Karlsruhe Institute of Technology

Vector-like fermions in Composite Higgs models

based on work in collaboration with M. Gillioz, A. Kapuvari and M. Mühlleitner
Ramona Gröber | 30.08.2013

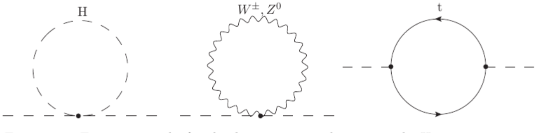
INSTITUTE FOR THEORETICAL PHYSICS

Outline

1. Motivation
2. Composite Higgs models
3. Electroweak precision tests
4. Higgs results

Fine-tuning problem

Quantum corrections to Higgs mass:



Effective field theory:

$$\frac{\delta m_h^2}{m_h^2} = \frac{3\Lambda^2}{8\pi^2 v^2}\left(\frac{4m_t^2}{m_h^2} - \frac{2m_W^2}{m_h^2} - \frac{m_Z^2}{m_h^2} - 1\right) = \left(\frac{\Lambda}{500\text{GeV}}\right)^2$$

or equivalently (in a renormalizable theory), a new heavy scalar with interaction $\lambda|H|^2|\Phi|^2$ would contribute with

$$\delta m_h^2 \approx \frac{\lambda}{16\pi^2} M^2 \ln \frac{M^2}{\mu^2} \, .$$

An enormous cancellation must take place $\rightarrow$ fine-tuning.

"Conspiracy between phenomena occuring at very different length scales." [Giudice]

Fine-tuning – Ways out

Why is there no quadratic dependence on cut-off for e.g. fermions?

Symmetry enhancement for $m_f \to 0$ (chiral symmetry).

$$\delta m_f \propto m_f \ln \frac{m_f}{\Lambda}$$

Ways out for scalar particles (Higgs boson):

- (Low-energy) SUSY: Links fermions and bosons, extends chiral symmetry to scalar sector.
- Composite Higgs Models: compositeness + additional global symmetry.
- ...

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Composite Higgs Models

- Additional strong sector → Higgs as resonance
- Why is the Higgs boson lighter than the other resonances?

⇝ similar to QCD: Higgs plays role of pion

Higgs is a pseudo Goldstone boson from a global symmetry G with

$$G \xrightarrow{\text{at scale } f} H \supset SU(2)_L \times SU(2)_R$$

Minimal models:

$$SO(5) \times U(1)_X \to SO(4) \times U(1)_X$$

[Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol]

- Describtion by non-linear σ-model

$$\mathcal{L} = \frac{f^2}{2}(D_\mu \Sigma)(D^\mu \Sigma), \qquad \Sigma = (0, 0, 0, \sin H/f, \cos H/f)$$

Expand $\mathcal{L}$ around $\langle H \rangle$ ⇝

$$g_{hVV} = g_{hVV}^{SM}\sqrt{1-\xi} \quad \text{with} \quad \xi = \frac{v^2}{f^2} = \sin^2 \frac{\langle H \rangle}{f}$$

- Higgs mass: Generated at loop level by explicit breaking of G through interactions of SM states with strong sector ⇒ Higgs mass is related to masses of other resonances

Light Higgs ⇔ Light fermionic resonances

[Matsedonskyi, Panico, Wulzer; Redi, Tesi; Marzocca, Serone, Shu; Pomarol, Riva]

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Fermionic resonances

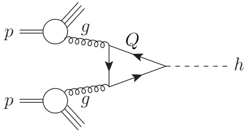
- New fermions are vector-like:

  Both right-handed and left-handed components transform in same way.
- Partial compositeness:
  SM fermion masses are generated through linear mixing with partners of strong sector, e.g.:
  $$\Delta\mathcal{L} = \lambda_L \bar{q}_L Q_L + \lambda_R \overline{T}_R t_R$$
  Phenomenologically most interesting for 3rd generation fermions
- Models with new vector-like fermions in full representations (fundamental) of $SO(5)$ can be compatible with EWPT [Gillioz; Anastasiou, Furlan, Santiago; Lodone; ...]

Top Partners

Higgs production:

Effects of top-partners can be described by low-energy theorem ($m_f \gg m_h$)



$\Longrightarrow$

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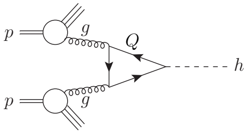

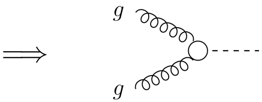

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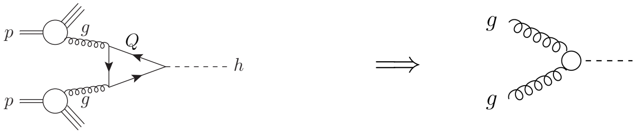
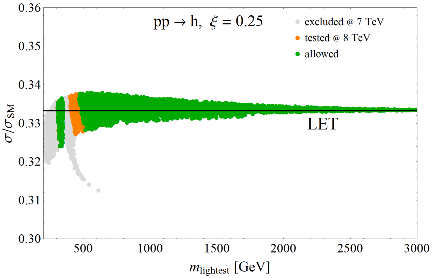


$$\mathcal{L}_{hgg} = \frac{g_s^2}{192\pi^2} G^{\mu\nu} G_{\mu\nu} \frac{h}{v} \times \frac{\partial}{\partial \log H} \log\det \underbrace{\mathcal{M}_t^2}_{\text{top mass matrix}} (H)$$

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

[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]

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

A “simple” model – New fermions

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

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

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

- $(\mathbf{3},\mathbf{1}) = \begin{pmatrix} \chi \\ u \\ d \end{pmatrix}$
- $(\mathbf{1},\mathbf{3}) = \begin{pmatrix} \chi_1 & u_1 & d_1 \end{pmatrix}$ — 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 has charge -1/3

A "simple" model – Lagrangian

Lagrangian:

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

$\mathcal{Q}$=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 $\sin\phi_L$ (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}

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 $\delta g_{Z\rightarrow b_L \bar{b}_L}$)

[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]

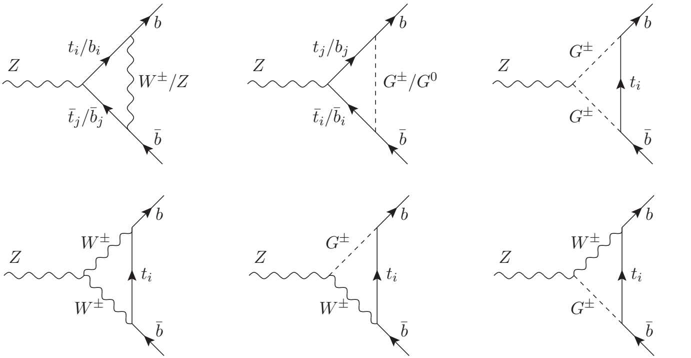
  Mixing with vector resonance ρ or axial vector resonance a:

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

  [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 for the renormalization necessary.

The constraint on ϵ_b

Bare Lagrangian

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

- 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; ...]

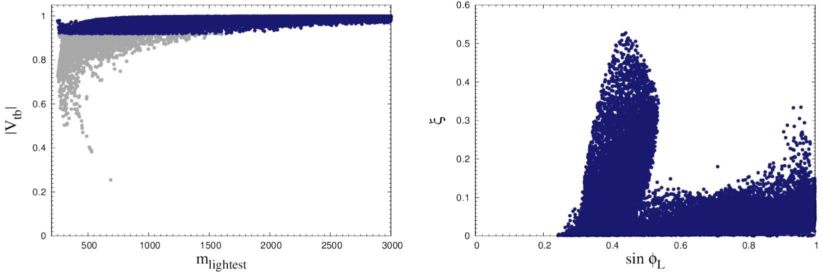
$$\delta u^L_{bot,ij} = \frac{1}{4}\left(\delta Z^L_{ij} - \delta Z^{L\,\dagger}_{ij}\right) .$$

Results on EWPTs

- $\delta g_{BSM} - \delta g_{SM}$ finite if mixing matrix renormalization included
- 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]



- Bottom partner can contribute up to $\approx 55\%$ to $\Delta\chi^2$
- Higgs contributions are small: $\lesssim 3\%$

Higgs results

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

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

$\rightsquigarrow$ 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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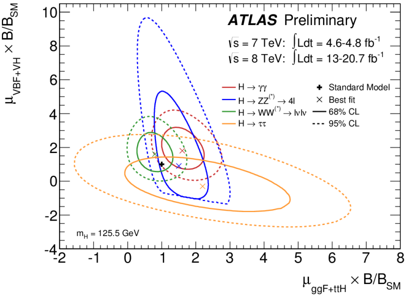
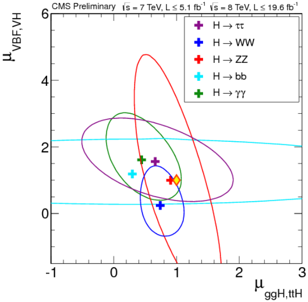




$$\chi^2 = \sum_{channnels} \sum_{i,j=1,2} (\mu_i^{exp} - \mu_i^{theo}) C_{ij}^{-1} (\mu_j^{exp} - \mu_j^{theo}) + \chi^2_{EWPT} + \frac{(|V_{tb}^{exp}| - |V_{tb}^{theo}|)^2}{(\Delta V_{tb})^2}$$

with

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

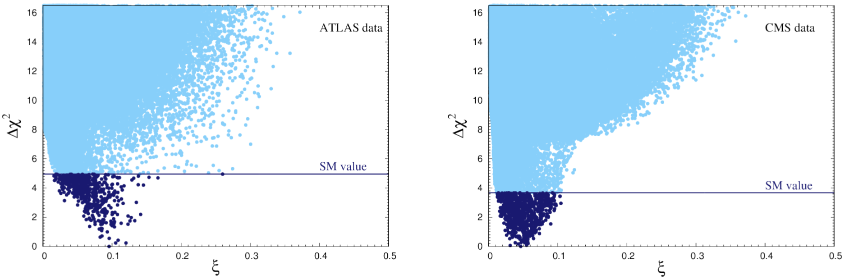
Exception: ATLAS $H \to b\bar{b}$

Higgs results

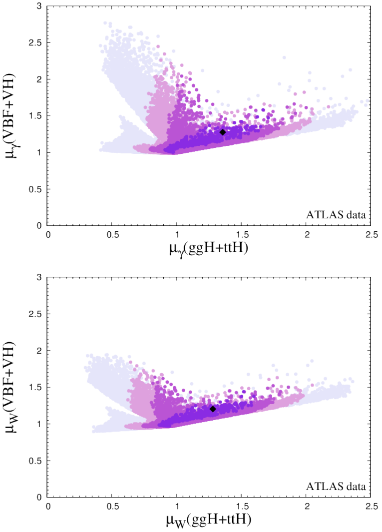
- Scan over parameter space

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

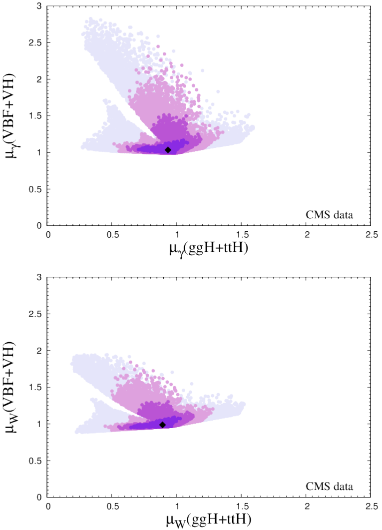
- Point rejected if excluded by direct searches for new fermions analogously to: [Gillioz, RG, Grojean, Mühlleitner, Salvioni]



Higgs Results: ATLAS



Higgs Results: CMS



Conclusion

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

Thanks for your attention!

Mass matrices

$$-\mathcal{L}_{m_t} = \overline{\begin{pmatrix} t_L \\ u_L \\ u_{1L} \\ t_{4L} \\ T_{4L} \end{pmatrix}} \begin{pmatrix} 0 & 0 & 0 & 0 & \lambda_q \\ 0 & \tilde{m}_a & -\frac{1}{4} fys_H^2 & -\frac{1}{4} fyc_H\, s_H & -\frac{1}{4} fyc_H s_H \\ \lambda_t & -\frac{1}{4} fys_H^2 & \tilde{m}_a & \frac{1}{4} fyc_H\, s_H & \frac{1}{4} fyc_H s_H \\ 0 & -\frac{1}{4} fyc_H s_H & \frac{1}{4} fyc_H s_H & \tilde{m}_b & -\frac{1}{4} fys_H^2 \\ 0 & -\frac{1}{4} fyc_H s_H & \frac{1}{4} fyc_H s_H & -\frac{1}{4} fys_H^2 & \tilde{m}_b \end{pmatrix} \begin{pmatrix} t_R \\ u_R \\ u_{1R} \\ t_{4R} \\ T_{4R} \end{pmatrix} + h.c.$$

$$-\mathcal{L}_{m_b} = \overline{\begin{pmatrix} b_L \\ d_L \\ d_{1L} \\ d_{4L} \end{pmatrix}} \begin{pmatrix} 0 & 0 & 0 & \lambda_q \\ 0 & \tilde{m}_a & -\frac{1}{4} fys_H^2 & fy\,\frac{c_H s_H}{2\sqrt{2}} \\ \lambda_b & -\frac{1}{4} fys_H^2 & \tilde{m}_a & -fy\,\frac{c_H s_H}{2\sqrt{2}} \\ 0 & fy\,\frac{c_H s_H}{2\sqrt{2}} & -fy\,\frac{c_H s_H}{2\sqrt{2}} & \tilde{m}_c \end{pmatrix} \begin{pmatrix} b_R \\ d_R \\ d_{1R} \\ d_{4R} \end{pmatrix} + h.c.$$

with

$$\tilde{m}_a = \frac{1}{4} fys_H^2 + M_{10}\ , \qquad \tilde{m}_b = \frac{1}{2} fy(1 - \frac{1}{2} s_H^2) + M_{10} \qquad \text{and} \qquad \tilde{m}_c = \frac{1}{2} fyc_H^2 + M_{10}$$

Approximative formulae for masses

Rotation for $v = 0$:

$$\begin{pmatrix} q_L \\ Q_L \end{pmatrix} \to \begin{pmatrix} \cos\phi_L & \sin\phi_L \\ -\sin\phi_L & \cos\phi_L \end{pmatrix} \begin{pmatrix} q_L \\ Q_L \end{pmatrix} \qquad \tan\phi_L = \lambda_q/(M_{10} + fy/2) \ ,$$

$$\begin{pmatrix} t_R \\ u_{1R} \end{pmatrix} \to \begin{pmatrix} \cos\phi_{Rt} & \sin\phi_{Rt} \\ -\sin\phi_{Rt} & \cos\phi_{Rt} \end{pmatrix} \begin{pmatrix} t_R \\ u_{1R} \end{pmatrix} \qquad \tan\phi_{Rt} = \lambda_t/M_{10} \ ,$$

$$\begin{pmatrix} b_R \\ d_{1R} \end{pmatrix} \to \begin{pmatrix} \cos\phi_{Rb} & \sin\phi_{Rb} \\ -\sin\phi_{Rb} & \cos\phi_{Rb} \end{pmatrix} \begin{pmatrix} b_R \\ d_{1R} \end{pmatrix} \qquad \tan\phi_{Rb} = \lambda_b/M_{10} \ ,$$

with $Q_L = (T_{4L}, d_{4L})$.

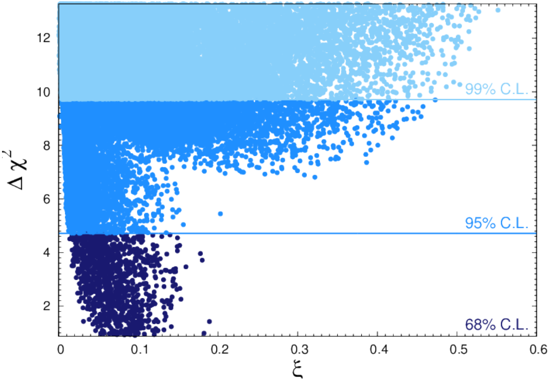
Masses of the new fermions:

$$\underbrace{M_{10}, \ \frac{M_{10}}{\cos\phi_{R,t}}, \ M_{10} + \frac{fy}{2}, \ \frac{M_{10} + \frac{fy}{2}}{\cos\phi_L}}_{tops}, \underbrace{M_{10}, \ \frac{M_{10}}{\cos\phi_{R,b}}, \ \frac{M_{10} + \frac{fy}{2}}{\cos\phi_L}}_{bottoms}, \underbrace{M_{10}, \ M_{10}, \ M_{10} + \frac{fy}{2}}_{\chi' s} .$$

At LO in v/f top and bottom quark are mass

$$m_{top} = \frac{y\ v}{4} \sin\phi_L \sin\phi_{Rt} \ , \qquad m_{bot} = \frac{y\ v}{2\sqrt{2}} \sin\phi_L \sin\phi_{Rb} \ .$$

More results on EWPT



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

Experiment	ξ	χ^2
ATLAS	0.096	12.78
CMS	0.046	6.42

$\longrightarrow$

Best fit points using approximative formula

Experiment	ξ	χ^2
ATLAS	0.067	14.15
CMS	0.051	7.28