Linear sigma model for the composite H – – experimental tests

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in collaboration with
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Rencontres de Moriond 2016, EW, YSF

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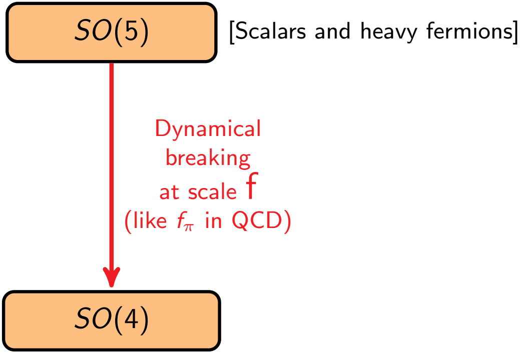
Some solutions to the hierarchy problem consider the BEH boson of a dynamical origin, (alike W_L, Z_L)
e. g. composite Higgs

Original idea: Georgi-Kaplan (1984) $SU(5) \to SO(5)$ (14 GBs)
Agashe, Contino, Pomarol (2005)



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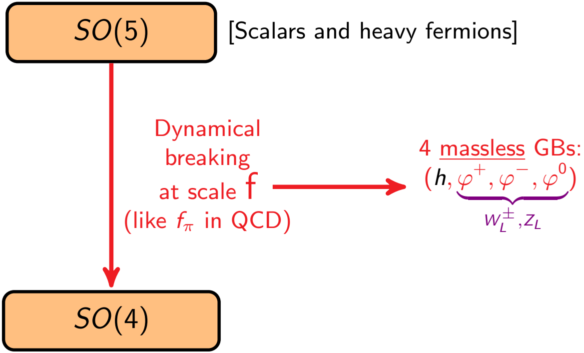

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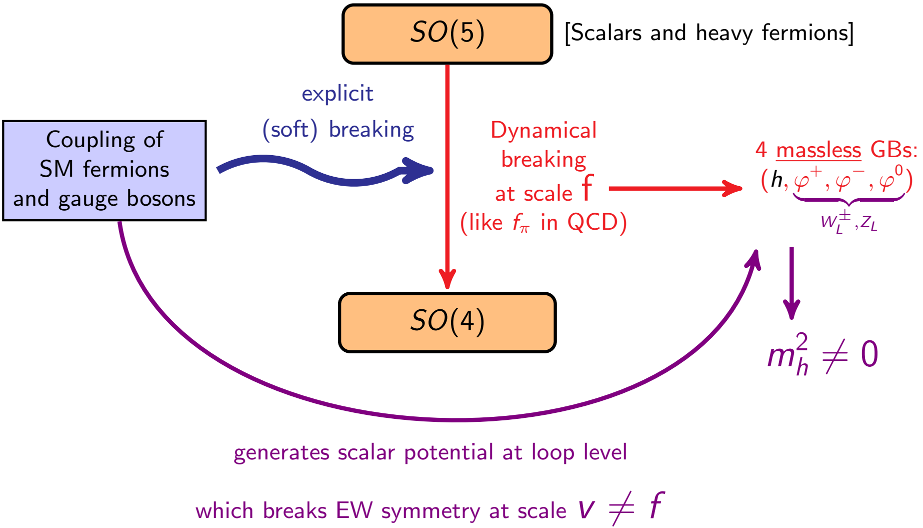

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Usually studied in non-linear (effective) realizations
(they appear to have some tension with data)

Agashe et al (2005), Contino et al (2011), Panico et al (2013), Carena et al (2014)...

We will use a linear (renormalizable) implementation

Barbieri et al (2007)

Cou
SM f
and gau

GBs:
$, \varphi^0)$
Z_L

$SO(4)$

$m_h^2 \neq 0$

generates scalar potential at loop level

which breaks EW symmetry at scale $v \neq f$

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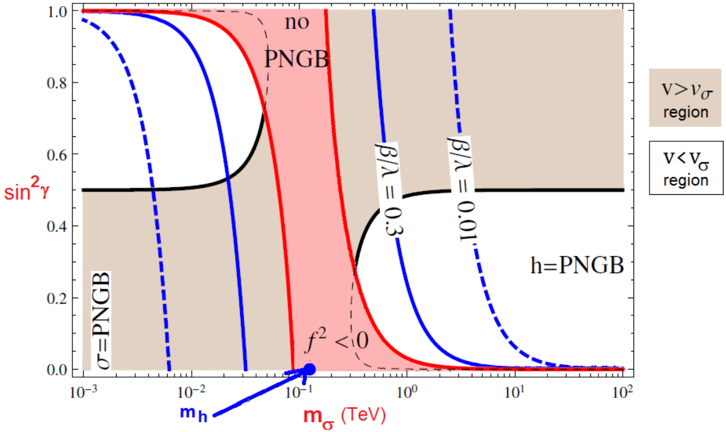
How light could the σ be?
Could it be hidden in the data?
Does it help alleviate the tension?

$$V(h,\sigma) = -\lambda\underbrace{(h^2+\sigma^2-f^2)^2}_{\text{spontaneous SO(5) breaking}} \quad + \underbrace{\alpha f^3\sigma - \beta f^2\, h^2}_{\text{explicit SO(5) breaking (Coleman-Weinberg)}}$$

$\Rightarrow$ the scalars mix:

$$\begin{pmatrix} \text{Light} \\ \text{Heavy} \end{pmatrix} = R(\gamma)\begin{pmatrix} h \\ \sigma \end{pmatrix}$$



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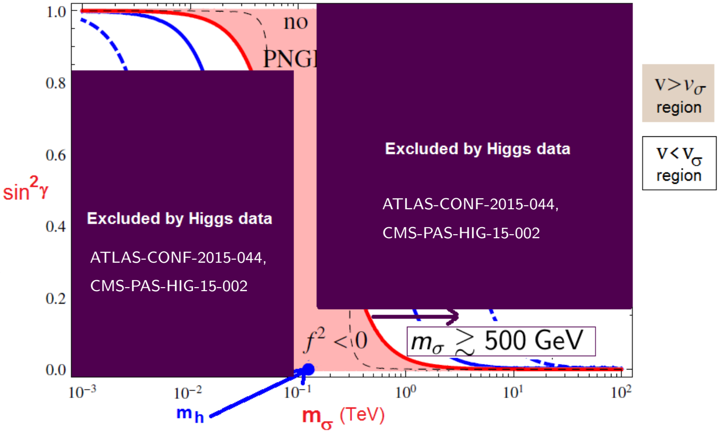
$\Rightarrow$ modifications to Higgs couplings

relation with non-linear:

$\xi \equiv \frac{v^2}{f^2} \approx \sin^2\gamma$

$(m_\sigma >> m_h)$

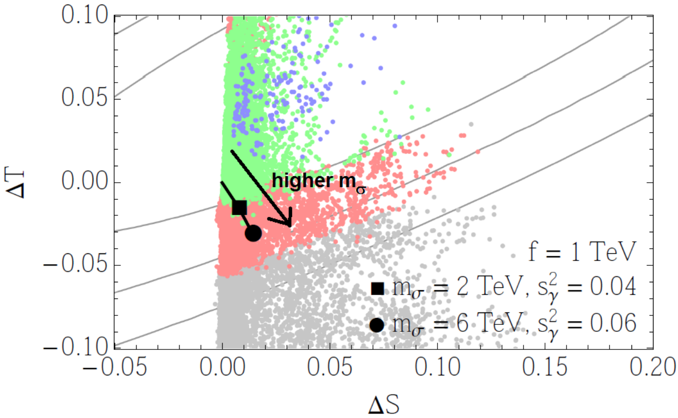
Panico et al (2012)
Panico, Wulzer (2015)



Precision tests: scalars and exotic fermions contributions

Computed with analytic formulas + numerical diagonalization of fermion mass matrix

Novikov, Okun, Vysotsky (1993)
Orgogozo, Rychkov (2012)
Dawson, Furlan (2012)
Lavoura, Silva (1993)

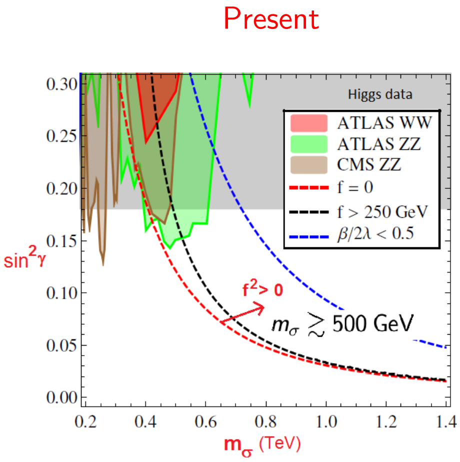


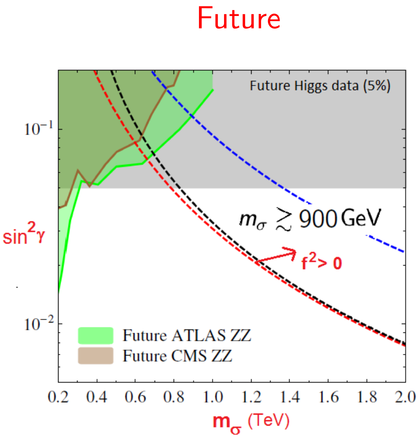
fermionic contribution 1σ, 2σ, 3σ regions for global fit to $(\Delta S, \Delta T, \Delta g_b)$

→ larger m_σ might lead to more tension with data

σ impact on LHC data

arXiv:1507.05930 (ATLAS), arXiv:1509.00389 (ATLAS), CMS PAS HIG-13-002, CMS PAS HIG-13-003, arXiv:1411.0322





Can it be the 750 GeV diphoton bump in diphoton?

ATLAS-CONF-2015-081, CMS-EXO-15-004

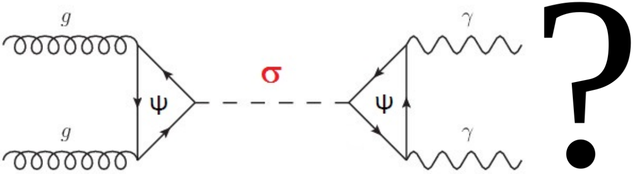
Very unnatural in our model:

- ⋆ the mixing needs to be very suppressed (no signal in other channels)

  $\Rightarrow f^2 < 0 \quad \to \lambda \ (h^2 + s^2 + f^2)^2 \quad \Rightarrow$ no spontaneous breaking

  also $\alpha << 1 \quad \Rightarrow$ strong fine-tuning of soft terms

- ⋆ higher fermion multiplicities required to increase gg production and $\gamma\gamma$ decay



Conclusions

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Conclusions

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- ⋆ There is interesting phenomenology: top and bottom partners, heavy scalar σ, deviations from SM couplings...
- ⋆ We find that a not too heavy σ shows less tension with precision tests
- ⋆ LHC data already probe the parameter space for a light σ. Could it be waiting in future data?

Thank you

BACKUP

The $SO(5)$ soft breaking induced by the couplings to the SM can be parametrized by two terms

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

Minimization of the potential:

$$\Rightarrow \qquad v_\sigma = -f \frac{\alpha}{2\beta}\,, \qquad v = f\sqrt{1 - \frac{\alpha^2}{4\beta^2} + \frac{\beta}{2\lambda}}$$

Consequence: the scalars mix in the mass eigenstates:

$$h_{phys} = h\cos\gamma - \sigma\sin\gamma\,, \qquad \sigma_{phys} = \sigma\cos\gamma + h\sin\gamma$$

$\Rightarrow$ the σ acquires a Higgs-like behaviour

$$\tan 2\gamma = \frac{4 v v_\sigma}{3 v_\sigma^2 - v^2 - f^2}$$

Renormalization parameters of the scalar sector:

$$\left\{ G_F \equiv (\sqrt{2}v^2)^{-1}, \qquad m_h, \qquad m_\sigma, \qquad \sin^2\gamma \right\}$$

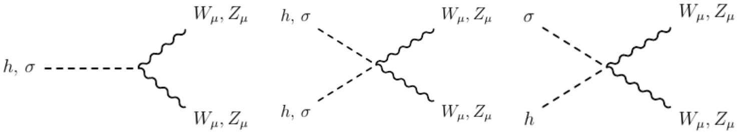
where the mixing angle can be related at leading order

$$\lambda = \frac{\sin^2\gamma m_\sigma^2}{8v^2}\left(1+\cot^2\gamma\frac{m_h^2}{m_\sigma^2}\right),$$

$$\frac{\beta}{4\lambda} = \frac{m_h^2 m_\sigma^2}{\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2},$$

$$\frac{\alpha^2}{4\beta^2} = \frac{\sin^2(2\gamma)(m_\sigma^2 - m_h^2)^2}{4(\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2)},$$

$$f^2 = \frac{v^2(\sin^2\gamma m_\sigma^4 + \cos^2\gamma m_h^4 - 2m_h^2 m_\sigma^2)}{\left(\sin^2\gamma m_\sigma^2 + \cos^2\gamma m_h^2\right)^2}.$$



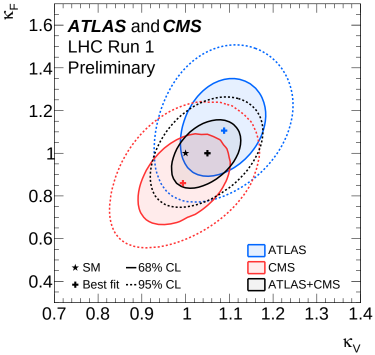
$$\mathcal{L}_{g,s} \subset \frac{1}{4}g^2 v^2 W^+_\mu W^{\mu -} + \frac{1}{2}\frac{1}{4}(g^2 + g'^2)v^2 Z_\mu Z^\mu$$
$$+ v(h \cos\gamma + \sigma \sin\gamma)\left(\frac{1}{2}g^2 W^+_\mu W^{\mu -} + \frac{1}{4}(g^2 + g'^2) Z_\mu Z^\mu\right)$$
$$+ (h^2 \cos^2\gamma + 2h\sigma \sin\gamma \cos\gamma + \sigma^2 \sin^2\gamma)(\frac{1}{4}g^2 W^+_\mu W^{\mu -} + \frac{1}{8}(g^2 + g'^2) Z_\mu Z^\mu)$$

- The σ also couples to the gauge bosons, with $\sin\gamma$
- h has the same couplings as in the SM, but suppressed by $\cos\gamma$
- M_W, M_Z impose for the h vev $v = 246$ GeV

$\Rightarrow$ the Higgs has the SM couplings to W, Z suppressed by $\cos\gamma$

$+$ also the gluon fusion is dominated by the SM top loop $\rightarrow$ it is also suppressed by $\cos\gamma$

ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002



$$k_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\Rightarrow \quad \cos^2\gamma > 0.82 \text{ at } 2\sigma$$

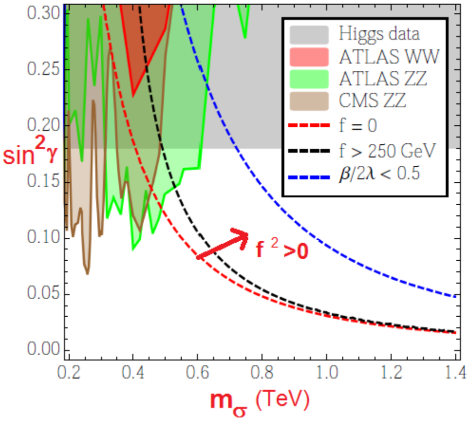
$$\Rightarrow \quad \boxed{\sin^2\gamma < 0.18 \text{ at } 2\sigma}$$

Constraints from LHC data on the σ

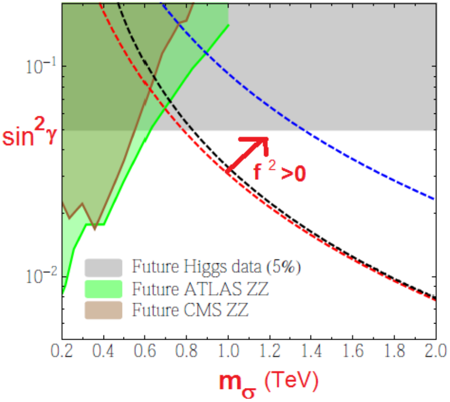
- Production assumed to be gluon fusion dominated by top loop
- The influence of vector fermions is model-dependent. In general they tend to weaken the constraints

Here assuming no impact from heavy fermions:

Present



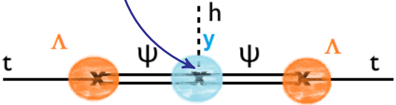
Future



$SO(5)$ soft breaking

SM - heavy fermion mixing

$SO(5)$ invariant yukawas

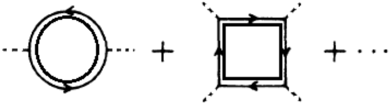


top yukawa:

$$\Rightarrow \qquad y_t \sim y \frac{\Lambda^2}{M_\Psi^2}$$

SM quarks do not couple directly to h

Coleman-Weinberg potential due to light-heavy mixing:

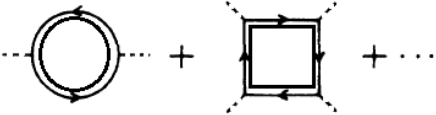


$$\longrightarrow \qquad V_{\rm loop}^{\cancel{SO(5)}}(h, \sigma)$$

The coupling of scalars to fermions breaks explicitly $SO(5)$.

They generate an effective potential for the scalars at loop level:

$$\mathcal{L} \subset \bar{\psi}_L \, \mathcal{M}(h,\sigma) \, \psi_R$$



Coleman, Weinberg (1973)

$$V_{\rm loop} = -\frac{1}{64\pi^2}\mathrm{Tr}\left(\underbrace{2\Lambda^2 \mathcal{M}\mathcal{M}^\dagger + \overbrace{(\mathcal{M}\mathcal{M}^\dagger)^2 \log\left(\frac{\mu^2}{\Lambda^2}\right)}_{\text{divergent}} + (\mathcal{M}\mathcal{M}^\dagger)^2 \log\left(\frac{\mathcal{M}\mathcal{M}^\dagger}{\mu^2}\right) - \frac{1}{2}(\mathcal{M}\mathcal{M}^\dagger)^2}^{SO(5)\text{breaking}} \right)$$

$$\mathrm{Tr}(\mathcal{M}\mathcal{M}^\dagger) = [SO(5)_{inv}]$$
$$\mathrm{Tr}((\mathcal{M}\mathcal{M}^\dagger)^2) = [SO(5)_{inv}] + A\sigma + Bh^2$$

$$\Rightarrow \quad V(h,\sigma) = \lambda\left(h^2+\sigma^2-f^2\right)^2 \; +\alpha f^3 \sigma \; -\beta f^2 h^2$$

As usual, the global symmetry is enlarged to have particles with same quantum numbers as SM quarks:

$$SO(5) \times U(1)_X \to SO(4) \times U(1)_X \approx SU(2)_L \times SU(2)_R \times U(1)_X \\ \to SU(2)_L \times U(1)_Y$$

$$Y = T_R^{(3)} + X$$

SM quarks hypercharge $y = 1/6, 2/3, -1/3 \implies$ 2 possible values for the x charge: $x = 2/3, -1/3$

We use vectorial fermions in **5** and **1** of $SO(5)$:

$$\psi^{(2/3)} \equiv \psi \sim (X, Q, T^{(5)}) \quad , \quad \psi^{(-1/3)} \equiv \psi' \sim (Q', X', B^{(5)})$$

$$\chi^{(2/3)} \equiv \chi \sim T^{(1)} \quad , \quad \chi^{(-1/3)} \equiv \chi' \sim B^{(1)} .$$

	X	Q	$T_{(1,5)}$	Q'	X'	$B_{(1,5)}$
$U(1)_X$	$+2/3$	$+2/3$	$+2/3$	$-1/3$	$-1/3$	$-1/3$
$T_R^{(3)}$	$+1/2$	$-1/2$	0	$1/2$	$-1/2$	0
$SU(2)_L \times U(1)_Y$	$(2, 7/6)$	$(2, 1/6)$	$(1, 2/3)$	$(2, 1/6)$	$(2, -5/6)$	$(1, -1/3)$
Q_{EM}	$X^u = 5/3$ $X^d = 2/3$	$Q^u = 2/3$ $Q^d = -1/3$	$2/3$	$Q'^u = 2/3$ $Q'^d = -1/3$	$X'^u = -1/3$ $X'^d = -4/3$	$-1/3$

$SO(5)$ explicit breaking terms for the 3^{rd} generation quarks:

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

2 particles with exotic electric charge

$SO(5)$ invariant heavy fermion kinetic terms and Yukawas:

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

$$\mathcal{L}_{\mathcal{M}} = -\bar{\Psi}_L\ \mathcal{M}(h,\sigma)\ \Psi_R, \quad \Psi = \left(X^u,\ \mathcal{T},\ \mathcal{B},\ X'^d\right),$$

$$\mathcal{T} = \left(t, Q^u, X^d, T^{(5)}, T^{(1)}, Q'^u\right), \quad \mathcal{B} = \left(b, Q'^d, X'^u, B^{(5)}, B^{(1)}, Q^d\right).$$

$$\mathcal{M}(h,\sigma) = \mathrm{diag}\left(M_5, \mathcal{M}^{\mathcal{T}}(h,\sigma), \mathcal{M}^{\mathcal{B}}(h,\sigma), M_5'\right),$$

$$\mathcal{M}^{\mathcal{T}}(h,\sigma) = \begin{pmatrix} 0 & \Lambda_1 & 0 & 0 & 0 & \Lambda_1' \\ 0 & M_5 & 0 & 0 & y_1\frac{h}{\sqrt{2}} & 0 \\ 0 & 0 & M_5 & 0 & y_1\frac{h}{\sqrt{2}} & 0 \\ \Lambda_2 & 0 & 0 & M_5 & y_1\sigma & 0 \\ \Lambda_3 & y_2\frac{h}{\sqrt{2}} & y_2\frac{h}{\sqrt{2}} & y_2\sigma & M_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & M_5' \end{pmatrix},$$

$$\mathcal{M}^{\mathcal{B}}(h,\sigma) = \mathcal{M}^{\mathcal{T}}(h,\sigma) \text{ with } \{y_i, \Lambda_i, M_i\} \leftrightarrow \{y_i', \Lambda_i', M_i'\}.$$

$M_f >> m_\sigma$ and heavy fermions are integrated out. Operators appearing:

$$O_{Hq}^{(1)} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L)$$

$$O_{Hq}^{(3)} \equiv (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}_L \tau^i \gamma^\mu q_L)$$

$$O_{t\sigma} \equiv \sigma \; \bar{q}_L \; \widetilde{H} \; t_R$$

$$O_{t\sigma^2} \equiv \sigma^2 \; \bar{q}_L \; \widetilde{H} \; t_R$$

$$O_{tH} \equiv |H|^2 \; \bar{q}_L \widetilde{H} t_R$$

$$\downarrow$$

top mass and top Yukawa

Georgi,Kaplan(1984),Banks (1984)
Dimopoulos, Georgi, Kaplan (1984)
Galison, Georgi, Kaplan (1984)
Dugan, Georgi, Kaplan (1985)
Agashe, Contino, Pomarol (2005)
Gripaios, Pomarol, Riva, Serra(2009)
...

E

Λ_s — Strong dynamics. Global symmetry G ($SO(5)$)
Heavy resonances are at this scale

f — Condensates break G to H ($SO(4)$), which embeds
$G_{SM} = SU(2)_L \times U(1)_Y$
This produces massless GBs

$\langle h \rangle$ — External (SM) vector bosons and fermions couple to h
This breaks explicitly G, generating a loop level potential for h
h potential breaks EW symmetry

v — v,f and $\langle h \rangle$ related by model-dependent relations
$\xi = \frac{v^2}{f^2}$ measures the non-linearity of the model