Axion in the MLσM

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S. Rigolin

Università degli Studi di Padova and INFN Padova

Mainly based on:	F. Feruglio et al. - JHEP 1606 (2016) 038 L. Merlo et al. - Eur.Phys.J. C78 (2018) 415 J. Alonso-Gonzalez et al. - 1807.08643
See also:	I. Brivio et al. 1710:07715

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  - The Higgs as a (p)NGB of a global symmetry breaking;
- **The Minimal Linear σ-model;**
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- **The KSVZ Axion in the MLσM;**
  - Adding an extra complex EW singlet d.o.f (a la KSVZ);
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The Higgs Hierarchy Problem

- If the resonance found @LHC is the SM Higgs then some NP@TeV should be present to stabilise its mass

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

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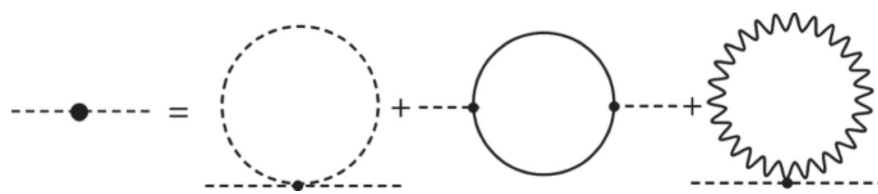

$$\mu^2 = \mu^2_{tree} + \sum_i \delta\mu_i^2 \quad \Longrightarrow \quad \frac{\delta\mu_i^2}{\mu^2} \simeq \pm \frac{g_i^2}{16\pi^2}\left(\frac{\Lambda_i^2}{\mu^2}\right)$$

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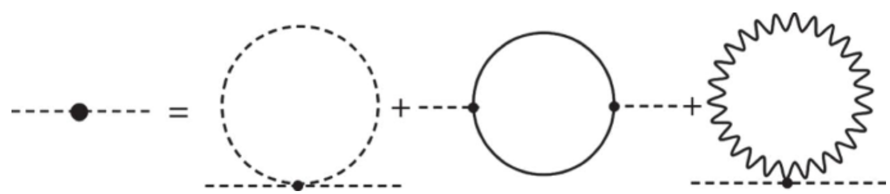

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EW HIERARCHY PROBLEM: $\Lambda_{NP} \gg v \approx m_H$

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Spontaneous Symmetry Breaking – scale f

dim($\mathcal{G}/\mathcal{H}$) massless GBs —— $\pi = (\pi_1, \pi_2, \pi_3, \mathbf{h}, \ldots)$

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HIGGS/EW HIERARCHY PROBLEM "SOLVED"

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+ (Mostly) Model Independent approach, providing a parameterisation of all possible UV completions;

− Contains polynomial dependence on GBs, it is non renormalisable: limited energy validity;

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Previous attempts only partially covered these items;

[Barbieri (2007), see also: Alanne (2014), Gertov (2015)]

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- Two types of heavy vector-like fermions in the 5 and 1 of SO(5) (top and bottom partners) and massless SM quarks:

$$\begin{aligned} \psi &\sim 5 \quad \rightarrow \quad M_5 \\ \chi &\sim 1 \quad \rightarrow \quad M_1 \end{aligned}$$

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$\not{SO(5)}$ SM mass terms

$$m_{t,b} \propto y_i v_h \Lambda_i^2 / M_i^2$$

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The MLσM scalar potential

The most general renormalisable scalar potential SO(4) invariant contains 8 parameters, but only 4 needed for consistency: [Barbieri (2007)]

$$V(h,\sigma) = \lambda(h^2 + \sigma^2 - f^2)^2 + \alpha f^3 \sigma - \beta f^2 h^2$$

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Explicit SO(5) breaking induced by fermionic loops

- One has the following expressions for vevs and masses:

$$v_\sigma^2 = f^2 \frac{\alpha^2}{4\beta^2} \quad , \quad v_h^2 = f^2\left(1 - \frac{\alpha^2}{4\beta^2} + \frac{\beta}{2\lambda}\right)$$

$$m_{h,\sigma}^2 = 4\lambda f^2 \left\{ \left(1 + \frac{3}{4}\frac{\beta}{\lambda}\right) \mp \left[1 + \frac{\beta}{2\lambda}\left(1 + \frac{\alpha^2}{4\beta^2} + \frac{\beta}{8\lambda}\right)\right]^{1/2} \right\}$$

for the physical light/heavy scalar states ($\tilde{h},\tilde{\sigma}$) rotated with respect to the original fields (h,σ) by an angle γ:

$$\begin{pmatrix} h \\ \sigma \end{pmatrix} = \begin{pmatrix} \tilde{h}\cos\gamma + \tilde{\sigma}\sin\gamma \\ \tilde{\sigma}\cos\gamma - \tilde{h}\sin\gamma \end{pmatrix} \quad \longleftrightarrow \quad \tan 2\gamma = \frac{4 v_h v_\sigma}{3v_\sigma^2 - v_h^2 - f^2}$$

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- The generalised fermionic mass matrix of heavy and SM fermions contains SO(5) breaking terms ($\mathbf{\Lambda}_1, \mathbf{\Lambda}_2$):

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- The SO(5) breaking propagates to the 1-loop scalar potential:

$$V_f^{\mathrm{CW}} = -\frac{1}{64\pi^2}\left(\mathrm{Tr}\left[\mathcal{M}_f^\dagger \mathcal{M}_f\right]\Lambda^2 - \mathrm{Tr}\left[\left(\mathcal{M}_f^\dagger \mathcal{M}_f\right)^2\right]\log\left(\frac{\Lambda^2}{\mu^2}\right) + \ldots\right)$$

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- To ensure (one—loop) renormalisability of the model:

$$V(h, \sigma) \supset \alpha f^3 \sigma - \beta f^2 h^2$$

Parameters renormalisation

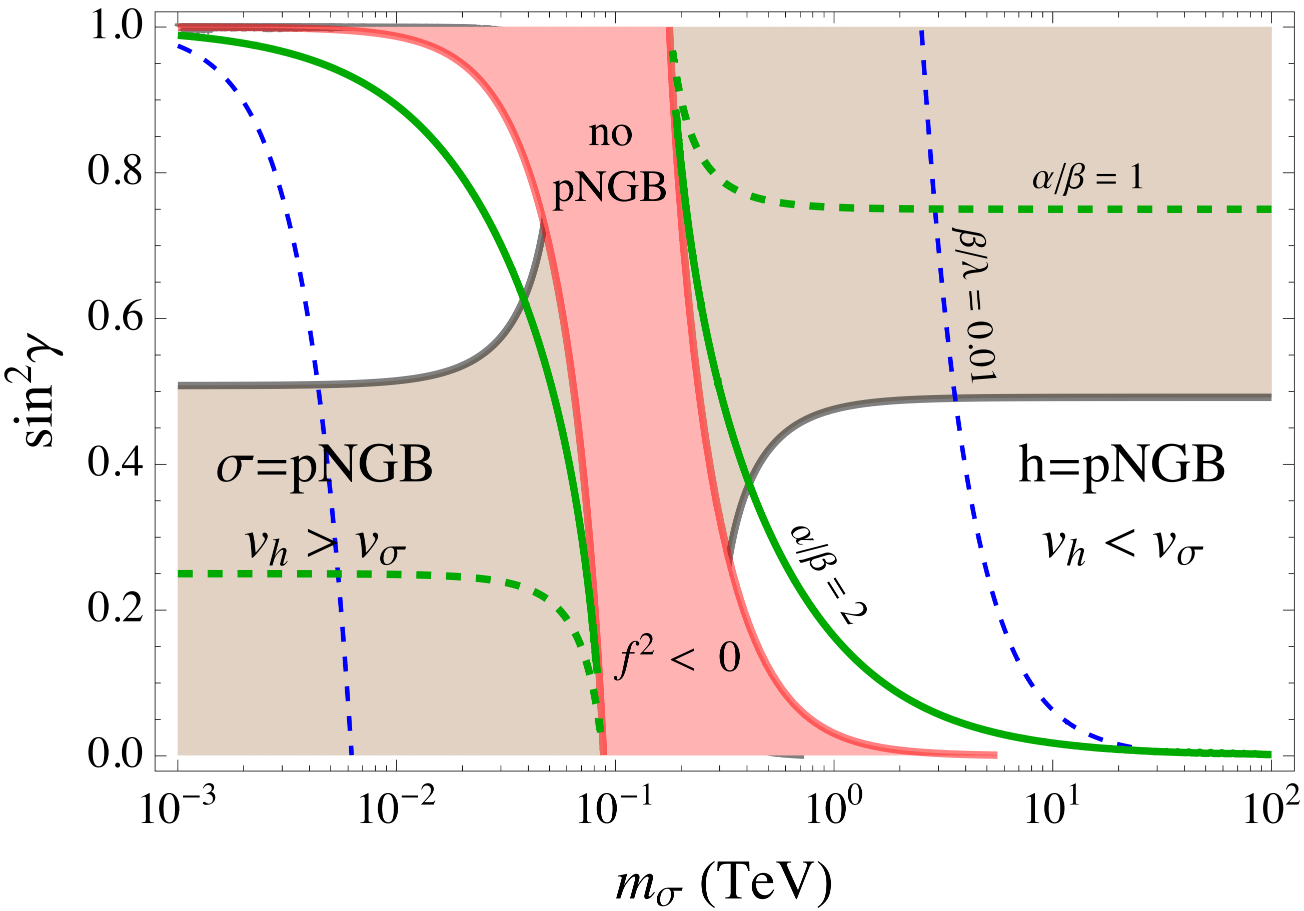
The 4 parameters appearing in the scalar Lagrangian can be expressed in terms of the 2 known + 2 unknown observables:

$$\left\{ G_F \equiv \left(\sqrt{2} v^2\right)^{-1} = 1.166 \times 10^{-5}\ \text{GeV}, \quad m_h = 125\ \text{GeV}, \quad m_\sigma, \quad sin^2\gamma \right\}$$

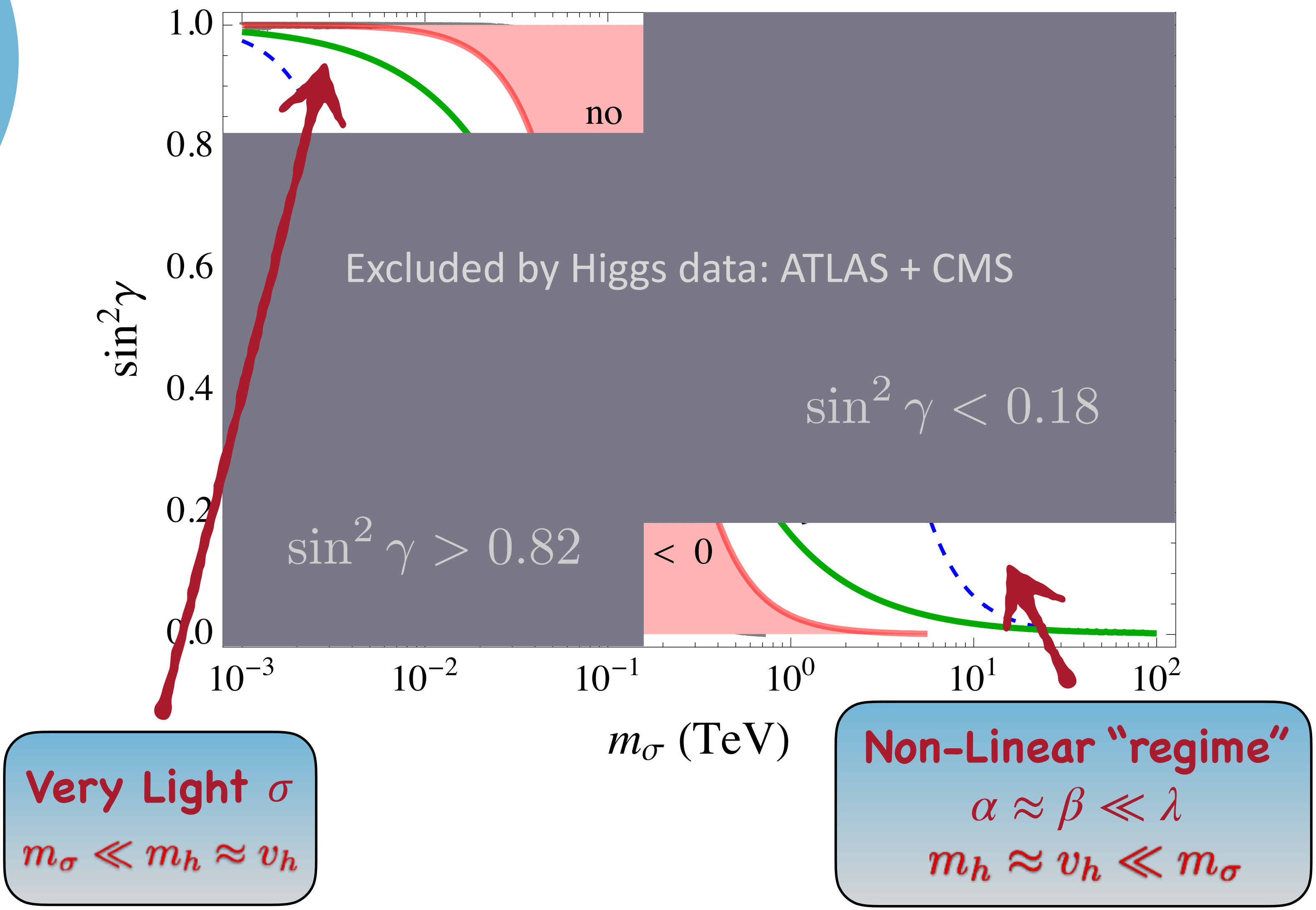
by the following exact relation:

$$\begin{aligned}
\lambda &= \frac{\sin^2\gamma m_\sigma^2}{8v^2}\left(1 + \cot^2\gamma \frac{m_h^2}{m_\sigma^2}\right), \\
\frac{\beta}{4\lambda} &= \frac{m_h^2 m_\sigma^2}{\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2}, \\
\frac{\alpha^2}{4\beta^2} &= \frac{\sin^2(2\gamma)(m_\sigma^2 - m_h^2)^2}{4(\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2)}, \\
f^2 &= \frac{v^2(\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2)}{(\sin^2\gamma m_\sigma^2 + \cos^2\gamma m_h^2)^2}.
\end{aligned}$$

TH-Available parameter space



Th&Exp Available parameter space



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- Q and s must transform non–trivially under an additional global $U(1)_{PQ}$ symmetry:

$$Q_{L,R} \to e^{in_{L,R}\beta} Q_{L,R} \qquad , \qquad s \to e^{i(n_L - n_R)\beta} s$$

$$\delta\mathcal{L}_s = \overline{Q}\, i\not{D}\, Q + y_a \left(\overline{Q}_L\, s\, Q_R + h.c.\right)$$

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- Dirac mass term for Q forbidden by the U(1)$_{PQ}$ symmetry;

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- The EW and $U(1)_{PQ}$ Soft Symmetry Breaking scalar potential:

$$V(H, s) = \lambda(2\,H^\dagger H - v^2)^2 + \lambda_s(2\,s^* s - f_s^2)^2 - 4\lambda_{s\phi}(s^* s)(H^\dagger H)$$

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- The Heavy Fermion get a mass term from SSB: $M_Q \propto y_s\, f_a$

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$$\langle h \rangle = v \quad , \quad \langle s \rangle = \frac{\langle r \rangle}{\sqrt{2}} = \frac{f_s}{\sqrt{2}} \equiv \frac{f_a}{\sqrt{2}}$$

- The Heavy Fermion get a mass term from SSB: $M_Q \propto y_s\, f_a$

- Anomalous couplings with Gluons and Photon:

$$\delta\mathcal{L}_{U(1)_{PQ}} = \frac{\alpha_s}{8\pi}\frac{c_{agg}}{f_a}\, a\, G^{a,\mu\nu}\widetilde{G}^a_{\mu\nu} + \frac{\alpha}{8\pi}\frac{c_{a\gamma\gamma}}{f_a}\, a\, F^{\mu\nu}\widetilde{F}_{\mu\nu} + \cdots$$

The KSVZ Inνisible Axion

- The EW and U(1)$_{PQ}$ Soft Symmetry Breaking scalar potential:

$$V(H,s) = \lambda(2\,H^\dagger H - v^2)^2 + \lambda_s(2\,s^* s - f_s^2)^2 - 4\lambda_{s\phi}(s^* s)(H^\dagger H)$$

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☆ Solve dynamically the Strong CP problem trough the anomaly;

☆ The most striking signature given by the $c_{a\gamma\gamma}$ coupling;

The Axion Minimal Linear σ-model

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- Extend the scalar sector: real scalar in the fundamental of SO(5) plus a complex scalar singlet of SO(5):

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$$\delta\mathcal{L}_s = \lambda_1 s\, (\overline{q}_L \Delta_{2\times 5})\psi_R + \lambda_2 s\, \overline{\psi}_L (\Delta_{5\times 1} t_R) + \lambda_3 s\, \overline{\chi}_L t_R$$

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Not considered in the following (non minimal KSVZ)

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$$V^{\rm CW}(\phi, s) = [SO(5)]_{\rm inv} + \tilde{d}_1\sigma + (\tilde{a}_1 + \tilde{d}_2)h^2 + \tilde{b}_1 h^4 + \hat{d}_1\sigma(s + s^*) + \hat{d}_2(\phi^T\phi)(s + s^*) + \hat{d}_3(\phi^T\phi)(ss + s^*s^*)$$

☆ 4 SO(5) breaking parameters and 3 $U(1)_{PQ}$ breaking parameters in the divergent CW one—loop term;

The scalar potential of the AMLσM

$$\tilde{d}_1 = 4(y_1 M_1 + y_2 M_5)\Lambda_2\Lambda_3$$
$$\tilde{d}_2 = y_2^2\Lambda_1^2 - 2\,y_1^2\Lambda_2^2$$

$$\tilde{a}_1 = \frac{1}{8}\,(g^2 + g'^2)$$
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$$\hat{d}_1 = 2\,y_1(z_1 + \tilde{z}_1)\Lambda_2\Lambda_3 + 2\,y_2(z_5 + \tilde{z}_5)\Lambda_2\Lambda_3$$
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$$\psi_{L,R} \to e^{in_{L,R}\beta}\psi_{L,R} \quad , \quad s \to e^{in_s\beta} s$$

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Minimal AMLσM $\quad \hat{d}_i = 0 \quad \& \quad \tilde{d}_i = 0$

[Merlo et al. (2017)]

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- In KSVZ frameworks the PQ symmetry is usually nonlinearly realised, i.e. the moduli field r is integrated out and only the axion remains at Low Energy: See F. Pobbe and J. Alonso posters for more pheno;

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- $f_R \approx f_s$ unless the unnatural condition $\lambda_{s\phi} \equiv 0$ is imposed;

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☆ Extended Invisible Axions (ALPS) natural frameworks ?

Backup Slides

The Heavy Fermion content

Two type of fermions with different charge under an extra $U(1)_X$ can be defined (X=2/3 and X=-1/3) for the 5 and the 1 of SO(5):

$$\psi^{(5)}_{+2/3} \sim (X, Q, T^{(5)}), \qquad \psi^{(1)}_{+2/3} \sim T^{(1)}$$

$$\psi^{(5)}_{-1/3} \sim (Q', X', B^{(5)}), \qquad \psi^{(1)}_{-1/3} \sim B^{(1)}$$

The decomposition of fermions under $SU(2)_L \times U(1)_Y$ group is shown

Charge/Field	X	Q	$T_{(1,5)}$	Q'	X'	$B_{(1,5)}$
$\Sigma_R^{(3)}$	$+1/2$	$-1/2$	0	$+1/2$	$-1/2$	0
$SU(2)_L \times U(1)_Y$	$(2,+7/6)$	$(2,+1/6)$	$(1,+2/3)$	$(2,+1/6)$	$(2,-5/6)$	$(1,-1/3)$
x	$+2/3$	$+2/3$	$+2/3$	$-1/3$	$-1/3$	$-1/3$
q_{EM}	$X^u = +5/3$ $X^d = +2/3$	$Q^u = +2/3$ $Q^d = -1/3$	$+2/3$	$Q'^u = +2/3$ $Q'^d = -1/3$	$X'^u = -1/3$ $X'^d = -4/3$	$-1/3$
		q_L	t_R	q_L		b_R

The Heavy Fermion Lagrangian

- The SO(5) preserving part of the Lagrangian includes the proto-Yukawa interactions with the scalar multiplet:

$$\begin{aligned}\mathcal{L}_{SO(5)} &= \bar{\psi}^{(2/3)}\left(i\not{D}-M_5\right)\psi^{(2/3)}+\bar{\psi}^{(-1/3)}\left(i\not{D}-M_5'\right)\psi^{(-1/3)}\\ &+ \bar{\chi}^{(2/3)}\left(i\not{D}-M_1\right)\chi^{(2/3)}+\bar{\chi}^{(-1/3)}\left(i\not{D}-M_1'\right)\chi^{(-1/3)}\\ &- y_1\,\bar{\psi}_L^{(2/3)}\phi\,\chi_R^{(2/3)}-y_2\,\bar{\psi}_R^{(2/3)}\phi\,\chi_L^{(2/3)}\\ &- y_1'\,\bar{\psi}_L^{(-1/3)}\phi\,\chi_R^{(-1/3)}-y_2'\,\bar{\psi}_R^{(-1/3)}\phi\end{aligned}$$

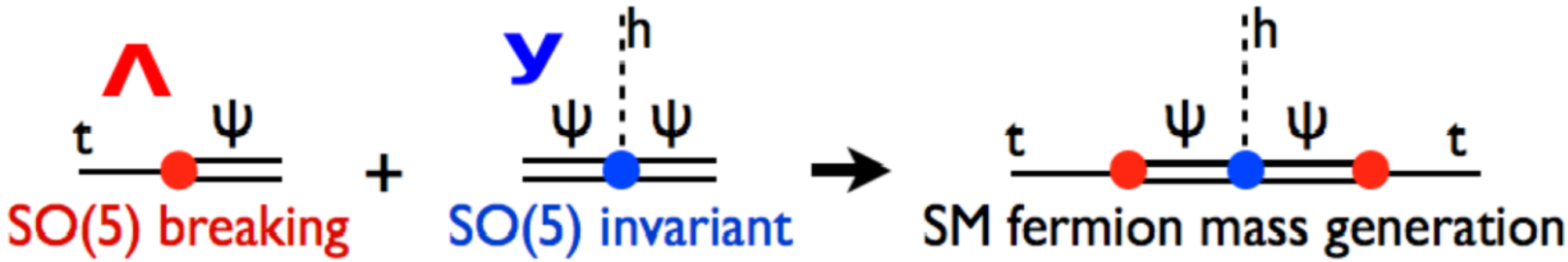
- The SO(5) breaking part of the fermionic Lagrangian is given by partial-compositeness couplings with SM (massless) fermion

[Kaplan '91]

$$\begin{aligned}\mathcal{L}_{\not{SO}(5)} &= -\left[\Lambda_1\bar{q}_L Q_R+\Lambda_2\bar{T}_L^{(5)}t_R+\Lambda_3\bar{T}_L^{(1)}t_R+h.c.\right]\\ &\quad -\left[\Lambda_1'\bar{q}_L Q_R'+\Lambda_2'\bar{B}_L^{(5)}b_R+\Lambda_3'\bar{B}_L^{(1)}b_R+h.c.\right]\end{aligned}$$

SM fermion mass generation

- Combining the SO(5) invariant proto-Yukawas with the SO(5) breaking partial composite interactions:



one gives rise to a see-saw mechanism for generating the SM fermion masses. The leading order can be obtained schematically

$$q_L \xrightarrow[\Lambda_1]{} Q_R \xrightarrow[M_5]{} Q_L \xrightarrow[y_1 \langle H \rangle]{} T_R^{(1)} \xrightarrow[M_1]{} T_L^{(1)} \xrightarrow[\Lambda_3]{} t_R$$

$$y_t \sim y_1 \frac{\Lambda_1 \Lambda_3}{M_1 M_5} v \qquad \text{and} \qquad y_b \sim y_1' \frac{\Lambda_1' \Lambda_3'}{M_1' M_5'} v$$

The SO(5)/SO(4) scalar-gauge sector

Setting the notation useful in the next slides:

$$H = \frac{(h+v)}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \longrightarrow \mathbf{U}(x) = e^{i\frac{\pi(x)}{f}}$$

$$\mathbf{D}_\mu \mathbf{U}(x) \equiv \partial_\mu \mathbf{U} + i\frac{g}{2} W_\mu^a \sigma_a \mathbf{U} - i\frac{g'}{2} B_\mu \mathbf{U} \sigma_3 \longrightarrow \mathbf{V}_\mu = (\mathbf{D}_\mu \mathbf{U})\, \mathbf{U}^\dagger$$

The SO(5)/SO(4) scalar-gauge sector reads (σ is a SM singlet)

$$\mathcal{L}_{g,s} \equiv (D_\mu H)^\dagger (D_\mu H) \supset \frac{v_h^2}{4} \langle \mathbf{V}_\mu \mathbf{V}^\mu \rangle + \frac{v_h}{2} \left(\tilde{h} \cos\gamma + \tilde{\sigma} \sin\gamma \right) \langle \mathbf{V}_\mu \mathbf{V}^\mu \rangle$$
$$+ \frac{1}{4} \left(\tilde{h}^2 \cos^2\gamma + 2\, \tilde{h}\, \tilde{\sigma} \sin\gamma \cos\gamma + \tilde{\sigma}^2 \sin^2\gamma \right) \langle \mathbf{V}_\mu \mathbf{V}^\mu \rangle$$

- The first term identify the Gauge Boson masses:

$$M_W^2 = \frac{g^2\, v_h^2}{4} \quad , \quad M_Z^2 = \frac{(g^2 + g'^2)\, v_h^2}{4} \quad \rightarrow \quad v_h \equiv v = 246\,\text{GeV}$$

- The scalar-gauge couplings are "SM like" but with a $\cos\gamma$ suppression for $\tilde{h}$ (and a $\sin\gamma$ suppression for $\tilde{\sigma}$)