The 4D Composite Higgs boson at the LHC and a LC

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Outline

Preamble:

- A Higgs(-like) signal has been observed at the LHC (supplemental earlier evidence from Tevatron as well)
- Both ATLAS and CMS confirm it, very SM-like
- Mass measurements around 125 GeV
- Candidate data samples: $\gamma\gamma$, $ZZ^*$, $WW^*$, $b\bar{b}$ and $\tau^+\tau^-$ (in order of decreasing accuracy and/or significance) plus invisible

Motivation:

- Some inconsistency with the SM predictions existed (still exists), particularly in the (most significant) $\gamma\gamma$ channel
- Either way, it is mandatory to explore BSM solutions
- Whereas the ‘fundamental Higgs’ hypothesis is being quantitatively tested in several models, the ‘composite Higgs’ one has only been marginally studied in comparison
- All (pseudo)scalar objects discovered in Nature have always been fermion composites
Disclaimer:

- This talk is about a phenomenological analysis aimed at capturing the essentials of CHMs, it is not about building them and/or comparing their pros and cons.
- It thus adopts a specific CHM realisation that it is entirely calculable, the 4DCHM, apart from its UV structure.
- For an analysis of the Higgs data, knowledge of the latter is not strictly necessary.

Content:

- The 4DCHM (touch and go)
- Implementation (trust me, it is damn complicated but it is correct)
- Results (not exciting as one might have hoped, yet not so frustrating as in many other BSM scenarios)
Even with discovery of a Higgs particle, SM may not the end of the story (hierarchy and naturalness problems)

Two possible scenarios

Weak coupling
- Supersymmetry

Strong coupling
- Technicolor
- Extra dimensions
- Composite Higgs

A possible Composite Higgs scenario
- Higgs doublet arise from a strong dynamics
- Higgs as a (Pseudo) Nambu-Goldstone Boson (PNGB)

Idea from the '80s: spontaneous breaking of a symmetry $G \rightarrow H$

:= \frac{SO(5)}{SO(4)} \rightarrow SO(4)

The coset \(SO(5)/SO(4)\) turn out to be one of the most economical:

4 Pseudo Nambu-Goldstone Bosons (PNGBs)
(minimum number to be identified with the SM Higgs doublet)

Potential generated by radiative corrections \(\rightarrow\) light Higgs

(a la Coleman, Weinberg ’73)

Extra-particle content is present

- Spin 1 resonances
- Spin 1/2 resonances
4DCHM

4DCHM of De Curtis, Redi, Tesi (arXiv:1110.1613): highly deconstructed 4D version of general 5D theory

- Just two sites: Elementary and Composite sectors
- Mechanism of partial compositeness (e.g. mixing between elementary and composite states - 3\textsuperscript{rd} generation quarks, cfr $\gamma - \rho$ mixing in QCD)

Effective 4D model, hence needs UV completion, (largely) irrelevant for Higgs sector

Minimal: single $SO(5)$ multiplet of resonances from composite sector (only dof’s accessible at the LHC)

The 4DCHM represents the framework to study CHMs in a complete and computable way

Generic features of all relevant CHMs are captured
**4DCHM**

**Bosonic sector**

Elementary sector

\[ SU(2)_L \otimes U(1)_Y \]

Composite Sector

\[ SO(5) \otimes U(1)_X \]

\[ SO(5) \otimes U(1)_X \]

\[ SO(4) \otimes U(1)_X \]

\[ g_0, \tilde{W} \]

\[ \Phi_2 \]

\[ g_*, \tilde{A} \]

De Curtis, Redi, Tesi '11

\[ \Omega_1 = \exp\left(\frac{i \Pi}{2f}\right) \]

\[ \Pi \text{ Goldstone Matrix} \]

\[ f \text{ scale of the symmetry breaking (compositeness scale)} \]

\[ \Phi_2 = \Omega_1 \phi_0 \]

\[ \phi_0 = (0, 0, 0, 0, 1) = \delta_{i5} \]

11 new gauge resonances

5 Neutral

6 Charged (c.c.)
**Bosonic sector mass spectrum**

\[ M_Z^2 \simeq \frac{f^2}{4} g_*^2 (s^2_{\theta} + \frac{s^2_{\psi}}{2}) \xi \]

\[ M_{Z_1}^2 = f^2 g_*^2 \]

\[
\begin{align*}
\tan \theta &= s_{\theta} / c_{\theta} = g_0 / g_* \\
\tan \psi &= s_{\psi} / c_{\psi} = \sqrt{2} g_0 Y / g_* \\
\xi &= \sin \left( \frac{\nu}{2f} \right) \simeq \frac{\nu}{2f} \\
\nu &= \langle h \rangle = 246 \text{ GeV}
\end{align*}
\]

Model parameters (gauge):

\[ f \simeq 1 \text{ TeV} \]

and \( g_* \) perturbative \((\leq 4\pi)\)

\[ M_* = f g_* \]

Gauge boson mass \( \geq 1.5 \text{ TeV} \)
from EWPTs
Explicit breaking of $SO(5)$ through Yukawas in composite sector $Y_T, Y_B$

20 new fermionic resonances

- 10 in the top sector
- 10 in the bottom sector

Model parameters (fermion sector)

\[
\begin{align*}
m_* \\
\Delta_{tL}, \Delta_{tR}, Y_T, m_{Y_T}, \\
\Delta_{bL}, \Delta_{bR}, Y_B, m_{Y_B}
\end{align*}
\]

- Elementary (3rd) fermions mix with composites via link fields $\Omega_1$
- First two generation quarks and all leptons considered as in SM
Fermionic sector mass spectrum

Top and bottom sector ($\tilde{X} = X/m_*$)

\[
m^2_b \propto \xi \frac{m^2_*}{2} \tilde{\Delta}^2_{bL} \tilde{\Delta}^2_{bR} \tilde{Y}_B^2
\]

\[
m^2_t \propto \xi \frac{m^2_*}{2} \tilde{\Delta}^2_{tL} \tilde{\Delta}^2_{tR} \tilde{Y}_T^2
\]

\[
m^2_{T_1} \simeq \frac{m^2_*}{2} \left( 2 + \tilde{M}_{Y_T}^2 - \tilde{M}_{Y_T} \sqrt{4 + \tilde{M}_{Y_T}^2} \right)
\]

\[
m^2_{B_1} \simeq \frac{m^2_*}{2} \left( 2 + \tilde{M}_{Y_B}^2 - \tilde{M}_{Y_B} \sqrt{4 + \tilde{M}_{Y_B}^2} \right)
\]

Fermionic resonance mass $\simeq 1 \text{ TeV}$
Recapping: Higgs sector at a glance

- Four PNGBs in the vector representation of $SO(4)$ one of which is composite Higgs boson
- Physical Higgs particle acquires mass through one-loop generated potential (Coleman-Weinberg)
- 4DCHM choice for fermionic sector gives finite potential, i.e., from location of minimum one extracts $m_H$ and $\langle h \rangle$
- Partial compositeness:
  1. SM gauge/fermion states couple to Higgs via mixing with composite particles
  2. 4DCHM gauge/fermion resonances couple to Higgs directly
- Zoo of new fermions and gauge bosons has potential to alter Higgs couplings via mixing and/or loops
For natural choice of parameters, $m_H$ consistent with 125 GeV

Masses of lightest fermionic partners $f$ as a function of Higgs mass with $165 \text{ GeV} \leq m_t \leq 175 \text{ GeV}$, for (left) $f = 500 \text{ GeV}$ and (right) $f = 800 \text{ GeV}$. Fermionic parameters are varied between 0.5 and 3 TeV. Gauge contribution corresponds to $M_{Z',W'} = 2.5 \text{ TeV}$. (From De Curtis, Redi, Tesi (arXiv:1110.1613).)
Particle spectrum

The particle spectrum of the 4DCHM is

- SM leptons: $e, \mu, \tau$, and $\nu_e, \nu_\mu, \nu_\tau$
- SM quarks: $u, d, c, s, t, b$
- SM gauge bosons: $\gamma, Z^0, W^\pm, g$
- 5 extra neutral gauge bosons: $Z_i' = 1, \ldots, 5$
- 3 extra charged gauge bosons: $W_i'^{\pm} = 1, 2, 3$
- 8 extra charged $2/3$ fermions: $t_i' = 1, \ldots, 8$
- 8 extra charged $-1/3$ fermions: $b_i' = 1, \ldots, 8$
- 2 charged $5/3$ fermions: $T_i' = 1, 2$
- 2 charged $-4/3$ fermions: $B_i' = 1, 2$
- Higgs boson
Calculation

- More than 3000 Feynman rules! A non-automated approach would have been impossible
- Implementation of the 4DCHM in numerical tools:
  - LanHEP for automated generation of Feynman rules by A. Semenov (arXiv:1005.1909)
  - CalcHEP for automated calculation of physical observables (cross sections, widths...) by Belyaev, Christensen and Pukhov (arXiv:1207.6082)
- Uploaded onto HEPMDB: http://hepmdb.soton.ac.uk/ under 4DCHM(HAA+HGG)
Experimental constraints

- Implemented outside LanHEP/CalcHEP tools:
  - $\alpha$, $M_Z$ and $G_F$
  - Top, bottom and Higgs masses (same for 4DCHM & SM)
    
    $165 \text{ GeV} \leq m_t \leq 175 \text{ GeV}$
    
    $2 \text{ GeV} \leq m_b \leq 6 \text{ GeV}$
    
    $124 \text{ GeV} \leq m_H \leq 126 \text{ GeV}$
  
  - $Zb\bar{b}$ and $Zt\bar{t}$ couplings

- Standalone Mathematica program performs scans on model parameters

- Output can be read by LanHEP/CalcHEP to compute physical observables
LHC results

Define benchmarks

- 4DCHM parameter scans with $f$ and $g^*$ fixed to:
  - (a) $f = 0.75$ TeV and $g^* = 2$
  - (b) $f = 0.8$ TeV and $g^* = 2.5$
  - (c) $f = 1$ TeV and $g^* = 2$
  - (d) $f = 1$ TeV and $g^* = 2.5$
  - (e) $f = 1.1$ TeV and $g^* = 1.8$
  - (f) $f = 1.2$ TeV and $g^* = 1.8$

- All other parameters varied:
  - $0.5$ TeV $\leq m^*, \Delta t_L, \Delta t_R, Y_T, M_{Y_T}, Y_B, M_{Y_B} \leq 5$ TeV
  - $0.05$ TeV $\leq \Delta b_L, \Delta b_R \leq 0.5$ TeV

- Total number of random points for each $(f, g^*)$: $\approx 15M$.
- Survival rate of $O(10^{-5})$, variations amongst $(f, g^*)s \leq 30\%$
- 4DCHM highly constrained, phenomenologically interesting
LHC results

Limits on heavy gauge bosons and fermions

Call these $Z'$, $W'$, $t'$ and $b'$

- **Bosons:**
  1. EWPTs (LEP, SLC & Tevatron) sets $M_{Z',W'} \geq 1.5$ TeV
  2. $Z'$, $W'$ have poor lepton rates, hence no stronger limits from direct searches (Tevatron & LHC)

- **Fermions:**
  1. Direct searches (LHC) more constraining, assume pair production (7 TeV)
  2. CMS with 5 fb$^{-1}$, BR($t' \rightarrow W^+ b$) = 100%
     CMS with 1.14 fb$^{-1}$, BR($t' \rightarrow Zt$) = 100%
  3. CMS with 4.9 fb$^{-1}$, BR($b' \rightarrow W^- t$) = 100%
     CMS with 4.9 fb$^{-1}$, BR($b' \rightarrow Zb$) = 100%
  4. Limit on $T_1$ and $B_1$ about 400 GeV, but it could be slightly lower
LHC results

**Limits on $m_{T_1}$**

Black line is cross section assuming 100% BRs, red line is 95% CL observed limit and purple circles are 4DCHM points for $f = 1$ TeV and $g_* = 2$. Dotted-red line corresponds to extrapolations of experimental results.
**LHC results**

**Limits on $m_{B_1}$**

Black line is cross section assuming 100% BRs, red line is 95% CL observed limit and purple circles are 4DCHM points for $f = 1$ TeV and $g_\star = 2$. Dotted-red line corresponds to extrapolations of experimental results.
LHC results

- Define $R(\mu)$ parameters, i.e., the observed events over SM:

$$R_{YY} = \frac{\sigma (pp \to HX)|_{4DCHM} \times \text{BR}(H \to YY)|_{4DCHM}}{\sigma (pp \to HX)|_{SM} \times \text{BR}(H \to YY)|_{SM}}$$

$YY = \gamma\gamma, \ b\bar{b}, \ WW, \ ZZ$ (neglect $\tau^+\tau^-$)

- Relevant hadro-production processes:

$$gg \to H \text{ (gluon – gluon fusion)} \quad q\bar{q}(') \to VH \text{ (Higgs – strahlung)}$$

$V = W, Z$

- Convenient to re-write (valid at LO and HO QCD)

$$R_{YY'}^{Y'Y'} = \frac{\Gamma(H \to Y'Y')|_{4DCHM} \times \Gamma(H \to YY)|_{4DCHM}}{\Gamma(H \to Y'Y')|_{SM} \times \Gamma(H \to YY)|_{SM}} \frac{\Gamma_{\text{tot}}(H)|_{SM}}{\Gamma_{\text{tot}}(H)|_{4DCHM}}$$

$Y'Y' = gg, VV$
LHC results

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\gamma\gamma}$</td>
<td>$1.8 \pm 0.4$</td>
<td>$1.564_{-0.419}^{+0.460}$</td>
</tr>
<tr>
<td>$R_{ZZ}$</td>
<td>$1.0 \pm 0.4$</td>
<td>$0.807_{-0.280}^{+0.349}$</td>
</tr>
<tr>
<td>$R_{WW}$</td>
<td>$1.5 \pm 0.6$</td>
<td>$0.699_{-0.232}^{+0.245}$</td>
</tr>
<tr>
<td>$R_{bb}$</td>
<td>$-0.4 \pm 1.0$</td>
<td>$1.075_{-0.566}^{+0.593}$</td>
</tr>
</tbody>
</table>

Summary of pre-Moriond LHC measurements of some $R$ parameters from latest ATLAS (ATLAS-CONF-2012-170) and CMS (CMS-PAS-HIG-12-045) data.

- For $YY = \gamma\gamma, WW, ZZ$ take $Y'Y' = gg$ while for $YY = b\bar{b}$ take $Y'Y' = VV$
- Use $f = 1$ TeV and $g_* = 2$ for illustration, features generic to 4DCHM
LHC results

- Mixing effects only: \( ZZ^* \rightarrow 4\ell \) and \( WW^* \rightarrow 2\ell 2\nu_\ell \)
  (corrections to BRs different in 4DCHM)
- Both below 1 mostly, some points above, strong correlation suggests common cause for effect

![Graph showing correlation between \( R_{\gamma\gamma} \) and \( R_{VV} \), with \( VV = WW \) (red) and \( ZZ \) (purple), for \( f = 1 \) TeV and \( g_* = 2 \). All points compliant with direct searches for \( t' \)s and \( b' \)s.](image-url)
LHC results

- Introduce reduced couplings a la LHC HXSWG (A. Denner et al (arXiv:1209.0040))
- We can cast $R_s$ in terms of $\kappa$’s

\[ R_{YY'} = \frac{\kappa_{YY'}^2}{\kappa_H^2} \]

$Y, Y' = b/\tau/g/\gamma/V$

\[ \kappa_{b/\tau/g/\gamma/V}^2 = \frac{\Gamma(H \rightarrow b\bar{b}/\tau^+\tau^-/gg/\gamma\gamma/VV)|_{4DCHM}}{\Gamma(H \rightarrow b\bar{b}/\tau^+\tau^-/gg/\gamma\gamma/VV)|_{SM}} \]

\[ \kappa_H^2 = \frac{\Gamma_{tot}(H)|_{4DCHM}}{\Gamma_{tot}(H)|_{SM}}. \]
LHC results

- $\kappa_H$ smaller: $b - b'$ mixing, all Higgs rates rise

Distribution of $\kappa_H$ versus (left) $m_{T_1}$ and (right) $m_{B_1}$ for $f = 1$ TeV and $g_* = 2$. Regions to left of vertical dashed-red lines excluded by $t'$ and $b'$ direct searches.
LHC results

- $\kappa_g$ smaller: $t - t'$ mixing, $t$-loop dominant
- Subtle cancellations/compensations

Distribution of $\kappa_g$ versus (left) $m_{T_1}$ and (right) $m_{B_1}$ for $f = 1$ TeV and $g_* = 2$. Regions to left of vertical dashed-red lines excluded by $t'$ and $b'$ direct searches.
LHC results

- $\kappa\gamma$ also smaller (less though): $t - t'$ mixing, $t$-loop subdominant
- Again, subtle cancellations/compensations

Distribution of $\kappa\gamma$ versus (left) $m_{T_1}$ and (right) $m_{B_1}$ for $f = 1$ TeV and $g_* = 2$. Regions to left of vertical dashed-red lines excluded by $t'$ and $b'$ direct searches.
LHC results

- $T_1$ and $B_1$ masses play significant role, revisit $R_{\gamma\gamma}$
- Leakage of points towards large $R_{\gamma\gamma} > 1$ at small masses
- Asymptotic result for $m_{T_1, B_1} \to \infty$ can be wrong by 10+%

Distributions of $R_{\gamma\gamma}$ versus (left) $m_{T_1}$ and (right) $m_{B_1}$ for $f = 1$ TeV and $g_* = 2$. Regions to left of vertical dashed-red lines excluded by $t'$ and $b'$ direct searches.
LHC results

- Compare all benchmarks to SM & data

4DCHM against data for all \((f, g_*)\) benchmarks. Points compliant with \(t'\) and \(b'\) direct searches.
LHC results

- Perform $\chi^2$ fit and compare to SM, can be better

4DCHM $\chi^2$ fits for all benchmarks in $(f, g_*)$. Line is SM. Points compliant with $t'$ and $b'$ direct searches.
LHC results

- Add $m_{\tilde{T}_1} > 600$ GeV (no limits on $m_{\tilde{B}_1}$)

4DCHM $\chi^2$ fits for all benchmarks in $(f, g_*)$. Line is SM. Points compliant with $t'$ and $b'$ plus $\tilde{T}_1$ direct searches.
LHC results

- After Moriond updates

4DCHM against data (left) and $\chi^2$ fits (right) for all benchmarks in $(f, g_*)$. Line is SM. Points compliant with $t'$ and $b'$ plus $\tilde{T}_1$ direct searches.
**LC results**

**Higgs-strahlung (ZH)**

- Production cross section affected by $Z'$s: define $R = \frac{\sigma_{4DCHM}}{\sigma_{SM}}$
- Visible at higher LC energies, needs $Z'$s to be wide

![Graph](image)

Corrections induced by mixing plus $Z_3$ exchange as a function of its width for benchmarks (b) (left) and (c) (right).
LC results

Higgs-strahlung times BRs

- Take low energies, 250 and 500 GeV, and look at leading $\zeta = v^2/f^2$ corrections
- Couplings rescale simply:
  $$\frac{g_{4DCHM}^{HHV}}{g_{SM}^{HHV}} = \sqrt{1 - \zeta}, \quad \frac{g_{4DCHM}^{Hff}}{g_{SM}^{Hff}} = \frac{1-2\zeta}{\sqrt{1-\zeta}}$$

$WW$, $ZZ$ (red), $\gamma\gamma$ (black) and $b\bar{b}/gg$ (blue) signal strength as function of $f$. In green ratio of inclusive $ZH$ cross sections. Horizontal for expected accuracies $\sigma \times$ BR for a 250 GeV and fb$^{-1}$ (left) and 500 GeV and fb$^{-1}$ (right) LC.
LC results

- Can disentangle model via couplings (use proper benchmarks)

Correlations among $R_s$ for HS (top) and VBF (bottom), with $f = 800$ GeV, $g_* = 2.5$ (green) and $f = 1000$ GeV, $g_* = 2$ (blue).
LC results

Top Yukawa coupling from $e^+e^- \rightarrow t\bar{t}H$

- $Z'$s & $t'$s in propagators other than mixing effects
- Optimistic, good experimental accuracy: 35%(9%) at a 500 GeV and fb$^{-1}$ (1000 GeV and fb$^{-1}$) LC.

Correlations among $R_{bb}$s with the inclusion of $t'$ quarks (left) and without these (right), with $f = 800$ GeV, $g_* = 2.5$ (green) and $f = 1000$ GeV, $g_* = 2$ (blue).
LC results

Higgs self-coupling from $Z(\rightarrow \ell^+ \ell^-)HH(\rightarrow 4b)$ and $\nu\bar{\nu}HH(\rightarrow 4b)$

- Rescaling is $\lambda_{4DCHM} = \lambda_{SM} \frac{1-2\zeta}{\sqrt{1-\zeta}}$
- Difficult, poor experimental accuracy: 64%(38%) for $ZHH(\nu\bar{\nu}HH)$ at a 500 GeV and fb$^{-1}$(1000 GeV and fb$^{-1}$) LC.

Correlations among $R_{Zb\bar{b}b\bar{b}}$ and $R_{\nu_e\bar{\nu}_e b\bar{b}b\bar{b}}^{\mu_{Zb\bar{b}b\bar{b}}}$ for two energy and luminosity stages, with $f = 800$ GeV, $g_* = 2.5$ (green) and $f = 1000$ GeV, $g_* = 2$ (blue).
Conclusions

- 4DCHM could provide explanation to LHC data pointing to Higgs discovery at 125–126 GeV (some better $\chi^2$'s than SM)
- Substantial parameter space scans show possible moderate enhancement in $H \rightarrow \gamma\gamma$, i.e., $R_{\gamma\gamma} \approx 1.1$
- $R_{\gamma\gamma}$ could grow to $\approx 1.3$, if $t'$ and $b'$ masses just below results of our extrapolations
- 4DCHM main effect is reduction of $Hbb$ ($b$-$b'$ mixing), smaller $\Gamma_{\text{tot}}(H)$
- Competing effects from $Hgg$ also smaller, $H\gamma\gamma$ almost stable
- Relevant by-product: approximations assuming $t'$ and $b'$ masses infinite cannot be accurate
- Composite Higgs solution to LHC data seemingly possible and wanting light fermionic partners
- Revisit $t'$, $b'$ searches in 4DCHM dependent way (in progress)
- Future LC ideal to test modified $hb\bar{b}$, $hW^+W^-$, $hZZ$ etc.
- LC can also probe altered top Yukawa and possibly $\lambda$
- LC sensitive to virtual $t'$, $Z'$ ($W'$ less) in Higgs processes
SM left doublet can be embedded in $(2, 2)_{2/3} \in \Psi_T$ as,

$$5_{2/3} = (2, 2)_{2/3} \oplus (1, 1)_{2/3}, \quad (2, 2)_{2/3} = \begin{pmatrix} T & T_{5/3}^3 \\ B & T_{2/3}^3 \end{pmatrix}$$

- $t_R$ coupled to singlet in different $5_{2/3}$ representation, $\Psi_{\tilde{T}}$
- $b_R$ coupled to singlet in a $5_{-1/3}$ ($\Psi_{\tilde{B}}$)
- To generate $b$ Yukawa it is necessary (by $U(1)_X$ symmetry) to couple SM doublet to second doublet in $5_{-1/3}$ ($\Psi_B$) which contains

$$5_{-1/3} = (2, 2)_{-1/3} \oplus (1, 1)_{-1/3}, \quad (2, 2)_{-1/3} = \begin{pmatrix} B_{-1/3} & T' \\ B_{-4/3} & B' \end{pmatrix}$$
Lagrangian (gauge and fermions)

\[ L_{\text{gauge}} = \frac{f_1^2}{4} \text{Tr}|D_\mu \Omega_1|^2 + \frac{f_2^2}{2} (D_\mu \Phi_2)(D_\mu \Phi_2)^T - \frac{1}{4} \tilde{A} \tilde{A}_{\mu\nu} - \frac{1}{4} F \tilde{W} F \tilde{W}_{\mu\nu} \]

(↑ composite ↑ elementary kinetic terms)

\[ L_{\text{fermions}} = L_{\text{fermions}}^\text{el} + (\Delta t_L \bar{q}_L^\text{el} \Omega_1 \psi_T + \Delta t_R \bar{t}_R^\text{el} \Omega_1 \psi \bar{\tau} + h.c.) \]

\[ + \bar{\psi}_T (i \hat{D} \tilde{A} - m_*) \psi_T + \bar{\psi} \bar{\tau} (i \hat{D} \tilde{A} - m_*) \psi \bar{\tau} \]

\[ - (Y_T \bar{\psi}_T, L \Phi_2^T \Phi_2 \psi \bar{\tau}, R + M_Y \bar{\psi}_T, L \psi \bar{\tau}, R + h.c.) + (T \rightarrow B). \]

- Covariant derivatives

\[ D^\mu \Omega_1 = \partial^\mu \Omega_1 - ig_0 \tilde{W} \Omega_1 + ig_* \Omega_1 \tilde{A}, \quad D_\mu \Phi_2 = \partial_\mu \Phi_2 - ig_* \tilde{A} \Phi_2 \]

\( \tilde{W}[\tilde{A}] \) mediators of \( SU(2)_L \otimes U(1)_Y \) \[ SO(5) \otimes U(1)_X \]
• \(SO(5) \otimes U(1)_X \rightarrow SO(4) \otimes U(1)_X\) from \(SO(5)\) vector
  \[
  \Phi_2 = \phi_0 \Omega_2^T \quad \text{where} \quad \phi_0 = \delta^{i5}.
  \]

• \(\Psi_{T,B}\) and \(\tilde{\Psi}_{T,B}\) fundamental representations of \(SO(5)\) [embedding composite fermions]

• SM third generation quarks embedded in incomplete representation of \(SO(5) \otimes U(1)_X\) to give correct 
  \(Y = T^{3R} + X\) under \(SU(2)_L \otimes U(1)_Y\)

• \(\Delta_{t,b/L,R}\) mixing parameters between elementary and composite sectors

• \(Y_{T,B}, M_{Y_{T,B}}\) Yukawa parameters of composite sector

• \(m_*\) mass parameter of fermionic resonances
Backup slides

**Higgs interactions**

In unitary gauge link fields \( \Omega_n = 1 + i \frac{s_n}{h} \Pi + \frac{c_n}{h^2} \Pi^2 \),

\[
s_n = \sin \left( \frac{f h}{f_n^2} \right), \quad c_n = \cos \left( \frac{f h}{f_n^2} \right), \quad h = \sqrt{h^\dagger h}, \quad \sum_{n=1}^{2} \frac{1}{f_n^2} = \frac{1}{f^2}
\]

Identify \( \Pi = \sqrt{2} h^\dagger T^\dagger \) GB matrix and \( T^\dagger \)'s \( SO(5)/SO(4) \) broken generators (\( \hat{a} = 1, 2, 3, 4 \))

\[
\Pi = \sqrt{2} h^\dagger T^\dagger = -i \begin{pmatrix} 0 & h \\ -h^T & 0 \end{pmatrix}, \quad h^T = (h_1, h_2, h_3, h_4).
\]

Relate \( h \) to usual SM \( SU(2)_L \) Higgs doublet

\[
H = \frac{1}{\sqrt{2}} \begin{pmatrix} -ih_1 - h_2 \\ -ih_3 + h_4 \end{pmatrix}.
\]
Use $\Omega_n = 1 + \delta \Omega_n$ to define Higgs interactions

$$L_{\text{gauge}, H} = - \frac{f_1^2}{2} g_0 g_* \text{Tr} \left[ \tilde{W} \delta \Omega_1 \tilde{A} + \tilde{W} \tilde{A} \delta \Omega_1^T + \tilde{W} \delta \Omega_1 \tilde{A} \delta \Omega_1^T \right]$$

$$+ \frac{f_2^2}{2} g_*^2 \left[ \phi_0^T \delta \Omega_2 \tilde{A} \tilde{A} \phi_0 + \phi_0^T \tilde{A} \tilde{A} \delta \Omega_2 \phi_0 + \phi_0^T \delta \Omega_2 \tilde{A} \delta \Omega_2 \phi_0 \right],$$

$$L_{\text{ferm}, H} = \Delta_{t_L} \overline{q}_L \phi_0 \delta \Omega_1 \psi_T + \Delta_{t_R} \overline{t}_R \tilde{\phi}_0 \delta \Omega_1 \psi_{\tilde{T}}$$

$$- Y_T \bar{\Psi}_{T,L} \left( \phi_0^T \phi_0 \delta \Omega_2^T + \delta \Omega_2 \phi_0^T \phi_0 \right) + h.c.$$

- In unitary gauge $h_1, h_2, h_3$ eaten by $W^\pm, Z$ and $h_4$ is $H$
- Expand $\delta \Omega_{1,2}$ to first order in $H$ to extract $g_{HV_i \nu_j}$ and $g_{Hf_i \bar{f}_j}$
- Couplings to mass eigenstates obtained after diagonalization.
Subtle loop cancellations/compensations

- Consider loop diagrams

\[ H \rightarrow \gamma\gamma \text{ induced by fermionic loop} \]

\[ H \rightarrow \gamma\gamma \text{ induced by a charged vector loop} \]
• Consider $HV_i V_i$ charged couplings (SM-like and Extra)

Couplings of Higgs boson in 4DCHM to charged gauge bosons ($W$ left, $W_2$ middle, $W_3$ right) normalised to SM values.
Backup slides

- Consider $HV_i V_i$ neutral couplings (SM-like and Extra)

Couplings of Higgs boson in 4DCHM to neutral gauge bosons ($Z$ left, $Z_2$ middle, $Z_3$ right) normalised to SM values.
• Consider $H f_i \bar{f}_i$ couplings (SM-like)

### Couplings of Higgs boson in 4DCHM to top (left) and bottom (right) quarks normalised to SM values vs $m_{T_1}$ and $m_{B_1}$ for $f = 0.8$ TeV and $g_* = 2.5$. 
• Consider $Hf_i\bar{f}_i$ couplings (extra light)

Couplings of Higgs boson in 4DCHM to lightest heavy top (left) and bottom (right) quarks normalised to SM values vs $m_{T_1}$ and $m_{B_1}$ for $f = 0.8$ TeV and $g_* = 2.5$. 
• Consider $H f_i \bar{f}_i$ couplings (extra heavy)

Couplings of Higgs boson in 4DCHM to second (left), third (middle) and fourth (right) lightest heavy top quarks normalised to SM values vs $m_{T_1}$ and $m_{B_1}$ for $f = 0.8$ TeV and $g_* = 2.5$. 
Backup slides

- Loop compensations between SM-like and Extra quarks ($gg$)

**Loop contributions to $H \rightarrow gg$ in 4DCHM normalised to SM vs $m_{T_1}$ for $f = 0.8$ TeV and $g_* = 2.5$.**
Backup slides

- Loop compensations between SM-like and Extra quarks ($\gamma\gamma$)

![Graphs showing loop contributions to $H \to \gamma\gamma$](image)

Loop contributions to $H \to \gamma\gamma$ in 4DCHM normalised to SM vs $m_{T_1}$ for $f = 0.8$ TeV and $g_* = 2.5$. 
Backup slides

- Loop cancellations between Extra quarks

Loop contributions to $H \rightarrow gg$ (left) and $\gamma\gamma$ (right) in 4DCHM normalised to SM amplitude vs $m_{T_1}$ for $f = 0.8$ TeV and $g_* = 2.5$. 
• **Outlook:**

1. ATLAS & CMS allow for $\kappa_H \geq 1$
2. Need $\kappa_H < 1$ in 4DCHM (also useful for other BSMs, e.g., SUSY, 2HDMs - Higgs mixing)

CMS fits to $\kappa_g$ and $\kappa_\gamma$ for (left) $\kappa_H = 1$ and (right) $\kappa_H > 1$. 