Lattice Gauge Theory Studies of Electroweak Symmetry Breaking

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with credits due to Richard Brower, Anna Hasenfratz, Evan Weinberg, Oliver Witzel and the LSD collaboration

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The electroweak theory after the Higgs

The discovery of the Higgs puts in place the final piece of the electroweak jigsaw puzzle,

but the model still needs an ultraviolet completion.

One possibility is an underlying strongly coupled theory.

Models of electroweak symmetry breaking based on strong dynamics

There is a long history of strongly coupled theories of electroweak symmetry breaking:

Technicolor Weinberg, Susskind (1979)

Extended Technicolor Dimopolous, Susskind '79; Eichten, Lane '80

Walking technicolor Appelquist, Terning, Wijewardhana (1991)

The Higgs and nothing else?

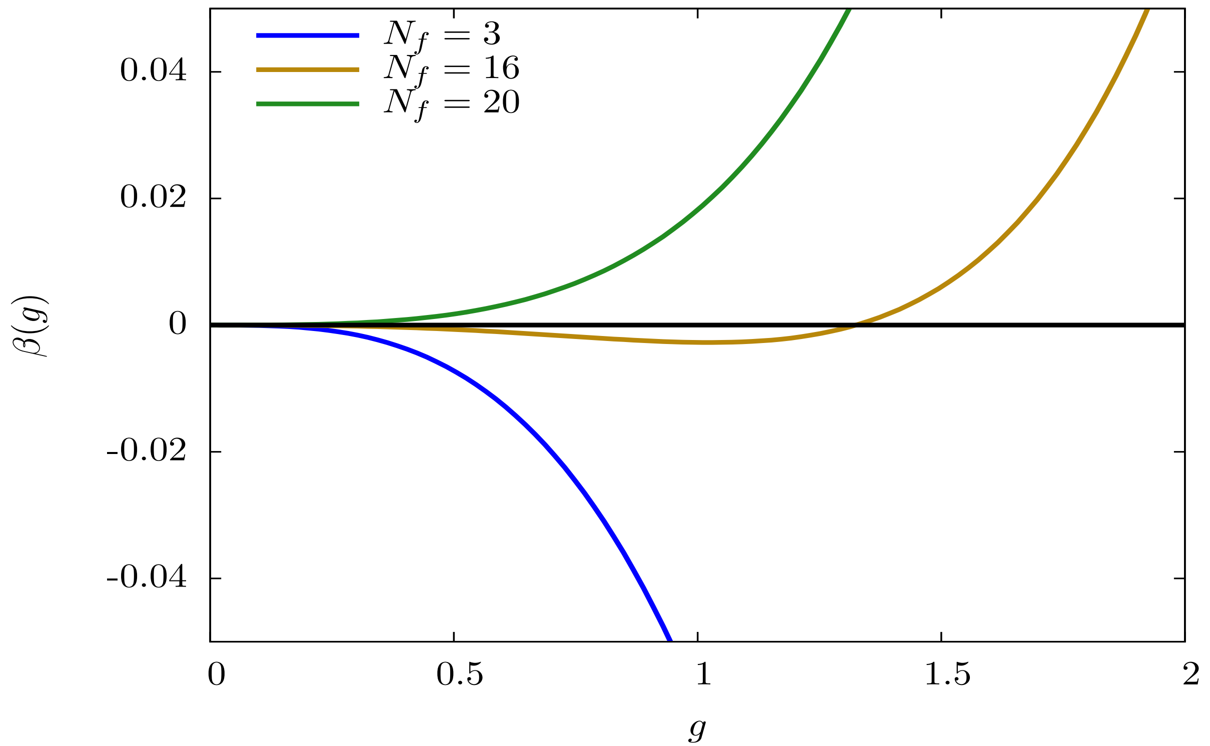
but these models now face challenges:

they must produce a 125GeV scalar, with standard model couplings to quarks and leptons;

3 massless Goldstone bosons, to provide the longitudinal components of the W's and Z;

and everything else must be pushed to a higher scale.

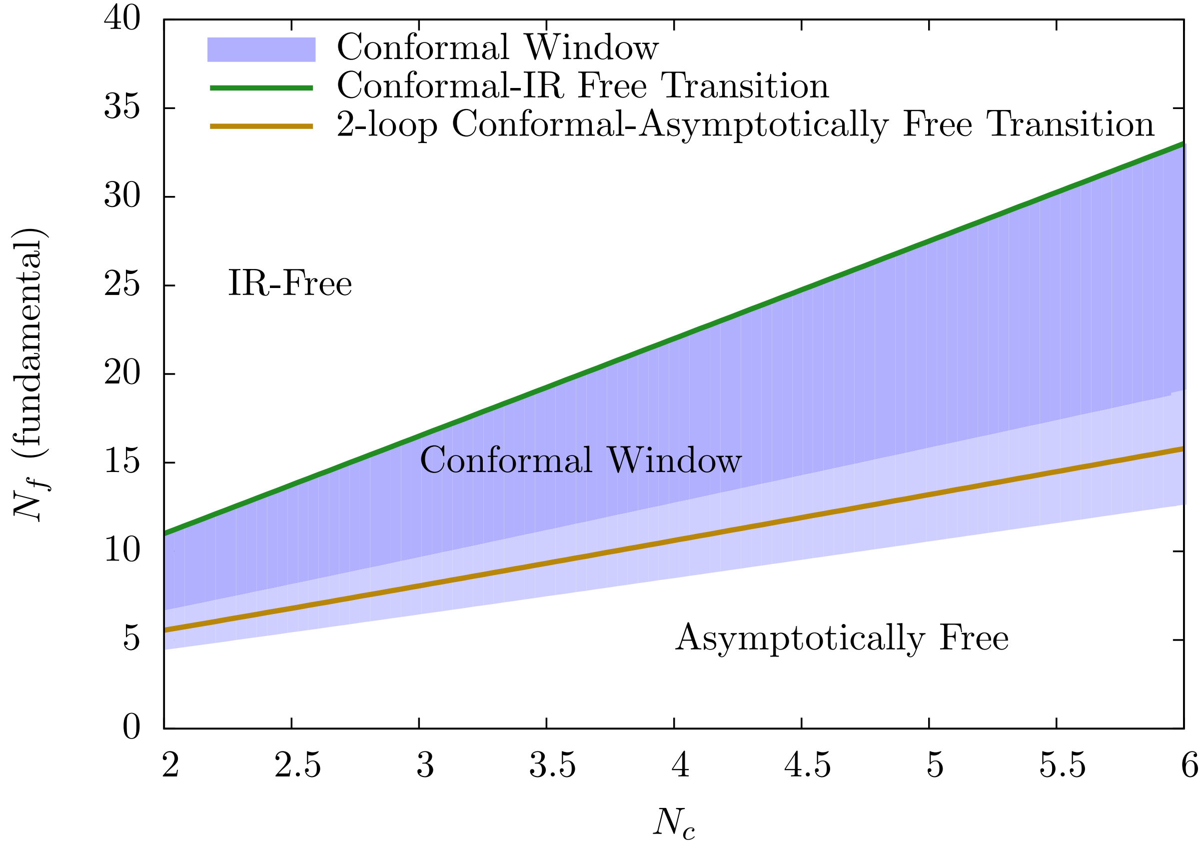
Conformal fixed point



$SU(3)$ with N_f flavors.

A possibility is that the theory has a conformal fixed point, or comes very close to one. Caswell (1974), Banks, Zaks (1982)

Searching for theories



Unlike QCD (SU(3) with given number of flavors) the spectrum of theories which need to be investigated is very large.

Computational framework

The study of strong dynamics requires lattice computational methods.

The numerical simulations proceed via the Hybrid Monte Carlo technique:

$$\langle \mathcal{O} \rangle = Z^{-1} \int dU d\Pi d\phi^* d\phi \langle \mathcal{O} \rangle_{\bar{\psi},\psi}(U) e^{-S_g(U) - \Pi^2 - \phi^* D(U)^{-1} \phi}$$

(This is oversimplified, extra bosonic variables may have to be introduced for computational efficiency.)

Computational challenges

The numerical simulations are very demanding.

Discretizations of the Dirac action:

Wilson convenient, but breaks chiral symmetry;

Kogut-Susskind or staggered preserves one non-singlet chiral symmetry, introduces extra fermions (taste);

domain wall, overlap preserve chiral symmetry, computationally costly.

Obtaining the correct topological distribution with Hybrid Monte Carlo may be a problem.

A world wide effort

Computational studies of electroweak symmetry breaking, based on lattice gauge theory techniques, are pursued by many groups throughout the world.

In the US many lattice gauge theorists are loosely bound within the BSM (Beyond the Standard Model) collaboration.

The LSD collaboration, of which I am a member, is more formally organized.

The Lattice Strong Dynamics collaboration

www.yale.edu/LSD/

Lattice Strong Dynamics Collaboration

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Joe Kiskis

David Schaich

Tom Appelquist
George Fleming

Mike Buchoff

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The LSD research program

Simulations: SU(3) with $N_f = 2, 6, 8, 10$, domain wall; SU(3), $N_f = 8$, staggered; SU(2), $N_f = 2, 6$, Wilson; SU(4), $N_f = 2, 3, 4$, Wilson.

Toward TeV Conformality (Phys.Rev.Lett. 104 (2010) 071601)

Parity Doubling and the S Parameter Below the Conformal Window (Phys.Rev.Lett. 106 (2011) 231601)

WW Scattering Parameters via Pseudoscalar Phase Shifts (Phys.Rev. D85 (2012) 074505)

Approaching Conformality with Ten Flavors (arXiv:1204.6000 hep-ph)

Lattice calculation of composite dark matter form factors (Phys.Rev. D88 (2013) 1, 014502)

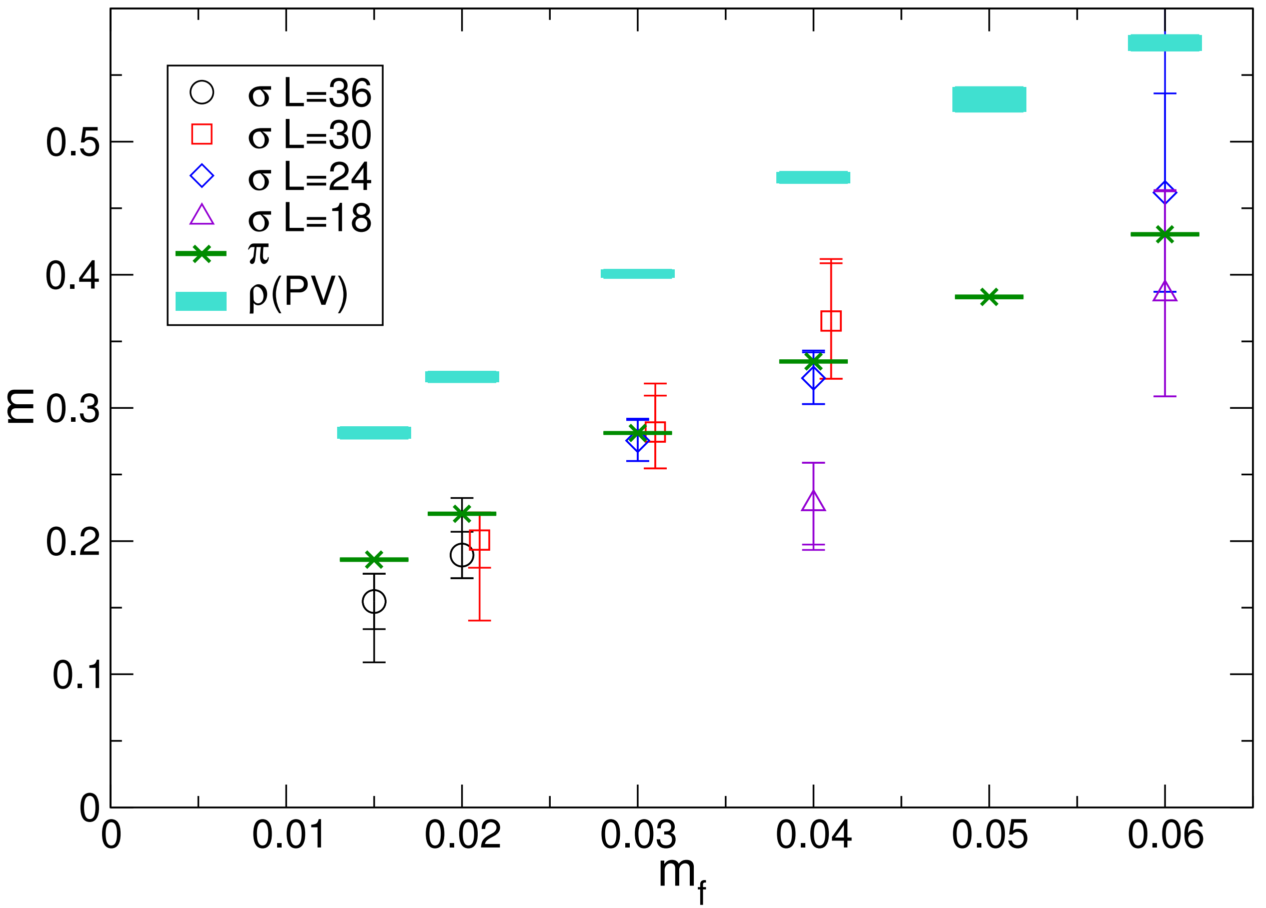
Two-Color Theory with Novel Infrared Behavior (Phys.Rev.Lett. 112 (2014) 111601)

Composite bosonic baryon dark matter on the lattice: SU(4) baryon spectrum and the effective Higgs interaction (arXiv:1402.6656 hep-lat)

Maximum-Likelihood Approach to Topological Charge Fluctuations in Lattice Gauge Theory (Phys.Rev. D90 (2014) 014503)

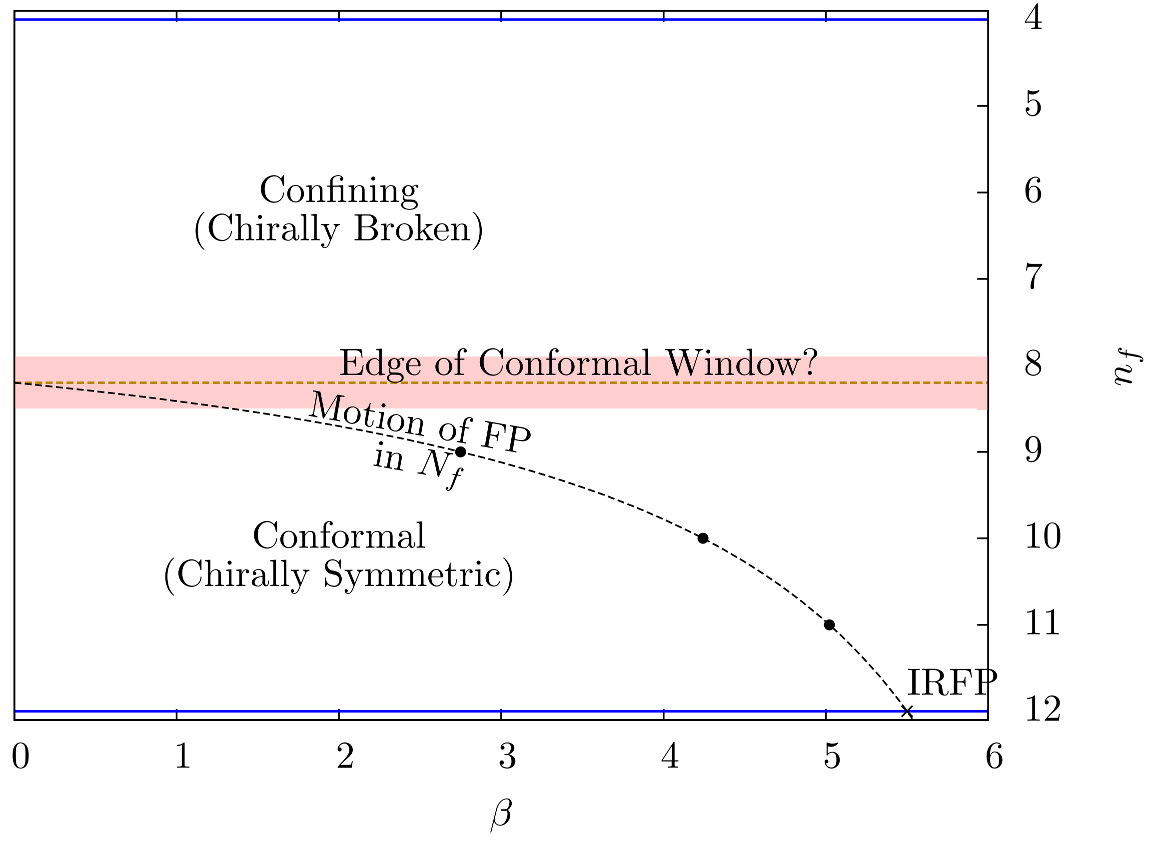
Lattice simulations with eight flavors of domain wall fermions in SU(3) gauge theory (arXiv:1405.4752 hep-lat)

Theories with a light scalar



Tantalizing evidence from the LatKMI collaboration (Y. Aoki et al., arXiv:1403.5000 [hep-lat])

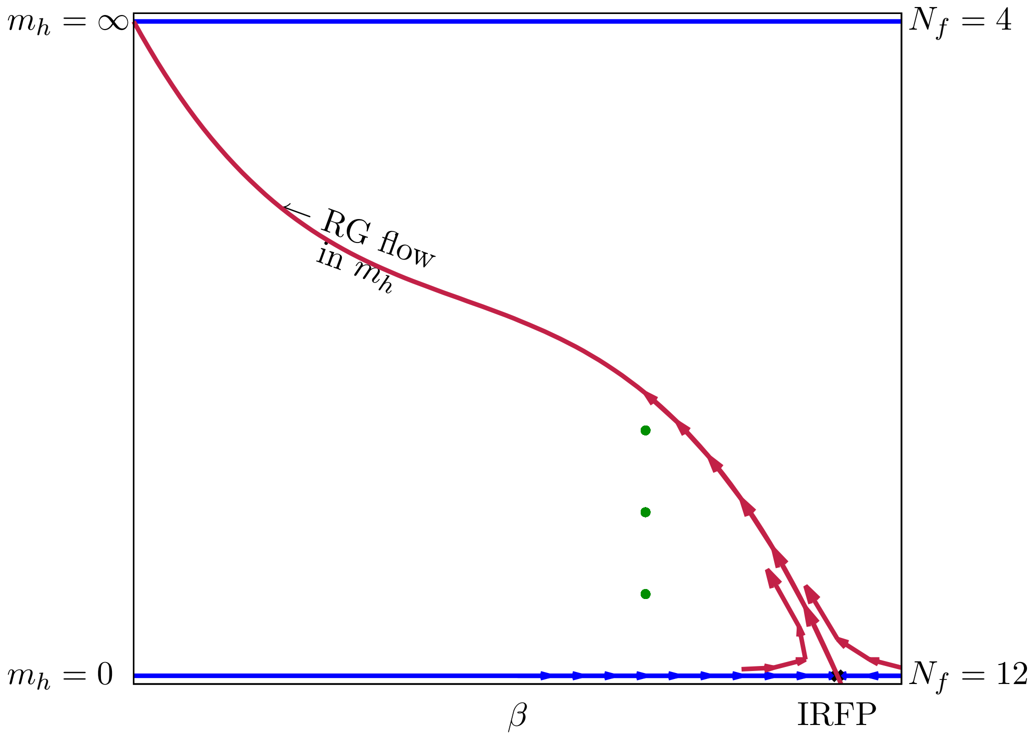
IRFP in SU(3)



Looking for a possible infrared fixed-point in an SU(3) theory with variable number of fermions. $\beta \propto 1/g^2$ (standard lattice notation)

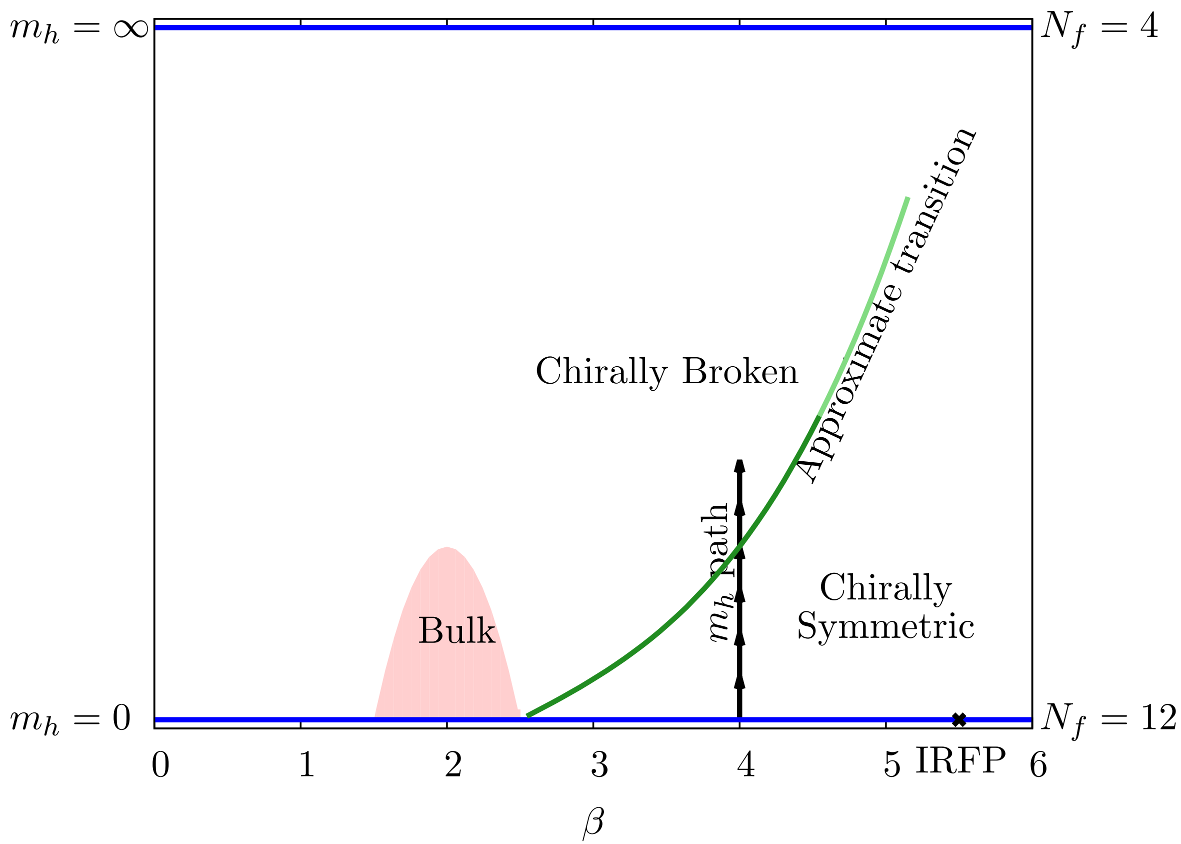
SU(3) with 4 light and 8 heavy flavors

A collaborative effort with Richard Brower, Anna Hasenfratz, Evan Weinberg, and Oliver Witzel.



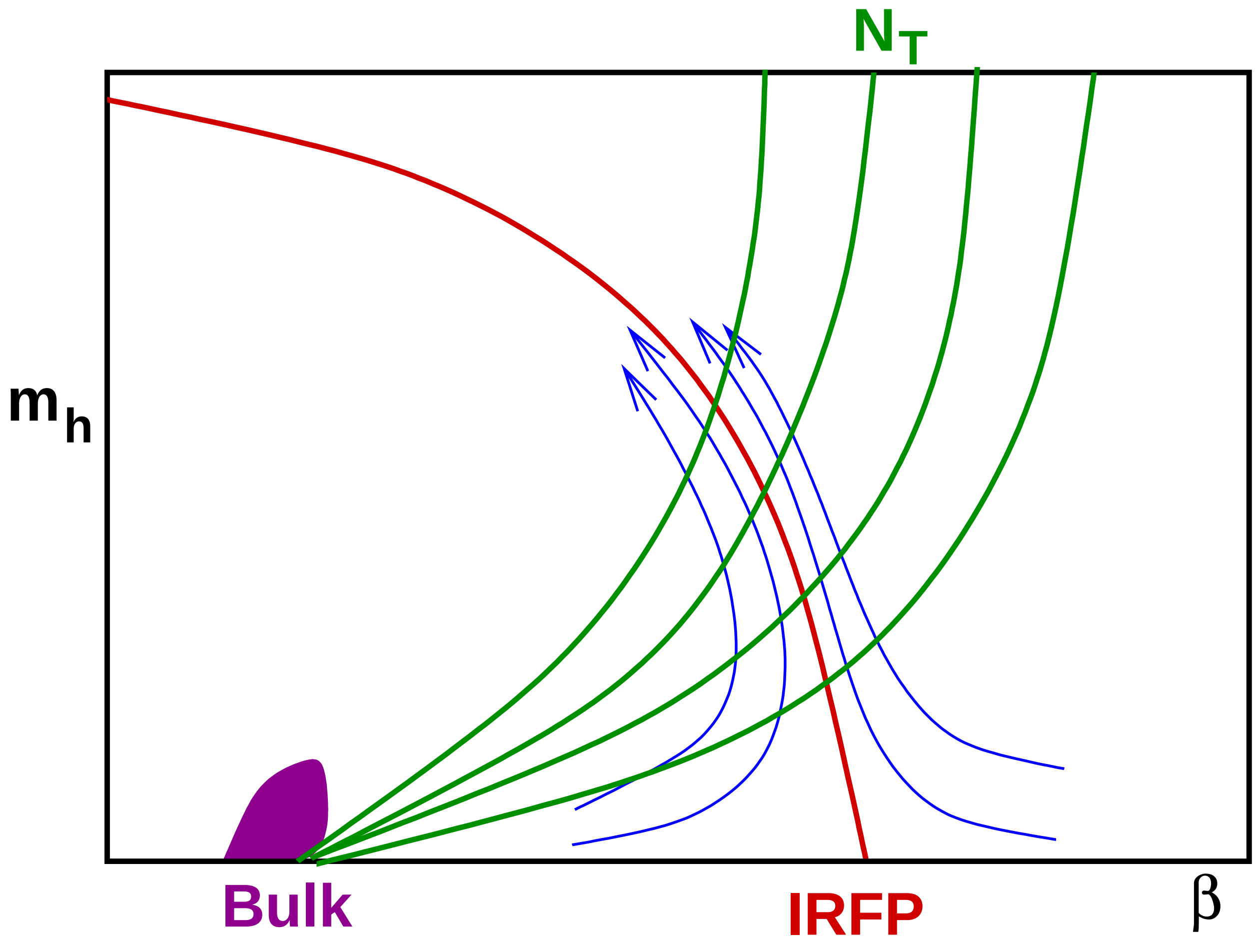
Varying N_f can only be done in steps. We consider an SU(3) theory with 4 light fermions plus 8 fermions of variable mass m_h.

4 light and 8 heavy flavors, continued



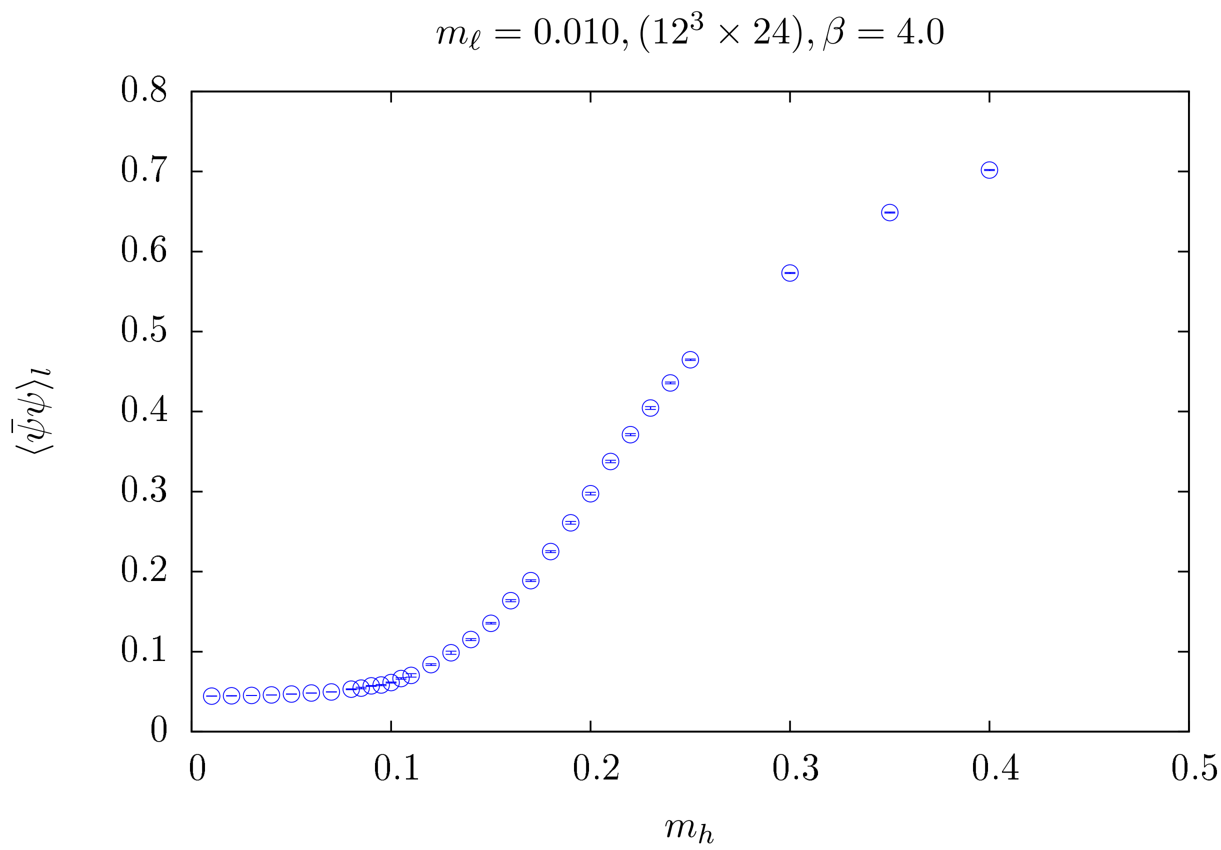
An important part of the effort is to find the appropriate window in β and m_h.

Another view, with T



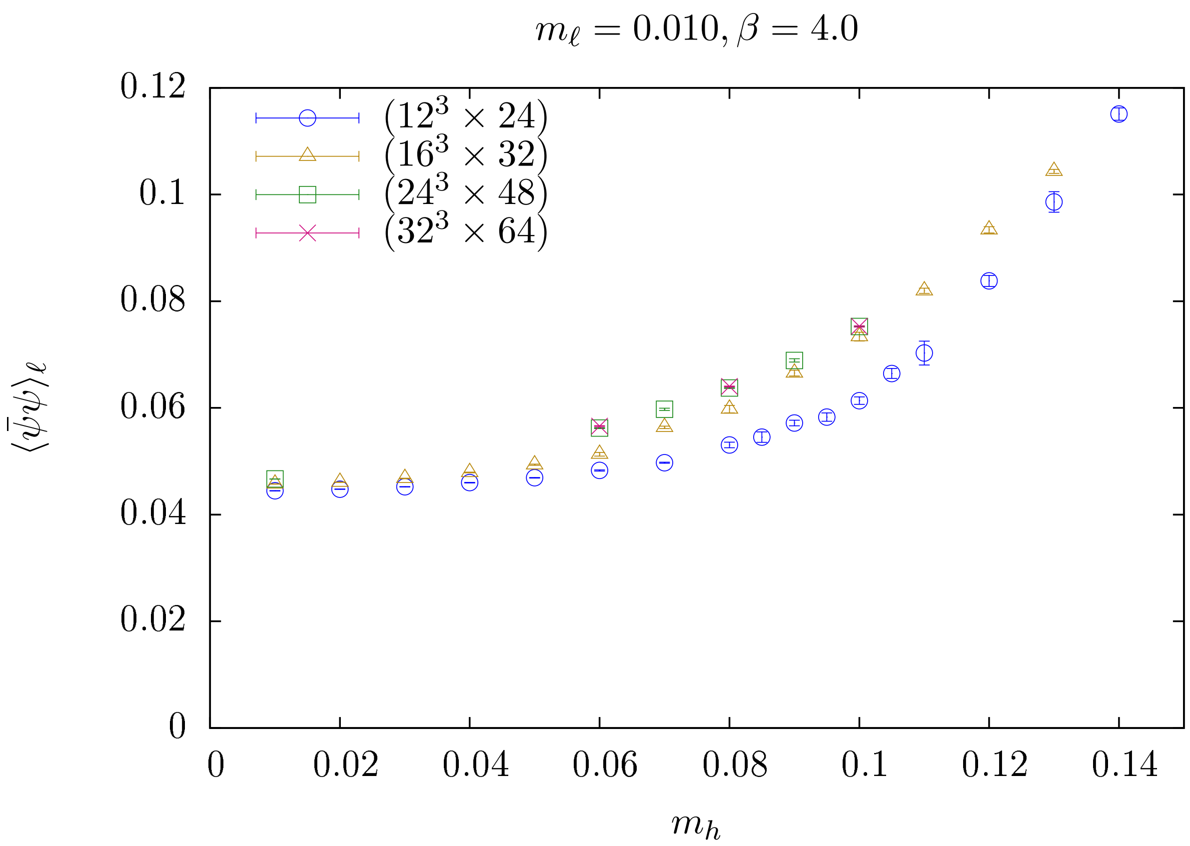
$T = 1/(N_T a)$ (a is the lattice spacing)

The light fermion condensate



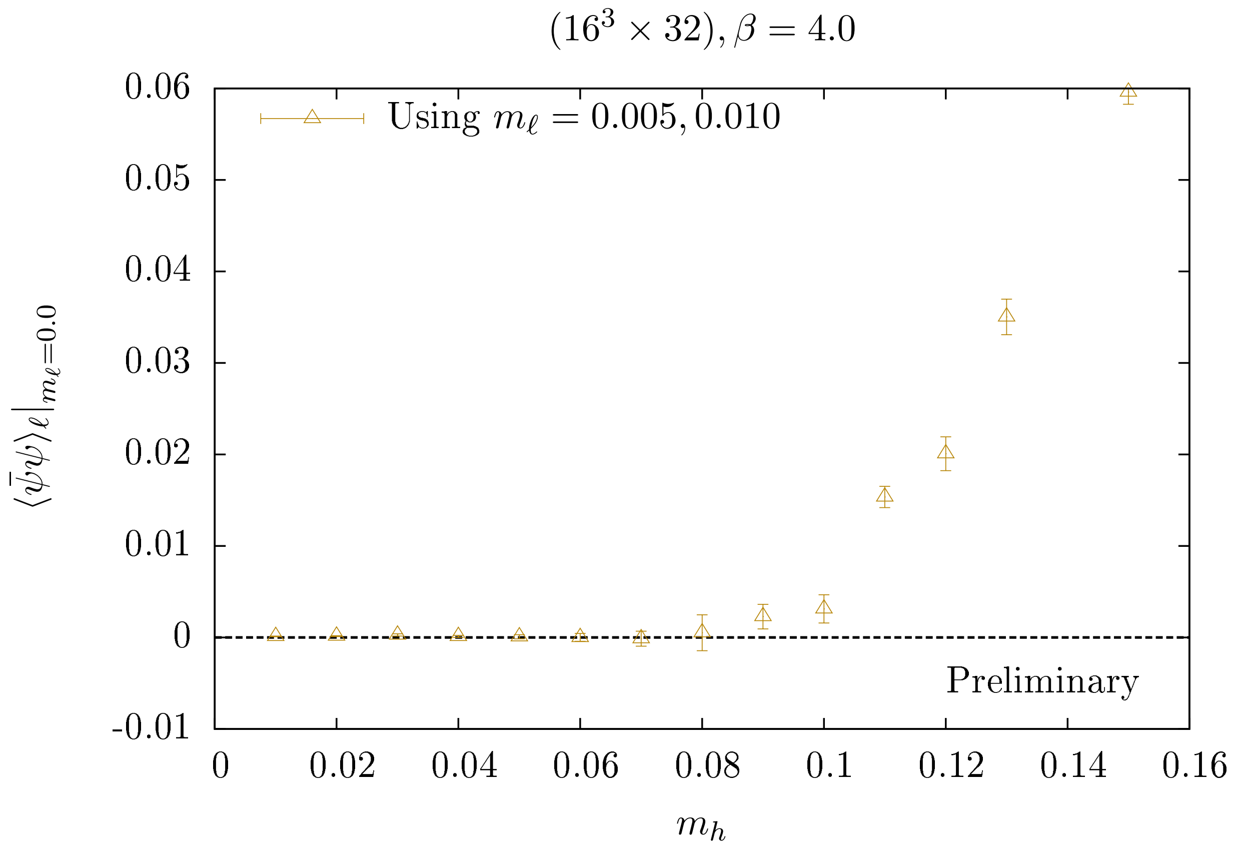
The light fermion condensate $\langle \bar{\psi}\psi \rangle$ shows a marked dependence on the mass of the 8 heavy fermions.

The light fermion condensate, volume dependence



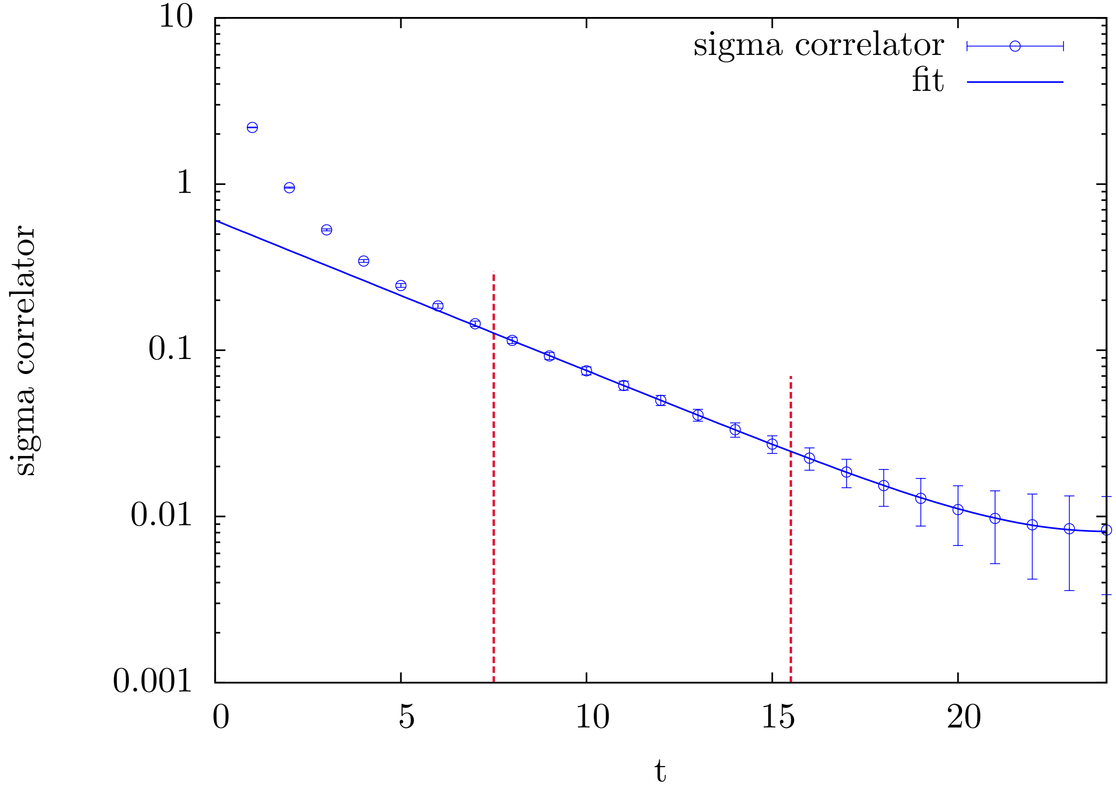
The transition appears to occur at smaller m_h as the volume increases.

The light quark condensate, extrap. to $m_l = 0$



The extrapolation to $m_l = 0$ indicates a transition from a chirally broken theory for $m_h \gtrsim 0.08$ to a chirally symmetric theory for $m_h \lesssim 0.08$.

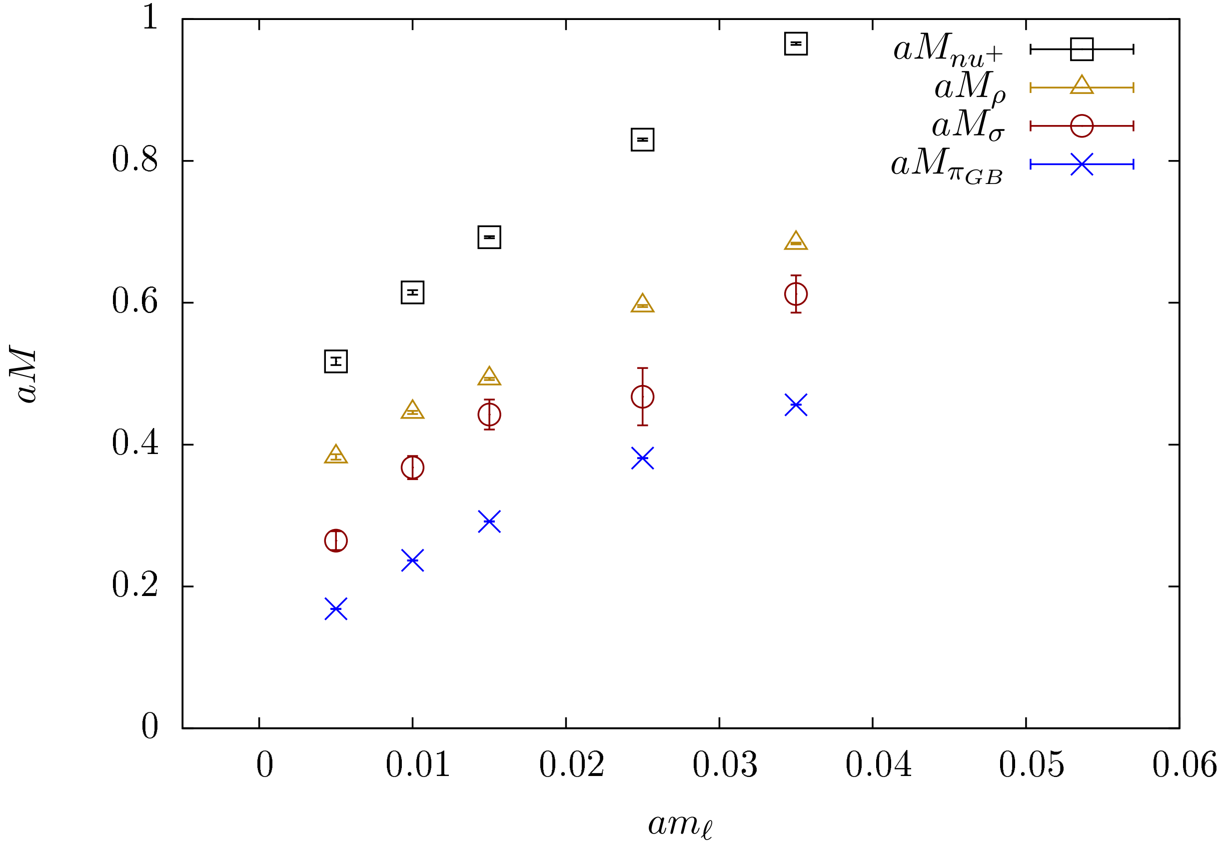
The singlet scalar correlator



Masses are evaluated from the rate of decay in Euclidean time of correlators: $\sum_{\vec{x}} \langle \bar{\psi}\psi(0)\bar{\psi}\psi(\vec{x},t)\rangle$. The singlet scalar correlator requires the calculation of disconnected diagrams.

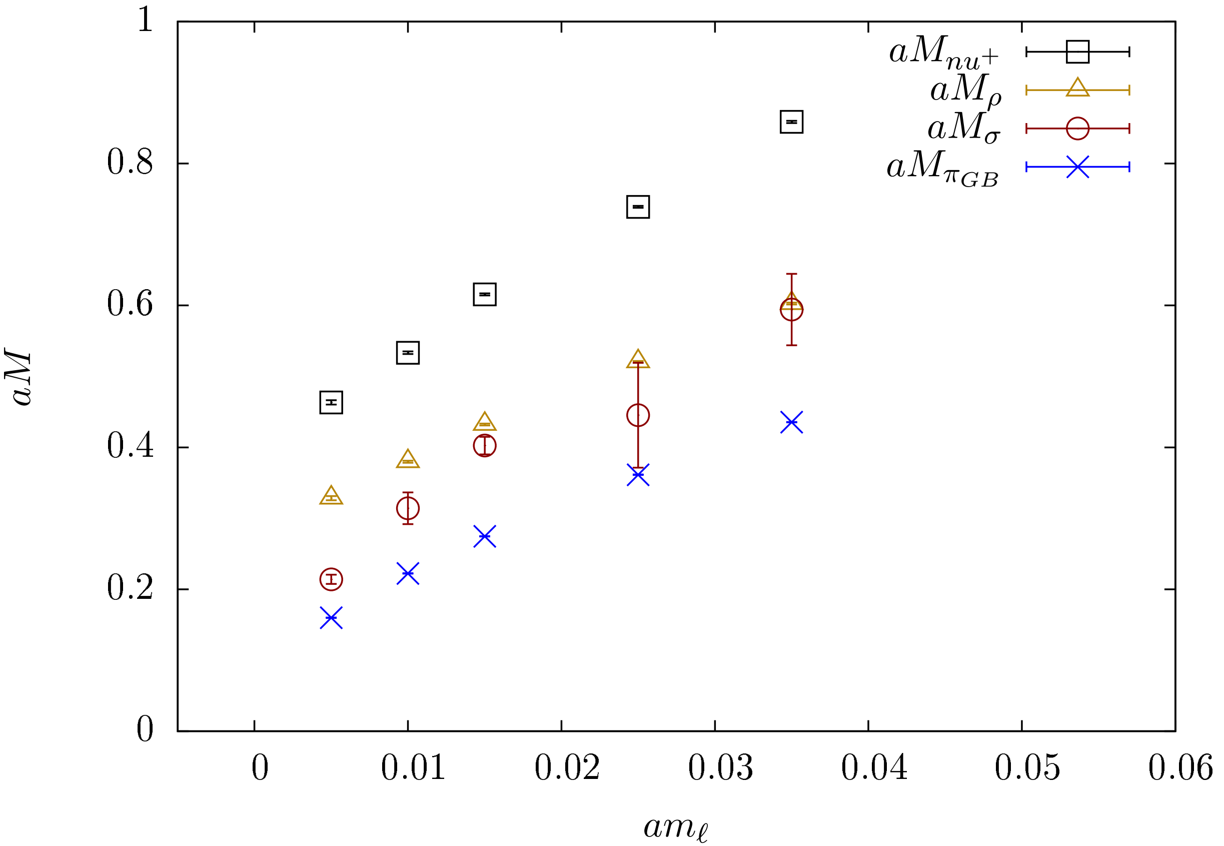
$(24^3 \times 48, m_l = 0.005, m_h = 0.080)$

The singlet scalar mass



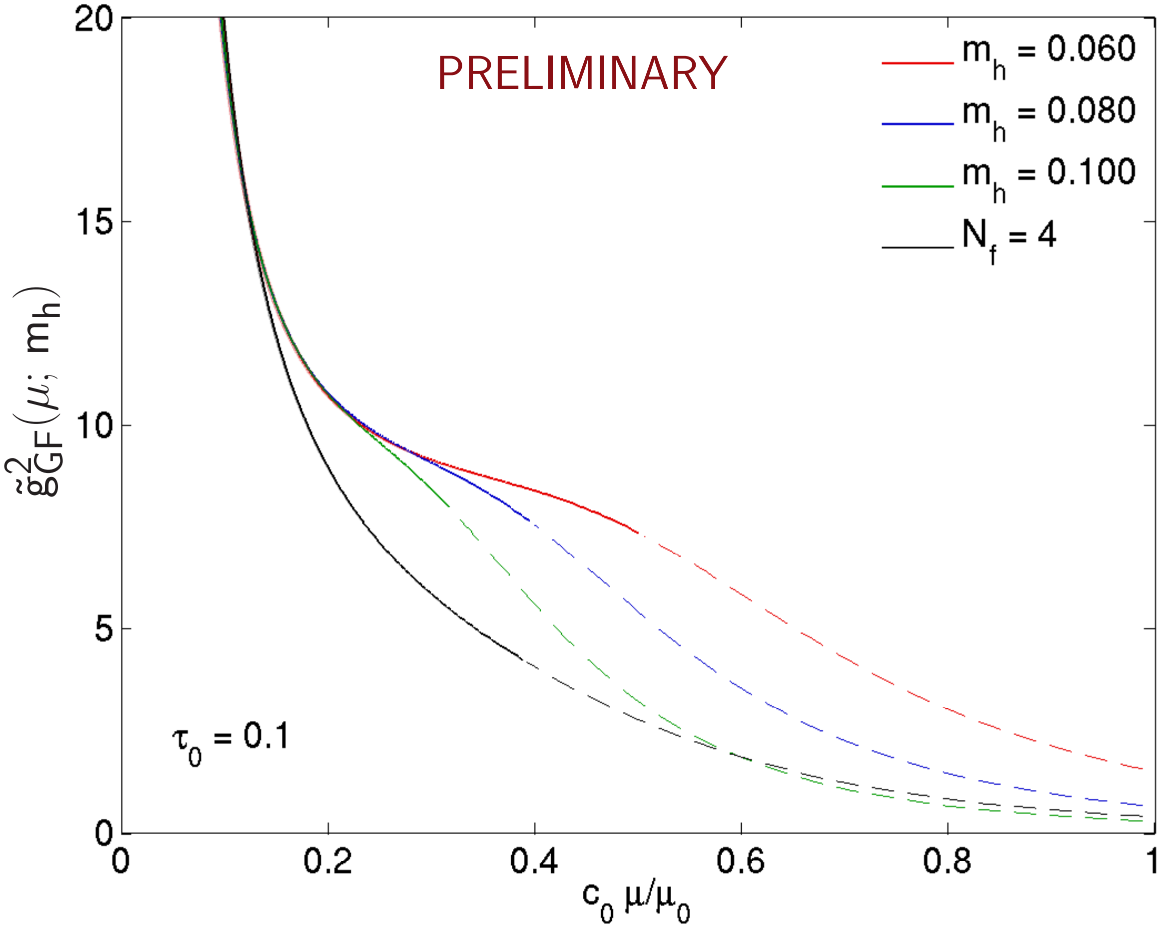
$$m_h = 0.100$$

The singlet scalar mass, continued



$$m_h = 0.080$$

Renormalization flow



The Wilson flow (Lüscher, 2010) may be used to study scaling.

Conclusions

The spectrum of non-QCD strongly coupled gauge theories with fermions is still largely unexplored.

Studying the properties of these theories is interesting per se.

The theory of electroweak symmetry breaking may be found among them.