BSM ON THE LATTICE

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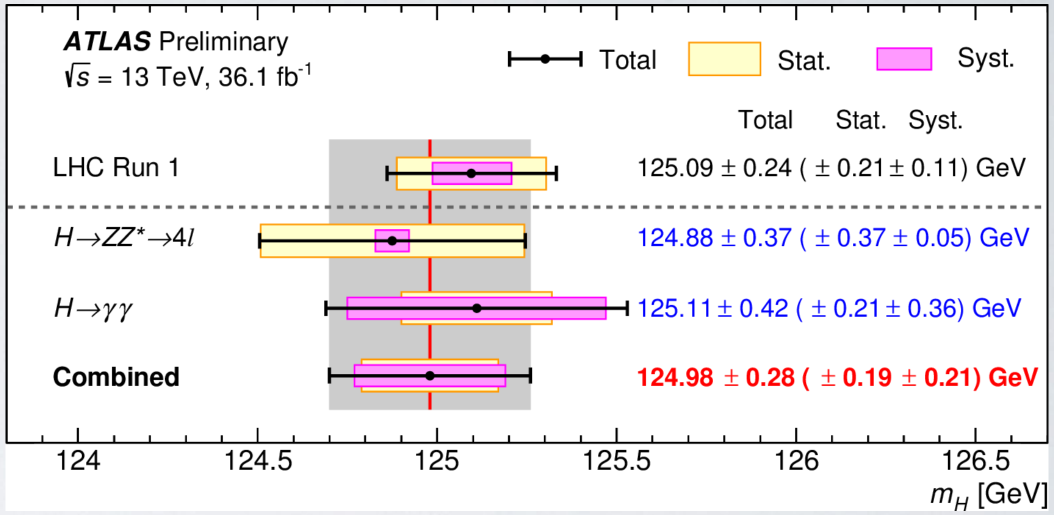
Higgs: the story so far

- Spin 0, scalar…
- Coupling to the other SM particles proportional to their masses?
- Quantum effect consistent with SM Higgs?
- Is the Higgs Elementary or Composite?

ATLAS and CMS are providing precise measurements of the properties of the Higgs and strong constraints on Beyond SM physics

THE SM works pretty well: Why BSM?

- Effective description / not UV complete
- EW scale stability / naturality
- EW vacuum meta-stability
- Flavour problem / undetermined fermion masses & mixing angle / Flavour physics anomalies?
- Matter–antimatter asymmetry
- Dark matter / Dark energy
- New particles?
- The Higgs itself!



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Don't bite off too much:

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

Why lattice BSM?

- Most models for BSM traditionally based on weakly-coupled/calculable extensions. Experimental bounds are now constraining many models to tight corners of parameter space
- Strongly coupled model requiring non-perturbative dynamics are becoming more popular. In particular for the Lattice: Walking Technicolor and pNGB Composite Higgs
- Phenomenology needs non-perturbative input for strongly coupled models: quantum symmetries, spectrum, low energy constants, ...

Why lattice BSM?

This talk follows the recent reviews by:

- B. Svetitsky at Lattice 2017 1708.04840
- C. Pica at Lattice 2016 1701.07782
- D. Nogradi and A. Patella IJMPA 1607.07638
- T. DeGrand in Rev. Mod. Phys. 1510.05018

I will mostly talk of:
Technicolor / "Dilatonic Higgs"
Higgs as a pseudo-Goldstone boson / "partially Composite top"

Apologies, although lattice investigations exist for all the topics below I will not be able to address (time)

- SUSY
- Extradimensions
- Gauge/gravity duality
- Asymptotic Safety
- Dark Matter
- Lattice constraints to BSM physics

Composite Higgs: how does it look like?

$\mathcal{L}_{SM-Higgs}$ Just the SM with no Higgs $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$

gauge group $\mathrm{SU}(N)/\mathrm{SP}(N)/\mathrm{SO}(N)$

$$\mathcal{L}_{SD} = -\frac{1}{4}F^2_{\mu\nu} + i\bar{\psi}\not{D}\psi$$

N_f fermions in some representation

Higgs impostor: scalar composite

W/Z mass generation, new resonances

$\mathcal{L}_{Int}$ Effective interactions with the SM. Generates masses for the fermions

$$\frac{1}{\Lambda^2_{UV}}\bar{q}qO_B, \frac{1}{\Lambda^2_{UV}}qO_F$$

Composite Higgs: how does it look like?

UV	10^3 - 10^4 TeV	5-10 TeV	1 TeV	IR
	$\mathcal{L}_{UV}$	$\mathcal{L}_{SM-Higgs} + \mathcal{L}_{SD} + \mathcal{L}_{Int}$	$\mathcal{L}_{SM}$ + new physics	

On the Lattice we only study the SD in isolation
Realistic phenomenology requires taking into account back-reactions from SM and other interactions.

Our plan:

- Identify quantities which only depend on the new SD
- Compute (small?) corrections from other sectors
- Anyway ruling in or out a realistic model always requires to consider the full setting!

Composite Higgs: how does it look like?

- If EWSB is due to a new of strongly-interacting sector with fermions, one would expect, in general, composite scalar particles
- To not be excluded by experiments, this scalar states should mimic a SM-like Higgs boson: correct mass and couplings
- This could happen if the composite scalar is a light pseudo-Goldstone boson of some broken symmetry:

Scale invariance symmetry
(dilaton)
Walking Technicolor

Flavour symmetry
(pNGB)
pNGB Higgs

Walking technicolor

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

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

- Chiral symmetry $SU(2)_L \times SU(2)_R \to SU(2)_V$
  - … leaving 3 Nambu–Goldstone bosons $\pi^\pm, \pi^0$
  - …which get eaten to give mass to $W^\pm, Z^0$.
  - …The Higgs is the lightest scalar of the sector

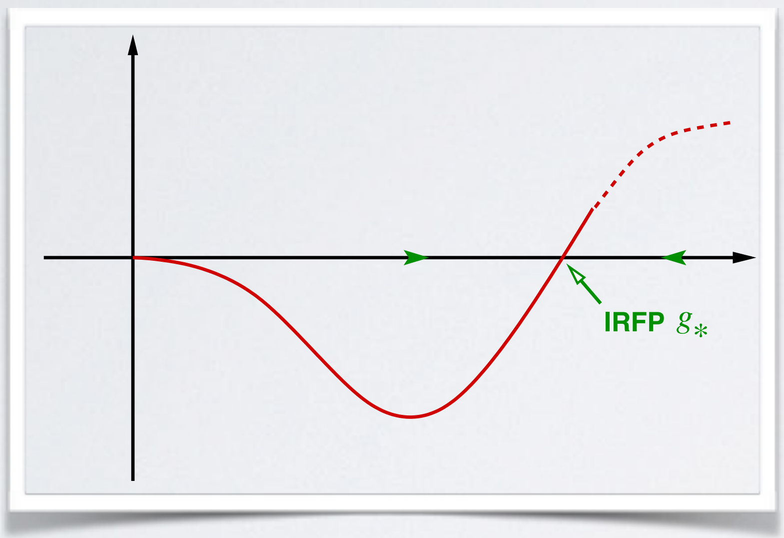
It simply doesn't work:
You can generate FCNC

$$\mathcal{L}_{Int} = \ldots + \frac{\gamma_{ab}}{\Lambda_{UV}^2}\bar{q}\,T^a q\bar{q}\,T^b q$$

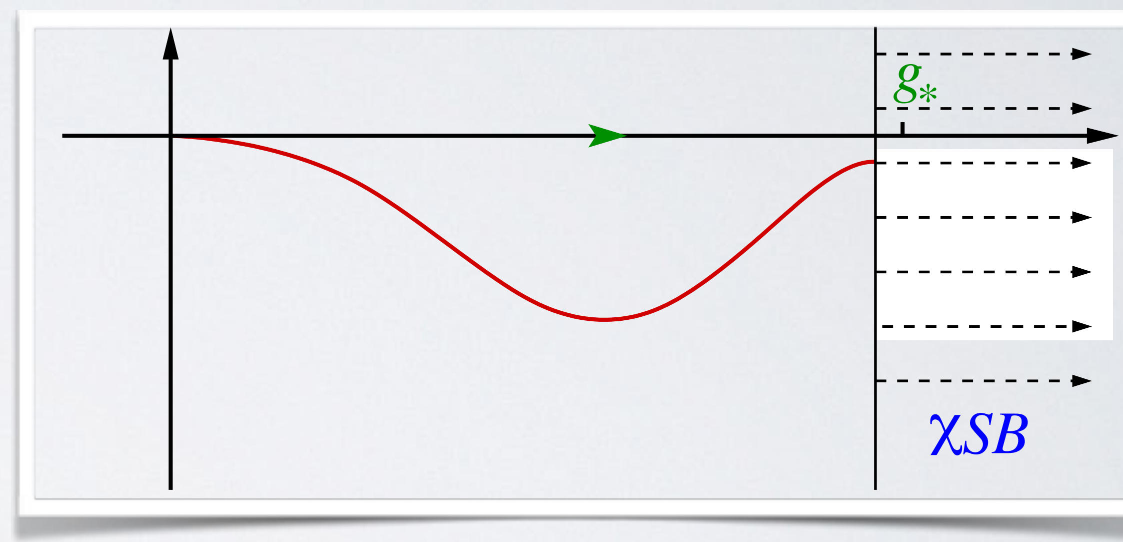
See [1005.5727], [1104.1255]

Walking technicolor

For a light scalar suppose APPROXIMATE SCALE INVARIANCE
For example by increasing Nf



IR fixed point $\Rightarrow$ scale invariance



Approximate scale invariance

Light scalar emerges as pseudo-Goldstone boson of approximate dilatation symmetry.

m_H is protected from UV, like any PGB (and Yukawa couplings $\propto$ m_q)

Scale separation driven by the anomalous dimension of the FP (γ)

pNGB Higgs and partial Composite

Higgs is a pseudo Goldstone boson, hence naturally light!

Easily recover the correct SM-like coupling between the composite Higgs and the electroweak gauge bosons.

Pattern of symmetry breaking G_F/H_F should be such that the custodial symmetry of the SM is preserved

$$G_F \to H_F \supseteq SU(2)_L \times SU(2)_R \times U(1)_X$$

To give the correct hyper-charge to all SM fields we need a NGB with

$$\mathrm{Higgs} = (2,2)_0 \in \mathrm{G_F}/\mathrm{H_F}$$

$4\ (\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$SU(4) \times SU(4)'/SU(4)_D$	**SU(3) Nf=4 Fund Dirac**
$4\ \psi_\alpha$ Pseudoreal	$SU(4)/Sp(4)$	**SU(2) Nf=2 Fund Dirac**
$5\ \psi_\alpha$ Real	$SU(5)/SO(5)$	**SU(4) Nf=2.5 2-A Dirac**

pNGB Higgs and partial Composite

EW interactions break the global symmetry of SD and generate a mass for the composite Higgs, as for charged pions in massless QCD.

EW symmetry must be broken via radiative corrections (top)

Finally the top could be partially composite

$G_{\rm HC}$	ψ	χ	G/H
$SO(7,9)$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$\frac{SU(5)}{SO(5)}\frac{SU(6)}{SO(6)}U(1)$
$SO(7,9)$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	
$Sp(4)$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$\frac{SU(5)}{SO(5)}\frac{SU(6)}{Sp(6)}U(1)$
$SU(4)$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$\frac{SU(5)}{SO(5)}\frac{SU(3)\times SU(3)'}{SU(3)_D}U(1)$
$SO(10)$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	
$Sp(4)$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$\frac{SU(4)}{Sp(4)}\frac{SU(6)}{SO(6)}U(1)$
$SO(11)$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	
$SO(10)$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\frac{SU(6)}{SO(6)}U(1)$
$SU(4)$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	
$SU(5,6)$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\frac{SU(3)\times SU(3)'}{SU(3)_D}U(1)$

As in TC, large anomalous dimensions are advocated to suppress FCNC

On the lattice

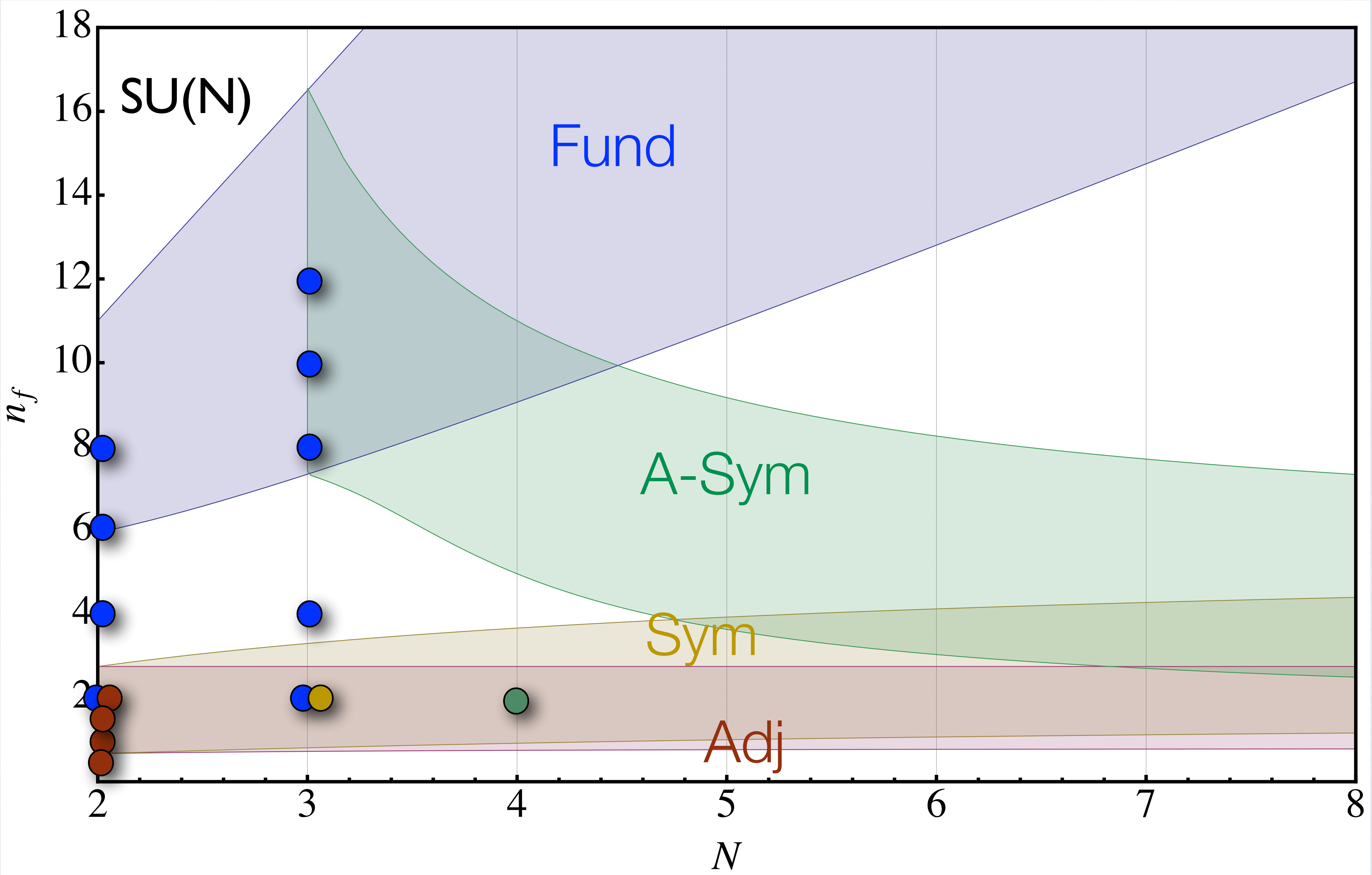
QUESTIONS FOR DIRECT CALCULATIONS:

- Where is the exact location of the conformal window?
- Inside the conformal window:
  What is the anomalous dimension of the mass/baryonic operators?
- Outside the conformal window:
  σ resonance is light and narrow? Is it a dilaton? What are the couplings to NGBs?
- Generally, how does the spectrum change with the number of fermion fields or when changing the number of colors or fermion representation?
- How big is the S-parameter for models just below the conformal window?

How can I investigate: Many approaches and as many caveats:

- Mass spectrum (finite volume/lattice artefacts)
- Finite-T transition (lattice artefacts)
- Dirac eigenvalues (fit dependant)
- Beta function (finite volume/definition of the coupling)

SU(N) phase diagram on the lattice



SU(3) phase diagram on the lattice

FINDING N_f^* — 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 —
- Danger: *slow* running (spontaneous χSB) is very similar to *no* running (fixed point)

  – possible fixed point at IR both scale L and a could be at strong coupling far from the continuum limit in UV

- RG was born for this purpose — compare L_1 to L_2 and obtain the beta function
- no scale Λ ($1/L < \Lambda < 1/a$) ⇒ everything is a function of a/L

  ⇒ continuum extrapolation equivalent to $L \to \infty$

SU(3) phase diagram on the lattice

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

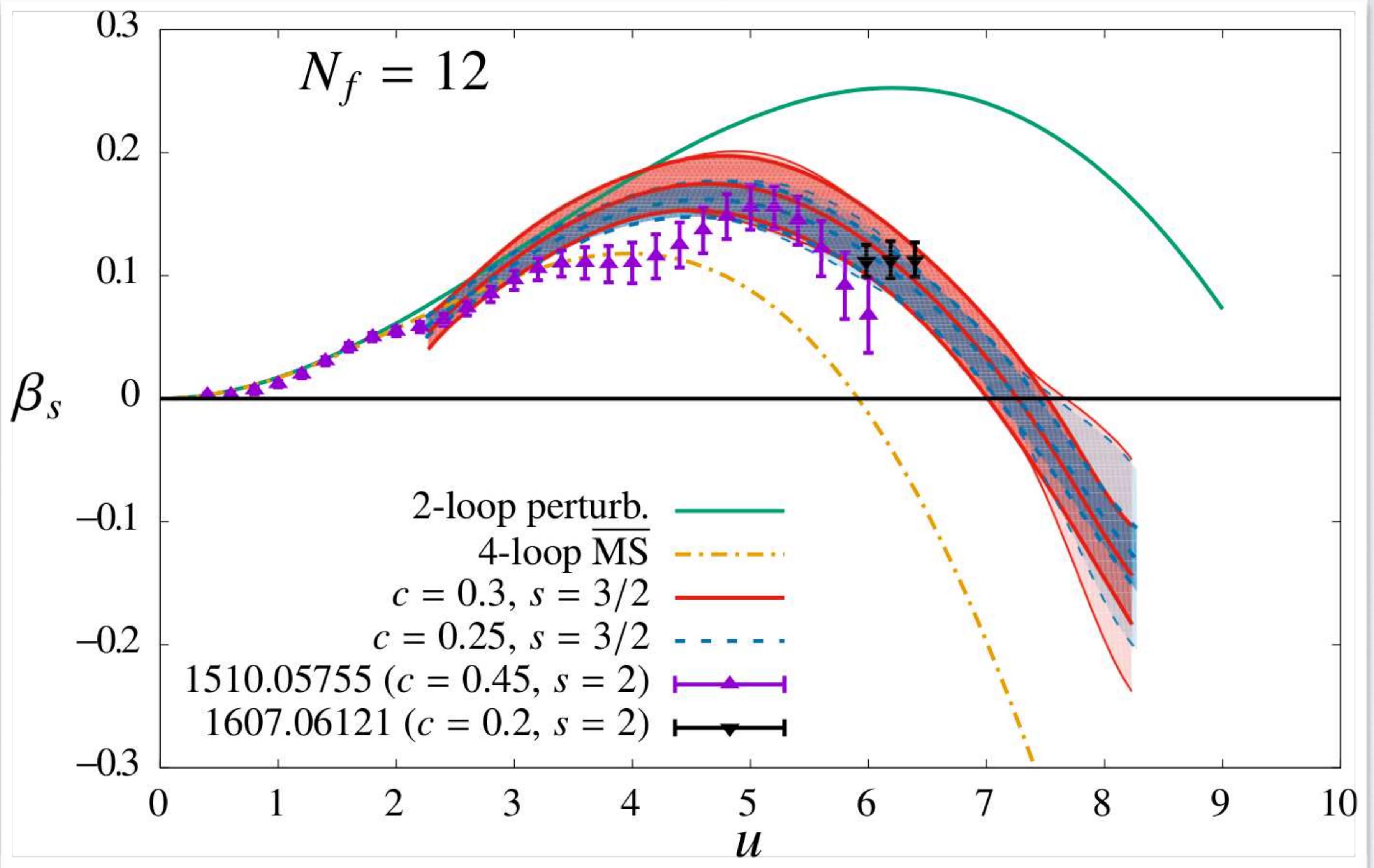
[Hasenfratz & Schaich 1610.10004, LatHiggs Fodor et al. 1607.06121, Lin, Ogawa, Ramos 1510.05755]

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

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

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

SU(3) phase diagram on the lattice



The controversy has a direct consequences also on smaller N_F

SU(3) phase diagram on the lattice

Going down to $N_f = 8$ Recall two-loops: $N_f^* = 8.05$.

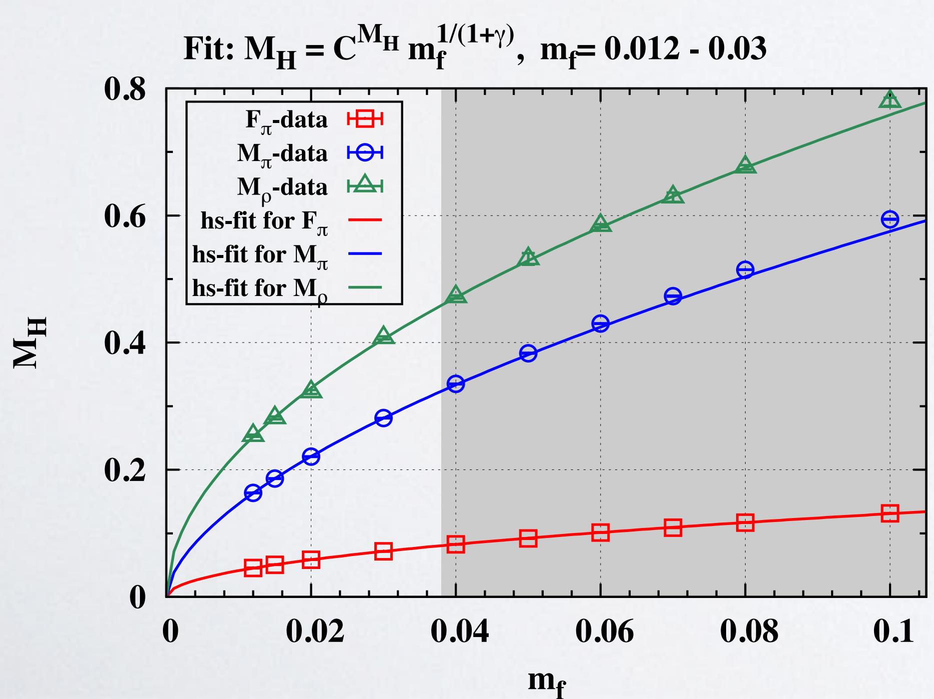
[LSD Appelquist et al. 1601.04027 + recent][LatKMI Y. Aoki et al. 1610.07011]

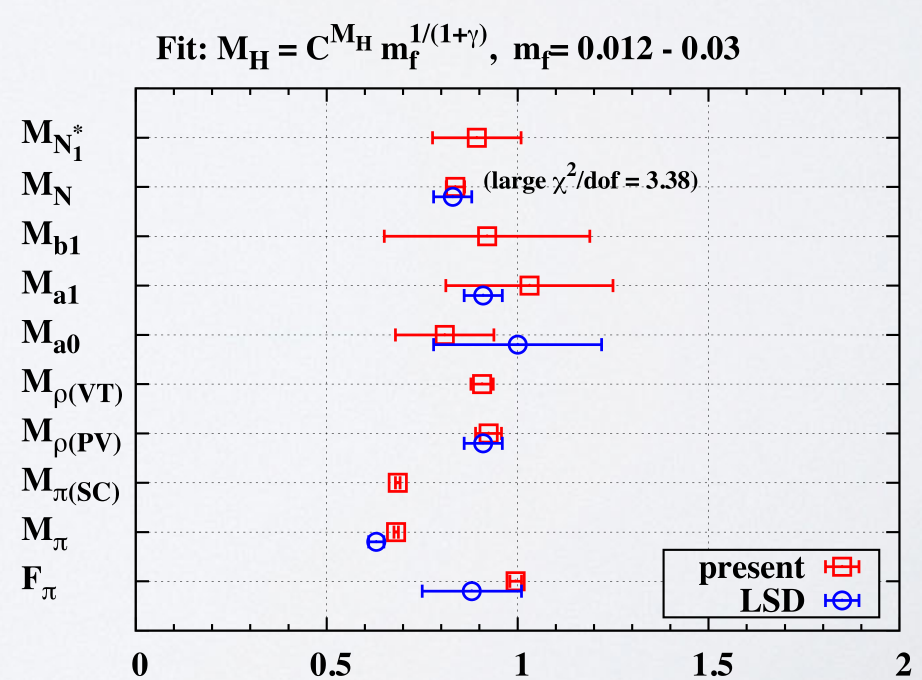
The claim is that $N_f = 8$ walks.

- 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 :

  Near a fixed point $M_H \sim m^{1/(1+\gamma)}$, $\gamma \simeq 1$
- Light scalar — degenerate with π over large range of m_f

  As $m_\pi \to 0$, where does the scalar end up?





Forcing a theory to walk

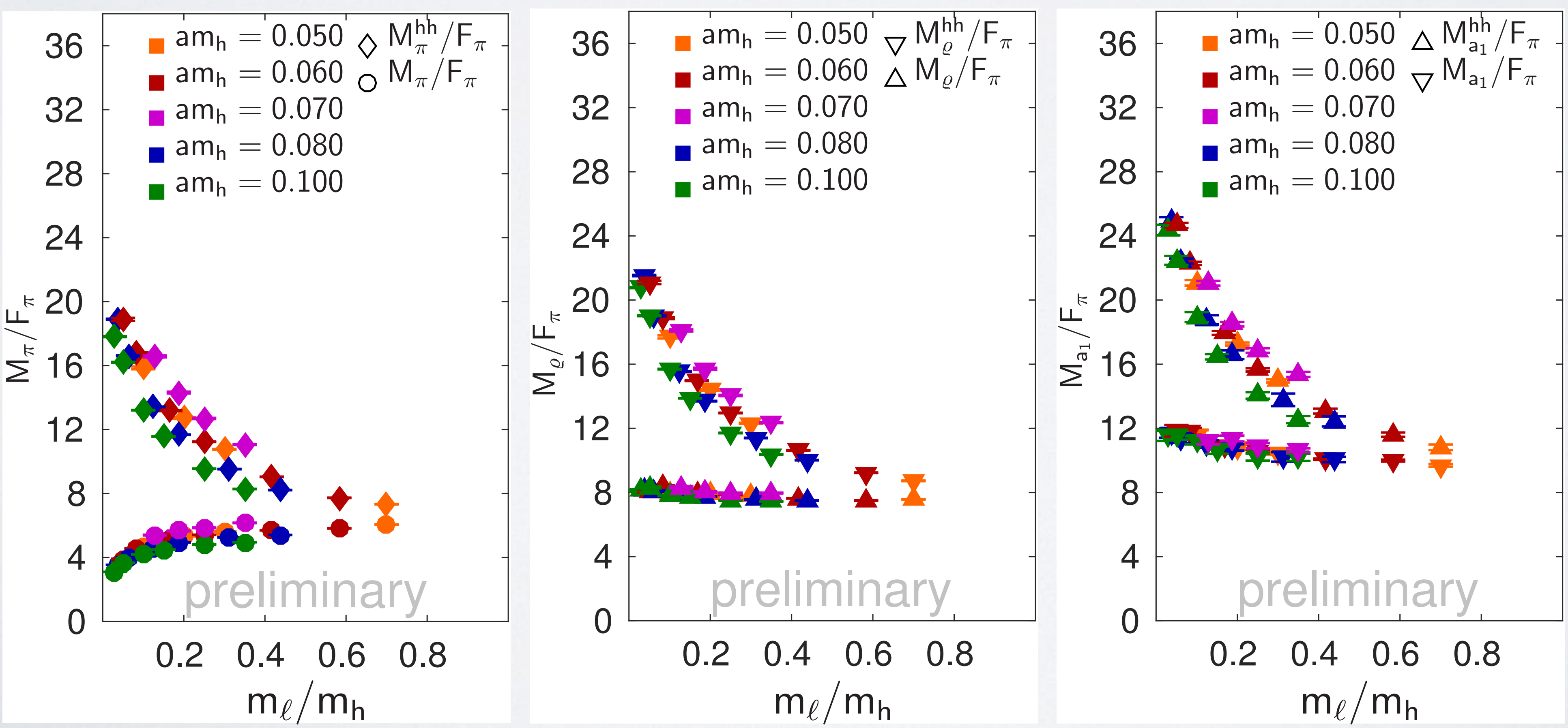
And up again $N_f = 8$ heavy + 4 light

[Hasenfratz, Rebbi, Witzel 1609.01401 + recent,]

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

Note m_h is artificial.

Extra Goldstones ($N_f = 4$) still to be addressed, maybe *composite Higgs* [Ma & Cacciapaglia].



Other SU(N)

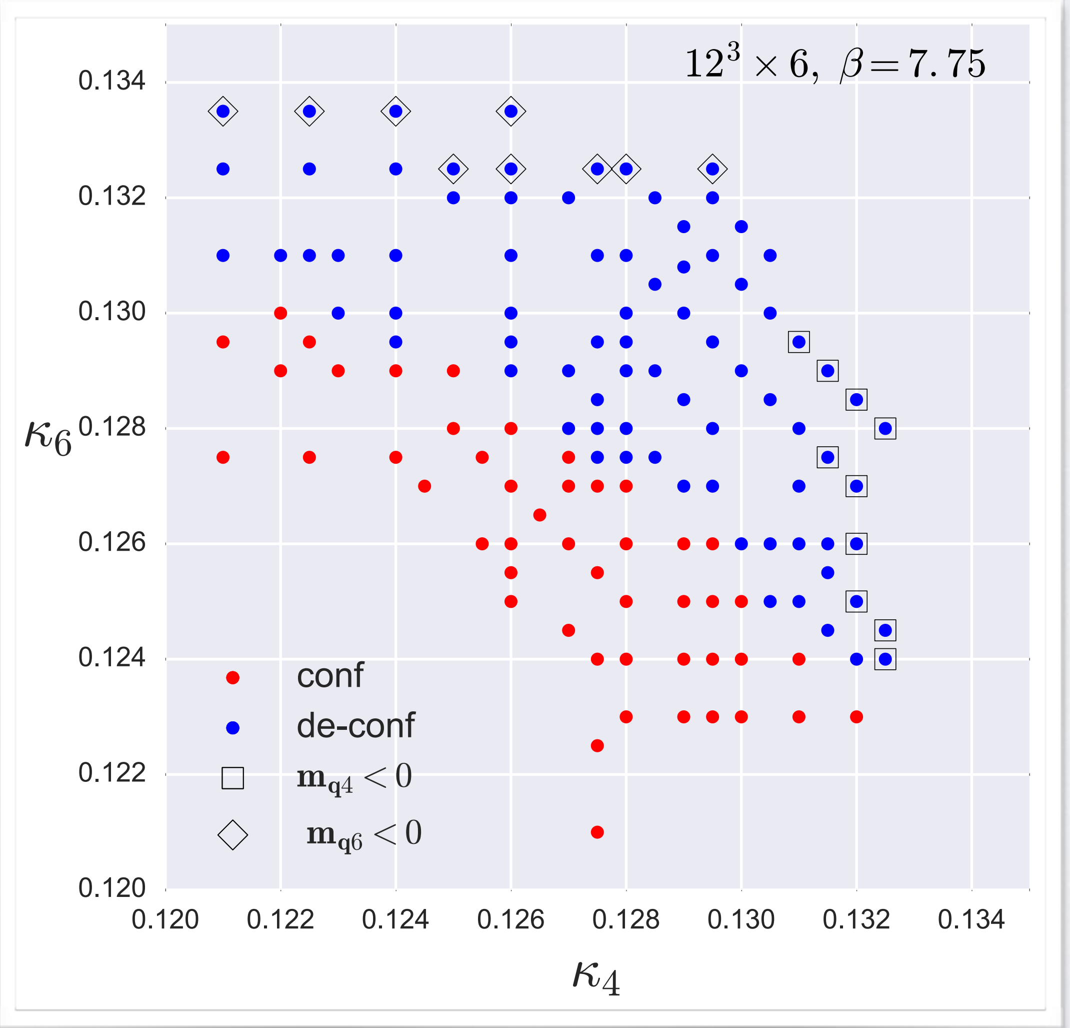
A summary of the results of last lattice conference.

- SU(2)/fund, Nf = 8 — in the conformal window [Leino et al. 1701.04666]
- SU(2)/adj, Nf = 1, 2 — straddling the sill [Athenodorou et al. 1605.04298][Bergner et al. 1610.01576]
- SU(2)/adj, Nf = 2 + NJL — induce walking with NJL term [Rantaharju, Pica, Sannino 1704.0397
- SU(3)/sextet, Nf = 2 — may walk, with light Higgs
  [Fodor et al. 1506.06599, 1601.03302 (staggered)][Hansen, Drach, Pica 1705.11010 (unimp. Wilson)]

Starting on the partial composite top

Current Work on Composite Higgs / Partially Composite Top
TACO [DeGrand et al.]

SU(4) gauge with {Nf = 2 × 6 *and* 2 × 4} on the way to The Real Thing: {5 × 6 (Majorana) *and* 3 × 4}



To conclude

1. Technicolor
    1. The effort to nail down the sill of the conformal window continues,
    2. If you know you're below the sill, it makes sense to look for walking as a mechanism for a light scalar that might be the Higgs boson.
    3. Has your walking theory really produced a light, dilatonic Higgs and a low scale for the Higgs vev?

2. Composite Higgs and partially composite top quark
    1. Multi-representation models are a whole new area for lattice simulations.
    2. There are many opportunities for lattice calculations of low-energy constants. Unfortunately, they will always depend on unknown mixing parameters that come from yet higher energies.

3. Phenomenological constraints from these theories might be premature, as the models aren't perfect.