

# Testing a 4D Composite Higgs model at the LHC and a LC

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Based on [arXiv:1302.2371](#), [arXiv:1306.6876](#) & [arXiv:1304.4639](#)

Scalars 2013 (Warsaw)

13 September 2013

# 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

# Outline

## 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)

## 4DCHM

Even with discovery of a Higgs particle, SM may not be 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 arises from strong dynamics
- Higgs as a (Pseudo) Nambu-Goldstone Boson (PNGB)

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

Georgi and Kaplan, Phys.Lett. B136, 183 (1984)

## 4DCHM

Simplest example was considered by [Agashe, Contino and Pomarol](#) ([arXiv:0412089](#))

- Symmetry pattern  $SO(5) \rightarrow SO(4)$

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<sup>rd</sup> 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

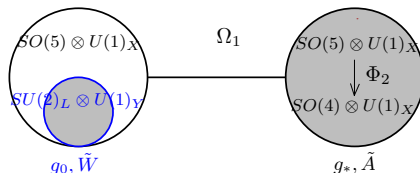
Generic features of all relevant CHMs are captured

# 4DCHM

## Bosonic sector

Elementary sector

Composite Sector



De Curtis, Redi, Tesi '11

$$\Omega_1 = \exp\left(\frac{i\Pi}{2f}\right) \quad \Pi \text{ Goldstone Matrix}$$

$f$  scale of the symmetry breaking (compositeness scale)

$$\Phi_2 = \Omega_1 \phi_0 \quad \phi_0 = (0, 0, 0, 0, 1) = \delta^{i5}$$

11 new gauge resonances

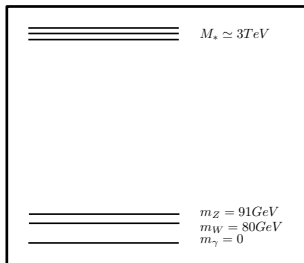
5 Neutral

6 Charged (c.c.)

## 4DCHM

Bosonic sector mass spectrum

Bosonic sector mass spectrum



$$M_Z^2 \simeq \frac{f^2}{4} g_*^2 (s_\theta^2 + \frac{s_\psi^2}{2}) \xi$$

$$M_{Z_1}^2 = f^2 g_*^2$$

$$\tan \theta = s_\theta / c_\theta = g_0 / g_*$$

$$\tan \psi = s_\psi / c_\psi = \sqrt{2} g_0 \gamma / g_*$$

$$\xi = \sin(\frac{\nu}{2f}) \simeq \frac{\nu}{2f}$$

$$\nu = \langle h \rangle = 246 \text{ GeV}$$

Model parameters (gauge):

$$f \simeq 1 \text{ TeV}$$

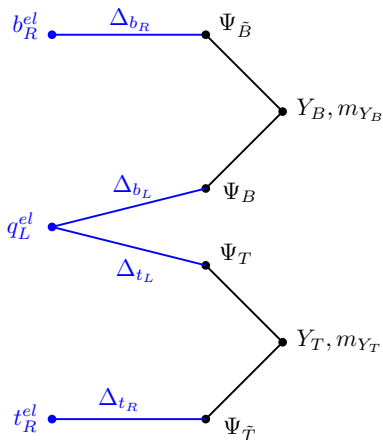
Gauge boson mass  $\geq 1.5 \text{ TeV}$  from EWPTs and  $g_*$  perturbative ( $\leq 4\pi$ )

$$M_* = f g_*$$



# 4DCHM

## Fermionic sector



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)

$$m_*$$

$$\Delta_{tL}, \Delta_{tR}, Y_T, m_{Y_T},$$

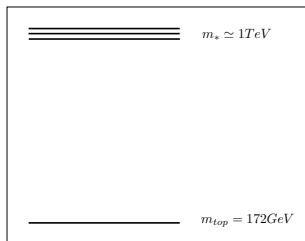
$$\Delta_{bL}, \Delta_{bR}, Y_B, m_{Y_B}$$

- Elementary ( $3^{rd}$ ) fermions mix with composites via link fields  $\Omega_1$
- First two generation quarks and all leptons considered as in SM

## 4DCHM

Fermionic sector mass spectrumTop and bottom sector ( $\tilde{X} = X/m_*$ )

Fermionic sector mass spectrum



$$m_b^2 \propto \xi \frac{m_*^2}{2} \tilde{\Delta}_{b_L}^2 \tilde{\Delta}_{b_R}^2 \tilde{Y}_B^2$$

$$m_t^2 \propto \xi \frac{m_*^2}{2} \tilde{\Delta}_{t_L}^2 \tilde{\Delta}_{t_R}^2 \tilde{Y}_T^2$$

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

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

Fermionic resonance mass  $\simeq 1$  TeV

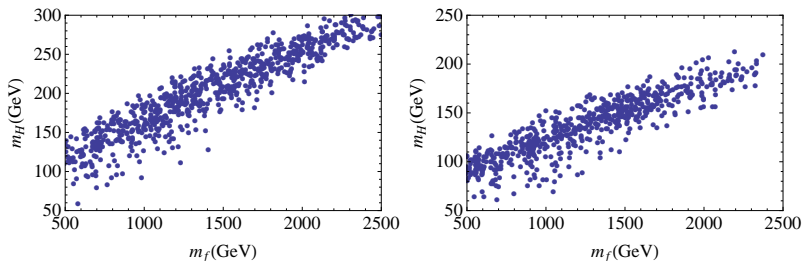
# 4DCHM

## 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

## 4DCHM

- 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:  $Z'_{i=1,\dots,5}$
- 3 extra charged gauge bosons:  $W'^{\pm}_{i=1,2,3}$
- 8 extra charged 2/3 fermions:  $t'_{i=1,\dots,8}$
- 8 extra charged -1/3 fermions:  $b'_{i=1,\dots,8}$
- 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 [A.Semenov \(arXiv:1005.1909\)](#)
  - CalcHEP for automated calculation of physical observables (cross sections, widths...) [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:  
 $0.5 \text{ TeV} \leq m_*, \Delta_{tL}, \Delta_{tR}, Y_T, M_{Y_T}, Y_B, M_{Y_B} \leq 5 \text{ TeV}$   
 $0.05 \text{ TeV} \leq \Delta_{bL}, \Delta_{bR} \leq 0.5 \text{ TeV}$
- Total number of random points for each  $(f, g_*)$ :  $\approx 15\text{M}$ .
- Survival rate of  $\mathcal{O}(10^{-5})$ , 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:

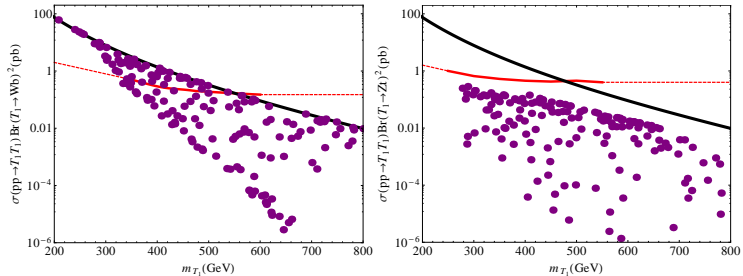
1. EWPTs (LEP, SLC & Tevatron) sets  $M_{Z',W'} \geq 1.5$  TeV
2.  $Z'$ ,  $W'$  have poor lepton rates, hence no stronger limits from direct searches (Tevatron & LHC)

- Fermions:

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

# LHC results

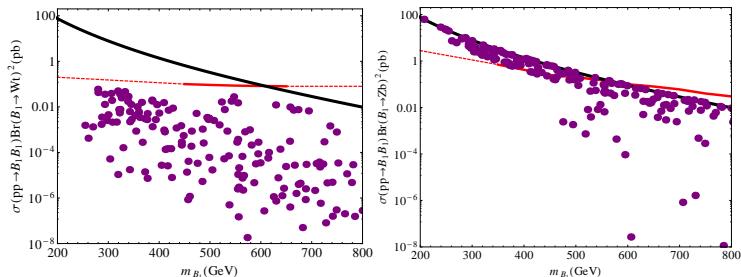
## Limits on $m_{T_1}$



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  $g_* = 2$ . Dotted-red line corresponds to extrapolations of experimental results.

# LHC results

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

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

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

- Relevant hadro-production processes:

$$gg \rightarrow H \text{ (gluon - gluon fusion)} \quad q\bar{q}(\prime) \rightarrow VH \text{ (Higgs - strahlung)}$$

$$V = W, Z$$

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

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

$$Y'Y' = gg, VV$$

## LHC results

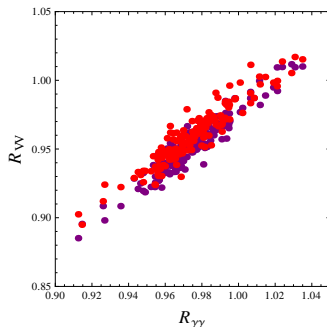
	ATLAS	CMS
$R_{\gamma\gamma}$	$1.8 \pm 0.4$	$1.564^{+0.460}_{-0.419}$
$R_{ZZ}$	$1.0 \pm 0.4$	$0.807^{+0.349}_{-0.280}$
$R_{WW}$	$1.5 \pm 0.6$	$0.699^{+0.245}_{-0.232}$
$R_{bb}$	$-0.4 \pm 1.0$	$1.075^{+0.593}_{-0.566}$

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  $\sqrt{s} = 1$  TeV and  $g_* = 2$  for illustration, features generic to 4DCHM

# LHC results

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



Correlation between  $R_{\gamma\gamma}$  and  $R_{VV}$ ,  $VV = WW$  (red) and  $ZZ$  (purple), for  $f = 1$  TeV and  $g_* = 2$ . All points compliant with direct searches for  $t'$ s and  $b'$ s.

# 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

$$R_{YY'}^{Y'Y'} = \frac{\kappa_{Y'}^2 \kappa_Y^2}{\kappa_H^2}$$

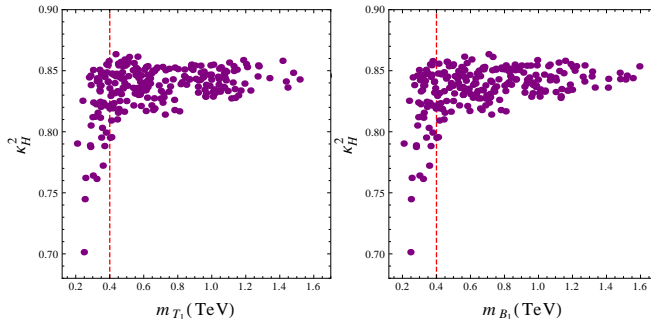
$$Y, Y' = b/\tau/g/\gamma/V$$

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

$$\kappa_H^2 = \frac{\Gamma_{\text{tot}}(H)|_{4\text{DCHM}}}{\Gamma_{\text{tot}}(H)|_{\text{SM}}}.$$

# LHC results

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

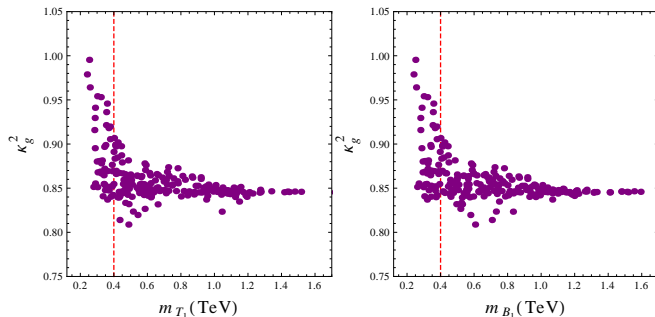


Distribution of  $\kappa_H$  versus (left)  $m_{T_1}$  and (right)  $m_{B_1}$  for  $f = 1$  TeV and  $g_* = 2$ . Regions to left of vertical dashed-red lines excluded by  $t'$  and  $b'$  direct searches.



# 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

also smaller (less though)  $t$   $t$













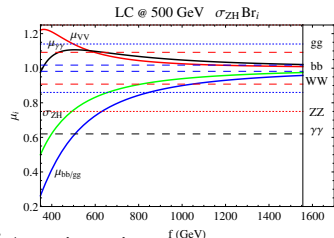
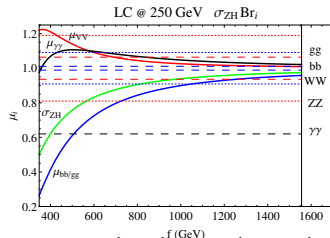


# LC results

## Higgs-strahlung times BRs

- Take low energies, 250 and 500 GeV, and look at leading  $\zeta = v^2/f^2$  corrections
- Couplings rescale simply:

$$\frac{g_{HVV}^{\text{SM}}}{g_{HVV}^{4\text{DCHM}}} = \sqrt{1-\zeta}, \quad \frac{g_{Hff}^{\text{SM}}}{g_{Hff}^{4\text{DCHM}}} = \frac{1-2\zeta}{\sqrt{1-\zeta}}$$

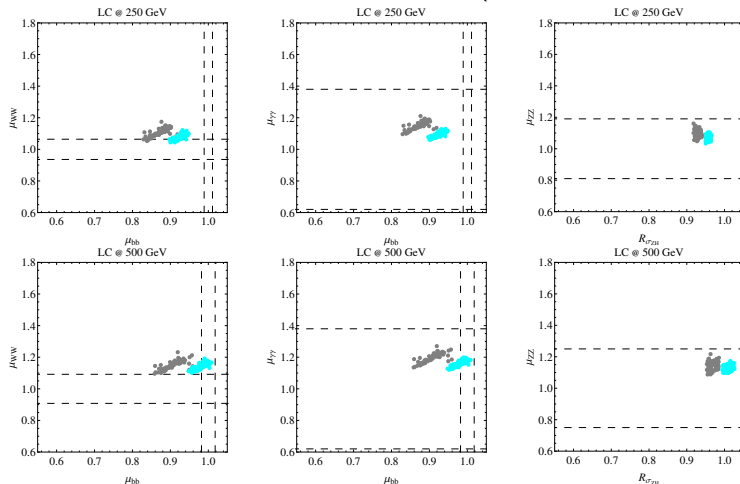


$WW$ ,  $ZZ$  (red),  $\gamma\gamma$  (black) and  $b\bar{b}/g\bar{g}$  (blue) signal strength as function of  $f$ . In green ratio of inclusive  $ZH$  cross sections.

Horizontal for expected accuracies  $\sigma \times \text{BR}$  for a 250 GeV and  $\text{fb}^{-1}$  (left) and 500 GeV and  $\text{fb}^{-1}$  (right) LC.

# LC results

- Can disentangle model via couplings (use proper benchmarks)



Scatter plot in  $\mu_{b\bar{b}}/\mu_{WW}$  (left),  $\mu_{b\bar{b}}/\mu_{\gamma\gamma}$  (center) and  $R_{\sigma_{ZH}}/\mu_{ZZ}$  (right) for  $f = 800$  GeV (grey) and  $f = 1000$  GeV (cyan).



## LC results

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

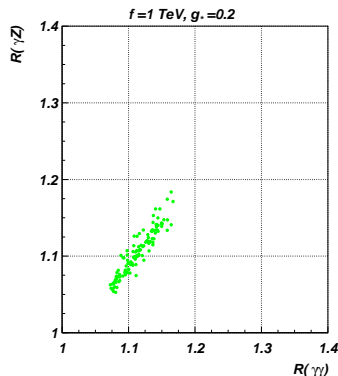
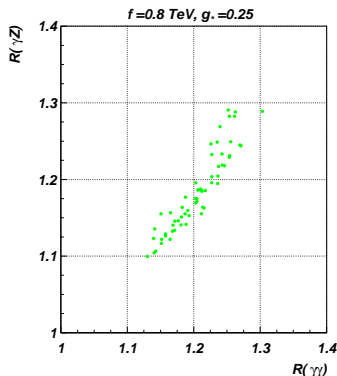
- Rescaling is  $\lambda_{4\text{DCHM}} = \lambda_{\text{SM}} \frac{1-2\zeta}{\sqrt{1-\zeta}}$
- Difficult, poor experimental accuracy: 64%(38%) for  $ZHH(\nu\bar{\nu}HH)$  at a 500 GeV and  $\text{fb}^{-1}$ (1000 GeV and  $\text{fb}^{-1}$ ) LC.

Scatter plot in  $R_{\sigma_{ZHH}}$  vs  $R_{\sigma_{ZHH}} R_{Br(H\rightarrow bb)}$  for  $f = 800$  GeV (grey) and  $f = 1000$  GeV (cyan) for a 500 GeV (left) and 1000 GeV (right) LC. (Same results for  $\nu\bar{\nu}HH$ .)

# LC results

## $\gamma\gamma$ versus $\gamma Z$ (only BRs)

- Smoking gun, they are equal in most BSM physics
- Deviations from off-diagonal  $t'$  and  $W'$  loops only in  $Z\gamma$



Scatter plot in  $R_{\gamma Z}$  vs  $R_{\gamma\gamma}$  for benchmarks (b) (left) and (c) (right).

## 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  $\lambda$
- $\gamma\gamma$  vs  $\gamma Z$  may also afford exploring at a LC

## Backup slides

- SM left doublet can be embedded in  $(\mathbf{2}, \mathbf{2})_{2/3} \in \Psi_T$  as,

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

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

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

## Backup slides

### Lagrangian (gauge and fermions)

$$\mathcal{L}_{gauge} = \frac{f_1^2}{4} \text{Tr} |D_\mu \Omega_1|^2 + \frac{f_2^2}{2} (D_\mu \Phi_2)(D_\mu \Phi_2)^T \\ - \frac{1}{4} \rho_{\mu\nu}^{\tilde{A}} \rho^{\tilde{A}\mu\nu} - \frac{1}{4} F_{\mu\nu}^{\tilde{W}} F^{\tilde{W}\mu\nu}$$

( $\uparrow$  composite  $\uparrow$  elementary kinetic terms)

$$\mathcal{L}_{fermions} = \mathcal{L}_{fermions}^{el} + (\Delta_{t_L} \bar{q}_L^{el} \Omega_1 \Psi_T + \Delta_{t_R} \bar{t}_R^{el} \Omega_1 \Psi_{\tilde{T}} + h.c.) \\ + \bar{\Psi}_T (i \hat{D}^{\tilde{A}} - m_*) \Psi_T + \bar{\Psi}_{\tilde{T}} (i \hat{D}^{\tilde{A}} - m_*) \Psi_{\tilde{T}} \\ - (Y_T \bar{\Psi}_{T,L} \Phi_2^T \Phi_2 \Psi_{\tilde{T},R} + M_{Y_T} \bar{\Psi}_{T,L} \Psi_{\tilde{T},R} + h.c.) + (T \rightarrow B).$$

- 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  $SU(2)_L \otimes U(1)_Y$  [ $SO(5) \otimes U(1)_X$ ]



## Backup slides

- $SO(5) \otimes U(1)_X \rightarrow SO(4) \otimes U(1)_X$  from  $SO(5)$  vector

$$\Phi_2 = \phi_0 \Omega_2^T \quad \text{where} \quad \phi_0^i = \delta^{i5}.$$

- $\Psi_{T,B}$  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  $\Omega_n = \mathbf{1} + i\frac{s_n}{h}\Pi + \frac{c_n-1}{h^2}\Pi^2$ ,

$$s_n = \sin(fh/f_n^2), \quad c_n = \cos(fh/f_n^2), \quad h = \sqrt{h^{\hat{a}}h^{\hat{a}}}, \quad \sum_{n=1}^2 \frac{1}{f_n^2} = \frac{1}{f^2}$$

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

$$\Pi = \sqrt{2}h^{\hat{a}}T^{\hat{a}} = -i \begin{pmatrix} 0_4 & \mathbf{h} \\ -\mathbf{h}^T & 0 \end{pmatrix}, \quad \mathbf{h}^T = (h_1, h_2, h_3, h_4).$$

Relate  $\mathbf{h}$  to usual SM  $SU(2)_L$  Higgs doublet

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} -ih_1 - h_2 \\ -ih_3 + h_4 \end{pmatrix}.$$

## Backup slides

Use  $\Omega_n = \mathbf{1} + \delta\Omega_n$  to define Higgs interactions

$$\mathcal{L}_{gauge,H} = -\frac{f_1^2}{2} g_0 g_* \text{Tr} \left[ \tilde{W} \delta\Omega_1 \tilde{A} + \tilde{W} \tilde{A} \delta\Omega_1^T + \tilde{W} \delta\Omega_1 \tilde{A} \delta\Omega_1^T \right] \\ + \frac{f_2^2}{2} g_*^2 \left[ \phi_0^T \delta\Omega_2^T \tilde{A} \tilde{A} \phi_0 + \phi_0^T \tilde{A} \tilde{A} \delta\Omega_2 \phi_0 + \phi_0^T \delta\Omega_2^T \tilde{A} \tilde{A} \delta\Omega_2 \phi_0 \right],$$

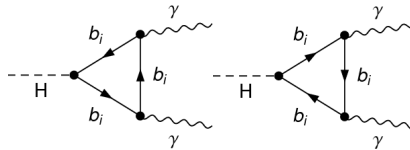
$$\mathcal{L}_{ferm,H} = \Delta_{t_L} \bar{q}_L^{el} \delta\Omega_1 \Psi_T + \Delta_{t_R} \bar{t}_R^{el} \delta\Omega_1 \Psi_{\tilde{t}} \\ - Y_T \bar{\Psi}_{T,L} (\phi_0^T \phi_0 \delta\Omega_2^T + \delta\Omega_2 \phi_0 \phi_0^T + \delta\Omega_2 \phi_0^T \phi_0 \delta\Omega_2^T) \Psi_{\tilde{t},R} \\ + (T \rightarrow B) + h.c.$$

- 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  $g_{H V_i V_j}$  and  $g_{H \tilde{f}_i \tilde{f}_j}$
- Couplings to mass eigenstates obtained after diagonalization

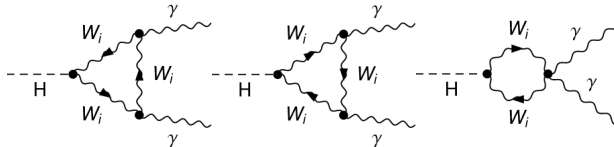
# Backup slides

## Subtle loop cancellations/compensations

- Consider loop diagrams



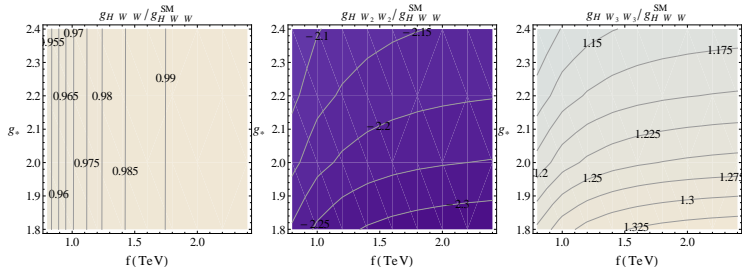
$H \rightarrow \gamma\gamma$  induced by fermionic loop



$H \rightarrow \gamma\gamma$  induced by a charged vector loop

# Backup slides

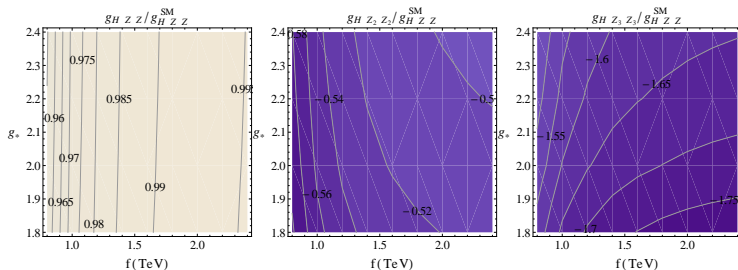
- Consider  $HV_i V_i$  charged couplings (SM-like and Extra)



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

# Backup slides

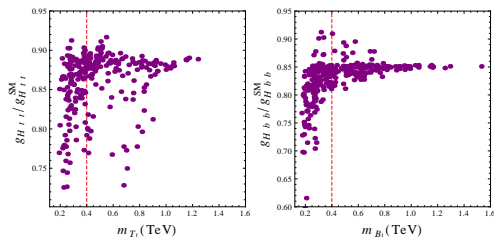
- Consider  $HV_i V_i$  neutral couplings (SM-like and Extra)



Couplings of Higgs boson in 4DCHM to neutral gauge bosons ( $Z$  left,  $Z_2$  middle,  $Z_3$  right) normalised to SM values.

# Backup slides

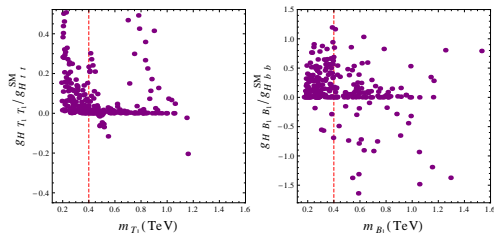
- Consider  $Hf_i\bar{f}_i$  couplings (SM-like)



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  $g_* = 2.5$ .

# Backup slides

- Consider  $Hf_i\bar{f}_i$  couplings (extra light)

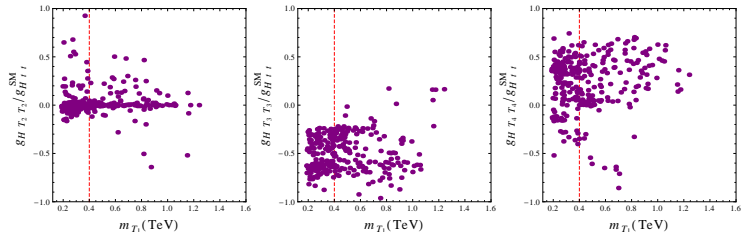


Couplings of Higgs boson in 4DCHM to lightest heavy top (left) and bottom (right) quarks normalised to SM values vs  $m_{T_1}$  and  $m_{B_1}$  for  $f = 0.8$  TeV and  $g_* = 2.5$ .



# Backup slides

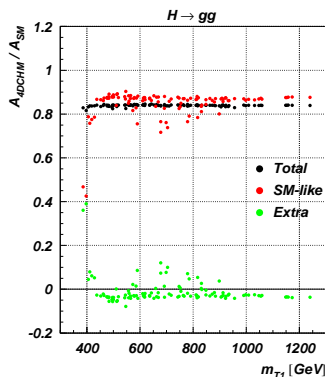
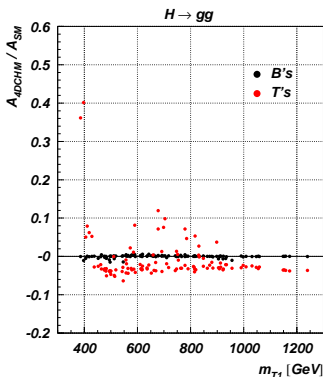
- Consider  $Hf_i\bar{f}_i$  couplings (extra heavy)



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

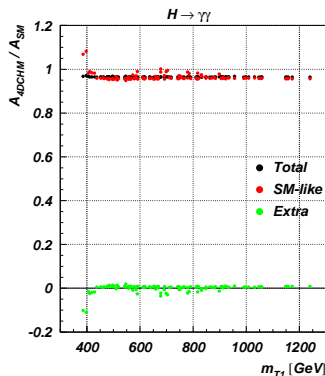
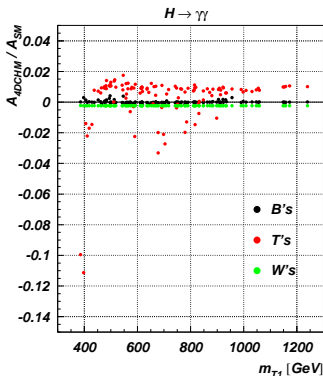
- Loop compensations between SM-like and Extra quarks ( $gg$ )



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

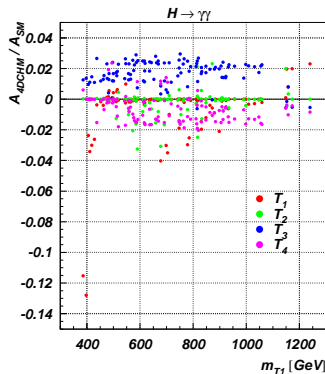
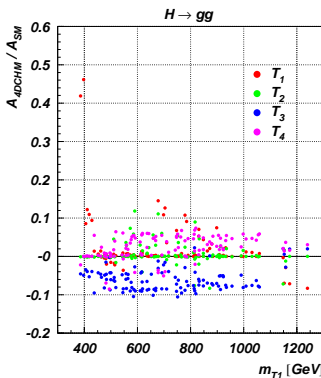
- Loop compensations between SM-like and Extra quarks ( $\gamma\gamma$ )



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

# Backup slides

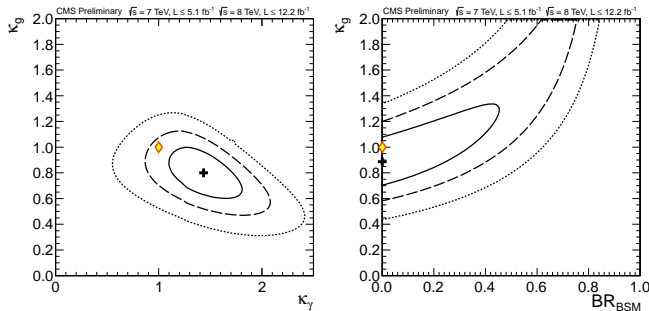
- Loop cancellations between Extra quarks



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  $g_* = 2.5$ .

# Conclusions

- 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)  $\kappa_H > 1$ .