Composite two–Higgs doublet model from dilaton effective field theory

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XV Quark Confinement and the Hadron Spectrum

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Outline

Ingredients

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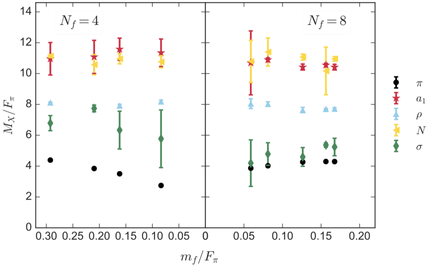
- $\mathcal{L}_{\text{SD}}$: Confines around 5 - 10 TeV. Study in isolation numerically on the lattice.
- $\mathcal{L}_{int}$: Contains irrelevant operators. Couplings between the SM and new strong sector which generate mass for the standard model fermions.

$\mathcal{L}_{\rm SD}$: SU(3) gauge theory with $N_f = 8$ Dirac fermions

Lattice studies indicate this theory has a light scalar: LatKMI '16, LSD '18



The lattice data can be described using a dilaton EFT with large anomalous dimension for $\langle\bar{\psi}\psi\rangle$: AIP '17, Fodor '19, Golterman '20.

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- These states are potentially within reach of future LHC direct searches.
- In general, 2HDMs have a large parameter space. What constraints do you get from assuming the Higgs doublets emerge as composites?
- Of course, compositeness solves hierarchy problem also in 2HDM case.

The W boson mass

SM Prediction:

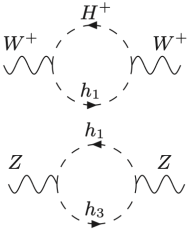
$$M_W = 80,357 \pm 6 \text{ MeV}/c^2$$

CDF II Experiment (2022):

$$M_W = 80,433.5 \pm 9.4 \text{ MeV}/c^2$$

- A 7σ discrepancy with SM.
- CDF II mass is *heavier*
- Based on data from Tevatron $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV.

Loops of second Higgs doublet states can contribute to gauge boson propagators



and explain the discrepancy.

SM Gauge Interactions

Based on the $N_f = 8$ gauge theory studied by LSD.

Fermion	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$SU(3)$
L_α	2	0	1	3
$R_{1,2}$	1	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	1	3
$\mathcal{T}$	1	2/3	3	3
$\mathcal{S}$	1	0	1	3

Table: SM quantum number assignments for 8 fermions same as in Vecchi '17, AIP '21

- 8 PNGBs have quantum numbers to form 2 Higgs doublets.
- Describe their low energy physics using dilaton EFT.

Dilaton EFT

- Matrix field Σ for 63 pNGBs, and real scalar field χ for dilaton.
- Chiral symmetry: $\mathrm{SU}(N_f)_L \times \mathrm{SU}(N_f)_R / \mathrm{SU}(N_f)_V$
  $\Sigma \to L \Sigma R^\dagger$.
- Scale invariance: Scale $\times$ Poincaré / Poincaré
  $\chi(x) \to e^\rho \chi(e^\rho x)$.
- Describe strong dynamics part of the model at low energies using dilaton EFT.

$$\mathcal{L}_{SD} = \frac{1}{2}(\partial\chi)^2 + \frac{F_\pi^2}{4}\left(\frac{\chi}{F_d}\right)^2 \mathrm{Tr}\left[D\Sigma D\Sigma^\dagger\right] + \frac{M_\pi^2 F_\pi^2}{4}\left(\frac{\chi}{F_d}\right)^y \mathrm{Tr}\left[\Sigma + \Sigma^\dagger\right] - V(\chi)\,. \quad (2)$$

$\mathcal{L}_{int}$: Interactions with SM fermions

1. Yukawa–like interaction to third family quarks

$$\mathcal{L}_Y = y_t F_\pi \left(\frac{\chi}{F_d}\right)^z \bar{Q}_L^\alpha \left(\mathrm{Tr}\left[P_\alpha \Sigma\right]\right) t_R + y_b F_\pi \left(\frac{\chi}{F_d}\right)^z \bar{Q}_L^\alpha \left(-i(\tau^2)_\alpha{}^\beta \mathrm{Tr}\left[P_\beta^\dagger \Sigma\right]\right) b_R + \mathrm{h.c}\,, \quad (3)$$

2. Extra potential for pNGBs and dilaton is generated from interactions with SM.

$$V_f = -\frac{C}{4}\left(\frac{\chi}{F_d}\right)^w \sum_\alpha \Big\{(1+\kappa)\left[(1+\lambda)\left|\mathrm{Tr}\left[P_\alpha\Sigma\right]\right|^2 + (1-\lambda)\left|\mathrm{Tr}\left[P_\alpha^\dagger\Sigma\right]\right|^2\right] + (1-\kappa)\left[(1+\lambda)\left|\mathrm{Tr}\left[R_\alpha\Sigma\right]\right|^2 + (1-\lambda)\left|\mathrm{Tr}\left[R_\alpha^\dagger\Sigma\right]\right|^2\right]\Big\}\,, \quad (4)$$

NB: The components of Σ representing the Higgs doublets are $H_{1\,\alpha} = \mathrm{Tr}\left[P_\alpha\Sigma\right]$ and $H_{2\,\alpha} = \mathrm{Tr}\left[R_\alpha\Sigma\right]$.

Vacuum Misalignment and Tuning

Only one of the Higgs doublets acquires a vacuum value, the second is inert.

$$v \equiv \sqrt{2} F_\pi \sin\theta \simeq 246\,\mathrm{GeV}\,. \tag{5}$$

We want the electroweak scale much smaller than the confinement scale $\Lambda \sim 4\pi F_\pi$. This involves some fine tuning:

$$\cos\theta = \frac{2 M_\pi^2 F_\pi^2}{C\,(1+\kappa)}\,. \tag{6}$$

We can easily satisfy collider bounds on new states if we take $F_\pi = 1$ TeV, which implies 2% tuning.

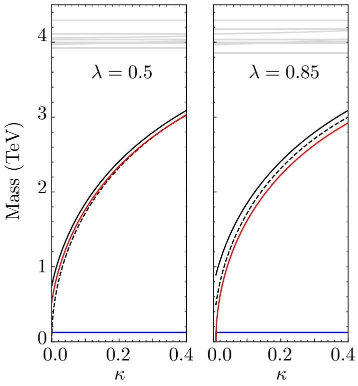
The 125 GeV Higgs

The 125 GeV Higgs is an admixture between one of the pNGBs and the dilaton.
This leads to a modification of its mass:

$$\frac{m_h^2}{v^2} \simeq \frac{M_\pi^2}{2F_\pi^2}\left(1 - \frac{2F_\pi^2 M_\pi^2 (y-w)^2}{F_d^2 M_d^2}\right) . \tag{7}$$

We can get $m_h/v \sim 1/2$ even when $M_\pi/F_\pi \sim 4$. This is the the parameter range for which we have lattice data from LSD collaboration.

Spectrum



- Majority of the 64 composite states have masses ~ 4 TeV.
- For small κ, just the 8 Higgs states can be made much lighter. There is an extra $U(1)$ symmetry in this limit.
- Hierarchy of Higgs masses controlled by λ.

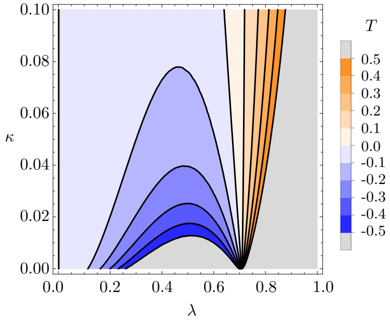
Two Higgs Doublet EFT

When $\kappa \ll 1$, the spectrum splits. An EFT involving just the two Higgs doublet states can be constructed.
Truncating this EFT to operators of $d \leq 4$ yields:

$$\begin{aligned} V = {} & m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - \left(m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right) \\ & + \frac{\beta_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\beta_2}{2}\left(H_2^\dagger H_2\right)^2 + \beta_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) \\ & + \beta_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left\{\frac{\beta_5}{2}\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right\} \\ & + \left\{\left[\beta_6\left(H_1^\dagger H_1\right) + \beta_7\left(H_2^\dagger H_2\right)\right]\left(H_1^\dagger H_2\right) + \text{h.c.}\right\} + \ldots \end{aligned} \tag{8}$$

The m_{ij}^2 and β_k can be computed by matching with underlying dilaton EFT.

S and T parameters



$|S| < 0.02$ everywhere with $\kappa > 0.01$.

- Second Higgs doublet states modify gauge boson propagators.
- Parametrize using precision electroweak parameters S, T, etc (Peskin '90).
- New CDF II result favors T in range $[0.1, 0.3]$ e.g. Silvestrini '22.
- S and T calculated from two Higgs doublet EFT parameters (Haber '00).

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1. We took the SU(3) gauge theory with $N_f = 8$ Dirac fermions and embedded a composite two Higgs doublet model within it.
2. We described the states $\lesssim 5$ TeV using dilaton EFT.
3. In part of the parameter space, the second Higgs doublet states are light ($\lesssim 1$ TeV). We describe this using two–Higgs doublet EFT.
4. This can shift the T parameter, compatible with CDF II measurement of W boson mass.

Thank you!

$U(1)_X$ Symmetry

The $U(1)_X$ symmetry acts on the PNGB fields:

$$\Sigma \to X \Sigma X^\dagger ,$$

where

$$X = \mathrm{diag}\left(e^{i\frac{\phi}{2}},\, e^{i\frac{\phi}{2}},\, e^{-i\frac{\phi}{2}},\, e^{-i\frac{\phi}{2}}, 1, 1, 1, 1 \right) .$$

Under the action of this symmetry, the two Higgs doublets are rotated into each other in the following way:

$$\mathrm{Tr}\left[P_\alpha \Sigma\right] \to \cos\phi \; \mathrm{Tr}\left[P_\alpha \Sigma\right] - \sin\phi \; \mathrm{Tr}\left[R_\alpha \Sigma\right] \; ,$$

$$\mathrm{Tr}\left[R_\alpha \Sigma\right] \to \cos\phi \; \mathrm{Tr}\left[R_\alpha \Sigma\right] + \sin\phi \; \mathrm{Tr}\left[P_\alpha \Sigma\right] \; .$$