# The 4-Dimensional Composite Higgs Model and the 125 GeV Higgs-like signals at the LHC

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Based on arXiv:1302.2371

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# Outline

Preamble:

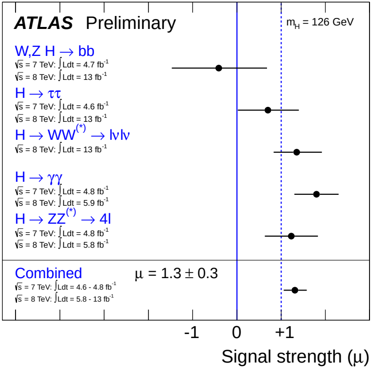
- A Higgs-like signal has been observed at the LHC (supplemental earlier evidence from Tevatron as well)
- Both ATLAS and CMS confirm it
- Mass measurements around 125 GeV
- Candidate data samples include $\gamma\gamma$, $ZZ^*$, $WW^*$, $b\bar{b}$ and $\tau^+\tau^-$ (in order of decreasing accuracy and/or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

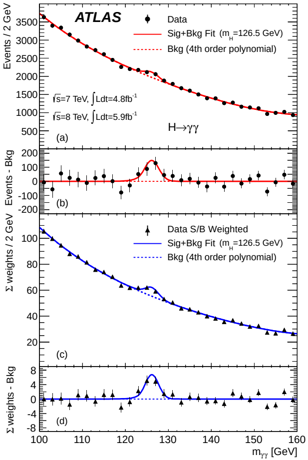
Motivation:

- Some inconsistency with the SM predictions exists, particularly in the (most significant) $\gamma\gamma$ channel
- It is therefore 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

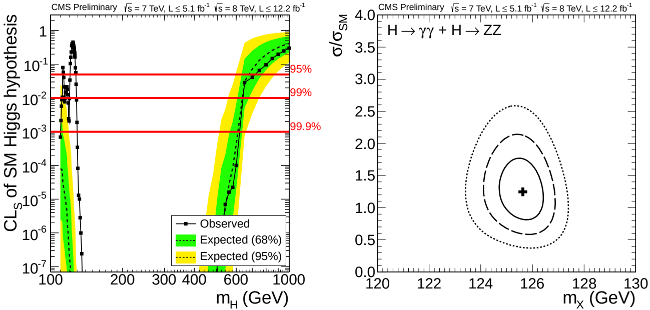



All channels (left) and $\gamma\gamma$ (right)

# Outline

- CMS results




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

# Outline

Desclaimer:

- 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-like 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 $G \to H$

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 compositness (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

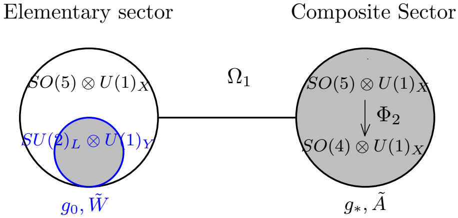
Fermions are embedded in fundamental representations of $SO(5) \otimes U(1)_X$

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

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

# 4DCHM

## Bosonic sector




De Curtis, Redi, Tesi '11

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

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

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

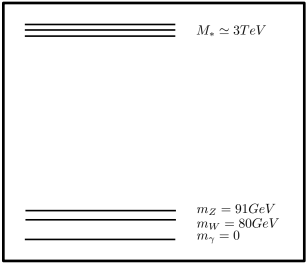
11 new gauge resonances

5 Neutral 6 Charged (c.c.)

# 4DCHM

## Bosonic sector mass spectrum

Bosonic sector mass spectrum




Gauge boson mass $\geq 1.5$ TeV

$$M_Z^2 \simeq \frac{f^2}{4} g_*^2 (s_\theta^2 + \frac{s_\psi^2}{2})\xi$$
$$M_{Z_1}^2 = f^2 g_*^2$$

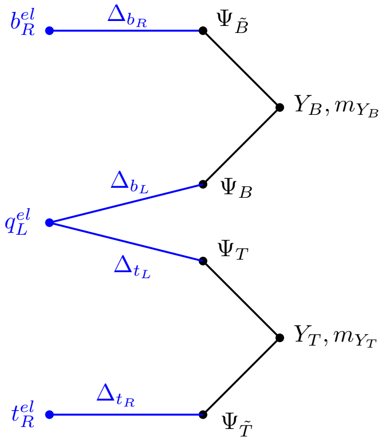
$\tan\theta = s_\theta / c_\theta = g_0 / g_*$
$\tan\psi = s_\psi / c_\psi = \sqrt{2} g_{0Y} / g_*$
$\xi = sin(\frac{v}{2f}) \simeq \frac{v}{2f}$
$v = \langle h \rangle = 246$ GeV

Model parameters (gauge):

$f \simeq 1$ 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)

$$m_*$$

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

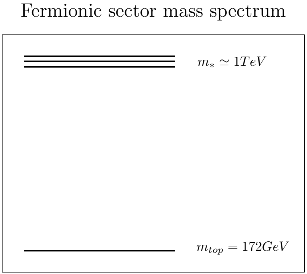
$$\Delta_{bL}, \Delta_{bR}, Y_B, m_{Y_B}$$

Elementary fermions mix with composite ones via link fields $\Omega_1$

# 4DCHM

## Fermionic sector mass spectrum

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




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

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

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

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

Fermionic resonance mass $\simeq$1 TeV

# 4DCHM

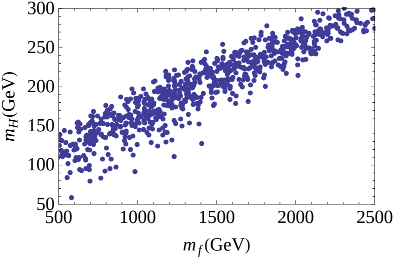
Higgs sector (at a glance)

- 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 compositness:

1. SM gauge/fermion states couple to Higgs via mixing with composite particles
2. 4DCHM gauge/fermion resonances couple to Higgs directly

# 4DCHM

- For natural choice of parameters, $m_H$ consistent with 125 GeV




Masses of lightest fermionic partners as a function of Higgs mass 165 GeV, with $\leq m_t \leq$ 175 GeV, for (left) $f = 500$ GeV and (right) $f = 800$ GeV. Fermionic parameters are varied between .5 and 3 TeV. Gauge contribution corresponds to $f_1 = f_2 = \sqrt{2}f$ and $M_{Z',W'} = 2.5$ 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: $W'^\pm_{i=1,2,3}$
- 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 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

# 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 $(f, g_*)$: $\approx$ 15M.
- Survival rate of $\mathcal{O}(10^{-7})$, variations amongst $(f, g_*)$s $\leq 30\%$
- 4DCHM highly constrained, phenomenologically interesting

# Results

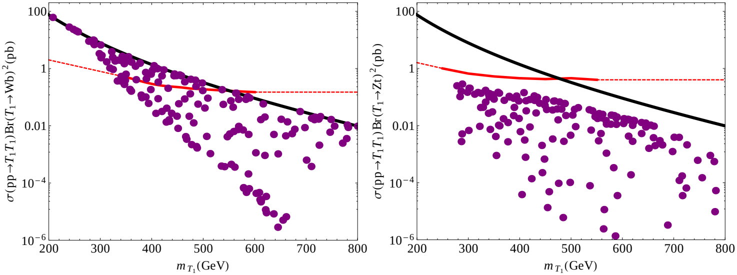
Limits on heavy gauge bosons and fermions

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 $\text{fb}^{-1}$, $\text{BR}(t' \to W^+ b) = 100\%$
     CMS with 1.14 $\text{fb}^{-1}$, $\text{BR}(t' \to Zt) = 100\%$
  3. CMS with 4.9 $\text{fb}^{-1}$, $\text{BR}(b' \to W^- t) = 100\%$
     CMS with 4.9 $\text{fb}^{-1}$, $\text{BR}(b' \to Zb) = 100\%$
  4. Limit on $T_1$ and $B_1$ about 400 GeV, but it could be slightly lower

# Results

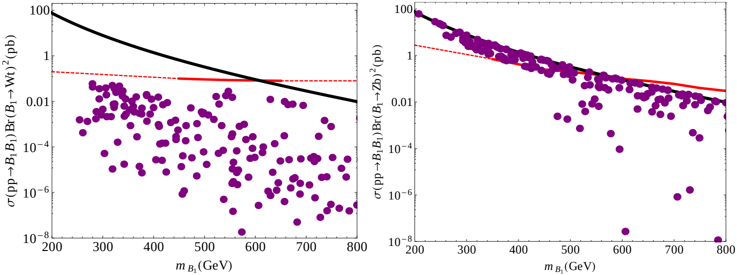
Limits on $m_{T_1}$




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

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

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

- Relevant hadro-production processes:

$$gg \to H\,({\rm gluon-gluon\ fusion}) \quad q\bar{q}(') \to VH\,({\rm Higgs-strahlung})$$

$V = W, Z$

- Convenient to re-write (valid at LO)

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

$Y'Y' = gg,\ VV$

# Results

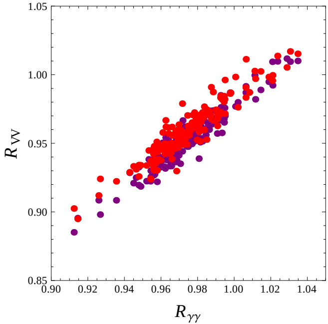
| | ATLAS | CMS |
|---|---|---|
| $R_{\gamma\gamma}$ | $1.8 \pm 0.4$ | $1.564^{+0.460}_{-0.419}$ |
| $R_{ZZ}$ | $1.0 \pm 0.4$ | $0.807^{+0.349}_{-0.280}$ |
| $R_{WW}$ | $1.5 \pm 0.6$ | $0.699^{+0.245}_{-0.232}$ |
| $R_{bb}$ | $-0.4 \pm 1.0$ | $1.075^{+0.593}_{-0.566}$ |

Summary of 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 $ZZ^* \to 4\ell$ and $WW^* \to 2\ell 2\nu_\ell$ (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 $\kappa$'s

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

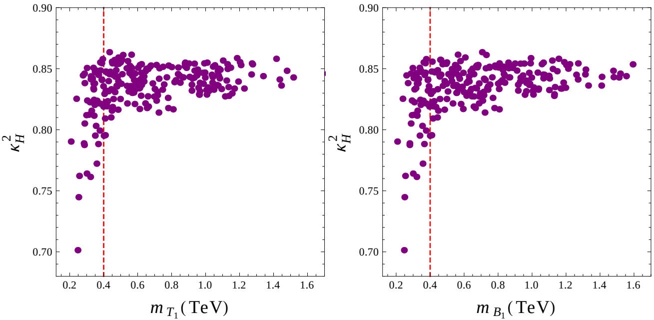
$Y, Y' = b/\tau/g/\gamma/V$

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

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

# Results

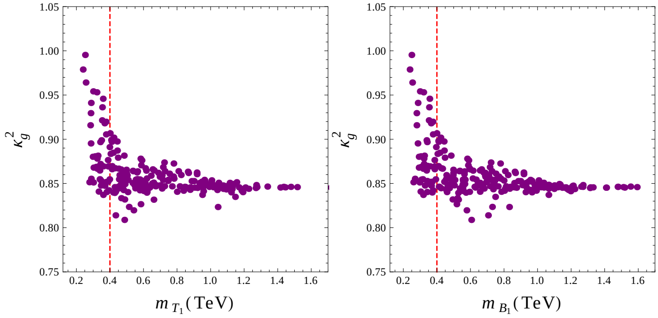
- $\kappa_H$ smaller: $b - b'$ mixing, all Higgs rates rise




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.

# Results

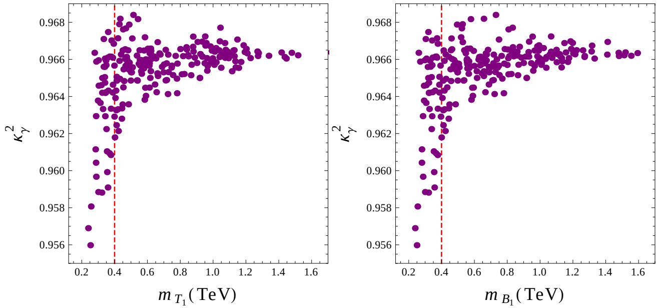
- $\kappa_g$ smaller: $t - t'$ mixing, $t$-loop dominant
- Subtle look cancellations/compensations




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.

# Results

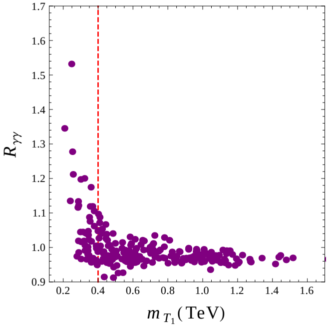
- $\kappa_\gamma$ (less) smaller: $t - t'$ mixing, $t$-loop subdominant
- Again, subtle look cancellations/compensations




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.

# Results

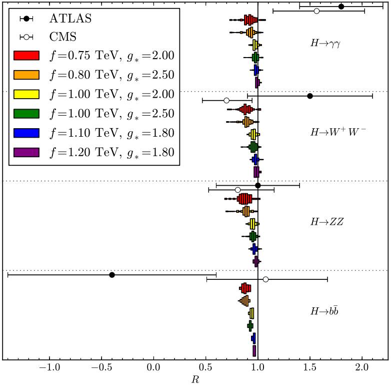
- $T_1$ and $B_1$ masses play significant role, revisit $R_{\gamma\gamma}$
- Leakage of points towars large $R_{\gamma\gamma} > 1$ at small masses
- Asymptotic result for $m_{T_1,B_1} \to \infty$ can be wrong by 10+%




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.

# Results

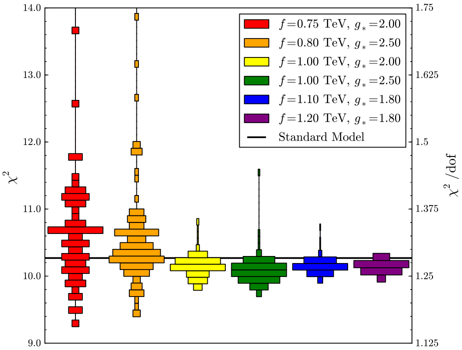
- Compare all benchmarks to SM & data




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

# Results

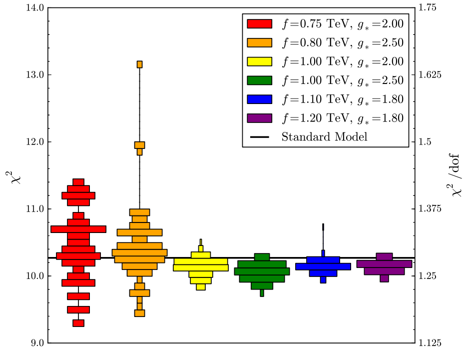
- Perform $\chi^2$ fit and compare to SM, can be better




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

# Results

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



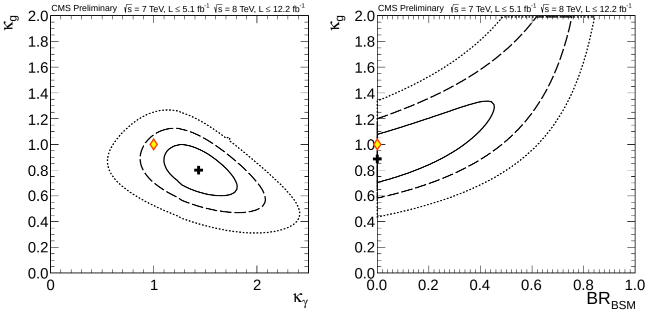

4DCHM $\chi^2$ fits for all benchmarks in $(f, g_*)$. Line is SM. Points compliant with $t'$ and $b'$ plus $\tilde{T}_1$ direct searches.

# Conclusions

- Summary:
  1. 4DCHM could provide better explanation than SM to LHC data pointing to Higgs discovery at 125–126 GeV (better $\chi^2$'s)
  2. Substantial parameter space scans show possible moderate enhancement in $H \to \gamma\gamma$, i.e., $R_{\gamma\gamma} \approx 1.1$
  3. $R_{\gamma\gamma}$ could grow to $\approx 1.3$, 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 $\Gamma_{\rm tot}(H)$
  5. Competing effects from $Hgg$ also smaller, $H\gamma\gamma$ almost stable
  6. Reduction of $\Gamma_{\rm tot}(H)$ calls for LHC XSGWG 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 (can use HPC behind HEPMDB)

# 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) $\kappa_H > 1$.

# Backup slides

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

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

- $t_R$ coupled to singlet in different $\mathbf{5}_{2/3}$ representation, $\Psi_{\widetilde{T}}$
- $b_R$ coupled to singlrt in a $\mathbf{5}_{-1/3}$ ($\Psi_{\widetilde{B}}$)
- 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

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

# Backup slides

Lagrangian (gauge and fermions)

$$\mathcal{L}_{gauge} = \frac{f_1^2}{4} Tr|D_\mu \Omega_1|^2 + \frac{f_2^2}{2}(D_\mu \Phi_2)(D_\mu \Phi_2)^T$$
$$- \frac{1}{4}\rho^{\tilde{A}}_{\mu\nu}\rho^{\tilde{A}\mu\nu} - \frac{1}{4}F^{\tilde{W}}_{\mu\nu}F^{\tilde{W}\mu\nu}$$
$$(\uparrow \text{composite} \uparrow \text{elementary kinetic terms})$$
$$\mathcal{L}_{fermions} = \mathcal{L}^{el}_{fermions} + (\Delta_{t_L}\bar{q}^{el}_L \Omega_1 \Psi_T + \Delta_{t_R}\bar{t}^{el}_R \Omega_1 \Psi_{\tilde{T}} + h.c.)$$
$$+ \bar{\Psi}_T(i\hat{D}^{\tilde{A}} - m_*)\Psi_T + \bar{\Psi}_{\tilde{T}}(i\hat{D}^{\tilde{A}} - m_*)\Psi_{\tilde{T}}$$
$$- (Y_T \bar{\Psi}_{T,L}\Phi_2^T \Phi_2 \Psi_{\tilde{T},R} + M_{Y_T}\bar{\Psi}_{T,L}\Psi_{\tilde{T},R} + h.c.) + (T \to B).$$

- Covariant derivatives

$$D^\mu \Omega_1 = \partial^\mu \Omega_1 - i g_0 \tilde{W}\Omega_1 + i g_* \Omega_1 \tilde{A}, \qquad D_\mu \Phi_2 = \partial_\mu \Phi_2 - i g_* \tilde{A}\Phi_2$$

$\tilde{W}[\tilde{A}]$ mediators of $SU(2)_L \otimes U(1)_Y$ $[SO(5) \otimes U(1)_X]$

# Backup slides

- $SO(5) \otimes U(1)_X \to SO(4) \otimes U(1)_X$ 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

<u>Higgs interactions</u>

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

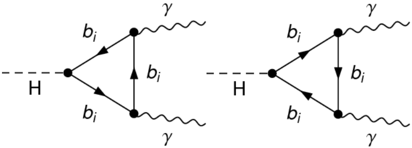
$$\begin{aligned}\mathcal{L}_{gauge,H} =& -\frac{f_1^2}{2} g_0 g_* Tr\left[\tilde{W}\delta\Omega_1\tilde{A} + \tilde{W}\tilde{A}\delta\Omega_1^T + \tilde{W}\delta\Omega_1\tilde{A}\delta\Omega_1^T\right] \\ &+ \frac{f_2^2}{2} g_*^2\left[\phi_0^T\delta\Omega_2^T\tilde{A}\tilde{A}\phi_0 + \phi_0^T\tilde{A}\tilde{A}\delta\Omega_2\phi_0 + \phi_0^T\delta\Omega_2^T\tilde{A}\tilde{A}\delta\Omega_2\phi_0\right], \\ \mathcal{L}_{ferm,H} =& \Delta_{t_L}\bar{q}_L^{el}\delta\Omega_1\Psi_T + \Delta_{t_R}\bar{t}_R^{el}\delta\Omega_1\Psi_{\tilde{T}} \\ &- Y_T\bar{\Psi}_{T,L}(\phi_0^T\phi_0\delta\Omega_2^T + \delta\Omega_2\phi_0\phi_0^T + \delta\Omega_2\phi_0^T\phi_0\delta\Omega_2^T)\Psi_{\tilde{T},R} \\ &+ (T \to B) + h.c.\end{aligned}$$

- 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 $g_{HV_iV_j}$ and $g_{Hf_i\bar{f}_j}$
- Couplings to mass eigenstates obtained after diagonalization

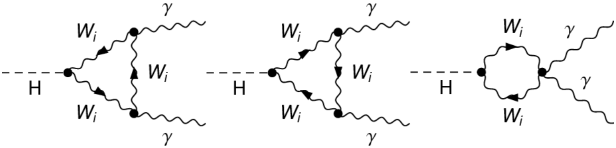
# Backup slides

<u>Subtle loop cancellations/compensations</u>

- Consider loop diagrams



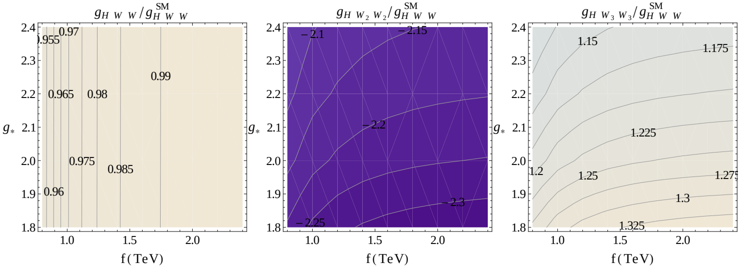

$H \to \gamma\gamma$ induced by fermionic loop




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

# Backup slides

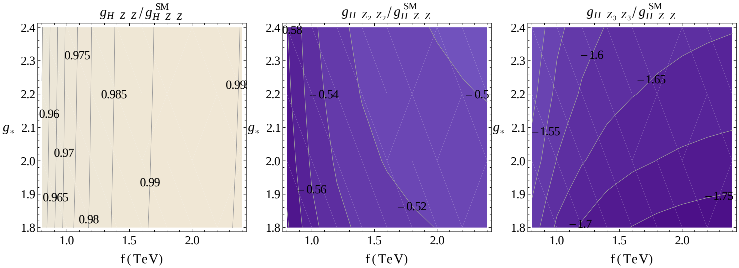
- Consider $HV_iV_i$ charged couplings (SM-like and Extra)




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

# Backup slides

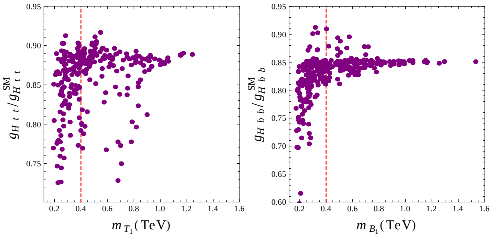
- Consider $HV_iV_i$ neutral couplings (SM-like and Extra)




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

# Backup slides

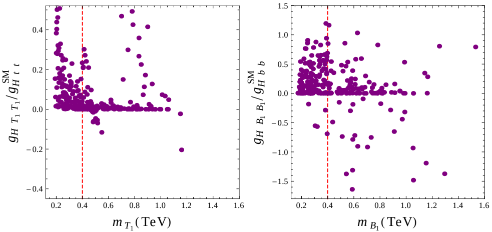
- Consider $Hf_i\bar{f}_i$ couplings (SM-like)




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

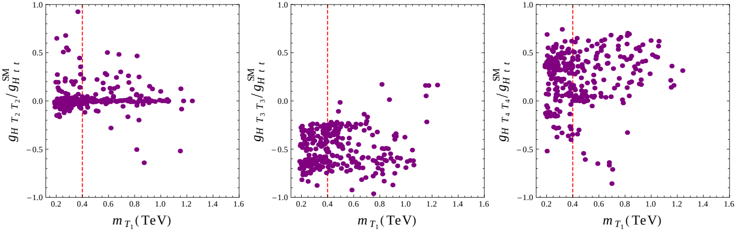
- Consider $Hf_i\bar{f}_i$ couplings (extra light)




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

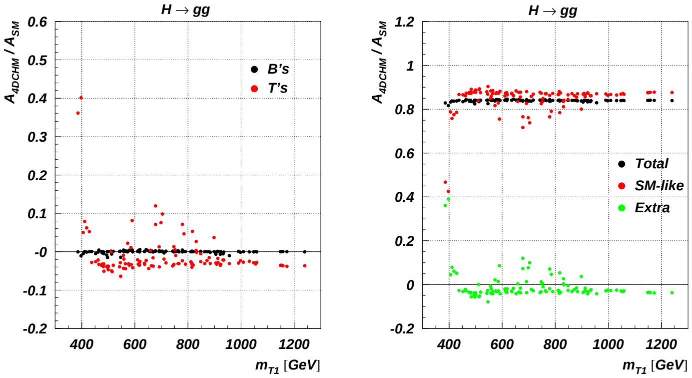
- Consider $Hf_i\bar{f}_i$ couplings (extra heavy)




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

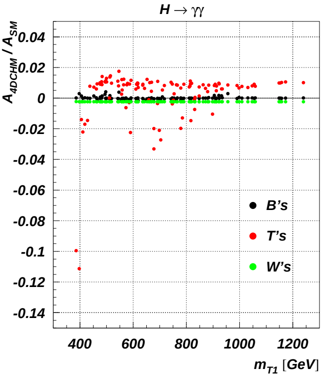
- Loop compensations between SM-like and Extra quarks ($gg$)

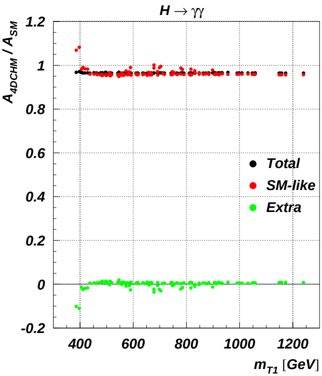



Loop contributions to $H \to gg$ in 4DCHM normalised to SM vs $m_{T_1}$ for $f = 0.8$ TeV and $g_* = 2.5$.

# Backup slides

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

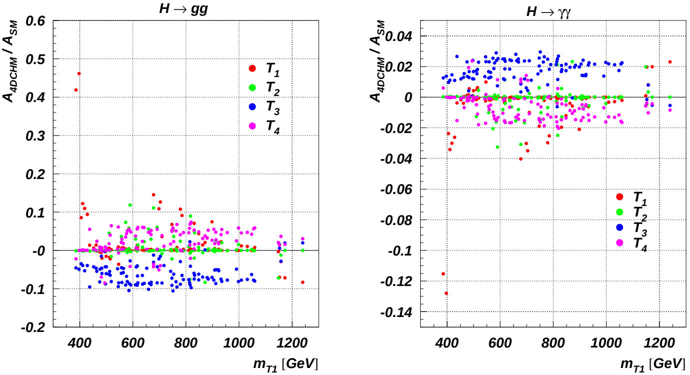



Loop contributions to $H \rightarrow \gamma\gamma$ in 4DCHM normalised to SM vs $m_{T_1}$ for $f = 0.8$ TeV and $g_* = 2.5$.

# Backup slides

- Loop cancellations between Extra quarks




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