Many flavors later... What have we learned?

Meifeng Lin (Yale / BU)
for the LSD Collaboration

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Motivations

- Before we found the "Higgs" boson...
  - If a new form of strong dynamics at TeV scale is responsible for the electroweak symmetry breaking...
  - Is technicolor a viable option? Can we produce a small S parameter, an enhanced chiral condensate, a large enough anomalous dimension?
  - Can we really see the "walking" behavior? And where is it in the Nf-Nc plane?
- Now that a Higgs-like particle has been observed...
  - LHC: new particle mass ~ 126 GeV
  - Can we produce a light composite scalar boson?

Outline

- Part I: Viability Tests
  - Condensate Enhancement
  - Reduced S Parameter
  - Large anomalous dimension
- Part II: Light Scalar
  - Can technicolor produce light scalars?

Lattice Strong Dynamics Collaboration

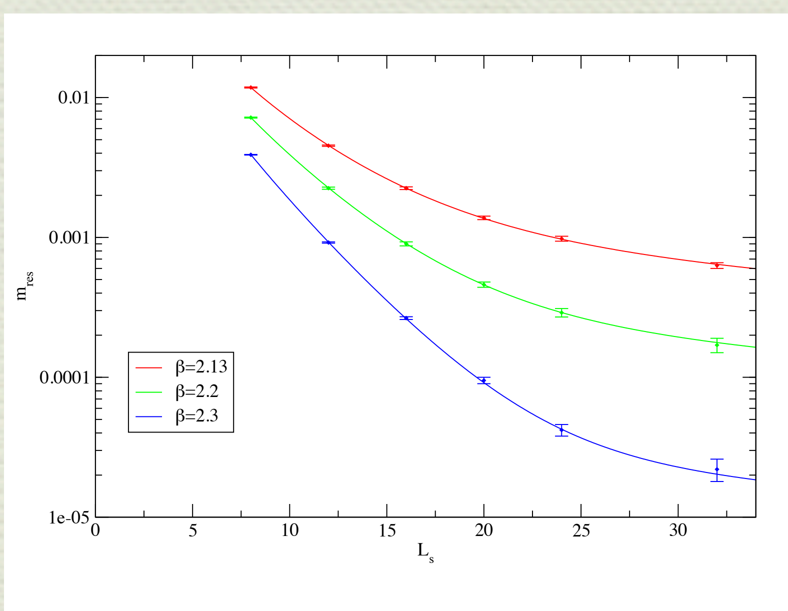
- Formed in 2007. Now has more than 20 members from 10 institutes.
- Goal: perform non-perturbative studies of strongly interacting gauge theories.
    - To provide input for BSM DEWSB model building: S parameter reduction, condensate enhancement, etc.
    - To study possible signatures that may be observed at LHC: hadron spectrum, ...
- Started with 2 and 6 flavors with SU(3) fundamental fermions. Now have computed 8 and 10 flavors. SU(2) in progress.

Lattice Strong Dynamics Collaboration

Tom Appelquist (Yale)	Heechang Na (ANL)
Ron Babich (NVIDIA)	Ethan Neil (Fermilab)
Rich Brower (Boston)	James Osborn (ANL)
Michael Buchoff (LLNL)	Claudio Rebbi (Boston)
Michael Cheng (Boston)	David Schaich (Boulder)
Mike Clark (NVIDIA)	Chris Schroeder (LLNL)
Saul Cohen (Washington)	Sergey Syritsyn (LBL)
George Fleming (Yale)	Joe Wasem (LLNL)
Joe Kiskis (Davis)	Oliver Witzel (Boston)
Meifeng Lin (Yale/Boston)	Gennady Voronov (Yale)
	Pavlos Vranas (LLNL)

Lattice Details

Domain Wall Fermion



D. J. Antonio et al., 2008

Chiral symmetry plays an important role

- **Fermion Action**: Domain Wall Fermions, with Ls=16.
- **Gauge Action**: Iwasaki.
- **Lattice Volume:** 32^3x64.
- SU(3) fundamental, with 2, 6, 8 and 10 flavors.

Part I: Viability Tests

Reminder

Perturbative 2-loop beta function

$$\beta(g) = -b_0 g^3 + b_1 g^5 + O(g^7),$$

with

$$b_0 = \frac{1}{48\pi^2}(11N_c - 2N_f),$$

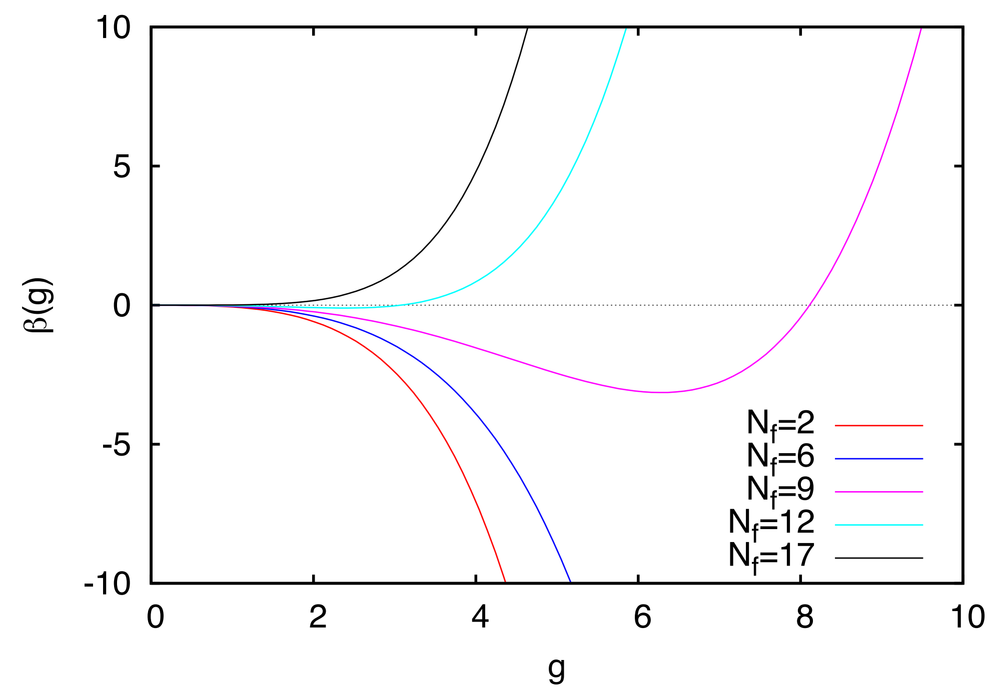
$$b_1 = -\frac{1}{(16\pi^2)^2}\left[\frac{34}{3}N_c^2 - \frac{1}{2}N_f\left(\frac{16}{3} + \frac{20}{3}N_c\right)\right].$$

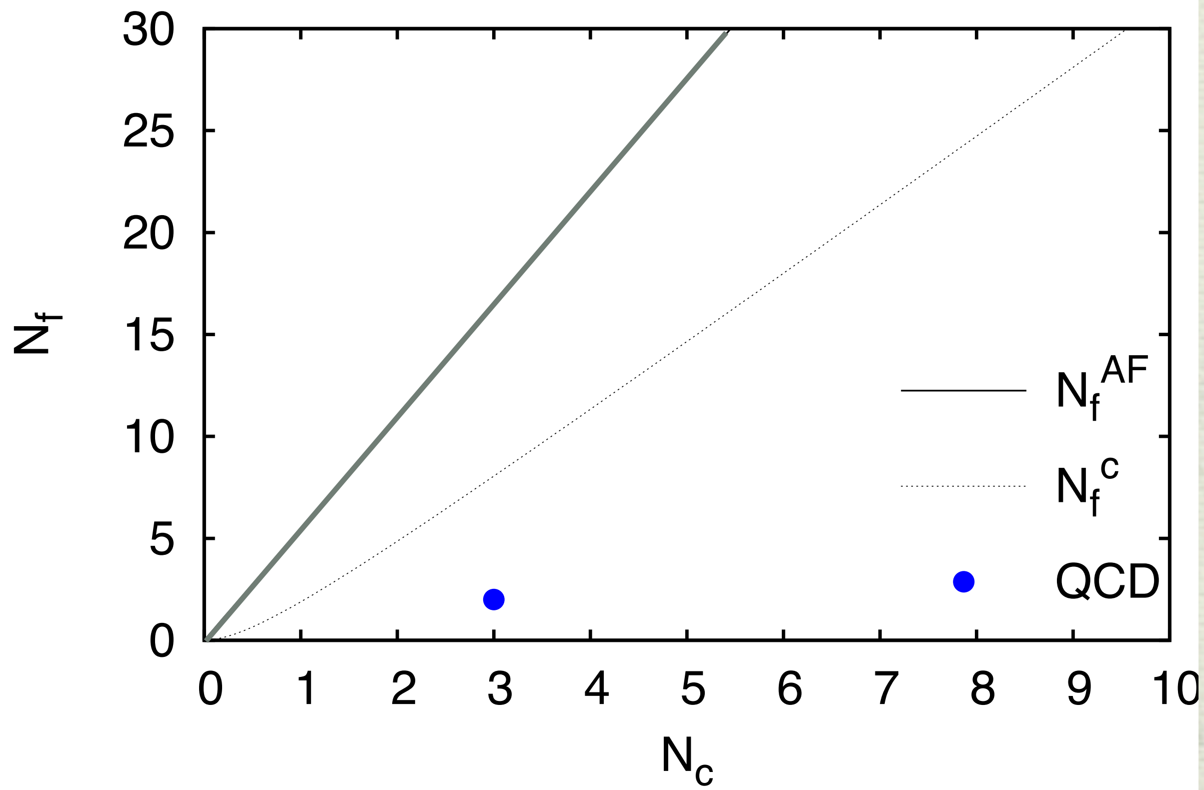
Two Questions:

- Where is conformal window?

- Do we see walking behaviors as we approach it from below?

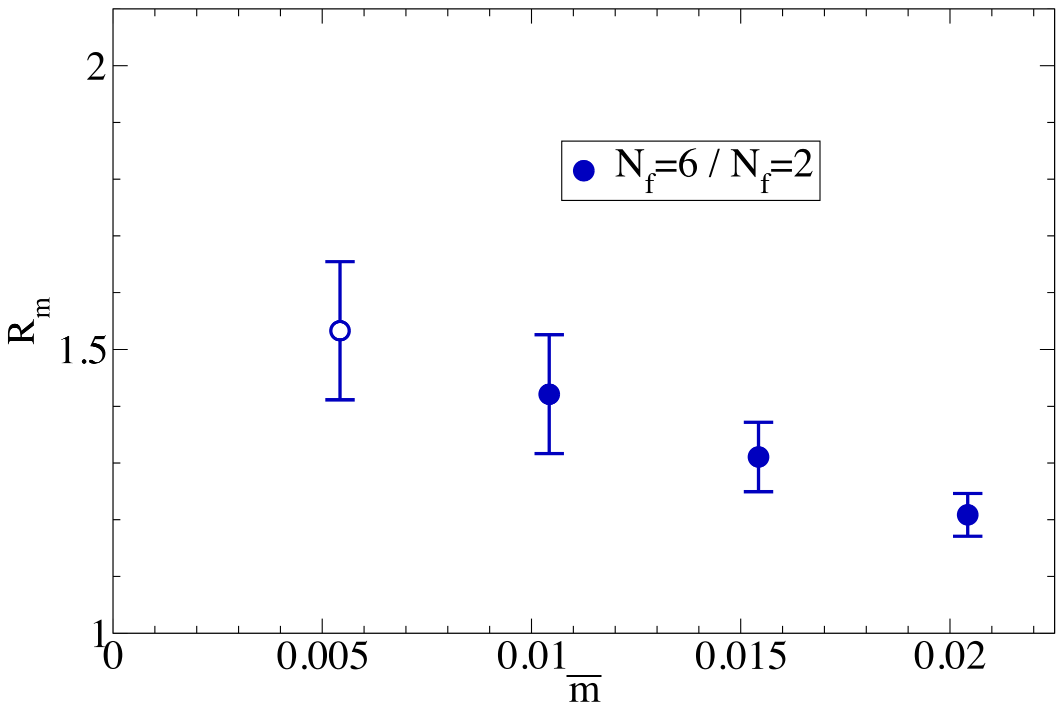
SU(3) Case





Condensate Enhancement

LSD Collaboration, PRL104, 071601(2010)



$$R_m \equiv \frac{M_m^2}{2mF_\pi}_{(N_f=6)} \Big/ \frac{M_m^2}{2mF_\pi}_{(N_f=2)}$$

As we go to the chiral limit, the ratio of the chiral condensate of 6f to 2f seems to be increasing.

Need chiral fits to find the value at the chiral limit.

ETC --> Quark Mass

$$m_{q,l} \simeq \frac{\langle \overline{Q}Q \rangle_{ETC}}{\Lambda^2_{ETC}}$$

Lambda_{ETC} needs to be large to suppress FCNC

$$\text{FCNC} : \propto \frac{\alpha_{ij}(\overline{q}q)_i(\overline{q}q)_j}{\Lambda^2_{ETC}}$$

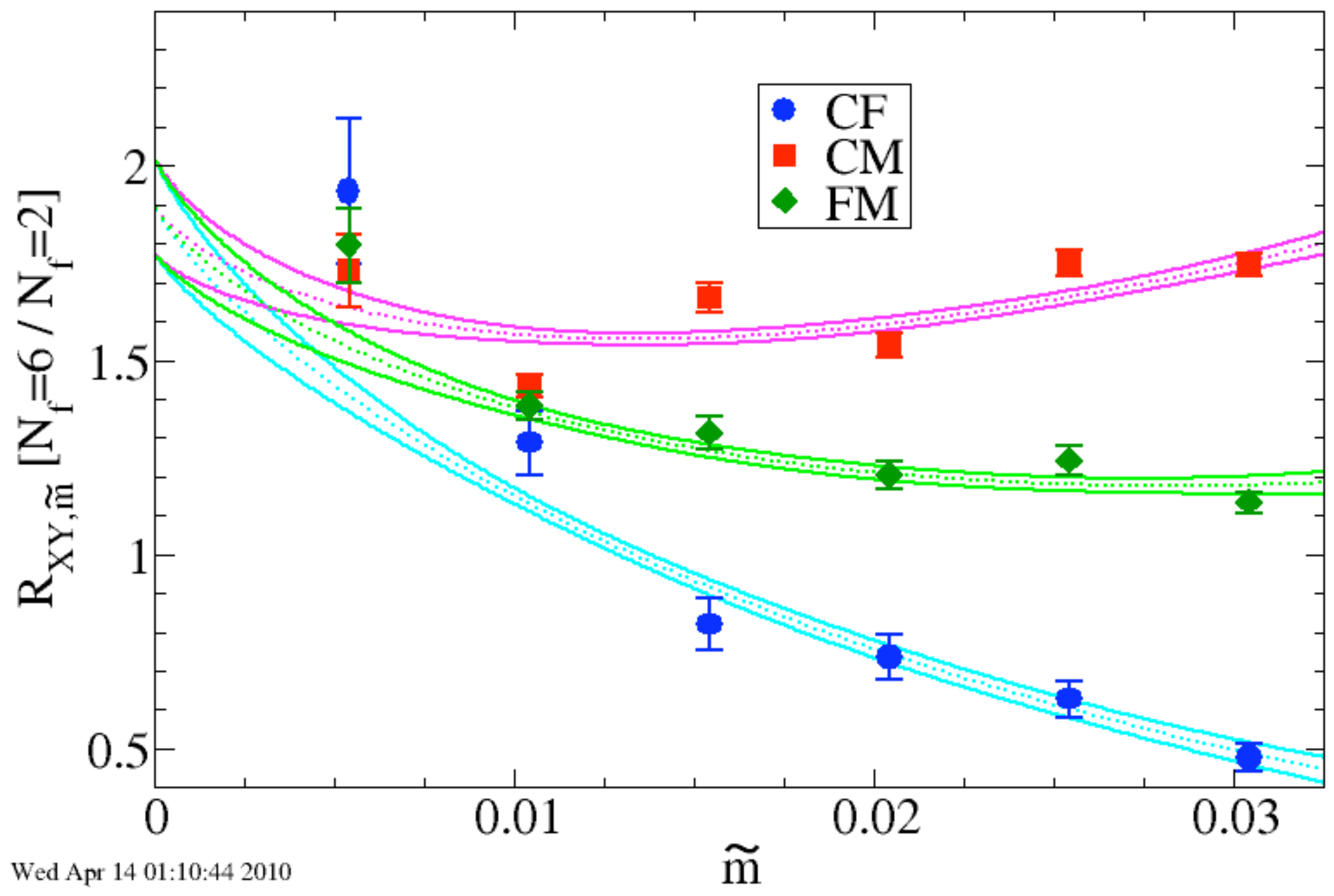
Need a large anomalous dimension & a large chiral condensate

$$\langle \overline{Q}Q \rangle_{ETC} \sim \langle \overline{Q}Q \rangle_{TC} \left(\frac{\Lambda_{UV}}{\Lambda_{IR}} \right)^{\gamma}$$

Chiral condensate from three GMOR ratios (in the chiral limit)

$$R = \frac{\langle\overline{\psi}\psi\rangle}{F_\pi^3} = \frac{M_\pi^3}{\sqrt{(2m)^3\langle\overline{\psi}\psi\rangle}} = \frac{M_\pi^2}{2mF_\pi}, m = m_f + m_{\mathrm{res}}$$

CF CM FM



$$\mathcal{R}_{XY,\widetilde{m}} \equiv \frac{R^{(N_f)}}{R^{(N_f=2)}}\left[1 + \widetilde{m}\left(\alpha_{XY,10} + \alpha_{11}\log\widetilde{m}\right)\right]$$

How about more flavors?

- Condensate enhancement only makes sense if we are in the chirally broken phase.
- As we increase the number of flavors, the likelihood that we are in the conformal phase increases.

↓

chiral condensate vanishes.

S Parameter

Definition

$$S = -4\pi \left[\Pi'_{VV}(0) - \Pi'_{AA}(0) \right] - \Delta S_{SM}, \; \Pi'(0) = \frac{d\Pi(q^2)}{dq^2}|_{q^2 \to 0}$$

where

$$\Pi^{\mu\nu}_{VV}(q) = \sum_x e^{iq\cdot x} \langle V^\mu(x) V^\nu(0) \rangle, \; \Pi^{\mu\nu}_{AA}(q) = \sum_x e^{iq\cdot x} \langle A^\mu(x) A^\nu(0) \rangle$$

ΔS_{SM} – Standard Model Higgs contributions

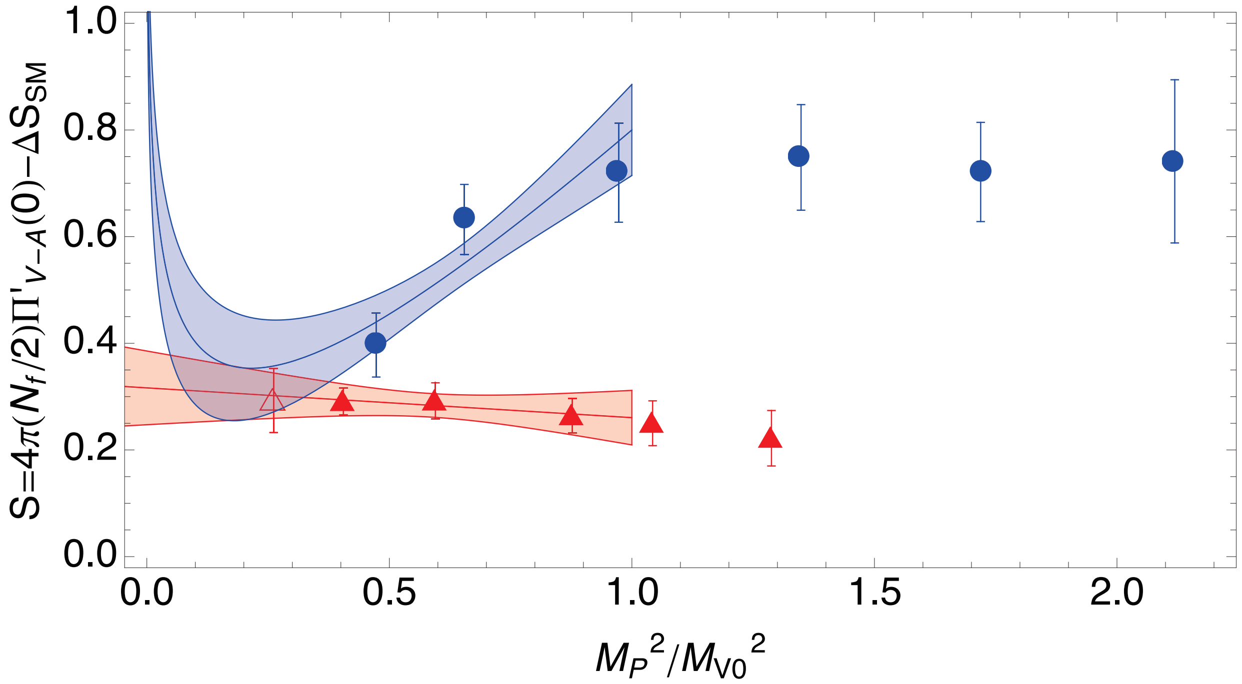
$$\Delta S_{SM} = \frac{1}{4} \int_0^\infty \frac{ds}{s} \left[1 - \left(1 - \frac{m_H^2}{s} \right)^3 \theta(s - m_H^2) \right]$$

m_H – reference Higgs mass.

Electroweak precision experiments find $S \approx 0$.
Scaled-up QCD with $N_f = 2$ gives $S \approx 0.3$.

S Parameter

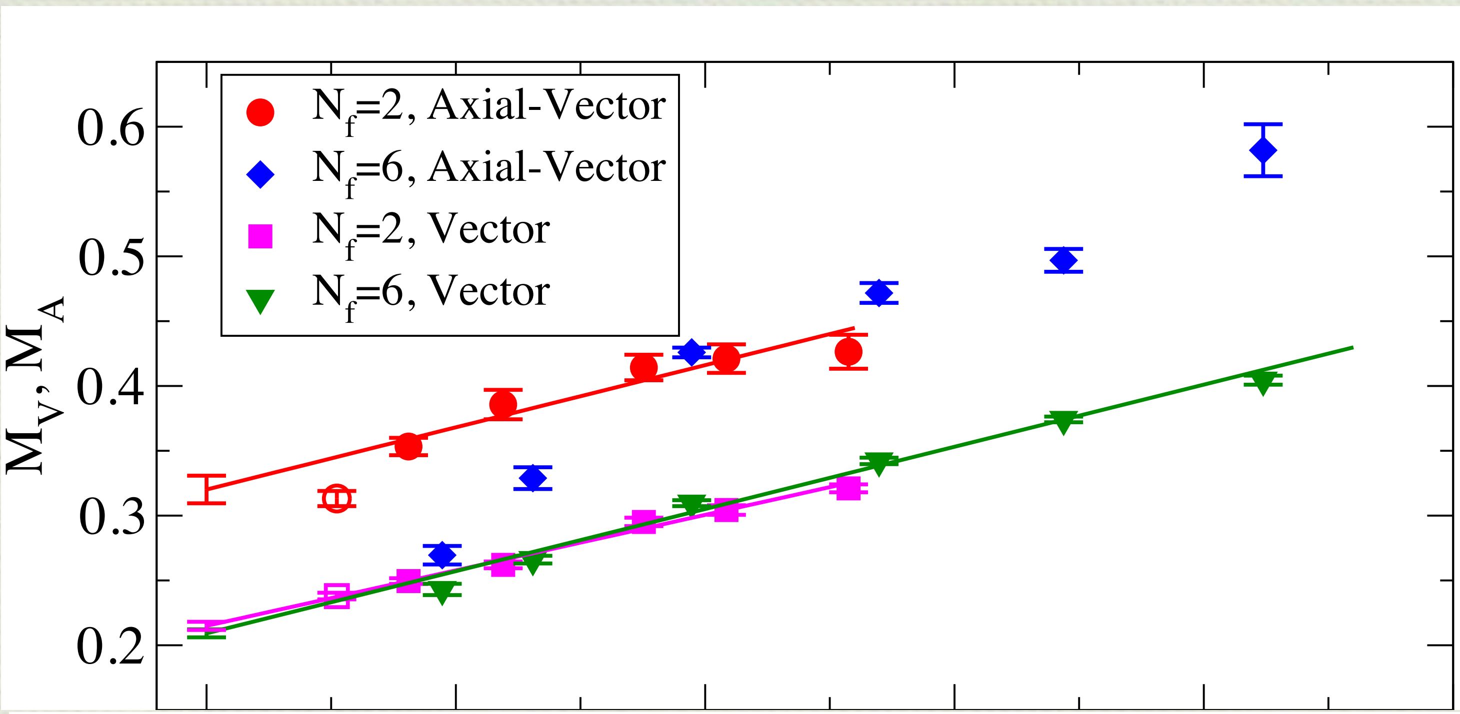
LSD Collaboration, PRL106, 231601 (2011)

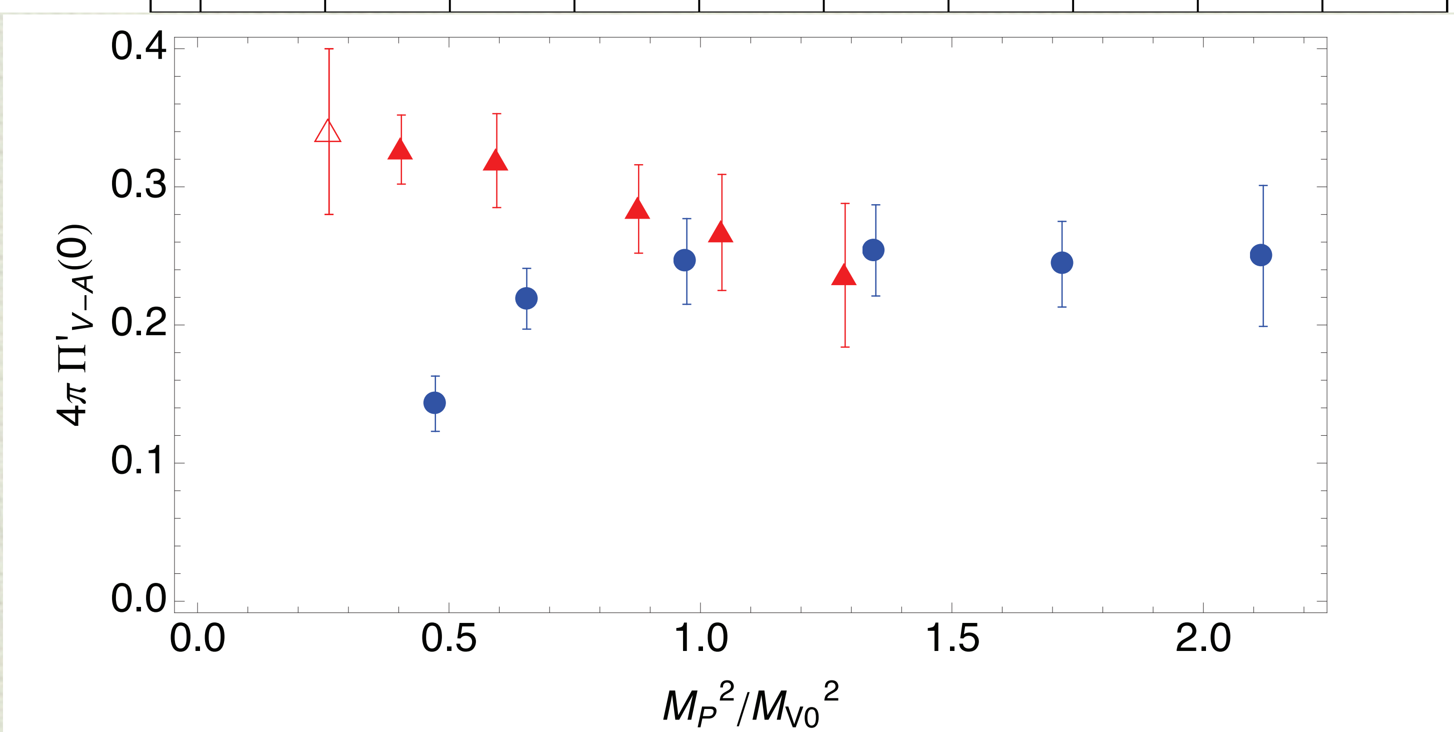


- $N_f = 2$, simple linear extrapolation for $M_P < M_{V0}$ gives $S = 0.32(5)$, consistent with the value obtained using scaled-up QCD data.
- For $N_f = 6$, at small mass, S drops below the value obtained by simply multiplying the $N_f = 2$ result by a factor of 3.
- However, there can be chiral log contributions, which will eventually make S turn up. Shown fit curve used form:

$$S = A + BM_P^2 + \frac{2}{3\pi} \log \frac{M_{V0}^2}{M_P^2}$$

S Parameter and Parity Doubling





Spectral representation of S

$$S = \frac{1}{3\pi}\int_0^\infty \frac{ds}{s}\left\{N_D\left[R_V(s)-R_A(s)\right] - \frac{1}{4}\left[1-\left(1-\frac{m_H^2}{s}\right)^3\theta(s-m_H^2)\right]\right\}$$

Single-pole dominance

$$S = 4\pi\left[\frac{F_V^2}{M_V^2}-\frac{F_A^2}{M_A^2}\right]$$

As we approach the conformal window, chiral symmetry breaking effects may be smaller. Vector and axialvector mesons may become more degenerate, such that S parameter gets smaller.

8 and 10 flavors

- So far we have only looked at 2f and 6f, and assume 6f is in the chirally broken phase.
- Which side are 8f and 10f on?
- We will first check if our 10f data are consistent with conformality. 8f analysis is on the way.

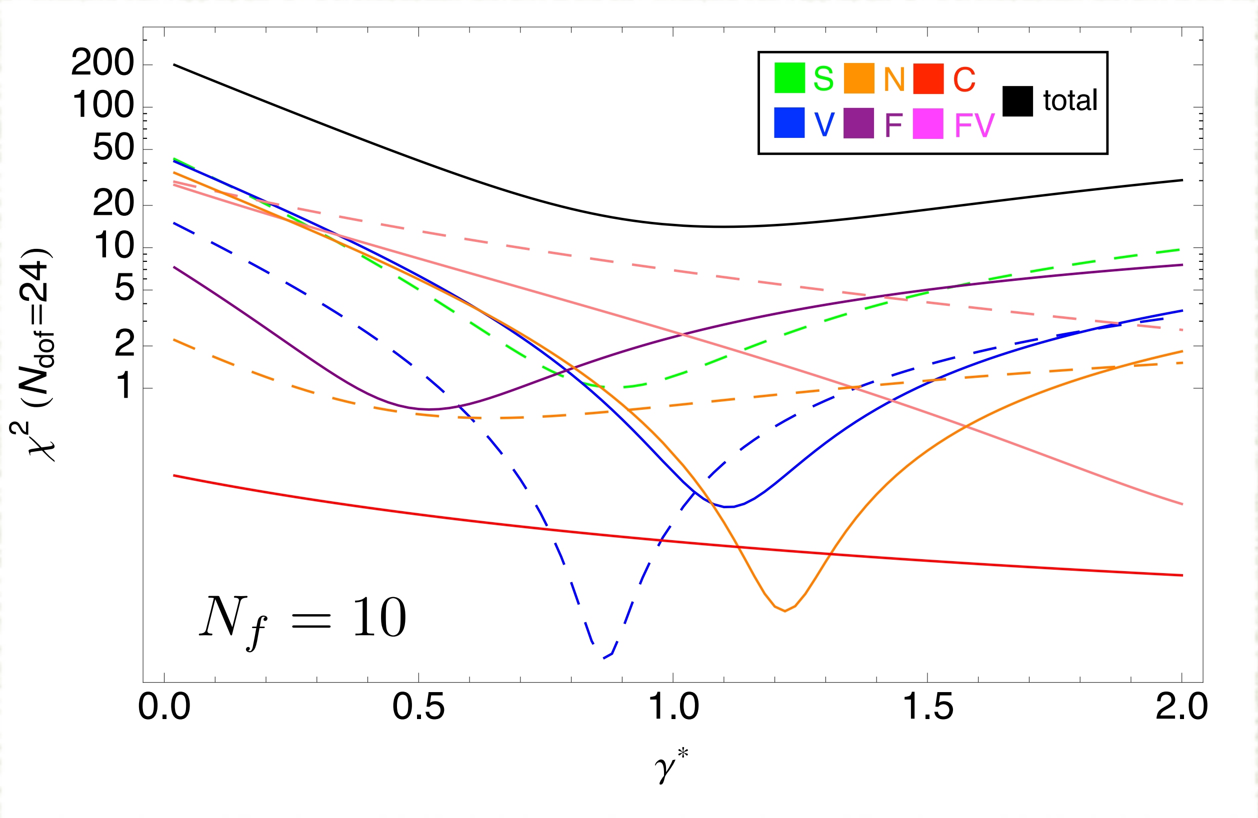
Conformality Test for 10-flavor

- In the conformal phase, there is no intrinsic scale (in the infinite volume and massless limit).
- With a finite mass, and assume volume is infinite,

$$M_X = C_X m^{\frac{1}{1+\gamma^*}}$$

In a finite volume, there will be volume dependence to be considered. => finite size scaling.

Our method: Scanning over a range of gamma^* to see if the minima of chi^2 are consistent for different observables.

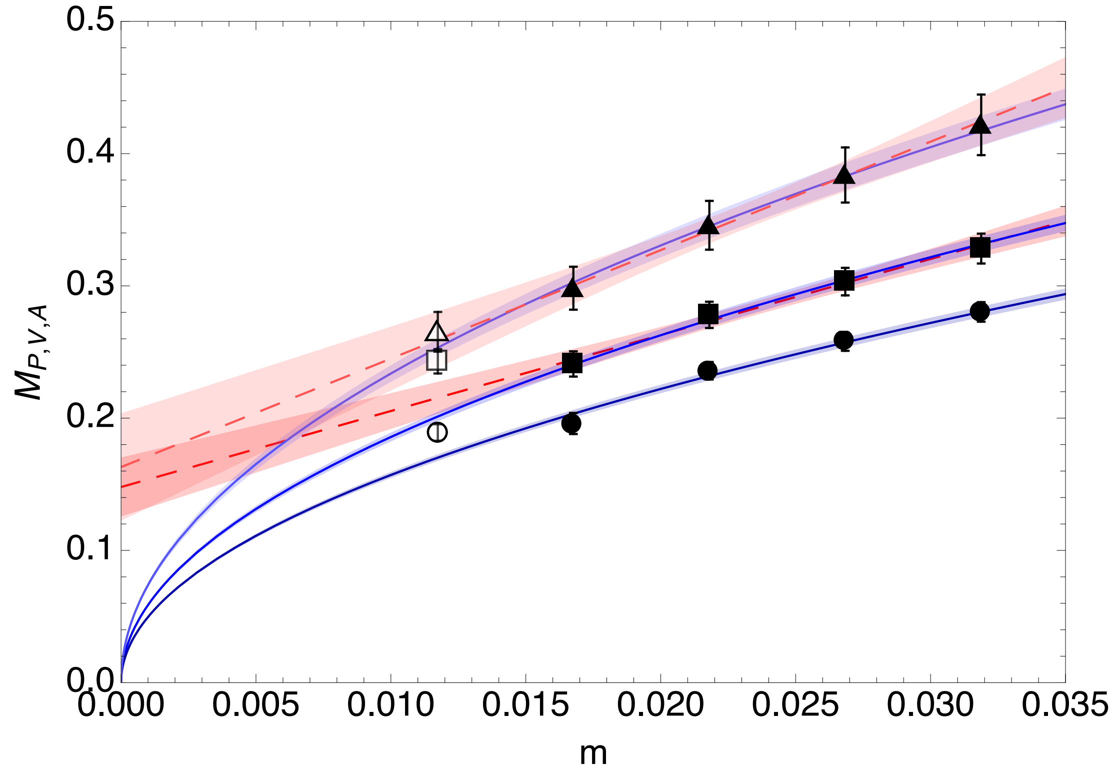


They are not exactly falling at the same point, but quite consistent within margin of errors.

Global best fit: gamma* = 1.10(17)

LSD Collaboration, arXiv:1204.6000

10-flavor Mass Fits



Sample fit curves to M_P, M_V and M_A with $\gamma^* = 1$.

For M_P, conformal fit and the leading-order ChPT fit are identical.

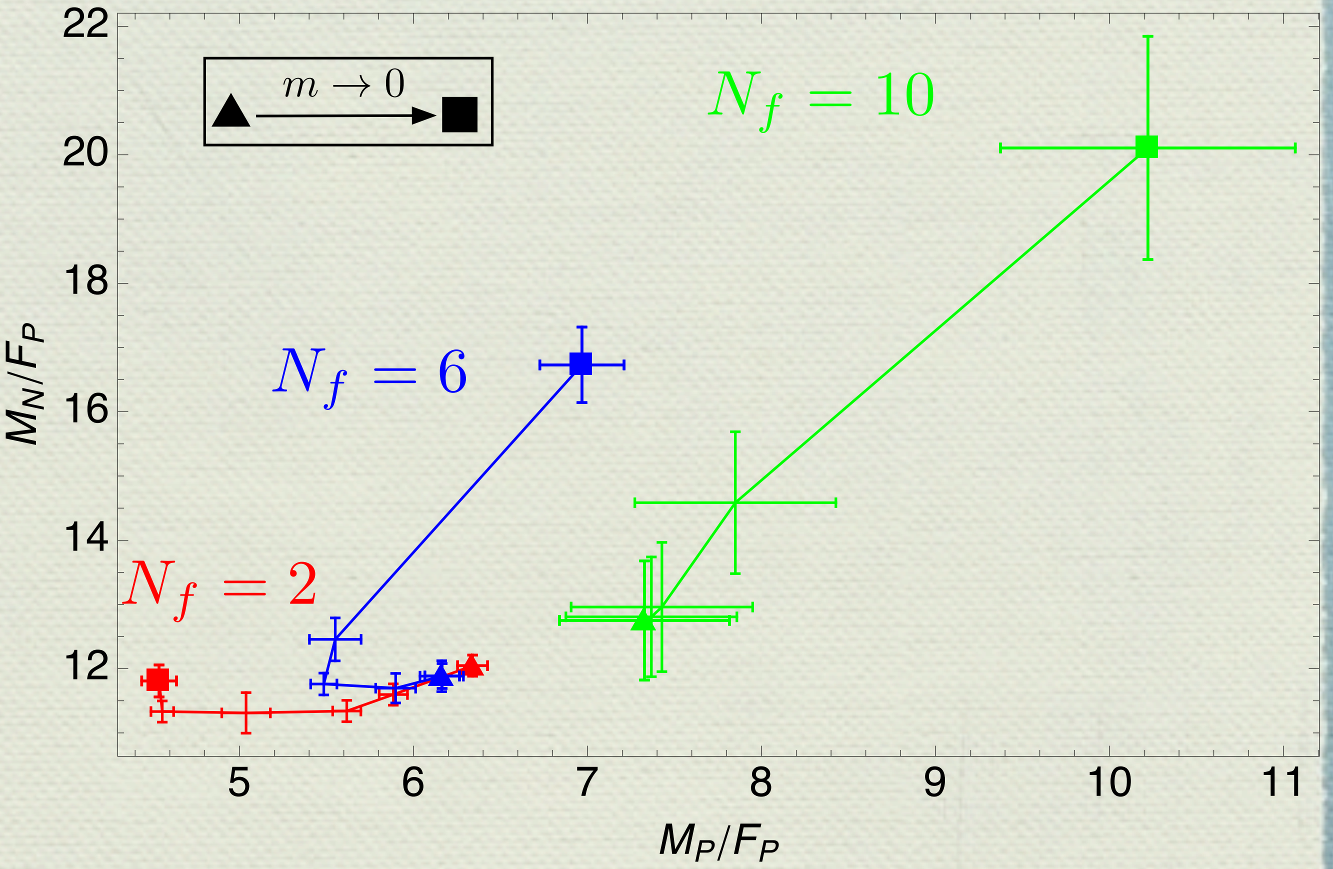
For M_V and M_A, linear fits and conformal fits are comparable.

$\rightarrow$ Even though the conformal fits are compatible with our data, we cannot exclude the possibility of chiral symmetry breaking.

However, our data suggest *if* $N_f = 10$ is in the conformal phase, we are likely to have a large $\gamma^* \approx 1$.

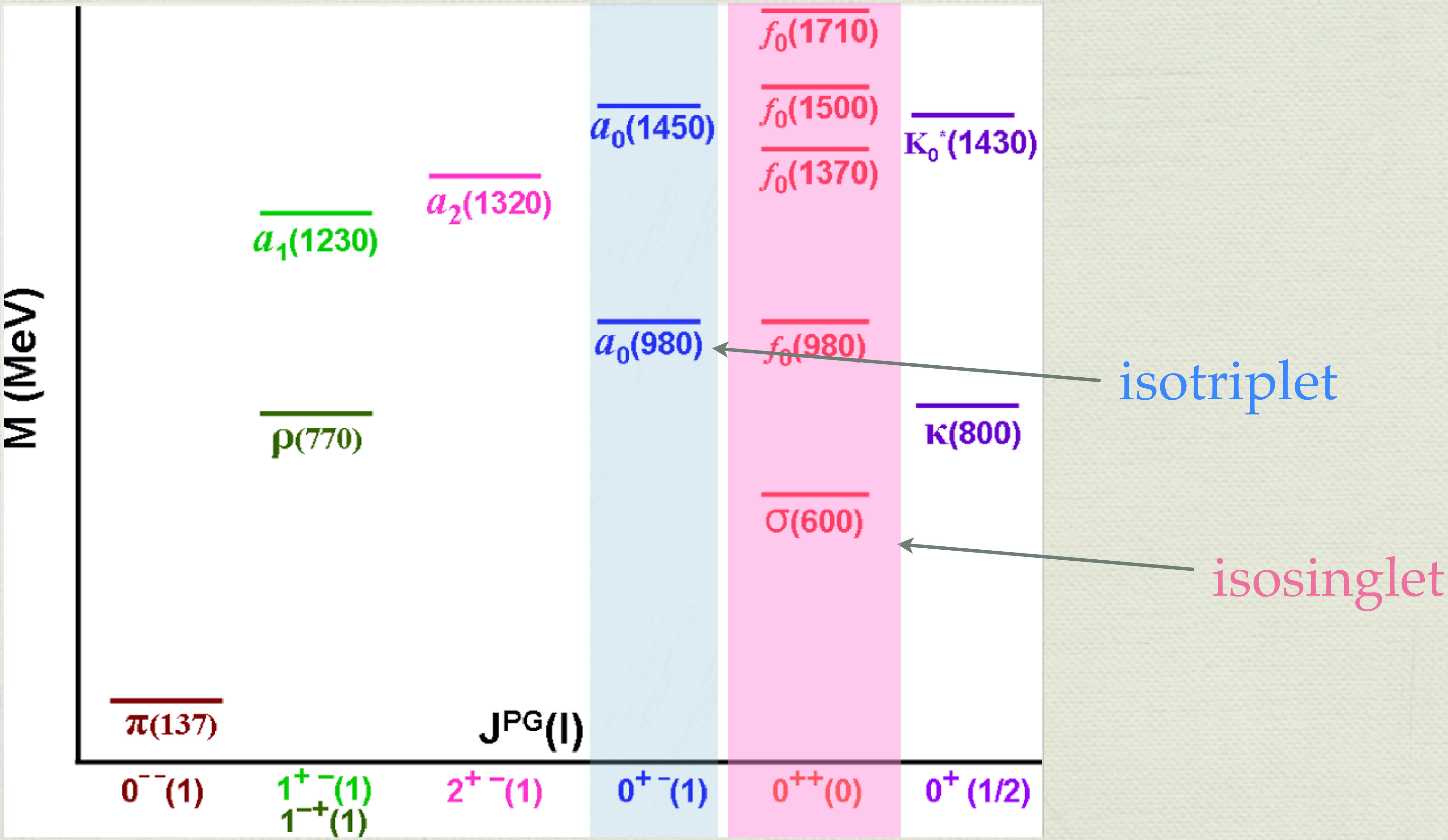
Word of Caution

- Be aware of the finite volume effects!
- Finite volume effects drive the points up and to the right.
- May need to worry about light mass points.
- Need to reexamine the results with larger volumes.



Part II: Light Scalar?

Scalar Mesons in QCD

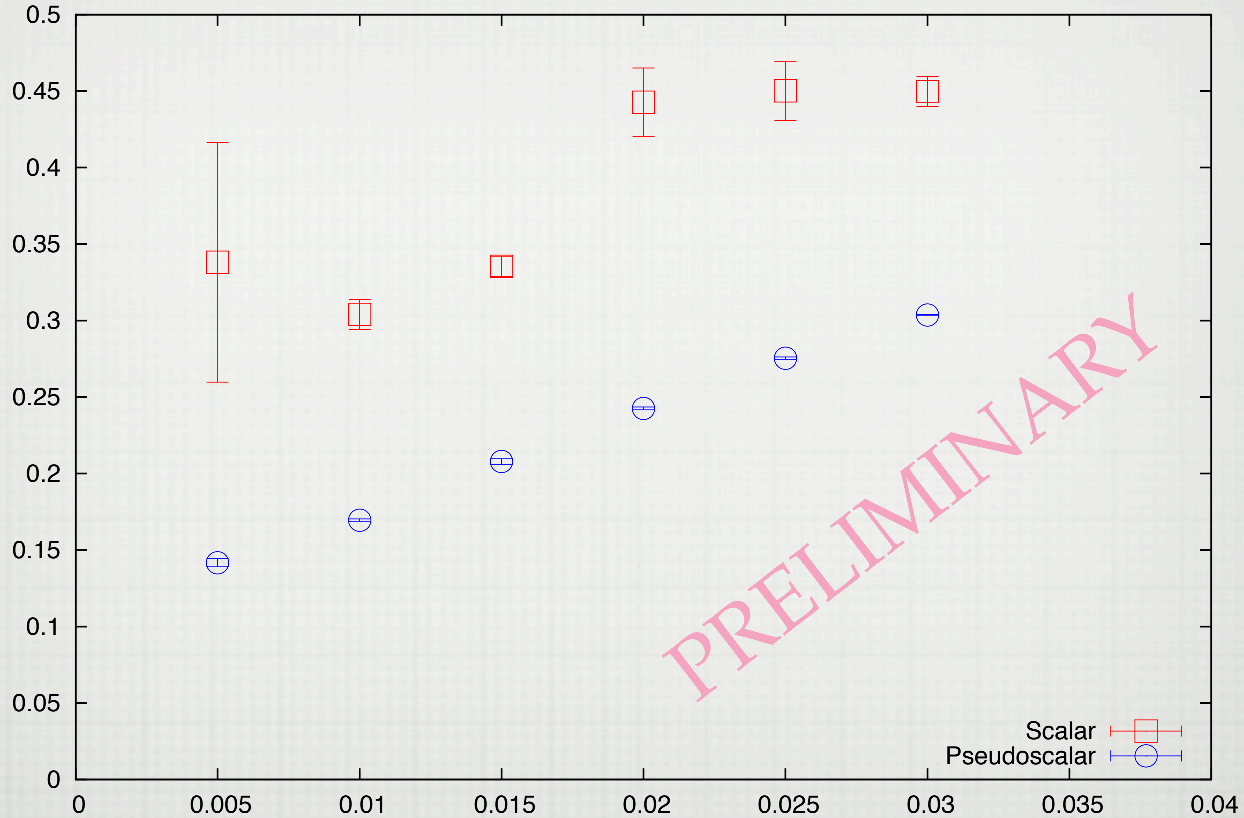


(Plot from N. Mathur et al. 2007.)

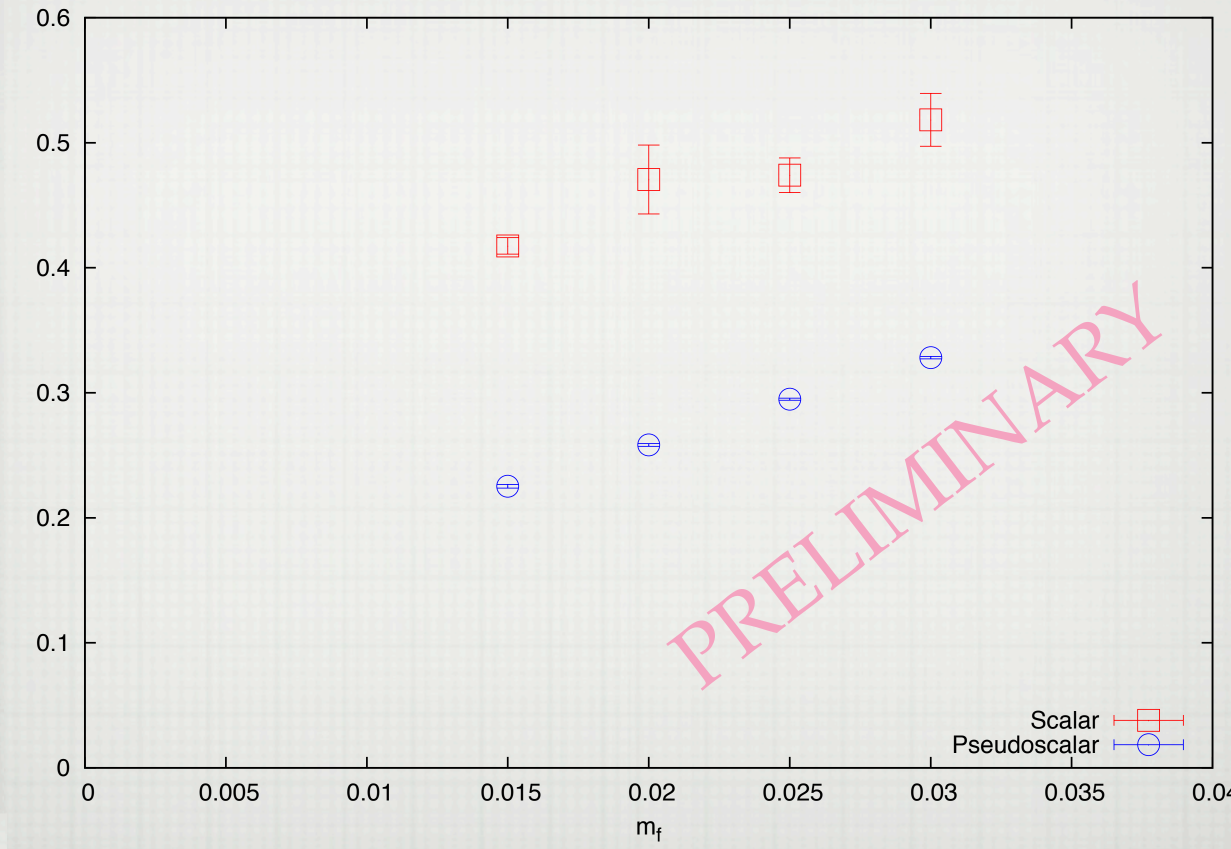
Light Scalars in Walking Technicolor?

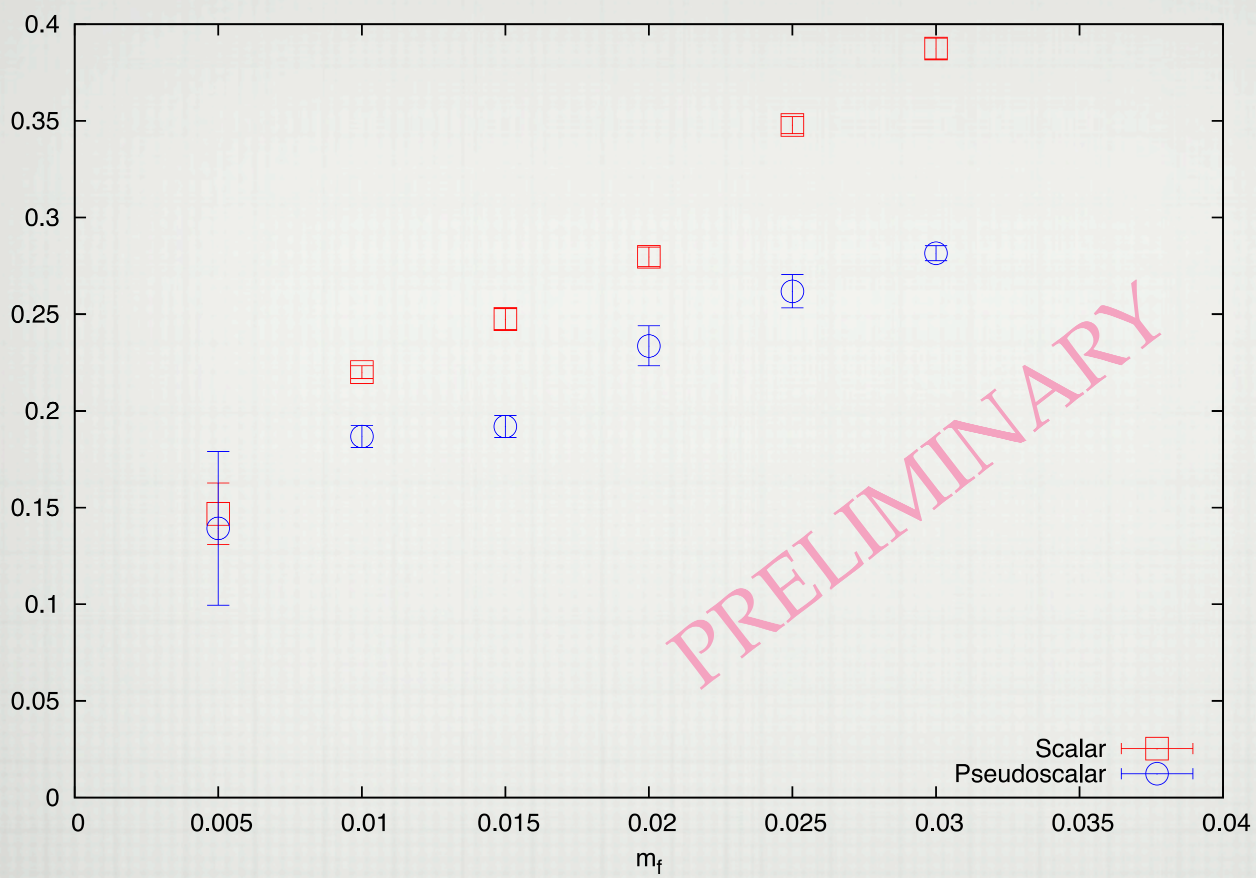
- Can we have light scalars in Walking Technicolor?
  - Model builders say yes.
  - See talks by Kuti, Grinstein, Evans, Matsuzaki, ...
- Can we produce light scalars on the lattice?

6 Flavors



8 Flavors





10 Flavors

- Connected diagrams only (isotriplet)
- Values in the chiral limit depend on extrapolations.
- At finite quark mass, the scalar becomes closer to the pseudoscalar as we increase the number of flavors.

Summary

- There are indications of condensate enhancement, reduced S parameter and a large anomalous dimension as we increase the flavor of fermions in the SU(3) gauge theory.
- With the discovery of a 125 GeV ``Higgs” boson, it is important for lattice to investigate the possibility of a light scalar in near-conformal gauge theories.