Higgs signal at the LHC for the 4D Composite Higgs model

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Based on arXiv:1302.2371

RAL NExT Meeting

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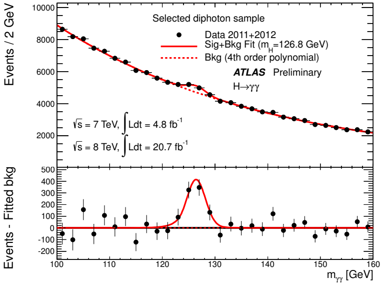
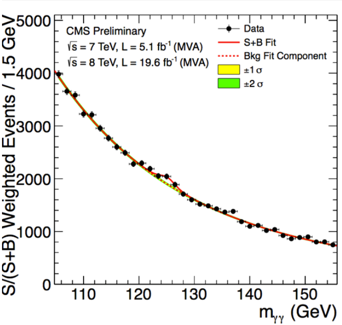
Outline

- Introduction
- Composite Models
- The 4-Dimensional Composite Higgs Model
- Implementation
- Results
- Outlook and Conclusions

Introduction

The Higgs boson has been discovered at the LHC from both ATLAS and CMS collaborations

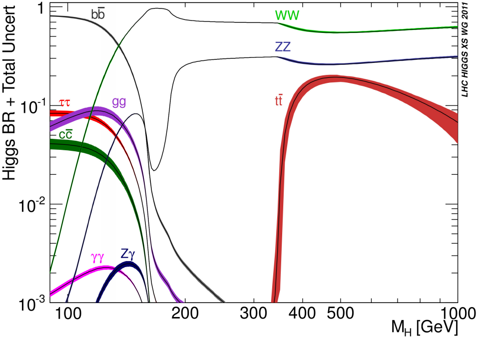




New boson mass around 125 GeV

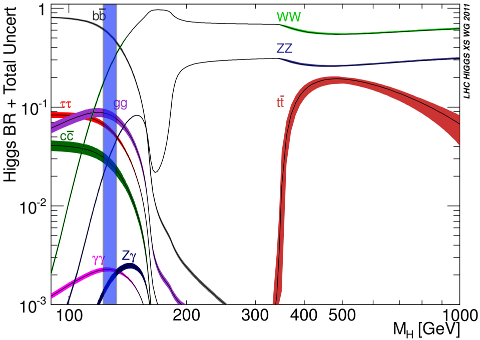
Introduction

Standard Model Higgs Branching ratios



Introduction

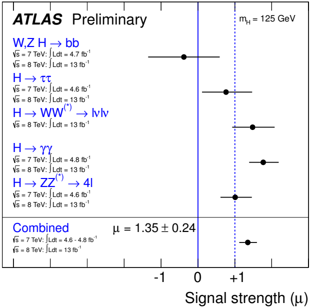
Standard Model Higgs Branching ratios

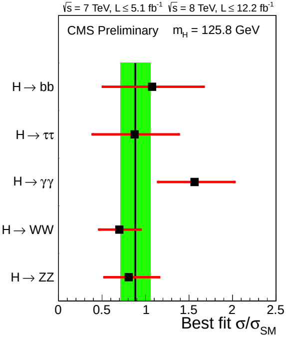


With a mass of 125 GeV nature has been really kind to us
Many decay channels accessible

Introduction

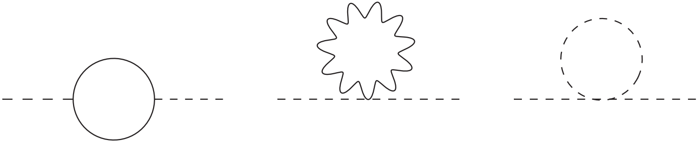
Interesting news: there could be hints of inconsistency with the SM predictions, for example in the $\gamma\gamma$ channel





Introduction

From a theoretical point of view the SM is unsatisfactory: hierarchy problem

 $\simeq \Lambda^2$

Therefore mandatory to explore BSM solutions

- Supersymmetry
- Technicolor
- Extra Dimensions
- Composite Higgs

Composite Higgs

- All scalars in nature have been discovered to be composite states
  - A composite Higgs solves radically the hierarchy problem

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  - A composite Higgs solves radically the hierarchy problem
- In the Standard Model the Higgs potential is put "by hand"
  - In Composite Higgs models the Higgs potential is computable

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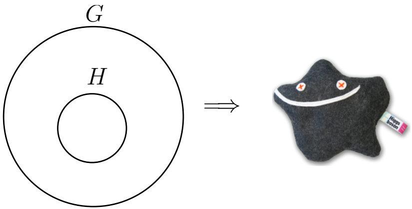
- All scalars in nature have been discovered to be composite states
    - A composite Higgs solves radically the hierarchy problem
- In the Standard Model the Higgs potential is put "by hand"
    - In Composite Higgs models the Higgs potential is computable

Interesting candidate and, compared to other hypotheses, less studied

Composite Higgs

- The Higgs boson is a bound state arising from a strong dynamic
- The Higgs boson is a pseudo Goldstone Boson

No hierarchy problem and the Higgs is naturally light



Idea from the '80s: spontaneously breaking of a symmetry $G \to H$

Georgi and Kaplan, Phys. Lett. B136, 183 (1994)

Composite Higgs

Simplest idea considered by Agashe, Contino and Pomarol

The Minimal Composite Higgs Model: arXiv:0412089

$$G \to H$$

$$G = SO(5) \quad H = SO(4)$$

- 4 Goldstone Bosons: minimum number to be identified with the SM Higgs doublet
- Potential generated at loop level (Coleman Weinberg potential): naturally light Higgs

The 4DCHM

The 4-D Composite Higgs model is a complete framework for the study of the Higgs as a pseudo Goldstone Boson

De Curtis, Redi and Tesi (arXiv:1110.1613)

- $SO(5) \rightarrow SO(4)$ breaking pattern for the Higgs sector
- Captures the relevant features of Composite Higgs model
- Mechanism of partial compositness
- Minimum number of d.o.f. that give a finite Higgs potential: realistic model

The 4DCHM

The gauge sector is described by two non linear σ models

$$\mathcal{L} = \frac{f^2}{4} tr[(\partial_\mu \Omega)^\dagger (\partial^\mu \Omega)] + \frac{f^2}{2} |\partial_\mu \Phi|^2$$

- $\Omega = exp(i\theta_A T^A)$ describes $SO(5)_L \otimes SO(5)_R \to SO(5)_{L+R}$
- $\Phi = exp(ih^{\hat{a}} T^{\hat{a}})\phi_0$ describes $SO(5) \to SO(4)$
  $\phi_0 = (0, 0, 0, 0, 1)$

Two σ models that don't speak each other
Lagrangian invariant under global symmetry

The 4DCHM

Introducing covariant derivatives for gauge invariant lagrangian
Make the two models interact

Son e Stephanov (arXiv:0304182), Becciolini et al. (arXiv:0906.4562)

$$\partial^\mu \Omega \to D^\mu = \partial^\mu \Omega - i g_0 A_0^\mu \Omega + i g_* \Omega A_1^\mu$$
$$\partial^\mu \Phi \to D^\mu = \partial^\mu \Phi - i g_* A_1^\mu \Phi$$

- $g_0, A_0^\mu \in SU(2)_L \otimes U(1)_Y$
- $g_*, A_1^\mu \in SO(5) \otimes U(1)_X$

$$\mathcal{L} = \frac{f^2}{4} tr[(D_\mu \Omega)^\dagger (D^\mu \Omega)] + \frac{f^2}{2} |D_\mu \Phi|^2 + \mathcal{L}_{kin}$$

The 4DCHM

Possible to define a unitary gauge

Son e Stephanov (arXiv:0304182)

$$\Omega = exp(i\frac{\Pi}{2f}) \quad \Pi = \sqrt{2}h^{\hat{a}}T^{\hat{a}}$$

<u>SM gauge fields</u>

$SU(2)_L \otimes U(1)_Y$ gauge fields

$\gamma, W^{\pm}, Z^0$

<u>Extra gauge fields</u>

$SO(5) \otimes U(1)_X$ massive gauge fields

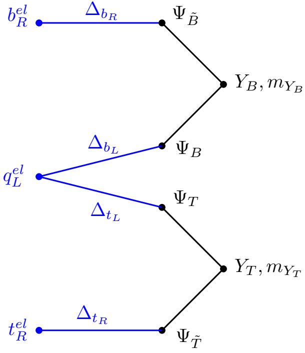
5 neutral (Z')

3 charged (W')

SM gauge fields and Extra gauge fields usually referred to as elementary and composite states

The 4DCHM

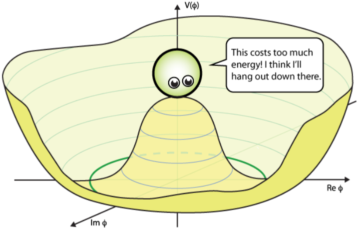
- New fermionic sector necessary for the Higgs potential
  (Agashe, Contino and Pomarol arXiv:0412089)
- Four fiveplets of fermions in the fundamental representation of $SO(5) \otimes U(1)_X$
- Partial compositness only with the 3th generation of quarks



- SM fermions
  - u, d, c, s, t, b
  - $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$
- Extra fermions
  - $8\ t'$, $8\ b'$ $\quad Q_{em} = \frac{2}{2}, -\frac{1}{3}$
  - $2\ \tilde{t}$, $2\ \tilde{b}$ $\quad Q_{em} = \frac{5}{3}, -\frac{4}{3}$

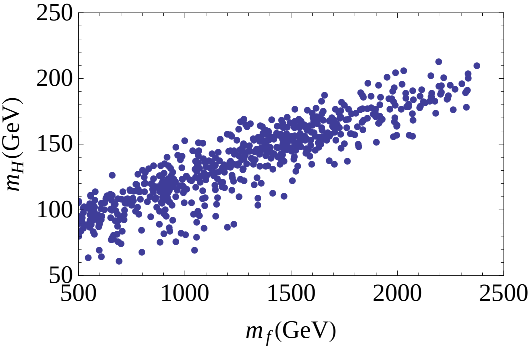
The 4DCHM

- The Higgs sector contains four pseudo Goldstone Bosons in the vector representation of $SO(4)$
- For the choice of the fermionic sector the potential is finite
- Coleman Weinberg potential generates the "mexican hat" $\rightarrow$ EWSB
- From the location of the minimum is possibile to extract m_H and $\langle h \rangle$



The 4DCHM

- For a natural choiche of the parameter of the model the Higgs mass is consistent with $125\,GeV$
- Light Higgs $\Longrightarrow$ Light fermionic partners



From De Curtis, Redi and Tesi (arXiv:1110.1613)

Implementation

- The particle spectrum is quite large

Leptons: $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$	Quarks: $T_{1,8}, B_{1,8}, \tilde{T}_{1,2}, \tilde{B}_{1,2}$
Quarks: u, d, c, s, t, b	Gauge Bosons: $Z'_{1,5}, W'_{1,3}$
Gauge Bosons: $\gamma, Z^0, W^\pm$	
Higgs Boson:H	
Gluons: g	

Gauge parameters: f, g_*
Fermionic parameters: $m_*, \Delta_{t_L}, \Delta_{t_R}, \Delta_{b_L}, \Delta_{b_R}, Y_B, Y_T, m_{Y_T}, m_{Y_B}$

- More than 3000 Feynman rules
- A non automated approach would have been impossible

Implementation

4D Composite Higgs Model implemented in numerical tools

- LanHEP: Package for the automatic generation of Feynman rules

  Semenov arXiv:1005.1909

- CalcHEP: Package for the automatic calculation of physical observables (cross sections, widths...)

  Belyaev, Christensen and Pukhov arXiv:1207.6082

- $gg \to H$ and $H \to \gamma\gamma$ vertices (without any approximation) also implemented
- Uploaded onto HEPMDB
  `http://hepmdb.soton.ac.uk`
  under the name 4DCHM(HAA+HGG)

Implementation

Outside LanHEP/CalcHEP tools scan over model parameters

- α, M_Z, G_F
- m_t, m_b
- m_H
- $Z_{b\bar{b}}$ coupling

Standalone Mathematica and/or AdScan (Brein arXiv:0407340) program perform scan

Output can be automatically read by CalcHEP to compute observables

Results

Parameter scan for the following model scales
(keeping $M_{Z'} \simeq 2TeV$)

- $f = 750$ GeV
- $f = 800$ GeV
- $f = 1000$ GeV
- $f = 1100$ GeV
- $f = 1200$ GeV

Other parameters varied between

- 500 GeV $\leq m_*, \Delta_{t_L}, \Delta_{t_R}, Y_T, m_{Y_T}, Y_B, m_{Y_B} \leq$ 5000 GeV
- 50 Gev $\leq \Delta_{b_L}, \Delta_{b_R} \leq$ 500 GeV (partial compositness spirit)

Results

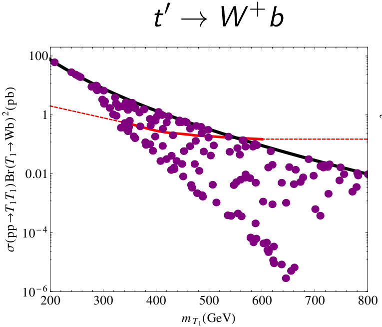
Limits on Z' and W'

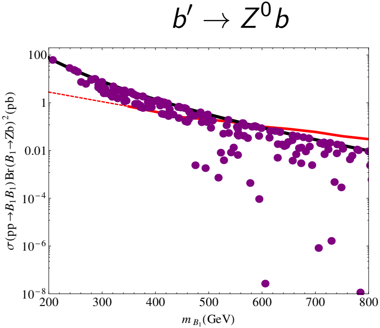
- From EWPT (mainly S parameter): $M_{Z',W'} \geq$1.5 TeV
- From LHC direct searches: no strong limits

Limits on t' and b'

- Assuming pair production @ 7 TeV LHC
  - CMS: $5fb^{-1}$, $Br(t' \to W^+ b) = 100\%$
  - CMS: $1.14fb^{-1}$, $Br(t' \to Zt) = 100\%$
  - CMS: $4.9fb^{-1}$, $Br(b' \to W^- t) = 100\%$
  - CMS: $5fb^{-1}$, $Br(b' \to Zb) = 100\%$
- Rescaling the Br to take in account real 4DCHM decay channels
- Limits on t' and b' $\simeq$ 400 GeV

Results





- Black line: Pair production cross section times 100% Br
- Red line: 95% CL observed limit
- Dotted red: extrapolation of experimental results
- Purple points: 4DCHM points
- Similar plots for other channels

Results

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

$$R_{YY} = \frac{\sigma(pp \to HX)_{4DCHM} \cdot Br(H \to YY)_{4DCHM}}{\sigma(pp \to HX)_{SM} \cdot Br(H \to YY)_{SM}}$$

$$YY = \gamma\gamma, b\bar{b}, W^+W^-, Z^0Z^0$$

Relevant production processes

$$gg \to H \;\; \text{gluon fusion} \qquad q\bar{q}(') \to VH \;\; \text{Higgs-strahlung}$$

At leading order

$$R_{YY} = \frac{\Gamma(H \to Y'Y')_{4DCHM} \cdot Br(H \to YY)_{4DCHM}}{\Gamma(H \to Y'Y')_{SM} \cdot Br(H \to YY)_{SM}}$$

Results

- Introduce reduced couplings a la LHC HXSWG (Denner et al arXiv:1209.0040)

$$\kappa^2_{b,g,\gamma,V} = \frac{\Gamma(H \to b\bar{b}, gg, \gamma\gamma, VV)_{4DCHM}}{\Gamma(H \to b\bar{b}, gg, \gamma\gamma, VV)_{SM}}$$

$$\kappa^2_H = \frac{\Gamma_{tot}(H)_{4DCHM}}{\Gamma_{tot}(H)_{SM}}$$

- We cast Rs in terms of κs

$$R^{Y'Y'}_{YY} = \frac{\kappa^2_{Y'}\kappa^2_Y}{\kappa^2_H}$$

Results

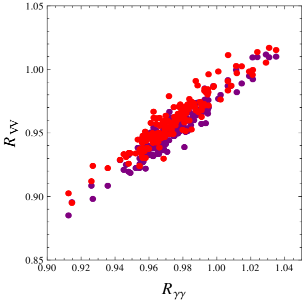
	ATLAS	CMS
$R_{\gamma\gamma}$	1.8 ± 0.4	$1.564^{+0.460}_{-0.419}$
R_{ZZ}	1.0 ± 0.4	$0.807^{+0.349}_{-0.280}$
R_{WW}	1.5 ± 0.6	$0.699^{+0.245}_{-0.232}$
$R_{b\bar{b}}$	-0.4 ± 1.0	$1.075^{+0.593}_{-0.566}$

LHC measurements from ATLAS and CMS

- For $YY = \gamma\gamma, WW, ZZ$ take $Y'Y' = gg$
- For $YY = b\bar{b}$ take $Y'Y' = VV$
- Results shown for a 1 TeV model scale

Results

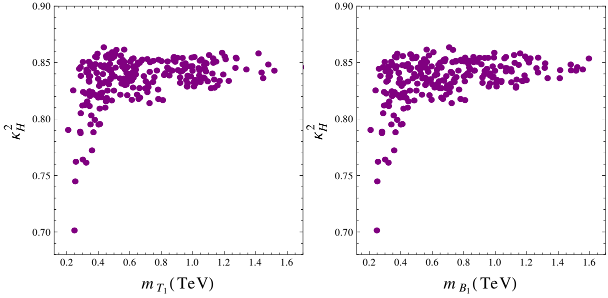
- Use $ZZ \to 4l$ and $WW \to 2l2\nu_l$
- Both points mostly below 1
- Few points above 1
- Strong correlation between the two



Red: WW Purple: ZZ

Results for κ_H

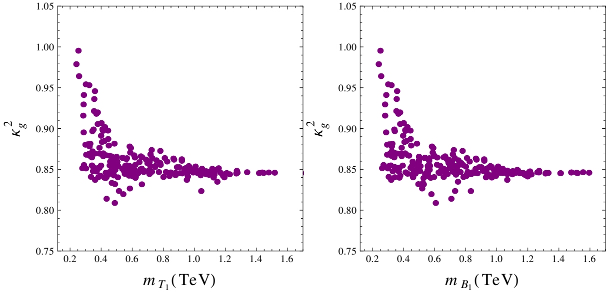
- $b - b'$ mixing $\Longrightarrow \kappa_H^2 < 1$



- Regions below $\simeq$ 400 GeV excluded by direct searches
- $\simeq$ 20% decrease with respect to the SM Higgs width

Results for κ_g

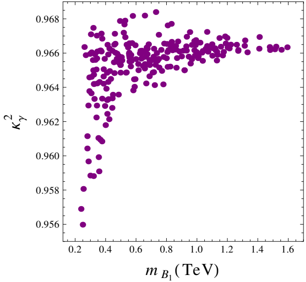
- $t - t'$ mixing $\Longrightarrow \kappa_g^2 < 1$
- t loop dominant

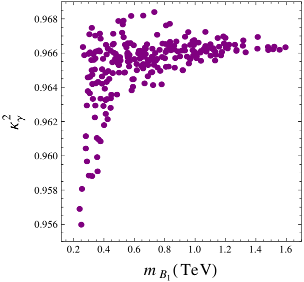


- Regions below $\simeq$ 400 GeV excluded by direct searches
- $\simeq$ 20% decrease with respect to the SM

Results for κ_γ

- $t - t'$ mixing $\Longrightarrow \kappa_\gamma^2 < 1$
- t loop subdominant, smaller effects



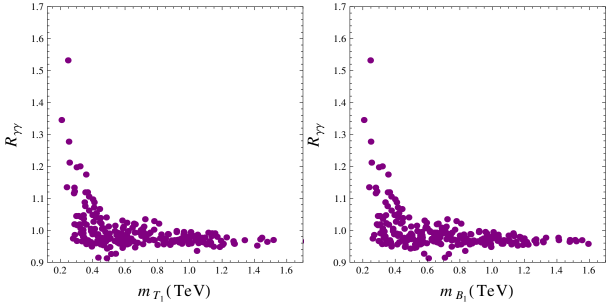


- Regions below $\simeq$ 400 GeV excluded by direct searches
- $\simeq$ 5% decrease with respect to the SM

Results for $R_{\gamma\gamma}$

- t' and b' masses play significant role
- $R_{\gamma\gamma}$ tend to be smaller than one
- Greater than one at smaller (but allowed) masses

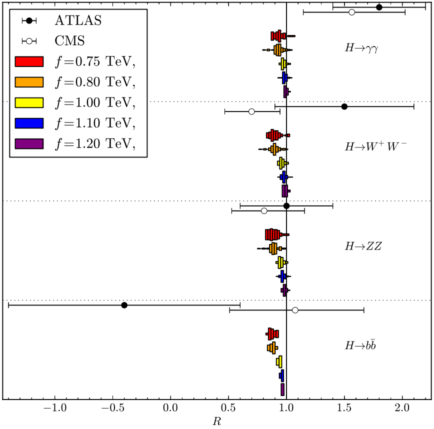
  $R_{YY}^{Y'Y'} = \frac{\kappa_{Y'}^2 \kappa_Y^2}{\kappa_H^2}$
- Difference with respect to the asymptotic results $\simeq 10\%$



- Regions below $\simeq$ 400 GeV excluded by direct searches

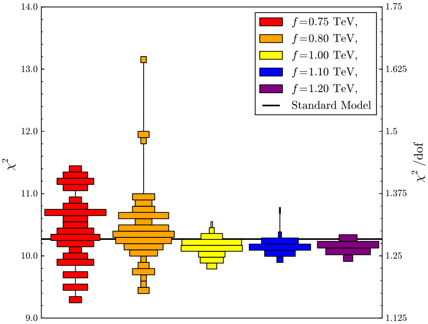
Results

- Comparing to SM and to data
- Showing only points compliant with direct searches



Results

- Performing χ^2
- 4DCHM could fit better than the SM
- Showing only points compliant with direct searches



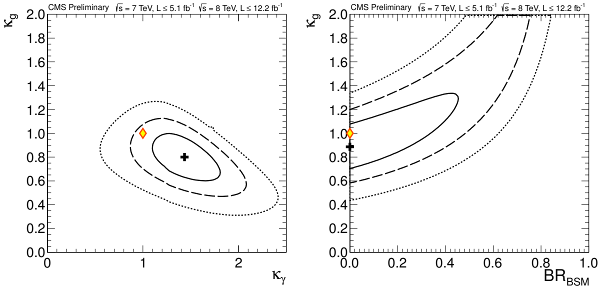
Conclusions

- 4DCHM could provide an alternative explanation than the SM to LHC data pointing to Higgs discovery at $\simeq$ 125 GeV
- Parameter space scan show possible (moderate) enhancement in $H \to \gamma\gamma$, that is $R_{\gamma\gamma} \simeq$1.1
- If t' and b' below results of our extrapolation $R_{\gamma\gamma}$ could be greater
- Revisit t' and b' searches in 4DCHM dependent way (can use HPC behind HEPMDB)
- 4DCHM (and general Composite Higgs model) main effect is the reduction of $\Gamma_{tot}(H)$ due to $b - b'$ mixing
- Also $H \to gg$ reduced so $H \to \gamma\gamma$ almost stable
- Reduction of $\Gamma_{tot}(H)$ (common to other BSM models) calls for LHC couplings fit with $\kappa_H \leq 1$
- Interesting: approximation assuming t' and b' infinitely massive is not totally accurate
- Composite Higgs interesting with respect to LHC data and wanting light fermionic partners

Thank you for the attention!

Outlook

- Atlas and CMS allow for $\kappa_H \geq 1$
- Need κ_H <1 in Composite Higgs model (also useful for other BSMs)

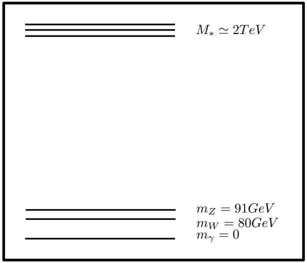


The 4DCHM

Gauge sector parameter

- $f \simeq 1 TeV$
- g_*

Bosonic sector mass spectrum



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

$$M_*^2 \simeq f^2 g_*^2$$

$$tan(\theta) = g_0 / g_*$$

$$tan(\psi) = g_{0y} / g_*$$

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

$$v = \langle h \rangle = 246 GeV$$

Unitary gauge

- $\Phi = \Omega \phi_0$
- Link fields $\Omega = \mathbf{1} + i\frac{s}{h}\Pi + \frac{c-1}{h^2}\Pi^2$

$$s = \sin(h/2f^2) \quad c = \cos(h/2f^2) \quad h = \sqrt{h^{\hat{a}} h^{\hat{a}}}$$

Identiy $\Pi = \sqrt{2} h^{\hat{a}} T^{\hat{a}}$ GBmatrix and $T^{\hat{a}}$ broken generators of $SO(5)/SO(4)$

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

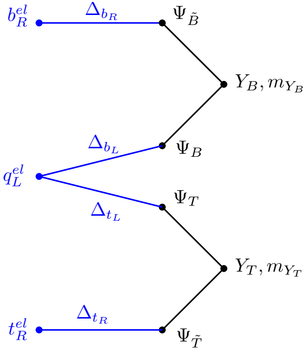
Relate **h** to the SM Higgs doublet

$$H = \frac{1}{\sqrt{2}} \left(\begin{array}{c} -ih_1 - h_2 \\ -ih_3 + h_4 \end{array} \right).$$

The 4DCHM

- The gauge contribution itself can't misalign the vacuum
  New fermionic sector is needed

  (Agashe, Contino and Pomarol arXiv:0412089)
- Fermions are embedded in fundamental representation of $SO(5) \otimes U(1)_X$
- Four fiveplet of new fermions are introduced
- Partial compositness only with the 3th generation of quarks



$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{el} \\
&+ \Delta_{t_L} \bar{q}_L \Omega_1 \Psi_T + \Delta_{t_R} \bar{t}_R \Omega_1 \tilde{\Psi}_T \\
&+ \bar{\Psi}_T (i \not{D} - m_*) \Psi_T + \bar{\tilde{\Psi}}_T (i \not{D} - m_*) \tilde{\Psi}_T \\
&- Y_T \bar{\Psi}_{T,L} \Phi^\dagger \Phi \tilde{\Psi}_T - m_{Y_T} \bar{\Psi}_{T,L} \tilde{\Psi}_{T,R} \\
&+ (T \to B)
\end{aligned}
$$

Fermion charge

$$\Psi_{T,B} \propto \begin{pmatrix} iQ_u + iq_d \\ q_d + Q_u \\ iQ_d - iq_u \\ q_u + Q_d \\ \sqrt{2}\chi \end{pmatrix}$$

- $Y = T^{3R} + X \quad Q = T^{3L} + Y$
- Quantum numbers for the fermions in the fundamental representation of $SO(5) \otimes U(1)_X$

$\mathbf{5}_{\frac{2}{3}}$	T_{3L}	Y	Q	T_{3R}
Q_u	$\frac{1}{2}$	$\frac{7}{6}$	$\frac{5}{3}$	$\frac{1}{2}$
Q_d	$-\frac{1}{2}$	$\frac{7}{6}$	$\frac{2}{3}$	$\frac{1}{2}$
q_u	$\frac{1}{2}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{2}$
q_d	$-\frac{1}{2}$	$\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
χ	0	$\frac{2}{3}$	$\frac{2}{3}$	0

$\mathbf{5}_{-\frac{1}{3}}$	T_{3L}	Y	Q	T_{3R}
Q_u	$\frac{1}{2}$	$\frac{1}{6}$	$\frac{2}{3}$	$\frac{1}{2}$
Q_d	$-\frac{1}{2}$	$\frac{1}{6}$	$-\frac{1}{3}$	$\frac{1}{2}$
q_u	$\frac{1}{2}$	$-\frac{5}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
q_d	$-\frac{1}{2}$	$-\frac{5}{6}$	$-\frac{4}{3}$	$-\frac{1}{2}$
χ	0	$-\frac{1}{3}$	$-\frac{1}{3}$	0

The 4DCHM

Working out the quantum numbers

$$Q_{em}(\Psi_T) = \frac{5}{3}, \frac{2}{3}, -\frac{1}{3}$$
$$Q_{em}(\Psi_B) = \frac{2}{3}, -\frac{1}{3}, -\frac{4}{3}$$

SM fermions	Extra fermions
u, d, c, s, t, b	$8\ t', 8\ b'$
$e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$	$2\ \tilde{t}, 2\ \tilde{b}$

SM fermions and extra fermions fields usually referred to as elementary and composite states

Fermion masses (an example)

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

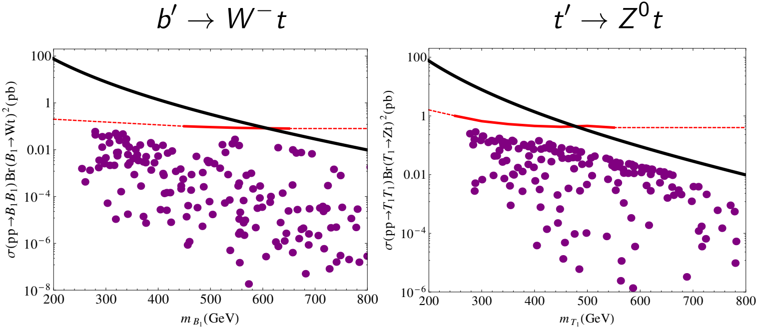
$$m_b^2 \propto \xi \frac{m_*^2}{2} \tilde{\Delta}_{b_L}^2 \tilde{\Delta}_{b_R}^2 \tilde{Y}_B^2$$

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

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

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

Results



- Black line: Pair production cross section times 100% Br
- Red line: 95% CL observed limit
- Dotted red: extrapolation of experimental results
- Purple points: 4DCHM points

Higgs Couplings

Defining $\quad \Omega_n = \mathbf{1} + \delta\Omega_n$

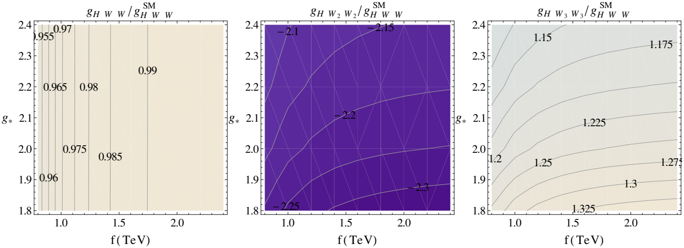
$$\begin{aligned}\mathcal{L}_{gauge,H} =& - f^2 g_0 g_* Tr\left[\tilde{W}\delta\Omega\tilde{A} + \tilde{W}\tilde{A}\delta\Omega^T + \tilde{W}\delta\Omega\tilde{A}\delta\Omega^T\right] \\ &+ f^2 g_*^2\left[\phi_0^T\delta\Omega^T\tilde{A}\tilde{A}\phi_0 + \phi_0^T\tilde{A}\tilde{A}\delta\Omega\phi_0 +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

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

- Expanding $\delta\Omega$ to extract $g_{HV_iV_j}$ and $g_{Hf_i\bar{f}_j}$
- Couplings to mass egeinstates obtained after diagonalization

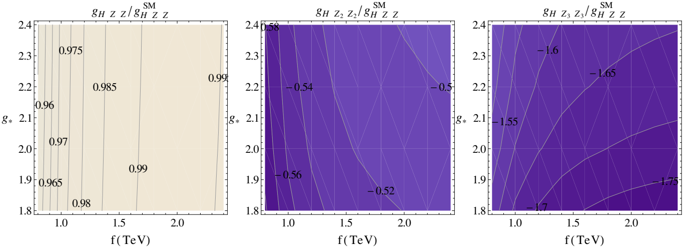
Higgs-Vector Couplings

- Consider HW_iW_i charged coupling
- Normalized to SM HW^+W^- value



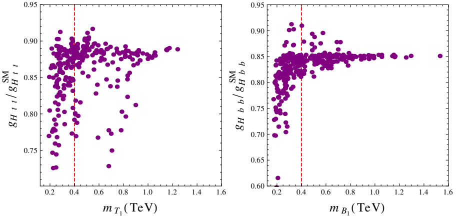
Higgs-Vector Couplings

- Consider HZ_iZ_i neutral coupling
- Normalized to SM HZ^0Z^0 value



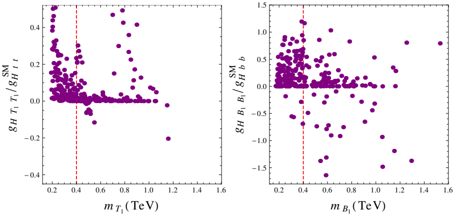
Higgs-fermions Couplings

- Consider *Htt* and *Hbb* coupling
- Normalized to SM value



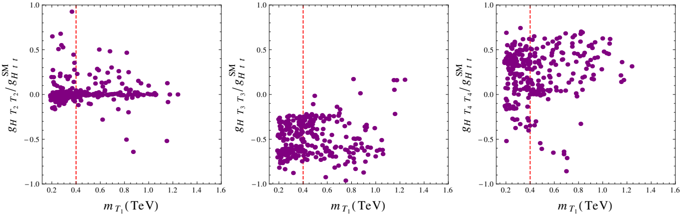
Higgs-fermions Couplings

- Consider HT_1T_1 and HB_1B_1 coupling
- Normalized to SM value



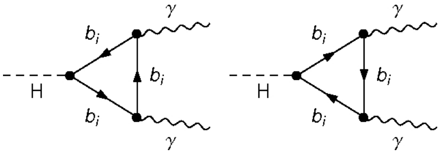
Higgs-fermions Couplings

- Consider HT_2T_2,HT_3T_3 and HT_4T_4
- Normalized to SM value

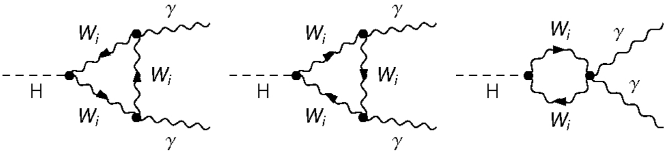


Loop calculations

- Loop Diagrams involving extra fermions and gauge bosons



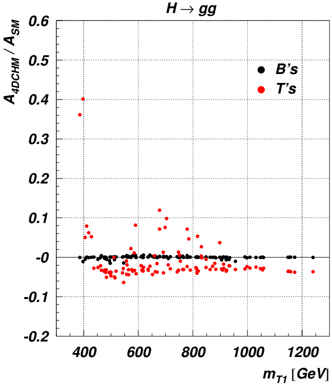
$H \to \gamma\gamma$ induced by fermionic loop

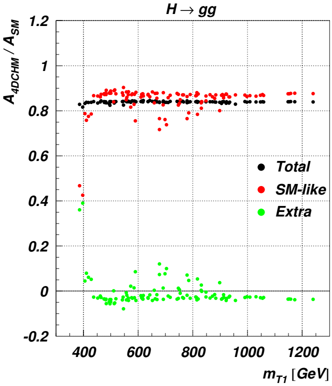


$H \to \gamma\gamma$ induced by charged vector loop

Loop effects

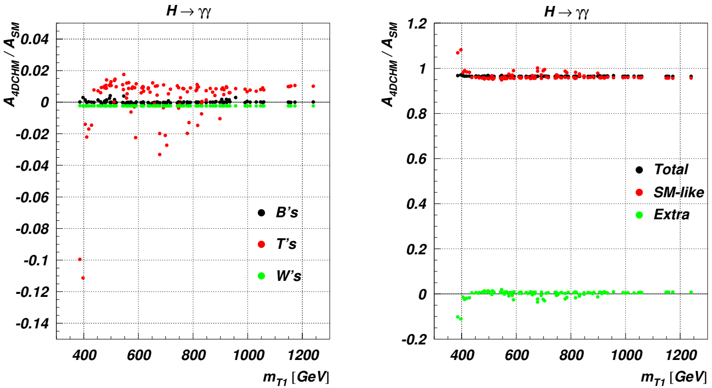
- Loop compensation between SM-like and Extra quarks for $H \to gg$





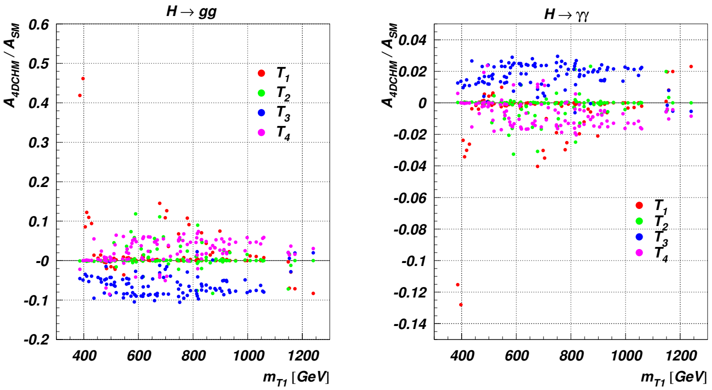
Loop effects

- Loop compensation between SM-like and Extra quarks for $H \to \gamma\gamma$



Loop effects

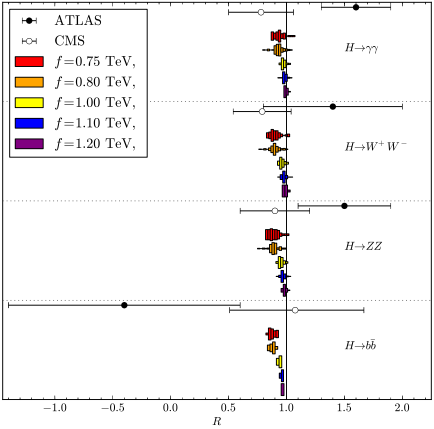
- Loop cancellations between extra quarks $H \to gg$ and $H \to \gamma\gamma$



Results

Post Moriond data

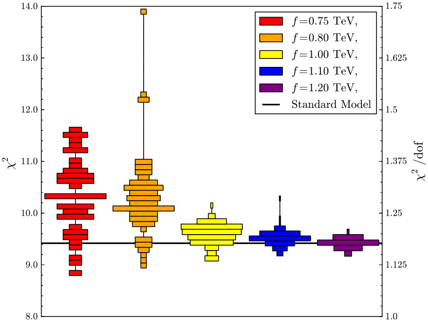
- Comparing to SM and to data
- Showing only points compliant with direct searches



Results

Post Moriond data

- Performing χ^2
- 4DCHM fit comparable with SM fit
- Showing only points compliant with direct searches



Results

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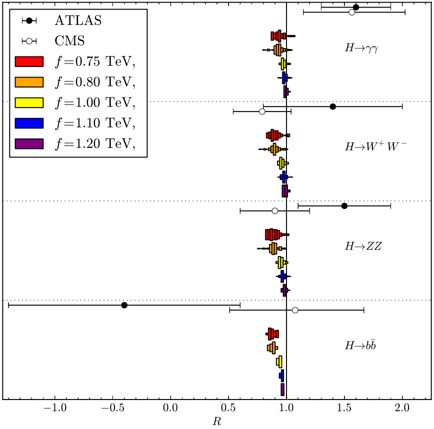

Results

Post Moriond data

- Performing χ^2
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