Non-unitarity & Non-standard Interactions (NSIs)

- Part 1: Non-unitarity (theory) – S. A.
- Part 2: Non-unitarity (bounds) – Mattias Blennow
- Part 3: NSIs (theory) – Enrique Fernandez-Martinez
- Part 4: NSIs (bounds) – Toshihiko Ota

Mensis workshop, UA Madrid, '09
Overview

- Origin of Non-Unitarity; minimal scheme (MUV)
- Recent study: Non-unitarity of $U_{\text{PMNS}}$ and leptogenesis?
Neutrinos in the Standard Model

- Symmetries of the SM:
  \[ \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_{\gamma} \]
  \[ <H> = v_{\text{EW}} \]
  \[ \text{SU}(3)_C \times \text{U}(1)_{\text{em}} \]

- Masses of elementary particles via the Higgs mechanism (exception: neutrinos remain massless)

- With symmetries and field content of the SM:
  - neutrinos are massless
  - no mixing
  - couple only to Z and W (in standard way)
However: Evidence for $\nu$ masses!

- Strong evidence for $\nu$-oscillations:
  - Neutrinos have mass
  - leptonic mixing matrix
  - new $\nu$-interactions (mechanism of mass generation)
Origin of neutrino masses?

See-saw (type I) 
(or type III)

See-saw (type II)

Radiative mechanisms

Smallness of $m_v$: Seesaw mechanism?

quite model independent: unique dim. 5 Operator

$$\delta L^{d=5} = \frac{1}{2} c_{\alpha \beta} \left( \overline{L^c} \tilde{\Phi}^* \right) \left( \tilde{\phi}^\dagger L_\beta \right) + h.c.$$
Origin of neutrino masses?

Smallness of $m_\nu$: ... or because lepton number symmetry is violated only by small amount?

Example: so-called 'Inverse seesaw'

\[
M_\nu = \begin{pmatrix}
0 & D_N^T & 0 \\
D_N & 0 & X_N^T \\
0 & X_N & \mu
\end{pmatrix}
\]

Quite model independent: unique dim. 5 Operator

\[
\delta L^{d=5} = \frac{1}{2} c_{\alpha\beta} \left( L^c_\alpha \tilde{\phi}^* \right) \left( \tilde{\phi}^\dagger L_\beta \right) + h.c.
\]
Origin of neutrino masses?

See-saw (type I)

See-saw (type II)

... or something completely different

Radiative mechanisms

Dirac neutrinos

M_{\text{Vr}}

m_{\text{V}}

\text{D5}_1 \ (g_{\text{Vr}}: \text{very small coupling})

\text{D5}_2 \ (g_{\text{Vr}}: \mathcal{O}(1) \text{ coupling})

\text{string theory}

\delta \mathcal{L}^{d=5} = \frac{1}{2} c_{\alpha \beta}^{d=5} \left( \bar{L}^c_{\alpha} \tilde{\phi}^* \right) \left( \tilde{\phi}^\dagger L_{\beta} \right) + \text{h.c.}

\text{unknown:}
- which mechanism?
- at which scale?
- which new interactions (effects beyond } m_{\text{V}} \text{)?
Status: Neutrino masses & mixing

Known:
- (At least) two of the light neutrinos are massive
- Large mixing

Unknown:
- Which mechanism generates the neutrino masses? Dirac or Majorana?
- At which scale?
- Which additional interactions are generated (effects beyond $\nu$-masses)

Since new interactions in the lepton sector are required (to generate $\nu$-masses):

Is the (effective low energy) leptonic mixing matrix unitary?

$U U^+ = 1?$
Non-unitarity (theory)
Origin of Non-Unitarity in Extensions of the SM

Typical situation, intuitively:

(Effective) mixing matrix of light neutrinos is part of a larger unitary mixing matrix (mixing with additional heavy particles)

$\Rightarrow U_{PMNS}$ non-unitary

Examples with possible large non-unitarity: 'inverse' seesaw or 'multiple' seesaw at TeV energies, SUSY with R-parity violation, large extra dimensions, ...
Non-unitary leptonic mixing

Lagrangian in the mass basis ...

\[ \mathcal{L}^{\text{eff}} = \frac{1}{2} (\bar{\nu}_i i \partial \nu_i - \bar{\nu}_i^c m_i \nu_i + \text{h.c.}) - \frac{g}{2\sqrt{2}} (W_\mu^+ \bar{l}_\alpha \gamma_\mu (1 - \gamma_5) N_{\alpha i} \nu_i + \text{h.c.}) \]

\[ - \frac{g}{2 \cos \theta_W} (Z_\mu \bar{\nu}_i \gamma^\mu (1 - \gamma_5) (N^\dagger N)_{ij} \nu_j + \text{h.c.}) + \ldots \]

Modification in neutral current interaction:
will be justified later ...
... now we change to the flavour basis

Field transformation: \( \nu_\alpha = N_{\alpha i} \nu_i \)

Non-unitary leptonic mixing ↔ Non-canonical kinetic term
Non-unitary leptonic mixing

Gauge invariant non-canonical kinetic term in the SM: e.g.

\[ \delta \mathcal{L}^{d=6} = c^{d=6}_{\alpha \beta} \left( \bar{L}_\alpha \tilde{\phi} \right) i\bar{\phi} \left( \tilde{\phi}^\dagger L_\beta \right) \]

unique dim. 6 operator leading to non-can. kinetic terms for neutrinos only

conserves L!

Effects after EW symmetry breaking (in mass basis):

\[ \mathcal{L}^{\text{eff}} = \frac{1}{2} \left( \bar{\nu}_i \gamma_\mu \nu_i - \bar{\nu}^c \gamma_\mu m_i \nu_i + \text{h.c.} \right) - \frac{g}{2\sqrt{2}} \left( W^+_\mu \bar{l}_\alpha \gamma_\mu \left( 1 - \gamma_5 \right) N_{\alpha i} \nu_i + \text{h.c.} \right) \]

- \[ - \frac{g}{2 \cos \theta_W} \left( Z_\mu \bar{\nu}_i \gamma_\mu \left( 1 - \gamma_5 \right) (N^\dagger N)_{ij} \nu_j + \text{h.c.} \right) + \ldots \]

in addition: modification in neutral current interaction

S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)
Non-unitary leptonic mixing

Which neutrino mass mechanisms (or other SM extensions) lead to non-unitary leptonic mixing?
Non-unitarity and neutrino masses from heavy fermionic singlets

Consider the SM + 'heavy' singlet fermions $F^i$ as effective field theory:

- 'heavy' = large mass compared to the energies of the experiment
- effective theory: below the masses of the singlet fermions
Non-unitarity and *neutrino masses* from heavy fermionic singlets

Consider the SM + 'heavy' singlet fermions $F^i$ as effective field theory:

- 'heavy' = large mass compared to the energies of the experiment
- effective theory: below the masses of the singlet fermions

At dimension 5 operator level:

![Diagram](image) 

violates L!
Non-unitarity and neutrino masses from heavy fermionic singlets

Consider the SM + 'heavy' singlet fermions $F^i$ as effective field theory:

- 'heavy' = large mass compared to the energies of the experiment
- effective theory: below the masses of the singlet fermions

At dimension 5 operator level:

$$\delta L^{d=5} = \frac{1}{2} c_{\alpha \beta}^{d=5} \left( \overline{L^c} \alpha \tilde{\phi}^* \right) \left( \tilde{\phi}^\dagger L^\beta \right) + h.c.$$  

After EW symmetry breaking:

$$m_\nu \equiv -\frac{v^2}{2} c_{d=5}$$

Seesaw (type I)

Weinberg ('79)
Non-unitarity and neutrino masses from heavy fermionic singlets

Consider the SM + 'heavy' singlet fermions $F_i$ as effective field theory:

- 'heavy' = large mass compared to the energies of the experiment
- effective theory: below the masses of the singlet fermions

At dimension 6 operator level:

```
\begin{align*}
\phi_d & \rightarrow \ell^g_{Lc} \\
\ell^f_{Lb} & \rightarrow \phi_a \\
F_i & \rightarrow \rho_i \\
p^2 & \ll (M^\Sigma)_{ii} \\
\end{align*}
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conserves L!
Non-unitarity and neutrino masses from heavy fermionic singlets

Consider the SM + 'heavy' singlet fermions $F^i$ as effective field theory:
- 'heavy' = large mass compared to the energies of the experiment
- effective theory: below the masses of the singlet fermions

At dimension 6 operator level:

After EW symmetry breaking: Non-unitarity via non-canonical kin. terms for neutrinos!

De Gouvea, Giudice, Strumia, Tobe ('01)
Broncano, Gavela Jenkins ('02)

S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)

Stefan Antusch
MPI für Physik (Munich)
Effective theory extension of SM: Minimal unitarity violation (MUV)

\[ \mathcal{L}^{\text{eff}} = \mathcal{L}_S + \delta \mathcal{L}^{d=5} + \delta \mathcal{L}^{d=6} + \ldots \]

where

\[ \delta \mathcal{L}^{d=5} = \frac{1}{2} c_{\alpha\beta} \left( \overline{L}_\alpha \phi^* \right) \left( \phi^\dagger L_\beta \right) + \text{h.c.} \]

\[ \delta \mathcal{L}^{d=6} = c_{\alpha\beta} \left( \overline{L}_\alpha \phi \right) i\phi \left( \phi^\dagger L_\beta \right) \]

unique dim. 5 operator for neutrino masses violates L!

unique dim. 6 operator leading to non-can. kinetic terms for neutrinos only conserves L!

Minimal unitarity violation:
All non-standard effects governed by (non-unitary) leptonic mixing matrix N

Consistent framework: Can now be confronted with experiment ...

\[ \rightarrow \text{talk by M. Blennow} \]

Stefan Antusch
MPI für Physik (Munich)
Non-Unitarity and Leptogenesis
Non-Unitarity and Leptogenesis

How does non-unitarity $U_{PMNS}$ affect leptogenesis?

As we will see: In 'low scale seesaw models' non-unitarity can lead to a strong enhancement of the decay asymmetries for leptogenesis!

Can the non-unitarity of $U_{PMNS}$ drive (testable) low scale leptogenesis?
Motivation: The baryon asymmetry of the universe

How was the observed baryon asymmetry of the universe (BAU) generated?

Observation today: \( n_B/n_\gamma \approx 6 \cdot 10^{-10} \)
Leptogenesis: The mechanism

- Out-of-equilibrium decay of heavy fermionic singlets (RH neutrinos) in the early universe
  ⇒ lepton asymmetries $\Delta L_\alpha$

- Sphaleron processes (conserve B – L but violate B and L) within SM (MSSM) partly convert lepton asymmetries into baryon asymmetry $\Delta B$

Fukugita, Yanagida ('86)
Kuzmin, Rubakov, Shaposhnikov ('85)

SM + 'heavy' singlet fermions can explain neutrino masses and the baryon asymmetry!
How much baryon asymmetry is produced?

$$\text{BAU} \propto \sum_\alpha \eta_\alpha \varepsilon_{1,\alpha}$$

$\eta_\alpha$: efficiency factors (from Boltzmann eqs., can be $O(1)$)

$\varepsilon_{1,\alpha}$: decay asymmetries ($\nu_R^1$ into $L_\alpha + H$); interference of tree-level decay with loop-diagrams;
assumed here: $\nu_R^1$ dominates leptogenesis
Decay Asymmetries and Non-Unitarity (in effective theory)

\[ m_\nu = -\frac{v^2}{2} \epsilon^{d=5} \]

$V_{R1}$

\[ L_\alpha \to c_{d=5}^{\alpha\beta} \to \bar{L}_\beta \]

$\phi^*$

$\phi$

related to neutrino masses!

\[ |NN^\dagger - 1|_{\alpha\beta} = \frac{v^2}{2} |\epsilon^{d=6}|_{\alpha\beta} \]

$V_{R1}$

\[ L_\alpha \to c_{d=6}^{\alpha\beta} \to L_\beta \]

$\phi^*$

$\phi$

related to non-unitarity!

\[ \varepsilon_{1,\alpha} \approx \frac{1}{8\pi(YY^\dagger)_{11}} \sum_\beta \left\{ \text{Im} \left[ -\frac{3M'}{2} Y^\dagger_{1\alpha} c_{d=5}^{\alpha\beta} Y_{\beta1} + M'^2 Y^\dagger_{1\alpha} c_{d=6}^{\alpha\beta} Y_{\beta1} \right] \right\} \]

assumed: $v_{R1}$ dominates; $M' = M_{vR1} \ll M_{vR2}, M_{vR3}$

S.A., Blanchet, Blennow, Fernandez-Martinez ('09)
Explicit example: minimal scenario

'Lepton number' symmetry allowed (leading order)

Lepton numbers
$\text{L}_1: 1$, $\text{N}_1: 0$, $\text{N}_2: +1$, $\text{N}_3: -1$

\[
Y_N = \begin{pmatrix}
0 & 0 & 0 \\
y_e & y_\mu & y_\tau \\
0 & 0 & 0
\end{pmatrix}, \quad M^N = \begin{pmatrix}
M' & 0 & 0 \\
0 & 0 & M \\
0 & M & 0
\end{pmatrix}
\]

'Lepton number' breaking terms (L breaking small)

\[
Y_N = \begin{pmatrix}
\mu_e' & \mu_\mu' & \mu_\tau' \\
y_e & y_\mu & y_\tau \\
\mu_e & \mu_\mu & \mu_\tau
\end{pmatrix}, \quad M^N = \begin{pmatrix}
M' & \mu_4' & \mu_5' \\
\mu_4 & \mu_4 & M \\
\mu_5' & M & \mu_5
\end{pmatrix}
\]

Non-unitarity!

\[
c^d=6_{\alpha\beta} = \frac{y_\alpha^* y_\beta}{M^2}
\]

unsuppressed by symmetry

\[
c^d=5_{\alpha\beta} \leftrightarrow m_v
\]

suppressed by symmetry

Stefan Antusch
MPI für Physik (Munich)
Explicit example: minimal scenario

'Lepton number' symmetry allowed (leading order)

\[ Y_N = \begin{pmatrix} 0 & 0 & 0 \\ y_e & y_\mu & y_\tau \\ 0 & 0 & 0 \end{pmatrix}, \quad M^N = \begin{pmatrix} M' & 0 & 0 \\ 0 & 0 & M \\ 0 & M & 0 \end{pmatrix} \]

'Lepton number' breaking terms (L breaking small)

\[ Y_N = \begin{pmatrix} \mu_e' & \mu_\mu' & \mu_\tau' \\ y_e & y_\mu & y_\tau \\ \mu_e & \mu_\mu & \mu_\tau \end{pmatrix}, \quad M^N = \begin{pmatrix} M' & \mu_4' & \mu_5' \\ \mu_4' & \mu_4 & M \\ \mu_5' & M & \mu_5 \end{pmatrix} \]

The \( d=6 \) contribution (\( \rightarrow \) non-unitarity) dominates flavoured decay asymmetries \( \varepsilon_{1,\alpha} \). This is generic in 'low scale seesaw' with approximate lepton number!

The d=5 contribution (unsuppressed by symmetry) is implied by

\[ c^{d=5}_{\alpha\beta} \leftrightarrow m_{\nu} \]

S.A., Blanchet, Blennow, Fernandez-Martinez ('09)
Non-unitarity driven (testable) low scale leptogenesis?

... operating, e.g., at TeV energies?

- **Promising**: Decay asymmetries can be strongly enhanced!

- **Note**: Flavour effects (different efficiencies for different flavours are crucial, since \( \sum \varepsilon_{1,\alpha} \) from d=6 operator vanished exactly)

\[
\text{BAU} \propto \sum_{\alpha} \eta_{\alpha} \varepsilon_{1,\alpha}
\]

different factors for different lepton flavours
However, non-unitarity has another important effect ...

- The $d=6$ operator for non-unitarity can also mediate \textit{flavour equilibration in the thermal bath!} 

\begin{align*}
\tilde{\phi}_d & \quad \ell_{Lc}^g \\
\ell_{Lb}^f & \quad V_R^i \\
\tilde{\phi}_a & \quad \ell_{Lc}^g \\
\ell_{Lb}^f & \quad \tilde{\phi}_a \\
p^2 \ll (M^\Sigma)_{ii} & \equiv \rho_i
\end{align*}

- If \textit{flavour equilibrating processes} dominate over the \textit{flavour-dependent washout processes}, then the $d=6$ operator can \textbf{not} successfully drive leptogenesis!

For other sources of flavour equilibration, see also: Sierra, Losada, Nardi ('09)
In a minimal realisation of non-unitarity driven leptogenesis ...

... we find that TeV scale leptogenesis with observable non-unitarity is not possible (but, nevertheless, leptogenesis bound relaxed to $M' > 10^8$ GeV)

S.A., Blanchet, Blennow, Fernandez-Martinez (’09)
Non-unitarity

- Typical signal of new physics in the lepton sector
- Minimal Unitarity Violation (MUV): Consistent minimal scheme

Leptogenesis and Non-unitarity

- Non-unitarity effects (d=6 operator) can strongly enhance the flavoured decay asymmetries for leptogenesis. Enhancement generic in low scale seesaw models with approximately conserved 'lepton number' symmetry!
- Additional effect: Same d=6 operator can mediate flavour equilibrating processes in the thermal bath
- Open question: Is there a well motivated model which realises low scale (testable) 'non-unitarity driven leptogenesis'?

Next: Part 2 - Bounds on non-unitarity, by M. Blennow