Strong Interactions - Lattice Simulations for BSM

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new strong dynamics BSM?

- no evidence for new states at the TeV scale so far
- exploit the large amounts of data from the LHC
- EFT approach to quantify the deviations from SM
- lower bounds on the scale of NP, structure of LECs
- LECs are NOT independent parameters - e.g. ChPT
- strongly-interacting dynamics and lattice gauge theories

[Pica 16, Svetitsky 17]

UV completions on the lattice

- choice of a UV-complete theory
- separation between the Higgs mass and the “hadronic” scale:

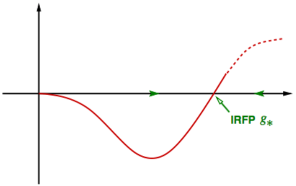
  technicolor (walking, conformal, dilaton, miracle...)
  composite Higgs: Higgs as PNGB
- numerical simulations $\longrightarrow$ spectrum/LECs/anomalous dimensions
- computationally expensive, difficult to explore the “space of theories”
- identify paradigms/try to understand what makes an impact
- beat down systematic errors for precise predictions

conformal window

For a light scalar — suppose APPROXIMATE SCALE INVARIANCE

In the Conformal Window:

$N_f > N_f^*$

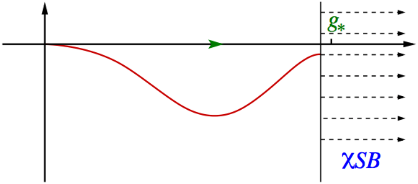


IR fixed point $\Rightarrow$ scale invariance

Below the sill:

N_f *slightly* $< N_f^*$

("WALKING technicolor")

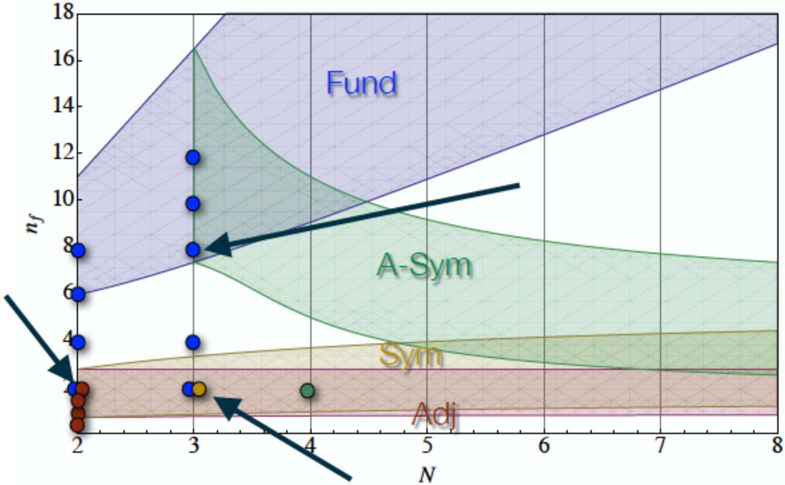


approximate scale invariance

- 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]

current lattice studies



[Pica & Sannino 10]

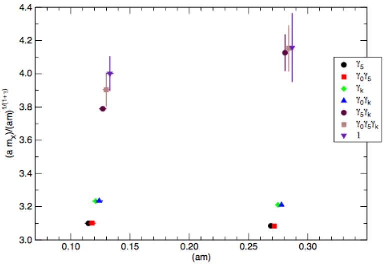
IR fixed point

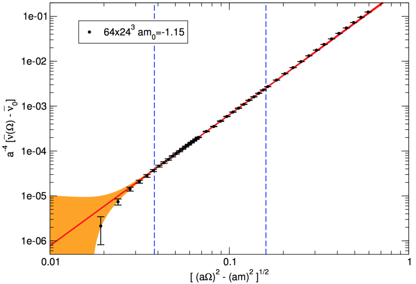
scaling relations

[LDD & Zwicky 10]

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

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

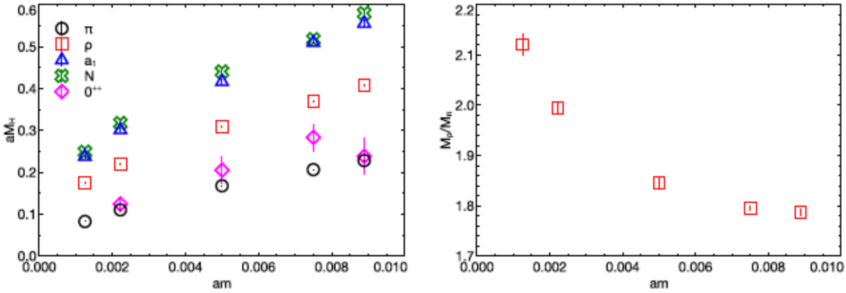




$$\gamma = 0.37 \pm 0.02$$

walking example - 1

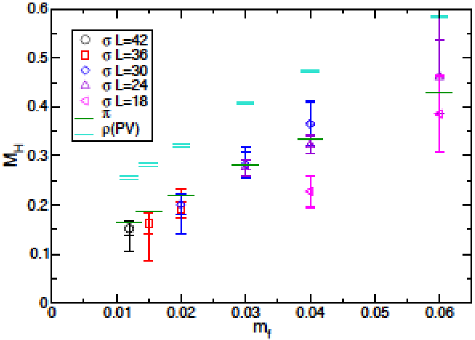
SU(3) $n_f = 8$ fund – theory in the chirally broken phase



[Appelquist et al 16]

walking example - 1

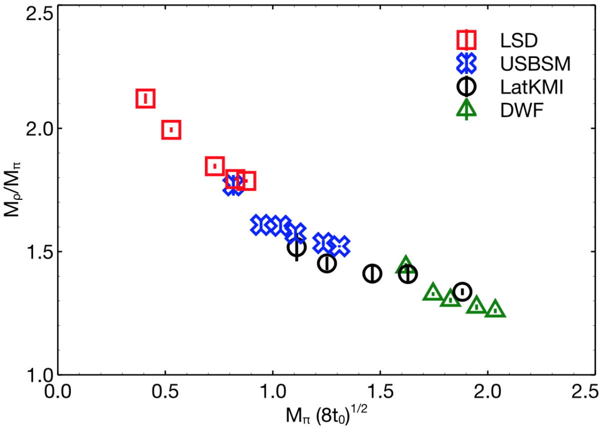
SU(3) $n_f = 8$ fund



[Aoki et al 16]

comparison

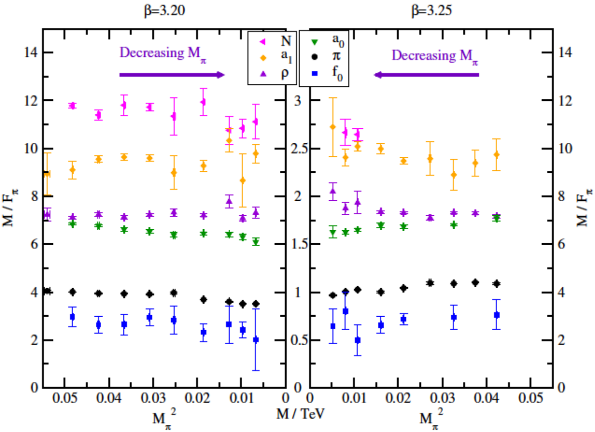
consistent results between different computations



[Svetitsky 17]

walking example - 2

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



[Fodor et al 16]

EFT analysis

EFT for dilaton + NGB

[Golterman & Shamir 16, Appelquist et al 17]

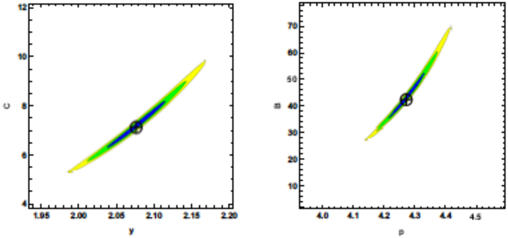
$$\mathcal{L} = \frac{1}{2}\partial_\mu \chi \partial^\mu \chi + \frac{f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^2 \mathrm{Tr}\ \left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right] + \frac{m_\pi^2 f_\pi^2}{4}\left(\frac{\chi}{f_d}\right)^y \mathrm{Tr}\ \left[\Sigma + \Sigma^\dagger\right] - V(\chi)$$

scaling laws:

$$M_\pi^2 F_\pi^{2-y} = Cm\,,$$
$$V \propto \chi^p \Longrightarrow M_\pi^2 = B F_\pi^{p-2}$$
$$V \propto \chi^p \Longrightarrow M_d^2 = \frac{y n_f}{2}\frac{f_\pi^2}{f_d^2}(p-y) B F_\pi^{p-2}$$

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

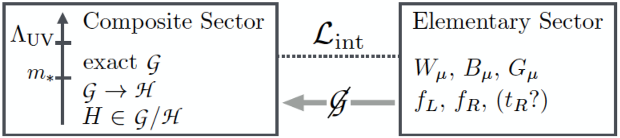


Figure 1.3: The basic structure of the composite Higgs scenario.

[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

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

$$B f^4 = C_{LR} \propto \int_0^\infty dq^2\, q^2\, \Pi_{LR}(q^2)$$

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

$$C_{\mathrm{top}} \propto \int \frac{d^4p}{(2\pi)^4} \frac{d^4q}{(2\pi)^4} \frac{p_\mu}{p^2} \frac{q_\nu}{q^2} \langle \bar{\mathcal{B}}_{Rk}(p) \gamma_\mu P_R \mathcal{B}_{Ri}(p) \bar{\mathcal{B}}_{Li}(q) \gamma_\nu P_L \mathcal{B}_{lk}(p) \rangle$$

[Golterman & Shamir 15]

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:

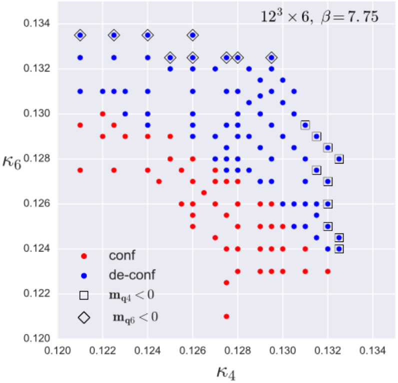
$$\boxed{m_t/v = \sqrt{2}\frac{f}{M} \frac{1}{\sqrt{1+\lambda_q^2 \frac{f^2}{M^2}}\sqrt{1+\lambda_t^2 \frac{f^2}{M^2}}}}$$

TACO collaboration

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

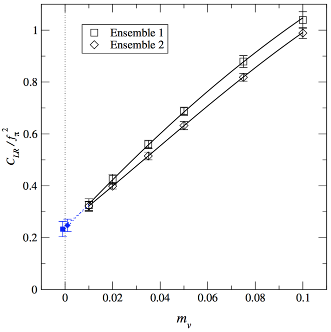
— on the way to The Real Thing: $\{5 \times \mathbf{6}\ (\mathrm{Majorana})$ *and* $3 \times \mathbf{4}\}$

(V. Ayyar)



challenges for lattice simulations

- simulations with multiple representations/Majorana
- extrapolation to the chiral limit
- computation of the baryonic spectrum [Degrand et al 16b]
- computation of $C_{\rm LR}$, $C_{\rm top}$ (20% error) [Degrand et al 16a]

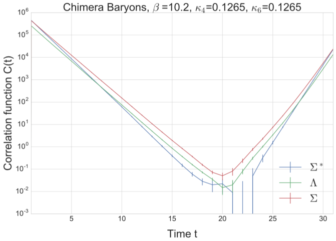


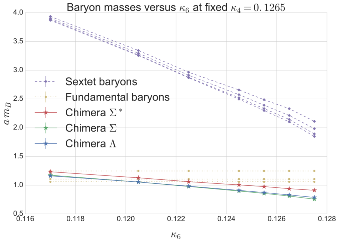
top partner mass

$$\langle \bar{\mathcal{B}}(t)\mathcal{B}(0)\rangle \propto Z_B e^{-Mt}$$

Baryon operators

$$\mathcal{B} \propto \psi\chi\chi, \{\psi\psi\psi\psi\psi\psi, \chi\chi\chi\chi\}\,.$$



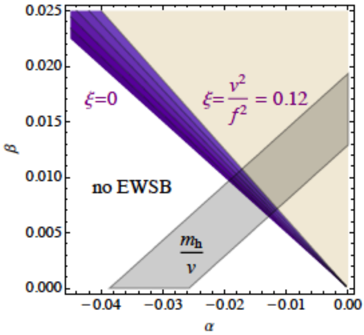


opportunities for lattice computations

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

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

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



[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]

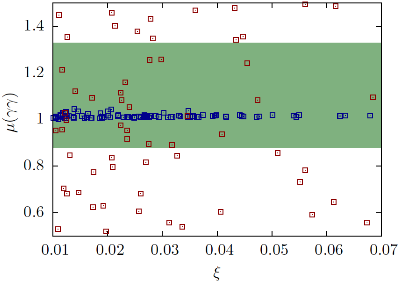
- $\lambda_t \in [0, 4\pi]$
  λ_q fixed by top mass

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

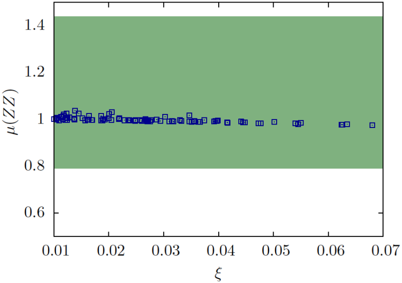
  $\text{SU}(3) \times \text{SU}(3) \rightarrow \text{SU}(3)$ breaking scale $> 6.5 \text{ TeV}$

[CMS]

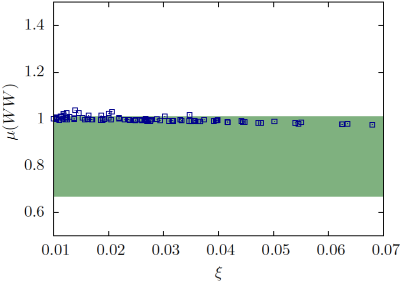
higgs signal strength



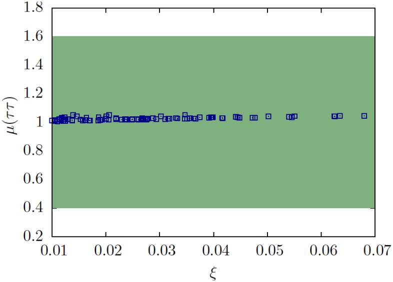
(a) $\gamma\gamma$ signal strength



(b) ZZ signal strength



(c) WW signal strength



(d) $\tau\tau$ signal strength

outlook

- work in progress/need to work with pheno
- theoretically interesting, but...
- computationally expensive
- need to identify the right questions!!

lattice constrained scan

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