Flavor Dependence of Yang-Mills

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Lattice Gauge Theory for LHC Physics
Wente Vineyards, Livermore, CA
02 May 2008

Outline

- New Strong Interactions at the LHC?
- The Flavor Dependence of Yang-Mills
- Lattice Strong Dynamics (LSD) Collaboration
  - 2008-2009 Research Plan

General features of DEWSB

- Dynamical Electroweak Symmetry Breaking (DEWSB) signals new strong interactions.
- The new strong sector will have several general features at the TeV scale:
  - Spontaneously broken global symmetry
  - At least three Nambu-Goldstone Bosons (NGB's).
  - Three NGB's "eaten" to become longitudinal W, Z bosons.
  - Any extra pseudo-NGB's (PNGB's) are massive (like Kaons).
  - Additional resonances expected (*e.g.* vector mesons).
- Many possible gauge groups, colors, flavors, representations.
- Which can/should be addressed using Lattice Gauge Theory on LHC discovery timescales?

Using LGT to study new strong interactions

- LGT can identify vector-like, asymptotically-free theories with the general features needed for DEWSB.
- QCD SU(3), $N_f = 2$ is best (only?) understood example theory. Small changes in number of colors/flavors should be similar.
- Larger number of flavors, *etc.* may exhibit novel phenomena: approximately conformal behavior, *i.e.* "walking". [Many talks]
- Current lattice methods are optimized for study of QCD. Will novel phenomena require new methods?

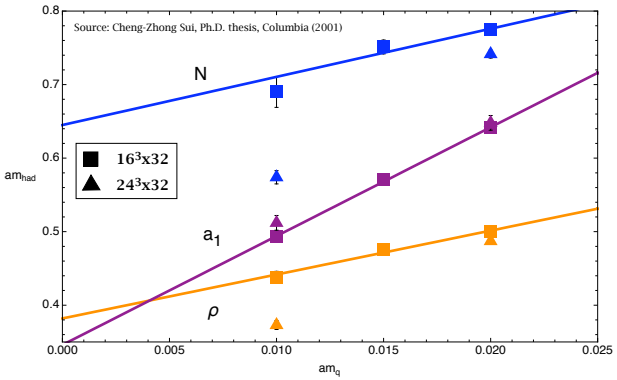
Scaled-up QCD at the LHC

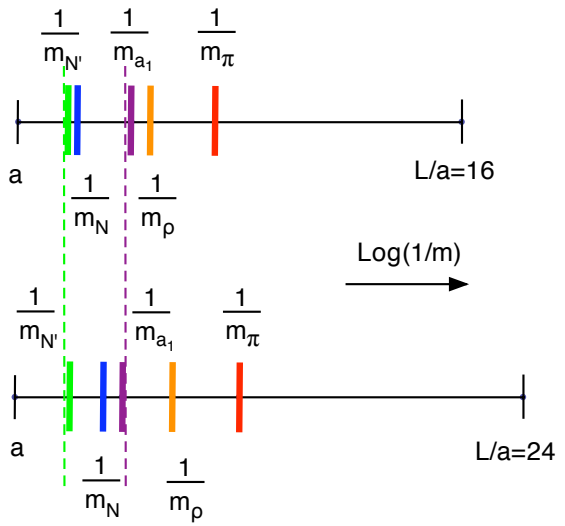
- Basic example is minimal technicolor: SU(3), N_f=2.
- χSB in techni-sector provides 3 NGB's to be eaten by EW bosons: $f_{\pi_T} \approx 250$ GeV.
- Lots of other resonances may be observable at LHC: $\rho_T, N_T, \ldots \sim$ few TeV, same as QCD.
- Natural theory of fermion flavor needs additional particle content and interactions, *i.e.* "extended technicolor".
- Only LQCD can verify Peskin-Takeuchi S parameter calculation. [Comments by R. Brower in discussion]
- Recent progress on S in QCD by JLQCD[1].
- Why not SU(2)? How different from QCD? What role do QQ baryons play?

[1] E. Shintani *et al*, PoS(LATTICE 2007)134

Columbia studies of SU(3) Yang-Mills with $N_f = 4$ [2] [3]

- Initial studies on $16^3 \times 32$ lattices suggested approximate parity doubling of hadron spectrum.
- Also, $\langle \overline{q}q \rangle / m_\rho^3$ about $1/4$ of QCD.
- Increasing $L/a \longrightarrow 24$ at fixed a restored QCD-like spectrum: finite volume effect.
- Open questions:
  - Is 24^3 big enough?
  - Finite lattice spacing errors?
  - Similar results with different fermion actions?

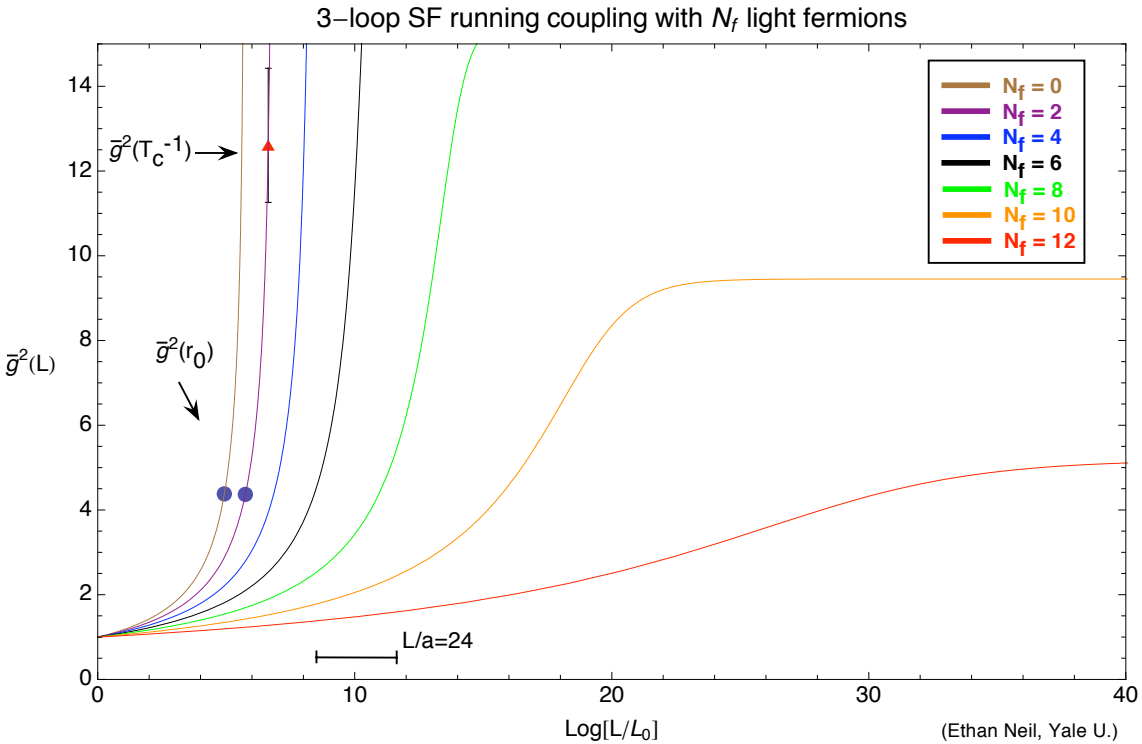




Source: Cheng-Zhong Sui, Ph.D. thesis, Columbia (2001)

[2] D. Chen, Ph.D. Thesis, 1996.
[3] C. Sui, Ph.D. Thesis, 2001.

3-loop SF running coupling in Yang-Mills



- *"Finite volume effect"* is simply a reflection that the renormalized coupling runs slower as $N_f \longrightarrow N_f^c$.

Flavor dependence of SU(3) Yang-Mills

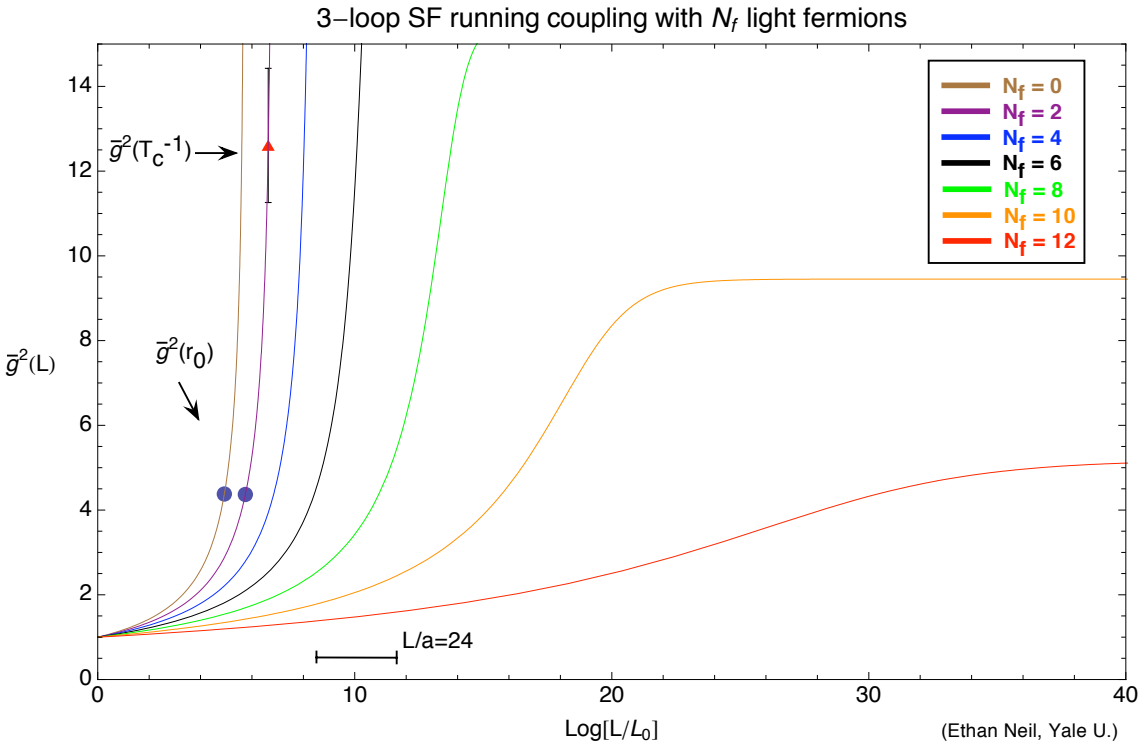
- SU(3) Yang-Mills with N_f=2 flavors is quite familiar.
- SU(3) Yang-Mills with N_f=4 flavors is not too different?
- The non-Abelian Coulomb phase exists for $N_f > 8$.
- What is the nature of the quantum phase transition[4] as $N_f \to N_f^c$? Is it first-order or continuous?

$$\lim_{N_f \to N_f^c} M/\Lambda = 0.$$

- M represents the scale of confinement, *e.g.* nucleon mass M_N, and Λ represents some UV scale, *e.g.* $\overline{g}^2(\Lambda) = 1.0$.
- If continuous, approximate scale invariance or "walking" may occur for $8 \lesssim N_f \lesssim N_f^c$.

[4] S. Sachdev, *Quantum Phase Transitions*, Cambridge Univ. Press, 2000.

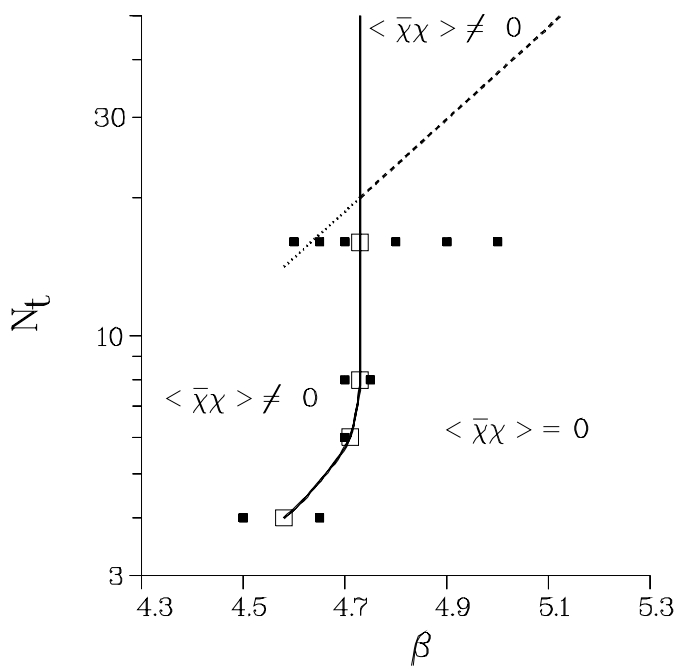
3-loop SF running coupling in Yang-Mills



- $M/\Lambda \to 0$ as $N_f \to N_f^c$ as a natural consequence of the N_f dependence of running.

SU(3) Yang-Mills with $N_f = 8$ [5] [6]

- Columbia worked on $16^3 \times N_t$ lattices, N_t=4–32. First-order transition at fixed $\beta_c = 6/g_0^2$ *vs.* N_t.
- Is this a bulk phase transition unrelated to continuum physics? Deuzeman *et al.* disagree.
- Behavior consistent with our N_f=8 SF running coupling.
  - Proposed phase diagram suggests continuum confined phase is accessible if $\beta > \beta_c$ and $L/a \gtrsim 24$.
  - Does something similar happen at N_f=6?



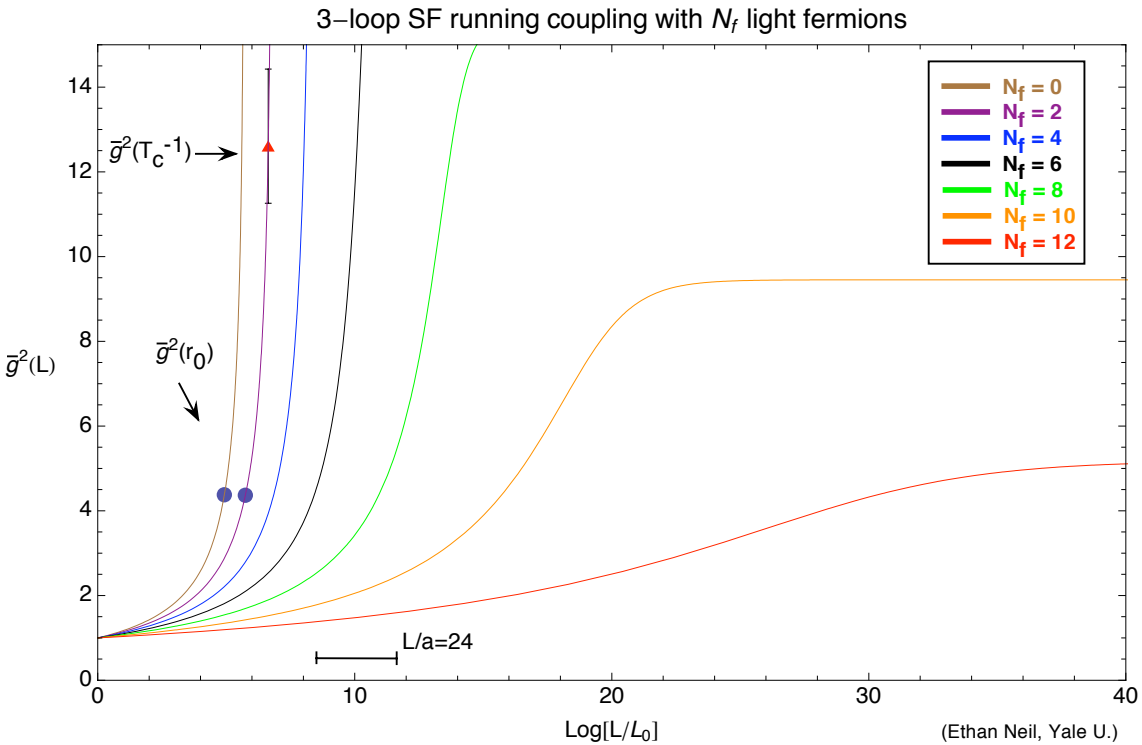
[5] F. Brown *et al.*, Phys. Rev. D **46**, 5655 (1992)
[6] Deuzeman, Lombardo, Pallante, arXiv:0804.2905 [hep-lat]

LHC and approximate conformal symmetry

- Near-conformal, or walking, behavior is useful to model builders because it dynamically generates two well-separated scales: the IR scale of confinement and the UV scale.
- SU(3) Yang-Mills with $8 < N_f < 12$: no direct evidence for walking yet. [Talk by E. Neil]
- Searching for edge of conformal window at N_f=10.
- SU(2) with Wilson fermions in **3** of SU(2). [Talk by S. Catterall]
- Recent work: SU(3), N_f=2 Wilson in **6** of SU(3).[7] Limited by $L/a = 4, 8$, questionable in SF scheme.

[7] T. DeGrand, Y. Shamir, B. Svetitsky, arXiv:0803.1706

3-loop SF running coupling in Yang-Mills



- Walking may occur for N_f=10 if $\overline{g}^2 \approx 9.4$ triggers χSB.

Lattice Strong Dynamics (LSD) Collaboration

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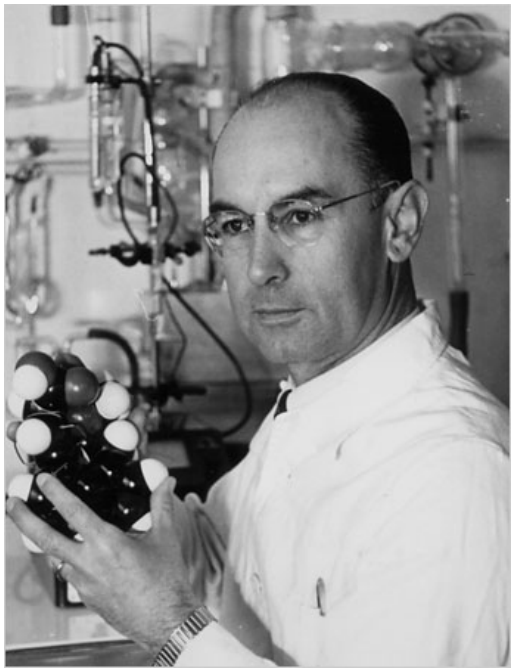

Albert Hofmann
1906–2008

LSD Collaboration Research Plan

- We've been awarded 2.5 Tflops-yr (sustained): 70% NSF Teragrid, 30% DOE USQCD.
- Compute the $N_f = 10$ running coupling in SU(3) Yang-Mills.
- Compute the S parameter in QCD.
- Compute the low energy spectrum of SU(3) Yang-Mills for $N_f = 4, 6, 8, \cdots$ on a single 24^3 volume at a single lattice spacing.