Higgs effective Hl_il_j vertex from heavy ν_R and applications to LFV phenomenology

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Work in collaboration based on:

E. Arganda., M. J. Herrero, X. Marcano, R. Morales and A. Szynkman,

Phys. Rev. D **95** (2017) no.9, 095029 [arXiv:1612.09290 [hep-ph]].

Motivation

Neutral LFV observed in Neutrino Oscillations!!!

Neutrino Oscillations $\Longrightarrow$ BSM for neutrino masses

$$\text{nLFV} \xrightarrow{\text{New Neutrino Physics}} \text{cLFV}$$

Low-scale seesaw models

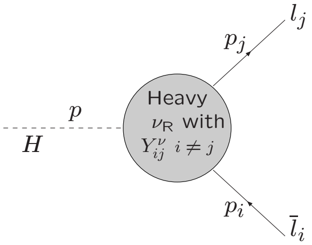
- Accommodate light neutrino data.
- Large Yukawa couplings, $Y_\nu^2/4\pi \sim \mathcal{O}(1)$, with $M_N \sim \mathcal{O}(1\ \text{TeV})$.
- New rich phenomenology: cLFV ($l_i \to l_j\gamma$, $l_i \to 3l_j$, $H \to l_i l_j$, $Z \to l_i l_j$..), heavy neutrinos reachable at LHC...

Mass insertion approximation (MIA) for loop-induced cLFV

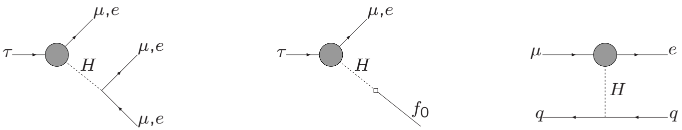
Provides simple formulas valid for any low-scale seesaw model

Our Goal

Compute the effective LFV vertex Hl_il_j from heavy ν_R in the loops



To be used in LFVHD and Higgs mediated LFV processes like:



Intense search program for cLFV

LFV transitions	LFV Present Bounds (90%CL)	Future Sensitivities
BR($\mu \to e\gamma$)	4.2×10^{-13} (MEG 2016)	6×10^{-14} (MEG-II)
BR($\tau \to e\gamma$)	3.3×10^{-8} (BABAR 2010)	10^{-9} (BELLE-II)
BR($\tau \to \mu\gamma$)	4.4×10^{-8} (BABAR 2010)	10^{-9} (BELLE-II)
BR($\mu \to eee$)	1.0×10^{-12} (SINDRUM 1988)	10^{-16} Mu3E (PSI)
BR($\tau \to eee$)	2.7×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
BR($\tau \to \mu\mu\mu$)	2.1×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
BR($\tau \to \mu\eta$)	2.3×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
CR($\mu - e$, Au)	7.0×10^{-13} (SINDRUM II 2006)	
CR($\mu - e$, Ti)	4.3×10^{-12} (SINDRUM II 2004)	10^{-18} PRISM (J-PARC)
CR($\mu - e$, Al)		3.1×10^{-15} COMET-I (J-PARC)
		2.6×10^{-17} COMET-II (J-PARC)
		2.5×10^{-17} Mu2E (Fermilab)

Bounds on	LEP(95%CL)	ATLAS(95%CL)	CMS(95%CL)
BR($Z \to \mu e$)	1.7×10^{-6}	7.5×10^{-7} PRD90(2014)072010	
BR($Z \to \tau e$)	9.8×10^{-6}		
BR($Z \to \tau\mu$)	1.2×10^{-5}	1.69×10^{-5} EPJC77(2017)70	
BR($H \to \mu e$)	-		3.5×10^{-4} PLB763(2016)472
BR($H \to \tau e$)	-	1.04×10^{-2} EPJC77(2017)70	6.1×10^{-3} CMS-PAS-HIG-17-001
BR($H \to \tau\mu$)	-	1.43×10^{-2} EPJC77(2017)70	2.5×10^{-3} CMS-PAS-HIG-17-001

CMS found 2.4σ excess: $\mathrm{BR}(H \to \tau\mu) = 0.84^{+0.39}_{-0.37}\%$ (95% C.L.) [PLB749(2015)337]

ATLAS found 1.3σ excess: $\mathrm{BR}(H \to \tau\mu) = 0.77 \pm 0.62\%$ (95% C.L.) [arXiv:1508.03372]

Focus on LFV Higgs(-mediated) processes induced by massive neutrinos

Type-I seesaw model

- Neutrino oscillations $\Longrightarrow$ Non-zero Neutrino masses m_ν
- Add ν_R to the SM $\Longrightarrow$ Dirac mass: $m_D = vY_\nu$
- ν_R is a SM singlet $\Longrightarrow$ Majorana mass: M

$$M_{\text{type-I}} = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$$

$$m_\nu \sim \frac{m_D^2}{M}$$

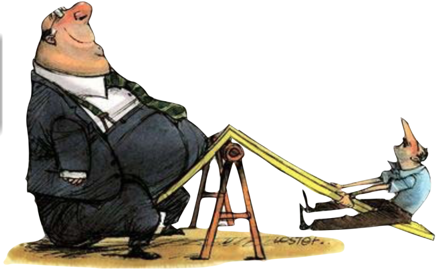
$$\left.\begin{array}{l} \text{Low } M \sim 1 \text{ TeV} \Longrightarrow \text{ small } Y_\nu \ll 1 \\ \text{Large coupling } Y_\nu \sim 1 \Longrightarrow \text{ heavy } M \sim 10^{14} \text{ GeV} \end{array}\right\} \begin{array}{c} \text{Suppressed} \\ \text{Pheno} \end{array}$$

Low-scale seesaw models

- Use symmetries to lower M yet keeping the coupling Y_ν large.
- Approximate Lepton Number conservation: $U(1)_L$
- Smallness of neutrino masses $\Longleftrightarrow$ small violation of $U(1)_L$

μ_X small scale $\not{L}$

$$m_\nu \propto \mu_X$$



Decouple M and Y_ν from m_ν:

$$\left.\begin{array}{l}\text{Low heavy masses } M \sim 1 \text{ TeV} \\ \text{Large coupling } Y_\nu \sim 1\end{array}\right\} \begin{array}{c}\text{Enhanced} \\ \text{Pheno}\end{array}$$

The inverse seesaw model

[Mohapatra and Valle, 1986]

SM extended with 3 pairs of fermionic singlets: $\nu_{Ri}(L=+1)$ & $X_j(L=-1)$

$$\mathcal{L}_{\rm ISS} = -Y_\nu^{ij}\overline{L_i}\tilde{H}\nu_{R_j} - M_R^{ij}\overline{\nu_{R_i}^C}X_j - \frac{1}{2}\mu_X^{ij}\overline{X_i^C}X_j + h.c. \quad i,j=1..3$$

Neutrino mass matrix

$$M_{\rm ISS} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix} \; ; \qquad U_\nu^T M_{\rm ISS} U_\nu = {\rm diag}(m_{n_1}, ..m_{n_9})$$

Use μ_X to accommodate low energy neutrino data. Arganda et al., PRD91(2015)1,015001

$$\mu_X = M_R^T m_D^{-1} U_{\rm PMNS}^* m_\nu U_{\rm PMNS}^\dagger m_D^{T^{-1}} M_R \sim \frac{M_R^2}{m_D^2} m_\nu$$

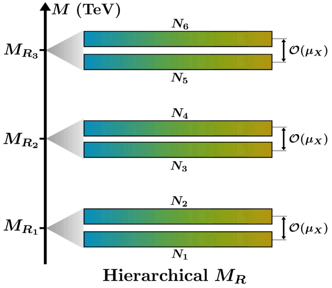
Working in the EW basis: **Input Parameters**

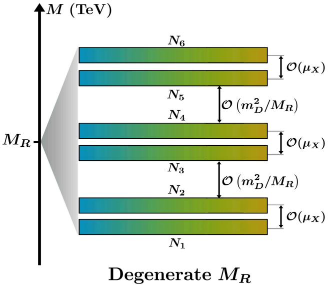
- $M_R \longrightarrow$ Masses of the 6 heavy Majorana neutrinos (3 pseudo-Dirac pairs)
- $Y_\nu \longrightarrow$ Yukawa interaction between ν_L-ν_R-H. Governs cLFV pheno.
- $\mu_X \longrightarrow$ light neutrinos pheno. Irrelevant for cLFV.

Relative size: $\mu_X \ll m_D = vY_\nu \ll M_R$

e.g. setting $m_\nu \sim 0.1$ eV, $Y_\nu \sim 1 \longrightarrow 10^{-8,-6} \ll 10^2 \ll 10^{3,4}$ (in GeV)

The heavy neutrinos of the ISS and cLFV

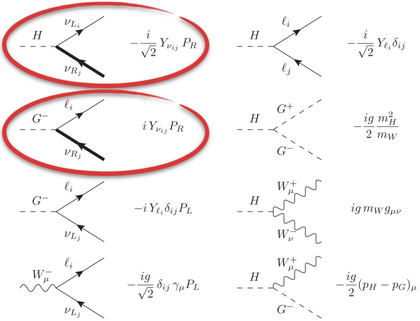




- 6 heavy N_i in 3 pseudo-Dirac pairs. Here one M_R: $m_{N_i} \sim M_R$ (degenerate)
- Mass basis involves $B_{l_i n_j}$ (in $W l_i n_j$) and $C_{n_i n_j}$ (in $H n_i n_j$) all derived from U_ν. EW basis involves directly Y_ν and M_R.
- Here work with the EW basis: Previous studies of loop induced $H l_i l_j$ from heavy ISS neutrinos used the mass basis:

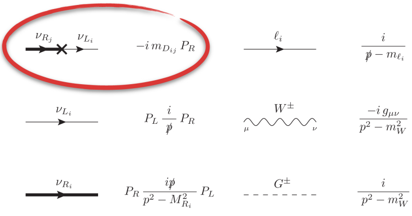
  E. Arganda, M.J. Herrero, X. Marcano, C. Weiland, PRD91(2015)1,015001
- The MIA works in the EW basis: optimal for tracking cLFV induced from non-diagonal (in flavor) $(Y_\nu)_{ij}$, $i \neq j$.

Feynman rules and *fat* propagators for the MIA



× denotes mass insertions that can change flavor

$m_{D_{ij}} = v(Y_\nu)_{ij}$



Fat propagators: M_R appears effectively in the denominator

$$P_R \, \frac{i\not p}{p^2 - |M_{R_i}|^2} \, P_L$$

Easier tracking of ν_R decoupling behavior at large $M_R \gg v$

The MIA expansion for cLFV

Diagramatic calculation of the one-loop effective vertex Hl_il_j in the MIA:

1.- Express $H(p_1) \to \ell_k(-p_2)\bar{\ell}_m(p_3)$ in terms of form factors $F_{L,R}$

$$i\mathcal{M} = -ig\bar{u}_{\ell_k}(-p_2)(F_L P_L + F_R P_R)v_{\ell_m}(p_3)$$

2.- Use previous Feynman rules and fat propagators: All 1-loop contributions given by an expansion in even powers of Y_ν:

$$F_{L,R}^{\mathrm{MIA}} = \left(Y_\nu Y_\nu^\dagger\right)^{km} f_{L,R}^{(Y^2)} + \left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km} f_{L,R}^{(Y^4)} + ...$$

3.- Expand all loop integrals in inverse powers of M_R

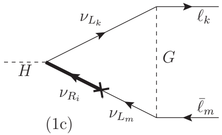
4.- Computation done in Feynman 't Hooft gauge.

Also in unitary gauge (checked gauge invariance)

- LO terms: $\mathcal{O}(Y_\nu Y_\nu^\dagger) \propto (v/M_R)^2$.
- NLO terms: $\mathcal{O}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger) \propto (v/M_R)^2$, genuine of LFV Higgs!!!
- $\mathcal{O}(Y_\nu^6) \propto (v/M_R)^4$: negligible!

MIA versus full results: $\mathcal{O}(Y_\nu^2)$

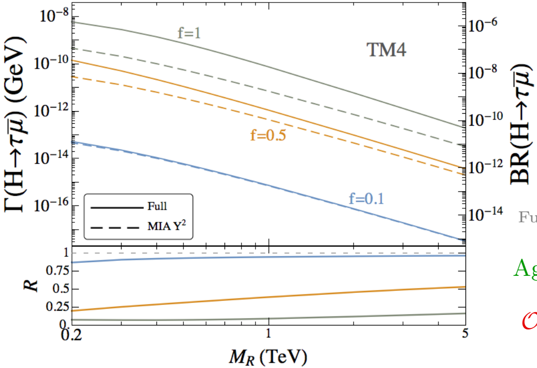
Example! (25 contributing diagrams)



$$F_L^{\mathrm{MIA(1c)\ (Y^2)}} = -\frac{1}{32\pi^2}\frac{m_{\ell_k}}{m_W}\left(Y_\nu Y_\nu^\dagger\right)^{km} m_{\ell_m}^2 C_{12}(p_2,p_1,m_W,0,M_R)$$

$$F_R^{\mathrm{MIA(1c)\ (Y^2)}} = -\frac{1}{32\pi^2}\frac{m_{\ell_m}}{m_W}\left(Y_\nu Y_\nu^\dagger\right)^{km} m_{\ell_k}^2 (C_0 + C_{11} - C_{12})$$

$\propto v^2/M_R^2$ (up to logarithms)



Scenario with suppressed μe and τe mixing

$$Y_\nu^{\mathrm{TM4}} = f\begin{pmatrix} 0.1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0.014 \end{pmatrix}$$

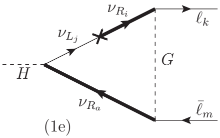
Full from: Arganda et al., PRD91(2015)1,015001

Agreement MIA/Full only for small f

$\mathcal{O}(Y_\nu^2)$ MIA insufficient for large f

MIA versus full results: $\mathcal{O}(Y_\nu^2 + Y_\nu^4)$

Example! (Besides previous 25 $\mathcal{O}(Y_\nu^2)$-diagrams, there are 14 $\mathcal{O}(Y_\nu^4)$-diagrams)

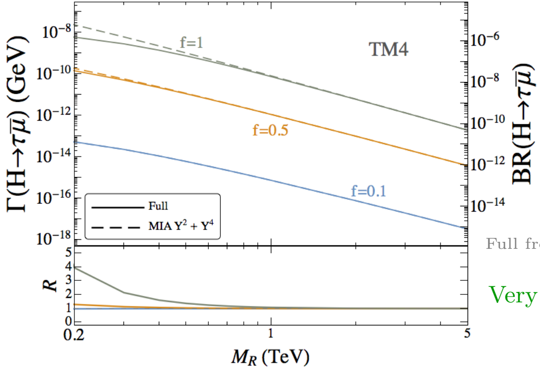


$$F_L^{\mathrm{MIA(1e)\ (Y^4)}} = -\frac{1}{32\pi^2}\frac{m_{\ell_k}}{m_W}\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km} v^2(C_{11} - C_{12})$$

$$F_R^{\mathrm{MIA(1e)\ (Y^4)}} = -\frac{1}{32\pi^2}\frac{m_{\ell_m}}{m_W}\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km} v^2(C_0 + C_{12})$$

$\propto v^2/M_R^2$ at large M_R

$$C_i = C_i(p_2, p_1, m_W, M_R, M_R)$$



Scenario with suppressed μe and τe mixing

$$Y_\nu^{\mathrm{TM4}} = f\begin{pmatrix} 0.1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0.014 \end{pmatrix}$$

Full from: Arganda et al., PRD91(2015)1,015001

Very good agreement for $M_R > 500$ GeV

1-loop effective vertex for LFVH in the MIA

For heavy ν_R, $m_{\ell_m} \ll m_{\ell_k} \ll m_W, m_H, m_D \ll M_R$, we get a very simple analytical result for $V^{\rm eff}_{Hl_kl_m}$, applicable to low-scale seesaw:

$$i\mathcal{M} = -ig\bar{u}_{l_k} V^{\rm eff}_{Hl_kl_m} P_L v_{l_m}$$

$$V^{eff}_{Hl_kl_m} = \frac{1}{64\pi^2}\frac{m_{\ell_k}}{m_W}\left[\frac{m_H^2}{M_R^2}\left(r\left(\frac{m_W^2}{m_H^2}\right) + \log\left(\frac{m_W^2}{M_R^2}\right)\right)\left(Y_\nu Y_\nu^\dagger\right)^{km} - \frac{3v^2}{M_R^2}\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km}\right]$$

Checked gauge invariance of the result (same in Feynmam 't Hooft and Unitary gauge)

$$r(\lambda) = -\frac{1}{2} - \lambda - 8\lambda^2 + 2(1-2\lambda+8\lambda^2)\sqrt{4\lambda-1}\,\arctan\left(\frac{1}{\sqrt{4\lambda-1}}\right) + 16\lambda^2(1-2\lambda)\,\arctan^2\left(\frac{1}{\sqrt{4\lambda-1}}\right) \simeq 0.3$$

Note that $\mathcal{O}(Y_\nu Y_\nu^\dagger)$ term depends on m_H but not $\mathcal{O}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)$ term.

Simple $\Gamma(H \to l_k \bar{l}_m) = \frac{g^2}{16\pi} m_H |V^{eff}_{Hl_kl_m}|^2$:

$$\Gamma = \frac{g^2 m_{\ell_k}^2 m_H}{2^{16}\pi^5 m_W^2}\left|\frac{m_H^2}{M_R^2}\left(r\left(\frac{m_W^2}{m_H^2}\right) + \log\left(\frac{m_W^2}{M_R^2}\right)\right)\left(Y_\nu Y_\nu^\dagger\right)^{km} - \frac{3v^2}{M_R^2}\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km}\right|^2$$

We also obtained the effective vertex for Higgs-mediated processes (zero external momenta):

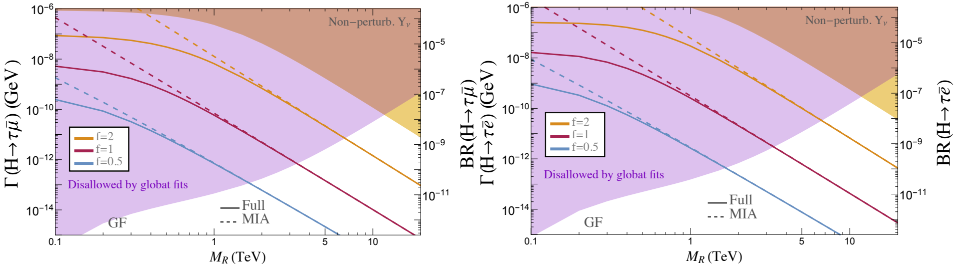
$$V^{eff\,(p^{\rm ext}=0)}_{Hl_kl_m} = -\frac{1}{32\pi^2}\frac{m_{\ell_k}}{m_W}\left(\frac{3m_W^2}{2M_R^2}\right)\left[\left(Y_\nu Y_\nu^\dagger\right)^{km} + v^2\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km}\right].$$

Pheno App: rapid estimates of $\mathrm{BR}^{\max}$ allowed by data

"Global Fits" constraints [E. Fernández-Martínez *et al.*, JHEP 1608 (2016) 033] imposed into the product $Y_\nu Y_\nu^\dagger$ by means of matrix $\eta = (v^2/(2M_R^2))(Y_\nu Y_\nu^\dagger)$, saturated at 3σ level defining a "maximum allowed by data" matrix:

$$\eta_{3\sigma}^{\max} = \begin{pmatrix} 1.62\times10^{-3} & 1.51\times10^{-5} & 1.57\times10^{-3} \\ 1.51\times10^{-5} & 3.92\times10^{-4} & 9.24\times10^{-4} \\ 1.57\times10^{-4} & 9.24\times10^{-4} & 3.67\times10^{-3} \end{pmatrix} \Rightarrow Y_\nu^{\rm GF} = f\begin{pmatrix} 0.33 & 0.83 & 0.6 \\ -0.5 & 0.13 & 0.1 \\ -0.87 & 1 & 1 \end{pmatrix}$$

in a parameter space line given by the ratio $f/M_R = (3/10)\,\mathrm{TeV}^{-1}$.



Maximum rates: $\mathrm{BR}(H\to\tau\mu)\sim 3\times10^{-8}$ and $\mathrm{BR}(H\to\tau e)\sim 2\times10^{-7}$

Conclusions

- MIA results very simple and useful:
  - Extremely good approximation valid for $M_R \gg v$.
  - Decoupling behavior with M_R is manifest.
  - Interesting implications for phenomenology.
  - Valid for any low-scale seesaw model with same Feynman rules.
- Maximum LFVHD rates allowed by data in the ISS of $\mathcal{O}(10^{-7} - 10^{-8})$. Not testable at the LHC.
- If ATLAS and CMS excesses on $h \to \tau\mu$ confirmed, no low-scale seesaw model can be responsible for this LFV.

Backup slides

Neutrino data

The lightest neutrino mass m_{ν_1} is assumed as a free input parameter in agreement with the upper limit on the effective electron neutrino mass in β decays from the Mainz [C. Kraus *et al.*, 2005] and Troitsk [V. N. Aseev *et al.*, 2011] experiments,

$$m_\beta < 2.05 \text{ eV} \quad \text{at } 95\% \text{ CL} . \tag{1}$$

The other two light masses are obtained from:

$$m_{\nu_2} = \sqrt{m_{\nu_1}^2 + \Delta m_{21}^2}\,, \quad m_{\nu_3} = \sqrt{m_{\nu_1}^2 + \Delta m_{31}^2}\,. \tag{2}$$

For simplicity, we set to zero the CP-violating phase of the U_{PMNS} matrix and we have used the results of the global fit [M. C. Gonzalez-Garcia *et al.*, 2012] leading to:

$$\begin{aligned} \sin^2\theta_{12} &= 0.306^{+0.012}_{-0.012}\,, & \Delta m_{21}^2 &= 7.45^{+0.19}_{-0.16} \times 10^{-5} \text{ eV}^2\,, \\ \sin^2\theta_{23} &= 0.446^{+0.008}_{-0.008}\,, & \Delta m_{31}^2 &= 2.417^{+0.014}_{-0.014} \times 10^{-3} \text{ eV}^2\,, \\ \sin^2\theta_{13} &= 0.0231^{+0.0019}_{-0.0019}\,, \end{aligned} \tag{3}$$

where we have assumed a normal hierarchy.

Geometrical parametrization for Y_ν

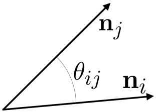
E. Arganda, M.J. Herrero, X. Marcano, C. Weiland, PRD91(2015)1,

Assuming $M_{R_{ij}} = M_R \delta_{ij}$ and real Y_ν matrix:

$$\boxed{\mathrm{LFV}_{ij} \longleftrightarrow \left(Y_\nu Y_\nu^T\right)_{ij}}$$

Y_ν 9 d.o.f $\longrightarrow$ 3 vectors (+ global strength f):

$$Y_\nu \equiv f \begin{pmatrix} \boldsymbol{n}_e \\ \boldsymbol{n}_\mu \\ \boldsymbol{n}_\tau \end{pmatrix} \left\{ \begin{array}{l} \text{3 modulus}: |\boldsymbol{n}_e|, |\boldsymbol{n}_\mu|, |\boldsymbol{n}_\tau| \\ \text{3 relative flavor angles:} \, \theta_{\mu e}, \theta_{\tau e}, \theta_{\tau\mu} \\ \text{global rotation } O(\theta_1, \theta_2, \theta_3), \;\; OO^T = 1 \end{array} \right.$$



$$Y_\nu Y_\nu^T = f^2 \begin{pmatrix} |\boldsymbol{n}_e|^2 & \boldsymbol{n}_e \cdot \boldsymbol{n}_\mu & \boldsymbol{n}_e \cdot \boldsymbol{n}_\tau \\ \boldsymbol{n}_e \cdot \boldsymbol{n}_\mu & |\boldsymbol{n}_\mu|^2 & \boldsymbol{n}_\mu \cdot \boldsymbol{n}_\tau \\ \boldsymbol{n}_e \cdot \boldsymbol{n}_\tau & \boldsymbol{n}_\mu \cdot \boldsymbol{n}_\tau & |\boldsymbol{n}_\tau|^2 \end{pmatrix}$$

Fully determined by ($c_{ij} \equiv \cos\theta_{ij}$)
($f, |\boldsymbol{n}_e|, |\boldsymbol{n}_\mu|, |\boldsymbol{n}_\tau|, c_{\mu e}, c_{\tau e}, c_{\tau\mu}$)

Independent of O

Exp. Searches: $\mathrm{LFV}_{\mu e}$ very suppressed $\Longrightarrow$ $\boxed{\mathrm{LFV}_{\mu e} = 0 \leftrightarrow \boldsymbol{n}_e \cdot \boldsymbol{n}_\mu = 0 \leftrightarrow c_{\mu e} = 0}$

(denote as ~~LFV~~$_{\mu e}$)

We can choose $Y_\nu = A \cdot O$ with $A = f \begin{pmatrix} |\boldsymbol{n}_e| & 0 & 0 \\ 0 & |\boldsymbol{n}_\mu| & 0 \\ |\boldsymbol{n}_\tau| c_{\tau e} & |\boldsymbol{n}_\tau| c_{\tau\mu} & |\boldsymbol{n}_\tau| \sqrt{1 - c_{\tau e}^2 - c_{\tau\mu}^2} \end{pmatrix}$

Examples of geometrical parametrization

Particular textures with extremely suppressed μe transitions but large LFV in $\tau\mu$ (TM scenarios) or τe sectors (TE scenarios), although not simultaneously:

$$Y_\nu^{\rm TM4} = f \begin{pmatrix} 0.1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0.014 \end{pmatrix}, \quad Y_\nu^{\rm TM5} = f \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix},$$

$$Y_\nu^{\rm TM9} = f \begin{pmatrix} 0.1 & 0 & 0 \\ 0 & 0.46 & 0.04 \\ 0 & 1 & 1 \end{pmatrix}, \quad Y_\nu^{\rm TE10} = f \begin{pmatrix} 0.94 & 0 & 0.08 \\ 0 & 0.1 & 0 \\ 1 & 0 & -1 \end{pmatrix}.$$

f is a scaling factor that characterizes global strength of Y_ν

$\Gamma(H \to \ell_k \bar{\ell}_m)$ to one-loop within the MIA

The decay amplitude of the process $H(p_1) \to \ell_k(-p_2)\bar{\ell}_m(p_3)$ can be generically decomposed in terms of two form factors $F_{L,R}$ by

$$i\mathcal{M} = -ig\bar{u}_{\ell_k}(-p_2)(F_L P_L + F_R P_R)v_{\ell_m}(p_3)\,,$$

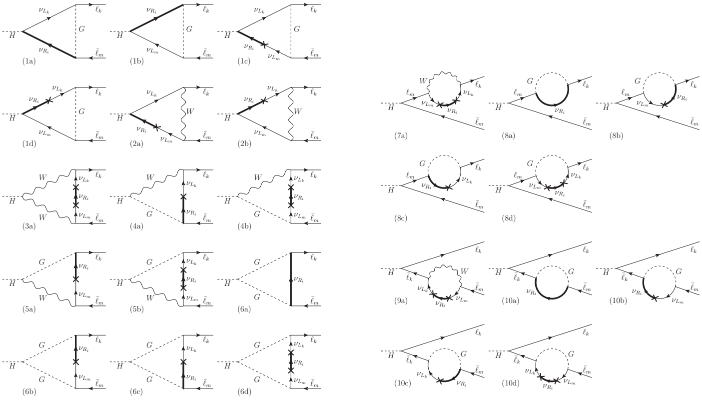
and the partial decay width can then be written as follows:

$$\Gamma(H \to \ell_k \bar{\ell}_m) = \frac{g^2}{16\pi m_H}\sqrt{\left(1-\left(\frac{m_{\ell_k}+m_{\ell_m}}{m_H}\right)^2\right)\left(1-\left(\frac{m_{\ell_k}-m_{\ell_m}}{m_H}\right)^2\right)} \times\left((m_H^2 - m_{\ell_k}^2 - m_{\ell_m}^2)\left(|F_L|^2+|F_R|^2\right) - 4m_{\ell_k}m_{\ell_m}Re(F_L F_R^*)\right).$$

We consider the 2 most relevant contributions in the expansion in even powers of Y_ν, which in terms of the form factors can be written in the following way:

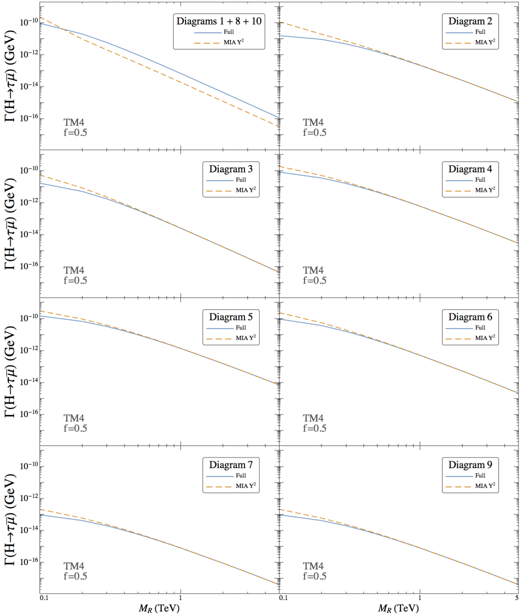
$$F_{L,R}^{\mathrm{MIA}\ (Y^2+Y^4)} = \left(Y_\nu Y_\nu^\dagger\right)^{km} f_{L,R}^{(Y^2)} + \left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km} f_{L,R}^{(Y^4)}\,.$$

MIA computation: diagrams contributing to $\mathcal{O}(Y_\nu^2)$



$$
\begin{aligned}
F_L^{\text{MIA}} = \frac{1}{32\pi^2}\frac{m_{\ell_k}}{m_W}\left(Y_\nu Y_\nu^\dagger\right)^{km}\Big(&\tilde{C}_0(p_2,p_1,m_W,0,M_R) - B_0(0,M_R,m_W)\\
&- 2m_W^2\left((C_0+C_{11}-C_{12})(p_2,p_1,m_W,0,M_R) + (C_{11}-C_{12})(p_2,p_1,m_W,M_R,0)\right)\\
&+ 4m_W^4(D_{12}-D_{13})(0,p_2,p_1,0,M_R,m_W,m_W)\\
&- 2m_W^2 m_H^2 D_{13}(0,p_2,p_1,0,M_R,m_W,m_W) + 2m_W^2(C_0+C_{11}-C_{12})(p_2,p_1,M_R,m_W,m_W)\\
&+ m_H^2(C_0+C_{11}-C_{12})(p_2,p_1,M_R,m_W,m_W)\Big)
\end{aligned}
$$

$\mathcal{O}(Y_\nu^2)$ MIA results: diagram by diagram



Scenario with suppressed μe and τe mixing

$$Y_\nu^{\rm TM4} = f \begin{pmatrix} 0.1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0.014 \end{pmatrix}$$

Sum 1+8+10 to have a finite contribution

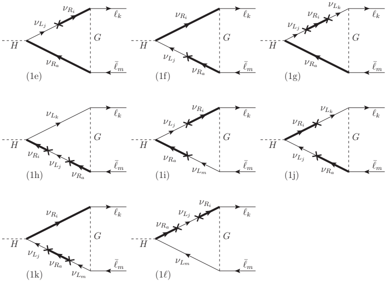
Diags. 2-7 and 9 good full/MIA agreement

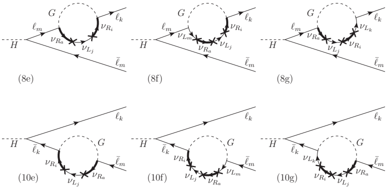
Sum 1+8+10 same behavior but mismatch

We need to include NLO terms
$\mathcal{O}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger) \propto (v/M_R)^2$
in MIA expansion

MIA computation: diagrams contributing to $\mathcal{O}(Y_\nu^4)$

We have to take into account only dominant diagrams 1, 8, and 10





$$F_L^{\text{MIA}} = \frac{1}{32\pi^2}\frac{m_{\ell_k}}{m_W}\left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger\right)^{km} v^2 \Big(-2(C_{11}-C_{12})(p_2, p_1, m_W, M_R, M_R)$$
$$+ \tilde{D}_0(p_2, 0, p_1, m_W, 0, M_R, M_R) + \tilde{D}_0(p_2, p_1, 0, m_W, 0, M_R, M_R) - C_0(0, 0, M_R, M_R, m_W)\Big)$$

The interaction Lagrangian of ISS in the mass basis

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \sum_{i=1}^{3} \sum_{j=1}^{9} W_\mu^- \bar{\ell}_i B_{\ell_i n_j} \gamma^\mu P_L n_j + h.c.,$$

$$\mathcal{L}_Z = -\frac{g}{4c_W} \sum_{i,j=1}^{9} Z_\mu \, \bar{n}_i \gamma^\mu \Big[C_{n_i n_j} P_L - C^*_{n_i n_j} P_R \Big] n_j,$$

$$\mathcal{L}_H = -\frac{g}{2m_W} \sum_{i,j=1}^{9} H \, \bar{n}_i C_{n_i n_j} \Big[m_{n_i} P_L + m_{n_j} P_R \Big] n_j,$$

$$\mathcal{L}_{G^\pm} = -\frac{g}{\sqrt{2}m_W} \sum_{i=1}^{3} \sum_{j=1}^{9} G^- \bar{\ell}_i B_{\ell_i n_j} \Big[m_{\ell_i} P_L - m_{n_j} P_R \Big] n_j + h.c\,,$$

$$\mathcal{L}_{G^0} = -\frac{ig}{2m_W} \sum_{i,j=1}^{9} G^0 \, \bar{n}_i C_{n_i n_j} \Big[m_{n_i} P_L - m_{n_j} P_R \Big] n_j,$$

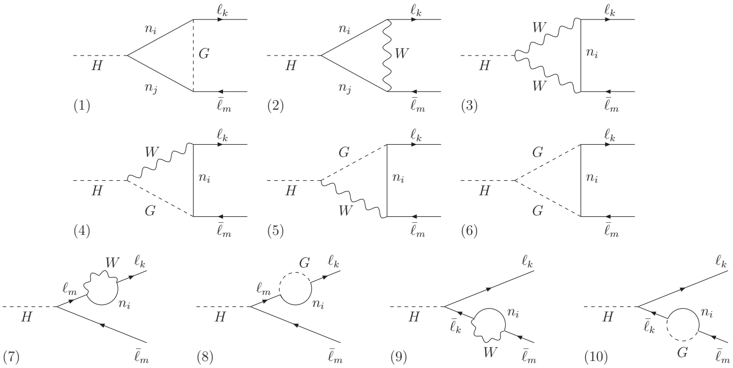
where,

$$B_{\ell_i n_j} = U^{\nu *}_{ij} \; \rightarrow \sum_{i \in \text{Heavy}} B_{\ell_k n_i} B^*_{\ell_m n_i} \simeq \frac{v^2}{m_N^2} \left(Y_\nu Y_\nu^\dagger \right)^{km}$$

$$C_{n_i n_j} = \sum_{k=1}^{3} U^\nu_{ki} U^{\nu *}_{kj} \; \rightarrow \sum_{i,j \in \text{Heavy}} B_{\ell_k n_i} C_{n_i n_j} B^*_{\ell_m n_j} \simeq \frac{v^4}{m_N^4} \left(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger \right)^{km}$$

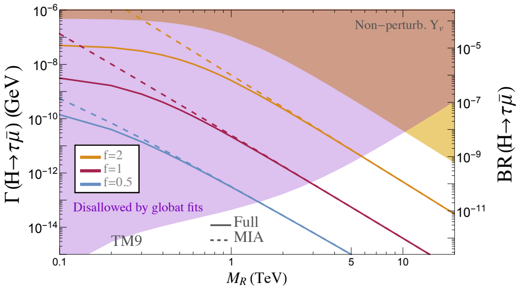
LFVHD within the ISS: full 1-loop calculation

E. Arganda., M.J. Herrero, X. Marcano, C. Weiland, PRD91(2015)1,015001



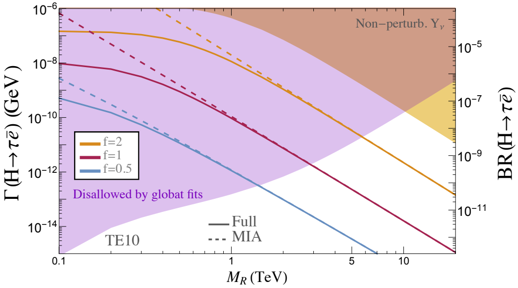
- Calculated in the Feynman-'t Hooft gauge.
- Formulas from [Arganda *et al.*, PRD71(2005)035011] and adapted for ISS.
- Diagrams 1, 8 and 10 divergent and dominant at large Y_ν and M_R.

Results on LFVHD in the ISS imposing Global Fits (II)



Scenario with suppressed μe and τe mixing

$$Y_\nu^{\rm TM9} = f\begin{pmatrix} 0.1 & 0 & 0 \\ 0 & 0.46 & 0.04 \\ 0 & 1 & 1 \end{pmatrix}$$



Scenario with suppressed μe and $\tau\mu$ mixing

$$Y_\nu^{\rm TE10} = f\begin{pmatrix} 0.94 & 0 & 0.08 \\ 0 & 0.1 & 0 \\ 1 & 0 & -1 \end{pmatrix}$$