Soft lepton number violation in multi-Higgs doublet Seesaw models

Elke Aeikens

University Vienna
PhD-advisor Prof. Walter Grimus

28th June 2016

Doktoratskolleg Particles and Interactions

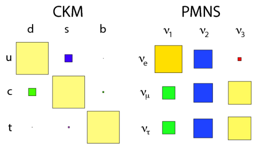
universität wien
Faculty of Physics

Why we care about neutrinos

experimentally unsolved: anomalies...

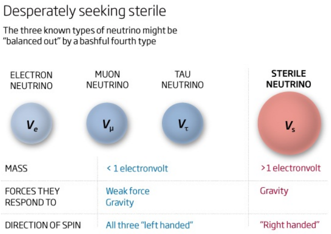
theoretical unsolved: (all about mass)

- different mixing matrices then quarks
- normal or inverted mass hierarchy
- hierarchy problem: very light mass
- origin of mass: Dirac, Majorana



properties:

- just weak interacting
- no observed right handed partner



Why we care about neutrinos

experimentally unsolved: anomalies...

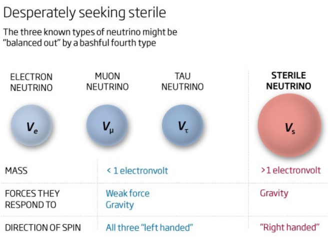
theoretical unsolved: (all about mass)

- different mixing matrices then quarks
- normal or inverted mass hierarchy
- hierarchy problem: very light mass
- origin of mass: Dirac, Majorana

$$\mathcal{L}_M \stackrel{?}{=} \mathcal{L}_{Dirac} + \mathcal{L}_{Majorana}$$
$$\sim \bar{\nu}_R M_D \nu_L + \bar{\nu}_\alpha M_M \nu_\beta + h.c.$$

properties:

- just weak interacting
- no observed right handed partner



introduce:
right handed neutrinos ν_R

Advantage of right handed neutrinos

- **Explain mass hierarchy** in right handed neutrino mass models via the seesaw mechanism. $[\mathrm{m}_{\nu_R} \gtrsim \mathrm{TeV}]$
  (with additional higgs doublets...)
- **Dark matter candidates** $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_R} \lesssim \mathrm{TeV}]$
- **Baryon asymmetry** via Leptogenesis in νMSM models $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_R} \lesssim \mathrm{GeV}]$
- **Detected anomalies** at: LSND, MiniBooNE, gallium detectors: GALLEX, SAGE, reactor experiments... $[\mathrm{m}_{\nu_R} \sim \mathrm{eV}]$
  (a.o. also IceCube)

tightest constrains from cosmology:

- **Boundaries from BBN**
- **CMB measurement** from PLANCK sets limits on N_ν and also the **Large Scale Structure**.

Advantage of right handed neutrinos

- **Explain mass hierarchy** in right handed neutrino mass models via the seesaw mechanism. $[\mathrm{m}_{\nu_R} \gtrsim \mathrm{TeV}]$ (with additional higgs doublets...)
- **Dark matter candidates** $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_R} \lesssim \mathrm{TeV}]$
- **Baryon asymmetry** via Leptogenesis in νMSM models $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_R} \lesssim \mathrm{GeV}]$
- **Detected anomalies** at: LSND, MiniBooNE, gallium detectors: GALLEX, SAGE, reactor experiments... $[\mathrm{m}_{\nu_R} \sim \mathrm{eV}]$ (a.o. also IceCube)

tightest constrains from cosmology:

- **Boundaries from BBN**

previous work

- **CMB measurement** from PLANCK sets limits on N_ν and also the **Large Scale Structure**.

Advantage of right handed neutrinos

- **Explain mass hierarchy** in right handed neutrino mass models via the seesaw mechanism. $[\mathrm{m}_{\nu_\mathrm{R}} \gtrsim \mathrm{TeV}]$
  (with additional higgs doublets...)

actual work

- **Dark matter candidates** $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_\mathrm{R}} \lesssim \mathrm{TeV}]$
- **Baryon asymmetry** via Leptogenesis in νMSM models $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_\mathrm{R}} \lesssim \mathrm{GeV}]$
- **Detected anomalies** at: LSND, MiniBooNE, gallium detectors: GALLEX, SAGE, reactor experiments... $[\mathrm{m}_{\nu_\mathrm{R}} \sim \mathrm{eV}]$
  (a.o. also IceCube)

tightest constrains from cosmology:

- **Boundaries from BBN**

previous work

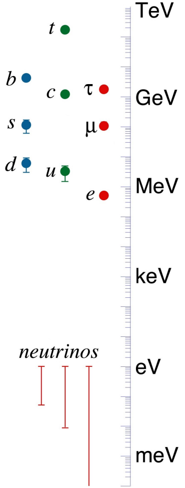
- **CMB measurement** from PLANCK sets limits on N_ν and also the **Large Scale Structure**.

First ingredient for a good model

Hierarchy problem:

Neutrino mass is small $m_\nu < 0.1\,\mathrm{eV}$ (exp. limits)
Masses are normally $m_e \simeq 0.5\,\mathrm{MeV}$ to $m_t \simeq 173\,\mathrm{GeV}$

$\Rightarrow$ *small Yukawa masses seem to be unnatural*

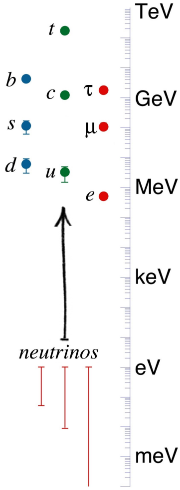


First ingredient for a good model: ν_R

Hierarchy problem:

Neutrino mass is small $m_\nu < 0.1\,\text{eV}$ (exp. limits)
Masses are normally $m_e \simeq 0.5\,\text{MeV}$ to $m_t \simeq 173\,\text{GeV}$

$\Rightarrow$ *small Yukawa masses seem to be unnatural*



Solution: **Seesaw mechanism**

Majorana neutrinos with right handed partners ν_R

flavour scale: $m_R \gtrsim \text{TeV}$, $m_D \sim m_e$

$$M_{maj} = \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix}$$

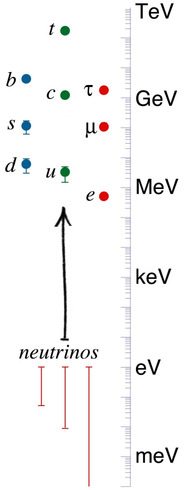
diagonalisation:
mass scale: $m_\nu = -m_D^2/m_R \quad \rightarrow \quad m_\nu$ small

First ingredient for a good model: ν_R

Hierarchy problem:

Neutrino mass is small $m_\nu < 0.1\,\text{eV}$ (exp. limits)
Masses are normally $m_e \simeq 0.5\,\text{MeV}$ to $m_t \simeq 173\,\text{GeV}$

$\Rightarrow$ *small Yukawa masses seem to be unnatural*



Solution: **Seesaw mechanism**

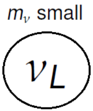
Majorana neutrinos with right handed partners ν_R

flavour scale: $m_R \gtrsim \text{TeV}$, $m_D \sim m_e$

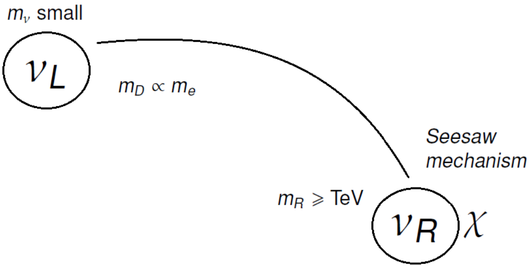
$$M_{maj} = \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix}$$

diagonalisation:
mass scale: $m_\nu = -m_D^2/m_R \quad \rightarrow \quad m_\nu$ small

The modell



The modell



m_ν small
ν_L
$m_D \propto m_e$
Seesaw mechanism
$m_R \geqslant$ TeV
ν_R
χ

Second ingredient for a good model

Problem:

Yukawa couplings $Y_\nu \simeq \frac{m_\nu}{v}$ small, when m_ν small ($v \sim 246\,\text{GeV}$, VEV)
Other gauge couplings large: e.g. Positron $e = \sqrt{4\pi\alpha} = 0.303$

$\Rightarrow$ *small Y_ν seem to be unnatural*

Second ingredient for a good model: Φ_k

Problem:

Yukawa couplings $Y_\nu \simeq \frac{m_\nu}{v}$ small, when m_ν small ($v \sim 246\,\mathrm{GeV}$, VEV)
Other gauge couplings large: e.g. Positron $e = \sqrt{4\pi\alpha} = 0.303$

$\Rightarrow$ *small Y_ν seem to be unnatural*

Solution: **multi-Higgs doublet model (mHdm)**

include n_H Higgs doublets

$$\Phi_k = \begin{pmatrix} \Phi_k^+ \\ \Phi_k^0 \end{pmatrix}, \quad \langle 0|\Phi_k^0|0\rangle = \frac{v_k}{\sqrt{2}}, \quad \sum_k |v_k|^2 \sim (246\,\mathrm{GeV})^2 \rightarrow \text{small } v_k \text{ so}$$

that $Y_\nu \sim \mathcal{O}(e)$.

lepton Yukawa couplings

$$\mathcal{L}_Y = -\sum_{k=1}^{n_H} \sum_{l,l'=e,\mu,\tau} \left[\left(\phi_k^-, \phi_k^{0*}\right) Y_{lkll'} \bar{l}_R + \left(\phi_k^0, -\phi_k^+\right) Y_{\nu kll'} \bar{\nu}_{lR} \right] \begin{pmatrix} \nu_{l'L} \\ l'_L \end{pmatrix} + \text{H.c.}$$

Second ingredient for a good model: Φ_k

Problem:

Yukawa couplings $Y_\nu \simeq \frac{m_\nu}{v}$ small, when m_ν small ($v \sim 246\,\text{GeV}$, VEV)
Other gauge couplings large: e.g. Positron $e = \sqrt{4\pi\alpha} = 0.303$

$\Rightarrow$ *small Y_ν seem to be unnatural*

Solution: **multi-Higgs doublet model (mHdm)**

include n_H Higgs doublets

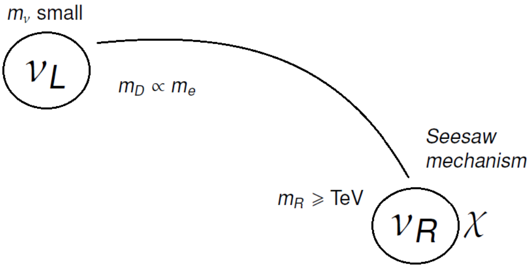
$\Phi_k = \begin{pmatrix} \Phi_k^+ \\ \Phi_k^0 \end{pmatrix}$, $\langle 0|\Phi_k^0|0\rangle = \frac{v_k}{\sqrt{2}}$, $\sum_k |v_k|^2 \sim (246\,\text{GeV})^2 \rightarrow$ small v_k so that $Y_\nu \sim \mathcal{O}(e)$.

interesting effect:
observable processes!

lepton Yukawa

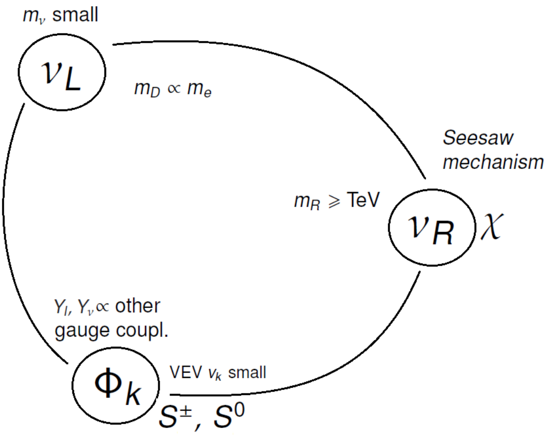
$$\mathcal{L}_Y = -\sum_{k=1}^{n_H} \sum_{l,l'=e,\mu,\tau} \left[\left(\phi_k^-, \phi_k^{0*}\right) Y_{lkll'} \bar{l}_R + \left(\phi_k^0, -\phi_k^+\right) Y_{\nu kll'} \bar{\nu}_{lR}\right] \begin{pmatrix} \nu_{l'L} \\ l'_L \end{pmatrix} + \text{H.c.}$$

The modell



m_ν small
ν_L
$m_D \propto m_e$
Seesaw mechanism
$m_R \geqslant$ TeV
ν_R
χ

The modell



experimentally testable processes

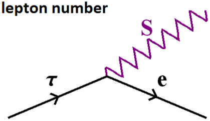
Third ingredient for a good model

mHdm Problem:

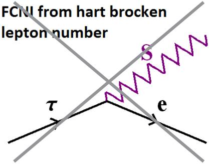
Flavour-changing neutral scalar interactions (FCNIs) at tree level appear.

$\Rightarrow$ *strong experimental bounds on FCNIs*

FCNI from hart brocken lepton number



Third ingredient for a good model: L_α



mHdm Problem:

Flavour-changing neutral scalar interactions (FCNIs) at tree level appear.

$\Rightarrow$ *strong experimental bounds on FCNIs*

Solution: **soft lepton number L_α violation** $\{\alpha = e, \mu, \tau\}$

L_α conservation:
in Yukawa interactions
$\Rightarrow$ diag. Y_l, Y_ν

$$M_l \sim \sum_k v_k^* Y_{lk}, \quad M_D \sim \sum_k v_k Y_{\nu k}$$

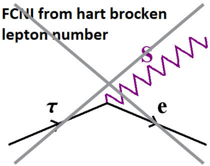
L_α explicit soft breaking:
in Majorana term $\Rightarrow$ **non-diag. $\mathbf{M}_R$**

Third ingredient for a good model: L_α

mHdm Problem:

Flavour-changing neutral scalar interactions (FCNIs) at tree level appear.

$\Rightarrow$ *strong experimental bounds on FCNIs*



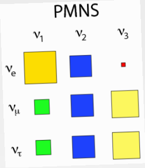
Solution: **soft lepton number L_α violation** $\{\alpha = e, \mu, \tau\}$

L_α conservation:
in Yukawa interactions
$\Rightarrow$ diag. Y_l, Y_ν $\Rightarrow$ **diag. $\mathbf{M}_l, \mathbf{M}_D$** $= diag(m_e, m_\mu, m_\tau)$

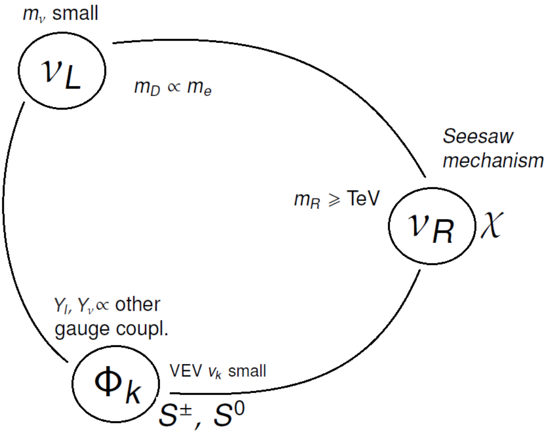
L_α explicit soft breaking:
in Majorana term $\Rightarrow$ **non-diag. $\mathbf{M}_R$**

additional advantages:

- explain atm. & sol. maxamal mixing [Grimus, 01]
- ampl. of FC processes are finite at one-loop
- ampl. are stable under radiative corrections

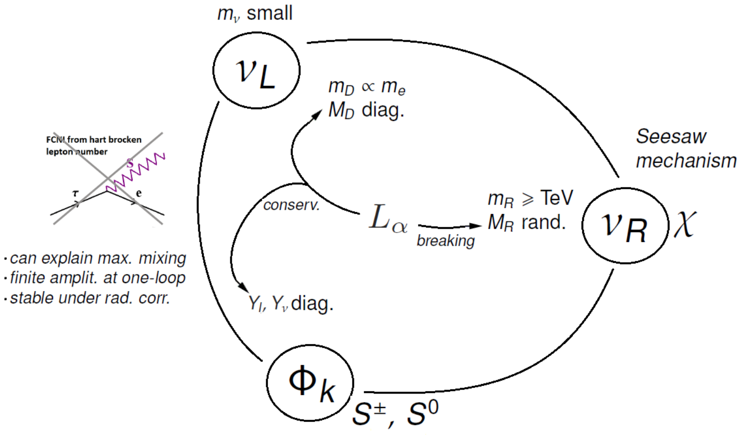


The model



<u>*experimentally testable processes*</u>

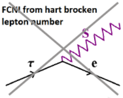
The model



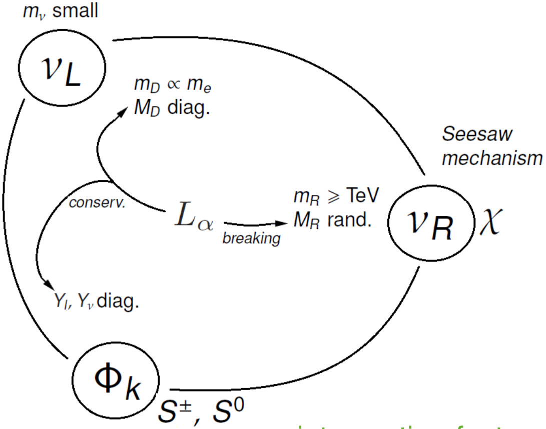
experimentally testable processes

The model

Nice model but: **Can it be tested? Does it bring Limits?**



- *can explain max. mixing*
- *finite amplit. at one-loop*
- *stable under rad. corr.*



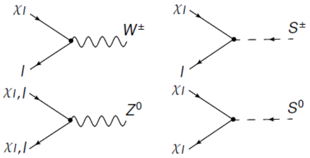
interessting feature

experimentally testable processes

The model

Evtl. experimentally testable processes:

Additional fermion interactions:



$$\mathcal{A}(\tau^- \to \mu^- \gamma) \propto 1/m_R^2,$$

$$\mathcal{A}(Z \to \tau^+ \mu^-) \propto 1/m_R^2,$$

$$\mathcal{A}(\tau^- \to \mu^- e^+ e^-) \propto \begin{cases} 1/m_R^2 & n_H = 1 \\ \text{const.} & n_H > 1 \end{cases}$$

Processes including the sub-process $l^- \to l'^- S^{0*}$, ($S^{0*} \to e^+ e^-$) have ($n_H \geq 2$) non-m_R-suppressed contributions from graphs with charged-scala exchange $S^\pm$ (plot) in their Amplitudes $\mathcal{A}$, [Grimus, Lavoura, 02].

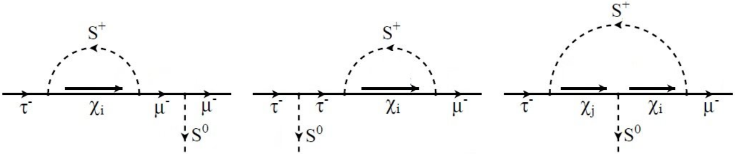
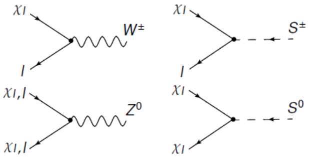


Figure: The tree diagrams for $\tau^- \to \mu^- S^{0*}$

The model

Evtl. experimentally testable processes:

Additional fermion interactions:



$$\begin{aligned} \mathcal{A}(\tau^- \to \mu^- \gamma) &\propto 1/m_R^2, \\ \mathcal{A}(Z \to \tau^+ \mu^-) &\propto 1/m_R^2, \\ \mathcal{A}(\tau^- \to \mu^- e^+ e^-) &\propto \begin{cases} 1/m_R^2 & n_H = 1 \\ \text{const.} & n_H > 1 \end{cases} \end{aligned}$$

Processes including the sub-process $l^- \to l'^- S^{0*}$, ($S^{0*} \to e^+ e^-$) have ($n_H \geq 2$) non-m_R-suppressed contributions from graphs with charged-scala exchange $S^\pm$ (plot) in their Amplitudes $\mathcal{A}$, [Grimus, Lavoura, 02].

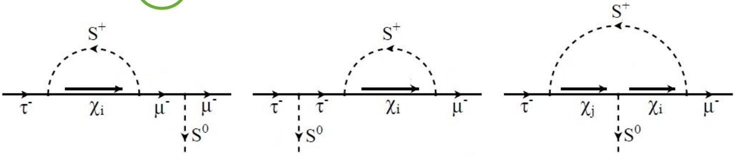


Figure: The tree diagrams for $\tau^- \to \mu^- S^{0*}$

Expected outcome and goals

Nice model but: **Can it be tested? Does it bring Limits?**

Expectations:

- Finding upper bounds on flavour diagonal Yukawa couplings (Y_l, Y_ν) at one loop (with $m_R \rightarrow \infty$)
- Finding lower benchmarks on seesaw scale m_R

  $\Rightarrow$ with comparing them to the experimental upper bounds on branching ratios.
- Pointing out experimental signatures.

Thank you!