

Non-Standard Neutrino Interactions

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Many thanks to F. Bonnet for discussions on this subject



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

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

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

$$\pi \rightarrow \mu + \nu_\beta \quad n + \nu_\beta \rightarrow p + l_\alpha$$



Direct bounds on prod/det NSI

$$2\sqrt{2}G_F \epsilon_{\alpha\beta}^{ud} (\bar{l}_\beta \gamma^\mu P_L v_\alpha) (\bar{u} \gamma_\mu P_{L,R} d)$$

$$2\sqrt{2}G_F \epsilon_{\alpha\beta}^{\mu e} (\bar{\mu} \gamma^\mu P_L v_\beta) (\bar{v}_\alpha \gamma_\mu P_L e)$$

$$|\epsilon^{ud}| < \begin{pmatrix} 0.042 & 0.025 & 0.042 \\ 2.6 \cdot 10^{-5} & 0.1 & 0.013 \\ 0.087 & 0.013 & 0.13 \end{pmatrix}$$

$$|\epsilon^{\mu e}| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

Preliminary bounds order $\sim 10^{-2}$

C. Biggio, M. Blennow and EFM work in progress



Introduction: NSI

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

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

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

$\nu_\alpha \rightarrow \nu_\beta$ 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

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

$$|\epsilon_m^e| < \begin{pmatrix} 0.14 & 0.1 & 0.44 \\ 0.1 & 0.03 & 0.1 \\ 0.44 & 0.1 & 0.5 \end{pmatrix} \quad |\epsilon_m^u| < \begin{pmatrix} 1 & 0.05 & 0.5 \\ 0.05 & 0.008 & 0.05 \\ 0.5 & 0.05 & 3 \end{pmatrix} \quad |\epsilon_m^d| < \begin{pmatrix} 0.6 & 0.05 & 0.5 \\ 0.05 & 0.015 & 0.05 \\ 0.5 & 0.05 & 6 \end{pmatrix}$$

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



Source of NSI

Neutrino masses already imply
physics beyond the SM...

... extensions to accommodate
neutrino masses can naturally lead to NSI



The Type I Seesaw Model

The **SM** is extended by:

$$\mathcal{L}^{SM} + i \overline{N_R} \partial N_R - \overline{\ell_L} \tilde{\phi} \textcolor{green}{Y}_N^\dagger N_R - \frac{1}{2} \overline{N_R} \textcolor{green}{M}_N N_R^c + \text{h.c.}$$

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



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

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

$\langle \phi \rangle = \frac{v}{\sqrt{2}}$

Weinberg 1979



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Weinberg 1979

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



Effective Lagrangian

$$L = i \bar{V}_\alpha \partial^\mu K_{\alpha\beta} V_\beta + \bar{V}_\alpha M_{\alpha\beta} V_\beta - \frac{g}{\sqrt{2}} (W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L V_\alpha + h.c.) - \frac{g}{\cos \theta_W} (Z_\mu \bar{V}_\alpha \gamma^\mu P_L V_\alpha + h.c.) + \dots$$



Effective Lagrangian

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



Diagonal mass and canonical kinetic terms

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



Effective Lagrangian

$$L = i \bar{V}_\alpha \partial^\mu K_{\alpha\beta} V_\beta + \bar{V}_\alpha M_{\alpha\beta} V_\beta - \frac{g}{\sqrt{2}} (W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L V_\alpha + h.c.) - \frac{g}{\cos \theta_W} (Z_\mu \bar{V}_\alpha \gamma^\mu P_L V_\alpha + h.c.) + \dots$$



Diagonal mass and canonical kinetic terms

$$L = i \bar{V}_i \partial^\mu V_i + \bar{V}_i m_{ii} V_i - \frac{g}{\sqrt{2}} (W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i} V_i + h.c.) - \frac{g}{\cos \theta_W} (Z_\mu \bar{V}_i \gamma^\mu P_L (N^\dagger N)_{ij} V_j + h.c.) + \dots$$

$$V_\alpha = N_{\alpha i} V_i$$

N is not unitary



Non-unitarity and NSI

The general matrix N can be parameterized as:

$$N = (1 + \varepsilon)U \quad \text{where} \quad \varepsilon = \varepsilon^\dagger$$

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



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

And production/detection NSI:

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

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



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

$$2\sqrt{2}G_F \mathcal{E}_{\alpha\beta}^m (\bar{\nu}_\beta \gamma^\mu P_L \nu_\alpha) (\bar{f} \gamma_\mu P_{L,R} f)$$

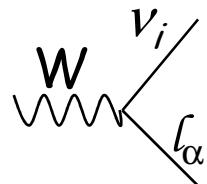
$$\mathcal{E}^m = \begin{pmatrix} \mathcal{E}_{ee}(n_n/n_e - 2) & \mathcal{E}_{e\mu}(n_n/n_e - 1) & \mathcal{E}_{e\tau}(n_n/n_e - 1) \\ \mathcal{E}_{e\mu}(n_n/n_e - 1) & \mathcal{E}_{\mu\mu} n_n/n_e & \mathcal{E}_{\mu\tau} n_n/n_e \\ \mathcal{E}_{e\tau}(n_n/n_e - 1) & \mathcal{E}_{\mu\tau} n_n/n_e & \mathcal{E}_{\tau\tau} n_n/n_e \end{pmatrix}$$

They are related to the production and detection NSI



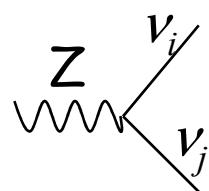
(NN^\dagger) from decays

- W decays



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

- Invisible Z

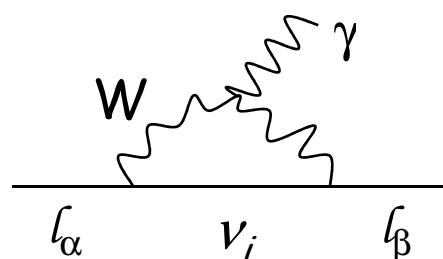


$$\rightarrow \frac{\sum_{\alpha\beta} (NN^\dagger)_{\alpha\beta}}{\sqrt{(NN^\dagger)_{ee}} \sqrt{(NN^\dagger)_{\mu\mu}}}$$

- Universality tests

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

- Rare leptons decays



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

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

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

After integrating out W and Z neutrino NSI induced



(NN^\dagger) from decays

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

Experimentally

E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228

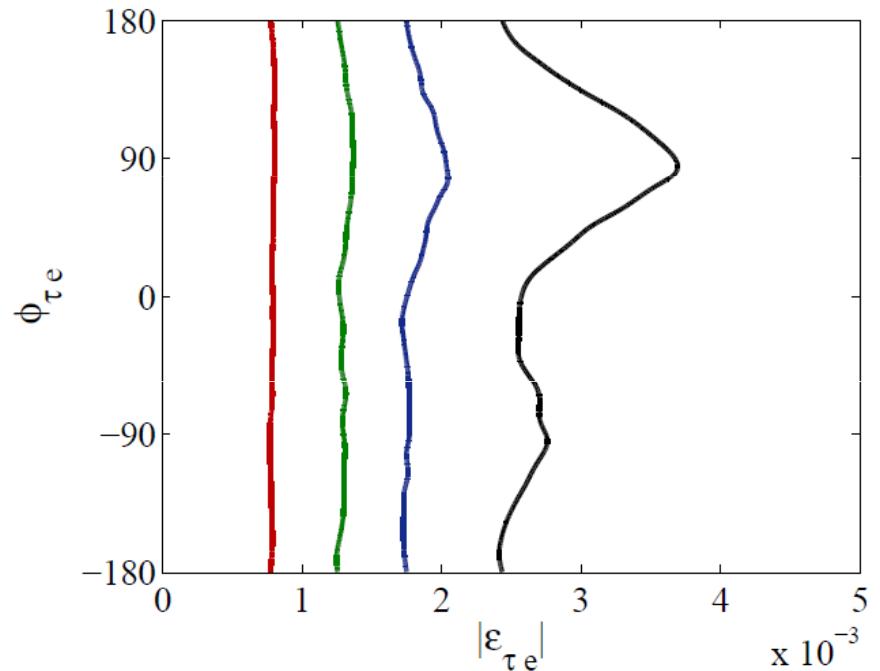
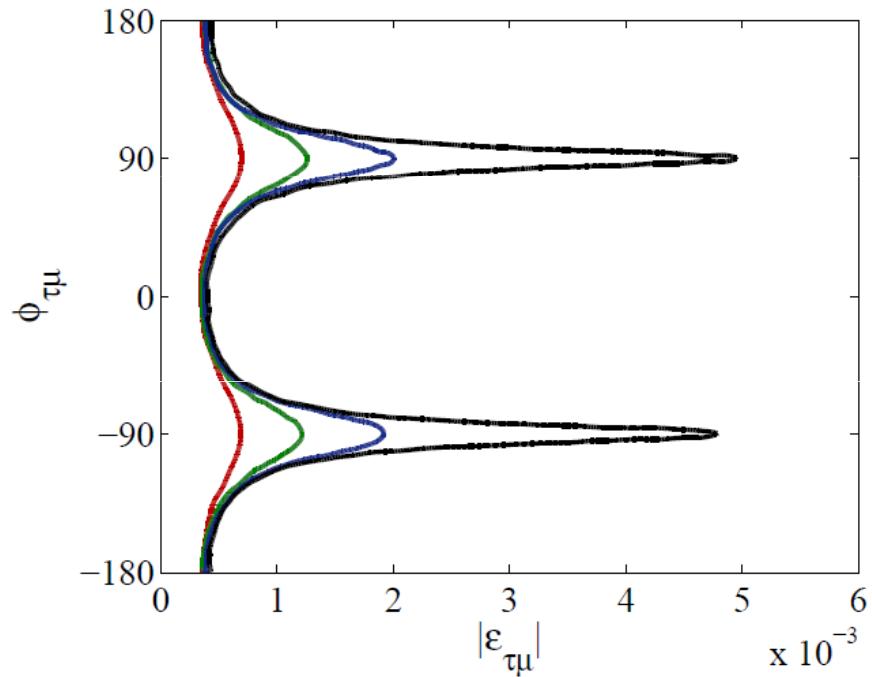
D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228

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 NF



Golden channel at **NF** is sensitive to $\epsilon_{\tau e}$

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

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

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

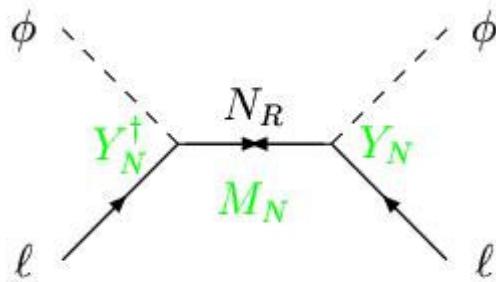
S. Antusch, M. Blennow, EFM and J. López-pavón 0903.3986

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,....



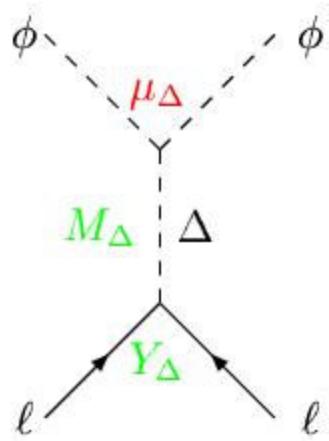
Other models for ν masses



Type I seesaw

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

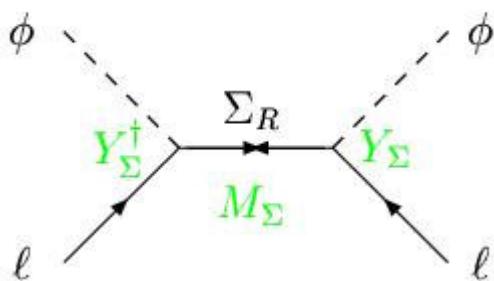
N_R fermionic singlet



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: $c_{\alpha\beta}^{d=6} \left(\overline{\ell_{L\alpha}} \tilde{\phi} \right) i\cancel{D} \left(\tilde{\phi}^\dagger \ell_{L\beta} \right)$

- non-unitary mixing in CC
- FCNC for ν

Type III: $c_{\alpha\beta}^{d=6} \left(\overline{\ell_{L\alpha}} \vec{\tau} \tilde{\phi} \right) i\cancel{D} \left(\tilde{\phi}^\dagger \vec{\tau} \ell_{L\beta} \right)$

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

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

- 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



Bounds for Type II and III Seesaw

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

| Decay | Constraint on | Bound |
|--|--|----------------------|
| $\mu^- \rightarrow e^- e^+ e^-$ | $ \varepsilon_{ee}^{e\mu} $ | 3.5×10^{-7} |
| $\tau^- \rightarrow e^- e^+ e^-$ | $ \varepsilon_{ee}^{e\tau} $ | 1.6×10^{-4} |
| $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ | $ \varepsilon_{\mu\mu}^{\mu\tau} $ | 1.5×10^{-4} |
| $\tau^- \rightarrow e^- \mu^+ e^-$ | $ \varepsilon_{e\mu}^{e\tau} $ | 1.2×10^{-4} |
| $\tau^- \rightarrow \mu^- e^+ \mu^-$ | $ \varepsilon_{\mu e}^{\mu\tau} $ | 1.3×10^{-4} |
| $\tau^- \rightarrow e^- \mu^+ \mu^-$ | $ \varepsilon_{\mu\mu}^{e\tau} $ | 1.2×10^{-4} |
| $\tau^- \rightarrow e^- e^+ \mu^-$ | $ \varepsilon_{\mu e}^{e\tau} $ | 9.9×10^{-5} |
| $\mu^- \rightarrow e^- \gamma$ | $ \sum_\alpha \varepsilon_{\alpha\alpha}^{e\mu} $ | 1.4×10^{-4} |
| $\tau^- \rightarrow e^- \gamma$ | $ \sum_\alpha \varepsilon_{\alpha\alpha}^{e\tau} $ | 3.2×10^{-2} |
| $\tau^- \rightarrow \mu^- \gamma$ | $ \sum_\alpha \varepsilon_{\alpha\alpha}^{\mu\tau} $ | 2.5×10^{-2} |
| $\mu^+ e^- \rightarrow \mu^- e^+$ | $ \varepsilon_{\mu e}^{\mu e} $ | 3.0×10^{-3} |

A. Abada, C. Biggio, F. Bonnet,
B. Gavela and T. Hambye 0707.4058
and M. Malinsky, T. Ohlsson
and H. Zhang 0811.3346



Bounds for Type II and III Seesaw

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

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| $\tau^- \rightarrow e^- \mu^+ e^-$ | $ \varepsilon_{e\mu}^{e\tau} $ | 1.2×10^{-4} |
| $\tau^- \rightarrow \mu^- e^+ \mu^-$ | $ \varepsilon_{\mu e}^{\mu\tau} $ | 1.3×10^{-4} |
| $\tau^- \rightarrow e^- \mu^+ \mu^-$ | $ \varepsilon_{\mu\mu}^{e\tau} $ | 1.2×10^{-4} |
| $\tau^- \rightarrow e^- e^+ \mu^-$ | $ \varepsilon_{\mu e}^{e\tau} $ | 9.9×10^{-5} |
| $\mu^- \rightarrow e^- \gamma$ | $ \sum_\alpha \varepsilon_{\alpha\alpha}^{e\mu} $ | 1.4×10^{-4} |
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| $\mu^+ e^- \rightarrow \mu^- e^+$ | $ \varepsilon_{\mu e}^{\mu e} $ | 3.0×10^{-3} |

A. Abada, C. Biggio, F. Bonnet,
B. Gavela and T. Hambye 0707.4058
and M. Malinsky, T. Ohlsson
and H. Zhang 0811.3346

Type III: $c_{\alpha\beta}^{d=6} \left(\overline{\ell_{L\alpha}} \vec{\tau} \tilde{\phi} \right) iD \left(\tilde{\phi}^\dagger \vec{\tau} \ell_{L\beta} \right)$

$$(\text{NN}^+ - 1)_{\alpha\beta} = \frac{v^2}{2} |c^{d=6}|_{\alpha\beta} = \frac{v^2}{2} |Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma|_{\alpha\beta} \lesssim \begin{pmatrix} 3 \cdot 10^{-3} & < 1.1 \cdot 10^{-6} & < 1.2 \cdot 10^{-3} \\ & < 1.1 \cdot 10^{-6} & 4 \cdot 10^{-3} \\ < 1.2 \cdot 10^{-3} & < 1.2 \cdot 10^{-3} & 4 \cdot 10^{-3} \end{pmatrix}$$

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



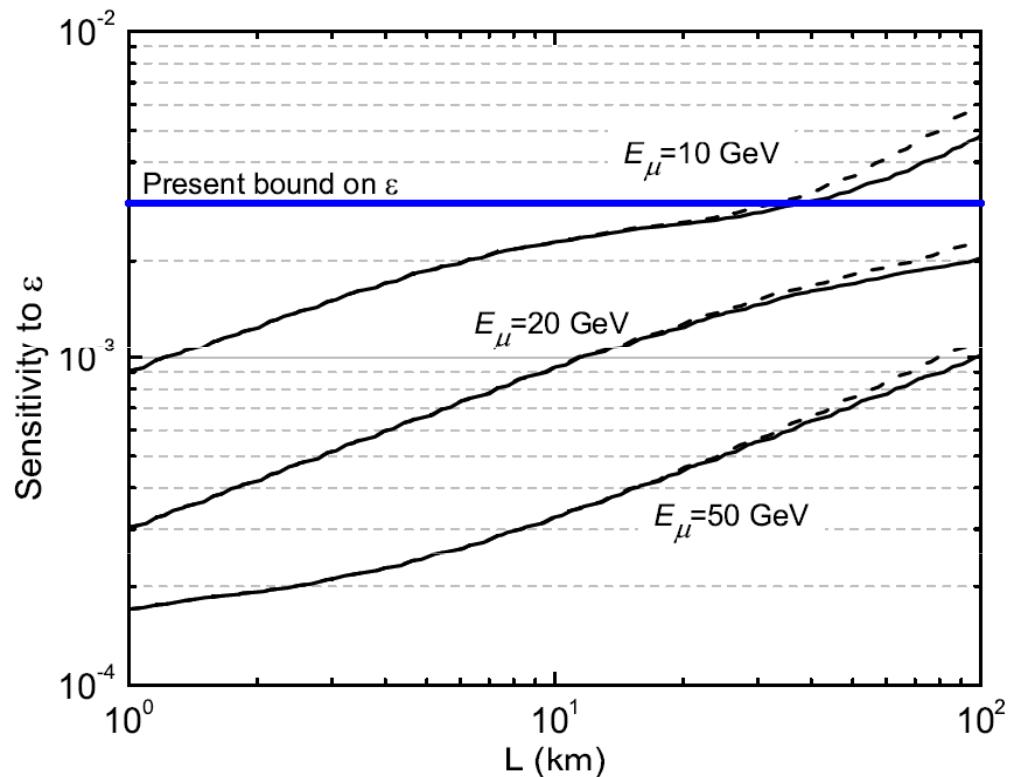
Type II Seesaw at a NF

Some hope for $\varepsilon_{\mu e}^{\mu e}$

that leads to

$$\mu \rightarrow e \nu_e \bar{\nu}_\mu$$

wrong sign μ at Nufact
near detector



M. Malinsky, T. Ohlsson and H. Zhang 0811.3346



Low scale seesaws

But

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

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



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



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Inverse (Type I) seesaw

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

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

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

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



Low scale seesaws

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

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

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

Type II seesaw

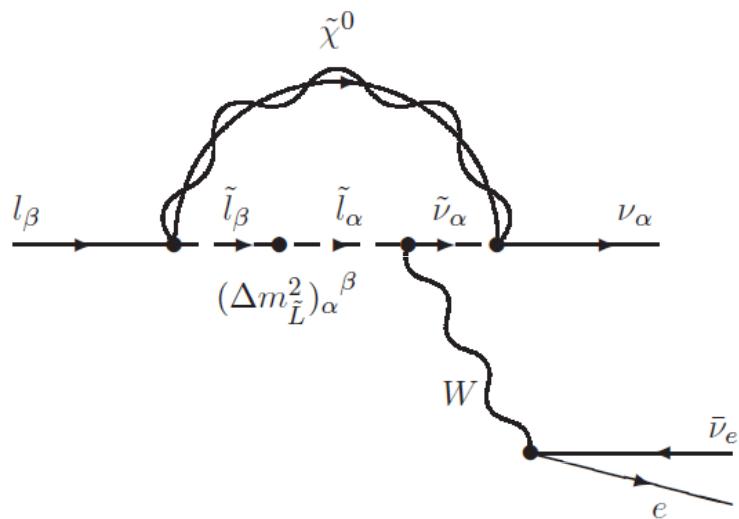
$$\bar{\ell}_L Y_\Delta (\vec{\tau} \cdot \vec{\Delta}) \ell_L - \mu_\Delta \tilde{\phi}^\dagger (\vec{\tau} \cdot \vec{\Delta})^\dagger \phi$$

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

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



NSI from the MSSM



Leads to $\epsilon_{e\tau}^{\mu e}$

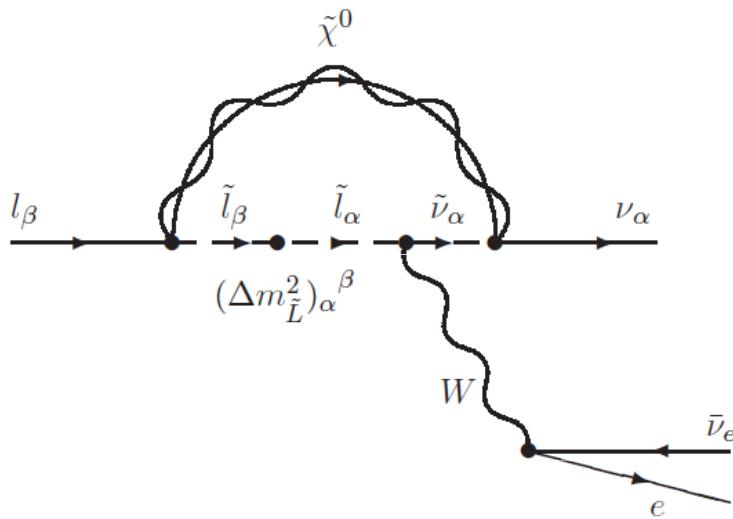
$$\mu \rightarrow e \nu_\tau \bar{\nu}_e$$

τ at near detectors in a Nufact

T. Ota and J. Sato hep-ph/0502124

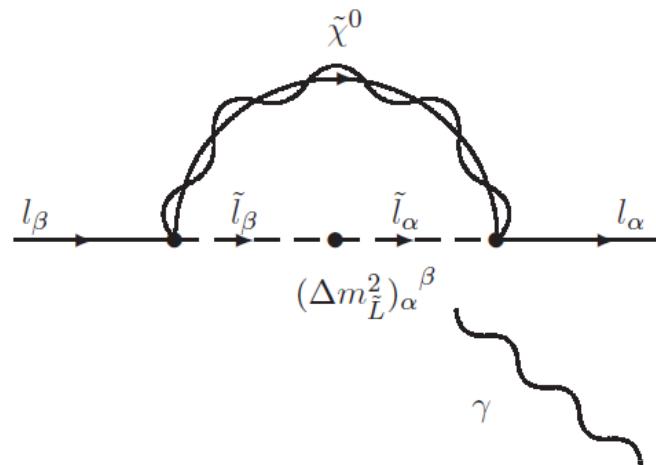


NSI from the MSSM



Leads to $\epsilon_{e\tau}^{\mu e}$

$$\mu \rightarrow e \nu_\tau \bar{\nu}_e$$



Related to $\tau \rightarrow \mu \gamma$

bounds $O(10^{-5})$

τ at near detectors in a Nufact

T. Ota and J. Sato hep-ph/0502124



Large NSI?

Can large **NSI** be realized with some other **SM** extension?

Can the mild model-independent bounds be saturated?

$$|\epsilon_m^e| < \begin{pmatrix} 0.14 & 0.1 & 0.44 \\ 0.1 & 0.03 & 0.1 \\ 0.44 & 0.1 & 0.5 \end{pmatrix} \quad |\epsilon_m^u| < \begin{pmatrix} 1 & 0.05 & 0.5 \\ 0.05 & 0.008 & 0.05 \\ 0.5 & 0.05 & 3 \end{pmatrix} \quad |\epsilon_m^d| < \begin{pmatrix} 0.6 & 0.05 & 0.5 \\ 0.05 & 0.015 & 0.05 \\ 0.5 & 0.05 & 6 \end{pmatrix}$$

What does it take to avoid the strong constraints?

S. Antusch, J. Baumann and EFM 0807.1003

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



Gauge invariance

However

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

is related to

$$2\sqrt{2}G_F \epsilon_{\alpha\beta}^m (\bar{l}_\beta \gamma^\mu P_L l_\alpha) (\bar{f} \gamma_\mu P_{L,R} f)$$

by gauge invariance and very strong bounds exist

$$\epsilon_{e\mu}^m < \sim 10^{-6}$$

$\mu \rightarrow e \gamma$

$$\epsilon_{e\tau}^m < \sim 10^{-2}$$

$\mu \rightarrow e$ in nuclei

$$\epsilon_{\mu\tau}^m < \sim 10^{-2}$$

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:

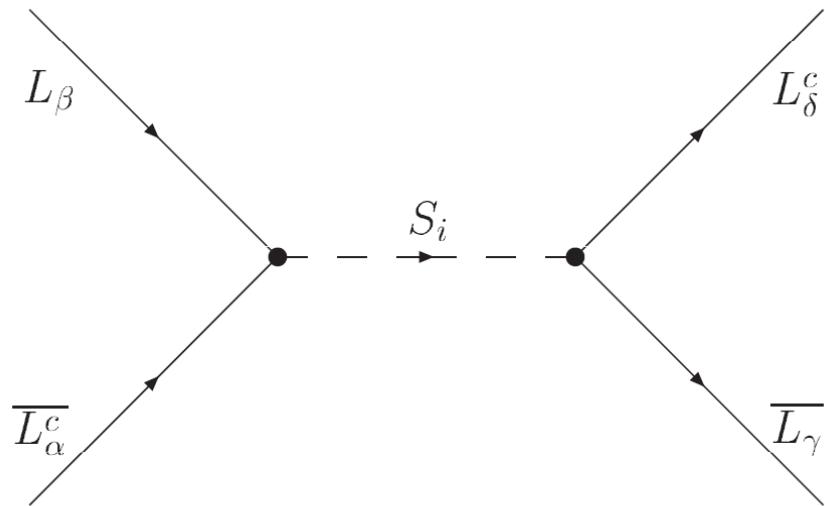
- Matter **NSI** are generated at tree level
- 4-charged fermion ops not generated at the same level
- No cancellations between diagrams with **different messenger particles** to avoid constraints
- The Higgs Mechanism is responsible for **EWSB**

S. Antusch, J. Baumann and EFM 0807.1003
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

$$\mathcal{L}_{int}^S = -\lambda_{\alpha\beta}^i \overline{L}_\alpha^c i\sigma_2 L_\beta S_i + \text{H.c.} = \lambda_{\alpha\beta}^i S_i (\overline{\ell}_\alpha^c P_L \nu_\beta - \overline{\ell}_\beta^c P_L \nu_\alpha) + \text{H.c.}$$

$$\mathcal{L}_{NSI}^{d=6,as} = c_{\alpha\beta\gamma\delta}^{d=6,as} (\overline{L}_\alpha^c i\sigma_2 L_\beta)(\overline{L}_\gamma^c i\sigma_2 L_\delta) \quad \varepsilon_{\alpha\beta}^{m,e_L} = \sum_i \frac{\lambda_{e\beta}^i \lambda_{e\alpha}^{i*}}{\sqrt{2} G_F m_{S_i}^2}$$

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:

$$|\varepsilon_{\mu\mu}^{m,e_L}| < 8.2 \cdot 10^{-4}$$

$$|\varepsilon_{\tau\tau}^{m,e_L}| < 8.4 \cdot 10^{-3}$$

$$|\varepsilon_{\mu\tau}^{m,e_L}| < 1.9 \cdot 10^{-3}$$

$\mu \rightarrow e \gamma$

μ decays

τ decays

CKM unitarity

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



Large NSI?

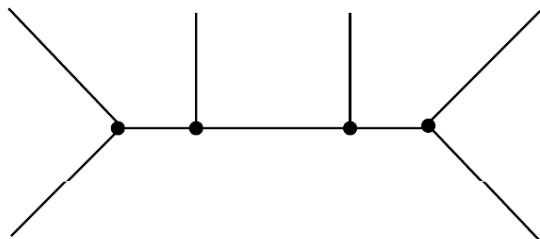
At $d=8$ more freedom

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

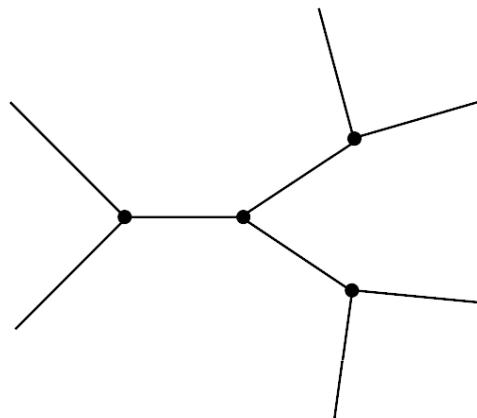
$$(\bar{L}_\beta i\sigma_2 H^*) \gamma^\mu (H^t i\sigma_2 L_\alpha) (\bar{f} \gamma_\mu f) \longrightarrow -v^2/2 (\bar{\nu}_\beta \gamma^\mu \nu_\alpha) (\bar{f} \gamma_\mu f)$$

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

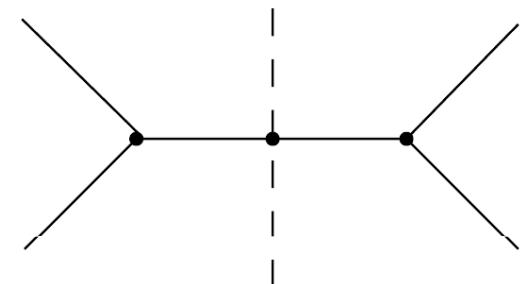
There are 3 topologies to induce effective $d=8$ ops with $HHLLff$ legs:



(a) Topology 1



(b) Topology 2



(c) Topology 3



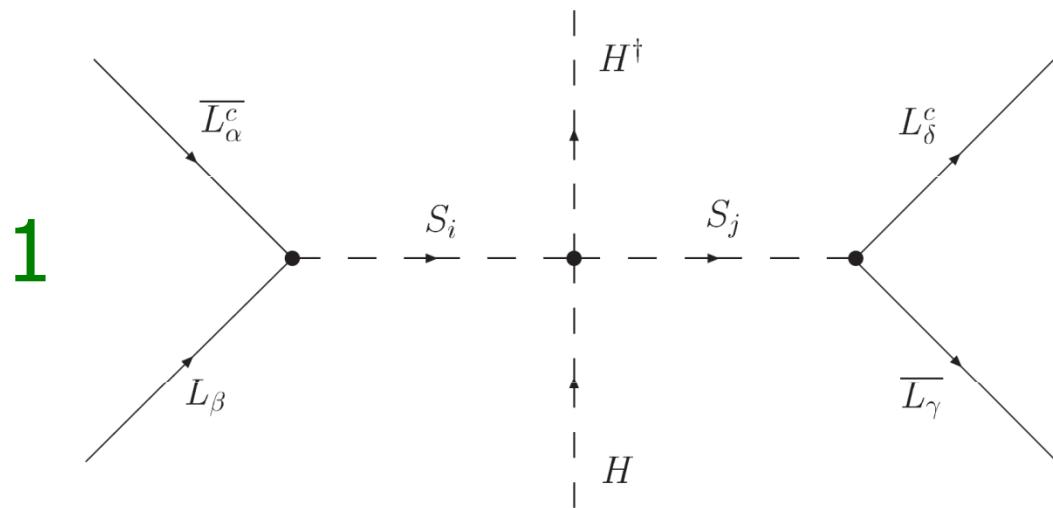
Large NSI?

We found three classes satisfying the requirements:



Large NSI?

We found three classes satisfying the requirements:



Just contributes to the scalar propagator after EWSB

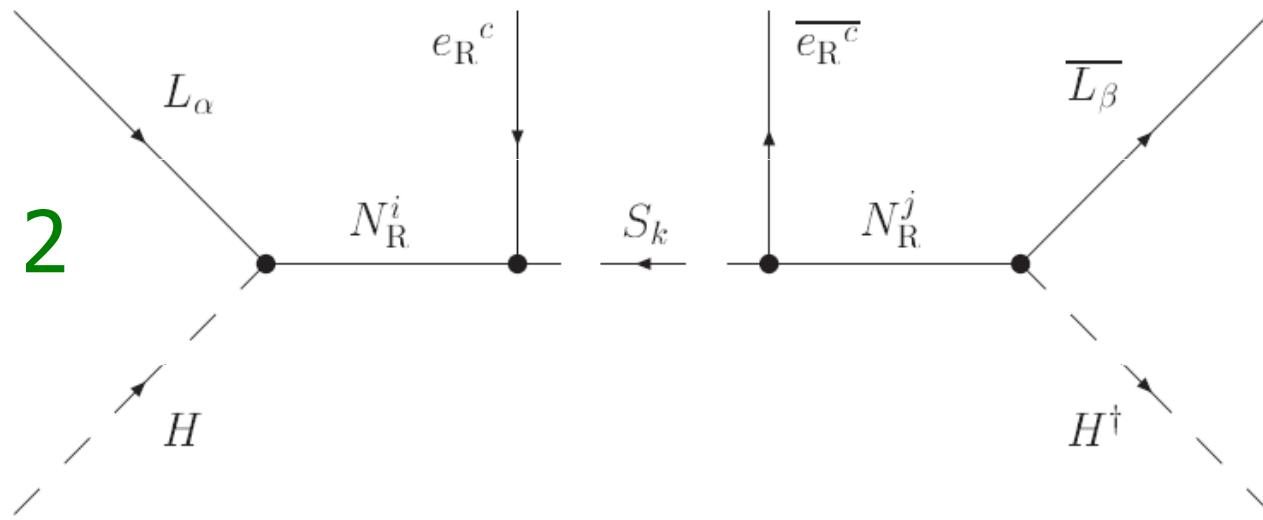
$$v^2/2 \left(\overline{L}_\alpha^c i \sigma_2 L_\beta \right) \left(\overline{L}_\gamma i \sigma_2 L_\delta^c \right)$$

Same as the d=6 realization with the scalar singlet



Large NSI?

We found three classes satisfying the requirements:



The Higgs coupled to the N_R selects ν after EWSB

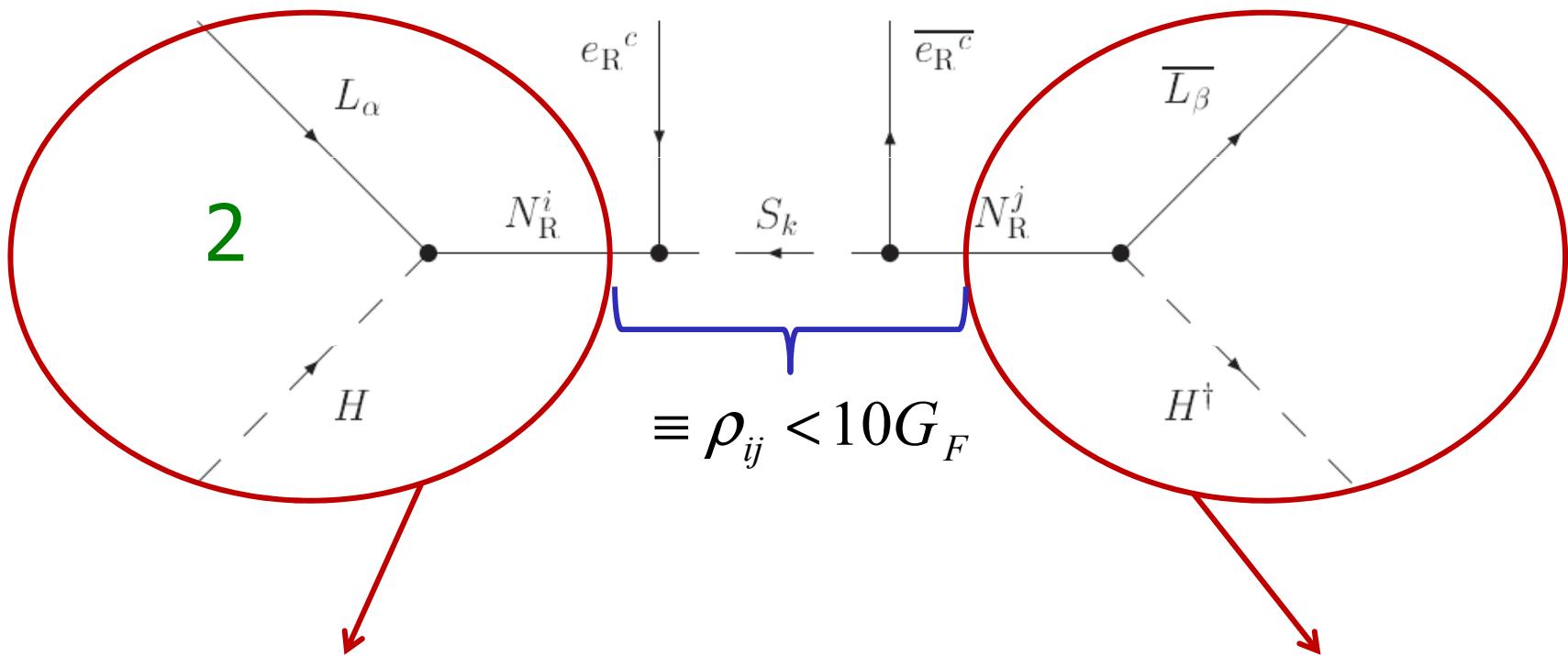
$$(\bar{L}_\beta i \sigma_2 H^*) \gamma^\mu (H^t i \sigma_2 L_\alpha) (\bar{f} \gamma_\mu f) \longrightarrow -\nu^2/2 (\bar{\nu}_\beta \gamma^\mu \nu_\alpha) (\bar{f} \gamma_\mu f)$$

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



Large NSI?

But can be related to **non-unitarity** and constrained



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



Large NSI?

For the matter **NSI**

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

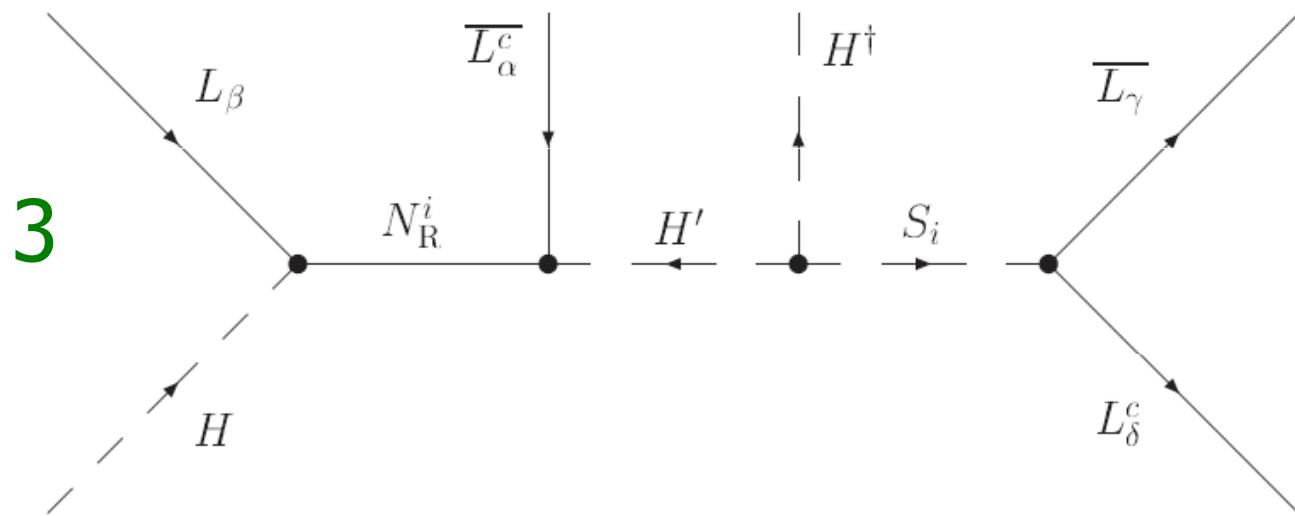
Where $\hat{\rho}^{(f)}$ is the largest eigenvalue of $\rho_{ij}^{(f)}$

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:

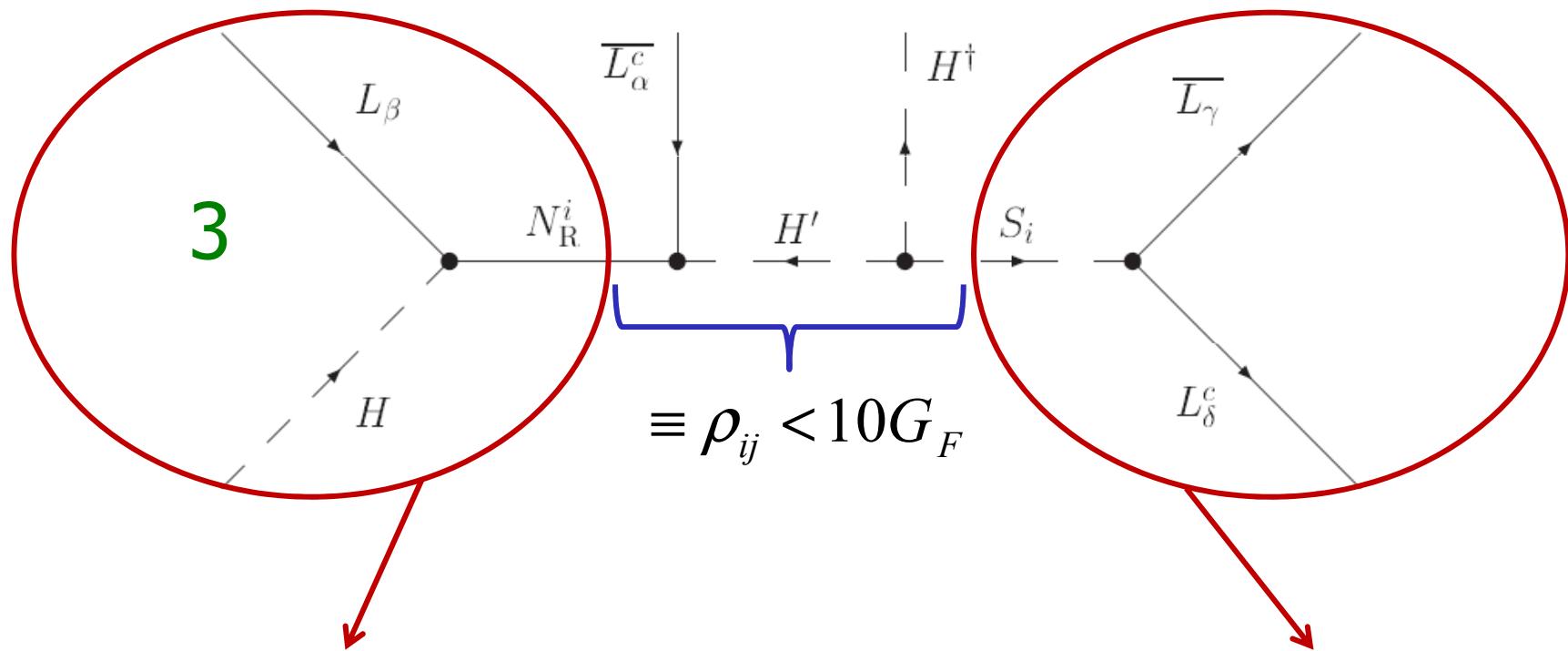


Mixed case, Higgs selects one ν and scalar singlet S the other



Large NSI?

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



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

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



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}_{LEH}^1 | \mathcal{C}_{LEH}^3 | $\mathcal{O}_{NSI}?$ | Mediators |
|--|--|-----------------------|-----------------------|----------------------|--|
| Combination $\bar{L}\bar{L}$ | | | | | |
| 1 | $(\bar{L}\gamma^\rho L)(\bar{E}\gamma_\rho E)(H^\dagger H)$ | 1 | | | 1_0^v |
| 2 | $(\bar{L}\gamma^\rho L)(\bar{E}H^\dagger)(\gamma_\rho)(HE)$ | 1 | | | $1_0^v + 2_{-3/2}^{L/R}$ |
| 3 | $(\bar{L}\gamma^\rho L)(\bar{E}H^T)(\gamma_\rho)(H^*E)$ | 1 | | | $1_0^v + 2_{-1/2}^{L/R}$ |
| 4 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}\gamma_\rho E)(H^\dagger \vec{\tau} H)$ | 1 | | | $3_0^v + 1_0^v$ |
| 5 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}H^\dagger)(\gamma_\rho \vec{\tau})(HE)$ | 1 | | | $3_0^v + 2_{-3/2}^{L/R}$ |
| 6 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}H^T)(\gamma_\rho \vec{\tau})(H^*E)$ | 1 | | | $3_0^v + 2_{-1/2}^{L/R}$ |
| Combination $\bar{E}\bar{L}$ | | | | | |
| 7 | $(\bar{L}E)(\bar{E}L)(H^\dagger H)$ | -1/2 | | | $2_{+1/2}^s$ |
| 8 | $(\bar{L}E)(\vec{\tau})(\bar{E}L)(H^\dagger \vec{\tau} H)$ | | -1/2 | | $2_{+1/2}^s$ |
| 9 | $(\bar{L}H)(H^\dagger E)(\bar{E}L)$ | -1/4 | -1/4 | ✓ | $2_{+1/2}^s + 1_0^R + 2_{-1/2}^{L/R}$ |
| 10 | $(\bar{L}\vec{\tau} H)(H^\dagger E)(\vec{\tau})(\bar{E}L)$ | -3/4 | 1/4 | | $2_{+1/2}^s + 3_{-1}^{L/R} + 2_{-1/2}^{L/R}$ |
| 11 | $(\bar{L}i\tau^2 H^*)(H^T E)(i\tau^2)(\bar{E}L)$ | 1/4 | -1/4 | | $2_{+1/2}^s + 1_{-1}^{L/R} + 2_{-3/2}^{L/R}$ |
| 12 | $(\bar{L}\vec{\tau} i\tau^2 H^*)(H^T E)(i\tau^2 \vec{\tau})(\bar{E}L)$ | 3/4 | 1/4 | | $2_{+1/2}^s + 3_{-1}^{L/R} + 2_{-3/2}^{L/R}$ |
| Combination $\bar{E}^c\bar{L}$ | | | | | |
| 13 | $(\bar{L}\gamma^\rho E^c)(\bar{E}^c\gamma_\rho L)(H^\dagger H)$ | -1 | | | $2_{-3/2}^v$ |
| 14 | $(\bar{L}\gamma^\rho E^c)(\vec{\tau})(\bar{E}^c\gamma_\rho L)(H^\dagger \vec{\tau} H)$ | | -1 | | $2_{-3/2}^v$ |
| 15 | $(\bar{L}H)(\gamma^\rho)(H^\dagger E^c)(\bar{E}^c\gamma_\rho L)$ | -1/2 | -1/2 | ✓ | $2_{-3/2}^v + 1_0^R + 2_{+3/2}^{L/R}$ |
| 16 | $(\bar{L}\vec{\tau} H)(\gamma^\rho)(H^\dagger E^c)(\vec{\tau})(\bar{E}^c\gamma_\rho L)$ | -3/2 | 1/2 | | $2_{-3/2}^v + 3_{-1}^{L/R} + 2_{+3/2}^{L/R}$ |
| 17 | $(\bar{L}i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2)(\bar{E}^c\gamma_\rho L)$ | -1/2 | 1/2 | | $2_{-3/2}^v + 1_{-1}^{L/R} + 2_{+1/2}^{L/R}$ |
| 18 | $(\bar{L}\vec{\tau} i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2 \vec{\tau})(\bar{E}^c\gamma_\rho L)$ | -3/2 | -1/2 | | $2_{-3/2}^v + 3_{-1}^{L/R} + 2_{+1/2}^{L/R}$ |
| Combination $H^\dagger\bar{L}$ | | | | | |
| 19 | $(\bar{L}E)(\bar{E}H)(H^\dagger L)$ | -1/4 | -1/4 | ✓ | $2_{+1/2}^s + 1_0^R + 2_{-1/2}^{L/R}$ |
| 20 | $(\bar{L}E)(\vec{\tau})(\bar{E}H)(H^\dagger \vec{\tau} L)$ | -3/4 | 1/4 | | $2_{+1/2}^s + 3_{-1}^{L/R} + 2_{-1/2}^{L/R}$ |
| 21 | $(\bar{L}H)(\gamma^\rho)(H^\dagger L)(\bar{E}\gamma_\rho E)$ | 1/2 | 1/2 | ✓ | $1_0^v + 1_0^R$ |
| 22 | $(\bar{L}\vec{\tau} H)(\gamma^\rho)(H^\dagger \vec{\tau} L)(\bar{E}\gamma_\rho E)$ | 3/2 | -1/2 | | $1_0^v + 3_{-1}^{L/R}$ |
| 23 | $(\bar{L}\gamma^\rho E^c)(\bar{E}^c H)(\gamma^\rho)(H^\dagger L)$ | -1/2 | -1/2 | ✓ | $2_{-3/2}^v + 1_0^R + 2_{+3/2}^{L/R}$ |
| 24 | $(\bar{L}\gamma^\rho E^c)(\bar{E}^c H)(\gamma^\rho)(H^\dagger L)$ | -3/2 | 1/2 | | $2_{-3/2}^v + 3_0^L + 2_{+3/2}^{L/R}$ |
| Combination $H\bar{L}$ | | | | | |
| 25 | $(\bar{L}E)(i\tau^2)(\bar{E}H^*)(H^T i\tau^2 L)$ | 1/4 | -1/4 | | $2_{+1/2}^s + 1_{-1}^{L/R} + 2_{-3/2}^{L/R}$ |
| 26 | $(\bar{L}E)(\vec{\tau} i\tau^2)(\bar{E}H^*)(H^T i\tau^2 \vec{\tau} L)$ | 3/4 | 1/4 | | $2_{+1/2}^s + 3_{-1}^{L/R} + 2_{-3/2}^{L/R}$ |
| 27 | $(\bar{L}i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2 L)(\bar{E}\gamma_\rho E)$ | -1/2 | 1/2 | | $1_0^v + 1_{-1}^{L/R}$ |
| 28 | $(\bar{L}\vec{\tau} i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2 \vec{\tau} L)(\bar{E}\gamma_\rho E)$ | -3/2 | -1/2 | | $1_0^v + 3_{-1}^{L/R}$ |
| 29 | $(\bar{L}\gamma^\rho E^c)(i\tau^2)(\bar{E}^c H^*)(\gamma_\rho)(H^T i\tau^2 L)$ | 1/2 | -1/2 | | $2_{-3/2}^v + 1_{-1}^{L/R} + 2_{+1/2}^{L/R}$ |
| 30 | $(\bar{L}\gamma^\rho E^c)(\vec{\tau} i\tau^2)(\bar{E}^c H^*)(\gamma_\rho)(H^T i\tau^2 \vec{\tau} L)$ | 3/2 | 1/2 | | $2_{-3/2}^v + 3_{-1}^{L/R} + 2_{+1/2}^{L/R}$ |

| # | Dim. eight operator | \mathcal{C}_{LLH}^{111} | \mathcal{C}_{LLH}^{331} | \mathcal{C}_{LLH}^{133} | \mathcal{C}_{LLH}^{313} | \mathcal{C}_{LLH}^{333} | $\mathcal{O}_{NSI}?$ | 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 | | | | | | 1_0^v |
| 32 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\gamma_\rho \vec{\tau} L)(H^\dagger H)$ | | 1 | | | | | 3_0^v |
| 33 | $(\bar{L}\gamma^\rho L)(\bar{L}\gamma_\rho L)(H^\dagger \vec{\tau} H)$ | | | 1 | | | | $1_0^v + 3_0^v$ |
| 34 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\gamma_\rho L)(H^\dagger \vec{\tau} H)$ | | | | 1 | | ✓ | $1_0^v + 3_0^v$ |
| 35 | $(-\text{ie}^{abc})(\bar{L}\gamma^\rho \tau^a L) \times \\ (\bar{L}\gamma_\rho \tau^b L)(H^\dagger \tau^c H)$ | | | | | 1 | | 3_0^v |
| 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 | | | ✓ | $1_0^v + 1_0^R$ |
| 37 | $(\bar{L}\gamma^\rho L)(\bar{L}\vec{\tau} H)(\gamma_\rho)(H^\dagger \vec{\tau} L)$ | 3/2 | | -1/2 | | | | $1_0^v + 3_{-1}^{L/R}$ |
| 38 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\vec{\tau} H)(\gamma_\rho)(H^\dagger L)$ | | 1/2 | 1/2 | 1/2 | ✓ | | $1_0^v + 1_R^R + 3_{-1}^{L/R}$ |
| 39 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}H)(\gamma_\rho)(H^\dagger \vec{\tau} L)$ | | 1/2 | 1/2 | -1/2 | ✓ | | $1_0^v + 1_R^R + 3_{-1}^{L/R}$ |
| 40 | $(-\text{ie}^{abc})(\bar{L}\gamma^\rho \tau^a L) \times \\ (\bar{L}\tau^b H)(\gamma_\rho)(H^\dagger \tau^c L)$ | | 1 | | -1 | | | $3_0^v + 1_0^R + 3_0^L$ |
| Combination $(\bar{L}^\beta L_\alpha)(\bar{L}^\delta H^\dagger)(L_\gamma H)$ | | | | | | | | |
| 41 | $(\bar{L}\gamma^\rho L)(\bar{L}i\tau^2 H^*)(\gamma_\rho)(H^T i\tau^2 L)$ | -1/2 | | 1/2 | | | | $1_0^v + 1_{-1}^{L/R}$ |
| 42 | $(\bar{L}\gamma^\rho L)(\bar{L}i\tau^2 H^*)(\gamma_\rho)(H^T i\tau^2 \vec{\tau} L)$ | -3/2 | | -1/2 | | | | $1_0^v + 3_{-1}^{L/R}$ |
| 43 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}i\tau^2 H^*)(\gamma_\rho)(H^T i\tau^2 L)$ | | -1/2 | 1/2 | 1/2 | | | $3_0^v + 1_{-1}^{L/R} + 3_{-1}^{L/R}$ |
| 44 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}i\tau^2 H^*)(\gamma_\rho)(H^T i\tau^2 \vec{\tau} L)$ | | -1/2 | 1/2 | -1/2 | | | $3_0^v + 1_{-1}^{L/R} + 3_{-1}^{L/R}$ |
| 45 | $(-\text{ie}^{abc})(\bar{L}\tau^a i\tau^2 L^c) \times \\ (\bar{L}\tau^b i\tau^2 H^*)(\gamma_\rho)(H^T i\tau^2 \tau^c L)$ | | -1 | -1 | | ✓ | | $3_0^v + 3_{-1}^{L/R}$ |
| Combination $(\bar{L}^\beta L^c)^\delta ((\bar{L}^c)_\alpha L_\gamma)(H^\dagger H)$ | | | | | | | | |
| 46 | $(\bar{L}i\tau^2 L^c)(\bar{L}i\tau^2 L)(H^\dagger H)$ | 1/4 | | -1/4 | | | ✓ | 1_{-1}^s |
| 47 | $(\bar{L}i\tau^2 L^c)(\bar{L}i\tau^2 \vec{\tau} L)(H^\dagger H)$ | -3/4 | | -1/4 | | | | 3_{-1}^s |
| 48 | $(\bar{L}i\tau^2 L^c)(\bar{L}i\tau^2 \vec{\tau} L)(H^\dagger \vec{\tau} H)$ | | 1/4 | -1/4 | -1/4 | ✓ | | $1_{-1}^s + 3_{-1}^s$ |
| 49 | $(\bar{L}i\tau^2 L^c)(\bar{L}i\tau^2 L)(H^\dagger \vec{\tau} H)$ | | -1/4 | 1/4 | -1/4 | ✓ | | $1_{-1}^s + 3_{-1}^s$ |
| 50 | $(-\text{ie}^{abc})(\bar{L}\tau^a i\tau^2 L^c) \times \\ (\bar{L}^c i\tau^2 \tau^c L)(H^\dagger \tau^c H)$ | | -1/2 | -1/2 | | | | 3_{-1}^s |
| Combination $(\bar{L}^\beta H^*)((\bar{L}^c)_\alpha L_\gamma)$ | | | | | | | | |
| 51 | $(\bar{L}i\tau^2 H^*)(H^T L^c)(\bar{L}^c i\tau^2 L)$ | 1/8 | -1/8 | 1/8 | -1/8 | 1/8 | ✓ | $1_{-1}^s + 1_0^L + 1_{-1}^{L/R}$ |
| 52 | $(\bar{L}\vec{\tau} i\tau^2 H^*)(H^T L^c \vec{\tau})(\bar{L}^c i\tau^2 L)$ | -3/8 | 3/8 | 1/8 | -1/8 | 1/8 | ✓ | $1_{-1}^s + 3_{-1}^{L/R} + 1_{-1}^{L/R}$ |
| 53 | $(\bar{L}\vec{\tau} i\tau^2 H^*)(H^T L^c)(\bar{L}^c i\tau^2 \vec{\tau} L)$ | -3/8 | -1/8 | -3/8 | -1/8 | 1/8 | ✓ | $3_{-1}^s + 1_0^L + 3_{-1}^{L/R}$ |
| 54 | $(\bar{L}i\tau^2 H^*)(H^T \vec{\tau} L^c)(\bar{L}^c i\tau^2 \vec{\tau} L)$ | 3/8 | 1/8 | -1/8 | -3/8 | -1/8 | | $3_{-1}^s + 3_0^L + 1_{-1}^{L/R}$ |
| 55 | $(-\text{ie}^{abc})(\bar{L}\tau^a i\tau^2 H^*) \times \\ (\bar{L}^c i\tau^2 \tau^c L)(H^T \tau^b L^c)$ | 3/4 | 1/4 | -1/4 | 1/4 | 1/4 | | $3_{-1}^s + 3_0^L + 1_{-1}^{L/R}$ |
| Combination $(\bar{L}^\beta (L^c)^\delta (H^\dagger (L^c)_\alpha)(L_\gamma H)$ | | | | | | | | |
| 56 | $(\bar{L}i\tau^2 L^c)(\bar{L}^c H^*)(H^T i\tau^2 L)$ | 1/8 | -1/8 | -1/8 | 1/8 | 1/8 | ✓ | $1_{-1}^s + 1_0^L + 1_{-1}^{L/R}$ |
| 57 | $(\bar{L}\vec{\tau} i\tau^2 L^c)(\bar{L}^c \vec{\tau} H^*)(H^T i\tau^2 L)$ | 3/8 | 1/8 | -3/8 | -1/8 | -1/8 | | $3_{-1}^s + 3_0^L + 1_{-1}^{L/R}$ |
| 58 | $(\bar{L}i\tau^2 L^c)(\bar{L}^c \vec{\tau} H^*)(H^T i\tau^2 \vec{\tau} L)$ | -3/8 | 3/8 | -1/8 | 1/8 | 1/8 | ✓ | $1_{-1}^s + 3_0^L + 3_{-1}^{L/R}$ |
| 59 | $(\bar{L}\vec{\tau} i\tau^2 L^c)(\bar{L}^c H^*)(H^T i\tau^2 \vec{\tau} L)$ | -3/8 | -1/8 | -1/8 | -3/8 | 1/8 | ✓ | $3_{-1}^s + 1_0^L + 3_{-1}^{L/R}$ |
| 60 | $(-\text{ie}^{abc})(\bar{L}\tau^a i\tau^2 L^c) \times \\ (\bar{L}^c \tau^b H^*)(H^T i\tau^2 \tau^c L)$ | 3/4 | 1/4 | 1/4 | -1/4 | 1/4 | | $3_{-1}^s + 3_0^L + 3_{-1}^{L/R}$ |



Large NSI?

| # | Dim. eight operator | \mathcal{C}_{LLH}^{111} | \mathcal{C}_{LLH}^{331} | \mathcal{C}_{LLH}^{133} | \mathcal{C}_{LLH}^{313} | \mathcal{C}_{LLH}^{333} | $\mathcal{O}_{\text{NSI}}?$ | 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 | | | | | | 1_0^v |
| 32 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\gamma_\rho \vec{\tau} L)(H^\dagger H)$ | | 1 | | | | | 3_0^v |
| 33 | $(\bar{L}\gamma^\rho L)(\bar{L}\gamma_\rho \vec{\tau} L)(H^\dagger \vec{\tau} H)$ | | | 1 | | | | $1_0^v + 3_0^v$ |
| 34 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\gamma_\rho L)(H^\dagger \vec{\tau} H)$ | | | | 1 | | | $1_0^v + 3_0^v$ |
| 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 | ✓ | 3_0^v |
| 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 | | | ✓ | $1_0^v + 1_0^R$ |
| 37 | $(\bar{L}\gamma^\rho L)(\bar{L}\vec{\tau} H)(\gamma_\rho)(H^\dagger \vec{\tau} L)$ | 3/2 | | -1/2 | | | | $1_0^v + 3_0^{L/R}$ |
| 38 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}\vec{\tau} H)(\gamma_\rho)(H^\dagger L)$ | 1/2 | | 1/2 | 1/2 | | ✓ | $1_0^v + 1_0^R + 3_0^{L/R}$ |
| 39 | $(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{L}H)(\gamma_\rho)(H^\dagger \vec{\tau} L)$ | 1/2 | | 1/2 | -1/2 | ✓ | | $1_0^v + 1_0^R + 3_0^{L/R}$ |
| 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 | | | | $3_0^v + 1_0^R + 3_0^{L/R}$ |

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

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

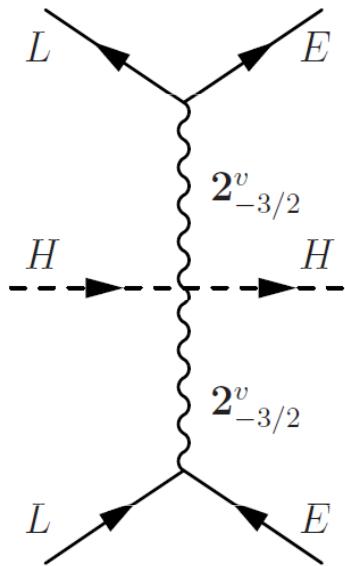
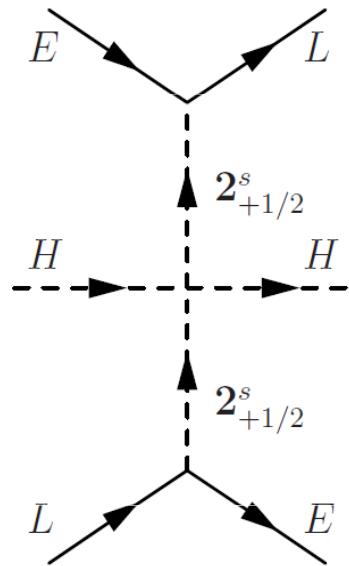


Large NSI?

There is **always** a 4 charged fermion op that needs canceling

Toy model

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\text{SM}} & - (y)_{\beta}^{\gamma} (\bar{L}^{\beta})^i E_{\gamma} \Phi_i - (g)_{\beta\delta} (\bar{L}^{\beta})^i \gamma^{\rho} (E^c)^{\delta} (V_{\rho})_i \\ & + \lambda_{1s} (H^{\dagger} H) (\Phi^{\dagger} \Phi) + \lambda_{3s} (H^{\dagger} \vec{\tau} H) (\Phi^{\dagger} \vec{\tau} \Phi) \\ & + \lambda_{1v} (H^{\dagger} H) (V_{\rho}^{\dagger} V^{\rho}) + \lambda_{3v} (H^{\dagger} \vec{\tau} H) (V_{\rho}^{\dagger} \vec{\tau} V^{\rho}) + \text{h.c.} + \dots\end{aligned}$$



Cancelling the **4-charged fermion ops.**

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

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

↓

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



NSI in loops

Even if we arrange to have

$$\begin{aligned} & \frac{O}{M^4} (\bar{L}_\alpha i \sigma_2 H^*) \gamma^\mu (H^t i \sigma_2 L_\beta) (\bar{E}_\gamma \gamma_\mu E_\delta) \\ &= \frac{O}{2M^4} [(\bar{L}_\alpha \gamma^\mu L_\beta) (H^\dagger H) - (\bar{L}_\alpha \gamma^\mu \vec{\tau} L_\beta) (H^\dagger \vec{\tau} H)] (\bar{E}_\gamma \gamma_\mu E_\delta) \end{aligned}$$



NSI in loops

Even if we arrange to have

$$\begin{aligned} & \frac{O}{M^4} (\bar{L}_\alpha i \sigma_2 H^*) \gamma^\mu (H^t i \sigma_2 L_\beta) (\bar{E}_\gamma \gamma_\mu E_\delta) \\ &= \frac{O}{2M^4} [(\bar{L}_\alpha \gamma^\mu L_\beta) (H^\dagger H) - (\bar{L}_\alpha \gamma^\mu \bar{\tau} L_\beta) (H^\dagger \bar{\tau} H)] (\bar{E}_\gamma \gamma_\mu E_\delta) \end{aligned}$$

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

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

NSIs and 4 charged fermion ops induced with equal strength



NSI in loops

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

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 $1/16\pi^2 > v^2/M^2$



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 excellent probes
- Saturating the mild model-independent bounds on matter NSI and decoupling them from production/detection requires strong fine tuning



Large NSI?

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

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

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

$$(\mathcal{O}_{LLH}^{111})_{\alpha\gamma}^{\beta\delta} = (\bar{L}^\beta \gamma^\rho L_\alpha)(\bar{L}^\delta \gamma_\rho L_\gamma) (H^\dagger H),$$

$$(\mathcal{O}_{LLH}^{331})_{\alpha\gamma}^{\beta\delta} = (\bar{L}^\beta \gamma^\rho \vec{\tau} L_\alpha)(\bar{L}^\delta \gamma_\rho \vec{\tau} L_\gamma) (H^\dagger H),$$

$$(\mathcal{O}_{LLH}^{133})_{\alpha\gamma}^{\beta\delta} = (\bar{L}^\beta \gamma^\rho L_\alpha)(\bar{L}^\delta \gamma_\rho \vec{\tau} L_\gamma) (H^\dagger \vec{\tau} H),$$

$$(\mathcal{O}_{LLH}^{313})_{\alpha\gamma}^{\beta\delta} = (\bar{L}^\beta \gamma^\rho \vec{\tau} L_\alpha)(\bar{L}^\delta \gamma_\rho L_\gamma) (H^\dagger \vec{\tau} H),$$

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

2 left + 2 right

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:

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

but

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

and

$$\mathcal{C}_{LLH}^{111} + \mathcal{C}_{LLH}^{331} = 0 \longrightarrow (\bar{L}_\alpha^c i\sigma_2 L_\beta) (\bar{L}_\gamma i\sigma_2 L_\delta^c) (H^\dagger H) \quad \text{scalar singlet}$$

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

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

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



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

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

$$|\epsilon^m| < \begin{pmatrix} 3.8 & \textcolor{red}{0.33} & 3.1 \\ \textcolor{red}{0.33} & 0.064 & 0.33 \\ 3.1 & 0.33 & 21 \end{pmatrix}$$

Rather weak bounds...

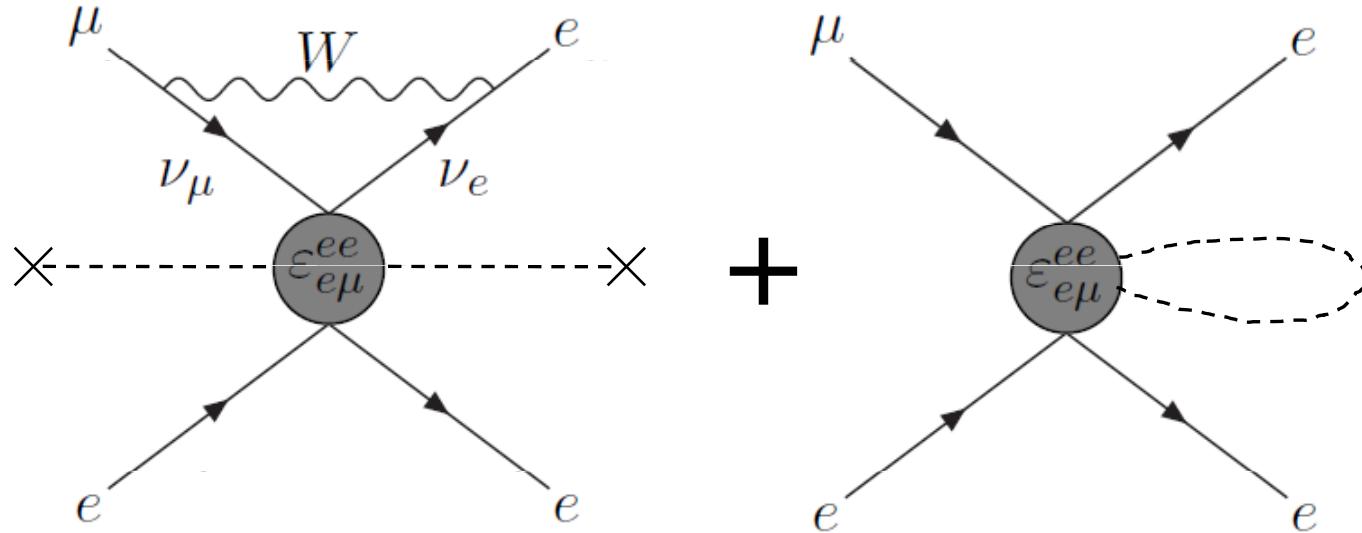
...can they be saturated avoiding additional constraints?

C. Biggio, M. Blennow and EFM 0902.0607



NSI in loops

This loop has to be added to:



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

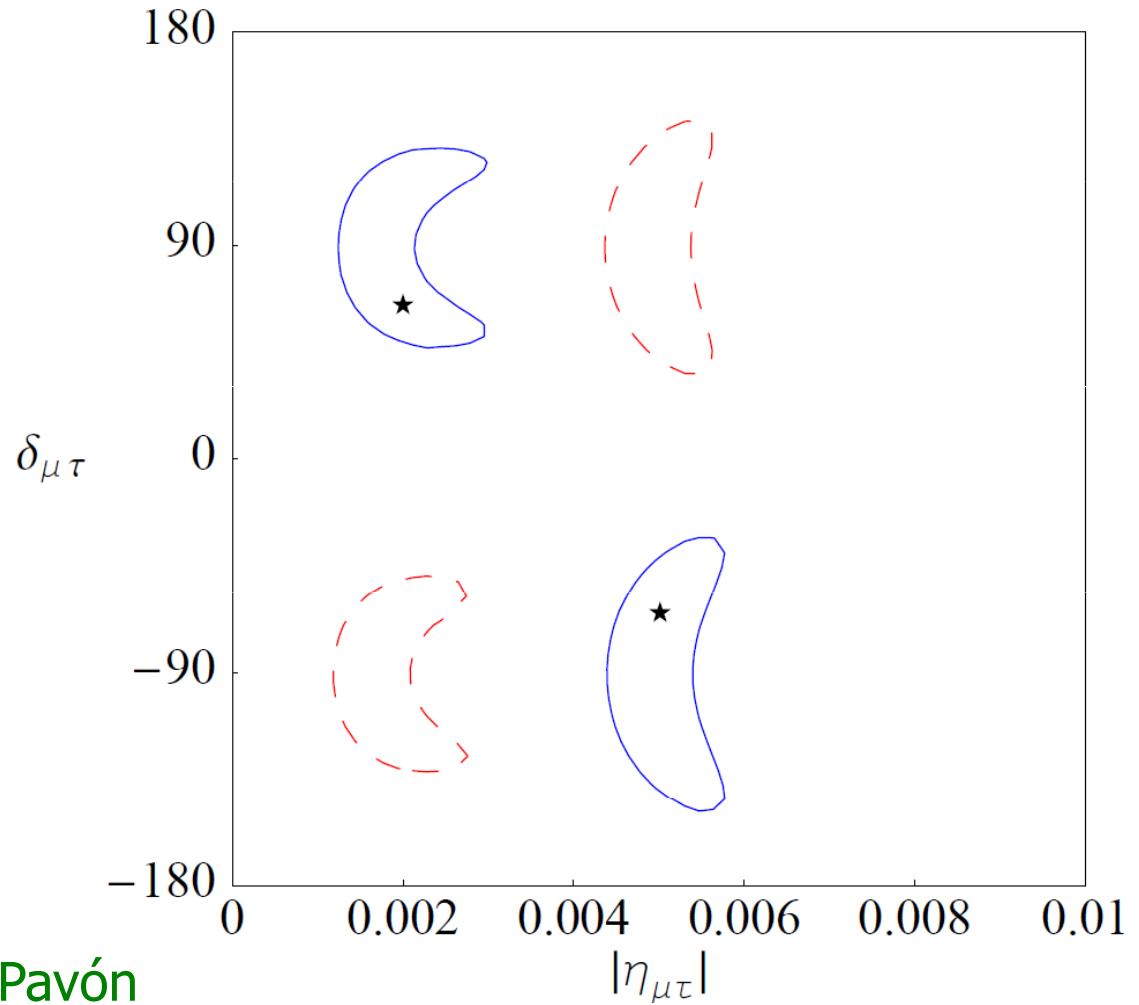
However the log cancels when adding the diagrams...



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

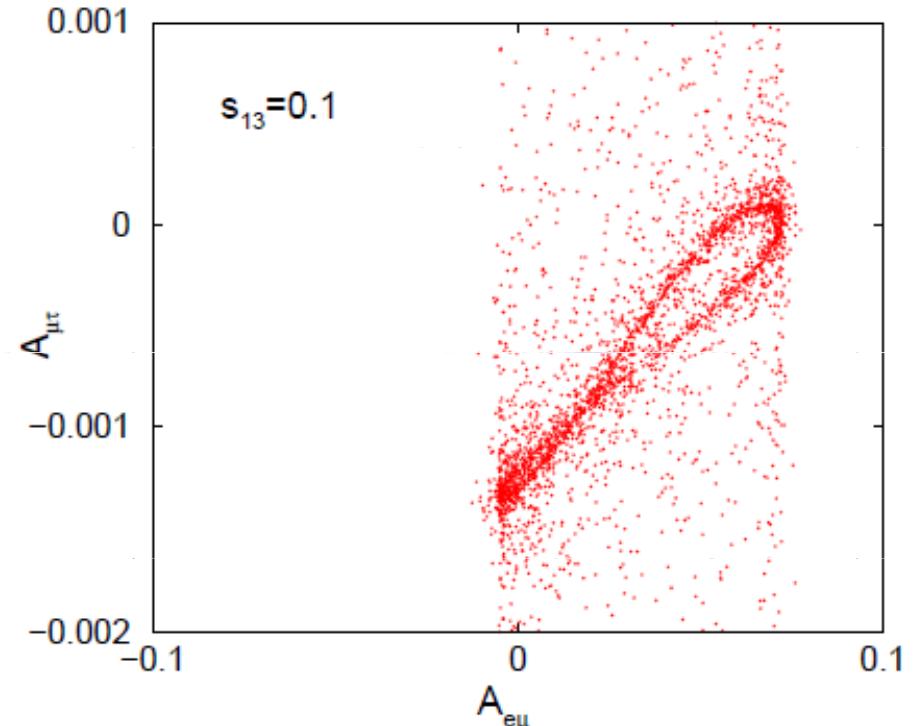
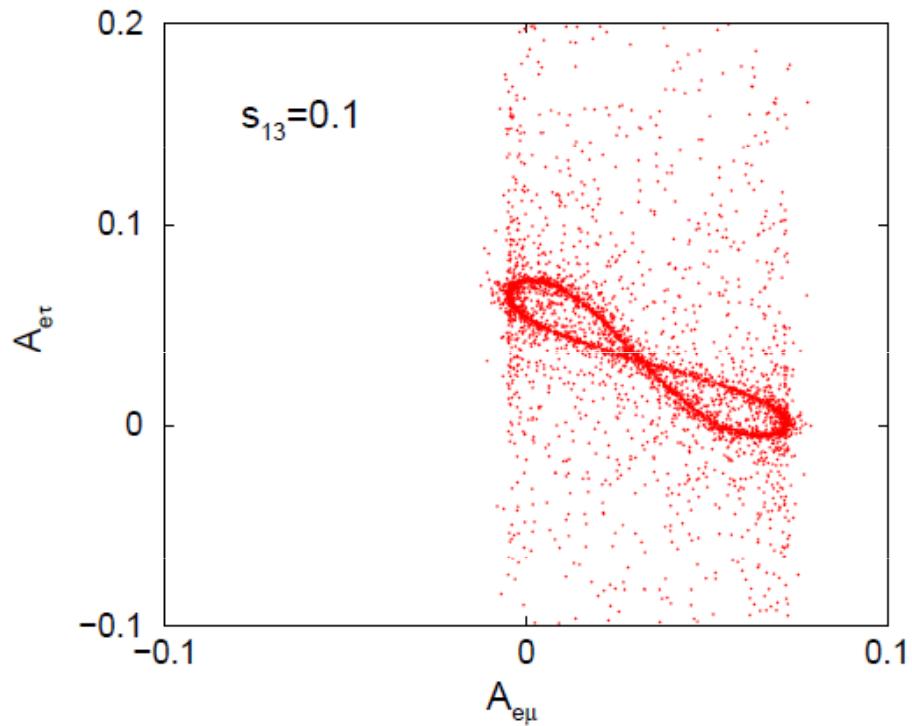


EFM, B. Gavela, J. López Pavón
and O. Yasuda hep-ph/0703098

See also S. Goswami and T. Ota 0802.1434



Measuring unitarity deviations



The CP asymmetry in the $e\mu$ channel cannot be far from the SM
But it can be very different for the $e\tau$ or $\mu\tau$ channels
Consistency check!

G. Altarelli and D. Meloni 0809.1041