Quantum corrections to neutrino mixing in the MSSM with righthanded neutrinos

International School Cargese 2012: Across the TeV frontier with the LHC

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Motivation

- Neutrinos seem to have mass
- Oscillations:
  - $\Delta m^2_{21} = 7.58 \times 10^{-5}\,\text{eV}^2$
  - $\Delta m^2_{31} = 2.35 \times 10^{-3}\,\text{eV}^2$
  - large mixing angles
- Unknown: Absolute neutrino mass scale $\rightarrow$ KATRIN
- possible upper limit: 0.2 eV, discovery: 0.35 eV

Compare CKM and PMNS mixing matrix:

$$V_{\text{CKM}} = \begin{pmatrix} \bullet & \cdot & \cdot \\ \cdot & \bullet & \cdot \\ \cdot & \cdot & \bullet \end{pmatrix} \quad U_{\text{PMNS}} = \begin{pmatrix} \bullet & \bullet & \cdot \\ \bullet & \bullet & \bullet \\ \cdot & \bullet & \bullet \end{pmatrix}$$

Neutrino masses and seesaw

Standard Model + righthanded Neutrinos = Seesaw Type I

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

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Neutrino mass matrix:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}.$$

What about m_R?

- righthanded neutrinos are SM singlets $\rightarrow$ no constraint for mass
- seesaw : $m_\nu = -m_D m_R^{-1} m_D \approx \mathcal{O}(0.1\text{ eV})$
- assumption: Dirac mass of order EW scale ($\mathcal{O}(10\ldots100\text{ GeV})$):
  $m_R \sim \mathcal{O}(10^{13\ldots14}\text{ GeV})$

The MSSM with righthanded neutrinos

Superpotential of the νMSSM

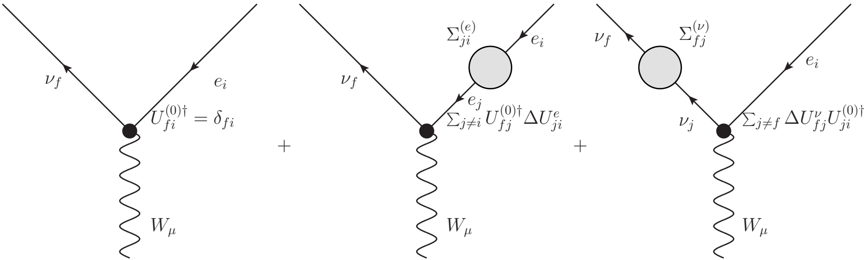
$$\mathcal{W}^{\ell} = \mu H_d \cdot H_u - Y_{\ell}^{IJ} H_d \cdot L_L^I E_R^J + Y_{\nu}^{IJ} H_u \cdot L_L^I N_R^J + \frac{1}{2} m_R^{IJ} N_R^I N_R^J,$$

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

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

radiative flavour violation in the lepton sector



PMNS matrix renormalization

$$i\frac{g}{\sqrt{2}}\gamma^\mu P_L U^\dagger_{\mathrm{PMNS}} \to i\frac{g}{\sqrt{2}}\gamma^\mu P_L \left(\mathbb{1} + \Delta U^e + \Delta U^\nu\right),$$

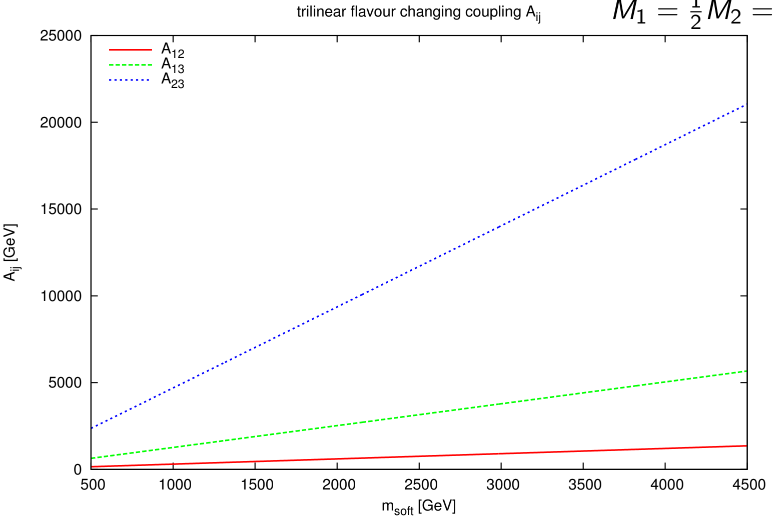
flavour changing self energies and sensitivity to neutrino mass

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

Numerical results

Flavour violation only in the neutrino A-Terms!

$$\mathcal{M}^2_{\text{soft}} = m_0 \mathbb{1}.$$
$$M_1 = \frac{1}{2} M_2 = m_0.$$



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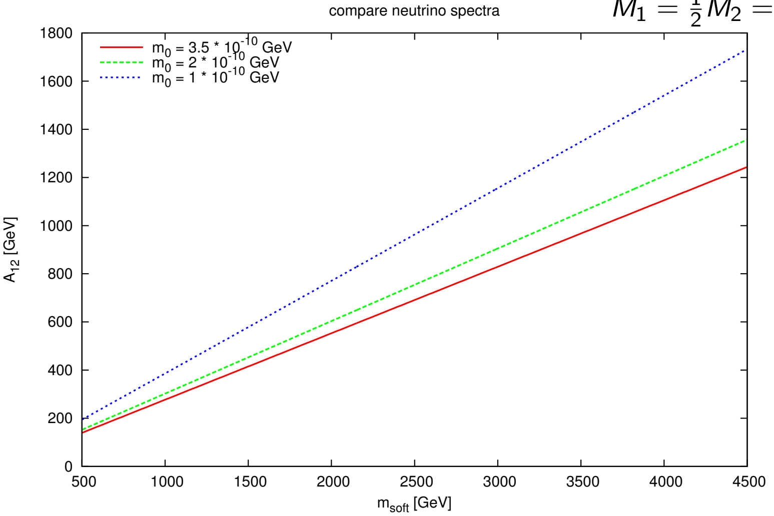

Conclusion

- supersymmetric seesaw incorporates additional flavour structures
- seesaw-like structure in sneutrino squared mass matrix
- sensitive to the degree of degeneracy of neutrino mass spectrum
- sensitive to scale of righthanded neutrinos
- possibly radiative generation of neutrino mixing
- no severe enhancement of LFV obervables

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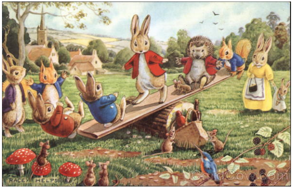

Backup

Slides

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

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

$$\begin{aligned}
\mathbf{m}^2_{\Delta L=0} &= \mathrm{MSSM} + \mathbf{m}_\nu^D \mathbf{m}_\nu^{D\dagger} - \mathbf{m}_\nu^D \mathbf{m}_R \left(\mathbf{m}_R^2 + \mathcal{M}^2_{\tilde{\nu}}\right)^{-1} \mathbf{m}_R \mathbf{m}_\nu^D, \\
\mathbf{m}^2_{\Delta L=2} &= X_\nu \mathbf{m}_\nu^D \left(\mathbf{m}_R^2 + \mathcal{M}^2_{\tilde{\nu}}\right)^{-1} \mathbf{m}_R \mathbf{m}_\nu^{DT} + (\rightarrowtail)^T \\
&\quad - 2\mathbf{m}_\nu^{D*} \mathbf{m}_R \left[\mathbf{m}_R^2 + (\mathcal{M}^2_{\tilde{\nu}})^T\right]^{-1} \mathbf{B} \left(\mathbf{m}_R^2 + \mathcal{M}^2_{\tilde{\nu}}\right)^{-1} \mathbf{m}_R \mathbf{m}_\nu^{D\dagger}.
\end{aligned}$$

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