Non-Standard Neutrino Interactions

Enrique Fernández-Martínez

Introduction: NSI

Generic new physics affecting ν oscillations can be parameterized as 4-fermion Non-Standard Interactions:

Production or detection of a ν_β associated to a l_α

$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R} f'\right)$$

So that $$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}|\nu_\beta\rangle$$

$$\pi \longrightarrow \mu + \nu_\beta \qquad n + \nu_\beta \longrightarrow p + l_\alpha$$

Y. Grossman hep-ph/9507344

Direct bounds on prod/det NSI

$$2\sqrt{2}G_F\varepsilon^{ud}_{\alpha\beta}\left(\bar{l}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{u}\gamma_\mu P_{L,R}d\right) \qquad 2\sqrt{2}G_F\varepsilon^{\mu e}_{\alpha\beta}\left(\bar{\mu}\gamma^\mu P_L\nu_\beta\right)\left(\bar{\nu}_\alpha\gamma_\mu P_L e\right)$$

$$\left|\varepsilon^{ud}\right| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.013 & 0.13 \end{pmatrix} \qquad \left|\varepsilon^{\mu e}\right| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

bounds order $\sim 10^{-2}$ from comparisons of measurements of G_F: μ, τ, π decays, CKM universality, $M_W + M_Z \ldots$

C. Biggio, M. Blennow and EFM 0907.0097

Introduction: NSI

Non-Standard ν scattering off matter can also be parameterized as 4-fermion Non-Standard Interactions:

$$2\sqrt{2}G_F\varepsilon^m_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$$

so that $$\tilde{V}_{\mathrm{MSW}} = a_{\mathrm{CC}}\begin{pmatrix} 1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix}$$

$\nu_\alpha \longrightarrow \nu_\beta$ in matter $f = e, u, d$

Direct bounds on matter NSI

If matter NSI are uncorrelated to production and detection direct bounds are mainly from ν scattering off e and nuclei

$$2\sqrt{2}G_F\varepsilon^m_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$$

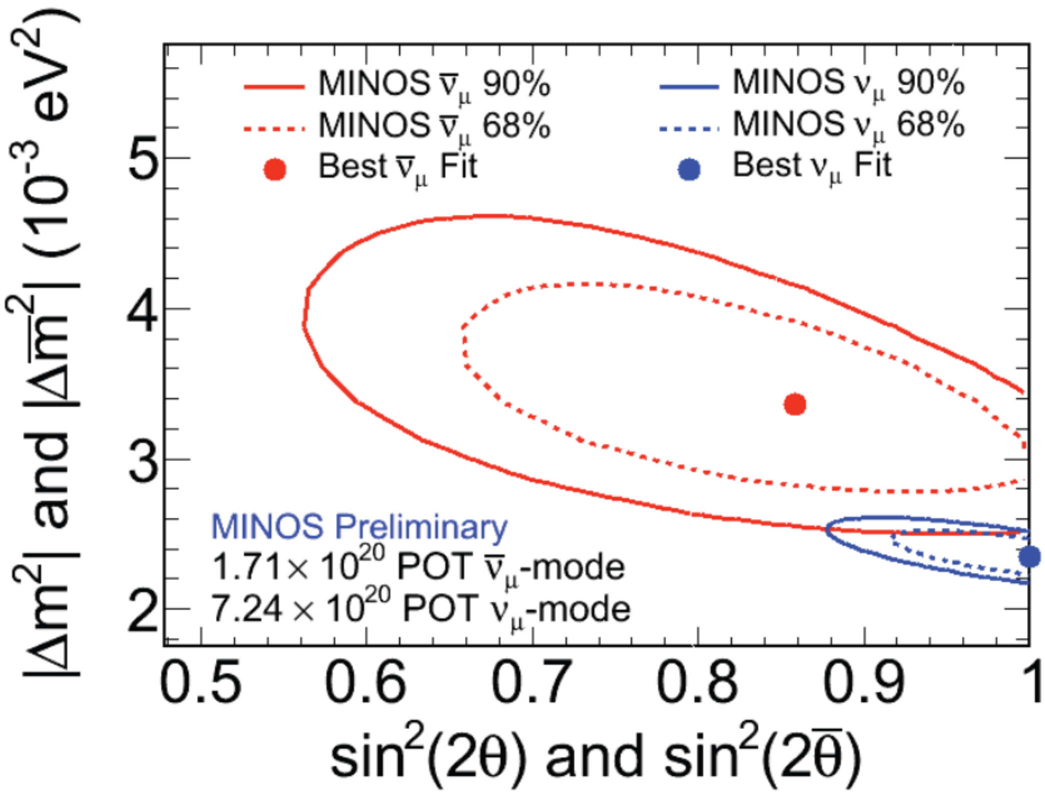
$$\left|\varepsilon^e_m\right| < \begin{pmatrix} 0.14 & 0.1 & 0.44 \\ 0.1 & 0.03 & 0.1 \\ 0.44 & 0.1 & 0.5 \end{pmatrix} \quad \left|\varepsilon^u_m\right| < \begin{pmatrix} 1 & 0.05 & 0.5 \\ 0.05 & 0.008 & 0.05 \\ 0.5 & 0.05 & 3 \end{pmatrix} \quad \left|\varepsilon^d_m\right| < \begin{pmatrix} 0.6 & 0.05 & 0.5 \\ 0.05 & 0.015 & 0.05 \\ 0.5 & 0.05 & 6 \end{pmatrix}$$

Rather weak bounds…

…can they be saturated avoiding additional constraints?

S. Davidson, C. Peña garay, N. Rius and A. Santamaria hep-ph/0302093
J. Barranco, O. G. Miranda, C. A. Moura and J. W. F. Valle hep-ph/0512195
J. Barranco, O. G. Miranda, C. A. Moura and J. W. F. Valle 0711.0698
C. Biggio, M. Blennow and EFM 0902.0607

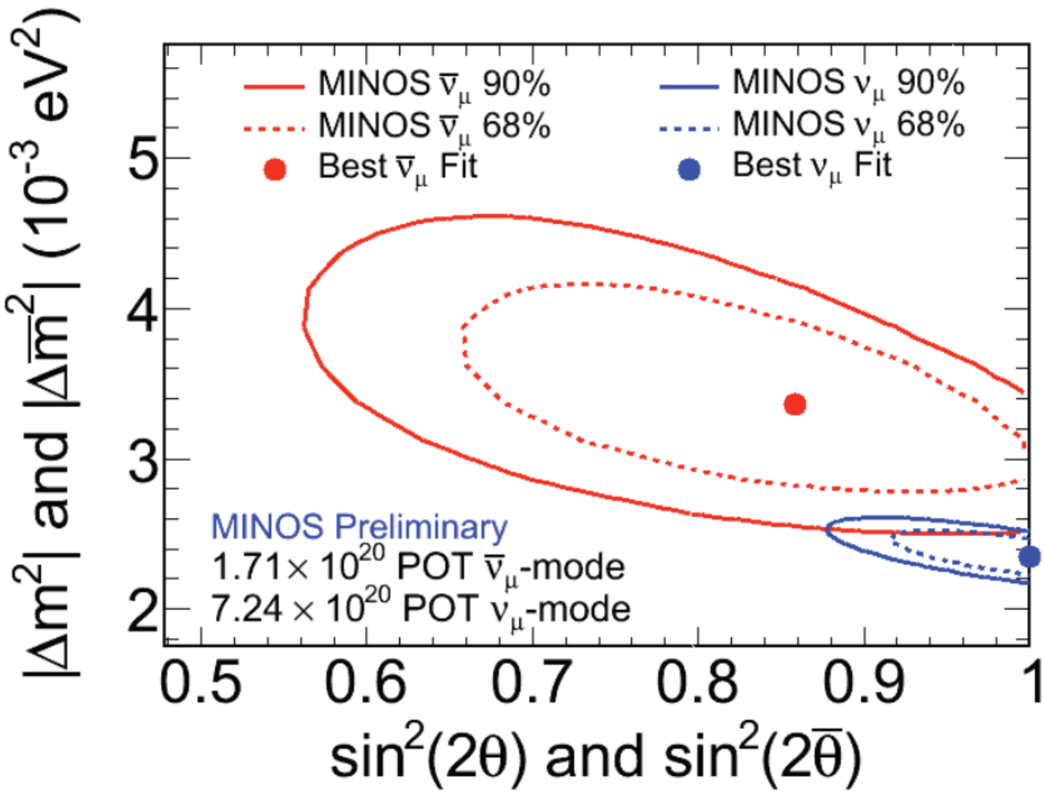
MINOS and LSND/MiniBooNE via NSI



Tension between MINOS nu and antinu data

P. Vahle @ Neutrino 2010

MINOS and LSND/MiniBooNE via NSI



Can be accommodated with matter NSI

$\varepsilon_{\mu\tau} \sim 0.4$

or detection NSI

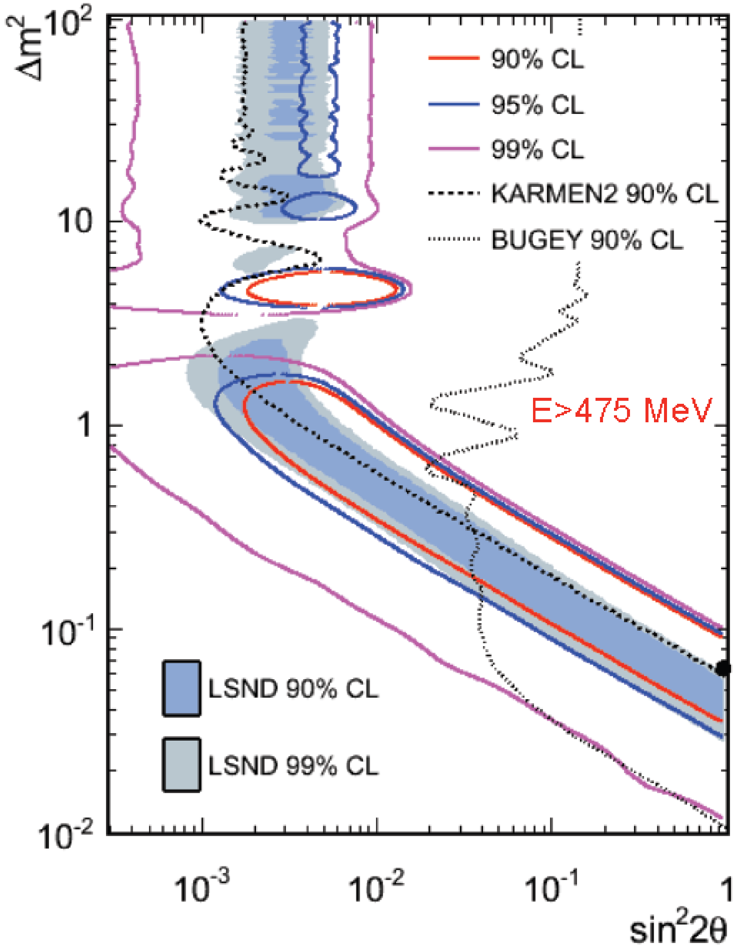
$\varepsilon_{\mu\tau} \sim 0.1$

W. A. Mann et al 1006.5720
J. Kopp et al 1009.0014

Tension between MINOS nu and antinu data

P. Vahle @ Neutrino 2010

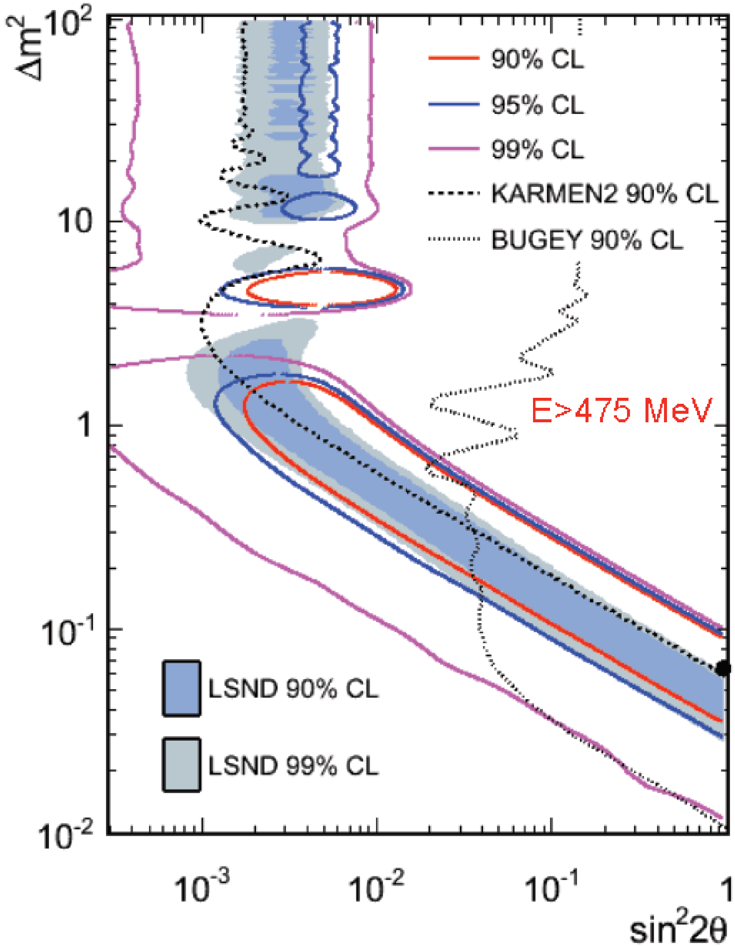
MINOS and LSND/MiniBooNE via NSI



Agreement between MiniBooNE and LSND antinu data

R. Van de Water @ Neutrino 2010

MINOS and LSND/MiniBooNE via NSI



Can be accommodated with production/detection NSI + sterile neutrinos

$\varepsilon_{e\mu} \sim 0.01$

E. Akhmedov and T. Schwetz 1007.4171

Agreement between MiniBooNE and LSND antinu data

R. Van de Water @ Neutrino 2010

Gauge invariance

However $2\sqrt{2}G_F\varepsilon^m_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$

is related to $2\sqrt{2}G_F\varepsilon^m_{\alpha\beta}\left(\bar{l}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$

by gauge invariance and very strong bounds exist

$\varepsilon^m_{e\mu} < \sim 10^{-6}$

$\varepsilon^m_{e\tau} < \sim 10^{-4}$

$\varepsilon^m_{\mu\tau} < \sim 10^{-4}$

$\mu \to e\,\gamma$
$\mu \to e$ in nuclei
τ decays

S. Bergmann et al. hep-ph/0004049
Z. Berezhiani and A. Rossi hep-ph/0111147
S. Antusch, M. Blennow, EFM and T. Ota, 1005.0756

Large NSI?

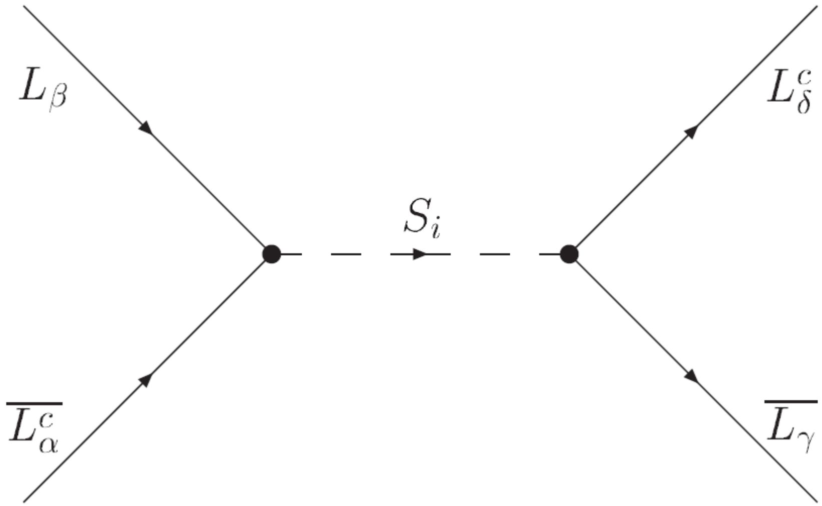
We search for gauge invariant SM extensions satisfying:

- Matter NSI are generated at tree level
- 4-charged fermion ops not generated at the same level
- No cancellations between diagrams with different messenger particles to avoid constraints
- The Higgs Mechanism is responsible for EWSB

S. Antusch, J. Baumann and EFM 0807.1003
B. Gavela, D. Hernández, T. Ota and W. Winter 0809.3451

Large NSI?

At d=6 only one direct possibility: charged scalar singlet



Present in Zee model or R-parity violating SUSY

$$\mathcal{L}^S_{int} = -\lambda^i_{\alpha\beta}\overline{L^c_\alpha} i\sigma_2 L_\beta S_i + \text{H.c.} = \lambda^i_{\alpha\beta} S_i(\overline{\ell^c_\alpha} P_L \nu_\beta - \overline{\ell^c_\beta} P_L \nu_\alpha) + \text{H.c.}$$

$$\mathcal{L}^{d=6,as}_{NSI} = c^{d=6,as}_{\alpha\beta\gamma\delta}\left(\overline{L^c_\alpha} i\sigma_2 L_\beta\right)\left(\overline{L_\gamma} i\sigma_2 L^c_\delta\right) \qquad \varepsilon^{m,e_L}_{\alpha\beta} = \sum_i \frac{\lambda^i_{e\beta}\lambda^{i*}_{e\alpha}}{\sqrt{2} G_F m^2_{S_i}}$$

M. Bilenky and A. Santamaria hep-ph/9310302

Large NSI?

Since $\lambda_{\alpha\beta} = -\lambda_{\beta\alpha}$ only $\varepsilon_{\mu\mu}$, $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau} \neq 0$

Very constrained:

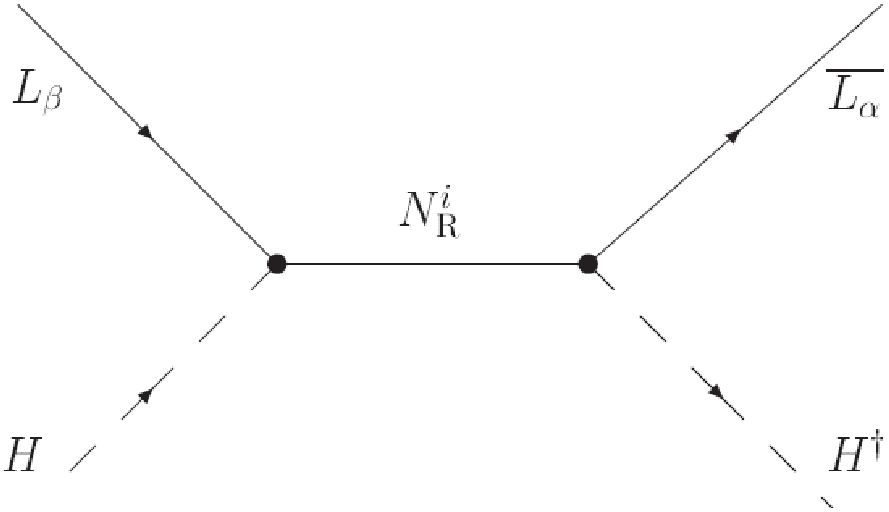
$$
\begin{aligned}
|\varepsilon_{\mu\mu}^{m,e_L}| &< 8.2 \cdot 10^{-4} \\
|\varepsilon_{\tau\tau}^{m,e_L}| &< 8.4 \cdot 10^{-3} \\
|\varepsilon_{\mu\tau}^{m,e_L}| &< 1.9 \cdot 10^{-3}
\end{aligned}
$$

$\mu \to e\,\gamma$
μ decays
τ decays
CKM unitarity

F. Cuypers and S. Davidson hep-ph/9310302
S. Antusch, J. Baumann and EFM 0807.1003

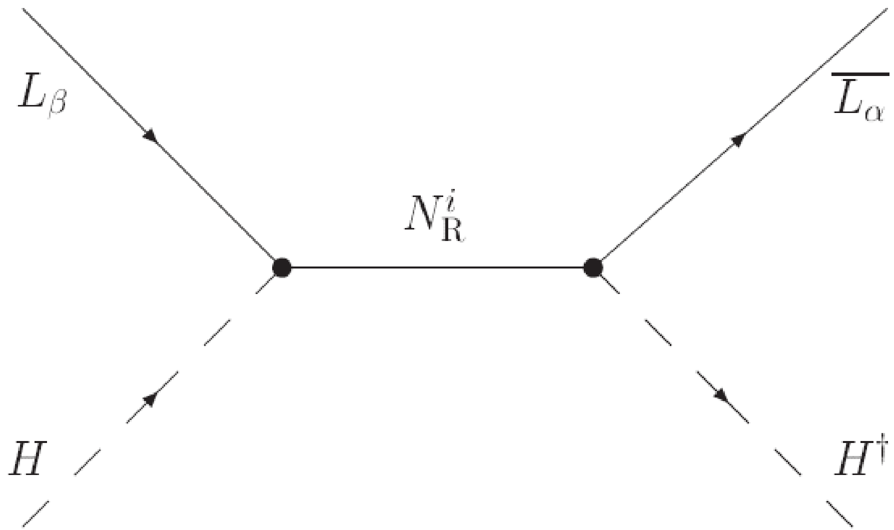
Large NSI?

At d=6 indirect way: fermion singlets



Large NSI?

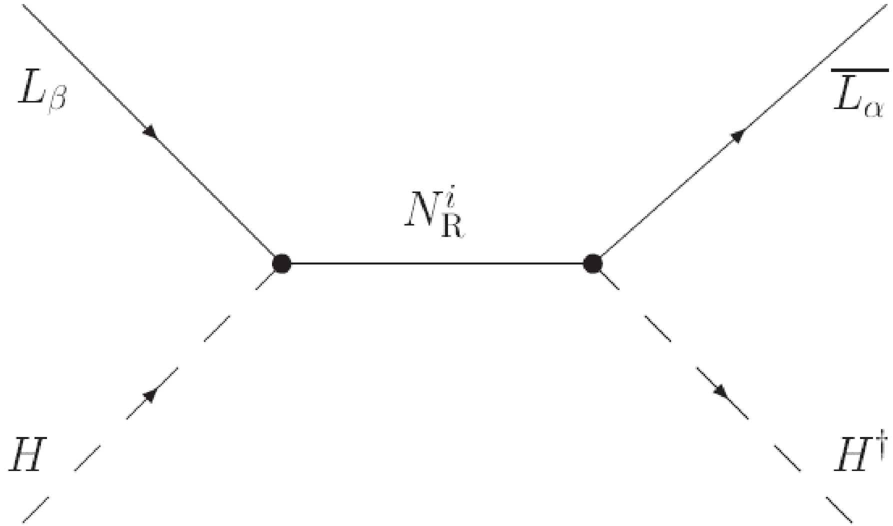
At d=6 indirect way: fermion singlets



$$Y_N^T \frac{1}{M_N} Y_N \qquad \left(\overline{L^c_\beta}\, i\sigma_2 H\right)\left(H^t i\sigma_2 L_\alpha\right) \xrightarrow[\langle\phi\rangle = \frac{v}{\sqrt{2}}]{\text{SSB}} m_\nu = Y_N^T \frac{1}{M_N} Y_N \frac{v^2}{2}$$

Large NSI?

At d=6 indirect way: fermion singlets



$$Y_N^T \frac{1}{M_N} Y_N \quad \left(\overline{L^c_\beta} i\sigma_2 H\right)\left(H^t i\sigma_2 L_\alpha\right) \xrightarrow[\langle\phi\rangle = \frac{v}{\sqrt{2}}]{\text{SSB}} m_\nu = Y_N^T \frac{1}{M_N} Y_N \frac{v^2}{2}$$

$$Y_N^\dagger \frac{1}{|M_N|^2} Y_N \left(\overline{L_\beta} i\sigma_2 H^*\right) i\partial\!\!\!/ \left(H^t i\sigma_2 L_\alpha\right) \xrightarrow[\langle\phi\rangle = \frac{v}{\sqrt{2}}]{\text{SSB}} i\overline{\nu}_\alpha \partial\!\!\!/ K_{\alpha\beta} \nu_\beta$$

Effective Lagrangian

$$L = i\,\overline{\nu}_\alpha \partial K_{\alpha\beta} \nu_\beta + \overline{\nu}_\alpha M_{\alpha\beta} \nu_\beta - \frac{g}{\sqrt{2}}\left(W_\mu^+ \overline{l}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \overline{\nu}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) + \ldots$$

Effective Lagrangian

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Diagonal mass and canonical kinetic terms

$$L = i\,\bar{\nu}_i \partial \nu_i + \bar{\nu}_i m_{ii} \nu_i - \frac{g}{\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i} \nu_i + h.c.\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_i \gamma^\mu P_L (N^\dagger N)_{ij} \nu_j + h.c.\right) + \ldots$$

Effective Lagrangian

$$L = i\,\bar{\nu}_\alpha \partial\!\!\!/ K_{\alpha\beta}\nu_\beta + \bar{\nu}_\alpha M_{\alpha\beta}\nu_\beta - \frac{g}{\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) + \ldots$$

Diagonal mass and canonical kinetic terms

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$$\nu_\alpha = N_{\alpha i}\nu_i$$

N is not unitary

Effective Lagrangian

$$L = i\,\bar{\nu}_\alpha \partial\!\!\!/ K_{\alpha\beta}\nu_\beta + \bar{\nu}_\alpha M_{\alpha\beta}\nu_\beta - \frac{g}{\sqrt{2}}\left(W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right) + \ldots$$

Diagonal mass and canonical kinetic terms

$$L = \underbrace{i\,\bar{\nu}_i \partial\!\!\!/ \nu_i + \bar{\nu}_i m_{ii} \nu_i}_{\text{unchanged}} - \frac{g}{\sqrt{2}}\left(W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i}\nu_i + h.c.\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_i \gamma^\mu P_L (N^\dagger N)_{ij}\nu_j + h.c.\right) + \ldots$$

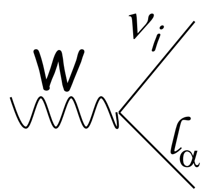
$$\nu_\alpha = N_{\alpha i}\nu_i$$

N is not unitary

$$\langle \nu_i | \nu_j \rangle = \delta_{ij}$$

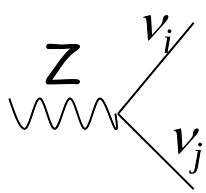
$(NN^\dagger)$ from decays

- W decays



$$\rightarrow \frac{(NN^\dagger)_{\alpha\alpha}}{\sqrt{(NN^\dagger)_{ee}}\sqrt{(NN^\dagger)_{\mu\mu}}}$$

- Invisible Z



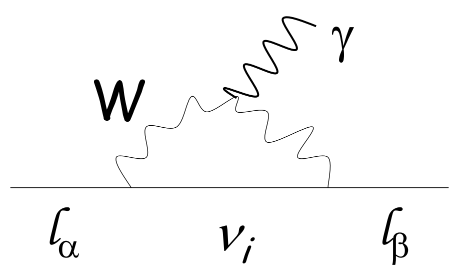
$$\rightarrow \frac{\sum_{\alpha\beta}(NN^\dagger)_{\alpha\beta}}{\sqrt{(NN^\dagger)_{ee}}\sqrt{(NN^\dagger)_{\mu\mu}}}$$

- Universality tests

$$\rightarrow \frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}$$

Info on $(NN^\dagger)_{\alpha\alpha}$

- Rare leptons decays



Info on $(NN^\dagger)_{\alpha\beta}$

$$\rightarrow \frac{\left|(NN^\dagger)_{\alpha\beta}\right|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}$$

After integrating out W and Z neutrino NSI induced

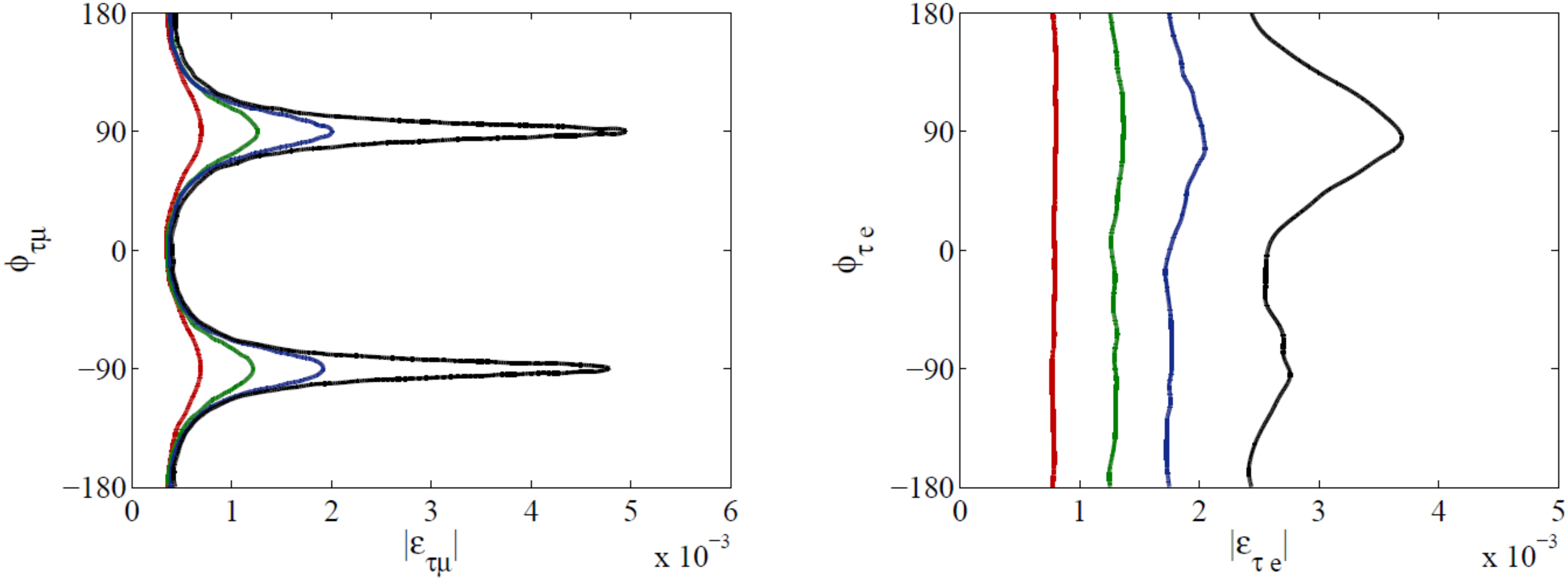
$(NN^\dagger)$ from decays

$$|\varepsilon| = 2\left|\delta - NN^\dagger\right| < \begin{pmatrix} 2.0\cdot 10^{-3} & 5.9\cdot 10^{-5} & 1.6\cdot 10^{-3} \\ 5.9\cdot 10^{-5} & 8.2\cdot 10^{-4} & 1.0\cdot 10^{-3} \\ 1.6\cdot 10^{-3} & 1.0\cdot 10^{-3} & 2.6\cdot 10^{-3} \end{pmatrix}$$

Experimentally

E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228
D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228
S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020
S. Antusch, J. Baumann and EFM 0807.1003

Non-Unitarity at a νFactory



Golden channel at νFactory is sensitive to $\varepsilon_{\tau e}$

ν_μ disappearance channel linearly sensitive to $\varepsilon_{\tau\mu}$ through matter effects

Near τ detectors can improve the bounds on $\varepsilon_{\tau e}$ and $\varepsilon_{\tau\mu}$

Combination of near and far detectors sensitive to the new CP phases

S. Antusch, M. Blennow, EFM and J. López-pavón 0903.3986

See also EFM, B. Gavela, J. López Pavón and O. Yasuda hep-ph/0703098;
S. Goswami and T. Ota 0802.1434; G. Altarelli and D. Meloni 0809.1041,….

Large NSI?

Without avoiding 4-charged fermion ops at the same level there is no direct way at d=6 to induce quark NSI

Constraints from gauge invariance at d=6 on flavour changing NSI very strong:

Operator	$(\mathcal{C}^1_{LQ})_\alpha{}^\tau$	$(\mathcal{C}^3_{LQ})_\alpha{}^\tau$	$(\mathcal{C}_{ED})_\alpha{}^\tau$	$(\mathcal{C}_{EU})_\alpha{}^\tau$	$(\mathcal{C}^\dagger_{ED})_\alpha{}^\tau$	$(\mathcal{C}^\dagger_{EU})_\alpha{}^\tau$
$\alpha = \mu$	$2.1 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$	$6.2 \cdot 10^{-4}$	$6.2 \cdot 10^{-4}$
$\alpha = e$	$2.4 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$6.9 \cdot 10^{-4}$	$7.1 \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$	$6.1 \cdot 10^{-4}$

But pseudoscalar operators have chiral enhancement in pion decay $\rightarrow$ production NSI ~ 0.01 in pion decay

S. Antusch, M. Blennow, EFM and T. Ota, 1005.0756

Chiral "enhancement" of NSI

Production NSI from meson decay can have be enhanced with respect to SM for pseudoscalar ops.

$$2\sqrt{2}G_F\left(\bar{\nu}_\alpha \gamma^\mu P_L l_\alpha\right)\left(\bar{d}\gamma_\mu P_{L,R} u\right) \qquad 2\sqrt{2}G_F \varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta P_L l_\alpha\right)\left(\bar{d} P_{L,R} u\right)$$

π or K decay requires chirality in SM

$$\left\langle 0\middle|\bar{u}\gamma_\mu\gamma_5 d\middle|\pi^-\right\rangle = i f_\pi p_\mu \qquad \left\langle 0\middle|\bar{u}\gamma_5 d\middle|\pi^-\right\rangle = -i f_\pi \frac{m_\pi^2}{m_u + m_d}$$

$$\frac{m_\pi^2}{m_\mu\left(m_u + m_d\right)} \approx 20$$

MINSIS

Main Injector Non Standard Interactions Search

OPERA-like detector at MINOS near detector site to search for ν_τ appearance in the NuMI beam at 1 km baseline

Could reach sensitivities ~10^{-6} $\longrightarrow$ test production/detection NSI mixing the μ and τ sectors down to 10^{-3}

Conclusions

- Models leading "naturally" to NSI imply:
  - $O(10^{-3})$ bounds on the NSI
  - Relations between matter and production/detection NSI
- Probing $O(10^{-3})$ NSI at future facilities very challenging but not impossible, near detectors good probes
- Saturating the mild model-independent bounds on matter NSI is hard: chiral enhancement on π decay or flavour conserving NSI

Sterile Neutrinos

- Similar to NSI if new Δm^2 is large oscillations will happen at short baselines:
  - Appearance seraches limited by background
  - Disappearance searches limited by systematics
- If E is small, oscillation length can be few m oscillations inside the detector!
- Expectation better than for NSI, favoured region for $O(10^{-2})$- $O(10^{-3})$ probabilities