Tau Compositeness and Higgs Decays

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Carmona, FG
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Outline

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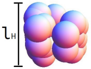
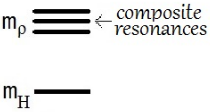
Composite Higgs Models

- 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 pion in QCD]



- Minimal viable symmetry-breaking pattern: $\boxed{SO(5) \rightarrow SO(4)}$
  $\Rightarrow$ Custodial Symmetry

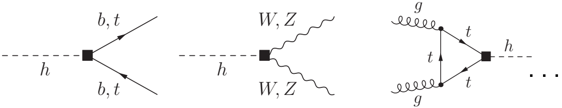
Outline

Higgs Production and Decay in Composite Models

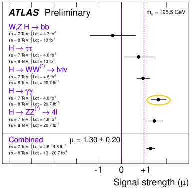
Higgs = Goldstone → non-linear realization $\Sigma_I = \left(Exp[iH_{\hat{a}} T^{\hat{a}}/f]\right)_{I5}$

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

⇒ Modification of Higgs couplings, scale as trigonometric functions of v/f ⇒ *indirect* signs of model



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



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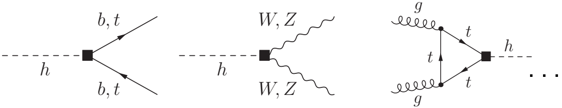


$$\kappa_p \equiv \frac{g_{hpp}}{g_{hpp}^{\mathrm{SM}}}$$

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 Fermion Resonances? Light 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

$$m_{\mathrm{cust}} \ll f$$

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

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

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

Light Custodians: MCHM_5

- For leptons, naively no such reason for light custodians
- However: explaining masses and mixings with the help of (flavor protecting) A_4
  $\rightarrow \tau$ more composite than naively expected
  $\rightarrow$ light τ custodians
  del Aguila, Carmona, Santiago, 1001.5151; Csaki, Delaunay, Grojean, Grossman, 0806.0356
- New light scale $m_{\mathrm{cust}} \ll f$ suggests that the effect of the light custodians (incl. mixing) is dominant in these models

Light Custodians: MCHM_5

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

$$\text{SM} + \text{light custodians}$$

- Vector-like lepton scenario
  [neglect other effects for the moment, see later] Carmona, FG, 1301.5856

Outline

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 τ and top custodians:

$$L_{1L,R}^{(0)} = \begin{pmatrix} N_{1L,R}^{(0)} \\ E_{1L,R}^{(0)} \end{pmatrix} \sim \mathbf{2}_{-\frac{1}{2}}, \quad L_{2L,R}^{(0)} = \begin{pmatrix} E_{2L,R}^{(0)} \\ Y_{2L,R}^{(0)} \end{pmatrix} \sim \mathbf{2}_{-\frac{3}{2}},$$

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

$Q = 0, -1, -1, -2$

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

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

MCHM_5

$$\mathcal{L}_L^m = -y\,\bar{l}_L^{(0)} H \tau_R^{(0)} - y' \left[\bar{L}_{1L}^{(0)} H + \bar{L}_{2L}^{(0)} \tilde{H} \right] \tau_R^{(0)} - M \left[\bar{L}_{1L}^{(0)} L_{1R}^{(0)} + \bar{L}_{2L}^{(0)} L_{2R}^{(0)} \right] + \mathrm{h.c.}$$

$\Downarrow$

Mixing with composite resonances $\Rightarrow$ $\boxed{\text{angle } s_R > 0}$

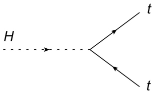
$\mathcal{O}(\mathrm{TeV}) \gg M \gg v$

- only τ sector coupled to new light resonances (top sector analogously)
- first 2 generations + ν,b behave SM-like

Described by 3 parameters: $\boxed{m_\tau, s_R, M}$, M: scale of light resonances (E_1, E_2)

MCHM$_5$: Higgs Couplings in Mass Basis

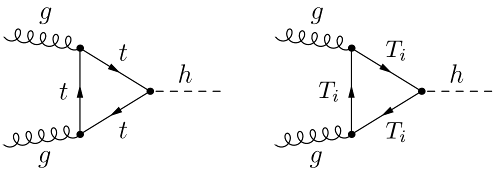
$$g^E_{h5} = \frac{1}{v}\begin{pmatrix} \boxed{c_R^2 m_\tau} & 0 & s_R c_R m_\tau \\ 0 & 0 & 0 \\ s_R c_R M_{E_2} & 0 & \boxed{s_R^2 M_{E_2}} \end{pmatrix}$$



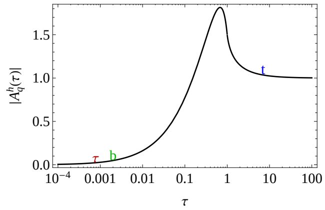
- Later consider also fermions in a **10** of $SO(5) \rightarrow$ richer structure

Higgs Production: Gluon Fusion

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



$$\kappa_g^5 \approx \frac{\kappa_t^5 \, A_q^h(\tau_t) + \kappa_b^5 \, A_q^h(\tau_b) \;\; + \;\; \nu_T^5}{A_q^h(\tau_t) + A_q^h(\tau_b)}$$



$$\tau_i = 4m_i^2/m_h^2, \quad A_q^h(\tau_t) \approx 1, \;\; A_q^h(\tau_b) \ll 1$$

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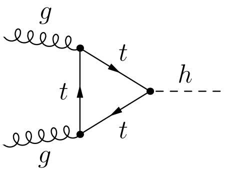
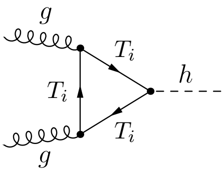
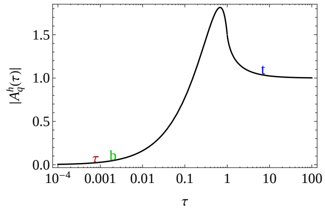




$$\kappa_g^5 \approx \frac{\kappa_t^5 + \kappa_b^5 A_q^h(\tau_b) \; + \; \nu_T^5}{1 + A_q^h(\tau_b)}$$



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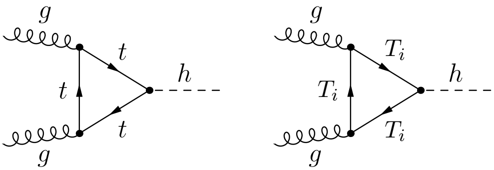


$$\kappa_g^5 = \frac{\kappa_t^5 + \kappa_b^5 A_q^h(\tau_b) \; + \; \nu_T^5}{1 + A_q^h(\tau_b)}$$

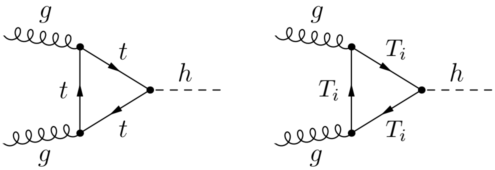
$$g_{h5}^T = \frac{1}{v} \begin{pmatrix} \boxed{(c_R^t)^2 m_t} & 0 & s_R^t c_R^t m_t \\ 0 & 0 & 0 \\ s_R^t c_R^t M_{T_2} & 0 & \boxed{(s_R^t)^2 M_{T_2}} \end{pmatrix}$$

$$\kappa_f^5 = \mathrm{Re}\left[(g_{h5}^F)_{11}\right] \frac{v}{m_f} \qquad \Rightarrow \boxed{\kappa_t^5 = (c_R^t)^2}, \quad \boxed{\kappa_b^5 = 1}$$

$$\nu_F^5 = v \sum_{n=2}^{3} \frac{\mathrm{Re}\left[(g_{h5}^F)_{nn}\right]}{m_{F_{n-1}}} \qquad \Rightarrow \boxed{\nu_T^5 = (s_R^t)^2}$$

measuring compositeness/
mixing with NP

Higgs Production: Gluon Fusion



$$\kappa_g^5 \approx \frac{(c_R^t)^2 + A_q^h(\tau_b) + (s_R^t)^2}{1 + A_q^h(\tau_b)} = 1 \qquad A_q^h(\tau_t) \approx 1,\, A_q^h(\tau_b) \ll 1$$

- Effects due to fermion mixing drop out after summing over SM-like top and resonances (same $A_q^h = 1$): $(c_R^t)^2 + (s_R^t)^2 = 1$
  see Falkowski, 0711.0828
- Fermion mixing seems not important?

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

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

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

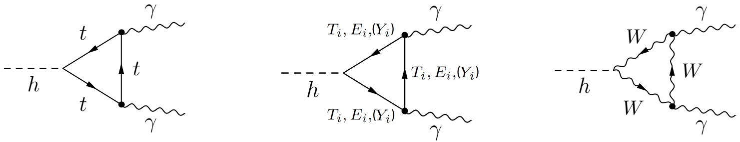
due to same cancellations as in κ_g^5?

Considered like this in previous literature on composite models:

However, not considered that there is a new case:
light fermion with a significant composite component: τ-lepton

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

Let's see what happens ...



$$\kappa_\gamma^5 \approx \frac{N_c(Q_t^2 + Q_b^2 A_q^h(\tau_b)) \; + \; Q_\tau^2((c_R^\tau)^2 A_q^h(\tau_\tau) + (s_R^\tau)^2) \; + \; A_W^h}{N_c(Q_t^2 + Q_b^2 A_q^h(\tau_b)) \; + \; Q_\tau^2 A_q^h(\tau_\tau) \; + \; A_W^h}$$

$A_W^h \approx -6.25$ dominates

- No cancellation!
- Due to different loop functions for light mode and resonances
- $\rightarrow$ surviving effect from fermion mixing!
- More recently similar effects considered in quark sector

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

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

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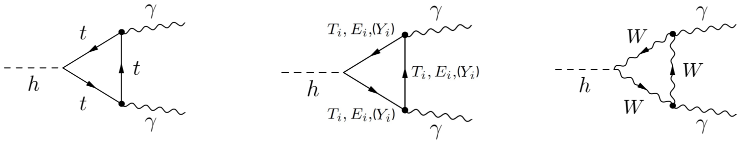

$$\kappa_\gamma^5 \approx \frac{N_c Q_t^2 + Q_\tau^2 (s_R^\tau)^2 + A_W^h}{N_c Q_t^2 + A_W^h}$$

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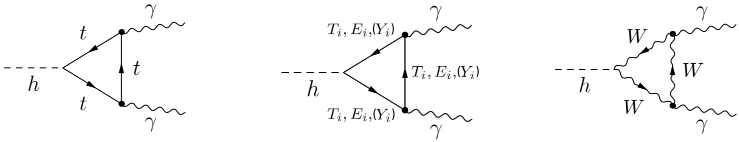

$$\kappa_\gamma^5 \approx 1 - \frac{(s_R^\tau)^2}{5} < 1$$

- No cancellation!
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Higgs Phenomenology

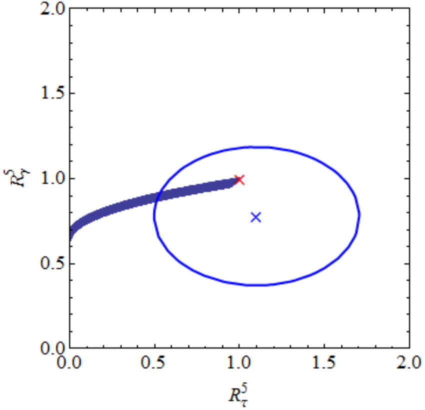
- Study change of Higgs production times branching

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

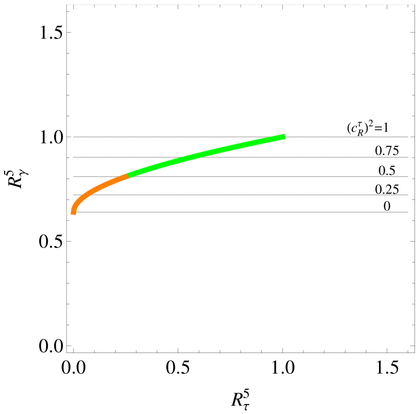
Also consider exclusive production channels

$$R_f^{i;\,5} \equiv \frac{[\sigma(i)\mathrm{Br}(h \to ff)]_{\mathrm{MCHM}_5}}{[\sigma(i)\mathrm{Br}(h \to ff)]_{\mathrm{SM}}}, \; i = gg \to h, \, \mathrm{VBF}, \, Vh, \, tth$$

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



latest CMS results

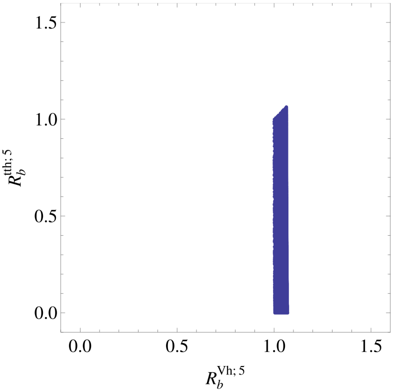


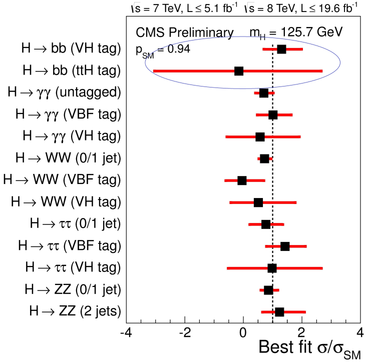
- Strong correlation allows to easily test the model
- Essentially only one parameter entering!

$$R_\gamma^5 \approx \frac{[\Gamma(h \to \gamma\gamma)]_{\mathrm{MCHM}_5}}{[\Gamma(h \to \gamma\gamma)]_{\mathrm{SM}}} \approx \left(1 - \frac{(s_R^\tau)^2}{5}\right)^2$$

$$R_\tau^5 \approx \frac{[\Gamma(h \to \tau\tau)]_{\mathrm{MCHM}_5}}{[\Gamma(h \to \tau\tau)]_{\mathrm{SM}}} = (c_R^\tau)^4$$

$$h \to bb$$

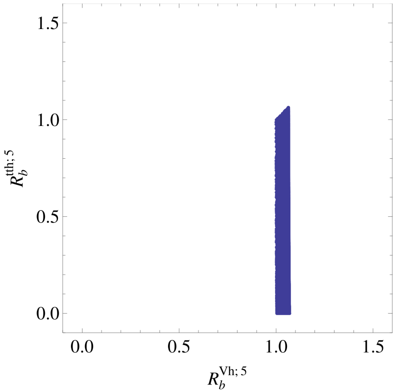


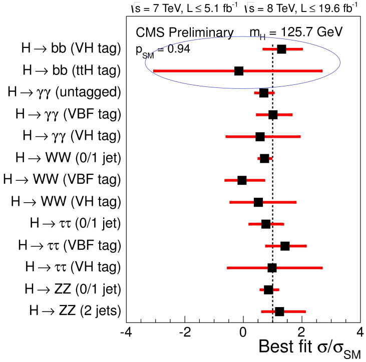


$gg \to t\bar{t}^* t^* \bar{t} \to t\bar{t}h,\ h \to b\bar{b}$ suppressed due to $\kappa_t^5 < 1$

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

$$\sigma(tth)_{\mathrm{MCHM}_5} = (\kappa_t^5)^2\, \sigma(tth)_{\mathrm{SM}} = (c_R^t)^4$$





Direct access to parameter of model

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

$$\sigma(tth)_{\mathrm{MCHM}_5} = (\kappa_t^5)^2\,\sigma(tth)_{\mathrm{SM}} = (c_R^t)^4$$

Study Other Fermion Representations

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

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

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

MCHM_{5+10}

Light τ custodians:

$$L_{1L,R}^{(0)} = \begin{pmatrix} N_{1L,R}^{(0)} \\ E_{1L,R}^{(0)} \end{pmatrix} \sim \mathbf{2}_{-\frac{1}{2}}, \quad L_{2L,R}^{(0)} = \begin{pmatrix} E_{2L,R}^{(0)} \\ Y_{2L,R}^{(0)} \end{pmatrix} \sim \mathbf{2}_{-\frac{3}{2}},$$

$$L_{3L,R}^{(0)} = \begin{pmatrix} N_{3L,R}^{(0)} \\ E_{3L,R}^{(0)} \\ Y_{3L,R}^{(0)} \end{pmatrix} \sim \mathbf{3}_{-1}, \quad N_{2L,R}^{(0)} \sim \mathbf{1}_0, \quad Y_{1L,R}^{(0)} \sim \mathbf{1}_{-2}$$

- top custodians same as before, didn't change quark sector

MCHM_{5+10}

Relevant mass matrices:

$$\mathcal{M}_E = \frac{v}{\sqrt{2}} \begin{pmatrix} y & 0 & 0 & -\tilde{y} \\ y' & \frac{\sqrt{2}}{v} M & 0 & -\hat{y} \\ y' & 0 & \frac{\sqrt{2}}{v} M & -\hat{y} \\ 0 & \bar{y} & \bar{y} & \frac{\sqrt{2}}{v} \tilde{M} \end{pmatrix} \quad \mathcal{M}_Y = v \begin{pmatrix} \frac{1}{v} \tilde{M} & -\bar{y} & 0 \\ \hat{y} & \frac{1}{v} M & -\hat{y} \\ 0 & \bar{y} & \frac{1}{v} \tilde{M} \end{pmatrix}$$

$$g_{h10}^{f(0)} = \frac{\partial \mathcal{M}_f}{\partial v}, \quad f = E, Y$$

$\Rightarrow$ Spectrum and physical Higgs couplings, scan parameterspace

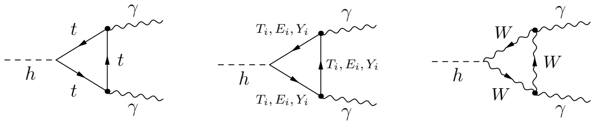
Analytic results for sum of Higgs couplings over masses via:

$$\kappa_\tau^{5+10} + \nu_E^{5+10} = v \mathrm{Re} \left[\frac{\partial \log(\det \mathcal{M}_E)}{\partial v} \right], \text{ etc.}$$

Higgs Decays: MCHM_{5+10}

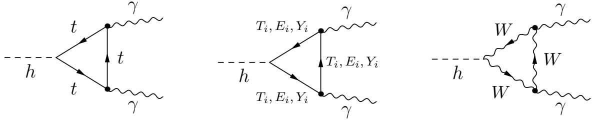
Only lepton sector modified

$\rightarrow$ all κ_i considered unchanged, besides κ_τ and κ_γ



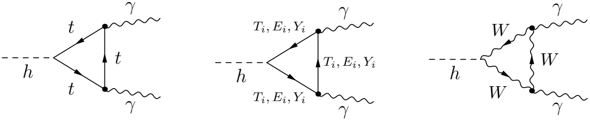
$$\kappa_\gamma^{5+10} \approx 1 - \frac{\nu_E^{5+10} + 4\nu_Y^{5+10}}{5}$$

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}



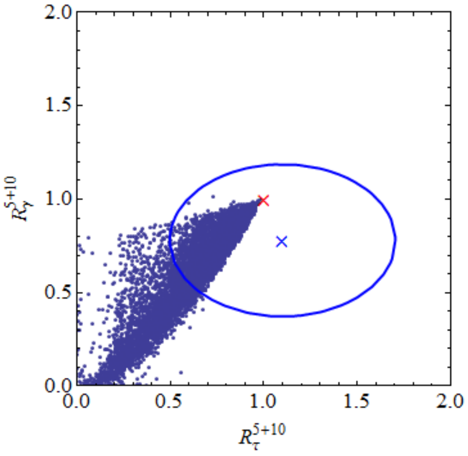
$$\kappa_\gamma^{5+10} \approx 1 - \frac{\nu_E^{5+10} + 4\nu_Y^{5+10}}{5} < 1$$

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

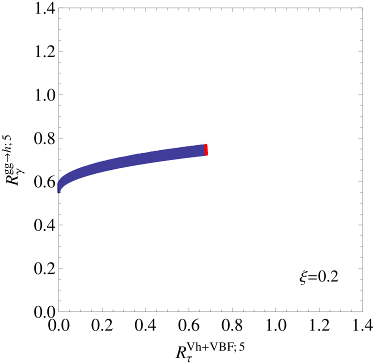
Higgs Phenomenology: MCHM_{5+10}

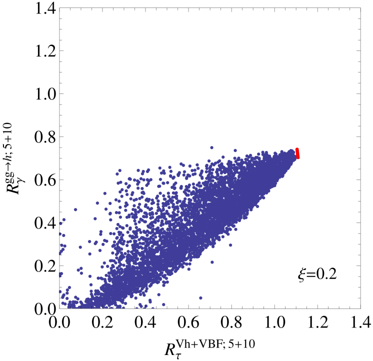
$$pp \to h \to \gamma\gamma$$
$$pp \to h \to \tau\tau$$

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

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
- 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 $f = m_\rho / g_\rho < m_\rho$

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 $f = m_\rho / g_\rho < m_\rho$

- 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

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

$+$ 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 $SU(2)_L \times SU(2)_R$]

Backup: Light Custodians: MCHM_5

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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

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

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

$l_L^{(0)}$, $\tau_R^{(0)}$, $q_L^{(0)}$, $t_R^{(0)}$: 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 $Q = \frac{5}{3}, \frac{2}{3}, -\frac{1}{3}$)

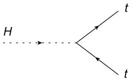
Additional heavier $Q = -1$ ($Q = 2/3$) state with

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

Backup: Higgs Decays

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

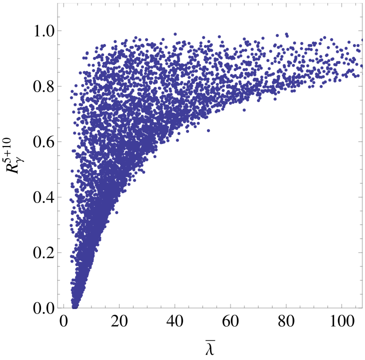
κ_t^5	$(c_R^t)^2$
κ_b^5	1
κ_g^5	≈ 1
κ_τ^5	$(c_R^\tau)^2$
$\kappa_W^5 = \kappa_Z^5$	1

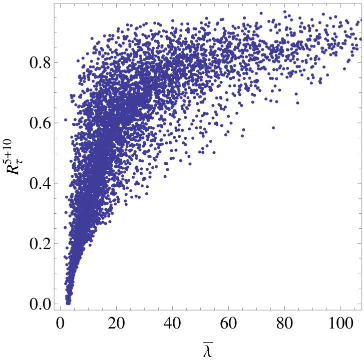


Backup: Yukawa and Mass Lagrangian for MCHM_{5+10}

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

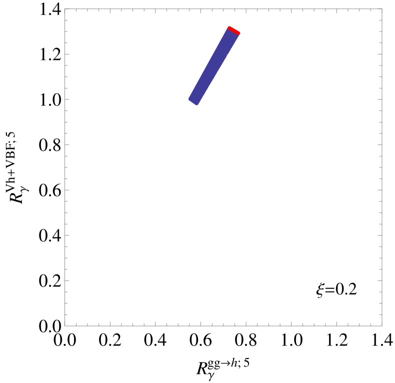
Backup: Dependence on Parameters

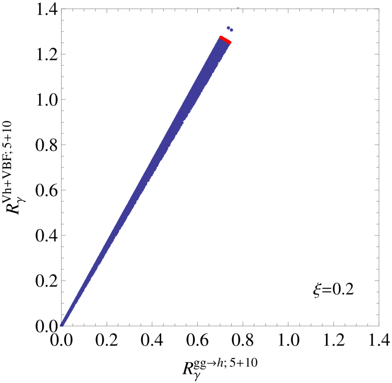




$$\bar{\lambda} = \frac{2M\tilde{M}}{v^2|\bar{y}\hat{y}|}$$

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