Fermionic extensions of the SM in light of the Higgs couplings

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based on arXiv: 1508.01645 with M. Frigerio

24 November 2015

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Framework

So far there is no discrepancies compare to the SM in the Higgs couplings measurements.
$\Rightarrow$ Important to understand where large effects of new physics are still possible.

We will consider the following framework:

- Renormalizable fermionic extensions of the SM.
- Minimal sets of new fermions with up to 4 new chiral multiplets.
- No mixing with the two SM light generations to avoid strong constraints coming from flavour observables.
- Modifications of the Higgs couplings because we are interested by Higgs phenomenology.

Requirements for the classification

We imposed that the extensions respect the 3 following requirements.

1) No gauge Anomalies (Theoretical consistency)

SM is anomaly free $\Longrightarrow$ Anomaly-cancellation imposed on the set of new fermions.

2) No massless fermions after EWSB (Phenomenological consistency)

We should have seen experimentally a massless fermions.

3) Modifications of the Higgs couplings (Focus of the analysis)

We require at least one Yukawa coupling associated to the new fermions.

Result of the classification

We found a large number of fermionic extensions of the SM.
They can be classified according to the way in which the fermions get their masses.

Three ways to get a mass

- From the Higgs vev only (purely chiral extensions).
- From Majorana mass terms (recover seesaw extensions).
- From Dirac mass terms (extensions with vector-like fermions).
  Vector-Like $\equiv$ Left and Right chiralities transform in the same way.

New fermions can modify the Higgs couplings in two different ways.

Two ways to affect the Higgs couplings

- By mixing with SM fermions.
- By Yukawa couplings involving the new fermions only (without mixing with the SM).

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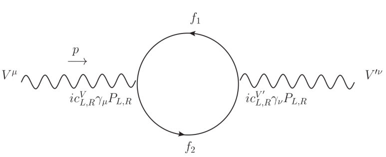
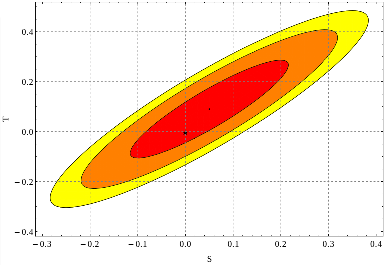
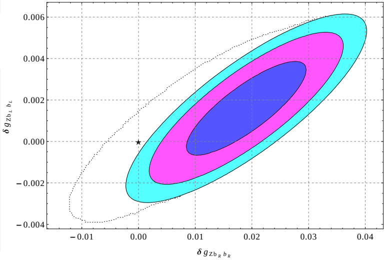
S and T parameters

Effects of new fermions in vacuum polarization amplitudes are parametrised by the S and T parameters.







$Zf\bar{f}$ couplings

New fermions mixing with the SM ones affect the $Zf\bar{f}$ couplings.

- New quarks: $Zb\bar{b}$ coupling
- New leptons: $Z \to \tau\tau$, invisible

Direct searches and Higgs couplings

Direct searches

Direct searches at colliders put a lower limit on the mass of the new fermions.

Higgs couplings

Constraints in Higgs couplings are expressed in term of signal strengths:

$$\mu_\alpha \equiv \frac{\sigma(pp \to h)}{\sigma^{SM}(pp \to h)} \frac{\Gamma(h \to \alpha)}{\Gamma^{SM}(h \to \alpha)} \frac{\Gamma_h^{SM}}{\Gamma_h} ,$$

$\alpha = \gamma\gamma, ZZ^*, WW^*, b\bar{b}, \tau\tau, \gamma Z, \cdots$

We consider only the leading order corrections to the Higgs couplings.

- Tree-level couplings: $hb\bar{b}$, $h\tau\tau$, hZZ^* and hWW^*.
- Loop-induced couplings: hgg, $h\gamma\gamma$ and $h\gamma Z$.

hgg, $h\gamma\gamma$ are strongly constrained but for $h\gamma Z$ there is still place for large deviations as $\mu_{\gamma Z} \lesssim 10$.

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Two vector-like leptons - Minimal case

We found many interesting features in the fermionic extensions that we have studied. Let me focus only on large deviations in the $h\gamma Z$ coupling.

Consider the minimal case with 2 vector-like leptons: a singlet and a doublet with free hypercharge and no mixing with the SM.

Minimal case $\psi_{1L}, \psi_{1R} \sim (1, 1, Y) + \psi_{2L}, \psi_{2R} \sim (1, 2, Y + \frac{1}{2})$

$$-\mathcal{L}_{\psi_1\psi_2} = \widetilde{\lambda}\overline{\psi_{1L}}\widetilde{H}\psi_{2R} + \lambda\overline{\psi_{2L}}H\psi_{1R} + M_1\overline{\psi_{1L}}\psi_{1R} + M_2\overline{\psi_{2L}}\psi_{2R} + h.c.$$

$\Rightarrow$ 5 real parameters: 2 Yukawas, 2 masses and 1 phase φ.

There is a mixing in the $Q = Y$ sector:

$$\mathcal{M}_Y = \begin{pmatrix} M_1 & \frac{\widetilde{\lambda}v}{\sqrt{2}} \\ \frac{\lambda v}{\sqrt{2}} & M_2 \end{pmatrix} = U_L diag(m_1, m_2) U_R^\dagger$$

$\Rightarrow$ The two mixing states have a free electric charge Q and they couple to the Higgs.

Higgs couplings to two photons ($h\gamma\gamma$)

The two mixing states contribute only to $h\gamma\gamma$ and $h\gamma Z$ couplings as they are colourless and don't mix with SM.

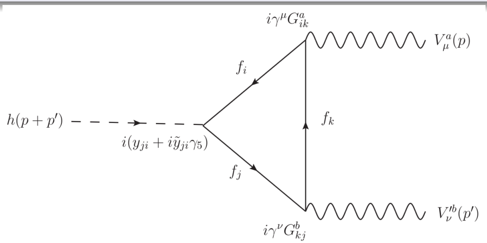
General expression with new fermions

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{256\pi^3 v^2} \left[\mid A_1(\tau_W) + \mathcal{A}_f^{\gamma\gamma} \mid^2 + \mid \tilde{\mathcal{A}}_f^{\gamma\gamma} \mid^2 \right]$$

CP-even and CP-odd parts:

$\mathcal{A}_f^{\gamma\gamma} = \sum_i \frac{y_i v}{m_i} N_{ci} Q_i^2 A_{1/2}(\tau_i)$, $\quad \tilde{\mathcal{A}}_f^{\gamma\gamma} = \sum_i \frac{\tilde{y}_i v}{m_i} N_{ci} Q_i^2 \tilde{A}_{1/2}(\tau_i)$

Form factors are constant (negligible) for heavy (light) masses.
$\Rightarrow$ Loop-induced couplings are sensitive to heavy new fermions.



Higgs couplings to photon Z ($h\gamma Z$)

We re-calculated the SM expressions and computed the most general expressions that apply to any models with new fermions.

General expression with new fermions

$$\Gamma(h \to \gamma Z) = \frac{\alpha g^2 c_w^2 m_h^3}{512\pi^4 v^2}\left(1 - \frac{m_Z^2}{m_h^2}\right)^3 \left[\mid A_1(\tau_W, \lambda_W) + \mathcal{A}_f^{Z\gamma} \mid^2 + \mid \tilde{\mathcal{A}}_f^{Z\gamma} \mid^2\right]$$

$$\mathcal{A}_f^{Z\gamma} = \sum_{j,k} \frac{N_{ck} Q_k v}{c_w^2 \sqrt{m_j m_k}} \left[\mathrm{Re}(g_{kj}^V y_{jk}) a_{1/2}(m_j, m_k, m_k) + i\mathrm{Im}(g_{kj}^A \tilde{y}_{jk}) b_{1/2}(m_j, m_k, m_k)\right]$$

$$\tilde{\mathcal{A}}_f^{Z\gamma} = \sum_{j,k} \frac{N_{ck} Q_k v}{c_w^2 \sqrt{m_j m_k}} \left[\mathrm{Re}(g_{kj}^V \tilde{y}_{jk}) \tilde{a}_{1/2}(m_j, m_k, m_k) + i\mathrm{Im}(g_{kj}^A y_{jk}) \tilde{b}_{1/2}(m_j, m_k, m_k)\right]$$

Generally a large $\mu_{\gamma Z}$ implies a too large deviation in the $\gamma\gamma$ channel.
However the structures of the two couplings are different, $h\gamma Z$ contains:

- Loops with 2 different mass eigenstates.
- Vector (g_{kj}^V) and axial (g_{kj}^A) Z couplings.

$\Rightarrow$ Exploiting this difference, we found two mechanisms realizing $\mu_{\gamma Z} \gg \mu_{\gamma\gamma}$.

First mechanism for a large γZ signal strength

Consider the possibility of two degenerate masses for the mixing states: $m_1 = m_2 \equiv m_\psi$

$h\gamma\gamma$ coupling

$$\mathcal{A}_{NP}^{\gamma\gamma} = 2Q^2 F\left(\theta_L, \theta_R, \varphi\right) A_{1/2}\left(\tau_\psi\right)$$

$F\left(\theta_L, \theta_R, \varphi\right) = s_L^2 c_R^2 + c_L^2 s_R^2 - 2 c_L s_L c_R s_R \cos\varphi$

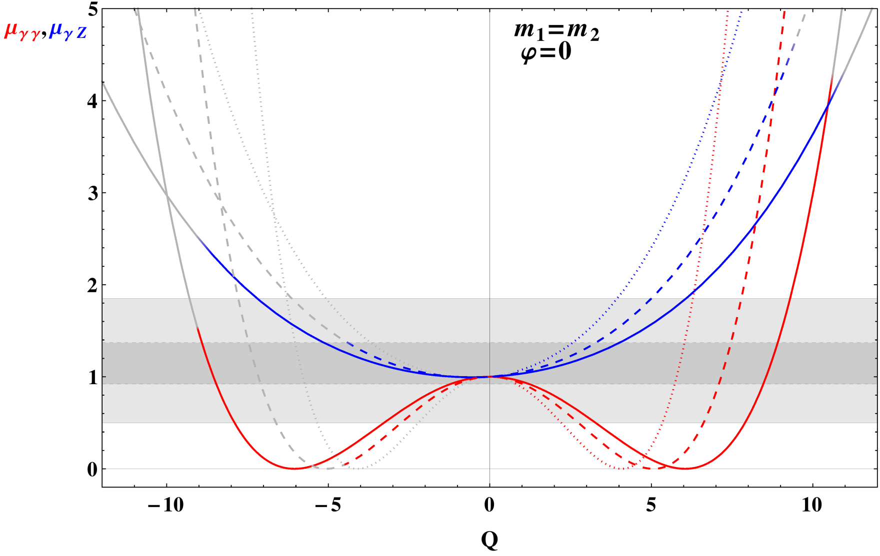
The interference with the SM is destructive.
$\Rightarrow$ $\mu_{\gamma\gamma}$ can be accidentally close to the SM if $\mathcal{A}_{NP}^{\gamma\gamma} \simeq -2\mathcal{A}_{SM}^{\gamma\gamma}$.

$h\gamma Z$ coupling

$$\mathcal{A}_{NP}^{\gamma Z} = \frac{Q}{c_w^2} F\left(\theta_L, \theta_R, \varphi\right) \left(-\frac{1}{2} - 2Qs_w^2\right) A_{1/2}\left(\tau_\psi, \lambda_\psi\right)$$

The interference with the SM is constructive at large Q.
$\Rightarrow$ Possible to reach $\mu_{\gamma Z} \simeq 7$ with $\mu_{\gamma\gamma} \simeq 1$
(if $\varphi \neq 0$ there is an additional contribution from $\widetilde{\mathcal{A}}_{NP}^{\gamma Z}$).

Two vector-like leptons



Second mechanism for a large γZ signal strength

Consider the possibility of two different masses $m_1 \neq m_2$ for the mixing states and no CP violation.

$h\gamma\gamma$ coupling

$\mathcal{A}_{NP}^{\gamma\gamma}$ is not proportional to the function $F\left(\theta_L, \theta_R, \varphi\right)$:

$$\mathcal{A}_{NP}^{\gamma\gamma} \simeq 2Q^2 \left[s_L^2 c_R^2 + c_L^2 s_R^2 - \left(\frac{m_1}{m_2} + \frac{m_2}{m_1} \right) c_L s_L c_R s_R \right] A_{1/2}\left(\tau_1\right)$$

$\Rightarrow$ Parameters can be tuned such that $\mathcal{A}_{NP}^{\gamma\gamma} \simeq 0$.

$h\gamma Z$ coupling

The contribution to the $h\gamma Z$ coupling is not cancelled in the same way.
$\Rightarrow$ Possible to reach $\mu_{\gamma Z} \simeq 2$ with $\mu_{\gamma\gamma} \simeq 1$.

Conclusion

I presented 2 mechanisms realizing $\mu_{\gamma Z} \gg \mu_{\gamma\gamma}$ with $\mu_{\gamma Z}$ few times larger than the SM prediction. These two mechanisms are realized for:

$$\mathcal{A}_{NP}^{\gamma\gamma} \simeq -2\mathcal{A}_{SM}^{\gamma\gamma}\ (\mu_{\gamma Z} \simeq 7) \qquad \text{or} \qquad \mathcal{A}_{NP}^{\gamma\gamma} \simeq 0\ (\mu_{\gamma Z} \simeq 2)$$

The projection for 300 fb^{-1} is $\Delta\mu_{\gamma Z}/\mu_{\gamma Z} \sim 0.5$
$\Rightarrow$ LHC will be able to probe these two mechanisms.

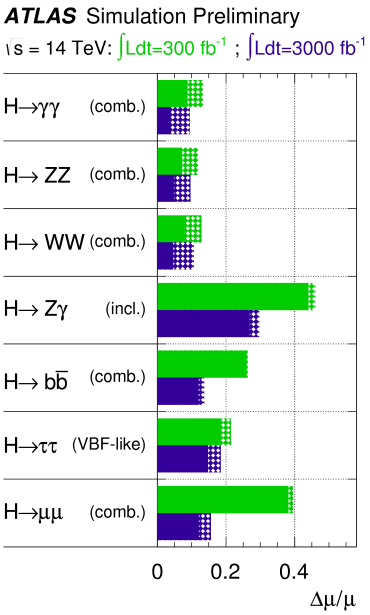
Others interesting features

We also found interesting features in the others fermionic extensions (1508.01647) that we have studied:

- Some chiral families are still allowed.
- The decays of the Higgs into leptons ($h \to \nu'\nu'$, $h\nu\nu'$ and $\tau\tau'$) can affect significantly the total Higgs width.
- A large mixing with the SM fermions is possible if there is a cancellation in the T parameter or a custodial symmetry protecting the T parameter and the $Zb\bar{b}$ couplings.

Thanks for your attention!

Projections of Higgs couplings measurements



More on $h\gamma\gamma$ and $h\gamma Z$ couplings

- $\Gamma^{SM}(h \to \gamma\gamma)/\Gamma^{SM}(h \to \gamma Z) \simeq 1.5$
- In the SM top and W loops dominate: $\mathcal{A}^{SM}_{\gamma\gamma} \simeq \mathcal{A}^{SM}_{\gamma\gamma,t} + \mathcal{A}^{SM}_{\gamma\gamma,W}$ and interfere destructively: $\mathcal{A}^{SM}_{\gamma\gamma,W}/\mathcal{A}^{SM}_{\gamma\gamma,t} \simeq -4.6$
- In the SM top and W loops dominate: $\mathcal{A}^{SM}_{\gamma Z} \simeq \mathcal{A}^{SM}_{\gamma Z,W} + \mathcal{A}^{SM}_{\gamma Z,t}$ and interfere destructively: $\mathcal{A}^{SM}_{\gamma Z,W}/\mathcal{A}^{SM}_{\gamma Z,t} \simeq -17.9$

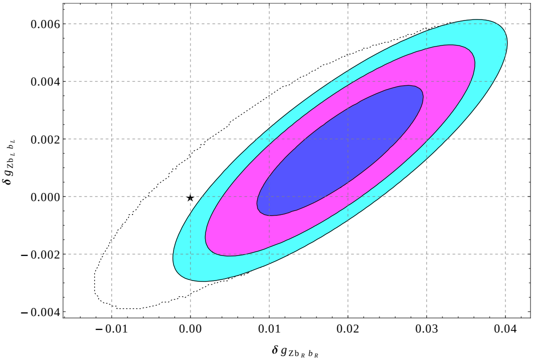
Limitation of the analysis

- Computation of the leading order corrections to the Higgs and gauge couplings.
- Not an ultraviolet complete theory:
  Effective theory valid only at the multi TeV scale.
  $\Longrightarrow$ No constraints from coupling evolution
  (vacuum stability, Landau poles, gauge unification, $\cdots$)
- No cosmological considerations:
  Rely in most case on specific assumptions on the early Universe evolution
  $\Longrightarrow$ No bounds on the relic abundance of the new fermions.

Deviations

$$\mathcal{L}_{Zb\bar{b}} = \frac{g}{c_w} Z_\mu \bar{b}\, \gamma^\mu \left[\left(g^L_{b\bar{b},SM} + \delta g^L_{b\bar{b}} \right) P_L + \left(g^R_{b\bar{b},SM} + \delta g^R_{b\bar{b}} \right) P_R \right] b$$

- tree-level correction if b mixes with b' with different T_3.
- 1 loop corrections from t' or quark with $Q = -4/3$.



Best fit incompatible with the SM at 2-3 σ (due to A^b_{FB})
→ Problem of measurement.
→ Effect of new physics.

We choose to conservatively enlarge the ellipse by adding a systematic error in the SM direction.

Requirements for the classification

1) No Anomalies (Theoretical consistency)

- Gauge anomalies:

$$\begin{array}{ccl} SU(3)_c - SU(3)_c - U(1)_Y & : & \sum_{i=1}^n N_{wi} C(R_{ci}) Y_i = 0 \\ SU(2)_w - SU(2)_w - U(1)_Y & : & \sum_{i=1}^n N_{ci} C(R_{wi}) Y_i = 0 \\ U(1)_Y - U(1)_Y - U(1)_Y & : & \sum_{i=1}^n N_{ci} N_{wi} Y_i^3 = 0 \\ grav - grav - U(1)_Y & : & \sum_{i=1}^n N_{ci} N_{wi} Y_i = 0 \end{array}$$

  New fermion $\psi_i \sim (R_{ci}, R_{wi}, Y_i)$ under $SU(3)_c \times SU(2)_w \times U(1)_Y$
- Global SU(2) anomaly: $\sum_{i=1}^n N_{ci} C(R_{wi})$ integer number

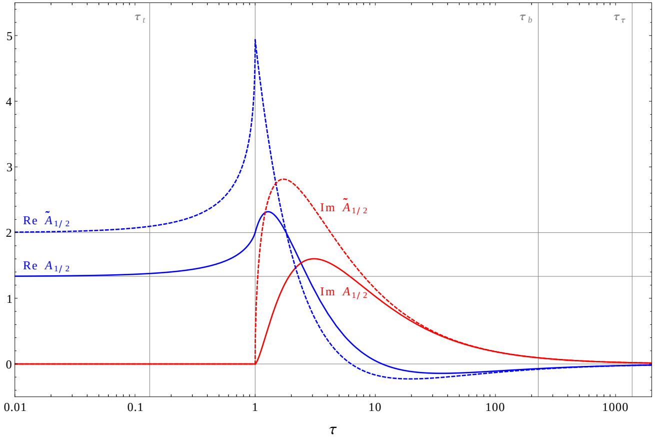
2) No massless fermions after EWSB (Phenomenological consistency)

Massless fermions (except SM ν) should have:

- No colour ($R_c = 1$)
- No electric charge ($Q = T_3 + Y = 0$)
- No couplings to the Z boson ($T_3 - \tan^2\theta_w Y = 0$)

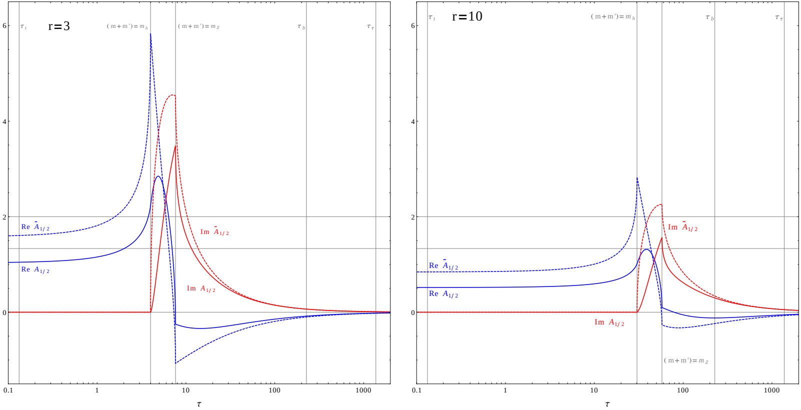
$\Rightarrow$ Majorana mass allowed.

$h\gamma\gamma$ form factors



- The form factors depend on $\tau_i = m_h^2/(4m_i^2)$.
- Heavy fermion limit: $A_{1/2}(0) = 4/3, \quad \widetilde{A}_{1/2}(0) = 2$
- Light fermions contributions are negligible.
- Imaginary parts are non-zero for $m_i < m_h/2$

$h\gamma Z$ form factors



Differences with respect to $h\gamma\gamma$:

- Form factors modified due to the Z mass.
- Two fermions may run at the same time in the loop ($r \equiv m_j/m_K$).
- Axial couplings to the Z boson.

Minimal chiral extension of the SM

The minimal chiral extension of the SM contains three coloured sextets.

$\psi_{1L} \sim (6, 2, 0)$, $\psi_{2R} \sim \left(6, 1, \frac{1}{2}\right)$, $\psi_{3R} \sim \left(6, 1, -\frac{1}{2}\right)$

$$-\mathcal{L}_{chiral} = \lambda_2 \overline{\psi_{1L}} \tilde{H} \psi_{2R} + \lambda_3 \overline{\psi_{1L}} H \psi_{3R} + h.c.$$

$\Rightarrow$ Two mass eigenstates with charge $Q = \pm 1/2$ and masses $\lambda_{2,3} v / \sqrt{2}$

Constraints

- Lightest fermion is stable and form a R-hadron $\Rightarrow m \gtrsim 1.4$ TeV
- One can respect the constraints on S and T.

Higgs couplings

$$\frac{\sigma(gg \to h)}{\sigma_{SM}(gg \to h)} \simeq [1 + 4C(R_c)]^2 \geq 121$$

$\Rightarrow$ Gluons fusion excludes all chiral models with coloured states.

Viable chiral extensions after LHC

Is there room for fermions that receive a mass from the Higgs vev only?

Two doublets + four singlets

$(2, Y)_L\,,\ (2, -Y)_L\,,\ (1, -Y + \frac{1}{2})_L\,,\ (1, -Y - \frac{1}{2})_L\,,\ (1, Y + \frac{1}{2})_L\,,\ (1, Y - \frac{1}{2})_L$

- No colour $\Rightarrow$ No contribution to *hgg* coupling.
- VL masses are possible but they can be forbid by a global symmetry.

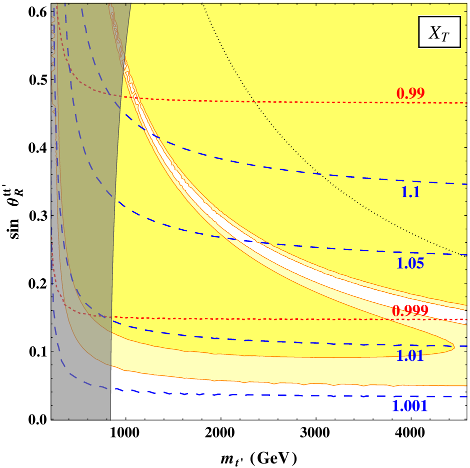
S and T parameters

In the custodial limit $T \simeq 0$ and $S \simeq \frac{1}{3\pi}$
$\Rightarrow$ S and T are small enough to be in the allowed region.

Higgs couplings

- $\mathcal{A}^{\gamma\gamma}_{new} = 4(1 + 4Y^2)/3$ is in agreement with measurements if
  1) $\mathcal{A}^{\gamma\gamma}_{new}$ small for $|Y| \lesssim 0.3$ 2) $\mathcal{A}^{\gamma\gamma}_{new} \sim -2\mathcal{A}^{\gamma\gamma}_{SM}$ for $1.4 \lesssim |Y| \lesssim 1.6$
- $\mathcal{A}^{\gamma Z}_{new} \simeq 2\left[1 - \left(1 + 8Y^2\right)\tan^2\theta_w\right]/3$
  $\Rightarrow \mu_{\gamma Z} \simeq 2.4$ for $|Y| = 1.6 \rightarrow$ Large contribution to γZ channel.

Large mixing- Cancellation in the T parameter



X_T is a vector-like quark transforming in $(3, 2, 7/6)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$.

$$T \simeq \frac{3 s_R^2}{16\pi c_W^2 s_W^2} \frac{m_{t'}^2}{m_Z^2} \left[\frac{4}{3} s_R^2 - \frac{m_t^2}{m_{t'}^2} \left(4 \ln \frac{m_{t'}^2}{m_t^2} - 6 \right) \right]$$

$\Rightarrow$ Cancellation leads to an upper limit on the mixing as large as ~ 0.5.

Large mixing- Custodial symmetry

$$-\mathcal{L}_{(X_T,Q)} = \frac{\lambda_\psi}{\sqrt{2}}\overline{(X_T \;\; Q)_L}\begin{pmatrix} H \\ \tilde{H} \end{pmatrix} t_R + M_\psi \overline{(X_T \;\; Q)_L}\begin{pmatrix} X_T \\ Q \end{pmatrix}_R + h.c.$$