Composite Higgs: searches for new physics at LCs

(Based on: arXiv:1302.2371, arXiv:1306.6876 and arXiv:1304.4639)

Giovanni Marco Pruna

Paul Scherrer Institut
Villigen, CH

LC13, ECT* Trento, 18 September 2013

Outline

- Introduction: Standard Model and Beyond
- The 4-D Composite Higgs Model
- Implementation and parameter space
- LHC physics and study of the couplings
- Phenomenology at LCs
- Conclusion

Outline

A crowning triumph for particle physics:

- a Higgs-like signal has been observed at the LHC;
- evidence from ATLAS and CMS, it is quite SM-like;
- mass measurements: ~ 125 GeV;
- candidate data samples: $\gamma\gamma$, ZZ^*, WW^*, $b\bar{b}$, $\tau^+\tau^-$ and X;

Motivation for compositeness:

- provides elegant solution for naturalness problems;
- few tensions with the SM prediction, not significant but…
- composite Higgs hypothesis has only been marginally studied in comparison with other “fundamental” scenarios;
- all scalar objects discovered in Nature have always been bound states of fermions.

4DCHM

SM may not be the end of the story

Among the possible scenarios

Extended symmetries

- Supersymmetry

Extended dyn./dim.

- 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)

From the '80s: spontaneous breaking of a symmetry $G \to H$

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

The main idea

Simplest realisation by Agashe et al. (arXiv:0412089)

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

The coset $SO(5)/SO(4)$: 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 $\to$ light Higgs

(à la Coleman-Weinberg (Phys. Rev. D**7** (1973) 1888-1910))

Extra-particle content is present

- Spin 1 resonances
- Spin 1/2 resonances

A minimal realisation

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

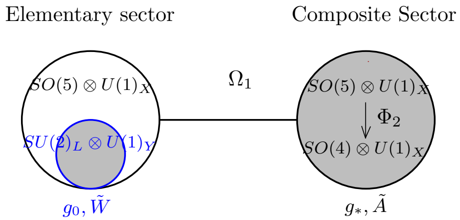
Effective 4D model, hence needs UV completion, irrelevant for the present analysis

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

Bosonic sector



De Curtis, Redi, Tesi '11

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

f scale of the symmetry breaking (compositeness scale)

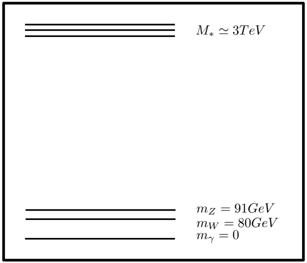
$$\Phi_2 = \Omega_1 \phi_0 \quad \phi_0 = (0,0,0,0,1) = \delta^{i5}$$

11 new gauge resonances

5 Neutral 6 Charged (c.c.)

Bosonic sector mass spectrum

Bosonic sector mass spectrum



Gauge boson mass ≥ 1.5 TeV from EWPTs

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

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

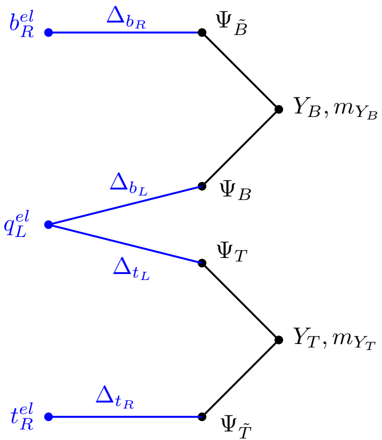
Model parameters (gauge):

$f \simeq 1$ TeV

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

$M_* = f\, g_*$

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)

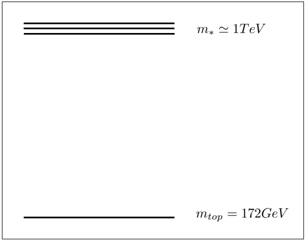
$$m_*$$
$$\Delta_{tL}, \Delta_{tR}, Y_T, m_{Y_T},$$
$$\Delta_{bL}, \Delta_{bR}, Y_B, m_{Y_B}$$

- Elementary(3^{rd}) fermions mix with composites via Ω_1
- First two generation quarks and all leptons $\sim$ SM

Fermionic sector mass spectrum

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

Fermionic sector mass spectrum



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

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

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

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

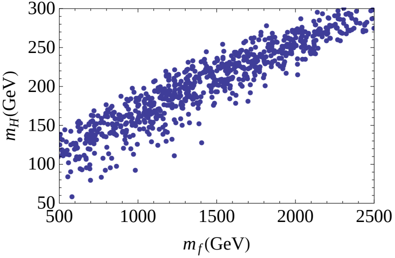
Fermionic resonance mass $\simeq$1 TeV

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(/Jungle) of new fermions and gauge bosons has potential to alter Higgs couplings via mixing and/or loops

A natural choice of parameters

m_H consistent with 125 GeV



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

Particle spectrum

The particle spectrum of the 4DCHM is

- SM leptons: e, 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: $Z'_{i=1,\ldots,5}$
- 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: $B'_{i=1,2}$
- 1 Higgs boson

Calculation

- More than 3000 Feynman rules!
  A non-automated approach... simply 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)”
- $H\gamma Z$ is fully evaluated and implemented but not public (yet)

Experimental constraints

- Implemented outside LanHEP/CalcHEP tools:
  - α, M_Z and G_F
  - Top, bottom and Higgs masses (same for 4DCHM & SM)

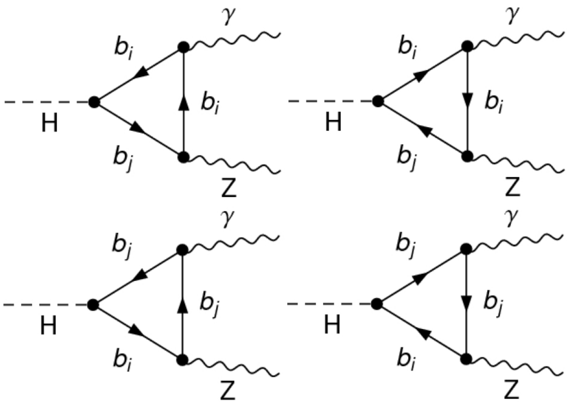
$$165 \text{ GeV} \leq m_t \leq 175 \text{ GeV}$$

$$2 \text{ GeV} \leq m_b \leq 6 \text{ GeV}$$

$$124 \text{ GeV} \leq m_H \leq 126 \text{ GeV}$$

  - $Zb\bar{b}$ and $Zt\bar{t}$ couplings
- Stand-alone Mathematica program performs scans on model parameters: 6 benchmarks were extracted
- Output is read by CalcHEP to compute physical observables

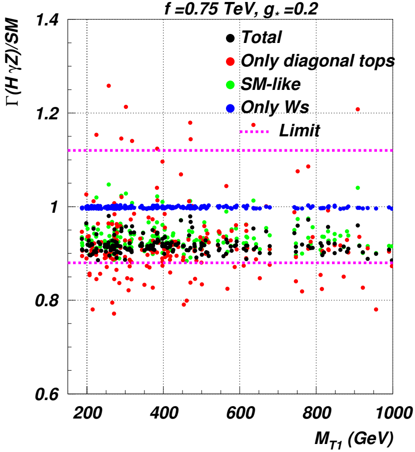
Two words about $H \to \gamma Z$ (1)



Different topologies: a 1-loop calculation that wasn't available!

Two words about $H \to \gamma Z$ (2)

While a sum rule is available for the case $H \to \gamma\gamma$ and $H \to gg$ (see arXiv:1110.5646), this is not the case for $H \to \gamma Z$.



PRELIMINARY

We have derived an upper bound for the sum of all the fermionic contributions:

$$|\mathcal{C}_t(H \to \gamma Z)| \leq 6 \cdot 10^{-6}\ \mathrm{GeV}^{-1},$$

$$|\mathcal{C}_t(H \to \gamma Z)| \leq \mathrm{Max}\{|C^R| + |C^L|\} \left| \frac{C_{\gamma t\bar{t}}(M_H^2 - 2M_Z^2) M_{T_8}}{\pi^2 v (M_H^2 - M_Z^2) M_t} \right| .$$

LHC results

Define benchmarks

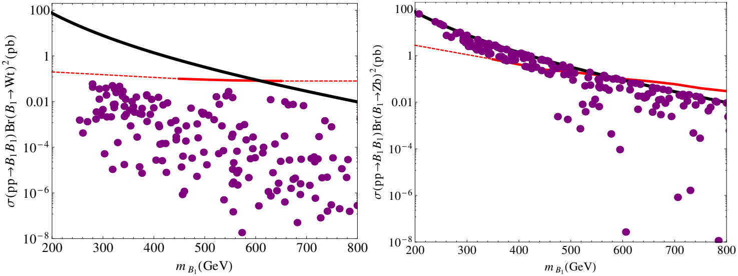
- 4DCHM parameter scans with f and g_* fixed to:
  (a) $f = 0.75$ TeV and $g^* = 2$
  (b) $f = 0.8$ TeV and $g^* = 2.5$
  (c) $f = 1$ TeV and $g^* = 2$
  (d) $f = 1$ TeV and $g^* = 2.5$
  (e) $f = 1.1$ TeV and $g^* = 1.8$
  (f) $f = 1.2$ TeV and $g^* = 1.8$
- All other parameters varied:
  0.5 TeV $\leq m_*, \Delta_{tL}, \Delta_{tR}, Y_T, M_{Y_T}, Y_B, M_{Y_B} \leq$ 5 TeV
  0.05 TeV $\leq \Delta_{bL}$, $\Delta_{bR} \leq$ 0.5 TeV
- Total number of random points for each (f, g_*): ≈ 15M.
- Survival rate of $\mathcal{O}(10^{-5})$, variations amongst $(f, g_*) \leq 30\%$
- 4DCHM is highly constrained

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

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.

R parameters

- Define R (μ) parameters, the observed events over SM:

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

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

- Relevant hadro-production processes at LHC:

$$gg \to H$$
$$q\bar{q}(') \to VH \qquad (V = W, Z)$$

LHC data

	ATLAS (new)	CMS (new)
$R_{\gamma\gamma}$	1.6 ± 0.3	0.77 ± 0.27
R_{ZZ}	1.5 ± 0.4	0.92 ± 0.28
R_{WW}	1.4 ± 0.6	0.68 ± 0.20
R_{bb}	-0.4 ± 1.0	1.15 ± 0.62

Table: LHC values of the R parameters from ATLAS&CMS.

- 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

Effective parametrisation

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

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

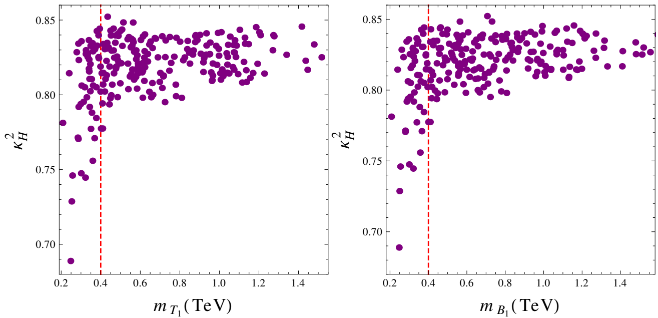
$$Y, Y' = b/\tau/g/\gamma/V$$

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

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

Higgs width

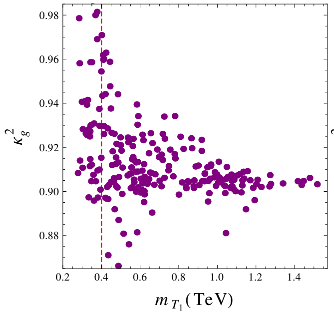
- κ_H smaller: $b - b'$ mixing, all Higgs rates rise



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.

Higgs to gluons

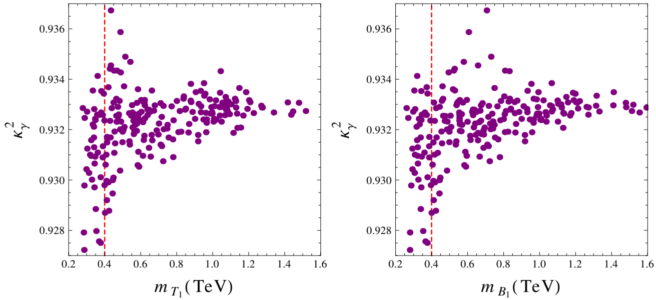
- κ_g smaller: $t - t'$ mixing, t-loop dominant
- Subtle cancellations/compensations



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.

Higgs to photons

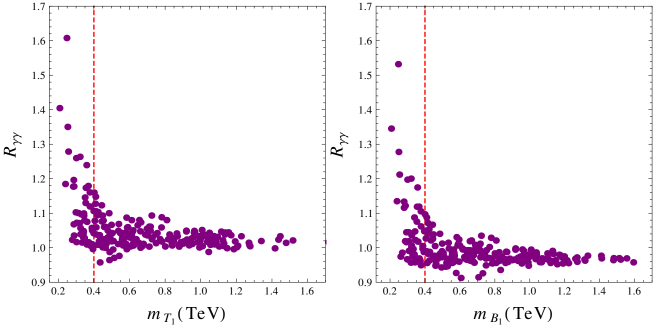
- κ_γ also smaller (less though): $t - t'$ mixing, t-loop subdominant
- Again, subtle cancellations/compensations



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.

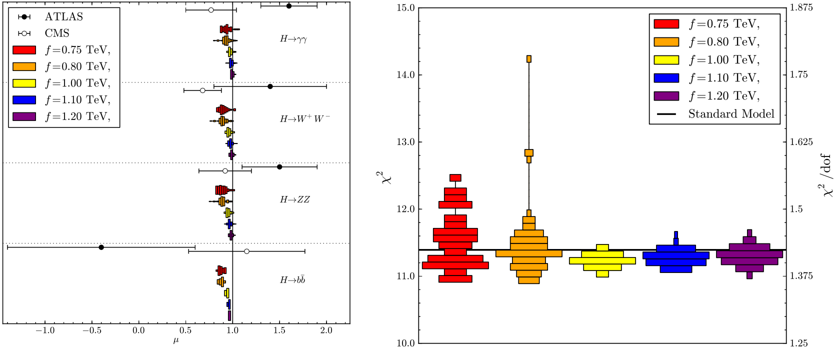
$R_{\gamma\gamma}$ in gluon fusion at the LHC

- 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 $m_{T_1} \to \infty$ 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 after Moriond

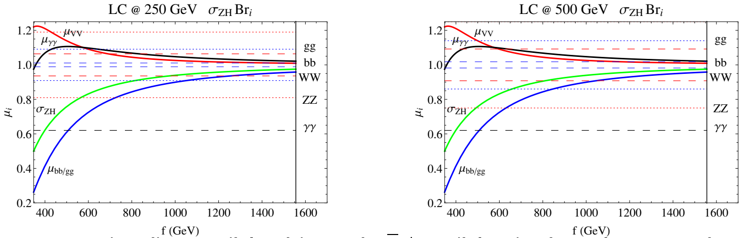


4DCHM against data (left) and χ^2 fits (right) for all benchmarks in (f, g_*). Line is SM. Points compliant with t' and b' plus $\tilde{T}_1$ direct searches.

LC results from an effective approach (1)

Higgs-strahlung times BRs: will this be correct?

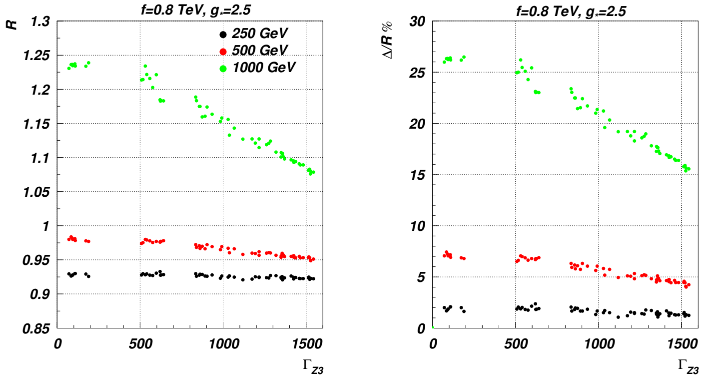
- Take low energies, 250 and 500 GeV, and look at leading $\zeta = v^2/f^2$ corrections
- Couplings rescale as: $\frac{g^{\rm SM}_{HVV}}{g^{\rm 4DCHM}_{HVV}} = \sqrt{1-\zeta}$, $\frac{g^{\rm SM}_{Hff}}{g^{\rm 4DCHM}_{Hff}} = \frac{1-2\zeta}{\sqrt{1-\zeta}}$



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.

PROPER LC results

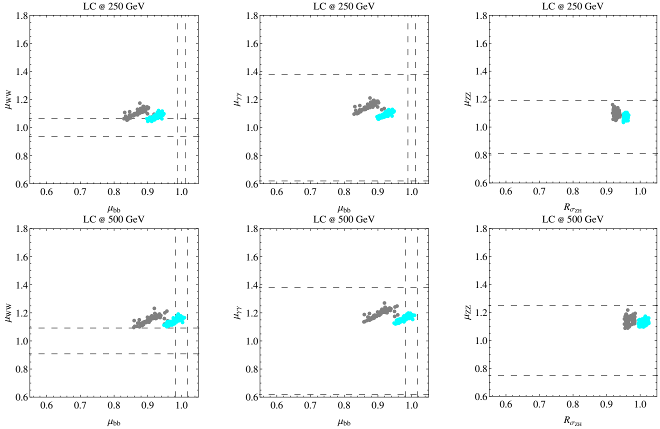
- Inclusive Higgs-strahlung is affected by Z's: define $R = \frac{\sigma_{4DCHM}}{\sigma_{SM}}$ and $\Delta = R - \kappa^2_{HZZ}$



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

LC results: HS×BR

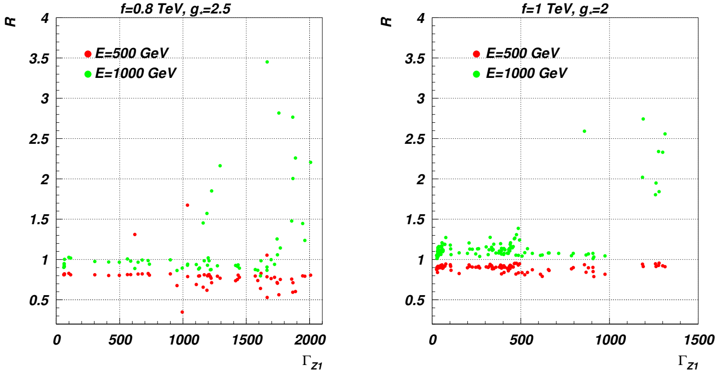
- This is finally allowing to disentangle models via couplings! (Error bars from arXiv:1306.6352, ILC TDR)



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: $e^+e^- \to t\bar{t}H$

- Again, Z'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.

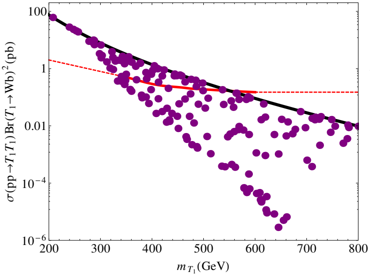


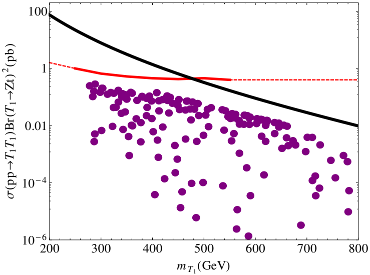
Corrections induced by mixing plus Z_1 exchange as a function of its width for benchmarks (b) (left) and (c) (right).

Conclusion

- We have presented a concrete realisation of a 4DCHM and its main theoretical and phenomenological features
- A full implementation is now available at `http://hepmdb.soton.ac.uk/`, fast tree-level calculations and event generation is possible, with the exception of the loop-induced $H- > \gamma Z$ vertex which is not public yet
- Higgs couplings were extensively studied and χ^2 fits were performed with respect to the LHC data
- A preliminary study of the phenomenology at LCs has been presented: we have shown that the usual effective approach could be not sufficient for natural choices of the scale f in vector-mediated processes, more to come (CS$\times$BR study in Higgs-strahlung processes, top Yukawa analysis, triple-H coupling, etc.)

Limits on m_{T_1}



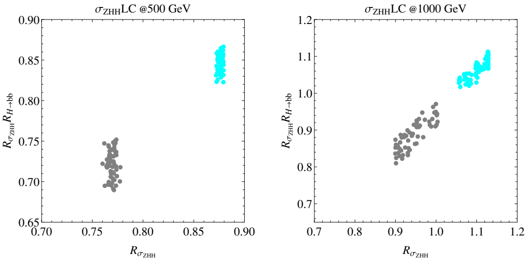


Black line is cross section assuming 100% BRs, red line is 95% CL observed limit and purple circles are 4DCHM points for $f = 1$ TeV and $g_* = 2$. Dotted-red line corresponds to extrapolations of experimental results.

LC results

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

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

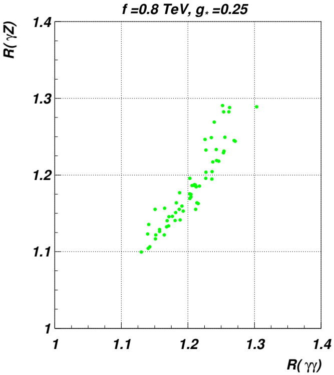


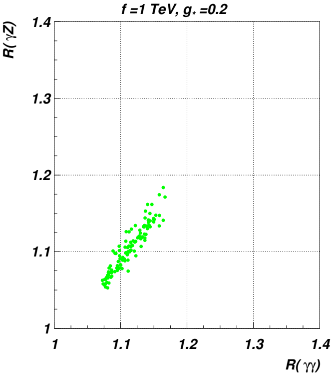
Scatter plot in $R_{\sigma_{ZHH}}$ vs $R_{\sigma_{ZHH}}R_{Br(H\to bb)}$ for $f = 800$ GeV (grey) and $f = 1000$ GeV (cyan) for a 500 GeV (left) and 1000 GeV (right) LC. (Same results for $\nu\bar{\nu}HH$.)

LC results

$\gamma\gamma$ versus γZ (only BRs)

- Smoking gun, they are egual in most BSM physics

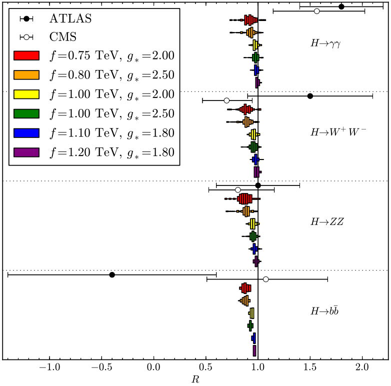




Scatter plot in $R_{\gamma Z}$ vs $R_{\gamma\gamma}$ for benchmarks (b) (left) and (c) (right).

LHC results

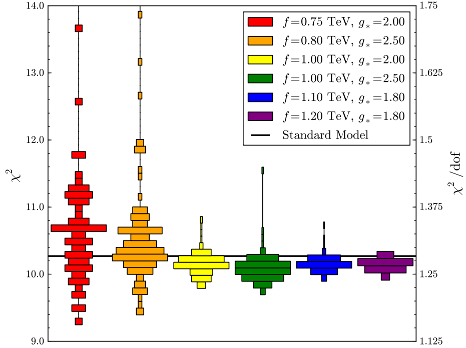
- Compare all benchmarks to SM & data



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

LHC results

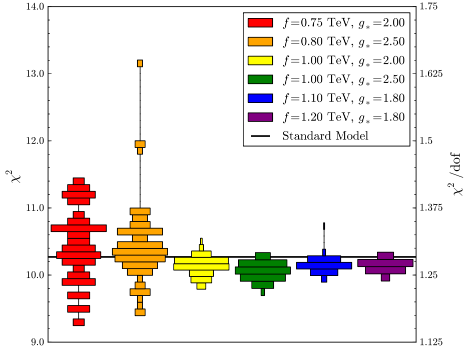
- Perform χ^2 fit and compare to SM, can be better



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

LHC results

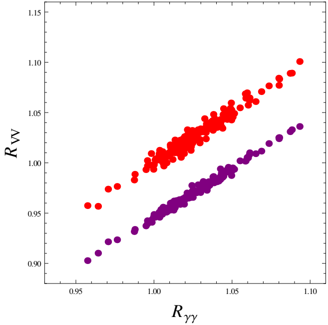
- Add $m_{\tilde{T}_1} > 600$ GeV (no limits on $m_{\tilde{B}_1}$)



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.

LHC results

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



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.

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, $\Psi_{\tilde{T}}$
- b_R coupled to singlrt 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

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

Backup slides

Lagrangian (gauge and fermions)

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

- Covariant derivatives

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

$\tilde{W}[\tilde{A}]$ 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

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 **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

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

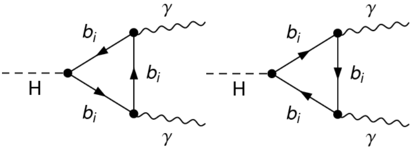
$$\mathcal{L}_{ferm,H} = \Delta_{t_L}\bar{q}_L^{el}\delta\Omega_1\Psi_T + \Delta_{t_R}\bar{t}_R^{el}\delta\Omega_1\Psi_{\tilde{T}}$$
$$-Y_T\bar{\Psi}_{T,L}(\phi_0^T\phi_0\delta\Omega_2^T + \delta\Omega_2\phi_0\phi_0^T + \delta\Omega_2\phi_0^T\phi_0\delta\Omega_2^T)\Psi_{\tilde{T},R}$$
$$+(T \to B) +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

- 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

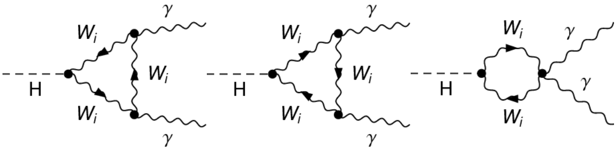
Backup slides

Subtle loop cancellations/compensations

- Consider loop diagrams



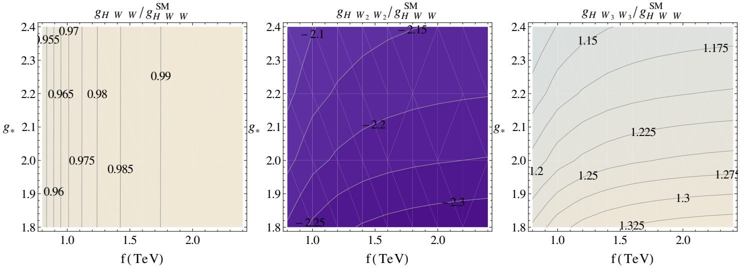
$H \to \gamma\gamma$ induced by fermionic loop



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

Backup slides

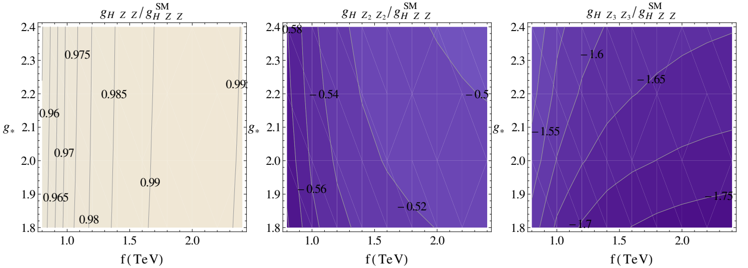
- Consider HV_iV_i charged couplings (SM-like and Extra)



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

Backup slides

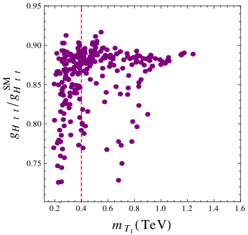
- Consider HV_iV_i neutral couplings (SM-like and Extra)

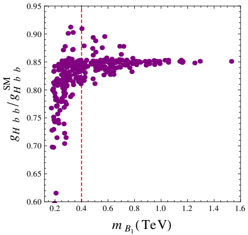


Couplings of Higgs boson in 4DCHM to neutral gauge bosons (Z left, Z_2 middle, Z_3 right) normalised to SM values.

Backup slides

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

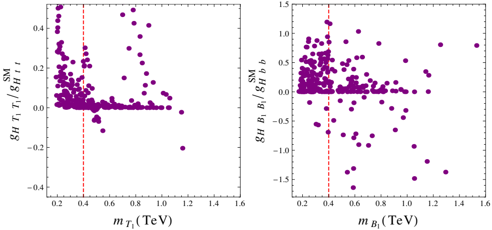




Couplings of Higgs boson in 4DCHM to top (left) and bottom (right) quarks normalised to SM values vs m_{T_1} and m_{B_1} for $f = 0.8$ TeV and $g_* = 2.5$.

Backup slides

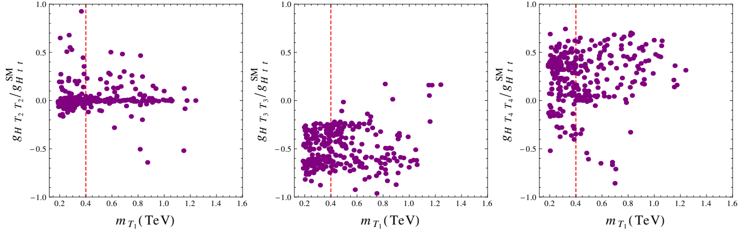
- Consider $Hf_i\bar{f}_i$ couplings (extra light)



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

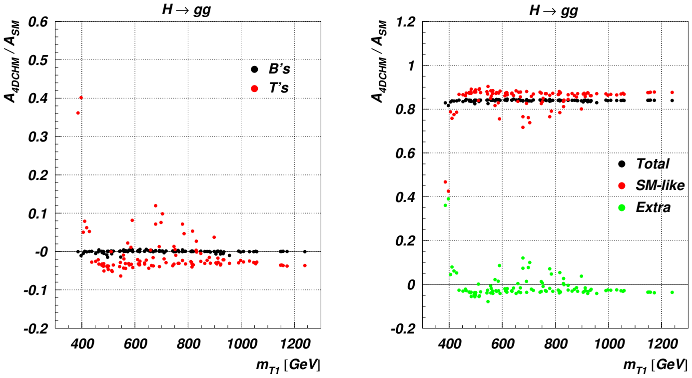
- Consider $H f_i \bar{f}_i$ couplings (extra heavy)



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

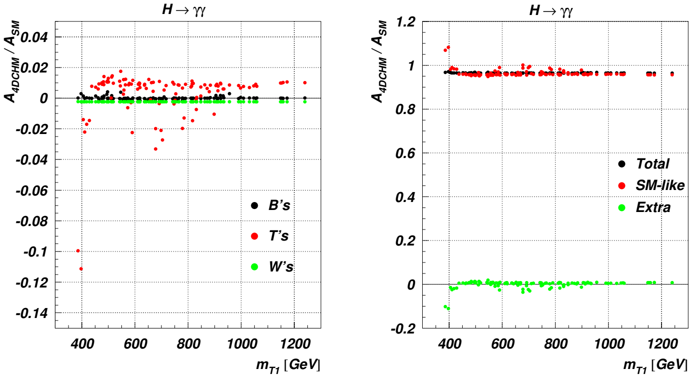
- Loop compensations between SM-like and Extra quarks (gg)



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

Backup slides

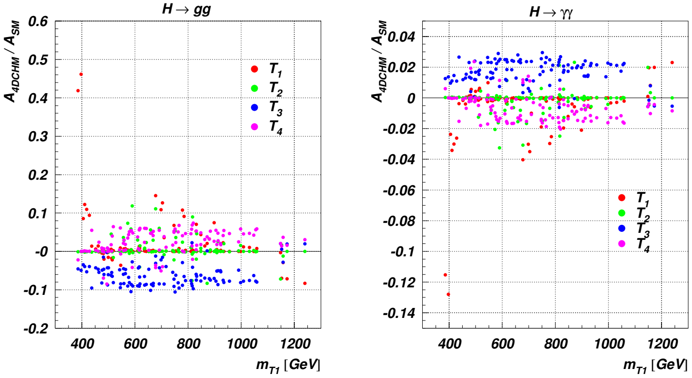
- Loop compensations between SM-like and Extra quarks ($\gamma\gamma$)



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