Minimal Composite Higgs at the LHC

Marcela Carena
Fermilab and U. of Chicago

IFT Workshop HEFT2014, Madrid, September 30th, 2014

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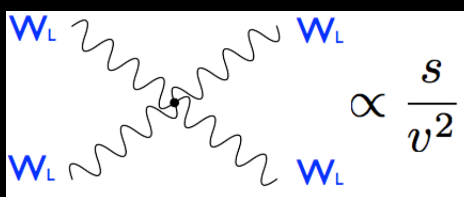
New Physics beyond the SM is needed to explain many observed phenomena

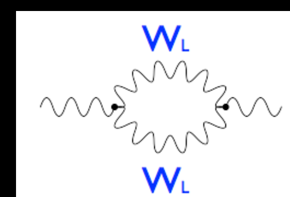
[Dark matter, matter-antimatter asymmetry, dynamical origin of fermion masses, mixings, CP violation,…]

- But none of the above demands NP at the EW

Before the Higgs discovery, we knew that some new phenomena had to exist at the EW scale, otherwise:

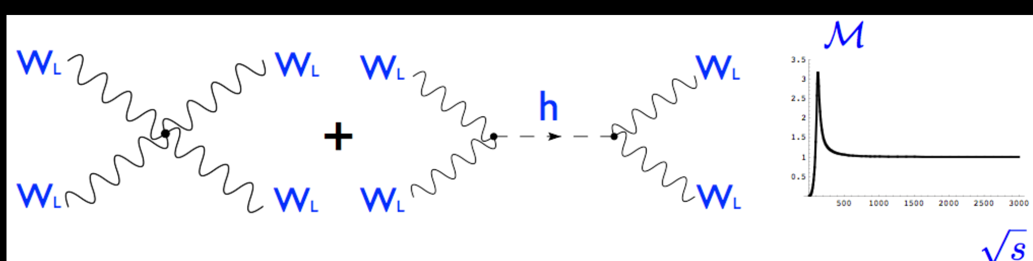


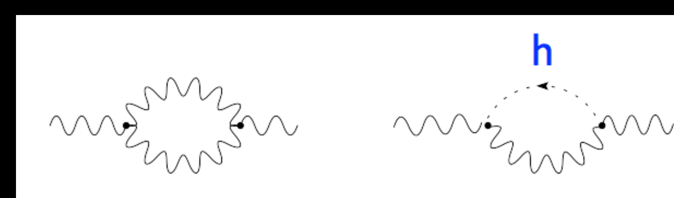
Unitarity lost at high energies



Loops are not finite

•The Higgs restores the calculability power of the SM





Loops are finite

Should we expect New Physics close to the TeV scale?

• The Higgs is special : it is a scalar

At quantum level scalar masses have quadratic sensitivity to UV physics

$$\mathcal{L} \propto m^2 |\phi|^2 \qquad\qquad \delta \mathbf{m^2} = \sum_{\mathbf{B,F}} \mathbf{g_{B,F}} (-1)^{\mathbf{2S}} \frac{\lambda^{\mathbf{2}}_{\mathbf{B,F}} \mathbf{m^2_{B,F}}}{\mathbf{32}\pi^{\mathbf{2}}} \log(\frac{\mathbf{Q^2}}{\mu^{\mathbf{2}}})$$

Although the SM with the Higgs is a consistent theory,
light scalars like the Higgs cannot survive
in the presence of heavy states at GUT/String/Planck scales

Fine tuning ⟷ **Naturalness problem**

Composite Higgs Models:

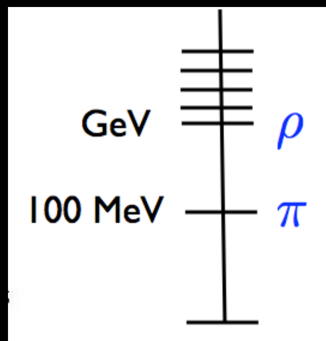
The Higgs does not exist above a certain scale, at which the new strong dynamics takes place ➔ dynamical origin of EWSB

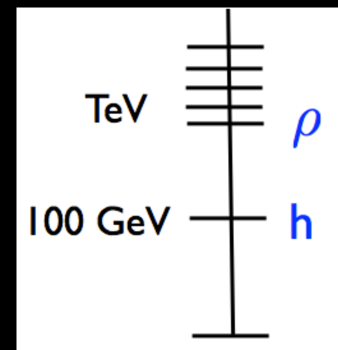
New strong resonance masses constrained by PEWT and direct searches

Higgs ➔ scalar resonance much lighter that other ones

Composite Higgs Models
The Higgs as a pseudo Nambu-Goldstone Bosons (pNGB)

Inspired by pions in QCD





QCD with 2 flavors: global symmetry $SU(2)_L \times SU(2)_R / SU(2)_V$.

π^{+-} π^0 are Goldstones associated to spontaneous breaking

$$g, g' \to 0 \quad \& \quad m_q \to 0 \quad \Rightarrow m_\pi = 0$$

$$m_q \neq 0 \Rightarrow m_\pi^2 \simeq m_q B_0$$

$$e \neq 0 \Rightarrow \delta m_{\pi^\pm}^2 \simeq \frac{e^2}{16\pi^2} \Lambda_{QCD}^2$$

Higgs is light because is the pNGB -- a kind of pion – of a new strong sector

Mass protected by the global symmetries

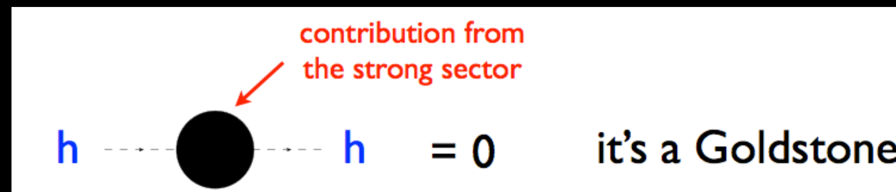
$\pi \rightarrow \pi + \alpha$

Georgi,Kaplan'84; Agashe et al '03

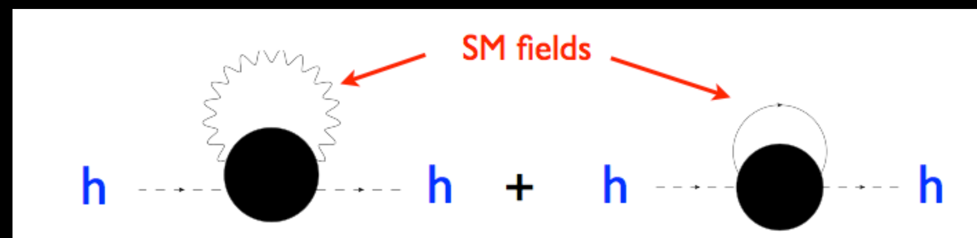
Higgs as a PNGB

Light Higgs since its mass arises from one loop

Higgs mass protected by global symmetry



Mass generated at one loop: explicit breaking of global symmetry due to SM couplings



Dynamical EWSB: large set of vacua, some of them break $SU(2)_L \times U(1)_Y$

V(h) depends on the chosen global symmetry AND on the fermion embedding

Higgs mass challenging to compute due to strong dynamics behavior

$$m_H^2 \approx m_t^2 M_T^2 / f^2$$

Higgs as a PNGB

Choosing the global symmetry G broken down to H at the scale f

- The SM EW group G_{SM} must be embeddable in the unbroken subgroup H
- G/H contains at least one $SU(2)_L$ doublet to be identified with the Higgs one

Simplest case: just G_{SM} is gauged by external vector bosons

Pattern of Symmetry breaking

$$\text{gauge:} \quad SU(2)_L \times U(1)_Y \longrightarrow U(1)_Q$$

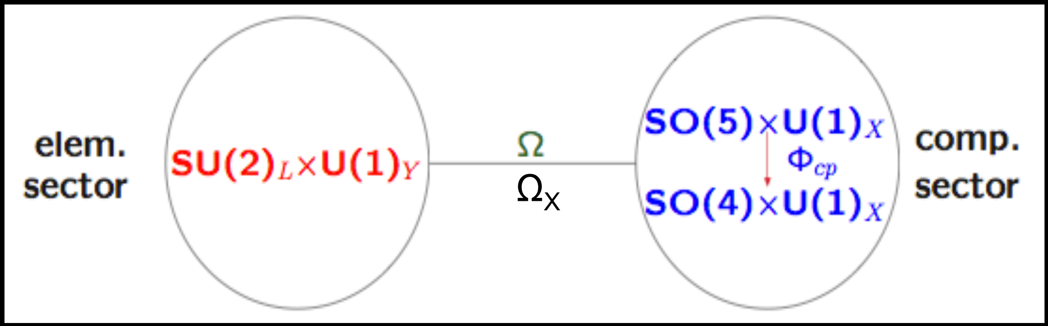
$$\uparrow \qquad\qquad\qquad \uparrow$$

$$\text{global:} \quad SO(5) \underset{E\sim f}{\rightarrow} SU(2)_L \times SU(2)_R \underset{E\sim v}{\rightarrow} SU(2)_V \ \text{custodial}$$

SO(5) ×U(1) smallest group: ⊃ G^{EW}_{SM} & cust. sym. & H = pNGB

Minimal pNGB Higgs Models

Effective description: 2 site model ➔ elementary/composite



Contino et al. ; Redi et al.
de Curtis et al.

non-linear σ-model fields Ω , Ω_X connecting sites and providing mixing between elementary and composite fermions

$$\mathcal{L} = \mathcal{L}_{el} + \mathcal{L}_{mix} + \mathcal{L}_{cp}$$

$$\mathcal{L}_{el} = \mathcal{L}_{SM}(\psi_L^{el}, \tilde{\psi}_R^{el}, A_\mu^{el})$$

$$\mathcal{L}_{cp}^{eff} = -\frac{1}{4} F_{\mu\nu}^{cp\ 2} + \bar{\psi}^{cp}(i\not{D}^{cp} - M_{cp})\psi^{cp} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{GB}$$

Local symmetry G_{SM}
massless fermions

No elementary Higgs

Each chiral SM-fermion $\rightarrow$ vector-like cp-fermion

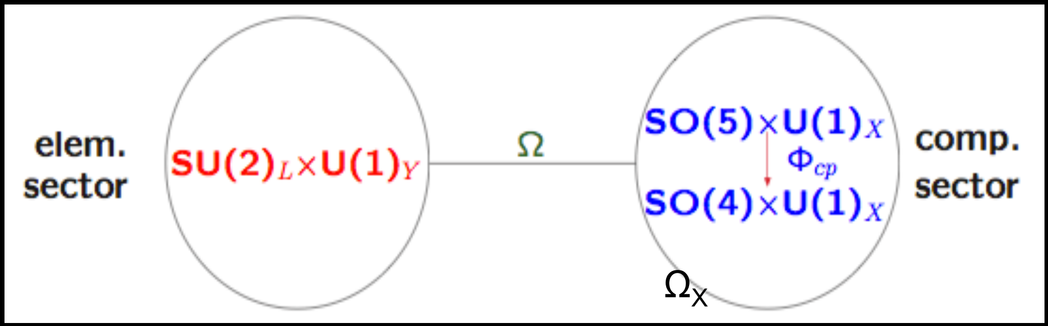
Spontaneous breaking parametrized by Φ^{cp}

Composite-sector characterized by a coupling $g_{cp} \gg g_{SM}$ and scale f ~ TeV

New heavy resonances ➔ $m_\rho \sim g_\rho f$ and $M_{cp} \sim m_\rho \cos_\psi$

Minimal pNGB Higgs Models

Effective description: 2 site model ➔ elementary/composite



Contino et al. ; Redi et al.
de Curtis et al.

non-linear σ-model field connecting sites $\Omega \longrightarrow g_{el}\Omega g_{cp}^{\dagger}$

$$\mathcal{L} = \mathcal{L}_{el} + \mathcal{L}_{mix} + \mathcal{L}_{cp}$$

$$\mathcal{L}_{mix}^{eff} \supset \frac{f_\Omega{}^2}{4}\mathrm{tr}|D_\mu\Omega|^2 + \bar{\psi}_L^{el}\Delta\Omega\mathcal{P}_\psi\psi_R^{cp} + \bar{\tilde{\psi}}_R^{el}\tilde{\Delta}\Omega\mathcal{P}_{\tilde{\psi}}\tilde{\psi}_L^{cp}$$

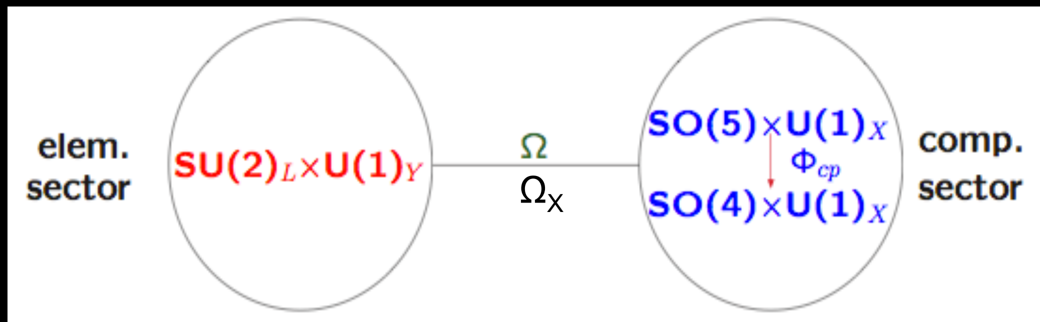
Partial compositness

small numbers from small mixings $\Delta, \tilde{\Delta}$ (*e.g.*: light fermions)

mixing angle: $\tan\theta_\psi = \frac{\Delta}{M_{cp}}$

Minimal pNGB Higgs Models

Effective description: 2 site model ➔ scalar sector



Contino et al. ; Redi et al.
de Curtis et al.

- $\Phi_{cp} = e^{i\Pi_{cp}/f_{cp}}(0,0,0,0,1)^t$, $\Pi = \sum_{\hat{a}=1,\ldots 4} \Pi^{\hat{a}} T^{\hat{a}}$, $T^{\hat{a}}$ **broken generators**
- $\Omega = e^{i\Pi_\Omega/f_\Omega}$, $\Pi_\Omega = \sum_{a=1,\ldots 10} \Pi^a_\Omega T^a$
- **in unitary gauge, before EWSB:** $\Phi = \frac{1}{h} \sin\frac{h}{f}(h_1, h_2, h_3, h_4, h \cot\frac{h}{f})^t$

  the other GB's provide longitudinal massive vectors
- **after EWSB:** $<h> = v \Rightarrow \langle\Phi\rangle = (0,0,0,\epsilon,\sqrt{1-\epsilon^2})^t$

$$\mathbf{h}^2 = \sum_{\hat{a}} h^{\hat{a}} h^{\hat{a}}$$

- **new parameter:** $\epsilon = \sin\frac{v}{f}$

Model Building

Based on the 1,5,10 and 14 Representations of SO(5)

In the unitary gauge

$$\mathcal{L}_f = \sum_{\psi=q_L,u_R,d_R} Z_\psi \bar{\psi} i \not{D} \psi + \bar{q}_L \Delta_q Q_R + \bar{u}_R \Delta_u U_L + \bar{d}_R \Delta_d D_L + \text{h.c.}$$
$$+ \sum_{\Psi=Q,U,D} \bar{\Psi}(i\not{D} - m_\Psi)\Psi + m_{y_u} \bar{Q}_L U_R + m_{y_d} \bar{Q}_L D_R + \mathcal{L}_y(Q_L, U_R, D_R, \Phi) + \text{h.c.}$$

- **The explicit form of the pNGB interactions with the composite fermions (proto-Yukawa terms) depend on the embedding**

$\mathbf{Z}b\bar{b}$ couplings are measured with great accuracy and the large value of mt requires large mixing that impacts the bottom sector and can generate large corrections

Choose proper reps. to protect Z couplings

$\Rightarrow$ t_L **embedded in** $5_{2/3}, 10_{2/3}, 14_{2/3}$**, . . . of SO(5)×U(1)**

With Notation $\text{MCHM}_{\text{Q-U-D}}$ →

5, 10,
5-5-10, 5-10-10, 10-5-10
14-14-10, 14-1-10

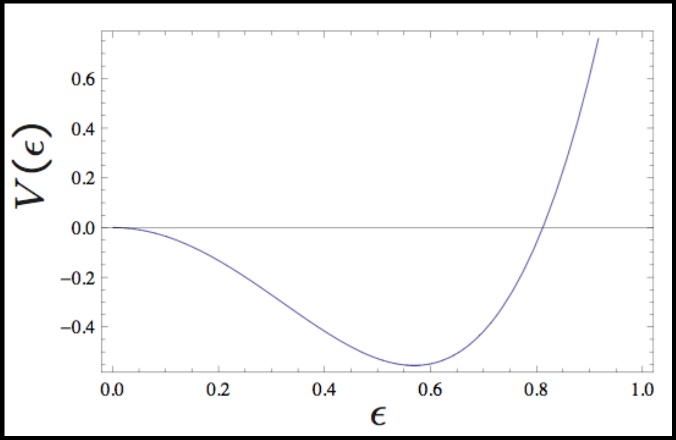
Electroweak Symmetry Breaking

- We constrain their chiral structure to obtain a finite one-loop Higgs potential
  only left and right composite fields that mixed with SM ones are present

Dynamical EWSB: large set of vacua, some of them break $SU(2)_L \times U(1)_Y$

W and Z : vacuum alignment ➔ no EWSB

Top and bottom : vacuum missalignment ➔ can induce EWSB



$$v_{SM} \simeq \epsilon f$$

$V(H)$ **depends on fermion embbeding:**

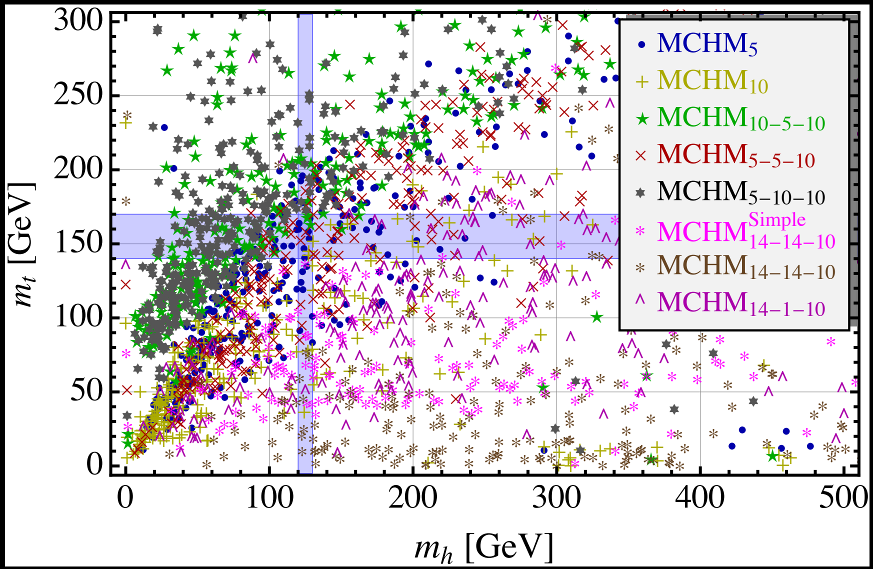
The Higgs potential can be computed using general properties on the asymptotic behavior of correlators or using the standard CW potential in terms of Higgs dependent gauge and fermion mass matrices

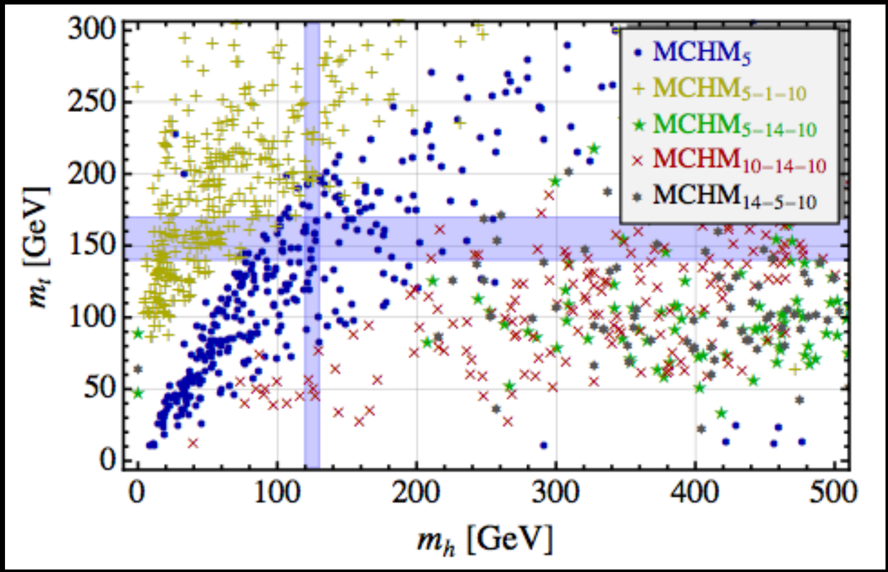
It is possible to estimate the Higgs mass

Marzoca, Serone, Shu'12,
Pomarol, Riva '12
MC, Da Rold, Ponto' 14

EWSB and the Higgs Mass: Numerical Scan

- We consider many different SO(5) fermion embeddings
- Random scan over a subset of physical masses, taking into account the elementary/composite mixing effects; including off diagonal masses and proto-Yukawas in the fermionic sector (perturbative)
- We require $\varepsilon = v_{SM}/f < 0.5$ ➔ PEWT, which implies f > 500 GeV
- W also require $m_\rho \sim g_\rho$ f > 2 TeV





Models in 14 representation tend to give too large mh

M.C., Da Rold, Ponton'14

HIGGS PHENOMENOLGY

Operators involved in Higgs production and decays at LHC

- Gluon fusion: $\mathcal{O}_g = hG_{\mu\nu}G^{\mu\nu}$
- photon decay: $\mathcal{O}_\gamma = hF_{\mu\nu}F^{\mu\nu}$
- Zγ decay: $hZ\gamma$: $\mathcal{O}_{hZ\gamma} = hF_{\mu\nu}Z^{\mu\nu}$
- VFB + VH: $\mathcal{O}_V = hV_\mu V^\mu$
- fermionic decays $\mathcal{O}_f = h\bar{f}f$

Two equivalent ways to compute Higgs couplings:

Obtain effective theory in elementary site and use i) zeroes of the correlators to find the spectrum and ii) info encoded in correlator's vev dependence for couplings.

Or just compute the gauge and fermions mass matrices including composite and elementary states and their mixings

$$\mathrm{g}_{hWW}^{(0)} \simeq \partial m_W^{2^{(0)}} / \partial v = F(\epsilon)$$

Higgs couplings to W/Z determined by the gauge groups involved

MCHM_X → SO(5)/SO(4)

$$\mathbf{y}_\psi^{(0)} \simeq \partial m_\psi^{(0)} / \partial v \qquad \psi = u, d$$

Higgs couplings to SM fermions depend on fermion embedding X

Giudice, Grojean, Pomarol Rattazzi'07
Pomarol, Riva'12; Montull, Riva, Salvioni, Torre'13

Gluon Fusion Effects

- Corrections come from explicit breaking: elementary/composite sectors mixing
- Corrections to gluon fusion from heavy resonances and deviations in SM Yukawas

$$\mathcal{A}(h \to gg) \;\propto\; v_{\rm SM} \sum_{\psi=t,b} \left\{ \frac{4}{3}\left[{\rm tr}(Y_\psi M_\psi^{-1}) - \frac{y_\psi^{(0)}}{m_\psi^{(0)}} \right] + \frac{y_\psi^{(0)}}{m_\psi^{(0)}} A_{1/2}\left(\frac{m_h^2}{4 m_\psi^{(0)\,2}} \right) \right\}$$

Heavy resonances are subleading: sum rule from pNBG Higgs nature

Falkowski'07;Azatov et al '11

$$\mathbf{r}_g^{\psi} \approx \sum_n \frac{y_\psi^{(n)}}{m_\psi^{(n)}} = Tr[Y_\psi M_\psi^{-1}] = \frac{F_\psi(\epsilon)}{\epsilon f}$$

Indep. of other model param.

Interesting: at leading order in ε, zero mode saturates the sum

$$\frac{y_\psi^{(0)}}{m_\psi^{(0)}} \approx \frac{1}{\epsilon f_h}\left[F_\psi(\epsilon) + \mathcal{O}(\epsilon^2 s_{\psi_L}^2) + \mathcal{O}(\epsilon^2 s_{\psi_R}^2) \right]$$

Yukawa corrections $\frac{\mathbf{y}_\psi^{(\mathbf{0})}}{\mathbf{y}_\psi^{\mathbf{SM}}}$

The mixing of both chiralities needs to be small to ensure extra suppression factors

Bottom sector corrections larger than expected

Montull et al'13; MC, Da Rold, Ponton'14

Higgs Production and Decays

Tree level decays:

$$\Gamma(h \to b\bar{b}, \tau\tau) \approx \Gamma_{\rm SM}(h \to b\bar{b}, \tau\tau) \times r_b^2(\epsilon) \; ,$$
$$\Gamma(h \to c\bar{c}) \approx \Gamma_{\rm SM}(h \to c\bar{c}) \times r_c^2(\epsilon) \; ,$$
$$\Gamma(h \to WW, ZZ) \approx \Gamma_{\rm SM}(h \to WW, ZZ) \times r_V^2(\epsilon)$$

Assumed τ leptons in same reps. as b quarks and

$$r_c(\epsilon) = r_t(\epsilon)$$

Loop level Higgs decays

$$\frac{\Gamma(h \to gg)}{\Gamma_{\rm SM}(h \to gg)} \approx \frac{|r_t(\epsilon)\, A_{1/2}(m_h^2/4m_t^2) + r_b(\epsilon)\, A_{1/2}(m_h^2/4m_b^2)|^2}{|A_{1/2}(m_h^2/4m_t^2) + A_{1/2}(m_h^2/4m_b^2)|^2}$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{\rm SM}(h \to \gamma\gamma)} \approx \frac{|r_V(\epsilon)\, A_1(\frac{m_h^2}{4m_W^2}) + N_c Q_t^2\, r_t(\epsilon)\, A_{1/2}(\frac{m_h^2}{4m_t^2}) + N_c Q_b^2\, r_b(\epsilon)\, A_{1/2}(\frac{m_h^2}{4m_b^2})|^2}{|A_1(m_h^2/4m_W^2) + N_c Q_t^2 A_{1/2}(m_h^2/4m_t^2) + N_c Q_b^2 A_{1/2}(m_h^2/4m_b^2)|^2}$$

In the case of the top we effectively considered the full effect of the heavy resonances plus the top itself. For the bottom sector we neglect the resonances that can be as large at the bottom quark itself ; max 10% effect, usually less.
We consider all effects in the parameter scan

Summary of corrections to couplings

Define: $r_X = c_x^{MCHM} / c_x^{SM}$

$F_1(\varepsilon)$ and $F_2(\varepsilon)$ codify most deviations at leading order
other functions have nontrivial dep. on the proto-Yukawas

$$F_1 = \frac{1-2\epsilon^2}{\sqrt{1-\epsilon^2}}$$ $$F_2 = \sqrt{1-\epsilon^2}$$

r/ MCHM	10-5-10	5-5-10	5-10-10, 5-1-10	5, 10, 14-1-10 14-10-10 10-14-10	14-14-10	14-5-10	5-14-10
r_t	F_2	F_1	F_2	F_1	F_3	F_4	F_5
r_b	F_1	F_2	F_2	F_1	F_1	F_1	F_1
r_V	F_2	F_2	F_2	F_2	F_2	F_2	F_2
r_g	F_2	F_1	F_2	F_1	F_3	F_4	F_5

r_γ depends on multiple (two) functions

W contribution: $r_\gamma^W = F_2$ top contribution : $r_\gamma^\Psi = r_g^\Psi$

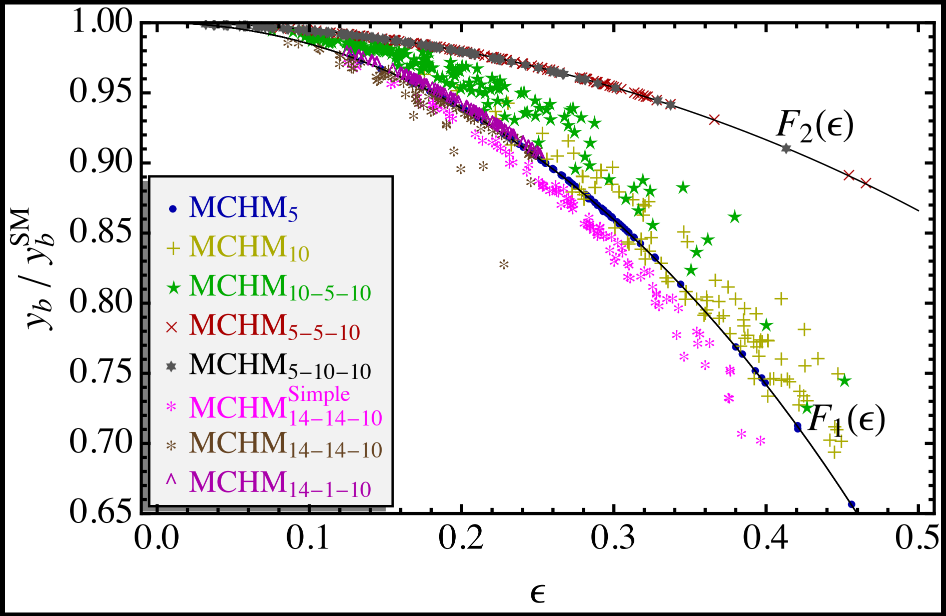
HIGGS PHENOMENOLGY:

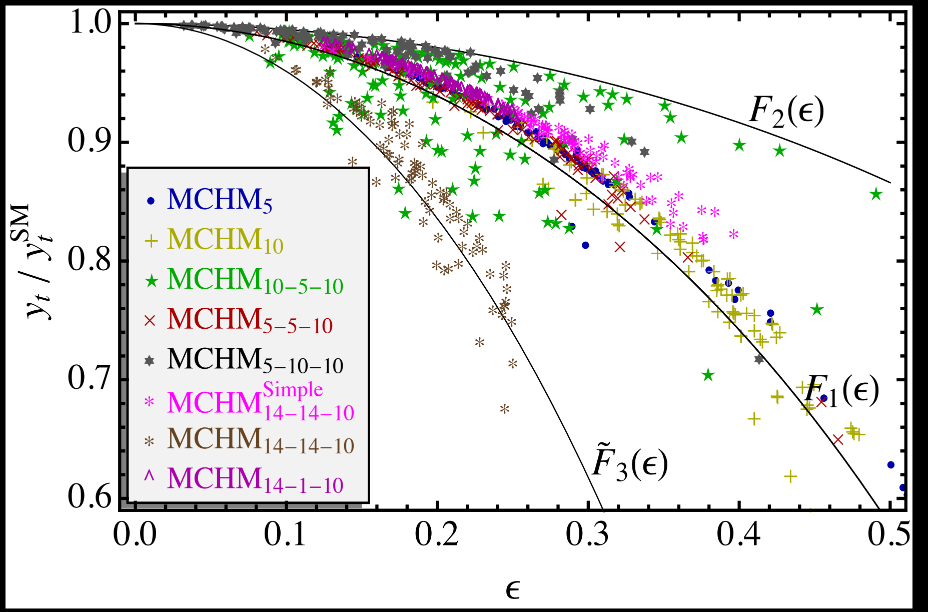
Main effects due to SM fermions and gauge bosons mixing with composite fermion and gauge boson sectors, respectively

Minimal effects from heavy/strong resonance effects in the loops

Generic features: Suppression of all partial decay widths

Higgs to bb and tt suppression





Suppression on HVV coupling ~ $F_2(\varepsilon)$

M.C., Da Rold, Ponton '14

HIGGS PHENOMENOLGY (cont'd)

Main effects due to SM fermions and gauge bosons mixing with composite fermion and gauge boson sectors, respectively

Minimal effects from heavy/strong resonance effects in the loops

Generic features:

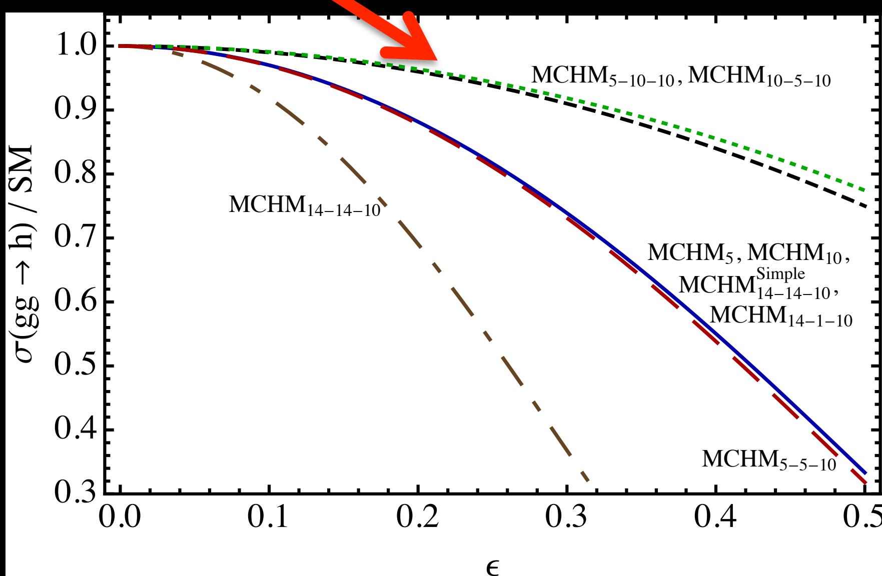
Higgs-gluon fusion and VVH/VH suppression

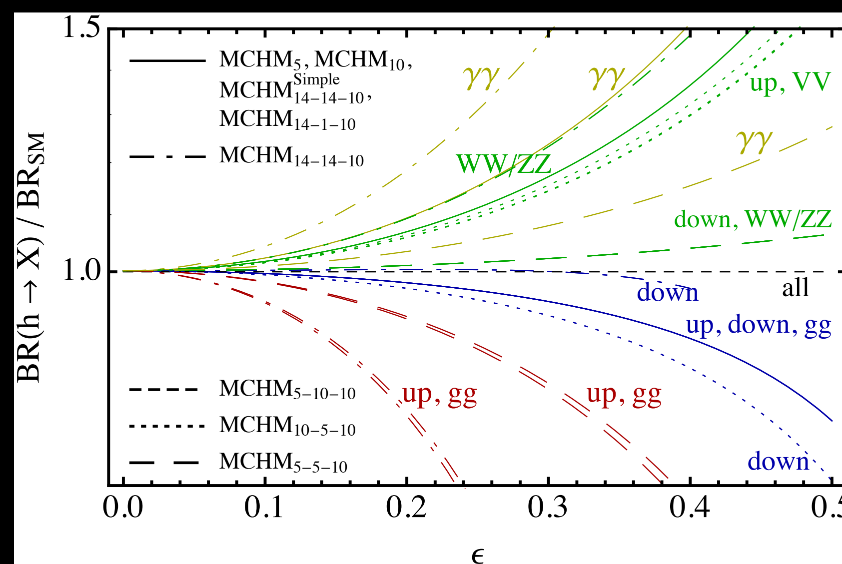
Enhancement or suppression of branching ratios

(Depending on the effct of the total width suppression)

σ(VVH/VH)/σ_{SM}

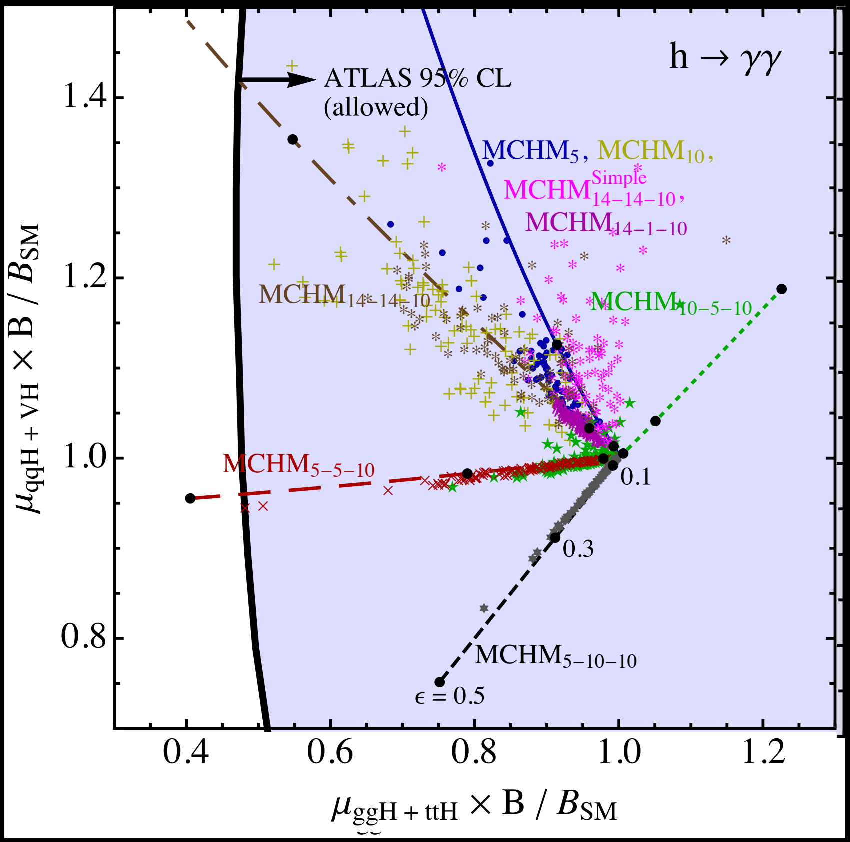
M.C., Da Rold, Ponton '14



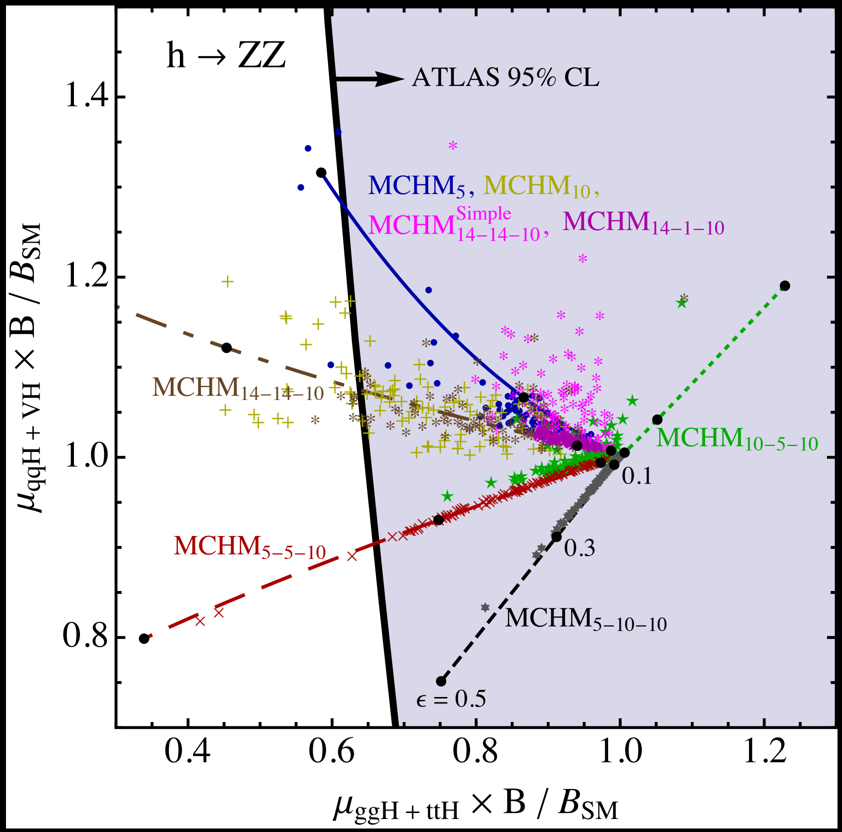


Minimal Composite Higgs models confronting data

h to di-photons



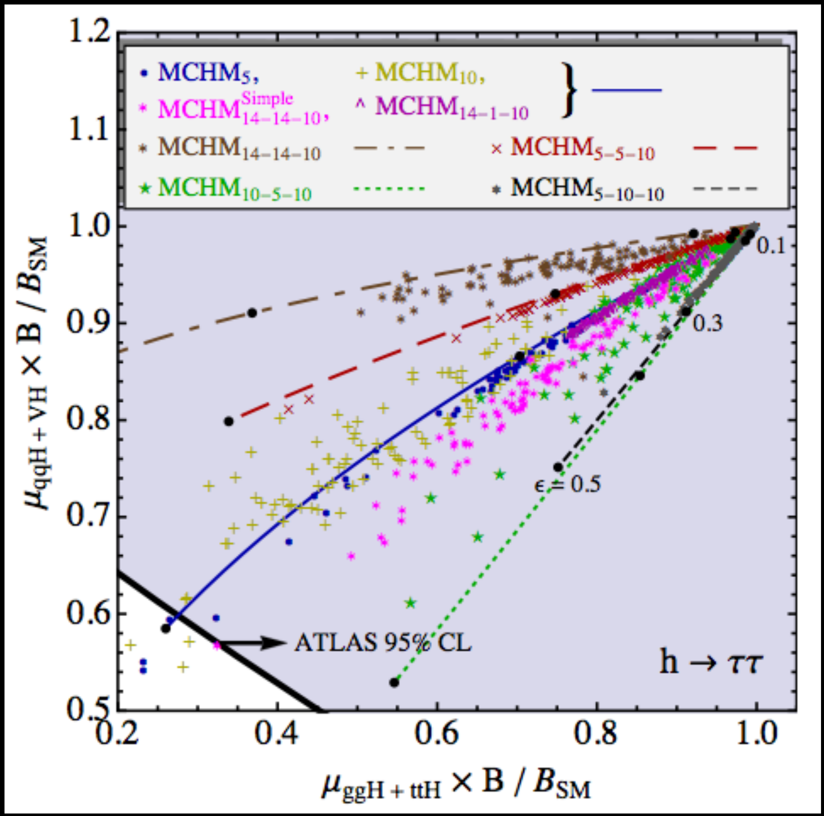
h to ZZ

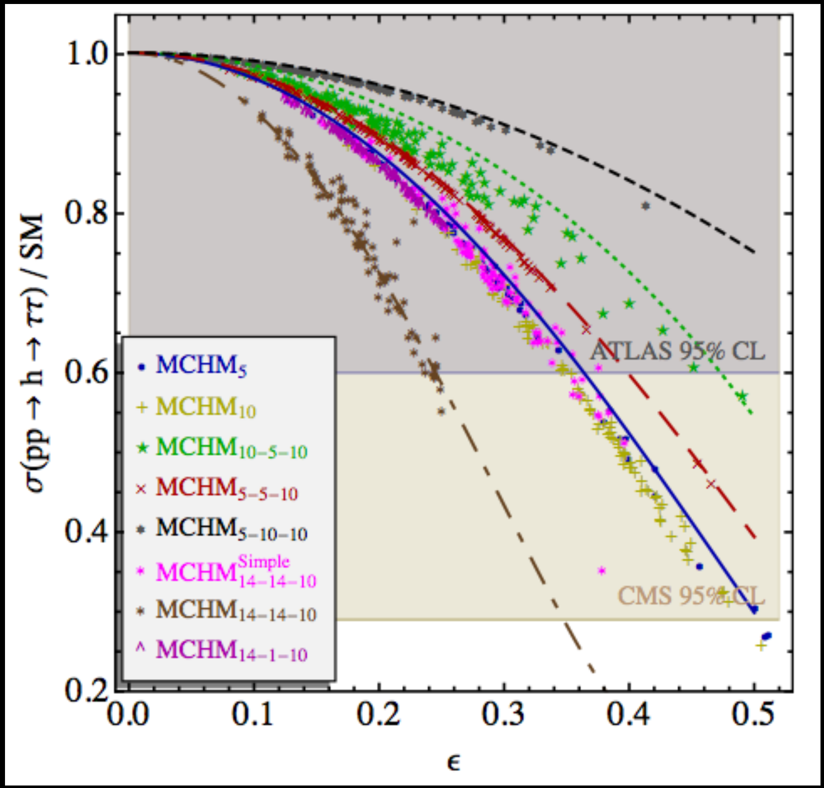


M.C., Da Rold, Ponton '14

Minimal Composite Higgs models confronting data

H to tau pairs





The inclusive in the ττ channel, normalized to the SM, versus ε.

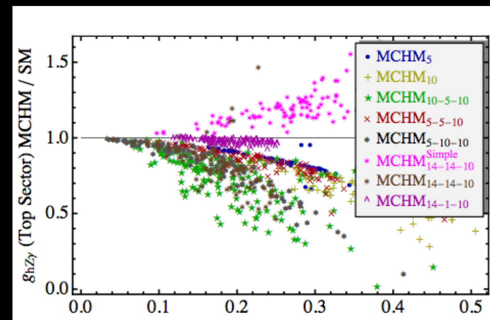
M.C., Da Rold, Ponton ‘14

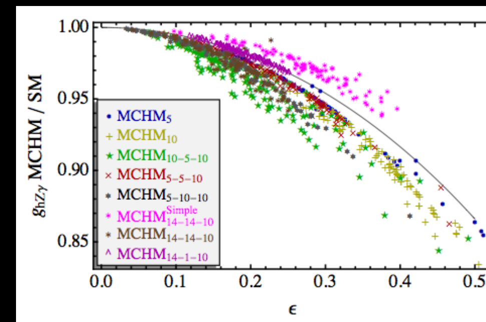
h→Zγ: not yet observed ….

M.C., Da Rold, Ponton '14

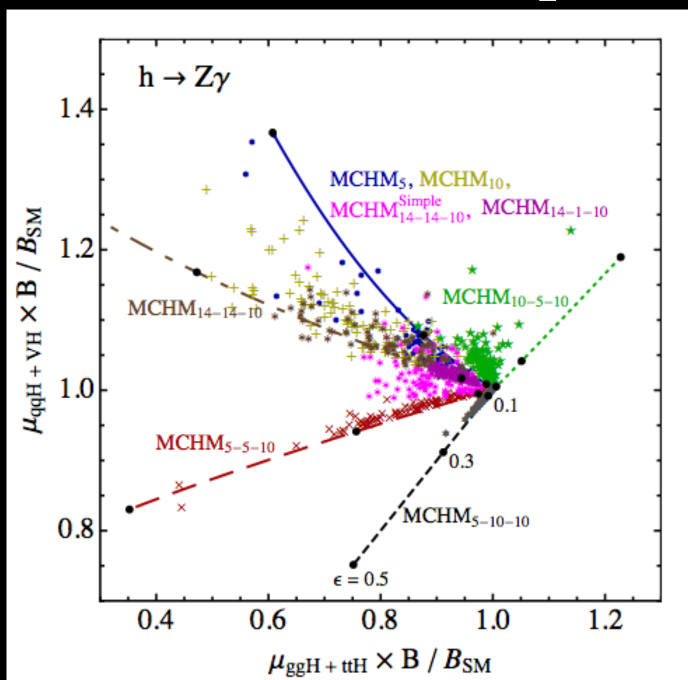
- Corrections from top and its partners can vary the SM vapue up to 50% → (only top sector, through mixing, breaks P_{LR} symmetry and contributes)

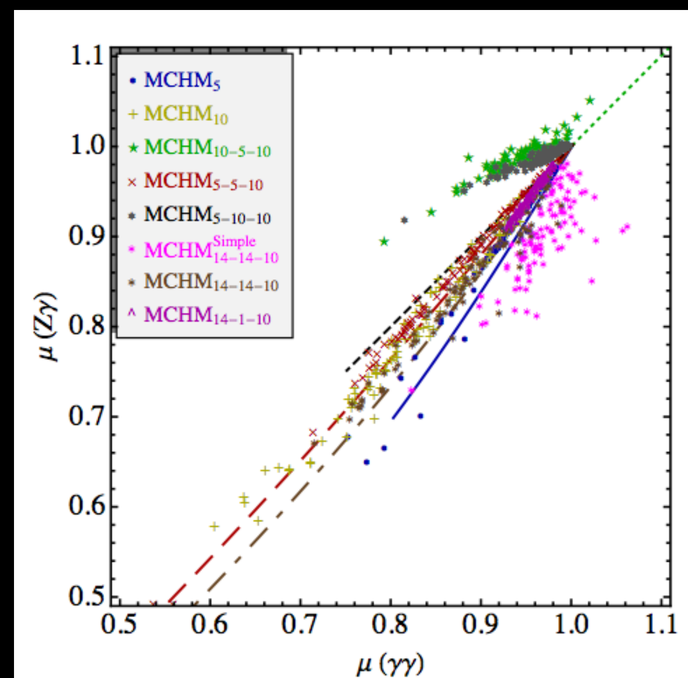
Azatov et al. '13





- W loop much dominant ~ $F_2(\varepsilon)$



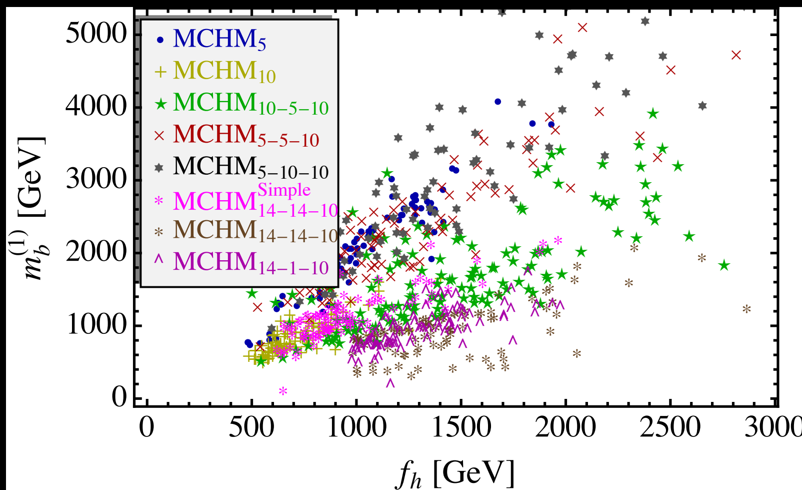


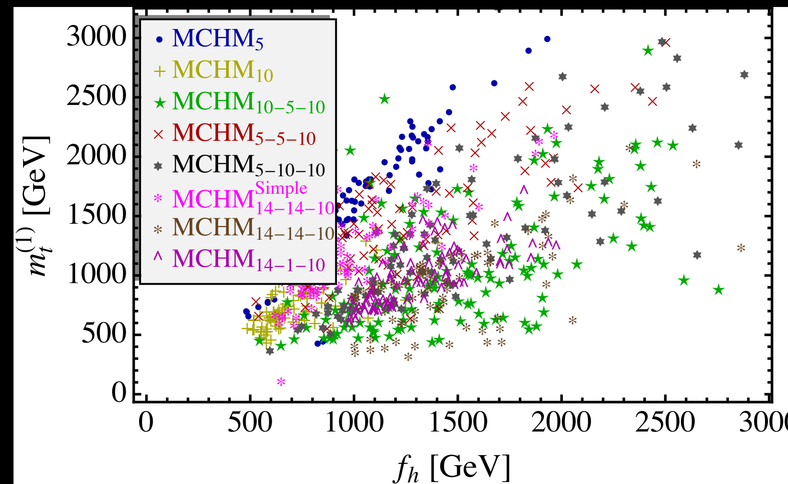
Main effects governed by zero modes
→ by rv and rt

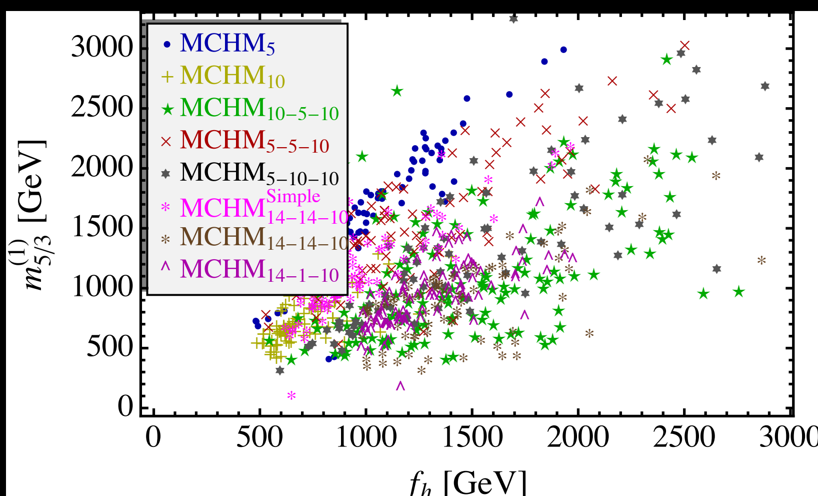
Zγ and γγ correlations differ for some models
→ allow to distinguish among models

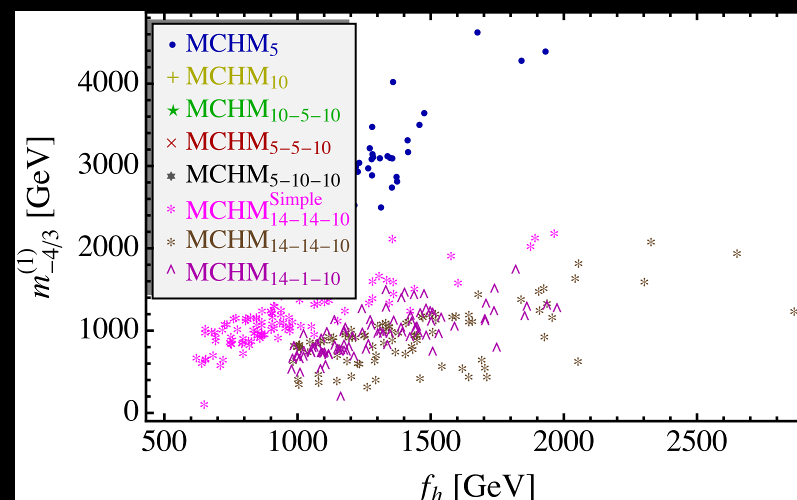
Composite models with extended symmetry predict light fermionic res.

$M_{cust.} \sim m_\rho f \cos_\psi$









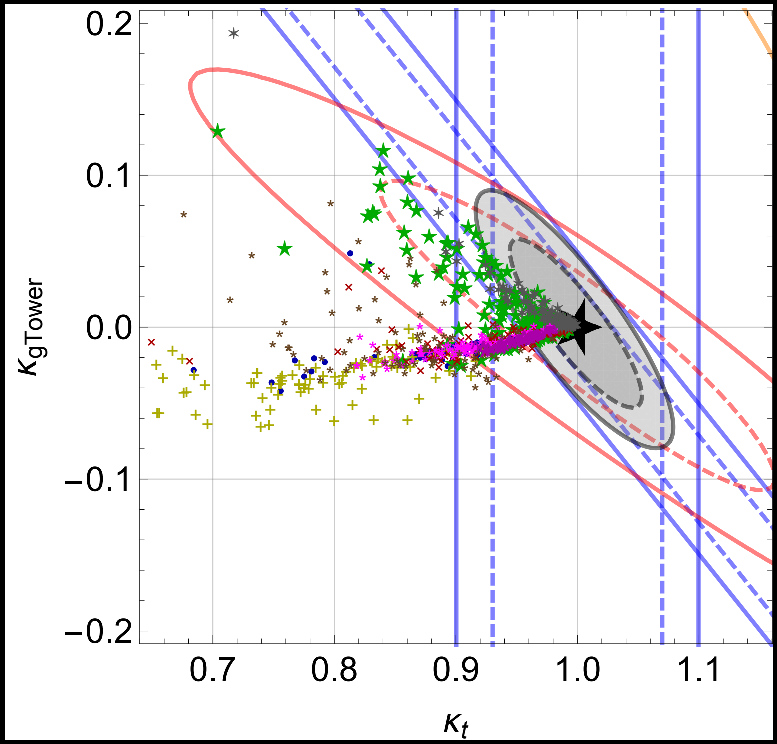
custodians can have charges Q = 2/3(T),−1/3(B),5/3,8/3,−4/3

➔ search for in single/double QCD production

What about the effect of kinematic distributions?

Disentangle effects of the tower?

M.C. Zhen Liu, Ponton et al, to appear



The vertical band is mainly from ttH cross sections and the diagonal band is from seven parameter fit for Higgs to di-gluon coupling (Snowmass report)

The solid and dashed lines represent conservative and optimistic projections for LHC 14 TeV at 3000 fb^{-1}

The red contours are from Higgs plus one and two jets differential cross sections studies

Grojean, salvioni, Schlaffer, Weiler'13; Buschmann, Englert, Goncalves, Plehn, Spannowsky'14

Outlook

Composite Higgs models with a pNGB Higgs provide a tantalizing alternative to the strong dynamics realization of EWSB

- At low energies pNGB Higgs can be described by an effective 4D theory including only the lightest resonances, characterized by g_ρ, m_ρ and mixings.

- There is freedom for composite fermion representations that yield very different predictions for Higgs physics.

- In general there is suppression of production rates and decay widths and a possible enhancement of Higgs BR's in di-bosons, due to the suppression of ($h \to \bar{b}b$) and/or gluon fusion.

- light fermions (TeV range and possibly exotic charges) may be at LHC reach

More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

EXTRAS

We are gathering clues from measuring the Higgs properties with the highest possible precision

- Measurements at LHC tell us about the Higgs coupling structure and the new physics that may modify them

How much precision is needed?
Can we use correlations among signals to pin down the nature of the underlying physics?

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	$5-8\%$

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu}\right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H.$$

Chiral Lagrangian for a light SM-like scalar boson

- Electroweak precision observables also constrain Higgs couplings

$$S = \frac{1}{12\pi}(1-a^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right) \qquad T = -\frac{3}{16\pi c_W^2}(1-a^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right)$$

$$\Lambda = 4\pi v/\sqrt{|1-a^2|}$$

Giudice et al; Contino et al;
Azatov et al. Silvestrini LHCP13

- $a = 1.02 \pm 0.02$
- $a \in [0.98, 1.07]$@95%
- Composite Higgs models typically generate $a < 1$

Falkowski,Rychkov&Urbano

- for $a < 1$, $\Lambda > 15$ TeV

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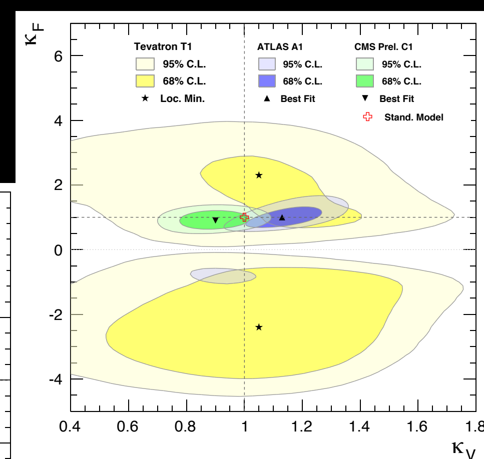
Chiral Lagrangian for a light SM-like scalar boson

$$\begin{aligned}\mathcal{L} = {} & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ & + \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu}\right) H \\ & - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f \bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f \bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f \bar{f} \right) H.\end{aligned}$$



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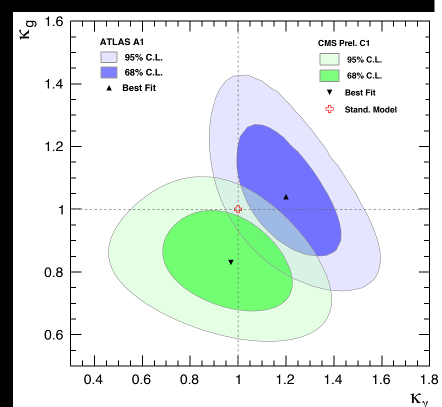
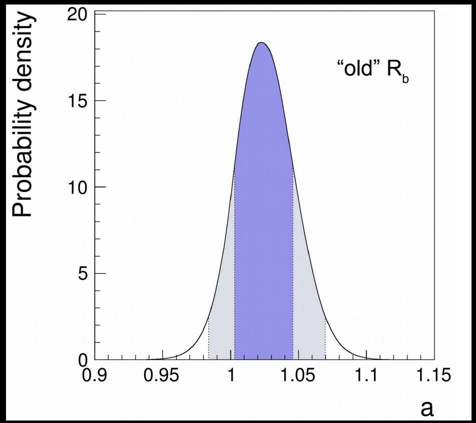


We are gathering clues from measuring the Higgs properties with the highest possible precision

- Electroweak precision observables also constrain Higgs couplings

- Consider an extension of the SM in which:
  - the only new light state below the cutoff is the Higgs boson
  - there is a custodial symmetry
  - there is no new source of flavour violation



Giudice et al;Contino et al;Azatov et al;Contino et al

- the main effect in EWPO is due to a possibly modified Higgs coupling a to vectors (GB's):

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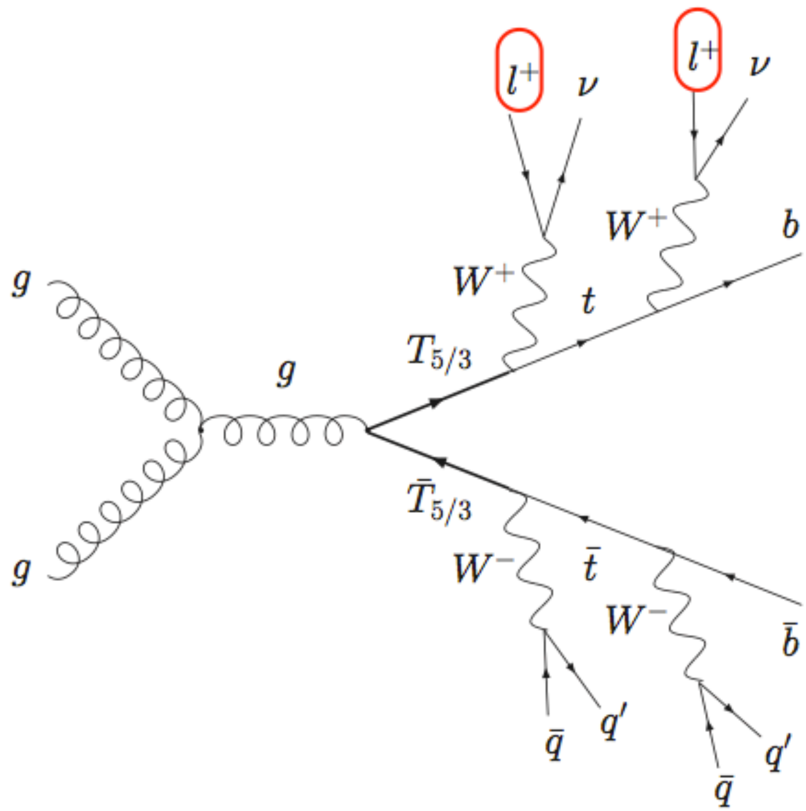
Composite Higgs Models at the LHC

Color vector-like fermions with charge 5/3:

If this fermion is light, it can be double produced:



same-sign di-leptons

Loop induced Couplings of the Higgs to Gauge Boson Pairs

Low energy effective theorems relate a heavy particle contribution
to the loop induced Higgs couplings to gauge bosons,
to that particle contribution to the two point function of the gauge bosons

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^\dagger_{F,i}\mathcal{M}_{F,i}\right) + \sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^2_{B,i}\right)\right] F_{\mu\nu}F^{\mu\nu}$$

Ellis, Gaillard, Nanopoulos'76, Shifman,Vainshtein,Voloshin, Zakharov'79, Kniehl and Spira '95
M. C, I. Low, Wagner '12

Similarly for the Higgs-gluon gluon coupling

Hence, W (gauge bosons) contribute negatively to Hγγ,
while top quarks (matter particles) contribute positively to Hgg and Hγγ

- New chiral fermions will enhance Hgg and suppress hγγ
- To reverse this behavior matter particles need to have negative values for

$$\frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^\dagger_{F,i}\mathcal{M}_{F,i}\right) \qquad \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^2_{B,i}\right)$$

For a study considering CP violating effects and connection with EDM's and MDM's
see Voloshin'12; Altmannshofer, Bauer, MC'13

Relation with SILH Operators

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \;,$$
$$\mathcal{O}_{GG} = |H|^2 G_{\mu\nu} G^{\mu\nu} \;,$$
$$\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) D^\nu W^a_{\mu\nu} \;,$$
$$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H)\, W^a_{\mu\nu}$$

$$\mathcal{O}_{y_f} = |H|^2 \bar{q}_L H f_R$$
$$\mathcal{O}_{BB} = |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_B = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H)\, B_{\mu\nu}$$

The Wilson coefficients c_H,c_W and c_B are universal for all the MCHM with SO(5)/SO(4) breaking $c_H = 1$ $c_W = c_B \simeq 1.0$

$$c_{y_t} = 1\;, \qquad \text{for the MCHM}_{5,\ 10,\ 14-14-10,\ 14-1-10,\ 5-5-10}\;,$$
$$c_{y_t} = 0\;, \qquad \text{for the MCHM}_{10-5-10,\ 5-10-10}\;,$$
$$c_{y_b} = 1\;, \qquad \text{for the MCHM}_{5,\ 10,\ 14-14-10,\ 14-1-10,\ 10-5-10}$$
$$c_{y_b} = 0\;, \qquad \text{for the MCHM}_{5-5-10,\ 5-10-10}\;.$$

O_H renormalizes the Higgs couplings to all the other SM fields. O_{GG},O_{BB} and $O_- = (O_W - O_B) - (O_{HW} - O_{HB})$ enter in the interactions hgg,hγγ and hZγ, respectively