Probing Composite Higgs Models at the LHC

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Fermilab and U. of Chicago

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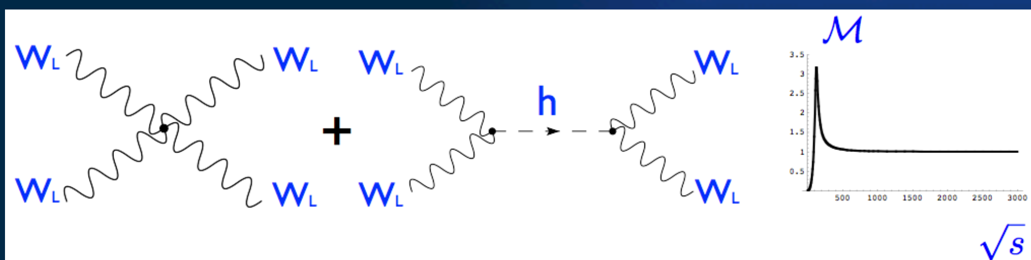
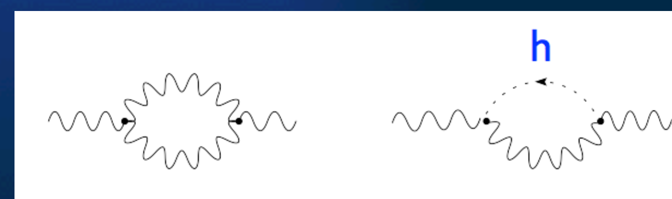
New Physics beyond the SM is needed to explain many observed phenomena

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

- But none of the above demands NP at the EW

The Higgs restored the calculability power of the SM





But, the Higgs is special: it's scalar

At quantum level, its mass has quadratic sensitivity to UV physics

Light scalars cannot survive in the presence of heavy states at GUT/String/Planck scales

Fine tuning $\longleftrightarrow$ Naturalness problem

Supersymmetry:

a fermion-boson symmetry :

The Higgs remains elementary but its mass is protected by SUSY

Composite Higgs Models

The Higgs does not exist above a certain scale, at which the new strong dynamics takes place

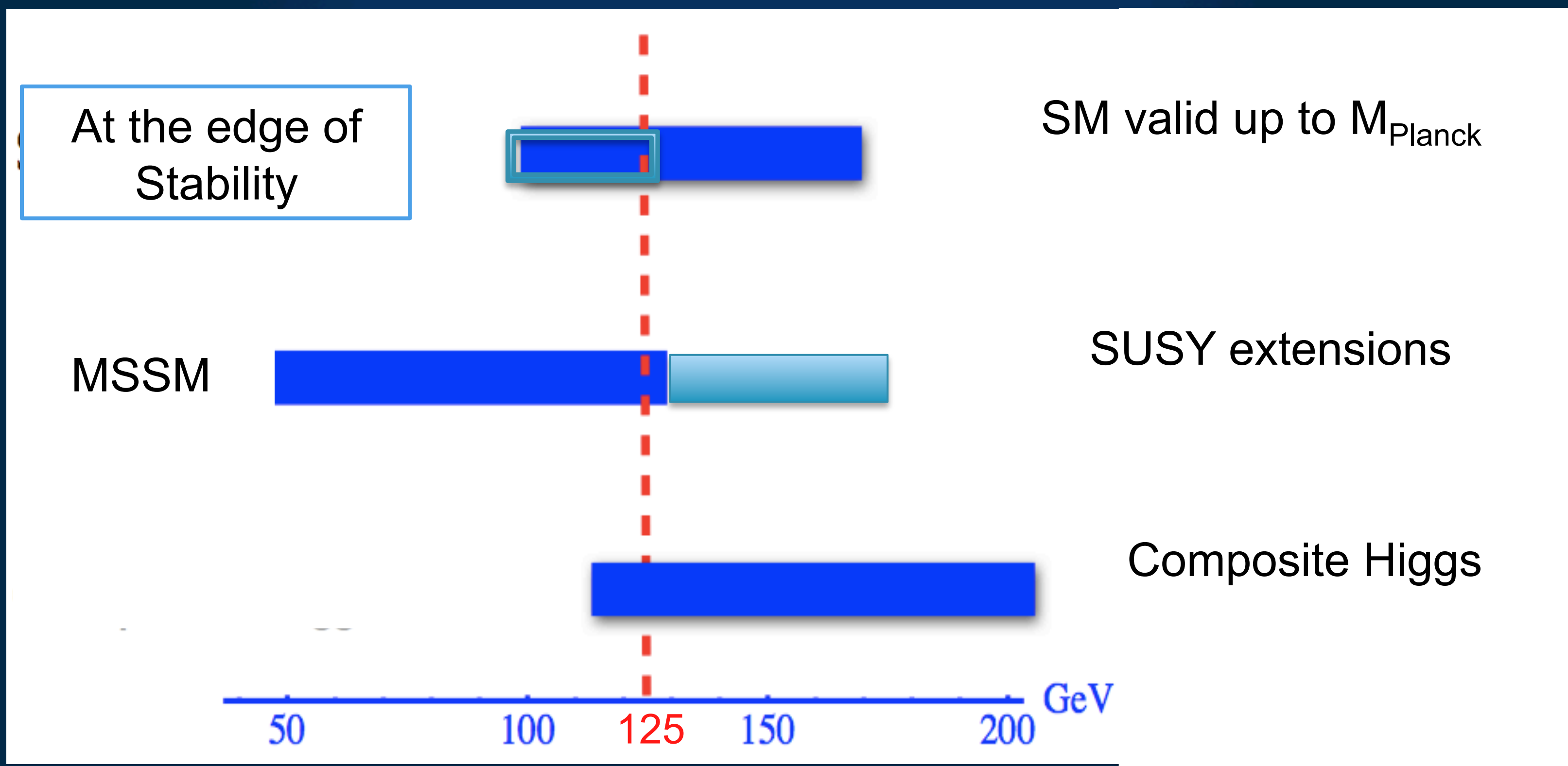
➔ dynamical origin of EWSB

New strong resonance masses constrained by PEWT and direct searches

Higgs ➔ scalar resonance much lighter that other ones

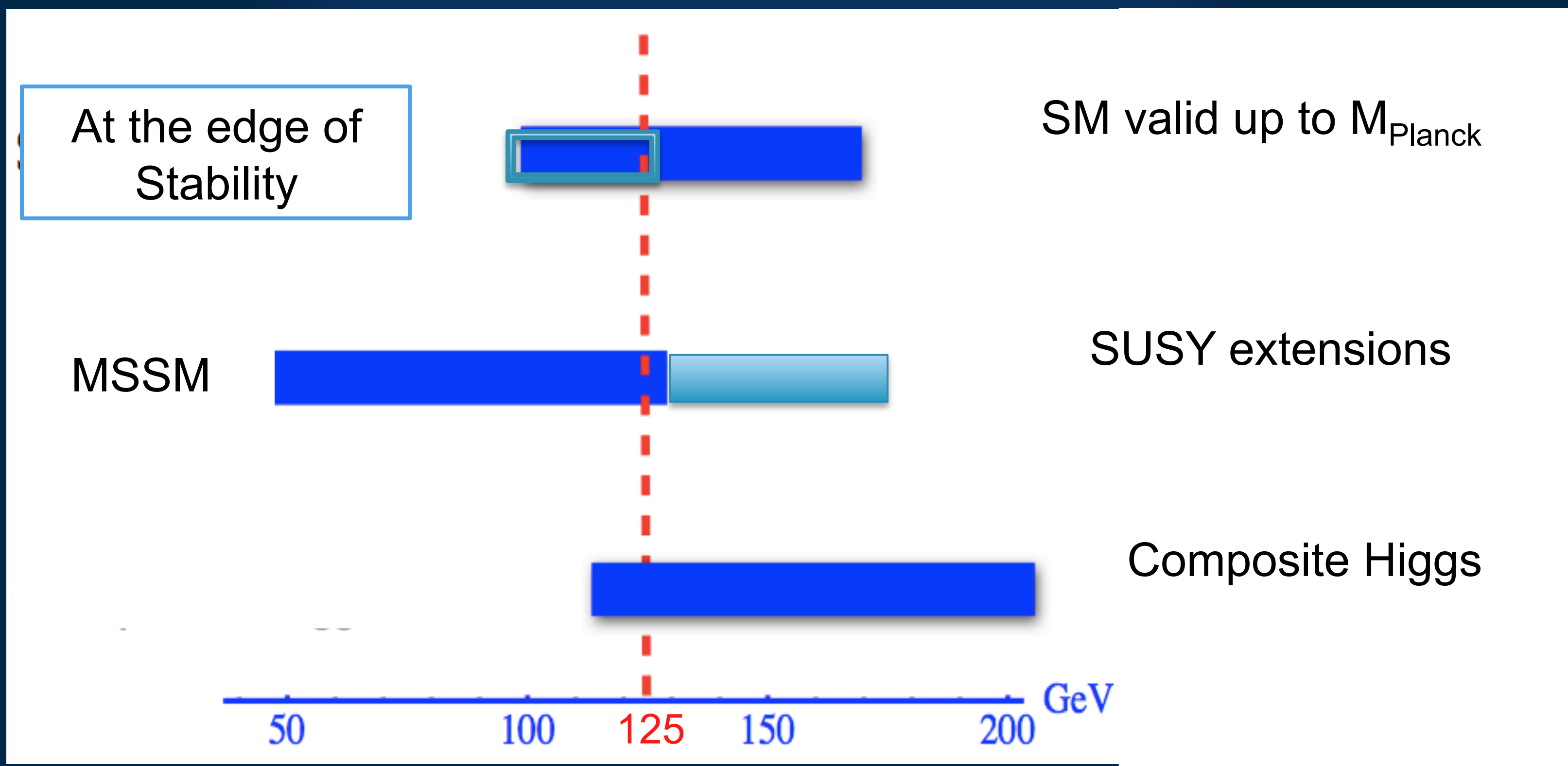
Both options imply changes in the Higgs phenomenology and beyond

What does a 125 GeV Higgs tell us?



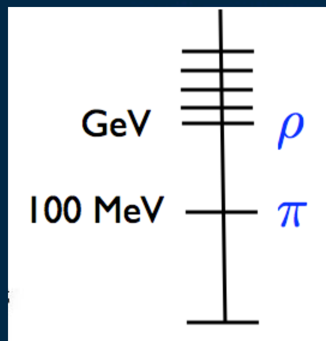
What does a 125 GeV Higgs tell us?

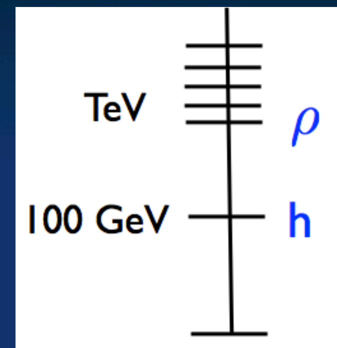
Theorists should be humble



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

$$g, g' \to 0 \quad \& \quad m_q \to 0$$
$$\Rightarrow m_\pi = 0$$
$$m_q \neq 0 \Rightarrow m_\pi^2 \simeq m_q B_0$$
$$e \neq 0 \Rightarrow \delta m_{\pi^\pm}^2 \simeq \frac{e^2}{16\pi^2} \Lambda_{QCD}^2$$

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

Mass protected by the global symmetries

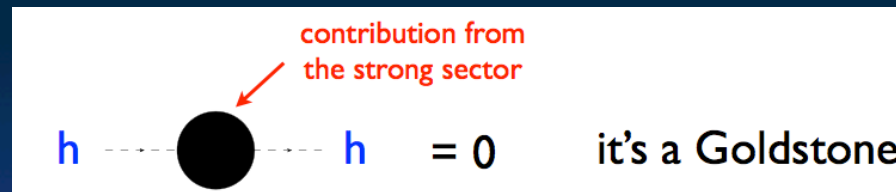
$\pi \rightarrow \pi + \alpha$

Georgi,Kaplan'84; Agashe et al '03

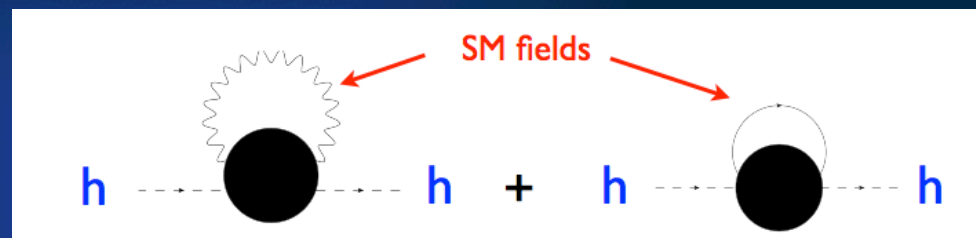
Higgs as a PNGB

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:	$SO(5) \xrightarrow[E \sim f]{}$	$SU(2)_L \times SU(2)_R$	$\xrightarrow[E \sim v]{}$	$SU(2)_V$ custodial

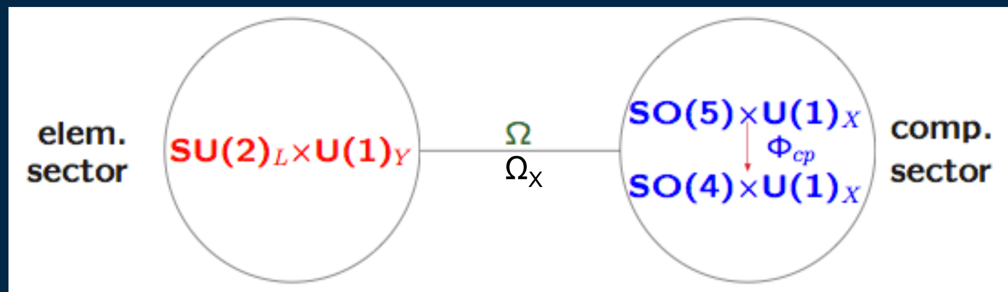
$\underbrace{SO(5) \times U(1)}_{\text{MCHM}}$ smallest group: $\supset G^{EW}_{SM}$ & cust. sym. & H = pNGB

Other symmetry patterns with additional Higgs Bosons

Model	Symmetry Pattern	Goldstone's
SM	SO(4)/SO(3)	W_L, Z_L
–	SU(3)/SU(2)×U(1)	W_L, Z_L, H
MCHM	SO(5)/SO(4)×U(1)	W_L, Z_L, H
NMCHM	SO(6)/SO(5)×U(1)	W_L, Z_L, H, a
MC2HM	SO(6)/SO(4)×SO(2) ×U(1)	$W_L, Z_L, h, H, H^{\pm}, a$

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

Partial compositness

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

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

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 $\rightarrow$ 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 $\text{MCHM}_{\text{Q-U-D}}$ $\longrightarrow$

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

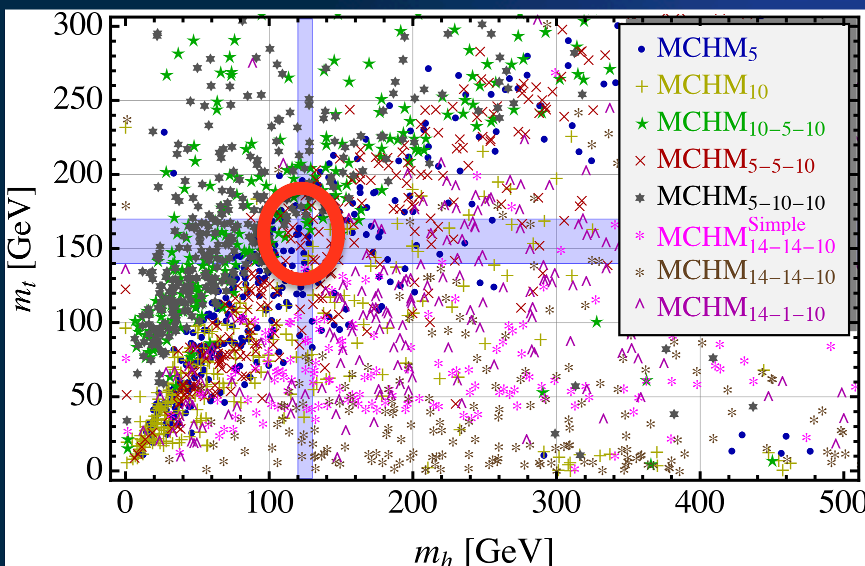
Higgs potential and Higgs mass can be calculated

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**

More stringent constraints from recent data

$\varepsilon < 0.2 – 0.3$

In prep. and also talk by Andrea Wulzer

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

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

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

$$\frac{y_\psi^{(0)}}{m_\psi^{(0)}} \approx \frac{1}{\epsilon f_h} \underbrace{\left[F_\psi(\epsilon) + \mathcal{O}(\epsilon^2 s_{\psi_L}^2) + \mathcal{O}(\epsilon^2 s_{\psi_R}^2)\right]}_{\text{Yukawa corrections } \frac{\mathbf{y}_\psi^{(0)}}{\mathbf{y}_\psi^{\rm SM}}}$$

In most models, the mixing of both chiralities needs to be small to ensure extra suppression

$\Downarrow$

Bottom sector corrections 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 as the bottom quark itself ; max 10% effect, usually less.
We consider all effects in the parameter scan

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

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

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

$\varepsilon = v_{SM}/f$

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

HIGGS PHENOMENOLGY:

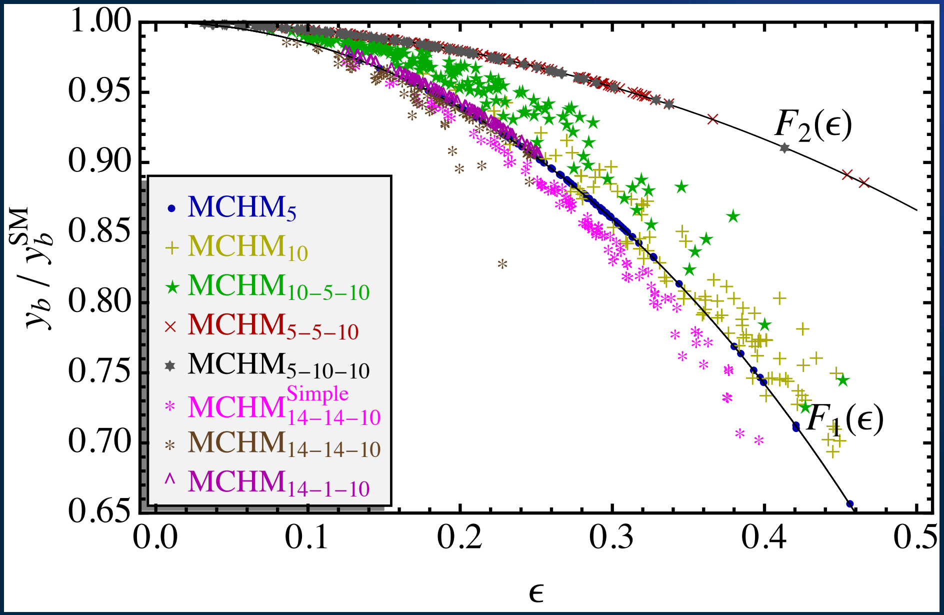
Main effects due to SM fermions and gauge bosons mixing with composite fermion and gauge boson sectors, respectively

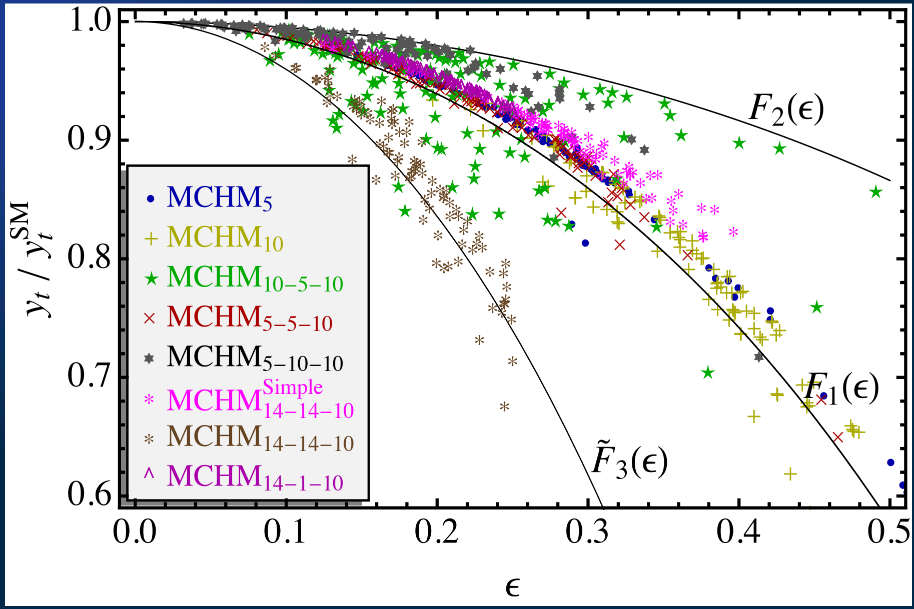
Subleading effects from heavy/strong resonance effects in the loops

➔ 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 of HVV coupling ~ $F_2(\varepsilon)$

M.C., Da Rold, Ponton '14

HIGGS PHENOMENOLGY (cont'd)

Generic features:

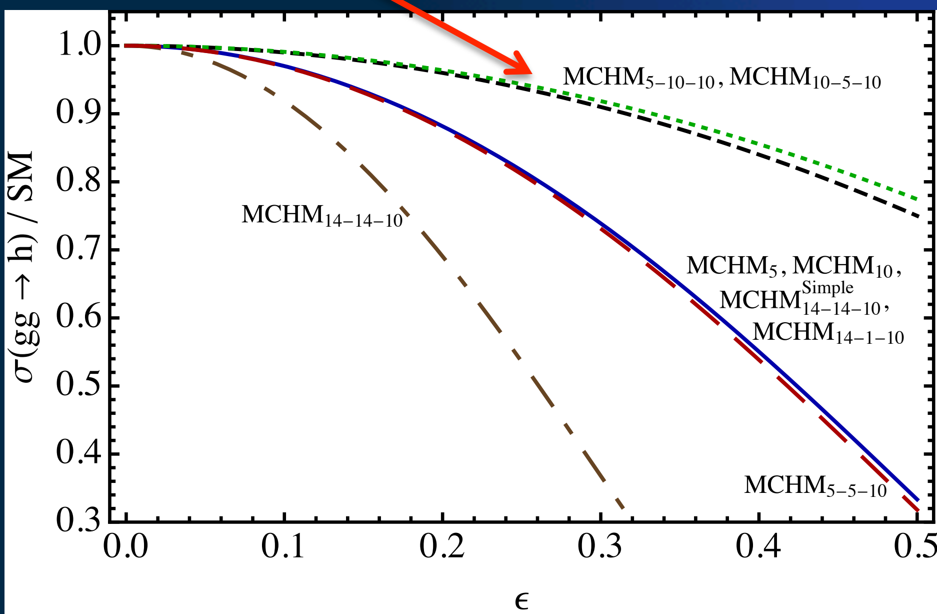
Higgs-gluon fusion and VVH/VH suppression

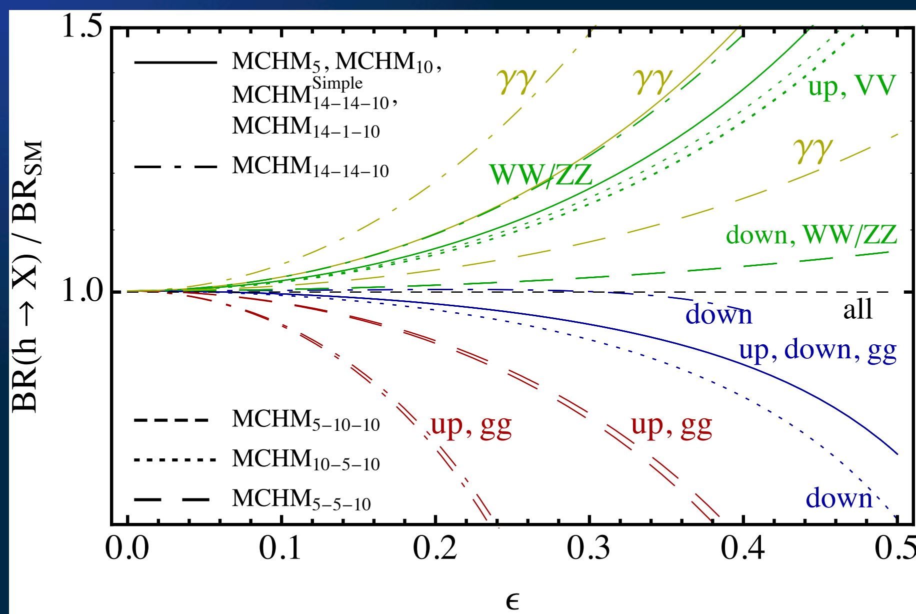
Enhancement or suppression of branching ratios

(Depending on the effect of the total width suppression)

$\sigma(VVH/VH)/\sigma_{SM}$

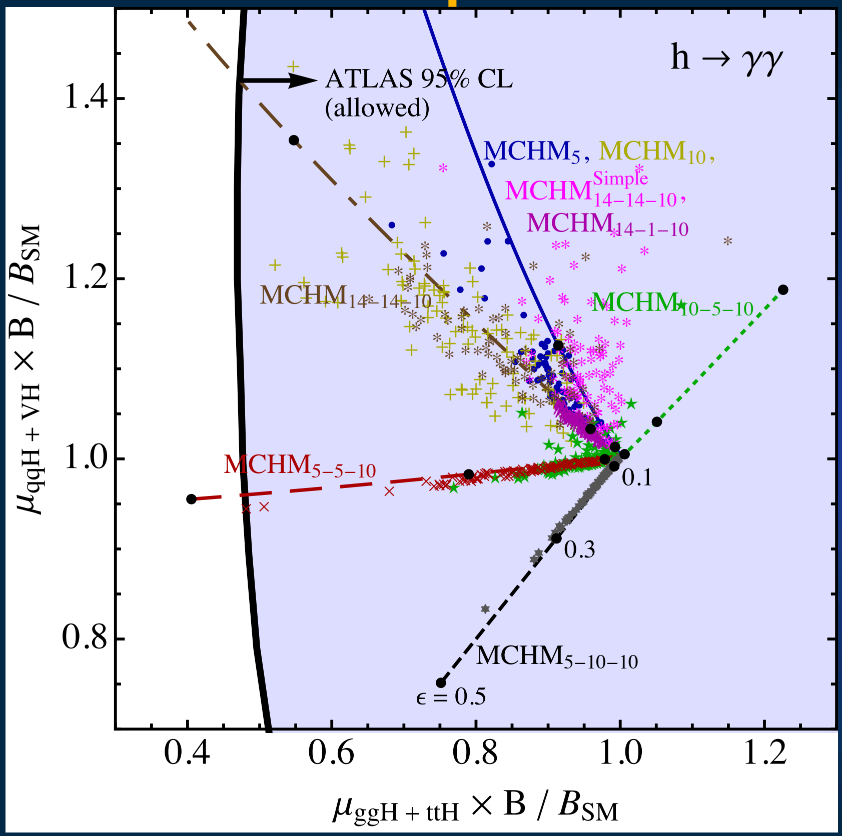
M.C., Da Rold, Ponton '14



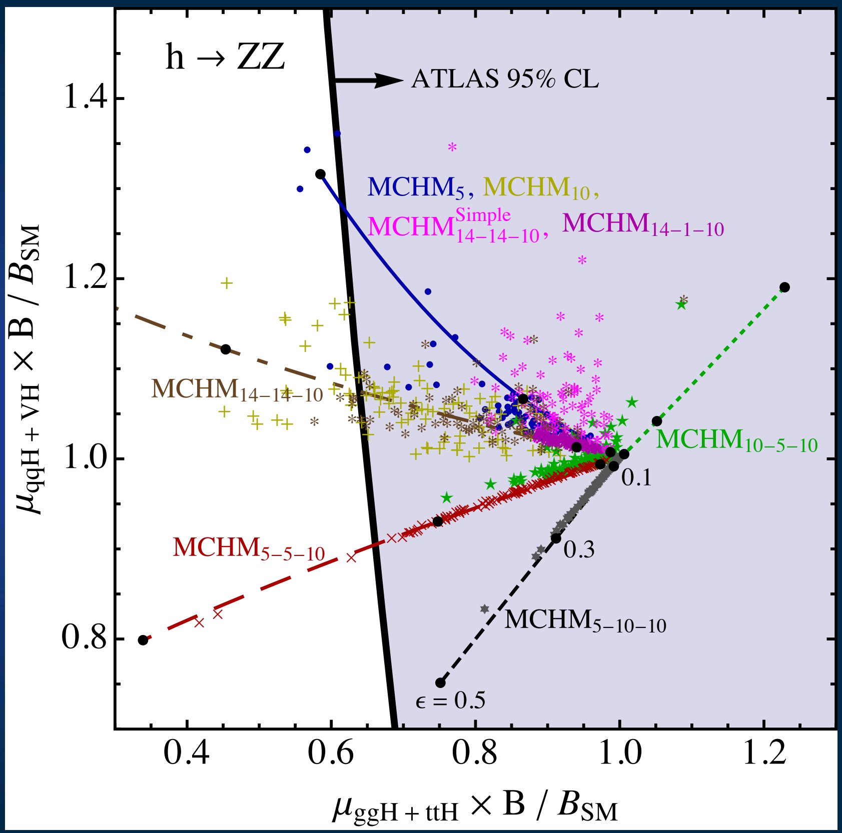


Minimal Composite Higgs models confronting data

h to di-photons



h to ZZ

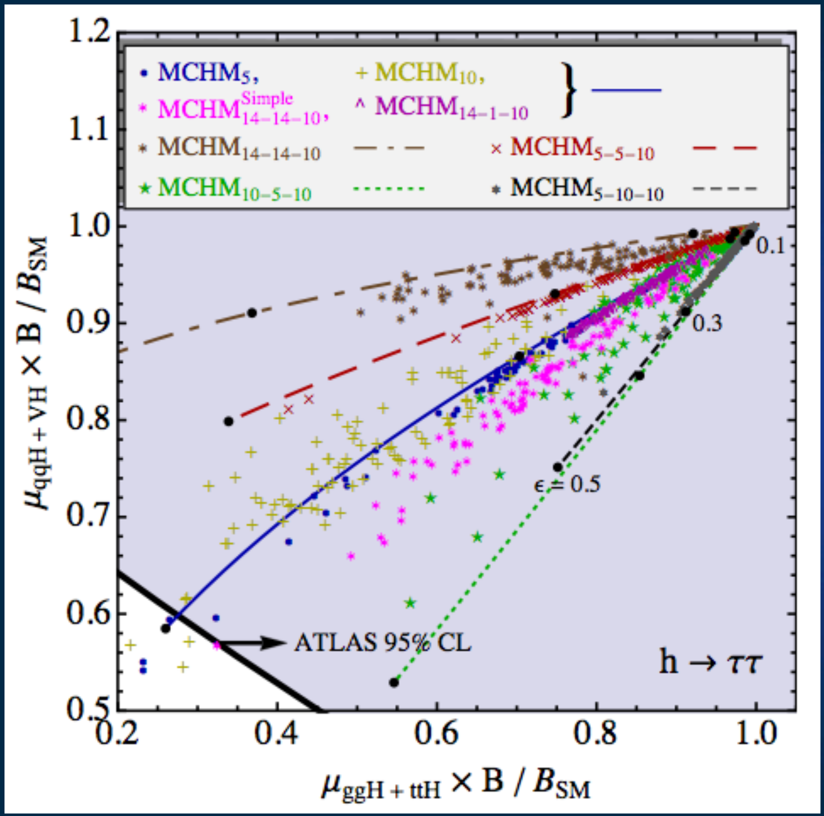


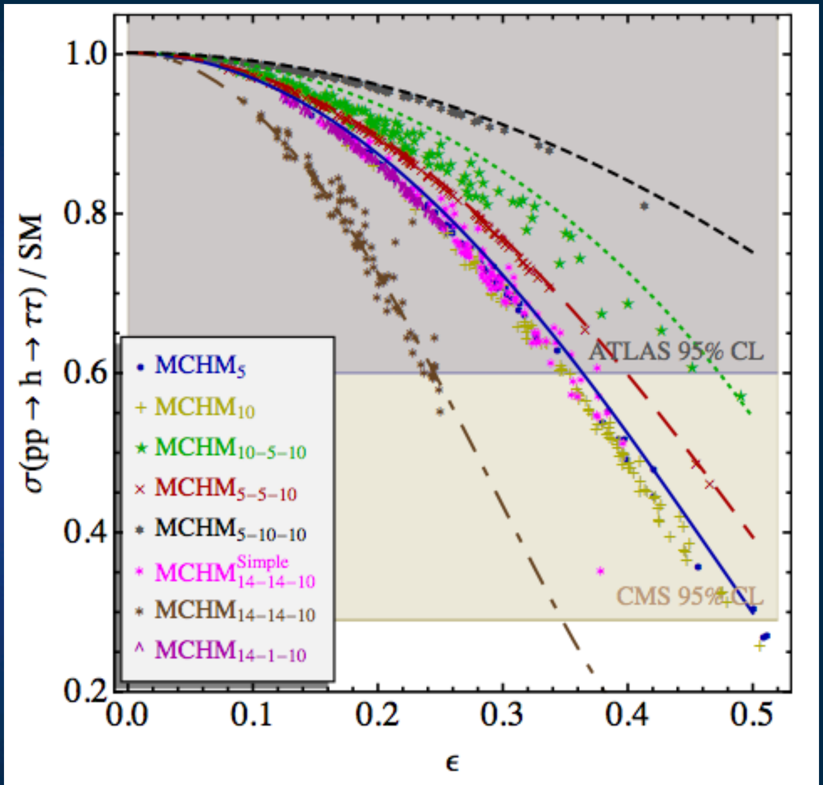
More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

M.C., Da Rold, Ponton '14

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.

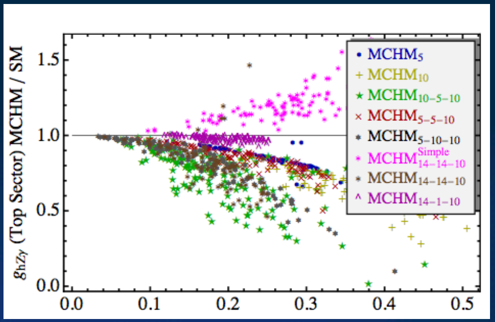
M.C., Da Rold, Ponton '14

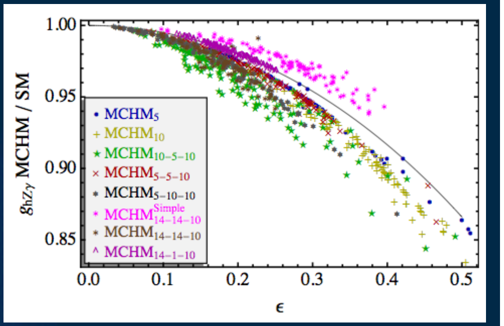
h→Zγ: not yet observed ….

M.C., Da Rold, Ponton '14

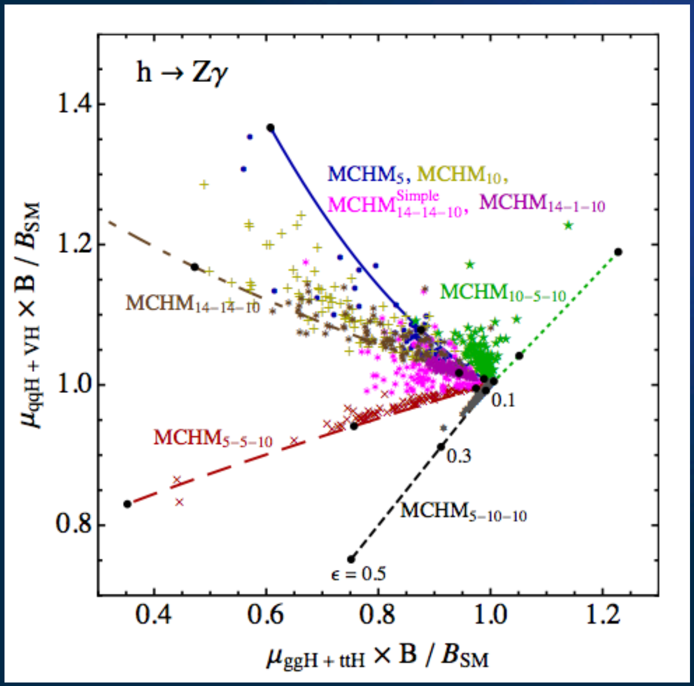
- Corrections from top and its partners can vary the SM value up to 50% → (only top sector, through mixing, breaks P_{LR} symmetry and contributes)

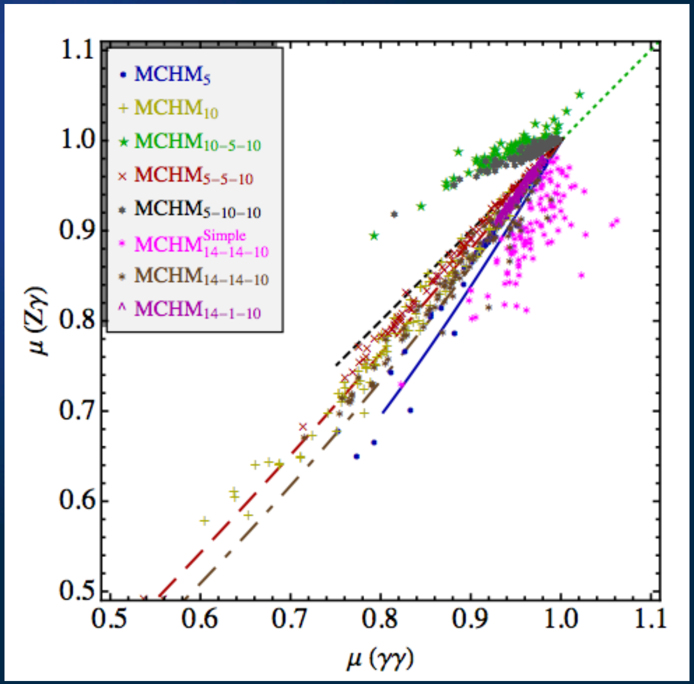
  Azatov et al. '13





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





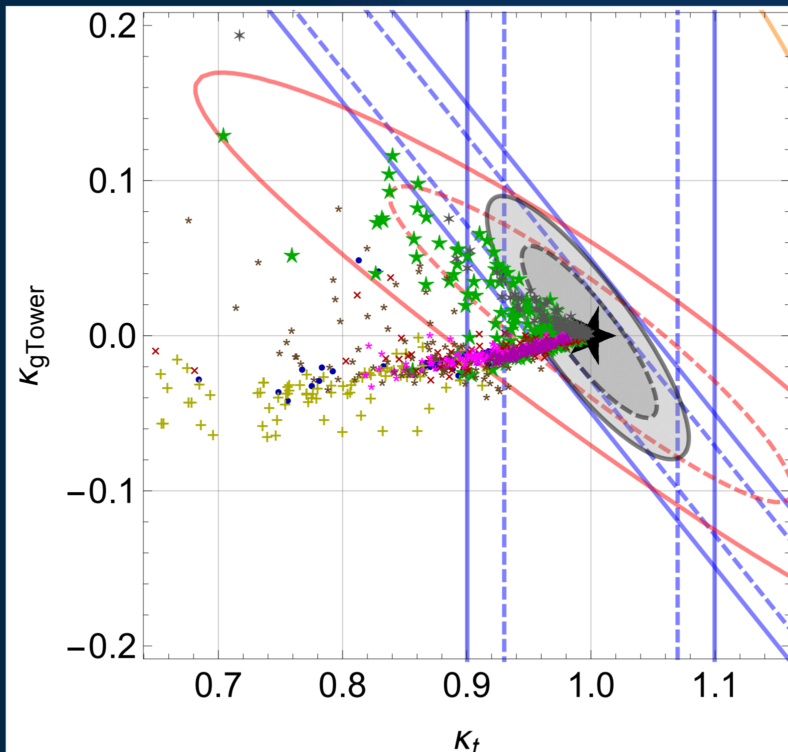
Main effects governed by zero modes
➔ by rv and rt

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

What about the effect of kinematic distributions?

Disentangle effects of the additional vector-like fermions ?
Learn about the degree of compositeness of the top quark?

M.C. Da Rold, Zhen Liu, Ponton, 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 & optimistic projections for LHC 14 TeV at 3000 fb^{-1}

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

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

Ellis, Sanz, You'14; Pomarol, Riva'14

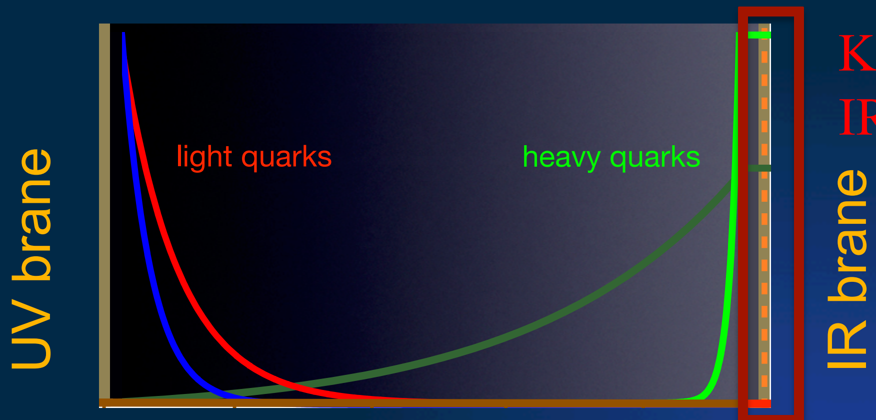
- Recent studies of kinematics of associated Higgs production at the Tevatron and LHC, as well as triple-gauge couplings at the LHC may shed light on coefficients of Dim. 6 operators in an HEFT approach ➔ connection with MCHM's

Other 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

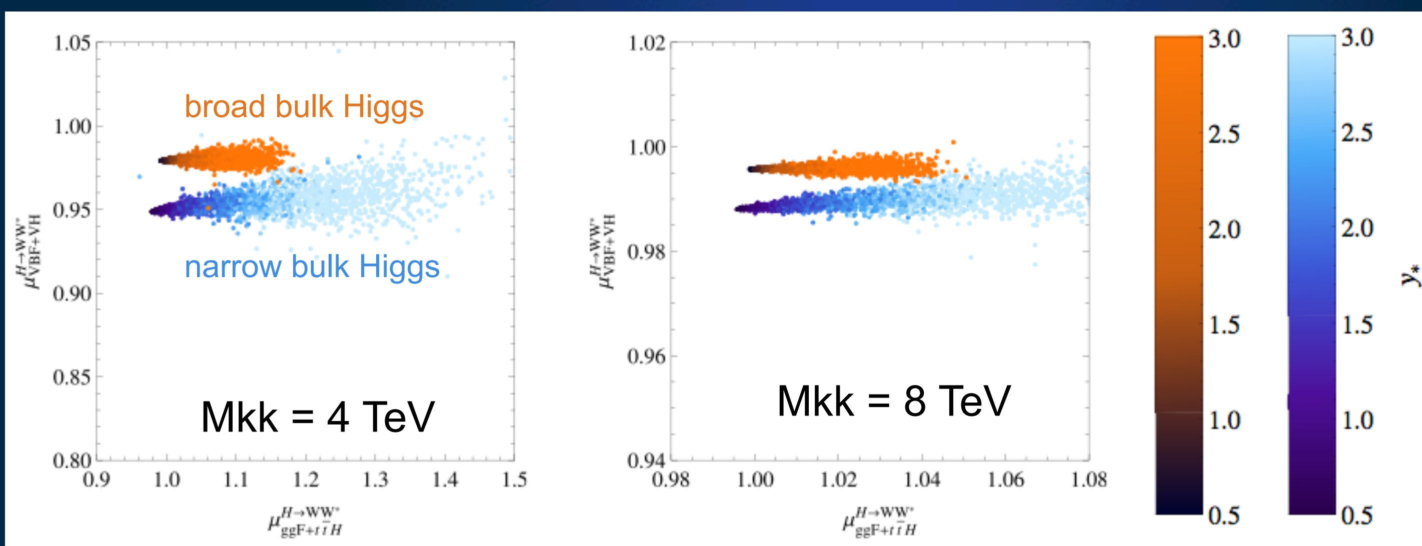


KK modes:
IR localized

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

Composite Higgs Models and NP searches

- Models contain New Vector-like Fermions and New Gauge bosons in the few/several TeV range and above

- If beyond LHC direct reach they might be accessible through departures from Higgs SM properties or in rare decays

- Heavy vector- like quarks at the LHC: some examples

Atre et al, Barducci et al,
Atre, Chala, Santiago
Les Houches 2013

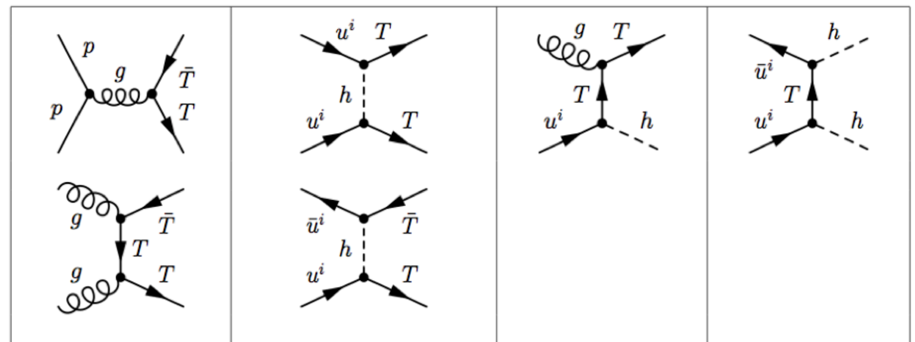
- SU(2) singlet top partner: T
- SU(2) doublet top/bottom partners: (T,B)
- SU(2) doublet with charge 5/3 and charge 2/3 quarks: (X,T)
- SU(2) doublet with charge -1/3 and charge -4/3 quarks: (B,Y)

Decay to either a light quark or a third gen quark, plus Z, W, or h

- $X \to W^+ u_i,$
- $T \to W^+ d_i\,,\; Z u_i\,,\; H u_i,$
- $B \to W^- u_i\,,\; Z d_i\,,\; H d_i,$
- $Y \to W^- d_i,$

Heavy vector-like quarks at the LHC

look for pair production,
single production,
or exotic Higgs production

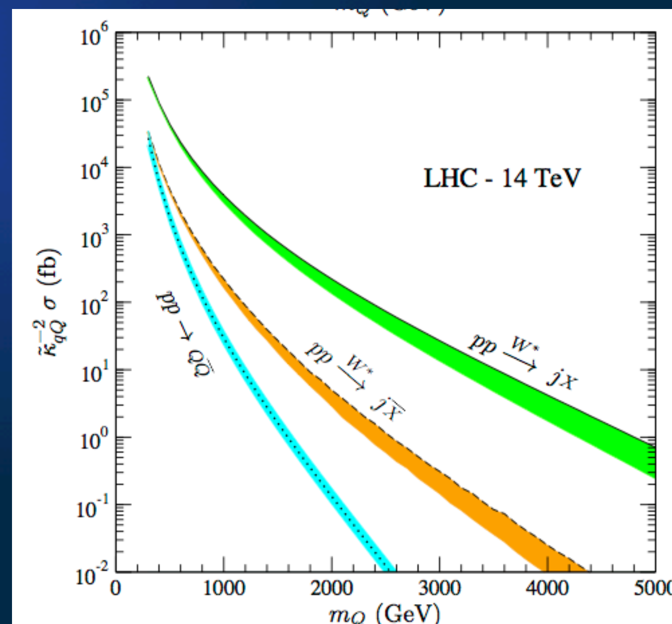


(a) QCD pair prod. (b) non-QCD pair prod. (c) single prod. (d) t-channel

Large variety of LHC signatures, many with energetic leptons

$$
\begin{aligned}
pp &\rightarrow T\bar{T} \rightarrow ZtZ\bar{q} \rightarrow l^+l^-l^+\nu b\bar{q}q'\bar{q}',\\
pp &\rightarrow X\bar{X} \rightarrow W^+tW^-\bar{q} \rightarrow l^+\nu l^-\nu l^-\nu b\bar{q},\\
pp &\rightarrow T\bar{T} \rightarrow ZtZ\bar{q} \rightarrow l^+l^-bq'\bar{q}'l^+l^-\bar{q},
\end{aligned}
$$

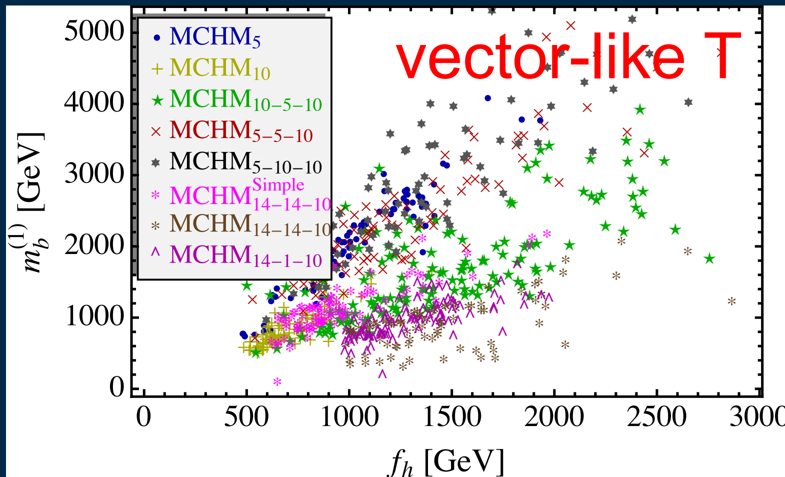
Single production looks most promising at high mass

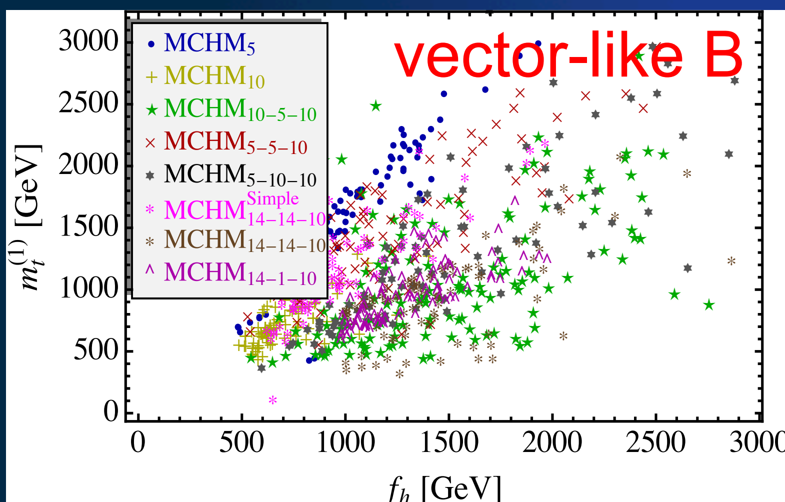


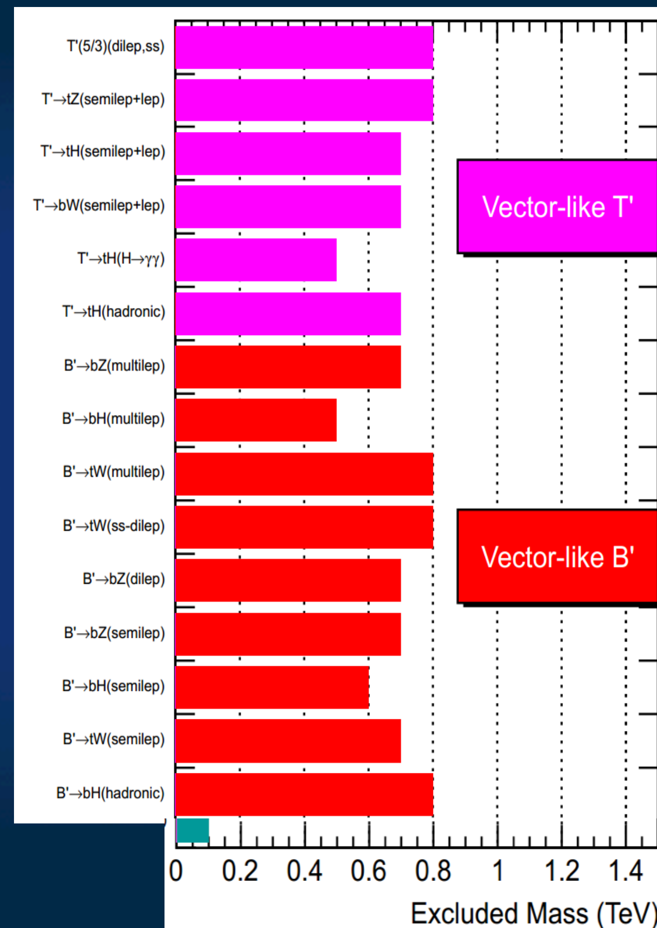
Atre, Azuelos, M.C., Han, Ozcan, Santiago, Unel ‘11
more recent: Matsedonskyi**a, Panico, Wulzer ‘14**

MCHM's (Higgs as a pNGB Higgs) with extended symmetry predict light fermionic res. $M_{cust.} \sim m_\rho \;\; \cos_\psi$

CMS Searches for NP beyond 2 Gen.
95% CL Exclusions (TeV)





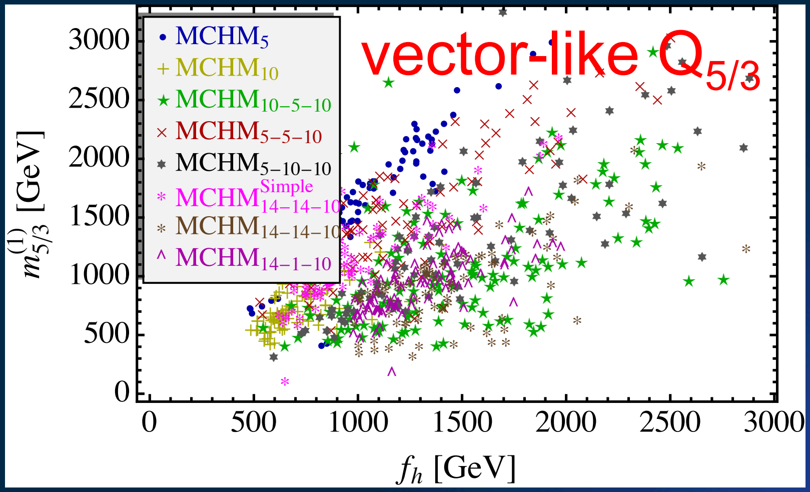


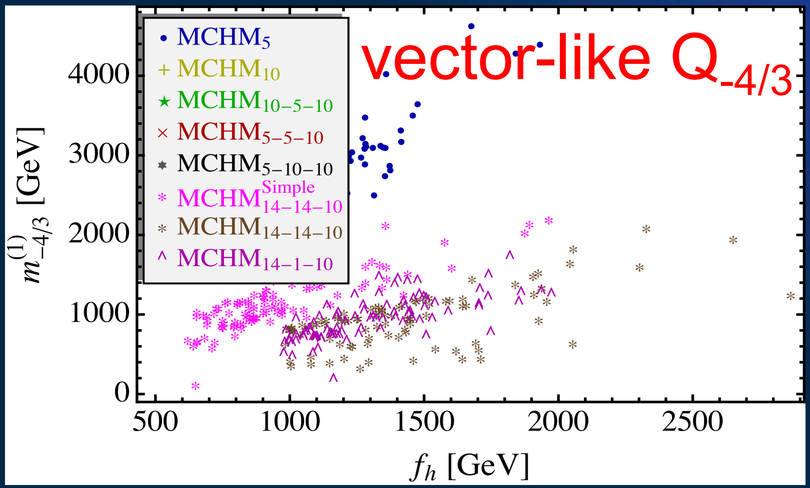
Light fermions (TeV range and possibly exotic charges: Q = 2/3(T),−1/3(B),5/3,8/3,−4/3

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

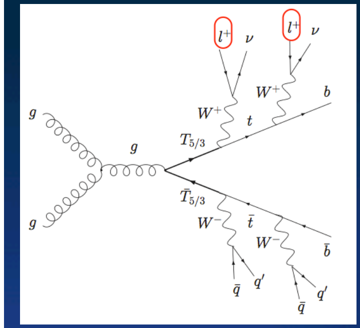
Composite models with extended symmetry predict light fermionic res.

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

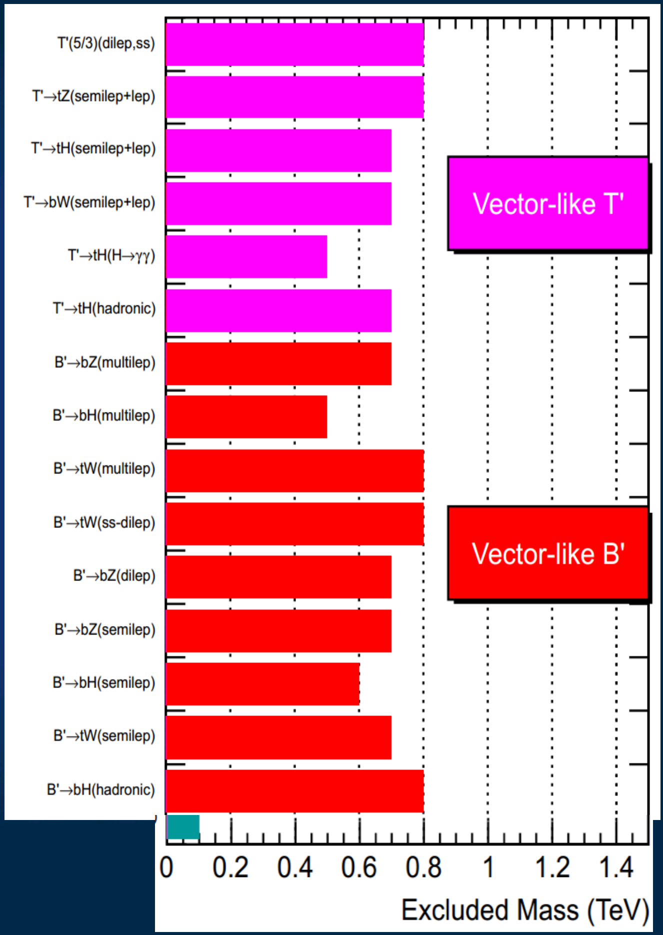




SS di-leptons



CMS Searches:
95% CL Exclusions (TeV)



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]

Outlook

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

Just starting to test them through Higgs precision measurements and vector-like fermion searches, with important constrains from PEWT

- Model Building depends on global symmetry group and composite fermion representations, that yield very different predictions for Higgs physics.
- MCHMs: suppression of production rates and decay widths but possible enhancement of Higgs BR's in di-bosons
- Light fermions, TeV range and possibly exotic charges at LHC reach
- More data on Higgs observables may distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics
- Direct searches for additional Higgs bosons (extended gauge symmetries) are as important as precise measurements of Higgs properties