

# Lepton number constraints from loop corrections to light neutrino masses in the low-scale SUSY Seesaw

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- We know that in SM:  $m_\nu = 0$
- In our work we consider the Type I Seesaw model to generate the light neutrino masses. ( $N_R$ )

$$-\mathcal{L}_\nu \sim (Y_\nu)_{as} \bar{L}_a \tilde{\Phi} \nu_{R_s} + \frac{1}{2} (M_R)_{ss'} \bar{\nu}_{R_s} \nu_{R_{s'}}^c + \text{H.c.} . \quad (1)$$

After EWSB, the full neutrino mass matrix can be written as:

$$M_\nu^{\text{tree}} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \quad (2)$$

Tree-level neutrino mass matrix as defined as:

$$M_{\text{light}}^{\text{tree}} = -M_D M_R^{-1} M_D^T . \quad (3)$$

The complete neutrino mass matrix:  $M_\nu^{\text{full}} = M_\nu^{\text{tree}} + \delta M_\nu$

$$\delta M_\nu = \begin{pmatrix} \delta M_L & \delta M_D \\ \delta M_D^T & \delta M_R \end{pmatrix} \quad (4)$$

$$(\delta M_L^Z)_{aa'} = \frac{1}{8\pi^2} \sum_{h,s,s'} (Y_\nu^*)_{as} U_{sh} M_h \left( \frac{M_h^2}{M_Z^2} - 1 \right)^{-1} \ln \frac{M_h^2}{M_Z^2} U_{s'h} (Y_\nu^*)_{a's'}$$

$$(\delta M_L^{H^0+G^0})_{aa'} = \frac{1}{32\pi^2} \sum_{h,s,s'} (Y_\nu^*)_{as} U_{sh} M_h \left[ \left( \frac{M_h^2}{M_H^2} - 1 \right)^{-1} \ln \frac{M_h^2}{M_H^2} - \left( \frac{M_h^2}{M_Z^2} - 1 \right)^{-1} \ln \frac{M_h^2}{M_Z^2} \right] U_{s'h} (Y_\nu^*)_{a's'}$$

$$M_\nu^{\text{full}} = M_\nu^{\text{tree}} + \left( \delta M_L^Z + \delta M_L^{H^0+G^0} \right) - \left( \delta M_D^{G^-} M_R^{-1} M_D^T + M_D M_R^{-1} \delta M_D^{G^- T} \right)$$

$$U_{a4} = i (U_{\text{PMNS}})_{a1} \sqrt{\frac{m_1}{M_4}} \quad (5)$$

$$U_{a5} = z_{56} Z_a \sqrt{\frac{m_3}{M_5}} \cosh \gamma_{56} e^{i z_{56} \rho_{56}} \quad (6)$$

$$U_{a6} = i Z_a \sqrt{\frac{m_3}{M_6}} \cosh \gamma_{56} e^{i z_{56} \rho_{56}} \quad (7)$$

$$Z_a = (U_{\text{PMNS}})_{a3} + i z_{56} \sqrt{\frac{m_2}{m_3}} (U_{\text{PMNS}})_{a2} \quad (8)$$

$$\begin{aligned}
(\delta M_L)_{aa'} &= \frac{1}{2} \sum_{h,s,s'} (Y_\nu^*)_{as} U_{sh} (Y_\nu^*)_{a's'} U_{s'h} f(M_h) \\
&\approx \frac{m_3}{v_{\text{SM}}^2} Z_a^* Z_{a'}^* [M_5 f(M_5) - M_6 f(M_6)] \cosh^2 \gamma_{56} e^{-2iz_{56}\rho_{56}}
\end{aligned}$$

where we have defined the loop function:

$$f(M) = \frac{M}{16\pi^2} \left[ 3 \left( \frac{M^2}{M_Z^2} - 1 \right)^{-1} \ln \frac{M^2}{M_Z^2} + \left( \frac{M^2}{M_H^2} - 1 \right)^{-1} \ln \frac{M^2}{M_H^2} \right] \quad (9)$$

We find that this expression is reasonably accurate for  $\gamma_{56} \gtrsim 4$ .

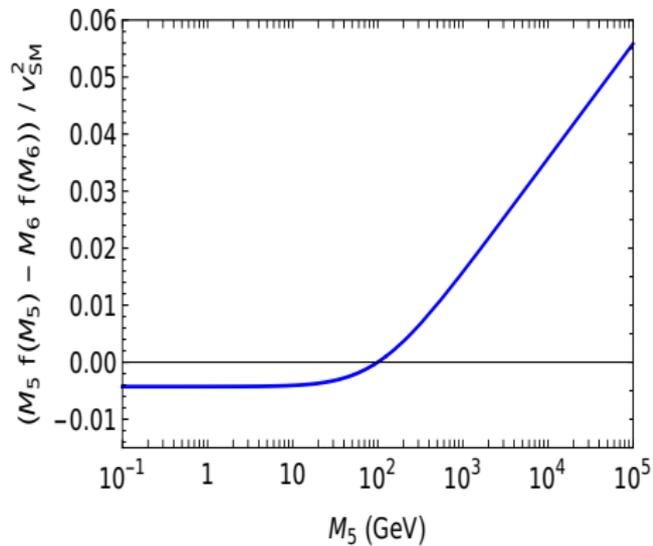
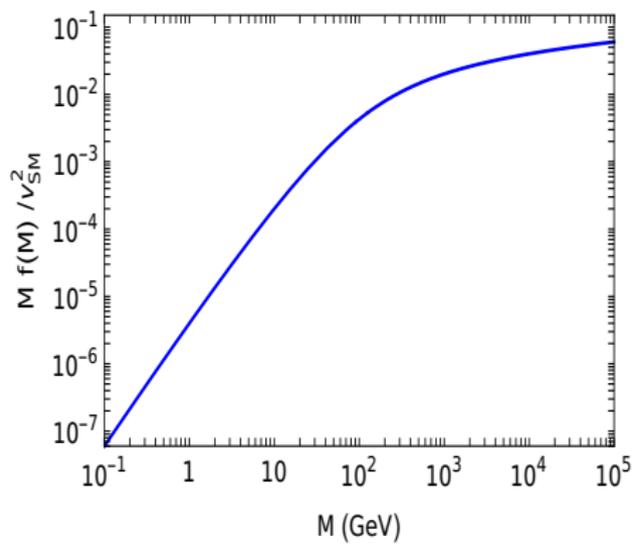
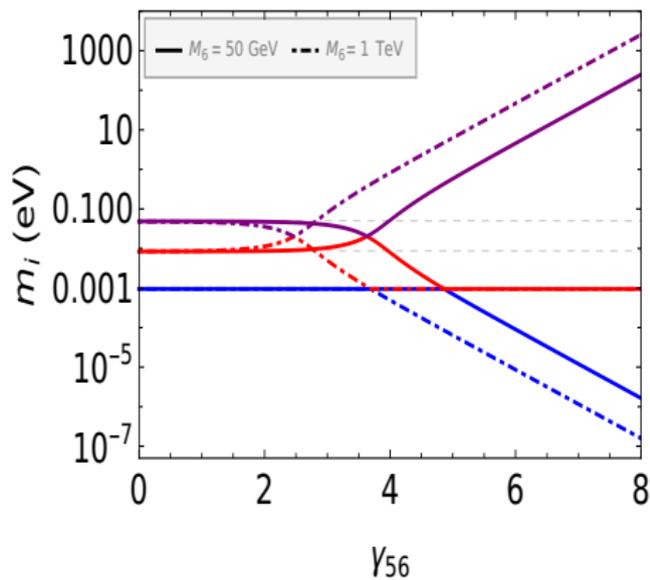
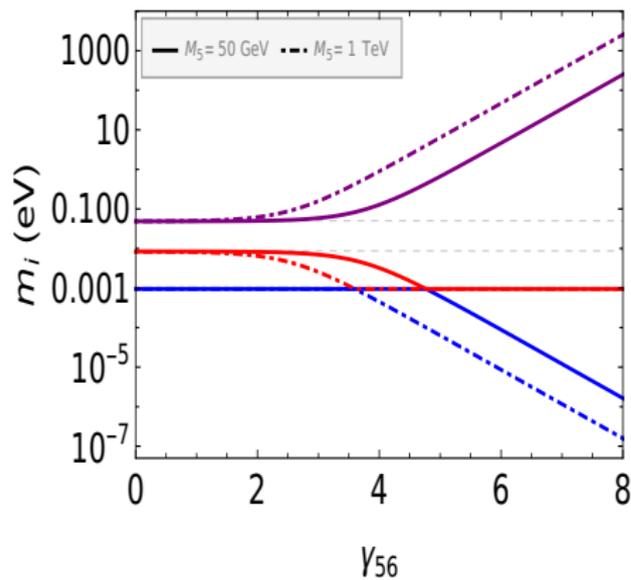
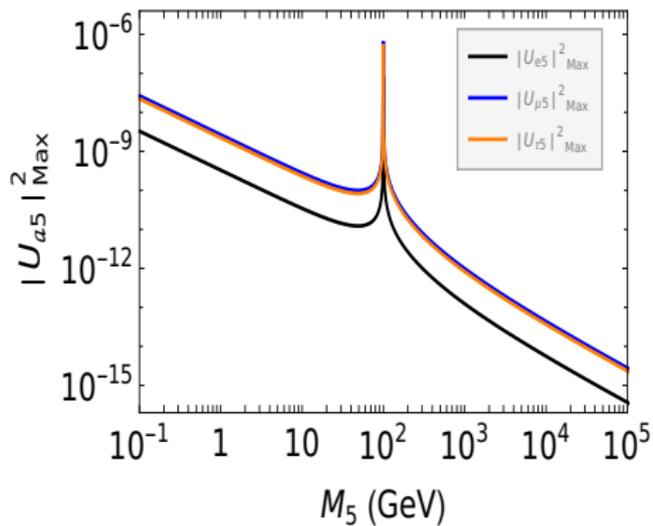
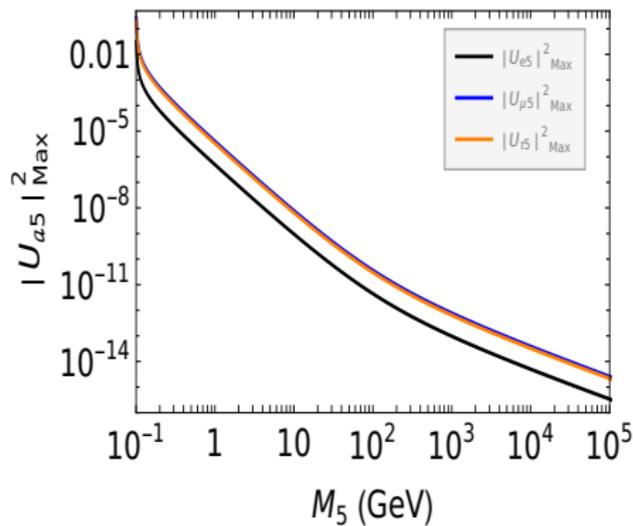


Figure 1:  $M_6=100$  GeV(Right)



**Figure 2:**  $M_6=100$  MeV(Left) and  $M_5=100$  MeV(Right)



**Figure 3:**  $M_6=100 \text{ MeV}$  (Left) and  $M_6=100 \text{ GeV}$  (Right)

$$U_{a4} \approx -z_{46} c_{45} Z_a \sqrt{\frac{m_3}{M_4}} \cosh \gamma_{46} \cosh \gamma_{56} e^{i(z_{46} \rho_{46} + z_{56} \rho_{56})} \quad (10)$$

$$U_{a5} \approx z_{46} s_{45} Z_a \sqrt{\frac{m_3}{M_5}} \cosh \gamma_{46} \cosh \gamma_{56} e^{i(z_{46} \rho_{46} + z_{56} \rho_{56})} \quad (11)$$

$$U_{a6} \approx i Z_a \sqrt{\frac{m_3}{M_6}} \cosh \gamma_{46} \cosh \gamma_{56} e^{i(z_{46} \rho_{46} + z_{56} \rho_{56})} \quad (12)$$

This approximation leads to the following loop correction for  $\delta M_L$ , valid for  $\gamma_{46} = \gamma_{56} \gtrsim 4$ :

$$(\delta M_L)_{aa'} \approx \frac{m_3}{v_{SM}^2} Z_a^* Z_{a'} \left[ c_{45}^2 M_4 f(M_4) + s_{45}^2 M_5 f(M_5) - M_6 f(M_6) \right] \cosh^2 \gamma_{46} \cosh^2 \gamma_{56} e^{-2i(z_{46} \rho_{46} + z_{56} \rho_{56})}$$

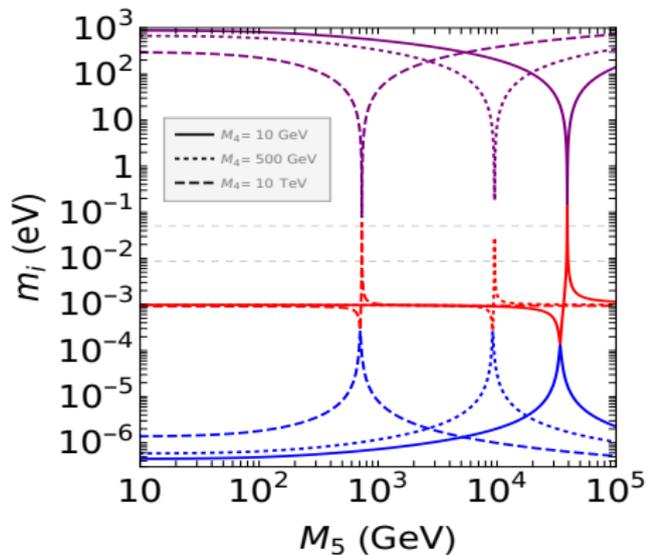
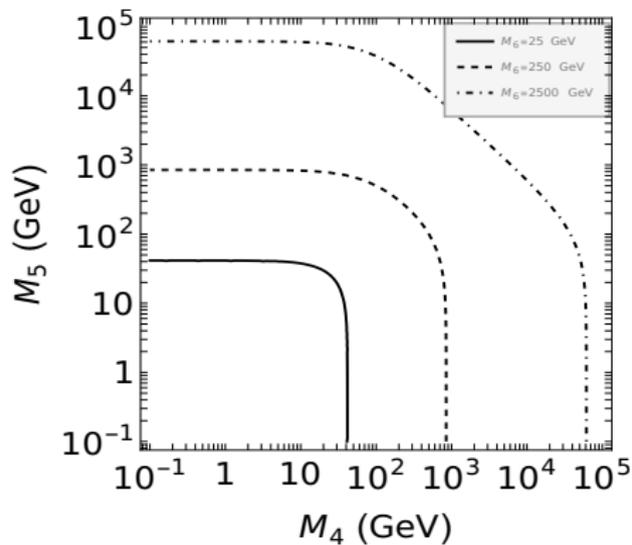


Figure 4:  $M_6=2500$  GeV (Right)

## 2HDM

$$-\mathcal{L} \supset -(Y_e)_{aa} \bar{L}_a \cdot H_d e_{R_a} + (Y_\nu)_{as} \bar{L}_a \cdot H_u \nu_{R_s} + \text{H.c.} \quad (13)$$

We parametrize the scalar doublets and their vevs following:

$$H_u = \begin{pmatrix} \phi_u^+ \\ \frac{1}{\sqrt{2}}(v_u + \eta_u + i\omega_u) \end{pmatrix}, \quad H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + \eta_d + i\omega_d) \\ \phi_d^- \end{pmatrix}, \quad (14)$$

$$\begin{aligned}
(\delta M_L^Z)_{aa'} &= \frac{\sin^2 \beta}{8\pi^2} \sum_{h,s,s'} (Y_\nu^*)_{as} U_{sh} M_h \left( \frac{M_h^2}{M_Z^2} - 1 \right)^{-1} \times \\
&\quad \ln \frac{M_h^2}{M_Z^2} U_{s'h} (Y_\nu^*)_{a's'} \\
\left( \delta M_L^{H_{1,2}^0 + G^0 + A^0} \right)_{aa'} &= \frac{1}{32\pi^2} \sum_x \sum_{h,s,s'} \rho_x (Y_\nu^*)_{as} U_{sh} M_h \left( \frac{M_h^2}{M_x^2} - 1 \right)^{-1} \times \\
&\quad \ln \frac{M_h^2}{M_x^2} U_{s'h} (Y_\nu^*)_{a's'}
\end{aligned}$$

$$\begin{aligned}
(\delta M_L)_{aa'} &\approx \frac{m_3}{v_{SM}^2 \sin^2 \beta} Z_a^* Z_{a'}^* [M_5 g(M_5, M_A, \tan \beta) - \\
&\quad M_6 g(M_6, M_A, \tan \beta)] \cosh^2 \gamma_{56} e^{-2iz_{56} \rho_{56}}
\end{aligned}$$

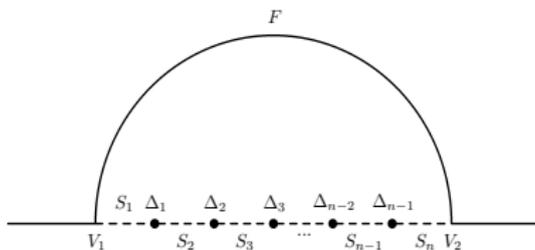
## One Loop Contributions in SUSY

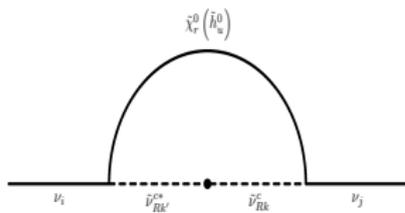
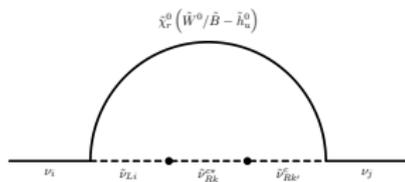
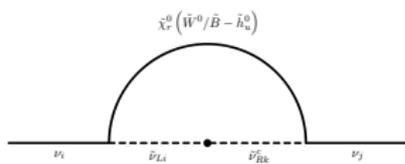
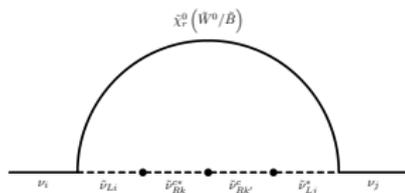
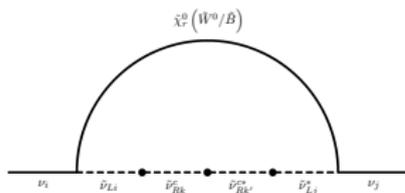
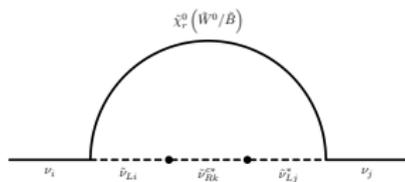
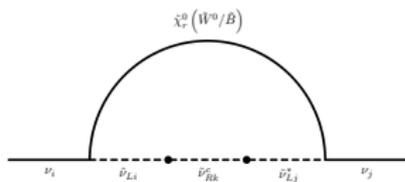
$$\mathcal{W} = \mathcal{W}_{\text{MSSM}} + (Y_\nu^*)_{as} \hat{L}_a \cdot \hat{H}_u \hat{\nu}_{Rs}^c + \frac{1}{2} (M_R)_{ss'} \hat{\nu}_{Rs}^c \hat{\nu}_{Rs'}^c \quad (15)$$

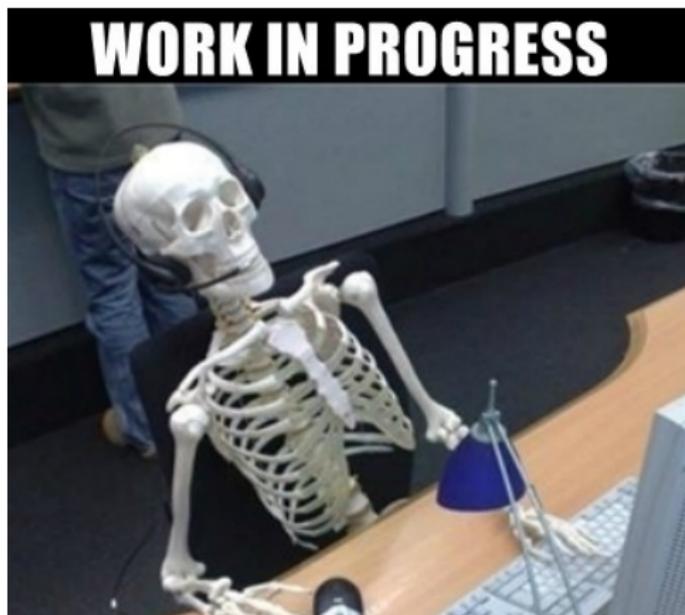
In addition, the following soft SUSY-breaking terms are allowed:

$$\mathcal{V}^{\text{soft}} = \mathcal{V}_{\text{MSSM}}^{\text{soft}} + (m_{\tilde{\nu}_R}^2)_{ss'} \tilde{\nu}_{Rs}^{c*} \tilde{\nu}_{Rs'}^c + \left( \frac{1}{2} (B_{\tilde{\nu}})_{ss'} \tilde{\nu}_{Rs}^c \tilde{\nu}_{Rs'}^c + (T_\nu^*)_{as} \tilde{L}_a \cdot H_u \tilde{\nu}_{Rs}^c + \text{H.c.} \right)$$

$$\begin{aligned}
\mathcal{L}_{\tilde{\nu}}^{\text{mass}} &= \mathcal{L}_{\tilde{\nu}}^{\text{LNC}} + \mathcal{L}_{\tilde{\nu}}^{\text{LNV}} \\
-\mathcal{L}_{\tilde{\nu}}^{\text{LNC}} &= \tilde{\nu}_{La}^* \left( (m_L^2)_{aa'} + \frac{v_u^2}{2} (Y_\nu)_{as} (Y_\nu^*)_{a's} + \frac{1}{2} m_Z^2 \cos 2\beta \delta_{aa'} \right) \tilde{\nu}_{La'} \\
&\quad + \tilde{\nu}_{Rs}^c \left( (m_\nu^2)_{s's} + \frac{v_u^2}{2} (Y_\nu^*)_{as} (Y_\nu)_{as'} + (M_R)_{ss'} (M_R^*)_{s's'} \right) \tilde{\nu}_{Rs'}^{c*} \\
&\quad + \tilde{\nu}_{Rs}^c \left( \frac{v_u}{\sqrt{2}} (T_\nu^*)_{as} - \frac{v_d}{\sqrt{2}} \mu^* (Y_\nu^*)_{as} \right) \tilde{\nu}_{La} \\
&\quad + \tilde{\nu}_{La}^* \left( \frac{v_u}{\sqrt{2}} (T_\nu)_{as} - \frac{v_d}{\sqrt{2}} \mu (Y_\nu)_{as} \right) \tilde{\nu}_{Rs}^{c*} \\
-\mathcal{L}_{\tilde{\nu}}^{\text{LNV}} &= \tilde{\nu}_{Rs}^c \left( \frac{1}{2} (B_\nu)_{ss'} \right) \tilde{\nu}_{Rs'}^c + \tilde{\nu}_{La}^* \left( \frac{v_u}{\sqrt{2}} (Y_\nu)_{as'} (M_R)_{s's} \right) \tilde{\nu}_{Rs}^c \\
&\quad + \tilde{\nu}_{La}^* \left( \frac{v_u}{\sqrt{2}} (Y_\nu^*)_{as'} (M_R^*)_{s's} \right) \tilde{\nu}_{Rs}^{c*}
\end{aligned}$$







Thanks



$$U = \begin{pmatrix} U_{a\ell} & U_{ah} \\ U_{s\ell} & U_{sh} \end{pmatrix}. \quad (16)$$

$$\begin{aligned} U_{a\ell} &= U_{\text{PMNS}} H, & U_{ah} &= i U_{\text{PMNS}} H \hat{m}_\ell^{1/2} R^\dagger \hat{M}_h^{-1/2}, \\ U_{s\ell} &= i \bar{W} \bar{H} \hat{M}_h^{-1/2} R \hat{m}_\ell^{1/2}, & U_{sh} &= \bar{W} \bar{H}, \end{aligned} \quad (17)$$

$$H = \left( I + \hat{m}_\ell^{1/2} R^\dagger \hat{M}_h^{-1} R \hat{m}_\ell^{1/2} \right)^{-1/2} \quad (18)$$

$$\bar{H} = \left( I + \hat{M}_h^{-1/2} R \hat{m}_\ell R^\dagger \hat{M}_h^{-1/2} \right)^{-1/2}. \quad (19)$$

$$R = \begin{pmatrix} \tilde{c}_{45} & \tilde{s}_{45} & 0 \\ -\tilde{s}_{45} & \tilde{c}_{45} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{c}_{46} & 0 & -\tilde{s}_{46} \\ 0 & 1 & 0 \\ \tilde{s}_{46} & 0 & \tilde{c}_{46} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \tilde{c}_{56} & \tilde{s}_{56} \\ 0 & -\tilde{s}_{56} & \tilde{c}_{56} \end{pmatrix}. \quad (20)$$

$$M_D = -i U_{\text{PMNS}}^* H^* \hat{m}_\ell^{1/2} \left( \hat{m}_\ell R^\dagger + R^T \hat{M}_h \right) \hat{M}_h^{-1/2} \bar{H} \quad (21)$$

$$M_R = \bar{H}^* \left( \hat{M}_h - \hat{M}_h^{-1/2} R^* \hat{m}_\ell^2 R^\dagger \hat{M}_h^{-1/2} \right) \bar{H}. \quad (22)$$

$$(\delta M_L)_{aa'} = \sum_{(i,j)} U_{ai}^* (B_L)_{ij} U_{a'j}^* \quad (23)$$

$$(\delta M_D)_{as} = \sum_{(i,j)} U_{ai}^* (B_L)_{ij} U_{sj}^* \quad (24)$$

$$(\delta M_R)_{ss'} = \sum_{(i,j)} U_{si}^* (B_L)_{ij} U_{s'j}^* \quad (25)$$

$$\sum_r U_{ar}^* m_r U_{a'r}^* = 0 \quad U_{al}^* m_l = \sum_s (m_D)_{as} U_{sl} \quad U_{ah}^* M_h = \sum_s (m_D)_{as} U_{sh} \quad (26)$$

$$\begin{aligned}
(\delta M_D^{H^0+G^0})_{as} &= \frac{1}{32\pi^2} \sum_{h,a',s'} (Y_\nu^*)_{as'} U_{s'h} M_h \times \\
&\quad \left[ \left( \frac{M_h^2}{M_H^2} - 1 \right)^{-1} \ln \frac{M_h^2}{M_H^2} - \left( \frac{M_h^2}{M_Z^2} - 1 \right)^{-1} \ln \frac{M_h^2}{M_Z^2} \right] U_{a'h} (Y_\nu^*)_{a's} \\
(\delta M_D^{G^-})_{as} &= -\frac{1}{16\pi^2} (Y_e^*)_{aa} m_a \left[ k - 1 + \ln \frac{m_a^2}{Q^2} + \left( \frac{m_a^2}{M_W^2} - 1 \right)^{-1} \ln \frac{m_a^2}{M_W^2} \right] (Y_\nu^*)_{as} \\
(\delta M_R^{H^0+G^0})_{ss'} &= \frac{1}{32\pi^2} \sum_{r,a,a'} (Y_\nu^*)_{as} U_{ah} M_h \times \\
&\quad \left[ \left( \frac{M_h^2}{M_H^2} - 1 \right)^{-1} \ln \frac{M_h^2}{M_H^2} - \left( \frac{M_h^2}{M_Z^2} - 1 \right)^{-1} \ln \frac{M_h^2}{M_Z^2} \right] U_{a'h} (Y_\nu^*)_{a's'}
\end{aligned}$$

$$\left(\delta M_D^{H^0_{1,2}+G^0+A^0}\right)_{as} = \frac{1}{32\pi^2} \sum_x \sum_{s', a', h} \rho_x (Y_\nu^*)_{as'} U_{s'h}^* M_h \left(\frac{M_h^2}{M_x^2} - 1\right)^{-1} \ln \frac{M_h^2}{M_x^2} U_{a'h} (Y_\nu^*)_{a's}$$

$$\begin{aligned} \left(\delta M_D^{H^-+G^-}\right)_{as} &= \frac{\sin 2\beta}{32\pi^2} (Y_e^*)_{aa} m_a \times \\ &\left[ \left(\frac{m_a^2}{M_{H^-}^2} - 1\right)^{-1} \ln \frac{m_a^2}{M_{H^-}^2} - \left(\frac{m_a^2}{M_W^2} - 1\right)^{-1} \ln \frac{m_a^2}{M_W^2} \right] (Y_\nu^*)_{as} \end{aligned}$$

$$\left(\delta M_R^{H^0_{1,2}+G^0+A^0}\right)_{ss'} = \frac{1}{32\pi^2} \sum_x \sum_{a, a', h} \rho_x (Y_\nu^*)_{as} U_{ah} M_h \left(\frac{M_h^2}{M_x^2} - 1\right)^{-1} \ln \frac{M_h^2}{M_x^2} U_{a'h} (Y_\nu^*)_{a's'}$$