Fermionic extensions of the SM in light of the Higgs couplings

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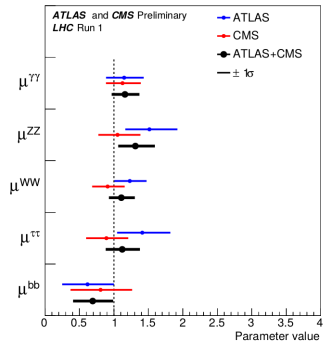
Standard Model (SM)

Higgs discovery

A SM-like Higgs boson has been discovered at CERN with mass $m_h = 125.09 \pm 0.24$ GeV.
$\Longrightarrow$ No unknown parameters in the SM which becomes predictive.

Higgs physics



- So far no deviations compare to the SM $\Longrightarrow$ SM is a successful theory up to the EW scale.
- LHC run 2 will increase the precision of the Higgs coupling measurements. $\Longrightarrow$ Maybe some deviations will appear.

Beyond the Standard Model (BSM)

The SM is a successful theory **BUT** several hints point in favour of BSM physics.

Observational facts

- Dark matter
- Baryon asymmetry
- Neutrinos masses
- ...

Theoretical puzzles

- Hierarchy problem
- Flavour puzzle
- Gauge coupling unification
- ...

The need of new physics

The SM has no answer to these observational and theoretical issues.
$\Longrightarrow$ SM is an effective model valid up to the EW scale.
$\Longrightarrow$ BSM physics has to be present.

Important to understand what kind of new physics is still experimentally allowed and can be visible at the LHC run 2.

Framework

- Renormalizable extensions of the SM at the EW scale:

$$\mathcal{L}_{BSM} = \mathcal{L}_{SM} + \sum_i c_i \mathcal{O}_i \ , \qquad [\mathcal{O}_i] \leq 4 \ .$$

- Model independent approach:
  Couplings c_i are not constrained by BSM symmetries like Supersymmetry, global symmetries, $\cdots$
  $\rightarrow$ phenomenological point of view
- Add only new fermions to the SM:
  The Higgs sector remains SM-like.
- Minimal sets of new fermions:
  Restrict up to $n = 4$ new multiplets. The phenomenological issues are already well illustrated and a detailed analysis for $n \geq 5$ is worth only in the context of well-motivated BSM theories.
- Higgs couplings:
  New fermions couple to the Higgs and modify its couplings.

Models considered = Effective theories containing the SM + up to $n = 4$ new fermionic multiplets.

Limitation of the analysis

Leading order corrections

Computation of the leading order corrections (due to new fermions) to the Higgs and gauge couplings.

No mixing with light generations

New fermions don't mix with the two SM light generations
$\Longrightarrow$ Avoid strong constraints coming from flavour observables

Not a UV theory

Effective theory valid up to a scale much larger than the EW one
$\Longrightarrow$ No constraints from coupling evolution such as vaccuum 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.

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Requirements for the classification

Theoretically self-consistent → No Gauge Anomalies

- SM is anomaly free by itself.
- Extra fermions much heavier than the EW scale (Effective theories) form vector-like pair with respect to the SM gauge group.
  → No play in the anomaly cancellation.

⟹ Anomaly-cancellation imposed on the set of new fermions only.

- Anomaly-cancellation conditions:

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

Theoretically self-consistent → No $SU(2)_w$ global Anomaly

Anomaly-cancellation condition: $\sum_{i=1}^n N_{ci} C(R_{wi})$ integer number

Requirements for the classification

Phenomenologically viable $\rightarrow$ No massless fermions after EWSB

Except the three SM neutrinos and gauge singlets.
Indeed massless fermions allowed only if they have:

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

$\Rightarrow \psi \sim (1, R_w \text{ odd}, 0) \rightarrow$ (Large) Majorana mass allowed.

with Non-zero corrections to the Higgs couplings

- At least one new Yukawa coupling with the Higgs doublet H.
  $\Longrightarrow$ SM Higgs couplings affected at tree or one loop level.
- If no new Yukawa, Higgs couplings affected at two loops level.

$$\psi \sim (R_c, R_w, Y) \text{ under } SU(3)_c \times SU(2)_w \times U(1)_Y$$

Three main kind of extensions.

1) Purely chiral extensions

Purely chiral $\equiv$ New fermions get their mass only from the Higgs vev
$\Longrightarrow$ No mass terms before EWSB.

- Three chiral fermions ($R_c \neq \overline{R_c}$, N_c even)

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

- Four chiral fermions ($R_c \neq \overline{R_c}$, N_c even if $\mathrm{N_w}$ odd)

$$\psi_{1L} \sim (R_c, R_w - 1, 0),\ \psi_{2L} \sim (R_c, R_w + 1, 0),$$
$$\psi_{3R} \sim \left(R_c, R_w, \frac{1}{2}\right),\ \psi_{4R} \sim \left(R_c, R_w, -\frac{1}{2}\right).$$

$\Rightarrow$ Mixing with SM not allowed in the two cases.

Results of the classification

2) Non chiral leptons

- Majorana leptons:

$$N_R \sim (1,1,0), \quad \Sigma_R = \begin{pmatrix} E^c \\ N \\ E \end{pmatrix} \Rightarrow \text{Seesaw Type I and III.}$$

- One Vector-Like (VL) lepton:
  VL≡ Left and Right chiralities transform in the same way (mass term before EWSB).

$$E, \; L = \begin{pmatrix} N \\ E \end{pmatrix}, \; \Lambda = \begin{pmatrix} E \\ F \end{pmatrix}, \; \Delta = \begin{pmatrix} N \\ E \\ F \end{pmatrix} \Rightarrow \text{Usual VL leptons.}$$

⇒ Always a mixing with SM in these cases.

$Q(N) = 0$, $Q(E) = -1$ and $Q(F) = -2$

2) Non chiral leptons

- Two VL leptons:
  - Trivial cases: 2 VL leptons mixing with SM but no direct coupling between each other.
  - Custodial case: (Λ, L) transforming as bi-doublet of $SU(2)_L \times SU(2)_R$.
  - General case (may not mix with SM)
    $\psi_{1L}, \psi_{1R} \sim (1, R_w, Y),\ \psi_{2L}, \psi_{2R} \sim (1, R_w + 1, Y + \frac{1}{2})$

$\Rightarrow R_w = 1,\ Y = -1$: τ compositeness (E+L).

New exotic VL multiplets can indirectly mix with the SM:

$$\Delta_G = \begin{pmatrix} E \\ F \\ G \end{pmatrix},\ \Omega = \begin{pmatrix} E^c \\ N \\ E \\ F \end{pmatrix},\ \Omega_G = \begin{pmatrix} N \\ E \\ F \\ G \end{pmatrix}$$

$Q(G) = -3$

Results of the classification

2) Non chiral leptons

- VL+ Majorana leptons:

- $\chi_R \sim (1, R_w, 0)$, $\psi_L, \psi_R \sim (1, R_w \pm 1, -1/2)$
  (Global anomaly cancellation $N_w \neq 2 + 4n$)
  - $\rightarrow$ $R_w = 1$: VL doublet L + sterile neutrino N.
  - $\rightarrow$ $R_w = 3$: VL doublet L or quartet Ω + sterile triplet Σ.

- $\chi_{1R} \sim (1, R_w, 0)$, $\psi_L, \psi_R \sim (1, R_w \pm 1, -1/2)$, $\chi_{2R} \sim (1, R_w, 0)$
  (N_w arbitrary)
  - $\rightarrow$ $R_w = 1$: VL doublet L + 2 sterile neutrino N.
  - $\rightarrow$ $R_w = 3$: VL doublet L or quartet Ω + 2 sterile triplet Σ.

- $\chi_{1R} \sim (1, R_w, 0)$, $\psi_L, \psi_R \sim (1, R_w + 1, -1/2)$, $\chi_{2R} \sim (1, R_w + 2, 0)$
  (N_w odd)
  - $\rightarrow$ $R_w = 1$: VL doublet L + sterile singlet N and triplet Σ.
    (generalization higgsinos + gauginos in Susy)
  - $\rightarrow$ $R_w = 3$: VL quartet Ω + sterile triplet Σ and quintuplet Ξ.

Results of the classification

3) Non chiral quarks

- One VL quark:

$$T, \quad B$$

$$X_T = \begin{pmatrix} X \\ T \end{pmatrix}, \quad Q = \begin{pmatrix} T \\ B \end{pmatrix}, \quad Y_B = \begin{pmatrix} B \\ Y \end{pmatrix}$$

$$X_Q = \begin{pmatrix} X \\ T \\ B \end{pmatrix}, \quad Y_Q = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$$

$\Rightarrow$ Usual VL quarks mixing with SM.

$Q(X) = 5/3$, $Q(T) = 2/3$, $Q(B) = -1/3$ and $Q(Y) = -4/3$

3) Non chiral quarks

- Two VL quarks:

  - Trivial cases: 2 VL quarks mixing with SM but no direct coupling between each other.

  - Custodial cases: (T, B), (X_T, Q), (Q, Y_B) and (X_Q, Y_Q) transforming as doublets of $SU(2)_R$.

  - General case (may not mix with SM)
    $\psi_{1L}, \psi_{1R} \sim (R_c, R_w, Y)$, $\psi_{2L}, \psi_{2R} \sim (R_c, R_w + 1, Y + \frac{1}{2})$

$\Rightarrow R_w = 1,\ Y = -2/3$: top compositeness (T+Q).
$\Rightarrow R_w = 1,\ Y = -1/3$: bottom compositeness (B+Q).

$\Rightarrow$ New exotic VL multiplets can indirectly mix with the SM:

$$Z_{X_T} = \begin{pmatrix} Z \\ X \\ T \end{pmatrix}, W_{Y_B} = \begin{pmatrix} B \\ Y \\ W \end{pmatrix}, \Omega_{X_T} = \begin{pmatrix} Z \\ X \\ T \\ B \end{pmatrix}, \Omega_Q = \begin{pmatrix} X \\ T \\ B \\ Y \end{pmatrix}, \Omega_{Y_B} = \begin{pmatrix} T \\ B \\ Y \\ W \end{pmatrix}$$

Q(Z)=8/3, Q(W)=-7/3

3) Non chiral quarks

- VL+ Majorana quarks ($R_c = \overline{R_c} \neq 1$):

  - $\chi_R \sim (R_c, R_w, 0),\ \psi_L, \psi_R \sim (R_c, R_w \pm 1, -1/2)$
    (Global anomaly cancellation R_c odd $\rightarrow N_w \neq 2 + 4n$)

  - $\chi_{1R} \sim (R_c, R_w, 0),\ \psi_L, \psi_R \sim (R_c, R_w + 1, -1/2),\ \chi_{2R} \sim (R_c, R_w, 0)$
    (N_w arbitrary)

  - $\chi_{1R} \sim (R_c, R_w, 0),\ \psi_L, \psi_R \sim (R_c, R_w + 1, -1/2),$
    $\chi_{2R} \sim (R_c, R_w + 2, 0)$
    (R_c odd $\rightarrow N_w$ odd)

$\Rightarrow$ Generalization of the uncoloured cases.
$\Rightarrow$ Mixing with SM is no longer possible.

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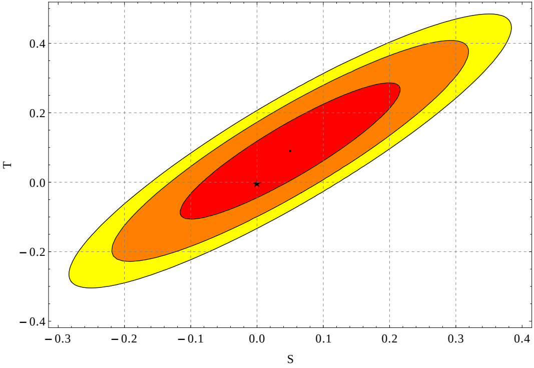
Obliques (Electroweak) precision tests

S and T parameters

$$T = \frac{1}{\alpha c_w^2 m_Z^2} \left[(\Pi_{33}(0) - \Pi_{33}^{SM}(0)) - (\Pi_{WW}(0) - \Pi_{WW}^{SM}(0)) \right] .$$

$$S = \frac{4 s_w c_w}{\alpha m_Z^2} \left[(\Pi_{30}(m_Z^2) - (\Pi_{30}(0)) - (\Pi_{30}^{SM}(m_Z^2) - \Pi_{30}^{SM}(0)) \right]$$

- $S_{SM} = T_{SM} \equiv 0.$
- Calculation 1 loop vacuum polarization amplitude of EW gauge boson.



Non-obliques precision tests

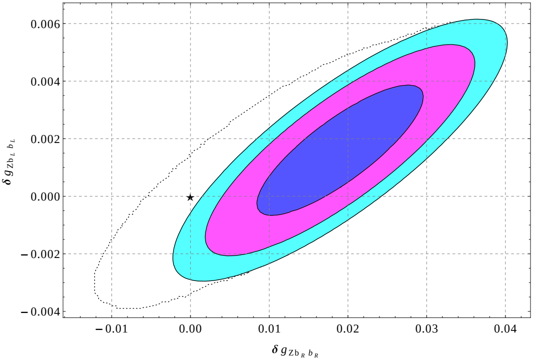
Non-oblique $\equiv$ Not flavor universal (depending on the SM generation).

Zbb couplings

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

$\rightarrow$ tree-level: b mix with b' which as different T_3 and Y.

$\rightarrow$ 1 loop-level: Modification in $Zt\bar{t}$, $Wt\bar{b}$ couplings (new t' or $Y_{-4/3}$ loops).



Best fit region incompatible with the SM (due to A^b_{FB})

$\rightarrow$ upward statistical fluctuation.

$\rightarrow$ Effect of NP.

We choose to conservatively enlarge the ellipse.

$Z \rightarrow \tau\tau$, *inv* are also strongly constraint.

Definition

At LHC, Higgs couplings are constrained by measurement of signal strengths:

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

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

- $\sigma(gg \to h)/\sigma(gg \to h) \simeq 85\%$ at $\sqrt{8}$ TeV in the SM.
  Restrict to gluon fusion $\to$ All μ_α depend on hgg coupling.
- $Br(h \to b\bar{b}) \simeq 57\%$ in the SM.
  $\Rightarrow$ All μ_α strongly depend on $hb\bar{b}$ through Γ_h.
- ZZ^*, WW^* decays are SM-like but not μ_{ZZ}, μ_{WW}.

$$R_\alpha \equiv \frac{\Gamma(h\to\alpha)}{\Gamma^{SM}(h\to\alpha)} = \frac{\sigma(h\to\alpha)}{\sigma^{SM}(h\to\alpha)} = 1 + \delta R_\alpha$$

General form

- General Yukawa couplings:
  $\psi_L \sim (R_c, R_w, Y)$, $\psi_R^{u,d} \sim (R_c, R_w - 1, Y \pm \frac{1}{2})$

$$-\mathcal{L}_Y = \sum_{\psi_L} \left[\sum_{\psi_R^u} y_{\psi_L \psi_R^u} \left(\overline{\psi_L} \psi_R^u \tilde{H} \right) + \sum_{\psi_R^d} y_{\psi_L \psi_R^d} \left(\overline{\psi_L} \psi_R^d H \right) \right] + h.c.$$

- After EWSB: $\rightarrow$ fermions mix through the mass matrix $\mathcal{M}$.

$$-\mathcal{L}_Y = \overline{f_{Lj}} \left[U_L^\dagger \mathcal{M}(v) U_R \right]_{jk} f_{Rk} + \overline{f_{Lj}} \left[U_L^\dagger \frac{\partial \mathcal{M}(v)}{\partial v} U_R \right]_{jk} f_{Rk}\, h + h.c.$$

$$= \sum_i m_i \overline{f_i} f_i + \overline{f_j} \left(y_{jk} + i \gamma_5 \tilde{y}_{jk} \right) f_k\, h\ .$$

$\Rightarrow$ CP-even (y) and odd ($\tilde{y}$) couplings depend on the form of $\mathcal{M}$:

$$y = \frac{\lambda + \lambda^\dagger}{2}\ , \qquad \tilde{y} = \frac{\lambda - \lambda^\dagger}{2i}\ , \qquad \lambda \equiv U_L^\dagger \frac{\partial \mathcal{M}(v)}{\partial v} U_R\ .$$

Higgs couplings to two gluons (hgg)

SM contributions

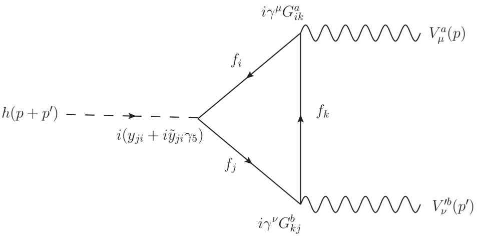
$\Gamma^{SM}(h \to gg) = \frac{\alpha_s^2 m_h^3}{72\pi^3 v^2} \left| \frac{3}{4} \sum_q A_{1/2}(\tau_q) \right|^2 \to$ SM quarks contribute.

$\Rightarrow$ Top loop dominates: $\mathcal{A}_{gg}^{SM} \simeq \mathcal{A}_{gg,t}^{SM} > 0$

Fermionic BSM contributions

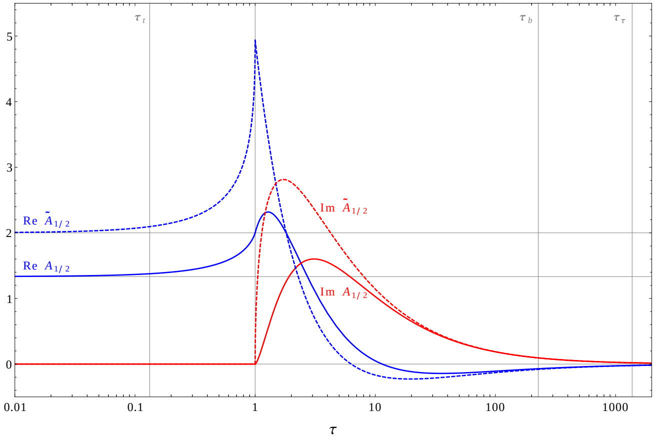
$$\Gamma(h \to gg) = \frac{\alpha_s^2 m_h^3}{72\pi^3 v^2} \left(| \mathcal{A}_f^{gg} |^2 + | \tilde{\mathcal{A}}_f^{gg} |^2 \right),$$

$$\mathcal{A}_f^{gg} = \frac{3}{2} \sum_i C(R_{ci}) \frac{y_i v}{m_i} A_{1/2}(\tau_i), \qquad \widetilde{\mathcal{A}}_f^{gg} = \frac{3}{2} \sum_i C(R_{ci}) \frac{\widetilde{y}_i v}{m_i} \widetilde{A}_{1/2}(\tau_i)$$



- Only diagonal loops (1 mass eigenstate runs in the loop) as color is unbroken.
- No interference between CP-even and CP-odd parts.
- Form factors depend on fermion mass $\tau_i = m_h^2/(4m_i^2)$

Higgs couplings- Loop induced form factors



- Heavy fermion limits: $A_{1/2}(0) = 4/3, \quad \widetilde{A}_{1/2}(0) = 2$
- Light fermions contributions are negligible ($\tau_t \simeq 0.13$ and $\tau_b \simeq 220$).
- Imaginary part when fermion can be put on-shell ie for $m_i < m_h/2$

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

SM contribution

$\Gamma^{SM}(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{256\pi^3 v^2} \left| A_1(\tau_W) + \sum_{f_i} N_{ci} Q_i^2 A_{1/2}(\tau_i) \right|^2$

$\to$ SM fermions but also W boson contribute.

$\Rightarrow$ Top and W loops dominate: $\mathcal{A}^{SM}_{\gamma\gamma} \simeq \mathcal{A}^{SM}_{\gamma\gamma,t} + \mathcal{A}^{SM}_{\gamma\gamma,W} < 0$

- Destructive interference between top and W loops: $\mathcal{A}^{SM}_{\gamma\gamma,t} \simeq 1.83, \quad \mathcal{A}^{SM}_{\gamma\gamma,W} \simeq -8.36$
- $gg \to \gamma\gamma$: $g_s^2 C(R_{ci}) \to e^2 Q_i^2 N_{ci}$

Fermionic BSM contributions

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

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

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

SM contribution

$\Gamma^{SM}(h \to \gamma Z) =$

$$\frac{\alpha g^2 c_w^2 m_h^3}{512\pi^4 v^2}\left(1-\frac{m_Z^2}{m_h^2}\right)^3 \left|A_1(\tau_W,\lambda_W)+\sum_{f_i}\frac{N_{ci}Q_i g_i^V}{c_w^2}A_{1/2}(\tau_i,\lambda_i)\right|^2$$

$\Rightarrow$ Top and W loops dominate: $\mathcal{A}_{\gamma Z}^{SM} \simeq \mathcal{A}_{\gamma Z,W}^{SM} + \mathcal{A}_{\gamma Z,t}^{SM} < 0$

- Destructive interference between top and W loops: $\mathcal{A}_{\gamma Z,t}^{SM} \simeq 0.37, \quad \mathcal{A}_{\gamma Z,W}^{SM} \simeq -6.64$
- $\gamma\gamma \to \gamma Z$: Not trivial due to Z mass.
- Higgs and Z boson massive $\tau_i = m_h^2/(4m_i^2)$, $\lambda_i = m_Z^2/(4m_i^2)$

Fermionic BSM contributions

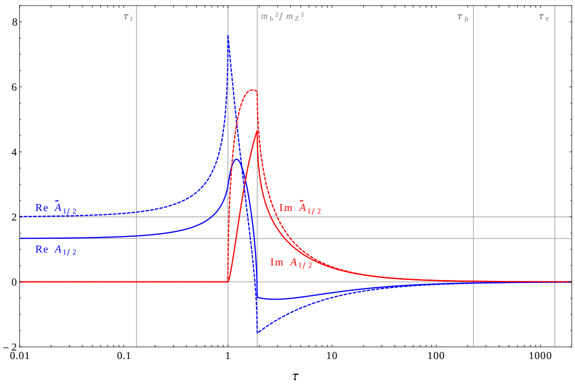
$$\Gamma(h \to \gamma Z) = \frac{\alpha g^2 c_w^2 m_h^3}{512\pi^4 v^2}\left(1-\frac{m_Z^2}{m_h^2}\right)^3 \left[\left| A_1(\tau_W,\lambda_W)+\mathcal{A}_f^{Z\gamma}\right|^2 + \left|\tilde{\mathcal{A}}_f^{Z\gamma}\right|^2\right]$$

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

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

- Off-diagonal loops present (h and Z couplings to 2 mass eigenstates).

Higgs couplings- Loop induced form factors



- $a_{1/2}(m,m,m) \equiv A_{1/2}(\tau,\lambda), \quad \tilde{a}_{1/2}(m,m,m) \equiv \tilde{A}_{1/2}(\tau,\lambda)$
  $b_{1/2}(m,m,m) = \tilde{b}_{1/2}(m,m,m) \equiv 0$
- Similar behaviour compare to $h\gamma\gamma$ (additional Z threshold).
  Same limits: $A_{1/2}(0,0) = A_{1/2}(0), \quad \tilde{A}_{1/2}(0,0) = \tilde{A}_{1/2}(0)$

Experimental constraints - Conclusion

EWPT

- Obliques: S and T parameters.
- Non-obliques: $Zb\bar{b}$, $Z\tau\tau$, $\cdots$

Higgs couplings

- Tree-level: $hb\bar{b}$, $h\tau\tau$, $\cdots$ $\to$ Also possibly large BSM couplings.
- Loop-level: gg, $\gamma\gamma$, γZ loop induced $\to$ sensitive to heavy NP in the loop.

  $\Rightarrow$ gg, $\gamma\gamma$ already a lot constrain.

  $\Rightarrow$ γZ still place for large deviations as $\mu_{\gamma Z} \lesssim 10$.

Other relevant constraints

- Direct searches at colliders: Lower limit on the mass.
- Perturbativity: Limit on the size of the couplings $\to \lambda \leqslant 2\pi$

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Minimal chiral extension of the SM

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

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

$\Rightarrow$ Minimal self-consistent chiral set of new fermions.

- $R_c \neq \overline{R_c}$, N_c even $\Rightarrow$ Minimal choice $N_c = 6$.
- Two mass eigenstates with charge $Q = \pm 1/2$ and masses $m_{2,3} = \lambda_{2,3} v/\sqrt{2}$

Limits

- Mass bounds: Lightest fermion stable and form R-hadrons. $\Rightarrow m \gtrsim 1.4$ TeV ($N_c = 6$).
- EWPT: $S \simeq N_c/(6\pi)$, $T \propto (m_2 - m_3)$ $\Rightarrow$ May respect constraints.

Higgs couplings

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

$\Rightarrow$ Gluons fusion generally kills chiral models with colored states (large enhancement as constructive interference with SM).

Viable chiral extensions after LHC

One viable extension = Two doublets + four singlets

$(2, Y)$, $(2, -Y)$, $\left(1, -Y + \frac{1}{2}\right)$, $\left(1, -Y - \frac{1}{2}\right)$, $\left(1, Y + \frac{1}{2}\right)$, $\left(1, Y - \frac{1}{2}\right)$
(all left-handed)

- No colour $\Rightarrow$ Avoid contribution to hgg coupling ($\mathcal{A}^{gg}_{new} = 0$).
- Global symmetry to forbid VL masses (Not purely chiral extension).

S and T parameters

Custodial limit: $T \simeq 0$ and $S \simeq \frac{1}{3\pi}$ **(Well known formulas for 1 doublet + 2 singlets).**
$\Rightarrow$ Easy to stay in the ellipse.

Higgs couplings

- $\mathcal{A}^{\gamma\gamma}_{new} = 4(1 + 4Y^2)/3 \rightarrow$ Agree with experiment if
  1) $\mathcal{A}^{\gamma\gamma}_{new} \simeq 0$ ie $|Y| \lesssim 0.6$ 2) $\mathcal{A}^{\gamma\gamma}_{new} \simeq -2\mathcal{A}^{\gamma\gamma}_{SM}$ ie $1.3 \lesssim |Y| \lesssim 1.6$
- $\mathcal{A}^{\gamma Z}_{new} \simeq 2\left[1 - \left(1 + 8Y^2\right)\tan^2\theta_w\right]/3$
  $\Rightarrow R_{\gamma Z} \simeq 1.55$ for $|Y| = 1.6 \rightarrow$ Large contribution to γZ channel.

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Usual Seesaw mechanism

Sterile neutrino $N_R \sim (1,1,0)$

$-\mathcal{L}_N = \lambda_N \overline{l_L} \widetilde{H} N_R + \frac{1}{2} M_N \overline{N_R^c} N_R + h.c. \Rightarrow$ Two parameters λ_N and M_N.

Mixing and neutrino masses

$$\mathcal{M}_\nu = \begin{pmatrix} O & m \\ m & M_N \end{pmatrix} = U\ diag(m_\nu, m_{\nu'})\ U^\dagger \Rightarrow \text{Mixing with SM.}$$

- Seesaw mechanism:
  For $\theta \equiv m/M_N \ll 1$ (small active-sterile neutrinos mixing)
  $m_{\nu_l} \simeq m^2/M_N, \quad m_{\nu_h} \simeq M_N.$
  $\Rightarrow$ Naturally small neutrino mass. $m = \lambda_N v/\sqrt{2}$

Higgs couplings

$h\nu_l\nu_h \propto \sqrt{m_{\nu_l} m_{\nu_h}}/v, \qquad h\nu_l\nu_l,\ h\nu_h\nu_h \propto m_{\nu_l}/v$

$\Rightarrow$ Negligibly small decay width ($m_{\nu_l} \lesssim 1$ eV).

Also true for deviation in Z couplings and contributions to S and T.

Model with two sterile neutrinos

Two sterile neutrino $N_{1R} \sim N_{2R} \sim (1,1,0)$

$$\mathcal{M}_\nu = \begin{pmatrix} O & m_1 & m_2 \\ m_1 & M_{N_1} & 0 \\ m_2 & 0 & M_{N_2} \end{pmatrix} \to \theta_i \equiv m_i / M_{N_i}$$

Large mixing

$$m_{\nu_l} \simeq |\theta_1^2 M_{N_1} + \theta_2^2 M_{N_2}| \lesssim 1 \text{ eV}$$

- $\theta_{1,2}$ small: Similar features compare to 1 N_R.
- Phase between θ_1 and θ_2: Possible large $\theta_{1,2}$ with cancellation. 0706.1732

$\Rightarrow$ If we admit tuning, large active-sterile mixings θ_i can be large.

Higgs decays

$\Gamma(h \to \nu_l \nu_{hi}) \simeq m_h m_{\nu_{hi}}^2 |\theta_i|^2/(8\pi v^2)$, $\quad \Gamma(h \to \nu_{hi}\nu_{hi}) \simeq m_h m_{\nu_{hi}}^2 |\theta_i|^4/(4\pi v^2)$

$\Rightarrow$ Possibly as large as $\Gamma_h^{SM} \simeq 4$ MeV.

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Vector-like singlet $E_{L,R} \sim (1,1,-1)$

$-\mathcal{L}_E = \lambda_E \overline{l_L} H E_R + M_E \overline{E_L} E_R + h.c.$ $\Rightarrow$ Two free parameters λ_E and M_E.

Mixing and masses

- $\mathcal{M}_e = \begin{pmatrix} \lambda_\tau \frac{v}{\sqrt{2}} & \lambda_E \frac{v}{\sqrt{2}} \\ 0 & M_E \end{pmatrix} = V_L diag(m_\tau, m'_\tau) V_R^T$, $\Rightarrow$ Mixing with SM.
- $V_\alpha = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \to s_R = \frac{m_\tau}{M_\psi} s_L$ $\Rightarrow$ Right mixing suppressed by τ mass.

Higgs couplings

$$y_{\tau\tau} \simeq \frac{m_\tau}{v}, \quad y_{\tau'\tau'} = s_L^2 \frac{m_{\tau'}}{v}, \quad y_{\tau\tau'} \simeq s_L \frac{m_{\tau'}}{2v} \simeq i\tilde{y}_{\tau\tau'}$$

$\Rightarrow$ Mixing generates diagonal τ' coupling **and** off-diagonal $\tau\tau'$ couplings

Vector-like singlet E

Constraints

- $\underline{Z \to \tau\tau}$: Small mixing $s_L \lesssim 6 \cdot 10^{-2}$ $\to$ S and T automatically respected.
- Direct searches: Light mass $m_{\tau'} \geqslant 100$ GeV (LEP limits).
  $\Rightarrow$ τ' can be lighter than the Higgs, not the case for other VL lepton multiplets.

Higgs decays

- $\delta R(\tau\tau, \gamma\gamma, \gamma Z) \sim s_L^2$ $\Rightarrow$ Negligible contributions to $h \to \tau\tau, \gamma\gamma, \gamma Z$.
- $\Gamma(h \to \tau\tau') \simeq \frac{1}{16\pi v^2} s_L^2 m_{\tau'}^2 m_h \left(1 - \frac{m_{\tau'}^2}{m_h^2}\right)^2 \lesssim 0.2\ \mathrm{MeV} \simeq 5\% \Gamma_h^{SM}$

$\Rightarrow$ Small mixing s_L compensates by large mass $m_{\tau'}$.
Interesting to do a dedicated search as LHC focus on $\tau\tau$, $\tau\mu$ and $\mu\mu$.

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One VL quarks doublet

VL doublets $X_T \sim (3,2,7/6)$ and $Y_B \sim (3,2,-5/6)$

$$-\mathcal{L}_\psi = \lambda_\psi \overline{\psi_L} \tilde{H} t_R(b_R) + M_\psi \overline{\psi_L} \psi_R + h.c.\ , \qquad \text{for } \psi = X_T(Y_B)$$

Mixing and masses

$X_T = \begin{pmatrix} X \\ T \end{pmatrix}$, $Y_B = \begin{pmatrix} B \\ Y \end{pmatrix}$ $\Rightarrow$ Exotic charges: Q(X)=5/3, Q(Y)=-4/3

$$\mathcal{M}_{t(b)} = \begin{pmatrix} \lambda_{t(b)} \frac{v}{\sqrt{2}} & 0 \\ \lambda_\psi \frac{v}{\sqrt{2}} & M_\psi \end{pmatrix}, \qquad m_{X(Y)} = M_\psi \leq m_{t'(b')}$$

$\rightarrow s_L = \frac{m_{t(b)}}{M_\psi} s_R \Rightarrow$ Left mixing suppressed by the top (bottom) mass.

Higgs couplings

- X_T: $y_{tt} = c_R^2 \frac{m_t}{v}$, $y_{t't'} = s_R^2 \frac{m_{t'}}{v}$, $y_{tt'} = c_R s_R \frac{m_t + m_{t'}}{2v}$, $\tilde{y}_{tt'} = c_R s_R \frac{m_t - m_{t'}}{2vi}$
- Y_B: $t \rightarrow b$ and $t' \rightarrow b'$

One VL quarks doublet

Z couplings

- X_T: Loop-induced deviations (No b') $\Rightarrow$ Weak constraints.
- Y_B: Tree-level deviations $\delta g^L_{Zb\bar{b}} = s_L^2 \simeq 0, \quad \delta g^R_{Zb\bar{b}} = s_R^2/2.$

S and T parameters

Gives upper limit on the mixing.

For X_T:Possible cancellation in T parameter

$$T \simeq \frac{3 s_R^2}{16\pi c_W^2 s_W^2} \frac{m_{t'}^2}{m_Z^2} \left[\frac{4}{3} s_R^2 + \frac{m_t^2}{m_{t'}^2} \left(4 \ln \frac{m_t^2}{m_{t'}^2} + 6 \right) \right], \quad S \simeq \frac{s_R^2}{2\pi} \left(\frac{4}{3} \ln \frac{m_t^2}{m_{t'}^2} + 5 \right)$$

$\Rightarrow$ Large mixing ~ 0.5 is allowed.

Direct searches

- Relevant decay channels: $X \to tW^+, \quad t' \to tZ, th, bW^+$
  $Y \to bW^-, \quad b' \to bZ, bh, tW^-$

$\Rightarrow$ Neutral currents relevant for VL quarks (Not the case for chiral quarks).

- Branching ratios: $Br\,(t' \to Zt, ht) \simeq 1/2, \quad Br\,(t' \to Wb) \simeq 0$
  $Br\,(b' \to Zb, hb) \simeq 1/2, \quad Br\,(b' \to Wt) \simeq 0$

One VL quark doublet-Collider searches

ATLAS and CMS limits on VL quarks → $m \geq 600 - 900$ GeV depending on the charge and branching.

heavy quark	branching ratios	mass bound
X $(Q = 5/3)$	$Br_{Wt} = 1$	$m_X \geq 840$ GeV
t' $(Q = 2/3)$	$Br_{Wb} = \frac{1}{2}, \ Br_{Zt} = Br_{ht} = \frac{1}{4}$	$m_{t'} \geq 800$ GeV
	$Br_{Wb} = 0, \ Br_{Zt} = Br_{ht} = \frac{1}{2}$	$m_{t'} \geq 855$ GeV
	$Br_{Wb} = 1, \ Br_{Zt} = Br_{ht} = 0$	$m_{t'} \geq 920$ GeV
	$Br_{Wb} = Br_{Zt} = 0, \ Br_{ht} = 1$	$m_{t'} \geq 950$ GeV
	$Br_{Wb} = Br_{ht} = 0, \ Br_{Zt} = 1$	$m_{t'} \geq 800$ GeV
	$Br_{Wb} + Br_{Zt} + Br_{ht} = 1$	$m_{t'} \geq 720$ GeV
b' $(Q = -1/3)$	$Br_{Wt} = \frac{1}{2}, \ Br_{Zb} = Br_{hb} = \frac{1}{4}$	$m_{b'} \geq 735$ GeV
	$Br_{Wt} = 0, \ Br_{Zb} = Br_{hb} = \frac{1}{2}$	$m_{b'} \geq 755$ GeV
	$Br_{Wt} = 1, \ Br_{Zb} = Br_{hb} = 0$	$m_{b'} \geq 810$ GeV
	$Br_{Wt} = Br_{Zb} = 0, \ Br_{hb} = 1$	$m_{b'} \geq 846$ GeV
	$Br_{Wt} = Br_{hb} = 0, \ Br_{Zb} = 1$	$m_{b'} \geq 775$ GeV
	$Br_{Wt} + Br_{Zb} + Br_{hb} = 1$	$m_{b'} \geq 582$ GeV
Y $(Q = -4/3)$	$Br_{Wb} = 1$	$m_Y \geq 770$ GeV

One VL quark doublet-Higgs couplings

X_T and Y_B contribute to hgg, $h\gamma\gamma$ and $h\gamma Z$ **BUT** contributions are quantitatively very different.

X_T: mixing in the top sector

- $A_{1/2}(t') - A_{1/2}(t) \simeq -0.04 \rightarrow$ Almost no changes in hgg and $h\gamma\gamma$.
- $g^V_{t'} A_{1/2}(t') - g^V_t A_{1/2}(t) \rightarrow$ Sizeable change in $h\gamma Z$.

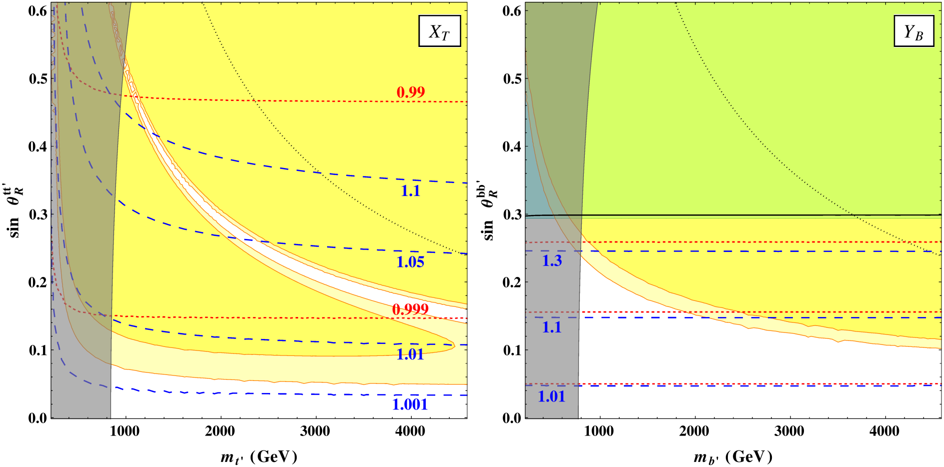
$\Rightarrow \delta\mu_{\gamma\gamma} \ll \delta\mu_{\gamma Z}$.

Y_B: mixing in the bottom sector

- $R_{b\bar{b}} = (1 - s_R^2)^2$
- $A_{1/2}(b') - A_{1/2}(b) \simeq +1.41 \rightarrow$ Constructive (destructive) interference in gg ($\gamma\gamma$) channel.

Production dominates the signal strength (no large W contribution in gg)
$\Rightarrow \delta\mu_{\gamma\gamma} \sim \delta\mu_{\gamma Z}$.

One VL quark doublet



- $\underline{X_T}$: $\delta\mu_{\gamma\gamma} \sim 0.01$ and $\delta\mu_{\gamma Z} \sim 0.13$
- $\underline{Y_B}$: $\delta\mu_{\gamma\gamma} \sim \delta\mu_{\gamma Z} \sim 0.3$

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Two VL leptons $\psi_{1L}, \psi_{1R} \sim (1,1,Y) + \psi_{2L}, \psi_{2R} \sim (1,2,Y+\frac{1}{2})$

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

$\Rightarrow$ 5 free parameter: 2 Yukawa, 2 Vectorial masses and 1 phase φ.

Mixing

- Two states with charges $Q = Y$:

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

$$U_L = \begin{pmatrix} c_L & s_L \\ -s_L & c_L \end{pmatrix} \begin{pmatrix} e^{i\varphi} & 0 \\ 0 & 1 \end{pmatrix}, \quad U_R = \begin{pmatrix} c_R & s_R \\ -s_R & c_R \end{pmatrix}$$

- One state with charge $Q = Y + 1$ and mass M_2.

Two VL leptons- Degenerated case

Parameters

Degenerated masses: $|M_1| = |M_2| \equiv M$, $|m_{12}| = |m_{21}| \equiv \mu$

$$\Rightarrow m_1 = m_2 = \sqrt{M^2 + \mu^2} \equiv m_\psi$$

$h\gamma\gamma$ coupling

$\mathcal{A}^{\gamma\gamma}_{f_1,f_2} = 2Q^2 F(\theta_L, \theta_R, \varphi) A_{1/2}(\tau_\psi) \geqslant 0 \Rightarrow$ Destructive interference with SM

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

$\Rightarrow$ Cancellation region where the rate is accidentally close to SM as $\mathcal{A}^{\gamma\gamma}_{f_1,f_2} \simeq -2\mathcal{A}^{\gamma\gamma}_{SM}$.

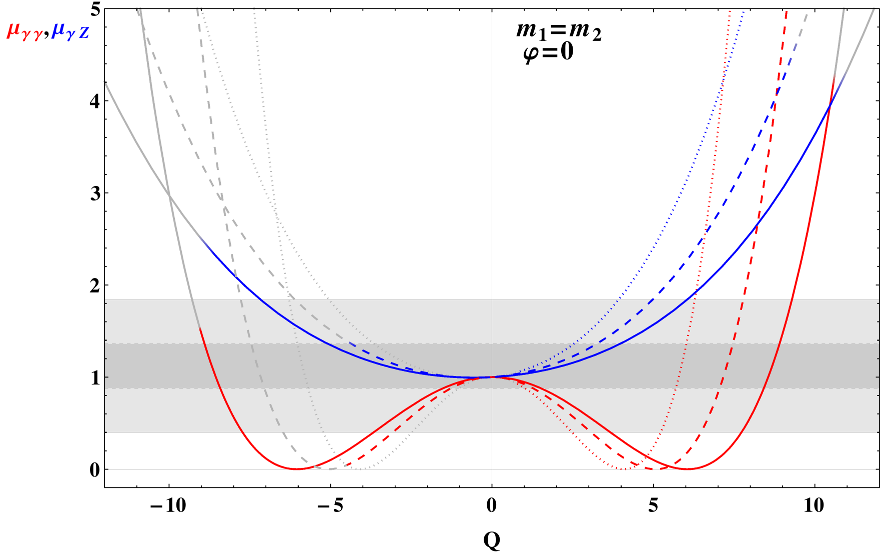
$h\gamma Z$ coupling

$\mathcal{A}^{\gamma Z}_{f1,f2} = \frac{Q}{c_w^2} F(\theta_L, \theta_R, \varphi) \left(g^V_{11} + g^V_{22}\right) A_{1/2}(\tau_\psi, \lambda_\psi)$,

$g^V_{11} + g^V_{22} = -\frac{1}{2} - 2Qs_w^2 \Rightarrow$ Always constructive interference at large Q

For $\varphi = 0$ possible to reach $\mu_{\gamma Z} \simeq 3$.

For $\varphi \neq 0$ additional contribution from $\widetilde{\mathcal{A}}^{\gamma Z}_{f1,f2}$: Possible to reach $\mu_{\gamma Z} \simeq 7$



$\mu_{\gamma\gamma}, \mu_{\gamma Z}$
$m_1 = m_2$
$\varphi = 0$
5
4
3
2
1
0
−10
−5
0
5
10
Q

Two VL leptons- Non degenerated case

$h\gamma\gamma$ and $h\gamma Z$ couplings

Case with different masses $m_1 \neq m_2$ and no CP violation:

- $\mathcal{A}^{\gamma\gamma}_{f_1,f_2} \simeq 2Q^2 \left[s_L^2 c_R^2 + c_L^2 s_R^2 - \left(\frac{m_1}{m_2} + \frac{m_2}{m_1} \right) c_L s_L c_R s_R \right] A_{1/2}(\tau_1)$

  $\Rightarrow$ Parameters can be tuned such that $\mathcal{A}^{\gamma\gamma}_{f_1,f_2} \simeq 0$.
- Possible to reach $\mu_{\gamma Z} \simeq 2$

Conclusion

A lot of Higgs couplings measured at LHC run 1: So far no discrepancy compare to SM.
$\Rightarrow$ Important to understand where large NP effects are still possible.

We systematically analysed extensions that modify Higgs couplings in a model independent way and up to 4 new fermionic multiplets.

- Chiral extensions with $\mathcal{A}^{\gamma\gamma}_{new} \simeq -2\mathcal{A}^{\gamma\gamma}_{SM}$ are in agreement with $h\gamma\gamma$ and can induced large contribution to $h\gamma Z$ ($\mu_{\gamma Z} \simeq 1.55$).
- Two sterile neurinos can induced large Higgs decays into $\nu'\nu'$ and $h\nu\nu'$ if a strong cancellation in the neutrinos mass is present.
- A VL singlet E can induced a large $h\tau\tau'$ coupling if the τ' is lighter than the Higgs.
- A VL quark X_T or Y_B can significantly contributes to $h\gamma Z$.
- Two VL leptons can lead to $\mu_{\gamma Z}$ as large as 7.

Large deviations in $h\gamma Z$, $h\tau\tau'$, $h\nu\nu'$ are possible.
$\Rightarrow$ **LHC run 2 will discards these extensions or (being optimistic) maybe see such deviations!**

Thanks for your attention!