

A 4D Composite Higgs model and LHC data

Stefano Moretti (NExT Institute, Southampton & RAL)

With D. Barducci, A. Belyaev, M.S. Brown, S. De Curtis and G.M. Pruna

Based on arXiv:1302.2371, arXiv:1306.6876 & arXiv:1304.4639

Beyond the LHC Workshop (Nordita)

27 July 2013

Outline

Preamble:

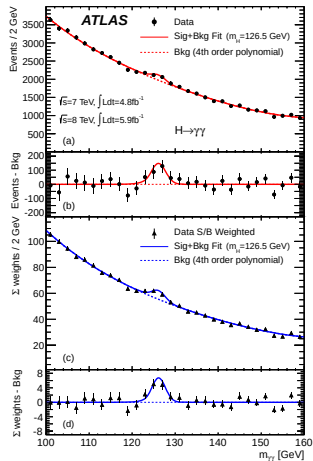
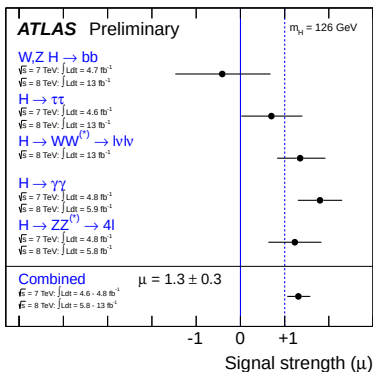
- A Higgs-like signal has been observed at the LHC (supplemental earlier evidence from Tevatron as well)
- Both ATLAS and CMS confirm it, very SM-like too
- Mass measurements around 125 GeV
- Candidate data samples include $\gamma\gamma$, ZZ^* , WW^* , $b\bar{b}$ and $\tau^+\tau^-$ (in order of decreasing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

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

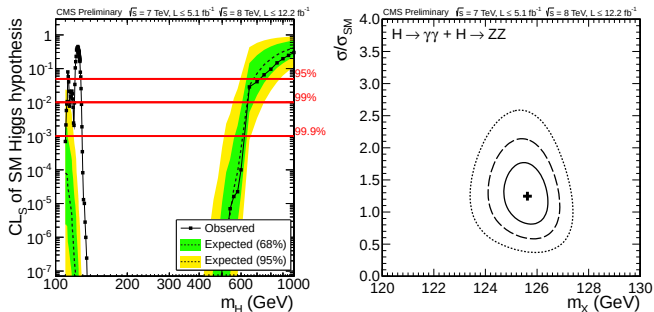
- ATLAS results (pre Moriond)



All channels (left) and $\gamma\gamma$ (right)

Outline

- CMS results (pre Moriond)



Whole mass range (left) and mass fit to excess (right)

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 the discovery of a Higgs particle we know that the SM is not the end of the story

- Hierarchy problem
- Naturalness problem

Two possible scenarios

Weak coupling

- Supersymmetry

Strong coupling

- Technicolor
- Extra dimensions
- Composite Higgs

4DCHM

A possible scenario

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

Higgs boson is naturally light

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^{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

Elementary sector and composite sector

ELEMENTARY SECTOR

- $SU(2)_L \otimes U(1)_Y$ fields
- Elementary fermions
 - t_L b_L t_R b_R

COMPOSITE SECTOR

- $SO(5) \otimes U(1)_X$
Gauge fields
- New physics fermions

Fermions are embedded in
fundamental
representations of
 $SO(5) \otimes U(1)_X$

$$\mathbf{5} \rightarrow (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{1}, \mathbf{1})$$

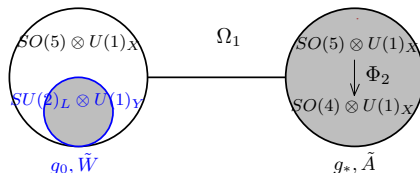
First two generation quarks and all leptons considered as in SM.

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

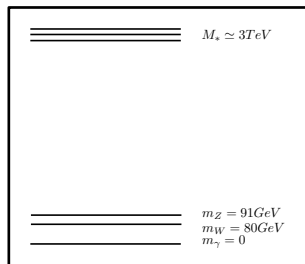
5 Neutral

6 Charged (c.c.)

4DCHM

Bosonic sector mass spectrum

Bosonic sector mass spectrum



Gauge boson mass ≥ 1.5 TeV

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

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

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

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

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

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

Model parameters (gauge):

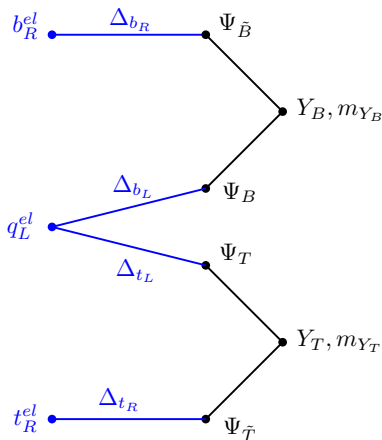
$$f \simeq 1 \text{ TeV}$$

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)

$$m_*$$

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

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

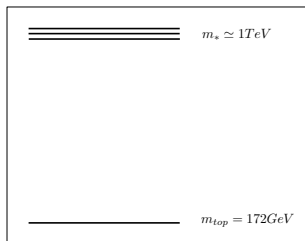
Elementary fermions mix with composite ones via link fields Ω_1

4DCHM

Fermionic sector mass spectrum

Top 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

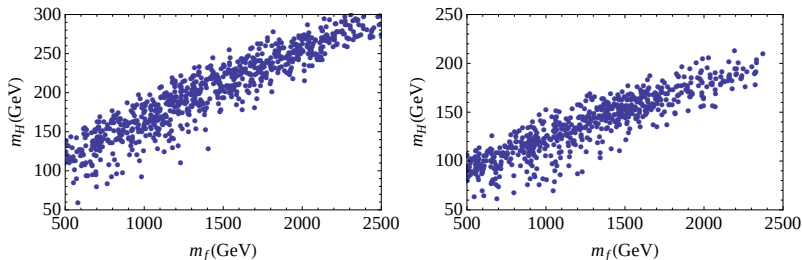
4DCHM

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 $f_1 = f_2 = \sqrt{2}f$ and $M_{Z',W'} = 2.5 \text{ TeV}$. (From [De Curtis, Redi, Tesi \(arXiv:1110.1613\)](#).)

Particle spectrum

The particle spectrum of the 4DCHM is

- SM leptons: e, μ, τ , and ν_e, ν_μ, ν_τ
- 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:
 - α , 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

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

Results

Limits on heavy gauge bosons and fermions

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

- Bosons:

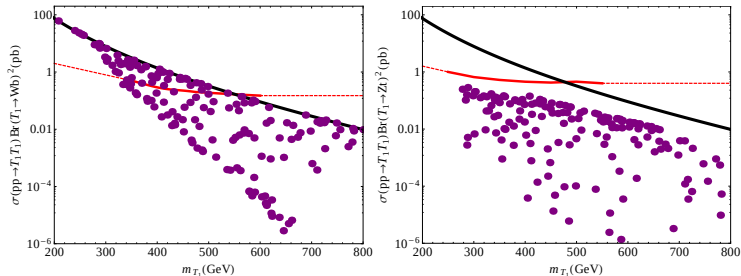
1. EWPTs (LEP, SLC & Tevatron) sets $M_{Z',W'} \geq 1.5$ TeV
2. Z' , W' have poor lepton rates, hence no stronger limits from direct searches (Tevatron & LHC)

- Fermions:

1. Direct searches (LHC) more constraining, assume pair production (7 TeV)
2. CMS with 5 fb^{-1} , $\text{BR}(t' \rightarrow W^+ b) = 100\%$
CMS with 1.14 fb^{-1} , $\text{BR}(t' \rightarrow Z t) = 100\%$
3. CMS with 4.9 fb^{-1} , $\text{BR}(b' \rightarrow W^- t) = 100\%$
CMS with 4.9 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

Results

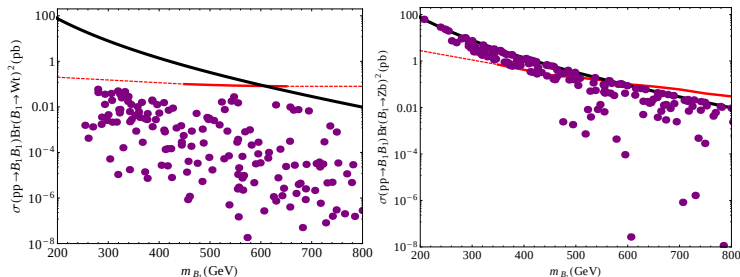
Limits on m_{T_1}



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.

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.

Results

- Define R (μ) 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)

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

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

Results

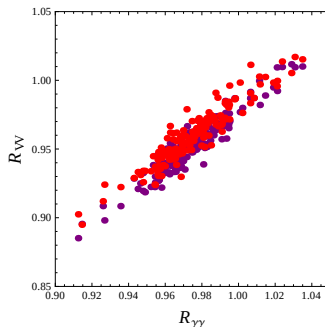
	ATLAS	CMS
$R_{\gamma\gamma}$	1.8 ± 0.4	$1.564^{+0.460}_{-0.419}$
R_{ZZ}	1.0 ± 0.4	$0.807^{+0.349}_{-0.280}$
R_{WW}	1.5 ± 0.6	$0.699^{+0.245}_{-0.232}$
R_{bb}	-0.4 ± 1.0	$1.075^{+0.593}_{-0.566}$

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 $f = 1$ TeV and $g_* = 2$ for illustration, features generic to 4DCHM

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.

Results

- Introduce reduced couplings a la LHC HXSWG ([A. Denner et al \(arXiv:1209.0040\)](#))
- We can cast R s in terms of κ 's

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

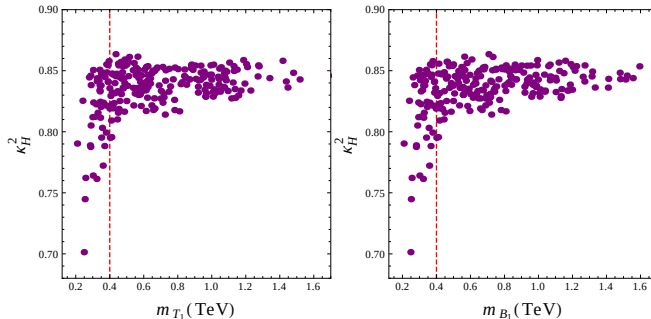
$$Y, Y' = b/\tau/g/\gamma/V$$

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

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

Results

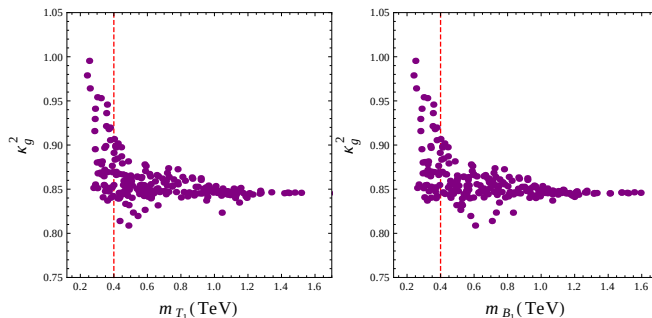
- κ_H smaller: $b - b'$ mixing, all Higgs rates rise



Distribution of κ_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.

Results

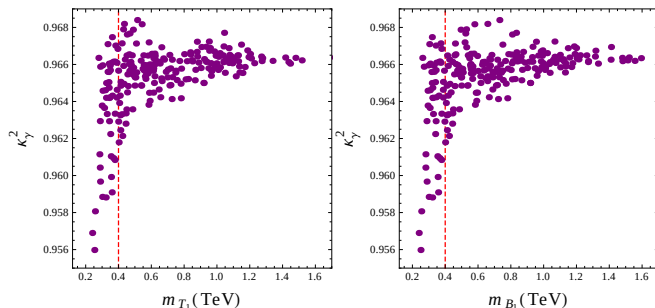
- κ_g smaller: $t - t'$ mixing, t -loop dominant
- Subtle cancellations/compensations



Distribution of κ_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.

Results

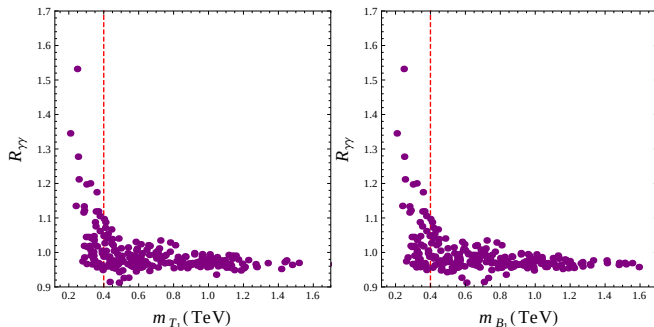
- κ_γ also smaller (less though): $t - t'$ mixing, t -loop subdominant
- Again, subtle cancellations/compensations



Distribution of κ_γ 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.

Results

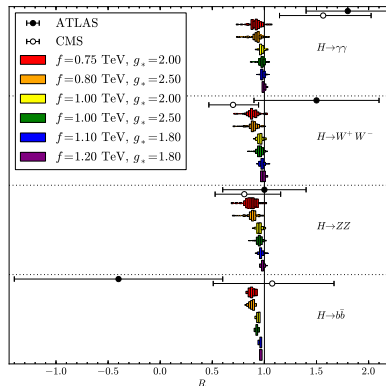
- T_1 and B_1 masses play significant role, revisit $R_{\gamma\gamma}$
- Leakage of points towards large $R_{\gamma\gamma} > 1$ at small masses
- Asymptotic result for $m_{T_1, B_1} \rightarrow \infty$ can be wrong by 10+%



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.

Results

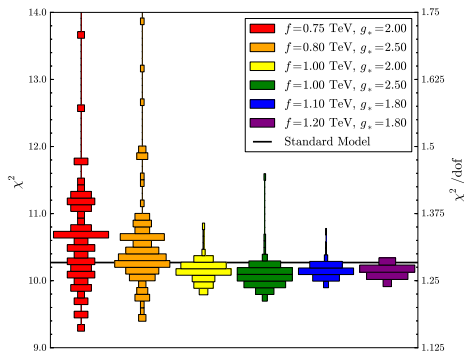
- Compare all benchmarks to SM & data



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

Results

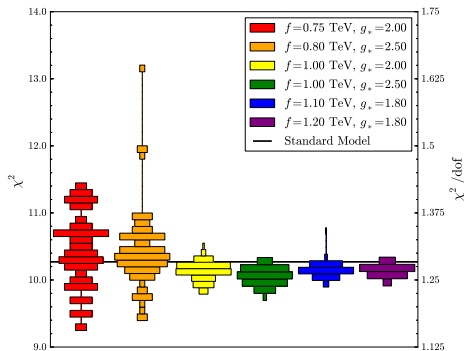
- Perform χ^2 fit and compare to SM, can be better



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

Results

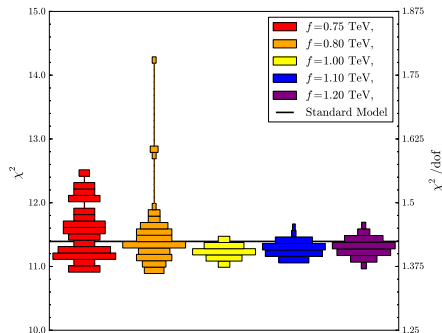
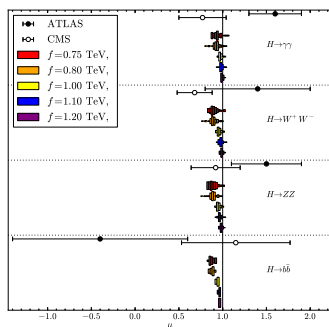
- Add $m_{\tilde{T}_1} > 600$ GeV (no limits on $m_{\tilde{B}_1}$)



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

Results

- After Moriond updates



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

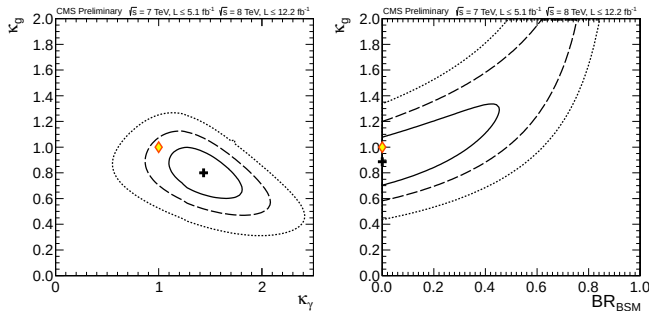
Conclusions

- Summary:

1. 4DCHM could provide explanation to LHC data pointing to Higgs discovery at 125–126 GeV (some better χ^2 's than SM)
2. Substantial parameter space scans show possible moderate enhancement in $H \rightarrow \gamma\gamma$, i.e., $R_{\gamma\gamma} \approx 1.1$
3. $R_{\gamma\gamma}$ could grow to ≈ 1.3 , if t' and b' masses just below results of our extrapolations
4. 4DCHM main effect is reduction of Hbb due to $b - b'$ mixing, smaller $\Gamma_{\text{tot}}(H)$
5. Competing effects from Hgg also smaller, $H\gamma\gamma$ almost stable
6. Reduction of $\Gamma_{\text{tot}}(H)$ calls for LHC XSWG coupling fits with $\kappa_H < 1$ (common to other BSM theories, e.g., SUSY)
7. Relevant by-product: approximations assuming t' and b' masses infinite cannot be accurate
8. Composite Higgs solution to LHC data seemingly possible and wanting light fermionic partners
9. Revisit t' & b' searches in 4DCHM dependent way
10. Future LC ideal to test modified $hb\bar{b}$, hW^+W^- and hZZ

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 κ_g and κ_γ for (left) $\kappa_H = 1$ and (right) $\kappa_H > 1$.

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 $\mathbf{5}_{-1/3}$ (Ψ_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

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

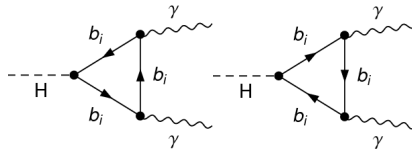
$$\begin{aligned} \mathcal{L}_{ferm,H} = & \Delta_{t_L} \bar{q}_L^{el} \delta\Omega_1 \Psi_T + \Delta_{t_R} \bar{t}_R^{el} \delta\Omega_1 \Psi_{\tilde{t}} \\ & - Y_T \bar{\Psi}_{T,L} (\phi_0^T \phi_0 \delta\Omega_2^T + \delta\Omega_2 \phi_0 \phi_0^T + \delta\Omega_2 \phi_0^T \phi_0 \delta\Omega_2^T)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

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

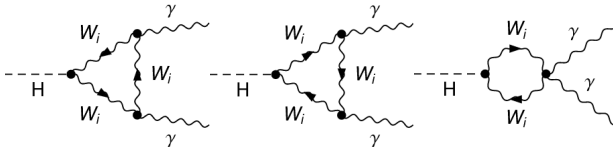
Backup slides

Subtle loop cancellations/compensations

- Consider loop diagrams



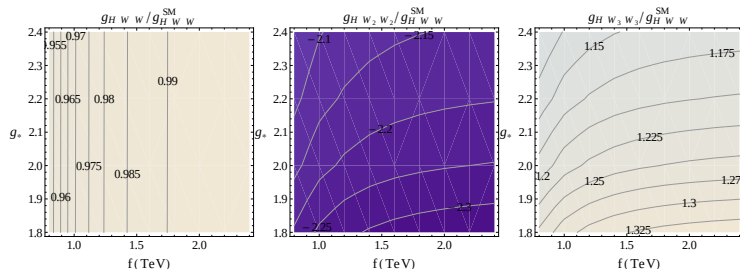
$H \rightarrow \gamma\gamma$ induced by fermionic loop



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

Backup slides

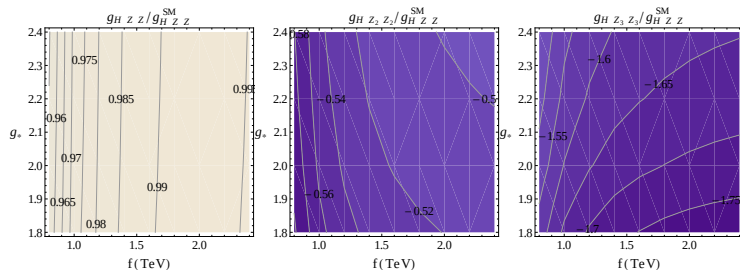
- Consider $HV_i V_i$ charged couplings (SM-like and Extra)



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

Backup slides

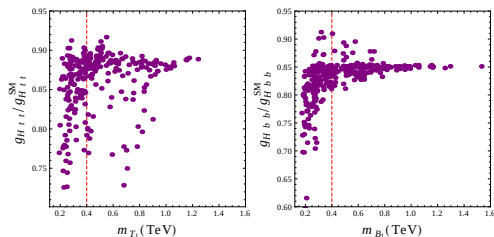
- Consider $HV_i V_i$ neutral couplings (SM-like and Extra)



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

Backup slides

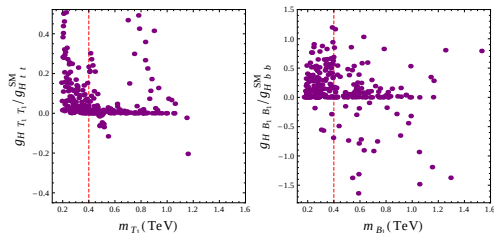
- Consider $Hf_i\bar{f}_i$ couplings (SM-like)



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 $f = 0.8 \text{ TeV}$ and $g_* = 2.5$.

Backup slides

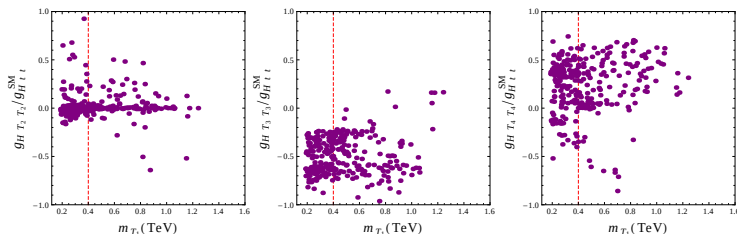
- Consider $Hf_i\bar{f}_i$ couplings (extra light)



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

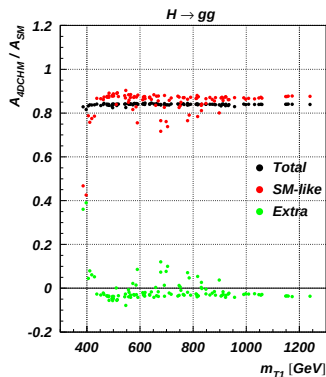
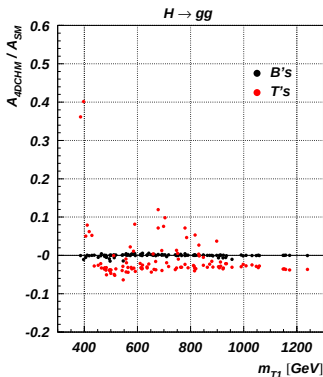
- Consider $Hf_i\bar{f}_i$ couplings (extra heavy)



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

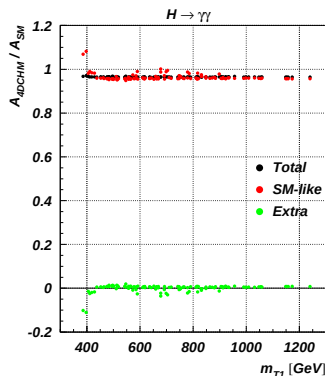
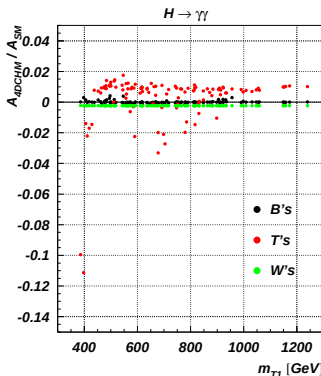
- Loop compensations between SM-like and Extra quarks (gg)



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

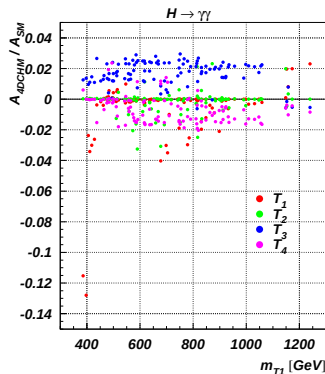
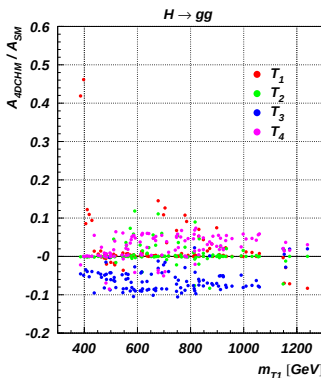
- Loop compensations between SM-like and Extra quarks ($\gamma\gamma$)



Loop contributions to $H \rightarrow \gamma\gamma$ in 4DCHM normalised to SM vs m_{T1} 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 $g_* = 2.5$.