

Non-standard neutrino interactions

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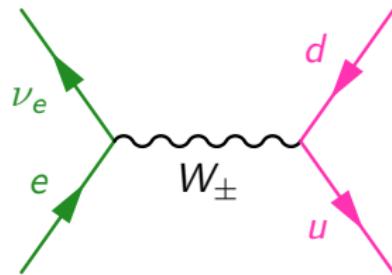
March 13, 2009

M. B. Gavela, DH, T. Ota and W. Winter

to be published PRD [arXiv:0809.3451]

Standard interactions in the SM

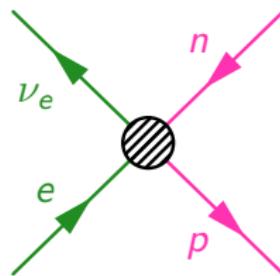
$$\mathcal{L}_{W-LL} = \cdots - i \frac{g}{\sqrt{2}} \bar{L}_L^e W L_L^e - i \frac{g}{\sqrt{2}} \bar{Q}_L^u W Q_L^u$$



All leptonic interactions **preserve $U(1)$ gauge symmetry**

Effective field theory → Four-Fermi interaction

$$\frac{g^2}{M_W^2} (\bar{e}_L \gamma^\mu \nu_L^e) (\bar{n} \gamma_\mu n)$$



What are Non Standard Neutrino Interactions (I)

Massive neutrinos \Rightarrow NEW PHYSICS!

*Mass Found in Elusive Particle;
Universe May Never Be the Same*

Discovery on Neutrino

*Detecting
Neutrinos*

*Neutrinos
pass through*

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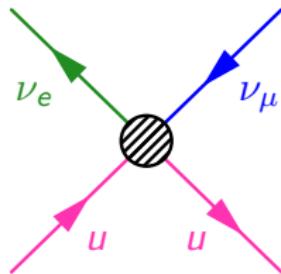
Discovery on Neutrino

Detecting Neutrinos

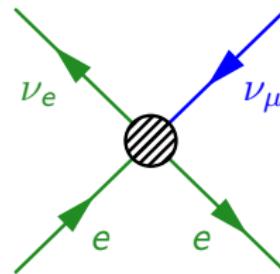
Neutrinos pass through

Is it possible some more new physics in the neutrino sector?

$$\frac{1}{\Lambda^2} \bar{\nu}_e \nu_\mu \bar{u} u$$



$$\frac{1}{\Lambda^2} \bar{\nu}_e \nu_\mu \bar{e} e$$



NSNI: Non-SM like, four fermion interactions (possibly flavour violating) involving neutrinos.

What are NSNIIs (II)

$$\mathcal{L}_{NC} \propto -\epsilon_{\alpha\beta}^{\ell}(\bar{\nu}^{\alpha}\gamma^{\rho}P_L\nu_{\beta})(\bar{\ell}\gamma_{\rho}\ell)$$

In matter propagation

$$\mathcal{H}_F = U \begin{pmatrix} 0 & & \\ & \frac{\Delta m_{21}^2}{2E} & \\ & & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger + V \begin{pmatrix} 1 + \epsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m \\ \epsilon_{\mu e}^m & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{\tau e}^m & \epsilon_{\tau\mu}^m & \epsilon_{\tau\tau}^m \end{pmatrix}$$

$$V \propto N_e$$

Where to find them? Cosmology, astrophysics, all over the place

Current bounds on NSI interactions

BOUNDS

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

Es in units of $2\sqrt{2}G_F$

S. Davidson, C. Peña-Garay, N. Rius, A. Santamaria

hep-ph/0302093

Gauge invariance and Effective Field Theory

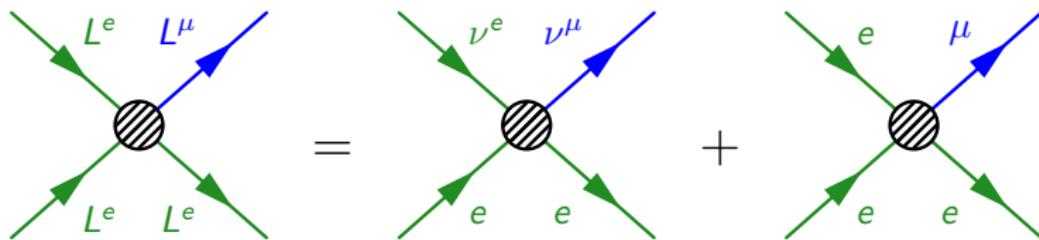
- Effective Field Theory (Remember Fermi?)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}_{d=5} + \frac{1}{\Lambda^2} \mathcal{L}_{d=6} + \dots$$

- Gauge invariance ($SU(3) \times SU(2) \times U(1)$)

$$\frac{1}{\Lambda^2} (\bar{\nu}^e \gamma^\rho P_L \nu^\mu) (\bar{e}_L \gamma_\rho e_L) \rightarrow \frac{1}{\Lambda^2} (\bar{L}^e \gamma^\rho L^\mu) (\bar{L}_e \gamma_\rho L_e)$$

Trouble, for instance $\mu \rightarrow eee$



Systematical analysis (I)

Two possibilities

A) There could be NO lepton charged processes involved

Ex: For $d = 6$

$$(\bar{L}^c i\tau^2 L)(\bar{L} i\tau^2 L^c) \rightarrow (\bar{\nu}_e^c e_L)(\bar{\nu}_\mu e_L^c)$$

Ex: For $d = 8$

$$(\bar{L} H)\gamma^\mu(H^\dagger L)(\bar{E}\gamma_\mu E) \rightarrow v^2(\bar{\nu}_e^e \gamma^\mu \nu_\mu^e)(\bar{e}_L \gamma_\mu e_L^e)$$

Systematical analysis (II)

Two possibilities

- B) In general, "fine tune" some of them to obtain desired suppression

Ex:

$$\mathcal{L}_{\text{eff}} = \frac{\mathcal{C}^1}{\Lambda^2} (\bar{L}^e \gamma^\rho L^\mu) (\bar{L}^e \gamma_\rho L^\mu) + \frac{\mathcal{C}^3}{\Lambda^2} (\bar{L}^e \gamma^\rho \vec{\tau} L^\mu) (\bar{L}^e \gamma_\rho \vec{\tau} L^\mu)$$

We can avoid charged lepton interactions $(\bar{e}_L \gamma^\mu P_L \mu)(\bar{e}_L \gamma_\mu P_L e)$ if

$$\mathcal{C}^1 + \mathcal{C}^3 \simeq 0$$

ALL cancelation conditions considered

TREE-LEVEL MEDIATOR DECOMPOSITION



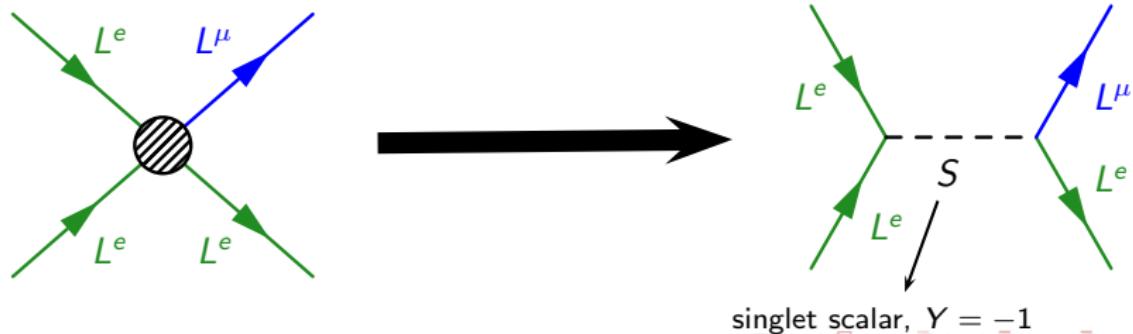
Tree level mediator decomposition

We can open the $d = 6$ vertex

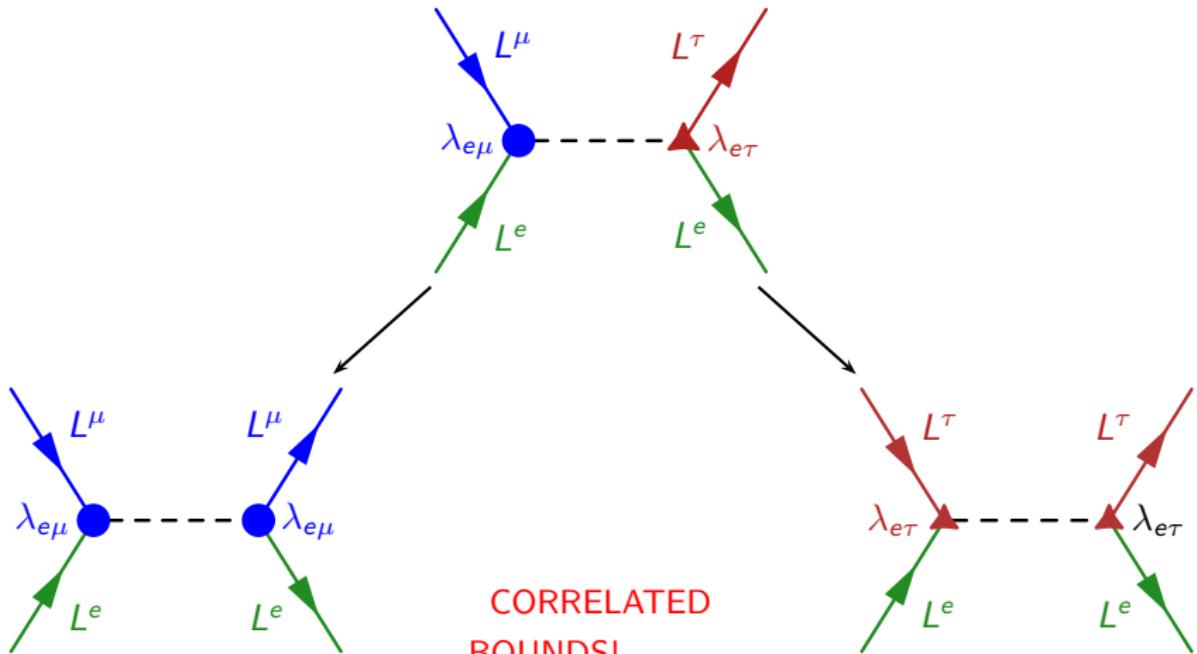
Tree level mediator decomposition

We can open the $d = 6$ vertex

Ex: For instance, take the $(\bar{L}^c i\tau^2 L)(\bar{L} i\tau^2 L^c)$



BUT



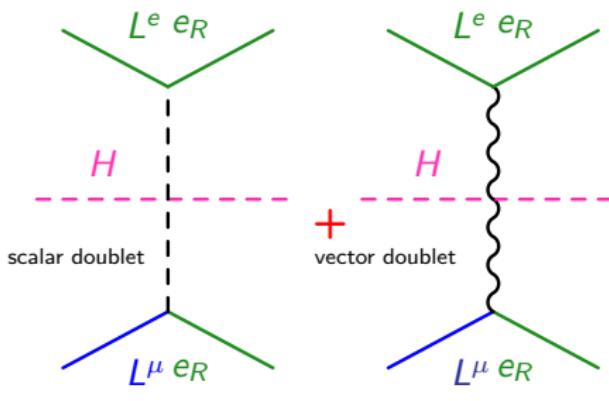
Mediator decomposition $d = 8$

Same idea... more laborious

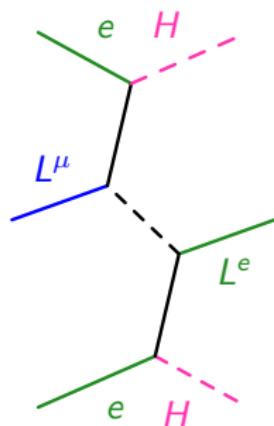
$$(\bar{L}H)\gamma^\mu(H^\dagger L)(\bar{E}\gamma_\mu E) \quad \text{for } d = 8$$

In general, $d = 8$ operators induce $d = 6$ four lepton interactions

Ex: With cancellations.



Ex: Without cancellations

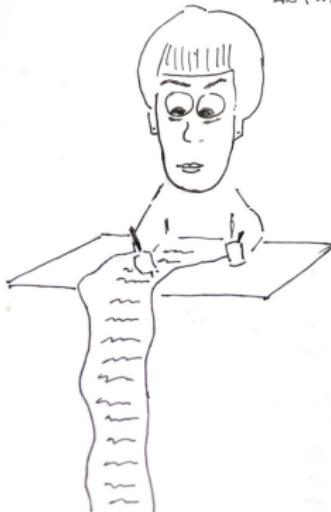


At least two new fields required

Operators with mediators

#	Dim.	eight operator	\mathcal{C}_{LEH}^1	\mathcal{C}_{LEH}^2	\mathcal{O}_{NSI} ?	Mediators
Combination EL						
1		$(\bar{L}\gamma^\mu L)(\bar{E}\gamma_\mu E)(H^\dagger H)$	1			$1_{\bar{b}}$
2		$(\bar{L}\gamma^\mu L)(\bar{E}H^\dagger)(\gamma_\mu)(HE)$	1			$1_{\bar{b}}^0 + 2_{-3/2}^{L/R}$
3		$(\bar{L}\gamma^\mu L)(\bar{E}H^\dagger)^2(\gamma_\mu)(H^\dagger E)$	1			$1_{\bar{b}}^0 + 2_{-1/2}^{L/R}$
4		$(\bar{L}\gamma^\mu L)(\bar{E}\gamma_\mu E)(H^\dagger \bar{H})$	1			$3_{\bar{b}}^0 + 1_{-1/2}$
5		$(\bar{E}\gamma^\mu L)(\bar{E}H^\dagger)(\gamma_\mu)(HE)$	1			$3_{\bar{b}}^0 + 2_{-1/2}^{L/R}$
6		$(\bar{L}\gamma^\mu L)(\bar{E}H^\dagger)(\gamma_\mu)(H^\dagger E)$	1			$3_{\bar{b}}^0 + 2_{-1/2}^{L/R}$
Combination EL						
7		$(\bar{L}E)(\bar{E}L)(H^\dagger H)$	-1/2			$2_{+1/2}^*$
8		$(\bar{L}E)(\tau^*(\bar{E}L)(H)^\dagger \tau H)$	-1/2			$2_{+1/2}^*$
9		$(\bar{L}H)(H^\dagger E)(\bar{E}L)$	-1/4	-1/4	✓	$2_{+1/2}^* + 1_{-1/2}^0 + 2_{-1/2}^{L/R}$
10		$(\bar{L}H)(H^\dagger E)(\tau(\bar{E}L))$	-3/4	1/4		$2_{+1/2}^* + 3_{-1/2}^{L/R} + 2_{-1/2}^{L/R}$
11		$(\bar{L}ir^2 H^*)^2(H^\dagger E)(ir^2)(\bar{E}L)$	1/4	-1/4		$2_{+1/2}^* + 1_{-1/2}^0 + 2_{-1/2}^{L/R}$
12		$(\bar{L}ir^2 H^*)(H^\dagger E)(ir^2)(\bar{E}L)$	3/4	1/4		$2_{+1/2}^* + 3_{-1}^{L/R} + 2_{-1/2}^{L/R}$
Combination $E'L$						
13		$(\bar{L}\gamma^\mu E^*)(\bar{E}^c\gamma_\mu L)(H^\dagger H)$	-1			$2_{-3/2}^*$
14		$(\bar{L}\gamma^\mu E^*)(\tau^*(\bar{E}^c\gamma_\mu L)(H^\dagger H))$	-1			$2_{-3/2}^*$
15		$(\bar{L}H)(\gamma^\mu)(H^\dagger E^*)(\bar{E}^c\gamma_\mu L)$	-1/2	-1/2	✓	$2_{-3/2}^* + 1_{-1/2}^0 + 2_{-1/2}^{L/R}$
16		$(\bar{L}T^R)(\tau^*(\bar{H}^T E^*)(\tau^*(\bar{E}^c\gamma_\mu L))$	-3/2	1/2		$2_{-3/2}^* + 3_{-1/2}^{L/R} + 2_{-1/2}^{L/R}$
17		$(\bar{L}ir^2 H^*)(\gamma^*(H^\dagger E^*)(ir^2)(\bar{E}^c\gamma_\mu L))$	-1/2	1/2		$2_{-3/2}^* + 1_{-1/2}^0 + 2_{-1/2}^{L/R}$
18		$(\bar{L}ir^2 H^*)(\gamma^*(H^\dagger E^*)(ir^2)(\bar{E}^c\gamma_\mu L))$	-3/2	-1/2		$2_{-3/2}^* + 3_{-1}^{L/R} + 2_{-1/2}^{L/R}$
Combination $H'L$						
19		$(\bar{L}E)(\bar{E}H)(H^\dagger L)$	-1/4	-1/4	✓	$2_{+1/2}^* + 1_{\bar{b}}^0 + 2_{-1/2}^{L/R}$
20		$(\bar{L}E)(\tau^*(\bar{E}H)(H^\dagger L))$	-3/4	1/4		$2_{+1/2}^* + 3_{-1/2}^{L/R} + 2_{-1/2}^{L/R}$
21		$(\bar{L}H)(\gamma^*(H^\dagger L)(\bar{E}\gamma_\mu E))$	1/2	1/2	✓	$1_{\bar{b}}^0 + 1_{-1/2}^0$
22		$(\bar{L}T^R)(\gamma^*(H^\dagger L)(\bar{E}\gamma_\mu E))$	3/2	1/2		$1_{\bar{b}}^0 + 3_{-1}^{L/R}$
23		$(\bar{L}Y^*(\bar{E}^c H)(\gamma^*(H^\dagger L))$	-1/2	-1/2	✓	$2_{-3/2}^* + 1_{-1/2}^0 + 2_{-1/2}^{L/R}$
24		$(\bar{L}\gamma^* E^*)(\bar{E}^c H)(\gamma^*(H^\dagger L))$	-3/2	1/2		$2_{-3/2}^* + 3_{-1}^{L/R} + 2_{-1/2}^{L/R}$
Combination HL						
25		$(\bar{L}E)(ir^2)(\bar{E}^*(H^*)^2(H^\dagger ir^2 L))$	1/4	-1/4		$2_{+1/2}^* + 1_{-1/2}^{L/R} + 2_{-1/2}^{L/R}$
26		$(\bar{L}E)(\tau^*(\bar{E}^*(H^*)^2(H^\dagger ir^2 L))$	3/4	1/4		$2_{+1/2}^* + 2_{-1}^{L/R} + 2_{-3/2}^{-1}$
27		$(\bar{L}ir^2 H^*)^2(\bar{E}^*(H^*)^2(H^\dagger ir^2 L))$	-1/9	1/9		$1_{\bar{b}}^0 + 1_{-1/2}^{L/R}$

WHY DO WE NEED STUDENTS ANYWAY?



Summary and Conclusions

- Two ways of achieving large NSIs: with or without fine tuning. Fine tuning conditions (pray for symmetries) are now clear.
- Unfortunately, gauge symmetries are a strong constraint to NSIs. At tree level two exotic fields are required to achieve large NSIs.
- However, not excluded! Most bounds are model dependent.

BACKUP SLIDES

SM plus neutrino masses

Two generations case

$$\mathcal{L}_{SM+m_\nu} = \cdots - \frac{g}{\sqrt{2}} \bar{\ell}_L \gamma^\mu U_L W_\mu$$

$$P(\nu_a \rightarrow \nu_b; t) = \left| \sum_j U_{bj} e^{-iE_j t} U_{ja}^\dagger \right| = \sin^2 \theta \sin^2 \left(\frac{\Delta m^2}{4E} t \right)$$

for the case of two species

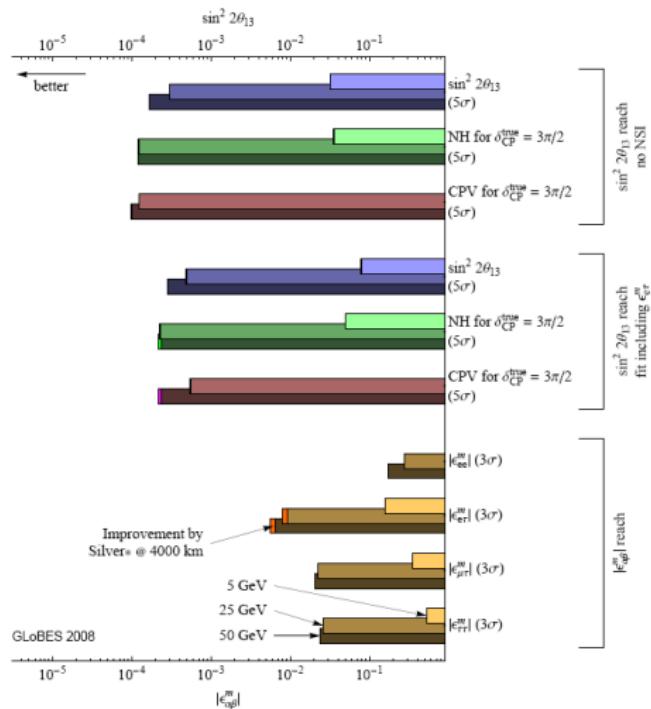
Inside matter

$$\frac{G}{\sqrt{2}} [\bar{e} \gamma_\mu (1 - \gamma_5) \nu_e] [\nu_e \gamma^\mu (1 - \gamma_5) e] \rightarrow \sqrt{2} G_F N_e \bar{\nu}_e \nu_e$$

Schrödinger equation

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_b \end{pmatrix} \begin{pmatrix} -A + \epsilon_{ee}^0 & B \\ B & A \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_b \end{pmatrix} \quad \text{with} \quad \begin{aligned} \epsilon_{ee} &= \sqrt{2} G_F N_e \\ A &= \frac{\Delta m^2}{4E} \cos 2\theta_0 \\ B &= \frac{\Delta m^2}{4E} \sin 2\theta_0 \end{aligned}$$

Future bounds from NF



J. Kopp, T. Ota and W. Winter

Future bounds from NF

Performance indicator	90% C.L.	3σ C.L.	5σ C.L.
Standard oscillation physics			
$\sin^2 2\theta_{13}$	$4.25 \cdot 10^{-5}$	$1.22 \cdot 10^{-4}$	$3.03 \cdot 10^{-4}$
Normal hierarchy (for $\delta_{\text{CP}}^{\text{true}} = 3\pi/2$)	$2.27 \cdot 10^{-5}$	$5.93 \cdot 10^{-5}$	$1.23 \cdot 10^{-4}$
Maximal CPV ($\delta_{\text{CP}}^{\text{true}} = 3\pi/2$, NH)	$1.49 \cdot 10^{-5}$	$4.68 \cdot 10^{-5}$	$1.23 \cdot 10^{-4}$
Standard oscillation physics polluted by non-standard $\epsilon_{\alpha\beta}^m$			
$\sin^2 2\theta_{13}$	$8.13 \cdot 10^{-5}$	$2.04 \cdot 10^{-4}$	$4.88 \cdot 10^{-4}$
Normal hierarchy (for $\delta_{\text{CP}}^{\text{true}} = 3\pi/2$)	$4.00 \cdot 10^{-5}$	$1.01 \cdot 10^{-4}$	$2.29 \cdot 10^{-4}$
Maximal CPV ($\delta_{\text{CP}}^{\text{true}} = 3\pi/2$, NH)	$4.69 \cdot 10^{-5}$	$1.39 \cdot 10^{-4}$	$5.52 \cdot 10^{-4}$
Non-standard oscillation physics with real $\epsilon_{\alpha\beta}^m$			
$\epsilon_{e\mu}^m$ (with $\text{Im } \epsilon_{e\mu}^m = 0$)	$[-1.77 \cdot 10^{-3}, 1.71 \cdot 10^{-3}]$	$[-3.70 \cdot 10^{-3}, 3.26 \cdot 10^{-3}]$	$[-6.33 \cdot 10^{-3}, 5.98 \cdot 10^{-3}]$
$\epsilon_{e\tau}^m$ (with $\text{Im } \epsilon_{e\tau}^m = 0$)	$[-4.46 \cdot 10^{-3}, 3.51 \cdot 10^{-3}]$	$[-9.18 \cdot 10^{-3}, 5.98 \cdot 10^{-3}]$	$[-1.37 \cdot 10^{-2}, 0.93 \cdot 10^{-2}]$
$\epsilon_{\mu\tau}^m$ (with $\text{Im } \epsilon_{\mu\tau}^m = 0$)	$[-3.69 \cdot 10^{-4}, 3.68 \cdot 10^{-4}]$	$[-6.76 \cdot 10^{-4}, 6.74 \cdot 10^{-4}]$	$[-1.16 \cdot 10^{-3}, 1.15 \cdot 10^{-3}]$
ϵ_{ee}^m	$[-1.37 \cdot 10^{-1}, 1.23 \cdot 10^{-1}]$	$[-2.77 \cdot 10^{-1}, 2.26 \cdot 10^{-1}]$	$[-3.48 \cdot 10^{-1}, 3.86 \cdot 10^{-1}]$
$\epsilon_{\mu\mu}^m$	$[-1.90 \cdot 10^{-2}, 1.89 \cdot 10^{-2}]$	$[-2.64 \cdot 10^{-2}, 2.59 \cdot 10^{-2}]$	$[-3.58 \cdot 10^{-2}, 3.55 \cdot 10^{-2}]$
$\epsilon_{\tau\tau}^m$	$[-1.90 \cdot 10^{-2}, 1.90 \cdot 10^{-2}]$	$[-2.62 \cdot 10^{-2}, 2.62 \cdot 10^{-2}]$	$[-3.57 \cdot 10^{-2}, 3.57 \cdot 10^{-2}]$
Non-standard oscillation physics with complex $\epsilon_{\alpha\beta}^m$			
$ \epsilon_{e\mu}^m $	$3.41 \cdot 10^{-3}$	$5.71 \cdot 10^{-3}$	$8.08 \cdot 10^{-3}$
$ \epsilon_{e\tau}^m $	$4.74 \cdot 10^{-3}$	$9.36 \cdot 10^{-3}$	$1.75 \cdot 10^{-2}$
$ \epsilon_{\mu\tau}^m $	$1.80 \cdot 10^{-2}$	$2.22 \cdot 10^{-2}$	$3.31 \cdot 10^{-2}$

Kopp, T. Ota and W. Winter

PONER REF



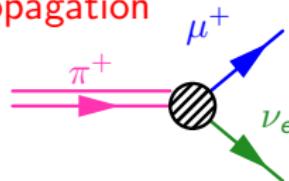
Charged Current NSIs

Charged currents

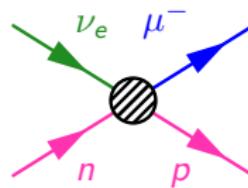
$$\mathcal{L}_{\text{CC}} \propto \tilde{\epsilon}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\rho \ell_\beta) (\bar{f}' \gamma_\rho f), \quad \alpha, \beta = e, \mu, \tau$$

Effects at **source**, **detector** and **matter propagation**

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon_{\alpha\gamma}^s |\nu_\gamma\rangle, \quad \text{e.g.}$$



$$\langle\nu_\alpha^d| = \langle\nu_\alpha| + \sum_{\gamma=e,\mu,\tau} \epsilon_{\gamma\alpha}^d \langle\nu_\gamma|, \quad \text{e.g.}$$



Systematical analysis III

In general

- ① Choose a **basis** of effective operators
- ② Find **cancellation conditions** for the **coefficients** of the basis
- ③ Express **cancellation conditions** for **any combination of generic operators** in terms of those of the basis

Systematical analysis: Choose basis

Choose a **basis** of effective operators

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

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

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

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

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

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

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

$$(\mathcal{O}_{EEH})_{\alpha\gamma}^{\beta\delta} = (\bar{E} \gamma^\rho E)(\bar{E} \gamma_\rho E)(H^\dagger H).$$

Systematical analysis: Find canc. conditions

Find cancellation conditions for the coefficients of the basis

For the $d = 8$ operator coefficients, the cancellation conditions read

$$\mathcal{C}_{LEH}^1 = \mathcal{C}_{LEH}^3, \quad \mathcal{C}_{LLH}^{111} + \mathcal{C}_{LLH}^{331} - \mathcal{C}_{LLH}^{133} - \mathcal{C}_{LLH}^{313} = 0, \quad \mathcal{C}_{LLH}^{333} \text{ arbitr.}, \quad \mathcal{C}_{EEH} = 0,$$

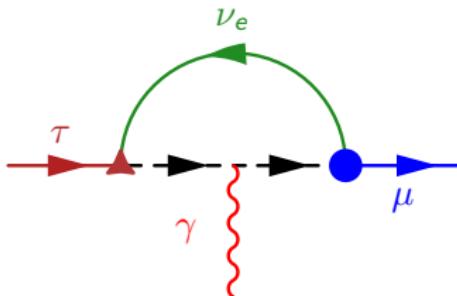
Systematical analysis: Canc. conditions for any op.

Combination $H^\dagger L$

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		$2_{+1/2}^s + 3_0^{L/R} + 2_{-1/2}^{L/R}$
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		$1_0^v + 3_0^{L/R}$
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		$2_{-3/2}^v + 3_0^{L/R} + 2_{+3/2}^{L/R}$

MOREOVER...

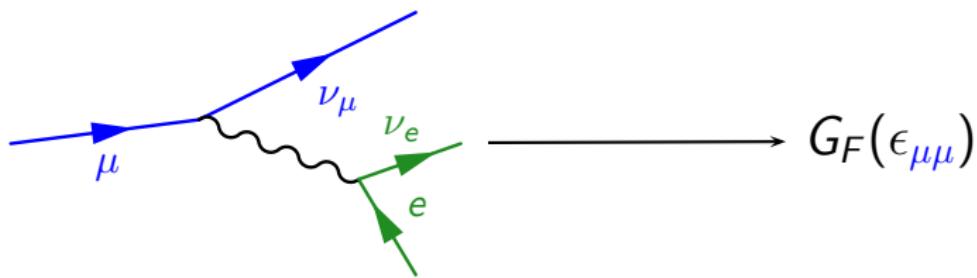
Radiative corrections: $\tau \rightarrow \mu$



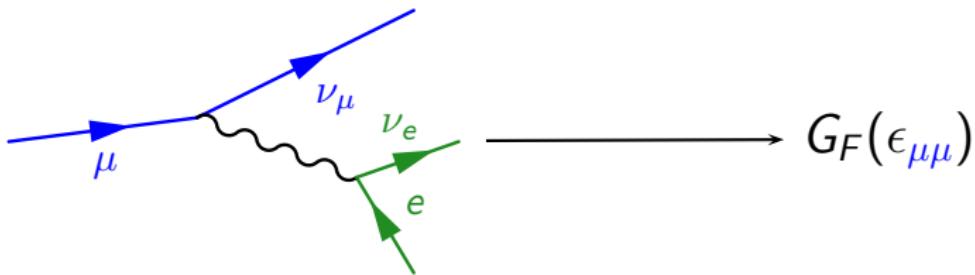
$$\frac{\Gamma(\tau \rightarrow \mu\gamma)}{\Gamma(\tau \rightarrow \mu\nu_\tau\nu_\mu)} \propto |\lambda_{\tau\alpha}\lambda_{\mu\alpha}^*|^2 \quad \text{implies} \quad |\epsilon_{\mu\tau}| < 3.0 \times 10^{-2}$$

[Antusch, Baumann, Fernández-Martinez, arXiv:0807.1003.]

Moreover...



Moreover...



and using this G_F find

$$\beta \text{ decays} + K \text{ decays} \\ \downarrow \quad \downarrow \\ |V_{ud}|^2 + |V_{us}|^2 \simeq 1$$

Therefore

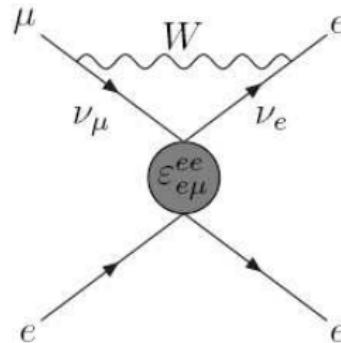
$$|\epsilon_{\mu\mu}| < 8.2 \cdot 10^{-4}$$

[Antusch, Baumann, Fernández-Martínez; arXiv:0807.1003]



Model dependent loop bounds

To set the $\epsilon_{\mu\mu}$ and $\epsilon_{\mu e}$ bounds



But for Zee's model

$$\varepsilon_{\gamma\delta}^{\alpha\beta} = -\varepsilon_{\alpha\delta}^{\gamma\beta} = -\varepsilon_{\gamma\beta}^{\alpha\delta} = \varepsilon_{\alpha\beta}^{\gamma\delta}.$$

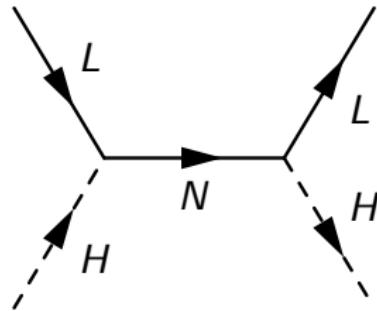
Implies additional $\mathcal{O}\left(\frac{m_\ell^2}{M_W^2}\right)$ suppression, hence weaker bounds

C. Biggio, M. Blennow, E. Fernandez-Martinez
arXiv:0902.0607

NSIs from Seesaws

Type I Seesaw

$$\mathcal{L}_{int} = -Y_{\alpha i} \bar{L} H^\dagger N^i + \text{h.c.}$$



gives the $d = 6$ modification to the L 's kinetic energy

$$\mathcal{L} = -c_{\alpha\beta} (\bar{L}_\alpha H^\dagger) \partial^\mu (H L_\beta)$$

And after diagonalization **NSIs**

NSIs from SUSY

Without R-parity violation

$$\begin{aligned} & \lambda_{ijk} L_i L_j E_k^c \\ & \lambda'_{ijk} L_i Q_j D_k^c \end{aligned}$$

Integrating, for instance, the heavy squark

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2} \sum_{\alpha\beta} \xi_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta) (\bar{d}_R \gamma_\mu d_R)$$

with

$$\xi_{\mu\mu} = \sum_j \frac{|\lambda'_{2j1}|^2}{4\sqrt{2} G_F m_{\tilde{q}_j}^2}$$

etc.