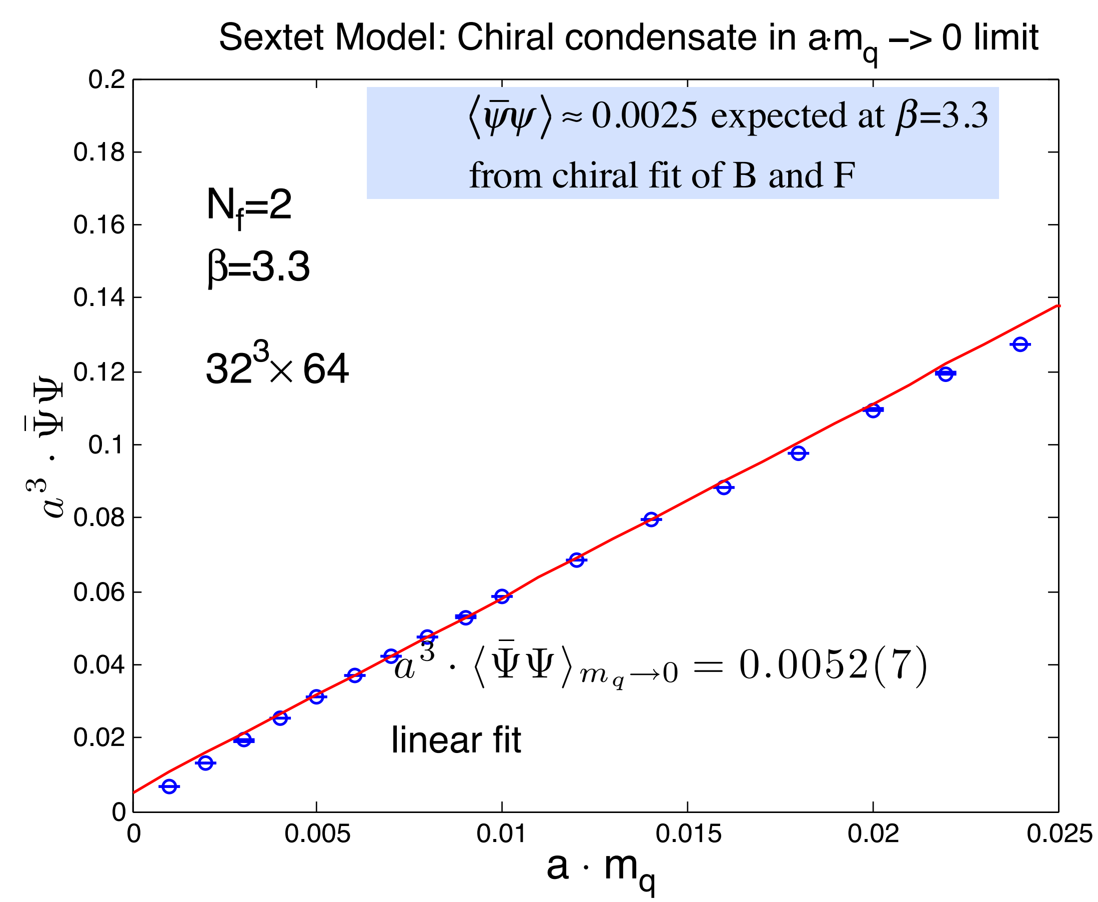
(6) We are running our couplings (Kieran Holland's talk)

The Nf=2 sextet model simulations









NLO chiral fitting procedure of the Nf=2 sextet model simulations

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

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

input

$$M_\pi(L_s,\eta) = M_\pi\Big[1 + \frac{1}{2N_f}\frac{M_\pi^2}{16\pi^2 F_\pi^2}\cdot \widetilde{g}_1(\lambda,\eta)\Big],$$

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

$$\lambda = M_\pi L, \qquad \eta = \frac{L_T}{L_S}$$

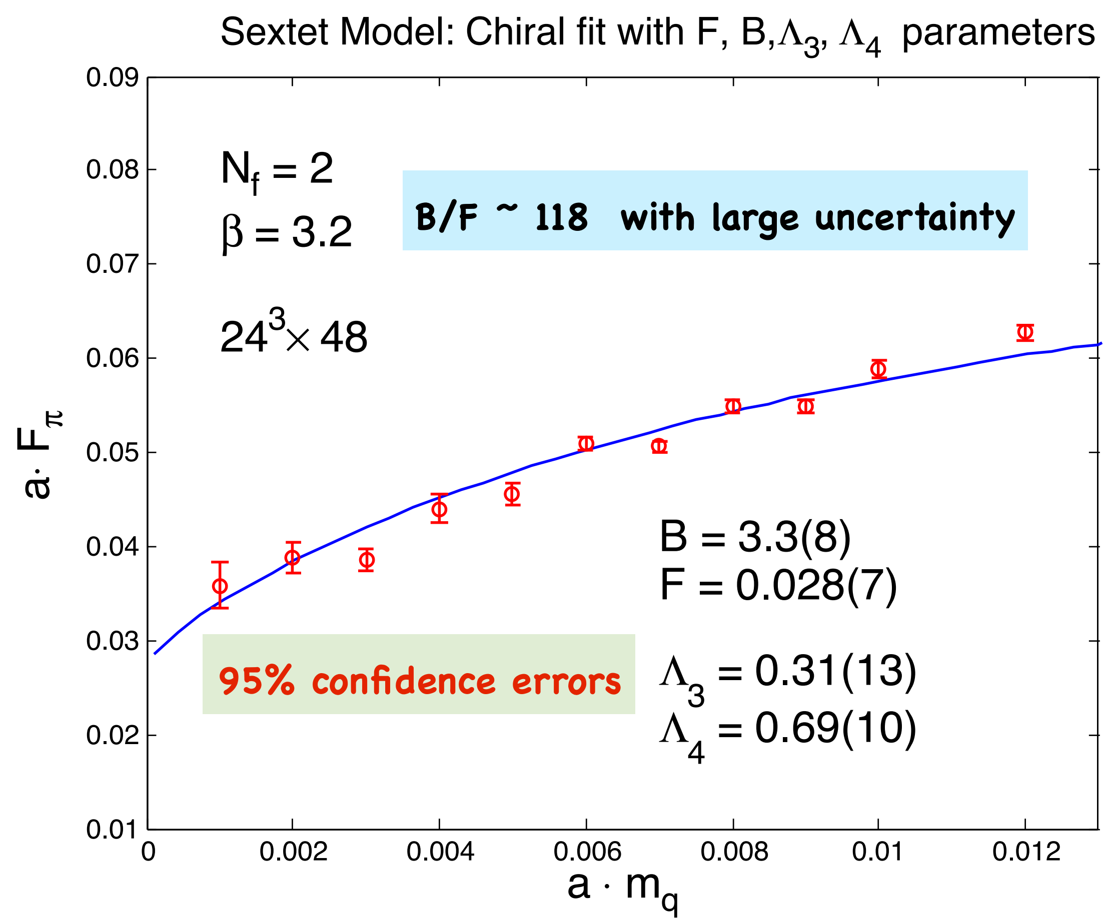
$\tilde{g}(\lambda,\eta)$ is a shape-dependent expansion in terms of infinite series of Bessel functions

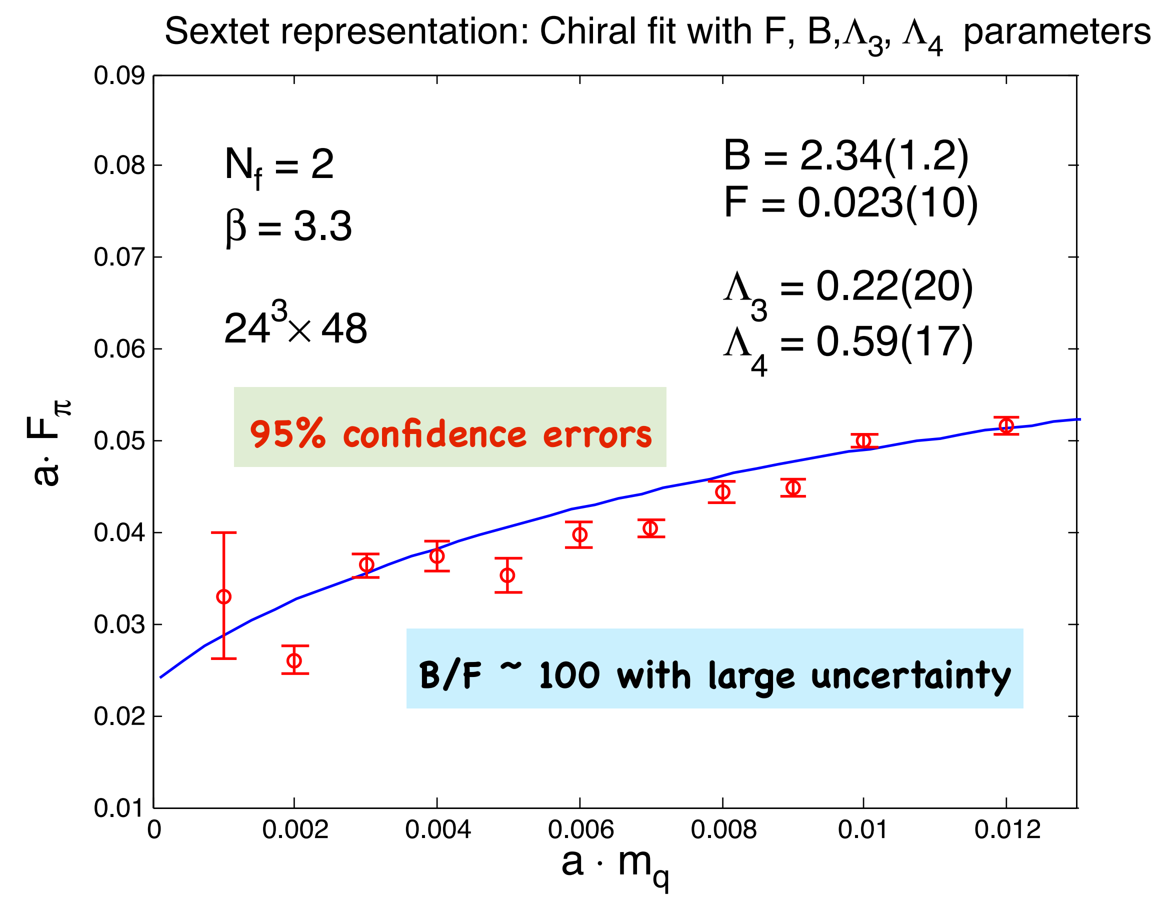
Next-to-leading-order fitting procedure of the chiral analysis

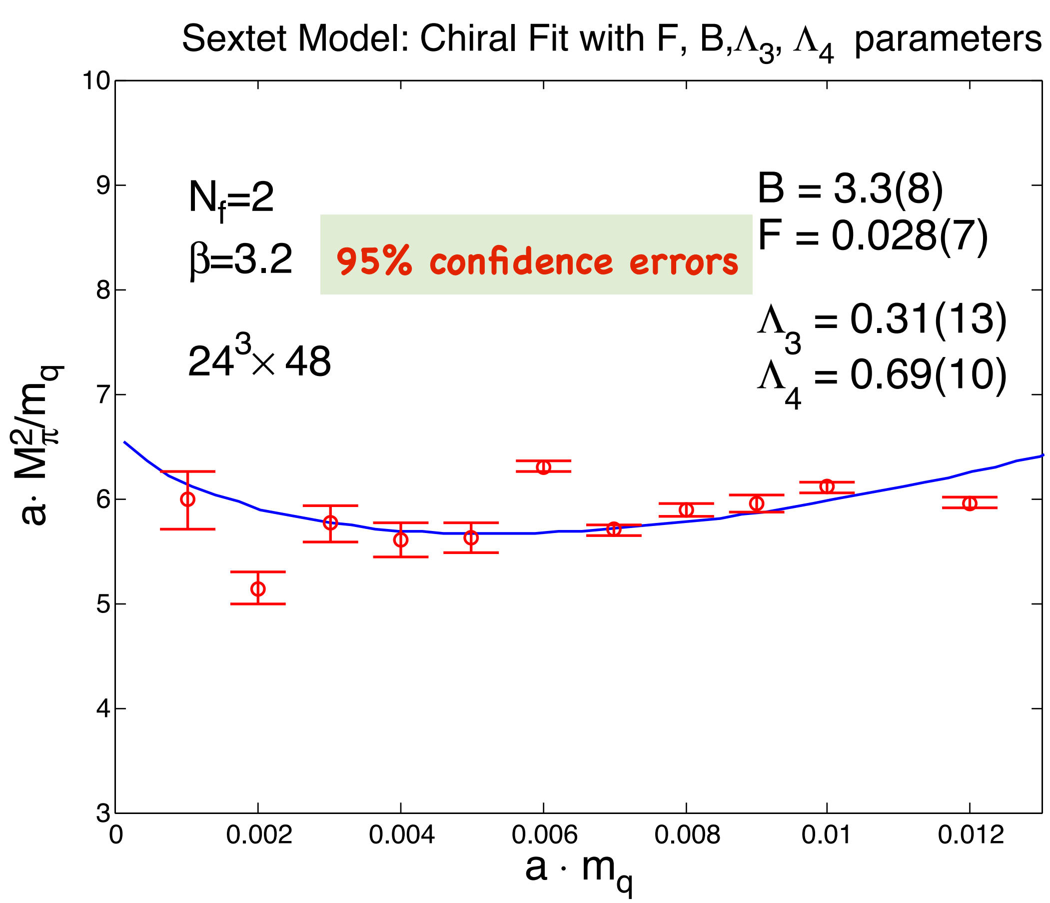
re-expand in $\xi = \dfrac{2Bm_q}{16\pi^2 F^2}$ to $O(\xi)$ accuracy

B, F, Λ_3, Λ_4 are the four fitted parameters

Our simulations of the model are not accurate for NNLO analysis with taste breaking


Sextet Model: Chiral fit with F, B,Λ3, Λ4 parameters
N_f = 2
β = 3.2
24^3× 48
B/F ~ 118 with large uncertainty
B = 3.3(8)
F = 0.028(7)
95% confidence errors
Λ3 = 0.31(13)
Λ4 = 0.69(10)
a· Fπ
a · mq


Sextet representation: Chiral fit with F, B,Λ3, Λ4 parameters
N_f = 2
β = 3.3
24^3× 48
B = 2.34(1.2)
F = 0.023(10)
Λ3 = 0.22(20)
Λ4 = 0.59(17)
95% confidence errors
B/F ~ 100 with large uncertainty
a· Fπ
a · mq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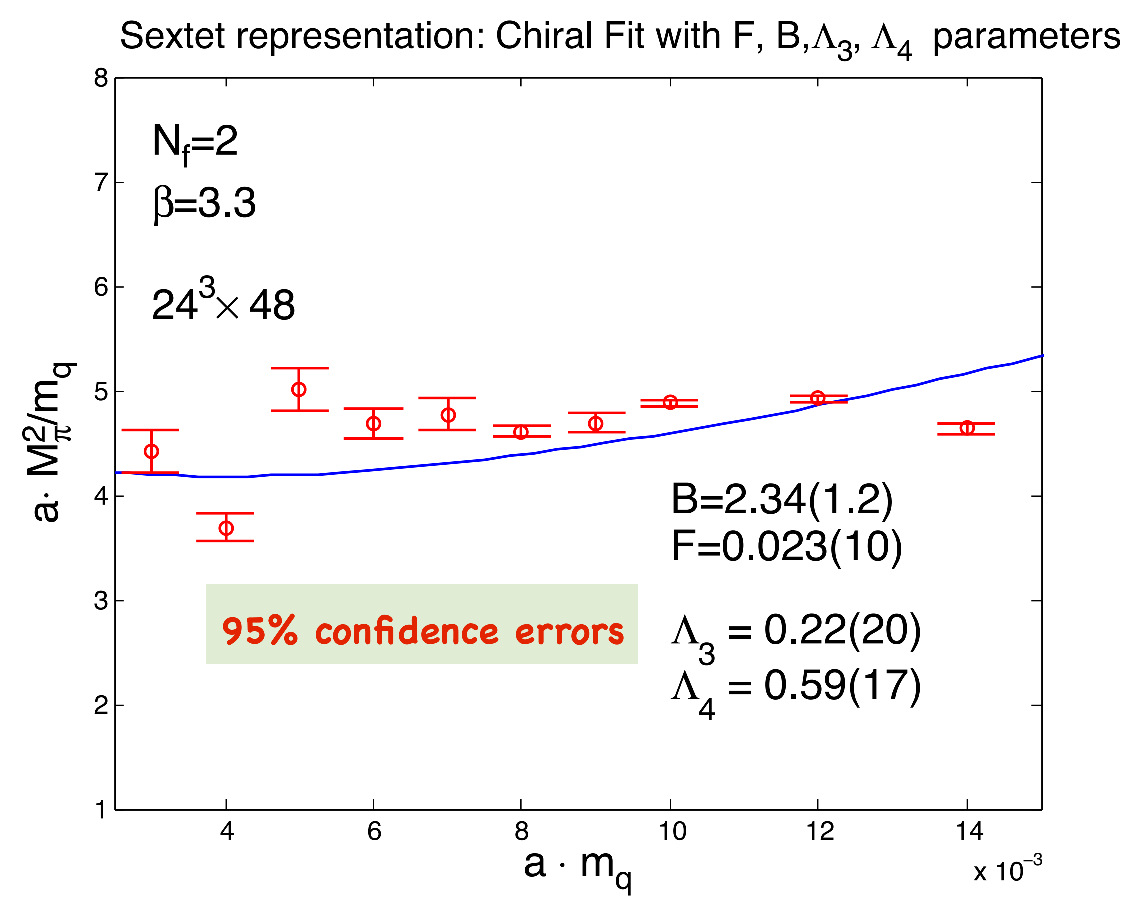
a· M²π/mq
a · mq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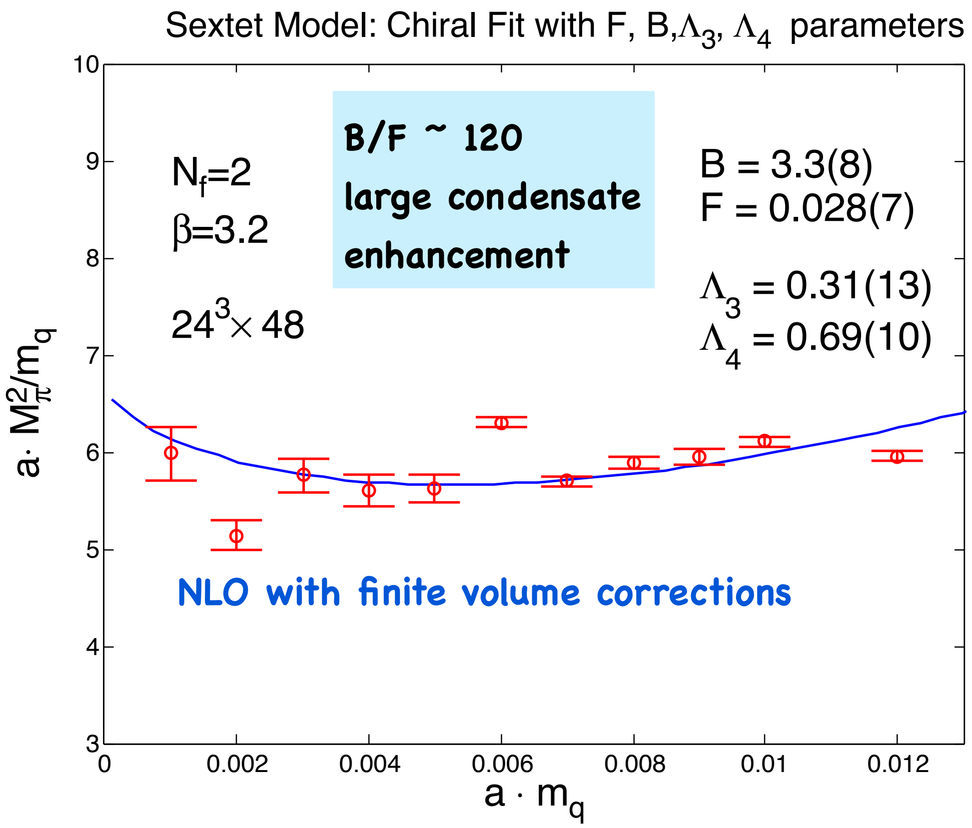
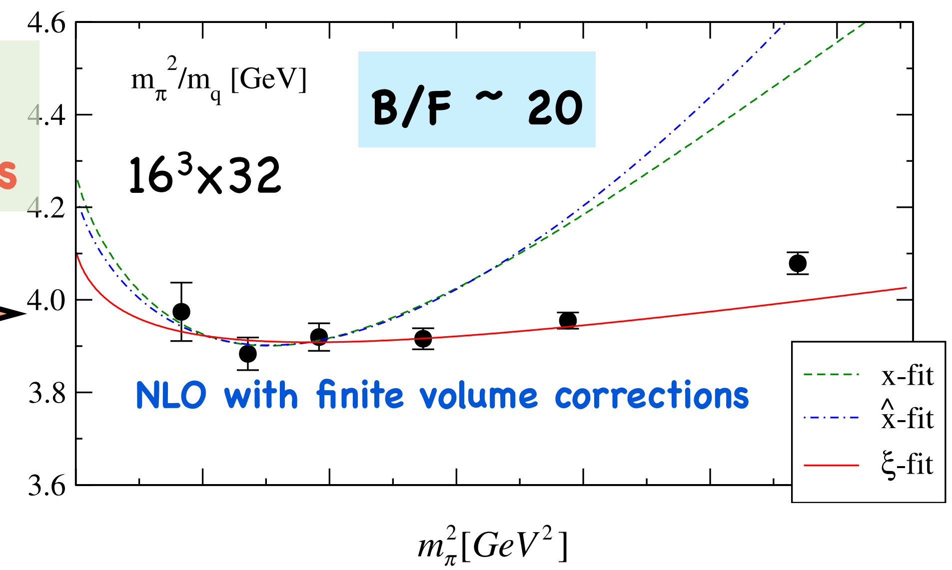
Λ4 = 0.59(17)
a· M²π/mq
a · mq
x 10^-3

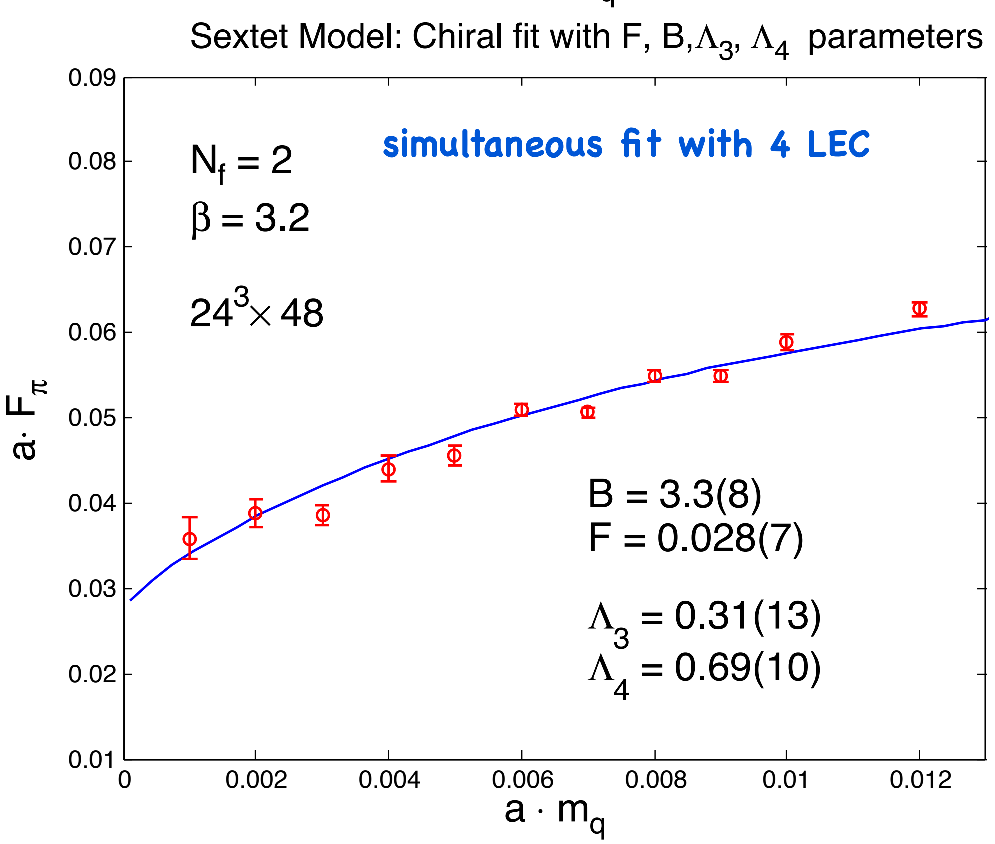
Nf=2 Sextet Chiral test
(staggered stout) LHC

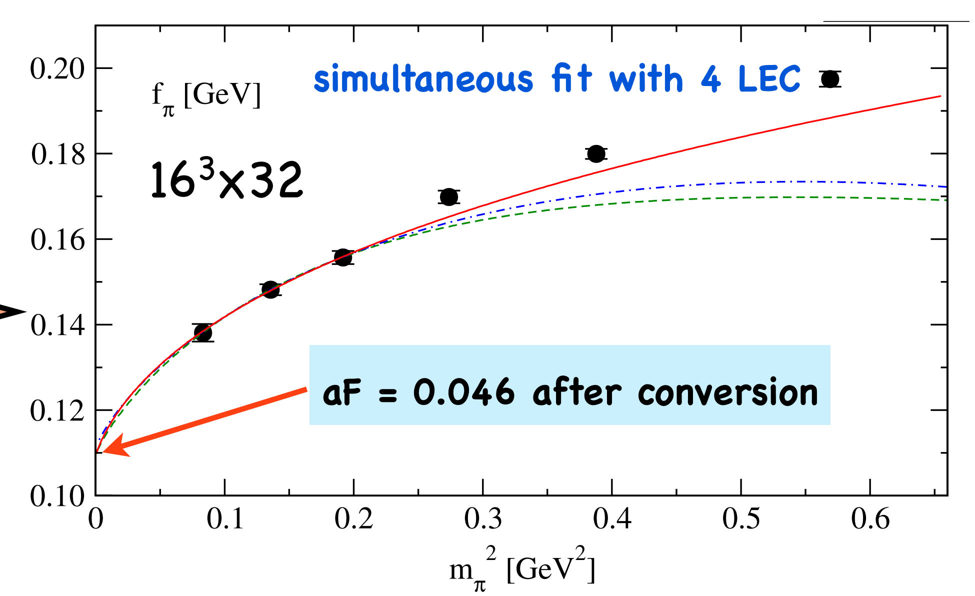
Nf=2 QCD Chiral test
(overlap) Noaki et al.



nearly identical fitting procedures







Conclusions and Outlook

1. Nf=12 is consistent with chiral symmetry breaking

- to overcome limitations would require big resources
- worth it?

2. Nf=2 sextet consistent with chiral symmetry breaking

- easier to control F*L and Nf expansions within our resources
- full chiral analysis can be done

3. Important to complement with running couplings