# Lattice perspectives on a composite Higgs particle

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## Motivation

- The Standard Model is in great shape!
- But there are some unwanted features / problems
- Plenty of extensions are around (SUSY, extra dimensions, ...)
- One class: strong dynamics - technicolor
- Non-perturbative phenomena $\longrightarrow$ lattice

## Motivation - strong dynamics - technicolor

- Invent a new strongly interacting sector coupled to the weak sector

- Non-abelian gauge theory + fermions $\rightarrow$ techni gluons + techni fermions

- Spontaneous chiral symmetry breaking (as in QCD) $\rightarrow$ electro weak symmetry breaking

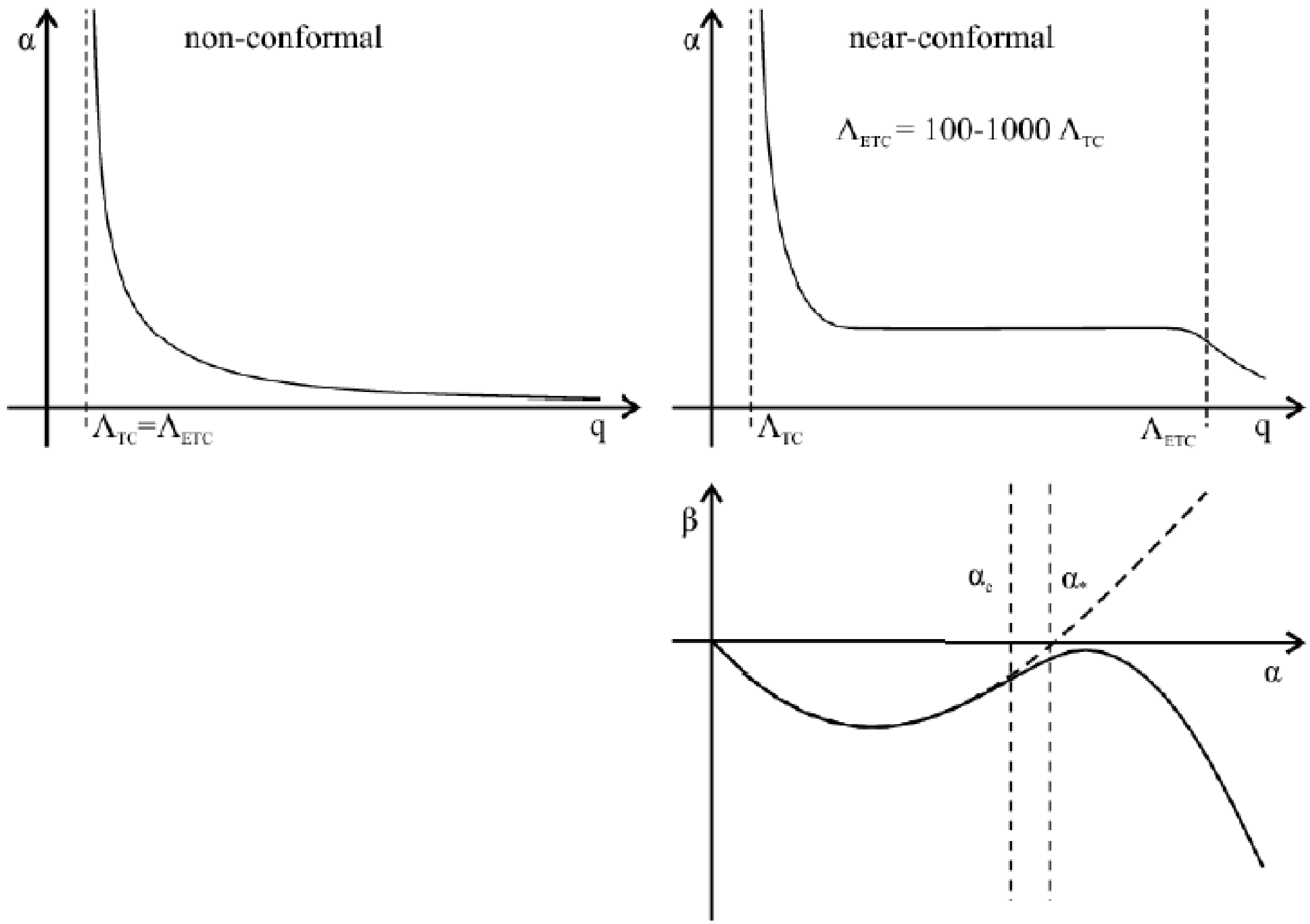
- Would-be techni pions eaten by $W$ and $Z$

- No fine tuning!

## Motivation - strong dynamics - walking technicolor

- Fermion masses?
- 4-fermi interactions, qqQQ
- FCNC too large?
- scaled up QCD $\Lambda_{QCD} \rightarrow \Lambda_{TC}$ does not work (using perturbative arguments)
- $\rightarrow$ walking $\rightarrow$ large non-perturbative effect

FCNC suppressed by large mass anomalous dimension $\gamma(\mu)$ for $\Lambda_{TC} < \mu < \Lambda_{ETC}$



## Motivation - strong dynamics - walking technicolor

Building blocks: $SU(N)$, $N_f$ flavors in representation $R$

Fix $SU(N)$, $R$, vary $N_f$

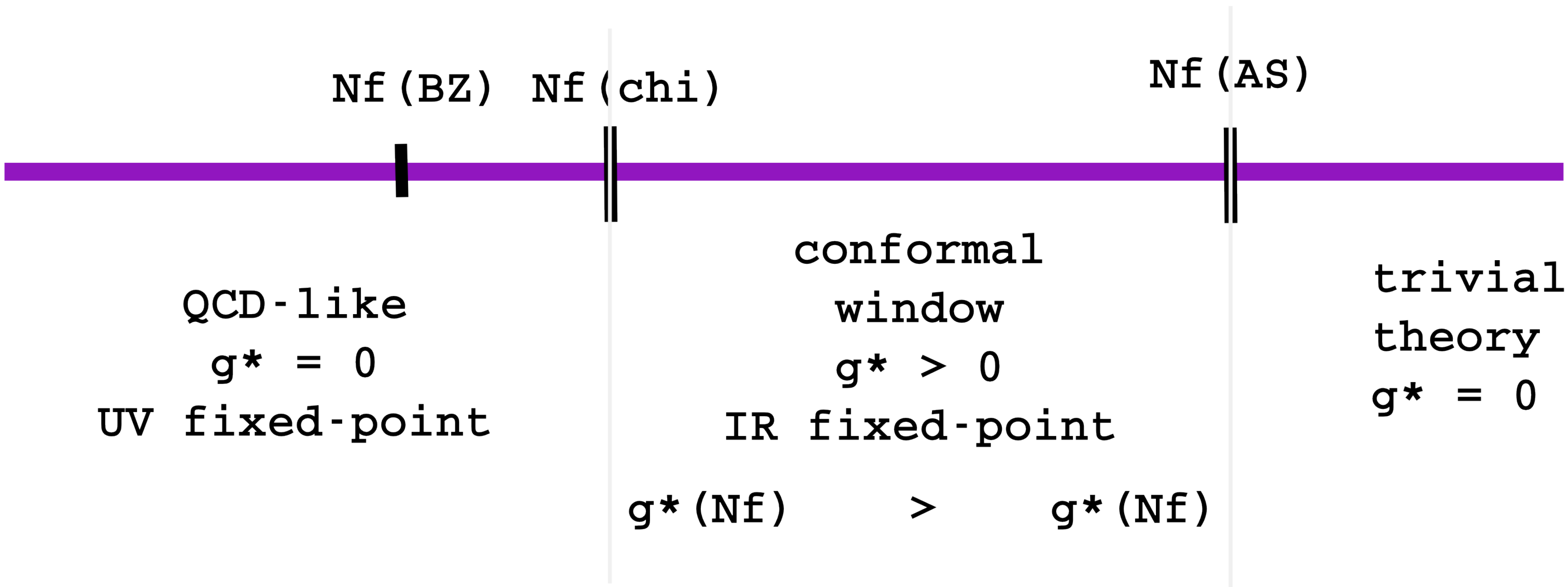
Low $N_f$: chiral symmetry breaks as in QCD

High $N_f$: asymptotic freedom lost: ${N_f}^{AF}(= 16.5$ for QCD)

Highest $N_f^* = N_f < {N_f}^{AF}$ where chiral symmetry still breaks: edge of the conformal window

Conformal window: $N_f^* < N_f < N_f^{AF} \rightarrow$ Banks-Zaks fixed point of 2-loop $\beta$-function

$N_f$ grows from left to right (gauge group, $R$ fixed)




Phenomenological constraints place us just below the conformal window.

In all these models the Higgs is a

composite ~~and/or heavy~~!

We are past July 4 2012 ....

Most knowledge so far: QCD i.e. $SU(3)$ with $R = fund$

Lower edge of conformal window uncertain $N_f^* \sim 10 - 14$.

In any case $N_f$ too large $\rightarrow$ large $S$-parameter, large number of techni pions

Try other representations?

## Outline - $SU(3)$ gauge theory with sextet fermions

- Why sextet?
- Modern history (2006 - 2011)
- Review of lattice techniques and approaches
- Our spectrum results
- Conclusions

## Why the sextet?

Problem with fundamental representation: $S_{pert} \sim N_f d(R) \to$ walking $N_f$ too high $\to$ increase $d(R)$ a bit but keep $N_f$ low

For $SU(3)$ and sextet (2-index symmetric)

- $N_f = 1$ special (no chiral symmetry, no pions, etc, etc )
- $N_f = 2$ Schwinger-Dyson: below conformal window and close
- $N_f = 3$ probably close to upper end of conformal window
- $N_f > 3.3$ asymptotic freedom is lost

If indeed $SU(3)$ with $N_f = 2$ sextet walks $\to$ 3 Goldstones

Gauge group not too large

# Lattice 2008 - 2011

Y. Shamir, B. Svetitsky, T. DeGrand, Phys. Rev. **D78**, 031502 (2008). [arXiv:0803.1707 [hep-lat]]. B. Svetitsky, Y. Shamir, T. DeGrand, PoS **LATTICE2008**, 062 (2008). [arXiv:0809.2885 [hep-lat]]. T. DeGrand, Y. Shamir, B. Svetitsky, PoS **LATTICE2008**, 063 (2008). [arXiv:0809.2953 [hep-lat]]. Z. Fodor, K. Holland, J. Kuti, D. Nogradi, C. Schroeder, PoS **LATTICE2008**, 058 (2008). [arXiv:0809.4888 [hep-lat]]. T. DeGrand, Y. Shamir, B. Svetitsky, Phys. Rev. **D79**, 034501 (2009). [arXiv:0812.1427 [hep-lat]]. Z. Fodor, K. Holland, J. Kuti, D. Nogradi, C. Schroeder, JHEP **0908**, 084 (2009). [arXiv:0905.3586 [hep-lat]]. T. DeGrand, [arXiv:0906.4543 [hep-lat]]. Z. Fodor, K. Holland, J. Kuti, D. Nogradi, C. Schroeder, JHEP **0911**, 103 (2009). [arXiv:0908.2466 [hep-lat]]. D. K. Sinclair, J. B. Kogut, PoS **LAT2009**, 184 (2009). [arXiv:0909.2019 [hep-lat]]. T. DeGrand, Phys. Rev. **D80**, 114507 (2009). [arXiv:0910.3072 [hep-lat]]. J. B. Kogut, D. K. Sinclair, Phys. Rev. **D81**, 114507 (2010). [arXiv:1002.2988 [hep-lat]]. D. K. Sinclair, J. B. Kogut, [arXiv:1003.0439 [hep-lat]]. T. DeGrand, Y. Shamir, B. Svetitsky, Phys. Rev. **D82**, 054503 (2010). [arXiv:1006.0707 [hep-lat]]. D. K. Sinclair, J. B. Kogut, PoS **LATTICE2010**, 071 (2010). [arXiv:1008.2468 [hep-lat]]. B. Svetitsky, Y. Shamir, T. DeGrand, PoS **LATTICE2010**, 072 (2010). [arXiv:1010.3396 [hep-lat]]. Z. Fodor, K. Holland, J. Kuti, D. Nogradi, C. Schroeder, [arXiv:1103.5998 [hep-lat]]. J. B. Kogut, D. K. Sinclair, [arXiv:1105.3749 [hep-lat]].

Large number of the lattice papers cite either or both of these

F. Sannino, K. Tuominen: Orientifold theory dynamics and symmetry breaking, Phys. Rev. **D71**, 051901 (2005). [hep-ph/0405209].

D. D. Dietrich, F. Sannino: Conformal window of SU(N) gauge theories with fermions in higher dimensional representations, Phys. Rev. **D75**, 085018 (2007). [hep-ph/0611341].

The relavance of higher dimensional representations is first emphasized!

Lattice groups and techniques

Schroedinger functional running coupling (Wilson):
deGrand/Shamir/Svetitsky

Thermodynamics (rooted staggered):
Kogut/Sinclair

Meson spectrum (rooted improved staggered):
Fodor/Holland/Kuti/N/Schroeder/Wong

Only discuss $N_f = 2$, but interesting results exist for $N_f = 0$ and 3.

deGrand/Shamir/Svetitsky

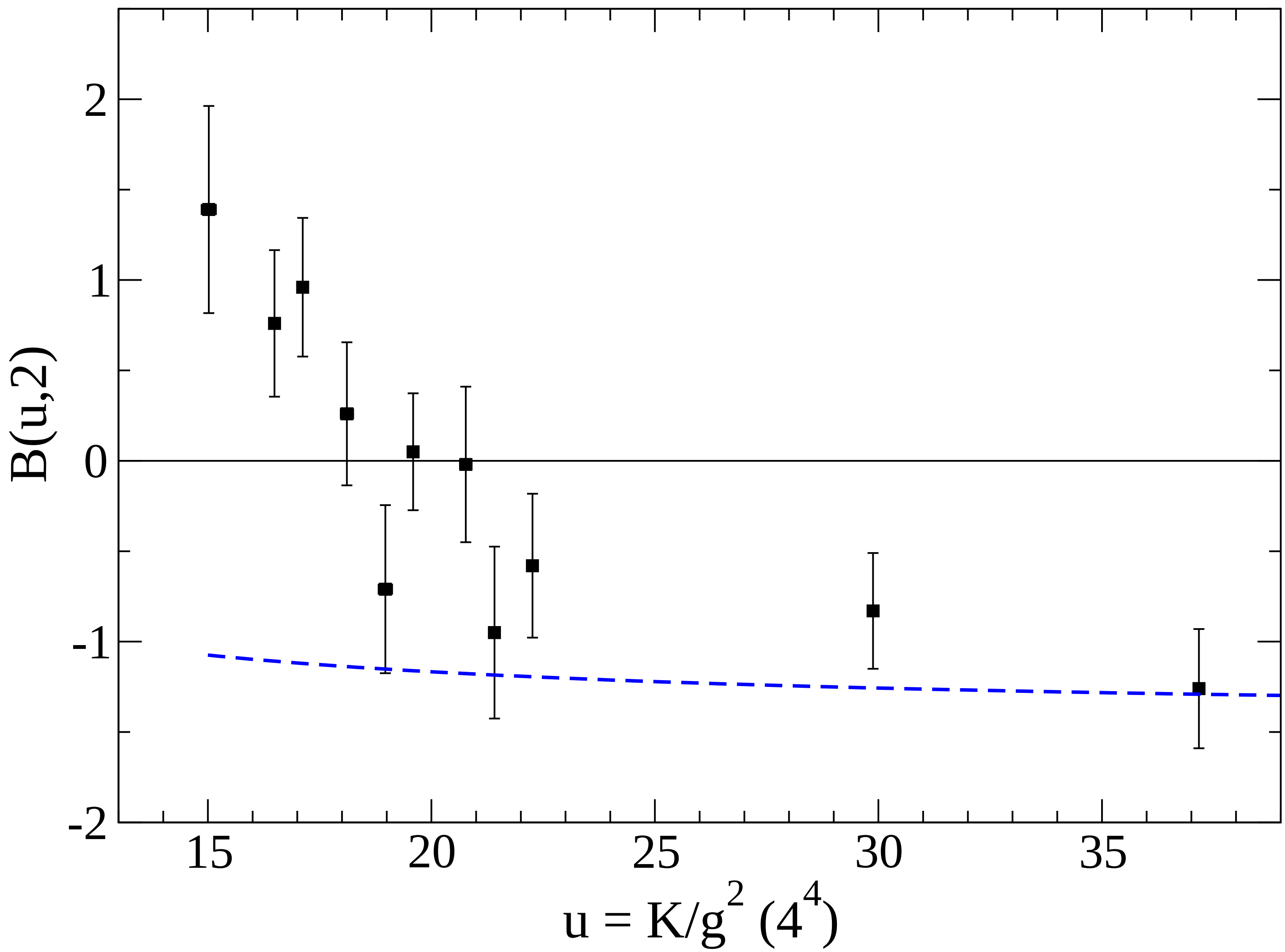
Wilson fermions, Schroedinger functional on $4^4$ – $16^4$ lattices

- 2008: found a fixed point

- 2010: no fixed point (was a lattice artifact)

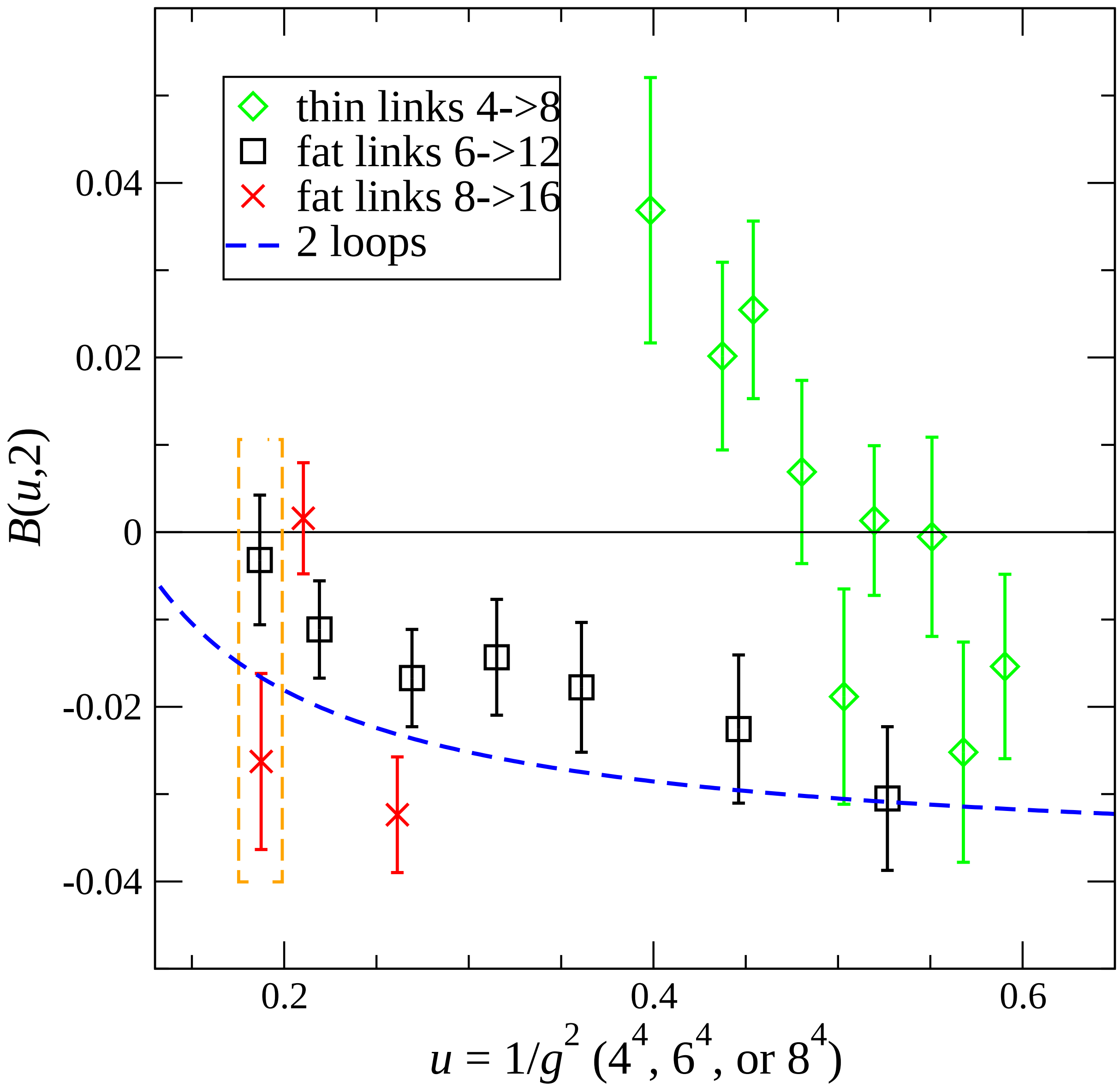
- 2011: found a fixed point again (absence was a lattice artifact)

deGrand/Shamir/Svetitsky (2008)



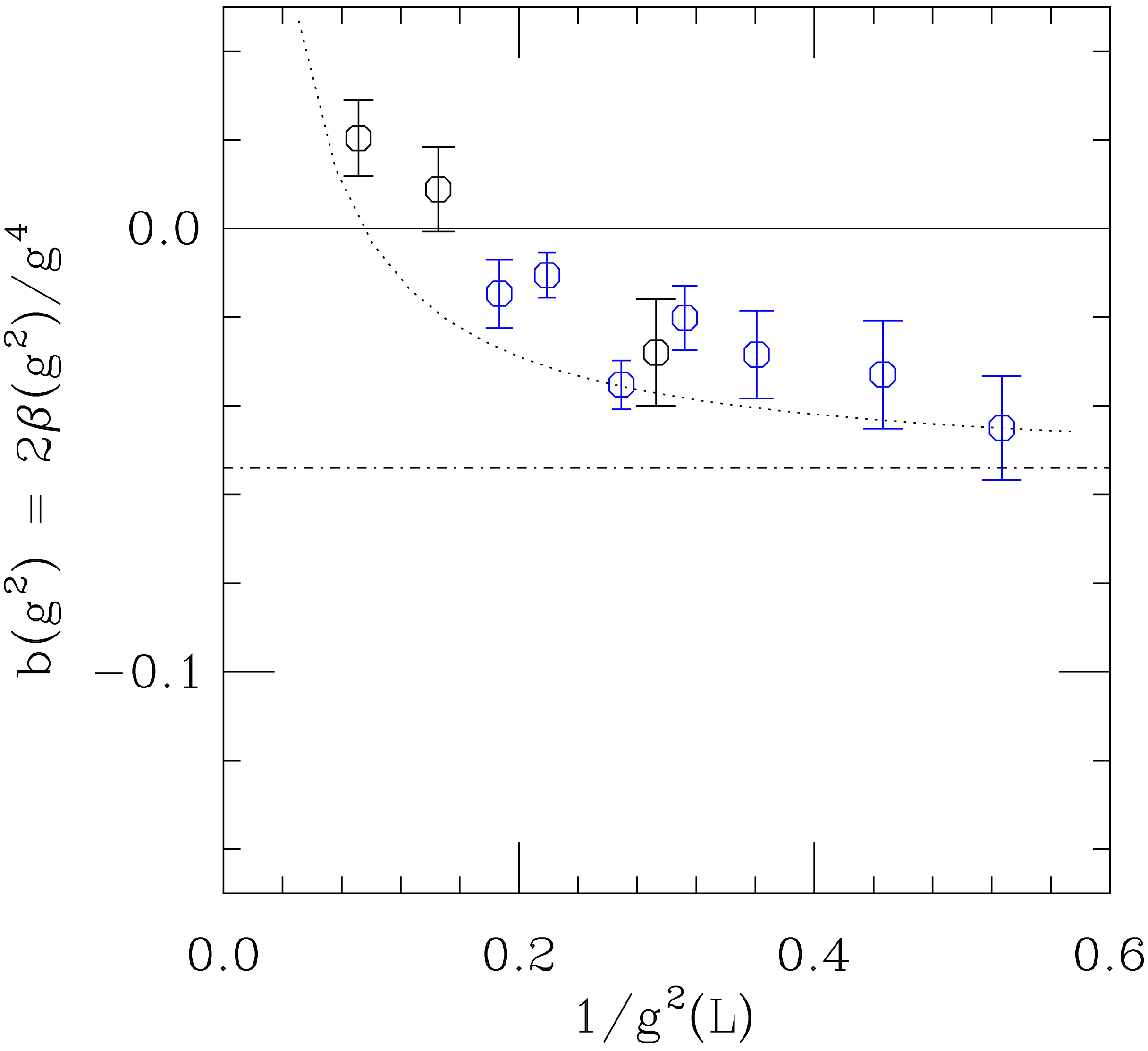

Using thin links, discrete beta function for scale change of 2

deGrand/Shamir/Svetitsky (2010)




Using thin and fat links, discrete beta function for scale change of 2

deGrand/Shamir/Svetitsky (2011)




With and without fat-link gauge action

Technique similar to Hasenfratz

deGrand/Shamir/Svetitsky

Existence of the fixed point depends on the details

$\longrightarrow$ still far from scaling region

$\longrightarrow$ can not extrapolate to continuum

Kogut/Sinclair

Rooted staggered fermions, thermodynamics

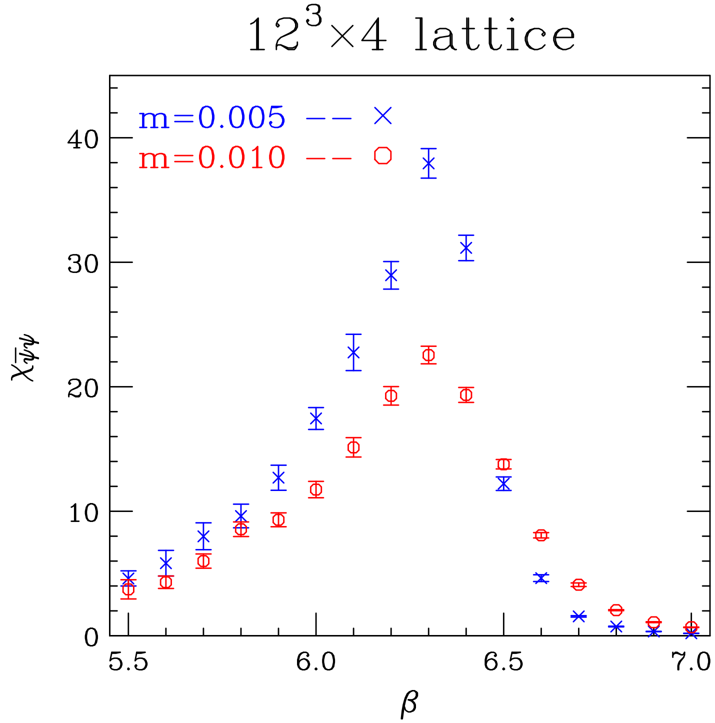
$$\beta_{\chi SB}(1/N_t) \qquad \beta_{deconf}(1/N_t)$$

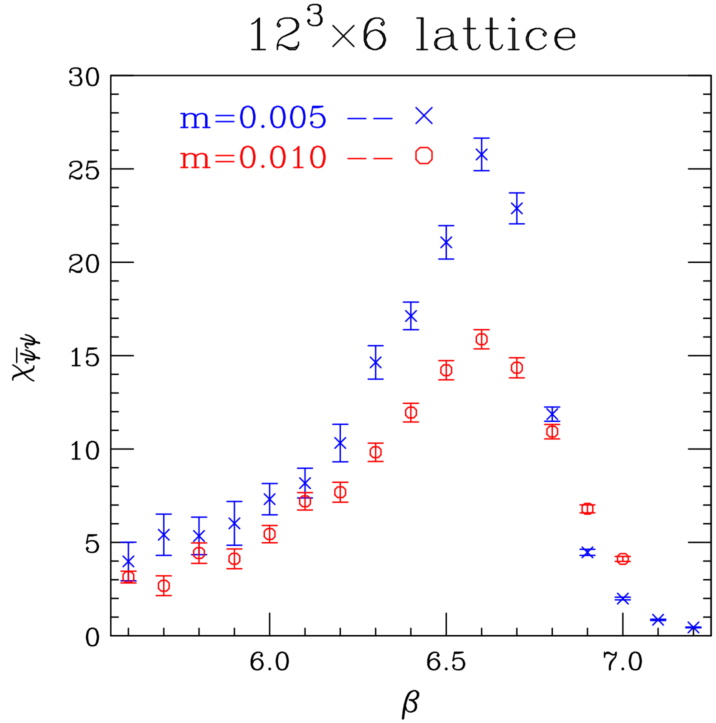
- 2010 $N_t = 4, 6$
- 2011 $N_t = 8, 12$

As $N_t$ grows the transitions move to higher $\beta \rightarrow$ chirally broken

But $N_t = 4, 6$ probably strong coupling (unimproved action)

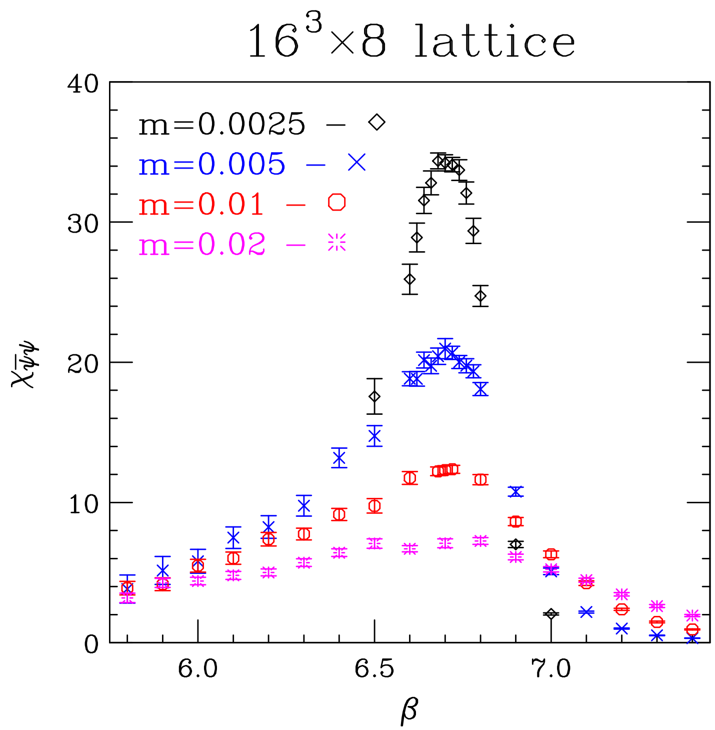
Kogut/Sinclair (2010)

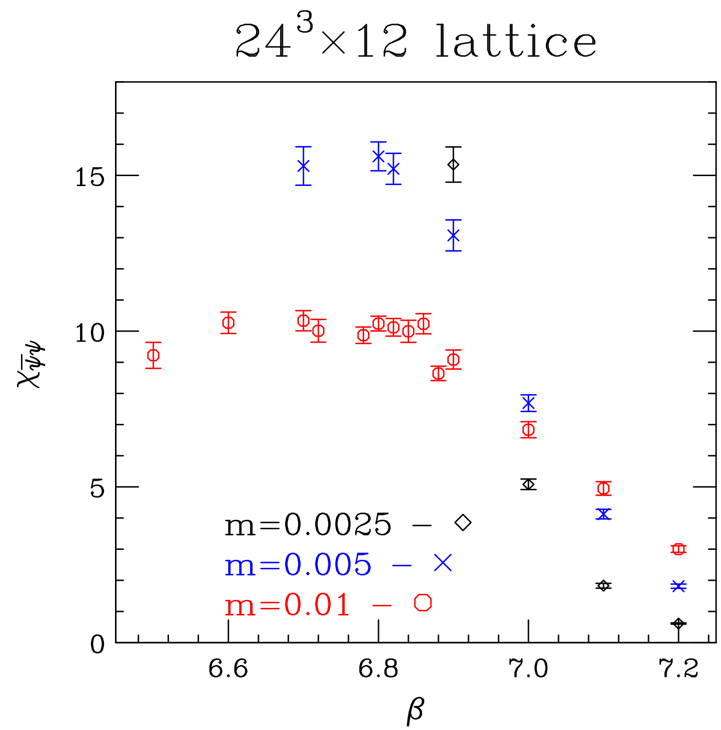



Chiral susceptibility, transition moves to larger $\beta$ as $N_t$ grows

Kogut/Sinclair (2011)




Chiral susceptibility, transition moves to larger $\beta$ as $N_t$ grows

Kogut/Sinclair

Can not extrapolate to continuum yet

$\longrightarrow$ need larger $N_t$

Fodor/Holland/Kuti/N/Schroeder

Rooted stout improved staggered fermions, meson spectrum on $32^3 \times 64$ lattices (and some $24^3 \times 48$ for checks) $\beta = 3.2$

Strategy:

- Measure $m_\pi,\ f_\pi,\ \bar{\psi}\psi$ as a function of $m$
- Make sure finite volume effects are small or under control
- Make sure taste splitting small or under control
- Pick fitting functions for $\chi SB$ hypothesis ($\chi$PT)
- Pick fitting functions for conformal hypothesis (scaling)
- Compare global $\chi^2/dof$ values

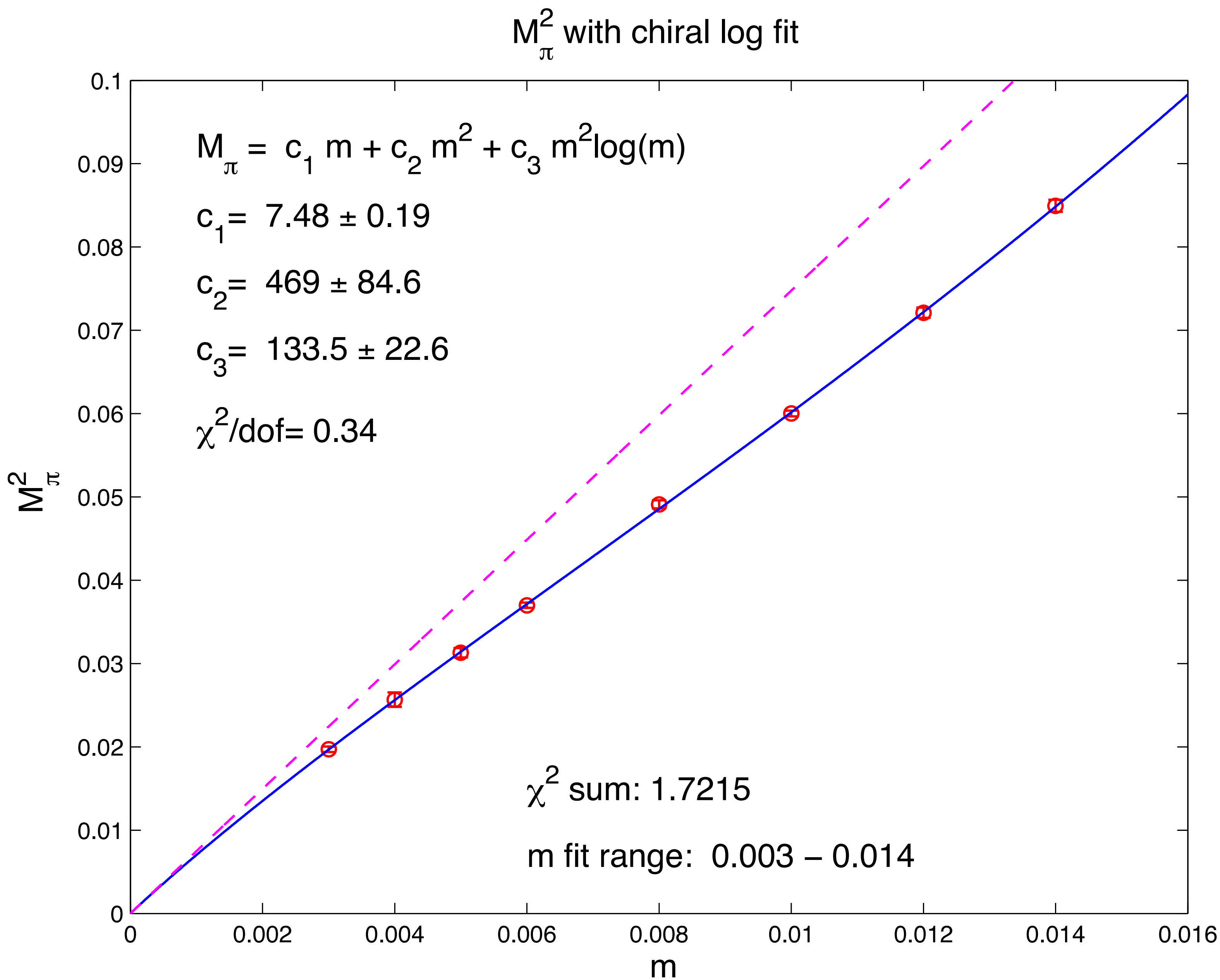
## Fit functions, $\chi SB$

- $m_\pi^2 = c_1 m + c_2 m^2 + c_3 m^2 \log(m)$
- $f_\pi = f_0 + f_1 m + f_2 m \log(m)$
- $\bar{\psi}\psi = c_0 + c_1 m + c_2 m^2, \qquad \bar{\psi}\psi - m\frac{\partial}{\partial m}\bar{\psi}\psi = c_0 - c_2 m^2$

## Fit functions, conformal (keep only leading non-analytic term)

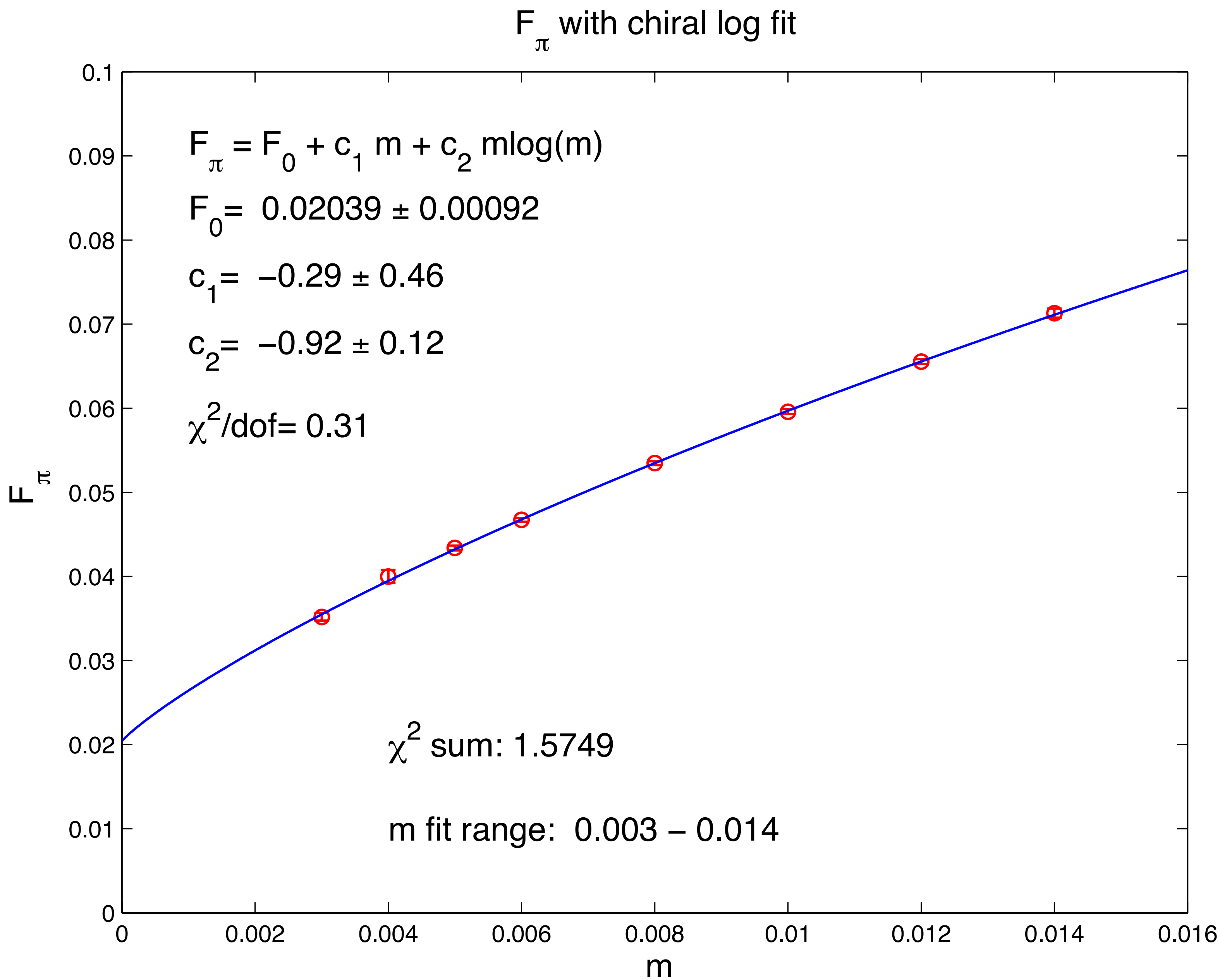
- $m_\pi,\ f_\pi = c\, m^{\frac{1}{1+\gamma}}$
- $\bar{\psi}\psi = c_1 m + c_2 m^{\frac{3-\gamma}{1+\gamma}}$

Results, $m_\pi$ typo in caption, $M_\pi^2$ magenta: linear term

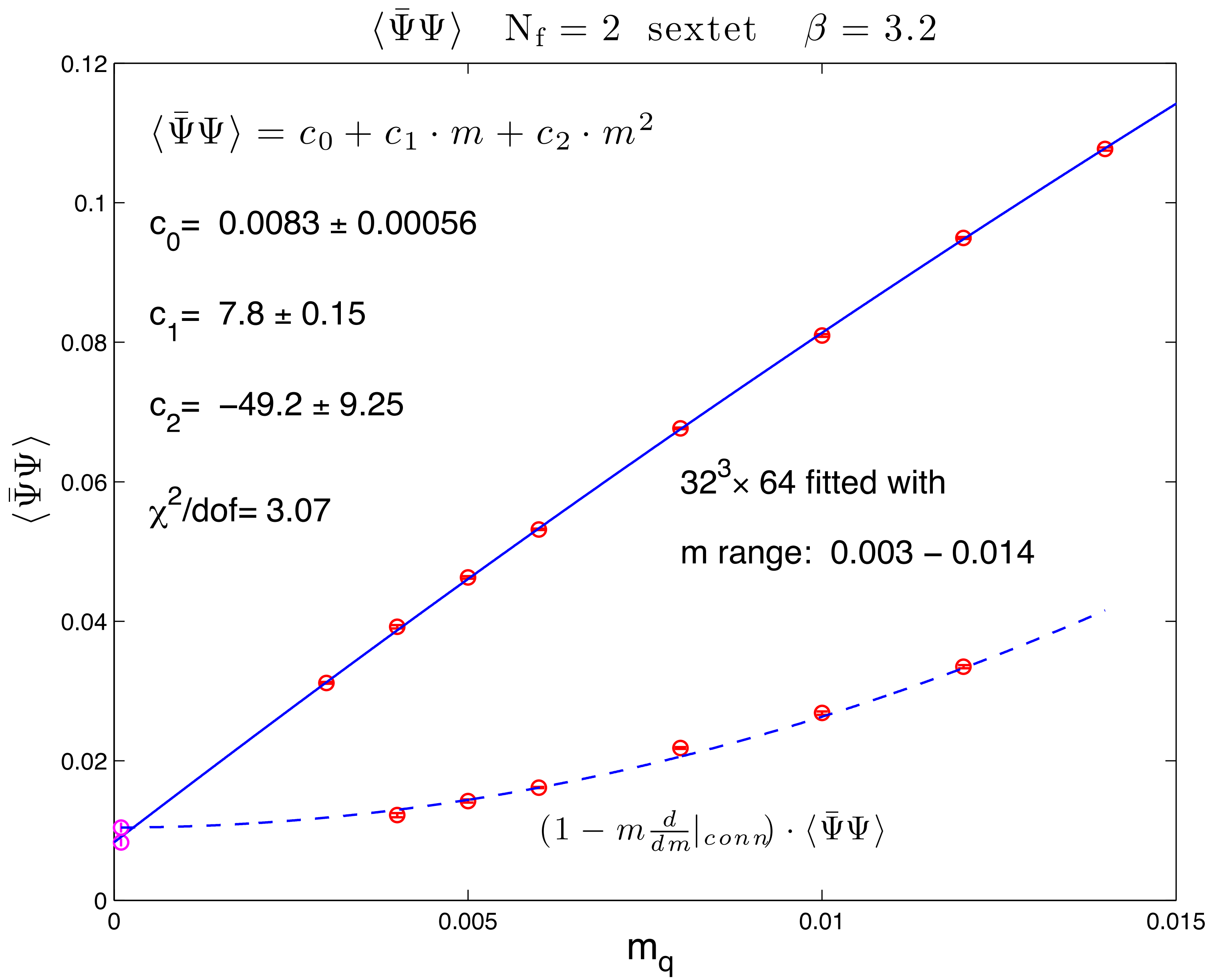


Results, $f_\pi$

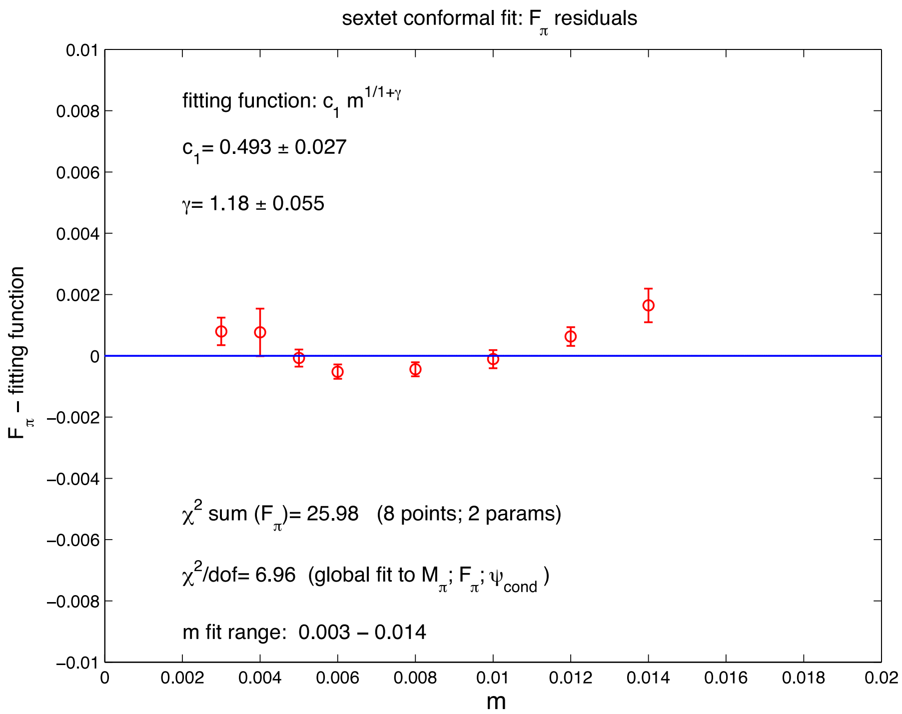
Note $f_\pi(m)L \gtrsim 1$

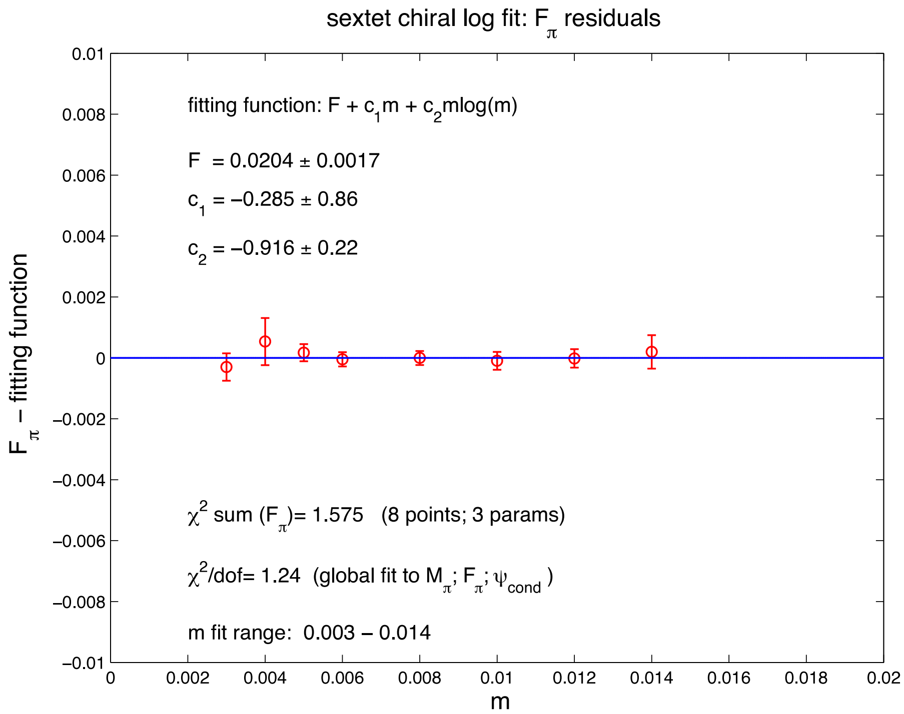


Results, $\bar{\psi}\psi$ With and without UV term $\sim m$

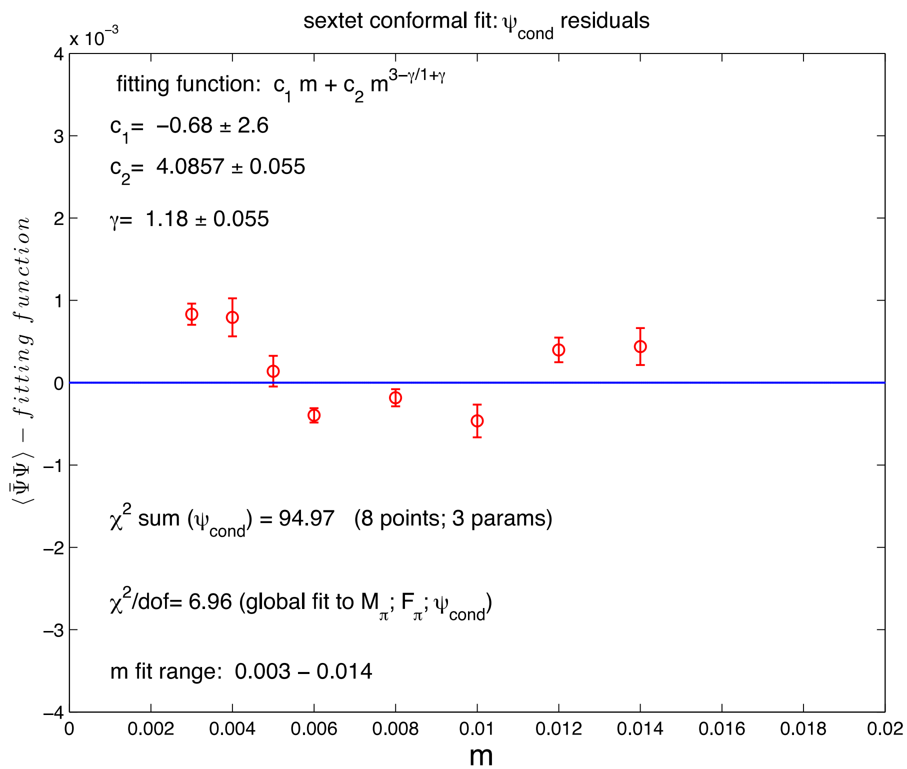


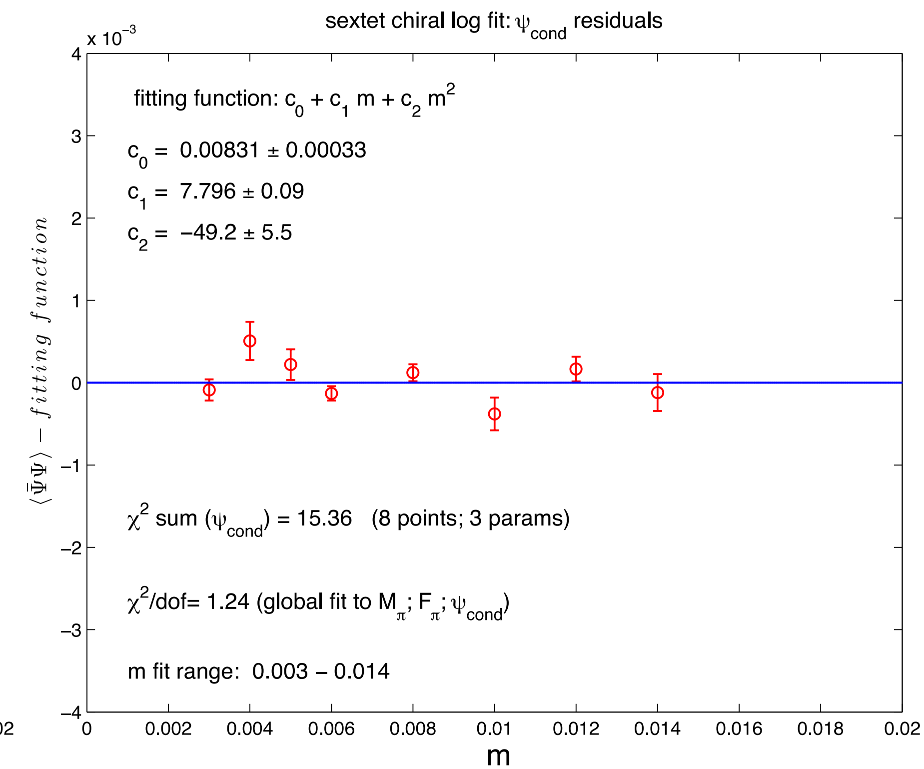
# Comparison of residuals (data - fit) $f_\pi$ global fit



# Comparison of residuals (data - fit) $\bar{\psi}\psi$ global fit



The verdict

$\chi SB:$ $\chi^2/dof = 1.24$

conformal: $\chi^2/dof = 6.96$

Based on global fitting of the 3 channels

## Limitations and stuff to work on

- Single lattice spacing so far!
- Smaller lattice spacing $\rightarrow$ finite volume effects might kill us
- Need larger volume for smaller $m$
- More volumes for finite size scaling for conformal analysis
- Subleading terms for conformal analysis?
- Measure more states, glueballs, 3-quark states?, string tension

## Conclusions

- Various groups do not agree about IR of $SU(3)$ with $N_f = 2$ sextet

- Meson spectrum favors $\chi SB$ at $\beta = 3.2$

- Nobody claims to have final continuum results

## Outlook

- Since $SU(3)$ $N_f = 2$ sextet can be relevant phenomenologically

  $\rightarrow$ need to have robust results

- Various approaches tried (good!)

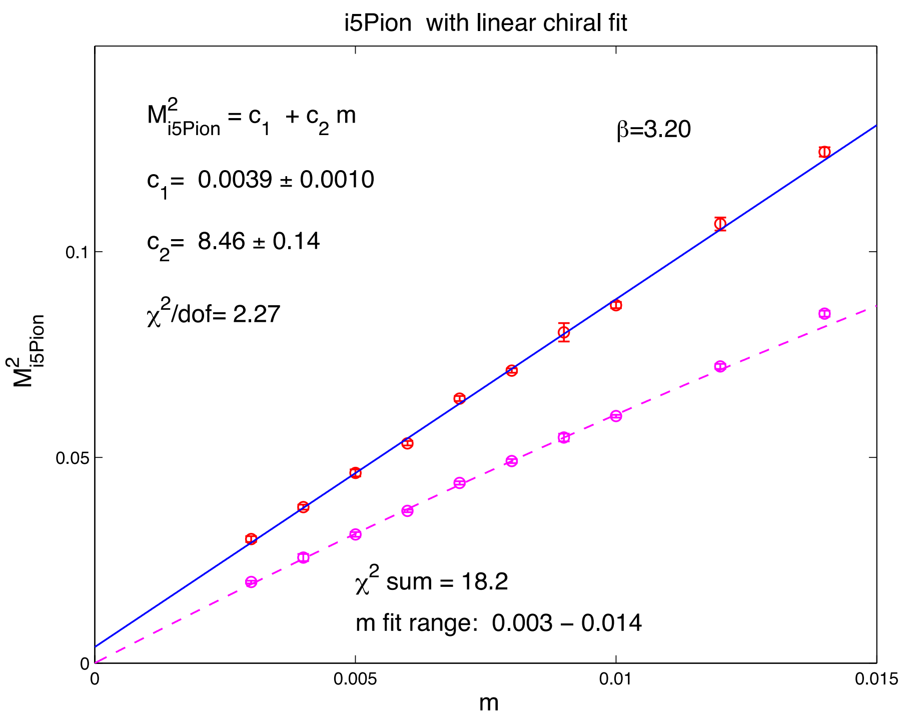
- Limitations clear (good!) $\rightarrow$ all groups can improve

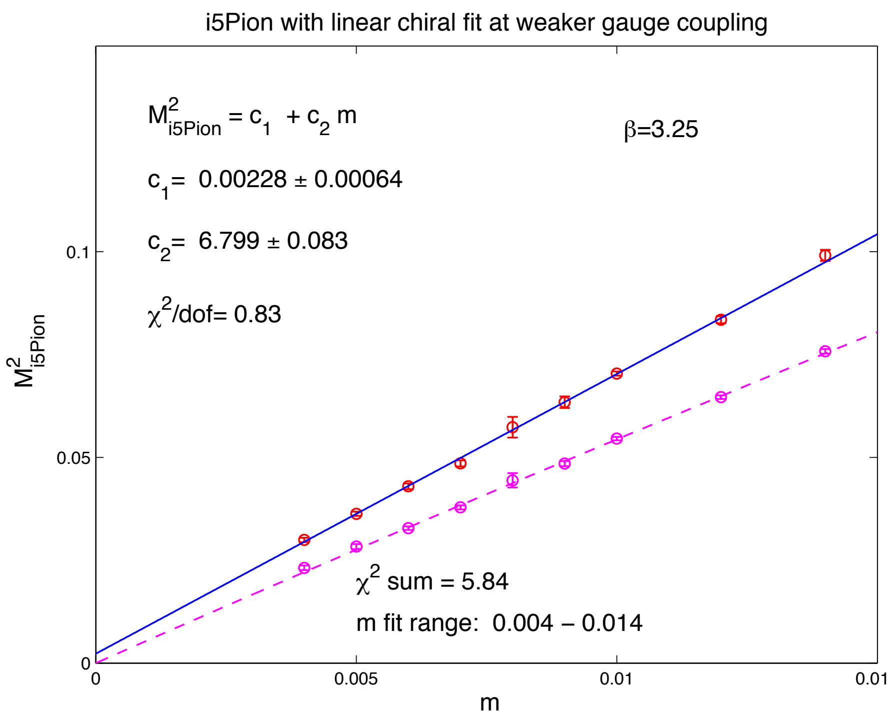
- Ideally: combine approaches
  - Finite $T$ transition $\rightarrow$ spectrum for $T < T_c$?
  - No fixed point $\rightarrow$ spectrum at strongest coupling?
  - Fixed point $\rightarrow$ finite $T$?

Backup slides

Taste breaking

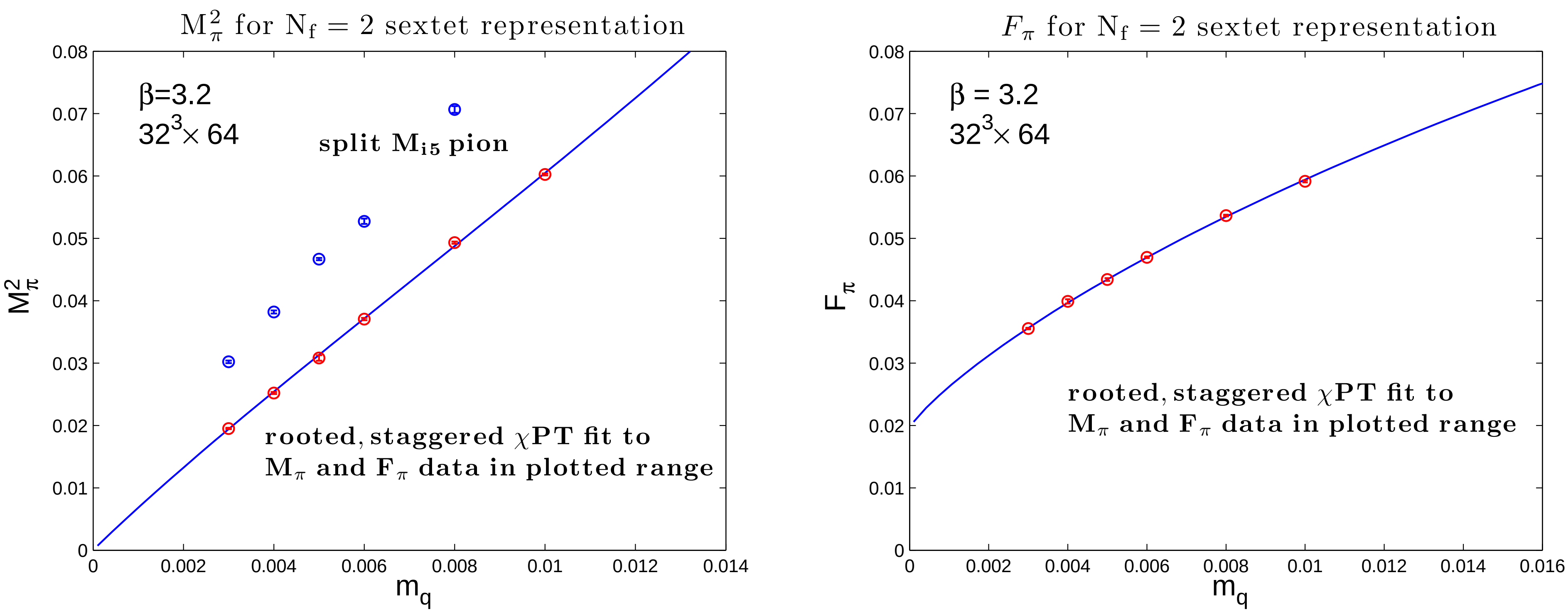
i5pion $\beta = 3.20$ vs. $\beta = 3.25$




Magenta: Goldstone pion

# Rooted staggered chiral perturbation theory




Simultaneous fit, same chiral limit $f_\pi(m \to 0)$ value