Higgs Bosons as the portal for New Physics at LHC

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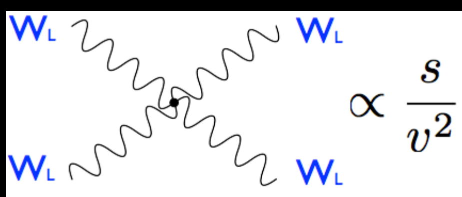
New Physics beyond the SM is needed to explain many observed phenomena

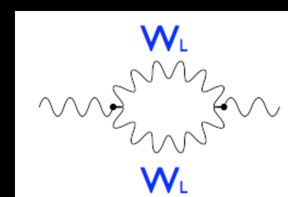
[Dark matter, matter-antimatter asymmetry, dynamical origin of fermion masses, mixings, CP violation,…]

- 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:

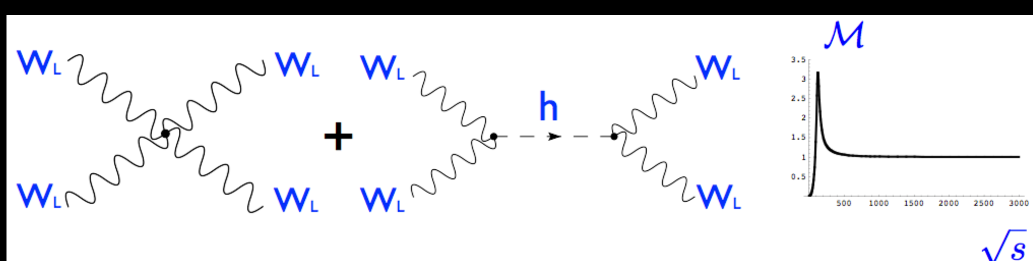


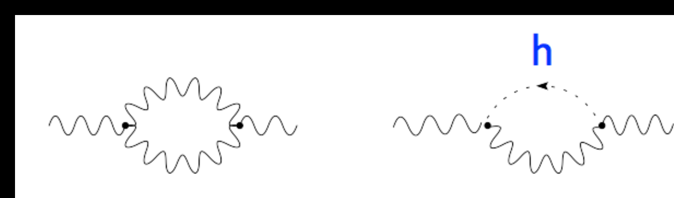
Unitarity lost at high energies



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, its mass has quadratic sensitivity to UV physics

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

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

Fine tuning ⟷ **Naturalness problem**

Supersymmetry: a fermion-boson symmetry : The Higgs remains elementary but its mass is protected by SUSY ➔ $\delta m^2 = 0$

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

Both options imply changes in the Higgs phenomenology and beyond

SUSY FC Bayern Vs COMPOSITE HSV

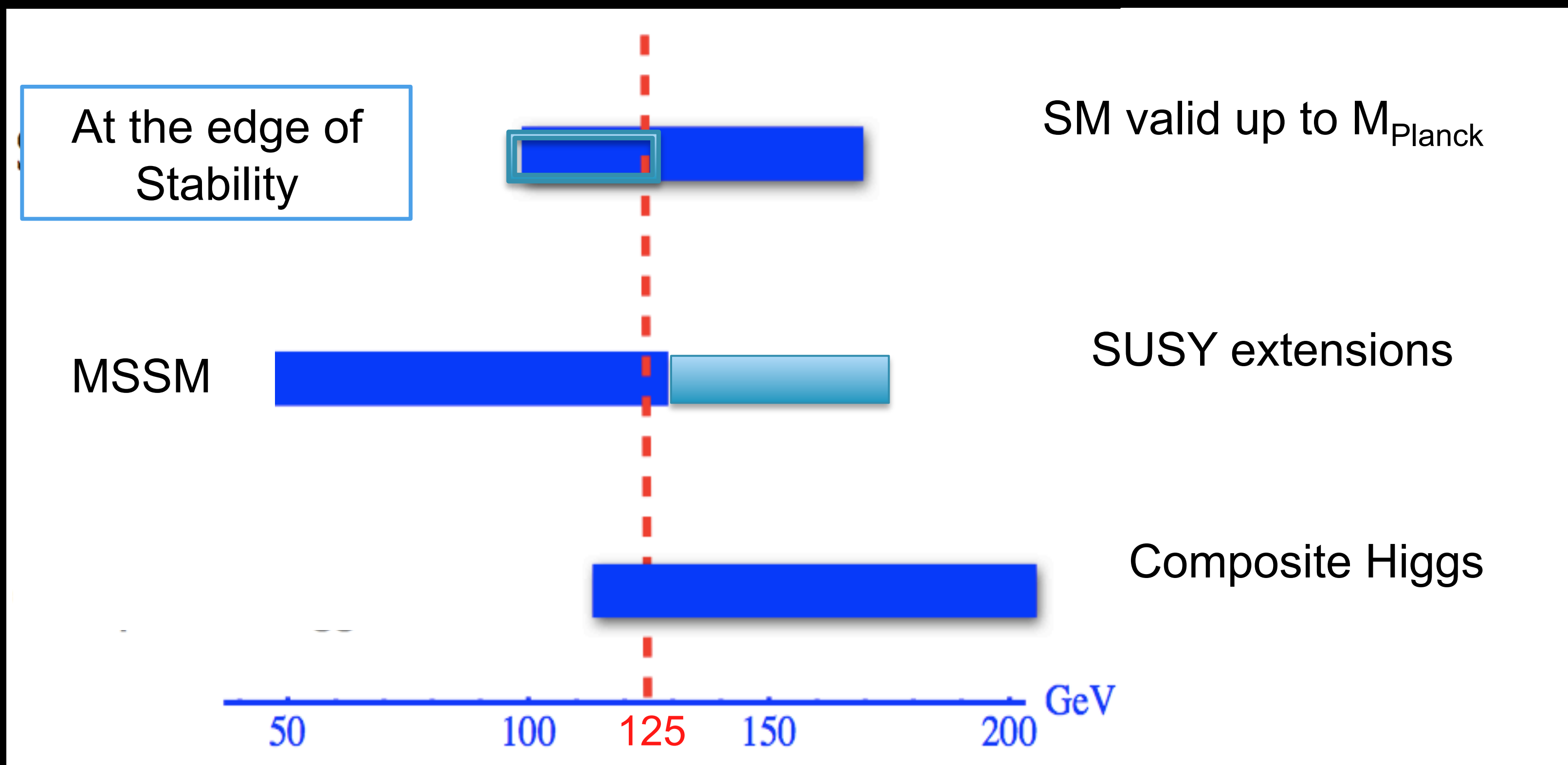
"A point against ~~*Bayern*~~ is a great result for a ~~*team in our situation"*~~

SUSY *theory without a UV completion*

Zinnbauer; HVF coach , September 20th, 2014

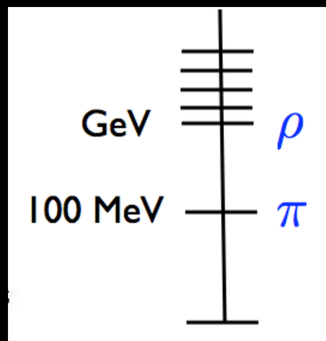
What does a 125 GeV Higgs tell us?

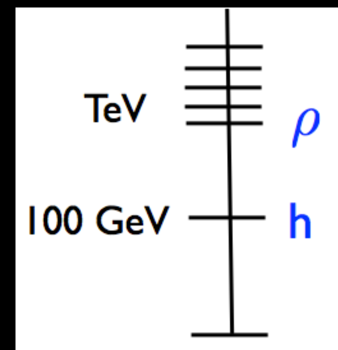
Theorists should be humble



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

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

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

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

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

Mass protected by the global symmetries

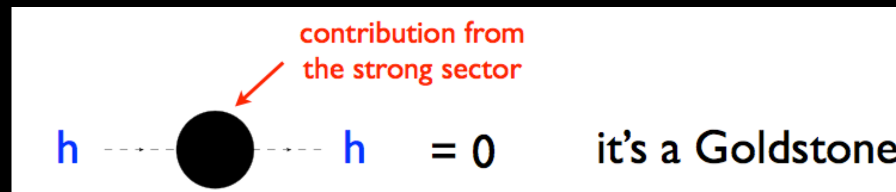
$\pi \rightarrow \pi + \alpha$

Georgi,Kaplan'84; Agashe et al '03

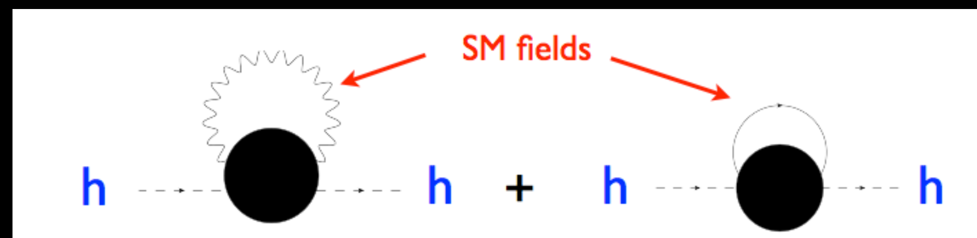
Higgs as a PNGB

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: All About Symmetries

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

gauge: $SU(2)_L \times U(1)_Y \longrightarrow U(1)_Q$

$\uparrow$ $\uparrow$

global: $SO(5) \rightarrow SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ custodial

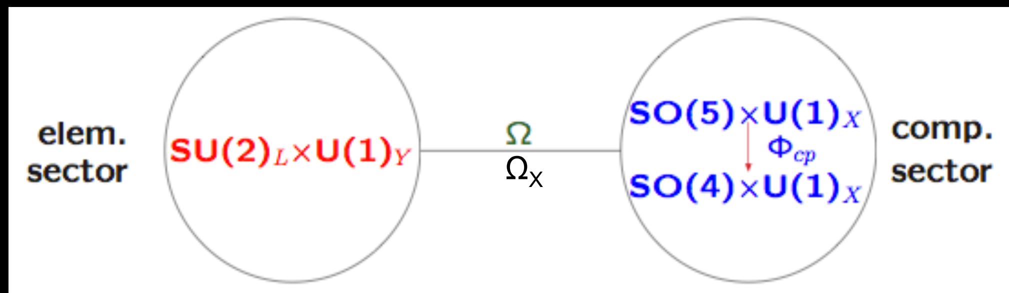
$E \sim f$ $E \sim v$

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

MCHM

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

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

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

Local symmetry G_{SM}

massless fermions/ No Higgs

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

Each chiral SM-fermion → vector-like cp-fermion

Spontaneous breaking parametrized by Φ^{cp} → h

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

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

After EWSB: $\varepsilon = \sin(v/f)$ and $v_{SM} = \varepsilon f$

Model Building

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

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

- **The explicit form of the pNGB interactions with the composite fermions (proto-Yukawa terms) depend on the embedding**
- We constrain the chiral structure to obtain a finite one-loop Higgs potential
  only left and right composite fields that mixed with SM ones are present

$\mathbf{Z}b\bar{b}$ couplings are measured with great accuracy and the large value of m_{top} 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

EWSB and the Higgs Mass

Dynamical EWSB: vacuum misalignment induced by top quark effects

Higgs potential and Higgs mass can be calculated

Marzoca, Serone, Shu'12,
Pomarol, Riva '12

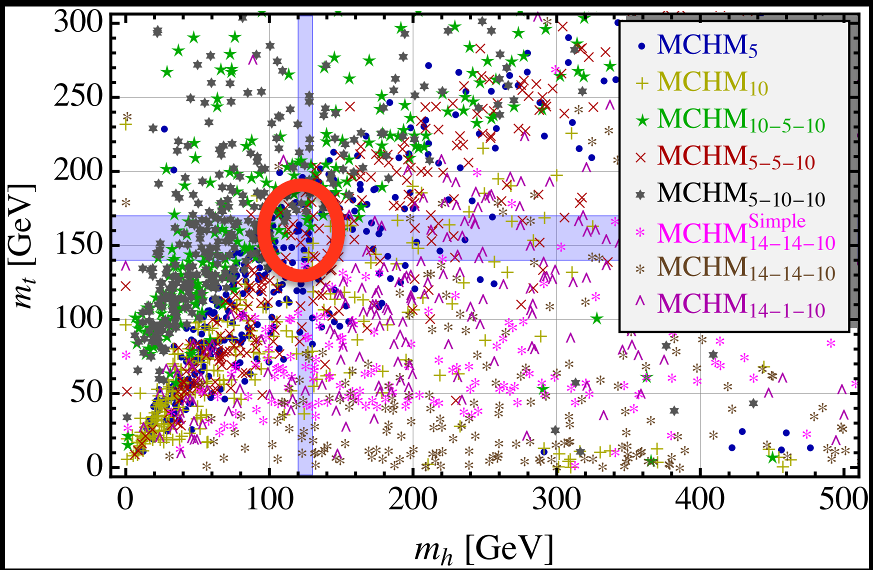
- **Higgs couplings to W/Z determine by the gauge groups involved**

•i.e. $MCHM_X$ ➔ SO(5)/SO(4)

- **Higgs couplin**gs to SM fermions depend on fermion embedding

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

We consider many different SO(5) fermion embeddings



M.C., Da Rold, Ponton'14

Random scan over models with EWSB requirement

•We require $\varepsilon = v_{SM}/f < 0.5$ ➔ PEWT, which implies $f > 500$ GeV

• We also require $m_\rho \sim g_\rho f > 2$ TeV

Models in 14 representation tend to give too large mh

Summary of corrections to Higgs 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:

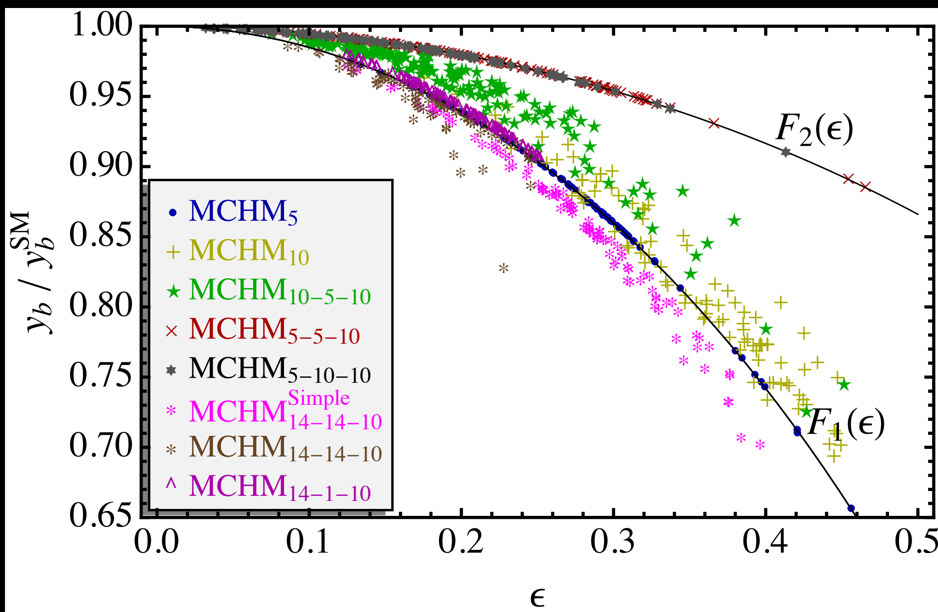
Main effects due to SM fermions and gauge bosons mixing with composite fermion and gauge boson sectors, respectively

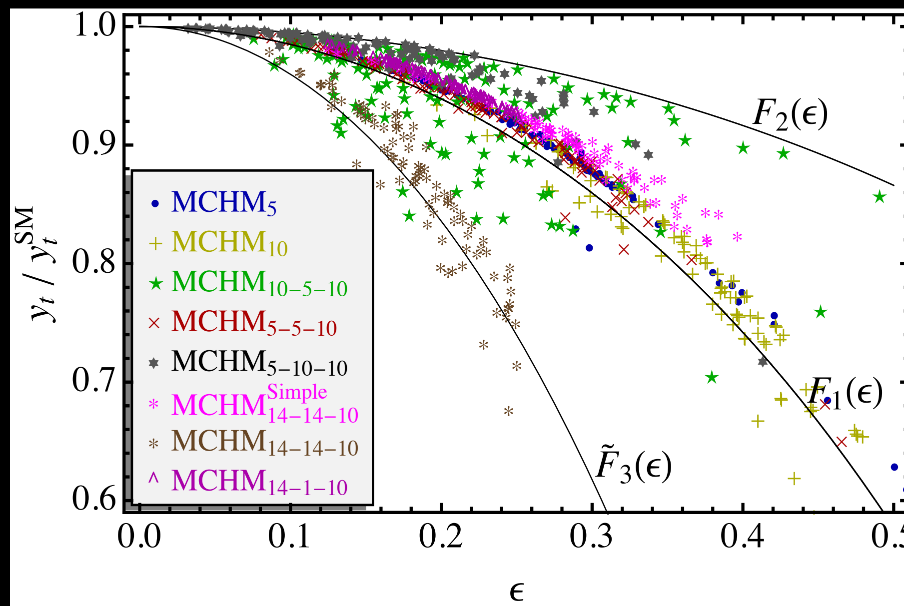
Subleading effects from heavy/strong resonance effects in the loops

➔sum rule from pNGB Higgs nature Falkowski'07;Azatov et al '11

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

Sub-leading effects from heavy/strong resonance effects in the loops

Generic features:

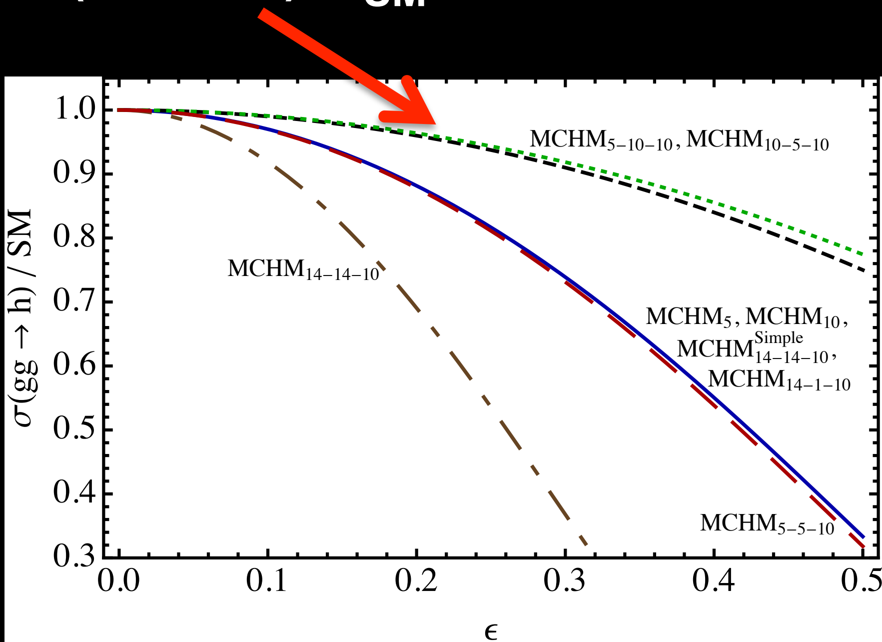
Higgs-gluon fusion and VVH/VH suppression

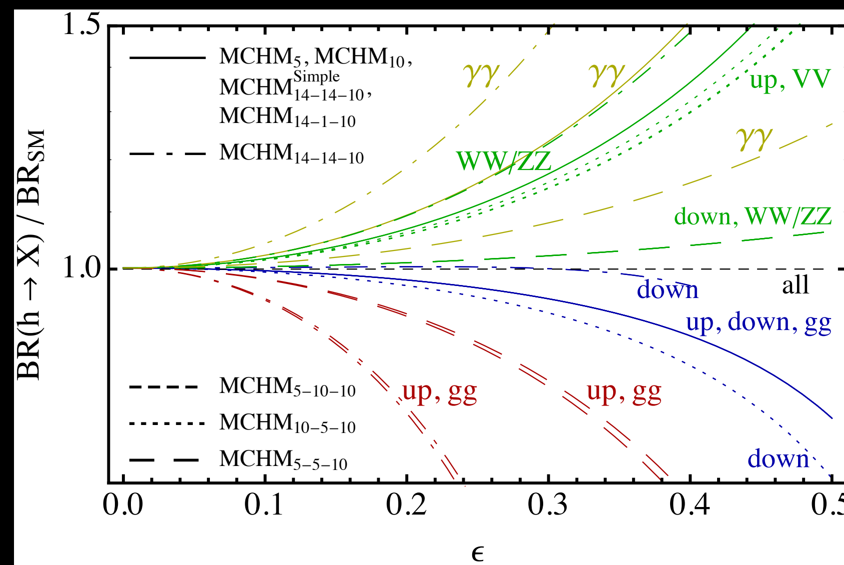
Enhancement or suppression of branching ratios

(Depending on the effect of the total width suppression)

σ(VVH/VH)/σ$_{SM}$

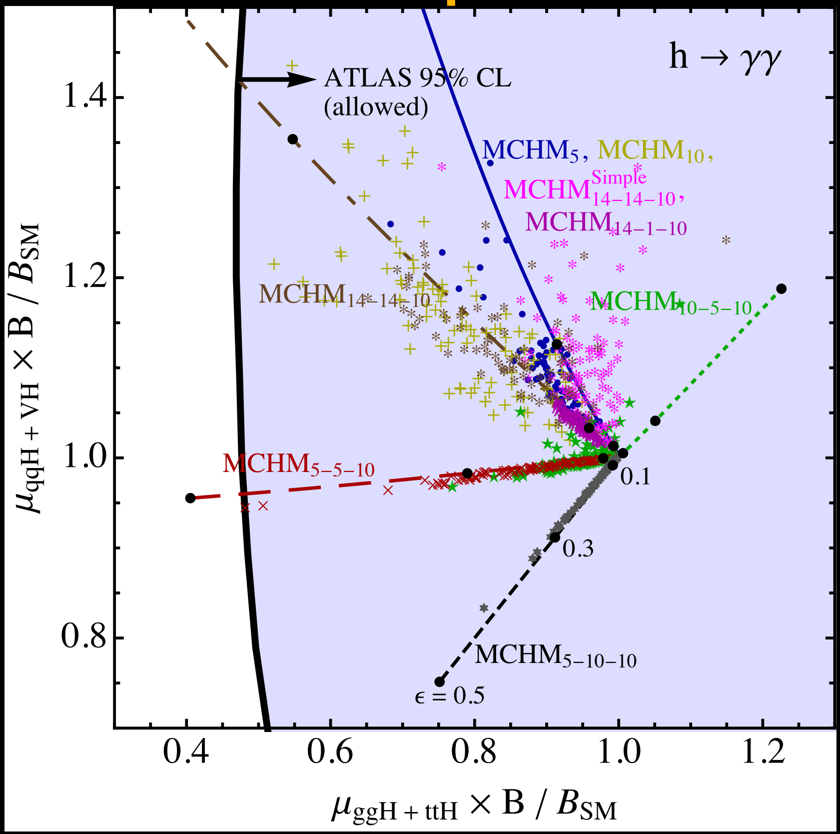
M.C., Da Rold, Ponton '14



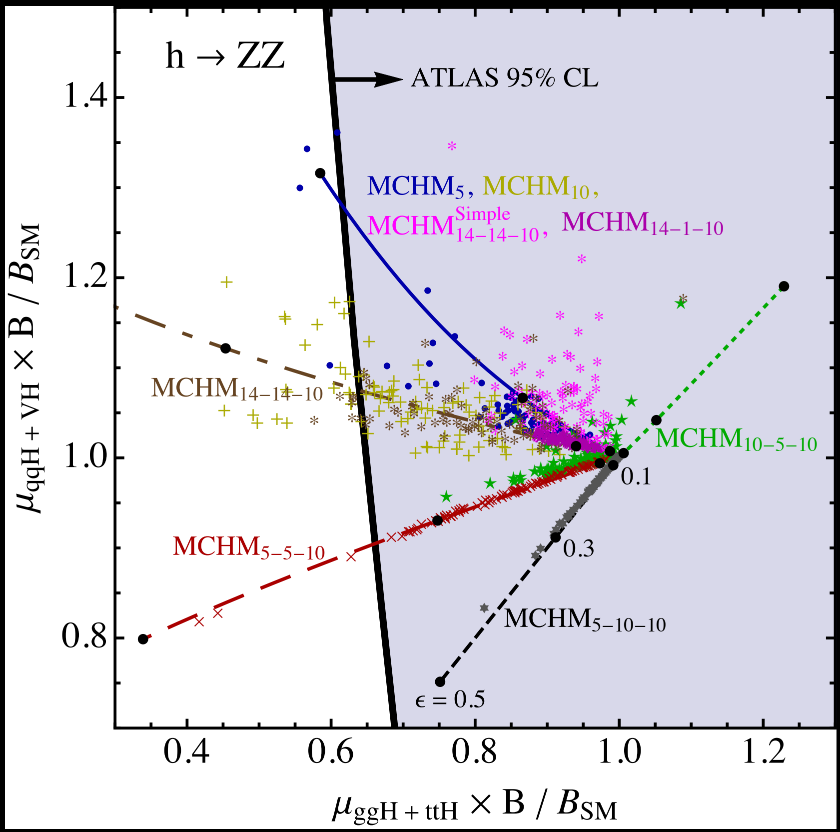


Minimal Composite Higgs models confronting data

h to di-photons



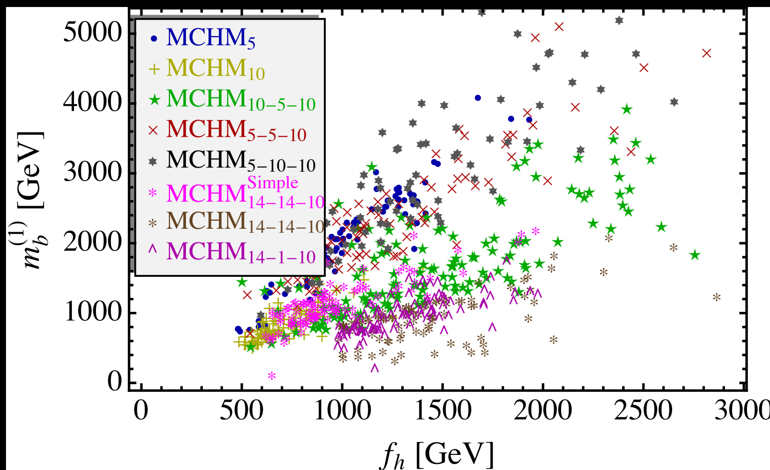
h to ZZ

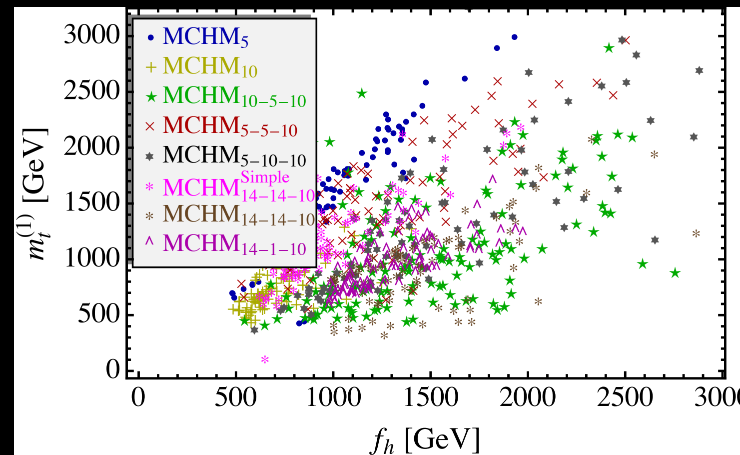


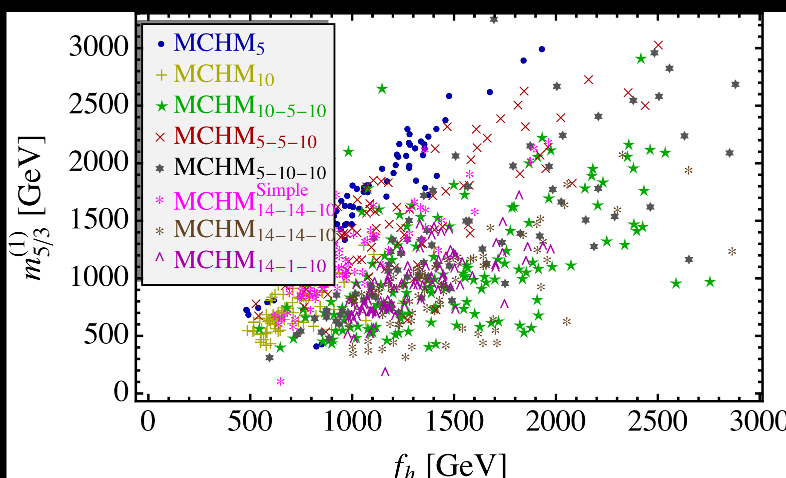
More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

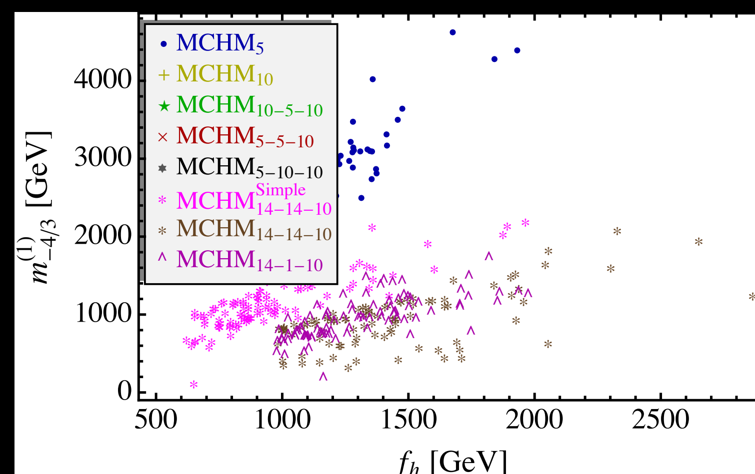
Composite models with extended symmetry predict light fermionic res.

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









Light fermions (TeV range and possibly exotic charges: $Q = 2/3(T), -1/3(B), 5/3, 8/3, -4/3$

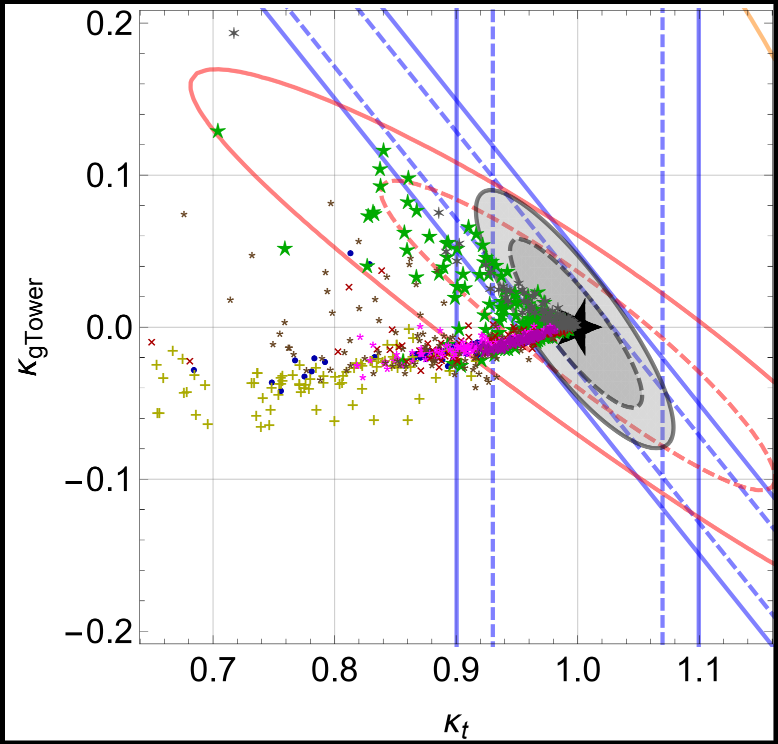
➔ search for in single/double QCD production [LHC exclusion for $M_{cust} < 800$ GeV]

What about the effect of kinematic distributions?

Disentangle effects of the tower?

Learn about the degree of compositeness of the top quark?

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

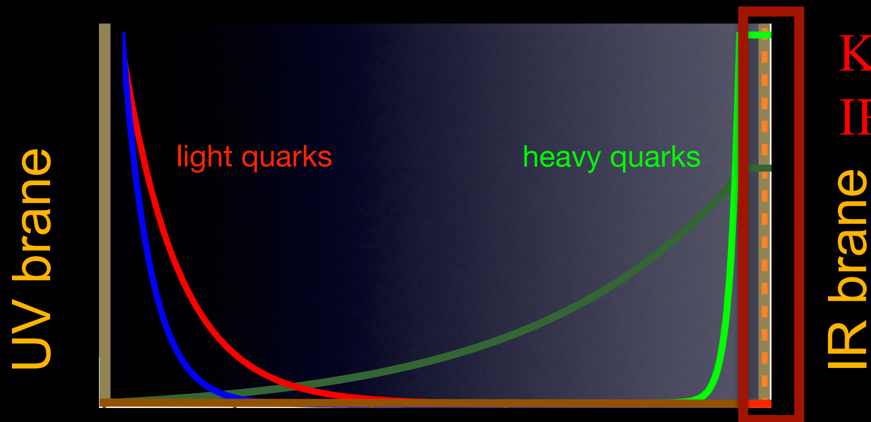
Grojean, Salvioni, Schlaffer, Weiler'13; Buschmann, Englert, Goncalves, Plehn, Spannowsky'14

Models of composite Higgs

Randall, Sundrum

- i.e. Embedding the SM (with the Higgs) in a 5D warped extra dimension

Gauge Higgs Unification Models or Higgs not a pNGB

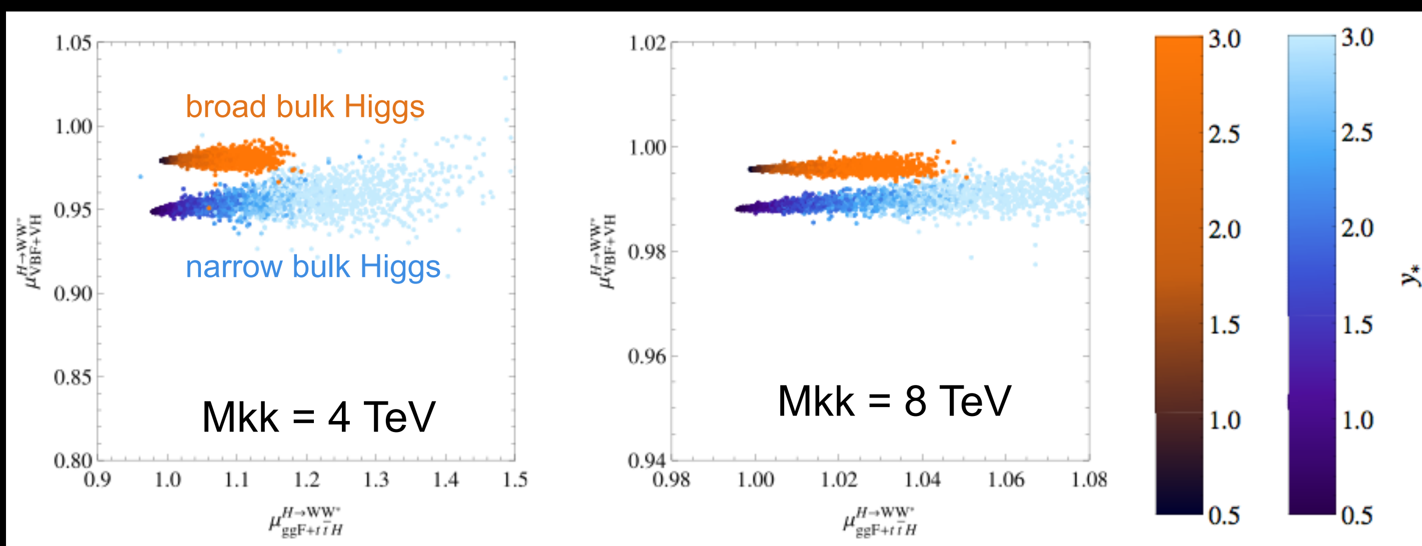


KK modes: IR localized

GHU: Agashe et al.'03; Contino et al'03
M.C, Ponton, Santiago, Wagner'04-07
M.C., Medina, Shah, Wagner'09

Higgs can be IR localized or partially in the bulk (partially composite Higgs)

Archer, MC, Carmona, Neubert '14



Enhancement of gluon fusion production

Leading effects from heavy/strong resonances in the loops

SUSY Weltschmerz*?

In practice, no SUSY yet ➔ SUSY broken in nature: $\delta m^2 \propto M^2_{SUSY}$

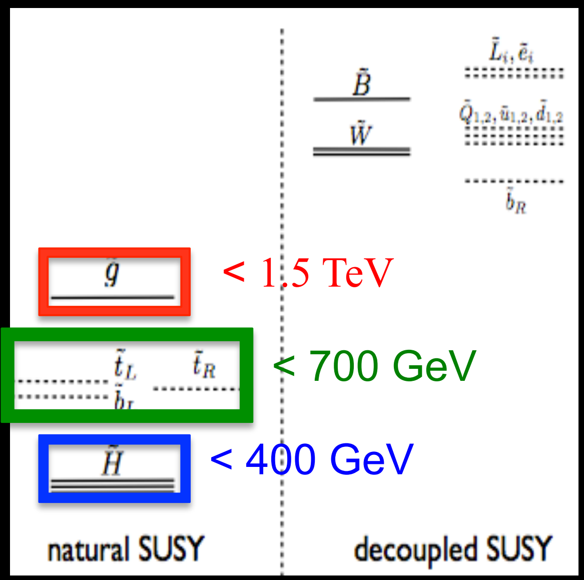
If $M_{SUSY} \sim M_{weak}$ ⟶ Natural SUSY

If $M_{SUSY} \ll M_{GUT}$ ⟶ big hierarchy

- **Not all SUSY particles play a role in the Higgs Naturalness issue**
  Higgsinos, stops (left handed sbottoms) and gluinos are special

ATLAS and CMS are aggressively pursuing the direct signatures of "naturalness".

What about precision Higgs measurements as a tool for Dicovery?



Papucci, Rudermann, Weiler '11

**The feeling experienced by someone who understands that physical reality can never satisfy the demands of the mind*

SUSY implies multiple Higgs bosons, differing in their masses and other properties

Minimal Higgs Sector: Two SU(2) doublets H_d and H_u (2HDM effective theory)

- One SM doublet: $H_{SM} = \mathrm{Re}\, H^o_d \cos\beta + \mathrm{Re}\, H^o_u \sin\beta$ with $\tan\beta = v_u / v_d$
- And an orthogonal combination of non-SM Higgs $H = \begin{pmatrix} H + iA \\ H^{\pm} \end{pmatrix}$

Strictly speaking, the CP-even modes mix and none behaves like the SM one

$$h = -\sin\alpha\, \mathrm{Re}\, H^o_d + \cos\alpha\, \mathrm{Re}\, H^o_u \qquad H = \cos\alpha\, \mathrm{Re}\, H^o_d + \sin\alpha\, \mathrm{Re}\, H^o_u$$

The lightest Higgs h behaves like the SM one when

$\sin\alpha = -\cos\beta$ [or equiv. $\cos(\beta-\alpha) = 0$]

and one recovers the SM as an effective theory

a) **In the DECOUPLING LIMIT ➔** all non-SM like Higgs are heavy ($M_A > 500$ GeV)

b) **In the ALIGNMENT LIMIT ➔** for certain values of the quartic couplings and tanβ, **independent of the non-SM-like Higgs mass values**

Observe: Naturalness demands A/H light for tanβ ~1 (e.g. NMSSM)

Alignment without Decoupling

Haber, Gunion '03
MC, Low, Shah, Wagner '13

$\sin\alpha = -\cos\beta$ ➔ h has SM like properties

Alignment Conditions:
Independent of m_A

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \ ,$$
$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

also

$$\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$$

$$m_h^2 = \lambda_{\rm SM} v^2$$

$$\lambda_{\rm SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + +\lambda_2 \sin^4\beta$$

Alignment solutions for
- **MSSM: sizeable μ and intermediate tanβ**
- **NMSSM: small μ and tanβ**

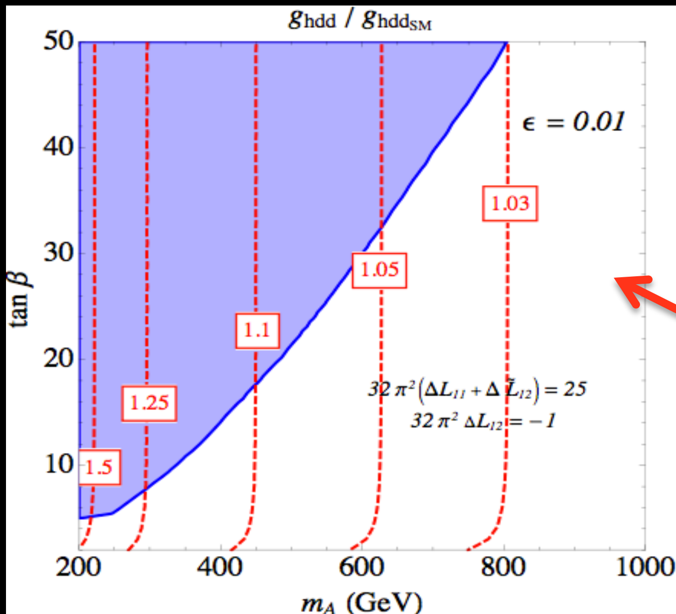
Analysis valid for any 2HDM

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + {\rm h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+\lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+\left\{\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + {\rm h.c.}\right\} \ ,$$

Is it more important to measure Higgs couplings with the highest precision possible
Or
Find new ways of searching for additional Higgs states?

Variation of the down fermion couplings in the MSSM

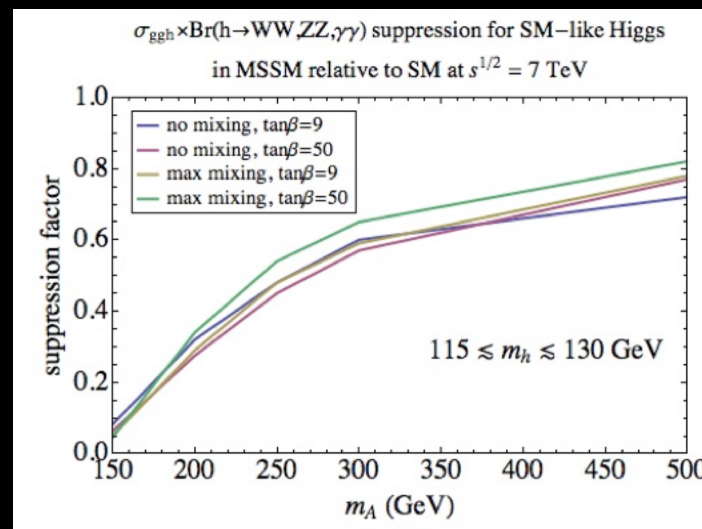
MC, Low, Shah, Wagner '13

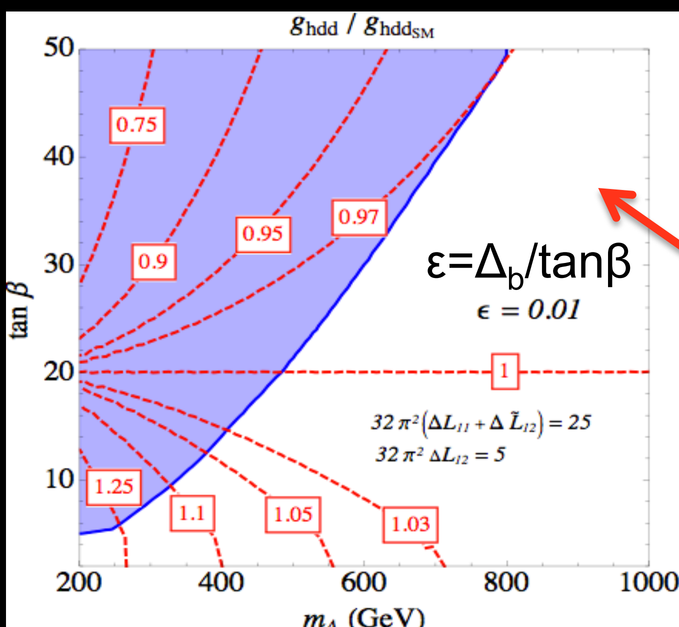


No alignment for small μ

Strong lower bounds on m_A from BR(h → WW/ZZ) variations due to enhancement in hbb coupling

All vector boson BRs suppressed indep. of tanβ





Alignment for large μ and tanβ ~O(10)

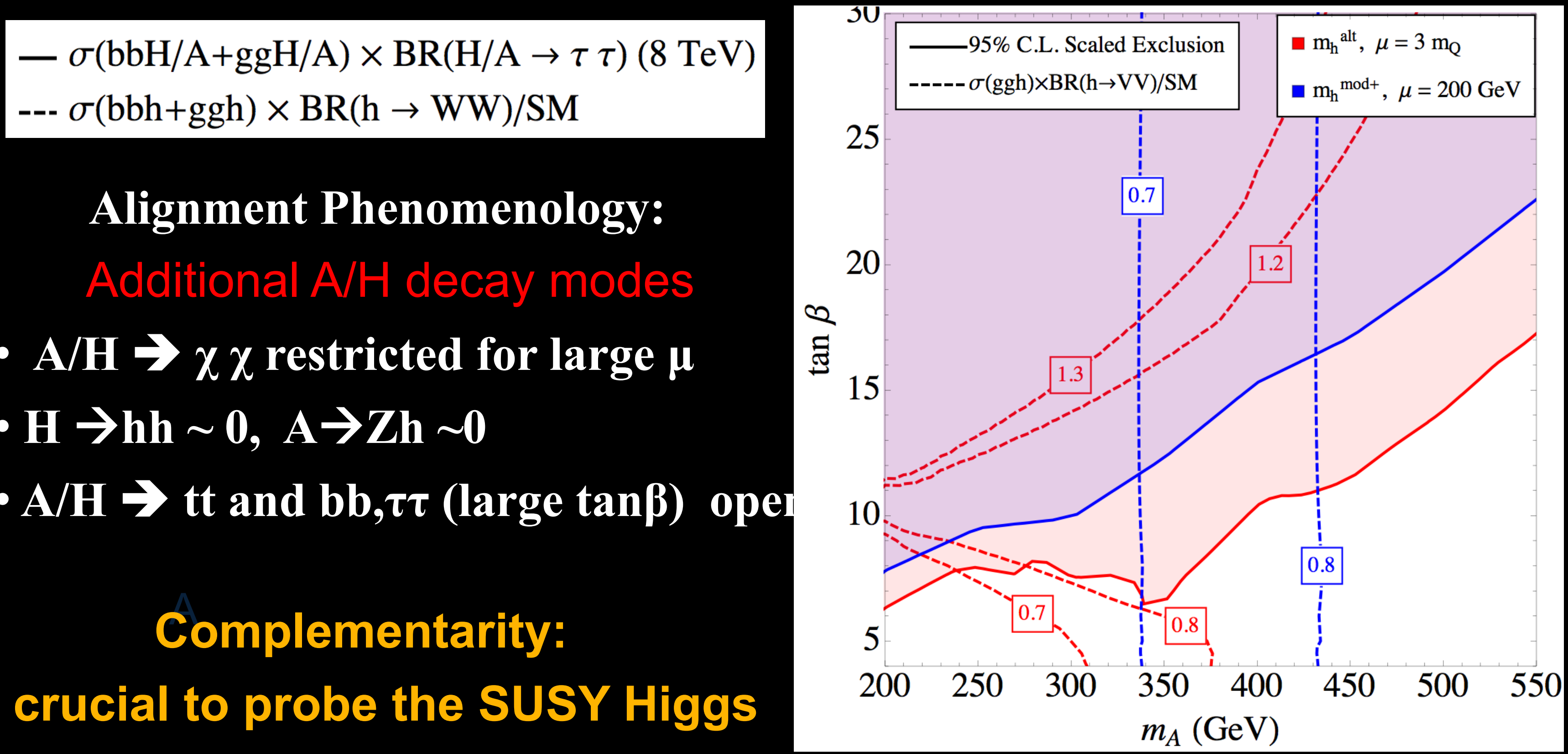
Weaker lower bounds on m_A, with strong tanβ dependence

e.g. Tauphobic Benchmark

MC, Heinemayer, Stal, Wagner, Weiglein'14

The new era of precision Higgs Physics

Additional Higgs Bosons Searches A/H → ττ and Precision Higgs



Alignment Phenomenology:

Additional A/H decay modes

- A/H → χ χ restricted for large μ
- H → hh ~ 0, A → Zh ~0
- A/H → tt and bb,ττ (large tanβ) oper

Complementarity:

crucial to probe the SUSY Higgs sector for low M_A and intermediate tanβ region

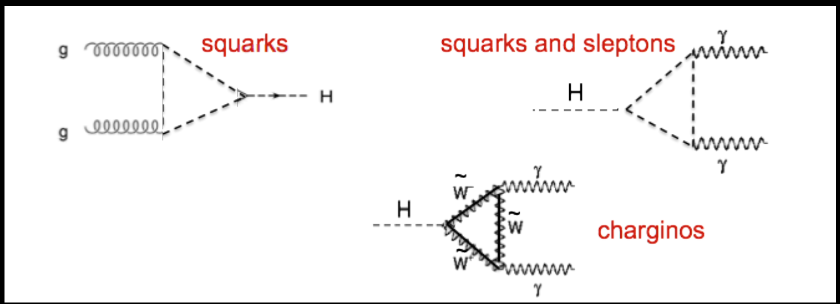
m_A [GeV]

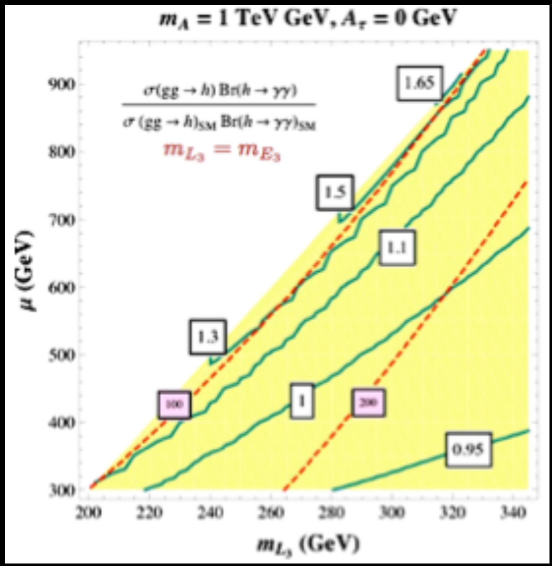
MC, Haber, Low, Shah, Wagner '13

The new era of precision Higgs Physics

There could be one or more “large” ~10% deviations in Higgs couplings versus the SM, detectable at LHC or HL-LHC running

- New light charged or colored particles in loop-induced processes (at LHC reach) →





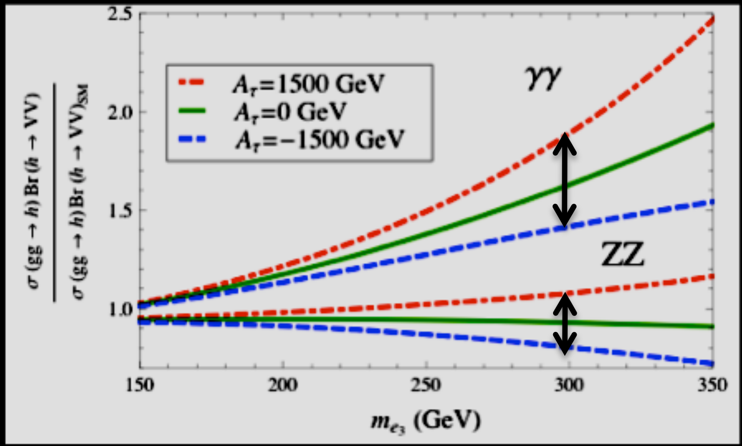
- Modification of tree level couplings due to Higgs mixing effects →

A

- Through vertex corrections to Higgs-fermion couplings: This destroys SM relation

  $BR(h \to bb)/BR(h \to \tau\tau) \sim m_b^2/m_\tau^2$

- Decays to new or invisible particles



MC, Low, Shah, Wagner ‘13

Outlook

Information on the mass and signal strengths and partial distributions of the observed Higgs boson may provide crucial info on BSM scenarios

Composite Higgs models, in particular 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.

• In general there is suppression of production rates and decay widths and possible enhancement of Higgs BR's in di-bosons, due to suppressed hbb and/or hgg couplings

• Light fermions, TeV range and possibly exotic charges, may be observed at the LHC

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

Natural SUSY models are being cornered by LHC data

- The complementarity between additional Higgs searches and precision Higgs measurements opens a window to probe interesting regions of parameter space
- Correlations between deviations in Higgs signals may reveal underlying physics

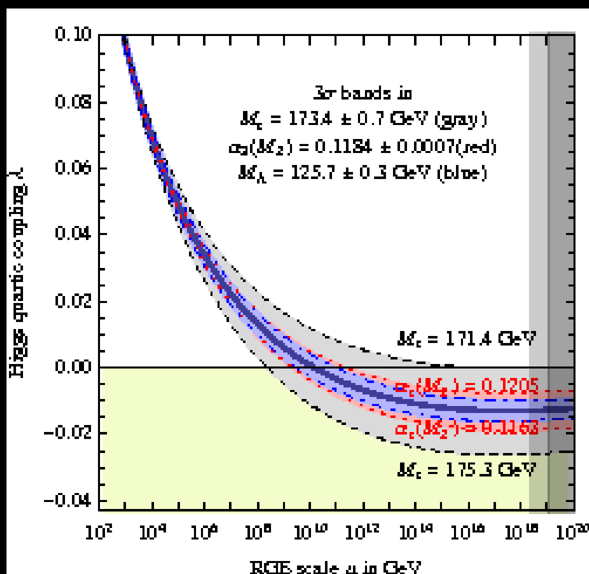
EXTRAS

The Higgs and the fate of our universe

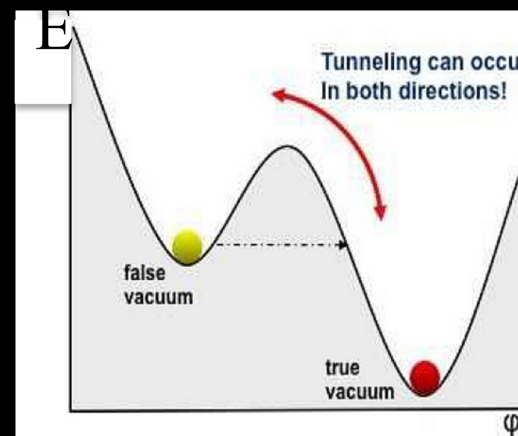
In the SM: $V(\Phi) = -m^2|\Phi|^2 + \lambda\,(\Phi^+\Phi)^2$ and $m^2_H = 2\,\lambda v^2$

➔ $\lambda \sim 0.13$ and $|m|^2 \sim 88$ GeV (v = 246 GeV)

λ evolves with energy



The EW vacuum is metastable

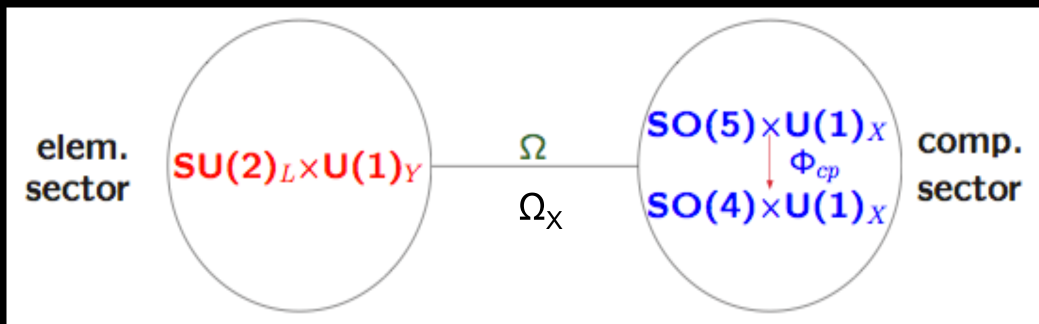


Slow evolution of λ at high energies saves the EW vacuum from early collapse

The peculiar behavior of λ:
A coincidence, some special dynamics/new symmetry at high energies?
Or not there at all ? ➔ new physics at low energy scale

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 $\Omega \longrightarrow g_{el}\Omega g_{cp}^{\dagger}$

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

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

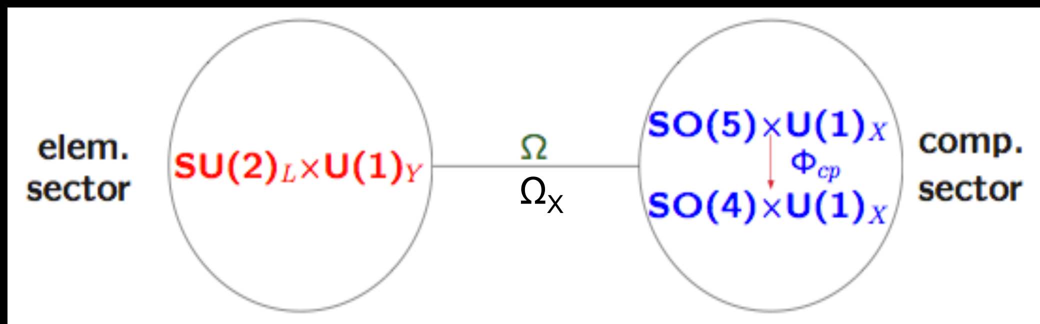
Partial compositness

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: $<h> = v \Rightarrow \langle\Phi\rangle = (0,0,0,\epsilon,\sqrt{1-\epsilon^2})^t$ $\qquad \mathbf{h}^2 = \sum_{\hat{a}} h^{\hat{a}} h^{\hat{a}}$
- new parameter: $\epsilon = \sin\frac{v}{f}$

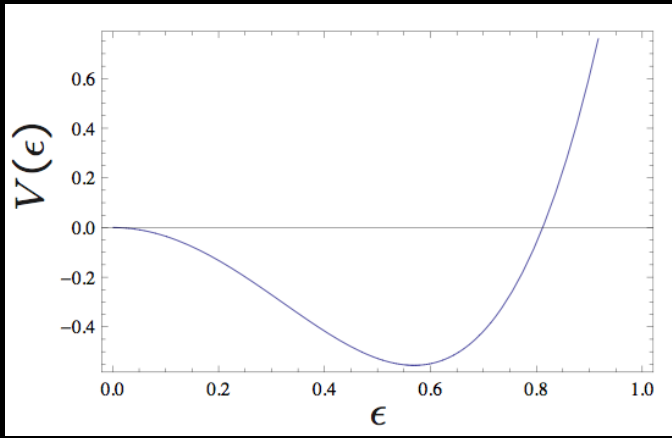
Electroweak Symmetry Breaking

- 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, 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 pNGB 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 $\frac{\mathbf{y}_\psi^{(0)}}{\mathbf{y}_\psi^{\rm SM}}$

The el-cp mixing in both chiralities needs to be small to ensure suppression of dependence on macroscopic model parameters

Bottom sector effects can be larger than expected

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

Higgs Production and Decays

Tree level decays:

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

Assumed τ leptons in same reps. as b quarks and

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

Loop level Higgs decays

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

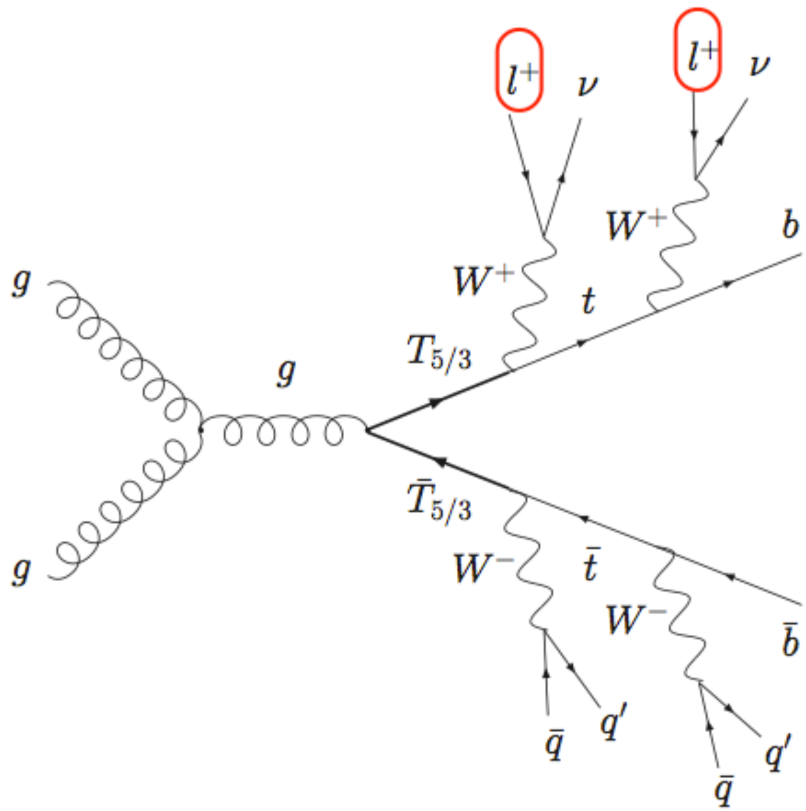
$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma_{\rm SM}(h\to\gamma\gamma)} \approx \frac{|r_V(\epsilon)\,A_1(\frac{m_h^2}{4m_W^2})+N_cQ_t^2\,r_t(\epsilon)\,A_{1/2}(\frac{m_h^2}{4m_t^2})+N_cQ_b^2\,r_b(\epsilon)\,A_{1/2}(\frac{m_h^2}{4m_b^2})|^2}{|A_1(m_h^2/4m_W^2)+N_cQ_t^2A_{1/2}(m_h^2/4m_t^2)+N_cQ_b^2A_{1/2}(m_h^2/4m_b^2)|^2}$$

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

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

The mixing angle α and Alignment (Decoupling)

$$\sin\alpha = \frac{\mathcal{M}_{12}^2}{\sqrt{\mathcal{M}_{12}^4 + (\mathcal{M}_{11}^2 - m_h^2)^2}}$$

CP-even scalar squared mass matrix

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11} & \mathcal{M}_{12} \\ \mathcal{M}_{12} & \mathcal{M}_{22} \end{pmatrix} \equiv m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}$$

$$-\tan\beta\, \mathcal{M}_{12}^2 = (\mathcal{M}_{11}^2 - m_h^2)$$ ➔ sinα= - cosβ

$$\begin{aligned} L_{11} &= \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 \,, \\ L_{12} &= (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 \\ L_{22} &= \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 \,. \end{aligned}$$

Haber, Gunion '03

Alignment Conditions independent of m_A:

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \,,$$

$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

MC, Low, Shah, Wagner '13

$$\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$$

Valid for any 2HDM

$$\begin{aligned} V = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} \,, \end{aligned}$$

Alignment Conditions

- If fullfilled, also the right Higgs mass can be obtained: $m_h^2 = \lambda_{\rm SM} v^2$

$$\lambda_{\rm SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + +\lambda_2 \sin^4\beta$$

- Case of vanishing λ_6 and λ_7 ➔ conditions simplify, tanβ of O(1)

$\lambda_1, \lambda_2 \geq \lambda_{SM} \geq \tilde{\lambda}_3$ or $\lambda_1, \lambda_2 \leq \lambda_{SM} \leq \tilde{\lambda}_3$

and $\lambda_2 - \lambda_{\rm SM} = \frac{\lambda_{\rm SM} - \tilde{\lambda}_3}{\tan^2\beta} = \frac{\lambda_1 - \lambda_{\rm SM}}{\tan^4\beta}$

-- Not achievable in the MSSM, where $\lambda_1, \tilde{\lambda}_3 < \lambda_{\rm SM}$ (small values of μ)

-- Possible in the NMSSM: $\tilde{\lambda}_3 > \lambda_{\rm SM} > \lambda_1$ due to tree level contributions from λ_S, after integration of the singlet

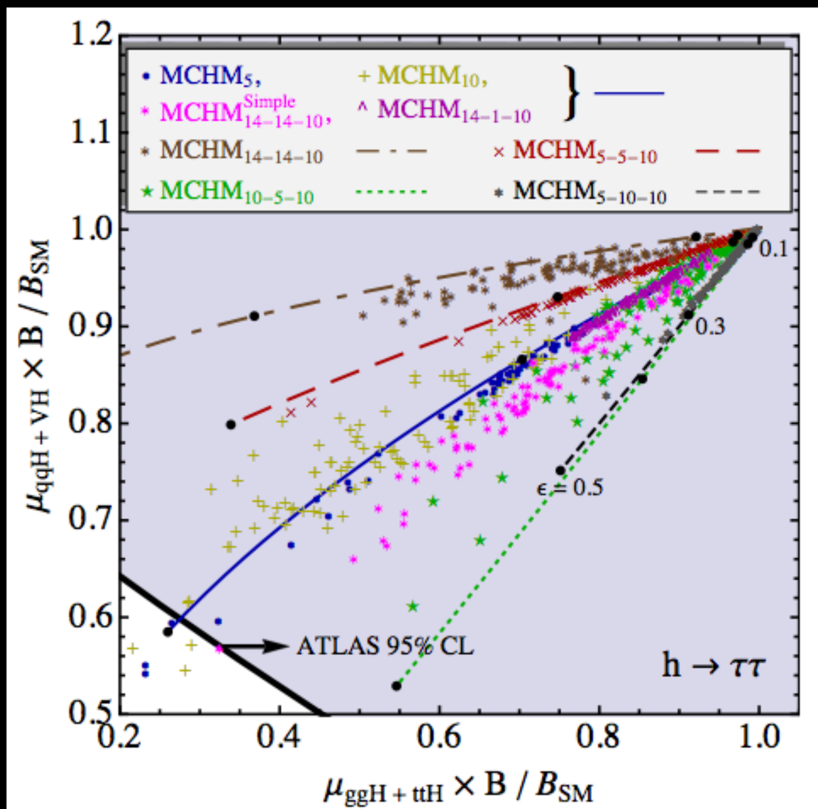
- Case of non-zero $\lambda_{6,7}$ (<< 1) ➔ tanβ cubic equations with natural solutions (indep. of specific values of λ_i's) for tanβ~ O(10)

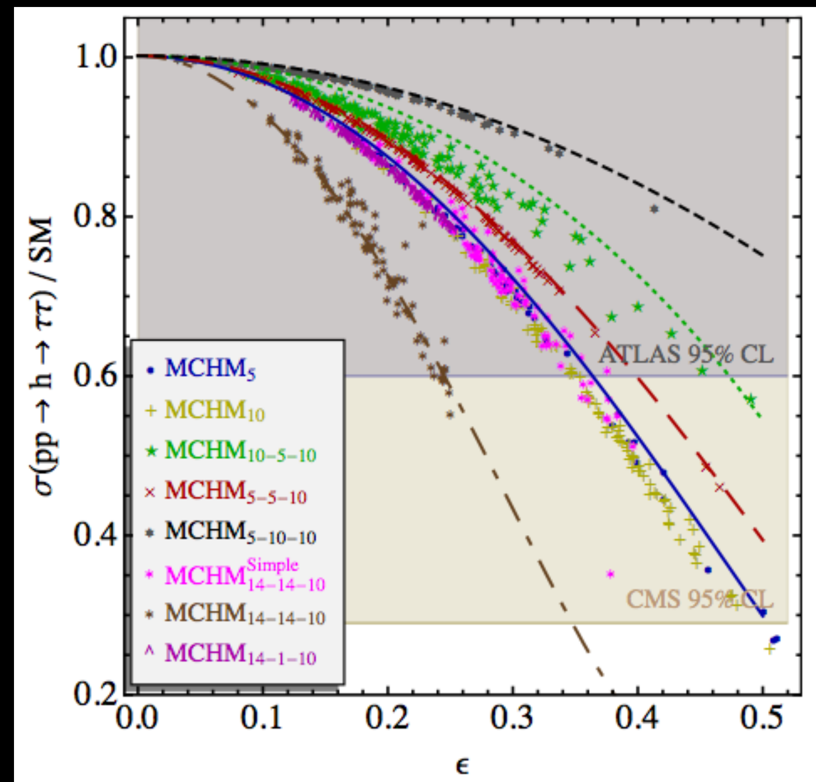
$$\tan\beta = \frac{\lambda_{\rm SM} - \tilde{\lambda}_3}{\lambda_7}, \qquad \lambda_2 \simeq \lambda_{\rm SM}$$

achievable in the MSSM for sizeable μ

Minimal Composite Higgs models confronting data

H to tau pairs





Freedom in choosing tau reps. (irrelevant for Higgs potential), may revert behavior

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

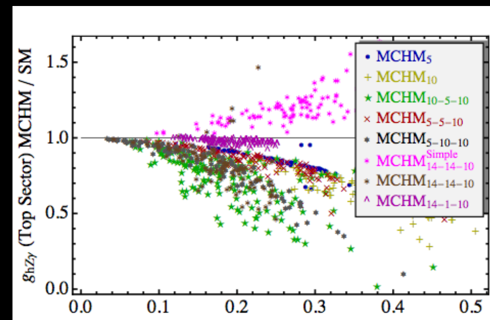
M.C., Da Rold, Ponton '14

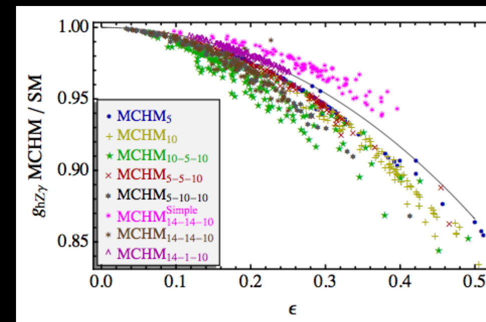
h→Zγ: not yet observed ….

M.C., Da Rold, Ponton '14

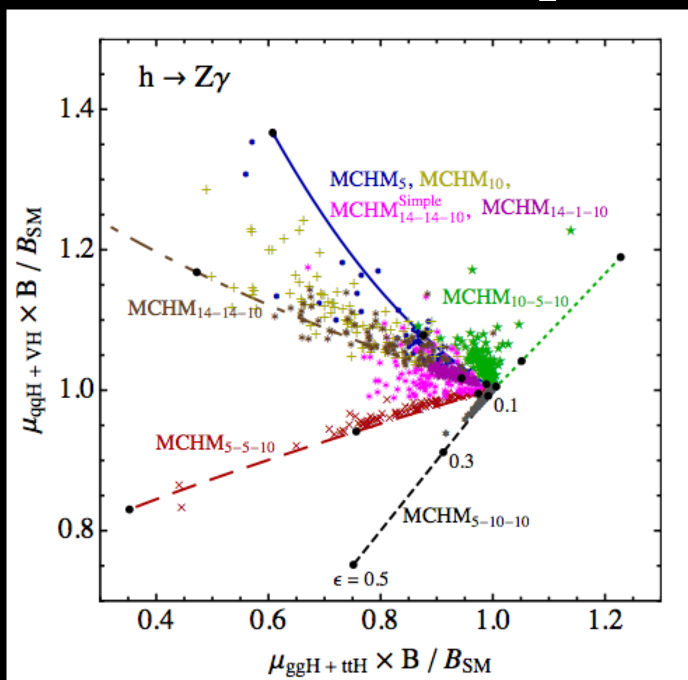
- Corrections from top and its partners can vary the SM value up to 50% → (only top sector, through mixing, breaks P_{LR} symmetry and contributes)

Azatov et al. '13

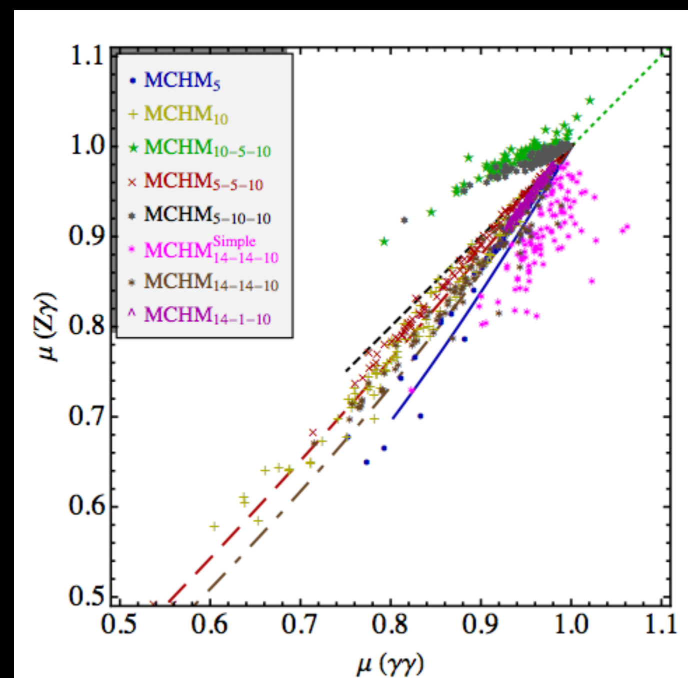




- W loop much dominant ~ $F_2(\varepsilon)$



Main effects governed by zero modes
➔ by rv and rt



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

Should we expect New Physics close to the TeV scale?

• The Higgs is special : it is a scalar

At quantum level, scalar masses has quadratic sensitivity to UV physics

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

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**

Two possible Solutions:

Supersymmetry: a fermion-boson symmetry

The Higgs remains elementary but its mass is protected by SUSY ➔ $\delta m^2 = 0$

In practice, no SUSY yet ➔ SUSY broken in nature: $\delta m^2 \propto M_{SUSY}^2$

If $M_{SUSY} \sim M_{weak}$ ⟶ Natural SUSY

If $M_{SUSY} \ll M_{GUT}$ ⟶ big hierarchy

- **Not all SUSY particles play a role in the Higgs Naturalness issue**
  Higgsinos, stops (left handed sbottoms) and gluinos are special

SUSY Weltschmerz ?

ATLAS and CMS are aggressively pursuing the direct signatures of "naturalness".

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

Both options imply changes in the Higgs phenomenology

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 $c_H = 1$ $c_W = c_B \simeq 1.0$

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

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