Non-Unitarity and Non-Standard Neutrino Interactions

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Based on collaborations with:

S. Antusch, J. Baumann, C. Biggio, M. Blennow, B. Gavela and J. López Pavón

Outline

- Non-unitary lepton mixing matrix
  - Neutrino masses and non-unitarity
  - Effects of non-unitarity in present oscillation data
  - Measurements of non-unitarity in future oscillation experiments
  - Non-unitarity as NSI

- Non Standard neutrino Interactions
  - Conditions to realize large NSI
  - Avoiding constraints without cancellations
  - Avoiding constraints with cancellations
  - NSI in loops

Neutrino masses in the SM

All SM fermions acquire Dirac masses via Yukawa couplings

$$Y_f \overline{f}_L \phi f_R$$

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$$Y_f \bar{f}_L \phi f_R \xrightarrow[\langle\phi\rangle = \frac{v}{\sqrt{2}}]{\text{SSB}} \frac{Y_f v}{\sqrt{2}} \bar{f}_L f_R \qquad m_f = \frac{Y_f v}{\sqrt{2}}$$

Adding ν_R to the SM, a Majorana mass is also allowed

$$M \bar{\nu}_R^C \nu_R$$

The only d = 5 operator is a Majorana mass for neutrinos

$$\frac{1}{M} \langle\phi\rangle\langle\phi\rangle \bar{\nu}_L^C \nu_L$$

This operator cannot be generated in the SM since it violates B – L, an accidental, non anomalous SM symmetry

Hints that this symmetry is broken at a scale M beyond the SM

The Type I Seesaw Model

The SM is extended by:

$$\mathcal{L}^{SM} + i\,\overline{N_R}\,\partial\!\!\!/\,N_R - \overline{\ell_L}\,\widetilde{\phi}\,Y_N^{\dagger}\,N_R - \frac{1}{2}\,\overline{N_R}\,M_N\,{N_R}^c + \text{h.c.}$$

If the right-handed neutrino N_R is heavy it can be integrated out:

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

Weinberg 1979

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Weinberg 1979

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

A. Broncano, M. B. Gavela and E. Jenkins hep-ph/0210192

Effective Lagrangian

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

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Diagonal mass and canonical kinetic terms

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

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

N is not unitary

Effective Lagrangian

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Diagonal mass and canonical kinetic terms

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

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

N is not unitary

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

The general idea…

$$U=\begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23}-s_{23}s_{13}c_{12}e^{-i\delta} & c_{12}c_{23}-s_{23}s_{13}s_{12}e^{-i\delta} & s_{23}c_{13} \\ s_{23}s_{12}-c_{23}s_{13}c_{12}e^{-i\delta} & -s_{23}c_{12}-c_{23}s_{13}s_{12}e^{-i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\downarrow$$

$$N=\begin{pmatrix} N_{e1} & N_{e2} & N_{e3} \\ N_{\mu 1} & N_{\mu 2} & N_{\mu 3} \\ N_{\tau 1} & N_{\tau 2} & N_{\tau 3} \end{pmatrix}$$

N elements from oscillations only

Atmospheric + K2K + MINOS: $\Delta_{12} \approx 0$

$$\hat{P}(\nu_\mu \to \nu_\mu) \cong \left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)^2 + |N_{\mu 3}|^4 + 2\left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)|N_{\mu 3}|^2 \cos(\Delta_{23})$$

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without unitarity
OSCILLATIONS

$$|N| = \begin{pmatrix} 0.75-0.89 & 0.45-0.66 & <0.34 \\ \left[\left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)^{1/2} \right. & \left. = \quad 0.57-0.86 \right] & 0.57-0.86 \\ ? & ? & ? \end{pmatrix}$$

3σ

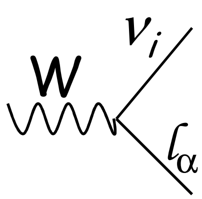
with unitarity
OSCILLATIONS

$$|U| = \begin{pmatrix} 0.79-0.88 & 0.47-0.61 & <0.20 \\ 0.19-0.52 & 0.42-0.73 & 0.58-0.82 \\ 0.20-0.53 & 0.44-0.74 & 0.56-0.81 \end{pmatrix}$$

M. C. González García hep-ph/0410030

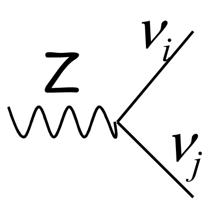
$(NN^\dagger)$ from decays

- W decays



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

- Invisible Z



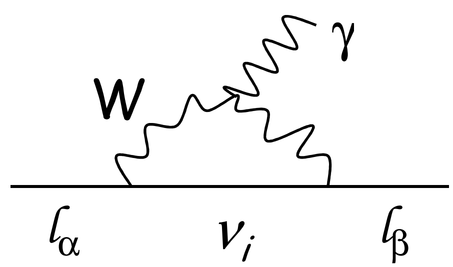
$$\rightarrow \frac{\sum_{\alpha\beta}\left(NN^\dagger\right)_{\alpha\beta}}{\sqrt{\left(NN^\dagger\right)_{ee}}\sqrt{\left(NN^\dagger\right)_{\mu\mu}}}$$

- Universality tests

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

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

- Rare leptons decays



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

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

$(NN^\dagger)$ and $(N^\dagger N)$ from decays

$$|NN^\dagger| \approx \begin{pmatrix} 0.994 \pm 0.005 & < 7.0\cdot 10^{-5} & < 1.6\cdot 10^{-2} \\ < 7.0\cdot 10^{-5} & 0.995 \pm 0.005 & < 1.0\cdot 10^{-2} \\ < 1.6\cdot 10^{-2} & < 1.0\cdot 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

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

The diagonal elements are somewhat smaller than 1 due to the nearly 2σ deviation from 3 in the number of ν measured by the Z width

$$N_\nu = 2.984 \pm 0.009$$

N elements from oscillations & decays

without unitarity
OSCILLATIONS
+DECAYS

$$|N| = \begin{pmatrix} 0.75-0.89 & 0.45-0.65 & <0.20 \\ 0.19-0.55 & 0.42-0.74 & 0.57-0.82 \\ 0.13-0.56 & 0.36-0.75 & 0.54-0.82 \end{pmatrix}$$

S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020

3σ

with unitarity
OSCILLATIONS

$$|U| = \begin{pmatrix} 0.79-0.88 & 0.47-0.61 & <0.20 \\ 0.19-0.52 & 0.42-0.73 & 0.58-0.82 \\ 0.20-0.53 & 0.44-0.74 & 0.56-0.81 \end{pmatrix}$$

M. C. González García hep-ph/0410030

Non-unitarity in future facilities

If we parametrize $N = (1+\varepsilon)\cdot U$ with $U \approx U_{PMNS}$

and

$$\varepsilon = \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$$P_{\alpha\beta} \approx \left| 2\varepsilon_{\alpha\beta} - i\sin(2\theta)\sin\left(\frac{\Delta m^2 L}{4E}\right)\right|^2$$

If L/E small

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If L/E small

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) - 2\,\mathrm{Im}(\varepsilon_{\alpha\beta})\sin(2\theta)\sin\left(\frac{\Delta m^2 L}{2E}\right) + 4\left|\varepsilon_{\alpha\beta}\right|^2$$

SM

CP violating interference

Zero dist. effect

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SM

CP violating interference

Zero dist. effect

At a Neutrino Factory of 50 GeV with L = 130 Km

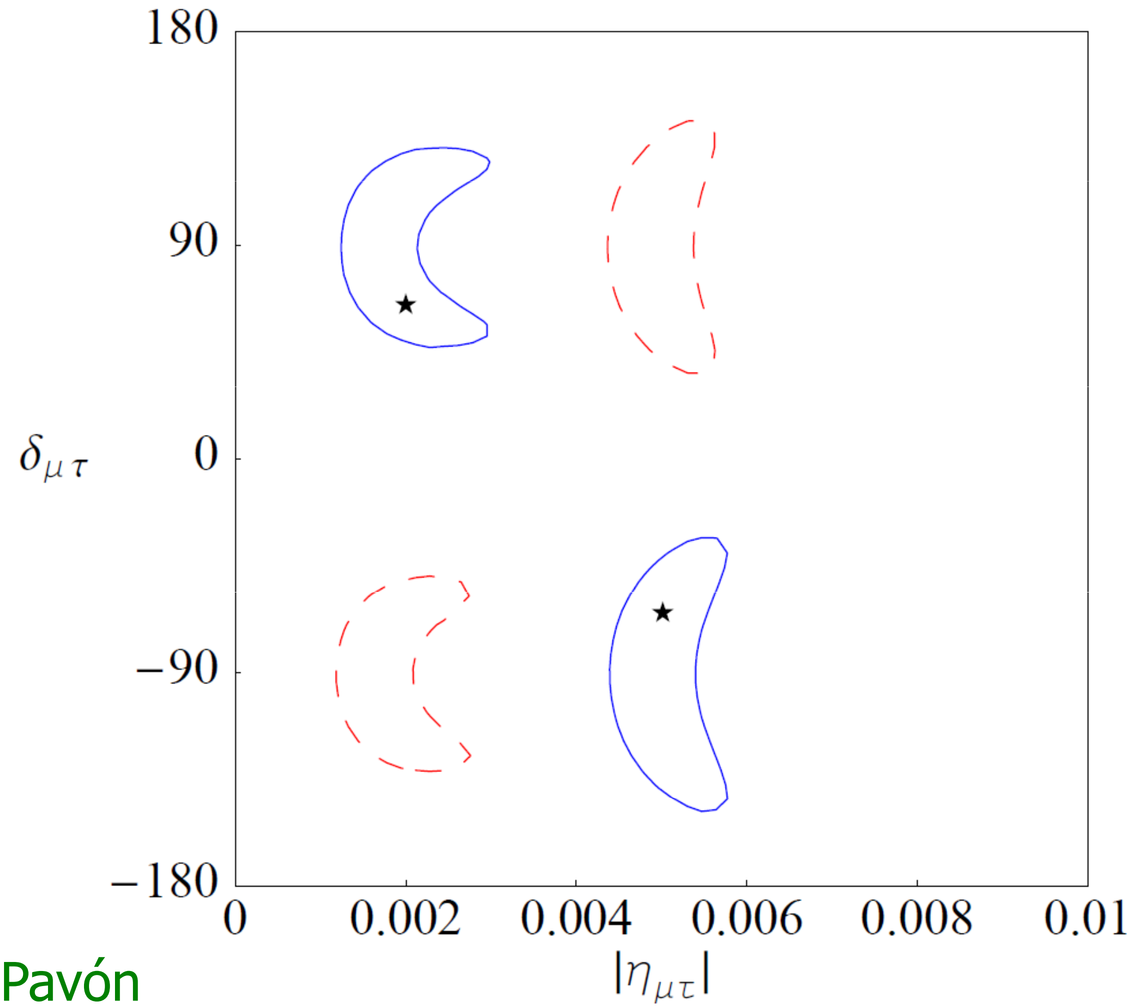
$$\sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) \approx 0.03 \longrightarrow$$

The SM background is suppressed

Measuring unitarity deviations

In $P_{\mu\tau}$ there is no $\sin\theta_{13}$ or Δ_{12} suppression

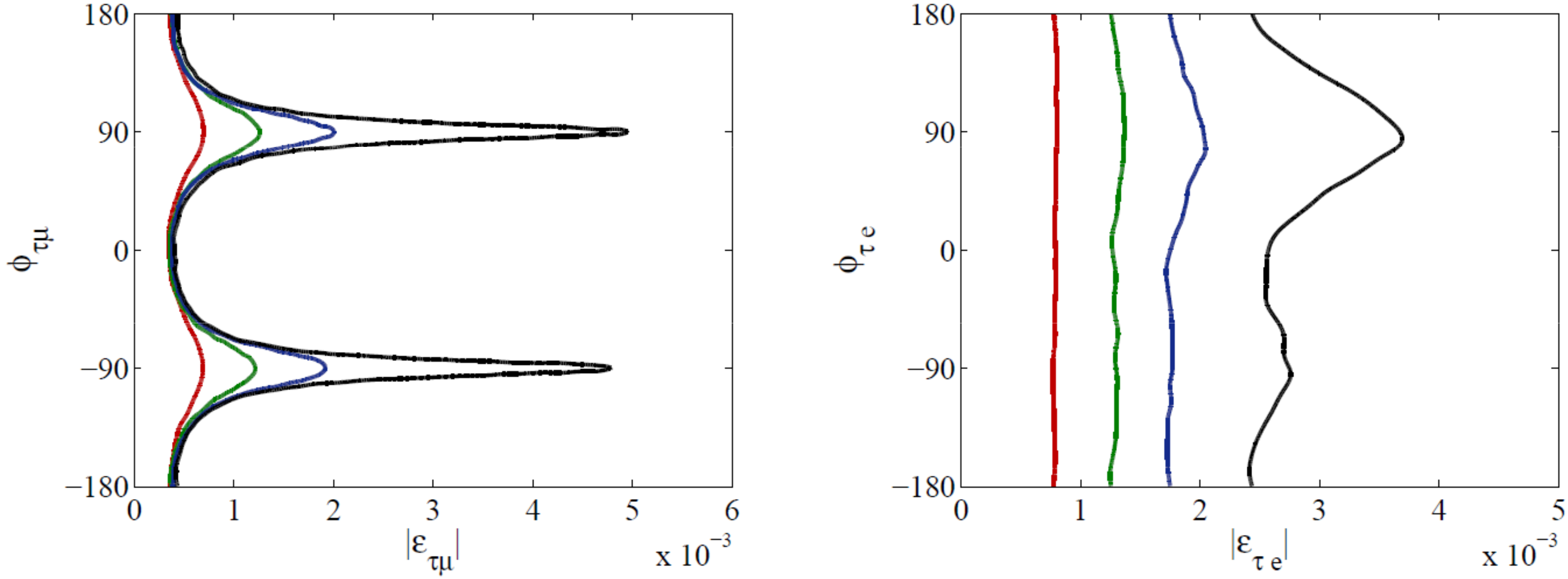
The CP phase $\delta_{\mu\tau}$ can be measured



EFM, B. Gavela, J. López Pavón and O. Yasuda hep-ph/0703098

See also S. Goswami and T. Ota 0802.1434

Non-Unitarity at a NF



Golden channel at NF 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,….

Non-unitarity and 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

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

$$\pi \rightarrow \mu + \nu_\beta$$

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

$$n + \nu_\beta \rightarrow p + l_\alpha$$

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$$n + \nu_\beta \longrightarrow p + l_\alpha$$

The general matrix N can be parameterized as:

$$N = (1+\varepsilon)U$$ where $$\varepsilon = \varepsilon^\dagger$$

Also gives $$|\nu_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}|\nu_\beta\rangle$$ but with $$\varepsilon_{\alpha\beta} = \varepsilon^*_{\beta\alpha}$$

Non-unitarity and NSI matter effects

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

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

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

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Integrating out the W and Z, 4-fermion operators are obtained also for the non-unitary mixing matrix

They are related to the production and detection NSI

Non-unitarity and NSI matter effects

Integrating out the W and Z, 4-fermion operators
for matter NSI are obtained from non-unitary mixing matrix

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

$$\varepsilon^m = \begin{pmatrix} \varepsilon_{ee}\left(n_n/n_e-2\right) & \varepsilon_{e\mu}\left(n_n/n_e-1\right) & \varepsilon_{e\tau}\left(n_n/n_e-1\right) \\ \varepsilon_{e\mu}\left(n_n/n_e-1\right) & \varepsilon_{\mu\mu}\, n_n/n_e & \varepsilon_{\mu\tau}\, n_n/n_e \\ \varepsilon_{e\tau}\left(n_n/n_e-1\right) & \varepsilon_{\mu\tau}\, n_n/n_e & \varepsilon_{\tau\tau}\, n_n/n_e \end{pmatrix}$$

They are related to the production and detection NSI

Non-unitarity and NSI

The bounds on

$$\left|NN^{\dagger}\right| = \left|(1+\varepsilon)^{2}\right| \approx \left|1+2\varepsilon\right|$$

Also apply to ε

$$|\varepsilon| \approx \begin{pmatrix} <2.5\cdot 10^{-3} & <3.6\cdot 10^{-5} & <8.0\cdot 10^{-3} \\ <3.6\cdot 10^{-5} & <2.5\cdot 10^{-3} & <5.0\cdot 10^{-3} \\ <8.0\cdot 10^{-3} & <5.0\cdot 10^{-3} & <2.5\cdot 10^{-3} \end{pmatrix}$$

Very strong bounds for NSI from non-unitarity…

…also for the related NSI in matter

Direct bounds on prod/det NSI

From μ, β, π decays and zero distance oscillations

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

$$\left|\varepsilon^{ud}\right| < \begin{pmatrix} 0.042 & 0.025 & 0.042 \\ 2.6\cdot 10^{-5} & 0.1 & 0.013 \\ 0.087 & 0.013 & 0.13 \end{pmatrix} \qquad \left|\varepsilon^{\mu e}\right| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

Bounds order $\sim 10^{-2}$

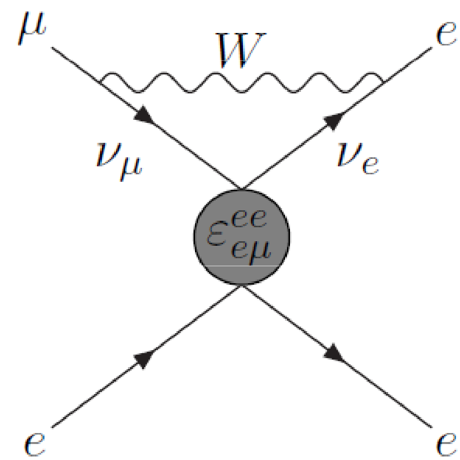
C. Biggio, M. Blennow and EFM 0907.0097

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

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

$$\left|\varepsilon^m\right| < \begin{pmatrix} 3.8 & 0.33 & 3.1 \\ 0.33 & 0.064 & 0.33 \\ 3.1 & 0.33 & 21 \end{pmatrix}$$

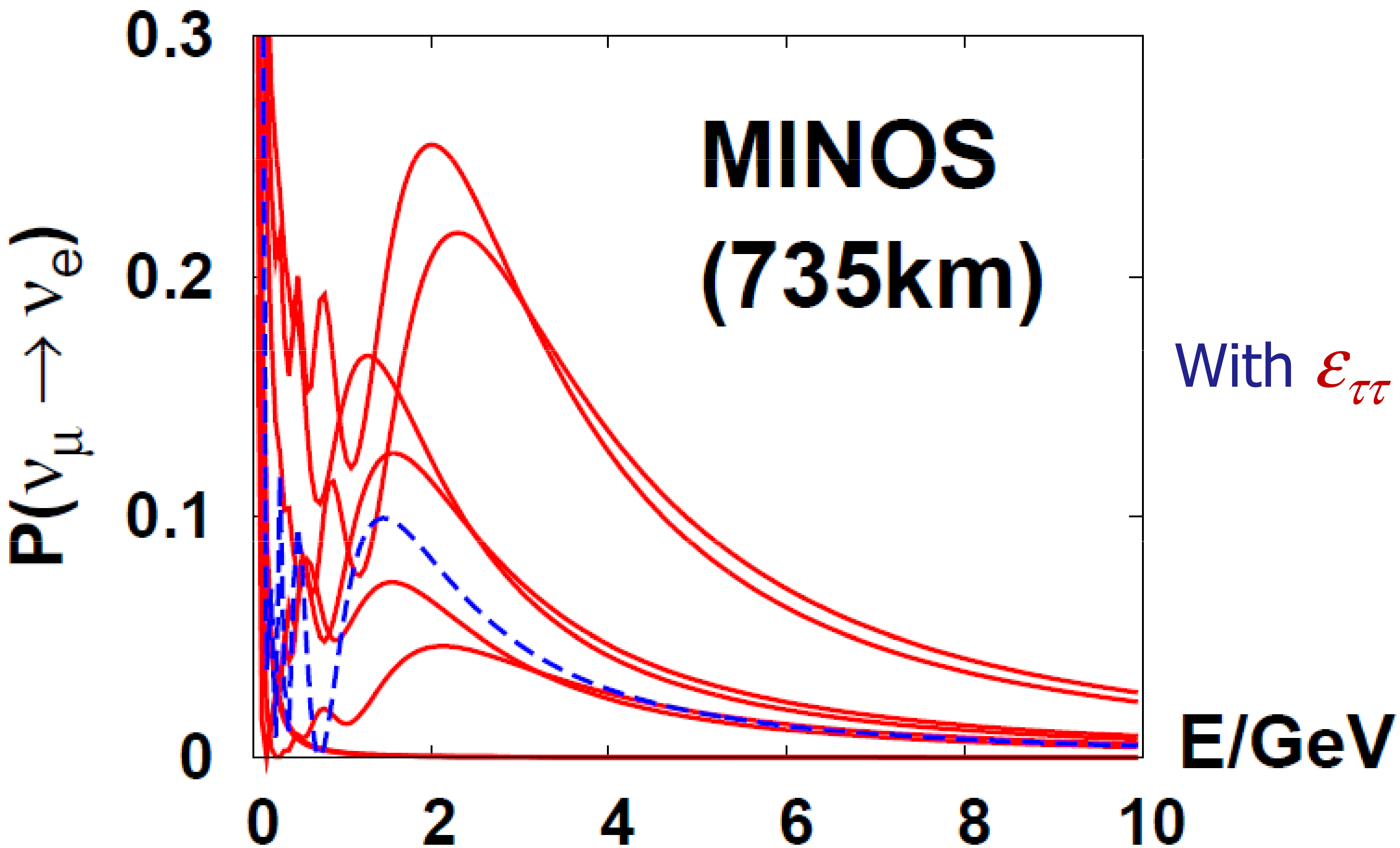


Rather weak bounds…

…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

Huge effects in ν oscillations



With $\varepsilon_{\tau\tau}$ and $\varepsilon_{e\tau}$ ~1

N. Kitazawa, H. Sugiyama and O. Yasuda hep-ph/0606013
See also M. Blennow, T. Ohlsson and J. Skrotzki hep-ph/0702059

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

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

$$\varepsilon^m_{e\tau} < \sim 10^{-2}$$

$$\varepsilon^m_{\mu\tau} < \sim 10^{-2}$$

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

S. Bergmann et al. hep-ph/0004049
Z. Berezhiani and A. Rossi hep-ph/0111147

Large NSI?

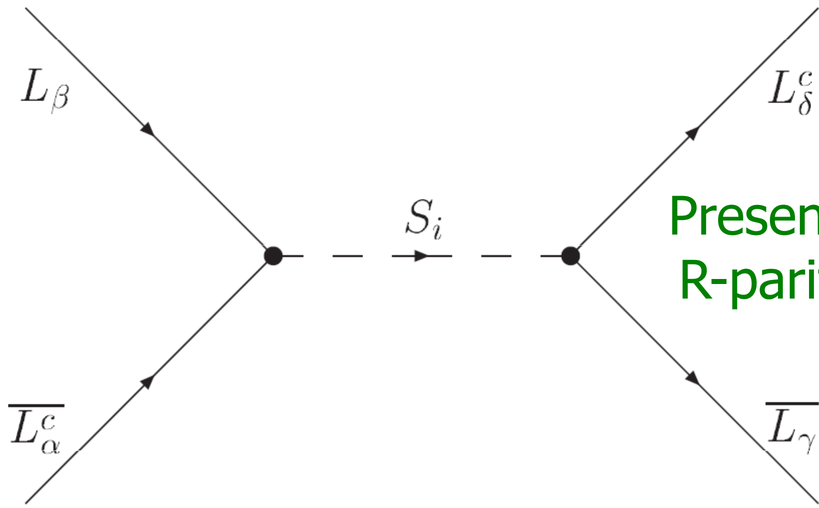
We search for gauge invariant SM extensions satisfying:

- 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

Large NSI?

At d=6 only one 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?

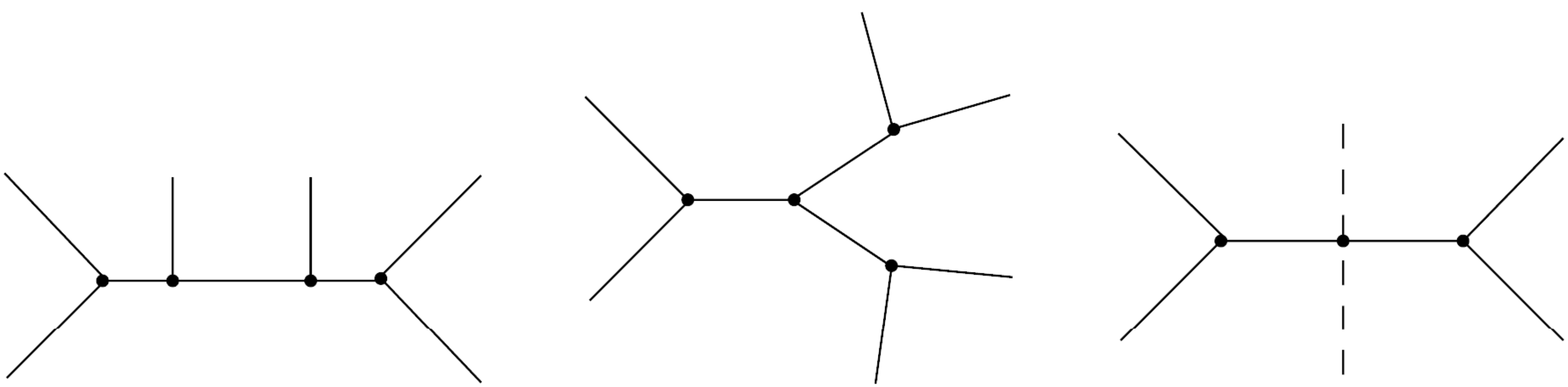
At d=8 more freedom

Can add 2 H to break the symmetry between ν and l with the vev

$$\left(\bar{L}_\beta i\sigma_2 H^*\right)\gamma^\mu\left(H^t i\sigma_2 L_\alpha\right)\left(\bar{f}\gamma_\mu f\right) \longrightarrow -v^2/2\ \left(\bar{\nu}_\beta\gamma^\mu\nu_\alpha\right)\left(\bar{f}\gamma_\mu f\right)$$

Z. Berezhiani and A. Rossi hep-ph/0111147; S. Davidson et al hep-ph/0302093

There are 3 topologies to induce effective d=8 ops with $HHLLff$ legs:



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

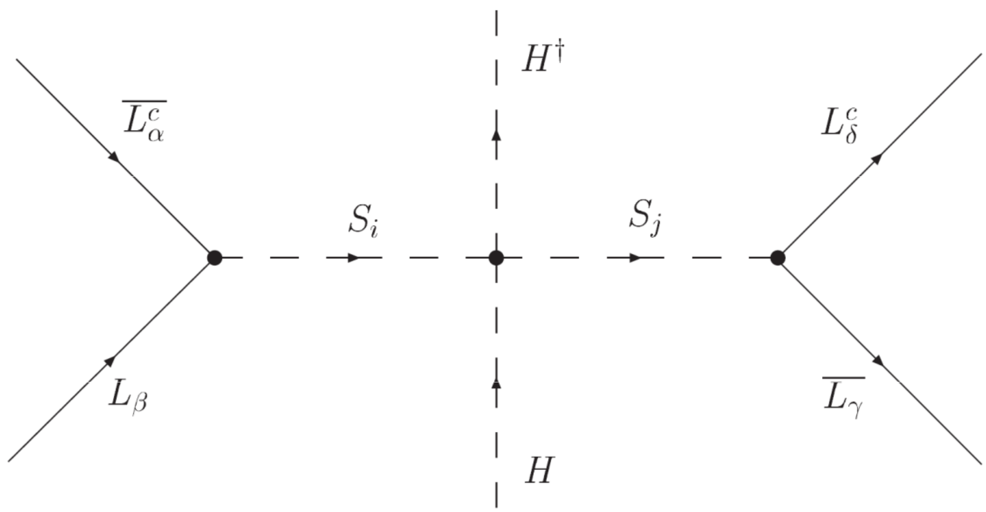
Large NSI?

We found three classes satisfying the requirements:

Large NSI?

We found three classes satisfying the requirements:

1



Just contributes to the scalar propagator after EWSB

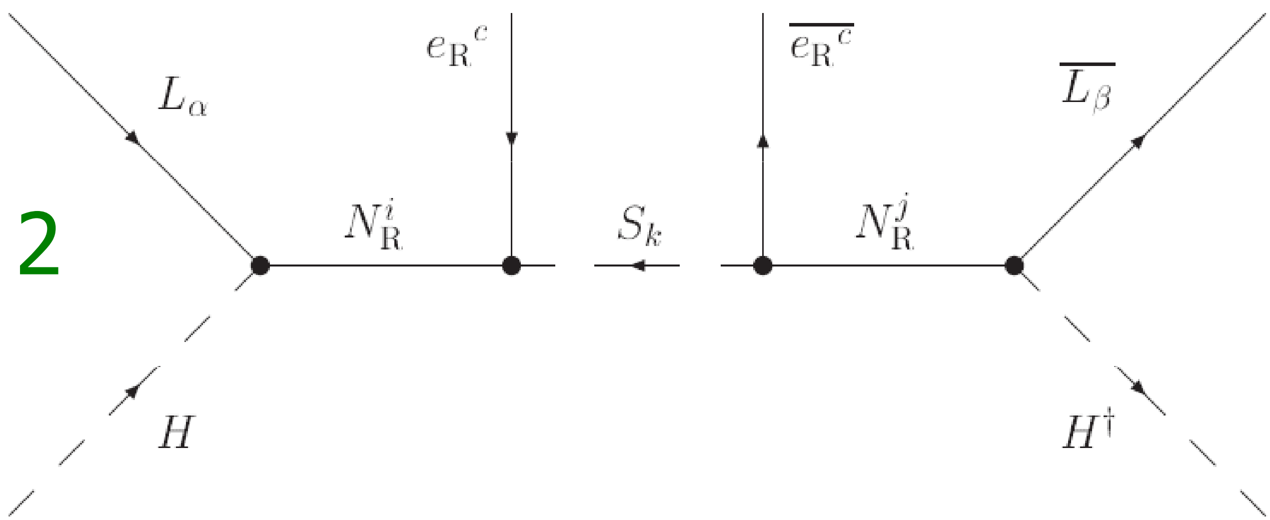
$$v^2/2\ \left(\overline{L^c_\alpha} i\sigma_2 L_\beta\right)\left(\overline{L_\gamma} i\sigma_2 L^c_\delta\right)$$

Same as the d=6 realization with the scalar singlet

Large NSI?

We found three classes satisfying the requirements:

2

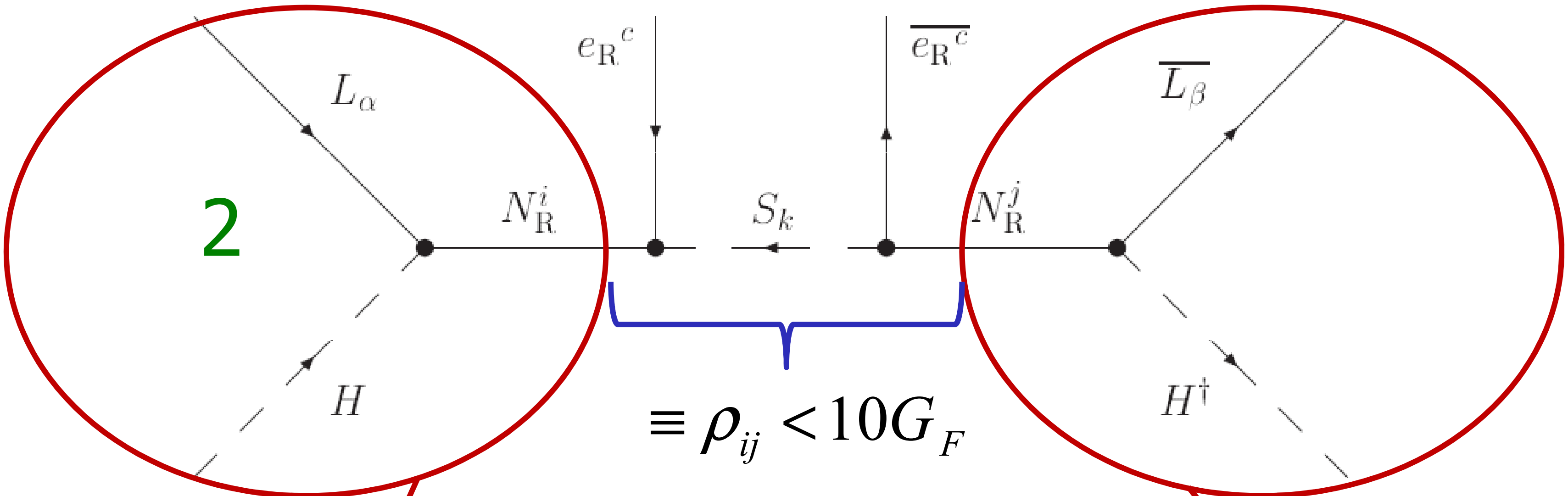


The Higgs coupled to the N_R selects ν after EWSB

$$\left(\bar{L}_\beta i\sigma_2 H^*\right)\gamma^\mu\left(H^t i\sigma_2 L_\alpha\right)\left(\bar{f}\gamma_\mu f\right) \longrightarrow -v^2/2\ \left(\bar{\nu}_\beta\gamma^\mu\nu_\alpha\right)\left(\bar{f}\gamma_\mu f\right)$$

Large NSI?

But can be related to non-unitarity and constrained



$$\frac{v}{\sqrt{2}}\sum_i \frac{Y_{\alpha i}}{M_i} < \sqrt{\frac{v^2}{2}\sum_i \left|\frac{Y_{\alpha i}}{M_i}\right|^2} = \sqrt{\left(NN^\dagger - 1\right)_{\alpha\alpha}}$$

$$\frac{v}{\sqrt{2}}\sum_j \frac{Y_{\beta j}}{M_j} < \sqrt{\frac{v^2}{2}\sum_j \left|\frac{Y_{\beta j}}{M_j}\right|^2} = \sqrt{\left(NN^\dagger - 1\right)_{\beta\beta}}$$

Large NSI?

For the matter NSI

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

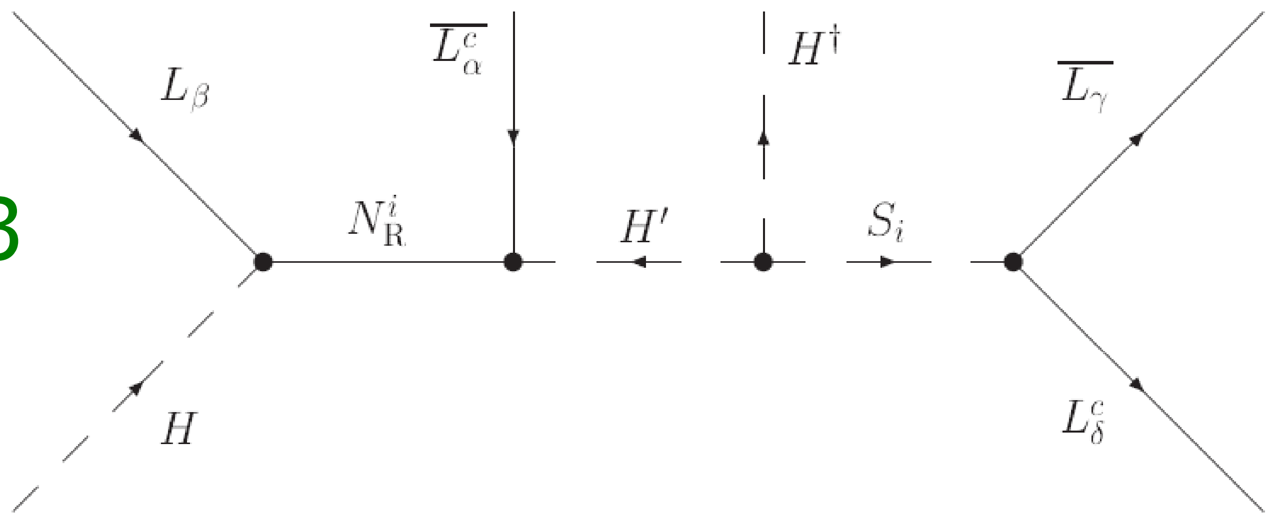
Where $\hat{\rho}^{(f)}$ is the largest eigenvalue of $\rho^{(f)}_{ij}$

And additional source, detector and matter NSI are generated through non-unitarity by the d=6 op

Large NSI?

We found three classes satisfying the requirements:

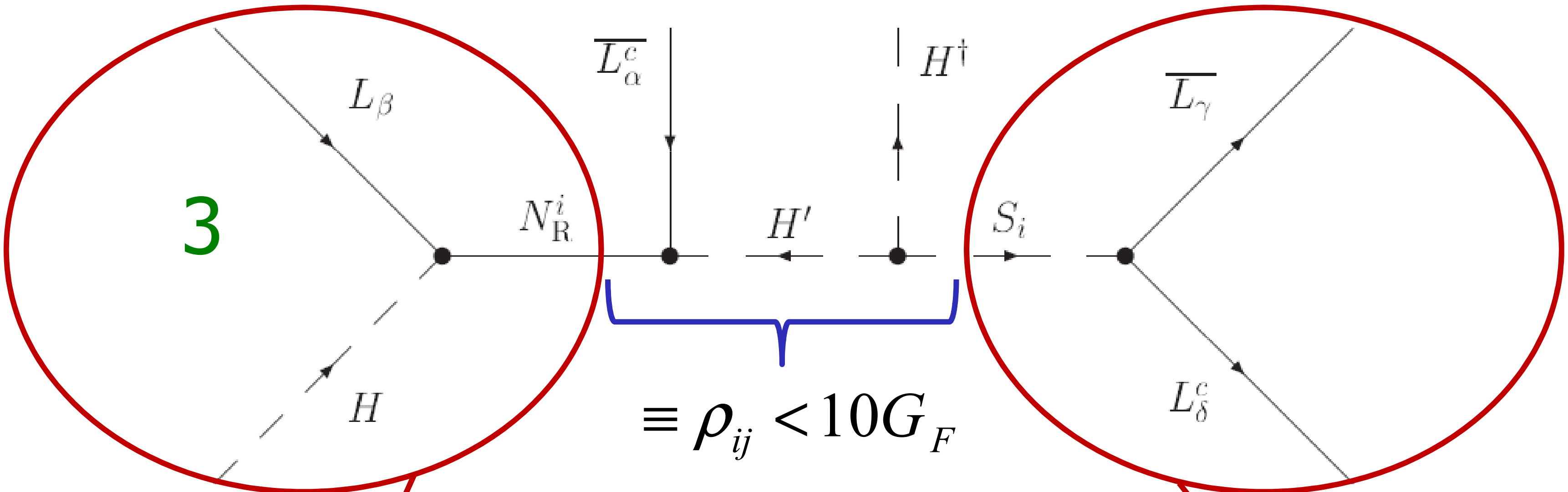
3



Mixed case, Higgs selects one ν and scalar singlet S the other

Large NSI?

Can be related to non-unitarity and the d=6 antisymmetric op



$$\frac{v}{\sqrt{2}}\sum_i \frac{Y_{\alpha i}}{M_i} < \sqrt{\frac{v^2}{2}\sum_i \left|\frac{Y_{\alpha i}}{M_i}\right|^2} = \sqrt{\left(NN^\dagger - 1\right)_{\alpha\alpha}}$$

$$v\sum_j \frac{\lambda^j_{\gamma\delta}}{M_{Sj}} < \sqrt{v^2 \sum_j \left|\frac{\lambda^j_{\gamma\delta}}{M_{Sj}}\right|^2}$$

Large NSI?

At d=8 we found no new ways of selecting ν

The d=6 constraints on non-unitarity and the scalar singlet apply also to the d=8 realizations

What if we allow for cancellations among diagrams?

B. Gavela, D. Hernández, T. Ota and W. Winter 0809.3451

Large NSI?

#	Dim. eight operator	$\mathcal{C}^1_{LEH}$	$\mathcal{C}^3_{LEH}$	$\mathcal{O}_{\rm NSI}$?	Mediators
Combination $\bar{L}L$					
1	$(\bar{L}\gamma^\rho L)(\bar{E}\gamma_\rho E)(H^\dagger H)$	1			$\mathbf{1}^v_0$
2	$(\bar{L}\gamma^\rho L)(\bar{E}H^\dagger)(\gamma_\rho)(HE)$	1			$\mathbf{1}^v_0 + 2^{L/R}_{-3/2}$
3	$(\bar{L}\gamma^\rho L)(\bar{E}H^T)(\gamma_\rho)(H^*E)$	1			$\mathbf{1}^v_0 + 2^{L/R}_{-1/2}$
4	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{E}\gamma_\rho E)(H^\dagger\vec{\tau}H)$		1		$\mathbf{3}^v_0 + \mathbf{1}^v_0$
5	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{E}H^\dagger)(\gamma_\rho\vec{\tau})(HE)$		1		$\mathbf{3}^v_0 + 2^{L/R}_{-3/2}$
6	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{E}H^T)(\gamma_\rho\vec{\tau})(H^*E)$		1		$\mathbf{3}^v_0 + 2^{L/R}_{-1/2}$
Combination $\bar{E}L$					
7	$(\bar{L}E)(\bar{E}L)(H^\dagger H)$	$-1/2$			$\mathbf{2}^s_{+1/2}$
8	$(\bar{L}E)(\vec{\tau})(\bar{E}L)(H^\dagger\vec{\tau}H)$		$-1/2$		$\mathbf{2}^s_{+1/2}$
9	$(\bar{L}H)(H^\dagger E)(\bar{E}L)$	$-1/4$	$-1/4$	✓	$\mathbf{2}^s_{+1/2} + 1^R_0 + 2^{L/R}_{-1/2}$
10	$(\bar{L}\vec{\tau}H)(H^\dagger E)(\vec{\tau})(\bar{E}L)$	$-3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_0 + 2^{L/R}_{-1/2}$
11	$(\bar{L}\mathrm{i}\tau^2H^*)(H^TE)(\mathrm{i}\tau^2)(\bar{E}L)$	$1/4$	$-1/4$		$\mathbf{2}^s_{+1/2} + 1^{L/R}_{-1} + 2^{L/R}_{-3/2}$
12	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2H^*)(H^TE)(\mathrm{i}\tau^2\vec{\tau})(\bar{E}L)$	$3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_{-1} + 2^{L/R}_{-3/2}$
Combination $\overline{E^c}L$					
13	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}\gamma_\rho L)(H^\dagger H)$	-1			$\mathbf{2}^v_{-3/2}$
14	$(\bar{L}\gamma^\rho E^c)(\vec{\tau})(\overline{E^c}\gamma_\rho L)(H^\dagger\vec{\tau}H)$		-1		$\mathbf{2}^v_{-3/2}$
15	$(\bar{L}H)(\gamma^\rho)(H^\dagger E^c)(\overline{E^c}\gamma_\rho L)$	$-1/2$	$-1/2$	✓	$\mathbf{2}^v_{-3/2} + 1^R_0 + 2^{L/R}_{+3/2}$
16	$(\bar{L}\vec{\tau}H)(\gamma^\rho)(H^\dagger E^c)(\vec{\tau})(\overline{E^c}\gamma_\rho L)$	$-3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_0 + 2^{L/R}_{+3/2}$
17	$(\bar{L}\mathrm{i}\tau^2H^*)(\gamma^\rho)(H^TE^c)(\mathrm{i}\tau^2)(\overline{E^c}\gamma_\rho L)$	$-1/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 1^{L/R}_{-1} + 2^{L/R}_{+1/2}$
18	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2H^*)(\gamma^\rho)(H^TE^c)(\mathrm{i}\tau^2\vec{\tau})(\overline{E^c}\gamma_\rho L)$	$-3/2$	$-1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_{-1} + 2^{L/R}_{+1/2}$
Combination $H^\dagger L$					
19	$(\bar{L}E)(\bar{E}H)(H^\dagger L)$	$-1/4$	$-1/4$	✓	$\mathbf{2}^s_{+1/2} + 1^R_0 + 2^{L/R}_{-1/2}$
20	$(\bar{L}E)(\vec{\tau})(\bar{E}H)(H^\dagger\vec{\tau}L)$	$-3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_0 + 2^{L/R}_{-1/2}$
21	$(\bar{L}H)(\gamma^\rho)(H^\dagger L)(\bar{E}\gamma_\rho E)$	$1/2$	$1/2$	✓	$\mathbf{1}^v_0 + 1^R_0$
22	$(\bar{L}\vec{\tau}H)(\gamma^\rho)(H^\dagger\vec{\tau}L)(\bar{E}\gamma_\rho E)$	$3/2$	$-1/2$		$\mathbf{1}^v_0 + 3^{L/R}_0$
23	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	$-1/2$	$-1/2$	✓	$\mathbf{2}^v_{-3/2} + 1^R_0 + 2^{L/R}_{+3/2}$
24	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	$-3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_0 + 2^{L/R}_{+3/2}$
Combination HL					
25	$(\bar{L}E)(\mathrm{i}\tau^2)(\bar{E}H^*)(H^T\mathrm{i}\tau^2L)$	$1/4$	$-1/4$		$\mathbf{2}^s_{+1/2} + 1^{L/R}_{-1} + 2^{L/R}_{-3/2}$
26	$(\bar{L}E)(\vec{\tau}\mathrm{i}\tau^2)(\bar{E}H^*)(H^T\mathrm{i}\tau^2\vec{\tau}L)$	$3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_{-1} + 2^{L/R}_{-3/2}$
27	$(\bar{L}\mathrm{i}\tau^2H^*)(\gamma^\rho)(H^T\mathrm{i}\tau^2L)(\bar{E}\gamma_\rho E)$	$-1/2$	$1/2$		$\mathbf{1}^v_0 + 1^{L/R}_{-1}$
28	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2H^*)(\gamma^\rho)(H^T\mathrm{i}\tau^2\vec{\tau}L)(\bar{E}\gamma_\rho E)$	$-3/2$	$-1/2$		$\mathbf{1}^v_0 + 3^{L/R}_{-1}$
29	$(\bar{L}\gamma^\rho E^c)(\mathrm{i}\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2L)$	$1/2$	$-1/2$		$\mathbf{2}^v_{-3/2} + 1^{L/R}_{-1} + 2^{L/R}_{+1/2}$
30	$(\bar{L}\gamma^\rho E^c)(\vec{\tau}\mathrm{i}\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2\vec{\tau}L)$	$3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_{-1} + 2^{L/R}_{+1/2}$

#	Dim. eight operator	$\mathcal{C}^{111}_{LLH}$	$\mathcal{C}^{331}_{LLH}$	$\mathcal{C}^{133}_{LLH}$	$\mathcal{C}^{313}_{LLH}$	$\mathcal{C}^{333}_{LLH}$	$\mathcal{O}_{\rm NSI}$?	Mediators
Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta L_\gamma)(H^\dagger H)$								
31	$(\bar{L}\gamma^\rho L)(\bar{L}\gamma_\rho L)(H^\dagger H)$	1						$\mathbf{1}^v_0$
32	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{L}\gamma_\rho\vec{\tau}L)(H^\dagger H)$		1					$\mathbf{3}^v_0$
33	$(\bar{L}\gamma^\rho L)(\bar{L}\gamma_\rho\vec{\tau}L)(H^\dagger\vec{\tau}H)$			1				$\mathbf{1}^v_0 + \mathbf{3}^v_0$
34	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{L}\gamma_\rho L)(H^\dagger\vec{\tau}H)$				1			$\mathbf{1}^v_0 + \mathbf{3}^v_0$
35	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\gamma^\rho\tau^aL)\times$ $(\bar{L}\gamma_\rho\tau^bL)(H^\dagger\tau^cH)$					1	✓	$\mathbf{3}^v_0$
Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta H)(H^\dagger L_\gamma)$								
36	$(\bar{L}\gamma^\rho L)(\bar{L}H)(\gamma_\rho)(H^\dagger L)$	$1/2$		$1/2$			✓	$\mathbf{1}^v_0 + 1^R_0$
37	$(\bar{L}\gamma^\rho L)(\bar{L}\vec{\tau}H)(\gamma_\rho)(H^\dagger\vec{\tau}L)$	$3/2$		$-1/2$				$\mathbf{1}^v_0 + 3^{L/R}_0$
38	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{L}\vec{\tau}H)(\gamma_\rho)(H^\dagger L)$		$1/2$		$1/2$	$1/2$	✓	$\mathbf{1}^v_0 + 1^R_0 + 3^{L/R}_0$
39	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{L}H)(\gamma_\rho)(H^\dagger\vec{\tau}L)$		$1/2$		$1/2$	$-1/2$	✓	$\mathbf{1}^v_0 + 1^R_0 + 3^{L/R}_0$
40	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\gamma^\rho\tau^aL)\times$ $(\bar{L}\tau^bH)(\gamma_\rho)(H^\dagger\tau^cL)$		1		-1			$\mathbf{3}^v_0 + 1^R_0 + 3^{L/R}_0$
Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta H^\dagger)(L_\gamma H)$								
41	$(\bar{L}\gamma^\rho L)(\bar{L}\mathrm{i}\tau^2H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2L)$	$-1/2$		$1/2$				$\mathbf{1}^v_0 + 1^{L/R}_{-1}$
42	$(\bar{L}\gamma^\rho L)(\bar{L}\vec{\tau}\mathrm{i}\tau^2H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2\vec{\tau}L)$	$-3/2$		$-1/2$				$\mathbf{1}^v_0 + 3^{L/R}_{-1}$
43	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{L}\vec{\tau}\mathrm{i}\tau^2H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2L)$		$-1/2$		$1/2$	$1/2$		$\mathbf{3}^v_0 + 1^{L/R}_{-1} + 3^{L/R}_{-1}$
44	$(\bar{L}\gamma^\rho\vec{\tau}L)(\bar{L}\mathrm{i}\tau^2H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2\vec{\tau}L)$		$-1/2$		$1/2$	$-1/2$		$\mathbf{3}^v_0 + 1^{L/R}_{-1} + 3^{L/R}_{-1}$
45	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\gamma^\rho\tau^aL)\times$ $(\bar{L}\tau^b\mathrm{i}\tau^2H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2\tau^cL)$		-1		-1		✓	$\mathbf{3}^v_0 + 3^{L/R}_{-1}$
Combination $(\bar{L}^\beta(L^c)^\delta)((\overline{L^c})_\alpha L_\gamma)(H^\dagger H)$								
46	$(\bar{L}\mathrm{i}\tau^2L^c)(\overline{L^c}\mathrm{i}\tau^2L)(H^\dagger H)$	$1/4$	$-1/4$				✓	$\mathbf{1}^s_{-1}$
47	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2L^c)(\overline{L^c}\mathrm{i}\tau^2\vec{\tau}L)(H^\dagger H)$	$-3/4$	$-1/4$					$\mathbf{3}^s_{-1}$
48	$(\bar{L}\mathrm{i}\tau^2L^c)(\overline{L^c}\mathrm{i}\tau^2\vec{\tau}L)(H^\dagger\vec{\tau}H)$			$1/4$	$-1/4$	$-1/4$	✓	$\mathbf{1}^s_{-1} + \mathbf{3}^s_{-1}$
49	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2L^c)(\overline{L^c}\mathrm{i}\tau^2L)(H^\dagger\vec{\tau}H)$			$-1/4$	$1/4$	$-1/4$	✓	$\mathbf{1}^s_{-1} + \mathbf{3}^s_{-1}$
50	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\tau^a\mathrm{i}\tau^2L^c)\times$ $(\overline{L^c}\mathrm{i}\tau^2\tau^bL)(H^\dagger\tau^cH)$			$-1/2$	$-1/2$			$\mathbf{3}^s_{-1}$
Combination $(\bar{L}^\beta H^\dagger)((L^c)^\delta H)((\overline{L^c})_\alpha L_\gamma)$								
51	$(\bar{L}\mathrm{i}\tau^2H^*)(H^TL^c)(\overline{L^c}\mathrm{i}\tau^2L)$	$1/8$	$-1/8$	$1/8$	$-1/8$	$1/8$	✓	$\mathbf{1}^s_{-1} + 1^L_0 + 1^{L/R}_{-1}$
52	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2H^*)(H^TL^c\vec{\tau})(\overline{L^c}\mathrm{i}\tau^2L)$	$-3/8$	$3/8$	$1/8$	$-1/8$	$1/8$	✓	$\mathbf{1}^s_{-1} + 3^{L/R}_0 + 1^{L/R}_{-1}$
53	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2H^*)(H^TL^c)(\overline{L^c}\mathrm{i}\tau^2\vec{\tau}L)$	$-3/8$	$-1/8$	$-3/8$	$-1/8$	$1/8$	✓	$\mathbf{3}^s_{-1} + 1^L_0 + 3^{L/R}_{-1}$
54	$(\bar{L}\mathrm{i}\tau^2H^*)(H^T\vec{\tau}L^c)(\overline{L^c}\mathrm{i}\tau^2\vec{\tau}L)$	$3/8$	$1/8$	$-1/8$	$-3/8$	$-1/8$		$\mathbf{3}^s_{-1} + 3^{L/R}_0 + 1^{L/R}_{-1}$
55	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\tau^a\mathrm{i}\tau^2H^*)\times$ $(H^T\tau^bL^c)(\overline{L^c}\mathrm{i}\tau^2\tau^cL)$	$3/4$	$1/4$	$-1/4$	$1/4$	$1/4$		$\mathbf{3}^s_{-1} + 3^{L/R}_0 + 1^{L/R}_{-1}$
Combination $(\bar{L}^\beta(L^c)^\delta)(H^\dagger(\overline{L^c})_\alpha)(L_\gamma H)$								
56	$(\bar{L}\mathrm{i}\tau^2L^c)(\overline{L^c}H^*)(H^T\mathrm{i}\tau^2L)$	$1/8$	$-1/8$	$-1/8$	$1/8$	$1/8$	✓	$\mathbf{1}^s_{-1} + 1^L_0 + 1^{L/R}_{-1}$
57	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2L^c)(\overline{L^c}\vec{\tau}H^*)(H^T\mathrm{i}\tau^2L)$	$3/8$	$1/8$	$-3/8$	$-1/8$	$-1/8$		$\mathbf{3}^s_{-1} + 3^{L/R}_0 + 1^{L/R}_{-1}$
58	$(\bar{L}\mathrm{i}\tau^2L^c)(\overline{L^c}\vec{\tau}H^*)(H^T\mathrm{i}\tau^2\vec{\tau}L)$	$-3/8$	$3/8$	$-1/8$	$1/8$	$1/8$	✓	$\mathbf{1}^s_{-1} + 3^{L/R}_0 + 3^{L/R}_{-1}$
59	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2L^c)(\overline{L^c}H^*)(H^T\mathrm{i}\tau^2\vec{\tau}L)$	$-3/8$	$-1/8$	$-1/8$	$-3/8$	$1/8$	✓	$\mathbf{3}^s_{-1} + 1^L_0 + 3^{L/R}_{-1}$
60	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\tau^a\mathrm{i}\tau^2L^c)\times$ $(\overline{L^c}\tau^bH^*)(H^T\mathrm{i}\tau^2\tau^cL)$	$3/4$	$1/4$	$1/4$	$-1/4$	$1/4$		$\mathbf{3}^s_{-1} + 3^{L/R}_0 + 3^{L/R}_{-1}$

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Large NSI?

#	Dim. eight operator	$\mathcal{C}^{111}_{LLH}$	$\mathcal{C}^{331}_{LLH}$	$\mathcal{C}^{133}_{LLH}$	$\mathcal{C}^{313}_{LLH}$	$\mathcal{C}^{333}_{LLH}$	$\mathcal{O}_{\mathrm{NSI}}$?	Mediators
Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta L_\gamma)(H^\dagger H)$								
31	$(\bar{L}\gamma^\rho L)(\bar{L}\gamma_\rho L)(H^\dagger H)$	1						$\mathbf{1}^v_0$
32	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\gamma_\rho \vec{\tau} L)(H^\dagger H)$		1					$\mathbf{3}^v_0$
33	$(\bar{L}\gamma^\rho L)(\bar{L}\gamma_\rho \vec{\tau} L)(H^\dagger \vec{\tau} H)$			1				$\mathbf{1}^v_0 + \mathbf{3}^v_0$
34	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\gamma_\rho L)(H^\dagger \vec{\tau} H)$				1			$\mathbf{1}^v_0 + \mathbf{3}^v_0$
35	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\gamma^\rho \tau^a L)\times$ $(\bar{L}\gamma_\rho \tau^b L)(H^\dagger \tau^c H)$					1	✓	$\mathbf{3}^v_0$
Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta H)(H^\dagger L_\gamma)$								
36	$(\bar{L}\gamma^\rho L)(\bar{L}H)(\gamma_\rho)(H^\dagger L)$	1/2		1/2			✓	$\mathbf{1}^v_0 + 1^R_0$
37	$(\bar{L}\gamma^\rho L)(\bar{L}\vec{\tau} H)(\gamma_\rho)(H^\dagger \vec{\tau} L)$	3/2		$-1/2$				$\mathbf{1}^v_0 + 3^{L/R}_0$
38	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\vec{\tau} H)(\gamma_\rho)(H^\dagger L)$		1/2		1/2	1/2	✓	$\mathbf{1}^v_0 + 1^R_0 + 3^{L/R}_0$
39	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}H)(\gamma_\rho)(H^\dagger \vec{\tau} L)$		1/2		1/2	$-1/2$	✓	$\mathbf{1}^v_0 + 1^R_0 + 3^{L/R}_0$
40	$(-\mathrm{i}\epsilon^{abc})(\bar{L}\gamma^\rho \tau^a L)\times$ $(\bar{L}\tau^b H)(\gamma_\rho)(H^\dagger \tau^c L)$		1		-1			$\mathbf{3}^v_0 + 1^R_0 + 3^{L/R}_0$

tick means selects ν at d=8 without 4-charged fermion

bold means induces 4-charged fermion at d=6, have to cancel it!!

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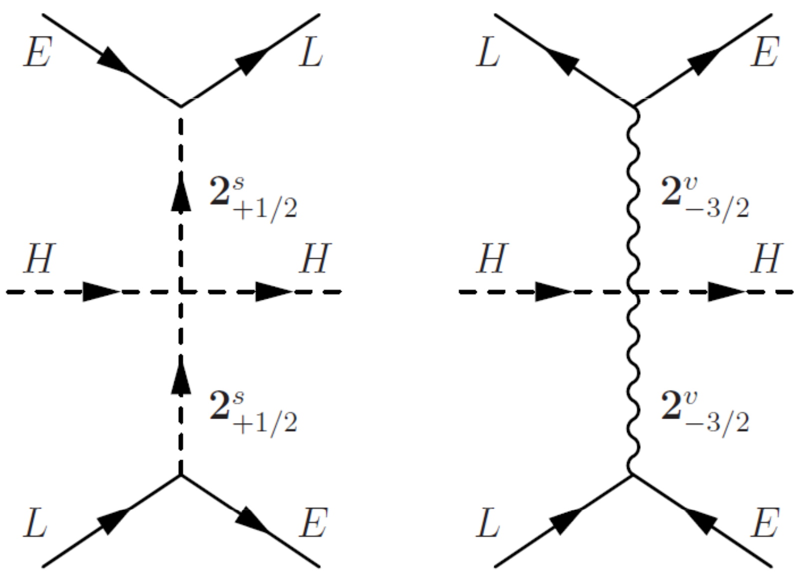
Large NSI?

There is always a 4 charged fermion op that needs canceling

Toy model

$$\mathscr{L} = \mathscr{L}_{\rm SM} - (y)_\beta{}^\gamma\,(\bar{L}^\beta)^i E_\gamma \Phi_i - (g)_{\beta\delta}\,(\bar{L}^\beta)^i \gamma^\rho (E^c)^\delta (V_\rho)_i$$
$$+ \lambda_{\mathbf{1}s}(H^\dagger H)(\Phi^\dagger\Phi) + \lambda_{\mathbf{3}s}(H^\dagger \vec{\tau} H)(\Phi^\dagger \vec{\tau}\Phi)$$
$$+ \lambda_{\mathbf{1}v}(H^\dagger H)(V_\rho^\dagger V^\rho) + \lambda_{\mathbf{3}v}(H^\dagger \vec{\tau} H)(V_\rho^\dagger \vec{\tau} V^\rho) + \text{h.c.} + \ldots$$



Cancelling the 4-charged fermion ops.

$$-2(g^\dagger)^{\gamma\alpha}(g)_{\beta\delta} + (y^\dagger)_\delta{}^\alpha (y)_\beta{}^\gamma = 0$$

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

$$\downarrow$$

$$\left(\overline{L}_\alpha i\sigma_2 H^*\right)\gamma^\mu\left(H^t i\sigma_2 L_\beta\right)\left(\overline{E}_\gamma \gamma_\mu E_\delta\right)$$

B. Gavela, D. Hernández, T. Ota and W. Winter 0809.3451

NSI in loops

Even if we arrange to have

$$\frac{O}{M^4}\left(\overline{L}_\alpha i\sigma_2 H^*\right)\gamma^\mu\left(H^t i\sigma_2 L_\beta\right)\left(\overline{E}_\gamma\gamma_\mu E_\delta\right)$$

$$=\frac{O}{2M^4}\left[\left(\overline{L}_\alpha\gamma^\mu L_\beta\right)\left(H^\dagger H\right)-\left(\overline{L}_\alpha\gamma^\mu\vec{\tau}L_\beta\right)\left(H^\dagger\vec{\tau}H\right)\right]\left(\overline{E}_\gamma\gamma_\mu E_\delta\right)$$

C. Biggio, M. Blennow and EFM 0902.0607

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We can close the Higgs loop, the triplet terms vanishes and

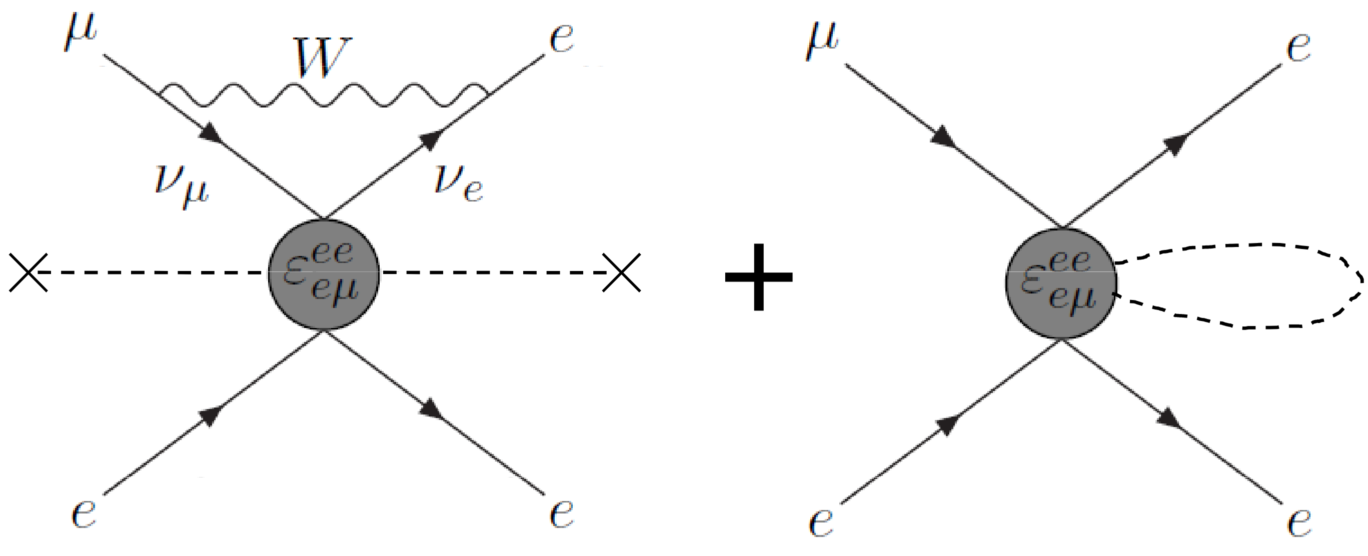
$$\frac{O}{2M^4}\frac{k\Lambda^2}{16\pi^2}\left(\overline{L}_\alpha\gamma^\mu L_\beta\right)\left(\overline{E}_\gamma\gamma_\mu E_\delta\right)$$

NSIs and 4 charged fermion ops induced with equal strength

C. Biggio, M. Blennow and EFM 0902.0607

NSI in loops

This loop has to be added to:



Used to set loop bounds on $\varepsilon_{e\mu}$ through the log divergence

However the log cancels when adding the diagrams…

C. Biggio, M. Blennow and EFM 0902.0607

NSI in loops

$$\frac{O}{2M^4}\frac{k\Lambda^2}{16\pi^2}\left(\overline{L}_\alpha\gamma^\mu L_\beta\right)\left(\overline{E}_\gamma\gamma_\mu E_\delta\right)$$

The loop contribution is a quadratic divergence

The coefficient k depends on the full theory completion

If no new physics below NSI scale $\Lambda = M$

Extra fine-tuning required at loop level to have k=0 or loop contribution dominates when $1/16\pi^2 > v^2/M^2$

C. Biggio, M. Blennow and EFM 0902.0607

Conclusions: non-unitarity

- SM extensions to accommodate ν masses often lead to a non-unitary lepton mixing matrix

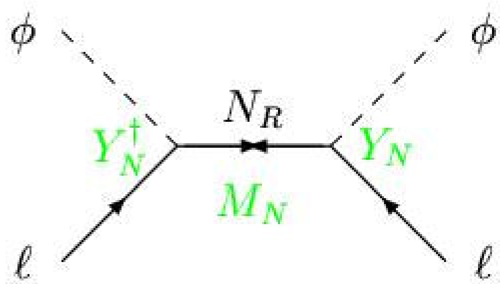
    - Present oscillation data can only measure half the matrix elements
    - Deviations from unitarity tightly constrained by decays
        - All matrix elements can be measured
        - Future facilities still sensitive to unitary deviations

- Non-unitarity is a particular realization of NSI, but very constrained

Conclusions: NSI

- Models leading "naturally" to NSI imply:
  - $O(10^{-2}$-$10^{-3})$ 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 excellent probes
- Saturating the mild model-independent bounds on matter NSI and decoupling them from production/detection requires strong fine tuning

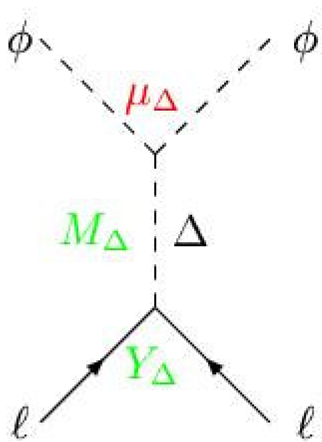
Other models for ν masses



Type I seesaw

Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, …

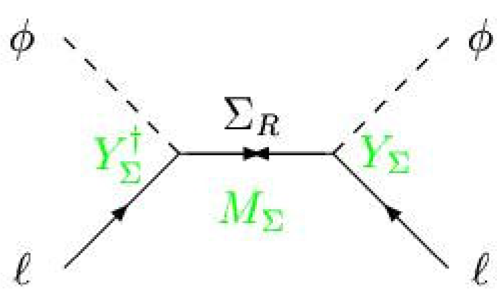
N_R fermionic singlet



Type II seesaw

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle, …

Δ scalar triplet



Type III seesaw

Foot, Lew, He, Joshi, Ma, Roy, Hambye et al., Bajc et al., Dorsner, Fileviez-Perez

Σ_R fermionic triplet

Different d=6 ops

Type I: $$c^{d=6}_{\alpha\beta}\left(\overline{\ell_{L\alpha}}\tilde{\phi}\right) i\not\partial\left(\tilde{\phi}^\dagger \ell_{L\beta}\right)$$

- non-unitary mixing in CC
- FCNC for ν

Type III: $$c^{d=6}_{\alpha\beta}\left(\overline{\ell_{L\alpha}}\vec{\tau}\tilde{\phi}\right) i\not D\left(\tilde{\phi}^\dagger\vec{\tau}\ell_{L\beta}\right)$$

- non-unitary mixing in CC
- FCNC for ν
- FCNC for charged leptons

Type II: $$\delta\mathcal{L}_{4F} = \frac{1}{{M_\Delta}^2}\left(\overline{\tilde{\ell}_L}\, Y_\Delta\, \vec{\tau}\ell_L\right)\left(\overline{\ell_L}\vec{\tau}\, Y_\Delta^\dagger\, \tilde{\ell}_L\right)$$

- LFV 4-fermions interactions

A. Abada, C. Biggio, F. Bonnet, B. Gavela and T. Hambye 0707.4058

Types II and III induce flavour violation in the charged lepton sector
Stronger constraints than in Type I

Low scale seesaws

But

$$d_5 = m_\nu = m_D^t M_N^{-1} m_D \quad \text{so}$$

$$d_6 = m_D^\dagger M_N^{-2} m_D \approx \frac{m_\nu}{M_N} \quad \text{!!!}$$

Low scale seesaws

The d=5 and d=6 operators are independent

Approximate $U(1)_L$ symmetry can keep d=5 (neutrino mass) small and allow for observable d=6 effects

See e.g. A. Abada, C. Biggio, F. Bonnet, B. Gavela and T. Hambye 0707.4058

Low scale seesaws

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Approximate $U(1)_L$ symmetry can keep d=5 (neutrino mass) small and allow for observable d=6 effects

See e.g. A. Abada, C. Biggio, F. Bonnet, B. Gavela and T. Hambye 0707.4058

Inverse (Type I) seesaw $\mu << M$

$$\begin{array}{cc} \text{L=} & \begin{array}{ccc} 1 & -1 & 1 \end{array} \\ & \begin{pmatrix} 0 & m_{D_1} & 0 \\ m_{D_1} & 0 & M_{N_1} \\ 0 & M_{N_1} & \mu \end{pmatrix} \end{array}$$

$$d_5 = m_D^t M_N^{-1} \mu M_N^{-1} m_D$$

$$d_6 = m_D^\dagger M_N^{-2} m_D$$

Wyler, Wolfenstein, Mohapatra, Valle, Bernabeu, Santamaría, Vidal, Mendez, González-García, Branco, Grimus, Lavoura, Kersten, Smirnov,….

Type II seesaw

$$\overline{\widetilde{\ell_L}} Y_\Delta (\overrightarrow{\tau} \cdot \overrightarrow{\Delta})\, \ell_L \quad \mu_\Delta \widetilde{\phi}^\dagger (\overrightarrow{\tau} \cdot \overrightarrow{\Delta})^\dagger \phi$$

$$d_5 = 4\mu_\Delta \frac{Y_\Delta}{M_\Delta^2} \qquad d_6 = \frac{Y_\Delta Y_\Delta^\dagger}{M_\Delta^2}$$

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle,…

N elements from oscillations: μ-row

Atmospheric + K2K: $\Delta_{12} \approx 0$

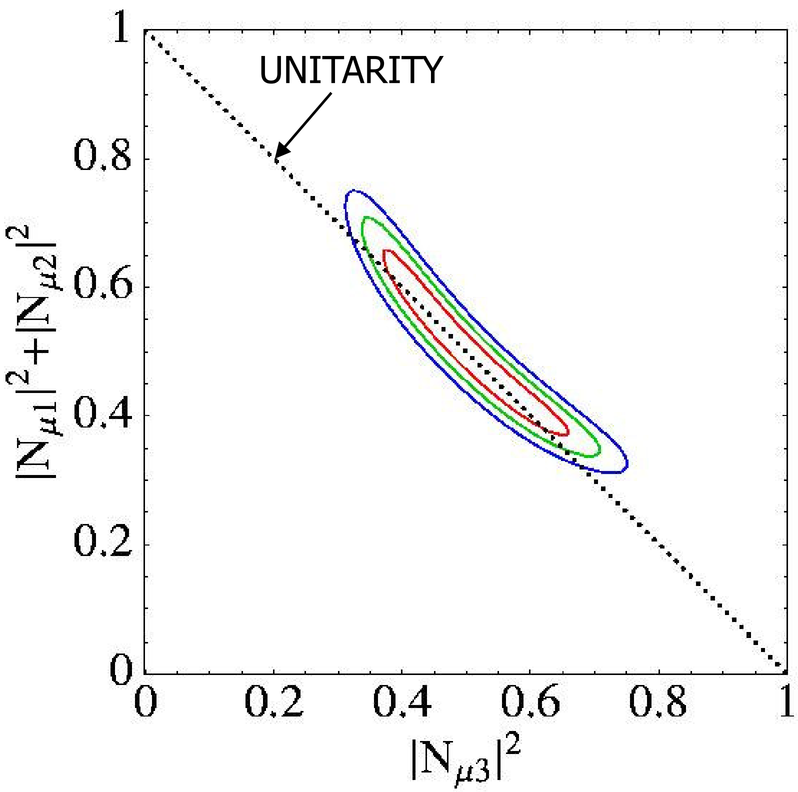
$$\hat{P}(\nu_\mu \to \nu_\mu) \cong \left(|N_{\mu1}|^2 + |N_{\mu2}|^2\right)^2 + |N_{\mu3}|^4 + 2\left(|N_{\mu1}|^2 + |N_{\mu2}|^2\right)|N_{\mu3}|^2 \cos(\Delta_{23})$$

1. Degeneracy

$$|N_{\mu1}|^2 + |N_{\mu2}|^2 \leftrightarrow |N_{\mu3}|^2$$

2. $|N_{\mu1}|^2$, $|N_{\mu2}|^2$

cannot be disentangled



N elements from oscillations: e-row

Only disappearance exps $\rightarrow$ information only on $|N_{\alpha i}|^2$

CHOOZ: $\Delta_{12} \approx 0$ $\qquad \Delta_{ij} = \Delta m_{ij}^2 L / 2E$

$$\hat{P}(\bar{\nu}_e \to \bar{\nu}_e) \cong \left(|N_{e1}|^2 + |N_{e2}|^2\right)^2 + |N_{e3}|^4 + 2\left(|N_{e1}|^2 + |N_{e2}|^2\right)|N_{e3}|^2 \cos(\Delta_{23})$$

K2K $(\nu_\mu \to \nu_\mu)$: Δ_{23}

1. Degeneracy

$$|N_{e1}|^2 + |N_{e2}|^2 \leftrightarrow |N_{e3}|^2$$

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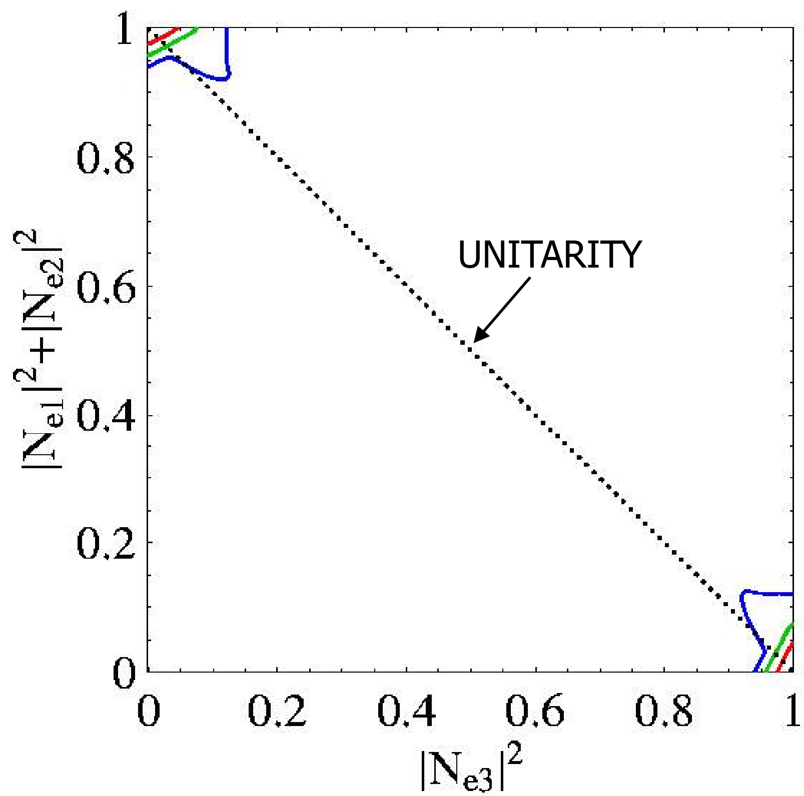


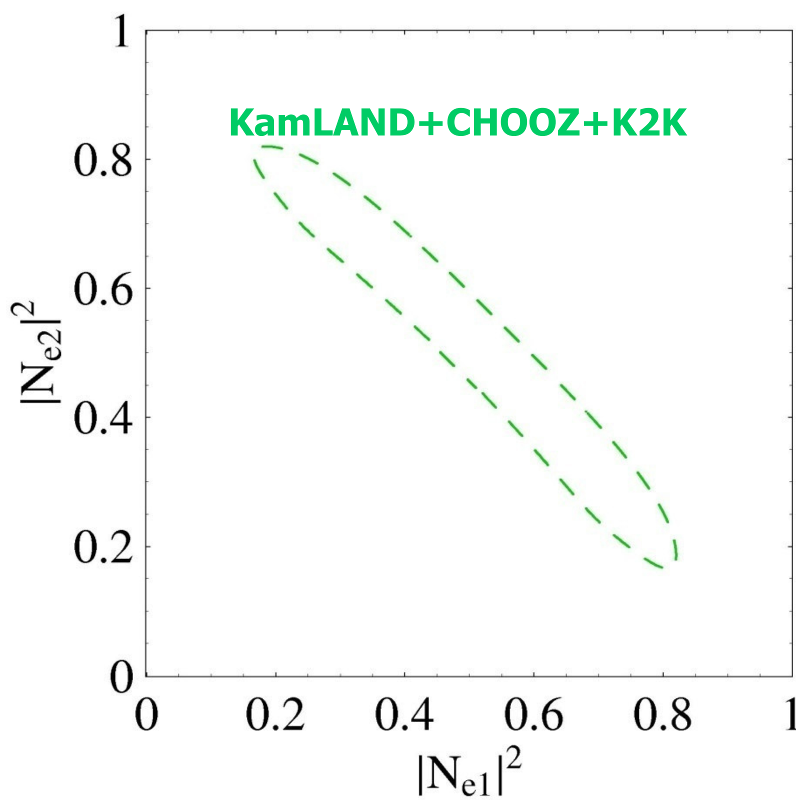
N elements from oscillations: e-row

KamLAND: $\Delta_{23} >> 1$

$$\hat{P}(\bar{\nu}_e \to \bar{\nu}_e) \cong |N_{e1}|^4 + |N_{e2}|^4 + |N_{e3}|^4 + 2|N_{e1}|^2 |N_{e2}|^2 \cos(\Delta_{12})$$

$$\begin{cases} |N_{e1}|^2 + |N_{e2}|^2 \approx 1 \\ |N_{e3}|^2 \approx 0 \end{cases}$$

→ first degeneracy solved



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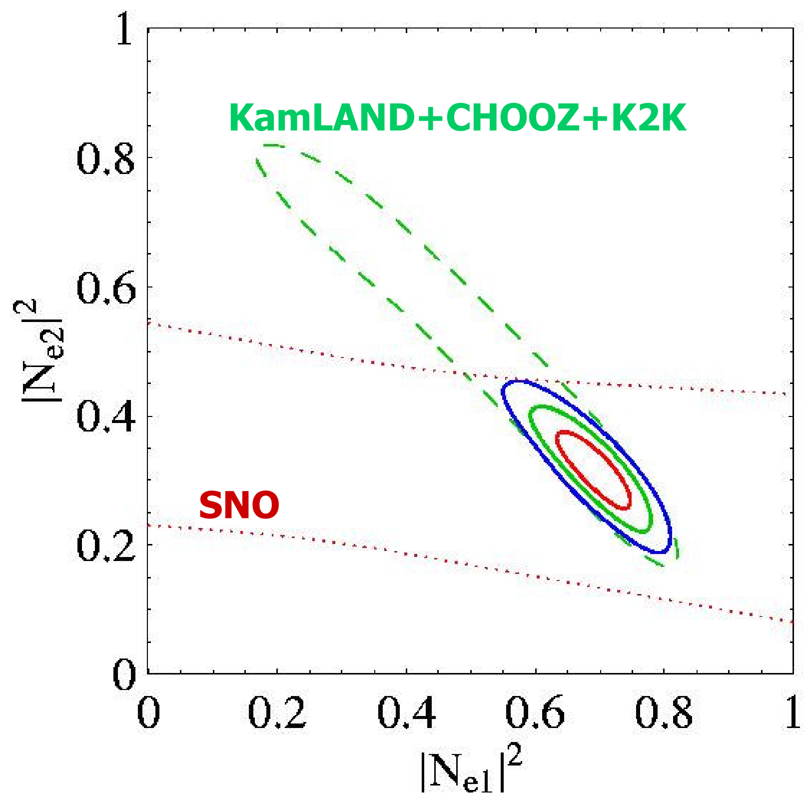
$$\begin{cases} |N_{e1}|^2 + |N_{e2}|^2 \approx 1 \\ |N_{e3}|^2 \approx 0 \end{cases}$$

$\rightarrow$ first degeneracy solved

SNO:

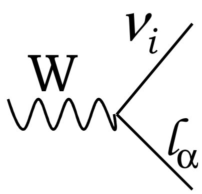
$$\hat{P}(\nu_e \to \nu_e) \cong 0.1|N_{e1}|^2 + 0.9|N_{e2}|^2$$

$\rightarrow$ all $|N_{ei}|^2$ determined



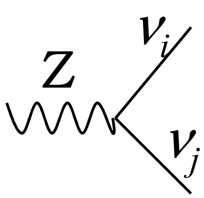
$(NN^\dagger)$ from decays: G_F

- W decays



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

- Invisible Z



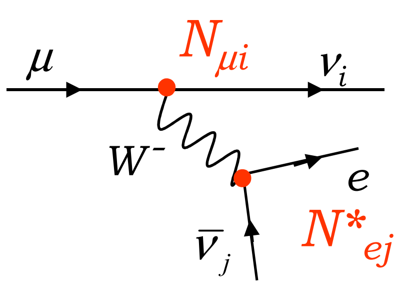
$$\rightarrow \frac{\sum_{ij}(N^+N)_{ij}}{\sqrt{(NN^+)_{ee}}\sqrt{(NN^+)_{\mu\mu}}}$$

- Universality tests

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

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

G_F is measured in μ-decay



$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}\sum_i |N_{\mu i}|^2 \sum_j |N_{ej}|^2$$

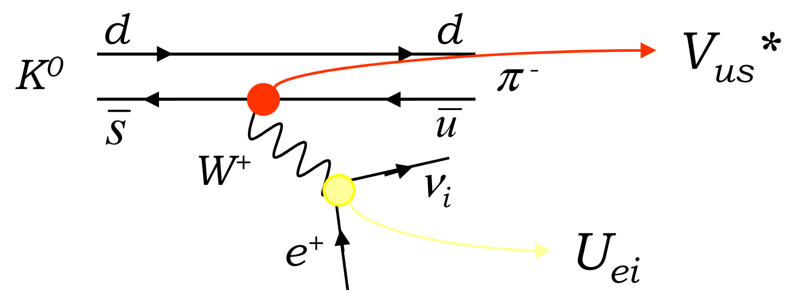
$$G_F^2 = \frac{G_{F,\exp}^2}{\sum_i |N_{\mu i}|^2 \sum_j |N_{ej}|^2}$$

Unitarity in the quark sector

Quarks are detected as mass eigenstates

$\rightarrow$ we can directly measure $|V_{ab}|$

ex: $|V_{us}|$ from $K^0 \rightarrow \pi^- e^+ \nu_e$



$\rightarrow$ $\sum_i |U_{ei}|^2 = 1$ if U unitary

With V_{ab} we check unitarity conditions:

ex: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0008 \pm 0.0011$

$\rightarrow$ *Measurements of V_{CKM} elements relies on U_{PMNS} unitarity*

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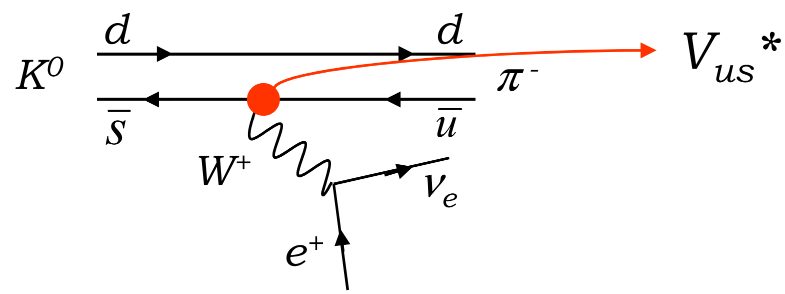

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$\rightarrow$ *Measurements of V_{CKM} elements relies on U_{PMNS} unitarity*

With leptons:

- decays $\rightarrow$ only $(NN^\dagger)$ and $(N^\dagger N)$
- N elements $\rightarrow$ we need oscillations
- to study the unitarity of N: no assumptions on V_{CKM}

ν oscillation in matter

$$-L^{\text{int}} = \underbrace{\sqrt{2}G_F n_e}_{V_{CC}}\bar{\nu}_e\gamma^0\nu_e - \underbrace{\frac{1}{\sqrt{2}}G_F n_n}_{V_{NC}}\sum_\alpha \bar{\nu}_\alpha\gamma^0\nu_\alpha$$

2 families

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \left[U^*\begin{pmatrix}E_1 & 0 \\ 0 & E_2\end{pmatrix}U^t + \begin{pmatrix}V_{CC} - \cancel{V_{NC}} & 0 \\ 0 & \cancel{-V_{NC}}\end{pmatrix}\right]\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

ν oscillation in matter

$$-L^{\text{int}} = \underbrace{\sqrt{2}G_F n_e}_{V_{CC}} \bar{\nu}_e \gamma^0 \nu_e - \underbrace{\frac{1}{\sqrt{2}} G_F n_n}_{V_{NC}} \sum_\alpha \bar{\nu}_\alpha \gamma^0 \nu_\alpha$$

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$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[U^*\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}U^t + \begin{pmatrix}V_{CC} \cancel{-V_{NC}} & 0\\ 0 & \cancel{-V_{NC}}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[N^*\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}(N^*)^{-1} + \begin{pmatrix}(V_{CC}-V_{NC})\sum_i |N_{ei}|^2 & -V_{NC}\sqrt{\frac{\sum_i |N_{\mu i}|^2}{\sum_i |N_{ei}|^2}}\sum_i N^*_{ei}N_{\mu i}\\ (V_{CC}-V_{NC})\sqrt{\frac{\sum_i |N_{ei}|^2}{\sum_i |N_{\mu i}|^2}}\sum_i N^*_{ei}N_{\mu i} & -V_{NC}\sum_i |N_{\mu i}|^2\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

1. non-diagonal elements
2. NC effects do not disappear

Large NSI?

General basis for d=8 ops. with two fermions and two H

$$(\mathcal{O}^{\mathbf{1}}_{LEH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^{\beta}\gamma^{\rho}L_{\alpha})(\bar{E}^{\delta}\gamma_{\rho}E_{\gamma})\left(H^{\dagger}H\right),$$
$$(\mathcal{O}^{\mathbf{3}}_{LEH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^{\beta}\gamma^{\rho}\vec{\tau}L_{\alpha})(\bar{E}^{\delta}\gamma_{\rho}E_{\gamma})\left(H^{\dagger}\vec{\tau}H\right),$$

2 left + 2 right

$$(\mathcal{O}^{\mathbf{111}}_{LLH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^{\beta}\gamma^{\rho}L_{\alpha})(\bar{L}^{\delta}\gamma_{\rho}L_{\gamma})(H^{\dagger}H),$$
$$(\mathcal{O}^{\mathbf{331}}_{LLH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^{\beta}\gamma^{\rho}\vec{\tau}L_{\alpha})(\bar{L}^{\delta}\gamma_{\rho}\vec{\tau}L_{\gamma})(H^{\dagger}H),$$
$$(\mathcal{O}^{\mathbf{133}}_{LLH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^{\beta}\gamma^{\rho}L_{\alpha})(\bar{L}^{\delta}\gamma_{\rho}\vec{\tau}L_{\gamma})(H^{\dagger}\vec{\tau}H),$$
$$(\mathcal{O}^{\mathbf{313}}_{LLH})^{\beta\delta}_{\alpha\gamma} = (\bar{L}^{\beta}\gamma^{\rho}\vec{\tau}L_{\alpha})(\bar{L}^{\delta}\gamma_{\rho}L_{\gamma})(H^{\dagger}\vec{\tau}H),$$
$$(\mathcal{O}^{\mathbf{333}}_{LLH})^{\beta\delta}_{\alpha\gamma} = (-\mathrm{i}\epsilon^{abc})(\bar{L}^{\beta}\gamma^{\rho}\tau^{a}L_{\alpha})(\bar{L}^{\delta}\gamma_{\rho}\tau^{b}L_{\gamma})(H^{\dagger}\tau^{c}H),$$

4 left

Z. Berezhiani and A. Rossi hep-ph/0111147
B. Gavela, D. Hernández, T. Ota and W. Winter 0809.3451

Large NSI?

To cancel the 4-charged fermion ops:

$$\mathcal{C}^{111}_{LEH} + \mathcal{C}^{331}_{LEH} = 0\,, \quad \mathcal{C}^{111}_{LLH} + \mathcal{C}^{331}_{LLH} + \mathcal{C}^{133}_{LLH} + \mathcal{C}^{313}_{LLH} = 0\,, \quad \mathcal{C}^{333}_{LLH}\ \text{arbitr.}$$

but

$$\mathcal{C}^{111}_{LEH} + \mathcal{C}^{331}_{LEH} = 0 \longrightarrow \left(\overline{L}_\alpha i\sigma_2 H^*\right)\gamma^\mu\left(H^t i\sigma_2 L_\beta\right)\left(\overline{E}_\gamma \gamma_\mu E_\delta\right) \qquad N_R$$

and

$$\mathcal{C}^{111}_{LLH} + \mathcal{C}^{331}_{LLH} = 0 \longrightarrow \left(\overline{L}^c_\alpha i\sigma_2 L_\beta\right)\left(\overline{L}_\gamma i\sigma_2 L^c_\delta\right)\left(H^\dagger H\right) \qquad \text{scalar singlet}$$

$$\mathcal{C}^{111}_{LLH} + \mathcal{C}^{313}_{LLH} = 0 \longrightarrow \left(\overline{L}_\alpha i\sigma_2 H^*\right)\gamma^\mu\left(H^t i\sigma_2 L_\beta\right)\left(\overline{L}_\gamma \gamma_\mu L_\delta\right) \qquad N_R$$

$$\mathcal{C}^{111}_{LLH} + \mathcal{C}^{133}_{LLH} = 0 \longrightarrow \left(\overline{L}_\alpha \gamma_\mu L_\beta\right)\left(\overline{L}_\gamma i\sigma_2 H^*\right)\gamma^\mu\left(H^t i\sigma_2 L_\delta\right) \qquad N_R$$

$$\mathcal{C}^{133}_{LLH} + \mathcal{C}^{313}_{LLH} = 0 \longrightarrow \mathcal{C}^{333}_{LLH} \qquad \text{after a Fierz transformation}$$