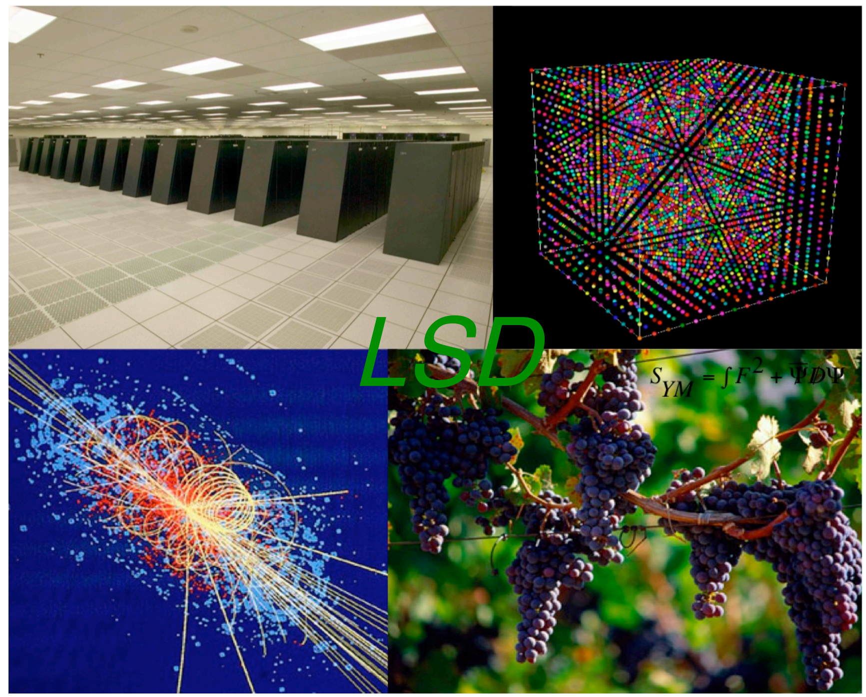
Condensate enhancement for mass generation in SU(3) gauge theory

Pavlos Vranas for the LSD collaboration

The Lattice Strong Dynamics collaboration

T. Appelquist (Yale U.),
A. Avakian (Boston U.)
R. Babich (Boston U.),
R. Brower (Boston U.),
M. Buchoff (LLNL),
M. Cheng (LLNL),
M. Clark (Harvard U.),
S. Cohen (JLab, BU),
G. Fleming (Yale U.),
F. Jiang (MIT),
J. Kiskis (UCD),
M. Lin (Yale),
E. Neil (Yale U.),
J. Osborn (ANL),
C. Rebbi (Boston U.),
D. Schaich (Boston U.),
P. Vranas (LLNL).



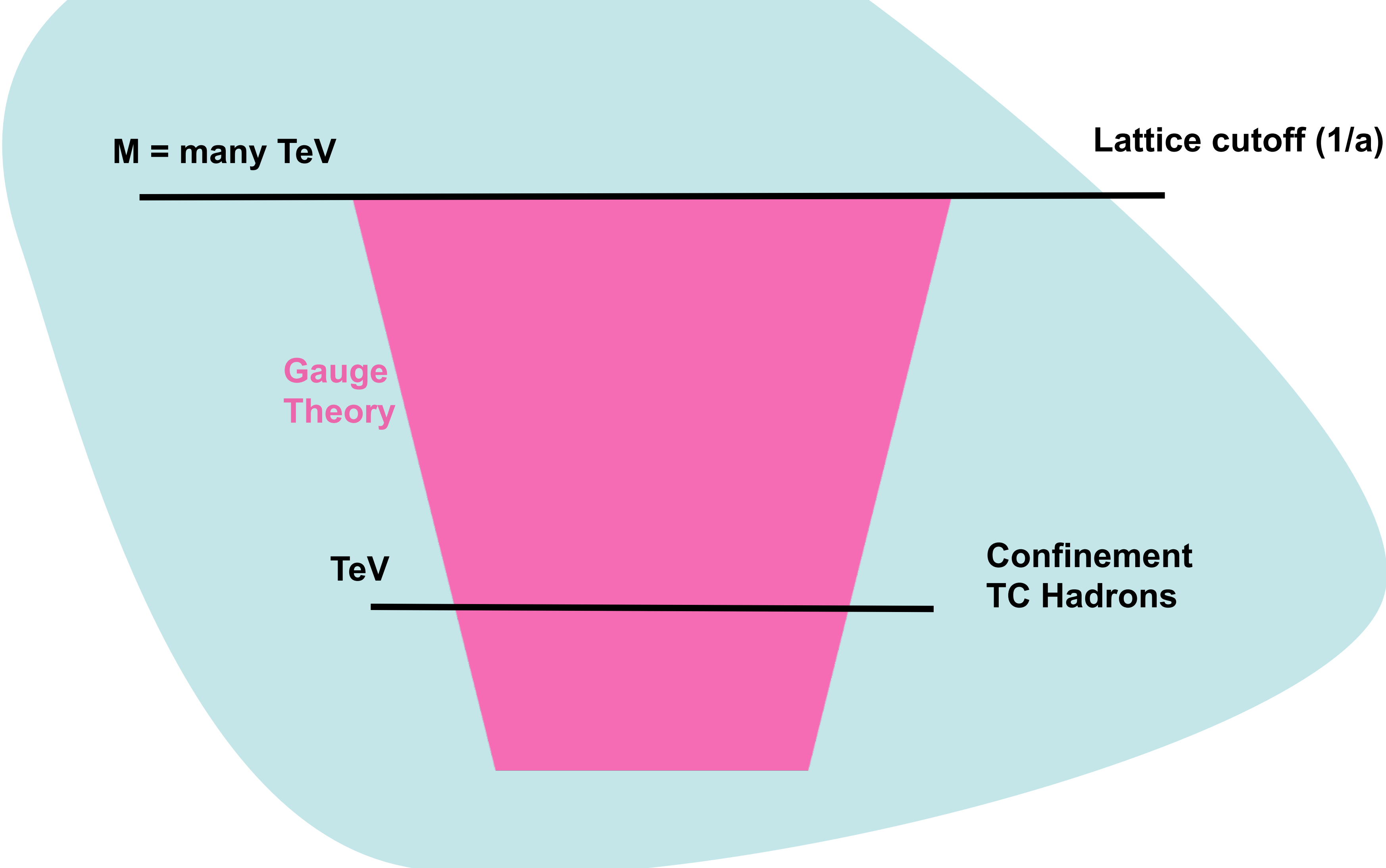
Our first thoughts

- TC and ETC models can use lattice non-perturbative input.
  - How do the properties of gauge theory change with N_f, N_C and R ?

- Chiral condensate enhancement $\frac{\langle \overline{\psi} \psi \rangle}{F^3}$
- S parameter
- Particle spectrum
- Dirac operator eigenvalue spectrum

How should we proceed?

A slice of ETC



Choices

- ETC is complicated enough:
  stay with fundamental reps
- Start from something we know:
  lattice QCD -- SU(3) color then move to SU(2) color
- Move slowly away from QCD and not too close to N_{fc}:
  first do 6 flavors then move to 10 flavors
- Chiral and flavor symmetries are crucial:
  use DWF
- To be able to observe enhancement:
  use large cutoff (small a)
- To be able to make direct comparisons:
  Do a 2-flavor simulation at the same cutoff

Higher demands

- Computing cost increases as $N_f^{3/2}$

- The lattice must have cutoff much larger than the confinement scale to take advantage of slower running. Larger lattice needed as we approach the IRFP.

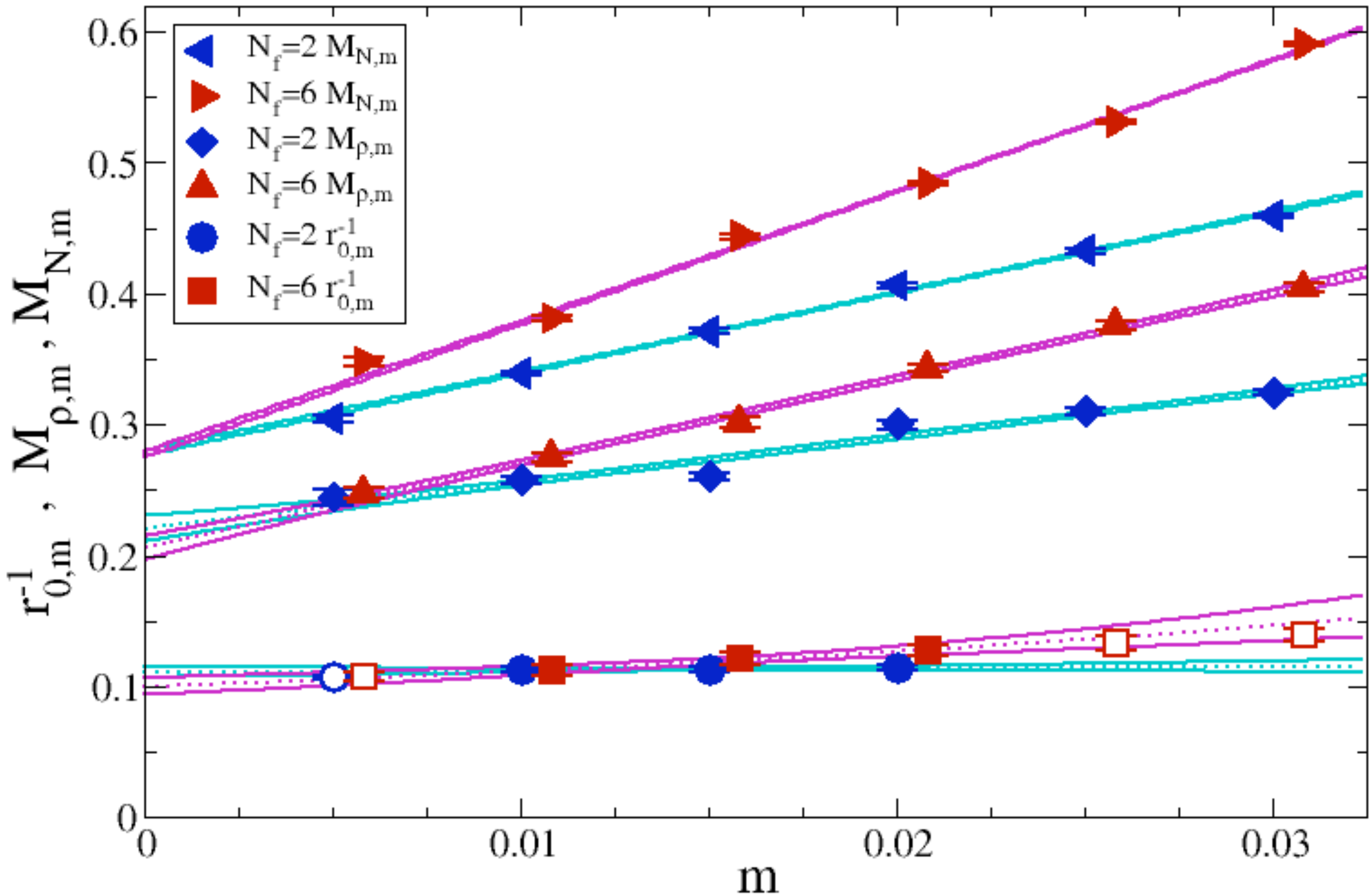
- We do not know the answer

Simulations

- Lattice Volume is 32^3 x 64
- Iwasaki gauge action with DWF at L_s= 16
- Input fermion masses m_f = 0.005 to 0.03
- m_{res} ~ 3×10^{-5} **(2f)**, 8×10^{-4} **(6f)**, 2×10^{-3} **(10f)**
- M_π L > 4
- **CPS:** HMC, multi-level simplectic integrator, mass preconditioning, chronological inversion
- Approximately matched lattice spacings :

  β = 2.76 **(2f)** ←→ β = 2.1 **(6f)** ←→ β=1.95 **(10f)**
- Goal: ~1,000 configurations per point

Scale matching 2f, 6f



Reasonable distance from cutoff with M_{ρ}~ cutoff / 5

Chiral perturbation theory

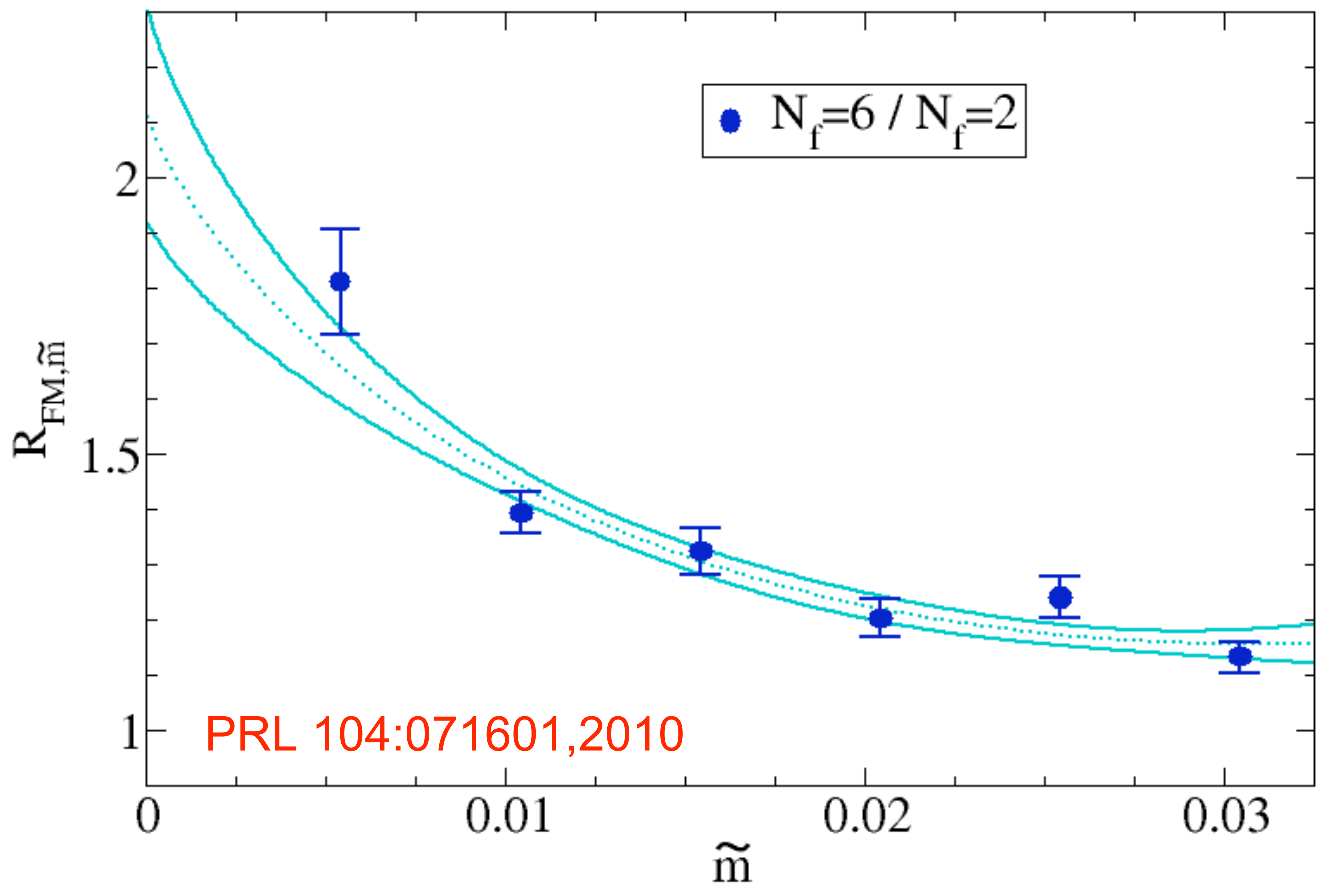
$$M_m^2 = \frac{2m\langle\bar{\psi}\psi\rangle}{F^2}\left\{1 + zm\left[\alpha_M + \frac{1}{N_f}\log(zm)\right]\right\}$$

$$F_m = F\left\{1 + zm\left[\alpha_F - \frac{N_f}{2}\log(zm)\right]\right\}$$

$$\langle\bar{\psi}\psi\rangle_m = \langle\bar{\psi}\psi\rangle\left\{1 + zm\left[\alpha_C - \frac{N_f^2 - 1}{N_f}\log(zm)\right]\right\}$$

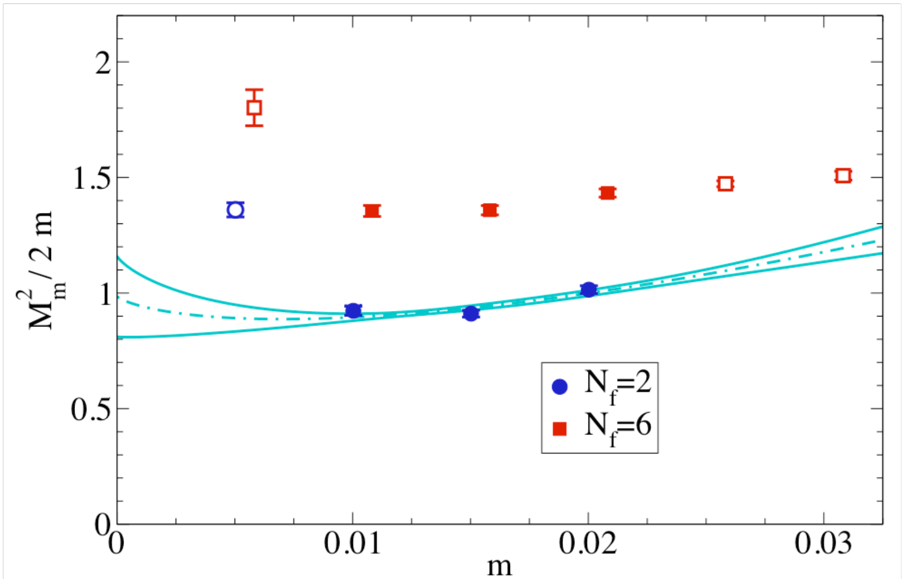
- ★ Log coefficients of $F_m, \langle\bar{\psi}\psi\rangle_m \sim N_f$
- ★ $\alpha_C \sim 1/a^2 \rightarrow \langle\bar{\psi}\psi\rangle_m$ difficult to measure
- ★ Instead measure (GMOR) $\frac{M_m^2}{2mF_m} \rightarrow \frac{\langle\bar{\psi}\psi\rangle}{F^3}$ at $m \rightarrow 0$

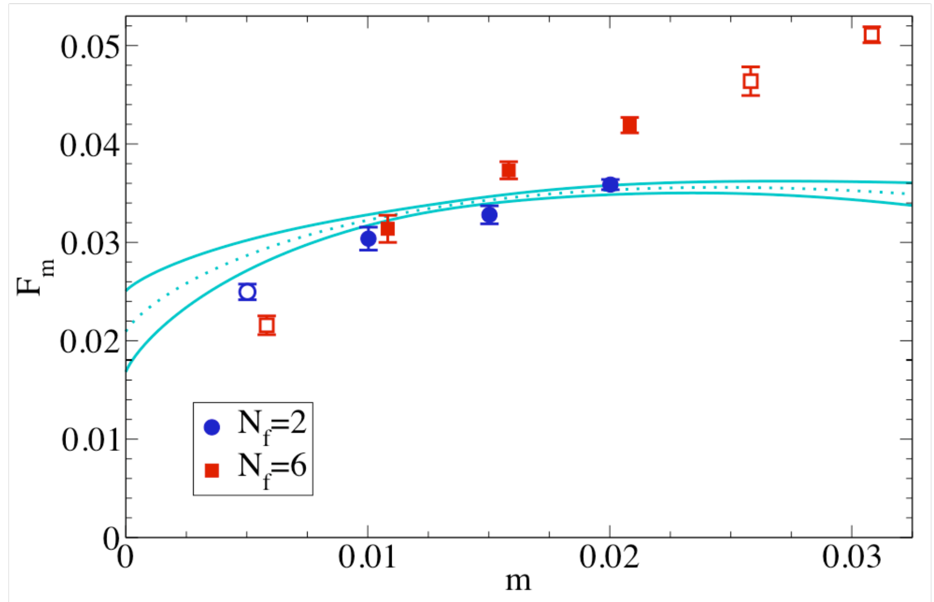
6-flavor over 2-flavor enhancement



- ★ $R_m = [M_m^2/2mF_m]_{6f} \;\; / \;\; [M_m^2/2mF_m]_{2f}$
- ★ Can compare directly 6f to 2f because they have same cutoff
- ★ Observing **~ 50% enhancment**

xPT fits and bound





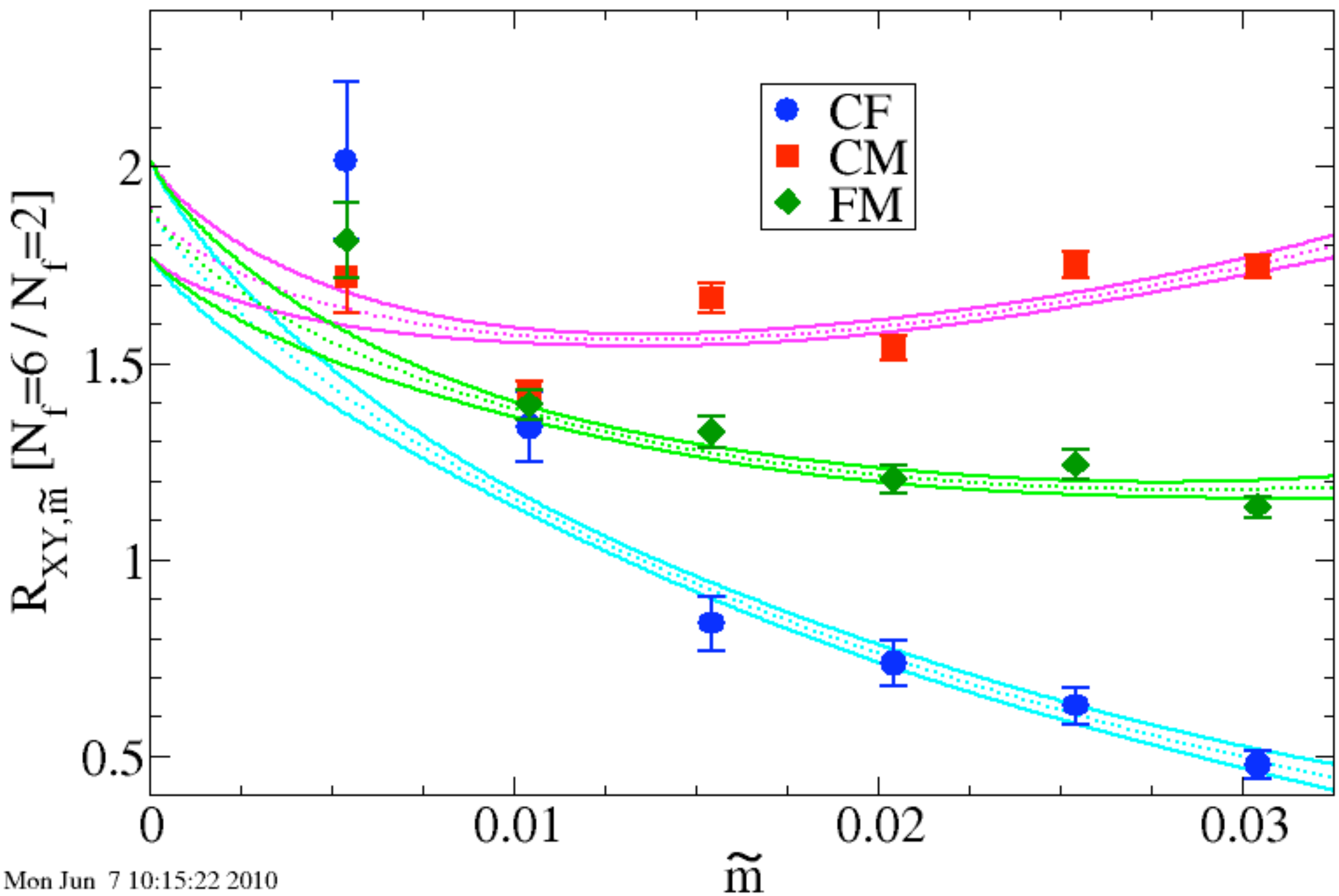
- ★ 2f give a reasonable combined fit for $M_m^2/2mF_m,\ F_m,\ \langle\bar\psi\psi\rangle_m$
- ★ 2f agree with phenomenology: $\langle\bar\psi\psi\rangle/F^3 = 47.1(17.6)_{\rm latt} = 36.2(6.5)_{\overline{\rm MS}}$
- ★ 6f because of larger slope need smaller masses (➔ larger lattices)
- ★ Linear fits on the 6-flavor data give a bound:

  28% increase: [= 47.1(17.6)]$_{2f}$ [> 60.0(8.0)]$_{6f}$

  absence of enhancement excluded at 73% confidence level

Enhancement 3 ways with GMOR

$$M_\pi^2 = \frac{2m < \bar{\Psi}\Psi >}{F_\pi^2}$$

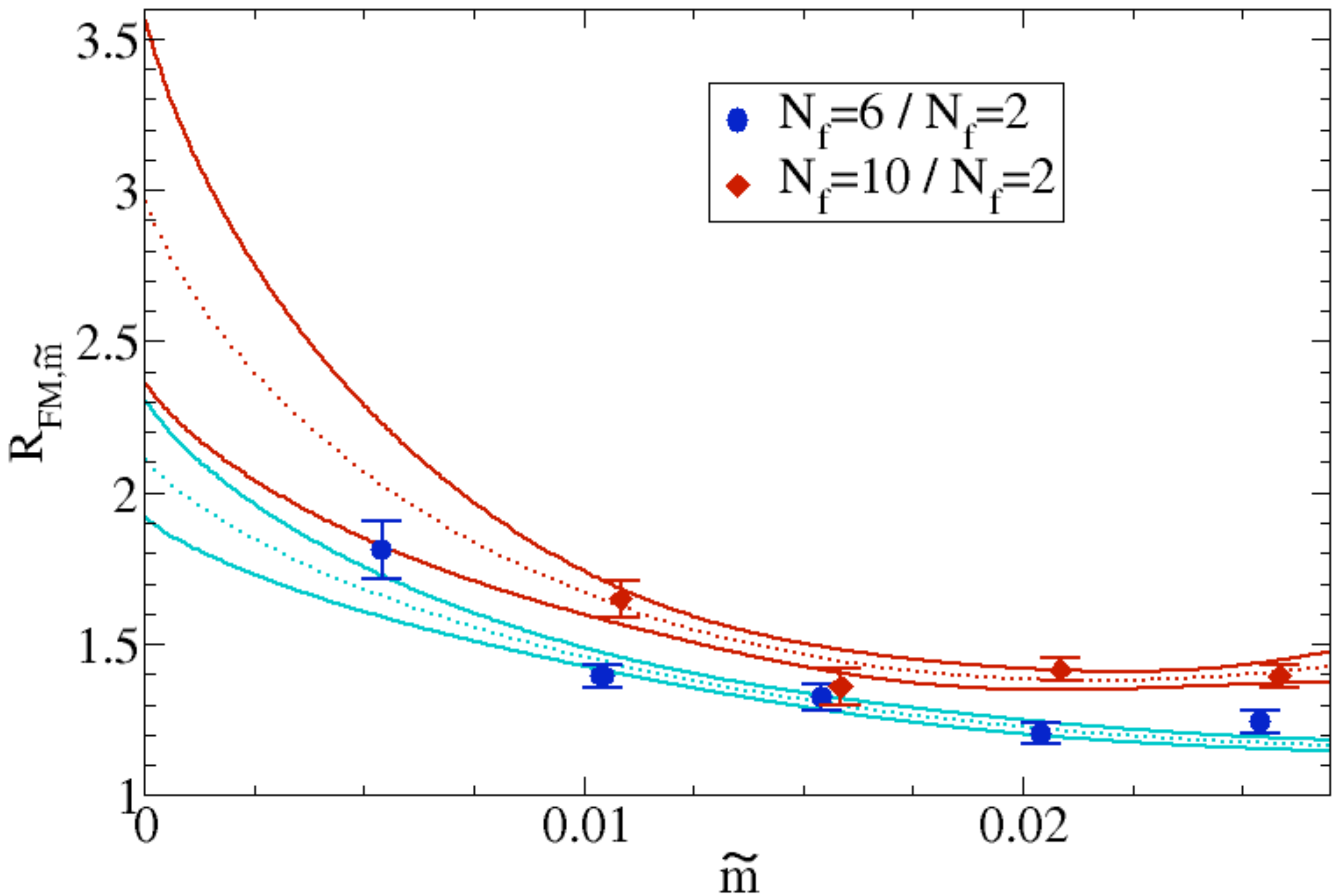


$$FM = M_\pi^2/2mF_\pi$$

$$CF =< \bar{\Psi}\Psi > /F_\pi^3$$

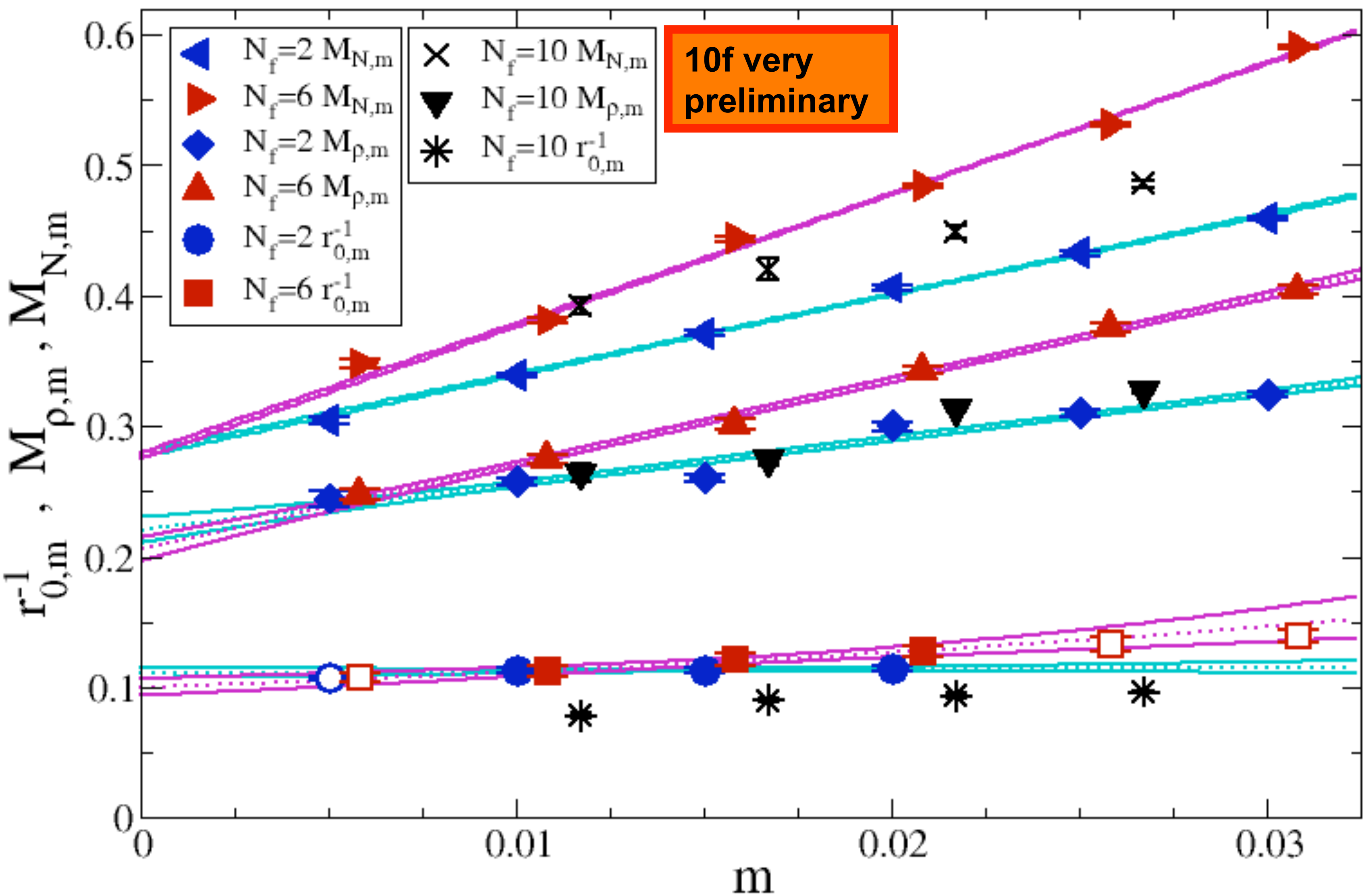
$$CM = \frac{< \bar{\Psi}\Psi >}{[\frac{\sqrt{2m\bar{\Psi}\Psi}}{m_\pi}]^3}$$

10 and 6 flavor over 2-flavor enhancement



✦**Very Preliminary:** Observing more enhancement at 10f

Scale matching 2f, 6f, 10f



Salient features: Topology

- ⌘ At small lattice spacing the barriers between TC sectors are large
- ⌘ At small m DWF HMC encounter barriers in changing global topology Q
- ⌘ At large volume Q is irrelevant but for us it is a finite size effect
- ⌘ For $0.01 \leq m$, Q evolves sufficiently: for $m = 0.005$ it does not

300 million core hours on LLNL BG/L

Near term LSD plans

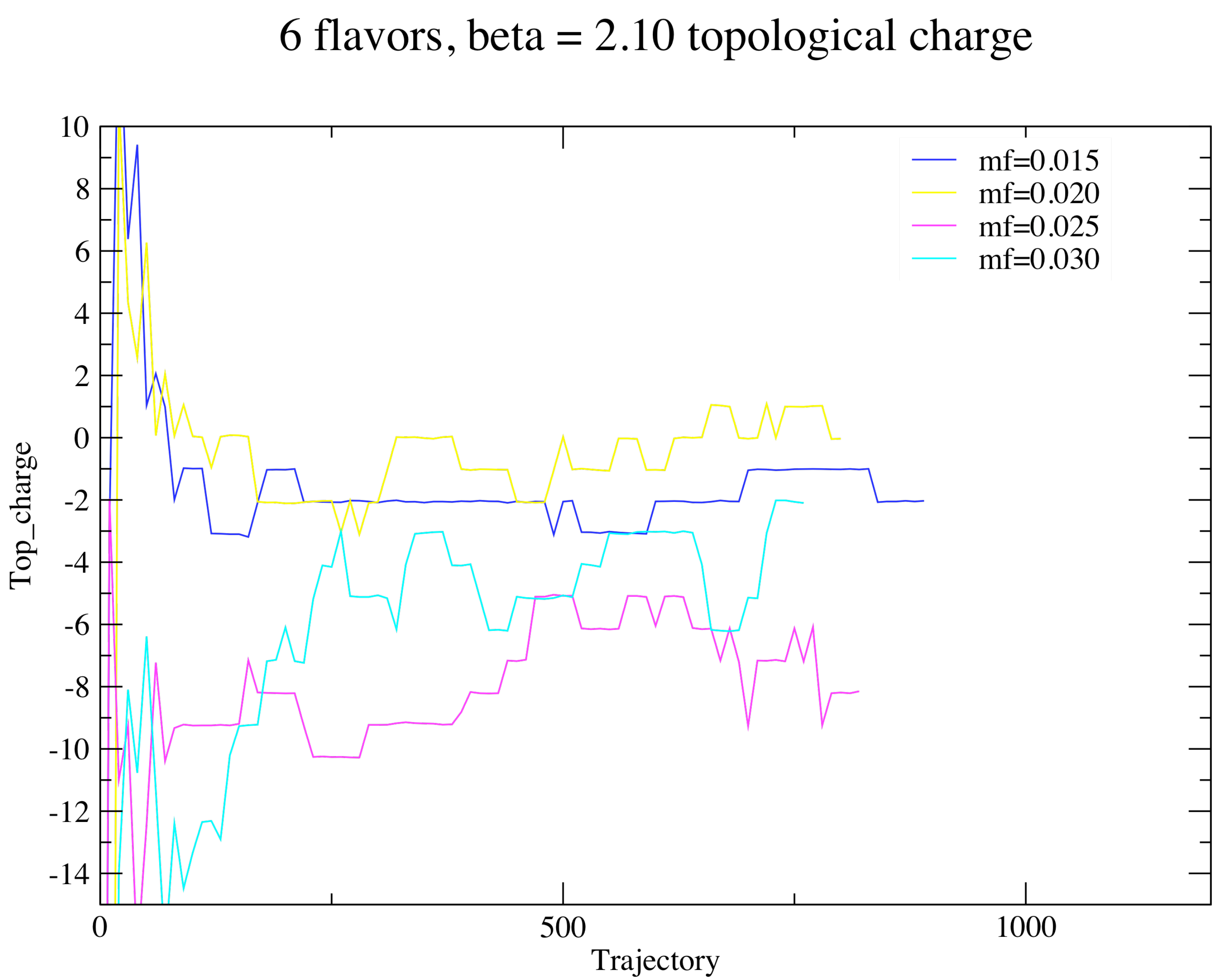
- 10-flavors $SU(3)_c$ fundamental at the same lattice spacing
- Measure enhancement at 2, 6 and 10 flavors
- Measure particle spectrum at 2, 6 and 10 flavors
- Measure S at 2, 6 and 10 flavors
- Measure Dirac eigenvalues at 2, 6 and 10 flavors
- Fundamental $SU(2)_c$

Conclusions

- 2 and 6 flavors $SU(3)_c$ fundamental at same lattice spacing
- 6 flavors condensate enhancement larger than 50%
  Excluded no-enhancement at 73% confidence level
- 10f very preliminary data indicate larger enhancement.

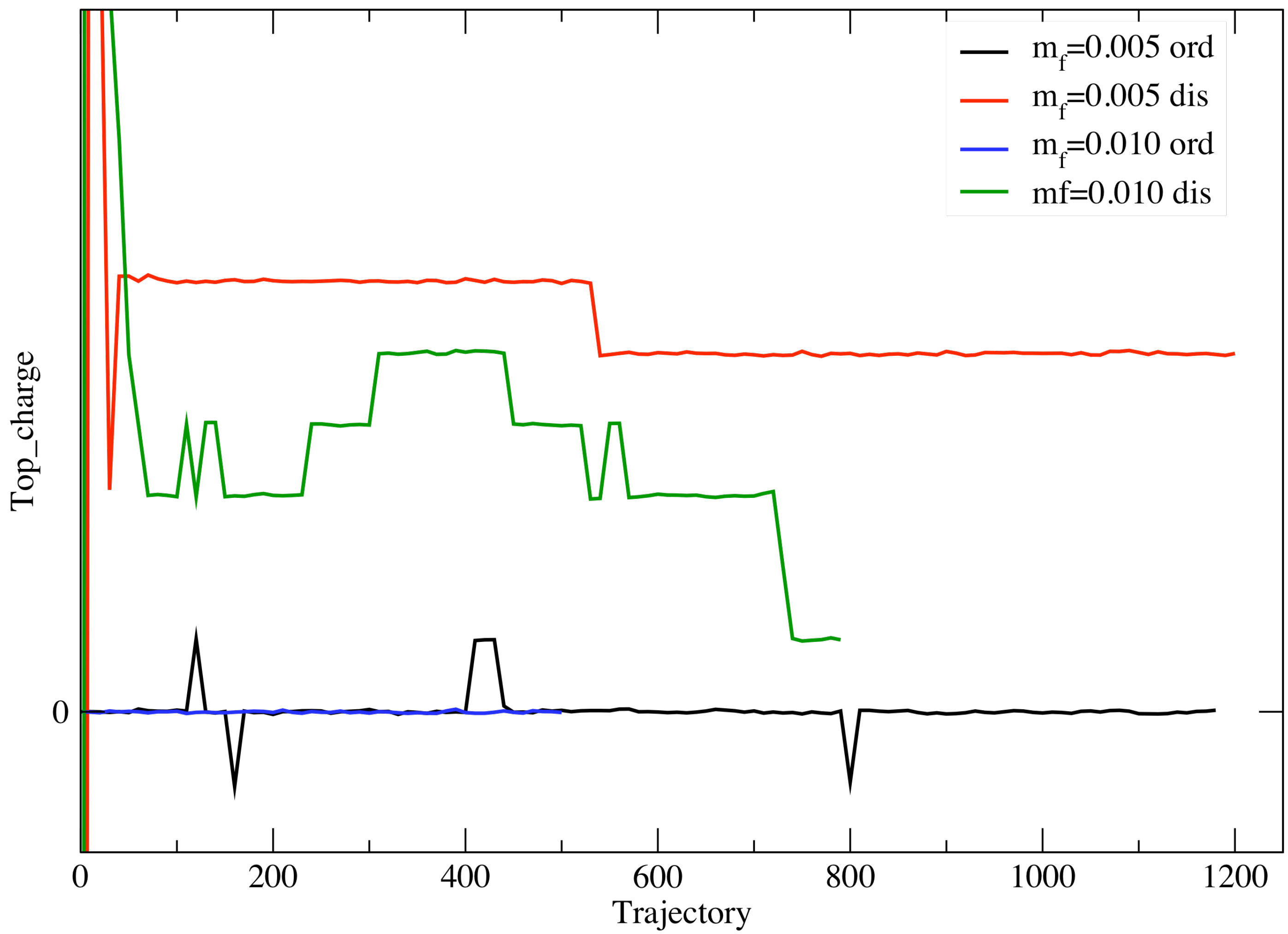
Backup slides

Topology (preliminary)

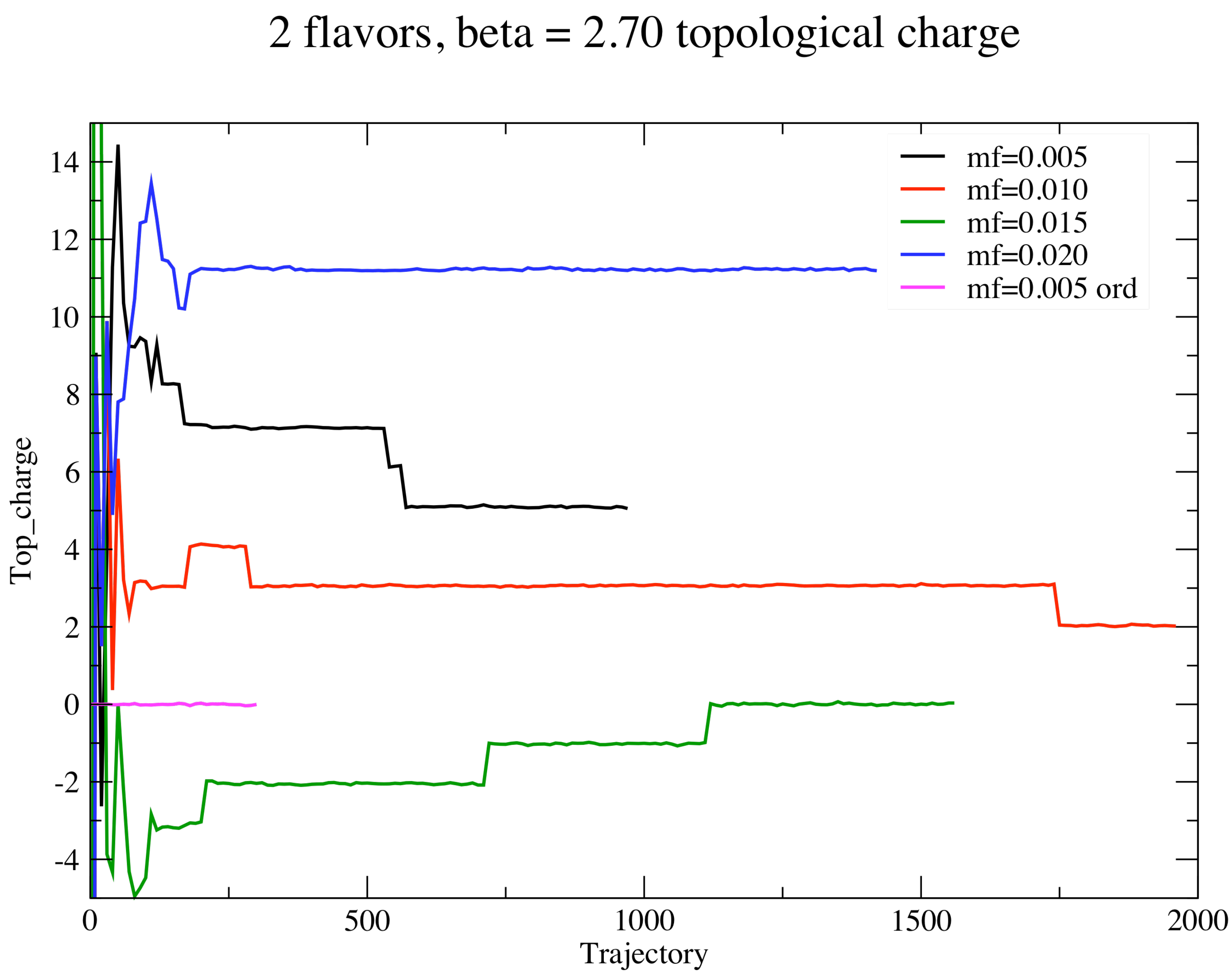


Topology (preliminary)

6 flavors, beta = 2.10 topological charge

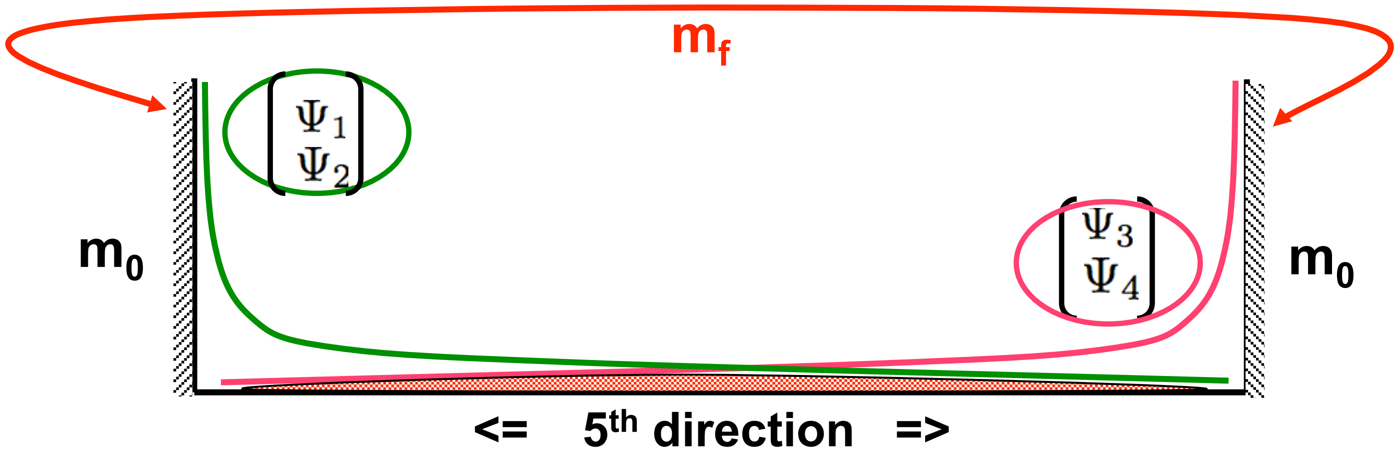


Topology (preliminary)



P. Vranas, LLNL

Domain Wall Fermions (DWF)



- Restoration of Lorentz symmetry : lim(a=0)
- Restoration of chiral symmetry : lim(L_s= infinity)
- The two limits are decoupled !!!
- Computing is only linear in L_s !!!
- Other fermions need 2^6 - 2^{10} more computing for a <= a/2.

Small worlds inside small worlds
Technicolor, take 2

Massless SU(2)
Gauge fields

$A_1 \quad A_2 \quad A_3$

A new strong force

Techni-quarks

Techni-gluons

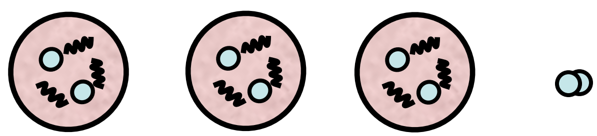
Massless particle
fermion fields

$\Psi_e, \Psi_\mu, \ldots$

Spontaneous chiral symmetry breaking by the strong dynamics

$\pi^+ \quad \pi^0 \quad \pi^-$

$W^+ \quad Z^0 \quad W^-$



$\bar{T}T\bar{\Psi}_e\Psi_e, \ldots$

$m_\pi = 0$

$\langle \bar{T}T \rangle \neq 0$

$m_{W,Z} \sim F_\pi^{tc}$

TC

$m_e \sim \langle \bar{T}T \rangle, \ldots$

ETC

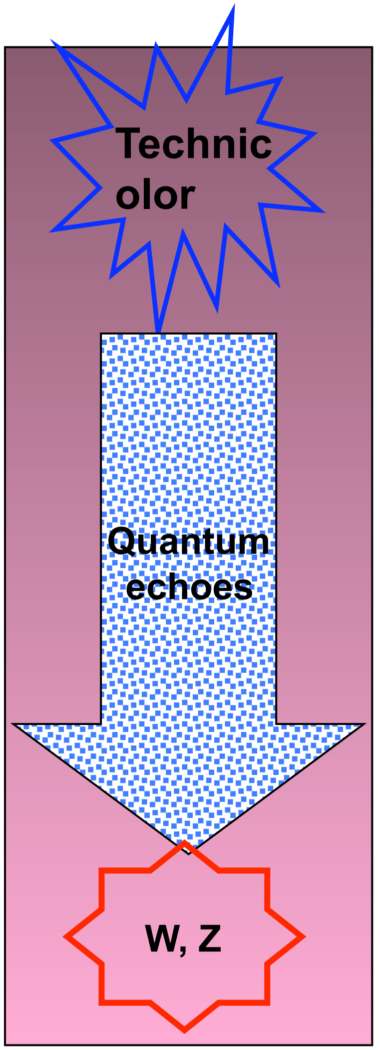
The virtues of TC/ETC

✓ Dynamical explanation of EWS breaking
✓ Asymptotically free:
  no unnatural fine tuning needed
  no hierarchy problem (breaking scale naturally much smaller than cutoff)
  it is not trivial
✓ ETC provides insights to flavor physics

The problems of TC/ETC

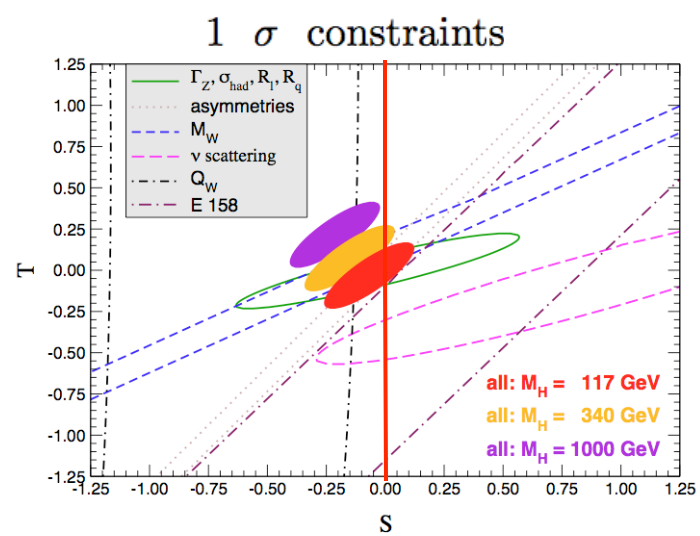
- o Flavor changing neutral currents (ETC)
- o Precision electroweak measurements (TC)
- o Large top quark mass

Precision EW constraints



The **S** parameter of Peskin & Takeuchi assumes a scaled version of QCD with N_f and N_c

$$S_{techni} \approx 0.25 \frac{N_F}{2} \frac{N_c}{3} \sim \frac{m_{a1}^2 - m_\rho^2}{m_{a1}^2}$$



$$S_{\exp} < S_{\text{techni}}$$

Flavor changing neutral currents

- Fermion masses need new interactions at scale $M >> \Lambda_{TC}$
- At scales well below $M \rightarrow \bar{\Psi}\Psi\bar{T}T \rightarrow m_f \sim \frac{<\bar{T}T>}{M^2}$
- But also have $\bar{\Psi}\Psi\bar{\Psi}\Psi$
- Flavor changing neutral currents: no known suppression mechanism
- Must keep the scale M very high ~ 1,000 TeV
- But then the quark and lepton masses become too small

Not so fast

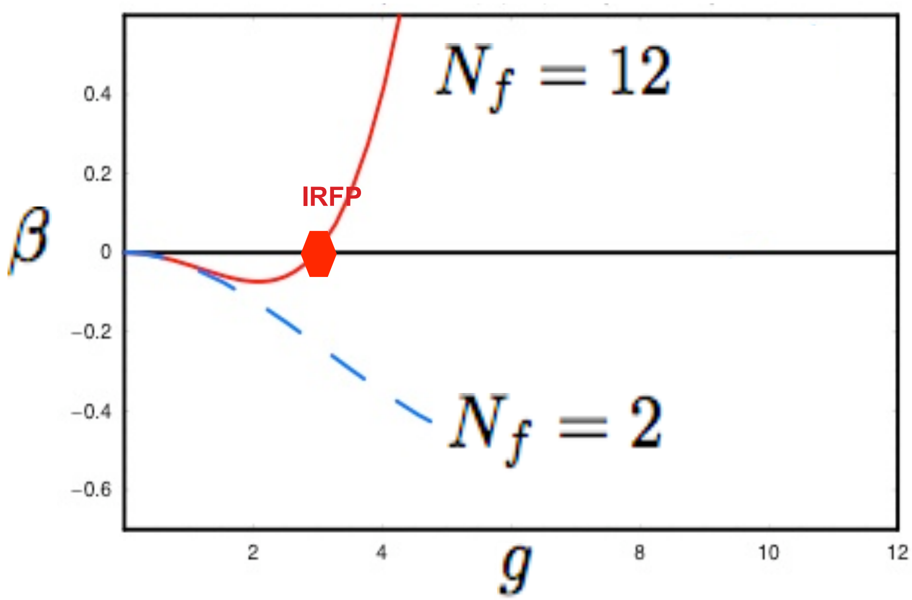
- Scaling QCD with the number of flavors and colors is not correct.

- QCD with many light flavors is a very different theory than QCD with 2 light flavors

$$L\frac{\partial}{\partial L}g(L) = \beta(g) \stackrel{g\to 0}{\sim} b_0 g^3 + b_1 g^5 + b_2 g^7 + \cdots$$

$$b_0 = -\frac{1}{(4\pi)^2}\left(\frac{11}{3}N_c - \frac{2}{3}N_f\right), \qquad b_1 = -\frac{1}{(4\pi)^4}\left[\frac{34}{3}N_c^2 - \left(\frac{13}{3}N_c - \frac{1}{N_c}\right)N_f\right].$$

Perturbative beta function



Walking

Low end of conformal window

$$8 \leq N_{fc} \leq 12$$

T. Appelquist, G. Fleming, E. Neil, Phys. Rev. Lett. 100, 171607 (2008), hep-lat/0901.3766

Possible effects of walking and the Lattice

- $\dfrac{m_{a1}^2 - m_\rho^2}{m_{a1}^2}$ ~ S may be smaller

- Coupling stays strong at larger scales: could enhance condensate relative to Λ_{TC}

- Need a true first principles calculation => Need the **Lattice**.

LHC
TeV physics