Lattice 2017

Granada

Looking Behind* the Standard Model

with Lattice Gauge Theory

B. Svetitsky

Tel Aviv University

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* *BSM: Behind, Beyond, . . . ?*

A MATTER OF PREPOSITIONS . . .

Beyond the SM

- Expt: New particles?
- Flavor physics anomalies?
- Matter–antimatter asymmetry
- Dark matter
- Dark energy
- Inflation
- Gravity

Behind the SM

- $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$
- 3 families
- Quark & lepton masses & angles (hierarchies)
- Neutrino masses & angles (more hierarchies)
- The Higgs

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The Higgs boson: not just another number to explain

THE HIGGS BOSON — THEORISTS' *BÊTE NOIRE*

As a fundamental scalar: *unnatural*

$$\begin{array}{ccc} m_H^2 & = & m_0^2 + \textit{const} \cdot M_{\rm Pl}^2 \\ (125\ \mathrm{GeV})^2 & \textit{vs.} & (10^{19}\ \mathrm{GeV})^2 \end{array}$$

Tamed by supersymmetry: quadratic divergence $\Longrightarrow$ log divergence
but the LHC sees no superpartners

General approach to a "UV completion":

- Make the Higgs (multiplet) emerge as composite states: integrals cut off by compositeness scale $\Lambda \gtrsim 5\ \mathrm{TeV}$ — but why is $m_H \ll \Lambda$??
- The fundamental theory is an asymptotically free gauge theory with spin-1/2 matter $\Longrightarrow$ again, only log divergences

In general, COMPOSITE STATES emerge from strong dynamics —

$\Longrightarrow$ enter Lattice Gauge Theory

Don't bite off too much:

- Look at a specific phenomenon
- ... in a class of model
- ... that explains something but not everything.

corresponding to modern phenomenology:*

- Connect sub-LHC physics (e.g. $m_H = 125$ GeV)
- ... to a super-LHC model ($\Lambda \gtrsim 5$ TeV)
- ... without trying to explain everything.

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*usually *without* a UV completion!

A MATTER OF PREPOSITIONS . . .

Lattice gauge theory: *Beneath* the Standard Model

THIS LECTURE:

Follows excellent reviews by

- C. Pica at Lattice 2016 1701.07782
- T. DeGrand in Rev. Mod. Phys. 1510.05018
- D. Nogradi and A. Patella IJMPA 1607.07638

Covers recent work on

- Technicolor — “Dilatonic Higgs” (most of the recent lattice work)
- Higgs as a pseudo-Goldstone boson — “Composite Higgs” (time permitting)

Whatever the UV theory is, it's not QCD.

QCD's lightest scalar σ (or f_0):

$$m_\sigma = 400\text{–}500 \text{ MeV}$$

vs. typical scale

$$m_\rho = 770 \text{ MeV},$$

and

$$\Gamma_\sigma = 400\text{–}700 \text{ MeV}$$

because of $\sigma \to \pi\pi$. But the Higgs boson:

$$\begin{aligned} m_H &= 125 \text{ GeV} \quad \ll \quad \Lambda \gtrsim 5 \text{ TeV}, \\ \Gamma_H &= 4 \text{ MeV} \qquad \text{(SM)} \\ &\lesssim 2\text{–}5 \text{ GeV} \qquad \text{(expt)} \end{aligned}$$

TECHNICOLOR:

Break the Standard Model's $\mathrm{SU}(2)_L \times \mathrm{U}(1)$ dynamically, without a scalar field

Original prototype: a copy of QCD with $\Lambda \sim f_\pi \sim v \simeq 245$ GeV

- Chiral symmetry $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \to \mathrm{SU}(2)_V$
- ... leaving 3 Nambu–Goldstone bosons $\pi^\pm, \pi^0$
- ... which get eaten to give mass to $W^\pm, Z^0$.

Only $3/4$ of the Higgs multiplet:

NO HIGGS PARTICLE

(like QCD!)

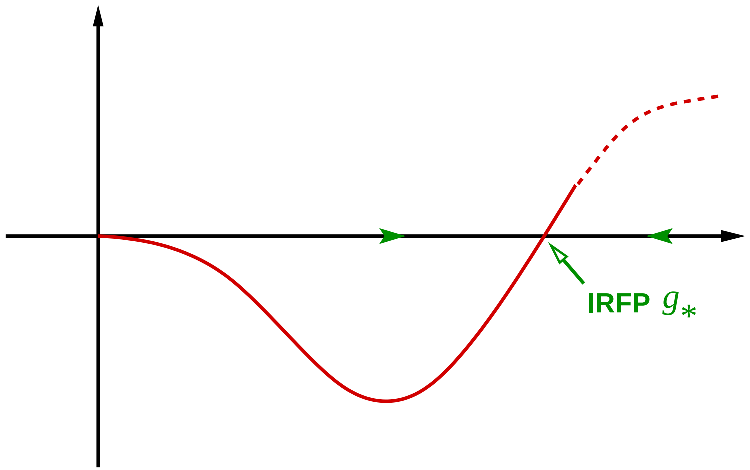
Technicolor:

Higgsless since 1976!

For a light scalar — suppose APPROXIMATE SCALE INVARIANCE

In the Conformal Window:

$N_f > N_f^*$

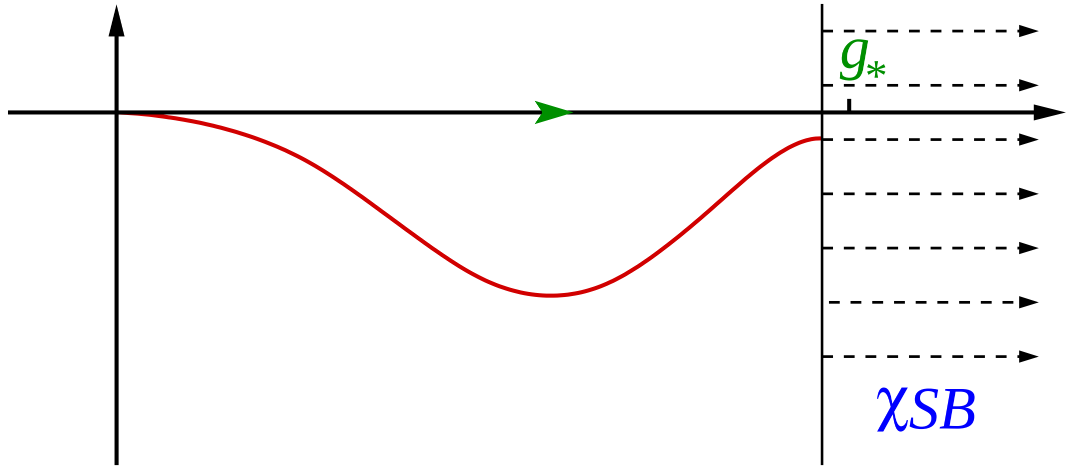


IR fixed point $\Rightarrow$ scale invariance

Below the sill:

N_f *slightly* $< N_f^*$

("WALKING technicolor")



approximate scale invariance

- Guess: Light scalar emerges as pseudo-Goldstone boson of approximate dilatation symmetry.
  $\Rightarrow m_H$ is protected from UV, like any PGB (and Yukawa couplings $\propto m_q$)

QUESTIONS FOR DIRECT CALCULATIONS:

1. Where is the sill N_f^*? (for given gauge group & fermion rep)
2. Is there a light scalar in theories below the sill?

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ANSWERS:

1. It might not matter too much — as long as we confirm $N_f < N_f^*$.
2. Yes.

FINDING N_f^* — $\mathrm{SU(3)/fund}$ 2 loops: $N_f^* = 8.05$

- $N_f = 4n$ popular because of staggered fermions*
- $N_f = 12$ — a long-running controversy
- many approaches: scaling of spectrum, finite-T transition, Dirac eigenvalues — point (mostly) towards conformality of $N_f = 12$
- Danger: *slow* running (spontaneous χSB) is very similar to *no* running (fixed point)
  - possible fixed point at IR scale L would be at strong coupling slow (or no) running $\Longrightarrow$ strong coupling at scale a as well, i.e. far from continuum limit in UV
- RG was born for this purpose — compare L_1 to L_2 and obtain β fn
- no scale Λ ($1/L < \Lambda < 1/a$) $\Longrightarrow$ everything is a function of a/L $\Longrightarrow$ continuum extrap equivalent to $L \to \infty$

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*watch for taste breaking

LATEST on $N_f = 12$ — β function from gradient flow

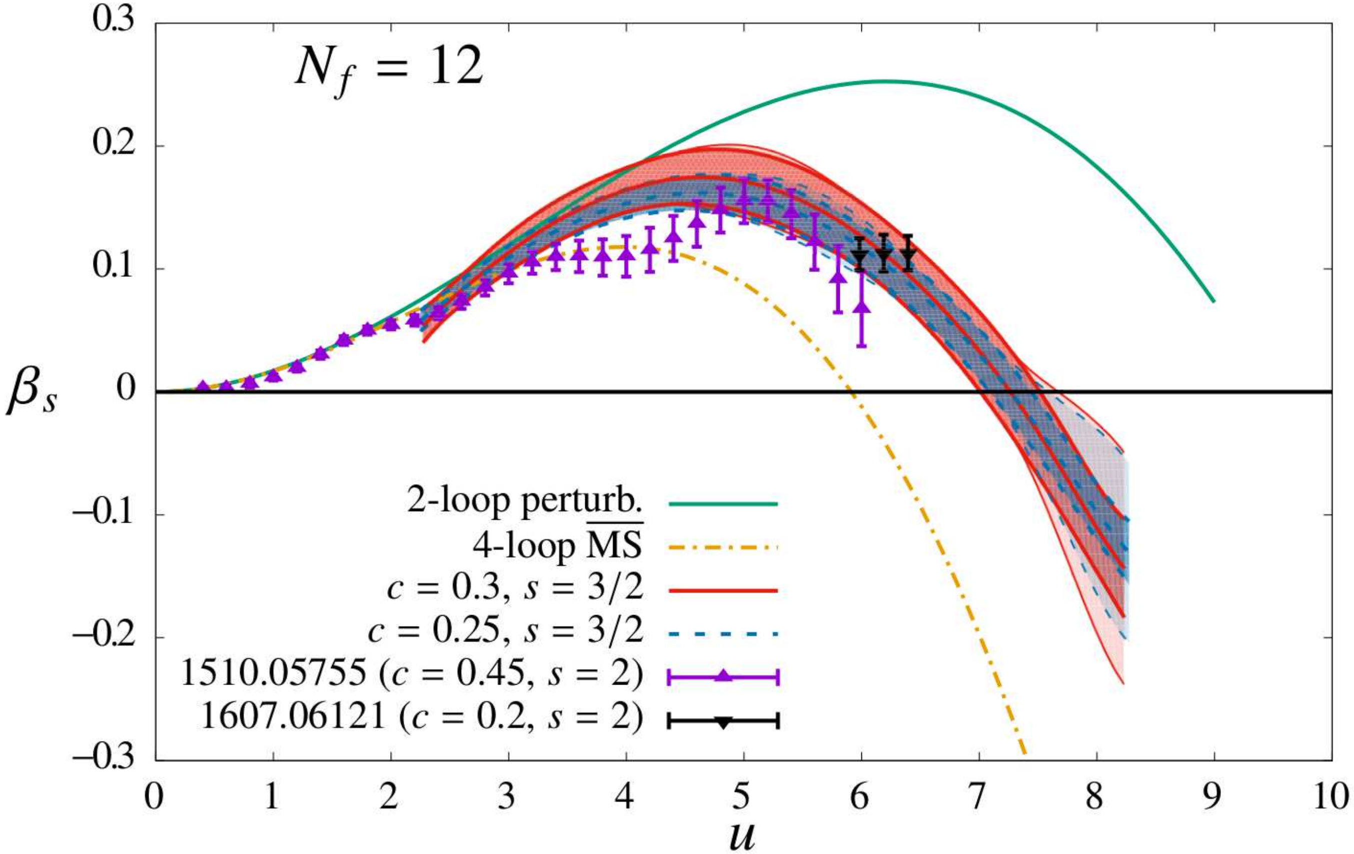
(Hasenfratz & Schaich 1610.10004, LatHiggs Fodor *et al.* 1607.06121, Lin, Ogawa, Ramos 1510.05755)

- Existence (or not) of fixed point g_* is universal
- Location is not. Neither is the β function.
  - Varies with scheme for defining g: Schrödinger functional vs. gradient flow; parameter c in gradient flow

$$g_{\rm GF}^2 = \frac{128\pi^2}{3(N^2-1)} \left\langle t^2 E(t) \right\rangle \quad \text{at scale} \quad \sqrt{8t} = cL$$

  - Shouldn't depend on: discretization/improvement of action (extrap. $a \to 0$); disc./imp. of E; scale factor $s \equiv L_2/L_1$

FIXED POINT from Hasenfratz & Schaich, consistent with previous work, but go to stronger couplings (nHYP action)



- The controversy continues (`recent LatHiggs`). . . .

  [Note $N_f = 10$ is conformal (`Chiu 1603.08854` *DWF*)]

DOES $N_f = 8$ DELIVER THE GOODS?

(LSD Appelquist *et al.* 1601.04027 + recent)

(LatKMI Y. Aoki *et al.* 1610.07011)

Recall two-loops: $N_f^* = 8.05$. The claim is that $N_f = 8$ walks.
Study m_f dependence of various quantities:

- As $m_f \to 0$, find χSB: $f_\pi \to$ *const* and massless π

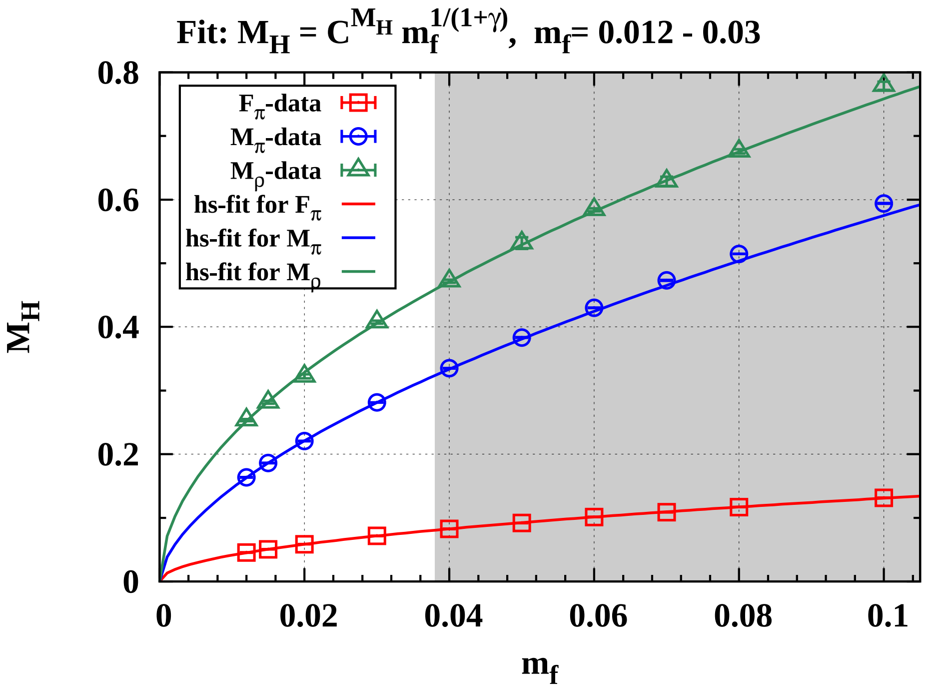
- Hyperscaling of all masses (*except the* π) for a large range of m_f:

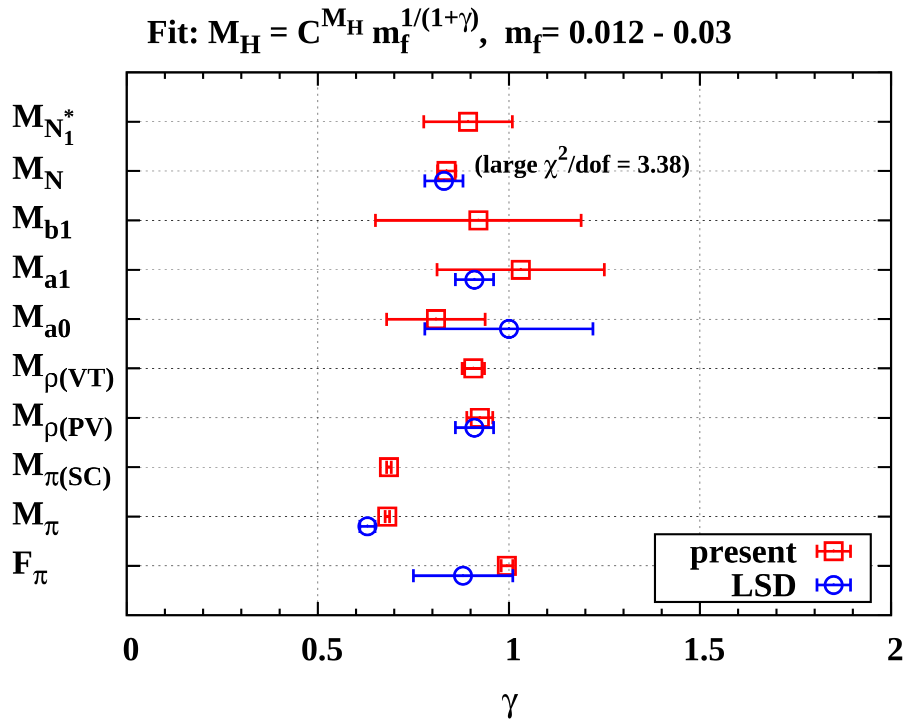
$$M_H \sim m_f^{1/(1+\gamma)}, \qquad \gamma \simeq 1$$

$\Longrightarrow$ nearby fixed point

- Light scalar — degenerate with π over large range of m_f
  As $m_\pi \to 0$, where does the scalar end up?

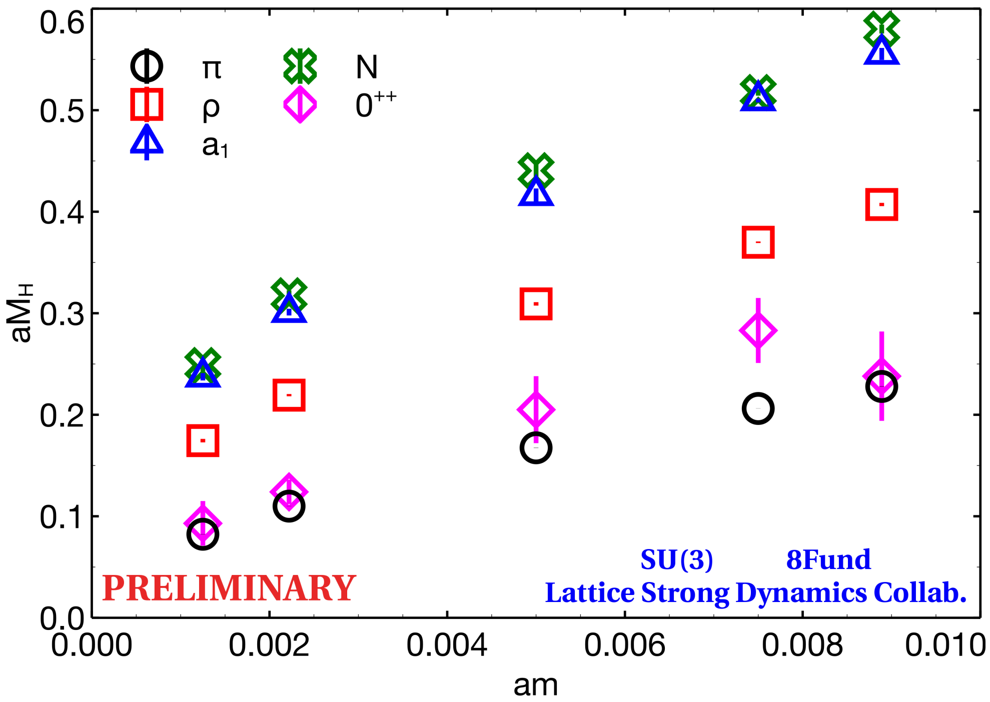
HYPERSCALING — `LatKMI [cf. LSD 1405.4752 (DWF)]`

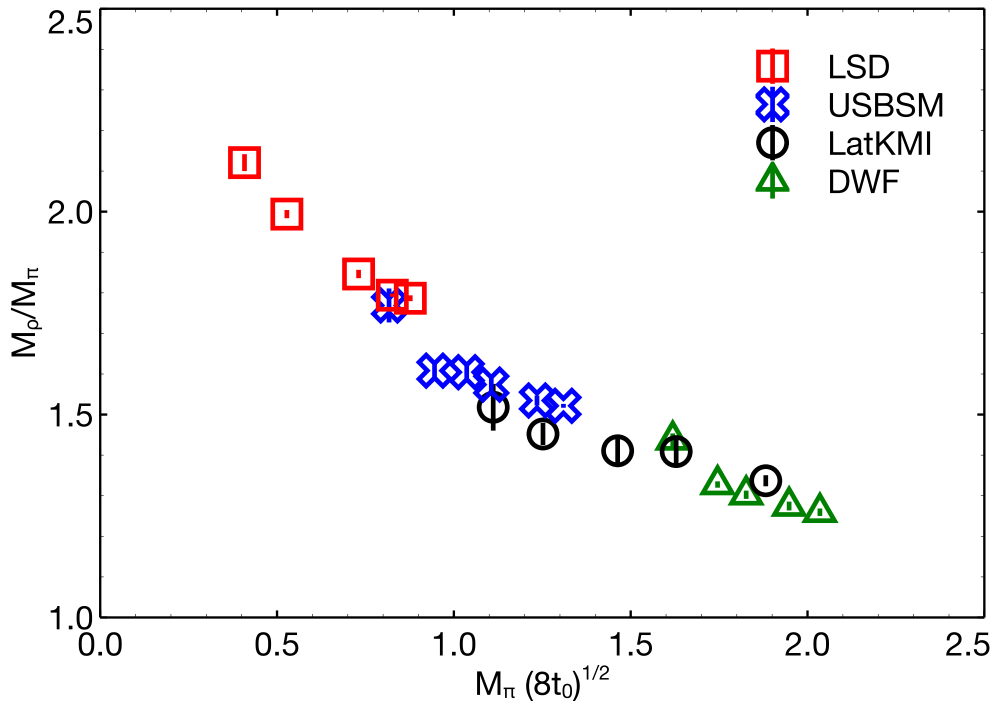




- Exponent γ common to all hadrons except π (and σ)
- Note: single value of $\beta = 6/g_0^2$ — not the same thing as a single lattice spacing

LIGHT SCALAR — updated LSD (D. Schaich)





- $M_\pi \to 0$ with m_f
- So far, $m_\sigma \simeq m_\pi$

- Edinburgh plot: M_ρ stays finite as $M_\pi \to 0$: χSB
- LSD's min M_π $\ll$ LatKMI, older work

FORCING A THEORY TO WALK : $N_f = 4\ell + 8h$

$N_f = 8$ has 63 Goldstone bosons. 3 are eaten. 36 are neutral under EW interactions! (& S parameter . . .)

$\Longrightarrow$ Give them a mass *explicitly,* but preserve near-conformality. Example:

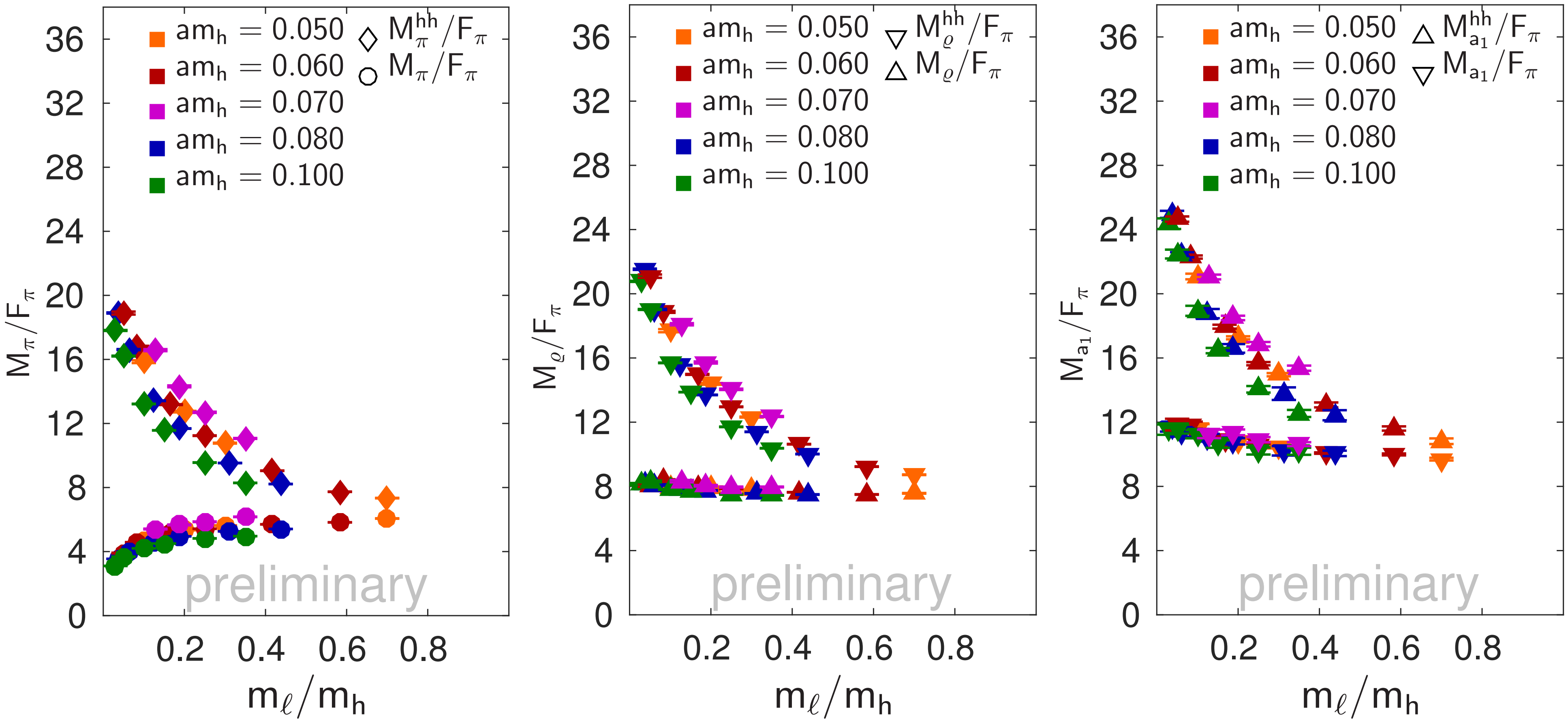
(Hasenfratz, Rebbi, Witzel 1609.01401 + recent, following Brower *et al.* 1512.02576)

- $\mathrm{SU}(3)$ with $N_f = 12$, nearly conformal at scale Λ.
- Lift 8 flavors with $m_h < \Lambda$.
- Low-energy theory sees 4 flavors with $m_\ell \to 0$.
- Appeal to near-conformality to give light Higgs as above.

Note m_h has to come from somewhere.

Extra Goldstones ($N_f = 4$) still have to *go* somewhere. Better for *composite Higgs* (Ma & Cacciapaglia).

HYPERSCALING in $N_f = 4\ell + 8h$ — O. Witzel (updated)



- Mass ratios depend only on ratio m_ℓ/m_h, even for hh mesons; β is irrelevant. Light $\pi \Rightarrow \chi$SB, $m_\sigma \simeq m_\pi$ (not shown).

IS THE LIGHT SCALAR A (pseudo-)DILATON? Compare to effective action.

Dilatation current $S_\mu = x_\nu T_{\mu\nu}$ is anomalous,

$$\partial_\mu S_\mu = T_{\mu\mu} = -\frac{\beta(g^2)}{4g^2} F^2 - (1+\gamma_m) m \bar{\psi}\psi$$

$\Rightarrow$ partially conserved if m and $\beta(g^2(\Lambda))$ are small.

- Conceptual question: What is the unperturbed theory? If $\beta = m = 0$ then the theory is conformal, *i.e.*, there are no GB's!
- Cf. broken chiral symmetry: $m_\pi^2 f_\pi^2 = m_q \langle \bar{\psi}\psi \rangle$, expansion around $m_q = 0$.

$\Rightarrow$ Construct an effective action for SSB of chiral & dilatation symmetries

(Golterman & Shamir 1603.04575, 1610.01752)

$$p^2/\Lambda^2 \;\sim\; m/\Lambda \;\sim\; 1/N_c \;\sim\; |N_f - N_f^*|/N_c \;\sim\; \delta$$

Dilaton action

$$\mathcal{L}_\tau = \frac{f_\tau^2}{2} V_\tau(\tau)\, e^{2\tau} (\partial_\mu \tau)^2 + f_\tau^2 B_\tau\, V_d(\tau)\, e^{4\tau} + \textit{coupling to } \pi$$

Expand potential $V_d = \sum c_n \tau^n$, $c_n = O(\delta^n)$: fix constants (including m_τ) from correlators in gauge theory.

See also: `Kasai, Okumura, Suzuki 1609.02264; Golterman & Shamir 1611.04275`

Fit to LSD $\mathrm{SU}(3)/N_f = 8$ data `(Appelquist, Ingoldby, Piai 1702.04410)`

- Not $\mathcal{L}_\tau$ above but *ad hoc* dilaton potential

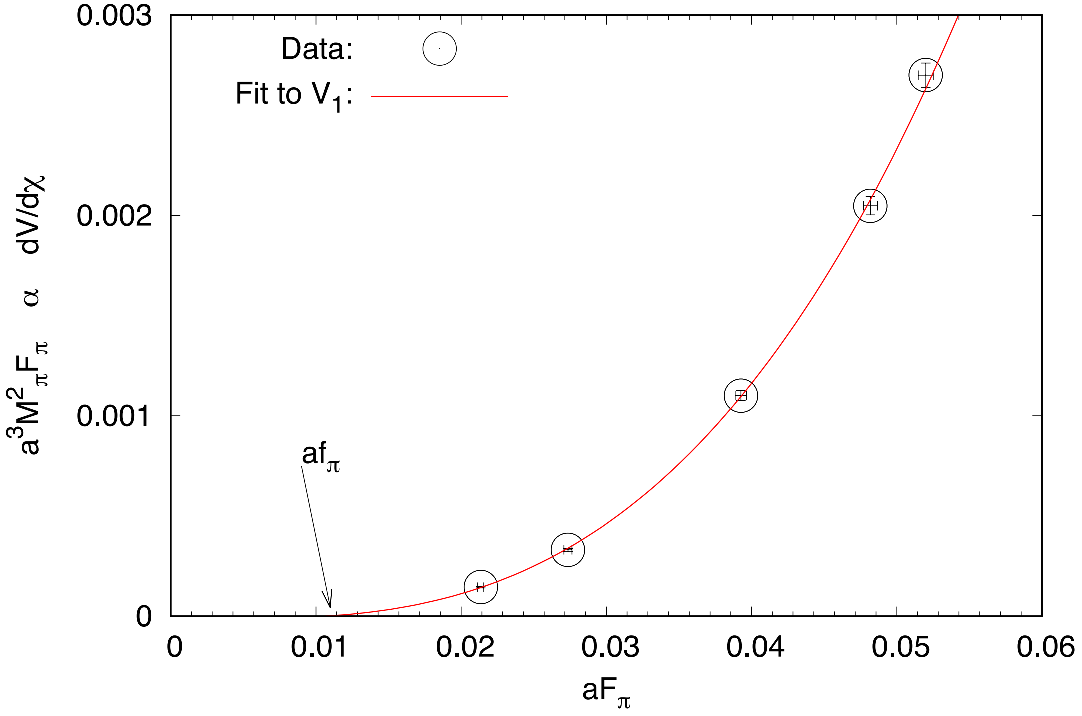
$$V_1 = \frac{m_\tau^2}{8 f_\tau^2} (\chi^2 - f_\tau^2)^2, \qquad \chi \equiv f_\tau e^\tau$$

- Fit to LO $\mathcal{L}_\tau$ is indistinguishable.

Fit to LSD $\mathrm{SU}(3)/N_f = 8$ data (Appelquist, Ingoldby, Piai 1702.04410)

$$V_1 = \frac{m_\tau^2}{8f_\tau^2}(\chi^2 - f_\tau^2)^2, \qquad \chi \equiv f_\tau e^\tau$$

- F_π has substantial m dependence, due to dilaton. Successful fit (in lattice units) shows how $v \sim F_\pi$ might be $\ll \Lambda$:



SIMILAR PHYSICS in OTHER GAUGE THEORIES

- $\mathrm{SU}(2)/\mathrm{fund}$, $N_f = 8$ — in the conformal window

  Leino *et al.* 1701.04666

- $\mathrm{SU}(2)/\mathrm{adj}$, $N_f = 1, 2$ — straddling the sill

  Athenodorou *et al.* 1605.04298; Bergner *et al.* 1610.01576

- $\mathrm{SU}(2)/\mathrm{adj}$, $N_f = 2$ + NJL — induce walking with NJL term

  Rantaharju, Pica, Sannino 1704.03977

- $\mathrm{SU}(3)/\mathrm{sextet}$, $N_f = 2$ — may walk, with light Higgs

  Fodor *et al.* 1506.06599, 1601.03302 (staggered)

  Hansen, Drach, Pica 1705.11010 (unimp. Wilson)

OTHER ISSUES: anomalous dimension γ_m, precision tests (e.g. S parameter)

COMPOSITE HIGGS (Georgi & Kaplan 1984)

- Hypercolor theory (with scale $f \gg v$) has spontaneous symmetry breaking with $\mathrm{SU}(2)_L \times \mathrm{U}(1)$ *unbroken.*
  Higgs multiplet $h \subset$ Goldstone bosons so $m_h = 0$ and in fact $V(h) = 0$

- Couple to gauge bosons/fermions of SM, generate

$$V_{\text{eff}}(h) = \alpha \cos(2h/f) - \beta \sin^2(2h/f)$$

  1st term: $\alpha = -\frac{1}{2}(3g^2 + g'^2)C_{LR} +$ top loops*

  2nd term: $\beta =$ top loops*

- If $\alpha + 2\beta > 0$ then $h = 0$ is unstable, $v = \sqrt{2}\,\langle h \rangle$ given by
  $\cos(\sqrt{2}v/f) = -\alpha/(2\beta) \quad \Longrightarrow \quad (v/f)^2 \approx 1 + \alpha/(2\beta)$

- $C_{LR} = \# \int_0^\infty dq^2 q^2\, \Pi_{LR}(q^2) =$ current correlator

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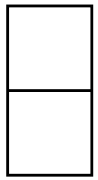
* Golterman & Shamir, in preparation

REALISTIC MODELS

⟹ Narrowed down by Ferretti & Karateev 1312.5330 to add the possibility of PARTIALLY COMPOSITE TOP QUARK. ⟸

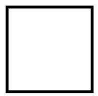
(Kaplan 1991)

For example:

$\mathrm{SU}(4)$ gauge theory with sextet fermions  — a real representation.

5 Majorana fermions give the global symmetry $\mathrm{SU}(5) \to \mathrm{SO}(5)$

— a good embedding for the Higgs multiplet

For a top partner, add fund rep fermions  ($3\times$ Dirac)

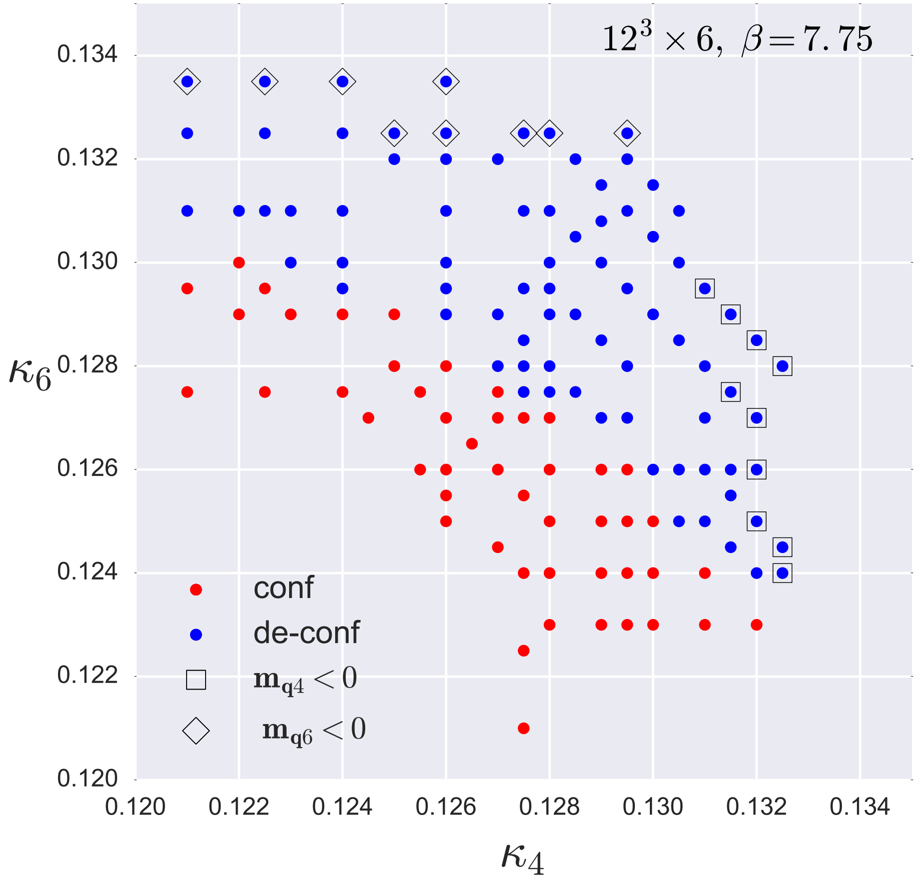
Note: Technicolor is *silent* on the top quark — much too heavy for ETC

CURRENT WORK on Composite Higgs / Partially Composite Top

TACO (`DeGrand et al.`): $\mathrm{SU}(4)$ gauge with $\{N_f = 2 \times \mathbf{6}$ *and* $2 \times \mathbf{4}\}$

— on the way to The Real Thing: $\{5 \times\ \mathbf{6}\ (\mathrm{Majorana})$ *and* $3 \times \mathbf{4}\}$

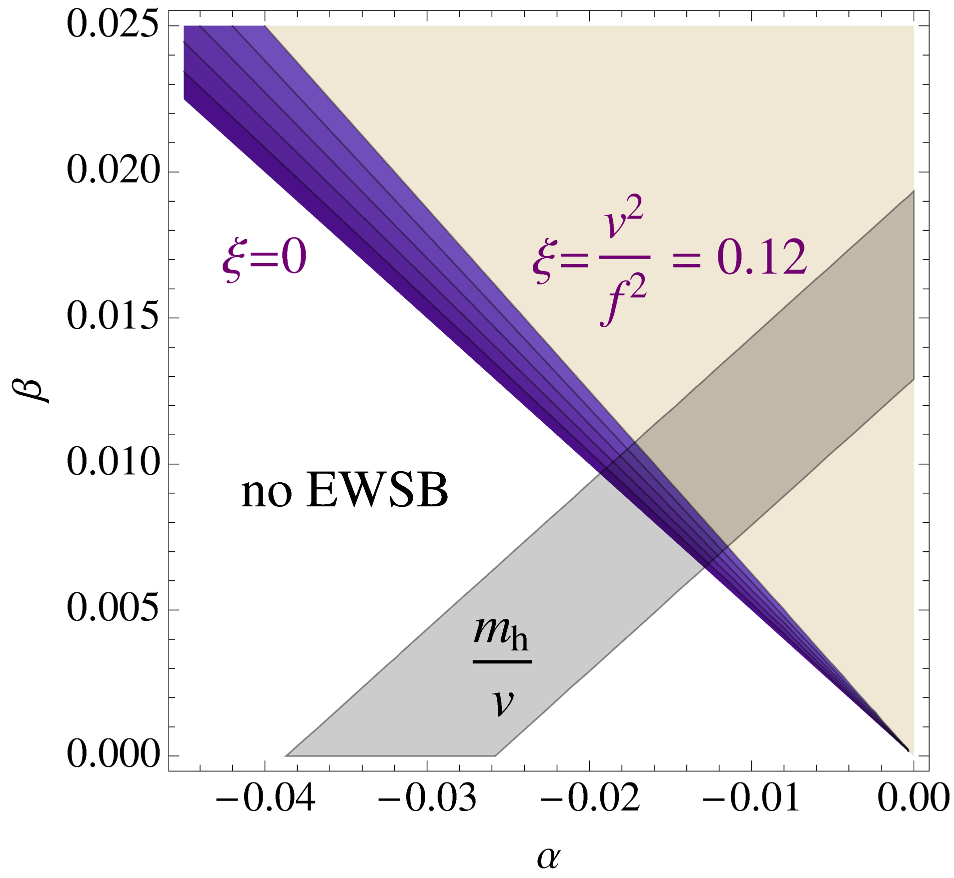
(`V. Ayyar`)



LHC CONSTRAINTS listed by `Del Debbio, Englert, Zwicky 1703.06064`

$\Longrightarrow$ E.g., Higgs potential $V_{\rm eff}(h) = \alpha\cos(2h/f) - \beta\sin^2(2h/f)$ constrained by

- $\alpha + 2\beta > 0$ for SSB
- $8(2\beta - \alpha) = m_h^2/v^2$ Higgs mass
- Future limits on exotic Goldstone bosons



N.B. *Problems with the model:* e.g., coupling of extra Goldstone fields to Higgs field

SUMMARY

TECHNICOLOR

1. Looking for the sill of the conformal window — $\mathrm{SU}(3):\ N_f^* < 12\ ?$
2. Looking for *walking* just below the sill ($N_f = 8$)
   ... or *forcing* a conformal theory to walk ($N_f = 4\ell + 8h$)
3. Checking that this yields a light ($m_h > 0\,!$), dilatonic Higgs — via low-energy effective action

COMPOSITE HIGGS & partially composite top

1. Many opportunities for lattice in calculating low-energy constants ($\mathrm{SU}(4) + 2$ reps)
2. Constraints from LHC data may be premature — models aren't perfect