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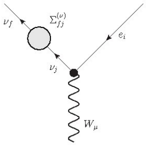

Radiative Lepton Flavour Violation in SUSY GUT models

in collaboration with Markus Bobrowski and Ulrich Nierste

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INSTITUT FÜR THEORETISCHE TEILCHENPHYSIK KIT

Motivation

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- puzzle of neutrino masses and mixings
    - explain smallness of masses and largeness of mixing
    - different situation as in the quark sector
    - radiative flavour violation: describing neutrino mixing out of radiative corrections

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- Standard Model of Particle Physics not symmetric under parity
  - restore parity at high scale $\rightarrow$ left-right symmetry
  - spontaneous parity breakdown
  - LR symmetry gives the see-saw mechanism for free

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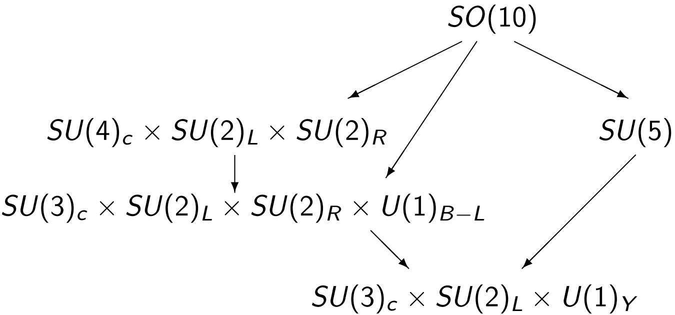
- Standard Model of Particle Physics not symmetric under parity
  - restore parity at high scale $\rightarrow$ left-right symmetry
  - spontaneous parity breakdown
  - LR symmetry gives the see-saw mechanism for free
- SUSYLR quite economic:
  - only one Dirac-like Yukawa coupling (for quarks and leptons each)
  - boundary conditions at high scale not far from GUT-scale

The top-down-approach

1. framework: SO(10) Grand Unification
2. breaking down SO(10) with intermediate steps to the Standard Model



CKM vs. PMNS matrix

- CKM matrix quasi diagonal

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

- assume tree-level matrix as unity matrix, generate mixings radiatively
- different pattern for the leptonic mixing matrix

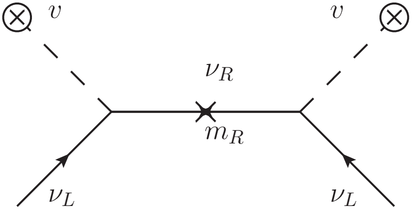
$$U_{\mathsf{PMNS}} = \begin{pmatrix} \huge\bullet & \Large\bullet & \cdot \\ \Large\bullet & \Large\bullet & \Large\bullet \\ \cdot & \Large\bullet & \Large\bullet \end{pmatrix}$$

- not at all diagonal
- rather large mixings instead in 1-2 and 2-3 blocks
- same assumption as for the CKM case justified?

Type I + II see-saw

Type I: righthanded singlet

$$-\mathcal{L}_{\mathrm{m}}^{\nu} = \bar{\nu}_L m_D \nu_R + \frac{1}{2}\overline{\nu_L^c} m_R \nu_R + \text{ h.c.}$$



$$\mathcal{M} = \begin{pmatrix} m_L & m_D \\ m_D^T & m_R \end{pmatrix}$$

$$m_{\nu_\ell} = -m_D m_R^{-1} m_D^T$$

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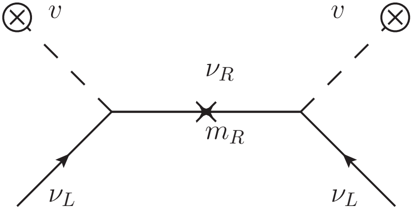

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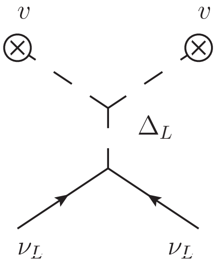
Type II: scalar triplet

$$-\mathcal{L}_{\rm m}^{\nu} = h_L \overline{\nu_R^c}\langle\Delta_L\rangle\nu_L + h_R \overline{\nu_L^c}\langle\Delta_R\rangle\nu_R$$



$$\langle\Delta_L\rangle \equiv v_L \approx \frac{\langle\Delta_R\Phi^2\rangle}{M^2} \approx \frac{v^2}{M}$$

“vev see-saw”

left-right symmetry and neutrino masses

- combined see-saw type I + II:

$$m_\nu = m_L - m_D m_R^{-1} m_D^T$$
$$\equiv v_L h_L - \frac{v_u^2}{v_R} y_\nu h_R^{-1} y_\nu^T ,$$

where

$$m_L = \langle \delta_L^0 \rangle h_L \equiv v_L h_L ,$$
$$m_R = \langle \delta_R^0 \rangle h_R \equiv v_R h_R \text{ and}$$
$$m_D = \langle h_u \rangle y_\nu \equiv v_u y_\nu$$

- left-right symmetry requires $y_\nu = y_e$ and $h_L = h_R$ (imposing parity)
- type II dominates

left-right symmetry and neutrino masses

- combined see-saw type I + II:

$$m_\nu = m_L - m_D m_R^{-1} m_D^T$$
$$\equiv v_L h_L - \frac{v_u^2}{v_R} y_\nu h_R^{-1} y_\nu^T,$$

$$h_L = h_R = \begin{pmatrix} \bullet & \cdot & \cdot \\ \cdot & \bullet & \cdot \\ \cdot & \cdot & \bullet \end{pmatrix}$$

- minimal SUSYLR: $y_e = y_\nu =$ diagonal
- $h_L = h_R \approx$ diagonal $\to$ ignore small off diagonal entries
- PMNS matrix at first approximation unity matrix

effective sneutrino mass matrix

$$\mathcal{M}^2_{\tilde{\nu}} = \begin{pmatrix} \mathcal{M}^2_{LL} & \mathcal{M}^2_{LR} \\ (\mathcal{M}^2_{LR})^\dagger & \mathcal{M}^2_{RR} \end{pmatrix} \approx \begin{pmatrix} \mathcal{O}(M^2_{\mathsf{SUSY}}) & \mathcal{O}(M_{\mathsf{SUSY}} m_R) \\ \mathcal{O}(M_{\mathsf{SUSY}} m_R) & \mathcal{O}(m_R^2) \end{pmatrix}$$

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12×12-matrix — see-saw-like structure

perturbative diagonalization: [Dedes, Haber, Rosiek 2007]

$$U^\dagger \mathcal{M}_{\tilde\nu} U = \begin{pmatrix} \mathcal{M}^2_{\tilde\nu_\ell} & \mathcal{O}(M^3_{\text{SUSY}} m_R^{-1}) \\ \mathcal{O}(M^3_{\text{SUSY}} m_R^{-1}) & \mathcal{M}^2_{RR} + \mathcal{O}(M^2_{\text{SUSY}}) \end{pmatrix},$$

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where $\mathcal{M}^2_{\tilde\nu_\ell} = \mathcal{M}^2_{LL} - \mathcal{M}^2_{LR} \left(\mathcal{M}^2_{RR}\right)^{-1} \left(\mathcal{M}^2_{LR}\right)^\dagger + \mathcal{O}(M^4_{\mathrm{SUSY}} m_R^{-2})$.

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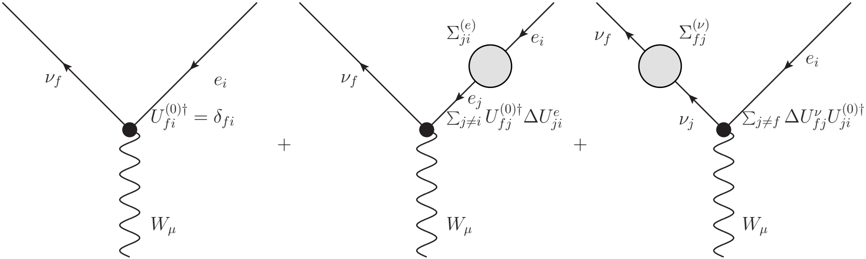
$$\mathbf{m}^2_{\Delta L=2} = X_\nu \mathbf{m}^D_\nu \left(\mathbf{m}^2_R + \mathcal{M}^2_{\tilde{\nu}}\right)^{-1} \mathbf{m}_R \mathbf{m}^{DT}_\nu + \dots$$

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

radiative flavour violation in the lepton sector



PMNS matrix renormalization

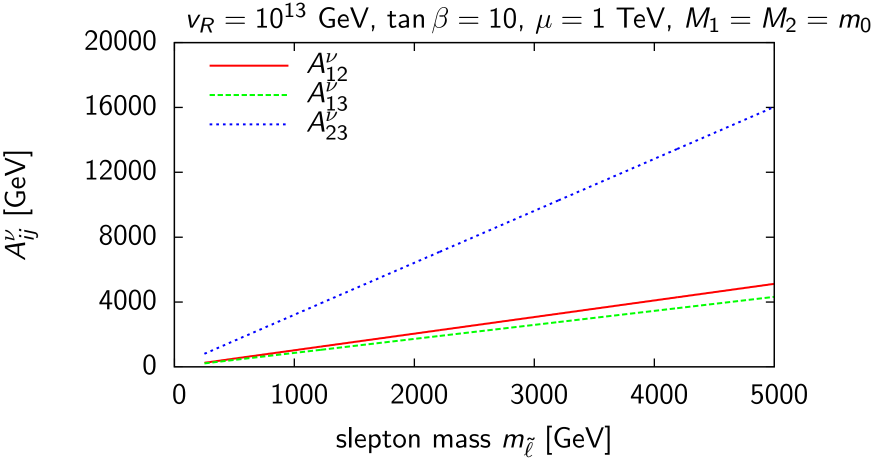
$$i \frac{g}{\sqrt{2}} \gamma^\mu P_L U^\dagger_{\mathrm{PMNS}} \to i \frac{g}{\sqrt{2}} \gamma^\mu P_L \left(\mathbb{1} + \Delta U^e + \Delta U^\nu \right),$$

flavour changing self energies and sensitivity to neutrino mass

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

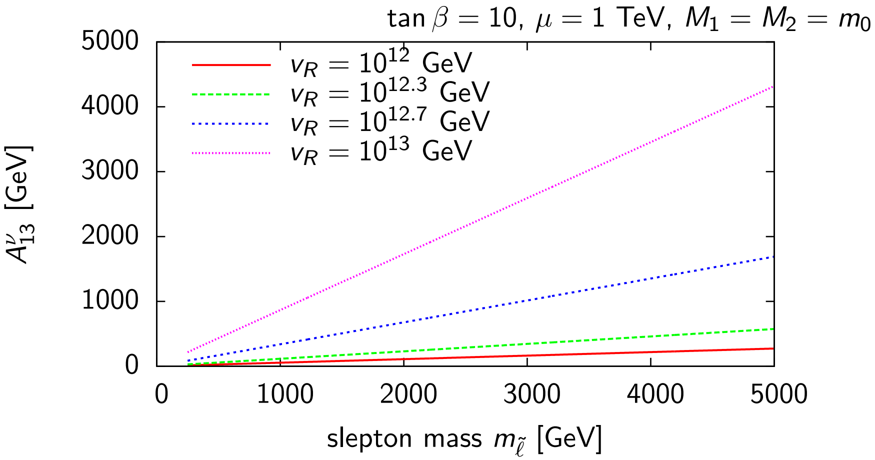
flavour mixing only in the trilinear couplings

- values for A^ν_{ij} producing U^{PMNS}_{ij}:



flavour mixing only in the trilinear couplings

- sensitivity to the LR scale (see-saw-like contribution $v_u A_\nu / v_R^2$):



Conclusion

- radiative flavour violation due to SUSY corrections
- flavour mixings in trilinear couplings
  - A_ν as remnant of heavy singlet neutrino superfields
  - smoking gun of high scale physics in effective sneutrino mass matrix
- entanglement of heavy neutrino mass scale (= LR scale) and SUSY breaking terms
- leptonic RFV prefers quasi-degenerate neutrino mass spectrum
  - KATRIN does so as well
  - sensitivity up to 0.2 eV

Backup Slides

See-saw and neutrino masses

Puzzle of neutrino masses

$$m_\nu \lesssim 1\ \text{eV} \quad \leftrightarrow \quad m_\tau \simeq 1\ \text{GeV}.$$

1. heavy singlet neutrino ("righthanded")
2. triplet scalar ("vev see-saw")
3. left-right symmetry combines both

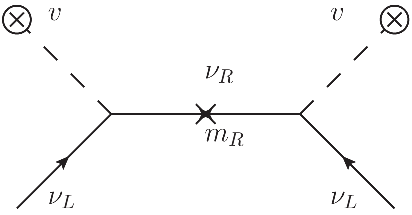
features of left-right symmetry $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- ESWB: Higgs Bidoublet $(\mathbf{2}, \mathbf{2}, 0)$ couples ℓ_L and ℓ_R via y_ℓ
- breaking $SU(2)_R \times U(1)_{B-L}$: Higgs triplet $\Delta_R = (\mathbf{1}, \mathbf{3}, 2)$ gives masses to ν_R — $m_R \sim \langle \Delta_R \rangle \equiv v_R \simeq 10^{12\ldots14}$ GeV
- LR symmetric form: $(\mathbf{3}, \mathbf{1}, 2)$ giving rise to see-saw type II

Type I + II see-saw

Type I: righthanded Singlet

$$-\mathcal{L}_{\mathrm{m}}^{\nu} = \bar{\nu}_L m_D \nu_R + \frac{1}{2}\overline{\nu_L^c} m_R \nu_R + \text{ h.c.}$$



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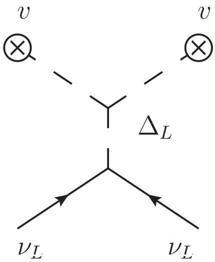
Type II: Scalar Triplet

$$-\mathcal{L}_{\mathrm{m}}^{\nu} = h_L \overline{\nu_R^c} \langle \Delta_L \rangle \nu_L + h_R \overline{\nu_L^c} \langle \Delta_R \rangle \nu_R$$



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"vev see-saw"

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

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

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

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

12×12-Matrix

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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

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

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

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

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

minimal SUSYLR model

Superpotential of the minimal SUSYLR model

$$\mathcal{W}_{\tilde{\ell}} = \frac{\mu}{2}\,\mathrm{Tr}[\Phi^T \epsilon \Phi \epsilon^T] + M\,\mathrm{Tr}[\Delta_{1L}\Delta_{2L} + \Delta_{1R}\Delta_{2R}] + y^{IJ} L_L^I \epsilon \Phi \epsilon^T L_R^J + h_L^{IJ} L_L^I \epsilon \Delta_{1L} L_L^J + h_R^{IJ} L_R^I \epsilon \Delta_{1R} L_R^J,$$

where the chiral superfields are $L_L = (\ell_L, \tilde{\ell}_L)$ (lefthanded) and $L_R = (\ell_R^c \equiv (\ell_R)^c, \tilde{\ell}_R^*)$ (righthanded).

Soft-breaking terms of SUSYLR

$$\mathcal{V}_{\text{soft}} = (\mathcal{M}_L^2)^{IJ} \tilde{L}_L^{I*} \tilde{L}_L^J + (\mathcal{M}_R^2)^{IJ} \tilde{L}_R^{I*} \tilde{L}_R^J + \left[A_\ell^{IJ} \tilde{L}_L^I \epsilon \Phi \epsilon^T \tilde{L}_R^J + \text{ h. c.} \right] + \left[{B_L}^{IJ} \tilde{L}_L^I \epsilon \Delta_{1L} \tilde{L}_L^J + {B_R}^{IJ} \tilde{L}_R^I \epsilon \Delta_{1R} \tilde{L}_R^J + \text{ h. c.} \right],$$

Particle content of the minimal SUSYLR model – Higgses and Leptons

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

[Cvetic, Pati 1984]

- scalar bidoublet (EWSB): $\Phi = (\mathbf{2}, \mathbf{2}, 0)$

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$$

- scalar triplets: $\Delta_L = (\mathbf{3}, \mathbf{1}, +2)$, $\Delta_R = (\mathbf{1}, \mathbf{3}, -2)$

$$\Delta_L = \begin{pmatrix} \delta_L^0/\sqrt{2} & \delta_L^+ \\ \delta_L^{++} & -\delta_L^0/\sqrt{2} \end{pmatrix}, \quad \Delta_R = \begin{pmatrix} -\delta_R^0/\sqrt{2} & -\delta_R^{--} \\ -\delta_R^- & \delta_R^0/\sqrt{2} \end{pmatrix}$$

- additional triplet fields: $\Delta_L' = (\mathbf{3}, \mathbf{1}, -2)$, $\Delta_R' = (\mathbf{1}, \mathbf{3}, +2)$

Particle content of the minimal SUSYLR model – Higgses and Leptons

$$\boxed{SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$$

[Cvetic, Pati 1984]

- lepton doublets: $L_L = (\mathbf{2}, \mathbf{1}, -1)$, $L_R = (\mathbf{1}, \mathbf{2}, +1)$
- both L_L *and* L_R left-chiral Superfields

$$L_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \qquad L_R \equiv \epsilon \begin{pmatrix} \nu_R^c \\ e_R^c \end{pmatrix} = \begin{pmatrix} e_R^c \\ -\nu_R^c \end{pmatrix}$$

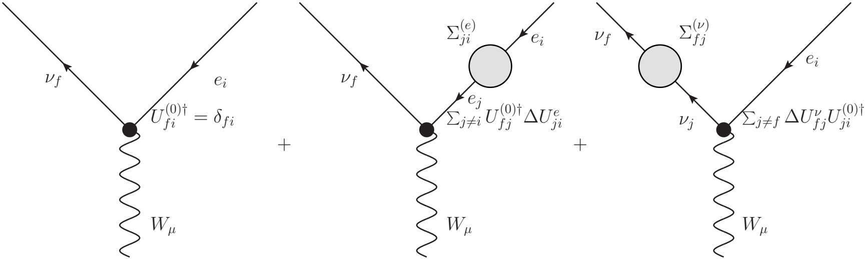
- Majorana mass terms out of triplet vev:

$$\langle \Delta_R \rangle = \begin{pmatrix} 0 & v_R \\ 0 & 0 \end{pmatrix} \quad \rightarrow \quad h_R L_R^T \epsilon \langle \Delta_R \rangle L_R = \nu_R^c m_R \nu_R^c$$

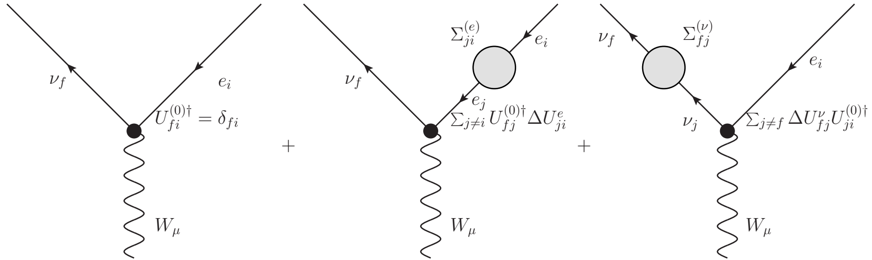
Particle content of the minimal SUSYLR model – leptonic and gauge sector

fields	#	multiplet of $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$	el. charge Q_{el}
$L_L = (\ell_L, \tilde{\ell}_L)$	3	$(\mathbf{2}, \mathbf{1}, -1)$	$(0, -1)$
$L_R = (\ell_R^c, \tilde{\ell}_R^*)$	3	$(\mathbf{1}, \mathbf{2}, +1)$	$(0, +1)$
Φ	1	$(\mathbf{2}, \mathbf{2}, 0)$	$-1, 0, +1$
Δ_{1L}	1	$(\mathbf{3}, \mathbf{1}, +2)$	$0, +1, +2$
Δ_{2L}	1	$(\mathbf{3}, \mathbf{1}, -2)$	$0, -1, -2$
Δ_{1R}	1	$(\mathbf{1}, \mathbf{3}, -2)$	$0, -1, -2$
Δ_{2R}	1	$(\mathbf{1}, \mathbf{3}, +2)$	$0, +1, +2$
$G^{\mu,a}$	1	$(\mathbf{8}, \mathbf{1}, \mathbf{1}, 0)$	0
$W_L^{\mu,i}$	1	$(\mathbf{1}, \mathbf{3}, \mathbf{1}, 0)$	$\pm 1, 0$
$W_R^{\mu,i}$	1	$(\mathbf{1}, \mathbf{1}, \mathbf{3}, 0)$	$\pm 1, 0$
B^μ	1	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, 0)$	0

radiative flavour violation in the lepton sector



radiative flavour violation in the lepton sector



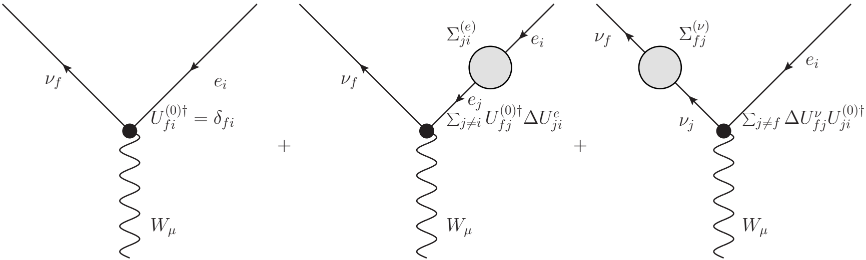
flavour changing self energies

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

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

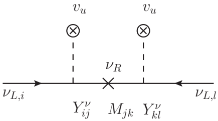


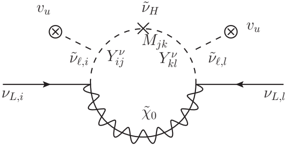
PMNS matrix renormalization

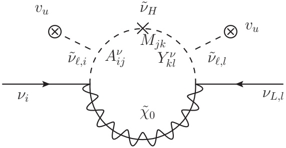
$$D_{L,fi} = \sum_{j\neq f} \frac{m_{\nu_f}\left(\Sigma^{(\nu)LR}_{fj} + m_{\nu_f}\Sigma^{(\nu)RR}_{fj}\right) + m_{\nu_j}\left(\Sigma^{(\nu)RL}_{fj} + m_{\nu_f}\Sigma^{(\nu)LL}_{fi}\right)}{m^2_{\nu_j} - m^2_{\nu_f}} U^{(0)\dagger}_{ji}$$

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

Majorana mass renormalization

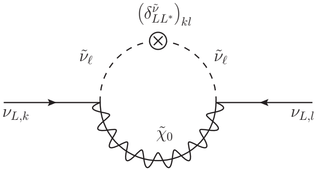






effects of righthanded Neutrinos

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

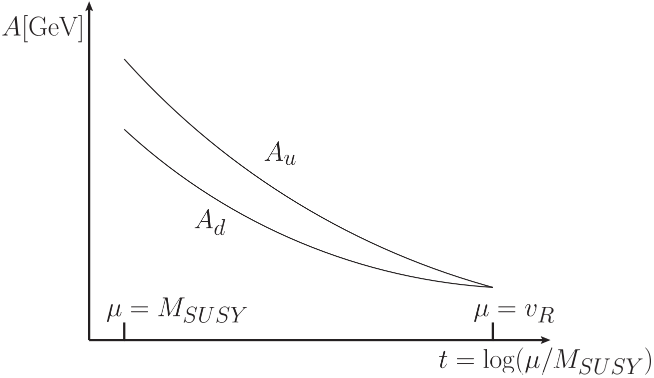


$$\delta_{LL^*}^{\tilde{\nu}} \sim X_\nu \mathbf{m}_\nu^D \left(\mathbf{m}_R^2 + \mathcal{M}_{\tilde{\nu}}^2\right)^{-1} \mathbf{m}_R \mathbf{m}_\nu^{DT}$$

$$\sim \frac{v_u A_\nu}{v_R^2} \qquad \text{with} \quad \mathbf{m}_R = v_R \mathbf{h}_R$$

LR symmetry at high scale

- $v_R \simeq 10^{12\ldots14}$ GeV out of neutrino data: seesaw scale $m_R \sim v_R$
- relating SUSY and LR scale: RGE running [Martin, Vaughn 1994]
- above the LR scale: using LR symmetric RGEs



flavour mixing only in the trilinear couplings

- sensitivity to the neutrino mass scale and degree of degeneracy: