BSM physics on the lattice

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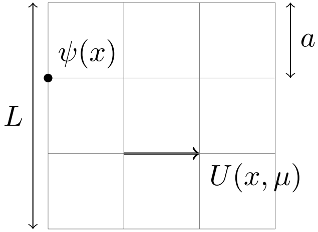
what BSM? why lattice?

- no evidence for new states at the TeV scale
- exploit the large amounts of data from the LHC
- EFT approach to quantify deviations from SM
- strong sector underlying (some) effective descriptions
- LECs/spectrum are NOT independent - e.g. ChPT and QCD
- lattice gauge theories: tool for first principle investigations

[Pica 16, Svetitsky 17]

lattice field theories



$$\boxed{Z = \int \mathcal{D}U \mathcal{D}\psi \mathcal{D}\bar{\psi}\; e^{-S[U,\psi,\bar{\psi}]}}$$

$$\langle \phi(x_1) \ldots \phi(x_n) \rangle = \frac{1}{Z} \int \mathcal{D}U \mathcal{D}\psi \mathcal{D}\bar{\psi}\; e^{-S[U,\psi,\bar{\psi}]}\, \phi(x_1) \ldots \phi(x_n)$$

lattice observables

$$\sum_{\mathbf{x}} \langle \Phi(t,\mathbf{x}) \Phi(0)^\dagger \rangle \propto |\langle 0|\Phi|H\rangle|^2 \exp\left(-M_H t\right)$$

$$\sum_{\mathbf{x},\mathbf{y}} \langle \Phi_1(0,0) V(t,\mathbf{y}) \Phi_2(T,\mathbf{x})^\dagger \rangle \propto$$
$$\langle H_1|V|H_2\rangle \exp\left(-M_1 t\right) \exp\left(-M_2(T-t)\right)$$

$$\sum_x e^{iqx} \langle J_\mu^{a,L}(x) J_\nu^{a,R}(0)\rangle$$

a strong sector beyond QCD

- improved algorithms and available computational power
- 10 years of development – several results have emerged

- gauge groups SU(N), Sp(2N)
- dynamical fermions in multiple representations

- $\hookrightarrow$ choice of a UV-complete theory: *divine inspiration*
- study the *“hadronic”* dynamics

directions

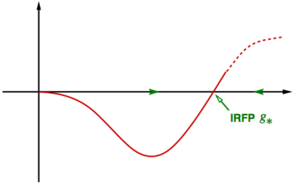
- separation between the Higgs mass and the “hadronic” scale
  - ◇ IR conformality (walking/crawling TC, dilaton, miracle...)
  - ◇ composite Higgs models (PNGB)
- dark matter, flavor anomalies... ?
- difficult to explore the “space of theories”
- computationally expensive, taming of systematic errors
- identify paradigms/try to understand what makes an impact

conformal window

For a light scalar — suppose APPROXIMATE SCALE INVARIANCE

In the Conformal Window:

$N_f > N_f^*$

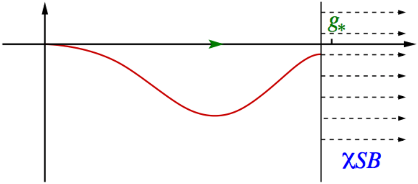


IR fixed point $\Rightarrow$ scale invariance

Below the sill:

N_f *slightly* $< N_f^*$

("WALKING technicolor")

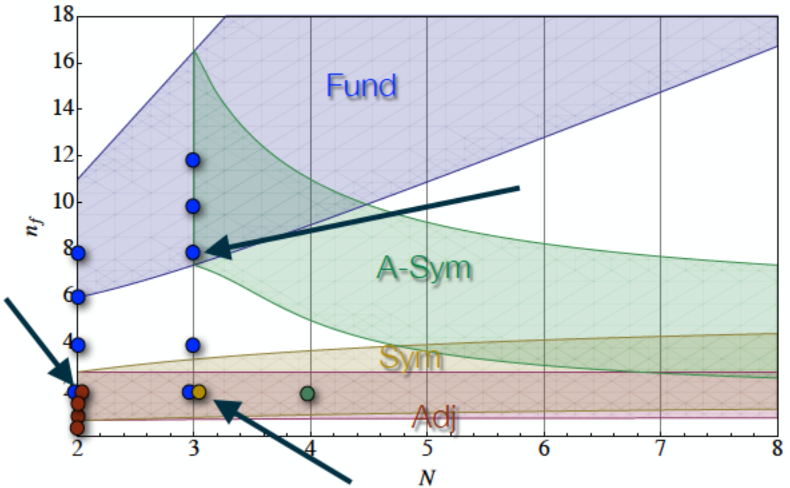


approximate scale invariance

- 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 $\propto m_q$)

[Svetitsky 17]

results - 1



[Pica & Sannino 10]

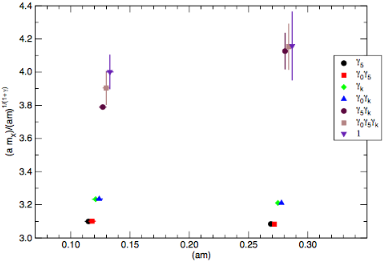
existence of an IR fixed point

scaling relations

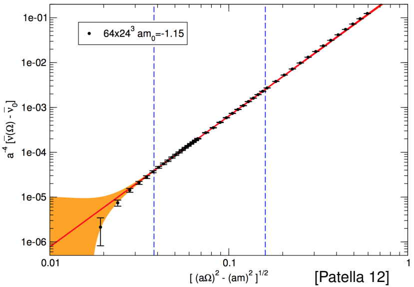
[LDD & Zwicky 10]

$$\boxed{M_H \propto m^{1/(1+\gamma)}\,, \quad \rho(\lambda) \sim \lambda^{(3-\gamma)/(1+\gamma)}}$$

SU(2) LGT with 2 adjoint fermions – small m, large V, $\hookrightarrow$ expensive!!



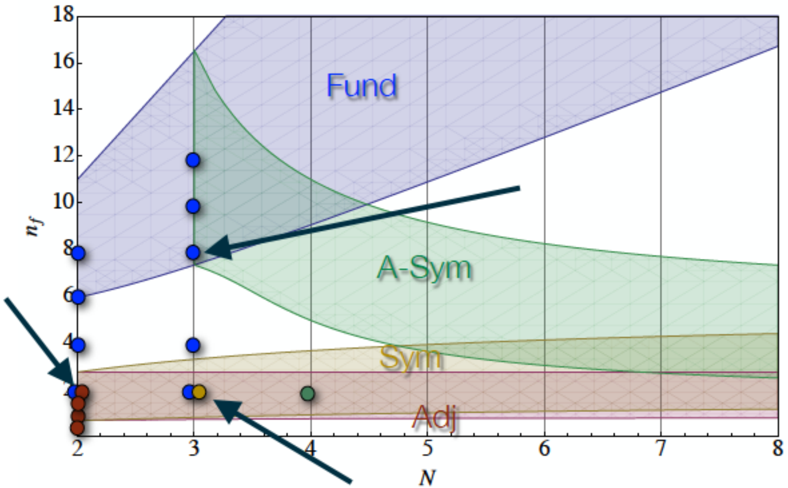
[LDD et al. 16]



[Patella 12]

$$\boxed{\gamma = 0.37 \pm 0.02}$$

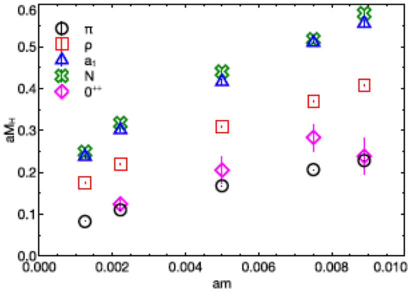
results - 2

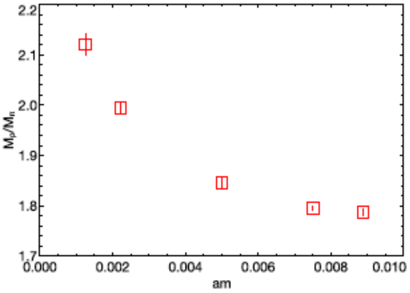


[Pica & Sannino 10]

walking spectrum

SU(3) $n_f = 8$ fund – theory in the chirally broken phase

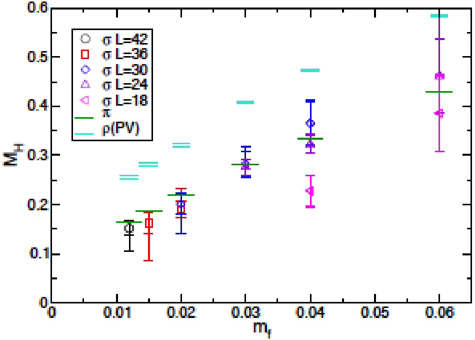




[Appelquist et al 16]

walking spectrum

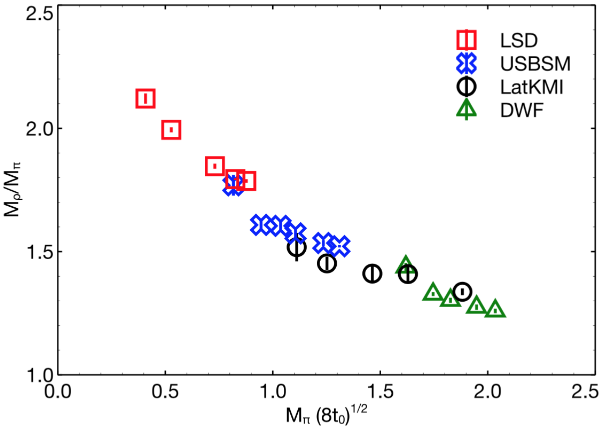
SU(3) $n_f = 8$ fund



[Aoki et al 16]

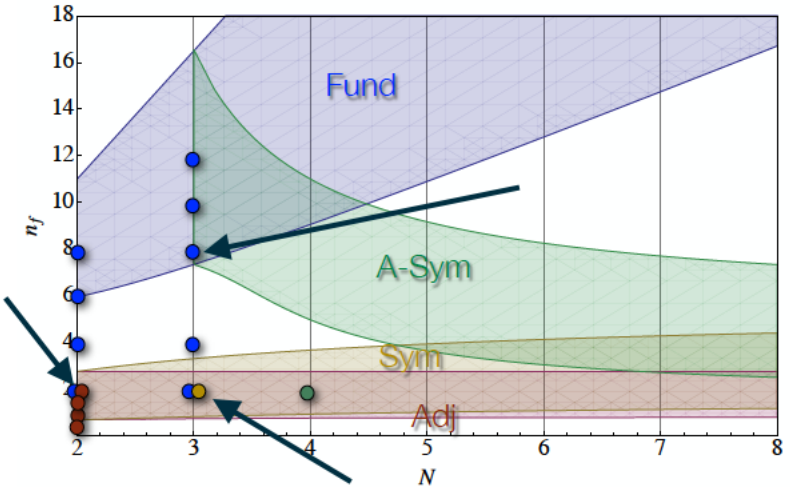
walking spectrum

consistent results between different computations



[Svetitsky 17]

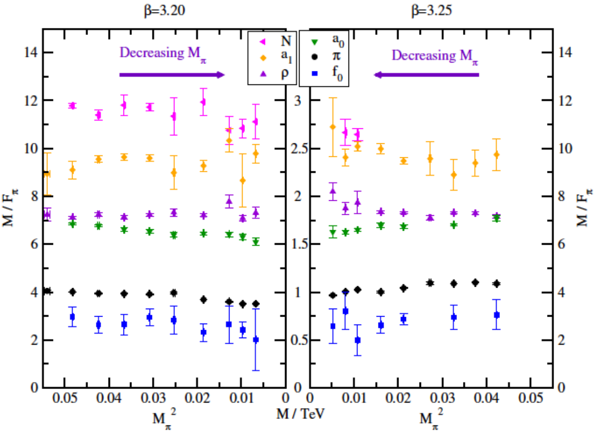
results - 3



[Pica & Sannino 10]

walking spectrum

SU(3) $n_f = 2$ sextet – also walking...



[Fodor et al 16]

EFT analysis

light dof: dilaton + NGB [Golterman & Shamir 16, Appelquist et al 17, Catà et al 18]

$$\mathcal{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi + \frac{f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^2 \mathrm{Tr}\ \left[\partial_\mu\Sigma\partial^\mu\Sigma^\dagger\right] + \frac{m_\pi^2 f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^y \mathrm{Tr}\ \left[\Sigma+\Sigma^\dagger\right] - V(\chi)$$

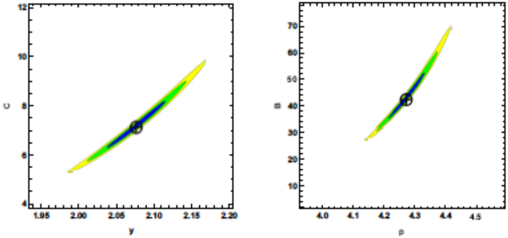
parametrization of the potential: $V \propto \chi^p$

$\hookrightarrow$ scaling relations

$$M_\pi^2 F_\pi^{2-y} = Cm\,,$$
$$M_\pi^2 = BF_\pi^{p-2}$$
$$M_d^2 = \frac{yn_f}{2}\frac{f_\pi^2}{f_d^2}(p-y)BF_\pi^{p-2}$$

results

$$\begin{cases} \mathrm{SU}(3), n_f = 8, \mathrm{fund}, & y = 2.1 \pm 0.1, p = 4.3 \pm 0.2, \frac{f_\pi^2}{f_d^2} = 0.08 \pm 0.04 \\ \mathrm{SU}(3), n_f = 2, \mathrm{sextet}, & y = 1.9 \pm 0.1, p = 4.4 \pm 0.3, \frac{f_\pi^2}{f_d^2} = 0.09 \pm 0.06 \end{cases}$$



[Appelquist et al 17]

composite Higgs

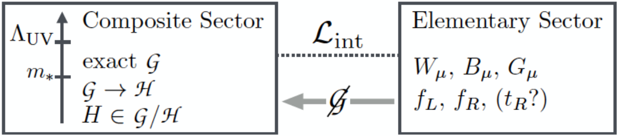


Figure 1.3: The basic structure of the composite Higgs scenario.

[Panico & Wulzer 15]

- NP dynamics is encoded in LEC describing the strong sector
- given one specific UV completion, LECs can be computed

Ferretti's model

	G_{HC}	G_{F}				
	$SU(4)$	$SU(5)$	$SU(3)$	$SU(3)'$	$U(1)_X$	$U(1)'$
ψ	$\mathbf{6}$	$\mathbf{5}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
χ	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$5/3$
$\tilde{\chi}$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$1/3$	$5/3$

[Ferretti 14, 16a,16b]

massless fermions, SSB of the global symmetry

$$\langle\psi\psi\rangle : \quad \mathrm{SU}(5) \longrightarrow \mathrm{SO}(5)$$
$$\langle\chi\tilde{\chi}\rangle : \quad \mathrm{SU}(3) \times \mathrm{SU}(3)' \longrightarrow \mathrm{SU}(3)_c$$

[Georgi & Kaplan 84]

pNGB potential

$$V(h) = \alpha \cos \frac{2H}{f} - \beta \sin^2 \frac{2H}{f}$$

[Ferretti 14]

where

$$\boxed{\begin{aligned} \alpha &= \frac{1}{2}\hat{F}_{\mathrm{LL}} - \hat{C}_{\mathrm{LR}} < 0 \\ \beta &= \frac{1}{2}\hat{F}_{\mathrm{EW}} - \frac{1}{4}\hat{F}_{\mathrm{LL}} \end{aligned}}$$

$$C_{LR} \propto \int_0^\infty dq^2\, q^2\, \Pi_{LR}(q^2)$$

$$\left(q^2 \delta_{\mu\nu} - q_\mu q_\nu\right) \Pi_{LR}(q^2) = \int d^4x\, e^{iqx} \left\langle J_\mu^{a,L}(x) J_\nu^{a,R}(0) \right\rangle$$

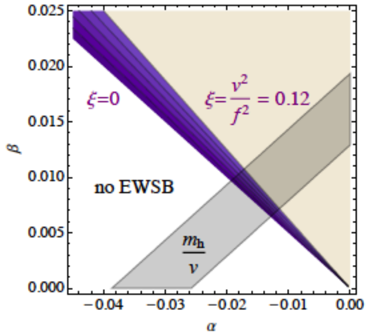
[Golterman & Shamir 15]

constraints on LECs

$$\alpha + 2\beta > 0$$

$$\xi = v^2/f^2 = -\alpha/(2\beta)$$

$$m_h^2/v^2 = 8\,(2\beta - \alpha)$$



[LDD, Englert, & Zwicky 17]

parameter scan

- $\xi \in [0, 0.1]$
- exotic Higgs masses: free parameters

$$m > 200 \text{ GeV} > m_H$$

- exotic top partners: $M > 1.5 \text{ TeV}$
  our scan: $M/\text{TeV} \in [1.5, 3.5]$

[Aad et al 12, CMS Collaboration 16, Matsedonskyi 15]

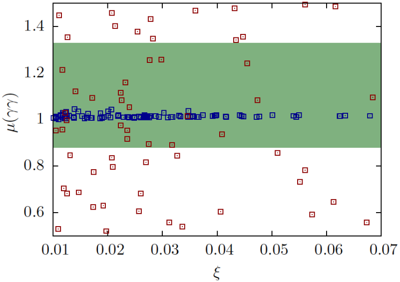
- $\lambda_t \in [0, 4\pi]$
  λ_q fixed by top mass

- pair produced color octet states: no evidence from Run-1, or first 13 TeV searches

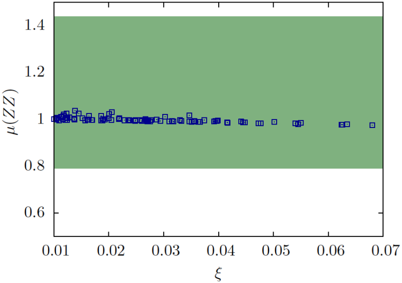
  $\text{SU}(3) \times \text{SU}(3) \to \text{SU}(3)$ breaking scale $> 6.5 \text{ TeV}$

[CMS]

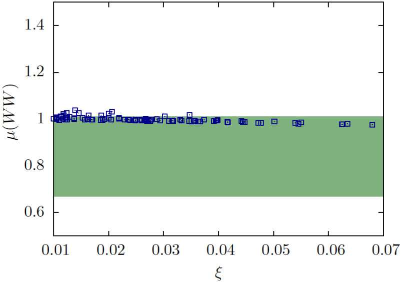
higgs signal strength



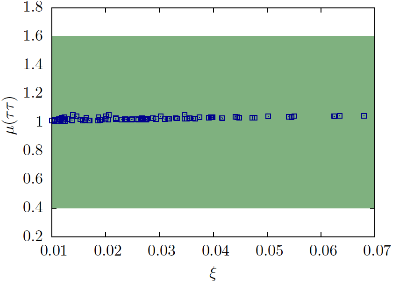
(a) $\gamma\gamma$ signal strength



(b) ZZ signal strength



(c) WW signal strength



(d) $\tau\tau$ signal strength

outlook

- work in progress/need to work with pheno
- other UV completions - composite leptoquarks/DM?
- theoretically interesting, but...
- computationally expensive
- need to identify the right questions!!

fermionic mass term

quadratic term involving the SM & BSM fermion fields

$$\mathcal{L}_{\text{eff}} \supset (\bar{t}_L, \bar{T}_L, \bar{Y}_L, \bar{R}_L) \cdot \mathcal{M}_T \cdot \begin{pmatrix} t_R \\ T_R \\ Y_R \\ R_R \end{pmatrix} + \ldots$$

top quark mass given by the lowest eigenvalue:

$$\boxed{m_t/v = \sqrt{2}\frac{f}{M} \frac{1}{\sqrt{1+\lambda_q^2 \frac{f^2}{M^2}}\sqrt{1+\lambda_t^2 \frac{f^2}{M^2}}}}$$

lattice constrained scan

$$m_t/v = \sqrt{2}\frac{f}{M}\frac{1}{\sqrt{1+\lambda_q^2\frac{f^2}{M^2}}\sqrt{1+\lambda_t^2\frac{f^2}{M^2}}}\,, \quad \rho_M = f/M = 0.2 \pm 0.04$$