The minimal linear sigma model for the Goldstone Higgs

Sara Saa

in collaboration with
F Feruglio, B Gavela, K Kanshin,
P Machado, S Rigolin

arXiv:1603.05668

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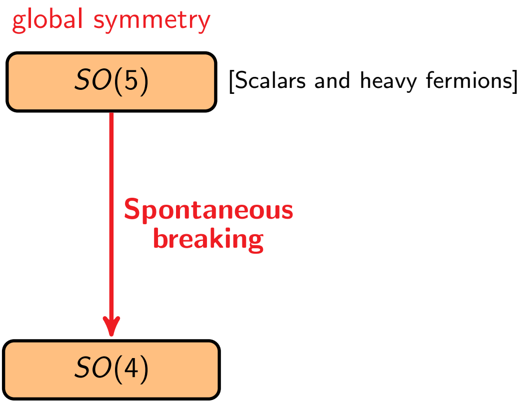
UNIVERSIDAD AUTÓNOMA DE MADRID

Instituto de Física Teórica UAM-CSIC

Some solutions to the hierarchy problem consider a dynamical origin for the Higgs boson h, (alike W_L, Z_L)

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



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global symmetry

$SO(5)$ [Scalars and heavy fermions]

Spontaneous breaking $\longrightarrow$

4 massless GBs at scale f

$$(\boldsymbol{h}, \underbrace{\varphi^+, \varphi^-, \varphi^0}_{W_L^\pm, Z_L})$$

$SO(4)$

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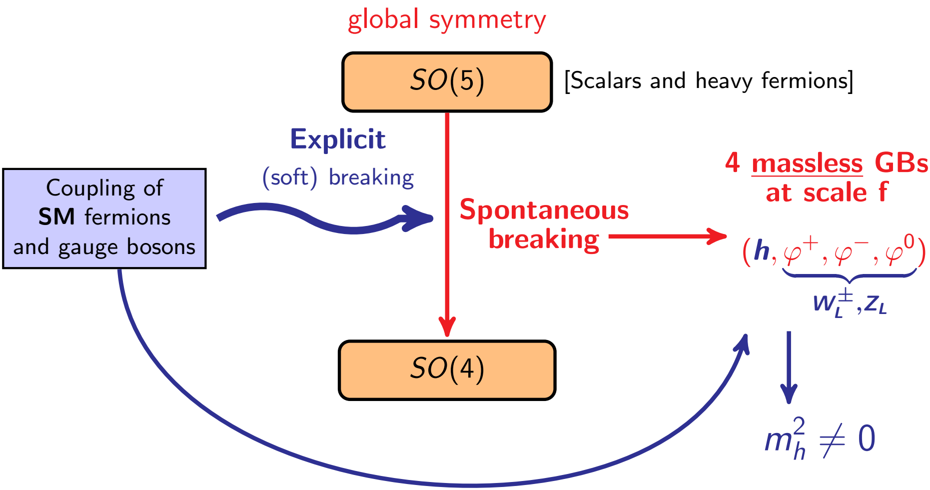

generates **scalar potential** at loop level

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

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

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

We will use a **linear** (renormalizable) implementation instead.

Cou
SM f
and gau

GBs
f

$, \varphi^0)$

$W_L^\pm, Z_L$

$SO(4)$

$m_h^2 \neq 0$

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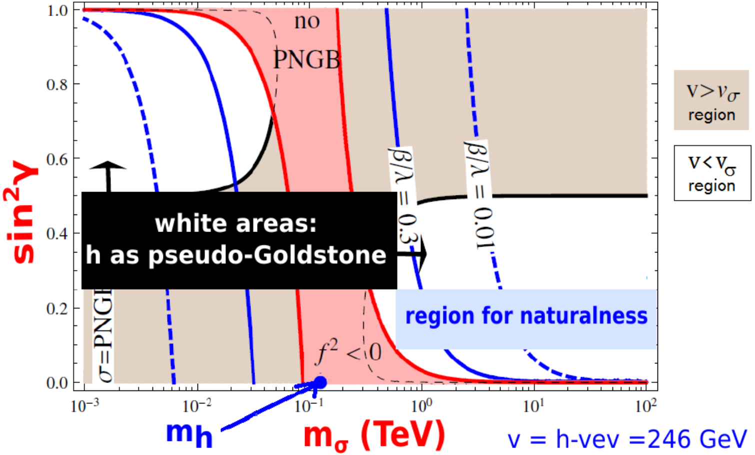
How light could the σ be?
Could it be hidden in the data?
Does it help alleviate the tension?

Barbieri et al (2007)

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

$\Rightarrow$ h and σ mix:



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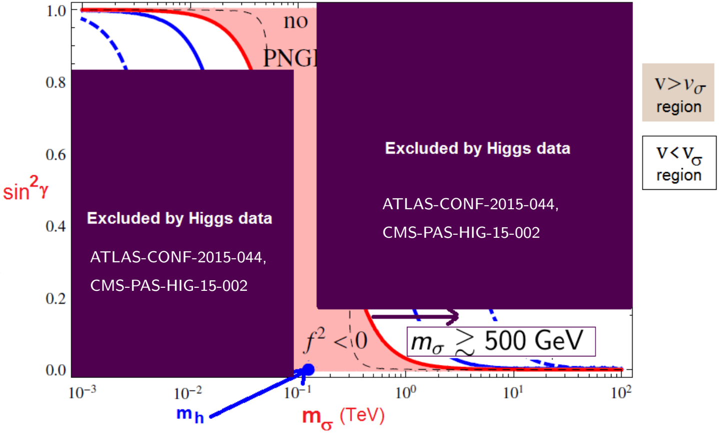
$\Rightarrow$ h and σ mix: $\Rightarrow$ modifications to Higgs couplings

relation with non-linear:

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

$(m_\sigma >> m_h)$

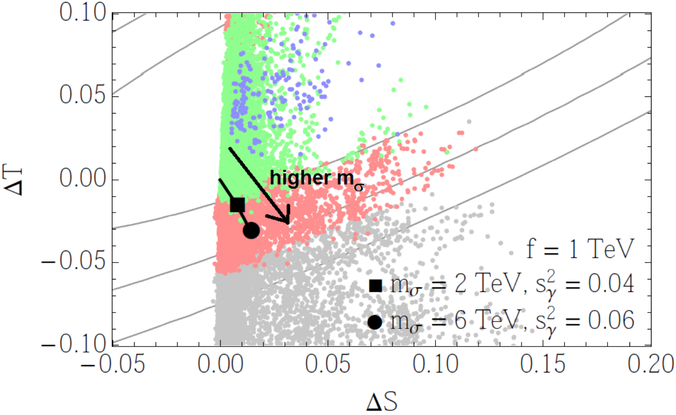
Panico et al (2012)
Panico, Wulzer (2015)



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 $(\Delta S, \Delta T, \Delta g_b)$

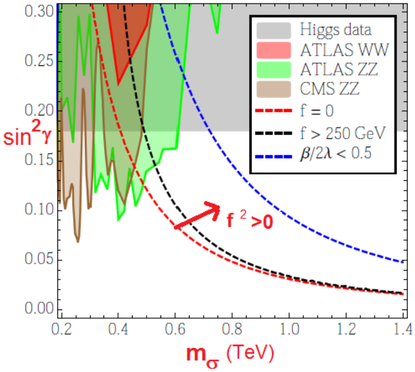
$\rightarrow$ larger m_σ might lead to more tension with data

σ particle and LHC data

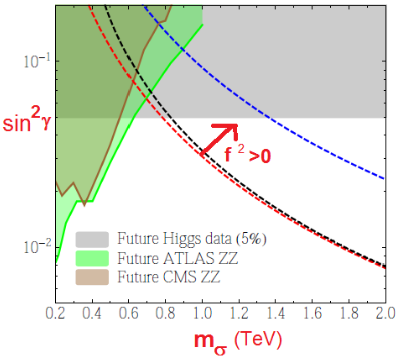
arXiv:1507.05930 (ATLAS), arXiv:1509.00389 (ATLAS), CMS PAS HIG-13-002, CMS PAS HIG-13-003, arXiv:1411.0322

Only SM top contribution (no added heavy fermions):

Present



Future



white area: SM + generic singlet allowed

natural h as pseudo-Goldstone boson(to the right of dashed black curve)

Other studies of global Higgs: Gersdorff et al (2015,2016), Sannino et al (2015,2016)

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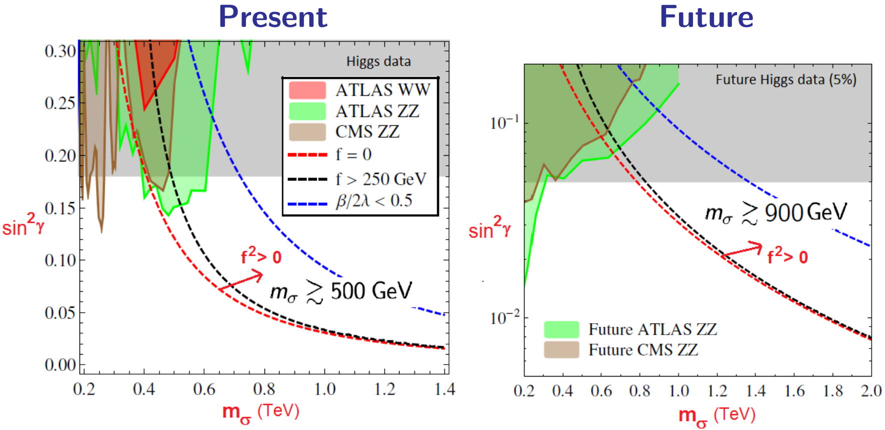
Adding heavy fermions the constraints might weaken:



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Other studies of global Higgs: Gersdorff et al (2015,2016), Sannino et al (2015,2016)

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

$$O_{Hq}^{(1)} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L)$$
$$O_{Hq}^{(3)} \equiv (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}_L \tau^i \gamma^\mu q_L)$$

$$O_{t,Yuk} \equiv \bar{q}_L \widetilde{H} t_R$$
$$O_{t\sigma} \equiv \sigma \bar{q}_L \widetilde{H} t_R$$
$$O_{t\sigma^2} \equiv \sigma^2 \bar{q}_L \widetilde{H} t_R$$
$$O_{tH} \equiv |H|^2 \bar{q}_L \widetilde{H} t_R$$

$\downarrow$

top mass and top Yukawa

Work in progress: effects of the σ integrated out

$\longrightarrow$ **See talk by K. Kanshin**

Conclusions

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Conclusions

- ⋆ We have defined a complete renormalizable model to understand scenarios with a Goldstone Higgs
- ⋆ 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

$$\text{SM Higgs} \xrightarrow{\text{substituted by}} \begin{cases} \text{Higgs } h \\ \text{sigma } \sigma \end{cases}$$

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

$\Longrightarrow$ Both h and σ get a vev:

$$v_\sigma = -f\,\frac{\alpha}{2\beta}$$

$$v = f\sqrt{1 - \frac{\alpha^2}{4\beta^2} + \frac{\beta}{2\lambda}}$$

$\Longrightarrow$ They mix:

$$\begin{pmatrix} \text{Light} \\ \text{Heavy} \end{pmatrix} = \begin{pmatrix} \cos\gamma & -\sin\gamma \\ \sin\gamma & \cos\gamma \end{pmatrix} \begin{pmatrix} h \\ \sigma \end{pmatrix}$$

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

4 renormalization parameters in the scalar sector:

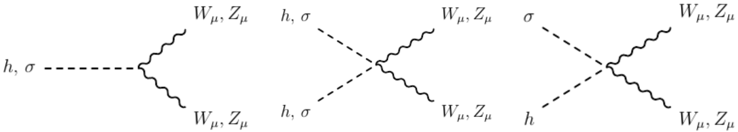
$$\left\{ G_F \equiv (\sqrt{2}v^2)^{-1}, \qquad m_h, \qquad m_\sigma, \qquad \sin^2\gamma \right\}$$

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

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

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

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



$$\mathcal{L}_{g,s} \supset \quad \frac{1}{4}g^2 v^2 W_\mu^+ W^{\mu -} + \frac{1}{2}\frac{1}{4}(g^2+g'^2)v^2 Z_\mu Z^\mu$$

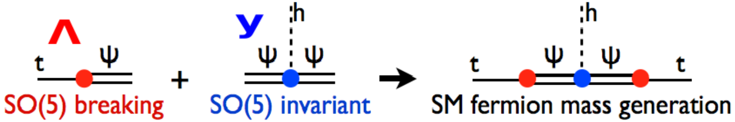
$$+ v(h\cos\gamma + \sigma\sin\gamma)\left(\frac{1}{2}g^2 W_\mu^+ W^{\mu -} + \frac{1}{4}(g^2+g'^2) Z_\mu Z^\mu\right)$$

$$+ (h^2\cos^2\gamma + 2h\sigma\sin\gamma\cos\gamma + \sigma^2\sin^2\gamma)\left(\frac{1}{4}g^2 W_\mu^+ W^{\mu -} + \frac{1}{8}(g^2+g'^2) Z_\mu Z^\mu\right)$$

- 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

Backup

Two types of terms in the fermion Lagrangian:



top yukawa:

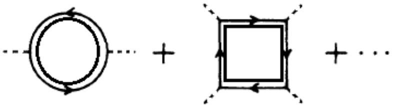
SO(5) breaking light-heavy mixing

light fermions do not couple directly to h

$y_t \sim y\, \Lambda^2 / M_\psi^2$

(à la seesaw)

Heavy fermion loops dominate the effective scalar potential:

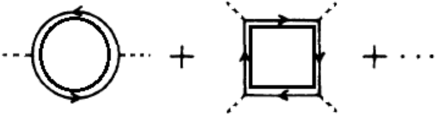


$$\longrightarrow \qquad V_{\text{loop}}^{\cancel{SO(5)}}(h, \sigma)$$

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

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

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



Coleman, Weinberg (1973)

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

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

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

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 $SO(5)$:

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

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

	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:

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

2 particles with exotic electric charge

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

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

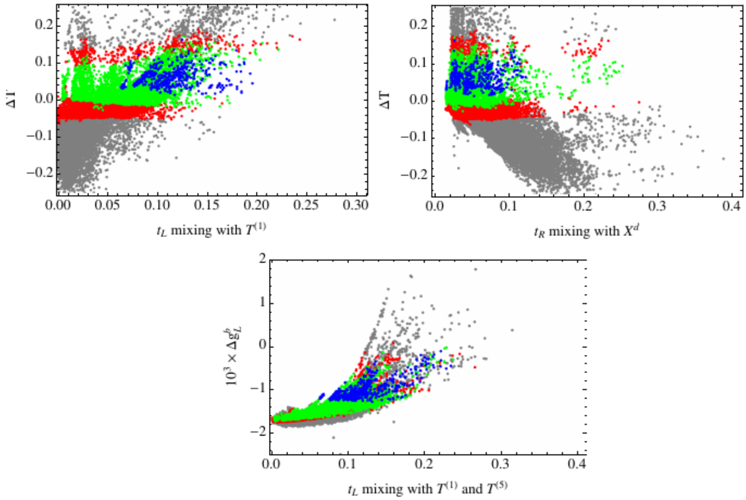
$$\mathcal{L}_{\mathcal{M}} = -\bar{\Psi}_L \; \mathcal{M}(h,\sigma) \; \Psi_R, \quad \Psi = \left(X^u, \; \mathcal{T}, \; \mathcal{B}, \; X'^d\right),$$

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

$$\mathcal{M}(h,\sigma) \;\; = \;\; \mathrm{diag}\left(M_5, \mathcal{M}^{\mathcal{T}}(h,\sigma), \mathcal{M}^{\mathcal{B}}(h,\sigma), M'_5\right),$$

$$\mathcal{M}^{\mathcal{T}}(h,\sigma) \;\; = \;\; \begin{pmatrix} 0 & \Lambda_1 & 0 & 0 & 0 & \Lambda'_1 \\ 0 & M_5 & 0 & 0 & y_1 \frac{h}{\sqrt{2}} & 0 \\ 0 & 0 & M_5 & 0 & y_1 \frac{h}{\sqrt{2}} & 0 \\ \Lambda_2 & 0 & 0 & M_5 & y_1 \sigma & 0 \\ \Lambda_3 & y_2 \frac{h}{\sqrt{2}} & y_2 \frac{h}{\sqrt{2}} & y_2 \sigma & M_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & M'_5 \end{pmatrix},$$

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



t_L mixing with exotic singlets correlated with $\Delta T > 0$ and $\delta g_{Zb_Lb_L}$

t_R mixing with exotic extra doublet correlated with $\Delta T < 0$

Dawson, Furlan (2012), Anastasiou, Furlan, Santiago (2009)

Connection with non-linear models: h coupling to fermions

relation with non-linear: $\xi \equiv \frac{v^2}{f^2} \approx \sin^2\gamma, \quad (m_\sigma >> m_h)$

$MCHM_{Q-T-B} = MCHM_{5-5,1-5,1}$= fermions in the **1** and **5** of $SO(5)$

$\rightarrow$ dim 4 yukawa operator: $(\bar{\psi}_5\phi)\psi_1$

$$\Rightarrow \kappa_F \equiv \kappa_{htt} = \sqrt{1-\xi} = \kappa_F^{MCHM_4}, \qquad \xi \equiv \frac{v^2}{f^2}$$

standard setup: $MCHM_5$= all fermions in **5** of $SO(5)$

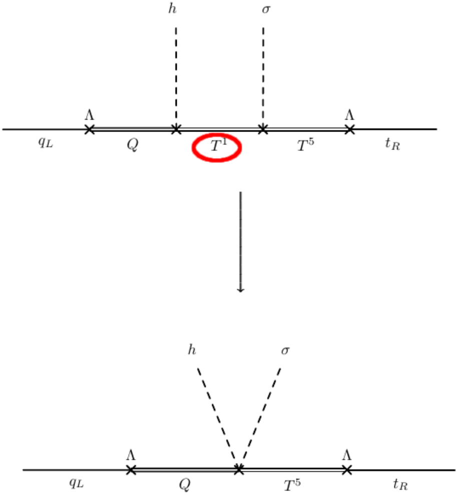
$\rightarrow$ dim 5 yukawa operator: $(\bar{\psi}_5\phi)(\phi^+\psi_5)$

$$\Rightarrow \kappa_F^{MCHM_5} = \frac{1-2\xi}{\sqrt{1-\xi}}$$

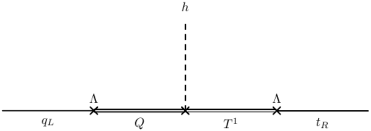
Panico, Wulzer (2015),

Carena, Da Rold, Pontón (2014)

$MCHM_{5-5-5}$



$MCHM_{5-5,1-5,1}$



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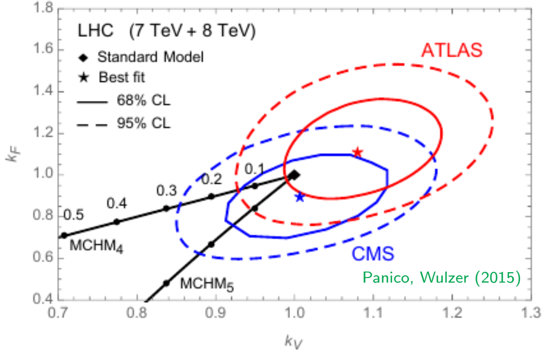
relation with non-linear: $\xi \equiv \frac{v^2}{f^2} \approx \sin^2\gamma, \quad (m_\sigma >> m_h)$

$$\kappa_V = \kappa_V^{MCHM_5} = \sqrt{1-\xi}$$

$$\kappa_F = \sqrt{1-\xi} \neq \kappa_F^{MCHM_5} = \frac{1-2\xi}{\sqrt{1-\xi}}$$



$\xi \lesssim 0.18$

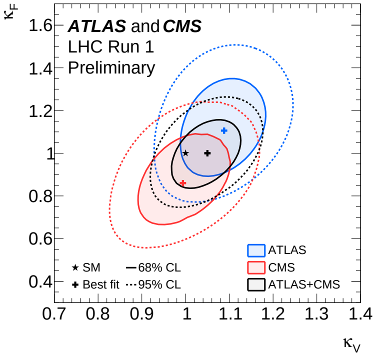
$\xi_{MCHM5} \lesssim 0.12$

combination, 2σ

$\Rightarrow$ 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



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

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

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