# UV Completions of Composite Higgs Models with Partial Compositeness

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# Outline

- Introduction
- The General Setup
- Model I
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- Comparison with Bottom-up Approaches
- Conclusions

# Motivation

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_{em} \qquad H(x) = \frac{1}{\sqrt{2}} e^{i\sigma^a \chi^a(x)/v} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$\delta m^2 \sim \frac{\#}{16\pi^2} \Lambda_{NP}^2, \qquad \Lambda_{NP} \sim M_{Pl}$$

UV free gauge theory $\longrightarrow$ Dimensional Transmutation $\longrightarrow$ $\Lambda_{NP} \ll M_{Pl}$ naturally

# Higgs as a pNGB

$$G_f/H_f, \qquad \mathrm{SU}(2)\times\mathrm{U}(1)\subseteq H_f$$

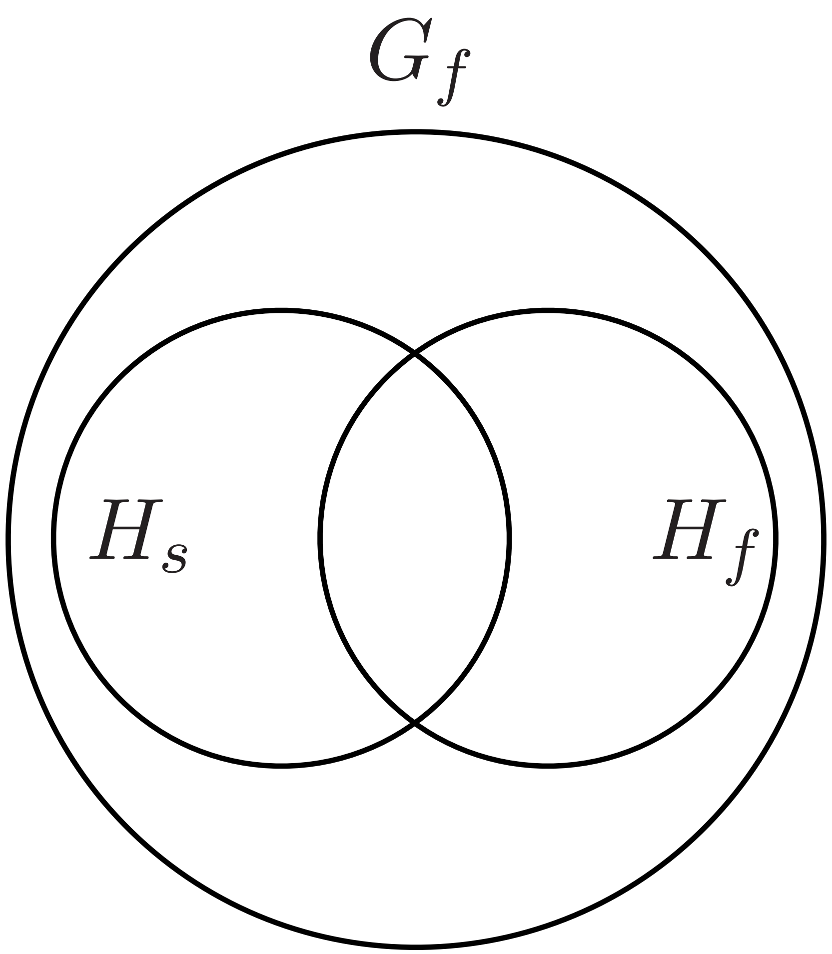
$$G_f = \mathrm{SO}(5)\times\mathrm{U}(1)_X$$

$$\downarrow$$

$$H_f = \mathrm{SO}(4)\times\mathrm{U}(1)_X$$

$$Y = T_{3R} + X$$

$$\Lambda_{NP} = \Lambda \approx 4\pi f$$




SM interactions ⇒ V(h)

$$\xi \equiv \frac{v^2}{f^2}$$

# Partial Compositeness

$$\mathcal{L} = \bar{\psi}_L \, i \, \partial\!\!\!/ \, \psi_L + \bar{\chi} \, (i \, \partial\!\!\!/ - m) \, \chi + \Delta_L \bar{\psi}_L \chi_R + h.c.$$

$$\tan \varphi_L = \frac{\Delta_L}{m}$$

$$|\text{light}\rangle = \cos \varphi_L |\psi\rangle + \sin \varphi_L |\chi\rangle$$

$$|\text{heavy}\rangle = - \sin \varphi_L |\psi\rangle + \cos \varphi_L |\chi\rangle$$

$$\mathcal{L} \supseteq \bar{\chi} Y_* H \tilde{\chi} + h.c. \qquad \Rightarrow \qquad y = Y_* \sin \varphi_L \sin \varphi_R$$

- Flavour hierarchies
- GIM-like mechanism suppressing FCNC and $\not{C}\!\!\not{P}$ processes

# Features of our Setup

- BSM sector giving rise to a (pseudo)NGB field with the quantum numbers of the Higgs;
- coupling of SM fields to BSM physics through Partial Compositeness;
- purely 4d strongly interacting sector;
- low energy description of strongly coupled physics with the help of supersymmetry, via Seiberg duality for gauge theories.

# Seiberg Duality for $\mathcal{N}=1$ SO(N) SQCD

| | $\mathrm{SO}(N)_g$ | $\mathrm{SU}(N_f)$ | $\mathrm{U}(1)_R$ |
|---|---|---|---|
| $Q_I^N$ | $\mathbf{N}$ | $\mathbf{N_f}$ | $\frac{(N_f-N+2)}{N_f}$ |

$$(N-2) < N_f < 3(N-2)$$

| | $\mathrm{SO}(N_f-N+4)_g$ | $\mathrm{SU}(N_f)$ | $\mathrm{U}(1)_R$ |
|---|---|---|---|
| $q_I^n$ | $\mathbf{N_f-N+4}$ | $\overline{\mathbf{N}}_\mathbf{f}$ | $\frac{N-2}{N_f}$ |
| $M_{IJ}$ | $\mathbf{1}$ | $\frac{\mathbf{1}}{\mathbf{2}}\mathbf{N_f(N_f+1)}$ | $\frac{2(N_f-N+2)}{N_f}$ |

$$\Lambda_{el}^{3(N-2)-N_f}\Lambda_{mag}^{3(N_f-N+2)-N_f} \propto (-1)^{N_f-N}\mu^{N_f}$$

$$(N-2) < N_f \leq \frac{3}{2}(N-2) \quad \Rightarrow \quad g_{mag} \xrightarrow{IR} 0$$

$$b = 3(N-2) - N_f$$

$$\Lambda_{el} = E\exp\left(-\frac{8\pi^2}{b\, g_{el}^2(E)}\right)$$

$$M_{IJ} \sim Q_I^N Q_J^N$$

$$W_{mag} \propto \frac{1}{\mu} q_I^n M^{IJ} q_J^n$$

# The General Setup

$\mathcal{N} = 1$ SUSY SO$(N)$ $\quad N_f = N$

$$W_{el} = m_{ab} Q^a Q^b + \lambda_{IJK} Q^I Q^J \xi^K$$

$$Q_I^N = \begin{pmatrix} Q_1^N \\ \vdots \\ Q_5^N \\ \hline Q_6^N \\ \vdots \\ Q_{N_f}^N \end{pmatrix} \begin{matrix} \left.\vphantom{\begin{matrix} Q \\ \vdots \\ Q \end{matrix}}\right\} Q_a^N \\ \left.\vphantom{\begin{matrix} Q \\ \vdots \\ Q \end{matrix}}\right\} Q_i^N \end{matrix}$$

$$m_{ab} = m_Q \delta_{ab} \qquad G_f = \mathrm{SO}(5) \times \mathrm{SU}(N-5)$$

$$\mathcal{N} = 1 \text{ SUSY SO}(N) \qquad N_f = N$$

$$\downarrow$$

$$N \leq 3(N-2)/2 \quad \Rightarrow \quad N \geq 6$$

$$\text{SO}(N_f - N + 4)_m = \text{SO}(4)_m$$

$$W_{mag} = q_I M^{IJ} q_J - \mu^2 M_{aa} + \epsilon_{IJK} M^{IJ} \xi^K$$

$$\epsilon_{IJK} = \lambda_{IJK}\Lambda, \qquad \mu^2 = -m_Q \Lambda$$

$$F_{M_{ab}} = q_a^n q_b^n - \mu^2 \delta_{ab}$$

$$\langle q_a^n \rangle = \left( \begin{array}{c|c} & 0 \\ \mu \mathbb{1}_4 & 0 \\ & 0 \\ & 0 \end{array} \right) \qquad\qquad a = (m,5),\ m,n = 1,2,3,4$$

$$\mathrm{SO}(4)_m \times \mathrm{SO}(5) \times \mathrm{SU}(N-5) \to \mathrm{SO}(4)_D \times \mathrm{SU}(N-5)$$

$$\begin{aligned} \mathrm{Re}\,(q_n^m - q_m^n)\ &:\ \text{along the broken}\, \mathrm{SO}(4)_m \times \mathrm{SO}(4) \text{ directions} \\ &\quad\ \text{eaten by the magnetic vector bosons}\,; \\ \sqrt{2}\,\mathrm{Re}\, q_5^n\ &:\ \text{along the broken}\, \mathrm{SO}(5)/\mathrm{SO}(4)_D \text{ directions} \\ &\quad\ \text{identified with the Higgs field}\,. \end{aligned}$$

The chiral multiplets $M_{ij}$ and $M_{i5}$ stay massless;
$\psi_{M_{55}}$ is the Goldstino.

# SM Gauge Group

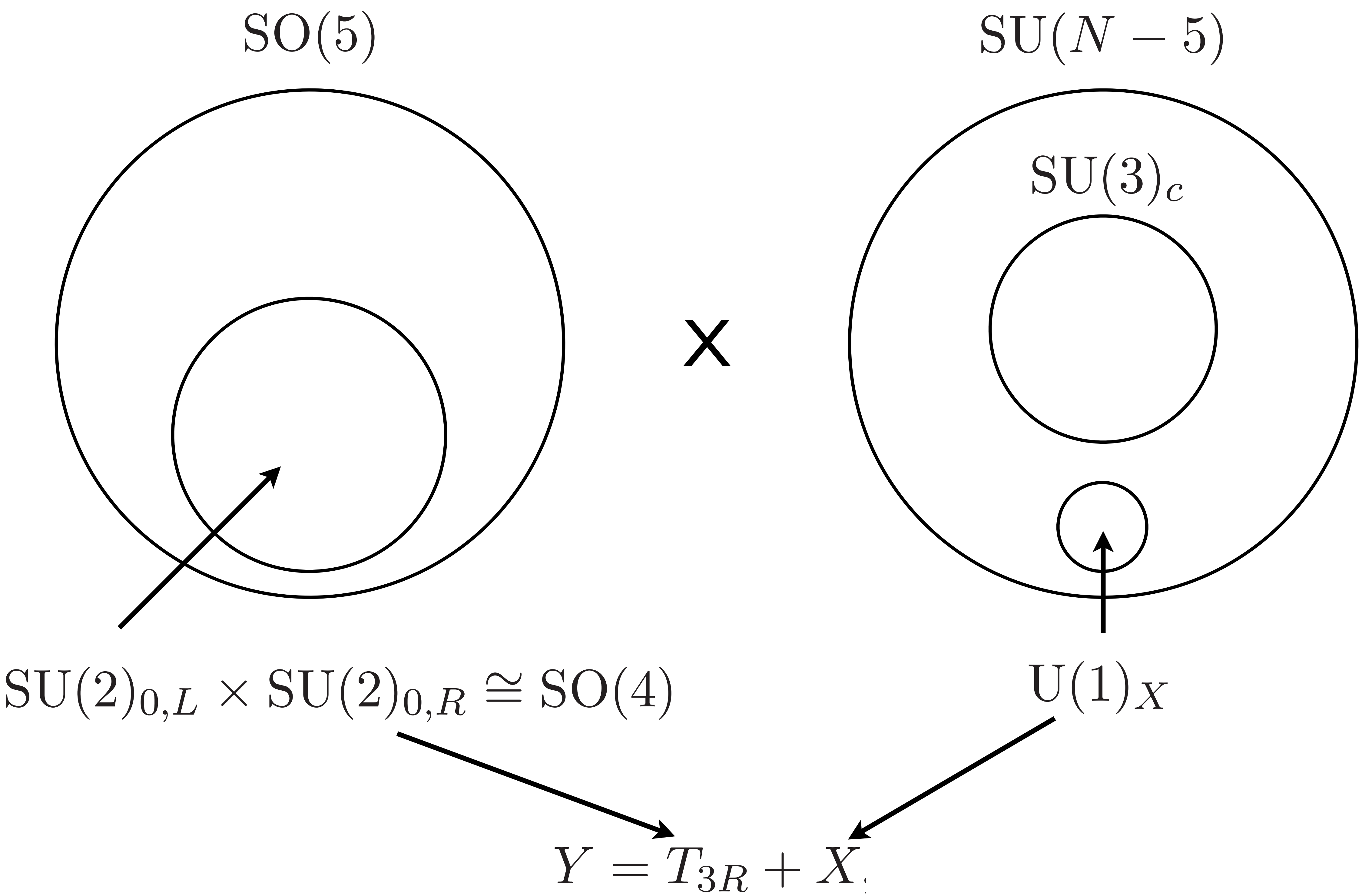
$$\mathrm{SO}(5) \times \mathrm{SU}(N-5) \supseteq \mathrm{SU}(3)_c \times \mathrm{SU}(2)_{0,L} \times \mathrm{U}(1)_{0,Y}$$

$$\mathrm{SU}(3)_c \subseteq \mathrm{SU}(N-5)$$

$$\mathrm{SU}(2)_{0,L} \times \mathrm{SU}(2)_{0,R} \cong \mathrm{SO}(4) \subseteq \mathrm{SO}(5)$$

$$Y = T_{3R} + X, \quad \mathrm{U}(1)_X \subseteq \mathrm{SU}(N-5)$$

# SM Gauge Group



# Model I

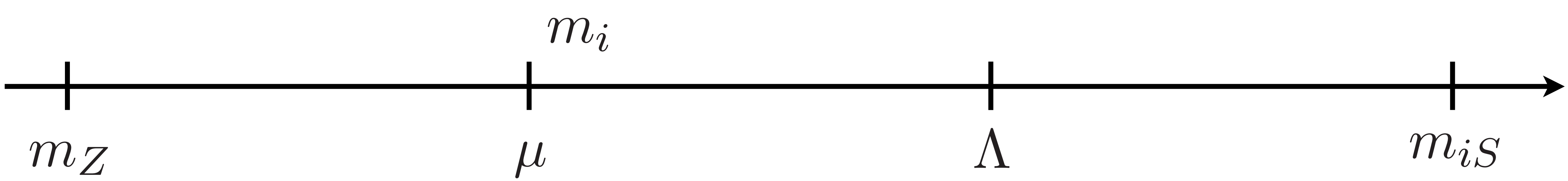
$N = N_f = 11$ $\qquad$ $G_f = \mathrm{SO}(5) \times \mathrm{SO}(6)$

$$W_{el} \supseteq \frac{1}{2} m_{1S} S_{ij}^2 + \lambda_1 Q^i Q^j S_{ij} + \frac{1}{2} m_{2S} S_{ia}^2 + \lambda_2 Q^i Q^a S_{ia}$$

| | $\mathrm{SO}(11)_{el}$ | $\mathrm{SO}(5)$ | $\mathrm{SO}(6)$ |
|---|---|---|---|
| $Q_i^N$ | $\mathbf{11}$ | $\mathbf{1}$ | $\mathbf{6}$ |
| $Q_a^N$ | $\mathbf{11}$ | $\mathbf{5}$ | $\mathbf{1}$ |
| $S_{ij}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{20} \oplus \mathbf{1}$ |
| $S_{ia}$ | $\mathbf{1}$ | $\mathbf{5}$ | $\mathbf{6}$ |

| | $\mathrm{SO}(4)_{mag}$ | $\mathrm{SO}(5)$ | $\mathrm{SO}(6)$ |
|---|---|---|---|
| $q_i^n$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{6}$ |
| $q_a^n$ | $\mathbf{4}$ | $\mathbf{5}$ | $\mathbf{1}$ |
| $M_{ij}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{20} \oplus \mathbf{1}$ |
| $M_{ia}$ | $\mathbf{1}$ | $\mathbf{5}$ | $\mathbf{6}$ |
| $M_{ab}$ | $\mathbf{1}$ | $\mathbf{14} \oplus \mathbf{1}$ | $\mathbf{1}$ |

$$W_{mag} \supset -\frac{1}{2} m_1 M_{ij}^2 - \frac{1}{2} m_2 M_{ia}^2$$



# Top Quark Partial Compositeness

$$W_{el} \supseteq \lambda_L (\xi_L)^{ia} Q_i Q_a + \lambda_R (\xi_R)^{ia} Q_i Q_a$$

$$\downarrow$$

$$W_{mag} \supseteq \epsilon_L (\xi_L)^{ia} M_{ia} + \epsilon_R (\xi_R)^{ia} M_{ia}$$

$$(\xi_L)^{ia} = \begin{pmatrix} b^1 & -ib^1 & t^1 & it^1 & 0 \\ -ib^1 & -b^1 & -it^1 & t^1 & 0 \\ b^2 & -ib^2 & t^2 & it^2 & 0 \\ -ib^2 & -b^2 & -it^2 & t^2 & 0 \\ b^3 & -ib^3 & t^3 & it^3 & 0 \\ -ib^3 & -b^3 & -it^3 & t^3 & 0 \end{pmatrix}_{2/3}, \quad (\xi_R)^{ia} = \begin{pmatrix} 0 & 0 & 0 & 0 & (t^c)^1 \\ 0 & 0 & 0 & 0 & i(t^c)^1 \\ 0 & 0 & 0 & 0 & (t^c)^2 \\ 0 & 0 & 0 & 0 & i(t^c)^2 \\ 0 & 0 & 0 & 0 & (t^c)^3 \\ 0 & 0 & 0 & 0 & i(t^c)^3 \end{pmatrix}_{-2/3},$$

# Explicit Soft SUSY Breaking

- ✦ Gauginos' masses
- ✦ SM Sparticles' masses

(as in the MSSM)

For simplicity we ignore SUSY breaking terms in the composite sector:

$$-\mathcal{L}_{\cancel{SUSY}} = \widetilde{m}_L^2|\widetilde{t}_L|^2 + \widetilde{m}_R^2|\widetilde{t}_R|^2 + \left(\epsilon_L B_L(\xi_L)_{ia} M_{ia} + \epsilon_R B_R(\xi_R)_{ia} M_{ia} + \frac{1}{2}\widetilde{m}_{g,\alpha}\lambda_\alpha\lambda_\alpha + h.c.\right)$$

$\Longrightarrow$ no qualitative change in the spectrum

General breaking:

$$\mathcal{L} \supseteq \widetilde{m}_{1el}^2 Q^{\dagger a} Q^a + \widetilde{m}_{2el}^2 Q^{\dagger i} Q^i + \left(\frac{1}{2}\widetilde{m}_\lambda \lambda^{ab}\lambda^{ab} + h.c.\right)$$

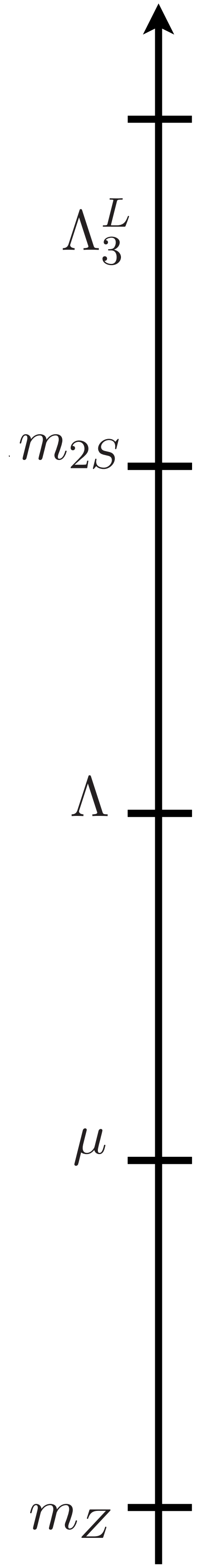
# Landau Poles

$$\Lambda_3^L = m_{2S}\ \exp\left(\frac{2\pi}{21\alpha_3(m_Z)}\right)\left(\frac{m_Z}{\mu}\right)^{-\frac{1}{3}}\left(\frac{\mu}{\Lambda}\right)^{\frac{2}{7}}\left(\frac{\Lambda}{m_{2S}}\right)^{\frac{16}{21}},$$

$$\Lambda_2^L = m_{2S}\ \exp\left(\frac{2\pi}{17\alpha_2(m_Z)}\right)\left(\frac{m_Z}{\mu}\right)^{-\frac{19}{102}}\left(\frac{\mu}{\Lambda}\right)^{\frac{22}{17}}\left(\frac{\Lambda}{m_{2S}}\right)^{\frac{11}{17}},$$

$$\Lambda_1^L = m_{2S}\ \exp\left(\frac{2\pi}{91\alpha_1(m_Z)}\right)\left(\frac{m_Z}{\mu}\right)^{\frac{41}{546}}\left(\frac{\mu}{\Lambda}\right)^{\frac{336}{546}}\left(\frac{\Lambda}{m_{2S}}\right)^{\frac{215}{273}}.$$

$$\Lambda_3^L \sim 10^2 - 10^3\ \text{TeV}$$



# Model II

$N = N_f = 9$

$W_{el} \supseteq \lambda Q^i Q^j S_{ij}$

$G_f = \mathrm{SO}(5) \times \mathrm{SU}(4)$

| | $\mathrm{SO}(9)_{el}$ | $\mathrm{SO}(5)$ | $\mathrm{SU}(4)$ |
|---|---|---|---|
| $Q_i^N$ | $\mathbf{9}$ | $\mathbf{1}$ | $\overline{\mathbf{4}}$ |
| $Q_a^N$ | $\mathbf{9}$ | $\mathbf{5}$ | $\mathbf{1}$ |
| $S_{ij}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{10}$ |

$W_{mag} \supseteq M M_{ij} S_{ij}$

| | $\mathrm{SO}(4)_{mag}$ | $\mathrm{SO}(5)$ | $\mathrm{SU}(4)$ |
|---|---|---|---|
| $q_i^n$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{4}$ |
| $q_a^n$ | $\mathbf{4}$ | $\mathbf{5}$ | $\mathbf{1}$ |
| $M_{ia}$ | $\mathbf{1}$ | $\mathbf{5}$ | $\overline{\mathbf{4}}$ |
| $M_{ab}$ | $\mathbf{1}$ | $\mathbf{14} \oplus \mathbf{1}$ | $\mathbf{1}$ |

$\mathrm{SU}(4) \supset \mathrm{SU}(3)_c \times \mathrm{U}(1)_X$

$\mathbf{4} = \mathbf{3}_{2/3} + \mathbf{1}_{-2}$

$M_{i5}$ stays massless:

$M_{\alpha 5}, \ \alpha = 6, 7, 8$

$M_{95}$

# Bottom-up Approach

$$\mathrm{SO}(5) \times \mathrm{SO}(4) \to \mathrm{SO}(4)_D$$

$$q_b^n = \exp\left(\frac{i\sqrt{2}}{f} h^{\hat{a}} T_{\hat{a}} + \frac{i}{2f}\pi^a T_a\right)_{bc} \widetilde{q}_c^m \exp\left(\frac{i}{2f}\pi^a T_a\right)_{mn}$$

**effective** $\mathrm{SO}(5)/\mathrm{SO}(4)$

$$U = \exp\left(i\frac{\sqrt{2}}{f} h^{\hat{a}} T_{\hat{a}}\right), \qquad U \to g\, U\, h^\dagger, \qquad f = \sqrt{2}\mu$$

$$m_W = \frac{gf}{2} \sin\frac{\langle h\rangle}{f} \equiv \frac{gv}{2}, \qquad m_Z = \frac{m_W}{\cos\theta_W}$$

# Conclusions

- Explicit 4d realization of pNGB Higgs idea
- Partial Compositeness
- SUSY

## Possible Future Directions

- Higgs potential
- ~~SUSY~~
- Non top SM fields masses ( $\lambda_{ab}\xi_L Q_a Q_b \xi_R$ )

Thank You