Minimal Neutral Naturalness Model

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1810.01882

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Origin of EWSB

- Landau Ginzburg Potential with its origin unexplained

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- Other Possibilities?

Origin of EWSB

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$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- Other Possibilities?
- Pseudo Nambu-Goldstone Higgs (coset G/H)
  - Naturalness problem solved $\quad m_h \sim a \frac{y_t f}{4\pi} \sim \frac{3M_T}{4\pi}$
  - Radiative Higgs potential $\quad$ Shift Symmetry $\pi \to \pi + c$
  - EWSB explained

Modeling EWSB

$$V(h) \simeq -\gamma \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right)$$

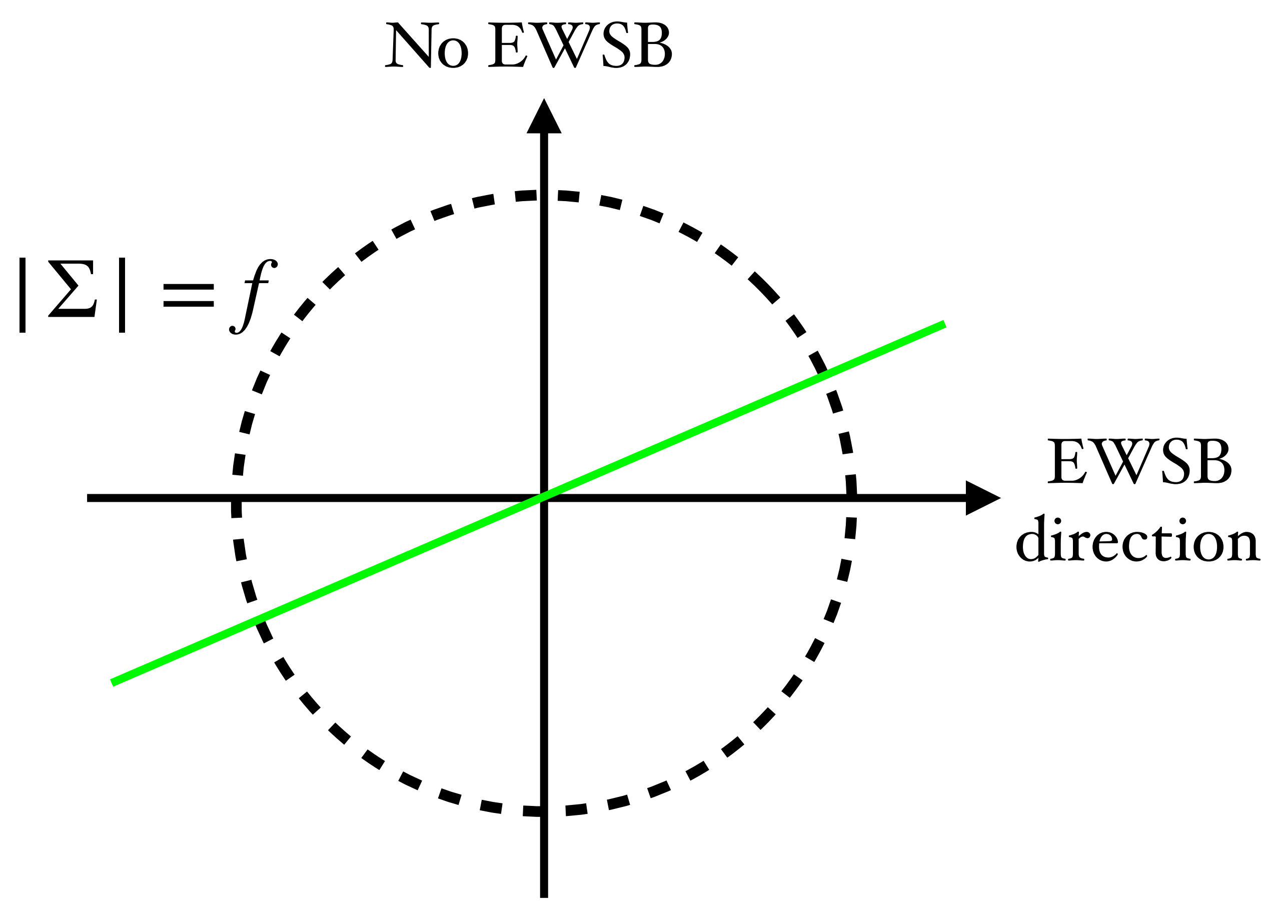
misalignment: $\frac{v^2}{f^2} = \frac{\gamma}{2\beta}$

Modeling EWSB

$$V(h) \simeq -\gamma \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right) \Rightarrow$$

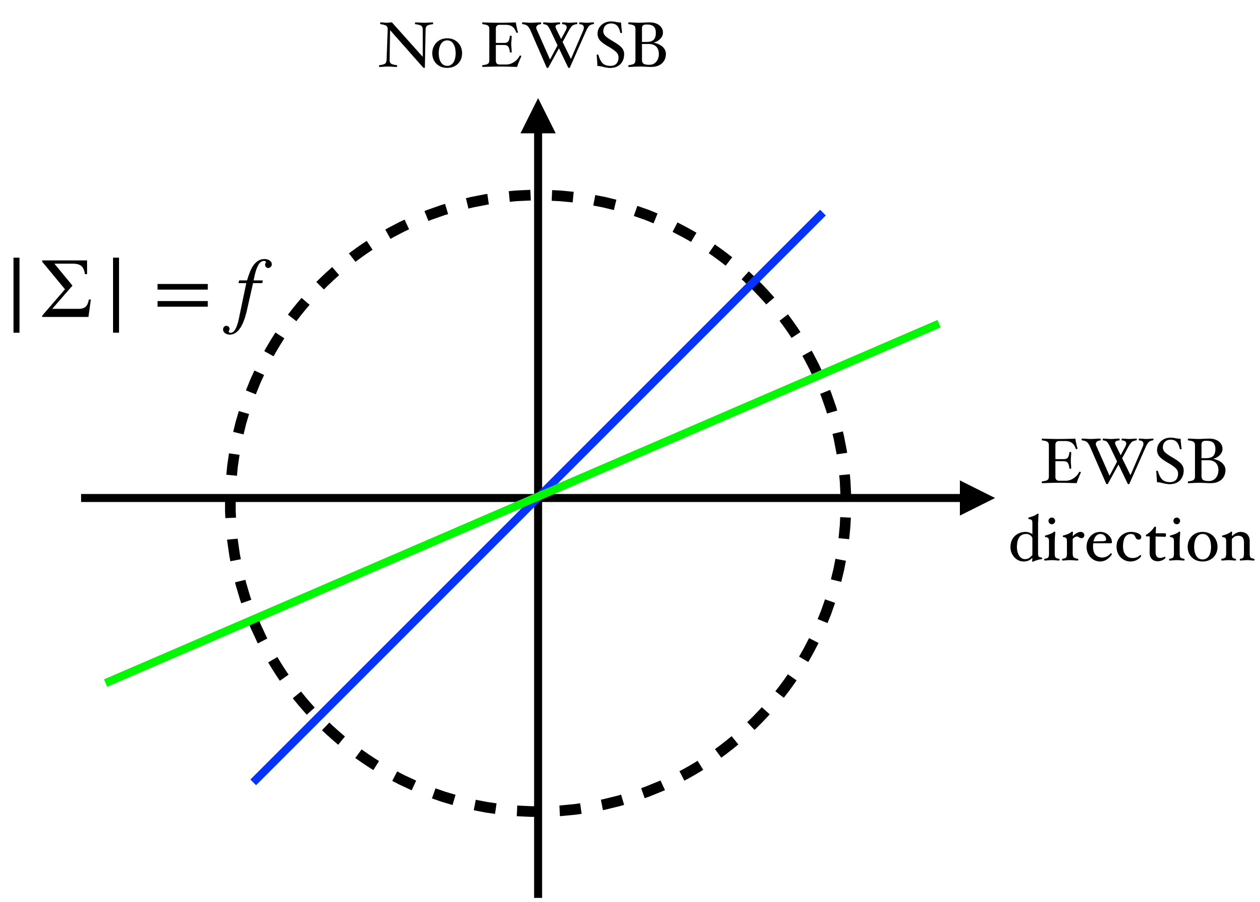
misalignment: $\frac{v^2}{f^2} = \frac{\gamma}{2\beta}$

$\beta \ll \gamma \left(\frac{v^2}{f^2} \sim 1\right)$



Modeling EWSB

$$V(h) \simeq -\gamma \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right) \quad \Rightarrow \quad \text{misalignment:} \quad \frac{v^2}{f^2} = \frac{\gamma}{2\beta}$$



$$\beta \ll \gamma \quad \left(\frac{v^2}{f^2} \sim 1\right)$$

$$\beta = \gamma \quad \left(\frac{v^2}{f^2} = 0.5\right)$$

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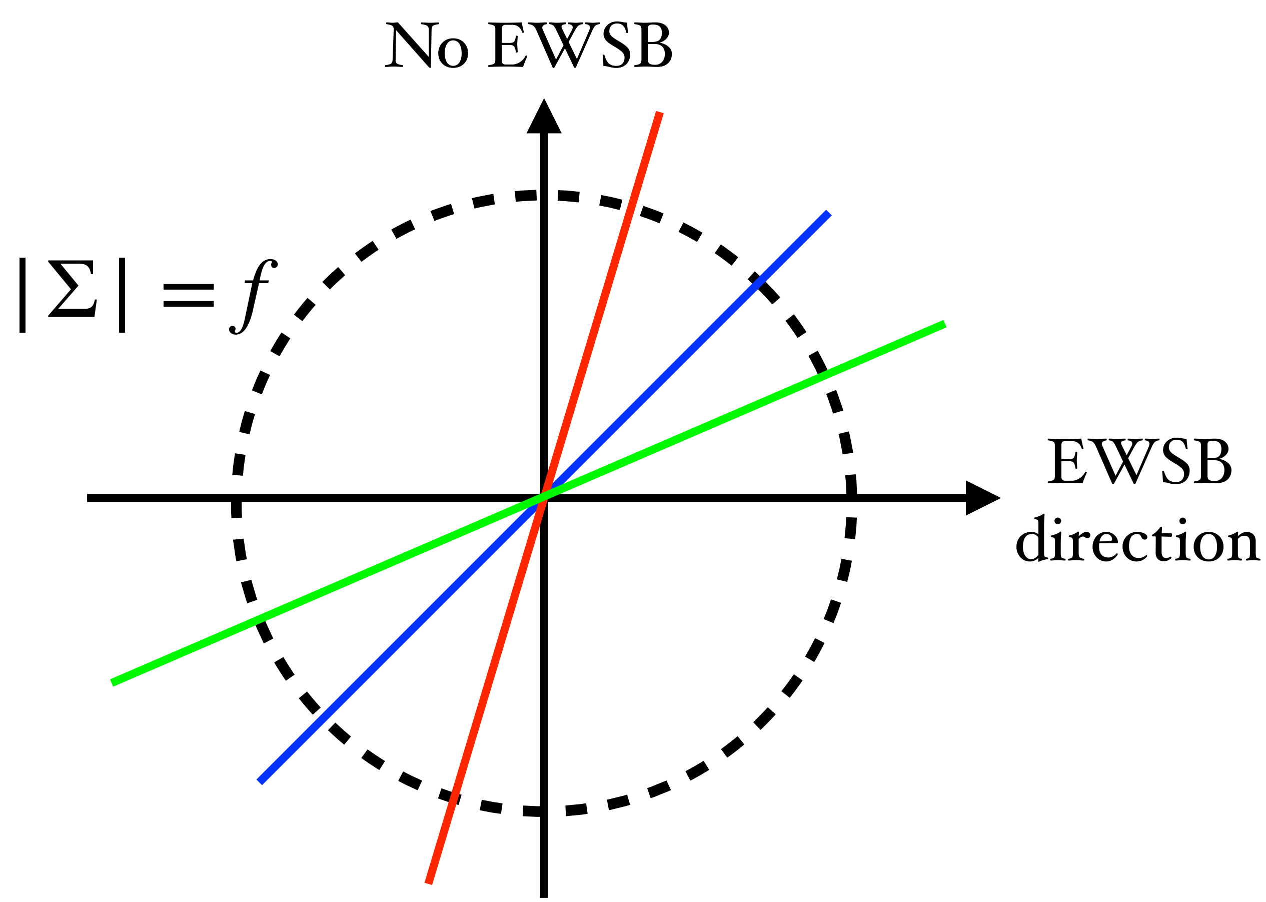

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as required by Higgs data

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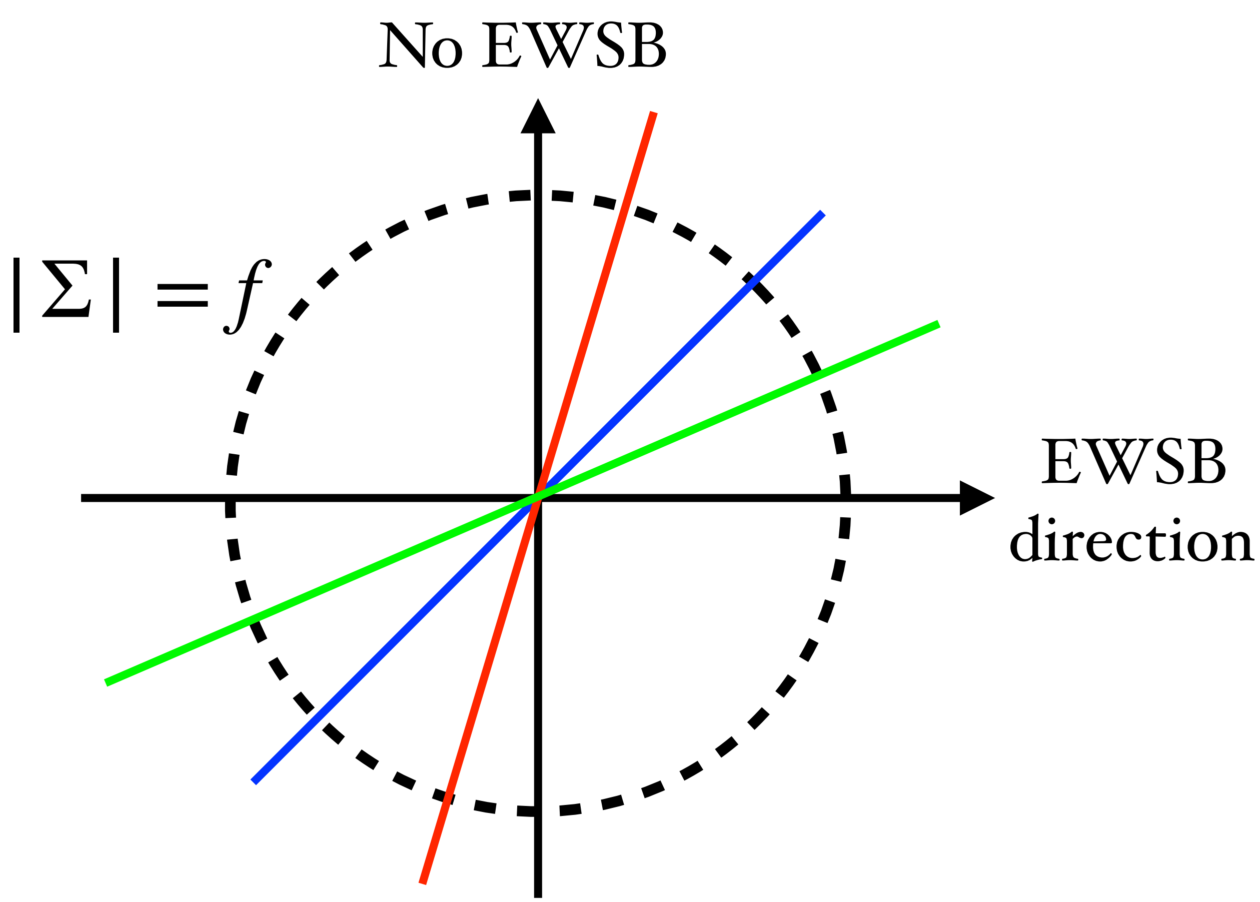

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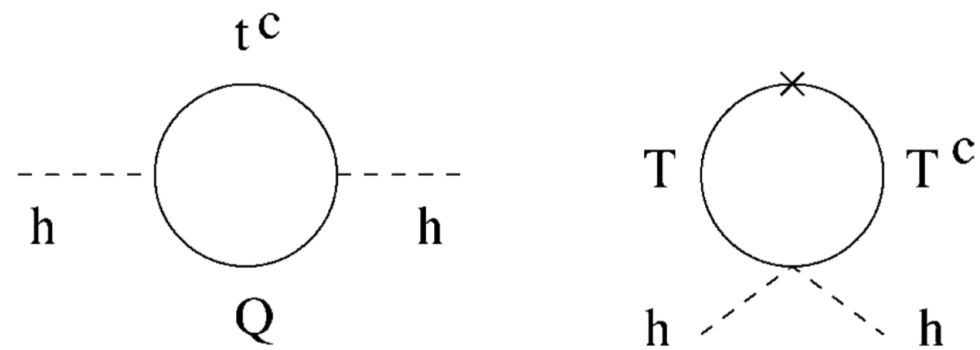
Can small misalignment angle be realized naturally?

Neutral Naturalness Era

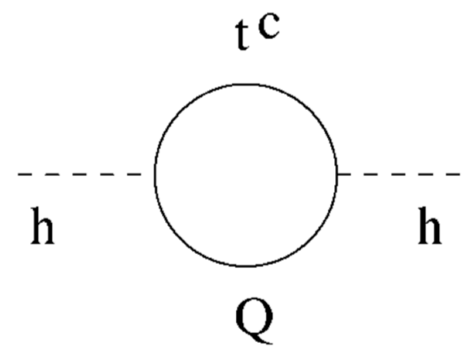


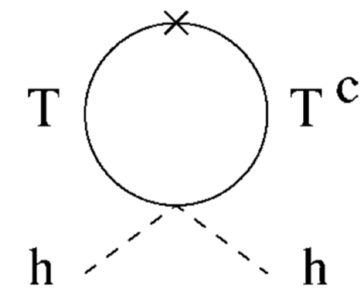
$$m_h \sim a\frac{y_t f}{4\pi} \sim \frac{3M_T}{4\pi}$$

sub-TeV top partner

Colorless top partners are highly motivated!

Neutral Naturalness Era





$$m_h \sim a\frac{y_t f}{4\pi} \sim \frac{3M_T}{4\pi}$$ → sub-TeV top partner

Colorless top partners are highly motivated!

- Neutral Naturalness Models (big apology if I miss your work)

Twin Higgs: Chacko, Goh, Harnik, 0506256

Quirky Little Higgs: Cai, Cheng, Terning, 0812.0843

Orbifold Higgs: Craig, Knapen, Longhi, 1410.6808

Composite Twin Higgs:
Geller, Telem, 1411.2974; Barbieri, Greco, Rattazzi, Wulzer, 1501.07803; Low, Tesi, Wang 1501.07890

Neutral Naturalness in SO(6)/SO(5) (trigonometric parity within coset):
Serra, Torre, 1709.05399; Csaki, Ma, Shu, 1709.08636; Dillon, 1806.10702

…

Twin Higgs as a benchmark of neutral naturalness:

- Mirror copy of the SM $\tilde{\nu}, \tilde{\gamma} \Rightarrow N_{eff}$
- Coset: SU(4)/SU(3) or SO(8)/SO(7)
- Additional Z_2-breaking sources needed for vacuum misalignment

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Our construction with minimal spectrum and coset:

- Vector-like top partners: one doublet and one singlet

$$\widetilde{q} \sim (3,1,2)_Y$$

$$\widetilde{T} \sim (3,1,1)_Y$$

$$SU(3)'_c \times SU(3)_c \times SU(2)_L \times U(1)_Y$$

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- Minimal coset SO(5)/SO(4), without compositeness at low energies

Agashe, Contino, Pomarol, 0412089

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- Natural vacuum misalignment even with only fermions

Fermion Embeddings

$$-\mathcal{L}_{\text{top}} = \; y\bar{Q}_L \Sigma t_R + \tilde{y}\bar{\widetilde{Q}}_L \Sigma \widetilde{T}_R - m_{\widetilde{q}} \bar{\widetilde{Q}}_L \widetilde{Q}_R + \text{h.c.}$$

$$Q_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \end{pmatrix} \subset \mathbf{5}$$

$$\widetilde{Q}_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \widetilde{b}_L \\ -i\widetilde{b}_L \\ \widetilde{t}_L \\ i\widetilde{t}_L \\ \sqrt{2}\widetilde{T}_L \end{pmatrix} \subset \mathbf{5}$$

$$\Sigma = f \; (0, 0, 0, s_h, c_h)^T$$

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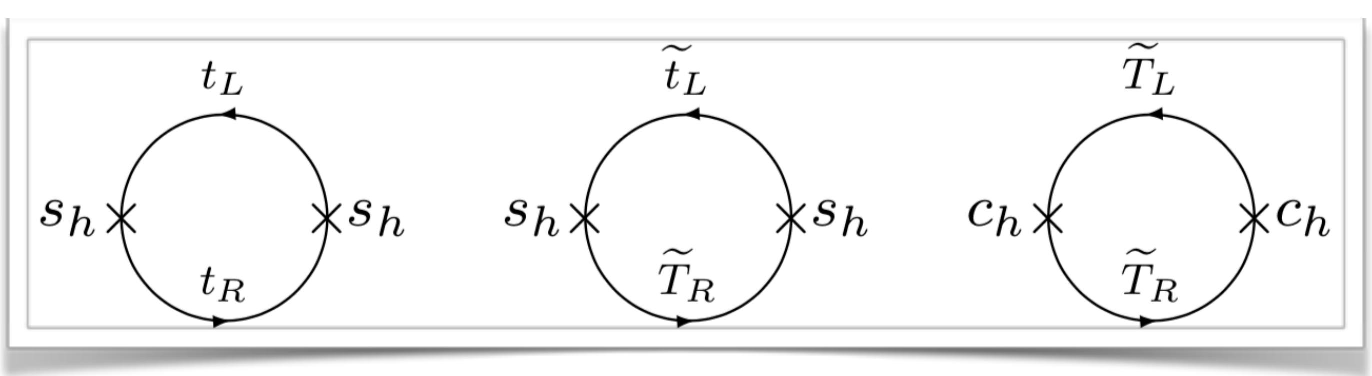

$$V(h) \sim \frac{y^2 f^2 N_c \Lambda^2}{16\pi^2}\left(\frac{1}{2}s_h^2 + \frac{1}{2}s_h^2 + c_h^2\right)$$

- Quadratic divergence cancellation from symmetry perspective

$$Z_2: \quad y\bar{Q}_L \Sigma t_R \longleftrightarrow \tilde{y}\bar{\widetilde{Q}}_L \Sigma \widetilde{T}_R$$

$$\mathcal{L}_{\rm top} \supset y\bar{\mathcal{Q}}_L \Sigma \mathcal{T}_R + \text{h.c.} \qquad \mathcal{Q}_L = (Q_L, \widetilde{Q}_L) \quad \mathcal{T}_R = (t_R, \widetilde{T}_R)$$

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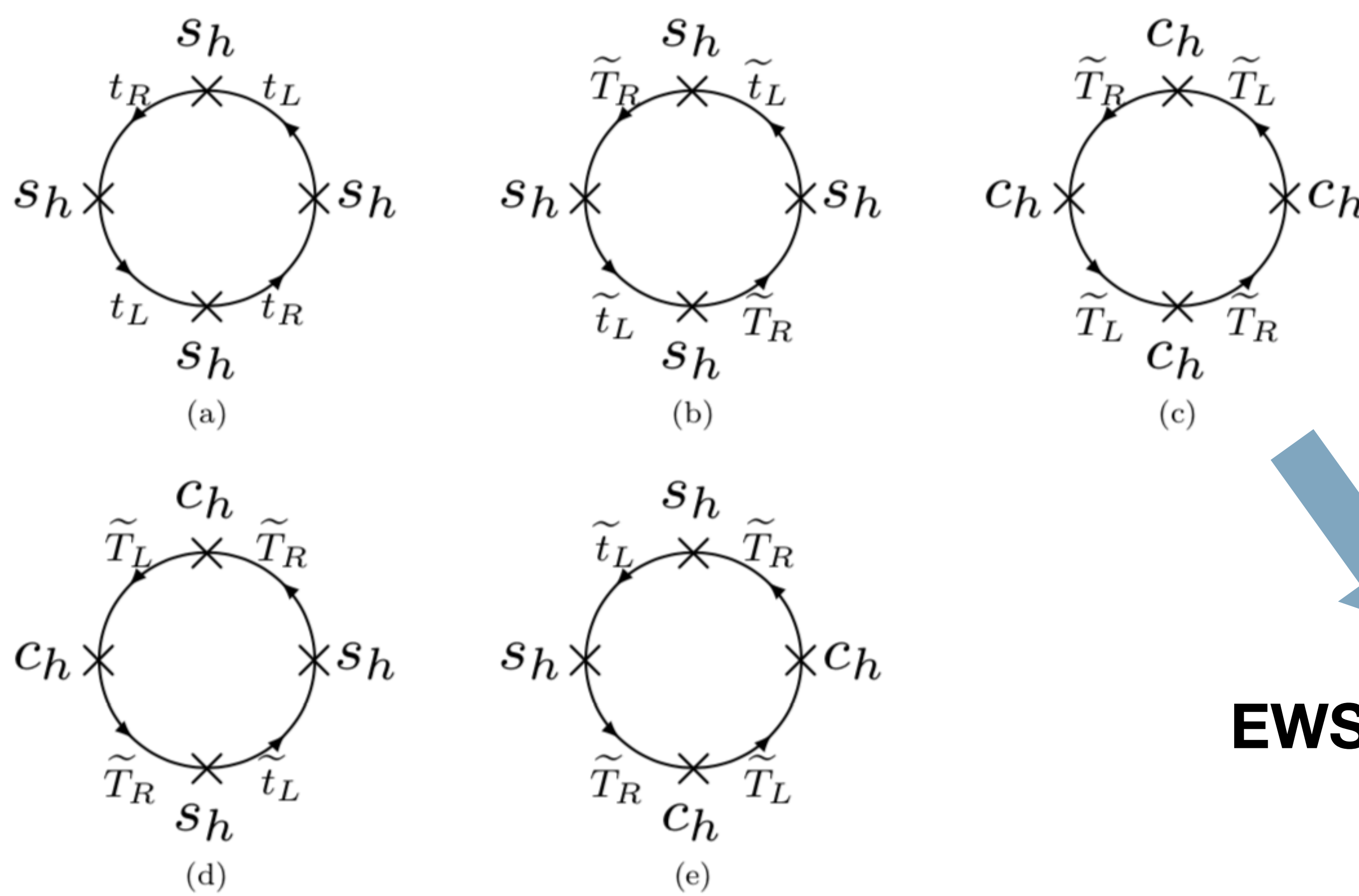
- Logarithmic divergent Higgs Potential from Yukawa terms



EWSB is triggered!

$$V(h) \sim \frac{y^4 f^4 N_c \log\Lambda^2}{16\pi^2}\left(\frac{1}{4}s_h^4 + \frac{1}{4}s_h^4 + c_h^4 + \frac{1}{2}s_h^2 c_h^2 + \frac{1}{2}s_h^2 c_h^2\right) \sim \frac{y^4 f^4 N_c \log\Lambda^2}{16\pi^2}\left(-s_h^2 + \frac{1}{2}s_h^4\right)$$

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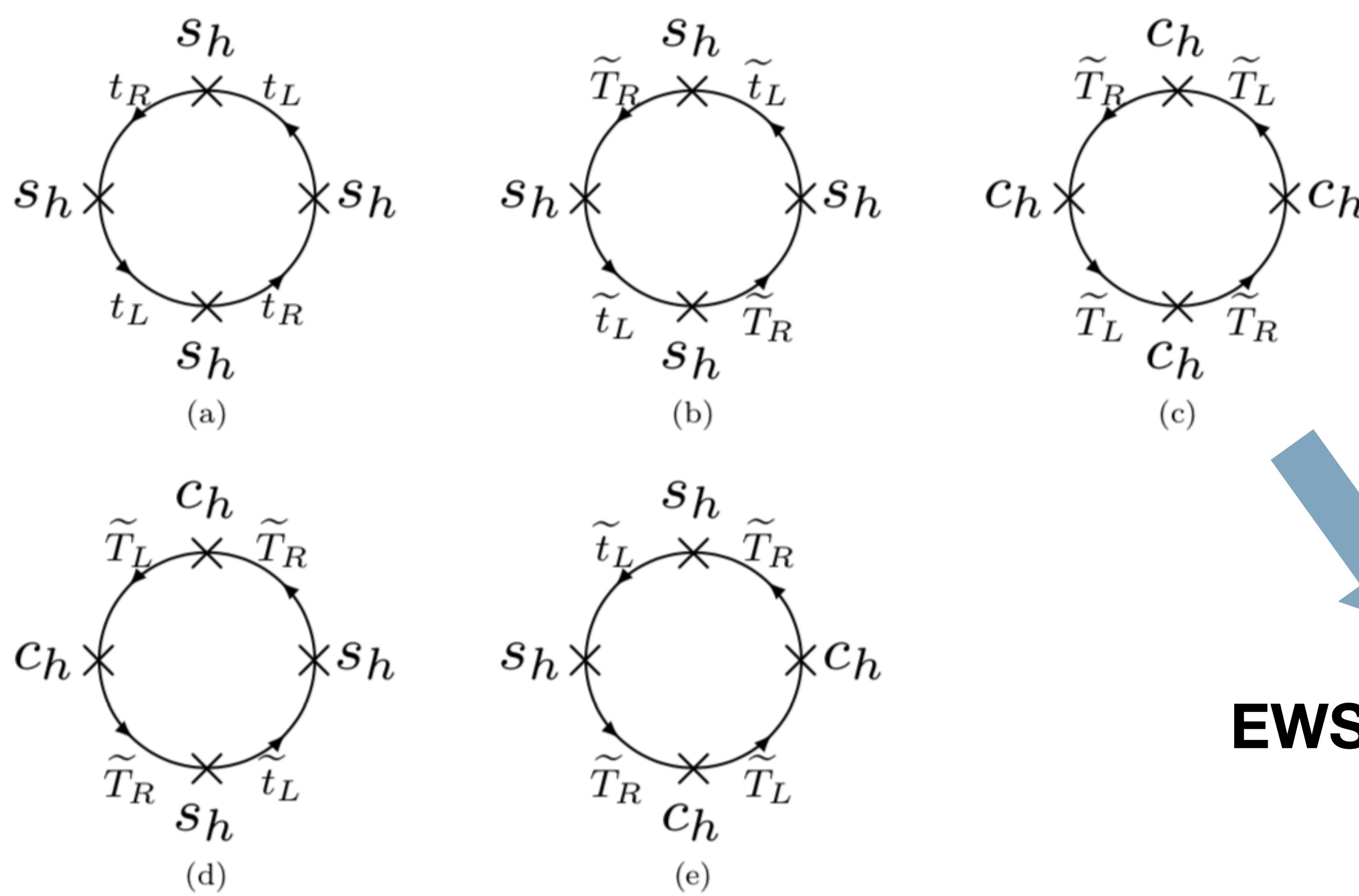

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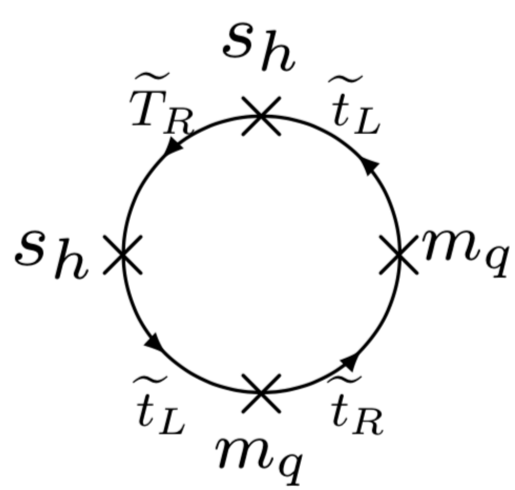
- So far, vacuum is not correctly misaligned

Vacuum Misalignment

- Logarithmic divergent Higgs Potential including the mass term

$$-\mathcal{L}_{\rm top} = y\bar{Q}_L\Sigma t_R + \tilde{y}\bar{\tilde{Q}}_L\Sigma\widetilde{T}_R - m_{\widetilde{q}}\bar{\tilde{Q}}_L\widetilde{Q}_R + \text{h.c.}$$



$$V(h) \sim \frac{y^2 f^2 N_c \;\log\Lambda^2}{16\pi^2}\; m_{\widetilde{q}}^2\; s_h^2$$

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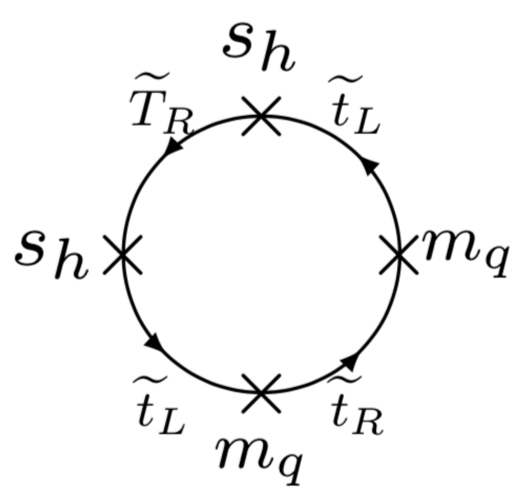

$$V(h) \sim \frac{y^2 f^2 N_c \;\log\Lambda^2}{16\pi^2}\; m_{\tilde{q}}^2\; s_h^2$$

- Total logarithmic divergent Higgs potential

$$V(h) \sim \frac{y^2 f^2 N_c \;\log\Lambda^2}{16\pi^2}\left[(m_{\tilde{q}}^2 - y^2 f^2) s_h^2 + \frac{y^2 f^2}{2} s_h^4\right]$$

$$\xi \equiv \frac{v^2}{f^2} \simeq 1 - \frac{m_{\tilde{q}}^2}{y^2 f^2}$$

Vacuum Misalignment

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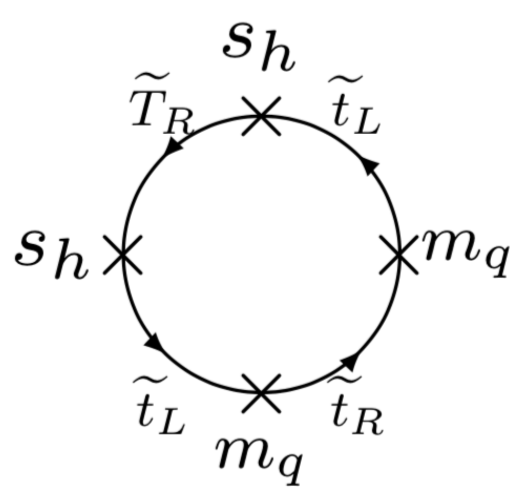

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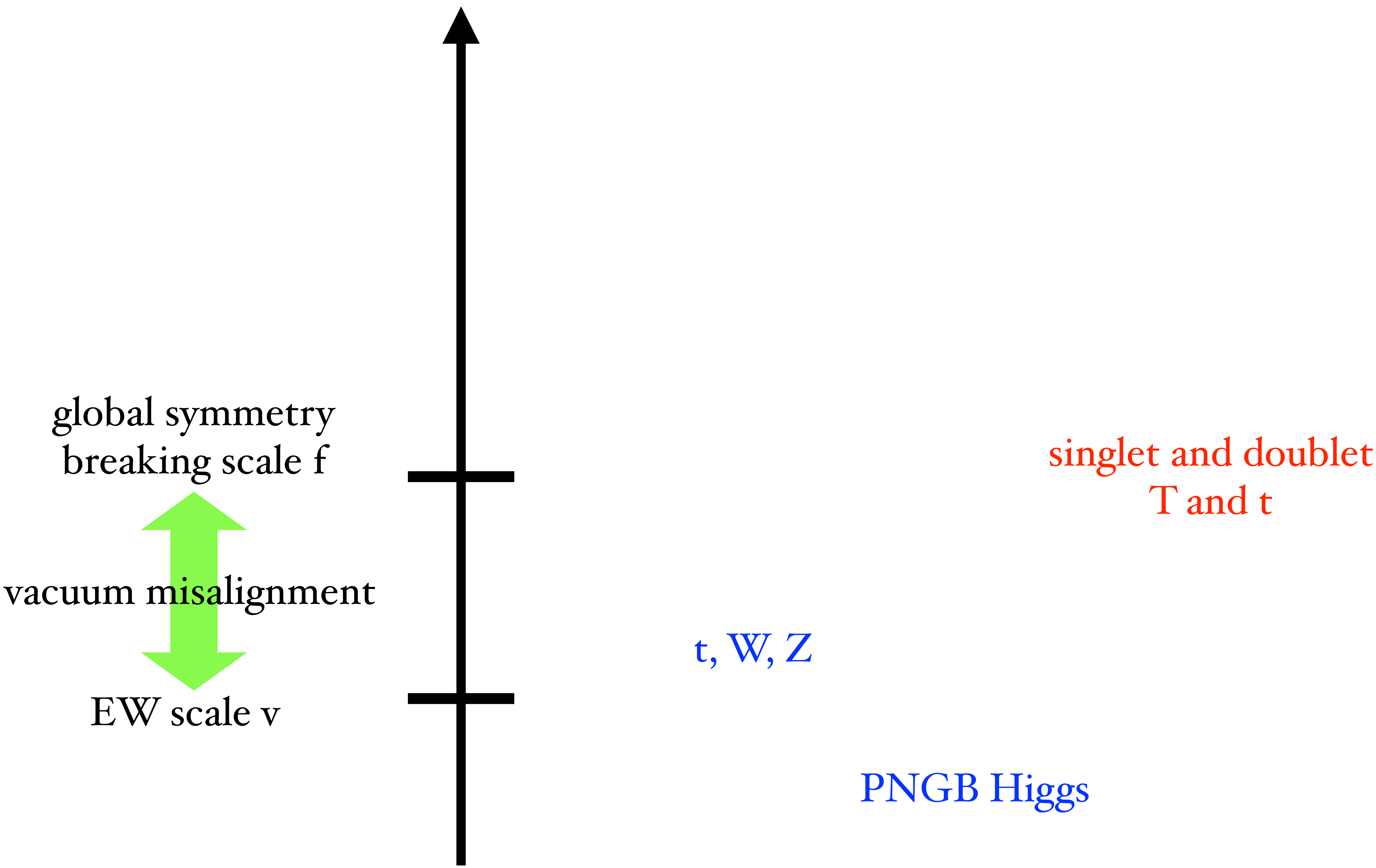
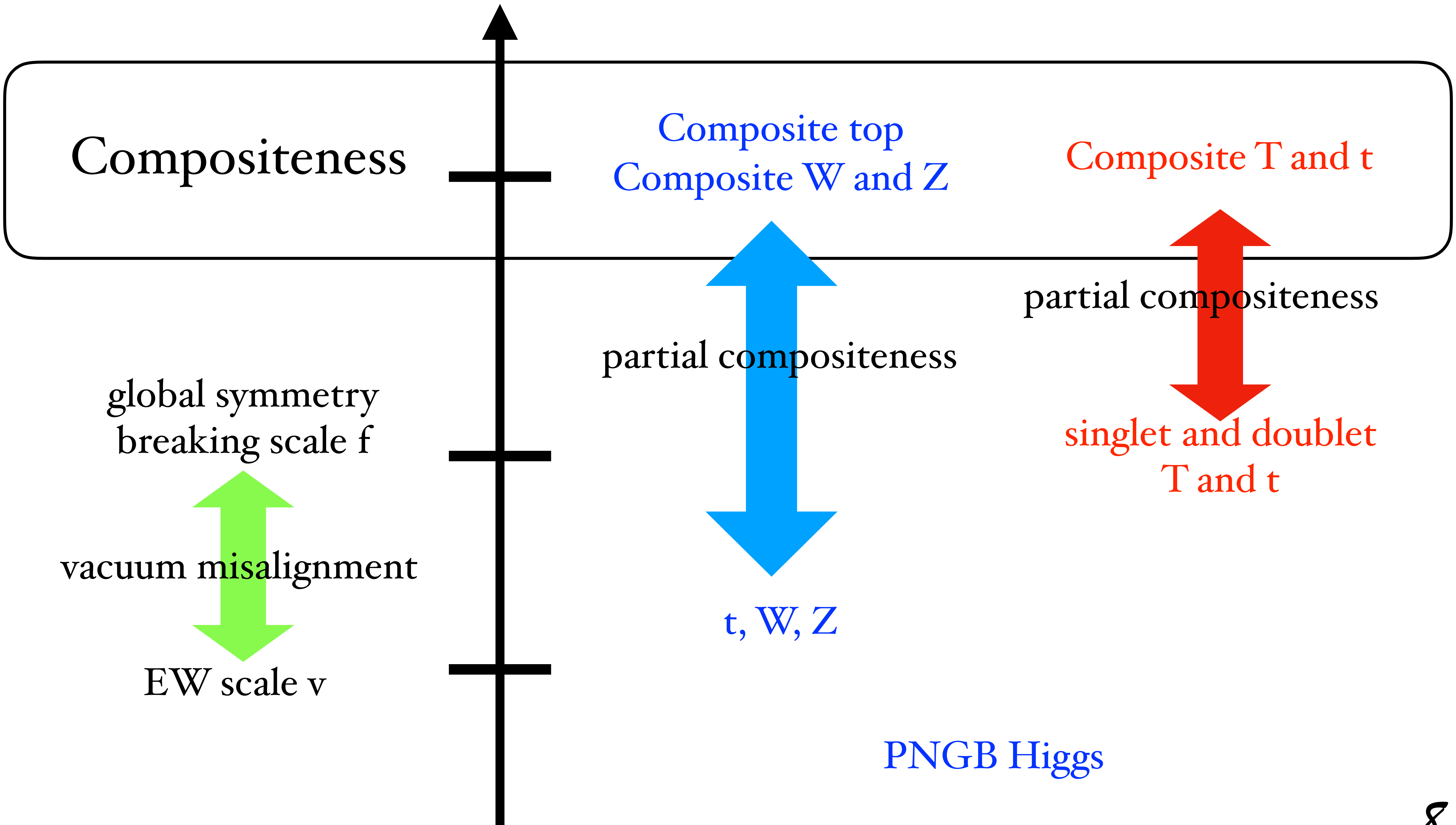
- Further including the finite part will not change the result

Spectrum of Minimal Setup



Composite/Holographic Extension



Two-site Construction

$$Q_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \end{pmatrix} \subset \mathbf{5}$$

$$\widetilde{Q}_R = \frac{1}{\sqrt{2}} \begin{pmatrix} \widetilde{b}_R \\ -i\widetilde{b}_R \\ \widetilde{t}_R \\ i\widetilde{t}_R \\ 0 \end{pmatrix} \subset \mathbf{5}$$

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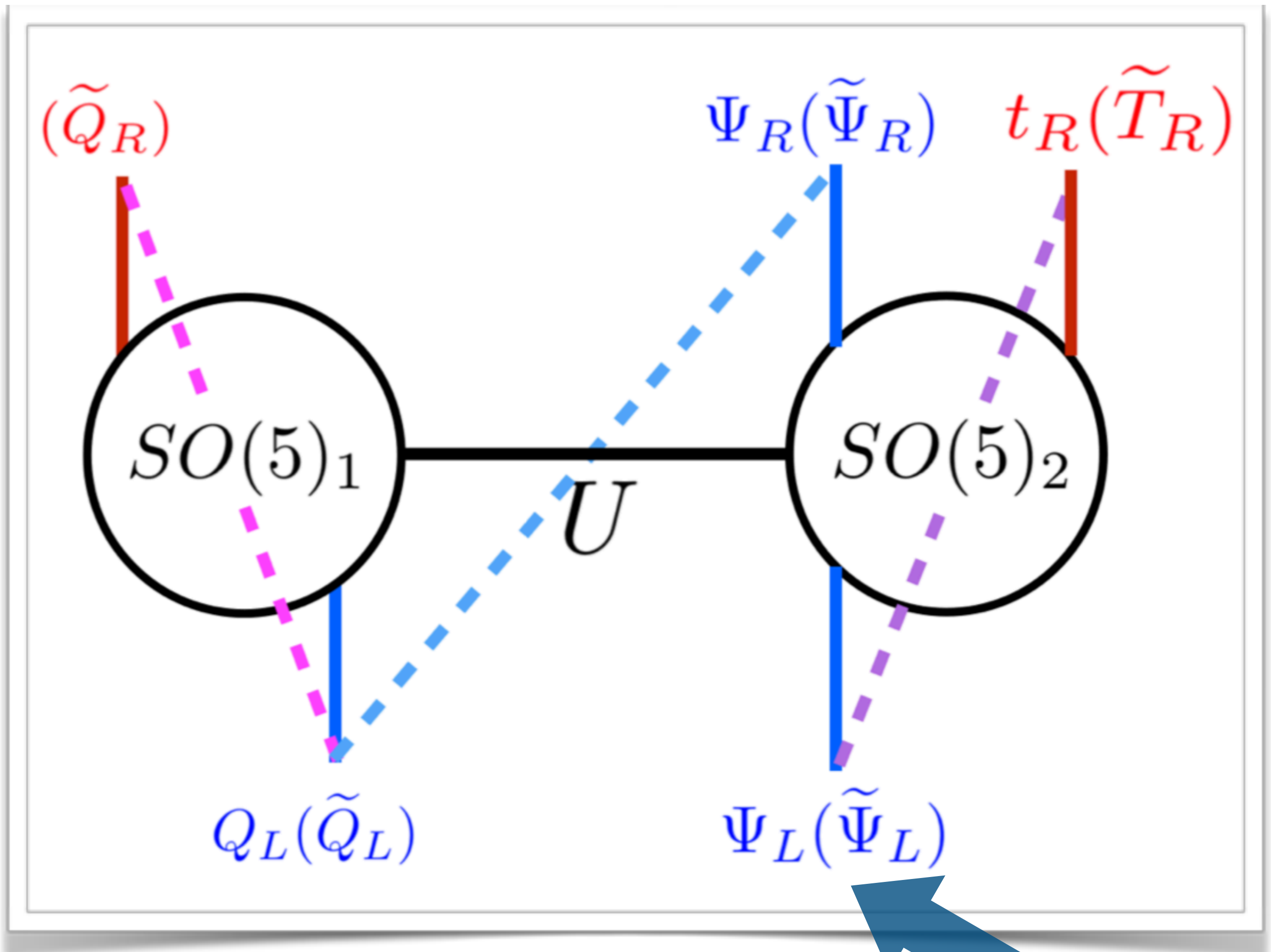

$$t_R \subset \mathbf{1}$$

$$\widetilde{T}_R \subset \mathbf{1}$$

composite states

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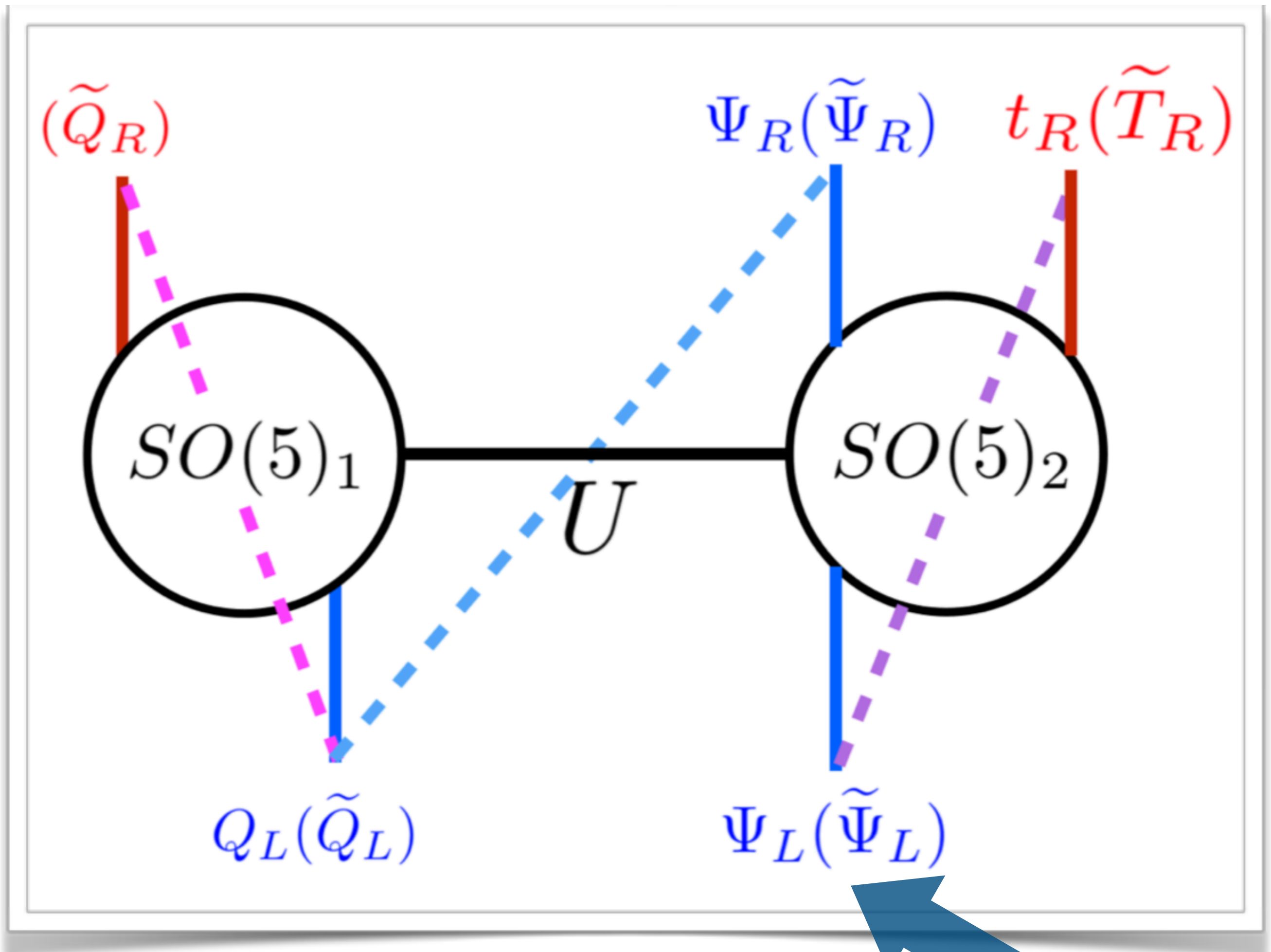

composite states

$t_R \subset \mathbf{1}$

$\widetilde{T}_R \subset \mathbf{1}$

collective breaking: explicit breaking SO(5)2

$$\mathcal{L} = yf\bar{Q}_L U \Psi_R - M\bar{\Psi}_L\Psi_R - m\bar{\Psi}_L^{(1)} t_R + \widetilde{y}f\bar{\widetilde{Q}}_L U\widetilde{\Psi}_R - \widetilde{M}\bar{\widetilde{\Psi}}_L\widetilde{\Psi}_R - \widetilde{m}\bar{\widetilde{\Psi}}_L^{(1)}\widetilde{T}_R - \widetilde{m}_q\bar{\widetilde{Q}}_L\widetilde{Q}_R + \text{h.c.}$$

Holographic Setup for SM Top

- Fermions living in the bulk

$$\xi_q = \begin{bmatrix} (2,2)^q_L = \begin{bmatrix} q'_L(-+) \\ q_L(++) \end{bmatrix} & (2,2)^q_R = \begin{bmatrix} q'_R(+-) \\ q_R(--) \end{bmatrix} \\ (1,1)^q_L(-+) & (1,1)^q_R(+-) \end{bmatrix}$$

$$\xi_t = \begin{bmatrix} (1,1)^t_L(--) & (1,1)^t_R(++) \end{bmatrix}$$

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- Zero modes as the low energy building blocks

$$Q_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \end{pmatrix} \subset \mathbf{5} \qquad\qquad t_R \subset \mathbf{1}$$

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- Breaking SO(5) on the IR brane

$$\mathcal{L} \supset \frac{m}{g_5^2}\, \overline{(1,1)^q_L}\, (1,1)^t_R\, (z_{IR} = L_1) + \text{h.c.}$$

- Otherwise Higgs is an exact Goldstone boson

Holographic Setup for Neutral Tops

- Fermions living in the bulk

$$\xi_{\widetilde{q}} = \begin{bmatrix} (2,2)^{\widetilde{q}}_L = \begin{bmatrix} \widetilde{q}'_L(-+) \\ \widetilde{q}_L(++) \end{bmatrix} & (2,2)^{\widetilde{q}}_R = \begin{bmatrix} \widetilde{q}'_R(+-) \\ \widetilde{q}_R(--) \end{bmatrix} \\ (1,1)^{\widetilde{q}}_L(++) & (1,1)^{\widetilde{q}}_R(--) \end{bmatrix}$$

$$\xi_{\widetilde{T}} = \begin{bmatrix} (1,1)^{\widetilde{T}}_L(--) & (1,1)^{\widetilde{T}}_R(++) \end{bmatrix}$$

- Zero modes as the low energy building blocks

$$\widetilde{Q}_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \widetilde{b}_L \\ -i\widetilde{b}_L \\ \widetilde{t}_L \\ i\widetilde{t}_L \\ \sqrt{2}\widetilde{T}_L \end{pmatrix} \subset \mathbf{5} \qquad \widetilde{T}_R \subset \mathbf{1}$$

- UV brane construction

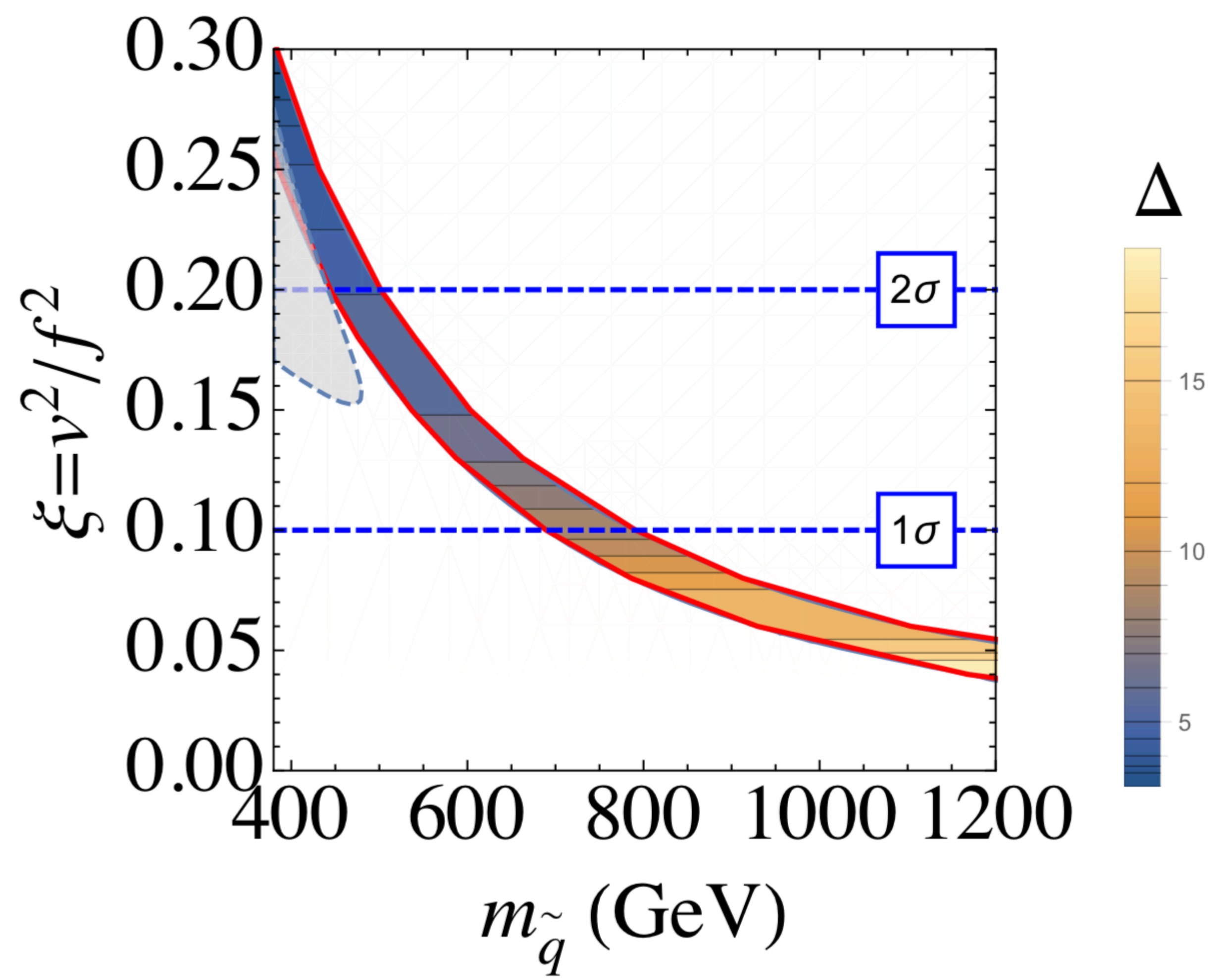
$$\widetilde{Q}_R = \tfrac{1}{\sqrt{2}} \begin{pmatrix} \widetilde{b}_R \\ -i\widetilde{b}_R \\ \widetilde{t}_R \\ i\widetilde{t}_R \\ 0 \end{pmatrix} \subset \mathbf{5} \qquad \mathcal{L} \supset -\frac{\widetilde{m}_q}{g_5^2}\ \bar{\widetilde{q}}_R\ \widetilde{q}_L(++)\ (z_{UV} = L_0) + \text{h.c.}$$

- Breaking SO(5) on the IR brane

$$\mathcal{L} \supset \frac{\widetilde{m}}{g_5^2}\ \overline{(1,1)^{\widetilde{q}}_L}\ (1,1)^{\widetilde{T}}_R\ (z_{IR} = L_1) + \text{h.c.}$$

Phenomenology

- Only two free parameters at low energies



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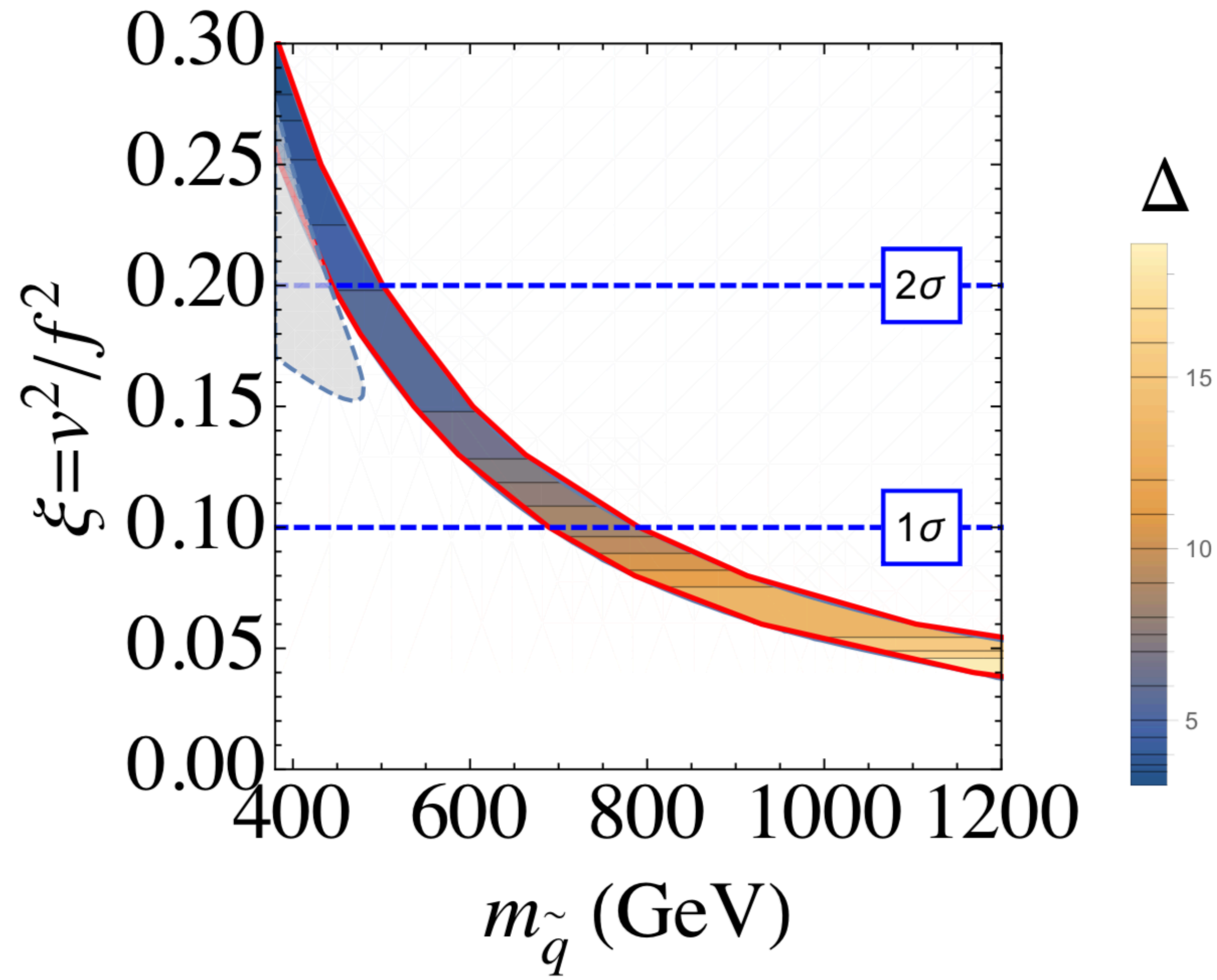


- Rich Phenomenology to be done in the future

  dark hadron spectra, heavy composites phenomenology,
  dark matter candidate, collider signatures and cosmological implications…

Concluding Remarks

- We present a neutral naturalness model with the Higgs boson identified as a PNGB of $SO(5)/SO(4)$

- Vacuum misalignment naturally obtained with only fermions

- UV realization in the holographic/composite Higgs framework

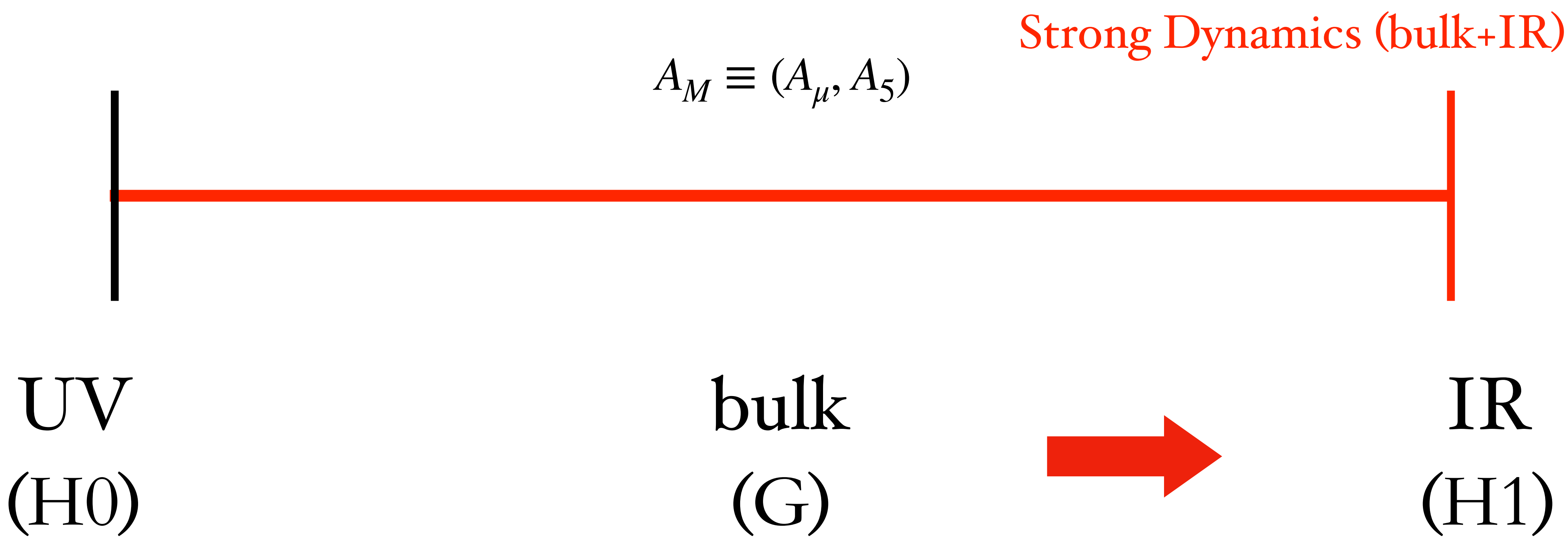
- Finite Higgs potential in holographic/composite framework

still many to explore in the future!

Thank you!

Backup Slides

Symmetry Breaking in 5D



realistic model:

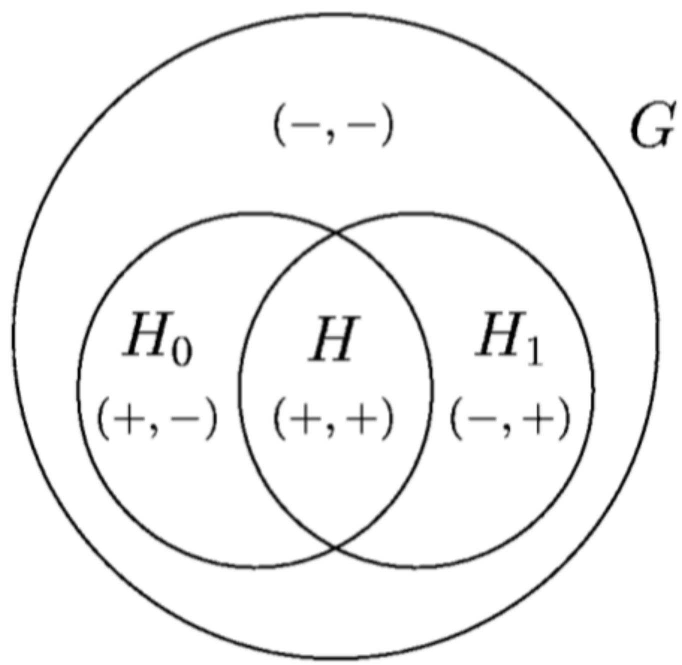
G: SO(5)

H1: SO(4)

H0: SU(2)×U(1)

Boundary Conditions

A_μ



G: SO(5)

H1: SO(4)

H0: SU(2)×U(1)

The boundary condition (+,+) reflects the fact that W, Z are massless before EWSB

$$U = \begin{pmatrix} \mathbf{1}_{3\times 3} & & \\ & c_h & s_h \\ & -s_h & c_h \end{pmatrix}$$

5D perspective: the Goldstone matrix corresponds to the Wilson line of A5 along the fifth dimension

Strong Dynamics at Low Energies

$$\mathcal{L}_{\text{eff}} = \bar{t}_L \not{p} \Pi_{t_L} t_L + \bar{t}_R \not{p} \Pi_{t_R} t_R - (\bar{t}_L \Pi_{t_L t_R} t_R + \text{h.c.})$$
$$+ \bar{\widetilde{L}} \not{p} \widetilde{\Pi}_L \widetilde{L} + \bar{\widetilde{R}} \not{p} \widetilde{\Pi}_R \widetilde{R} - \left(\bar{\widetilde{L}} \widetilde{\Pi}_{LR} \widetilde{R} + \text{h.c.} \right)$$

$$\widetilde{L} = \begin{pmatrix} \widetilde{t}_L \\ \widetilde{T}_L \end{pmatrix} \qquad \widetilde{R} = \begin{pmatrix} \widetilde{t}_R \\ \widetilde{T}_R \end{pmatrix}$$

- Information of heavy particles encoded in form factors

$$\Pi_{t_L t_R} = \frac{iyf}{\sqrt{2}} s_h \frac{Mm}{p^2 - M^2} \qquad \widetilde{\Pi}_{LR} = \begin{pmatrix} \widetilde{m}_q & \frac{-i\widetilde{y}f}{\sqrt{2}} s_h \frac{\widetilde{m}\widetilde{M}}{p^2 - \widetilde{M}^2} \\ 0 & \widetilde{y} f c_h \frac{\widetilde{m}\widetilde{M}}{p^2 - \widetilde{M}^2} \end{pmatrix}$$

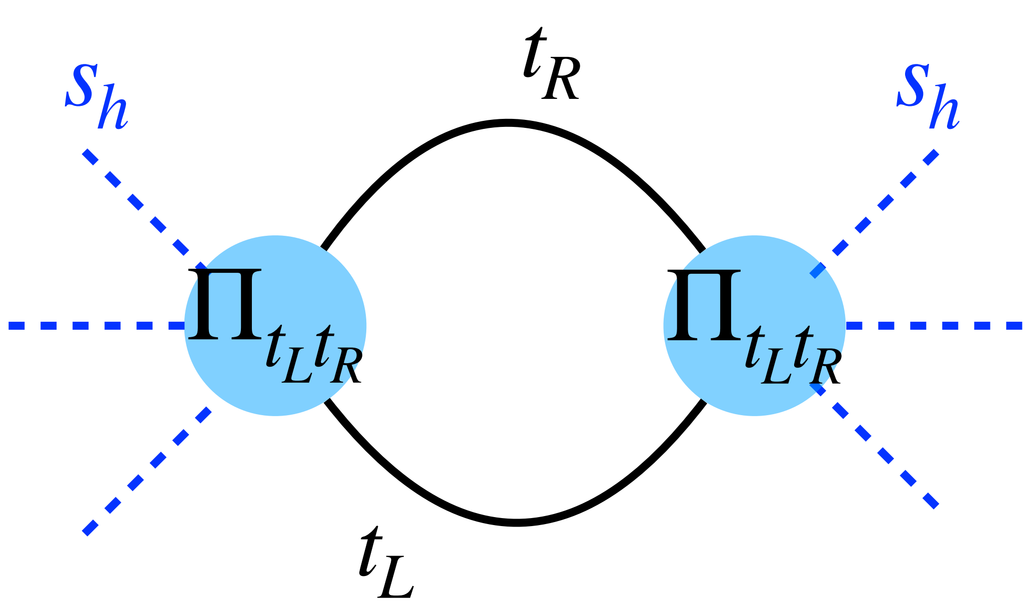
$$\Pi_{t_L t_R} = \frac{i \, \Pi_{LR}(m)}{\sqrt{2}} s_h \qquad \widetilde{\Pi}_{LR} = \begin{pmatrix} \widetilde{m}_q & -\frac{i}{\sqrt{2}} \widetilde{\Pi}_{LR}(\widetilde{m}) s_h \\ 0 & -\widetilde{\Pi}_{LR}(\widetilde{m}) c_h \end{pmatrix}$$

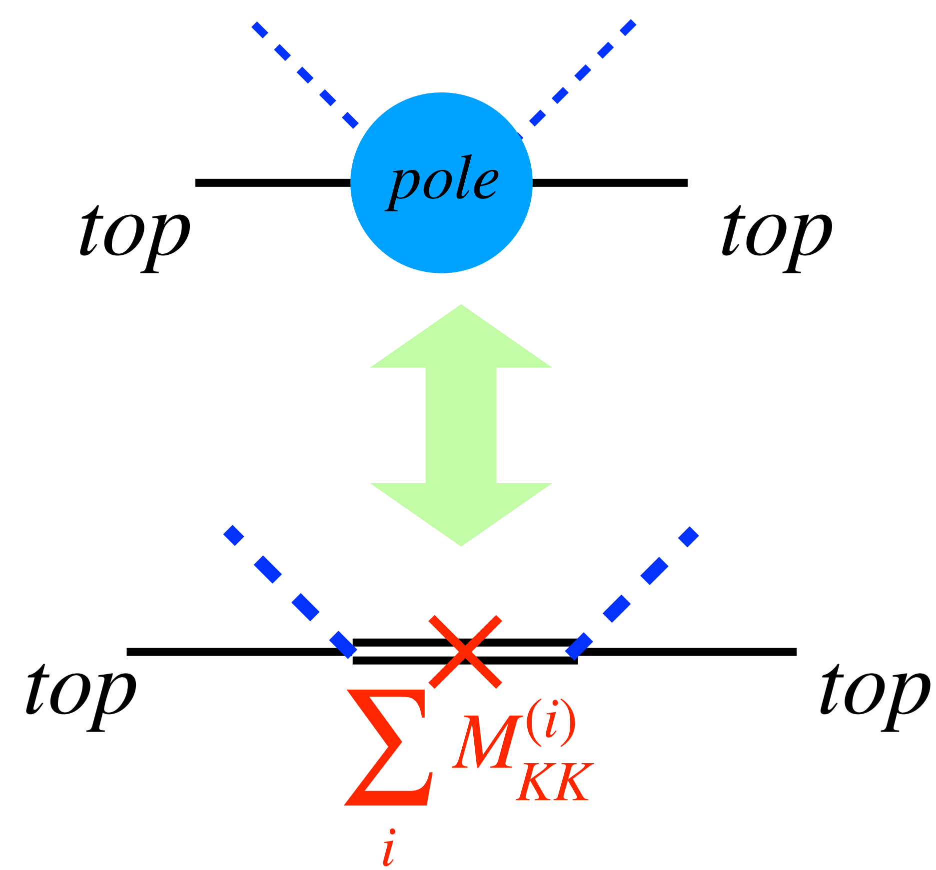
- Identical to the spectrum of the minimal setup

- Explicitly check: Higgs is an exact Goldstone if all the mixings vanish

Higgs Potential in Composite Models

$$V(h) = -\frac{2N_c}{16\pi^2}\int dQ^2 Q^2 \,\log\left[\Pi_{t_L}\Pi_{t_R}\cdot Q^2 + |\Pi_{t_L t_R}|^2\right]$$
$$-\frac{2\widetilde{N}_c}{16\pi^2}\int dQ^2 Q^2 \,\mathrm{Tr}\left\{\log\left(1+\frac{\widetilde{\Pi}_{LR}\widetilde{\Pi}_R^{-1}\widetilde{\Pi}_{LR}^{\dagger}\widetilde{\Pi}_L^{-1}}{Q^2}\right)\right.$$
$$\left.+\log\left(1+(\widetilde{\Pi}_L-\widetilde{\Pi}_{L0})\widetilde{\Pi}_{L0}^{-1}\right)+\log\left(1+(\widetilde{\Pi}_R-\widetilde{\Pi}_{R0})\widetilde{\Pi}_{R0}^{-1}\right)\right\}$$





The contribution of the whole tower of Kaluza-Klein states has been resummed