

# 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 experiment
- EFT approach: determine LECs, quantify deviations from SM
- LECs are NOT independent parameters - e.g. ChPT
- opportunities for 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

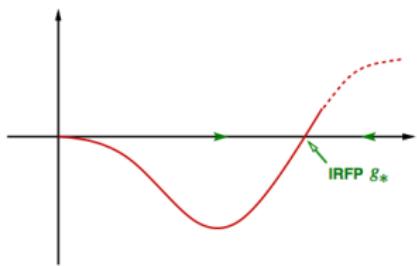
- numerical simulations → spectrum/LECs/anomalous dimensions
- computationally expensive, difficult to explore the “space of theories”
- identify paradigms/understand what makes an impact

# conformal window

For a light scalar — suppose APPROXIMATE SCALE INVARIANCE

In the Conformal Window:

$$N_f > N_f^*$$

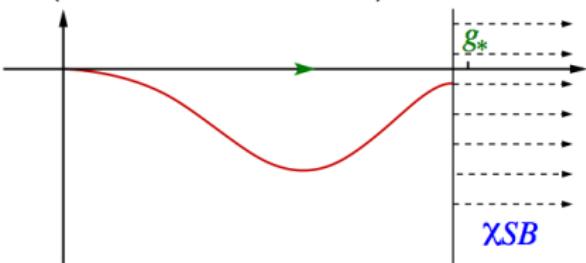


IR fixed point  $\Rightarrow$  scale invariance

Below the sill:

$$N_f \text{ slightly } < N_f^*$$

("WALKING technicolor")

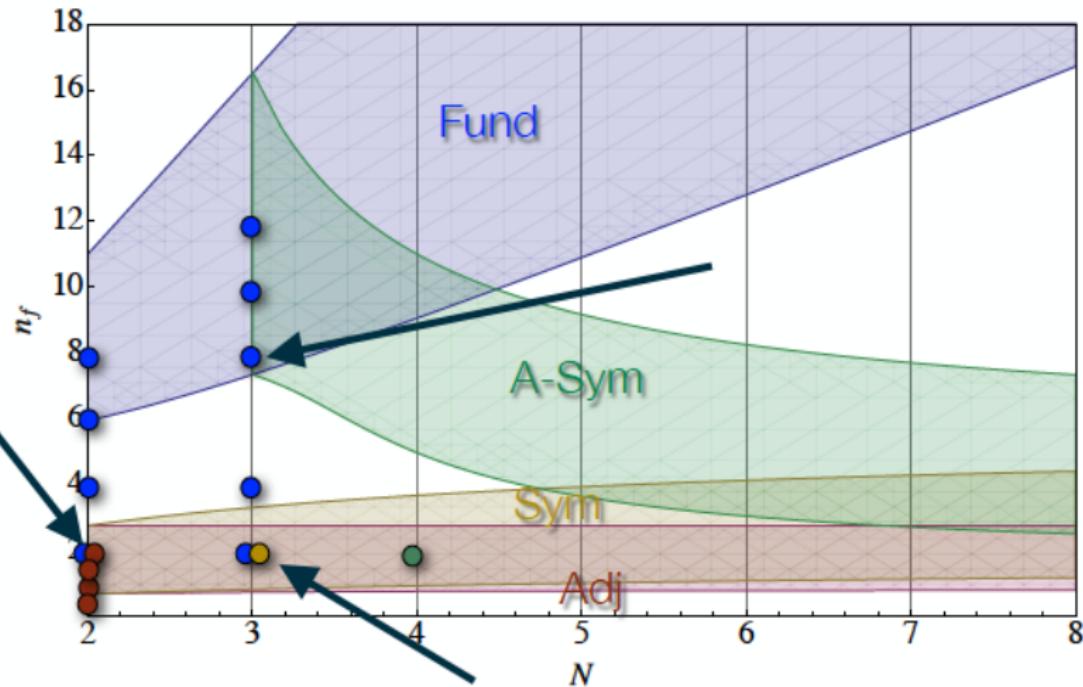


approximate scale invariance

- 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]

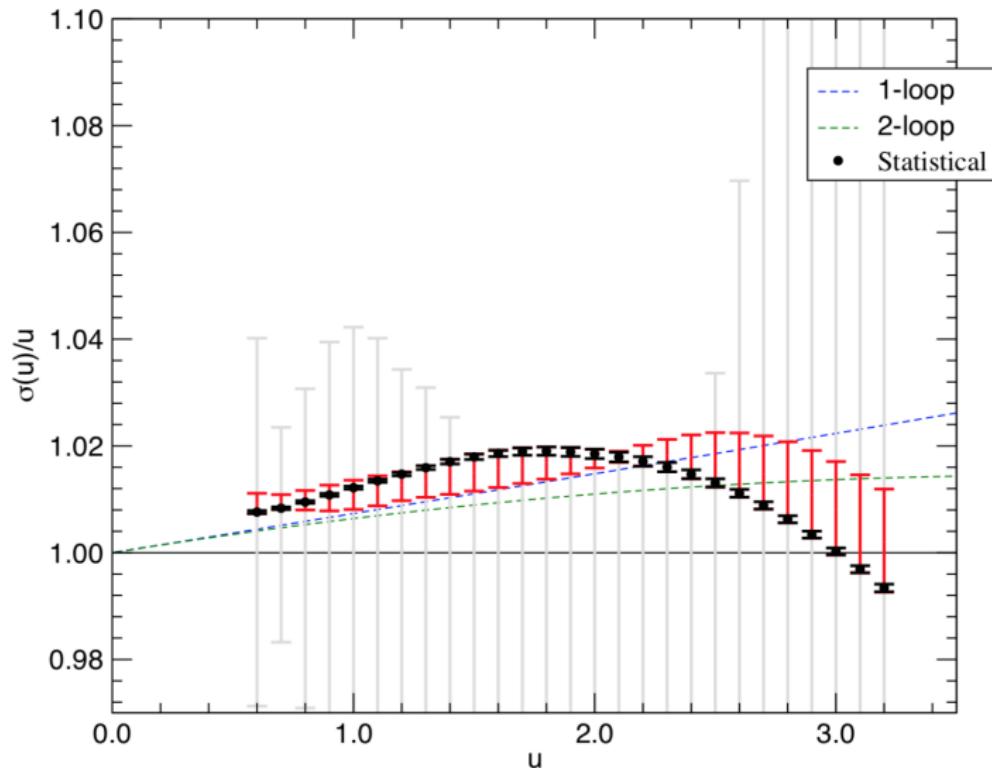
# current lattice studies



[Pica & Sannino 10]

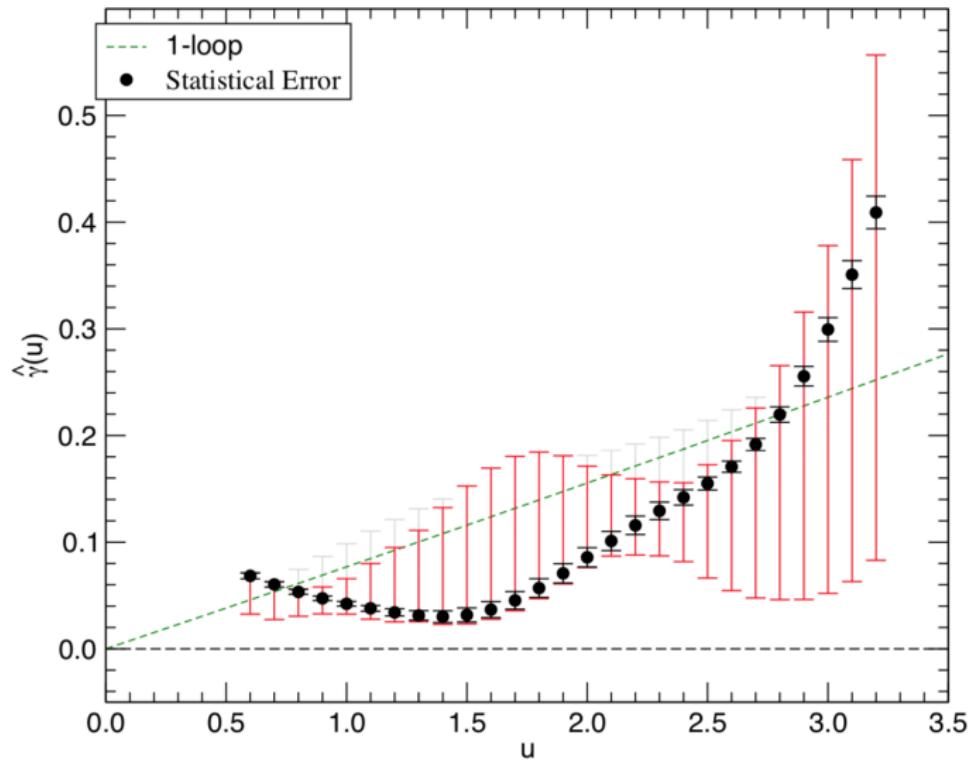
# IR fixed point

SU(2) gauge,  $n_f = 2$  adjoint representation - Schrödinger functional



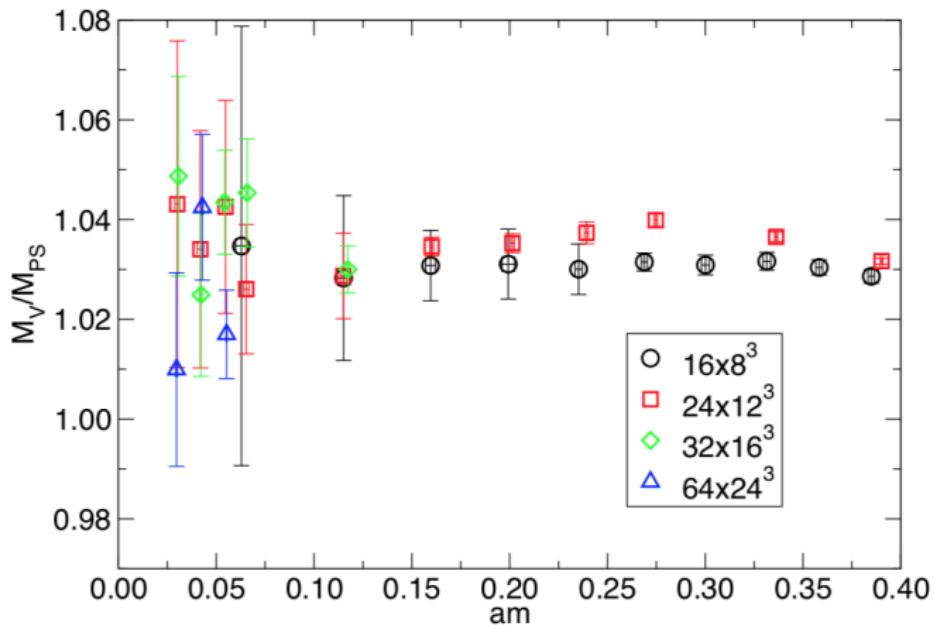
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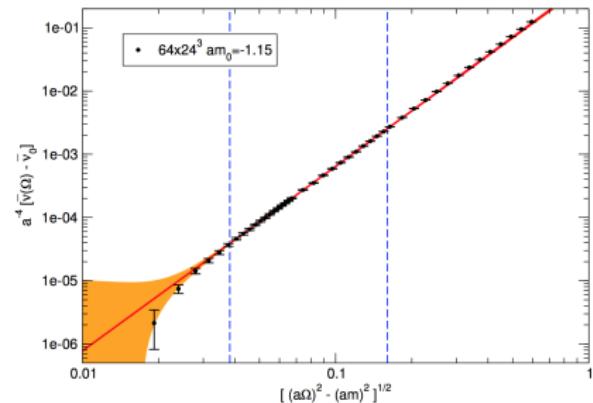
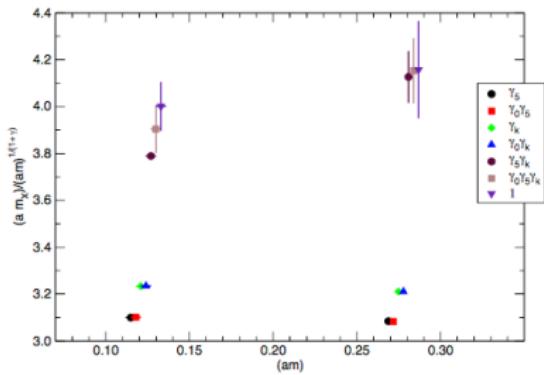


# IR fixed point

scaling relations for the spectrum

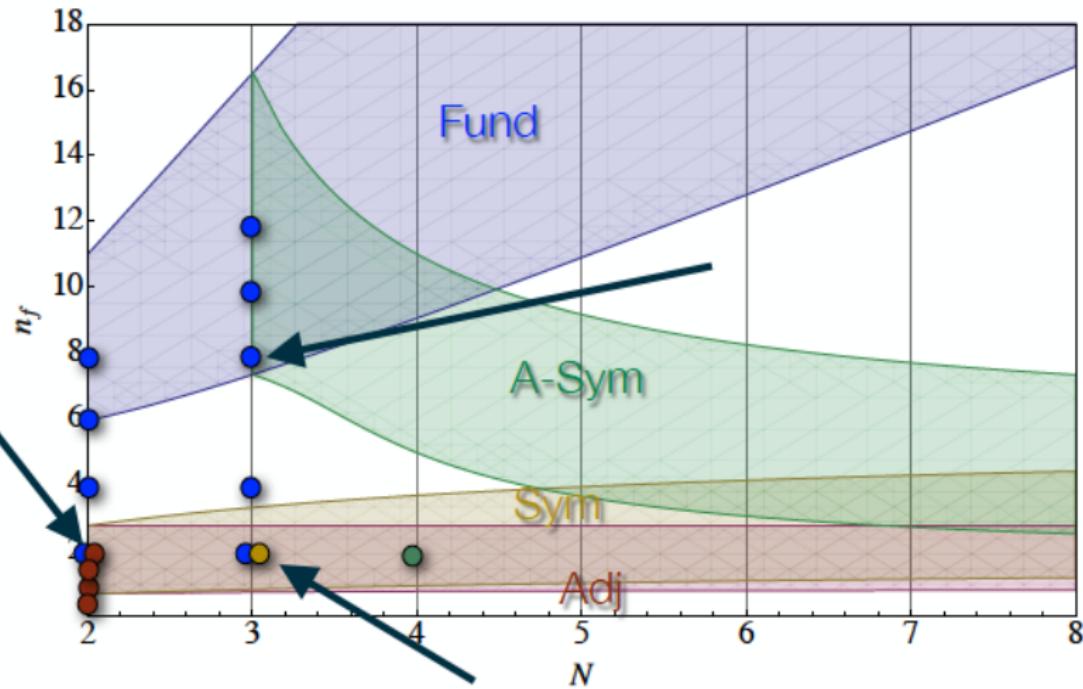
[LDD & Zwicky 10]

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



$$\gamma = 0.37 \pm 0.02$$

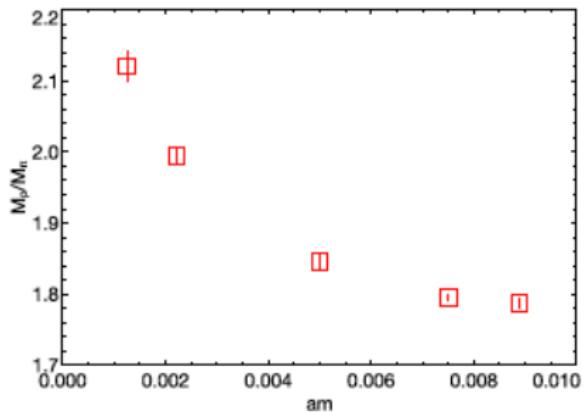
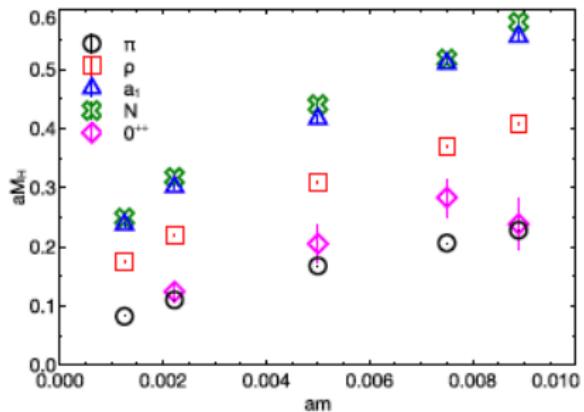
# current lattice studies



[Pica & Sannino 10]

# walking example - 1

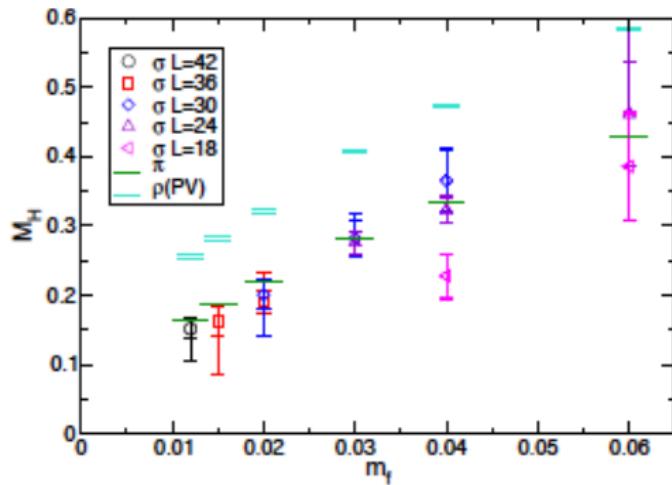
SU(3)  $n_f = 8$  fund – theory in the chirally broken phase



[Appelquist et al 16]

# walking example - 1

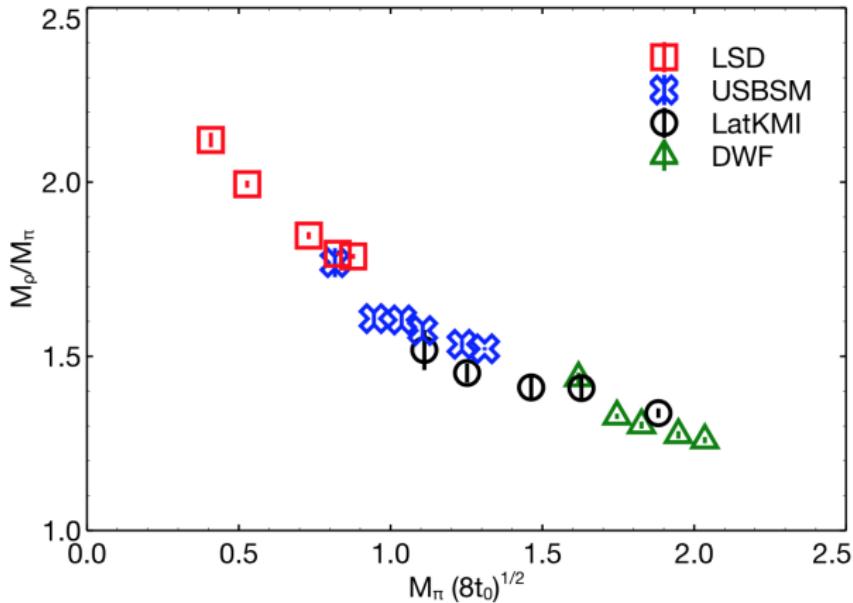
SU(3)  $n_f = 8$  fund



[Aoki et al 16]

# comparison

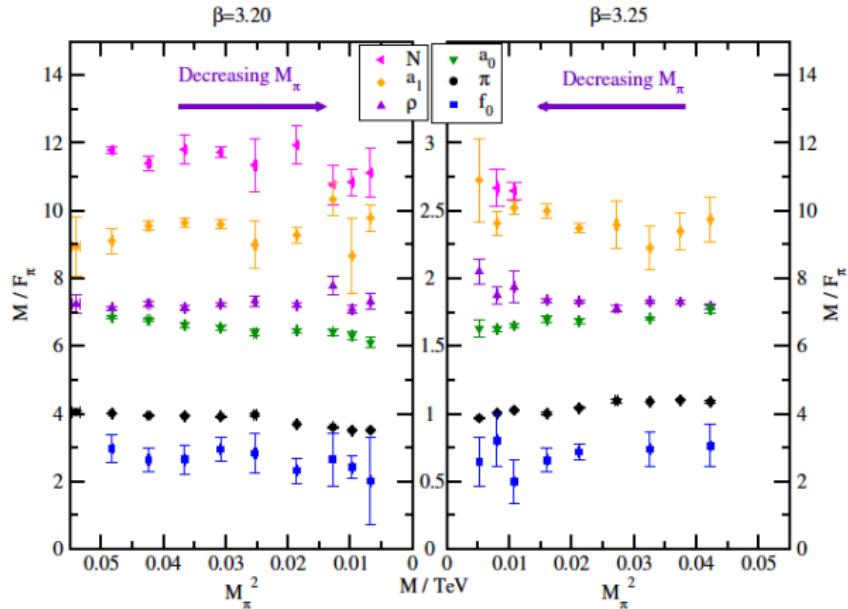
consistent results between different computations



[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]

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

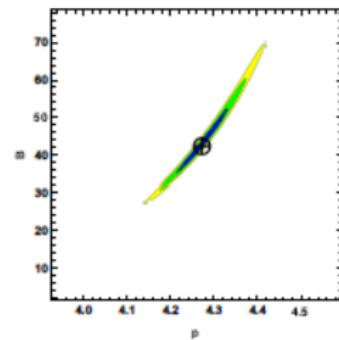
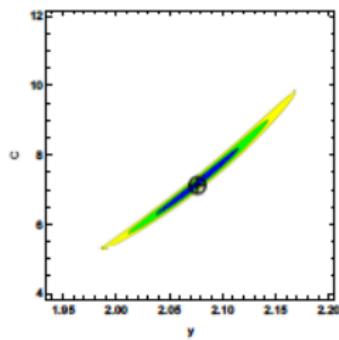
scaling laws:

$$M_\pi^2 F_\pi^{2-y} = C m,$$

$$V \propto \chi^p \implies \begin{cases} M_\pi^2 = B F_\pi^{p-2} \\ M_d^2 = \frac{y n_f}{2} \frac{f_\pi^2}{f_d^2} (p-y) B F_\pi^{p-2} \end{cases}$$

# results

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



[Appelquist et al 17]

# composite Higgs

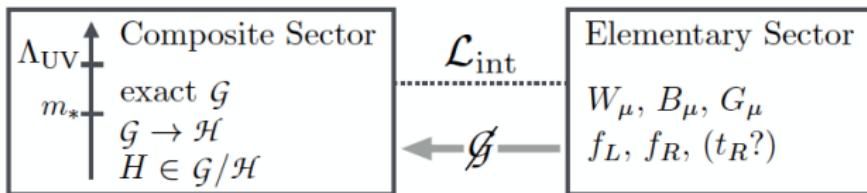


Figure 1.3: The basic structure of the composite Higgs scenario.

[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

	$G_{HC}$	$G_F$				
	$SU(4)$	$SU(5)$	$SU(3)$	$SU(3)'$	$U(1)_X$	$U(1)'$
$\psi$	<b>6</b>	<b>5</b>	<b>1</b>	<b>1</b>	0	-1
$\chi$	<b>4</b>	<b>1</b>	<b>3</b>	<b>1</b>	-1/3	5/3
$\tilde{\chi}$	<b><math>\bar{4}</math></b>	<b>1</b>	<b>1</b>	<b><math>\bar{3}</math></b>	1/3	5/3

[Ferretti 14, 16a,16b]

massless fermions, SSB of the global symmetry

$$\begin{aligned} \langle\psi\psi\rangle : & \quad \text{SU}(5) \longrightarrow \text{SO}(5) \\ \langle\chi\tilde{\chi}\rangle : & \quad \text{SU}(3) \times \text{SU}(3)' \longrightarrow \text{SU}(3)_c \end{aligned}$$

[Georgi & Kaplan 84]

# pNGB potential

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

[Ferretti 14]

where

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

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

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

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

[Golterman & Shamir 15]

# fermionic mass term

quadratic term involving the SM & BSM fermion fields

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

top quark mass given by the lowest eigenvalue:

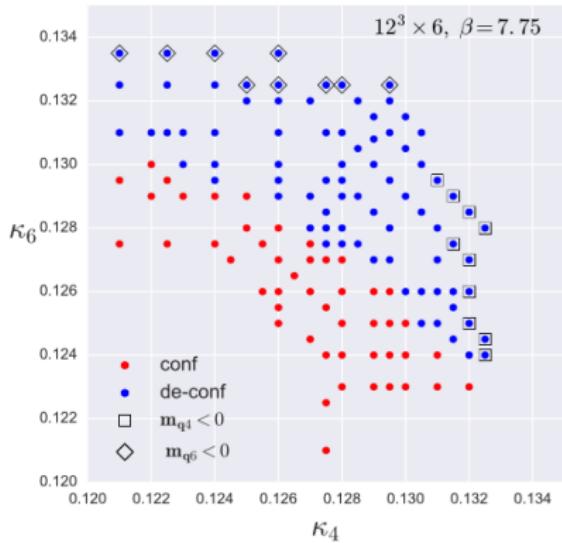
$$m_t/v = \sqrt{2} \frac{f}{M} \frac{1}{\sqrt{1 + \lambda_q^2 \frac{f^2}{M^2}}} \sqrt{1 + \lambda_t^2 \frac{f^2}{M^2}}$$

# TACO collaboration



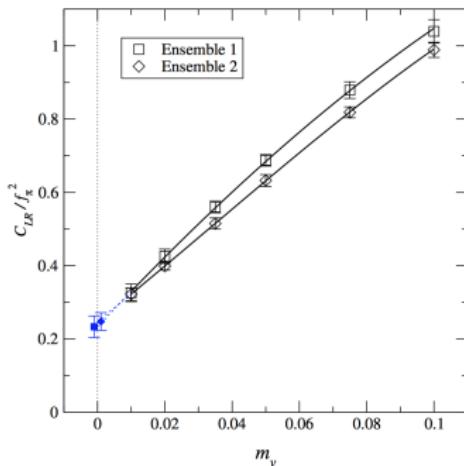
TACO (DeGrand et al.):  $SU(4)$  gauge with  $\{N_f = 2 \times \mathbf{6} \text{ and } 2 \times \mathbf{4}\}$   
— on the way to The Real Thing:  $\{\mathbf{5} \times \mathbf{6} \text{ (Majorana) and } \mathbf{3} \times \mathbf{4}\}$

(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  $C_{\text{LR}}, C_{\text{top}}$  (20% error) [Degrand et al 16a]

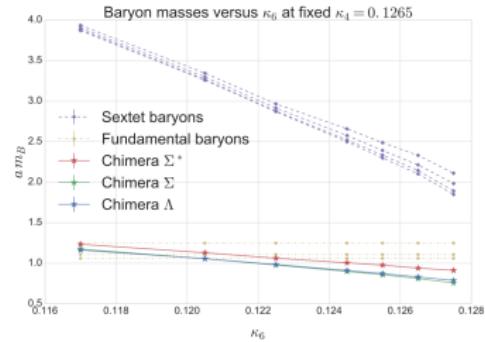
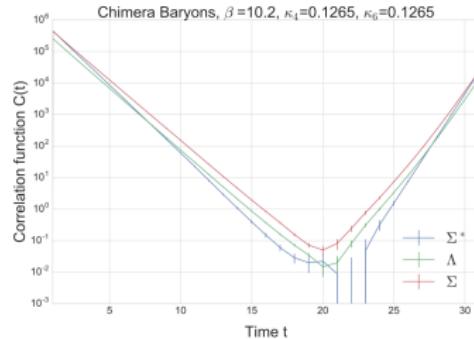


# top partner mass

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

## Baryon operators

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

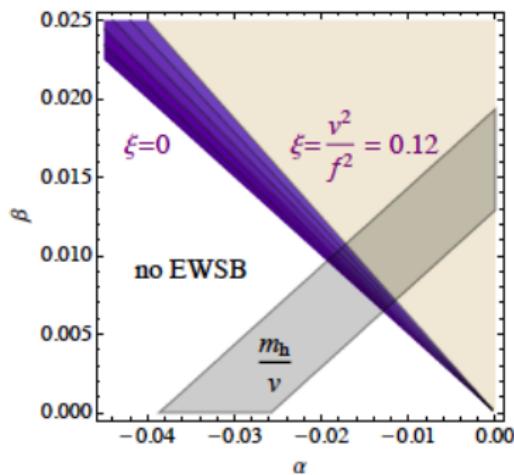


# opportunities for lattice computations

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

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

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



[Idd, 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:  $M/\text{TeV} \in [1.5, 3.5]$

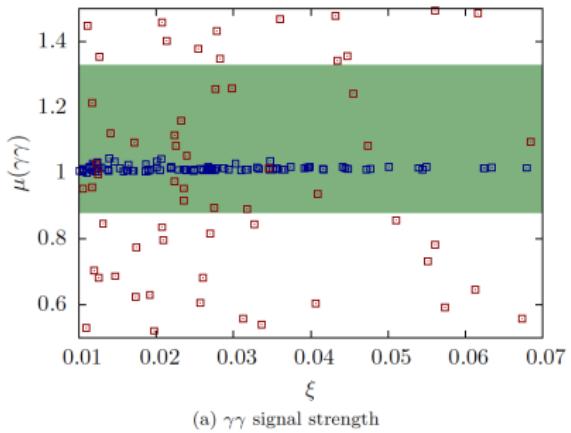
[Aad et al 12, CMS Collaboration 16, Matsedonskyi 15]

- $\lambda_t \in [0, 4\pi]$   
 $\lambda_q$  fixed by top mass
- pair produced color octet states: no evidence from Run-1, or first 13 TeV searches

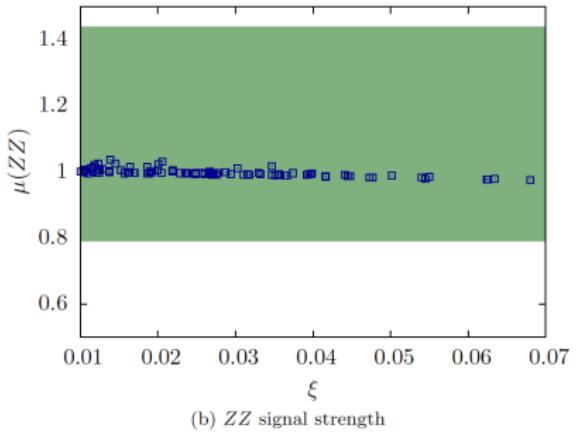
$SU(3) \times SU(3) \rightarrow SU(3)$  breaking scale  $> 6.5 \text{ TeV}$

[CMS]

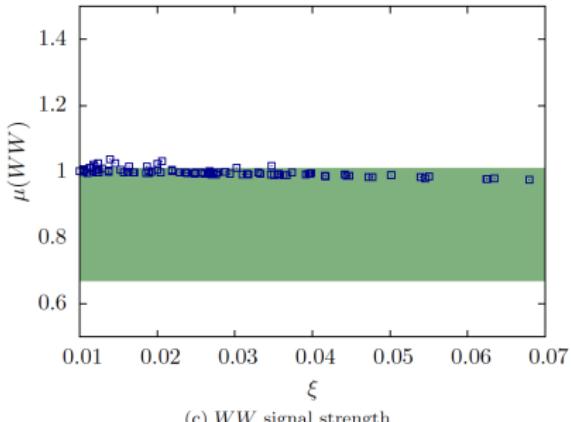
# higgs signal strength



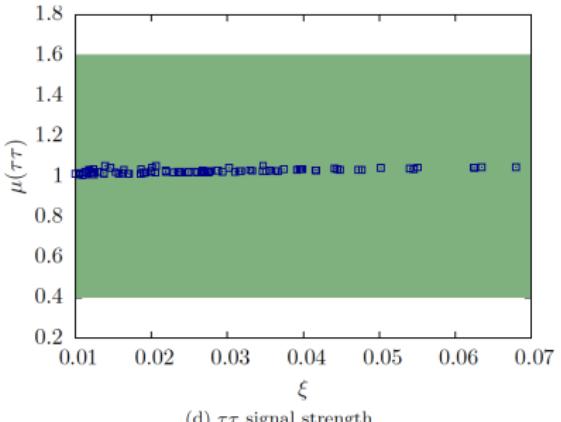
(a)  $\gamma\gamma$  signal strength



(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

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

