Karlsruhe Institute of Technology

Summer School and Workshop on the Standard Model and Beyond — Corfu, Greece 2013

Neutrino Mixing from SUSY breaking

in collaboration with Ulrich Nierste

Wolfgang Gregor Hollik | September 5, 2013

INSTITUT FOR THEORETICAL PARTICLE PHYSICS — KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT)

CKM vs. PMNS matrix

- CKM matrix close to unity

$$V_{\mathrm{CKM}} = \begin{pmatrix} \huge\bullet & \bullet & \cdot \\ \bullet & \huge\bullet & \cdot \\ \cdot & \cdot & \huge\bullet \end{pmatrix}$$

- small off-diagonal: get them from loops?
- different pattern for the leptonic mixing matrix:

$$U_{\mathrm{PMNS}} = \begin{pmatrix} \huge\bullet & \Large\bullet & \bullet \\ \Large\bullet & \Large\bullet & \Large\bullet \\ \bullet & \Large\bullet & \huge\bullet \end{pmatrix}$$

- large mixings
- non-vanishing θ_{13}: possible CP violation in ν oscillations

  [T2K, DoubleChooz, Reno, DayaBay]
- try to model quark and lepton mixing using the same mechanism?

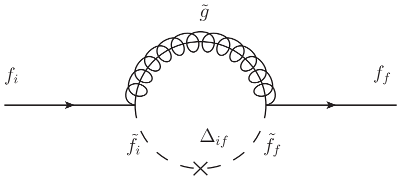
Radiative Flavour Violation in the MSSM

Theories with Additional Sources of Flavour Violation

- non-minimal flavour violating MSSM
- arbitrary flavour structure in the soft breaking terms?

$$\mathcal{M}^2_{\tilde{Q}}, \mathcal{M}^2_{\tilde{u}}, \mathcal{M}^2_{\tilde{d}}, \mathcal{M}^2_{\tilde{\ell}}, \mathcal{M}^2_{\tilde{e}}, \qquad A^u, A^d, A^e$$

- additional flavour mixing in fermion–sfermion–gaugino interaction
- especially non-CKM-like: e.g. quark–squark–gluino and lepton–slepton–neutralino



[Crivellin, Nierste 2009]

Radiative Flavour Violation in the MSSM

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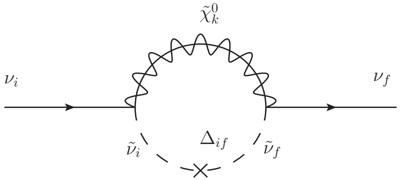


Do the same for sleptons and sneutrinos!

The MSSM with righthanded neutrinos

Superpotential of the νMSSM

$$\mathcal{W}^\ell = \mu H_d \cdot H_u - Y_\ell^{IJ} H_d \cdot L_L^I E_R^J + Y_\nu^{IJ} H_u \cdot L_L^I N_R^J + \frac{1}{2} m_R^{IJ} N_R^I N_R^J,$$

with $L_L = (\ell_L, \tilde{\ell}_L) \in SU(2)_L$ and $E_R = (e_L^c, \tilde{e}_R^*)$, $N_R = (\nu_L^c, \tilde{\nu}_R^*)$.

Soft-breaking terms

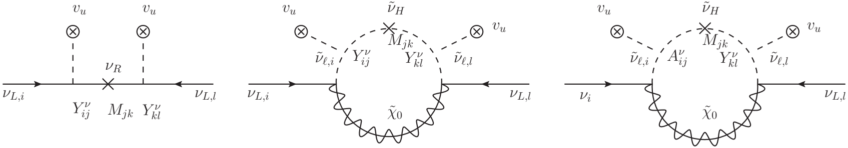
$$\begin{aligned}\mathcal{V}_{\text{soft}} =& (\mathcal{M}_{\tilde{\ell}}^2)^{IJ} \tilde{L}_L^{I*} \tilde{L}_L^J + (\mathcal{M}_{\tilde{e}}^2)^{IJ} \tilde{e}_R^I \tilde{e}_R^{J*} + (\mathcal{M}_{\tilde{\nu}}^2)^{IJ} \tilde{\nu}_R^I \tilde{\nu}_R^{J*} \\ & - \left[(B_\nu)^{IJ} \tilde{\nu}_R^{I*} \tilde{\nu}_R^{J*} + A_e^{IJ} H_1 \cdot \tilde{L}_L^I \tilde{e}_R^{J*} - A_\nu^{IJ} H_2 \cdot \tilde{L}_L^I \tilde{\nu}_R^{J*} + \text{h.c.} \right].\end{aligned}$$

Neutrino masses and seesaw

Standard Model + righthanded Neutrinos = Seesaw Type I

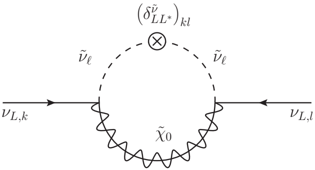
$$-\mathcal{L}_{\nu,\text{mass}} = \underbrace{\bar{\nu}_L m_D \nu_R}_{\text{Dirac mass}} + \frac{1}{2} \underbrace{\overline{\nu_L^c} m_R \nu_R}_{\text{Majorana mass}} + \text{h. c.}$$

SUSY seesaw loops



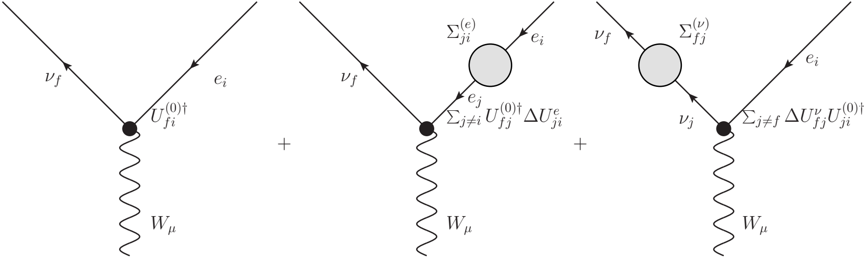
effects of righthanded Neutrinos

- trilinear couplings A_ν
- see-saw-like terms in sneutrino mass matrix



$$\delta^{\tilde\nu}_{LL^*} \sim X_\nu \mathbf{m}^D_\nu \left(\mathbf{m}^2_R + \mathcal{M}^2_{\tilde\nu}\right)^{-1} \mathbf{m}_R \mathbf{m}^{DT}_\nu \sim \frac{v_u A_\nu}{m_R}$$

radiative lepton flavour violation



PMNS matrix renormalization

$$i\frac{g}{\sqrt{2}}\gamma^\mu P_L U^\dagger_{\mathrm{PMNS}} \to i\frac{g}{\sqrt{2}}\gamma^\mu P_L \left(U^{(0)\dagger} + \Delta U^e U^{(0\dagger)\dagger} + \Delta U^\nu U^{(0\dagger)\dagger}\right),$$

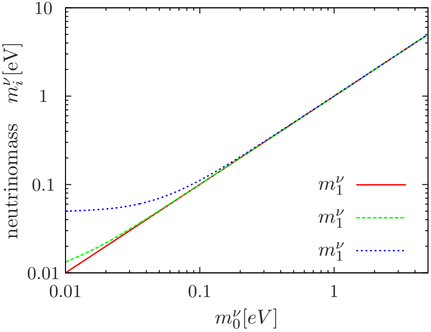
flavour changing self energies and sensitivity to neutrino mass

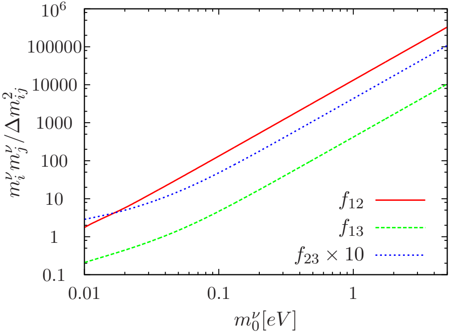
$$\Delta U^\nu_{fi} \sim \frac{m_{\nu_f}\Sigma_{fi}}{\Delta m^2_{fi}}$$

enhanced corrections to PMNS mixing

enhancement by degeneracy of neutrino mass spectrum

$$\Delta U^{\nu}_{fi} \sim \frac{m_{\nu_f} \Sigma_{fi}}{\Delta m^2_{\nu}} \sim \frac{m_{\nu_f} m_{\nu_i}}{\Delta m^2_{fi}} \leq 5 \times 10^3 \text{ for } m^{(0)}_{\nu} \sim 0.35 \text{ eV and } f, i = 1, 2$$

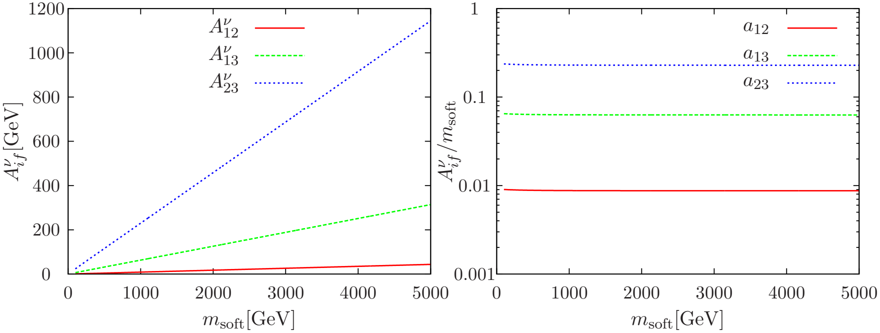




$f_{ij} = m_{\nu_i} m_{\nu_j} / \Delta m^2_{ij}$

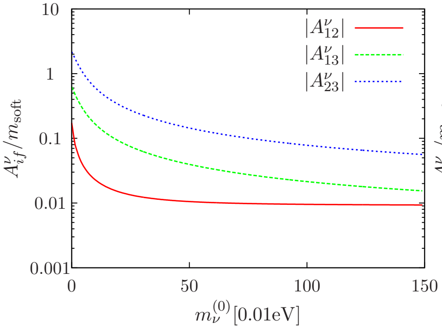
Some results

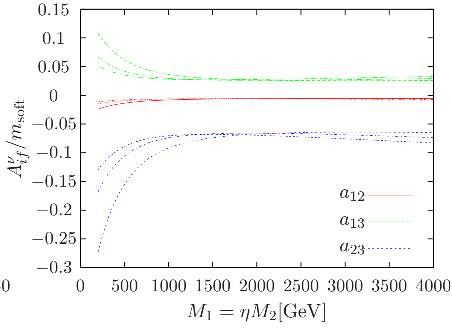
- non-decoupling effect if all SUSY parameters scaled the same way
- e.g. $\tan\beta = 24$, $m_\nu^{(0)} = 0.3\mathrm{eV}$, $\mathcal{M}^2_{\tilde{\ell},\tilde{e},\tilde{\nu}} = m^2_{\mathrm{soft}}\mathbb{1}$, $M_{1,2} = m_{\mathrm{soft}}$:



Some results

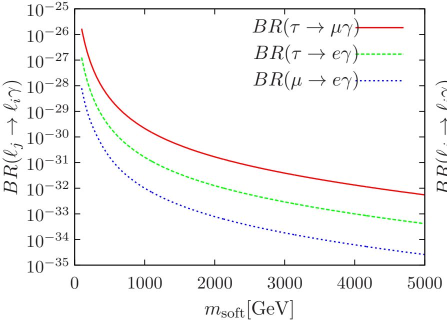
- correlation: light neutrino mass scale $\Leftrightarrow$ flavour changing SUSY breaking parameters
- left: basically no influence from gaugino masses ($m_{\text{soft}} = 2000\text{GeV}$)

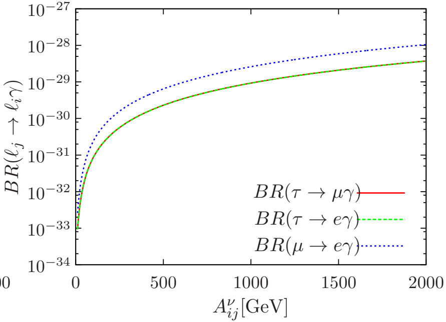




Some results

- safe: contributions to radiative lepton flavour decays on top of others negligible
- charged lepton effects neglected so far





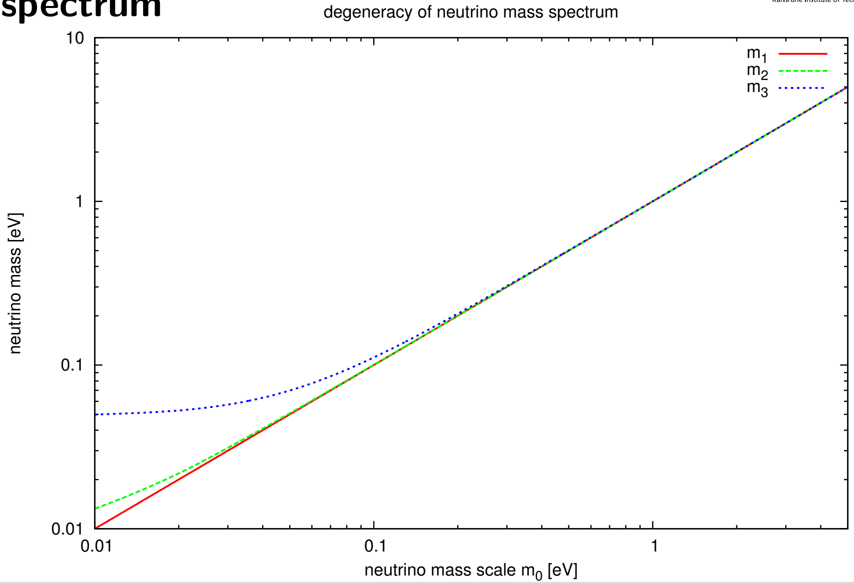
Conclusion

- described corrections very general to theories with new flavour structures
- can completely spoil tree-level mixing patterns
- simple extension of MSSM to incorporate ν masses can lead to lepton mixing from SUSY breaking in *sneutrino* sector
- non-decoupling effect
- most likely for quasi-degenerate neutrino masses
- new flavour structure in sneutrino sector: no large $\mathcal{BR}(\ell_j \to \ell_i\gamma)$

Backup

Slides

Splitting of the neutrino mass spectrum



see-saw extended MSSM

Superpotential of the νMSSM

$$\mathcal{W}^\ell = \mu H_d \cdot H_u - Y_\ell^{IJ} H_d \cdot L_L^I E_R^J + Y_\nu^{IJ} H_u \cdot L_L^I N_R^J + \frac{1}{2} m_R^{IJ} N_R^I N_R^J,$$

where the chiral superfields are $L_L = (\ell_L, \tilde{\ell}_L) \in SU(2)_L$ and $E_R = (e_R^c \equiv (e_R)^c, \tilde{e}_R^*)$, $N_R = (\nu_L^c, \tilde{\nu}_R^*) \in SU(2)_R$, but leftchiral.

Soft-breaking terms

$$\begin{aligned}\mathcal{V}_{\text{soft}} =& (\mathcal{M}_{\tilde{\ell}}^2)^{IJ} \tilde{L}_L^{I*} \tilde{L}_L^J + (\mathcal{M}_{\tilde{e}}^2)^{IJ} \tilde{e}_R^I \tilde{e}_R^{J*} + (\mathcal{M}_{\tilde{\nu}}^2)^{IJ} \tilde{\nu}_R^I \tilde{\nu}_R^{J*} \\ &- \left[(B_\nu)^{IJ} \tilde{\nu}_R^{I*} \tilde{\nu}_R^{J*} + A_e^{IJ} H_1 \cdot \tilde{L}_L^I \tilde{e}_R^{J*} - A_\nu^{IJ} H_2 \cdot \tilde{L}_L^I \tilde{\nu}_R^{J*} + \text{h.c.} \right],\end{aligned}$$

effects on sneutrino mass matrix

- charged slepton mass matrix as in the MSSM
- sneutrino mass matrix in the MSSM: simple

$$\mathcal{M}^2_{\tilde{\nu}} = \begin{pmatrix} \mathcal{M}^2_{\tilde{\ell}} + M_Z^2 T_{3L}^{\tilde{\nu}} \cos 2\beta \mathbb{1} & \mathbb{1} \\ \mathbb{1} & \mathbb{0} \end{pmatrix}$$

- Majorana mass term $\nu_R^T m_R \nu_R$ inflates sneutrino mass matrix: additional terms $\sim \tilde{\nu}_R \tilde{\nu}_R, \tilde{\nu}_R^* \tilde{\nu}_R^*$

$$\mathcal{M}^2_{\tilde{\nu}} = \begin{pmatrix} \mathcal{M}^2_{L^*L} & \mathcal{M}^2_{L^*L^*} & \mathcal{M}^2_{L^*R^*} & \mathcal{M}^2_{L^*R} \\ \mathcal{M}^2_{LL} & \mathcal{M}^2_{LL^*} & \mathcal{M}^2_{LR^*} & \mathcal{M}^2_{LR} \\ \mathcal{M}^2_{RL} & \mathcal{M}^2_{RL^*} & \mathcal{M}^2_{RR^*} & \mathcal{M}^2_{RR} \\ \mathcal{M}^2_{R^*L} & \mathcal{M}^2_{R^*L^*} & \mathcal{M}^2_{R^*R^*} & \mathcal{M}^2_{R^*R} \end{pmatrix}$$

12×12-Matrix

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$$\mathcal{M}^2_{\tilde{\nu}} = \begin{pmatrix} \mathcal{M}^2_{LL} & \mathcal{M}^2_{LR} \\ (\mathcal{M}^2_{LR})^\dagger & \mathcal{M}^2_{RR} \end{pmatrix}$$

12×12-Matrix

full sneutrino squared mass matrix in the νMSSM

$$\mathcal{M}^2_{\tilde\nu} = \frac{1}{2}\begin{pmatrix} \mathcal{M}^2_{LL} & \mathcal{M}^2_{LR} \\ (\mathcal{M}^2_{LR})^\dagger & \mathcal{M}^2_{RR} \end{pmatrix}$$

$$\mathcal{M}^2_{LL} = \begin{pmatrix} \mathcal{M}^2_{\tilde\ell} + \frac{1}{2}M_Z^2\cos 2\beta\mathbf{1} + \mathbf{m}_\nu\mathbf{m}_\nu^\dagger & \mathbf{0} \\ \mathbf{0} & (\searrow)^* \end{pmatrix},$$

$$\mathcal{M}^2_{RL} = \begin{pmatrix} \frac{1}{2}\mathbf{m}_\nu\mathbf{m}_R & -\mu\cot\beta\mathbf{m}_\nu - v_2\mathbf{A}_\nu^* \\ -\mu^*\cot\beta\mathbf{m}_\nu^* - v_2\mathbf{A}_\nu & \frac{1}{2}\mathbf{m}_\nu^*\mathbf{m}_R^* \end{pmatrix},$$

$$\mathcal{M}^2_{RR} = \begin{pmatrix} (\mathcal{M}^2_{\tilde\nu})^T + \mathbf{m}_\nu^T\mathbf{m}_\nu^* + \frac{1}{2}\mathbf{m}_R^*\mathbf{m}_R & -2\mathbf{B}^* \\ -2\mathbf{B} & \mathcal{M}^2_{\tilde\nu} + \mathbf{m}_\nu^\dagger\mathbf{m}_\nu + \frac{1}{2}\mathbf{m}_R\mathbf{m}_R^* \end{pmatrix}.$$

effective sneutrino mass matrix

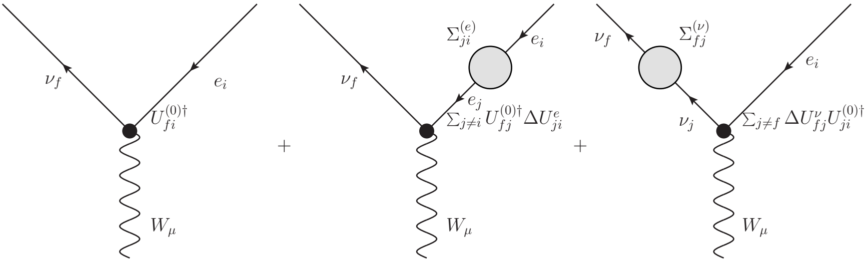
$$\mathcal{M}^2_{\tilde{\nu}\ell} = \begin{pmatrix} \mathbf{m}^2_{\Delta L=0} & (\mathbf{m}^2_{\Delta L=2})^* \\ \mathbf{m}^2_{\Delta L=2} & (\mathbf{m}^2_{\Delta L=0})^* \end{pmatrix} + \mathcal{O}\left(M^2_{\mathrm{SUSY}} m_R^{-2}\right),$$

$$\mathbf{m}^2_{\Delta L=0} = \mathrm{MSSM} + \mathbf{m}_\nu^D \mathbf{m}_\nu^{D\dagger} - \mathbf{m}_\nu^D \mathbf{m}_R \left(\mathbf{m}_R^2 + \mathcal{M}^2_{\tilde{\nu}}\right)^{-1} \mathbf{m}_R \mathbf{m}_\nu^D,$$

$$\mathbf{m}^2_{\Delta L=2} = X_\nu \mathbf{m}_\nu^D \left(\mathbf{m}_R^2 + \mathcal{M}^2_{\tilde{\nu}}\right)^{-1} \mathbf{m}_R \mathbf{m}_\nu^{DT} + (\rightarrowtail)^T$$
$$- 2\mathbf{m}_\nu^{D*} \mathbf{m}_R \left[\mathbf{m}_R^2 + (\mathcal{M}^2_{\tilde{\nu}})^T\right]^{-1} \mathbf{B} \left(\mathbf{m}_R^2 + \mathcal{M}^2_{\tilde{\nu}}\right)^{-1} \mathbf{m}_R \mathbf{m}_\nu^{D\dagger}.$$

$$\boxed{X_\nu \mathbf{m}_\nu^D = -\mu^* \cot\beta\, \mathbf{m}_\nu^{D*} - v_2 \mathbf{A}_\nu}$$

radiative flavour violation in the lepton sector



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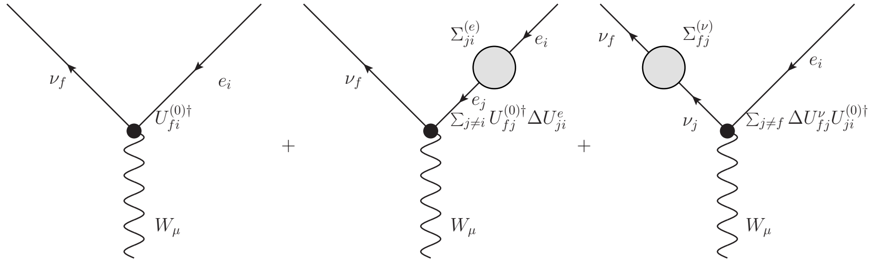


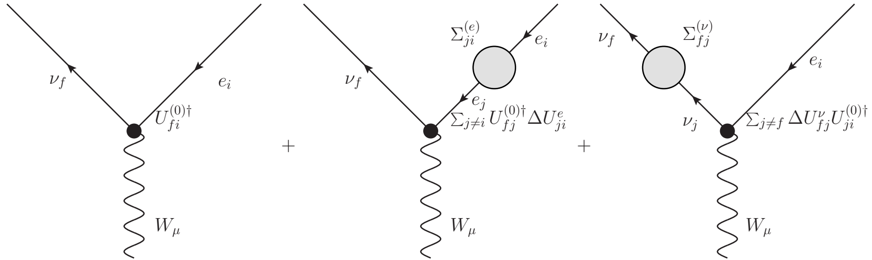
flavour changing self energies

$$\Sigma_{fi}^{\ell}(p) = \Sigma_{fi}^{\ell RL}(p^2)P_L + \Sigma_{fi}^{\ell LR}(p^2)P_R + \not{p}\left[\Sigma_{fi}^{\ell LL}(p^2)P_L + \Sigma_{fi}^{\ell RR}(p^2)P_R\right]$$

PMNS matrix renormalization

$$i\frac{g}{\sqrt{2}}\gamma^\mu P_L U^\dagger \to i\frac{g}{\sqrt{2}}\gamma^\mu P_L \left(\mathbb{1} + D_{L,fi} + D_{R,fi}\right),$$

radiative flavour violation in the lepton sector



PMNS matrix renormalization

$$D_{L,fi} = \sum_{j\neq f} \frac{m_{\nu_f}\left(\Sigma^{(\nu)LR}_{fj} + m_{\nu_f}\Sigma^{(\nu)RR}_{fj}\right) + m_{\nu_j}\left(\Sigma^{(\nu)RL}_{fj} + m_{\nu_f}\Sigma^{(\nu)LL}_{fi}\right)}{m^2_{\nu_j} - m^2_{\nu_f}} U^{(0)\dagger}_{ji}$$

$$\equiv \sum_{j=1}^{3} [\Delta U^\nu_L]_{fj}\, U^{(0)\dagger}_{ji}$$