Custodial Leptons and Higgs Decays

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Carmona, FG
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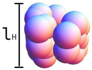
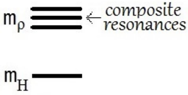
Composite Higgs Models

- Higgs is composite at small distances $E \gg 1/l_H \sim f$
  Kaplan, Georgi, Dimopoulos,...
  $\Rightarrow m_H$ saturated in IR $\Rightarrow$ Hierarchy Problem solved



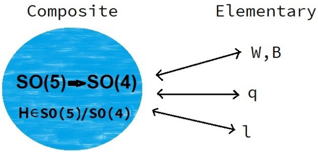
- Higgs as (pseudo-)Goldstone Boson $\Rightarrow m_H \ll m_\rho$ [like QCD pions]



- Minimal viable symmetry-breaking pattern:

  $$SO(5) \to SO(4)$$

  $\Rightarrow$ Custodial Symmetry
  The Minimal Composite Higgs Model (MCHM), Agashe, Contino, Pomarol

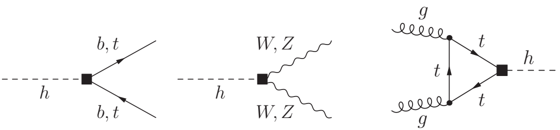


Higgs Production and Decay in Composite Models

Higgs = Goldstone → non-linear realization $\Sigma_I = \left(Exp[iH_{\hat{a}} T^{\hat{a}}/f] \right)_{I5}$

Higgs decay constant $f = m_\rho / g_\rho < m_\rho$

⇒ Modification of Higgs couplings due to $\boxed{\text{Goldstone nature}}$, scale as trigonometric functions of $\boxed{v/f}$ ⇒ *indirect* signs of model



…

$$\boxed{\kappa_p \equiv \frac{g_{hpp}}{g_{hpp}^{\mathrm{SM}}}}$$

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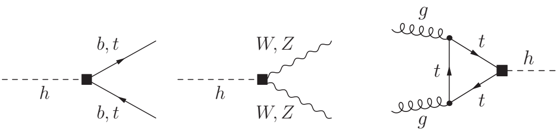

. . .

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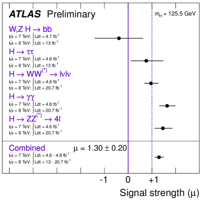

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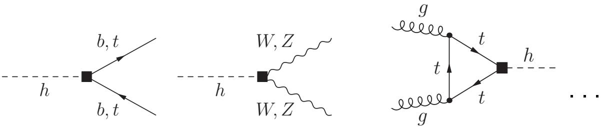


$$\kappa_p \equiv \frac{g_{hpp}}{g_{hpp}^{\mathrm{SM}}}$$

MCHM$_5$: fermions in **5** of $SO(5)$

$$\kappa_f^5 = \frac{\cos(2v/f)}{\cos(v/f)} < \kappa_{W,Z}$$

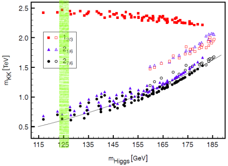
$$\kappa_{W,Z} = \cos(v/f)$$

Giudice, Grojean, Pomarol, R. Rattazzi, hep-ph/0703164

Effects of Resonances/Mixing? Light Top Custodians!

- Composite Higgs models (gauge-Higgs unification) feature generically light resonances associated to the (RH) top quark
  Carena, Ponton, Santiago, Wagner, hep-ph/0607106; Contino, Da Rold, Pomarol, hep-ph/0612048

$$\boxed{m_{\rm cust} \ll f}$$



- Consequence of large m_t (5D: IR localized) and enlarged fermion representations that protect $Zb\bar{b}$ (P_{LR})

$$\zeta_R^t = \begin{bmatrix} (\mathbf{2},\mathbf{2})_R^t[-+] \\ (\mathbf{1},\mathbf{1})_R^t[+,+] \end{bmatrix}$$

$$\zeta_L^t = [+ \leftrightarrow -]$$

[+ 3 other **5**s of $SO(5)$
$\cong$ ($\mathbf{2} \otimes \mathbf{2} \oplus \mathbf{1}$) of $SU(2)_L \times SU(2)_R$]

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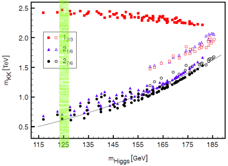

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New light scale $m_{\text{cust}} \ll f$ suggests that the effect of the light top custodians (incl. mixing) is dominant in these models

Low Energy Model: Vector-Like Fermion Scenario

- Possible to describe effects due to mixing with fermion resonances in transparent way by only considering

  SM + light custodians

- Motivated *vector-like fermion scenario*, featuring custodial protection
  [neglect other effects for the moment, see later] Carmona, FG, 1301.5856

MCHM_5

IR model: SM + new bi-doublets $\subset \zeta_R^{t,\tau} = \begin{bmatrix} (\mathbf{2},\mathbf{2})_R^{t,\tau}[-+] \\ (\mathbf{1},\mathbf{1})_R^{t,\tau}[+,+] \end{bmatrix}$

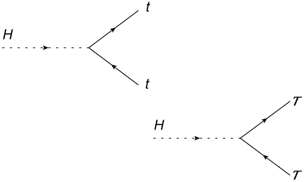
Light top custodians:

$$Q_{1L,R}^{(0)} = \begin{pmatrix} \Lambda_{1L,R}^{(0)} \\ T_{1L,R}^{(0)} \end{pmatrix} \sim \mathbf{2}_{\frac{7}{6}}, \quad Q_{2L,R}^{(0)} = \begin{pmatrix} T_{2L,R}^{(0)} \\ B_{2L,R}^{(0)} \end{pmatrix} \sim \mathbf{2}_{\frac{1}{6}}$$

$Q = 5/3,\ 2/3,\ 2/3,\ 1/3$

MCHM$_5$: Higgs Couplings of Top Sector in Mass Basis

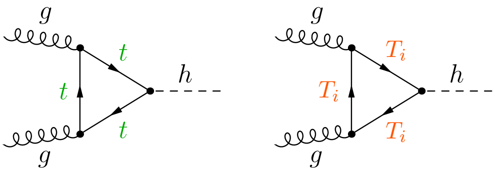
$$g_{h5}^{T} = \frac{1}{v}\begin{pmatrix} \boxed{c_R^2 m_t} & 0 & s_R c_R m_t \\ 0 & 0 & 0 \\ s_R c_R M_{T_2} & 0 & \boxed{s_R^2 M_{T_2}} \end{pmatrix}$$



- Mixing parameter $1 \geq s_R^2 = 1 - c_R^2 \geq 0$: function of yukawas and vector-like masses, measures compositeness of zero mode (mixing with resonances, negligible for light quarks)
- Coupling of SM mode depleted by c_R^2

Effects of Top Custodians: $gg \to h$ and $h \to \gamma\gamma$

$$\sigma(gg \to h)_{\mathrm{MCHM}_5} = |\kappa_g^5|^2\, \sigma(gg \to h)_{\mathrm{SM}}$$



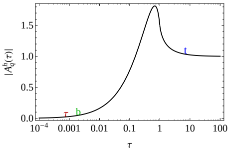
$$\kappa_g^5 \approx \frac{(c_R^t)^2 A(\tau_t) \;+\; (s_R^t)^2 A(\tau_{T_2})}{A(\tau_t)}\;;$$

loop functions

$A(\tau_t) \approx 1 \approx A(\tau_{T_2})$

neglect b (=SM) for simplicity

$$\tau_i = 4m_i^2/m_h^2$$



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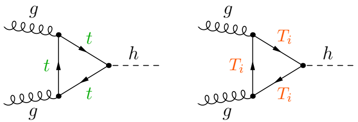

$$\kappa_g^5 \approx (c_R^t)^2 + (s_R^t)^2 = 1$$

- Effects due to quark mixing drop out after summing over SM-like top and resonances, due to $A(\tau_t) \approx A(\tau_{T_2}) \approx 1$ see Falkowski, 0711.0828

  $\Rightarrow$ No indirect information about details of spectrum and couplings

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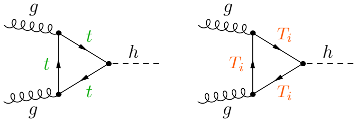

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  $\Rightarrow$ No indirect information about details of spectrum and couplings
- Light fermions considered elementary $\Rightarrow$ no effect at first place in that sector ($\leftrightarrow$ warped models Casagrande, FG, Haisch, Neubert, Pfoh, 1005.4315; Azatov, Toharia, Zhu, 1006.5939;...)
- Not much about fermion mixing (s_R) in past Higgs literature

  $\rightarrow$ only v/f effects ...

Very recently: top mixing accessible in Higgs+jets Banfi, Martin, Sanz, 1308.4771

Higgs Decays: $h \to \gamma\gamma$

$$\Gamma(h \to ff)_{\mathrm{MCHM}_5} = |\kappa_f^5|^2 \, \Gamma(h \to ff)_{\mathrm{SM}}$$

$$\boxed{\kappa_\gamma^5 = 1\,??}$$

... due to same cancellations as in κ_g^5?

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Indeed, top contributions cancel in the same way!

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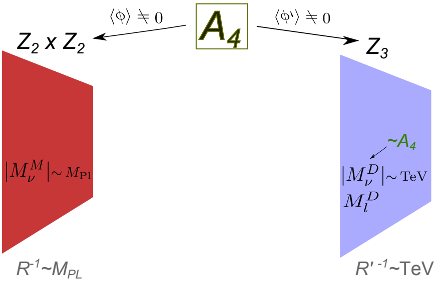
Indeed, top contributions cancel in the same way!

However, not considered before:

- $h \to \gamma\gamma$ features lepton contributions
- Negligible compositeness $\to$ no effect ?
- Not necessarily true!

Light Custodians: $MCHM_5$

- For leptons, naively no reason for light custodians
- However: explaining masses and mixings with the help of (flavor protecting) A_4



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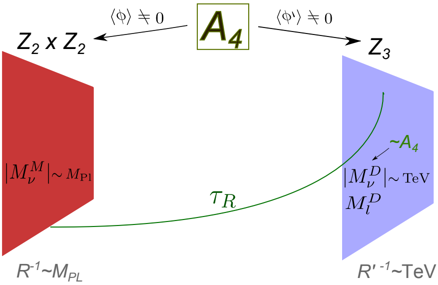
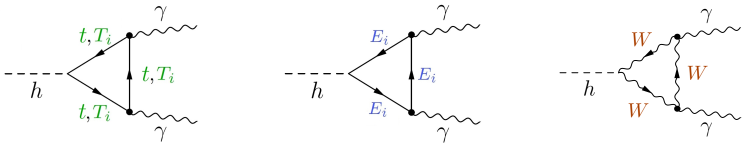


$\rightarrow$ τ more composite than naively expected
$\rightarrow$ light τ custodians (setup analogous to top custodians)
del Aguila, Carmona, Santiago, 1001.5151; Csaki, Delaunay, Grojean, Grossman, 0806.0356

Higgs Decays: $h \to \gamma\gamma$

Let's see what happens ...



$$\kappa_\gamma^5 \approx \frac{N_c Q_t^2 \; + \; Q_\tau^2((c_R^\tau)^2 A(\tau_\tau) + (s_R^\tau)^2) \; + \; A_W}{\mathrm{SM}}$$

$A_W \approx -6.25$ dominates

- *No cancellation* due to different loop fns. $A(\tau_\tau) \ll A(\tau_{E_2}) \approx 1$

Higgs Decays: $h \to \gamma\gamma$

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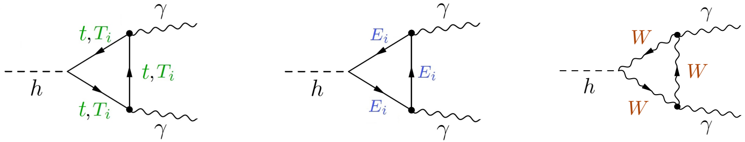

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- Surviving effect from fermion mixing: τ custodian, compositeness of light mode $\to s_R > 0$

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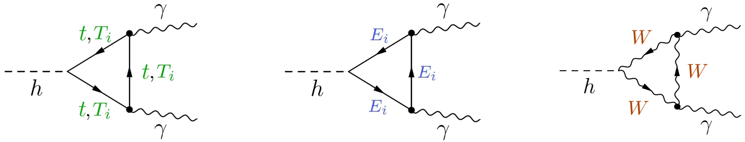

$$\kappa_\gamma^5 \approx 1 - \frac{(s_R^\tau)^2}{5} < 1$$

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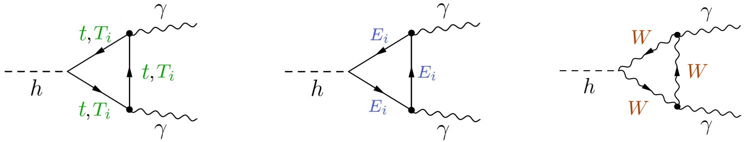

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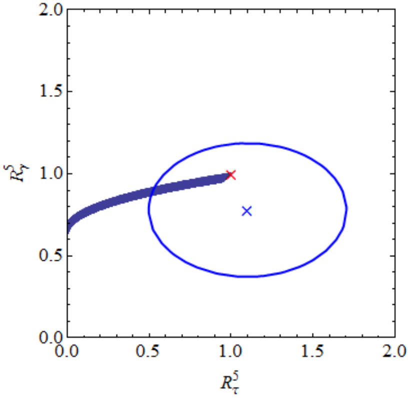
- Surviving effect from fermion mixing: τ custodian, compositeness of light mode $\to s_R > 0$
- More recently similar effect studied for composite light quarks

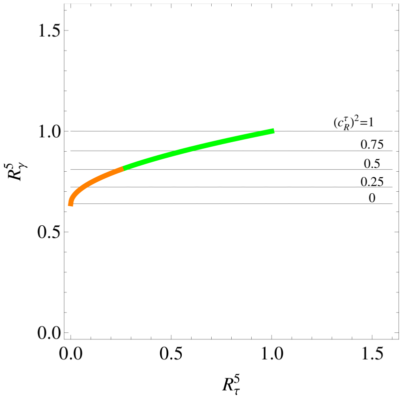
see Delaunay, Grojean, Perez, 1303.5701; see also Azatov, Galloway, 1110.5646

$$pp \to h \to \gamma\gamma$$
$$pp \to h \to \tau\tau$$

$$R_f^5 \equiv \frac{[\sigma(pp \to h)\mathrm{Br}(h \to ff)]_{\mathrm{MCHM}_5}}{[\sigma(pp \to h)\mathrm{Br}(h \to ff)]_{\mathrm{SM}}}$$



latest CMS results

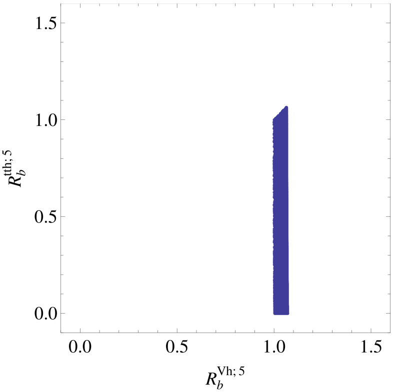


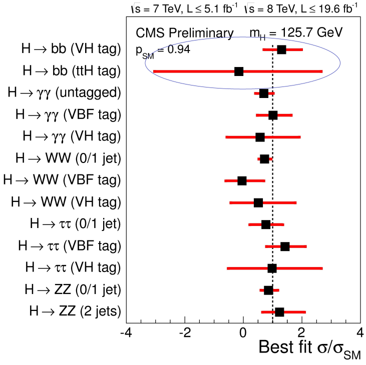
- Strong correlation allows to easily test the model
- Essentially only one parameter entering!

$$R_\gamma^5 \approx \left(1 - \frac{(s_R^\tau)^2}{5}\right)^2$$

$$R_\tau^5 \approx (c_R^\tau)^4$$

$h \to bb$

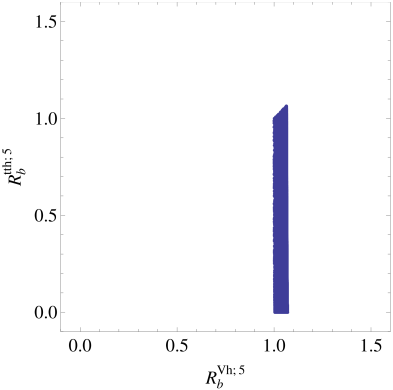


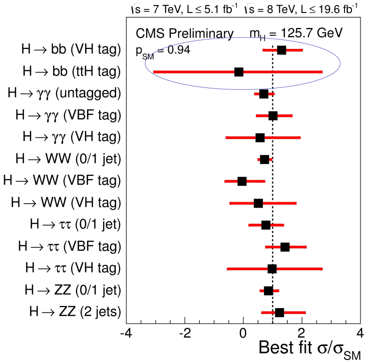


$gg \to t\bar{t}^* t^* \bar{t} \to t\bar{t}h,\ h \to b\bar{b}$ suppressed due to $\kappa_t^5 < 1$

$\Rightarrow$ Nice possibility to test the model in the future!

$$\sigma(tth)_{\rm MCHM_5} = (c_R^t)^4\, \sigma(tth)_{\rm SM}$$





Another option for (direct) access to parameter of model

$$(c_R^t)^2 \approx \sqrt{R_b^{tth;\,5}}$$

$$\sigma(tth)_{\mathrm{MCHM}_5} = (c_R^t)^4\,\sigma(tth)_{\mathrm{SM}}$$

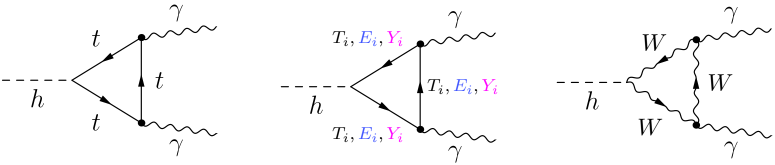
Study Other Fermion Representations

- Put τ_R into adjoint representation, **10** of SO(5)

$$\zeta_R^\tau = \left[\begin{array}{c} (\mathbf{2},\mathbf{2})_R^\tau[-,+] = \begin{pmatrix} N_{1R}[-,+] & E_{2R}[-,+] \\ E_{1R}[-,+] & Y_{2R}[-,+] \end{pmatrix} \\ (\mathbf{3},\mathbf{1})_R^\tau[-.+] = \begin{pmatrix} N_{3R}[-,+] \\ E_{3R}[-,+] \\ Y_{3R}[-,+] \end{pmatrix} \\ (\mathbf{1},\mathbf{3})_R^\tau = \begin{pmatrix} N_{2R}[-,+] & \tau_R[+,+] & Y_{1R}[-,+] \end{pmatrix} \end{array} \right]$$

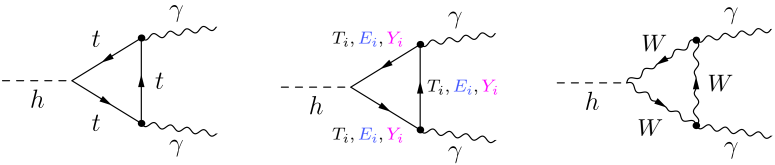
$\boxed{\text{MCHM}_{5+10}}$

Higgs Decays: MCHM_{5+10}



$$\kappa_\gamma^{5+10} \approx 1 - \frac{\nu_E^{5+10} + 4\nu_Y^{5+10}}{5} \begin{array}{l} > 1 \\ < 1 \end{array}$$

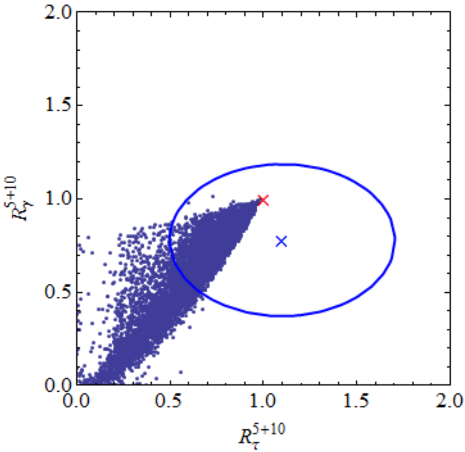
Higgs Decays: MCHM_{5+10}



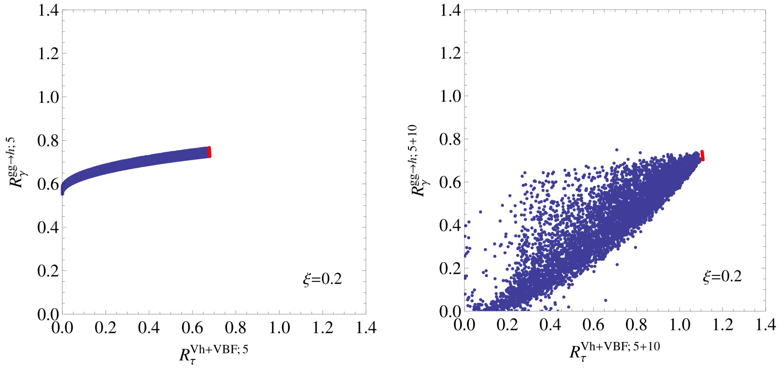
$$\kappa_\gamma^{5+10} \approx 1 - \frac{\nu_E^{5+10} + 4\nu_Y^{5+10}}{5} < 1$$

5D constraints on parameters $\Rightarrow \nu_E^{5+10} > 0,\ \nu_Y^{5+10} > 0$

Higgs Phenomenology: "5D" $MCHM_{5+10}$

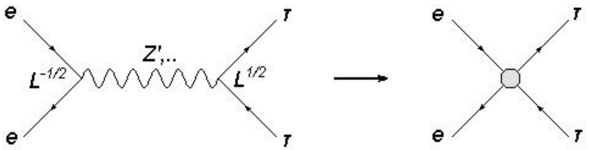


Effects of Non-Linearity of Higgs Sector



- Trigonometric rescalings on top of fermion mixings, now also VBF and *Vh* production get reduced
- Qualitative picture from fermion-mixing still valid in $gg \to h$
- Usually neglected mixing effects are relevant in general

Tau Compositeness: Estimates



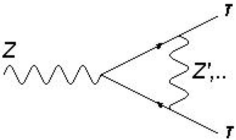
Bounds on 4fermi operators
$(\bar{e}\,\gamma^\mu P_{L,R}\, e)(\bar{\tau}\gamma_\mu P_{L,R}\tau)$:

$C_{ee\tau\tau} < [(1-2)\,\mathrm{TeV}]^{-2}$

see e.g. Raidal et al., 0801.1826

In composite $A4$ models:
$C_{ee\tau\tau} \sim g^2\, 1/\sqrt{L} * \sqrt{L}\;\; 1/m_\rho^2$

$m_\rho \sim 1$ TeV ok
for $s_R^\tau \sim \mathcal{O}(1)$!



Similar considerations
$\rightarrow s_R^\tau \sim O(1)$ still possible

$\rightarrow$ exact calculation in progress

Summary

- Lepton custodians lead to distinct phenomenology with respect to previous studies of composite models
  $\Rightarrow$ Interesting scenario to consider
- Complementarity between direct searches for fermion partners and looking for indirect effects
- Precise measurement of Higgs couplings desirable
- Outlook: study full 5D model
- As we have seen that large signals are not to be expected from the quark sector, it could be the unexpected compositeness of the τ-lepton that leads to first signals of compositeness in Higgs physics at the LHC

Summary

Thank you for your attention!

Backup: Minimal Composite Higgs Models

Starting point for description of PGB-Higgs $(E < 4\pi f)$:

Non-linear sigma model

$$\mathcal{L}_\Sigma = D_\mu \Sigma^T D^\mu \Sigma, \quad \Sigma_I = \left(Exp[iH_{\hat{a}} T^{\hat{a}}/f] \right)_{I5}$$

$T^{\hat{a}}$: (broken) generators of coset $SO(5)/SO(4)$

Higgs decay constant $f = m_\rho/g_\rho < m_\rho$

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Starting point for description of PGB-Higgs $(E < 4\pi f)$:

Non-linear sigma model

$$\mathcal{L}_\Sigma = D_\mu \Sigma^T D^\mu \Sigma, \quad \Sigma_I = \left(Exp[iH_{\hat{a}} T^{\hat{a}}/f] \right)_{I5}$$

$T^{\hat{a}}$: (broken) generators of coset $SO(5)/SO(4)$

Higgs decay constant $f = m_\rho/g_\rho < m_\rho$

- Expect Higgs couplings to scale as trigonometric functions of v/f
- MCHM_5 (MCHM_{10}): fermions in **5** (**10**) of $SO(5)$

Backup: Light Custodians: MCHM_5

$$\zeta_R^u = \begin{bmatrix} (\mathbf{2},\mathbf{2})_R^u[-+] \\ (\mathbf{1},\mathbf{1})_R^u[+,+] \end{bmatrix}$$

$+$ 3 other **5**s of $SO(5)$

t_R (residing mostly in $(\mathbf{1},\mathbf{1})_R^u$) is composite
$\Rightarrow$ RH (would-be) 0-modes in ζ^u localized moderately strong in IR
$\Rightarrow$ BCs support ultra-light KKs in $(\mathbf{2},\mathbf{2})_R^u[-+]$

Contino, Da Rold, Pomarol, hep-ph/0612048
del Aguila, Carmona, Santiago, 1001.5151

[**5** of $SO(5) \cong (\mathbf{2} \otimes \mathbf{2} \oplus \mathbf{1})$ of $SU(2)_L \times SU(2)_R$]

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[$\mathbf{5}$ of $SO(5) \cong (\mathbf{2}\otimes\mathbf{2}\oplus\mathbf{1})$ of $SU(2)_L \times SU(2)_R$]

Light top custodians:

$$Q_{1L,R}^{(0)} = \begin{pmatrix} \Lambda_{1L,R}^{(0)} \\ T_{1L,R}^{(0)} \end{pmatrix} \sim \mathbf{2}_{\frac{7}{6}}, \quad Q_{2L,R}^{(0)} = \begin{pmatrix} T_{2L,R}^{(0)} \\ B_{2L,R}^{(0)} \end{pmatrix} \sim \mathbf{2}_{\frac{1}{6}}$$

$$T_R^3 : (\tfrac{1}{2}, -\tfrac{1}{2})$$

Backup: MCHM_5

$$\mathcal{L}_L = -y_l\, \bar{l}_L^{(0)} \varphi \tau_R^{(0)} - y_l' \left[\bar{L}_{1L}^{(0)} \varphi + \bar{L}_{2L}^{(0)} \tilde{\varphi} \right] \tau_R^{(0)} - M_l \left[\bar{L}_{1L}^{(0)} L_{1R}^{(0)} + \bar{L}_{2L}^{(0)} L_{2R}^{(0)} \right] + \text{h.c.}$$

$$\mathcal{L}_Q = -y_q\, \bar{q}_L^{(0)} \varphi t_R^{(0)} - y_q' \left[\bar{Q}_{1L}^{(0)} \varphi + \bar{Q}_{2L}^{(0)} \tilde{\varphi} \right] t_R^{(0)} - M_Q \left[\bar{Q}_{1L}^{(0)} Q_{1R}^{(0)} + \bar{Q}_{2L}^{(0)} Q_{2R}^{(0)} \right] + \text{h.c.}$$

$l_L^{(0)}$, $\tau_R^{(0)}$, $q_L^{(0)}$, $t_R^{(0)}$: third generation SM fields, $\varphi = 1/\sqrt{2}\,(0, v+h)^T$

- First two generations: negligible couplings to resonances, effects of their resonances on Higgs physics negligible (different in warped XD)
- $b_R^{(0)}$,$\nu_R^{(0)}$ behave SM-like since there are no new resonances to which they could couple
- P_{LR} symmetry: $SU(2)_L \leftrightarrow SU(2)_R$, protects $Z \to b_L b_L$, $Z \to \tau_R \tau_R$

Backup: MCHM$_5$: Spectrum

$$\mathcal{M}_E^5 = \begin{pmatrix} \frac{v}{\sqrt{2}} y & 0 & 0 \\ \frac{v}{\sqrt{2}} y' & M & 0 \\ \frac{v}{\sqrt{2}} y' & 0 & M \end{pmatrix}$$

Three heavy particle with degenerate mass

$$m_N = m_{E_1} = m_Y = M$$

$Q = 0, -1, -2$ (quarks analogous $Q = \frac{5}{3}, \frac{2}{3}, -\frac{1}{3}$)

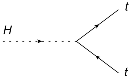
Additional heavier $Q = -1$ ($Q = 2/3$) state with

$$m_{E_2} = \frac{M}{c_R} \sqrt{1 - s_R^2 \frac{m_\tau^2}{M^2}}$$

Backup: Higgs Decays

$$\Gamma(h \to ff)_{\mathrm{MCHM}_5} = |\kappa_f^5|^2 \, \Gamma(h \to ff)_{\mathrm{SM}}$$

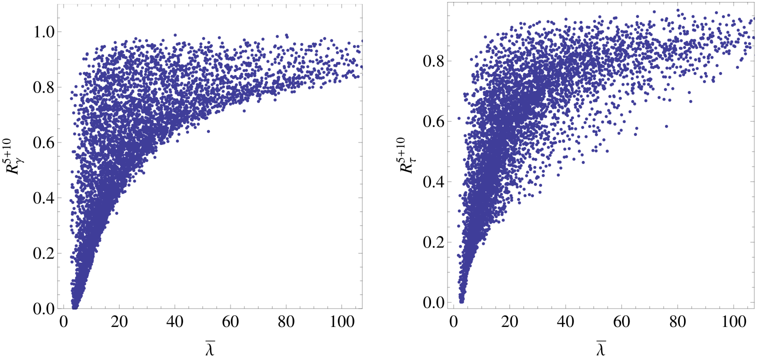
κ_t^5	$(c_R^t)^2$
κ_b^5	1
κ_g^5	≈ 1
κ_τ^5	$(c_R^\tau)^2$
$\kappa_W^5 = \kappa_Z^5$	1



Backup: Yukawa and Mass Lagrangian for MCHM_{5+10}

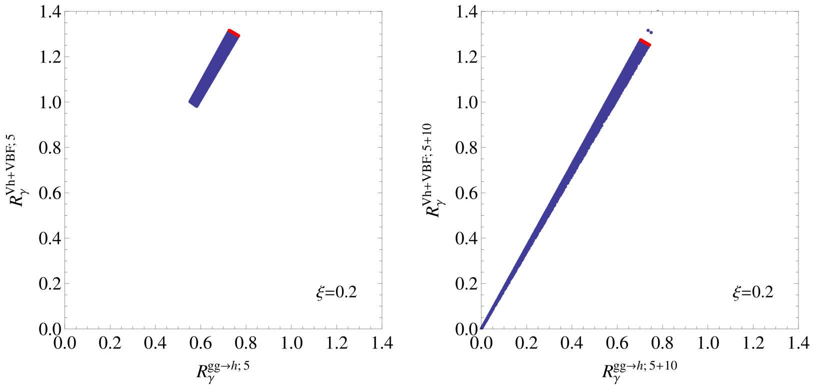
$$
\begin{aligned}
\mathcal{L} \;=\;& -y\,\bar{l}_L^{(0)}\varphi\tau_R^{(0)} - y'\left[\bar{L}_{1L}^{(0)}\varphi + \bar{L}_{2L}^{(0)}\tilde{\varphi}\right]\tau_R^{(0)} - M\left[\bar{L}_{1L}^{(0)}L_{1R}^{(0)} + \bar{L}_{2L}^{(0)}L_{2R}^{(0)}\right] \\
& - \tilde{M}\left[\bar{L}_{3L}^{(0)}L_{3R}^{(0)} + \bar{Y}_{1L}^{(0)}Y_{1R}^{0}\right] - \tilde{y}\,\bar{l}_L^{(0)}\sigma^I\varphi L_{3R}^{(0)I} - \hat{y}\left[\bar{L}_{1L}^{(0)}\sigma^I\varphi - \bar{L}_{2L}^{(0)}\sigma^I\tilde{\varphi}\right]L_{3R}^{(0)I} \\
& - \sqrt{2}\hat{y}\bar{L}_{2L}^{(0)}\varphi Y_{1R}^{(0)} + \bar{y}^*\left[\bar{L}_{1R}^{(0)}\sigma^I\varphi - \bar{L}_{2R}^{(0)}\sigma^I\tilde{\varphi}\right]L_{3L}^{(0)I} + \sqrt{2}\bar{y}^*\bar{L}_{2R}^{(0)}\varphi Y_{1L}^{(0)} + \text{h.c.}
\end{aligned}
$$

Backup: Dependence on Parameters



$$\bar{\lambda} = \frac{2M\tilde{M}}{v^2|\bar{y}\hat{y}|}$$

Backup: Effects of Non-Linearity of Higgs Sector



Backup: Effects of Non-Linearity of Higgs Sector

Pseudo-Goldstone Nature of Higgs (leading order) $\Rightarrow$

$$\kappa_W = \kappa_Z = \cos\left(\frac{v}{f}\right) \approx \sqrt{1-\xi}, \quad \xi = v^2/f^2$$

$\Rightarrow$ trivial rescaling of VBF and Vh

$$\kappa_f^5 \to \kappa_f^5 \cos\left(\frac{2v}{f}\right) / \cos\left(\frac{v}{f}\right) \approx \kappa_f^5 (1-2\xi)/\sqrt{1-\xi}$$

$$\kappa_g^5 \approx \cos\left(\frac{2v}{f}\right) / \cos\left(\frac{v}{f}\right) \approx (1-2\xi)/\sqrt{1-\xi}$$

$$\kappa_\tau^{5+10} \to \kappa_\tau^{5+10} \cos\left(\frac{v}{f}\right) \approx \kappa_\tau^{5+10}\sqrt{1-\xi}$$

see Giudice, Grojean, Pomarol, R. Rattazzi, hep-ph/0703164; Azatov, Galloway, 1110.5646