Non-Standard Neutrino Interactions & Non-Unitarity

talk by Stefan Antusch

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

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The Standard Model

- Symmetries of the SM:
  \[ SU(3)_C \times SU(2)_L \times U(1)_Y \]
  \[ \langle H \rangle = v_{EW} \quad SU(3)_C \times U(1)_{em} \]

- Masses of particles by the Higgs mechanism
  - Higgs particle(s) not observed so far
    \[ \rightarrow \text{search @ LHC} \]

- With symmetries and field content of the SM:
  - neutrinos are massless
  - no mixing
  - couple only to Z and W
Evidence for neutrino masses

- Strong evidence for ν-oscillations:
  - Neutrinos have mass
  - leptonic mixing matrix
  - new ν-interactions (mechanism of mass generation)

![Image of supernova and neutrino oscillations](image-url)
Origin of neutrino masses?

See-saw (type I)

(or type III)

See-saw (type II)

Radiative mechanisms

Seesaw mechanism

quite model independent: unique dim. 5 Operator

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

P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, Magg, Wetterich, Ma, Foot, Lew, He, Joshi, ...
Origin of neutrino masses?

See-saw (type I)

See-saw (type II)

... or something completely different

Radiative mechanisms

Dirac neutrinos

Quite model independent: unique dim. 5 Operator

\[ \delta \mathcal{L}^{d=5} = \frac{1}{2} C_{\alpha \beta}^{d=5} \left( \overline{L^c_\alpha \tilde{\phi}^*} \right) \left( \tilde{\phi}^\dagger L^c_\beta \right) + h.c. \]
Typically: **New $\nu$-interactions will affect neutrino oscillations** ...

New interactions ... at the source
... during propagation in matter
... at the detector
Typically: **New ν-interactions will affect neutrino oscillations** ...

New interactions ... at the source

... during propagation in matter

... at the detector

NSI parameterisation:

$$\mathcal{L}_{\text{NSI}} = 2\sqrt{2} G_F \epsilon^{f}_{\alpha\beta} (\bar{\nu}_{\alpha L} \gamma^{\delta} \nu_{\beta L}) (\bar{f}_{L,R} \gamma^{\delta} \bar{f}_{L,R})$$

At present neutrino oscillation (and also @ non-oscillation) experiments: No clear signals of such new interactions yet ...

Y. Grossman ('95)
Future: Precision neutrino experiments

... aim mainly at measuring the remaining unknown parameters of the leptonic mixing matrix.

In the presence of New Physics:

- Confusion problem?
- Discovery chance?
two generic examples for New Physics effects on neutrino oscillations

- Non-unitarity of leptonic mixing matrix (and its relations to Non-Standard neutrino Interactions (NSIs))
- NSIs during propagation through matter: How large can they be in explicit gauge invariant SM extensions?

... many other interesting NP effects: neutrino decays, decoherence, light sterile neutrinos, CPT and/or Lorentz-invariance violation, non-locality, ...

(but no time to discuss them in this talk)
Non-Unitarity
of the Leptonic Mixing Matrix
**Neutrino Oscillations**

- Flavour conversion $\nu_\alpha \rightarrow \nu_\beta$ when neutrinos travel from source → detector
- Required:
  i) mixing between flavour & mass eigenstates
  ii) neutrino masses: $m_{\nu_i}^2 - m_{\nu_j}^2 \neq 0$
- In usual analyses of the neutrino data:
  Unitarity of the mixing matrix $U$ (i.e. $U U^* = 1$) is assumed!

**Oscillation probability (U unitary):**

$$P_{\alpha\beta} = 4 \sum_{i < j} U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j} \sin^2\Delta_{ij}$$

where

$$\Delta_{ij} = \frac{(m_i^2 - m_j^2)L}{4E}$$

Stefan Antusch
MPI für Physik (Munich)


**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)

  ⇒ \(U_{\text{MNS}}\) non-unitary

Examples with possible large non-unitarity: 'inverse' seesaw or 'multiple' seesaw at TeV energies, SUSY with R-parity violation, large extra dimensions, ...
**Origin of Non-Unitarity in Extensions of the SM**

- **Generic class of SM extensions** which generate Non-Unitarity: SM + heavy singlet fermions $N_i$

  By 'heavy', I mean:
  - large mass compared to the energies of a $\nu$-oscillation exp.

  'This is a *minimal* realisation of Non-Unitarity, in the sense that:
  - only introduce new physics in neutrino sector
  - only 3 light neutrinos

- @ high energies: still many possible models ...
  @ low energies: physics contained in only two effective operators!
Origin of Non-Unitarity in Extensions of the SM

- Effective theory viewpoint: integrate out SM gauge-singlet fields $N_i$:
  - **dim. 5 operator**: generates neutrino masses
  - **dim. 6 operator**: contributes to $\nu$ kinetic terms after EWSB; generates non-unitary leptonic mixing matrix after canonical normalisation

Seesaw (type I) violates L!

these are the lowest dimensional effective operators ... !

conserves L!
Effective theory extension of SM: Minimal unitarity violation (MUV)

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

where

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

unique dim. 5 operator for neutrino masses violates \( L! \)

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

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

Consistent effective theory with non-unitary leptonic mixing → can now be confronted with experiments ...
**Minimal unitarity violation (MUV)**

After EWSB, dim=6 operator generates non-canonical kinetic terms (only for neutrinos!):

\[ \mathcal{L}^{\text{eff}} = \frac{1}{2} \left( i \bar{\nu}_\alpha \, \mathcal{D} \,(NN^\dagger)_{\alpha\beta}^{-1} \nu_\beta \right. \left. - \bar{\nu}^c_\alpha \, [(N^{-1})^t m N^{-1}]_{\alpha\beta} \, \nu_\beta + \text{h.c.} \right) \]

\[ - \frac{g}{2\sqrt{2}} \left( W^+_{\mu} \, \bar{\ell}_\alpha \, \gamma^\mu \, (1 - \gamma_5) \, \nu_\alpha + \text{h.c.} \right) \]

\[ - \frac{g}{2 \cos \theta_W} \left( Z^\mu_{\mu} \, \bar{\nu}_\alpha \, \gamma^\mu \, (1 - \gamma_5) \, \nu_\alpha + \text{h.c.} \right) + \ldots , \]
**Minimal unitarity violation (MUV)**

- Canonically normalising the neutrino states and switching to the mass basis (by $\nu_\alpha = N_{\alpha i} \nu_i$) ...

\[
\mathcal{L}_{\text{eff}} = \frac{1}{2} (\bar{\nu}_i \partial \nu_i - \bar{\nu}_i m_i \nu_i + \text{h.c.}) - \frac{g}{2\sqrt{2}} (W^+_\mu l_\alpha \gamma_\mu (1 - \gamma_5) N_{\alpha i} \nu_i + \text{h.c.}) - \frac{g}{2 \cos \theta_W} (Z_\mu \bar{\nu}_i \gamma^\mu (1 - \gamma_5) (N^\dagger N)_{i i} \nu_j + \text{h.c.}) + \ldots
\]

In addition: modification in neutral current interaction
MUV and Non-Standard $\nu$ Interactions

In the MUV scheme, weak interactions are modified:

- $W^-$ interaction:
  \[ W^- \approx N_{\alpha i} \]

- $Z$ interaction:
  \[ Z \approx (N^+ N)_{ij} \]

Non-unitary leptonic matrix $N$
MUV and Non-Standard $\nu$ Interactions

In the MUV scheme, weak interactions are modified:

$$W^- \approx N_{\alpha i}$$

Consequence: NSIs at the source/detector and in matter

NSI parameterisation:

$$N \approx (1 + \varepsilon) \cdot U$$

$$\nu_\alpha^s \cong N_{\beta i}^* |\nu_i\rangle \approx (1 + \varepsilon^s)_{\alpha\beta} U^*_{\beta i} |\nu_i\rangle = (1 + \varepsilon^s)_{\alpha\beta} |\nu_{\beta}\rangle$$

Also: NSIs at detector and with matter related to $N$!

Rigorous treatment of $\nu$-oscillations with non-unitary $N$:
S. A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)
Minimal unitarity violation (MUV)

- Constraints on non-unitarity from:
  - W decays and invisible Z-decays
  - Universality tests
  - Rare decays of charged leptons, e.g.: $l_\alpha \rightarrow l_\beta \gamma$
  - ...

- Finally ... combined constraints (at 90% cl)

\[
|(NN^\dagger)_{\alpha\beta} - \delta_{\alpha\beta}| = \frac{v^2}{2} |c_{\alpha\beta}^{d=6,kin}| < \begin{pmatrix}
4.0 \cdot 10^{-3} & 1.2 \cdot 10^{-4} & 3.2 \cdot 10^{-3} \\
1.2 \cdot 10^{-4} & 1.6 \cdot 10^{-3} & 2.1 \cdot 10^{-3} \\
3.2 \cdot 10^{-3} & 2.1 \cdot 10^{-3} & 5.3 \cdot 10^{-3}
\end{pmatrix}
\]

~ bounds on the NSIs @ source/detector and on NSIs with matter

S.A., Baumann, Fernandez-Martinez (0807.1003)

S. A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)
Minimal unitarity violation (MUV)

- Effects on neutrino oscillations in vacuum (schematically, 2 family example)

\[ P_{\alpha\beta} = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) + 2 \text{Im}(\epsilon_{\alpha\beta}) \sin(2\theta) \sin \left( \frac{\Delta m^2 L}{2E} \right) + 4|\epsilon_{\alpha\beta}|^2 \]

- SM
- CP violating interference
- Zero dist. effect

Remark: Near detector very important for testing non-unitarity (& new neutrino interactions in general). Desirable: \(\tau\)-identification!

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MPI für Physik (Munich)
Which is the source of CP violation in $\nu$-oscillations?

- Within MUV: deviations from the standard picture of CP violation (MUV parameters within present bounds)

G. Altarelli, D. Meloni (0809.1041)

See also: Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda ('07), Goswami, Ota ('08)
Non-unitarity at a Neutrino Factory

S. A., Blennow, Fernandez-Martinez, Lopez-Pavon ('09)

NF excellent sensitivity to probe non-unitarity

- $\text{Re}(\epsilon_{\tau\mu}) \sim O(10^{-4})$ from matter effects in $\nu_{\mu}$-disapp., $|\epsilon_{\tau\mu}| \sim O(10^{-3})$ from ND

- $\epsilon_{\tau e}$ up to $O(10^{-3})$, dominated by near detector (ND)

- Far detector + ND combined: CP violation

$\nu$-Factory (IDS setup) + near Emulsion Cloud Chamber (ECC) $\tau$-detector (10 kton, 1 kton, 100 tons, no)

S. A., Blennow, Fernandez-Martinez, Lopez-Pavon ('09)

GLoBES, MonteCUBES

$\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}| \exp(i \phi_{\alpha\beta})$

Notation:
Measurement of non-unitarity?

S. A., Blennow, Fernandez-Martinez, Lopez-Pavon ('09)

NF could in fact really measure non-unitarity parameters and determine the source of CP violation! (No 'confusion problem'!)

- Factory (IDS setup) + near Emulsion Cloud Chamber (ECC) τ-detector (10 kton, 1 kton, 100 tons, no)

 Günter Blennow, Fernandez-Martinez, Lopez-Pavon ('09)

GLoBES, MonteCUBES

v-Factory (IDS setup) + near Emulsion Cloud Chamber (ECC) τ-detector (10 kton, 1 kton, 100 tons, no)

NF could in fact really measure non-unitarity parameters and determine the source of CP violation! (No 'confusion problem'!)
Can there be large NSIs in matter?

\[ \mathcal{L}_{\text{NSI}} = 2\sqrt{2} G_F \epsilon_{\alpha \beta}^f (\bar{\nu}_\alpha \gamma^\delta \nu_\beta)(\bar{f}_{L,R} \gamma^\delta f_{L,R}) \]
Non-Standard $\nu$ Interactions (NSIs)

... a parameterisation of BSM physics effects (local QFT, stable $\nu$'s, ...)

New physics effects on propagation through matter:

$$\mathcal{L}_{\text{NSI}} = 2\sqrt{2}G_F \varepsilon_{\alpha\beta} (\bar{\nu}_L \gamma^\delta \nu_{\beta L})(\bar{f}_{L,R} \gamma^\delta f_{L,R})$$

Large NSIs in matter? - Direct bounds

\[ \mathcal{L}_{\text{NSI}} = 2\sqrt{2} G_F \, \epsilon^f_{\alpha \beta} \, (\bar{\nu}_\alpha \gamma^\delta \nu_{\beta L}) (\bar{f}_{L,R} \gamma^\delta f_{L,R}) \]

'Direkt' bounds on NSIs with matter (example: with electrons)

\[
\begin{align*}
|\epsilon^{m}_{ee}| &< 0.7 & |\epsilon^{m}_{\mu\mu}| &< 0.1 & |\epsilon^{m}_{e\tau}| &< 0.5 \\
* & & |\epsilon^{m}_{\mu\tau}| &< 0.03 & |\epsilon^{m}_{\mu\mu}| &< 0.1 \\
* & * & & |\epsilon^{m}_{\tau\tau}| &< 7
\end{align*}
\]

Davidson, Pena-Garay, Rius, Santamaria ('03,'09), Barranco, Miranda, Moura, Valle ('05,'07), Biggio, Blennow, Fernandez-Martinez ('09)

Several 'direct' bounds very weak!
Sensitivities of Neutrino Factory to NSIs in matter

Plots from:
Kopp, Lindner, Ota ('07)

Early works:
Huber, Valle ('01),
Ota, Sato, Yamashita ('01),
Huber, Schwetz, Valle ('02), ...

✿ Sensitivities for $\varepsilon^{m}_{\alpha\beta}$ (NSIs) up to $O(10^{-2})$ ... $O(10^{-3})$
Large NSIs in matter? - Effects ...

Large O(1) NSIs with matter would have dramatic effects!

Can such large NSIs be realised in explicit models for BSM physics?

Examples from:
Kitazawa, Sugiyama, Yasuda (’06)

S.A., J. P. Baumann, E. Fernandez-Martinez (0807.1003)
M.B. Gavela, D. Hernandez, T. Ota, W. Winter (0809.3451)
Large NSIs in matter?

To address this question we are looking for:

- $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ – gauge invariant formulation of NSIs
- Explicit SM extensions (not effective theories)
'Strategy' to generate large NSIs

We search for gauge invariant extensions of the SM which lead to NSIs with matter and satisfy the following conditions:

- **no new 4cFI are generated** at the same level (already quite constrained!)
- NSIs with matter are generated at tree-level
- Higgs mechanism is responsible for EWSB
- **no cancellations** between diagrams with different messenger particles to avoid constraints

Systematic scan over SM extensions...

S.A., J. P. Baumann, E. Fernandez-Martinez (0807.1003)
At d=6 we found \textbf{two possibilities to satisfy our search criteria:}

\textbf{Possibility 1:} singly charged scalar fields $\rightarrow$ antisymmetric d=6 operator

\[ L_{\alpha}^c \rightarrow L_\beta^\gamma \rightarrow S_i \rightarrow L_\delta^c \]

\[ L_{\alpha}^c \rightarrow L_\gamma \rightarrow S_i \rightarrow L_\delta^c \]

\[ \mathcal{L}_{NSI}^{d=6,as} = c_{\alpha \beta \gamma \delta}^{d=6,as} (\bar{L}_\alpha^c \cdot L_\beta)(\bar{L}_\gamma \cdot L_\delta^c) \]

\[ \text{Bounds:} \]
\[ |\varepsilon_{\mu \mu}^{m,CL}| < 8.2 \cdot 10^{-4} \]
\[ |\varepsilon_{\tau \tau}^{m,CL}| < 8.4 \cdot 10^{-3} \]
\[ |\varepsilon_{\mu \tau}^{m,CL}| < 1.9 \cdot 10^{-3} \]

Remark: Also NSIs at the source and/or detector!

S.A., J. P. Baumann, E. Fernandez-Martinez (0807.1003)

A. Bilenky, A. Santamaria ('93),
F. Cuypers, S. Davidson ('93)
**Large NSIs? - dim=6 operators**

- **Possibility 2:** fermionic singlets → d=6 operator contribution to neutrino kinetic terms

\[
\mathcal{L}_{kin}^{d=6} = -c_{\alpha\beta}^{d=6,kin} (\bar{L}_\alpha \cdot H^\dagger) i\bar{\theta} (H \cdot L_\beta)
\]

after canonical normalisation: non-unitary leptonic mixing matrix

... has already been discussed earlier in my talk
Large NSIs? - dim=8 operators

At d=8, more possibilities to satisfy our research criteria because:

- one can add two Higgs fields $H$ to break the symmetry between $\nu_\alpha$ and $l_\alpha$ (which helps to avoid 4cFIs)
- Systematic treatment: **Three topologies** to generate gauge invariant $d=8$ operators with external fields $\bar{L}L \bar{f}f H H^*$ ...

![Diagrams](image-url)

(a) Topology 1  
(b) Topology 2  
(c) Topology 3

Large NSIs possible from $d=8$ operators?
At \( d=8 \) level we found **three classes of possibilities**:

**Class I:** \( 2 \times \) coupling of \( L \) and \( H \) to a fermionic singlet \( N \)

\[
\mathcal{L}_{NSI}^{d=8,I} = c_{\alpha\beta}^{d=8,f,I} \left( \vec{L}_\alpha \cdot H^\dagger \right) f^c \bar{f}^c \left( H \cdot L_\beta \right)
\]

Remark: also for \( L \) or quarks as external fields \( f \)

Note: At eff. operator level, this would allow for large NSIs with matter!
Large NSIs? - dim=8 operators

- Bounds from relation to $d=6$ operator which modifies neutrino kinetic terms

\[ v |Y_{\alpha i}/M_i| < v \sqrt{|c_{d=6,kin}^{\alpha\alpha}|} \]

\[ \equiv \rho_{ij}^{(f)} < 10 \, G_F \]

\[ |\varepsilon_{\alpha\beta}^{m,f}| < \begin{pmatrix} 1.4 \cdot 10^{-3} & 6.4 \cdot 10^{-4} & 1.1 \cdot 10^{-3} \\ 6.4 \cdot 10^{-4} & 5.8 \cdot 10^{-4} & 7.3 \cdot 10^{-4} \\ 1.1 \cdot 10^{-3} & 7.3 \cdot 10^{-4} & 1.9 \cdot 10^{-3} \end{pmatrix} \frac{\rho^{(f)}}{G_F} \]

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MPI für Physik (Munich)
**Large NSIs?**

- **Class II**: $2 \times$ antisymmetric coupling of $\bar{L} L$ to singly charged scalars $S$

  e.g.:

  \[
  \mathcal{L}^{d=8}_{NSI,II} = c^{d=8,f,II}_{\alpha\beta\gamma\delta} (\bar{L}^c_\alpha \cdot L_\beta) (\bar{L}_\gamma \cdot L^c_\delta) (H^\dagger H)
  \]

  Remark: after EWSB

  \[
  \frac{v^2}{2} \left( \bar{L}^c_\alpha i \sigma_2 L_\beta \right) \left( \bar{L}_\gamma i \sigma_2 L^c_\delta \right)
  \]

  (same bounds as for anti-symmetric $d=6$ op.)

Stefan Antusch
MPI für Physik (Munich)
Large NSIs?

Class III: mixed case: L and H to N and $\bar{L} L$ to singly charged scalars S

Bounds from $d=6$ (kin):
\[ v \left| \frac{Y_{\alpha i}}{M_i} \right| < v \sqrt{c_{\alpha\alpha}^{d=6,\text{kin}}} \]
and $d=6$ (anti-symm):
\[ v \left| \frac{\lambda_{\epsilon\mu}^i}{m_{S_i}} \right| < 2.9 \cdot 10^{-2} \]
\[ v \left| \frac{\lambda_{\epsilon\tau}^i}{m_{S_i}} \right| < 9.2 \cdot 10^{-2} \]

S.A., J. P. Baumann, E. Fernandez-Martinez (0807.1003)

Remark: only for leptons; bounds again $\varepsilon^{m}_{\alpha\beta} < 10^{-2}$

Remark: Operators of type I, II and III form a basis for $d=8$ operators which select neutrinos and avoid tree-level 4cFIs

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MPI für Physik (Munich)
Large NSIs? - Results

- In explicit SM extensions (and under the assumptions we have made)

→ NSIs with matter are much more constrained than in many phenomenological studies ($\varepsilon_{\alpha\beta}^m < 10^{-2}$)!

→ In addition to NSIs with matter, NSIs at the source and detector are generated as well.
Summary and Conclusions

- **Non-unitarity of leptonic mixing matrix**: typical signal of 'new physics' in the lepton sector. In 'MUV': \((NN^+ - 1)_{\alpha\beta} \sim \varepsilon_{s,d,m}^{\alpha\beta} < 10^{-2} \ldots 10^{-3}\)

- **Non-standard neutrino interactions**: parameterisation of new physics effects; in gauge invariant SM extensions \(\varepsilon_{\alpha\beta}^m < O(10^{-2}), \varepsilon_{\tau\tau}^m < 0.2\)

... compared to expected sensitivities of a possible future neutrino factory of up to \(\varepsilon_{\alpha\beta} \sim 10^{-2} \ldots 10^{-3} \ldots 10^{-4}\) (or better?)

![Diagram](image.png)