Models leading to Non-Standard Neutrino Interactions

Enrique Fernández-Martínez

MPI für Physik Munich

Based on collaborations with:

S. Antusch, J. Baumann, C. Biggio, M. Blennow,

B. Gavela and J. López Pavón

Introduction: NSI

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

Production or detection of a ν_β associated to a l_α

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

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

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

Introduction: NSI

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

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

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

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

Direct bounds on matter NSI

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

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

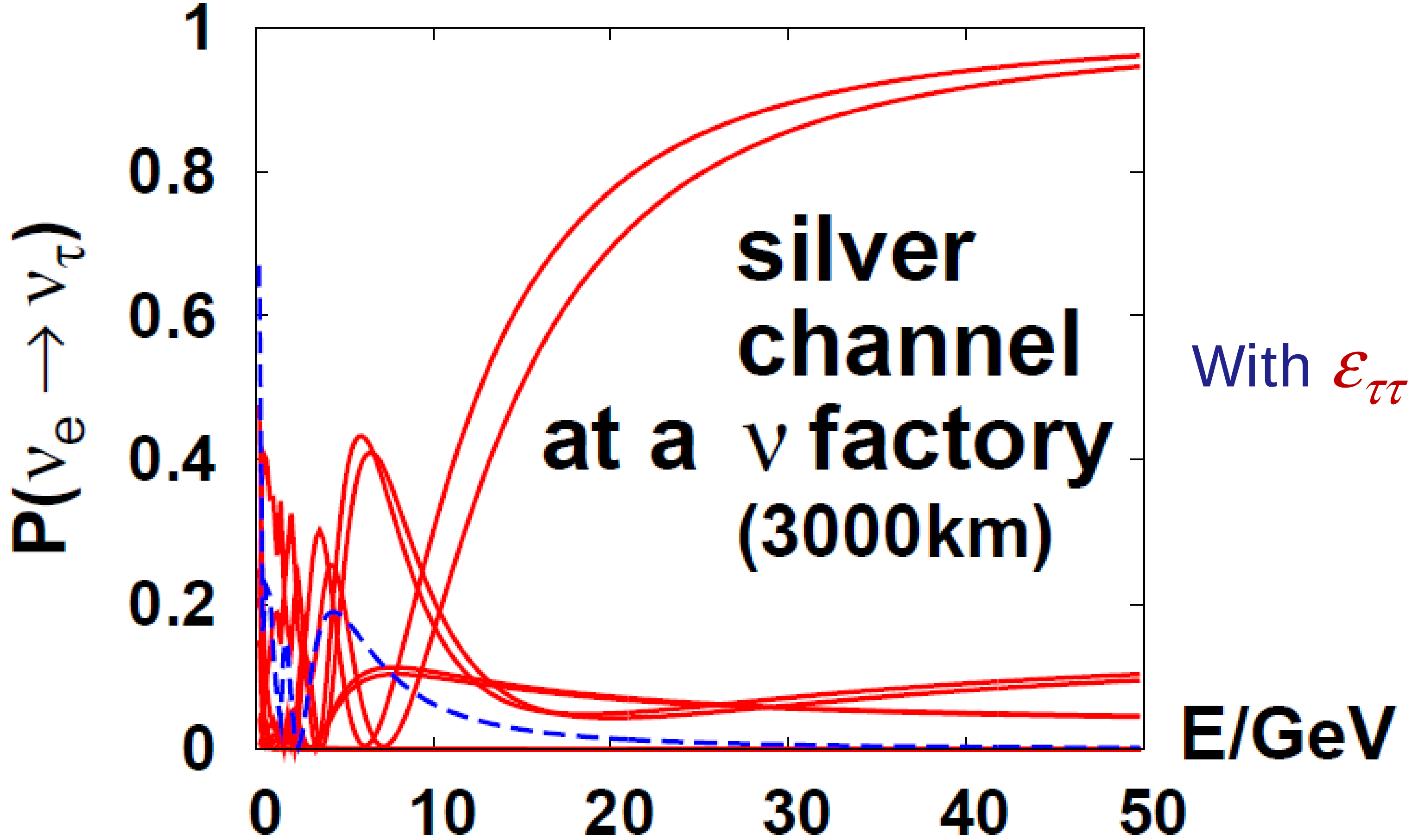
$$\left|\varepsilon^m\right| < \begin{pmatrix} 0.6 & 0.1 & 0.5 \\ 0.1 & 0.015 & 0.05 \\ 0.5 & 0.05 & 6 \end{pmatrix}$$

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

Huge effects in ν oscillations



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

N. Kitazawa, H. Sugiyama and O. Yasuda hep-ph/0606013

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?

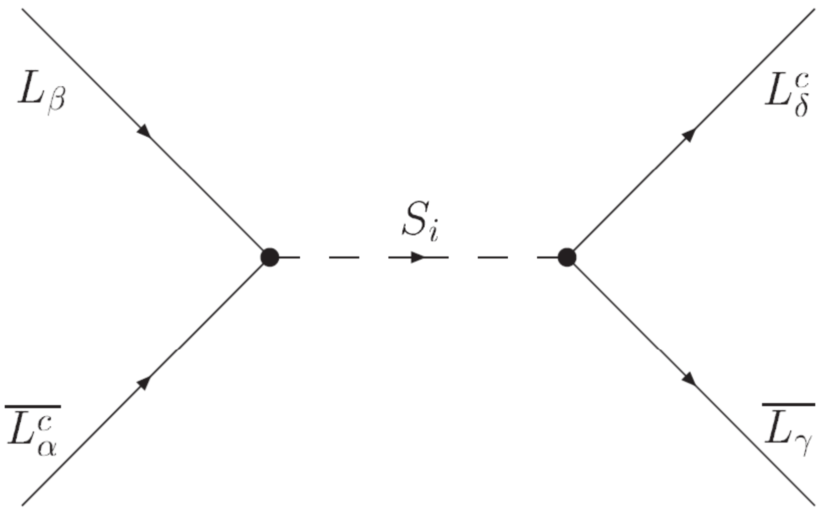
We search for gauge invariant SM extensions satisfying:

- 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 See also next talk
and B. Gavela, D. Hernández, T. Ota and W. Winter 0809.3451

Large NSI?

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



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

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

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:

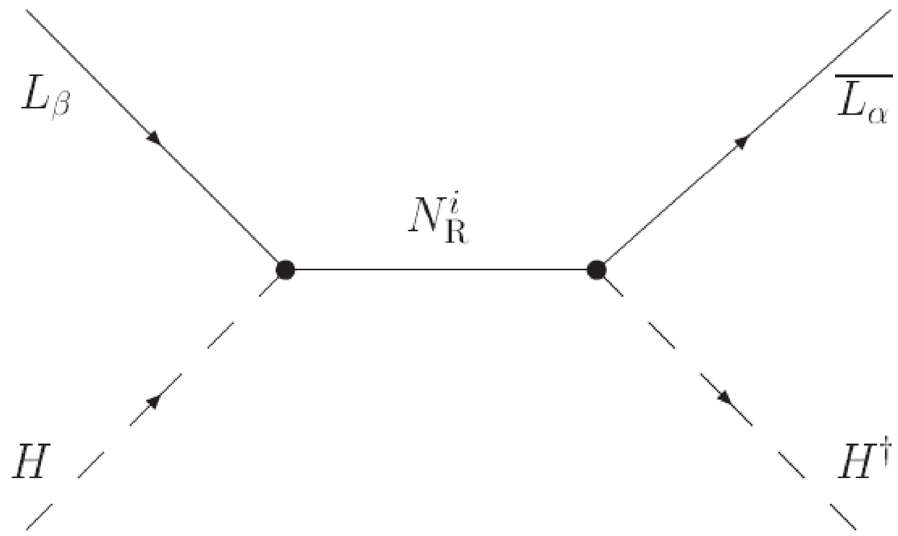
$$|\varepsilon^{m,e_L}_{\mu\mu}| < 8.2 \cdot 10^{-4}$$
$$|\varepsilon^{m,e_L}_{\tau\tau}| < 8.4 \cdot 10^{-3}$$
$$|\varepsilon^{m,e_L}_{\mu\tau}| < 1.9 \cdot 10^{-3}$$

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

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

Large NSI?

At d=6 indirect way: fermion singlets



Effective Lagrangian

- 3 light ν
- all unitarity violation from NP with $\Lambda > v$
- flavour universality

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

Effective Lagrangian

- 3 light ν
- all unitarity violation from NP with $\Lambda > v$
- flavour universality

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

Diagonal mass and canonical kinetic terms

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

Effective Lagrangian

- 3 light ν
- all unitarity violation from NP with $\Lambda > \mathrm{v}$
- flavour universality

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

Diagonal mass and canonical kinetic terms

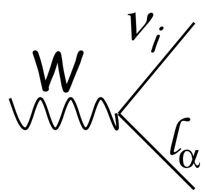
$$L = i\,\bar{\nu}_i \partial \nu_i + \bar{\nu}_i m_{ii} \nu_i - \frac{g}{\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i} \nu_i + h.c.\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_i \gamma^\mu P_L (N^\dagger N)_{ij} \nu_j + h.c.\right) + \ldots$$

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

N is not unitary

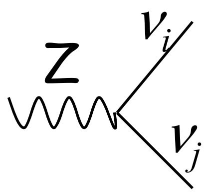
$(NN^\dagger)$ from decays

- W decays



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

- Invisible Z



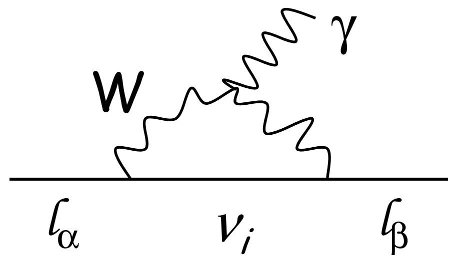
$$\rightarrow \frac{\sum_{\alpha\beta}(NN^\dagger)_{\alpha\beta}}{\sqrt{(NN^\dagger)_{ee}}\sqrt{(NN^\dagger)_{\mu\mu}}}$$

- Universality tests

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

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

- Rare leptons decays



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

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

After integrating out W and Z neutrino NSI induced

$(NN^\dagger)$ from decays

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

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

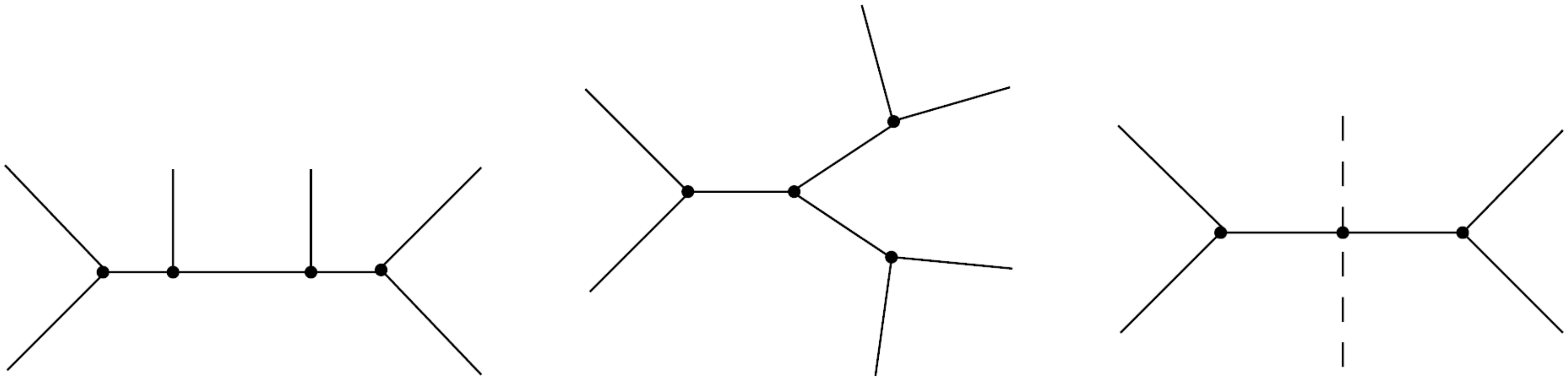
$$N_\nu = 2.984 \pm 0.009$$

Large NSI?

At d=8 more freedom

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

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



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

We distributed the 6 fields among the legs in the different topologies and studied if the resulting operators satisfied the restrictions

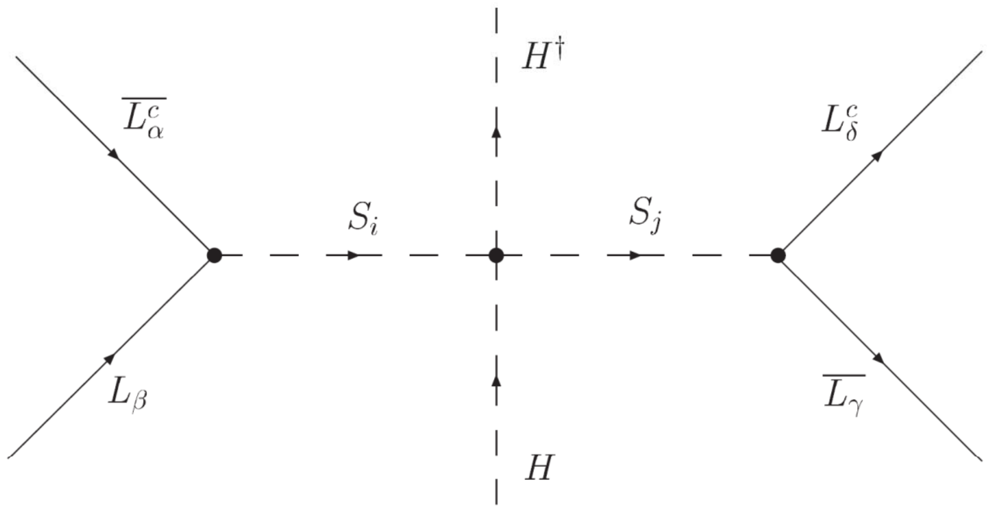
Large NSI?

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

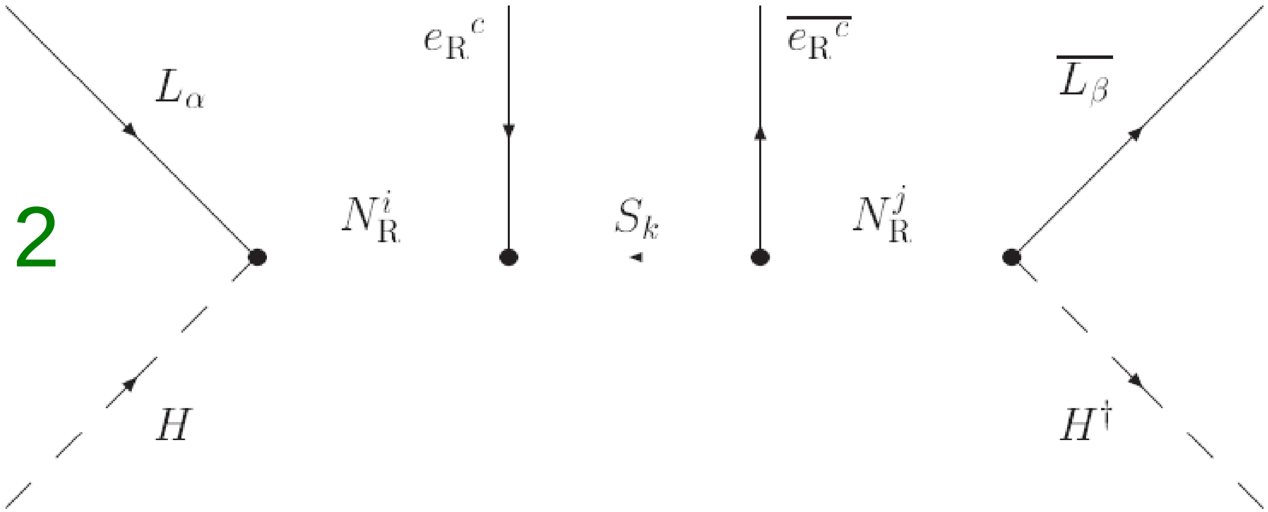
$$v^2/2 \left(\overline{L^c_\alpha} i\sigma_2 L_\beta\right)\left(\overline{L_\gamma} i\sigma_2 L^c_\delta\right)$$

Same as the d=6 realization with the scalar singlet

Large NSI?

We found three classes satisfying the requirements:

2

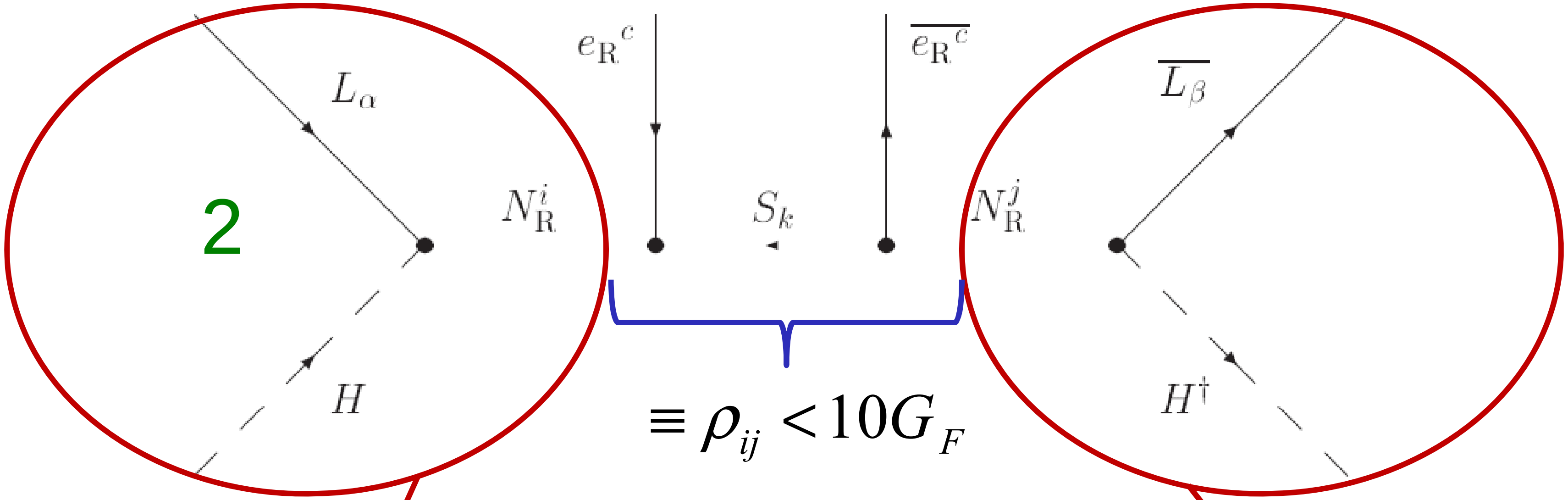


The Higgs coupled to the N_R selects ν after EWSB

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

Large NSI?

But can be related to non-unitarity and constrained



$$\equiv \rho_{ij} < 10 G_F$$

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

Large NSI?

For the matter NSI

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

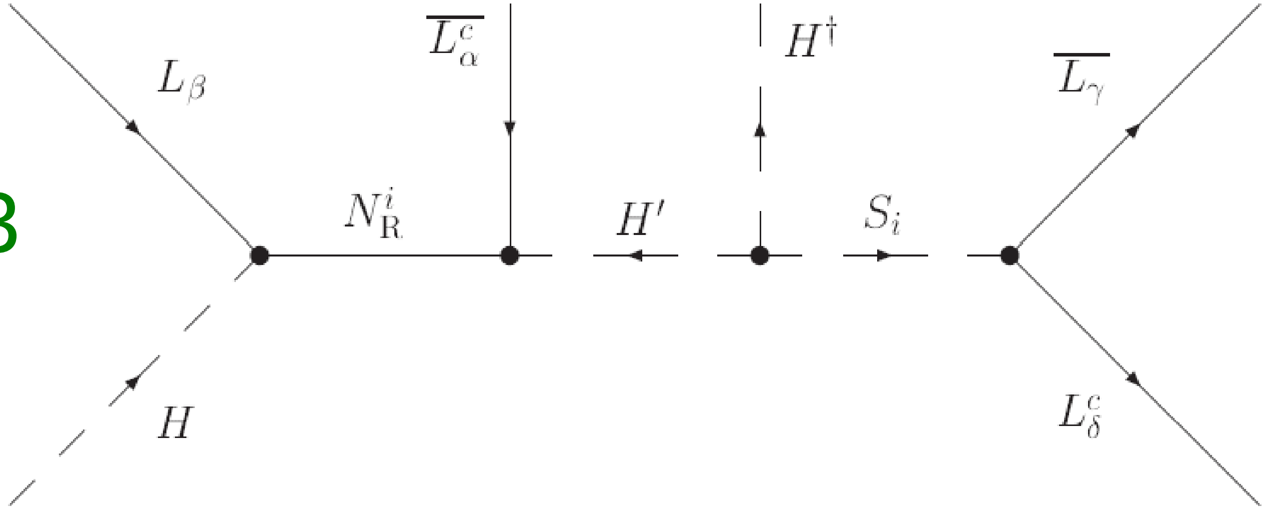
Where $\hat{\rho}^{(f)}$ is the largest eigenvalue of $\rho_{ij}^{(f)}$

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:

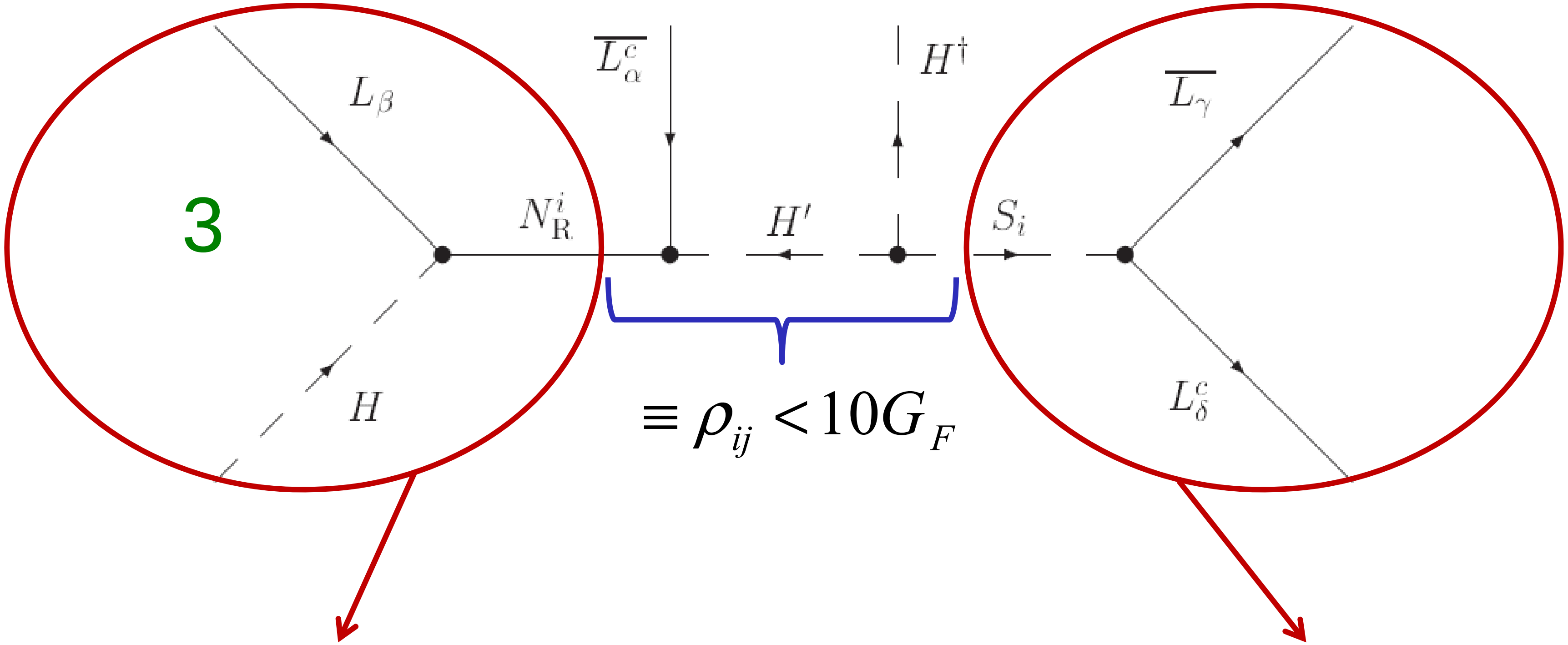
3



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



$$\equiv \rho_{ij} < 10 G_F$$

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

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

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?

See next talk by T. Ota to see how to obtain

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

cancelling the 4 charged fermion operators

NSI in loops

Even if we arrange to have

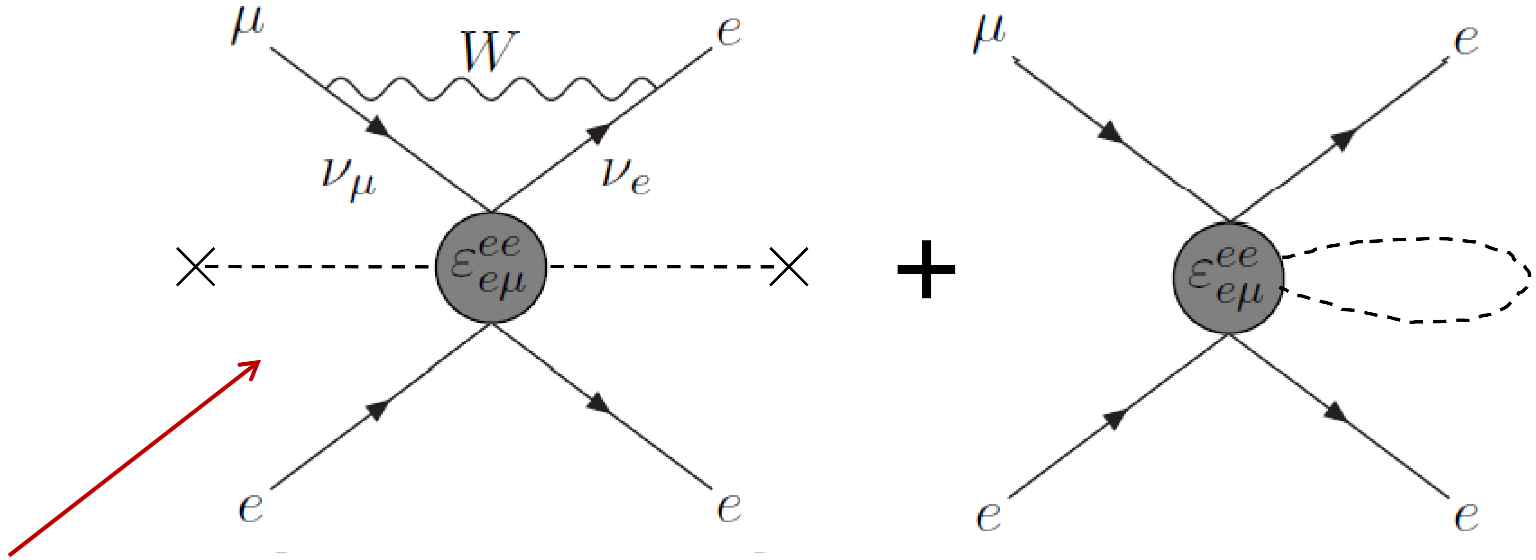
$$\frac{O}{M^4}\left(\overline{L}_\alpha i\sigma_2 H^*\right)\gamma^\mu\left(H^t i\sigma_2 L_\beta\right)\left(\overline{E}_\gamma\gamma_\mu E_\delta\right)$$

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

C. Biggio, M. Blennow and EFM 0902.0607

NSI in loops

These loops are related by gauge invariance:



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:

- Without cancellations $k \sim O(1)$
  - At least $\Lambda \sim M_W$ → old bounds are recovered $\varepsilon_{e\mu} < 8\cdot 10^{-4}$
  - If no other new physics $\Lambda = M$ → *NSI = 4CF* if $1/16\pi^2 > v^2/M^2$
- Allowing cancellations also at loop level $k = 0$
  - Only direct 0.1 bound on $\varepsilon_{e\mu}$

C. Biggio, M. Blennow and EFM 0902.0607

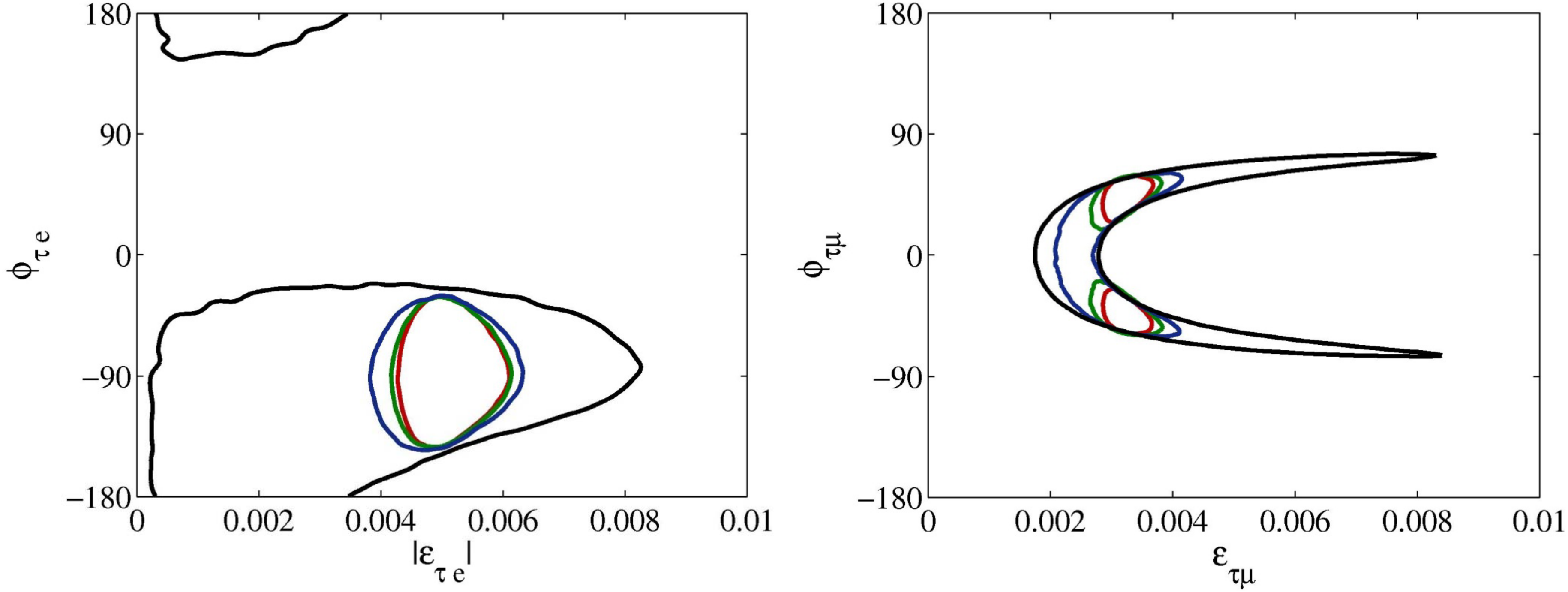
Conclusions: NSI

- To realize large NSI related 4-charged fermion operators must be avoided

  - It can be realized at d=6 by the exchange of a scalar singlet or a N_R, but very constrained
  - At d=8 no new possibilities without cancellations, similar bounds apply
  - 4-charged fermion ops can be avoided through cancellations between diagrams: to cook a model check the ingredient list in arXiv:0809.3451 and next talk

- Even tuning at tree level large 4-charged fermion ops induced at one loop: cancellations also needed at 1 loop

Non-Unitarity at a NF



Golden channel at NF is sensitive to $\varepsilon_{\tau e}$ beyond present bound

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

Near τ detectors can improve the bounds around 1 order of magnitude

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

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