Non-standard neutrino interactions

future bounds and models

Toshihiko Ota

Institut für Theoretische Physik und Astrophysik
Universiät Würzburg

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.****]

Preface

Within the current precision — Leading Order (LO)

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

$$\underbrace{P_{\nu_\mu \to \nu_e}}_{0} + P_{\nu_\mu \to \nu_\mu} + \underbrace{P_{\nu_\mu \to \nu_\tau}}_{1 - P_{\nu_\mu \to \nu_\mu}} = 1 \qquad \text{(unitarity)}$$

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Future experiments are sensitive to the Next LO

$$P_{\nu_\mu\to\nu_e} = 0$$ Leading Order

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$$P_{\nu_\mu\to\nu_e} = 0 \qquad \boxed{\text{Leading Order}}$$
$$+ \mathcal{O}(s_{13}^2) \qquad \boxed{\text{Mass-Texture, LFV Prediction...}}$$
$$+ \mathcal{O}(s_{13}\Delta m^2_{21}/\Delta m^2_{31}) \qquad \boxed{\text{CP violation (Leptogenesis)...}}$$

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$$\begin{aligned} P_{\nu_\mu \to \nu_e} = \; & 0 && \boxed{\text{Leading Order}} \\ & + \mathcal{O}(s^2_{13}) && \boxed{\text{Mass-Texture, LFV Prediction...}} \\ & + \mathcal{O}(s_{13} \Delta m^2_{21} / \Delta m^2_{31}) && \boxed{\text{CP violation (Leptogenesis)...}} \\ & + && \boxed{\text{Direct evidence of New Physics}} \end{aligned}$$

Outline

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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

Introduction — NSIs

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

Standard oscillation

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu_\alpha \rangle \right|^2 ,$$

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

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NSIs

$$\mathcal{L}_{\mathrm{CC}} = 2\sqrt{2} G_F \tilde{\epsilon}^{\mathrm{CC}}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\rho \mathrm{P}_L \ell_\beta)(\bar{f}' \gamma_\rho \mathrm{P}_{L/R} f)$$

$$\mathcal{L}_{\mathrm{NC}} = 2\sqrt{2} G_F \tilde{\epsilon}^{\mathrm{NC}}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\rho \mathrm{P}_L \nu_\beta)(\bar{f} \gamma_\rho \mathrm{P}_{L/R} f)$$

Introduction — NSIs

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

Oscillation with NSIs

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu^d_\beta | \mathrm{e}^{-\mathrm{i}(H + V_{\mathrm{NSI}})L} | \nu^s_\alpha \rangle \right|^2$$

- CC type NSI — flavour mixture states at source and detector
  Grossmann PLB**359** (1995) 141.

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon^s_{\alpha\gamma} |\nu_\gamma\rangle, \qquad \text{e.g., } \pi^+ \xrightarrow{\epsilon^s_{\mu e}} \mu^+ \nu_e$$

$$\langle \nu^d_\alpha| = \langle \nu_\alpha| + \sum_{\gamma=e,\mu,\tau} \epsilon^d_{\gamma\alpha} \langle \nu_\gamma|, \qquad \text{e.g., } \nu_\tau N \xrightarrow{\epsilon^d_{\tau e}} e^- X$$

- NC type NSI — extra matter effect in propagation
  Wolfenstein PRD**17** (1978) 2369. Valle PLB**199** (1987) 432. Guzzo Masiero Petcov PLB**260** (1991) 154. Roulet PRD**44** (1991) R935. etc.

$$(V_{\mathrm{NSI}})_{\beta\alpha} = \sqrt{2} G_F N_e \epsilon^m_{\beta\alpha}$$

Outline

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.

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

From atmospheric neutrinos

Gonzalez-Garcia Maltoni Phys. Rept. **460** 1.

$$|\epsilon^m_{\mu\tau}| < 0.038, \quad |\epsilon^m_{\mu\mu} - \epsilon^m_{\tau\tau}| < 0.12, \quad \text{(90\%CL)}.$$

- Bounds from non-osc. to tau-associated NSI are not strict.
  — Oscillation experiments can play an important role!

(Part of) References on sensitivities

MINOS

Blennow Ohlsson Skrotzki Phys Lett **B660** 522-528. Friedland Lunardini, Phys Rev **D74** 033012.

OPERA

Esteban-Pretel Valle Huber arXiv:0803.1790. Blennow Meloni Ohlsson Terranova Westerberg arXiv:0804.2744.

Atmospheric

Friedland Lunardini Maltoni Phys Rev **D70** 111301. Gonzalez-Garcia Maltoni Phys Rev **D70** 033010.

Atmospheric+K2K

Friedland Lunardini Phys Rev **D72** 053009.

T2K+D-Chooz

Kopp Lindner O Sato Phys Rev **D77** 013007.

T2KK

Ribeiro Nunokawa Kajita Nakayama Ko Minakata Phys Rev **D77** 073007.

Solar

Friedland Lunardini Peña-Garay Phys Lett **B594** 347.

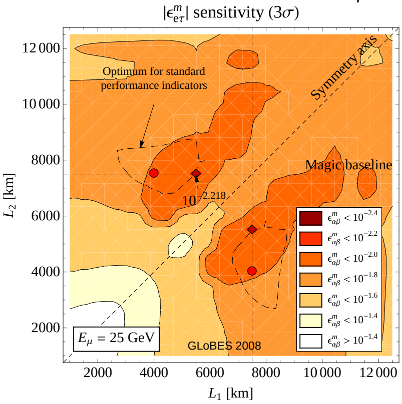
Advanced superbeam experiments, Beta beam, NuFact ...

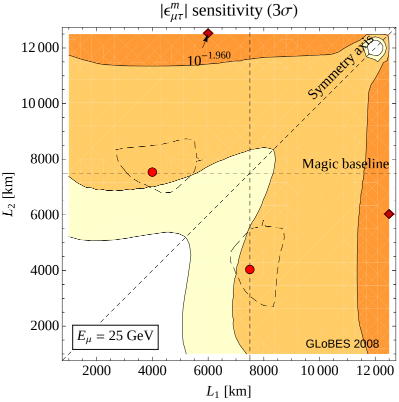
Ribeiro Minakata Nunokawa Uchinami Zukanovich-Funchal, JHEP **12** 002...

Optimization for NSIs — Two-golden-detector setup NuFACT

Kopp O Winter arXiv:0804.2261.

- Sensitivity to $\epsilon^m_{e\tau}$ and $\epsilon^m_{\mu\tau}$





- L ∼4000 km + 7500 km is good also for the NSI.

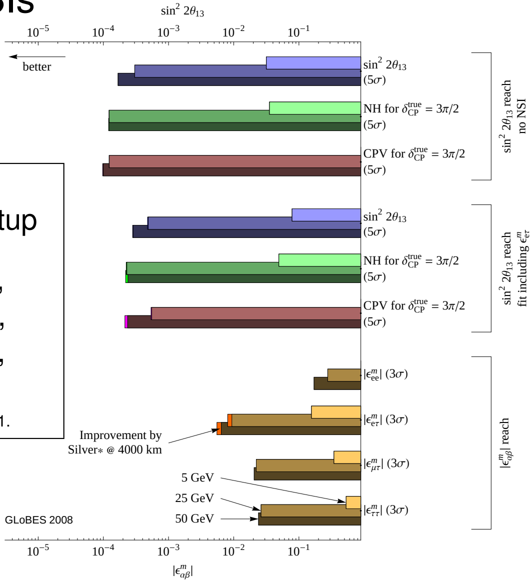
Optimization for NSIs

Sensitivity reach of Two-Golden det. setup

$$|\epsilon^m_{e\tau}| > 4.7 \cdot 10^{-3},$$
$$|\epsilon^m_{\mu\tau}| > 1.8 \cdot 10^{-2},$$
$$|\epsilon^m_{\tau\tau}| > 1.9 \cdot 10^{-2},$$

(90% CL).

Kopp O Winter arXiv:0804.2261.



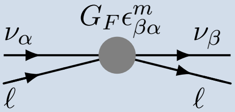
Outline

Bottom-up to Models

We concentrate on pure lepton processes

Bottom: Effective interaction

— but with lepton doublet L



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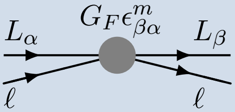

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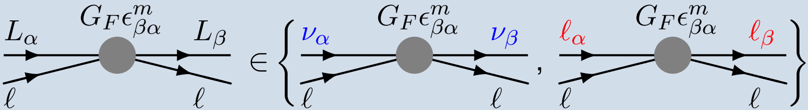

— NSIs accompanied with charged lepton processes

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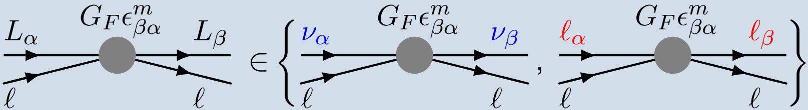
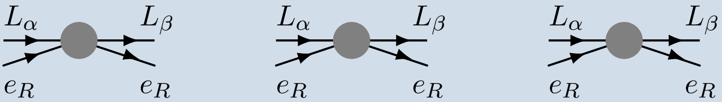


— NSIs accompanied with charged lepton processes

One step up from the bottom:

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



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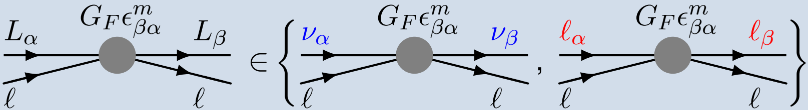

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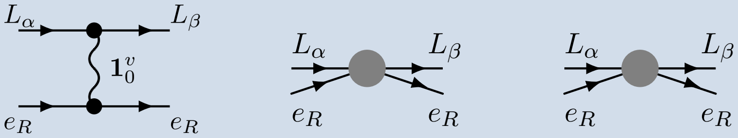

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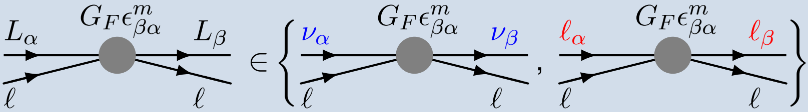

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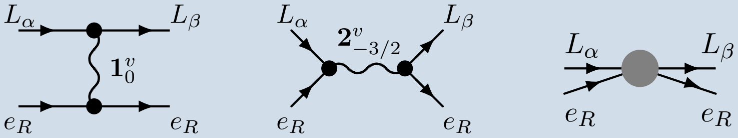

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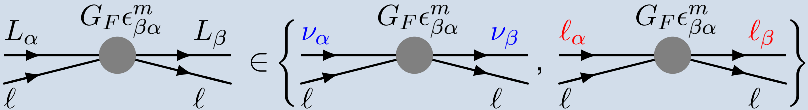

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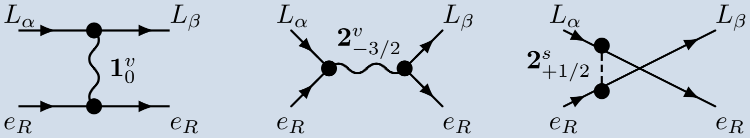


$\bar{L}L\bar{L}L$

Two effective ops, Buchmüller Weyler NP**B268** 621

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

$\bar{L}L\bar{L}L$

Two effective ops, Buchmüller Weyler NP**B268** 621

$$\begin{aligned}\mathcal{L}_{\text{eff}} &= \frac{(\mathcal{C}^{\mathbf{1}}_{LL})^{\alpha\gamma}_{\beta\delta}}{\Lambda^2}(\bar{L}^{\beta}\gamma^{\rho}L_{\alpha})(\bar{L}^{\delta}\gamma_{\rho}L_{\gamma}) + \frac{(\mathcal{C}^{\mathbf{3}}_{LL})^{\alpha\gamma}_{\beta\delta}}{\Lambda^2}(\bar{L}^{\beta}\gamma^{\rho}\vec{\tau}L_{\alpha})(\bar{L}^{\delta}\gamma_{\rho}\vec{\tau}L_{\gamma}) \\ &= \frac{(\mathcal{C}_{\text{NSI}})^{\alpha e}_{\beta e}}{\Lambda^2}\underbrace{(\bar{\nu}_{\beta}\gamma^{\rho}\text{P}_L\nu_{\alpha})(\bar{e}\gamma_{\rho}\text{P}_L e)}_{\text{NSI}} + \frac{(\mathcal{C}^{\mathbf{1}}_{LL}+\mathcal{C}^{\mathbf{3}}_{LL})^{\alpha e}_{\beta e}}{\Lambda^2}\underbrace{(\bar{\ell}_{\beta}\gamma^{\rho}\text{P}_L\ell_{\alpha})(\bar{e}\gamma_{\rho}\text{P}_L e)}_{\text{Charged Lepton Interactions (CLI)}} \\ &\quad + \cdots\end{aligned}$$

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

$$\mathcal{C}^{\mathbf{1}}_{LL} + \mathcal{C}^{\mathbf{3}}_{LL} = 0.$$

$\bar{L}L\bar{L}L$

Two effective ops, Buchmüller Weyler NP**B268** 621

$$\mathcal{L}_{\rm eff} = \frac{(\mathcal{C}^{\mathbf{1}}_{LL})^{\alpha\gamma}_{\beta\delta}}{\Lambda^2}(\bar{L}^\beta\gamma^\rho L_\alpha)(\bar{L}^\delta\gamma_\rho L_\gamma) + \frac{(\mathcal{C}^{\mathbf{3}}_{LL})^{\alpha\gamma}_{\beta\delta}}{\Lambda^2}(\bar{L}^\beta\gamma^\rho\vec{\tau}L_\alpha)(\bar{L}^\delta\gamma_\rho\vec{\tau}L_\gamma)$$

$$= \frac{(\mathcal{C}_{\rm NSI})^{\alpha e}_{\beta e}}{\Lambda^2}(\bar{\nu}_\beta\gamma^\rho {\rm P}_L\nu_\alpha)(\bar{e}\gamma_\rho {\rm P}_L e) + \frac{(\mathcal{C}^{\mathbf{1}}_{LL}+\mathcal{C}^{\mathbf{3}}_{LL})^{\alpha e}_{\beta e}}{\Lambda^2}(\bar{\ell}_\beta\gamma^\rho {\rm P}_L\ell_\alpha)(\bar{e}\gamma_\rho {\rm P}_L e) + \cdots$$

NSI

Charged Lepton Interactions (CLI)

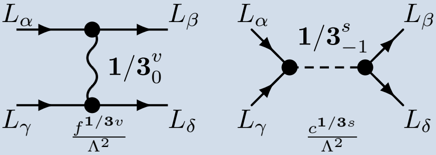
- We can avoid CLI at the effective-op level, taking

$$\mathcal{C}^{\mathbf{1}}_{LL} + \mathcal{C}^{\mathbf{3}}_{LL} = 0.$$

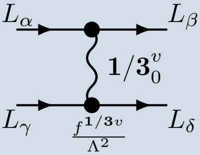
- But, with mediators, NSI are still constrained.
  Bergmann Grossman Pierce PR**D61** 053005, Antusch Baumann Fernández-Martinez arXiv0807.1003.

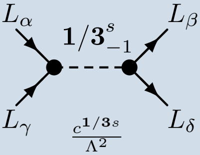
Let me explain this at the following two slides...

$\bar{L}L\bar{L}L$


L_α
L_β
$\mathbf{1}/\mathbf{3}^v_0$
L_γ
L_δ
$\frac{f^{\mathbf{1}/\mathbf{3}v}}{\Lambda^2}$
L_α
$\mathbf{1}/\mathbf{3}^s_{-1}$
L_β
L_γ
L_δ
$\frac{c^{\mathbf{1}/\mathbf{3}s}}{\Lambda^2}$

$\bar{L}L\bar{L}L$

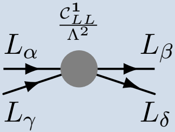


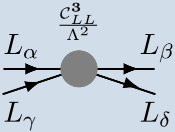


In effective op basis

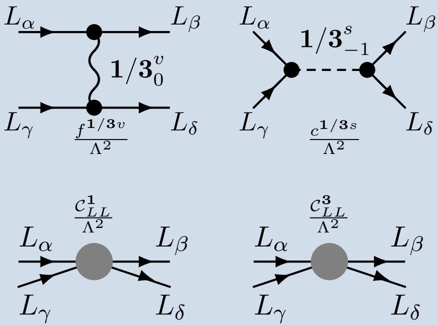
$$\mathcal{C}^{\mathbf{1}}_{LL} = f^{\mathbf{1}v} + \frac{1}{4}c^{\mathbf{1}s} - \frac{3}{4}c^{\mathbf{3}s}$$

$$\mathcal{C}^{\mathbf{3}}_{LL} = f^{\mathbf{3}v} - \frac{1}{4}c^{\mathbf{1}s} - \frac{1}{4}c^{\mathbf{3}s}$$





$\bar{L}L\bar{L}L$



In effective op basis

$$\mathcal{C}^{\mathbf{1}}_{LL} = f^{\mathbf{1}v} + \frac{1}{4}c^{\mathbf{1}s} - \frac{3}{4}c^{\mathbf{3}s}$$

$$\mathcal{C}^{\mathbf{3}}_{LL} = f^{\mathbf{3}v} - \frac{1}{4}c^{\mathbf{1}s} - \frac{1}{4}c^{\mathbf{3}s}$$

No CLI condition

$$\mathcal{C}^{\mathbf{1}}_{LL} + \mathcal{C}^{\mathbf{3}}_{LL} = 0$$

$$\rightarrow \boxed{f^{\mathbf{1}v} + f^{\mathbf{3}v} - c^{\mathbf{3}s} = 0}$$

$\mathbf{1}^s_{-1}$ does not induce CLI.

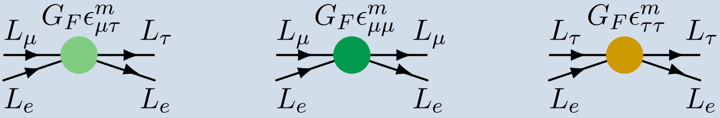
— The others need plural numbers of mediators to cancel CLI.

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}

Bergmann Grossman Pierce PR**D61** 053005, Antusch Baumann Fernández-Martinez arXiv0807.1003.

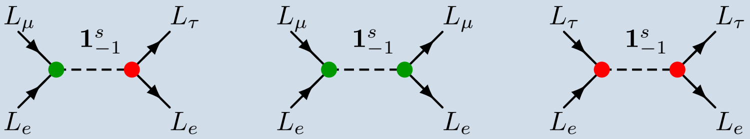
1. At the effective op. level, they are independent



e.g., $\epsilon^m_{\mu\tau}$ from $\bar{L}^\tau L_e \bar{L}^e L_\mu$ with $\mathbf{1}^s_{-1}$

Bergmann Grossman Pierce PR**D61** 053005, Antusch Baumann Fernández-Martinez arXiv0807.1003.

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 $\bar{L}^\tau L_e \bar{L}^e L_\mu$ with $\mathbf{1}^s_{-1}$

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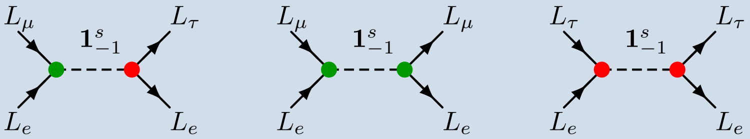
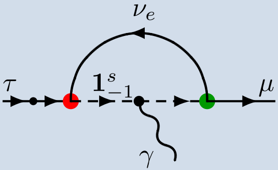


— $\epsilon^m_{\mu\tau}$ is constrained from G_F measurement...

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



e.g., $\epsilon^m_{\mu\tau}$ from $\bar{L}^\tau L_e \bar{L}^e L_\mu$ with $\mathbf{1}^s_{-1}$

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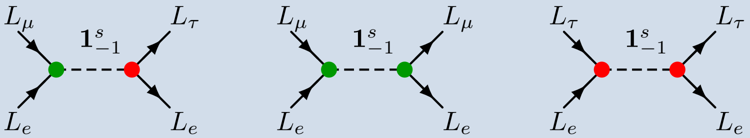

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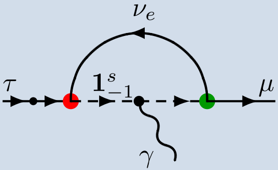

Although $\bar{L}^\tau L_e \bar{L}^e L_\mu$ with $\mathbf{1}^s_{-1}$ is CLI-free at the effective-op level, it is constrained when we take into account mediators.

- Beyond the four-fermion (dimension six) effective ops...

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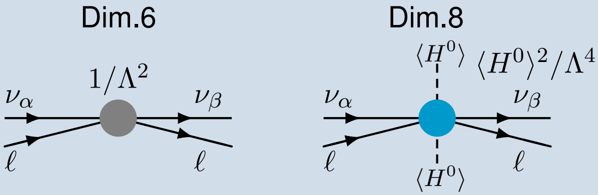
- NSI from dimension eight operators with Higgs doublets.
  Berezihiani Rossi PL**B535** 207, Davidson Peña-Garay Rius Santamaria JHEP**03** 011

Dimension eight operators

Dim.8: 4-Fermi+2 Higgs



Many effective ops.

— Many possibilities to cancel CLI and avoid bounds

Berezhiani Rossi, PL**B535** 207, Davidson Peña-Garay Rius Santamaria JHEP**03** 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...

- Dim.8 NSI induced by one diagram is always constrained!
  Antusch Baumann Fernández-Martinez arXiv0807.1003.

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- 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 NP**B268** 621, Berezhiani Rossi, PL**B535** 207.

$$\mathcal{L}_{\text{eff}}^{\text{dim6}} = \frac{(\mathcal{C}_{LE})^{\alpha}_{\beta}}{\Lambda^2} (\bar{L}^{\beta i} e_R)(\overline{e_R} L_{\alpha i})$$

only one possibility in dim6
— NSI always with CLI

$$\mathcal{L}_{\text{eff}}^{\text{dim8}} = \frac{(\mathcal{C}^{\mathbf{1}}_{LEH})^{\alpha}_{\beta}}{\Lambda^4} (\bar{L}^{\beta} \gamma^{\rho} L_{\alpha})(\overline{e_R} \gamma_{\rho} e_R)(H^{\dagger} H) + \frac{(\mathcal{C}^{\mathbf{3}}_{LEH})^{\alpha}_{\beta}}{\Lambda^4} (\bar{L}^{\beta} \gamma^{\rho} \vec{\tau} L_{\alpha})(\overline{e_R} \gamma_{\rho} e_R)(H^{\dagger} \vec{\tau} H)$$

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

What we want is...

Berezhiani Rossi, PL**B535** 207, Davidson Peña-Garay Rius Santamaria JHEP**03** 011.

$$\mathcal{O}_{\text{NSI}} = \left\{ (\bar{L}^i H_i) \gamma^{\rho} (H^{\dagger i} L_i) \right\} (\overline{e_R} \gamma_{\rho} e_R), \qquad \text{where } H_i = (H^0 \ H^-)^{\mathsf{T}}$$

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What we want is...

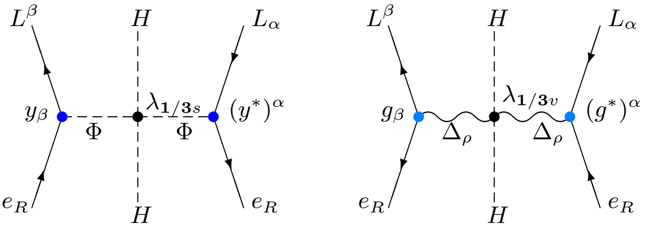
Berezhiani Rossi, PL**B535** 207, Davidson Peña-Garay Rius Santamaria JHEP**03** 011.

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

To form $\mathcal{O}_{\text{NSI}}$: Any combinations with $\mathcal{C}^{\mathbf{1}}_{LEH} = \mathcal{C}^{\mathbf{3}}_{LEH}$.
—To cancel dim=6: $\mathcal{C}_{LE} = 0$.

A Toy Model

— with 2 mediators $\Phi(\mathbf{2}^s_{+1/2})$ and $\Delta_\rho(\mathbf{2}^v_{-3/2})$



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): $\lambda_{\mathbf{1}s} + \lambda_{\mathbf{1}v} = \lambda_{\mathbf{3}s} + \lambda_{\mathbf{3}v} \neq 0$

— Systematic study Gavela Hernandez O Winter

Outline

Current and future bounds

— Oscillation exps have a good sensitivity to τ-associated NSI.

- Current: From atmospheric neutrinos
  $$|\epsilon^m_{\mu\tau}| < 3.8 \times 10^{-2}, \qquad |\epsilon^m_{\tau\tau}| < 1.2 \times 10^{-1}.$$
- Future: NuFact with two Golden detectors (IDS-NF)
  $$|\epsilon^m_{e\tau}| < 4.7 \cdot 10^{-3}, \quad |\epsilon^m_{\mu\tau}| < 1.8 \cdot 10^{-2}, \quad |\epsilon^m_{\tau\tau}| < 1.9 \cdot 10^{-2}.$$

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Bottom-up to models with NSI

- Effective op

$\xrightarrow{\text{to}}$ Possible physically motivated models

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Bottom-up to models with NSI

- Effective op $\xrightarrow{\text{Bottom-up!}}$ Decomposition to fundamental ops $\xrightarrow{\text{to}}$ 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.

Back Up Slides

$\bar{L}L\bar{E}E$ at dim.6

Effective op basis Buchmüller Weyler NP**B268** 621

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$$= -\frac{(\mathcal{C}_{LE})^{\alpha}_{\beta}}{2\Lambda^2}\left[(\bar{\nu}^{\beta}\gamma^{\rho}\mathrm{P}_L\nu_{\alpha}) + (\bar{\ell}^{\beta}\gamma^{\rho}\mathrm{P}_L\ell_{\alpha})\right](\overline{e_R}\gamma_{\rho}e_R).$$

NSI — charged lepton int. (CLI)

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

$|\epsilon^{m}_{\tau\tau}| \lesssim 0.1,$ Berezihiani Rossi PL**B535** 207, LEP $e^+e^- \to \tau^+\tau^-$.

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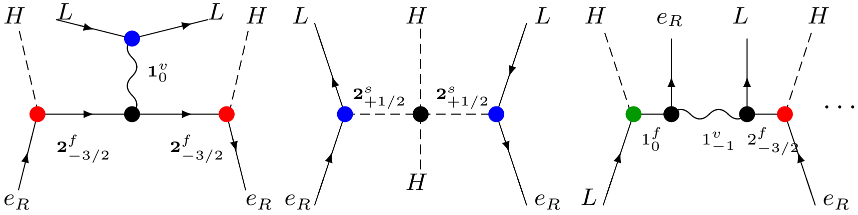
On the other hand, $\bar{L}L\bar{L}L$ has more possibilities...

Summary



1: Diagram including vertex $(f_{\rm SM} f'_{\rm SM})$

- Bounds from Dim.6

2: Not including $(f_{\rm SM} f'_{\rm SM})$ but including (LH)

- Bounds from Non-unitarity of PMNS matrix

Antusch Baumann Fernández-Martinez arXiv0807.1003.

3: Not including $(f_{\rm SM} f'_{\rm SM})$ but including (EH)

- Bounds from electroweak precision data

e.g., Langacker London PR**D38** 886.