Higgs Couplings to Weak Gauge Bosons: Probing 2 New Physics Scales at Once!

Florian Nortier

CEA Paris-Saclay, DRF/IPhT, Orme des Merisiers, Gif-sur-Yvette, France

florian.nortier@ipht.fr

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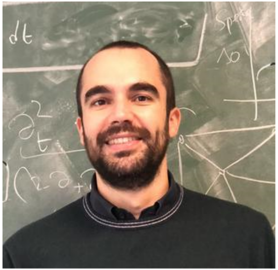
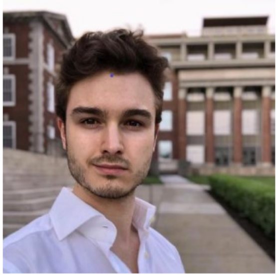
Contents

- Based on Upcoming Preprint: arXiv:230X.XXXX (Work in Progress).
- Co-Workers at IPhT:



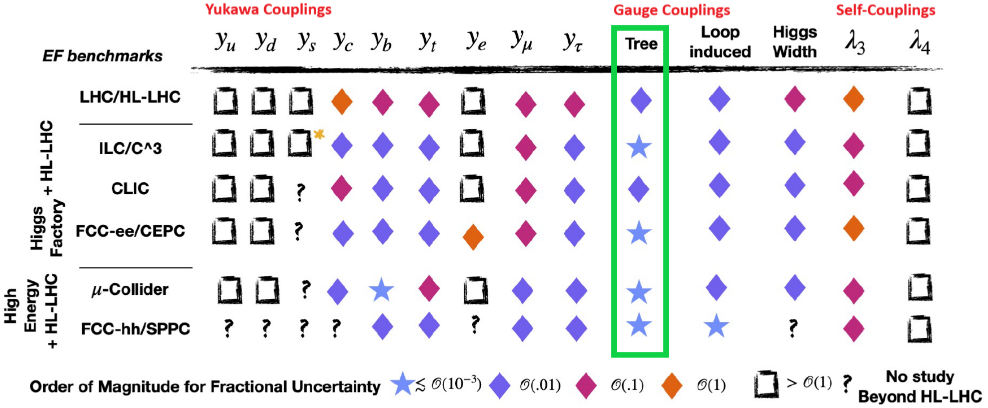
Raffaele Tito D'AGNOLO
(Supervisor)



Gabriele RIGO
(Postdoc)

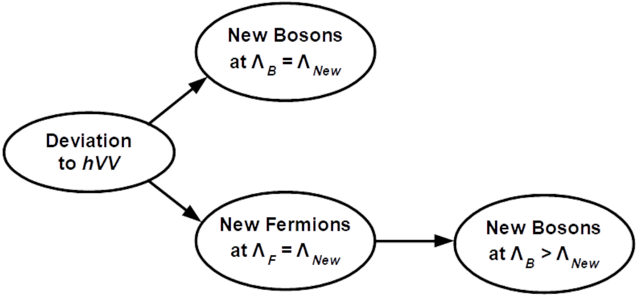
Pablo SESMA
(PhD Student)

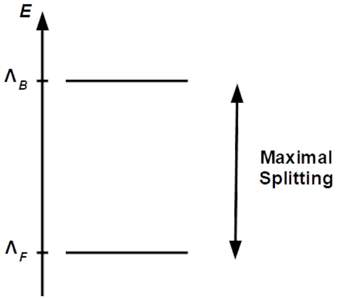
- **Precision Era:** Measurement of Higgs Boson Couplings ⇒ Indirect Probe of New Physics!
- **Claim:** $hVV \equiv hWW$ or hZZ Coupling Deviation ⇒ Upper Bound on Scale of New Bosons!
- **Goal:** Isolate a Model with the Most Conservative Bound (Even If Fine-Tuned).
- Projections of Higgs Coupling Sensitivity at Future Colliders [Snowmass 2021, arXiv.2211.11084]:



1. Introduction – Basic Idea

- hVV Deviation from New Particles at Scale $\Lambda_{New} \Rightarrow$ Bosonic Λ_B AND/OR Fermionic Λ_F:





- SMEFT Analysis $\Rightarrow$ Only Information on Λ_{New}.
- Our Work: Beyond SMEFT $\Rightarrow$ Probing 2 New Scales at Once!
- Strategy Already Applied to Other Higgs Boson Couplings:
  - [Arkani-Hamed, Blum, D'Agnolo, Fan, JHEP 01 (2013) 149];
  - [Blum, D'Agnolo, Fan, JHEP 03 (2015) 166].

2. Benchmark Model – Vectorlike Fermions

- **Pure BSM Fermionic Extensions:** Classification in [Bizot, Frigerio, JHEP 01 (2016) 036].
- **Benchmark Model:** 2 Vectorlike Pairs (1 Hypercharge Not Fixed):

$$L = (r, n)_Y \, , \quad N^c = (\overline{r}, n-1)_{-Y-1/2} \qquad L^c = (\overline{r}, n)_{-Y} \, , \quad N = (r, n-1)_{Y+1/2}$$

- **Renormalizable Lagrangian** $\Rightarrow$ Vectorlike Masses & Yukawa Couplings:

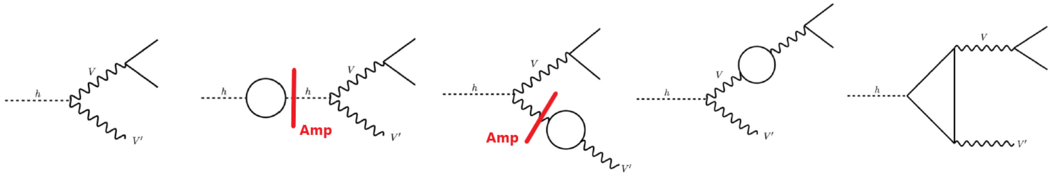
$$\mathcal{L}_4 = -yLHN^c - y^c L^c H^\dagger N - M_L L L^c - M_N N N^c + \text{h.c.}$$

(+ Suppressed or Vanishing Mixings with SM Fermions).

- **1 Physical Phase:** $\varphi = 0, \pi$ (No Constraints from CP Violation).
- **Perturbativity** $\Rightarrow |y|, |y^c| \leq \mathcal{O}(1)$.
- **Decoupling Limit:** $\Lambda_F \sim M_L, M_N \gg \Lambda_{EW}$.

2. Benchmark Model – New Fermion Contributions to hVV^*

- **3 Body Decays:** $h \to W^+W^{-*} \to W^+e^-\overline{\nu}_e$ & $h \to ZZ^* \to Ze^-e^+$.
- **1-Loop Contributions from New Fermions:**



- **Relative Coupling Deviation:** Maximal when $M_L = M_N$ & $y = (-1)^n y^c$ (Heavy Fermions).

$$\delta\mu_{hVV} \equiv \frac{g_{hVV} - g_{hVV}^{\rm SM}}{g_{hVV}^{\rm SM}} = \sqrt{\frac{\Gamma(h \to VV^{(*)})}{\Gamma^{\rm SM}(h \to VV^{(*)})}} - 1$$

- **Renormalization:** $\overline{\rm MS}$ Parameters in Terms of Electroweak Precision Observables:
  - QED Fine-Structure Constant $\alpha_e(M_Z)$;
  - Fermi Constant G_F;
  - Z-Boson Pole Mass M_Z.

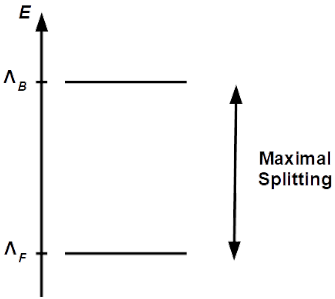
$\Rightarrow$ μ-Independence of $\delta\mu_{hVV}$ ($\mu \equiv$ Renormalization Scale).

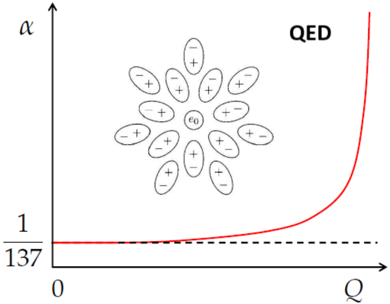
2. Benchmark Model – New Fermions ⇒ Cutoff ≡ New Bosonic Scale

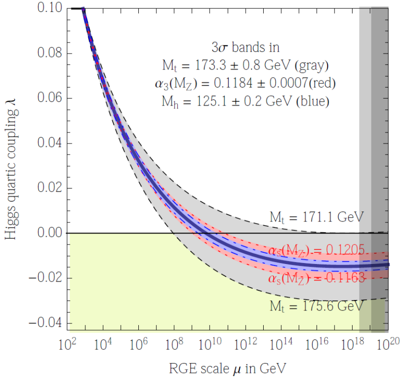
- hVV^* at Tree Level in SM ⇒ $y, y^c \sim \mathcal{O}(1)$ for Observable $\delta\mu_{hVV}$.
  ⇒ **Finite Range of Validity** ⇒ Cutoff Λ_B ≡ **New Bosonic Scale!**
- **Instability of Higgs Potential** OR **Landau Poles for Yukawa Couplings:**

$$\frac{d\lambda}{d\log\mu} \sim -\frac{y^4}{16\pi^2} \quad \text{and} \quad \frac{dy}{d\log\mu} \sim \frac{y^3}{16\pi^2}$$

e.g. Top Quark in SM ⇒ Instability?
[Buttazzo et al., JHEP 12 (2013) 089]

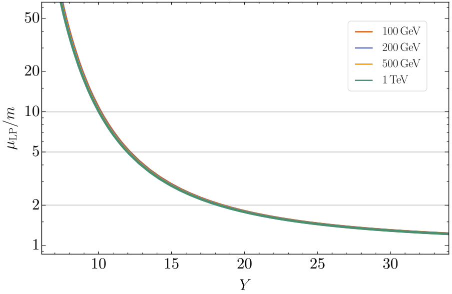


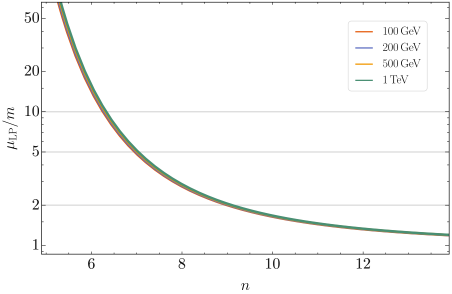




2. Benchmark Model – Reducing the Number of Representations

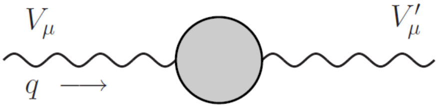
- **Goal:** Find the Most Conservative Upper Bound on Λ_B.
  $\rightarrow$ Intuitively: Doublet + Singlet ($n = 2$, $Y = -1/2$) $\Rightarrow$ 2 Neutral + 1 Charged (+1).
- **Scaling Arguments:** Focus on 1 Generation of **Vectorlike Leptons**! (cf. Backup).
  - No Clear Scaling Argument to Exclude Larger n or Y.
  - Colored Representations OR Multiple Generations $\Rightarrow$ Lower Λ_B.
- **Landau Poles μ_{LP} for Electroweak Gauge Couplings:** (1-Loop RGE's, Mass Scale $m \equiv \Lambda_F$)
  - $U(1)_Y$ Weak Hypercharge with $(n = 2, y = y^c = 0)$ $\Rightarrow$ $n \lesssim 6$.
  - $SU(2)_W$ Weak Isospin with $(Y = 0, y = y^c = 0)$ $\Rightarrow$ $Y \lesssim 10$.

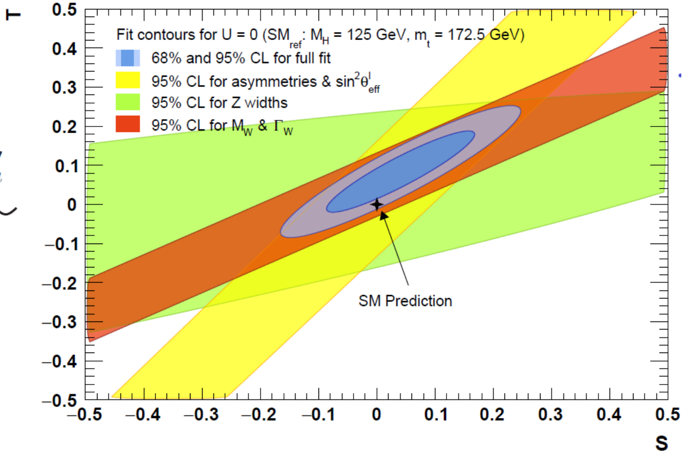




2. Benchmark Model – New Fermions ⇒ Oblique Electroweak Corrections

- New Fermions ⇒ 1-Loop Corrections to Self-Energies of EW Gauge Bosons ⇒ Main Constraints.
- Peskin-Takeuchi Parameters: S, T & U [Peskin, Takeuchi, PRD 46 (1992) 381-409].
  ⇒ S & T Fit with $U = 0$ [Gfitter Group, EPJC 78 (2018) 8, 675]:

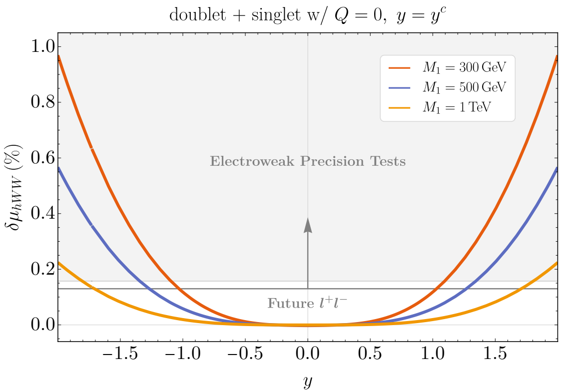


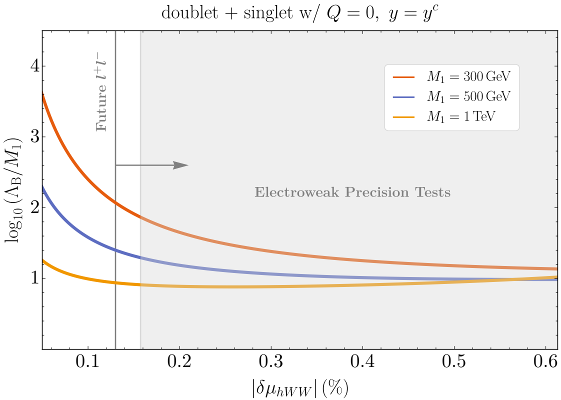


3. Results & Plot Gallery for $h \to WW^*$

3. Results for $h \to WW^*$ – Doublet + Singlet

Doublet + Singlet Leptons ($n = 2$, $Y = -1/2$) $\Rightarrow$ 2 Neutral ($Q = 0$) + 1 Charged (+1):

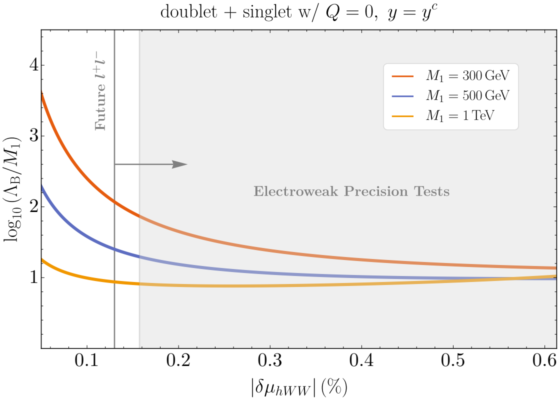


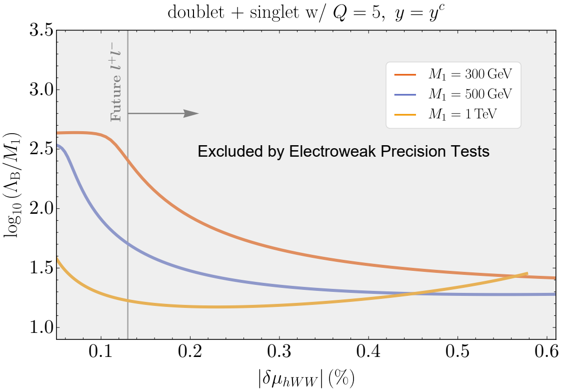


Plots for $M_L = M_N$ (2-Loop RGE's with SARAH).

3. Results for $h \to WW^*$ – Higher-Hypercharge

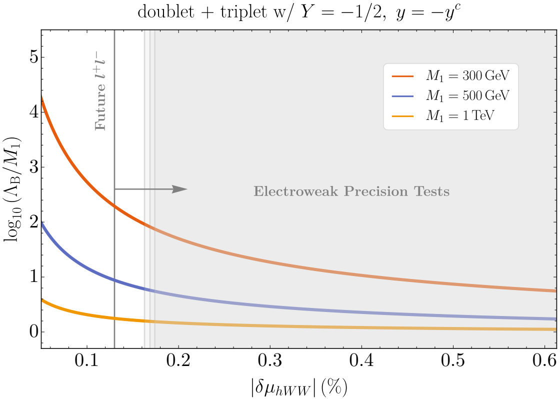
Increasing $Y \Rightarrow$ Excluded by S & T.

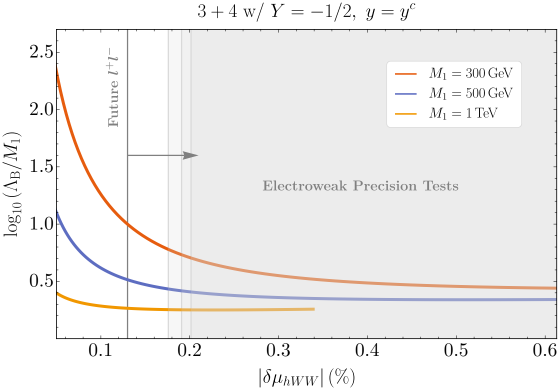




Plots for $M_L = M_N$ (2-Loop RGE's with SARAH).

Increasing $n \Rightarrow$ Lower Λ_B for Heavy Leptons:





Plots for $M_L = M_N$ (2-Loop RGE's with SARAH).

4. Epilogue (1/2)

4. Epilogue (2/2)

- **Work in Progress:**
  - Doublet + Singlet Leptons ($Y = -1/2$) $\Rightarrow$ Light Neutral Lepton.
    $\Rightarrow$ Collider Constraints? ($\sim$ Higgsino-Bino System) Oblique EW Corrections?
  - Collider Constraints for Higher-Representations? Higher-Hypercharges?
  - Study of $\delta\mu_{hZZ}$ $\Rightarrow$ Similar Results.

- **3 Punchlines:**
  - **Pure Fermionic Extensions** of SM $\Rightarrow$ **Finite Range of Validity:**
    $\Rightarrow$ Upper Bound on New Bosonic Scale!
    $\Rightarrow$ Most Conservative Upper Bound ($\delta\mu_{hVV} \neq 0$) For Doublet + Singlet ($Q = 0$).
  - If $\delta\mu_{hVV} \neq 0$ at **HL-LHC** ($\sim 1\%$ Sensitivity) $\Rightarrow$ **Look for New Bosons!** (Minimal Model)
  - If $\delta\mu_{hVV} \neq 0$ at **FCC** ($\sim 0.1\%$ Sensitivity) $\Rightarrow$ **New Fermions?** $\Rightarrow$ **New Bosons Not Far!**

Thank You for Your Attention!

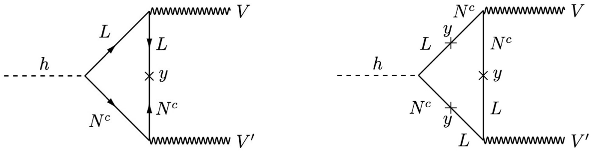
5. Backup

5. Backup – Model Selection

- **Pure BSM Fermionic Extensions:** Classification in [Bizot, Frigerio, JHEP 01 (2016) 036].
  $\Rightarrow$ Consider Only Relevant Models for Higgs Couplings.
- **Minimal Extension:** 1 Vectorlike Pair + 1 Majorana $\Rightarrow$ Fixed Hypercharged.
- **Benchmark Model:** 2 Vectorlike Pairs (1 Hypercharge Not Fixed):
  $L = (r, n)_Y \, , \quad N^c = (\overline{r}, n-1)_{-Y-1/2} \qquad L^c = (\overline{r}, n)_{-Y} \, , \quad N = (r, n-1)_{Y+1/2}$
- **Renormalizable Lagrangian:**
  $$\mathcal{L}_4 = -yLHN^c - y^c L^c H^\dagger N - M_L L L^c - M_N N N^c + \text{h.c.}$$
- **Few Special Cases:** $r = \overline{r}$, $Y = 0$, $(n-1 \text{ odd}) \Rightarrow$ Other Possible Terms.
  $\Rightarrow$ Qualitatively Similar (No Detailed Study).
- **Landau Pole:** QCD Coupling g_s Blows Up Near $\Lambda_F \Rightarrow r \leq 8$.

5. Backup – Scaling Arguments (1/2)

- **Scaling of δg_{hVV} from 2 Diagrams:**



$$\delta g_{hVV} = \frac{g_V^2}{16\pi^2}\left(\beta_1 \frac{y^2 v^2}{\Lambda_F^2} + \beta_2 \frac{y^4 v^2}{\Lambda_F^2}\right)$$

- **Colored Fermions:** Future Colliders ($\delta\mu_{hVV} \gtrsim 0.1\%$) $\Rightarrow y^4$ Term Dominates!
  - $\Lambda_B \equiv$ **Landau Pole:** Fixed $y_r = \sqrt{r}y \Rightarrow$ Same Λ_B for Any r:

$$\delta g_{hVV} \sim \frac{g_V^2}{16\pi^2} \cdot \frac{y_r^4 v^2}{r\,\Lambda_F^2}\,.$$

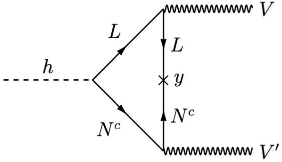
  - $\Lambda_B \equiv$ **Vacuum Instability:** Fixed $y_r = \sqrt[4]{r}y \Rightarrow$ Same Λ_B for Any r:

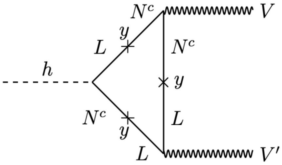
$$\delta g_{hVV} \sim \frac{g_V^2}{16\pi^2} \cdot \frac{y_r^4 v^2}{\Lambda_F^2}\,.$$

$\Rightarrow$ Smaller δg_{hVV} than for Color Singlets + Stronger Collider Constraints on $\Lambda_F \Rightarrow$ Lower Λ_B.

- $\mathcal{N}$ **Generations of Vectorlike Fermions:** Similar Arguments.

- **Scaling of δg_{hVV} from 2 Diagrams:**



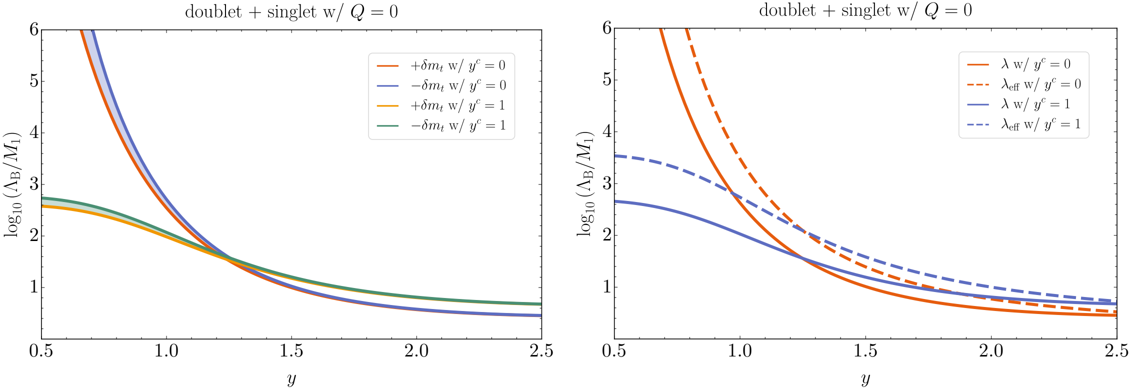


- **Higher-Isospin Representations:** Large n:

$$\delta g_{hVV} \sim \frac{g_V^2}{16\pi^2} \left(\beta_1 \, n^3 \, \frac{y^2 v^2}{\Lambda_F^2} + \beta_2 \, n \, \frac{y^4 v^2}{\Lambda_F^2} \right) , \quad 16\pi^2 \frac{dy}{d \log \mu} \sim n y^3 , \quad 16\pi^2 \frac{d\lambda}{d \log \mu} \sim -n y^4 + n \lambda y^2 .$$

$\Rightarrow$ No Scaling Argument to Exclude Higher-Representations! Likewise for Higher-Hypercharges!

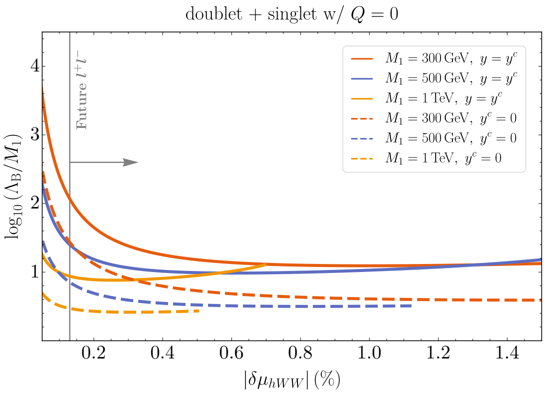
- **Instability Scale Not Sensitive to Top Quark Mass** (M_t vs $2M_t$ on Left Plot).
- **Ambiguity on Higgs Quartic Coupling:** (Right Plot)
  - Gauge Invariant (Solid Lines) $\Rightarrow$ The One We Used.
  - Effective Potential (Dashed Lines) $\Rightarrow$ Not So Different.



Plots for Doublet + Singlet ($Q = 0$), $M_L = M_N$, (2-Loop RGE's with SARAH)

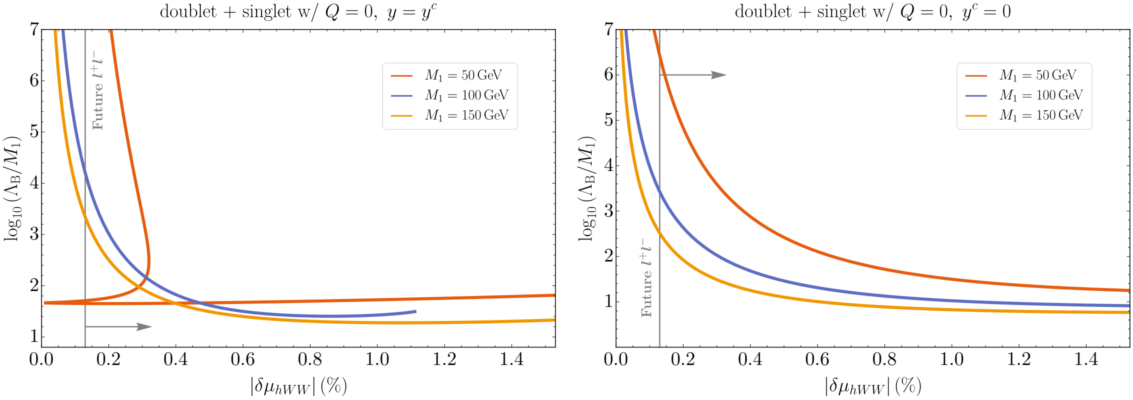
5. Backup – Different Yukawa Couplings

Work in Progress: Doublet + Singlet Leptons ($Y = -1/2$) with $y \neq y^c$.
$\Rightarrow$ Lower Cutoff Λ_B (Need to Add S & T Constraints).



Plot for $M_L = M_N$ (2-Loop RGE's with SARAH).

Work in Progress: Doublet + Singlet Leptons ($Y = -1/2$) $\Rightarrow$ Light Neutral Lepton.
$\rightarrow$ Oblique EW Corrections?



Plots for $M_L = M_N$ (2-Loop RGE's with SARAH).

5. Backup – Low Mass (2/2)

Work in Progress: Collider Constraints ∼ Higgsino-Bino System (Plot for $M_L = M_N$):