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Vector-like Bottom Quarks in Composite Higgs models

work in collaboration with M. Gillioz, A. Kapuvari and M. Mühlleitner [JHEP03 (2014) 037]

Ramona Gröber | 16.09.2014

INSTITUTE FOR THEORETICAL PHYSICS

Outline

Composite Higgs Models

u	c	t
d	s	b
e^-	μ^-	τ^-
ν_e	ν_μ	ν_τ

elementary particles

gluon g
photon γ
$W^\pm, Z$

light, since pseudo-Goldstone boson

spin 0: H, ...

spin 1/2: T, B, $X^{5/3}$,...

spin 1: ρ, a,...

strongly interacting sector

- Top quark t can mix with fermionic resonances of the strongly-interacting sector ("top partner" T)
- Higgs boson is pseudo-Goldstone boson of spontaneous symmetry breaking of global symmetry at scale f
  Minimal model: $SO(5) \times U(1)/SO(4) \times U(1)$ [Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol]
- global symmetry explicitly broken $\rightarrow$ Higgs potential generated by quantum corrections

Phenomenology of Composite Higgs Models

- Couplings of Higgs boson modified ($\xi = v^2/f^2$)

$$g_{hVV} = \sqrt{1-\xi}\, g_{hVV}^{SM} \qquad g_{hhVV} = (1-2\xi) g_{hhVV}^{SM}$$

$hf\bar{f}$, hhh, ... couplings depend on fermion embedding

- Novel Higgs couplings, such as e.g. $hhf\bar{f}$ coupling [RG, Mühlleitner]
- New resonances of strong sector
- Higgs mass: Generated at loop level by explicit breaking of G through interactions of SM states with strong sector $\Rightarrow$ Low tuning implies light fermionic resonances

Light Higgs $\Leftrightarrow$ Light Top partners [Matsedonskyi, Panico, Wulzer; Redi, Tesi; Marzocca, Serone, Shu; Pomarol, Riva]

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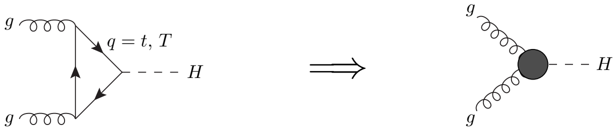
Phenomenology of CHMs – Top partner

Higgs production:

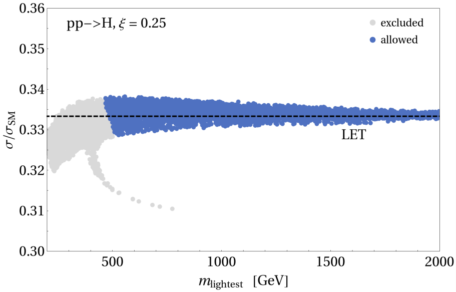


Effects of top-partners can be described by low-energy theorem

$$\mathcal{L}_{hgg} = \frac{g_s^2}{192\pi^2} G^{\mu\nu} G_{\mu\nu} \frac{h}{v} \times \frac{\partial}{\partial \log H} \log \det \underbrace{\mathcal{M}_t^2}_{\text{top mass matrix}}(H)$$

$$= \frac{g_s^2}{192\pi^2} G^{\mu\nu} G_{\mu\nu} \frac{h}{v} \frac{1-2\xi}{\sqrt{1-\xi}}$$

[Gillioz, RG, Grojean, Mühlleitner, Salvioni]



⇒ Depends only on $\xi = v^2/f^2$! Not on details of spectrum! [Falkowski; Low, Vichi; Azatov, Galloway; Gillioz, RG, Grojean, Mühlleitner, Salvioni]

Vector-like fermions in Composite Higgs Models

- Partial compositeness:
  SM fermion masses are generated through linear mixing with partners of strong sector, e.g.:
  $$\Delta\mathcal{L} = \lambda_L \bar{Q}_R q_L + \lambda_R \bar{T}_L t_R$$
- They enter as full multiplets under $SO(5)$, e.g.
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  $\underbrace{\text{spinorial (4)}}_{\text{↯ EWPTs}}$, $\underbrace{\text{fundamental (5)}}_{\text{several multiplets necessary to generate both bottom and top mass by partial compositeness}}$, $\underbrace{\text{antisymmetric (10)}}_{\text{here}}$, ...

Fermion representation

Antisymmetric representation ($\mathbf{10}_{2/3}$ under $SO(5)$):
Simplest single representation, which can give a mass to both top and bottom quark.

Decomposition under $SU(2)_L \times SU(2)_R$

$$(\mathbf{10}) = (\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3}) \oplus (\mathbf{2},\mathbf{2})$$

- $(\mathbf{3},\mathbf{1}) = \begin{pmatrix} \chi \\ u \\ d \end{pmatrix}$
- $(\mathbf{1},\mathbf{3}) = \begin{pmatrix} \chi_1 & u_1 & d_1 \end{pmatrix}$ — d_1 / u_1 mixes with b_R / t_R
- $(\mathbf{2},\mathbf{2}) = \begin{pmatrix} \chi_4 & T_4 \\ t_4 & d_4 \end{pmatrix}$ — (T_4, d_4) mixes with (t_L, b_L)

χ_i has charge 5/3
u, u_1, t_4, T_4 have charge 2/3
d, d_1, d_4 have charge -1/3

Model Lagrangian

Lagrangian:

$$\Delta\mathcal{L}_{ferm} = i\,\mathrm{Tr}(\overline{\mathcal{Q}}_R \not{D} \mathcal{Q}_R) + i\,\mathrm{Tr}(\overline{\mathcal{Q}}_L \not{D} \mathcal{Q}_L) + i\bar{q}_L \not{D} q_L + i\bar{b}_R \not{D} b_R$$
$$+ i\bar{t}_R \not{D} t_R - M_{10}\mathrm{Tr}(\overline{\mathcal{Q}}_R \mathcal{Q}_L) - y\, f \left(\Sigma^\dagger \overline{\mathcal{Q}}_R \mathcal{Q}_L \Sigma\right)$$
$$- \lambda_t \bar{t}_R u_{1L} - \lambda_b \bar{b}_R d_{1L} - \lambda_q (\overline{T}_{4R}, \overline{d}_{4R}) q_L + h.c.\ ,$$

$\mathcal{Q}$ = ten-plet of new vector-like fermions

Goldstone field (in unitary gauge):

$$\Sigma = (0, 0, 0, \sin(H/f), \cos(H/f))$$

Parameters:
$\xi = v^2/f^2$, y, M_{10} and $\sin\phi_L$ (describes admixture of strong sector in left-handed top/bottom before EWSB, with $\tan\phi_L = \lambda_q/(M_{10} + f\ y/2)$)

λ_t/λ_b fixed by requirement that an entry after diagonalization of the mass matrices is m_{top}/m_{bot}

What effects do bottom partners have on electroweak precision tests and Higgs results?

Electroweak precision tests

LEP: Measurement of resonant production of Z boson with high precision
$\rightarrow$ New physics models have to fulfill constraints

Parametrisation with $\epsilon_1, \epsilon_2, \epsilon_3$ and ϵ_b:

(or equivalently S, T, U [Peskin, Takeuchi] and $\delta g_{Z \to b_L \bar{b}_L}$)

[Altarelli, Barbieri, Caravaglios, Jadach]

- ϵ_1 (or T):
  Divergent contribution due to modified Higgs couplings to vector bosons:

$$\Delta\epsilon_1^{IR} = -\frac{3\alpha(m_Z^2)}{16\pi \sin^2\theta_W}\xi \log\left(\frac{m_\rho^2}{m_Z^2}\right) \ .$$

[Barbieri, Bellazzini, Rychkov, Varagnolo]

  Cut-off by mass of first vector resonance m_ρ.

  Contributions from new fermions in loop.

[Lavoura, Silva; Anastasiou, Furlan, Santiago; Agashe, Contino; Gillioz]

- ϵ_3 (or S):
  Divergent contribution due to modified Higgs couplings:

$$\Delta\epsilon_3^{IR} = \frac{\alpha(m_Z^2)}{48\pi \sin^2\theta_W}\xi \log\left(\frac{m_\rho^2}{m_Z^2}\right) \ .$$

[Barbieri, Bellazzini, Rychkov, Varagnolo]

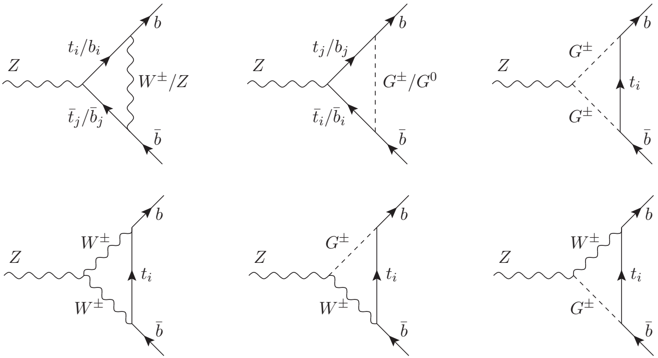
  Mixing with vector resonance ρ or axial vector resonance a:

$$\Delta\epsilon_3^{UV} = \frac{m_W^2}{m_\rho^2}\left(1 + \frac{m_\rho^2}{m_a^2}\right) \ .$$

[Contino]

The constraint on ϵ_b

Previous works: No mixing of bottom quark [e.g.: Anastasiou, Furlan, Santiago]



NEW: Full mixing of bottom quark with partners!
New counterterms necessary for renormalization.

The constraint on ϵ_b

Bare Lagrangian

$$\mathcal{L}_{Z\bar{b}_L b_L} = -\frac{e}{s_W c_W} \bar{b}^0_{L,i}\, \gamma_\mu\, U^{0L}_{ij} \left(T_{3,L} - 2 s_W^2 Q\right)_{jj} U^{0L\,\dagger}_{jk}\, b^0_{L,k}\, Z^\mu \ .$$

- Renormalization of bare field:

$$b^0_{L,i} \to \left(\delta_{ij} + \frac{1}{2}\delta Z_{ij}\right) b_{L,j}$$

- Renormalization of mixing matrix:

$$U^0_{ij} \to \left(\delta_{ik} + \delta u_{ik}\right) U_{kj}$$

The counterterm is defined anti-hermitian to ensure unitarity [Denner, Sack; Yamada; Gambino, Grassi, Madricardo; ...]

$$\delta u^L_{bot,ij} = \frac{1}{4}\left(\delta Z^L_{ij} - \delta Z^{L\,\dagger}_{ij}\right) .$$

Results on EWPTs

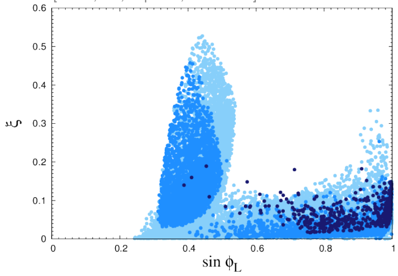
- Our results can easily be applied to other models
- Scan over

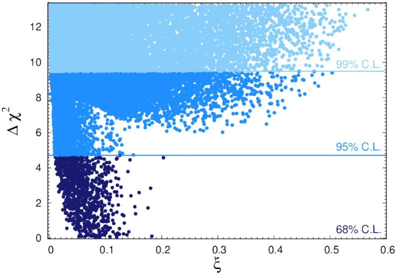
$$0 \leq \xi \leq 1\,, \qquad 0 < \sin\phi_L \leq 1\,, \qquad |y| < 4\pi\,, \qquad 0 \leq M_{10} \leq 10\ \text{TeV}\,.$$

- $$\chi^2 = \sum_{i,j=1,2,3,b} \left(\epsilon_i^{th} - \epsilon_i^{exp}\right) C_{ij}^{-1} \left(\epsilon_j^{th} - \epsilon_j^{exp}\right) \qquad \chi^2 - \chi^2_{min} < 13.28$$

- Additional constraint: $|V_{tb}| > 0.92$ [CMS collaboration]

[Gillioz, RG, Kapuvari, Mühlleitner]





- Bottom partner can contribute up to factor of 2 to $\Delta\chi^2$
- Higgs contributions are small: $\lesssim 3\%$

Direct searches

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Due to pair production of new vector-like fermions.

- Lightest new fermion in the model is exotic 5/3 charged fermion.
- Decays to 100% into Wt
- At time of the analysis:

$$m_\chi \geq 770 \text{ GeV}$$

[CMS-PAS-B2G-12-012]

(Now: $m_\chi \geq 800$ GeV)

- Limits on bottom partners were weaker.
- Limits of top partners were partially stronger, depending on BR's.
- They are given under the assumption of

$$BR(T \to th) + BR(T \to Zt) + BR(T \to W^+ b) = 1$$

- Strongest bound for $BR(T \to ht) = 1 \Rightarrow m_T \geq 850$ GeV [ATLAS-CONF-2013-018]
- Even though $m_T > m_\chi$ the bounds of this search can be applied here, as point is either already excluded by [CMS-PAS-B2G-12-012] or decay $T \to \chi_{5/3} W^-$ is kinematically not allowed.

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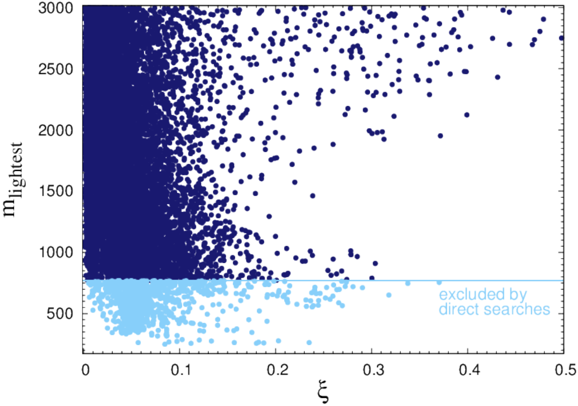
Direct searches– Results



→ Searches on 2/3 charged fermions did not give any additional exclusion to the search [CMS-PAS-B2G-12-012] of 5/3 charged fermions.

Higgs results

The gluon fusion cxn cannot be described by LET anymore, because $m_b \ll m_h$:

$$\mathcal{L}_{hgg} = \frac{g_s^2}{192\pi^2} G^{\mu\nu} G_{\mu\nu} \frac{h}{v} \left(\frac{\partial}{\partial \log H} \log \det \mathcal{M}^2(H) - \sum_{m_i < m_h} \frac{y_{ii} v}{M_i} \right)$$

$\rightsquigarrow$ dependence on spectrum [Azatov, Galloway]

Procedure:

- Higgs production:
  Heavy quark loops for $gg \to h$ implemented in HIGLU [Spira] (at NLO QCD)

$$\sigma_{Hq\bar{q}} = \sigma^{SM}_{Hq\bar{q}} (1-\xi)\,, \qquad \sigma_{WH/ZH} = \sigma^{SM}_{WH/ZH} (1-\xi)\,, \qquad \sigma_{t\bar{t}H} = \sigma^{SM}_{t\bar{t}H} \left(g_{ht\bar{t}} / g^{SM}_{ht\bar{t}} \right)^2$$

- Higgs decays:
  Implemented in HDECAY [Djouadi, Kalinowski, Mühlleitner, Spira]

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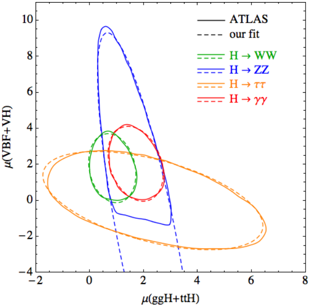
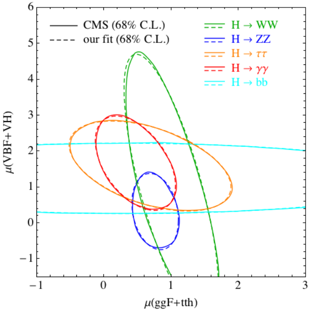
Higgs results based on [ATLAS-CONF-2013-034] and [CMS-PAS-HIG-13-005]

[Gillioz, RG, Kapuvari, Mühlleitner]





$$\chi^2 = \sum_{channnels} \sum_{i,j=1,2} (\mu_i^{exp} - \mu_i^{theo}) C_{ij}^{-1} (\mu_j^{exp} - \mu_j^{theo}) + \chi^2_{EWPT} + \frac{(|V_{tb}^{exp}| - |V_{tb}^{theo}|)^2}{(\Delta V_{tb})^2}$$

with

$$C = \begin{pmatrix} \Delta\mu^2_{ggH+ttH} & \rho\Delta\mu_{ggH+ttH}\,\Delta\mu_{VBF+VH} \\ \rho\Delta\mu_{ggH+ttH}\,\Delta\mu_{VBF+VH} & \Delta\mu^2_{VBF+VH} \end{pmatrix} \qquad \Delta\mu = \sqrt{\Delta\mu^2_{exp} + \Delta\mu^2_{theo}}$$

Exception: ATLAS $H \to b\bar{b}$

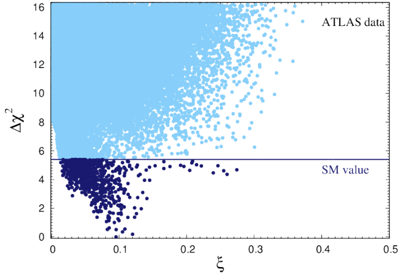
Higgs results

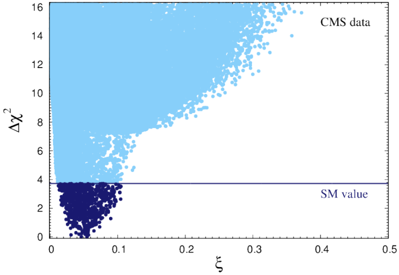
- Scan over parameter space

$$0 \leq \xi \leq 1 \,, \qquad 0 < \sin\phi_L \leq 1 \,, \qquad |y| < 4\pi \,, \qquad 0 \leq M_{10} \leq 10 \text{ TeV} \,.$$

- Point excluded from scan if not allowed by direct searches

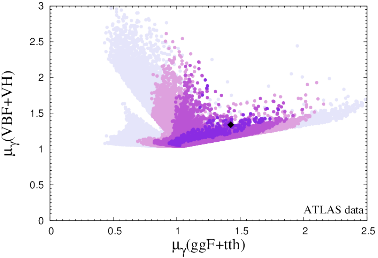
[Gillioz, RG, Kapuvari, Mühlleitner]

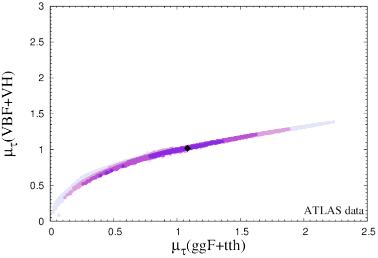


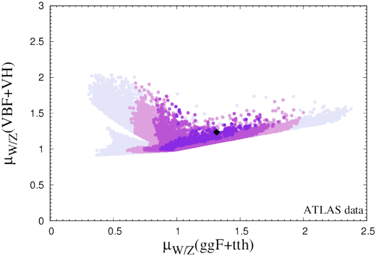


Higgs Results: ATLAS

[Gillioz, RG, Kapuvari, Mühlleitner]



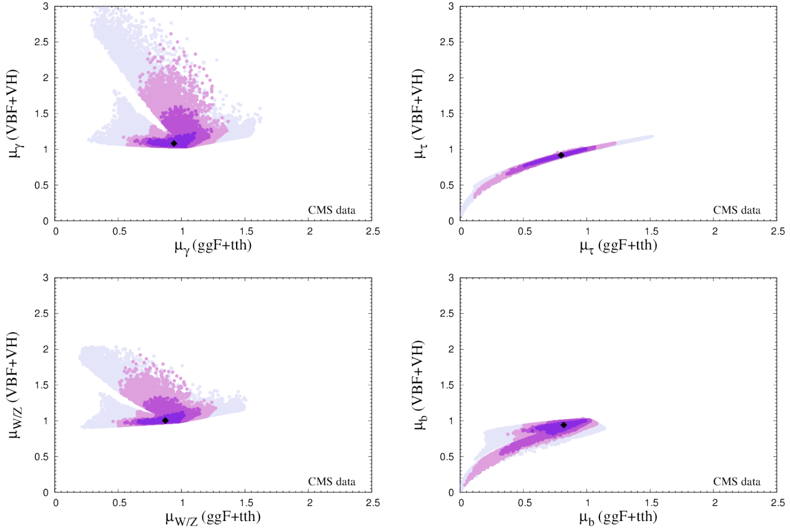




$$\mu_a(i+j) = \frac{(\sigma_i + \sigma_j)BR(h \to aa)}{(\sigma_i^{SM} + \sigma_j^{SM})BR^{SM}(h \to aa)}$$

Higgs Results: CMS

[Gillioz, RG, Kapuvari, Mühlleitner]



Conclusions

- We investigated the effects of new vector-like fermionic bottom partners in the framework of *partial compositeness*.
- Bottom partners can directly influence EWPTs through loop contributions. Mixing of the bottom quark with partners needs to be taken into account.
- Bottom partners lead to a dependence of Higgs cross sections on spectrum.
- Simple model can pass EWPTs, direct searches for new fermions, constraint on V_{tb} and current Higgs results.

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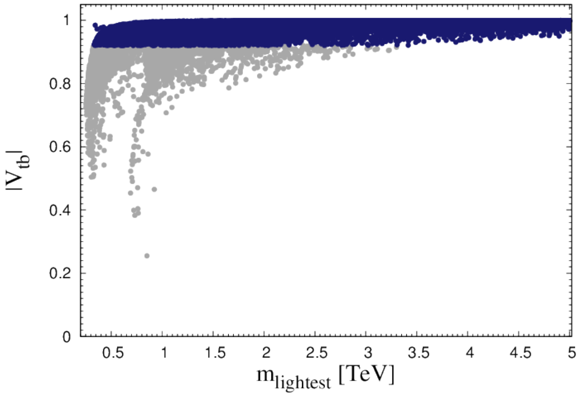
Thanks for your attention!

Constraint on V_{tb}



Light Higgs – Light Resonance

For a light Higgs boson light top partners are needed.

Approximative formula:

[Pomarol, Riva]

$$m_Q \leq \frac{m_h \pi v}{m_t \sqrt{N_c} \sqrt{\xi}}$$

Best fit points

	ξ	χ^2
ATLAS	0.096	12.34
CMS	0.057	6.63

$\longrightarrow$

Best fit points using approximative formula

	ξ	χ^2	$m_{T_{lightest}}$
ATLAS	0.067	13.71	0.8 TeV
CMS	0.055	7.17	1.3 TeV