Strong Interactions for the LHC

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Lattice 2008
Williamsburg, VA
19 Jul 2008

Outline

- Dynamical Electroweak Symmetry Breaking (DEWSB)
  - *Wasn't technicolor ruled out more than a decade ago?*
- The Conformal Window of $SU(N)$ Yang-Mills Theories
- Lattice Strong Dynamics for the LHC

Brief History of Electroweak Symmetry

- 1967: S. Weinberg publishes the electroweak (EW) sector of the standard model.
  - He speculated that it might be renormalizable.
  - The paper was completely ignored for four years.
- 1971: G. 't Hooft proves renormalizability of EW theory.
  - Now, Weinberg's 1967 paper most-cited in SPIRES.
- Mid 1970's: Growing appreciation of the hierarchy problem for the standard model Higgs boson:
  - Technical naturalness: New physics should appear at the TeV scale to explain why Higgs is so much lighter than the Planck/GUT scale: SUSY, ...
- 1976–9: S. Weinberg describes dynamical electroweak symmetry breaking (DEWSB), dubbed *technicolor* (TC) by L. Susskind, obviated the need for a scalar Higgs field.

General features of DEWSB

- Dynamical Electroweak Symmetry Breaking (DEWSB) signals new strong interactions.
- New strong sector has several general features at TeV scale:
    - Spontaneously broken global chiral symmetry producing at least three Nambu-Goldstone Bosons (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.
- Additional extended technicolor (ETC) fields and interactions are needed to describe how fermions get their masses.
    - Effectively generated by $(\overline{Q}Q)(\overline{q}q)/\Lambda^2_{\mathrm{ETC}}$.
- A scaled-up copy of QCD has all the ingredients, but ...

Wasn't technicolor ruled out more than a decade ago?

Aren't flavor-changing neutral currents (FCNC's) too large?

- NO, *if TC generates modestly enhanced condensates*
- In extended technicolor (ETC)[1], masses and FCNC's from

$$\text{Masses}: \quad \frac{(\overline{Q}Q)(\overline{q}q)}{\Lambda^2_{\rm ETC}} \qquad \text{FCNC's}: \quad \frac{(\overline{q}q)(\overline{q}q)}{\Lambda^2_{\rm ETC}}$$

- For current limits on FCNC's involving strange quarks

$$\Lambda_{\rm ETC} \gtrsim 1000 \text{ TeV}$$

- So, the natural scale for strange quark mass in ETC

$$m_s \sim \langle \overline{Q}Q \rangle / \Lambda^2_{\rm ETC}$$

- In QCD $\langle \overline{\psi}\psi \rangle \sim (3f_\pi)^3$, so in QCD-like TC ($v \sim 250$ MeV)

$$\langle \overline{Q}Q \rangle \sim (3v)^3 \sim (750 \text{ GeV})^3 \quad \Longrightarrow \quad m_s \sim 0.4 \text{ MeV}$$

- Enhancement of about $4\times$ is sufficient

$$\langle \overline{\psi}\psi \rangle \gtrsim (12f_\pi)^3 \quad \Longrightarrow \quad m_s \sim 27 \text{ MeV}$$

[1] T. Appelquist, M. Piai, R. Shrock, Phys. Rev. D **69**,105002 (2004)

Wasn't technicolor ruled out more than a decade ago?

Aren't precision electroweak constraints violated?

- NO, *unless TC is QCD-like and ...*
- The S parameter[2] is a *one-loop* EW radiative correction
$$\Pi^{\mu\nu}_{LR}(q) = ig^{\mu\nu}\Pi_{LR}(q^2) + \cdots \equiv \int d^4x e^{-iqx} \left\langle J^\mu_L(x) J^\nu_R(0) \right\rangle$$
$$S \equiv -4\pi \lim_{q^2\to 0} \frac{d}{dq^2}\Pi_{LR}(q^2)$$
- Naively counts d.o.f. connecting left and right EW currents
$$\text{Naive TC estimate}: \quad S \simeq 0.3 \left[\frac{N_{TC}N_{TF}}{2}\right]$$
- χPT $\bar{\ell}_5$ (or $\bar{L}_{10}$)[3] leads to better estimate of S in QCD-like TC and 2.6 σ discrepancy with experiment [Fri. N. Yamada]
$$S_{\mathrm{QCD-like}} \approx 0.42 \quad S_{\mathrm{expt}} \approx -0.07(19) \quad m_H^{\mathrm{ref}} = 117\ \mathrm{GeV}$$
- For larger N_{TF} chiral symmetry is unbroken and S is zero. How reliable is naive N_{TF} dependence?

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[2] M. Peksin and T. Takeuchi, Phys. Rev. D **46**, 381 (1992)

[3] E. Shintani *et al.*, arXiv:0806.4222 [hep-lat].

Wasn't technicolor ruled out more than a decade ago?

The Bottom Line

- **FCNC's:** ETC models indicate TC should produce enhanced condensates: $\langle\overline{\psi}\psi\rangle \gtrsim (12f_\pi)^3$. This is incompatible with QCD-like TC.
- **The S Parameter:** Currently, about $2.5\ \sigma$ tension between experiment and QCD-like TC. Could disfavor QCD-like TC *or* could indicate higher-order effects are important.
- **Bottom line:** So much is known about QCD, it's easy to argue against QCD-like TC. For other TC theories, so little is known that model-building becomes a baroque exercise based on conjecture and too many free parameters.
- **Our Challenge:** Can we find new confining gauge theories whose properties are sufficiently different from QCD?

Using LGT to study new strong interactions

- Lattice gauge theory (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”.
- Walking behavior is conjectured to enhance UV contributions to condensates.
- Changing the color representation of fermions may also exhibit walking due to the increased number of fermionic d.o.f. To date, no higher rep. ETC models have been constructed.
- Current lattice methods are optimized for study of QCD. Will novel phenomena require new methods?

Flavor dependence of $SU(3)$ Yang-Mills

- The running coupling g of QCD is characterized by two important features: asymptotic freedom ($g \to 0$ in the UV) and confinement ($g \to \infty$ in the IR.)
- These properties are strongly dependent on the number of fermion flavors, N_f:

	Short-distance (UV)	Long-distance (IR)
$0 < N_f < N_f^c$	Free ($g \to 0$)	Confined ($g \to \infty$)
$N_f^c < N_f < 16.5$	Free ($g \to 0$)	Fixed point ($g \to g^\star$)
$N_f > 16.5$	Divergent ($g \to \infty$)	Trivial ($g \to 0$)

- Theories in the first row are useful for DEWSB model-building.
- The second row defines the conformal window.
- Pert. theory is unreliable near bottom of conformal window. N_f^c *must be computed non-perturbatively.*

Analytic guesstimates of N_f^c in SU(3) Yang-Mills

- Original two-loop beta function[4]: $N_f^c > 8.05$
- Two-loop ladder gap equation[5]: $N_f^c = 11.9\cdots$
- Instanton-driven χSB[6]: $N_f^c \gtrsim 11.1$
- Conjectured thermal inequality bound[7]: $N_f^c \leq 11.9\cdots$
- Conjectured superconvergence of gluon prop.[8]: $N_f^c \geq 9.75$
- There are several more estimates [see writeup]. By a large margin, the majority suggest $8 < N_f^c < 12$.
- **Caution:** All these estimates are strongly influenced by two-loop perturbation theory, but the bottom of the conformal window is where the IRFP coupling should be largest.

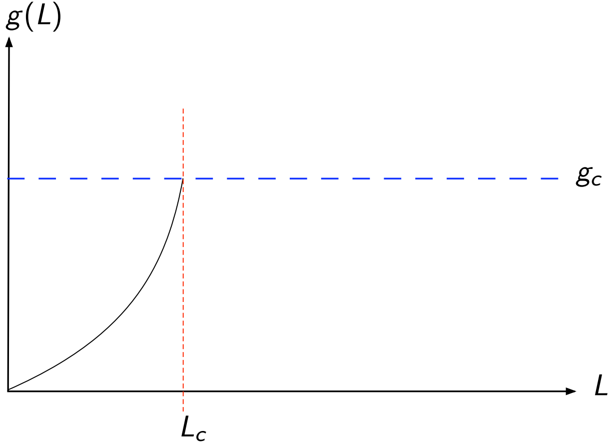
[4] W. E. Caswell, Phys. Rev. Lett. **33**, 244 (1974)
[5] Appelquist, Terning, Wijewardhana, Phys. Rev. Lett. **77**, 1214 (1996)
[6] T. Appelquist and S. Selipsky, Phys. Lett. B **400**, 364 (1997)
[7] T. Appelquist, A. Cohen, M. Schmaltz, Phys. Rev. D **60**, 045003 (1999)
[8] E. Gardi and G. Grunberg, JHEP **03**, 024 (1999)

Prior LGT estimates for N_f^c in SU(3) Yang-Mills

- Starting with Kogut *et al.*[9], many studies done through the 1980's and early 1990's that are generally inconclusive.
- Iwasaki *et al.*[10] predicted $6 < N_f^c < 7$ using Wilson fermions based on absence of Goldstone modes in strong coupling expansion and on relatively coarse lattices.
- Columbia[11] staggered $N_f = 8$ calculation had strong evidence for confinement, but rendered inconclusive by bulk transition.
- Damgaard *et al.*[12] had evidence of confinement **(!)** for staggered $N_f = 16$ correctly associated with a bulk transition.
- Heller[13] at Lattice '97 clearly showed staggered $N_f = 16$ backward flow from strong UV coupling at bulk transition towards known weak IRFP. *No citations before Dec, 2007!*

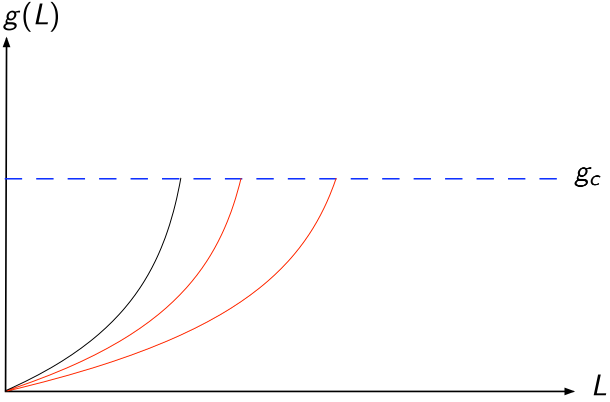
[9] Kogut, Polonyi, Wyld, Sinclair, Phys. Rev. Lett. **54**, 1475 (1985)
[10] Iwasaki *et al.*, Phys. Rev. D **69**, 014507 (2004)
[11] F. Brown *et al.*, Phys. Rev. D **46**, 5655 (1992)
[12] Damgaard, Heller, Krasnitz, Olesen, Phys. Lett. B **400**, 169 (1997)
[13] U. M. Heller, Nucl. Phys. (Proc. Suppl.) **63**, 248 (1998)

A cartoon of dynamical scales in SU(N) Yang-Mills



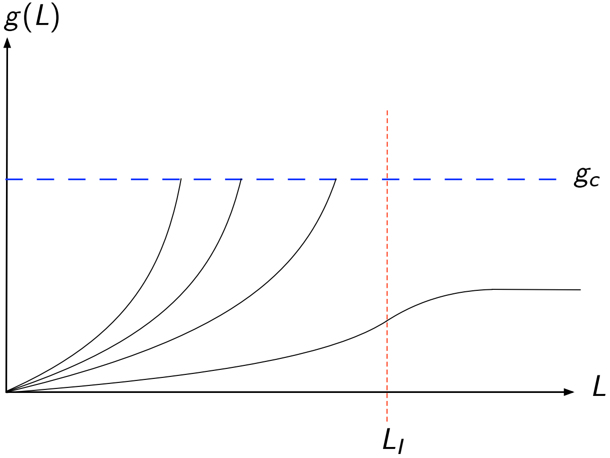
QCD is a one-scale theory where L_c is confinement scale.

A cartoon of dynamical scales in SU(N) Yang-Mills



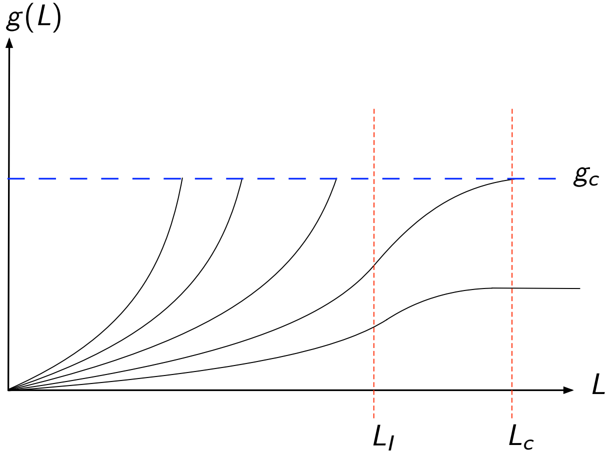
Increasing N_f pushes confinement scale to longer distances.

A cartoon of dynamical scales in SU(N) Yang-Mills



For large N_f an appropriate scale is the inflection point L_I.

A cartoon of dynamical scales in SU(N) Yang-Mills



A "walking" theory can have both scales L_I and L_c. Condensates are enhanced by modes between L_I and L_c [a].

[a] Appelquist, Terning, Wijewardhana, Phys. Rev. D **44**, 871 (1991)

Determining N_f^c from the running coupling

- We have logically extended Heller's Lattice '97 $N_f = 16$ study to smaller N_f starting from existing MILC (v6) code.
- We continued with *unrooted* staggered fermions for reduced computational cost and ease of setting bare mass to zero.
  - $N_f = 4$: Clearly in the confining phase[14]
  - $N_f = 8$: presence of IRFP unknown
  - $N_f = 12$: should be in the conformal window
  - $N_f = 16$: very perturbative IRFP

[14] C. Sui, Ph.D. Thesis, Columbia U., 2001

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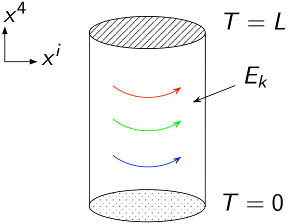
Simulate here!

[14] C. Sui, Ph.D. Thesis, Columbia U., 2001

The Schrödinger Functional[15]



Schrödinger Functional simulations introduce Dirichlet boundaries in time; boundary gauge fields are chosen to give a constant chromoelectric background field. Boundary conditions enable simulations with massless fermions.

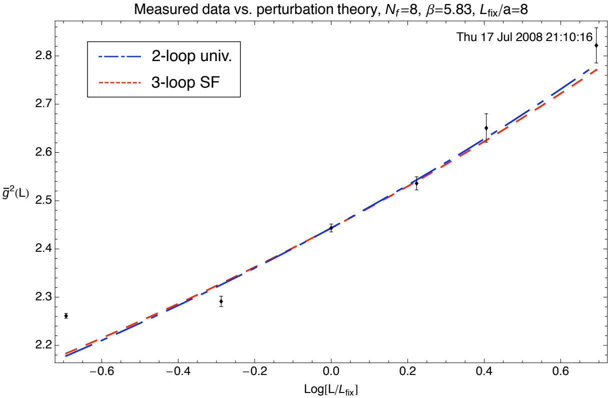
Running coupling

The SF running coupling $\overline{g}^2(L)$ is defined to vary inversely with the response of the action to the strength η of the background field,

$$\frac{dS}{d\eta} = \frac{k}{\overline{g}^2(L)}\bigg|_{\eta=0}$$

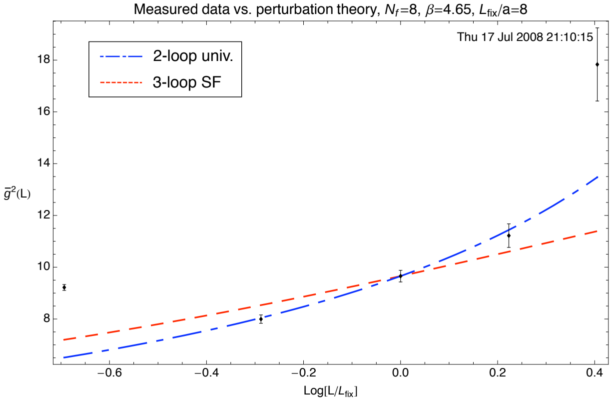
[15] Comprehensive review by R. Sommer, hep-lat/0611020

The SF running coupling at fixed lattice spacing



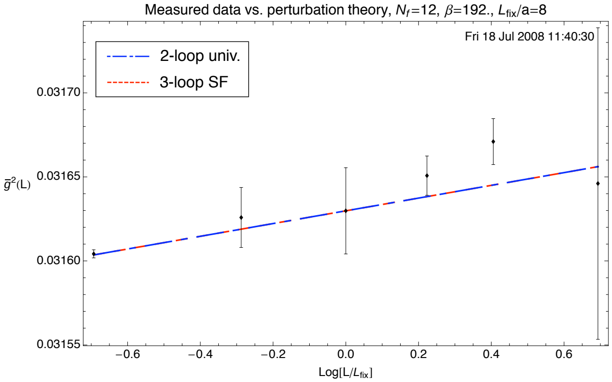
For $N_f = 8$, modest $\beta = 5.83$: agrees with 2,3-loop PT up to $O(a/L)$ lattice artifacts.

The SF running coupling at fixed lattice spacing



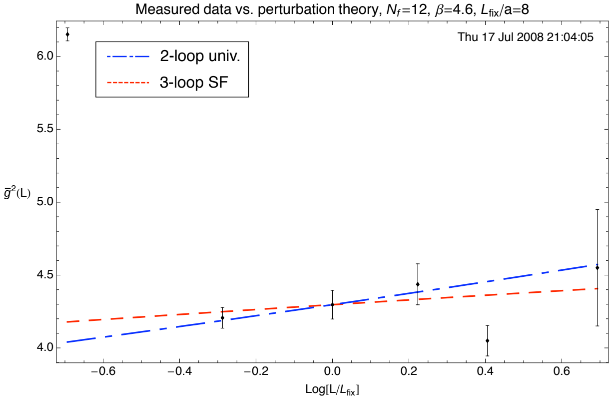
For $N_f = 8$, strong $\beta = 4.65$: outpaces PT. No obvious fixed point.

The SF running coupling at fixed lattice spacing



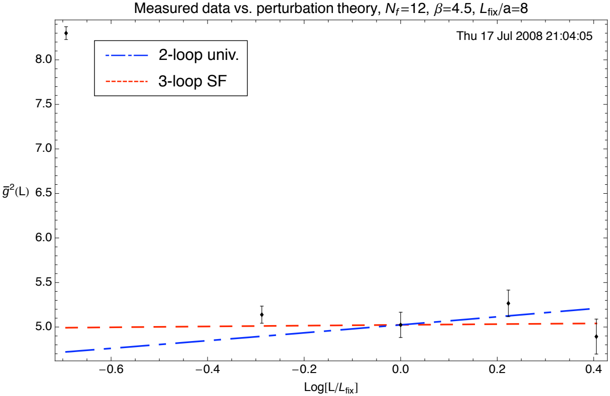
For $N_f = 12$, very weak $\beta = 192.0$: no one-loop artifacts.

The SF running coupling at fixed lattice spacing



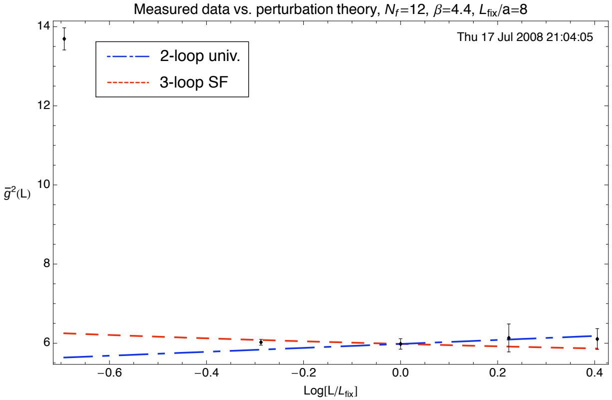
For $N_f = 12$, $\beta = 4.6$: fixed point here?

The SF running coupling at fixed lattice spacing



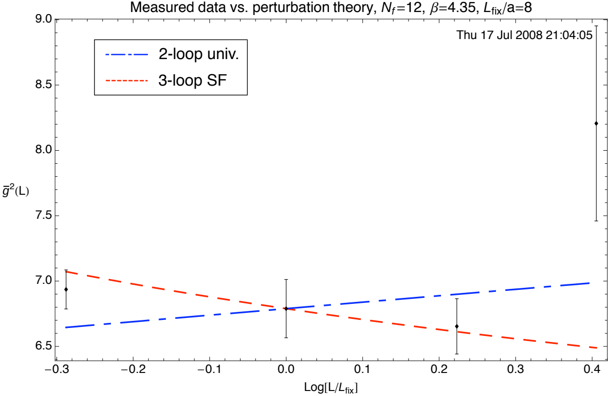
For $N_f = 12$, $\beta = 4.5$: fixed point here?

The SF running coupling at fixed lattice spacing



For $N_f = 12$, $\beta = 4.4$: fixed point here?

The SF running coupling at fixed lattice spacing



For $N_f = 12$, $\beta = 4.35$: or fixed point here?

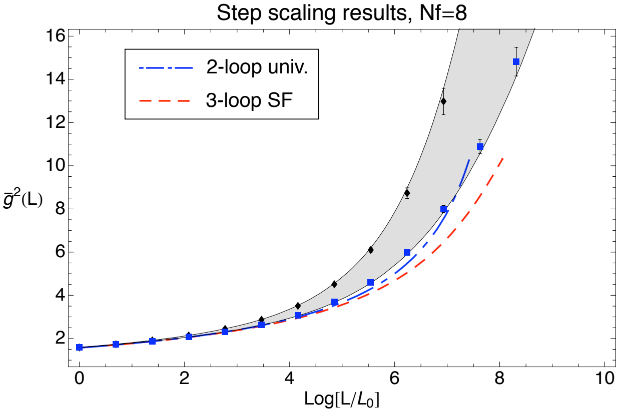
Extracting the continuum running coupling

- The Schrödinger Functional coupling $\overline{g}^2(L)$, defined directly at the scale L, avoids introducing additional scales.
- In order to compute the evolution of $\overline{g}^2(L)$, we use the step scaling procedure to link together results of simulations at many different lattice spacings a. Calculate in discrete steps: $\overline{g}^2(L) \to \overline{g}^2(2L) \to \ldots$
- Conformal invariance means $\overline{g}^2(L) = \overline{g}^2(2L)$.
- Define the step-scaling function,

$$\Sigma(2, \overline{g}^2(L), a/L) \equiv \overline{g}^2(2L) + O(a/L)$$

  The continuum limit $\sigma(2, u) \equiv \lim_{a\to 0} \Sigma(2, u, a/L)$ is a discrete analogue of the beta function.
- $\overline{g}^2(L)$ will not be conformal at any finite lattice spacing due to $O(a/L)$ terms.

Results for $N_f = 8$ SU(3) Yang-Mills[16]

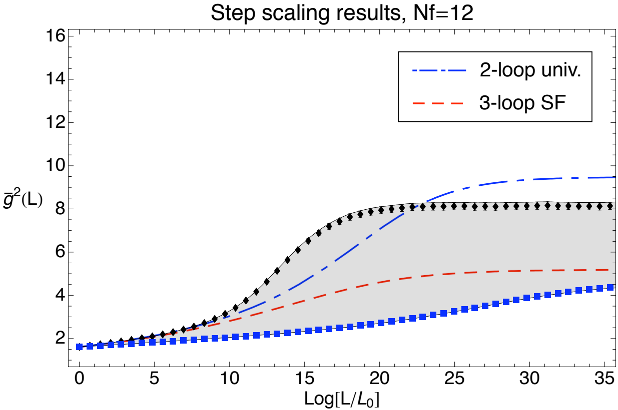


No evidence for an IR fixed point at $N_f = 8$.

Shaded area is systematic error of continuum extrapolation.

[16] T. Appelquist, G. Fleming and E. Neil, Phys. Rev. Lett. **100**, 171607 (2008)

Results for $N_f = 12$ SU(3) Yang-Mills[17]



The conformal window extends to $N_f = 12$.
Running consistent with 3-loop PT in SF scheme.

17 T. Appelquist, G. Fleming and E. Neil, Phys. Rev. Lett. **100**, 171607 (2008)

Further studies of the conformal window

- Study of asqtad $N_f = 8, 12$ finite temperature transition[18] [Tue. talks by Dueuzeman, Pallante]. Indications of a physical confined phase for $N_f = 8$ and a bulk transition for $N_f = 12$.
- Columbia zero temperature spectrum study of staggered $N_f = 8$ with DBW2 gauge action. Clear indications of confined spectrum properly scaling towards continuum limit. [Tue. talk by X. Jin]
- Study of staggered $N_f = 8, 12$ eigenvalue distributions look quite similar and don't agree with RMT predictions. Need better predictions for distributions inside the conformal window. [Fri. talk by K. Holland]
- A promising new scheme was presented to compute the running coupling from Wilson loops in a finite box. Direct simulation at zero quark mass doesn't seem possible requiring chiral extrapolation. Quenched studies underway. [Thu. talks by Kurachi and Itou]

[18] Deuzeman, Lombardo, Pallante, arXiv:0804.2905 [hep-lat]

Conformal windows for higher color representations

- More d.o.f. per flavor means N_f^c is smaller[19]
- $N_f = 2$ Wilson fermions in the **6** of SU(3) may have an IRFP[20] and a novel deconfined yet chirally-broken phase. Explorations continue. [Fri. talks by DeGrand and Svetitsky]
- Eigenvalue distributions of $N_f = 2$ overlap fermions in the **6** of SU(3) were studied on small volumes at fixed zero topology. Do not fit RMT predictions for χSB. f_π not measured yet, so may not be in epsilon-regime. [Tue. talk by Nógrádi]
- Three groups are studying SU(2) with $N_f = 2$ adjoint Wilson fermions[21][22] and producing consistent results. Clear evidence for bulk transition at $\beta = 2$. For $\beta > 2$ vector mesons seem very light at small quark masses. Is it a finite volume effect? [Fri. talks by A. Patella and A. Hietanen]

[19] F. Sannino and K. Tuominen, Phys. Rev. D **71**, 051901 (2005)

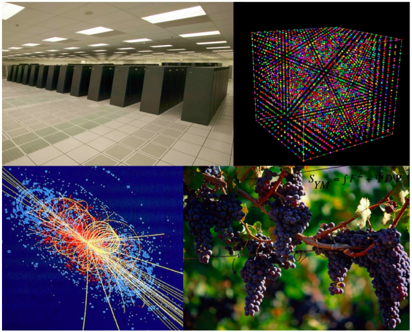
[20] Shamir, Svetitsky and DeGrand, arXiv:0803.1707 [hep-lat]

[21] Del Debbio, Patella and Pica, arXiv:0805.2058 [hep-lat]

[22] Catterall, Giedt, Sannino and Schneible, arXiv:0807.0792 [hep-lat]

Workshop on Lattice Gauge Theory for LHC Physics

May 2–3, 2008, Wente Vineyards, Livermore, CA



http://www.yale.edu/LSD/workshop.html

Workshop on Dynamical Electroweak Symmetry Breaking

9–13 September 2008
Odense, Denmark
`http://hep.sdu.dk/dewsb`

Registration extended to Monday!!!

The LHC is coming ...

- **Ten groups** presented calculations relevant to DEWSB at the LHC. Last year there were none. The excitement is apparently contagious.
- Predominantly, the effort is currently focused on finding the edge of the conformal window.
- First non-perturbative calculation of a (non-SUSY) IRFP for SU(3) with $N_f = 12$ inside a conformal window, using Schrödinger functional running coupling. Confirmation by other methods in progress.
- Walking theories, with two dynamically generated scales, may live near the edge of the conformal window.
- **Challenge:** Current lattice methods optimized for QCD. *Which methods can be used to study a walking theory?*