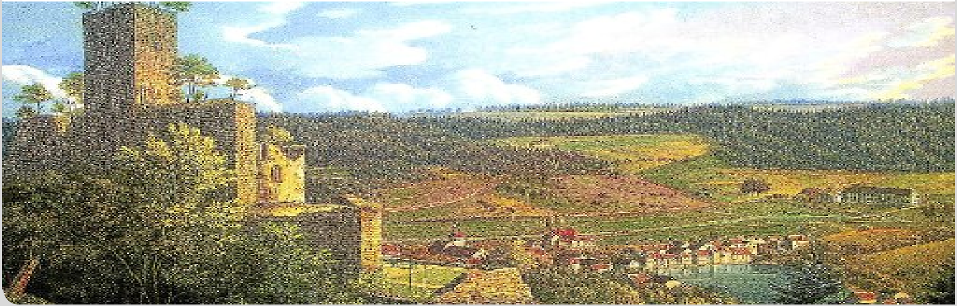
SUSY models of neutrino masses and mixings: the left-right connection

GK Workshop Bad Liebenzell

Wolfgang Gregor Hollik | October 10, 2012

INSTITUT FÜR THEORETISCHE TEILCHENPHYSIK | KIT CAMPUS SÜD



outline

Motivation

- Neutrinos seem to have mass
- Oscillations:
  - $\Delta m_{21}^2 = 7.58 \times 10^{-5}\,\text{eV}^2$
  - $\left|\Delta m_{31}^2\right| = 2.35 \times 10^{-3}\,\text{eV}^2$
  - large mixing angles

- Unknown: Absolute neutrino mass scale $\rightarrow$ KATRIN

- possible upper limit: 0.2 eV, discovery: 0.35 eV

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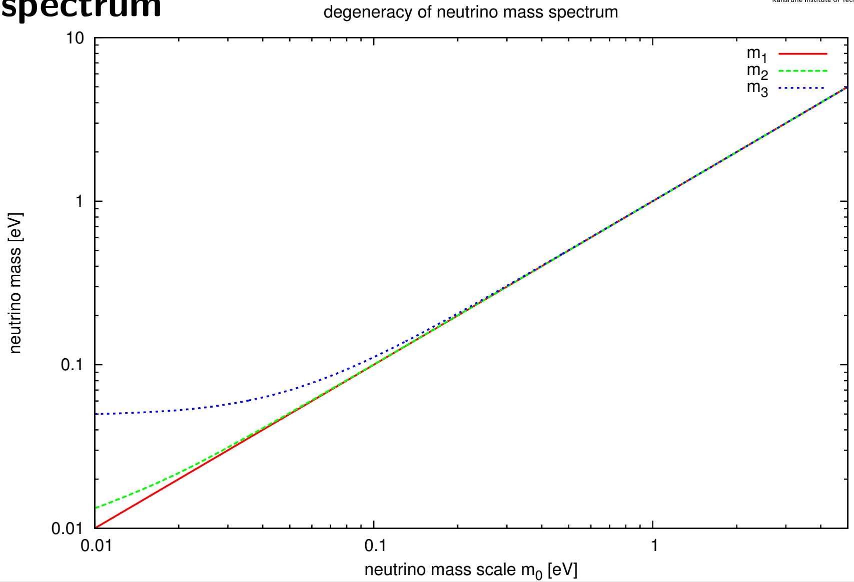
Splitting of the neutrino mass spectrum



CKM vs. PMNS matrix

- CKM matrix close to unity

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

- small off-diagonal: generate mixings radiatively ?

[Weinberg 1972]

- different pattern for the leptonic mixing matrix:

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

- 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?

Models of neutrino mass generation

"Seesaw" mechanisms

[Minkowski; Mohapatra, Senjanovic; Magg, Wetterich; . . .]

The one and only

Extend Standard Model Lagrangian by one single nonrenormalizable operator: [Weinberg 1979]

$$\mathcal{O}_{\mathrm{W}} = \frac{\lambda_{ij}}{M} \left(L_i^T \phi \right) C \left(\phi^T L_j \right)$$

- $C = i\gamma_2\gamma_0$: charge conjugation matrix
- ϕ: standard Higgs doublet
- λ: dimensionless parameter
- M: some high scale
- rough estimate: $m_\nu \sim \frac{\lambda_{ij}}{M} \cdot v^2$, $v = \langle \phi \rangle \approx 174$ GeV
- if $\lambda \sim \mathcal{O}(1)$ and $\mathcal{O}(0.1\text{eV})$: $M = 3 \times 10^{14}$ GeV

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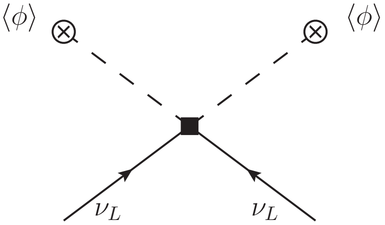

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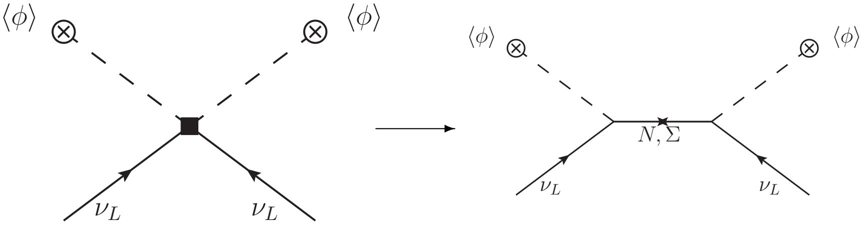

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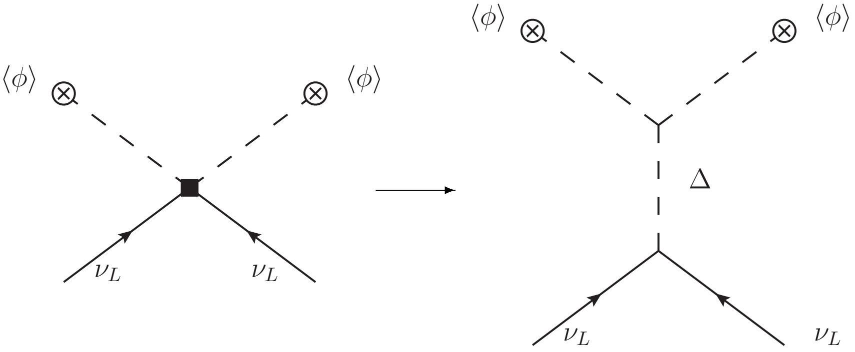
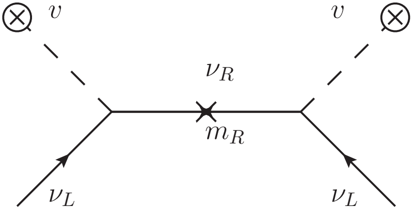


Type I + II see-saw

Type I: righthanded singlet

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



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

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

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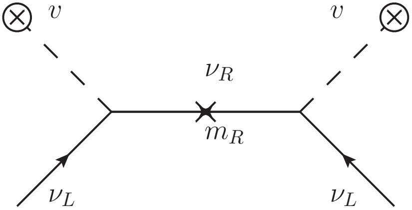

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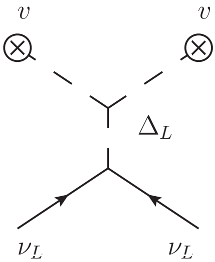
Type II: scalar triplet

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



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

“vev see-saw”

Left-Right Symmetry

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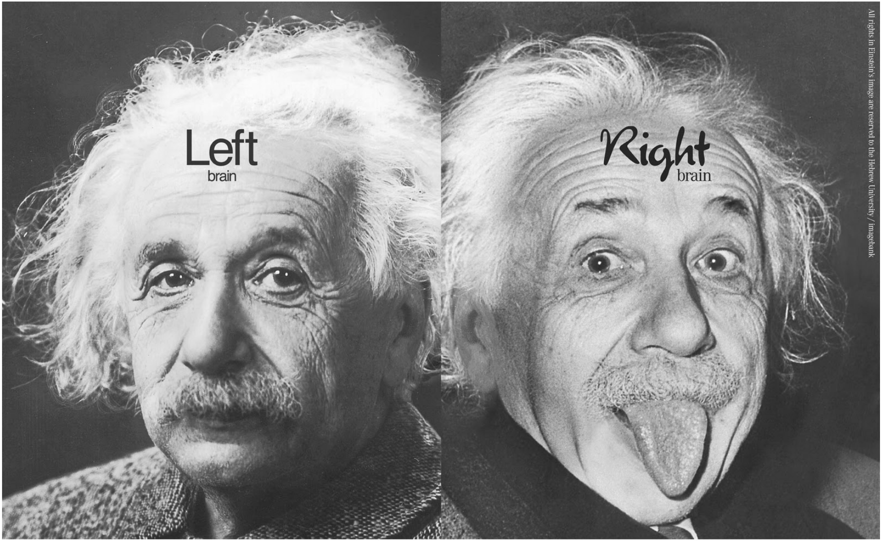

Left-Right Symmetry

Extend the Standard Model Gauge Group

$$SU(3)_c \times SU(2)_L \times U(1)_Y \;\rightarrow\; SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

[Pati, Salam; Mohapatra, Pati; Mohapatra, Senjanovic; 1975]

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- $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(2)_L \times U(1)_Y$
  via triplet under $SU(2)_R$ with $B-L$ charge:

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix}, \qquad \begin{array}{l} \Delta_L = (\mathbf{1},\mathbf{3},\mathbf{1},2)\,, \\ \Delta_R = (\mathbf{1},\mathbf{1},\mathbf{3},2) \end{array}$$

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- electric charge: $Q = T_{3L} + T_{3R} + \frac{B-L}{2}$
- scalar bidoublet (EWSB): $\Phi = (\mathbf{2},\mathbf{2},0)$

$$\Phi = \begin{pmatrix} \phi^0_1 & \phi^+_2 \\ \phi^-_1 & \phi^0_2 \end{pmatrix}, \quad \langle\Phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix}, \quad \tan\beta = \frac{v_2}{v_1}$$

left-right symmetric neutrino masses

Leptonic Yukawa Lagrangian

$$\mathcal{L}_\ell^{\text{Yuk}} = y_{ij}\bar{L}_i \Phi R_j + \tilde{y}_{ij}\bar{L}_i \tilde{\Phi} R_j + h_{ij}\left(L_i^T C \Delta_L L_j + R_i^T C \Delta_R R_j \right) + \text{h. c.},$$

where $L = (\nu_L, e_R) \in SU(2)_L$ and $R = (\nu_R, e_R) \in SU(2)_R$.

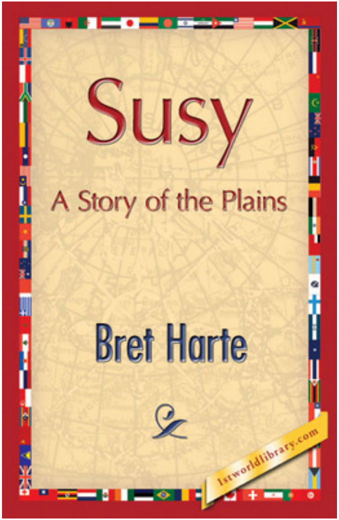
- Charged lepton mass: $m_e = v_1 y + v_2 \tilde{y}$,
- Dirac neutrino mass: $m_D = v_1 \tilde{y} + v_2 y$,
- Majorana neutrino masses: $m_L = v_L h$, $m_R = v_R h$. [1]
- combined see-saw type I + II:

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

$$m_{\nu_\ell} = m_L - m_D \left(m_R\right)^{-1} m_D^T$$

[1] If parity symmetry is assumed, i.e. $\mathcal{L}$ inv. under $L \leftrightarrow R$

SUSY's tale



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- Extending Poincaré symmetry: SM particles become part of larger multiplets (chiral and vector supermultiplets)
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Superpotential of the minimal SUSYLR model

$$\mathcal{W}_\ell = y_{ij} L_i \Phi R_j + h_{ij} \left(L_i \Delta_L L_j + R_i \Delta_R R_j \right),$$

[Cvetic, Pati 1984]

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).

SUSY's tail

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SUSY has to be broken

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Soft-breaking terms of MSSM w/o squarks

$$\begin{aligned}\mathcal{V}_{\text{soft}} =& \tilde{\ell}^*_{iL}\left(\mathcal{M}^2_{\tilde{\ell}}\right)_{ij}\tilde{\ell}_{jL} + \tilde{e}^*_{iR}\left(\mathcal{M}^2_{\tilde{e}}\right)_{ij}\tilde{e}_{jR} \\ &+ A^e_{ij} h_1 \cdot \tilde{\ell}_{iL}\tilde{e}^*_{jR} + \text{ h. c.} \\ &+ m_1^2|h_1|^2 + m_2^2|h_2|^2 + (m_{12}^2 h_1 \cdot h_2 + \text{h. c.}) \\ &+ \frac{1}{2}\left(M_1 \bar{\tilde{\lambda}}_0 P_L \tilde{\lambda}_0 + \text{h. c.}\right) + \frac{1}{2}\left(M_2 \bar{\vec{\tilde{\lambda}}} P_L \vec{\tilde{\lambda}} + \text{h. c}\right)\end{aligned}$$

SUSY's tail

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Soft-breaking terms of SUSYLR

$$\mathcal{V}_{\text{soft}} = \tilde{L}_i^* (\mathcal{M}_L^2)_{ij} \tilde{L}_j + \tilde{R}_i^* (\mathcal{M}_R^2)_{ij} \tilde{R}_j + \left[A_{ij}^{\ell} \tilde{L}_i \Phi \tilde{R}_j^* + \text{ h. c. } \right] + \left[B_{ij} \left(\tilde{L}_i \Delta_L \tilde{L}_j + \tilde{R}_i \Delta_R \tilde{R}_j \right) + \text{ h. c. } \right],$$

- SUSYLR constrains the soft breaking parameter space
- relations between up and down sector ($A^u = A^d$, $A^\nu = A^e$ and $\mathcal{M}_{\tilde{Q}}^2 = \mathcal{M}_{\tilde{u}}^2 = \mathcal{M}_{\tilde{d}}^2$, $\mathcal{M}_{\tilde{\ell}}^2 = \mathcal{M}_{\tilde{e}}^2 = \mathcal{M}_{\tilde{\nu}}^2$) @ LR scale
- RGE connection between SUSY and LR scale

super-seesaw mechanism

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effective sneutrino mass matrix

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

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12×12-matrix — see-saw-like structure

perturbative diagonalization: [Dedes, Haber, Rosiek 2007]

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

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

super-seesaw mechanism

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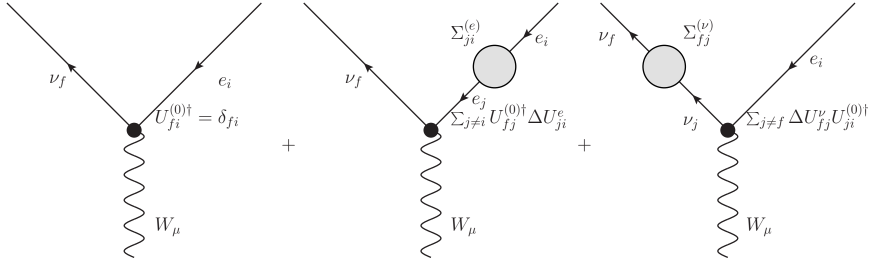
$$\mathbf{m}^2_{\Delta L = 2} = X_\nu \mathbf{m}^D_\nu \left(\mathbf{m}^2_R + \mathcal{M}^2_{\tilde\nu}\right)^{-1} \mathbf{m}_R \mathbf{m}^{DT}_\nu + \ldots$$

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

radiative lepton flavour violation



PMNS matrix renormalization

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

flavour changing self energies and sensitivity to neutrino mass

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

enhanced corrections to PMNS mixing

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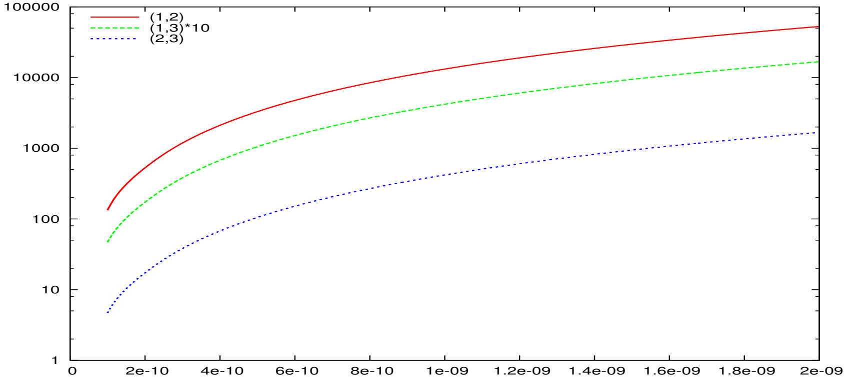
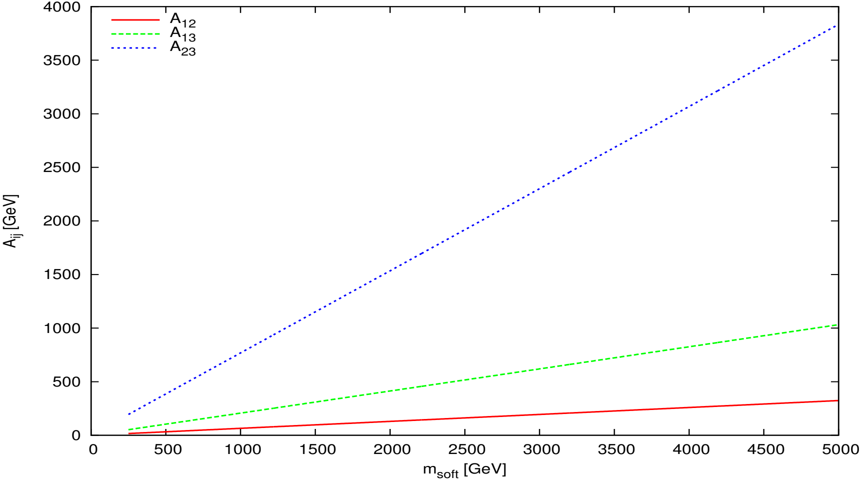
flavour changing self energies and sensitivity to neutrino mass

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



Results: $\mathbf{m}_\nu^{(0)} = 0.3$ eV

- Choice of parameters: $\mathcal{M}^2_{\tilde{\ell}} = \mathcal{M}^2_{\tilde{e}} = \mathcal{M}^2_{\tilde{\nu}} \equiv m^2_{\tilde{\ell}} \mathbb{1}$ @ start
- $v_R = 10^{12.5}$ GeV, $\tan\beta = 20$, $\mu_H = 500$ GeV, $M_1 = \frac{1}{2} M_2 = m_{\tilde{\ell}}$



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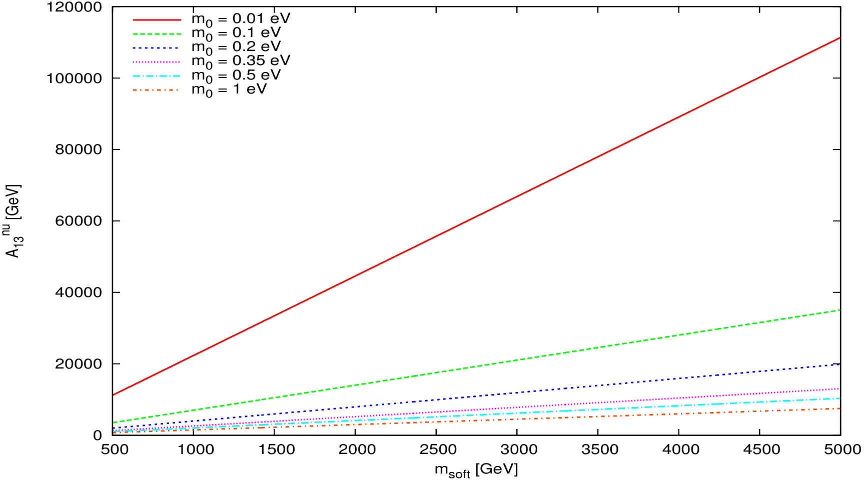

Conclusion

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- radiative flavour violation (RFV) 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
- ensure left-right symmetric boundary conditions at the high scale ($\sim 10^{12\ldots13}$ GeV)
- leptonic RFV prefers quasi-degenerate neutrino mass spectrum

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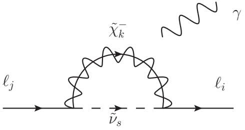
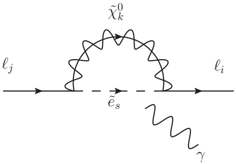
- ensure left-right symmetric boundary conditions at the high scale ($\sim 10^{12\ldots13}$ GeV)
- leptonic RFV prefers quasi-degenerate neutrino mass spectrum
- BUT: LR symmetry in connection with RFV induces dangerously large LFV processes ($\ell_j \to \ell_i\gamma$)





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

How the mixing comes into the game

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SM: Lefthanded fields doublets, righthanded singlets under $SU(2)$:
$Q_{L,i}, u_{R,i}, d_{R,i}, L_{L,i}, e_{R,i}$. $i = 1, \ldots, N$ generation index.

Charged electroweak current:

$$\mathcal{L}_{cc} = -\frac{i\,g}{2\sqrt{2}}\, W^+_\mu \left(\bar{u}_{L,i}\,\gamma^\mu\, d_{L,i} + \bar{e}_{L,i}\,\gamma^\mu\, \nu_{L,i} + \text{h.c.}\right),$$

flavour blind, only lefthanded.

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Yukawa Lagrangian and fermion masses:

$$\mathcal{L}_{\text{Yuk}} = y^d_{ij}\,\bar{Q}_{L,i}\phi d_{R,j} + y^u_{ij}\,\bar{Q}_{L,i}\tilde{\phi} u_{R,j} + y^e_{ij}\,\bar{L}_{L,i}\tilde{\phi} e_{R,j} + \text{ h.c.}$$

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Masses: $\mathbf{m}^f = v\,y^f \to \mathbf{m}^f_{\text{diag}} = V_L^{f\dagger}\mathbf{m}^f V_R$, $\quad V^\dagger_{L,R} V_{L,R} = \mathbb{1}$,
such that $f_{X,i} \to f_{X,i} = (V_X)_{ia} f_{X,a}$, $X = L, R$.

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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

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

Karlsruhe Institute of Technology

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

[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

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

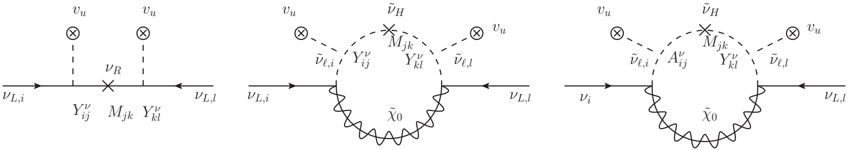
- Majorana mass terms out of triplet vev:

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

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

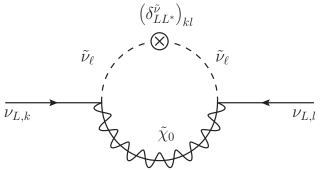
fields	#	multiplet of $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$	el. charge Q_{el}
$L_L = (\ell_L, \tilde{\ell}_L)$	3	$(\mathbf{2}, \mathbf{1}, -1)$	$(0, -1)$
$L_R = (\ell^c_R, \tilde{\ell}^*_R)$	3	$(\mathbf{1}, \mathbf{2}, +1)$	$(0, +1)$
Φ	1	$(\mathbf{2}, \mathbf{2}, 0)$	$-1, 0, +1$
Δ_{1L}	1	$(\mathbf{3}, \mathbf{1}, +2)$	$0, +1, +2$
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

Majorana mass renormalization



effects of righthanded Neutrinos

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



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

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

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