Non-standard neutrino interactions
future bounds and models

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J. Kopp, TO, and W. Winter
to be published PRD [arXiv:0804.2261]

and

M. B. Gavela, D. Hernandez, TO and W. Winter
[arXiv:0809.****]
Within the current precision — Leading Order (LO)

Oscillation probabilities for $\nu_\mu \rightarrow \nu_\alpha$  

$$P_{\nu_\mu \rightarrow \nu_e} + P_{\nu_\mu \rightarrow \nu_\mu} + P_{\nu_\mu \rightarrow \nu_\tau} = 1 \quad \text{(unitarity)}$$

Future experiments are sensitive to the Next LO $P_{\nu_\mu \rightarrow \nu_e} = 0$ Leading Order $+ \mathcal{O}(s_{13}^2)$

Mass-Texture, LFV Prediction... $+ \mathcal{O}(s_{13}^2 \frac{\Delta m_{31}^2}{\Delta m_{21}^2})$ CP violation (Leptogenesis)...

Direct evidence of New Physics

T. Ota (Uni Würzburg)  NSI: future bounds and models
Within the current precision — Leading Order (LO)

Oscillation probabilities for $\nu_\mu \rightarrow \nu_\alpha$ (@atmospheric region $\Delta m^2_{31} L/E \sim 1$)

\[
\begin{align*}
P_{\nu_\mu \rightarrow \nu_e} + P_{\nu_\mu \rightarrow \nu_\mu} + P_{\nu_\mu \rightarrow \nu_\tau} & = 1 \\ 0 + 1 - P_{\nu_\mu \rightarrow \nu_\mu} & = 1 \quad \text{(unitarity)}
\end{align*}
\]

Future experiments are sensitive to the Next LO

\[
P_{\nu_\mu \rightarrow \nu_e} = 0 \quad \text{Leading Order}
\]
Preface

Within the current precision — Leading Order (LO)

Oscillation probabilities for $\nu_\mu \rightarrow \nu_\alpha$  

\[
P_{\nu_\mu \rightarrow \nu_e} + P_{\nu_\mu \rightarrow \nu_\mu} + \frac{P_{\nu_\mu \rightarrow \nu_\tau}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} = 1 \quad \text{(unitarity)}
\]

Future experiments are sensitive to the Next LO

\[
P_{\nu_\mu \rightarrow \nu_e} = 0 \quad \text{Leading Order}
\]

\[
+ O(s_{13}^2) \quad \text{Mass-Texture, LFV Prediction...}
\]

\[
+ O(s_{13} \Delta m_{21}^2 / \Delta m_{31}^2) \quad \text{CP violation (Leptogenesis)...}
\]
Preface

Within the current precision — Leading Order (LO)

Oscillation probabilities for $\nu_\mu \rightarrow \nu_\alpha$ (@atmospheric region $\Delta m^2_{31} L/E \sim 1$)

$$P_{\nu_\mu \rightarrow \nu_e} + P_{\nu_\mu \rightarrow \nu_\mu} + P_{\nu_\mu \rightarrow \nu_\tau} = 1 \quad \text{(unitarity)}$$

Future experiments are sensitive to the Next LO

$$P_{\nu_\mu \rightarrow \nu_e} = 0 \quad \text{Leading Order}$$

$$+ \mathcal{O}(s_{13}^2) \quad \text{Mass-Texture, LFV Prediction...}$$

$$+ \mathcal{O}(s_{13} \Delta m^2_{21} / \Delta m^2_{31}) \quad \text{CP violation (Leptogenesis)...}$$

$$+ \text{Direct evidence of New Physics}$$

T. Ota (Uni Würzburg) NSI: future bounds and models
Outline

1. Introduction: NSI in oscillation experiments
2. Current bounds and sensitivity in future experiments
3. For building models with NSI
   - Dimension six op. — four-Fermi
   - Dimension eight op. — four-Fermi + two Higgs
     - Toy model
4. Summary
Outline

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4. Summary
Introduction — NSIs

- **NSI** — Non-standard (could-be flavour-violating) interactions with neutrinos parametrized as 4-Fermi ints.

<table>
<thead>
<tr>
<th>Standard oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\nu_\alpha \rightarrow \nu_\beta} = \left</td>
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<tr>
<td>$H = \frac{1}{2E} \left{ U \begin{pmatrix} 0 &amp; \Delta m^2_{21} \ \Delta m^2_{31} &amp; \end{pmatrix} U^\dagger + \begin{pmatrix} a_{CC} &amp; 0 \ 0 &amp; 0 \end{pmatrix} \right}.$</td>
</tr>
</tbody>
</table>
Introduction — NSIs

- NSI — Non-standard (could-be flavour-violating) interactions with neutrinos parametrized as 4-Fermi ints.

**Standard oscillation**

\[ P_{\nu_\alpha \rightarrow \nu_\beta} = \left| \langle \nu_\beta | e^{-iHL} | \nu_\alpha \rangle \right|^2, \]

\[ H = \frac{1}{2E} \left\{ U \begin{pmatrix} 0 & \Delta m_{21}^2 \\ \Delta m_{31}^2 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} a_{CC} & 0 \\ 0 & 0 \end{pmatrix} \right\}. \]

**NSIs**

\[ \mathcal{L}_{CC} = 2\sqrt{2}G_F \tilde{\epsilon}_{\alpha\beta}^{CC} (\bar{\nu}_\alpha \gamma^\rho P_L \ell_\beta)(\bar{f}' \gamma^\rho P_L/R f) \]

\[ \mathcal{L}_{NC} = 2\sqrt{2}G_F \tilde{\epsilon}_{\alpha\beta}^{NC} (\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta)(\bar{f} \gamma^\rho P_L/R f) \]
Introduction — NSIs

- NSI — Non-standard (could-be flavour-violating) interactions with neutrinos parametrized as 4-Fermi ints.

Oscillation with NSIs

\[ P_{\nu_\alpha \rightarrow \nu_\beta} = \left| \langle \nu_\beta \rangle e^{-i(H + V_{NSI})L} \langle \nu_\alpha \rangle \right|^2 \]

- **CC type NSI** — flavour mixture states at source and detector
  
  \[ |\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon_{\alpha\gamma}^s |\nu_\gamma\rangle, \quad \text{e.g., } \pi^+ \xrightarrow{\epsilon_{\mu e}^s} \mu^+ \nu_e \]

  \[ \langle \nu_\alpha^d \rangle = \langle \nu_\alpha \rangle + \sum_{\gamma=e,\mu,\tau} \epsilon_{\gamma\alpha}^d \langle \nu_\gamma \rangle, \quad \text{e.g., } \nu_\tau N \xrightarrow{\epsilon_{\tau e}^d} e^- X \]

- **NC type NSI** — extra matter effect in propagation


\[ (V_{NSI})_{\beta\alpha} = \sqrt{2} G_F N_e \epsilon_{\beta\alpha}^m \]
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Current bounds

**From non-oscillation experiments**
Yasuda talk at NuFact08, Davidson Peña-Garay Rius Santamaria JHEP **03** 011, Barranco Miranda Moura Valle Phys. Rev. **D77** 093014.

\[
\begin{pmatrix}
-4 < \epsilon_{ee}^m < 2.6 \\
|\epsilon_{e\mu}^m| < 1.4 \cdot 10^{-4} \\
-0.05 < \epsilon_{\mu\mu}^m < 0.08 \\
|\epsilon_{e\tau}^m| < 1.9 \\
|\epsilon_{\mu\tau}^m| < 0.25 \\
|\epsilon_{\tau\tau}^m| < 19 \\
\end{pmatrix}, \quad (90\%\text{CL}).
\]

**From atmospheric neutrinos**
Gonzalez-Garcia Maltoni Phys. Rept. **460** 1.

\[
|\epsilon_{\mu\tau}^m| < 0.038, \quad |\epsilon_{\mu\mu}^m - \epsilon_{\tau\tau}^m| < 0.12, \quad (90\%\text{CL}).
\]

- Bounds from non-osc. to tau-associated NSI are not strict.
  — Oscillation experiments can play an important role!
(Part of) References on sensitivities

**MINOS**

**OPERA**

**Atmospheric**

**Atmospheric+K2K**
Friedland Lunardini Phys Rev D72 053009.

**T2K+D-Chooz**

**T2KK**

**Solar**

**Advanced superbeam experiments, Beta beam, NuFact ...**
Ribeiro Minakata Nunokawa Uchinami Zukanovich-Funchal, JHEP 12 002...
Optimization for NSIs — Two-golden-detector setup

NuFACT


- Sensitivity to $\epsilon^{m}_{\tau}$ and $\epsilon^{m}_{\mu \tau}$

\[ |\epsilon^{m}_{\tau}| \text{ sensitivity (3}\sigma) \]

$E_\mu = 25 \text{ GeV}$

GLoBES 2008

- $L \sim 4000 \text{ km} + 7500 \text{ km}$ is good also for the NSI.

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Optimization for NSIs

Current bounds and sensitivity in future experiments

Sensitivity reach of Two-Golden det. setup

\[
|\epsilon_{e\tau}^m| > 4.7 \cdot 10^{-3}, \\
|\epsilon_{\mu\tau}^m| > 1.8 \cdot 10^{-2}, \\
|\epsilon_{\tau\tau}^m| > 1.9 \cdot 10^{-2},
\]

(90% CL).

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Bottom-up to Models

We concentrate on pure lepton processes

**Bottom: Effective interaction**

— but with lepton doublet $L$

$$\nu_\alpha \quad G_F \epsilon_{\beta\alpha}^m \quad \nu_\beta$$

\[ \ell \quad \ell \]
Bottom-up to Models
We concentrate on pure lepton processes

Bottom: Effective interaction

— but with lepton doublet $L$

$$L_{\alpha} \rightarrow G_F \epsilon_{\beta\alpha}^m L_{\beta}$$
Bottom-up to Models
We concentrate on pure lepton processes

Bottom: Effective interaction
— but with lepton doublet $L$

![Diagram showing effective interactions involving $L$, $\ell$, $\nu$, and $G_F \epsilon_{\beta\alpha}^m$.]

— NSIs accompanied with charged lepton processes
Bottom-up to Models

We concentrate on pure lepton processes

**Bottom: Effective interaction**

— but with lepton doublet \( L \)

\[
L_\alpha \quad G_F \epsilon_{\beta \alpha}^m \quad L_\beta
\]

\( \ell \quad \ell \)

\[
\{ \nu_\alpha \quad G_F \epsilon_{\beta \alpha}^m \quad \nu_\beta \}, \quad \ell_\alpha \quad G_F \epsilon_{\beta \alpha}^m \quad \ell_\beta
\]

— NSIs accompanied with charged lepton processes

**One step up from the bottom:**

Decompose effective int. into fundamental ones, e.g. \( \bar{LL}EE \)

\[
L_\alpha \quad L_\beta \\
e_R \quad e_R
\]

\[
L_\alpha \quad L_\beta \\
e_R \quad e_R
\]

\[
L_\alpha \quad L_\beta \\
e_R \quad e_R
\]

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NSI: future bounds and models
Bottom-up to Models
We concentrate on pure lepton processes

**Bottom: Effective interaction**

— but with lepton doublet $L$

\[ L_\alpha \quad \quad G_F \epsilon_{\beta \alpha} \quad \quad L_\beta \quad \quad \ell \quad \quad \ell \]

\[ \nu_\alpha \quad \quad G_F \epsilon_{\beta \alpha} \quad \quad \nu_\beta \quad \quad \ell \quad \quad \ell \]

\[ \ell_\alpha \quad \quad G_F \epsilon_{\beta \alpha} \quad \quad \ell_\beta \quad \quad \ell \quad \quad \ell \]

— NSIs accompanied with charged lepton processes

**One step up from the bottom:**

Decompose effective int. into fundamental ones, e.g. $\bar{L}L\bar{E}E$

\[ L_\alpha \quad \quad L_\beta \quad \quad 1^\nu_0 \quad \quad e_R \quad \quad e_R \]

\[ L_\alpha \quad \quad L_\beta \quad \quad e_R \quad \quad e_R \]

\[ L_\alpha \quad \quad L_\beta \quad \quad e_R \quad \quad e_R \]

T. Ota (Uni Würzburg)
Bottom-up to Models
We concentrate on pure lepton processes

Bottom: Effective interaction
— but with lepton doublet $L$

\[ L_\alpha \quad G_F \epsilon_{\beta\alpha}^m \quad L_\beta \quad \in \left\{ \nu_\alpha \quad G_F \epsilon_{\beta\alpha}^m \quad \nu_\beta \quad , \quad \ell_\alpha \quad G_F \epsilon_{\beta\alpha}^m \quad \ell_\beta \right\} \]

— NSIs accompanied with charged lepton processes

One step up from the bottom:
Decompose effective int. into fundamental ones, e.g. $\bar{L}L\bar{E}E$

T. Ota (Uni Würzburg)
NSI: future bounds and models
Bottom-up to Models
We concentrate on pure lepton processes

Bottom: Effective interaction
— but with lepton doublet \( L \)

\[
\begin{align*}
\ell_{\alpha} & \quad \quad G_F \epsilon_{\beta\alpha}^m \quad L_{\beta} \\
\ell & \quad \quad \ell \\
\end{align*}
\]

\[
\begin{align*}
\nu_{\alpha} & \quad \quad G_F \epsilon_{\beta\alpha}^m \quad \nu_{\beta} \\
\ell & \quad \quad \ell \\
\end{align*}
\]

— NSIs accompanied with charged lepton processes

One step up from the bottom:
Decompose effective int. into fundamental ones, e.g. \( \bar{L}L\bar{E}E \)
Two effective ops, Buchmüller Weyler NPB268 621

\[ \mathcal{L}_{\text{eff}} = \frac{(C_{LL}^1)_{\alpha\gamma}^\beta}{\Lambda^2} (\bar{L}^\beta \gamma^\rho L_\alpha) (\bar{L}^\delta \gamma_\rho L_\gamma) + \frac{(C_{LL}^3)_{\alpha\gamma}^\beta}{\Lambda^2} (\bar{L}^\beta \gamma^\rho \tau L_\alpha) (\bar{L}^\delta \gamma_\rho \tau L_\gamma) \]
Two effective ops, Buchmüller Weyler NPB268 621

\[
\mathcal{L}_{\text{eff}} = \frac{(C_{1LL})^{\alpha\gamma}_{\beta\delta}}{\Lambda^2} (\bar{L}^\beta \gamma^\rho L_\alpha)(\bar{L}^\delta \gamma_\rho L_\gamma) + \frac{(C_{3LL})^{\alpha\gamma}_{\beta\delta}}{\Lambda^2} (\bar{L}^\beta \gamma^\rho \bar{\tau} L_\alpha)(\bar{L}^\delta \gamma_\rho \bar{\tau} L_\gamma)
\]

\[
= \frac{(C_{\text{NSI}})^{\alpha e}_{\beta e}}{\Lambda^2} (\bar{\nu}_\beta \gamma^\rho P_L \nu_\alpha)(\bar{e}\gamma_\rho P_L e) + \frac{(C_{1LL} + C_{3LL})^{\alpha e}_{\beta e}}{\Lambda^2} (\bar{\ell}_\beta \gamma^\rho P_L \ell_\alpha)(\bar{e}\gamma_\rho P_L e)
\]

\[
+ \ldots \quad \text{NSI}
\]

- We can avoid CLI at the effective-op level, taking

\[
C_{1LL}^1 + C_{3LL}^3 = 0.
\]
Two effective ops, Buchmüller Weyler NPB268 621

\[ L_{\text{eff}} = \left( \frac{C_{LL}^1}{\Lambda^2} \right)_{\alpha\gamma}^{\alpha\gamma} \left( \bar{L}^\beta \gamma^\rho L_\alpha \right) \left( \bar{L}^\delta \gamma_\rho L_\gamma \right) + \left( \frac{C_{LL}^3}{\Lambda^2} \right)_{\beta\delta}^{\alpha\gamma} \left( \bar{L}^\beta \gamma^\rho \bar{\tau} L_\alpha \right) \left( \bar{L}^\delta \gamma_\rho \bar{\tau} L_\gamma \right) \]

\[ = \left( \frac{C_{NSI}}{\Lambda^2} \right)_{\beta e}^{\alpha e} \left( \bar{\nu}_\beta \gamma^\rho P_L \nu_\alpha \right) \left( \bar{e} \gamma_\rho P_L e \right) + \left( \frac{C_{LL}^1 + C_{LL}^3}{\Lambda^2} \right)_{\beta e}^{\alpha e} \left( \bar{\ell}_\beta \gamma^\rho P_L \ell_\alpha \right) \left( \bar{e} \gamma_\rho P_L e \right) \]

NSI

- We can avoid CLI at the effective-op level, taking \( C_{LL}^1 + C_{LL}^3 = 0 \).

- But, with mediators, NSI are still constrained.


Let me explain this at the following two slides...
For building models with NSI

Dimension six op. — four-Fermi

\[ L_\alpha \rightarrow L_\beta \]

\[ L_\gamma \rightarrow f^{1/3V} \]

\[ 1/3^0 \]

\[ L_\gamma \rightarrow \frac{c^{1/3s}}{\Lambda^2} \]

\[ L_\alpha \rightarrow L_\beta \]

\[ 1/3^{s-1} \]

\[ L_\gamma \rightarrow L_\delta \]

\[ 1/3^0 \] does not induce CLI.

---

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NSI: future bounds and models
For building models with NSI

In effective op basis

\[ C_{LL}^1 = f^1 v + \frac{1}{4} c^1 s - \frac{3}{4} c^3 s \]

\[ C_{LL}^3 = f^3 v - \frac{1}{4} c^1 s - \frac{1}{4} c^3 s \]
For building models with NSI
Dimension six op. — four-Fermi

In effective op basis
\[ C^1_{LL} = f^1 v + \frac{1}{4} c^{1s} - \frac{3}{4} c^{3s} \]
\[ C^3_{LL} = f^3 v - \frac{1}{4} c^{1s} - \frac{1}{4} c^{3s} \]

No CLI condition
\[ C^1_{LL} + C^3_{LL} = 0 \]
\[ f^1 v + f^3 v - c^{3s} = 0 \]

\[ \frac{1}{3} \] does not induce CLI.
— The others need plural numbers of mediators to cancel CLI.

It seems to be free from the bounds but...
e.g., $\epsilon^m_{\mu\tau}$ from $\bar{L}^\tau L_e \bar{L}^e L_\mu$ with $1^s_{-1}$


1. At the effective op. level, they are independent
For building models with NSI
Dimension six op. — four-Fermi

1. With the mediator, they are related with each other.

\[ \epsilon_{m \mu \tau} \] is constrained from \( G_F \) measurement...

---

e.g., \( \epsilon_{m \mu \tau} \) from \( L^\tau L_e L^e L_\mu \) with \( 1_{-1}^s \)

1. With the mediator, they are related with each other.

\[ \epsilon_{m_{\mu\tau}} \] from \( \bar{L}^\tau L^e \bar{L}^e L^\mu \) with \( 1^s_{-1} \)

\[ \epsilon_{m_{\mu\tau}} \] is constrained from \( GF \) measurement...

2. ... and we also have a loop diagram for \( \tau \rightarrow \mu \gamma \),

\[ \nu_e \]

\[ \gamma \]
For building models with NSI

Dimension six op. — four-Fermi

1. With the mediator, they are related with each other.

\[ \epsilon_{\mu\tau}^m \text{ from } \bar{L}^\tau L_e \bar{L}^e L \mu \text{ with } 1_{-1}^s \]

\[ \text{Bergmann Grossman Pierce PRD61 053005, Antusch Baumann Fernández-Martinez arXiv0807.1003.} \]

2. ... and we also have a loop diagram for \( \tau \to \mu \gamma \),

Although \( \bar{L}^\tau L_e \bar{L}^e L \mu \) with \( 1_{-1}^s \) is CLI-free at the effective-op level, it is constrained when we take into account mediators.
Beyond the four-fermion (dimension six) effective ops...
Beyond the four-fermion (dimension six) effective ops...

NSI from dimension eight operators with Higgs doublets.
Berezhiani Rossi PLB535 207, Davidson Peña-Garay Rius Santamaria JHEP03 011
Dimension eight operators

**Dim.8: 4-Fermi+2 Higgs**

**Dim.6**

\[ \nu_\alpha \quad 1/\Lambda^2 \quad \nu_\beta \]

\[ \ell \quad \ell \]

**Dim.8**

\[ \left\langle H^0 \right\rangle \] \[ \left\langle H^0 \right\rangle^2 / \Lambda^4 \]

\[ \nu_\alpha \quad \nu_\beta \]

\[ \ell \quad \ell \]

Many effective ops.
— Many possibilities to cancel CLI and avoid bounds

Berezhiani Rossi, PLB535 207, Davidson Peña-Garay Rius Santamaria JHEP03 011.

- We apply the bottom-up approach to dim.8 ops. like dim.6,
  — i.e., decompose dim.8 ops.
- More than 100 possible decompositions, but they can be
categorized into the small numbers of categories...

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Dim.8 NSI induced by one diagram is always constrained!

Dim.8 NSI induced by one diagram is always constrained!

One diagram — is not the simplest.

Simplicity in a fundamental theory is the number of new fields = mediators
— the number of diagrams is determined by the particle contents.

Let me show an example of models for NSI with 2 mediators...
**Basis operators**
Buchmüller Weyler NPB268 621, Berezhiani Rossi, PLB535 207.

\[ L_{\text{dim}6}^{\text{eff}} = \frac{(C_{LE})^\alpha_\beta}{\Lambda^2} (\bar{L}^{\beta} e_R)(\bar{e}_R L^{\alpha}_i) \]  
only one possibility in dim6  
— NSI always with CLI

\[ L_{\text{dim}8}^{\text{eff}} = \frac{(C_{LEH})^\alpha_\beta}{\Lambda^4} (\bar{L}^{\beta} \gamma^\rho L^{\alpha}_i)(\bar{e}_R \gamma^\rho e_R)(H^\dagger H) \]

\[ + \frac{(C_{LEH}^3)^\alpha_\beta}{\Lambda^4} (\bar{L}^{\beta} \gamma^\rho \bar{\tau} L^{\alpha}_i)(\bar{e}_R \gamma^\rho e_R)(H^\dagger \bar{\tau} H) \]

All diagrams with \( \bar{L} L \bar{e}_R e_R (H^\dagger H) \) have to be reduced to these effective ops.

**What we want is...**
Berezhiani Rossi, PLB535 207, Davidson Peña-Garay Rius Santamaria JHEP03 011.

\[ O_{\text{NSI}} = \left\{ (\bar{L}^i H_i) \gamma^\rho (H^{\dagger i} L_i) \right\} (\bar{e}_R \gamma^\rho e_R), \quad \text{where} \ H_i = (H^0 \ H^-)^T \]
**Basis operators**

Buchmüller Weyler NPB268 621, Berezhiani Rossi, PLB535 207.

\[
\mathcal{L}_{\text{eff}}^{\text{dim}6} = \frac{(C_{LE})_{\beta}^{\alpha}}{\Lambda^2} (\bar{L}^i e_R)(\bar{e}_R L_{\alpha i})
\]

only one possibility in dim6 — NSI always with CLI

\[
\mathcal{L}_{\text{eff}}^{\text{dim}8} = \frac{(C_{LEH})_{\beta}^{\alpha}}{\Lambda^4} (\bar{L}^\gamma \gamma^\rho L_{\alpha})(\bar{e}_R \gamma_\rho e_R)(H^\dagger H)
\]

\[
+ \frac{(C_{LEH})_{\beta}^{\alpha}}{\Lambda^4} (\bar{L}^\gamma \gamma^\rho \tau L_{\alpha})(\bar{e}_R \gamma_\rho e_R)(H^\dagger \tau H)
\]

All diagrams with \(\bar{L}L e_R e_R (H^\dagger H)\) have to be reduced to these effective ops.

**What we want is...**

Berezhiani Rossi, PLB535 207, Davidson Peña-Garay Rius Santamaria JHEP03 011.

\[
\mathcal{O}_{\text{NSI}} = \frac{1}{2} (\bar{L}^\beta \gamma^\rho L_{\alpha})(\bar{e}_R \gamma_\rho e_R)(H^\dagger H) + \frac{1}{2} (\bar{L}^\beta \gamma^\rho \tau L_{\alpha})(\bar{e}_R \gamma_\rho e_R)(H^\dagger \tau H)
\]

To form \(\mathcal{O}_{\text{NSI}}\): Any combinations with \(C_{LEH}^1 = C_{LEH}^3\).

—To cancel dim=6: \(C_{LE} = 0\).
A Toy Model
— with 2 mediators $\Phi(2^s_{1/2})$ and $\Delta_\rho(2^v_{3/2})$

Masses and coefficients should be related ...

Assuming $M_\Delta = M_\Phi$
— To cancel all dim.6: $2(g^*)^\alpha g_\beta = (y^*)^\alpha y_\beta$
— To form $\mathcal{O}_{\text{NSI}}$(cancel dim.8 CLI): $\lambda_{1s} + \lambda_{1v} = \lambda_{3s} + \lambda_{3v} \neq 0$

— Systematic study Gavela Hernandez O Winter

T. Ota (Uni Würzburg)
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Current and future bounds

— Oscillation exps have a good sensitivity to $\tau$-associated NSI.

- **Current:** From atmospheric neutrinos
  \[ |\epsilon_{\mu\tau}^m| < 3.8 \times 10^{-2}, \quad |\epsilon_{\tau\tau}^m| < 1.2 \times 10^{-1}. \]

- **Future:** NuFact with two Golden detectors (IDS-NF)
  \[ |\epsilon_{e\tau}^m| < 4.7 \cdot 10^{-3}, \quad |\epsilon_{\mu\tau}^m| < 1.8 \cdot 10^{-2}, \quad |\epsilon_{\tau\tau}^m| < 1.9 \cdot 10^{-2}. \]
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Bottom-up to models with NSI

- Effective op
  \[ \xrightarrow{\text{to}} \text{Possible physically motivated models} \]
Current and future bounds

— Oscillation exps have a good sensitivity to $\tau$-associated NSI.

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  \[ |\epsilon^{m}_{\mu\tau}| < 3.8 \times 10^{-2}, \quad |\epsilon^{m}_{\tau\tau}| < 1.2 \times 10^{-1}. \]

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  \[ |\epsilon^{m}_{e\tau}| < 4.7 \cdot 10^{-3}, \quad |\epsilon^{m}_{\mu\tau}| < 1.8 \cdot 10^{-2}, \quad |\epsilon^{m}_{T\tau}| < 1.9 \cdot 10^{-2}. \]

Bottom-up to models with NSI

• Effective op \( \textbf{Bottom-up!} \) Decomposition to fundamental ops \( \rightarrow \) Possible physically motivated models
Summary

Current and future bounds

— Oscillation exps have a good sensitivity to $\tau$-associated NSI.

- **Current**: From atmospheric neutrinos
  \[
  |\epsilon_{\mu\tau}^m| < 3.8 \times 10^{-2}, \quad |\epsilon_{\tau\tau}^m| < 1.2 \times 10^{-1}.
  \]

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  \[
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  \]

Bottom-up to models with NSI

- Effective oper $\rightarrow$ Decomposition to fundamental ops $\rightarrow$ Possible physically motivated models

- Dim.8 NSI from one diagram is constrained
  — Bounds from Dim.6, Non-uni, and EWPD etc.

- A Toy model
  — Dim.8 NSI induced by 2 mediators with related couplings.

T. Ota (Uni Würzburg)
Back Up Slides
**LLĒE at dim.6**

Effective op basis Buchmüller Weyler NPB268 621

\[ \mathcal{L}_{\text{eff}} = \frac{(C_{LE})^\alpha_\beta}{\Lambda^2} (\bar{L}^{\beta i} e_R)(\bar{e}_R L^{\alpha i}) \]

only one possibility — all decompositions are reduced to this eff. op.

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NSI: future bounds and models
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\[ = - \frac{(C_{\text{LE}})}{2\Lambda^2} \left[ (\overline{\nu}^\beta \gamma^\rho P_L \nu_\alpha) + (\overline{\ell}^\beta \gamma^\rho P_L \ell_\alpha) \right] (\overline{e}_R \gamma^\rho e_R). \]

NSI charged lepton int. (CLI)

- We cannot avoid CLI.
- Within the bounds of CLI, we can still have

\[ |\epsilon^{m}_{\tau\tau}| \lesssim 0.1, \]

Berezhiani Rossi PLB535 207, LEP \( e^+ e^- \rightarrow \tau^+ \tau^- \).
**Summary**

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On the other hand, $\bar{L}L\bar{L}L$ has more possibilities...
1: Diagram including vertex \( (f_{SM}f'_{SM}) \)
- Bounds from Dim.6

2: Not including \( (f_{SM}f'_{SM}) \) but including \( (LH) \)
- Bounds from Non-unitarity of PMNS matrix

3: Not including \( (f_{SM}f'_{SM}) \) but including \( (EH) \)
- Bounds from electroweak precision data
e.g., Langacker London PRD38 886.

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