objective: minimal realization of light composite Higgs

Lattice Higgs Collaboration (LaHC)
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What is our composite Higgs terminology?

the Higgs doublet field

\[ H = \frac{1}{\sqrt{2}} \left( \begin{array}{c} \pi_2 + i \pi_1 \\ \sigma - i \pi_3 \end{array} \right) \]

\[ D_\mu M = \partial_\mu M - ig W_\mu M + ig' M B_\mu , \quad \text{with} \quad W_\mu = W_\mu^a \frac{\tau^a}{2} , \quad B_\mu = B_\mu \frac{\tau^3}{2} \]

The Higgs Lagrangian is

Higgs mechanism

\[ \mathcal{L} = \frac{1}{2} \text{Tr} \left[ D_\mu M^\dagger D^\mu M \right] - \frac{m^2}{2} \text{Tr} \left[ M^\dagger M \right] - \frac{\lambda}{4} \text{Tr} \left[ M^\dagger M \right]^2 \]

\[ \mathcal{L}_{\text{Higgs}} \rightarrow -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{Q} \gamma_\mu D^\mu Q + \ldots \]

strongly coupled gauge theory

\[ N_f \] fermions in gauge group reps

needle in the haystack?

or, just one of the haystacks?
Probing technicolor theories with staggered fermions

Kieran Holland

Figure 1: The conformal window for $SU(N)$ gauge theories with $N_f$ techniquarks in various representations, from [3]. The shaded regions are the windows, for fundamental (gray), 2-index antisymmetric (blue), 2-index symmetric (red) and adjoint (green) representations.

1. Introduction

The LHC will probe the mechanism of electroweak symmetry breaking. A very attractive alternative to the standard Higgs mechanism, with fundamental scalars, involves new strongly-interacting gauge theories, known as technicolor [1, 2]. Such models avoid difficulties of theories with scalars, such as triviality and fine-tuning. Chiral symmetry must be spontaneously broken in a technicolor theory, to provide the technipions which generate the $W^\pm$ and $Z$ masses and break electroweak symmetry. Although this duplication of QCD is appealing, precise electroweak measurements have made it difficult to find a viable candidate theory. It is also necessary to enlarge the theory (extended technicolor) to generate quark masses, without generating large flavor-changing neutral currents, which is challenging.

Technicolor theories have lately enjoyed a resurgence, due to the exploration of various techniquark representations [3]. Feasible candidates have fewer new flavors, reducing tension with electroweak constraints. If a theory is almost conformal, it is possible this generates additional energy scales, which could help in building the extended technicolor sector. There are estimates of which theories are conformal for various representations, shown in Fig. 1. For $SU(N)$ gauge theory, if the number of techniquark flavors is less than some critical number, conformal and chiral symmetries are broken and the theory is QCD-like. For future model-building, it is crucial to go beyond these estimates and determine precisely where the conformal windows are. There have been a number of recent lattice simulations of technicolor theories, attempting to locate the conformal windows for various representations [4, 5, 6, 7, 8].

2. Dirac eigenvalues and chiral symmetry

The connection between the eigenvalues of the Dirac operator and chiral symmetry breaking

Outline

Near-conformal SCGT?
- light scalar close to conformal window
- effective theory?
- scale setting and spectroscopy
- systematics and mixed action

Chiral Higgs condensate
- GMOR and mode number
- epsilon regime and RMT
- large mass anomalous dimension?

Scale dependent renormalized coupling
- matching scale dependent coupling from form UV to IR with chiSB

Early universe
- EW phase transition, sextet baryon, and dark matter

Summary

Close to scale invariance?
- $n_f=2$ sextet rep
- massless fermions
- SU(2) doublet
- minimal EW embedding
- 3 Goldstones morph into weak bosons
- minimal realization
- QCD intuition for near-conformal compositeness is just plain wrong
- Technicolor thought to be scaled up QCD
- motivation of the project:
- composite Higgs-like scalar close to the conformal window
light 0++ scalar and spectrum

test of scalar technology:

\[ C_{\text{non-singlet}}(t) = \sum_n [A_n e^{-m_n (\Gamma_S \otimes \Gamma_T)t} + (-1)^t B_n e^{-m_n (\gamma_4 \gamma_5 \Gamma_S \otimes \gamma_4 \gamma_5 \Gamma_T)t}] \]

staggered correlator

\[ C_{\text{singlet}}(t) \sim \exp(-M_{0^{++}} t) \] fitting function:

- \( aM_{0^{++}} = 0.304(18) \)
- \( 24^3 \times 48 \) lattice simulation
- 200 gauge configs
- \( \beta = 2.2 \), \( am = 0.025 \)

\( N_f = 12 \)

LaHC and LaKMI

Non-singlet:

- Lowest non-singlet scalar from connected correlator
- \( aM_{\text{non-singlet}} = 0.420(2) \)
- \( \beta = 2.2 \), \( am = 0.025 \)
- \( N_f = 12 \)

Singlet:

- Lowest 0++ scalar state from singlet correlator
- \( C_{\text{singlet}}(t) \sim \exp(-M_{0^{++}} t) \) fitting function:
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light 0++ scalar and spectrum

near-conformal resonance spectrum separated from light scalar
moving up to 2-3 TeV with refined scale setting
within reach of LHC Run 2?

A. Geometric Scaling of the TC Higgs mass

From the composite Higgs mechanism:
Goldstone decay constant F is setting the EWSB scale

\[ M_H/F \sim 1-3 \text{ range} \]

circa Lattice 2013

\[ \delta M_{H}^{2} \sim -12\pi^{2}t_{1}m_{t}^{2} \sim -\pi^{2}t_{1}^{2}(600 \text{ GeV})^{2} \]
light 0++ scalar and spectrum

\[ \beta = 3.20 \text{ (with PCA analysis)} \quad 48^3 \times 96 \quad m = 0.002 \]

\[ \chi^2 = 0.019 \quad Q = 1 \]

- number of blocks = 16
- block size = 4
- eigenvalue threshold of PCA = 0.004
- error threshold of PCA = 2

\[ M_{\text{Higgs}} = 0.0548 \pm 0.0175 \]
fitted range = 5 – 10

new, preliminary

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circa Lattice 2013

0++ triplet state
connected

0++ singlet state
(disconnected)

\[ \beta = 3.20 \]
\[ 28^3 \times 56, \ 32^3 \times 64 \]
m fit range 0.003 - 0.008
light 0++ scalar and spectrum  \[ \text{sextet model} \] \[ \text{LatHC} \]

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light 0++ scalar and spectrum sextet model LatHC

Figure: Preliminary chiral extrapolation of $F$ and $p$. The calculation is performed on lattices with $b = 3.20$, $V = 48^3 \times 96$ for $m = 0.003$ and $V = 32^3 \times 64$ for the rest, using 200-300 configurations. Hadron spectroscopy at $b = 3.20$ in physical units (right).

$M/F$, $M/\text{TeV}$

$a_0$ scalar isovector?

$0^{++}$ scalar Higgs?

strong gauge dynamics coupling to SM?
light $0^{++}$ scalar and spectrum  sextet model  LatHC

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- $0^{++}$ scalar Higgs?
- $a_0$ scalar isovector?
- strong gauge dynamics coupling to SM?
- partial compositeness
- ETC?
- ETC?
- ETC?
light 0++ scalar and spectrum  sextet model  LatHC
Search for a new resonance decaying to a $W$ or $Z$ boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$ final states with the ATLAS Detector

The ATLAS Collaboration

Abstract

A search for a new resonance decaying to a $W$ or $Z$ boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$ final states is performed using 20.3 fb$^{-1}$ of $pp$ collision data recorded at $\sqrt{s} = 8$ TeV with the ATLAS detector at the Large Hadron Collider. The search is conducted by examining the $WH/ZH$ invariant mass distribution for a localized excess. No significant deviation from the Standard Model background prediction is observed. The results are interpreted in terms of constraints on the Minimal Walking Technicolor model and on a simplified approach based on a phenomenological Lagrangian of Heavy Vector Triplets.
light 0++ scalar and spectrum sextet model LatHC

(a) $R^0(V^0) \rightarrow ZH, H \rightarrow b\bar{b}$

(b) $R^\pm(V^\pm) \rightarrow WH, H \rightarrow b\bar{b}$

R$_1$ and R$_2$ couplings:

$\hat{g}$ is the coupling in SU(4) vector boson

g/$\hat{g}$ is the coupling to fermions
systematics and mixed action
taste breaking to improve

$M^2 = c_0 + c_1 m$

linear fit range: $m = 0.003 - 0.007$

Decreasing lattice spacing

ChiSB in Goldstone spectrum vanishes only at zero lattice spacing

New runs here
**systematics and mixed action**

- **idea:**
  - use the gauge configurations generated with sea fermions
  - taste breaking makes chiPT analysis unnecessarily complicated
  - in the analysis use valence Dirac operator with gauge links on the gradient flow
  - taste symmetry is restored in valence spectrum
  - Mixed Action analysis should agree with original standard analysis when cutoff is removed: cross check
systematics and mixed action

taste breaking to improve idea:

- use the gauge configurations generated with sea fermions
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- Mixed Action analysis should agree with original standard analysis when cutoff is removed: cross check

\[ M^2 = c_{sc} m + \Lambda_{sc} \]

\[ c_{sc} = 0.0047 \pm 0.0009 \]

\[ \Lambda_{sc} = 0.003 \]

\[ c_{sc} = 6.68 \pm 0.22 \]

\[ \chi^2/\text{dof} = 1.6 \]

chiSB in Goldstone spectrum vanishes only at zero lattice spacing

descending lattice spacing

Quartets of \( Q = -1 \) Dirac spectrum on gradient flow
degenerate quartets \( \Rightarrow \) valence chiral symmetry restored

\[ \beta = 3.20 \]

\( 32^3 \times 64 \) \( m = 0.004 \)

\( 120 \) eigenvalues

\[ \beta = 3.25 \]

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\( 120 \) eigenvalues

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\( 48^3 \times 96 \) \( m = 0.003 \)

\( \chi^2/\text{dof} = 0.126 \)

\[ \Lambda_{sc} = 0.0016 \pm 0.0009 \]

\[ c_{sc} = 0.0047 \pm 0.0009 \]

\[ c_{sc} = 6.68 \pm 0.22 \]

\[ \chi^2/\text{dof} = 1.6 \]

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\[ \chi^2/\text{dof} = 0.197 \]

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taste breaking and mixed action

epsilon regime, p regime to epsilon regime crossover, valence pqChiPT with Mixed Action:

Figure 2: The chiral condensate (top) and Dirac spectral density (bottom) for the case with $m_u = m_d = 10$ MeV, $L = 2$ fm. The result of this paper is given by the thick line which smoothly connects the one in the $\epsilon$-regime (solid) with the one of $p$-regime (dotted). Parameters have been chosen as $\Sigma_1^3 = 250$ MeV, $F = 90$ MeV, $\lambda < 0.77$ GeV) = 0.05 × 10^{-3}$, $\lambda > 8$ (µ sub = 0.77 GeV) = 0.5 × 10^{-3}$ and $H_{\nu 2}^2$ (µ sub = 0.77 GeV) = 0.1 × 10^{-3}.

new analysis in crossover and RMT regime opens up with mixed action on gradient flow
taste breaking and mixed action

epsilon regime, p regime to epsilon regime crossover, valence pqChiPT with Mixed Action:

- 30 configurations with $Q=0$
- 300 eigenvalues
- flow time $t=3$

Figure 2: The chiral condensate (top) and Dirac spectral density (bottom) for the case with $m_u = m_d = 10$ MeV, $L = 2$ fm. The result of this paper is given by the thick line which smoothly connects the one in the $\epsilon$-regime (solid) with the one of the $p$-regime (dotted). Parameters have been chosen as $\Sigma \approx 250$ MeV, $F \approx 90$ MeV, $L_r \approx (\mu_{sub}=0.77\text{GeV}) = 0.05 \times 10^{-3}$, $L_r \approx (\mu_{sub}=0.77\text{GeV}) = 0.5 \times 10^{-3}$ and $H_r \approx (\mu_{sub}=0.77\text{GeV}) = 0.1 \times 10^{-3}$.

- RMT regime on gradient flow

new analysis in crossover and RMT regime opens up with mixed action on gradient flow
taste breaking and mixed action

epsilon regime, p regime to epsilon regime crossover, valence pqChiPT with Mixed Action:

- B drops by large factor after matching, with some small decrease in $F$
- GMOR implies large drop of order $O(10)$ in the chiral condensate $\Sigma$
- $\Sigma$ is not RG invariant, requires rescaling
- in original analysis $m\Sigma V \sim O(100\text{-}200)$
  to reach RMT regime close to CW requires large resources
- in Mixed Action analysis $\lambda \Sigma V \sim O(10\text{-}20)$ RMT regime can be reached
The chiral condensate full spectrum new method

- \( h \) eigenvalue scale
- spectral density of full Dirac spectrum (sextet rep)
  
  \[ 48^3 \times 96 \quad \beta = 3.20 \quad m = 0.002 \quad L_\text{at HC} \]
  
  63,700,992 eigenvalues in \( D^+D \) (Chebyshev expansion)
  
  \( \Sigma = 2 \pi \rho(0) \) Banks–Casher relation (\( nf=2 \))
  
  topology: \( Q=0 \)

- IR scale
- UV scale

- nf=2 sextet example illustrates results from the Chebyshev expansion

- full spectrum with 6,000 Chebyshev polynomials in the expansion

- the integrated spectral density counts the sum of all eigenmodes correctly

- Jackknife errors are so small that they are not visible in the plots.
The chiral condensate

GMOR test in far IR

GMOR relation (nf=2): \(2B F^2 = \Sigma\) \((\Sigma \text{ is the chiral condensate})\)

\(F\): decay constant of Goldstone pion \(M_{\pi}^2 = 2B \cdot m\) in LO \(\chi PT\)

from chiral perturbation theory of the condensate in the p-regime:

\[
\frac{\Sigma_{\text{eff}}}{\Sigma} = 1 + \frac{\Sigma}{32\pi^3 N_F F^4} \left[ 2N_F^2 |\Lambda| \arctan \frac{|\Lambda|}{m} - 4\pi |\Lambda| - N_F^2 m \log \frac{\Lambda^2 + m^2}{\mu^2} - 4m \log \frac{|\Lambda|}{\mu} \right]
\]

Improved determination of the chiral condensate \(\Sigma\) compared from Dirac spectra and the Chebyshev expansion.

With the additive NLO cutoff term separated from \(B\) and new fit to \(F\), the improved result on \(\Sigma\) eliminates previous discrepancies in the GMOR relation.
The chiral condensate mass anomalous dimension

Boulder group pioneered fitting procedure

\[ \nu_R(M_R, m_R) = \nu(M, m) \approx \text{const} \cdot M^{4/(1+\gamma_m(M))}, \]

or equivalently, \( \nu(M, m) \approx \text{const} \cdot \lambda^{4/(1+\gamma_m(\lambda))} \), with \( \gamma_m(\lambda) \) fitted

\[ \lambda^{-1} \sim \text{footprint of gradient flow?} \]

How to match \( \lambda \) scale and \( g^2 \)?
The chiral condensate mass anomalous dimension

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anomalous mass dimension from full Dirac spectrum (sextet rep)

\( 48^3 \times 96 \) (magenta) \( \beta = 3.20 \) \( m = 0.003 \) \( L_{\text{at HC}} \)

\( 48^3 \times 96 \) \( \beta = 3.20 \) \( m = 0.002 \) data: blue circles

\( \lambda^{-1} \sim \) footprint of gradient flow?

How to match \( \lambda \) scale and \( g^2 \)?
scale-dependent coupling matching IR to UV

leading dependence of $g^2(t,m)$ on $M_\pi^2$ is linear based on gradient flow chiPT  Bär and Golterman

works better than expected  chiral logs are not detectable

\[ \sim 2\sqrt{8t} \]
the running coupling and the $\beta$ function

finite volume

The monotonic increase of $g^2$ with scale is consistent with:
- mass deformed spectroscopy at low fermion mass
- chiral condensate
- GMOR
- mass anomalous dimension
- connection with $g^2(t,m)$ in bulk with chiSB

Lattice step functions: 12→18, 16→24, 20→30, 24→36
The last two step functions are critical in the analysis:
SSC vs. WSC are consistent at large flow times which requires the large volumes
the running coupling and the $\beta$ function

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This is disagreement is between two analyses nothing to do with staggered formulation

besides: promoting a beta function zero to conformal IRFP would require to remove the cutoff with the $\omega$ scaling exponent
Early universe

Kogut-Sinclair work consistent with $\chi$SB EW phase transition
Relevance in early cosmology (order of the phase transition?)
LatHC is doing a new analysis using different methods

- $N_f=2$ $Q_u=2/3$ $Q_d=-1/3$ fundamental rep
  udd neutral dark matter candidate

- dark matter candidate sextet $N_f=2$
  electroweak active in the application

- 1/2 unit of electric charge (anomalies)

- rather subtle sextet baryon
  construction (symmetric in color)

- charged relics not expected?

Three $SU(3)$ sextet fermions can give rise to a color singlet.
The tensor product $6 \otimes 6 \otimes 6$ can be decomposed into irreducible representations of $SU(3)$ as,

$$6 \otimes 6 \otimes 6 = 1 \oplus 2 \times 8 \oplus 10 \oplus \overline{10} \oplus 3 \times 27 \oplus 28 \oplus 2 \times 35$$

where irreps are denoted by their dimensions and $\overline{10}$ is the complex conjugate of 10.

Fermions in the 6-representation carry 2 indices, $\psi_{ab}$, and transform as

$$\psi_{aa'} \rightarrow U_{ab} U_{a'b'} \psi_{bb'}$$

and the singlet can be constructed explicitly as

$$\epsilon_{abc} \epsilon_{a'b'c'} \psi_{aa'} \psi_{bb'} \psi_{cc'}.$$
Summary: simplest composite scalar is probably very light (near conformality)

- successful knock on LHC door
  - ATLAS analysis and CMS plan

- very efficient staggered BG/Q code
  - 30-40 percent CG efficiency sextet Janos

- light scalar (dilaton-like?) emerging
  - close to conformal window

- spectroscopy
  - emerging resonance spectrum $\sim 2-3\text{ TeV}$

- chiral condensate, large $\gamma(\lambda)$
  - new method is very promising

- scale-dependent coupling
  - difficult, Gradient Flow is huge improvement

- Electroweak phase transition and baryon
  - intriguing