Neutrinos Beyond the νStandard Model

Belén Gavela
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Beyond**S**tandard**M**odel **because**

1) Experimental evidence for new particle physics:

*** **Neutrino masses**
*** **Dark matter**
** **Matter-antimatter asymmetry**

2) SM fine-tunings/uneasiness

SU(3) x SU(2) x U(1) x classical gravity

We ~understand ordinary particles= excitations over the vacuum

We DO NOT understand the vacuum = state of lowest energy:

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We DO NOT understand the vacuum = state of lowest energy:

- The **gravity** vacuum: cosmological cte. Λ , $\Lambda \sim 10^{-123}\, M_{Planck}^4$

* The **QCD** vacuum : Strong CP problem, $\theta_{QCD} < 10^{-10}$

* The **electroweak** vacuum: Higgs-mass, v.e.v.~O (100) GeV

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We DO NOT understand the vacuum = state of lowest energy:

•The **gravity** vacuum: cosmological cte. Λ , $\Lambda \sim 10^{-123}\, M_{Planck}^{4}$

* The **QCD** vacuum : Strong CP problem, $\theta_{QCD} \lesssim 10^{-10}$

* The **electroweak** vacuum: Higgs-mass, v.e.v.~O (100) GeV

The Higgs excitation has the quantum numbers of the EW vacuum

BSM because

1) **Experimental evidence** for new particle physics:

*** **Neutrino masses**
*** **Dark matter**
** **Matter-antimatter asymmetry**

2) **SM fine-tunings/uneasiness**, i.e. in electroweak:

*** **Hierarchy problem**
*** **Flavour puzzle**

More wood for the Flavour Puzzle

Leptons

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & ?(<10^o) \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & +0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} = \begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

Why so different?

More wood for the Flavour Puzzle

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Maybe because of Majorana neutrinos?

Dirac o Majorana ?

- The only thing we have really understood in particle physics is the gauge principle

- SU(3)xSU(2)xU(1) gauge allow Majorana masses....

Lepton number was an accidental symmetry of the SM: unless you impose it by hand, Majorana masses will be there

Anyway, it is for experiment to decide

Main physics goals in ν physics

- To determine the absolute scale of masses
- To determine whether they are Majorana
- To discover Leptonic CP-violation

Let us go for those discoveries !

Can we foresee how to go beyond?

Neutrino masses indicate new physics beyond the SM

Maybe new physics could appear also in neutrino couplings ?

Neutrino masses indicate new physics beyond the SM

?

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Neutrino masses indicate new physics beyond the SM

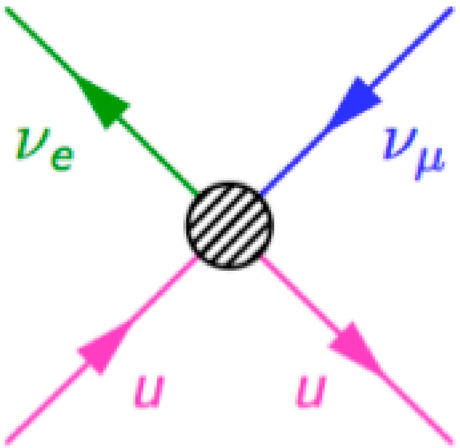
?

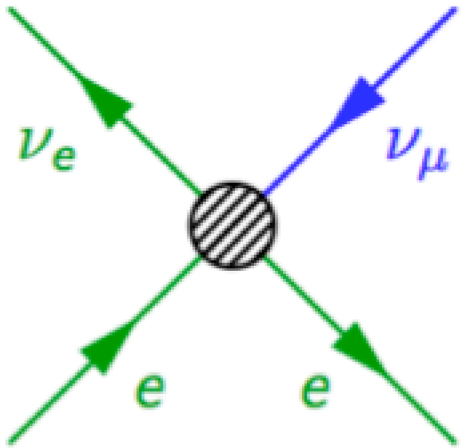
Maybe new physics could appear also in NSI ?

NSI = non-standard neutrino interactions

What are non-standard neutrino interactions (NSI)?

Four-fermion interactions that do not preserve flavour, i.e.





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

$$\Lambda > v$$

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

Two topics

- “Seesaw NSI” and the flavour puzzle

- “Why not” NSI

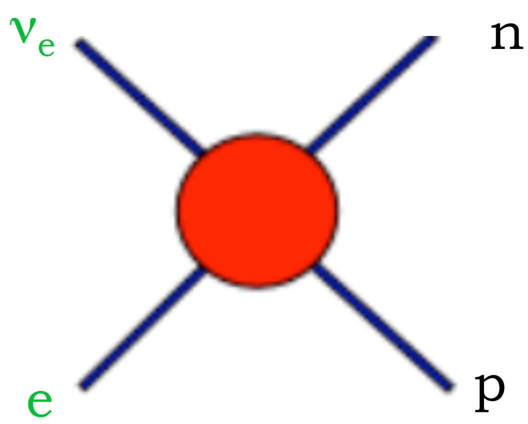
How to go about it model-independent ?....

Effective field theory

Recall Fermi's times,

$\longrightarrow$ Four-Fermi interaction

$G_F\ (\bar{e}_L\ \gamma_\mu\ \nu_e)\ (\bar{n}\ \gamma_\mu\ p)$



$U(1)_{em}$ gauge invariant

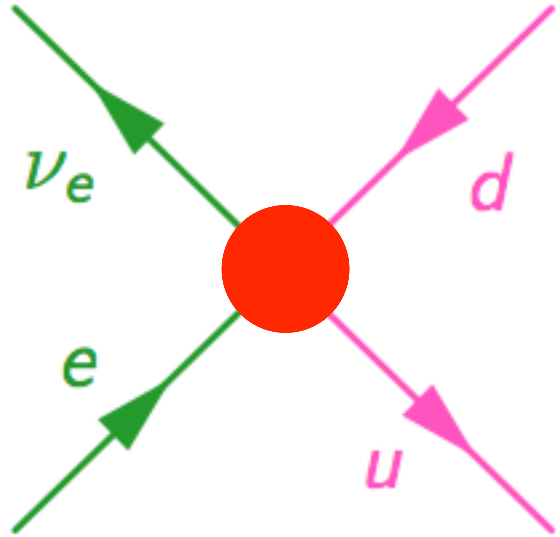
How to go about it model-independent ?....

Effective field theory

Glashow, Weinberg, Salam times:

$\longrightarrow$ Four-Fermi interaction

$$G_F\ (\bar{e}_L \gamma^\mu \nu_L^e)(\bar{u}\gamma_\mu d_L)$$



$U(1)_{em}$ gauge invariant

How to go about it model-independent ?....

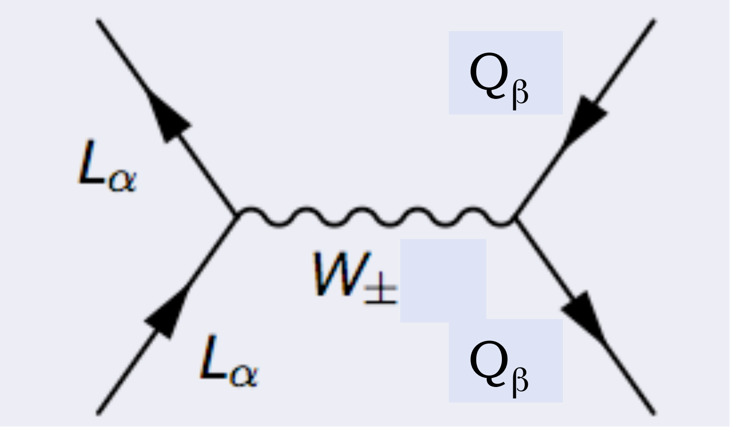
Effective field theory

Glashow, Weinberg, Salam era:

→ Four-Fermi interaction

$$\frac{g^2}{M_W^2}\,(\bar{L}_\alpha \gamma_\mu L_\alpha)\,(\bar{Q}_{L\beta}\, \gamma_\mu Q_\beta)$$

Mediator decomposition



SU(2) xU(1)$_{em}$ gauge invariant

ν masses and couplings beyond the SM

In the spirit of Fermi,

Can we build Standard Model operators that

give mass to the neutrinos

and/or new flavoured couplings ?

YES!

If new physics scale $M > v$

$$\mathcal{L} = \mathcal{L}_{low\text{-}energy} + \frac{O^{d=5}}{M} + \frac{O^{d=6}}{M^2} + \ldots\ldots$$

If new physics scale M > v

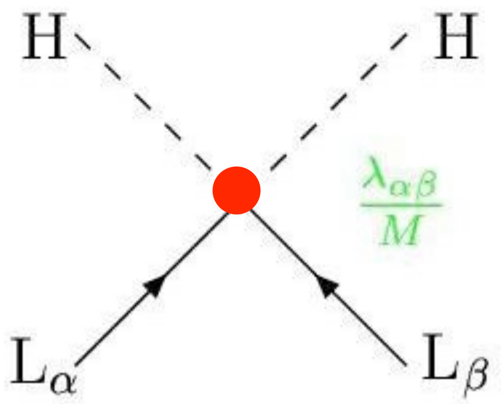
$$\mathcal{L} = \mathcal{L}_{SU(3)xSU(2)xU(1)} + \frac{O^{d=5}}{M} + \frac{O^{d=6}}{M^2} + \ldots\ldots$$

ν masses beyond the SM

The Weinberg operator

Dimension 5 operator:

$$\lambda/M\ (\underbrace{L\ L\ H\ H}_{O^{d=5}}) \rightarrow \lambda v^2/M\ (\nu\nu)$$



It's unique → very special role of ν masses:
lowest-order effect of higher energy physics

ν masses beyond the SM

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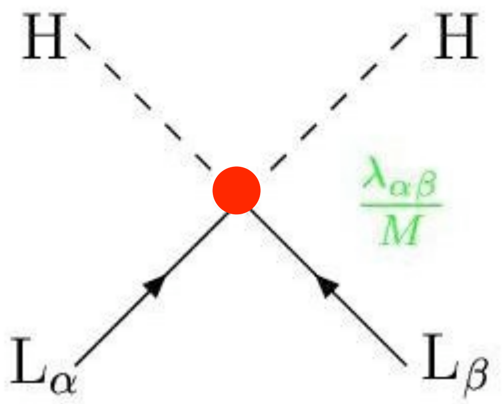

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This mass term violates lepton number (B-L)
→ Majorana neutrinos

ν masses beyond the SM

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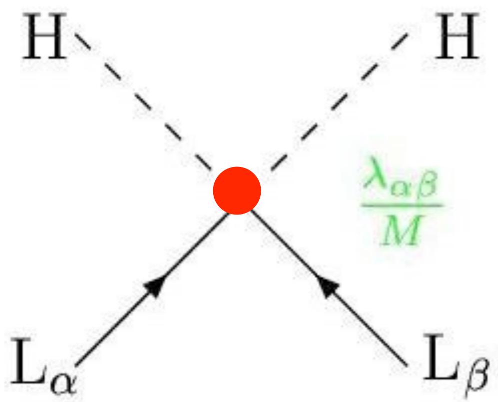


It's unique → very special role of ν masses:
lowest-order effect of higher energy physics

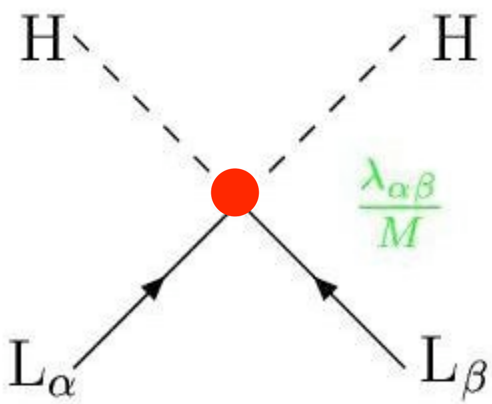
This mass term violates lepton number (B-L)
→ Majorana neutrinos

$O^{d=5}$ *is common to all models of Majorana* ν*s*

New Standard Model νSM ?

$$\mathcal{L}_{\nu SM} = \mathcal{L}_{SM} + c^{d=5} \frac{O^{d=5}}{\Lambda_{LN}} + \ldots\ldots$$

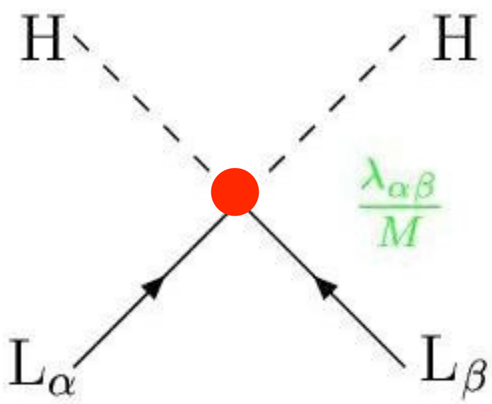
ν masses beyond the SM : tree level



$$\delta L = c^{d=5}\, O^{d=5}$$

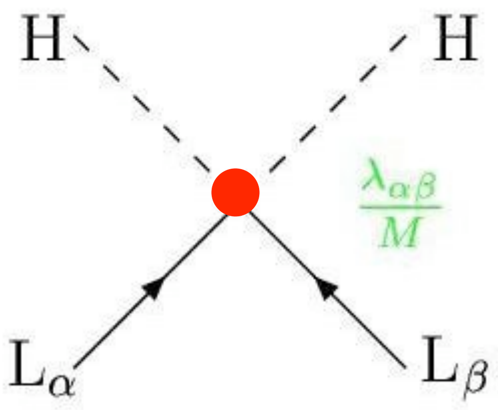
3 generic types (Ma)

ν masses beyond the SM : tree level



2 x 2 = 1 + 3

ν masses beyond the SM : tree level



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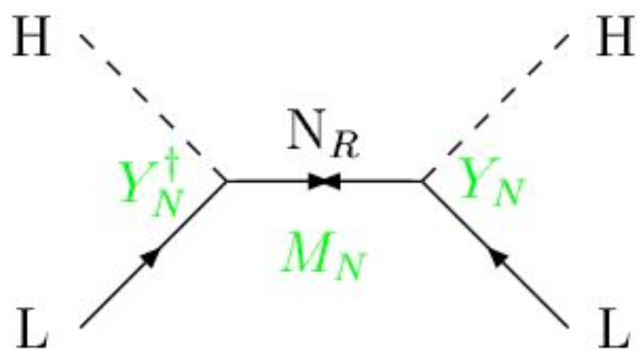
ν masses beyond the SM : tree level

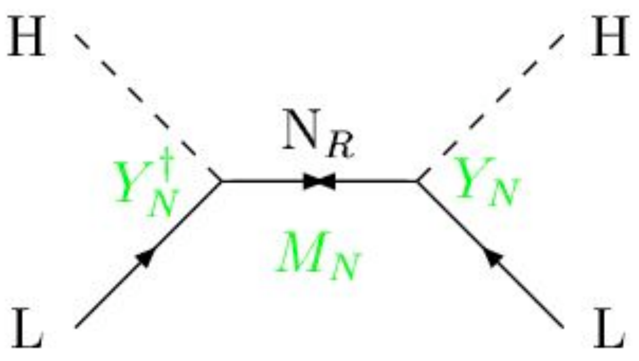


Fermionic Singlet
Seesaw (or type I)

2 x 2 = 1 + 3

$$m_\nu \sim v^2\, c^{d=5} = v^2\, Y_N^T Y_N / M_N$$

ν masses beyond the SM : tree level



Fermionic Singlet
Seesaw (or type I)

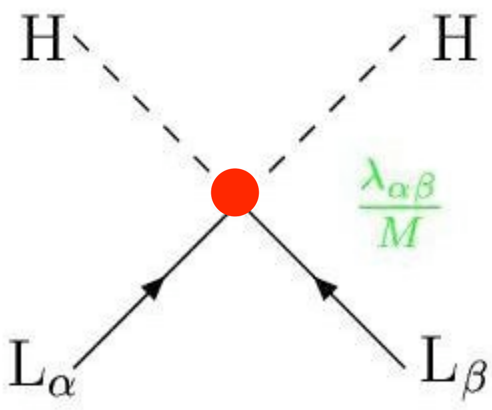
2 x 2 = 1 + 3

$$m_\nu \sim v^2\, c^{d=5} = v^2\, Y_N^T Y_N / M_N$$

Which allows $Y_N \sim 1$ --> $M \sim M_{Gut}$

$Y_N \sim 10^{-6}$ --> $M \sim TeV$

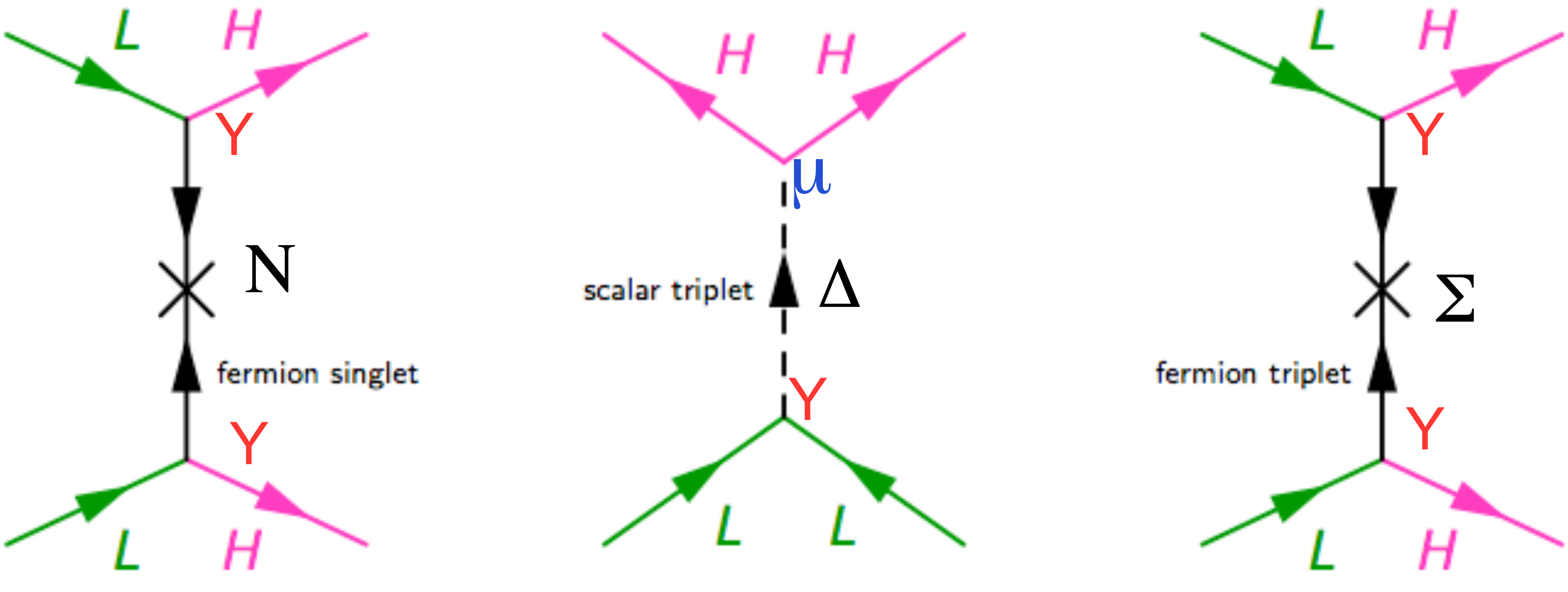
ν masses beyond the SM : tree level



$2 \times 2 = 1 + 3$

The Seesaw models

- Three types of models yield the Weinberg operator at tree level



Type I

Type II

Type III

$m_\nu \sim v^2 \; Y_N^T \frac{1}{M_N} Y_N$

$m_\nu \sim v^2 \; Y_\Delta \frac{\mu}{M_\Delta^2}$

$m_\nu \sim v^2 \; Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$

The Seesaw models

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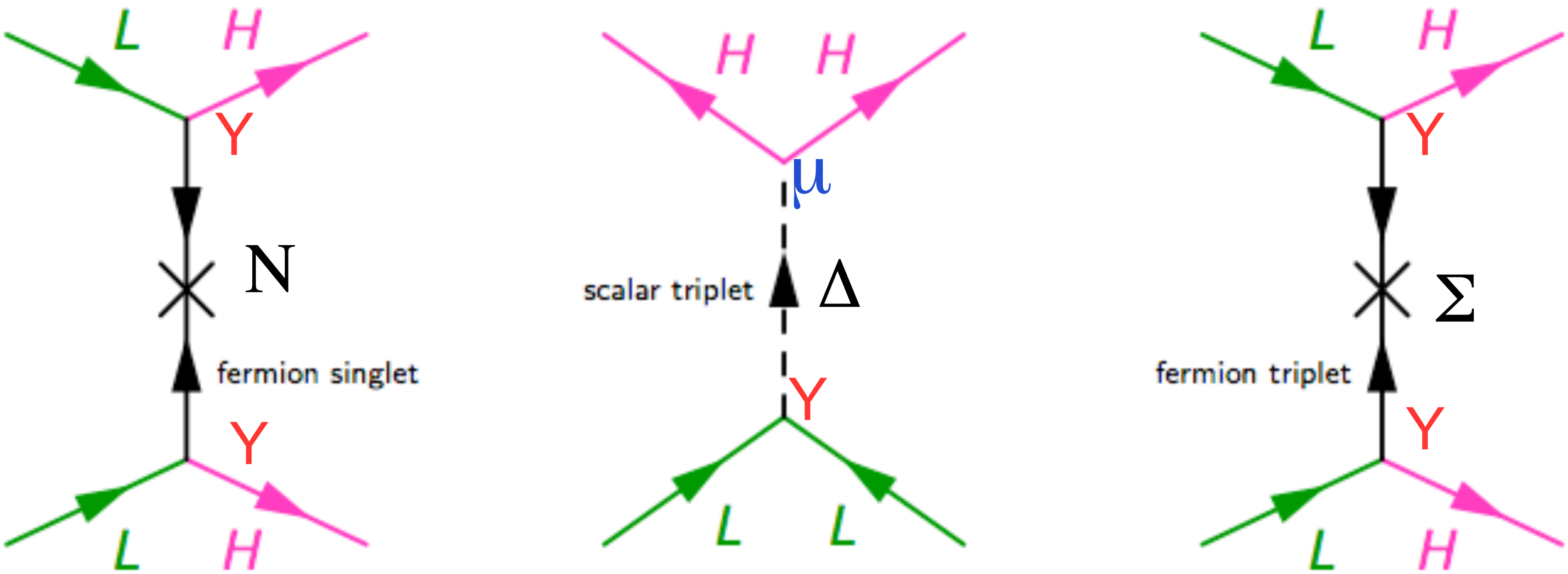

Type I

Heavy fermion singlet N_R

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

Type II

Heavy scalar triplet Δ

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

Type III

Heavy fermion triplet Σ_R

Ma, Roy, Senjanovic, Hambye et al.,

Those fields, N_R , Δ, Σ_R, would mediate other processes too....

Which are the new exotic couplings,

that is, d=6 operators, in Seesaws?

Model	Effective Lagrangian $\mathcal{L}_{eff} = c_i \mathcal{O}_i$		
	$c^{d=5}$	$c_i^{d=6}$	$\mathcal{O}_i^{d=6}$
Fermionic Singlet (type I)	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N^\dagger \frac{1}{\lvert M_N \rvert^2} Y_N$	$\left(\overline{L}\widetilde{H}\right) i\not\partial \left(\widetilde{H}^\dagger L\right)$
Fermionic Triplet (type III)	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	$Y_\Sigma^\dagger \frac{1}{\lvert M_\Sigma \rvert^2} Y_\Sigma$	$\left(\overline{L}\vec{\tau}\widetilde{H}\right) i\not{D} \left(\widetilde{H}^\dagger \vec{\tau} L\right)$
Scalar Triplet (type II)	$4Y_\Delta \frac{\mu_\Delta}{\lvert M_\Delta \rvert^2}$	$Y_\Delta^\dagger \frac{1}{2\lvert M_\Delta \rvert^2} Y_\Delta$	$\left(\overline{\widetilde{L}}\vec{\tau} L\right)\left(\overline{L}\vec{\tau}\widetilde{L}\right)$
		$\frac{\lvert \mu_\Delta \rvert^2}{\lvert M_\Delta \rvert^4}$	$\left(H^\dagger \vec{\tau} \widetilde{H}\right)\left(\overleftarrow{D}_\mu \overrightarrow{D^\mu}\right)\left(\widetilde{H}^\dagger \vec{\tau} H\right)$
		$-2\left(\lambda_3 + \lambda_5\right) \frac{\lvert \mu_\Delta \rvert^2}{\lvert M_\Delta \rvert^4}$	$\left(H^\dagger H\right)^3$

(Abada, Biggio, Bonnet, Hambye, M.B.G.)

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Scalar Triplet (type II)	$4Y_\Delta \frac{\mu_\Delta}{\lvert M_\Delta\rvert^2}$	$Y_\Delta^\dagger \frac{1}{2\lvert M_\Delta\rvert^2} Y_\Delta$	$\left(\overline{\widetilde{L}}\vec{\tau}L\right)\left(\overline{L}\vec{\tau}\widetilde{L}\right)$
		$\frac{\lvert\mu_\Delta\rvert^2}{\lvert M_\Delta\rvert^4}$	$\left(H^\dagger\vec{\tau}\widetilde{H}\right)\left(\overleftarrow{D}_\mu \overrightarrow{D}^\mu\right)\left(\widetilde{H}^\dagger\vec{\tau}H\right)$
		$-2\left(\lambda_3+\lambda_5\right)\frac{\lvert\mu_\Delta\rvert^2}{\lvert M_\Delta\rvert^4}$	$\left(H^\dagger H\right)^3$

$$C^{d=6} \sim \frac{Y^+ Y}{M^2} \longleftrightarrow \text{NSI}$$

(Abada, Biggio, Bonnet, Hambye, M.B.G.)

Non-unitariry NSI

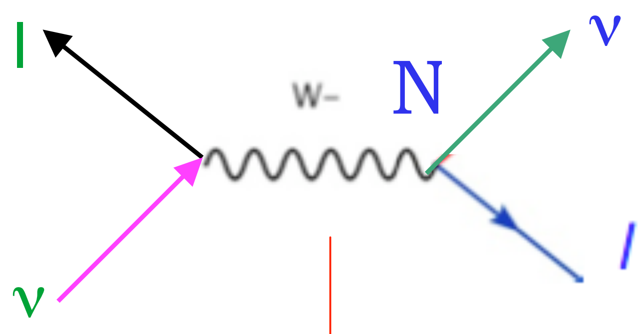
The complete theory of ν masses is unitary.

In all fermionic seesaws

the neutrino mass matrix is larger than 3x3

$$\begin{pmatrix} \begin{pmatrix} 3 \times 3 \end{pmatrix} & \\ & \end{pmatrix}$$

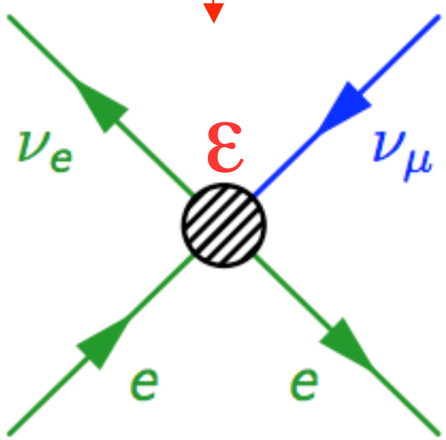
All fermionic Seesaws exhibit non-unitary mixing i.e.



$$N = (1 + \varepsilon)\, U_{PMNS}$$

at low energies

NSI



$$\varepsilon_{\alpha\beta} = \frac{v^2}{2}\left|Y^\dagger \frac{1}{|M|^2} Y\right|_{\alpha\beta}$$

All fermionic Seesaws exhibit non-unitary mixing

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

Very strong bounds for NSI from non-unitarity…

Antusch, Biggio, Fdez-Martinez, Lopez-Pavon, MBG

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Very strong bounds for NSI from non-unitarity...

..... because non-unitarity affects simultaneously:

matter propagation + production and detection (= rare decays...)

Antusch, Biggio, Fdez-Martinez, Lopez-Pavon, MBG

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		$-2(\lambda_3+\lambda_5)\frac{\lvert \mu_\Delta \rvert^2}{\lvert M_\Delta \rvert^4}$	$\left(H^\dagger H\right)^3$

$$C^{d=6} \sim \frac{Y^+ Y}{M^2} \longleftrightarrow \text{Exotic lepton couplings}$$

(Abada, Biggio, Bonnet, Hambye, M.B.G.)

For all scalar and fermionic Seesaw models, present bounds:

$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y^\dagger \frac{1}{M^2} Y|_{\alpha\beta} \lesssim 10^{-2}$$

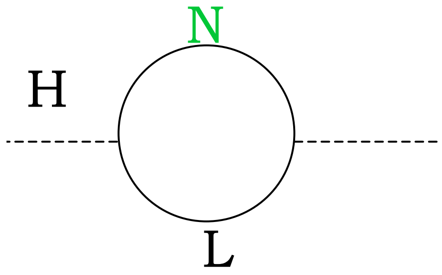
$$\Longrightarrow \quad \boxed{|Y| \lesssim 10^{-1} \frac{M}{1TeV}}$$

or stronger

Observable effects?

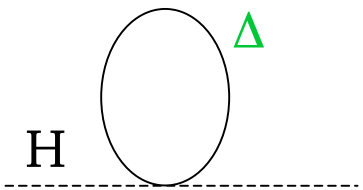
Obviously requires scale near the TeV

M~1 TeV is suggested by electroweak hierarchy problem



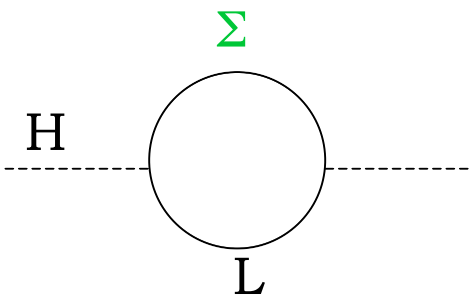
$$\delta m_H^2 = -\frac{Y_N^\dagger Y_N}{16\pi^2}\left[2\Lambda^2 + 2M_N^2 \log\frac{M_N^2}{\Lambda^2}\right]$$

(Vissani, Casas et al., Schmaltz)



$$\delta m_H^2 = -3\frac{\lambda_3}{16\pi^2}\left[\Lambda^2 + M_\Delta^2\left(\log\frac{M_\Delta^2}{\Lambda^2} - 1\right)\right] - \frac{\mu_\Delta^2}{2\pi^2}\log\left(\left|\frac{M_\Delta^2 - \Lambda^2}{M_\Delta^2}\right|\right)$$

(Abada, Biggio, Bonnet, Hambye, M.B.G.)



$$\delta m_H{}^2 = -3\frac{Y_\Sigma^\dagger Y_\Sigma}{16\pi^2}\left[2\Lambda^2 + 2M_\Sigma^2 \log\frac{M_\Sigma^2}{\Lambda^2}\right]$$

Could d=6 be stronger than d=5 ?

* Two independent scales in d=5, d=6 may result from a symmetry principle: lepton number

Cirigliano et al; Kersten,Smirnov; Abada et al

* d=5 requires to violate lepton number

* d=6 does not violate any symmetry

$$\Lambda_5 \sim \Lambda_{LN} >> \Lambda_6 \sim \Lambda_{LFV} \sim \text{TeV}$$

$$\Lambda_{\mathrm{LN}} >> \Lambda_{\mathrm{fl}} \sim \mathrm{TeV}\ ?$$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha}{\Lambda_{LN}} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2_{\text{flavour}}} O_i^{d=6} + \dots$$

Cirigliano, et al

There is a sensible physics motivation:

- Origin of lepton/quark flavour violation linked/close to the EW scale

- (Effective) Lepton number breaking scale higher and responsible for the gap between ν and other fermion

Seesaw mechanism

vs

Minimal Flavour Violation

T. Hambye, D. Hernández, P. Hernández, MBG

Minimal Flavour violation (MFV)

- Flavour data (i.e. B physics) consistent with all flavour physics coming from Yukawa

MFV Hypothesis $\equiv$ The Yukawas are the only sources (*irreducible*) of flavour violation. in BSM

R. S. Chivukula and H. Georgi, Phys. Lett. B **188**, 99 (1987).

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It is very predictive for quarks: $O^{d=6} \sim \overline{Q}_\alpha Q_\beta \overline{Q}_\gamma Q_\delta$

$$\mathcal{L} = \mathcal{L}_{SM} + c^{d=6}\, O^{d=6} + \ldots\ldots$$

i.e. $c^{d=6} \sim \dfrac{Y^{+}_{\alpha\beta}\, Y_{\gamma\delta}}{\Lambda^2_{\text{flavour}}}$ $\qquad O^{d=6} \sim \overline{Q}_\alpha Q_\beta \overline{Q}_\gamma Q_\delta$

WHY MFV?

FOR QUARKS

- Hierarchy Problem points to $\Lambda \sim$ TeV

$c_{d=6} \equiv c_{d=6}(Y_u, Y_d)$

$\mathcal{O}^i_{d=6}$	Λ_{fl}	$c_{d=6} = 1$
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	

WITHOUT MFV: $\Lambda_{fl} \gtrsim 10^2$ TeV

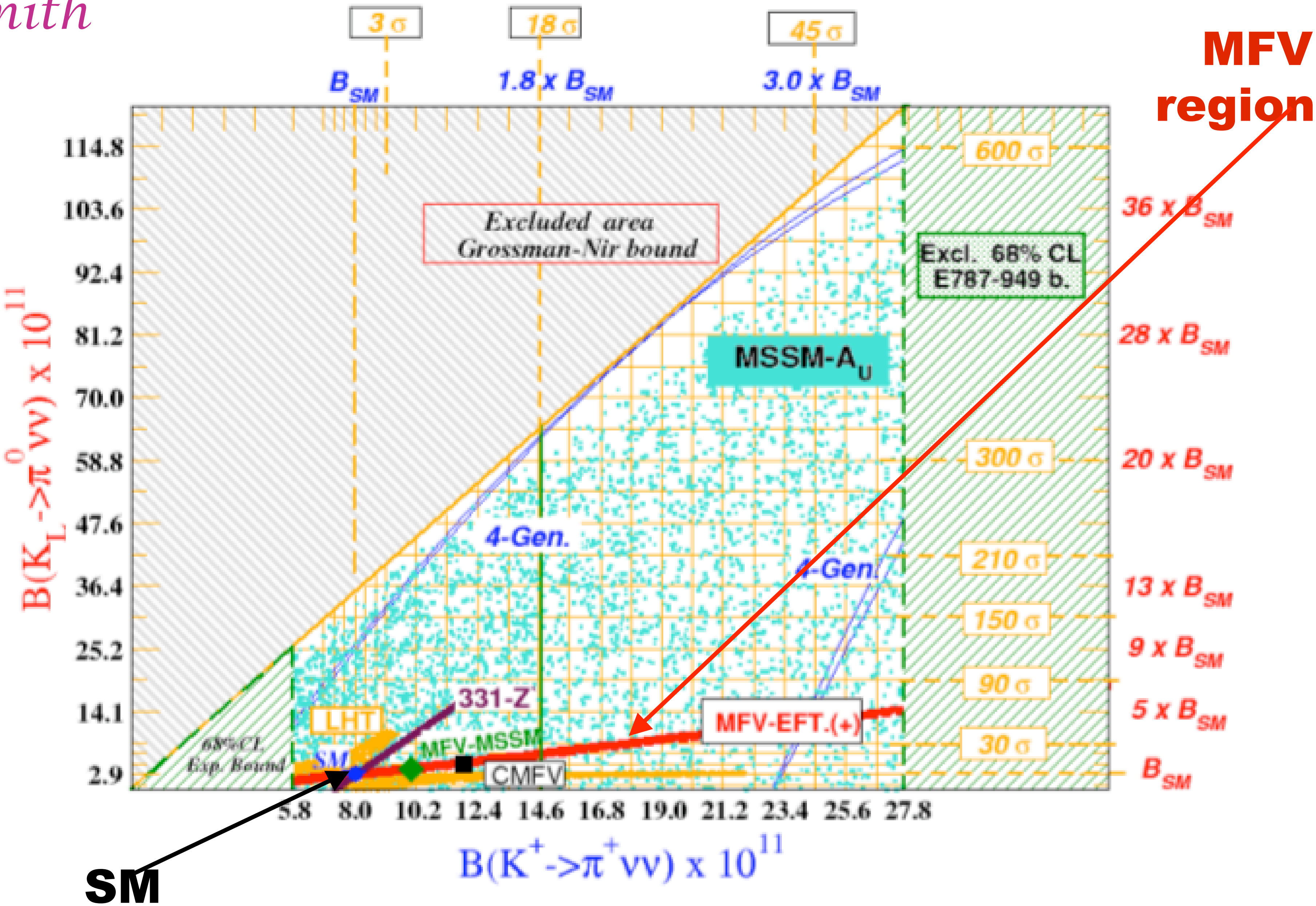
$\mathcal{O}^i_{d=6}$	Λ_{fl}
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(e F_{\mu\nu})$	6.1 TeV
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)\left(\overline{E}_R \gamma_\mu E_R\right)$	2.7 TeV
$i\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)\left(\overline{L}_L \gamma_\mu L_L\right)$	1.7 TeV
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)(e D_\mu F_{\mu\nu})$	1.5 TeV

WITH MFV: $\Lambda_{fl} \gtrsim$ TeV

G. Isidori, Y. Nir, G. Perez, 1002.0900

I. NA62 main targets are the rare K decays ($Br \lesssim 10^{-11}$), e.g. $K^+ \to \pi^+ \nu\bar{\nu}$ s

Smith



What happens in the presence of neutrino masses?

Cirigliano, Isidori, Grinstein, Wise

In the lepton sector

$$\mathcal{L} = \underbrace{\cdots + Y_e \bar{L} \phi e_R}_{\mathcal{L}_{SM}} + \sum_i \underbrace{c^i_{d=5}}_{\Lambda_{LN}} \mathcal{O}^i_{d=5} + \underbrace{c^i_{d=6}}_{\Lambda_{\text{flavour}}} \mathcal{O}^i_{d=6} \cdots$$

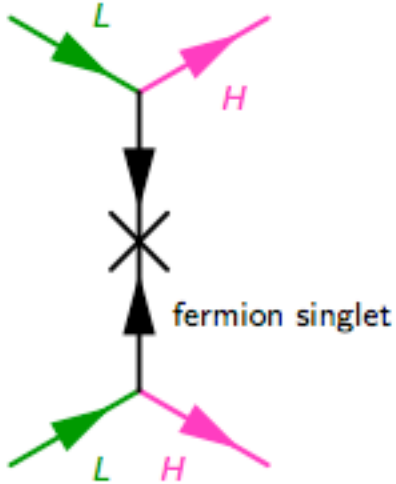
Delicate:

* Majorana masses are model dependent : $c^{d=5}(Y_e, ?)$, $c^{d=6}(Y_e, ?)$

* Requires to separate lepton number from flavour origin

An unsuccessful model: simplest type I

Standard Seesaw (Type I) doesn't work



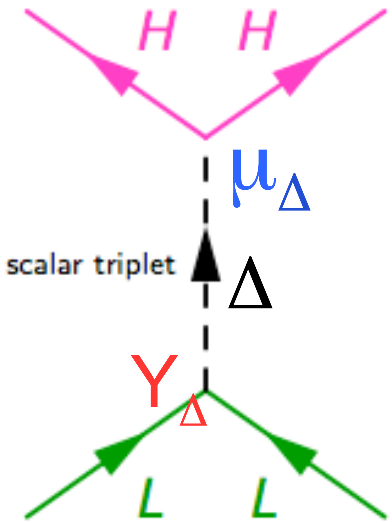
N

$$\mathscr{L} = \cdots - Y_N \bar{N} \phi^\dagger L_L - \Lambda_{LN} \bar{N}^c N \ldots$$

- Neutrino masses: Ok. $m_\nu \propto Y_N^T \frac{1}{\Lambda_{LN}} Y_N$
- Measurable flavour: NOT OK!. $\Lambda_{fl} \equiv \Lambda_{LN}$
- Predictivity: More or less Ok. $c_{d=5} \propto c_{d=6}$ *if no CP*

Hambye, Hernandez[2], Gavela

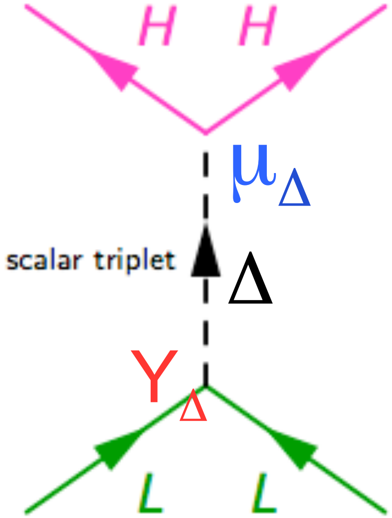
A successful model: Scalar-triplet Seesaw (type II)



$$\mathscr{L}_\Delta = \cdots + (D_\mu \Delta)^\dagger (D^\mu \Delta) - M_\Delta{}^2\, \Delta^\dagger \Delta + +$$

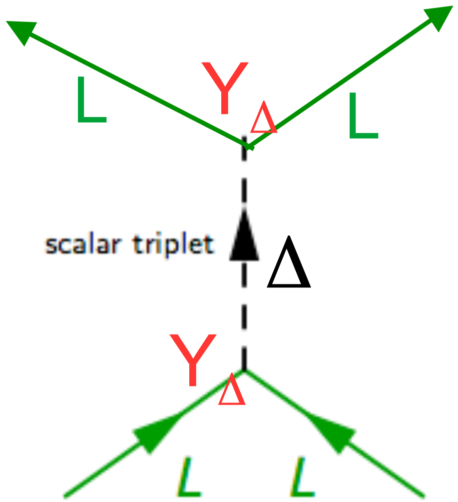
$$+\, Y_\Delta^{\alpha\beta}\, \overline{\widetilde{\mathrm{L}}}\, (\tau \cdot \Delta)\, \mathrm{L} + \mu_\Delta \widetilde{\phi}^\dagger (\tau \cdot \Delta)^\dagger \phi + \ldots$$

A successful model: Scalar-triplet Seesaw (type II)



$\Lambda_{fl} = M_\Delta$

$\Lambda_{LN} = M_\Delta^2 / \mu_\Delta$

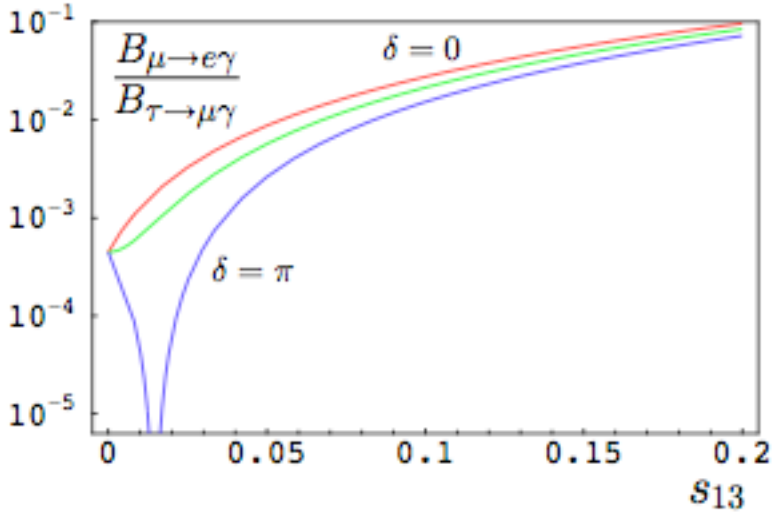


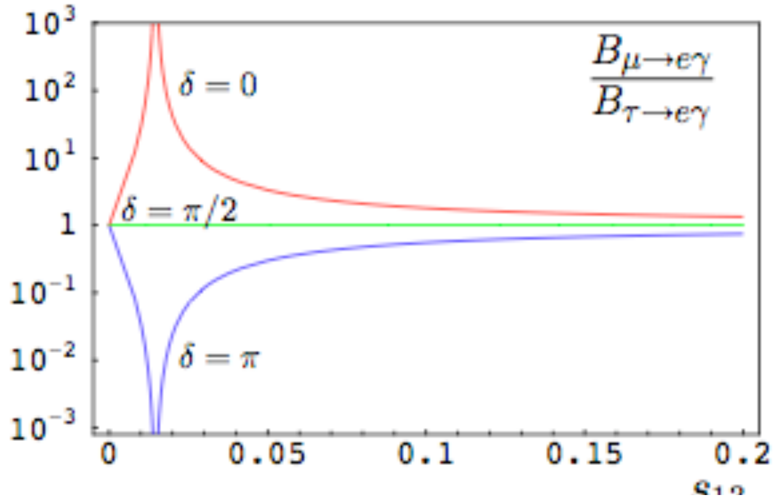
$$\mathscr{L}_\Delta = \cdots + (D_\mu \Delta)^\dagger (D^\mu \Delta) - M_\Delta^2\, \Delta^\dagger \Delta + +$$

$$+ Y_\Delta^{\alpha\beta}\, \overline{\widetilde{L}}\, (\tau \cdot \Delta)\, L + \mu_\Delta \widetilde{\phi}^\dagger (\tau \cdot \Delta)^\dagger \phi + \dots$$

Correlations among
weak processes, i.e.

$\mu \longrightarrow e\gamma \,/\tau \longrightarrow e\gamma \,/\tau \longrightarrow \mu\gamma$





V. Cirigliano, B. Grinstein, G. Isidori, M. Wise, hep-ph/050700
M. B. Gavela, T. Hambye, P. Hernández, D.H., 0906.1

* Neutrino masses OK
* Measurable flavour OK
* Predictivity OK

Successful fermionic-mediated Seesaws:

One more mediator, one more scale…. i.e. Inverse seesaws

Instead of $\mathcal{L}_{m} = \begin{pmatrix} 0 & Y_N^T v \\ Y_N v & M_N \end{pmatrix}$

Successful fermionic-mediated Seesaws:

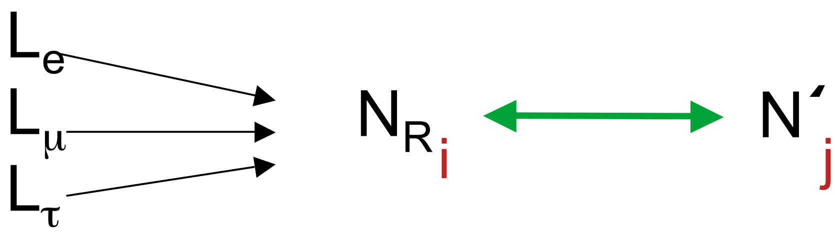
One more mediator, one more scale…. i.e. Inverse seesaws

$$\mathscr{L}_{M_\nu} = \begin{array}{cccc} & \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ & \multicolumn{3}{c}{\left(\begin{array}{ccc} 0 & Y_N^T v & 0 \\ Y_N v & 0 & \Lambda^T \\ 0 & \Lambda & 0 \end{array}\right)} \end{array}$$

Successful fermionic-mediated Seesaws:

One more mediator, one more scale…. i.e. Inverse seesaws

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \end{array} \\ \begin{pmatrix} 0 & Y_N^T v & 0 \\ Y_N v & 0 & \Lambda^T \\ 0 & \Lambda & 0 \end{pmatrix} \end{array}$$



Successful fermionic-mediated Seesaws:

One more mediator, one more scale…. i.e. Inverse seesaws

$$\mathscr{L}_{M_\nu} = \begin{array}{cccc} & \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ & \left(\begin{array}{c} 0 \\ Y_N v \\ 0 \end{array}\right. & \begin{array}{c} Y_N^T v \\ 0 \\ \Lambda \end{array} & \left.\begin{array}{c} 0 \\ \Lambda^T \\ 0 \end{array}\right) \end{array}$$

Lepton number conserved

U(1)

$$\boxed{\begin{array}{l} \Lambda_{fl} = \Lambda \\ \Lambda_{LN} = \infty \end{array}}$$

$$c^{d=6} \sim \frac{Y^+ Y}{\Lambda^2}$$

Successful fermionic-mediated Seesaw:

One more mediator, one more scale…. i.e. Inverse seesaws

$$\mathcal{L}_{M_\nu} = \begin{array}{c} \begin{array}{ccc} \bar{L}_i & \quad \bar{N}^c & \quad \bar{N}'^c \end{array} \\ \begin{pmatrix} 0 & Y_N^T v & Y_N'^T v \\ Y_N v & \mu' & \Lambda^T \\ Y_N' v & \Lambda & \mu \end{pmatrix} \end{array}$$

Lepton number violated
by any of those 3 entries

Wyler,Wolfenstein; Mohapatra,Valle, Branco,Grimus,Lavoura,Malinsky, Romao…

Successful fermionic-mediated Seesaw:

One more mediator, one more scale…. i.e. Inverse seesaws

$$
\mathscr{L}_{M_\nu} = \begin{array}{cccc} & \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ & \left(\begin{array}{c} 0 \\ Y_N v \\ Y'_N v \end{array}\right. & \begin{array}{c} Y_N^T v \\ \mu' \\ \Lambda \end{array} & \left.\begin{array}{c} Y_N'^T v \\ \Lambda^T \\ \mu \end{array}\right) \end{array}
$$

Lepton number violated
by any of those 3 entries

Λ may be ~ TeV and Ys ~1, and be ok with m_ν

Wyler,Wolfenstein; Mohapatra,Valle, Branco,Grimus,Lavoura,Malinsky, Romao…

Case: Three light active families + one N_R + one N_R'

$$\mathscr{L}_{M_\nu} = \begin{array}{cccc} & \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ & \left(\begin{array}{c} 0 \\ Y_N v \\ \epsilon Y'_N v \end{array} \right. & \begin{array}{c} Y_N^T v \\ \mu' \\ \Lambda \end{array} & \left. \begin{array}{c} \epsilon Y_N'^T v \\ \Lambda^T \\ \mu \end{array} \right) \end{array}$$

μ' is irrelevant (at tree-level)

-- one massless neutrino
-- just one low-energy Majorana phase

arguably the simplest model of neutrino mass

Hambye, Hernandez[2], B.G. 09

Case: Three light active families + one N_R + one N_R'

$$\begin{array}{cccc} & \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ \mathscr{L}_{M_\nu} = & \left(\begin{array}{c} 0 \\ Y_N v \\ \epsilon Y'_N v \end{array} \right. & \begin{array}{c} Y_N^T v \\ \mu' \\ \Lambda \end{array} & \left. \begin{array}{c} \epsilon Y_N'^T v \\ \Lambda^T \\ \mu \end{array} \right) \end{array}$$

μ' is irrelevant (at tree-level)

FUNDAMENTAL

	moduli	phases
Y_N	3	3
Y'_N	3	3
Λ	1	1

vs

LOW ENERGY

- 3 angles and 2 phases in the U_{PMNS}
- 2 masses and 0 phases in M_ν
- 2 overall factors and 5 phases absorbed.

***Yukawas are completely determined from U_{PMNS}+m_ν**, except for a normalization + a degeneracy in the Majorana phase

Hambye, Hernandez[2], B.G. 09

Case: Three light active families + one N_R + one N_R'

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \end{array}$$

$$\mathscr{L}_{M_\nu} = \begin{pmatrix} 0 & Y_N^T v & \epsilon Y_N'^T v \\ Y_N v & \mu' & \Lambda^T \\ \epsilon Y_N' v & \Lambda & \mu \end{pmatrix}$$

μ' is irrelevant (at tree-level)

i.e.

$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta} s_{13} + e^{-i\alpha} s_{12} r^{1/4} \\ s_{23}\left(1 - \frac{\sqrt{r}}{2}\right) + e^{-i\alpha} r^{1/4} c_{12} c_{23} \\ c_{23}\left(1 - \frac{\sqrt{r}}{2}\right) - e^{-i\alpha} r^{1/4} c_{12} s_{23} \end{pmatrix} \qquad r = \frac{|\Delta m_{12}^2|}{|\Delta m_{13}^2|}$$

Normal hierarchy

***Yukawas are completely determined from U_{PMNS}+m_ν**, except for a normalization + a degeneracy in the Majorana phase

Hambye, Hernandez[2], B.G. 09

Normal hierarchy:

Up to terms of $\mathcal{O}(\sqrt{r}, s_{13})$, we find

$$r = \frac{|\Delta m^2_{12}|}{|\Delta m^2_{13}|}$$

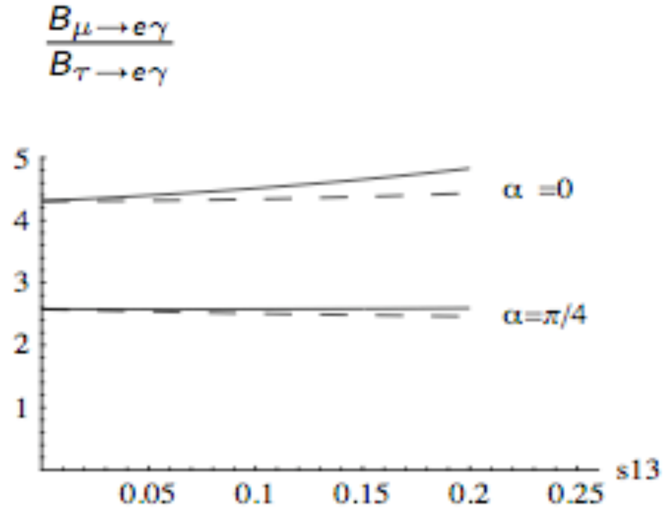
$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta} s_{13} + e^{-i\alpha} s_{12} r^{1/4} \\ s_{23}\left(1 - \frac{\sqrt{r}}{2}\right) + e^{-i\alpha} r^{1/4} c_{12} c_{23} \\ c_{23}\left(1 - \frac{\sqrt{r}}{2}\right) - e^{-i\alpha} r^{1/4} c_{12} s_{23} \end{pmatrix} .$$

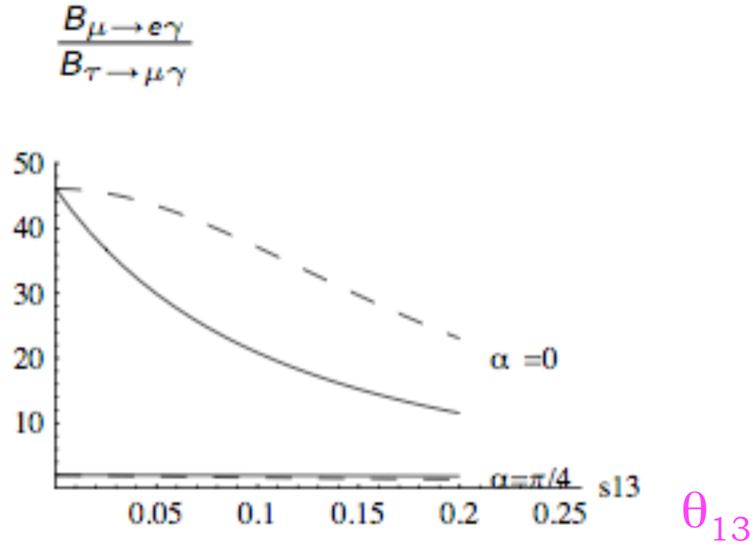
Inverted hierarchy:

$$Y_N^T \simeq \frac{y}{\sqrt{2}} \begin{pmatrix} c_{12} e^{i\alpha} + s_{12} e^{-i\alpha} \\ c_{12}\left(c_{23} e^{-i\alpha} - s_{23} s_{13} e^{i(\alpha-\delta)}\right) - s_{12}\left(c_{23} e^{i\alpha} + s_{23} s_{13} e^{-i(\alpha+\delta)}\right) \\ -c_{12}\left(s_{23} e^{-i\alpha} + c_{23} s_{13} e^{i(\alpha-\delta)}\right) + s_{12}\left(s_{23} e^{i\alpha} - c_{23} s_{13} e^{-i(\alpha+\delta)}\right) \end{pmatrix}$$

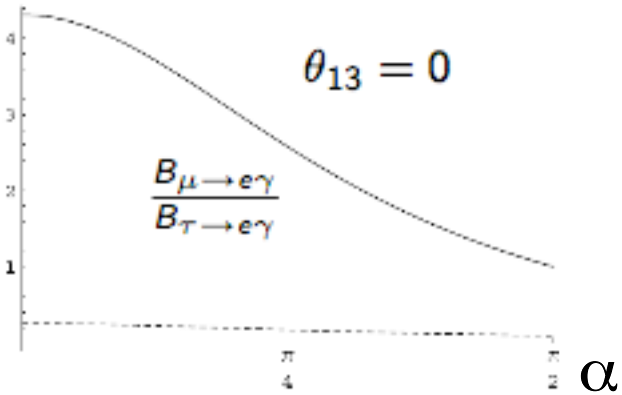
$$\boxed{B_{\mu \to e\gamma} \propto |Y_{N_e} Y_{N_\mu}|^2}$$

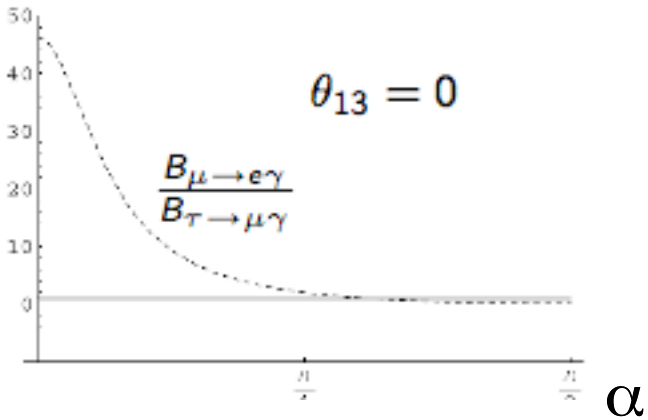
NORMAL HIERARCHY | INVERTED HIERARCHY





Strong dependence on the Majorana phase!





Degeneracy in the Majorana phase α

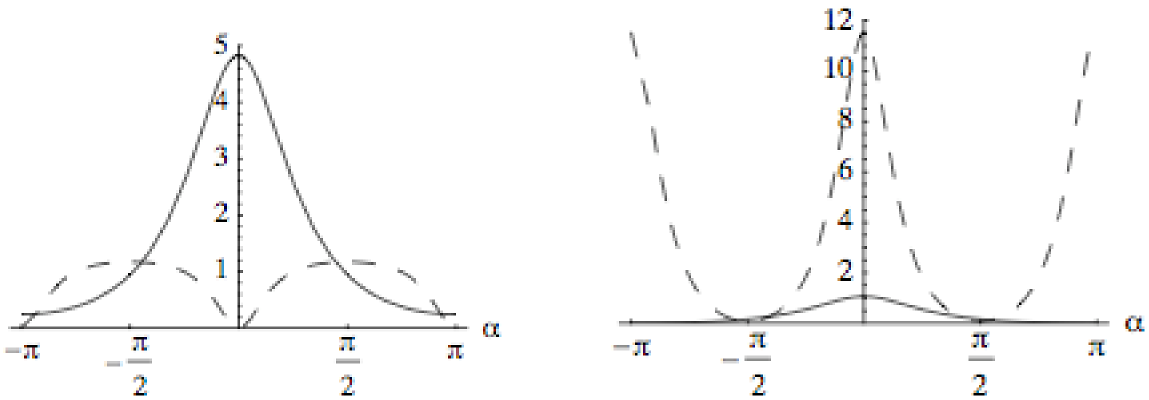
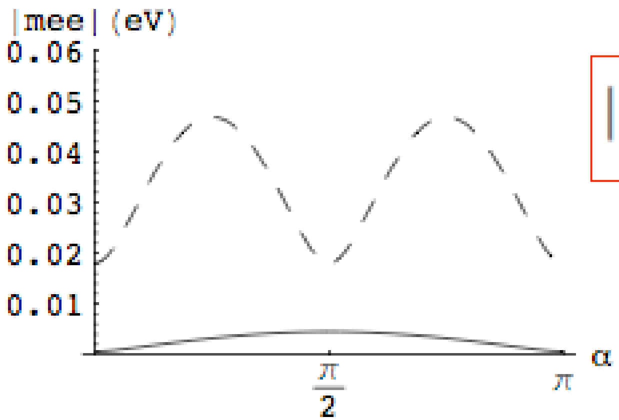


Figure 3: Left: Ratio $B_{e\mu}/B_{e\tau}$ for the normal hierarchy (solid) and the inverse hierarchy (dashed) as a function of α for $(\delta, s_{13}) = (0, 0.2)$. Right: the same for the ratio $B_{e\mu}/B_{\mu\tau}$.



$$|m_{ee}|_{IH} \simeq |s_{12}^2 e^{-2i\alpha} - c_{12}^2 e^{2i\alpha}|$$

Figure 5: m_{ee} as a function of α for the normal (solid) and inverted (dashed) hierarchies, for $(\delta, s_{13}) = (0, 0.2)$.

This model with just 2 heavy neutrinos added to SM:

*Leptogenesis OK for small mass splittings between the right handed (heavy) neutrinos

(Blanchet, Hambye, Josse-Michaux 09)

NON UNITARITY

*

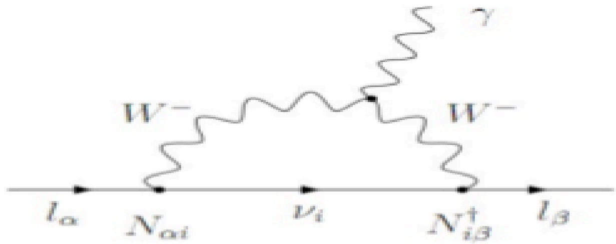
There are bounds on non-unitarity coming from:

Rare decays

Weak decays

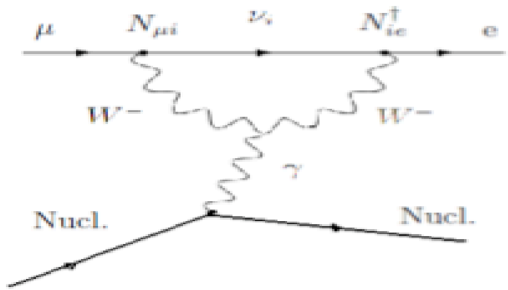
Invisible Z width

Neutrino Oscillations



(and future experiments that will test it further)

mu to e conversion



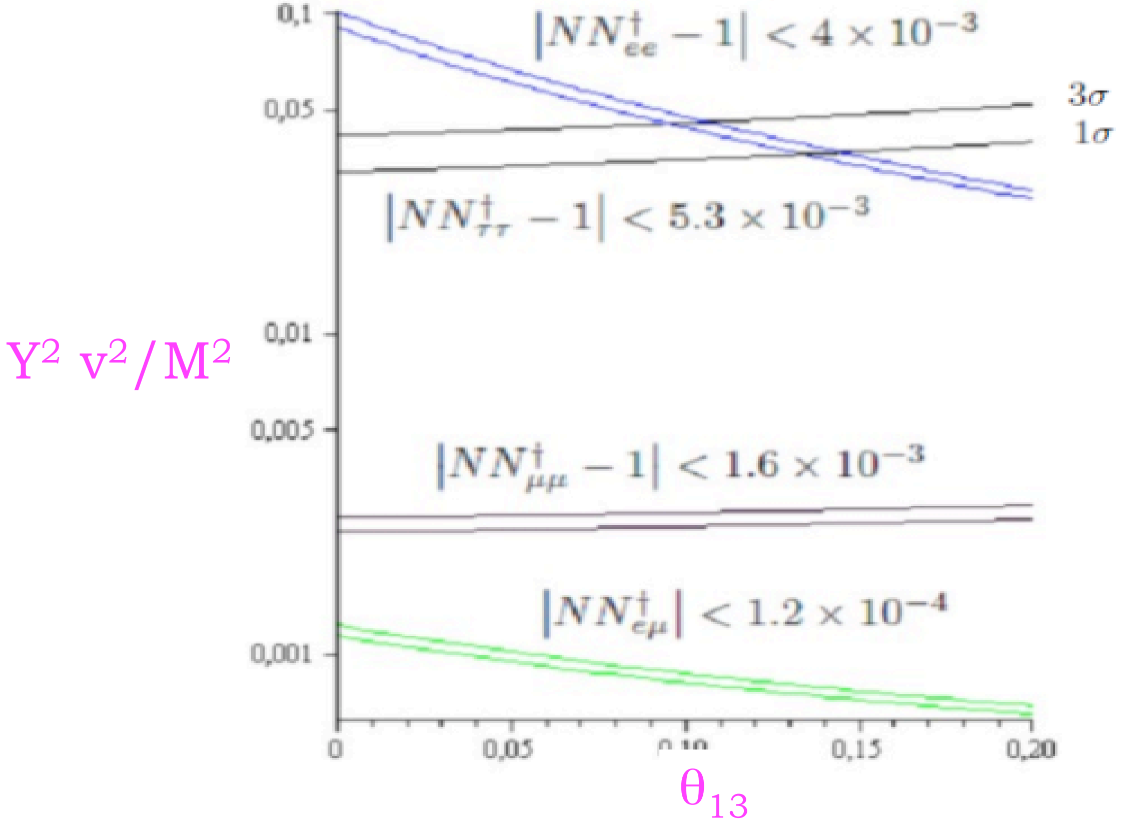
that we can use to restrict the parameters in our model:

(Alonso, Gavela, Hernandez,Li ongoing)

Normal hierarchy:

$Y^2\, v^2/M^2$ vs θ_{13}

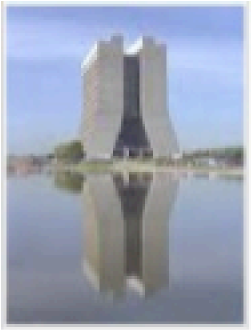
$N \sim U_{PMNS} + Y^+Y\, v^2/M^2$



Actual Data

To date, the best Bound comes from the rare decay $\mu \to e\gamma$ $\sim< 10^{-4}$

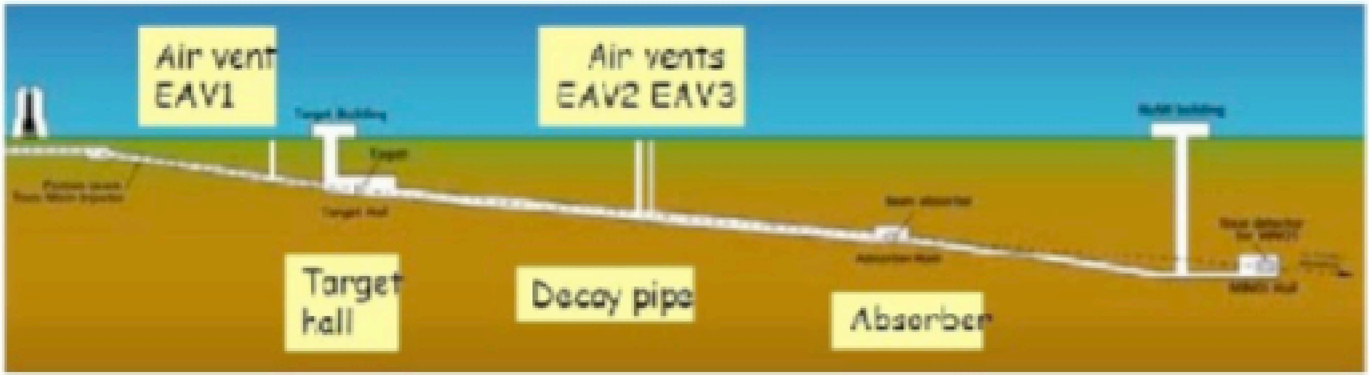
(Alonso, Gavela, Hernandez,Li …ongoing)



MINSIS

Main
Injector
Non **S**tandard
Interaction**S**

Minsis is a project for a **short baseline** experiment in Fermilab



That would look for ν_μ dissappearance

$\nu_\mu \dashrightarrow \nu_\tau$

$$\boxed{B_{\mu\to e\gamma} \propto |Y_{N_e} Y_{N_\mu}|^2}$$

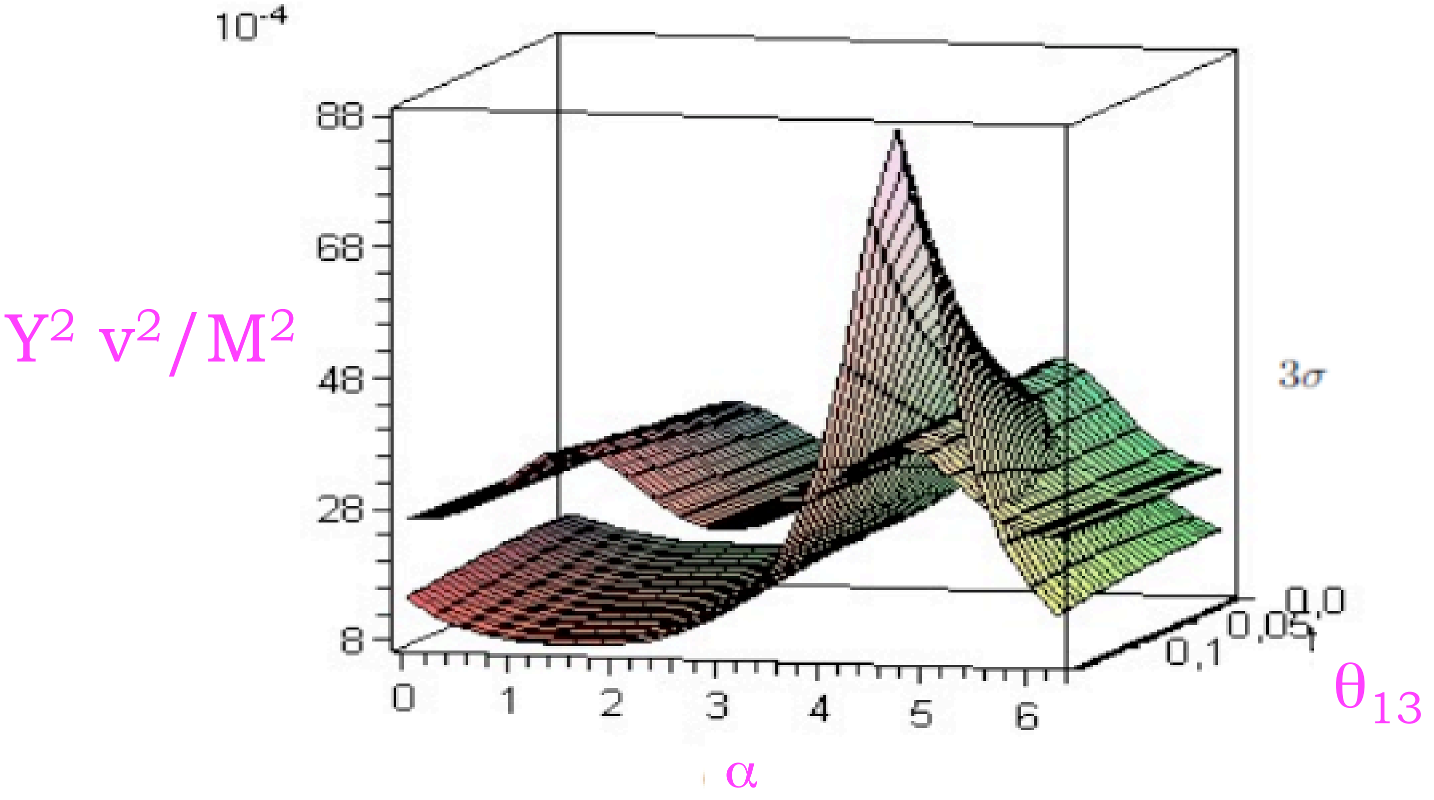
i.e.

$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta}s_{13} + e^{-i\alpha}s_{12}r^{1/4} \\ s_{23}\left(1-\frac{\sqrt{r}}{2}\right) + e^{-i\alpha}r^{1/4}c_{12}c_{23} \\ c_{23}\left(1-\frac{\sqrt{r}}{2}\right) - e^{-i\alpha}r^{1/4}c_{12}s_{23} \end{pmatrix} \qquad r = \frac{|\Delta m^2_{12}|}{|\Delta m^2_{13}|}$$

Normal hierarchy

Normal hierarchy: MINSIS and MFV

If we explore a wider range of parameters



We find that there are regions where an experiment as MINSIS
would improve the present bounds on our Model

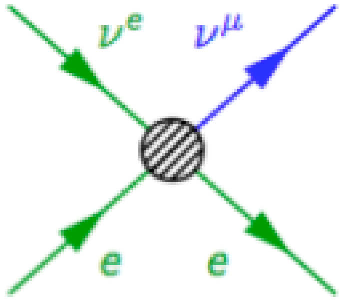
MINSIS could also improve by two orders of magnitude the search for light steriles coupled to the heavier families

… but this is another story

“Why not” NSIs

(Non-Seesaw NSIs)

i.e., purely matter NSI?



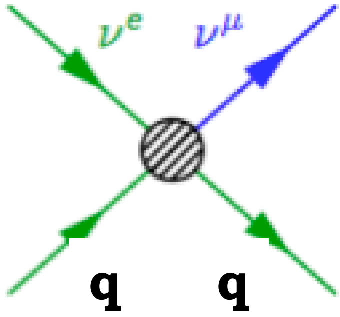
Extra effects in matter propagation

$$\mathscr{L}_{\mathrm{NSI}} \propto -\epsilon^{\ell}_{\alpha\beta}(\bar{\nu}^{\alpha}\gamma^{\rho}P_L\nu_{\beta})(\bar{\ell}\gamma_{\rho}\ell)$$

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

$$V \propto N_e$$

i.e., purely matter NSI?



Extra effects in matter propagation

$$\mathscr{L}_{\mathrm{NSI}} \propto -\epsilon^{\ell}_{\alpha\beta}(\bar{\nu}^{\alpha}\gamma^{\rho}P_L\nu_{\beta})\,(\bar{q}\,\gamma_{\mu}\,q)$$

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

$$V \propto N_e$$

BOUNDS

*Absolute maxima:

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

from ν scattering
in NuTev
and in CHARM II

C. Biggio, M. Blennow, E. Fdez-Mtnez, 0907.0097

BOUNDS

*Absolute maxima:

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

from ν scattering
in NuTev
and in CHARM II

C. Biggio, M. Blennow, E. Fdez-Mtnez, 0907.0097

•Also from atmospheric data, unless cancellations among epsilons:

$$|\varepsilon_{\mu\tau}| < 5\ 10^{-2}$$

Fornengo, Maltoni, Tomás-Bayo, Valle,hep-ph 0108043

Potential Trouble:

NSI $\xrightarrow{\text{SU(2) x U(1) gauge invariance}}$ Dangerous four charged lepton couplings

Potential Trouble:

NSI $\xrightarrow{\text{SU(2) x U(1) gauge invariance}}$ Dangerous four charged lepton couplings

$\Lambda > v$

The new physics has to CONTAIN the SM

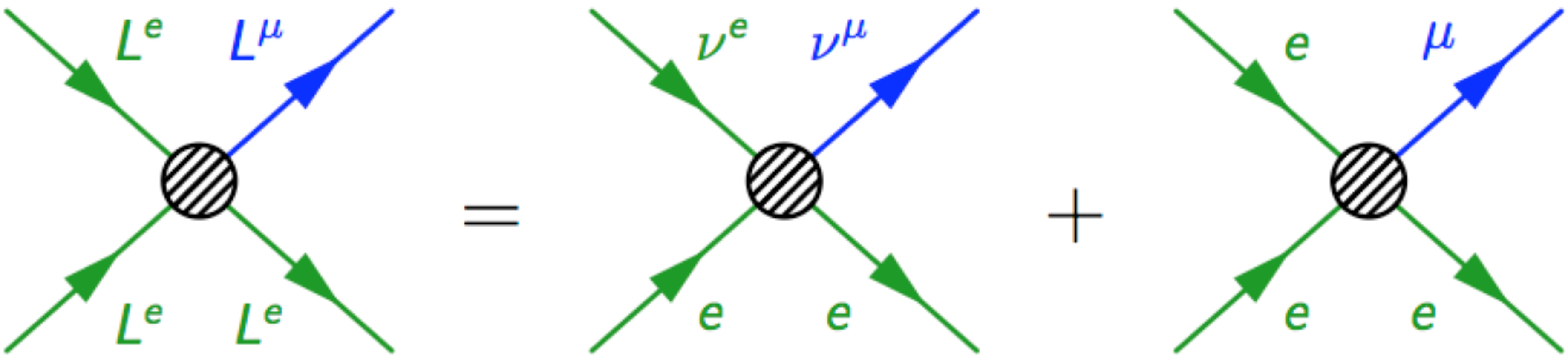
$\Longrightarrow$

The new couplings MUST have a SU(3)xSU(2) xU(1) gauge invariant formulation

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

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

Trouble, for instance $\mu \to eee$



$\mu \to eee$

Systematical analysis

Two possibilities

A) There could be NO lepton charged processes involved

Ex: For $d = 6$

(Davidson, Kuypers) $$(\bar{L^c} i\tau^2 L)(\bar{L} i\tau^2 L^c) \rightarrow (\bar{\nu^c_\tau}\; e_L)(\bar{\nu}_\mu e_L^c)$$

Ex: For $d = 8$

$$O_{NSI} = (\bar{L}H)\gamma^\mu(H^\dagger L)(\bar{E}\gamma_\mu E) \rightarrow v^2(\bar{\nu}_\tau\, \gamma^\mu \nu^\mu)(\bar{e}_L\gamma_\mu e)$$

(Berezhiani, Rossi)

Systematical analysis

Two possibilities

A) There could be NO lepton charged processes involved

Ex: For $d = 6$

(Davidson, Kuypers) $(\bar{L^c} i\tau^2 L)(\bar{L} i\tau^2 L^c) \rightarrow (\bar{\nu^c_\tau}\; e_L)(\bar{\nu}_\mu e^c_L)$

But it also produces $\tau \dashrightarrow \mu\, \nu_e \bar{\nu}_e$!

And $\mu \dashrightarrow e\, \nu_\tau \bar{\nu}_e$

Ex: For $d = 8$

$\boxed{\varepsilon_{\mu\tau} < 3\; 10^{-2}}$

Fdez-Martinez

$$O_{NSI} = (\bar{L}H)\gamma^\mu(H^\dagger L)(\bar{E}\gamma_\mu E) \rightarrow v^2(\bar{\nu}_\tau\, \gamma^\mu \nu^\mu)(\bar{e}_L \gamma_\mu e)$$

(Berezhiani, Rossi)

Systematical analysis

Two possibilities

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

Ex:

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

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

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

ALL cancellation conditions examined

(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

Finally, gauge invariance implies:

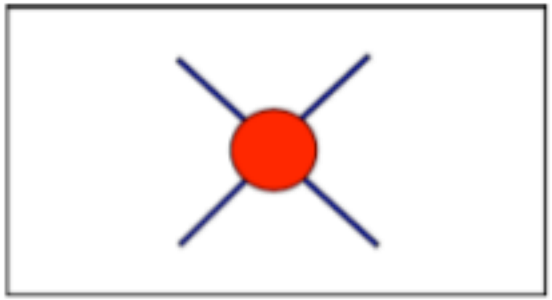
- **From d=6 ops.:** $\varepsilon_{\mu\tau} < 3\ 10^{-2}$

- **Or you avoid alltogether d=6 ops. combining d=8 ones with a very strong -unbelievable- fine-tuning !** (check cancellantions in our table if you have the stomach for it)

TREE-LEVEL MEDIATOR DECOMPOSITION

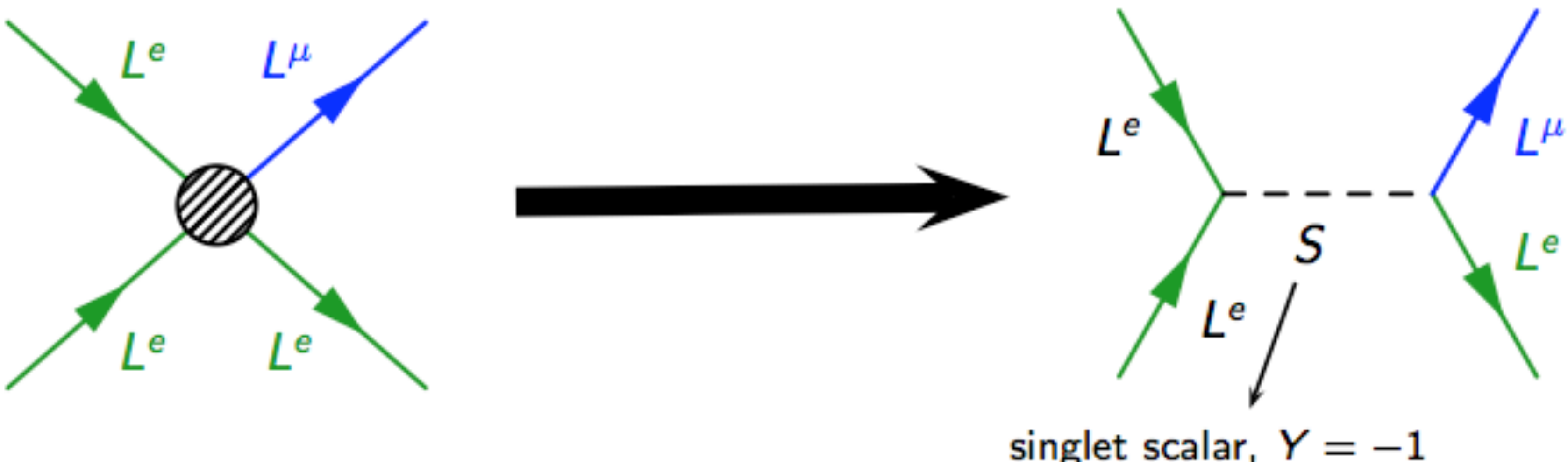
Would give even stronger bounds...

Constraints are then stronger and odds even worse:

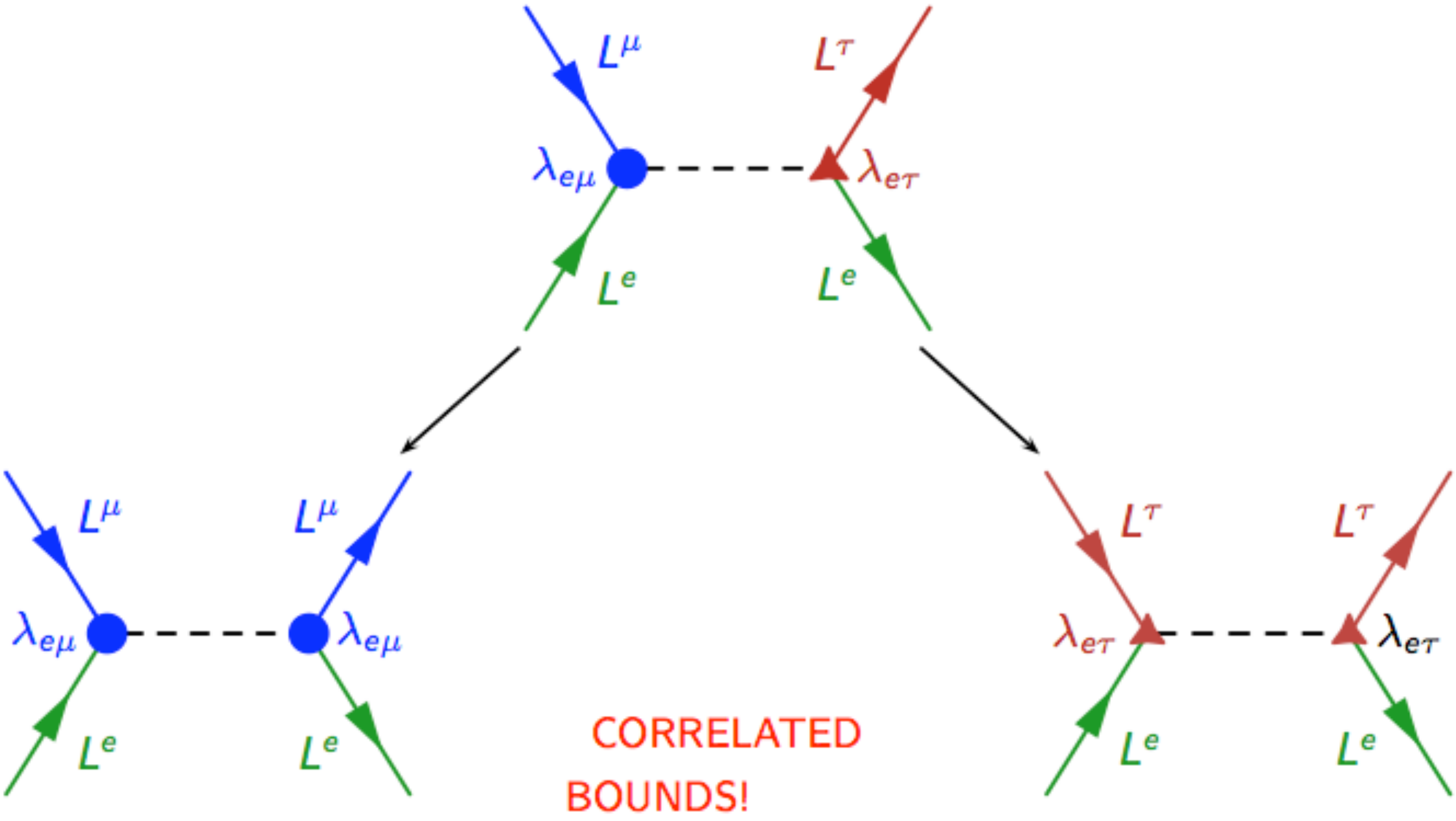


We can open the $d = 6$ vertex (remember Fermi, Weinberg?)

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



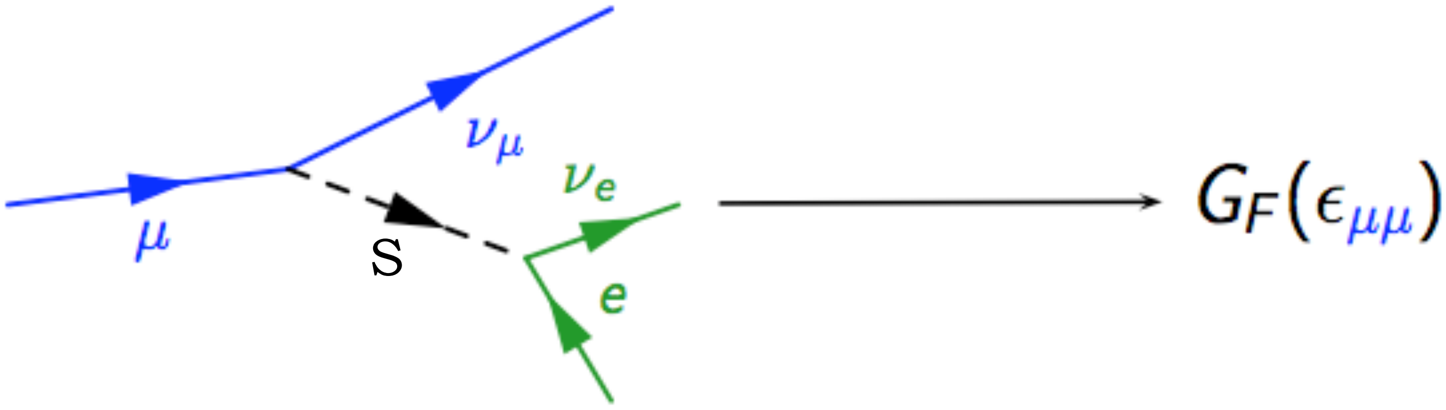
BUT... you might run into troubles



SEVERELY CONSTRAINED:

S. Antusch, J. P. Baumann, E. Fdez-Mtnez; 0807.1003
F. Cuypers, S. Davidson; hep-ph/ 9609487

Moreover...



Davidson+Kuypers..... Antusch,Baumann, Fdez.-Martinezz

$$\boxed{\varepsilon_{\mu\tau} < 2\ 10^{-3}}$$

•This S is disconnected from the seesaw mechanism... although connected to radiatively generated masses -Zee model-

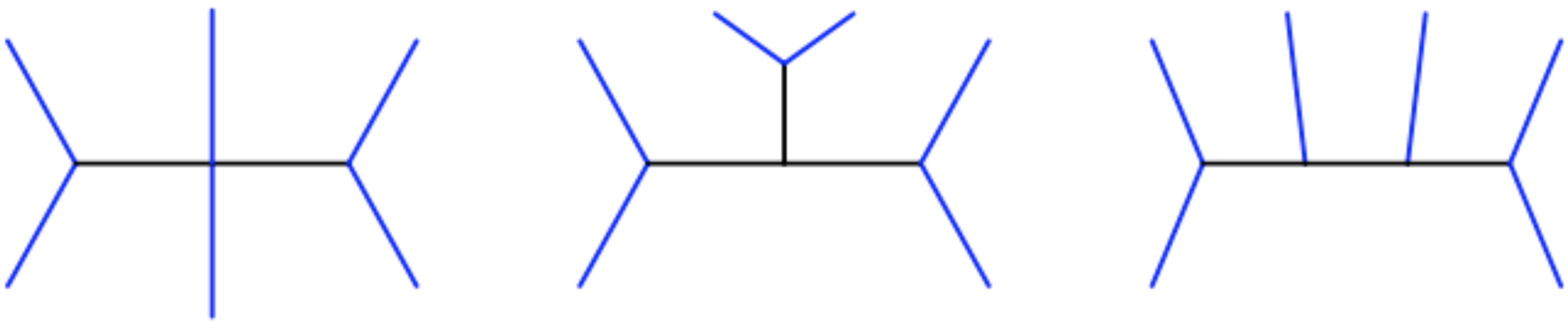
•d=6 NSI are very very constrained.

Bottom line: $d = 6$ doesn't look promising

Maybe things get better at $d = 8$

Is it possible to generate $d = 8$ and NO $d = 6$ operators??

Several possibilities



(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

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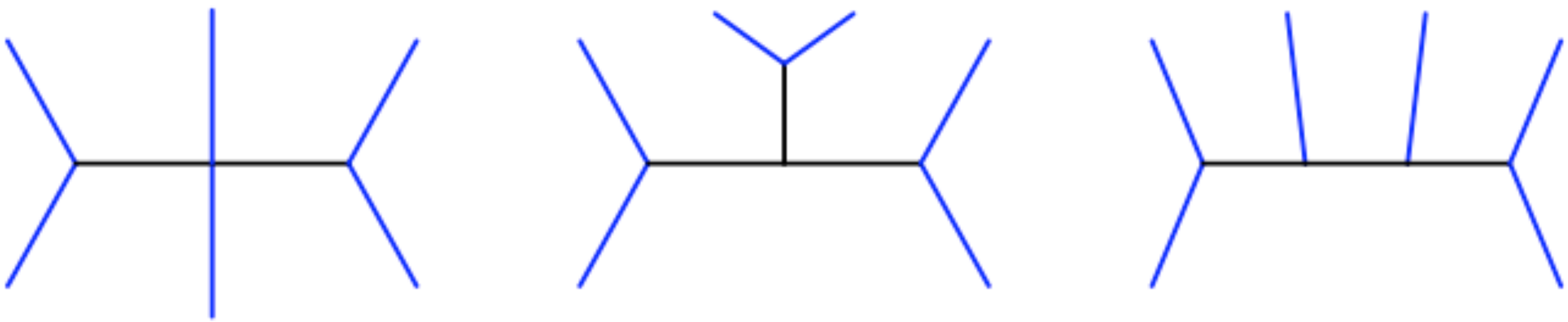

Require at least 2 new fields (and unrelated to seesaw)

(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

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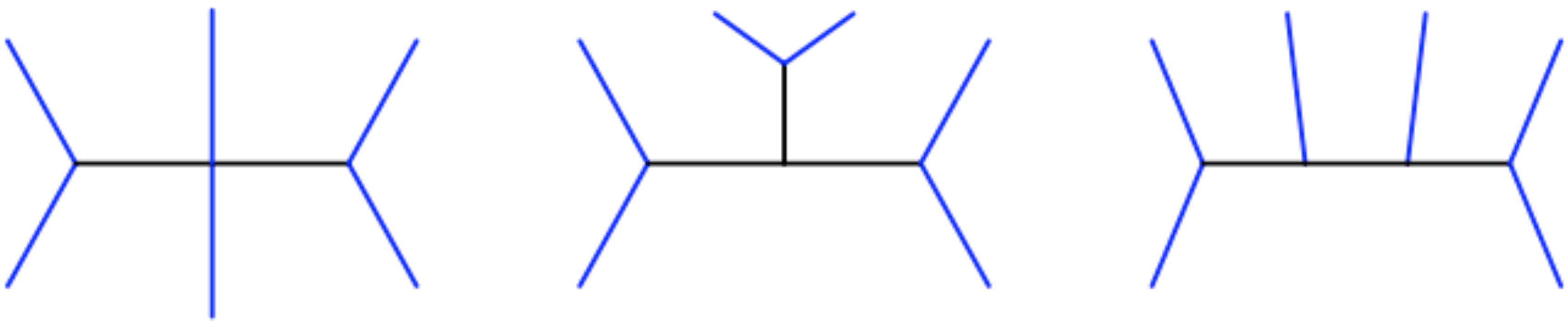


$\boxed{\textbf{TERRIBLY COMPLICATED}}$

(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

Complete list of d=8 operators and their mediators

#	Dim. eight operator	C^1_{LEH}	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	$(\bar{L}i\tau^2 H^*)(H^T E)(i\tau^2)(\bar{E}L)$	$1/4$	$-1/4$		$\mathbf{2}^s_{+1/2} + 1^{L/R}_{-1} + 2^{L/R}_{-3/2}$
12	$(\bar{L}\vec{\tau} i\tau^2 H^*)(H^T E)(i\tau^2 \vec{\tau})(\bar{E}L)$	$3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_{-1} + 2^{L/R}_{-3/2}$
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	$(\bar{L}i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2)(\overline{E^c}\gamma_\rho L)$	$-1/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 1^{L/R}_{-1} + 2^{L/R}_{+1/2}$
18	$(\bar{L}\vec{\tau} i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2 \vec{\tau})(\overline{E^c}\gamma_\rho L)$	$-3/2$	$-1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_{-1} + 2^{L/R}_{+1/2}$
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	$(\bar{L}E)(i\tau^2)(\bar{E}H^*)(H^T i\tau^2 L)$	$1/4$	$-1/4$		$\mathbf{2}^s_{+1/2} + 1^{L/R}_{-1} + 2^{L/R}_{-3/2}$
26	$(\bar{L}E)(\vec{\tau} i\tau^2)(\bar{E}H^*)(H^T i\tau^2 \vec{\tau} L)$	$3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_{-1} + 2^{L/R}_{-3/2}$
27	$(\bar{L}i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2 L)(\bar{E}\gamma_\rho E)$	$-1/2$	$1/2$		$\mathbf{1}^v_0 + 1^{L/R}_{-1}$
28	$(\bar{L}\vec{\tau} i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2 \vec{\tau} L)(\bar{E}\gamma_\rho E)$	$-3/2$	$-1/2$		$\mathbf{1}^v_0 + 3^{L/R}_{-1}$
29	$(\bar{L}\gamma^\rho E^c)(i\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T i\tau^2 L)$	$1/2$	$-1/2$		$\mathbf{2}^v_{-3/2} + 1^{L/R}_{-1} + 2^{L/R}_{+1/2}$
30	$(\bar{L}\gamma^\rho E^c)(\vec{\tau} i\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T i\tau^2 \vec{\tau} L)$	$3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_{-1} + 2^{L/R}_{+1/2}$

Table 3: Complete list of $\bar{L}L\bar{E}E$-type $d = 8$ interactions which involve two SM fields at any possible vertex of interaction (field bilinears within brackets). The columns show an ordinal for each operator, the $d = 8$ interaction, the corresponding combination of interactions in the BR basis, whether $\mathcal{O}_{\rm NSI}$ is satisfied and the necessary mediators, respectively. Those mediators leading as well to $d = 6$ operators in Table 2 are in boldface. The superscript L/R indicates massive vector fermions. The flavor structure is to be understood as $\bar{L}^\beta L_\alpha \bar{E}^\delta E_\gamma$.

D. Hernandez, Ota, Winter + MBG

$(\bar{L}H)(H^\dagger E)(\bar{E}L)$	$-1/4$	$-1/4$	✓	$\mathbf{2}^s_{+1/2} + 1^R_0 + 2^{L/R}_{-1/2}$

MINOS: neutrino/antineutrino difference (?)
in ν_μ disappearance ??

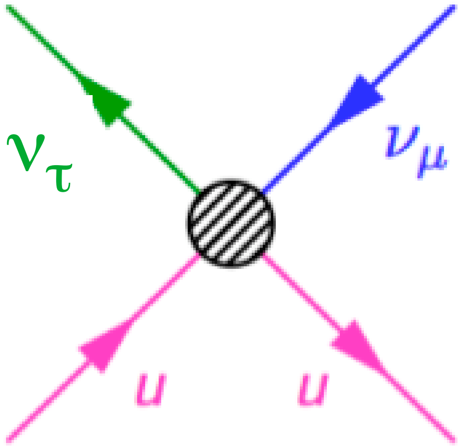
Could MINOS effect, if ever it becomes a signal (which is NOT), be NSI?

- Certainly not NSI related to non-unitarity (ie. Seesaw related),

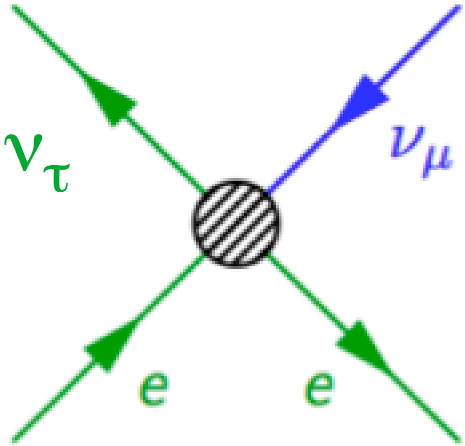
$$|\varepsilon| \approx \begin{pmatrix} <2.5\cdot10^{-3} & <3.6\cdot10^{-5} & <8.0\cdot10^{-3} \\ <3.6\cdot10^{-5} & <2.5\cdot10^{-3} & <5.0\cdot10^{-3} \\ <8.0\cdot10^{-3} & <5.0\cdot10^{-3} & <2.5\cdot10^{-3} \end{pmatrix}$$

*What about a Why Not” NSI, i.e. purely matter NSI?

Could MINOS effect, if ever it becomes a signal (which is NOT), be matter NSI?



$$\frac{1}{\Lambda^2}\bar{\nu}_\tau \nu_\mu \; \bar{u} u$$



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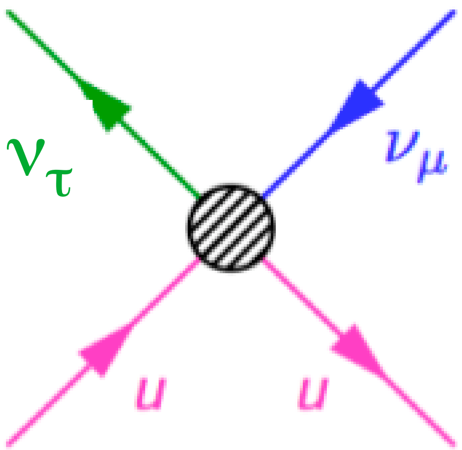
Two weeks ago: Mann et al.: $\varepsilon_{\mu\tau}$
arXiv:1006.5720



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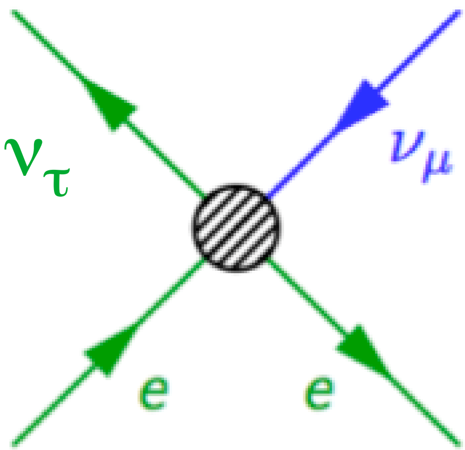

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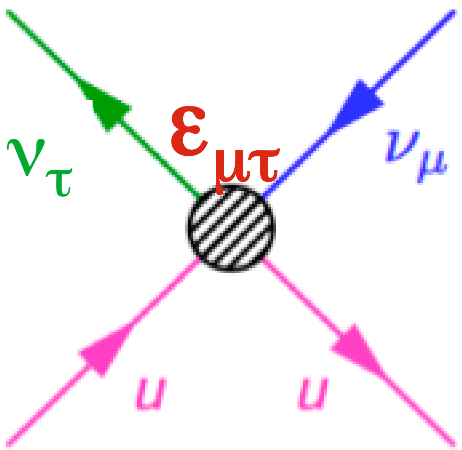

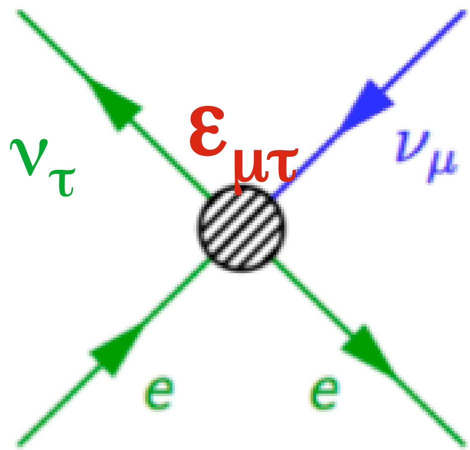

$$\mathcal{P}\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu\right) \simeq 1 - \sin^2\left(\left|\frac{\Delta m^2_{32}}{4E_\nu} \mp \varepsilon_{\mu\tau}|V_e|\right| L\right).$$

They claim $\varepsilon_{\mu\tau} = -(0.12 \pm 0.21)$, $\Delta m^2_{32} = 2.56^{+0.27}_{-0.24} \times 10^{-3}\ \text{eV}^2$

$\sin^2 2\theta_{23} = 0.90 \pm 0.05$.

To be compared with the bounds:

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

C. Biggio, M. Blennow, E. Fdez-Mtnez, 0907.0097

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Plausible? NO! : gauge invariance -> $\varepsilon_{\mu\tau} < 3\ 10^{-2}$ from d=6, or d=8 ops. with ad hoc cancellat.

This morning: Kopp, Machado, Parke

arXiv:0076594 "Could it be $\varepsilon_{\mu\tau}$ matter NSI?"

* It is a similar analysis, but taking into account both $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$ and performing a simulation of MINOS event spectrum:

They claim

$$\epsilon_{\mu\tau} = 0.41\, e^{0.95 i\pi} \qquad \sin^2\theta_{23} = 0.38$$

$$\epsilon_{\tau\tau} = -2.12 \qquad \Delta m^2_{31} = +2.83 \times 10^{-3}\ \mathrm{eV}^2$$

(Signs can be changed, eightfold degeneracy)

* Discovery at NOνA in less than one nominal year

* They acknowledge that gauge invariance disfavours d=6 ops., and d=8 ops. unlikely:

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breaking 4-fermion couplings can arise. However, dimension 8 operators of this type are typically accompanied by phenomenologically problematic dimension 6 operators unless the coefficients of different operators obey certain cancellation conditions [32]. Thus, if the MINOS results were indeed caused by NSI, this would point to a rather non-trivial model of new physics.

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My conclusion:

a $\bar{\nu}_\mu / \nu_\mu$ difference in MINOS

based on matter ν_μ <--> ν_τ NSI ($\Lambda > v$)

is terribly unlikely

because of gauge invariance

Anyway, at maximum $\varepsilon_{\mu\tau} < 0.33$

AND

Atmospheric indicate $< 5\ 10^{-2}$ unless brutal cancellations among different ε

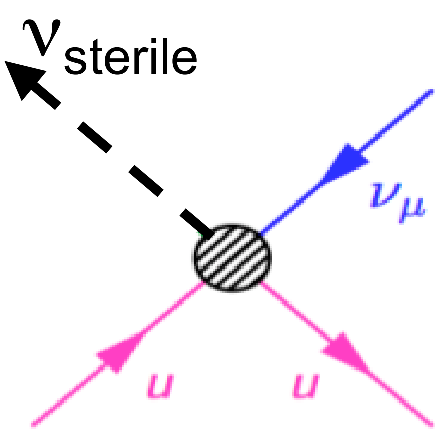
Why everybody forgets atmospherics?

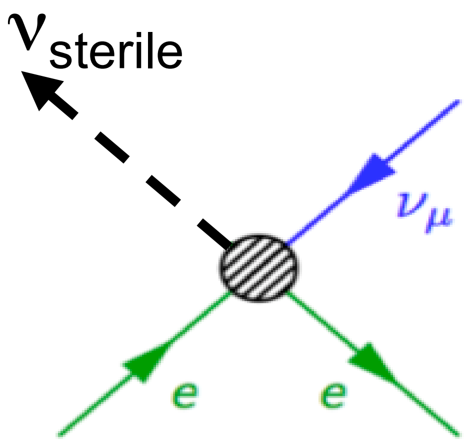
More promising ? :

What about steriles lighter than the electroweak scale, with matter effects, for the MINOS "would-be" effect?

Steriles lighter than M_W evade non-unitarity bounds and some of the pure matter NSI bounds

Ie. Ann Nelson and collab.; light steriles, gauged B-L





Engelhardt, Nelson and Walsh, arXiv:1002.4452

All this underlies the importance

of searching for ν_μ <--> ν_τ transitions

in general (i.e. at near detectors)

And light steriles for the new MiniBoone data?

•Interesting: Same L/E than LSND, but different L and E
--> different backgrounds

CP in vacuum?:CP does not depend on L/E if matter effects negligible, but differs for neutrinos and antineutrinos

seems difficult (arXiv:0906.1997 and arXiv:0705.0107) but.. ?

And light s ta?

•Interesti nd E

CP i atter effects
ntineutrinos

5.0107) but.. ?

Anyway,

all those Fnal data are only 2 σ !!!

only combined they are intriguing

And light s ta?

Recall: Paul the octopus predictions

are a 2.6 σ effect!!!

•Interesti and E

CP i atter effects
ntineutrinos

5.0107) but.. ?

2.6 σ effect for the world cup ! (Marc Sher)

It is an appearance experiment (Spain)

Conclusions

Neutrino masses and mixings have added a precious

piece to the flavour puzzle

Hopefully we will get to the physics behind it...

..... if new scale under # TeV

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Neutrino masses and mixings have added a precious

piece to the flavour puzzle

Hopefully we will get to the physics behind it...

..... if new scale under # TeV

- Scalar seesaws and extended fermionic seesaws respect Minimal Flavour Violation

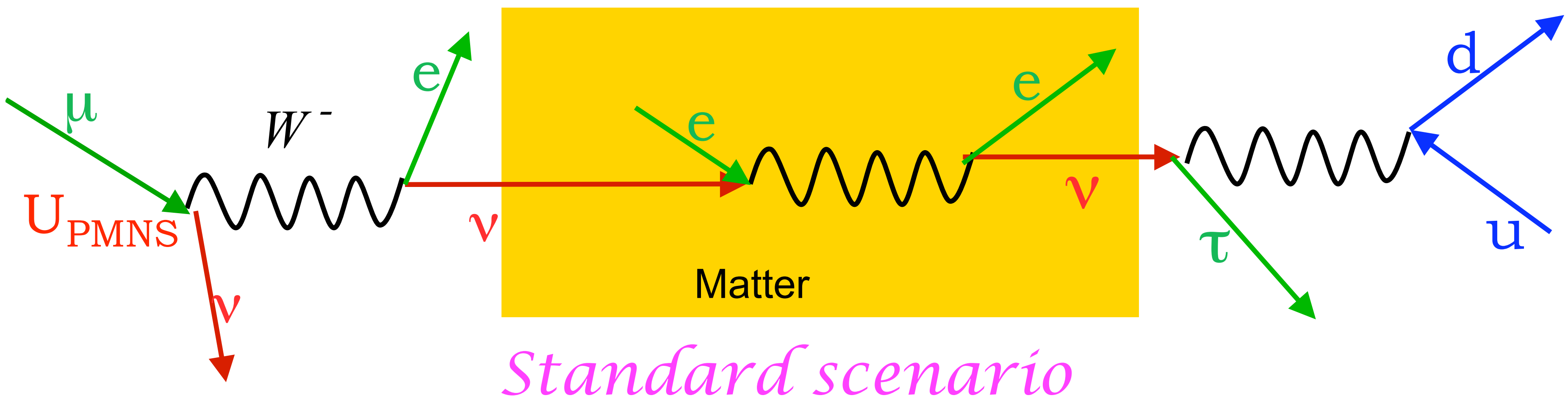
- SM + 2 heavy neutrinos, with approximate $U(1)_{LN}$ is very successful: almost fully determined by light masses and mixings

- Non-unitary mixing is a NSI characteristic of fermionic seesaws. Keep improving bounds!

- Pure matter-NSI severely constrained by gauge invariance; unlikely explanation of the (non-existing) MINOS $\bar{\nu}/\nu$ signal. But keep tracking $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_{sterile}$ couplings

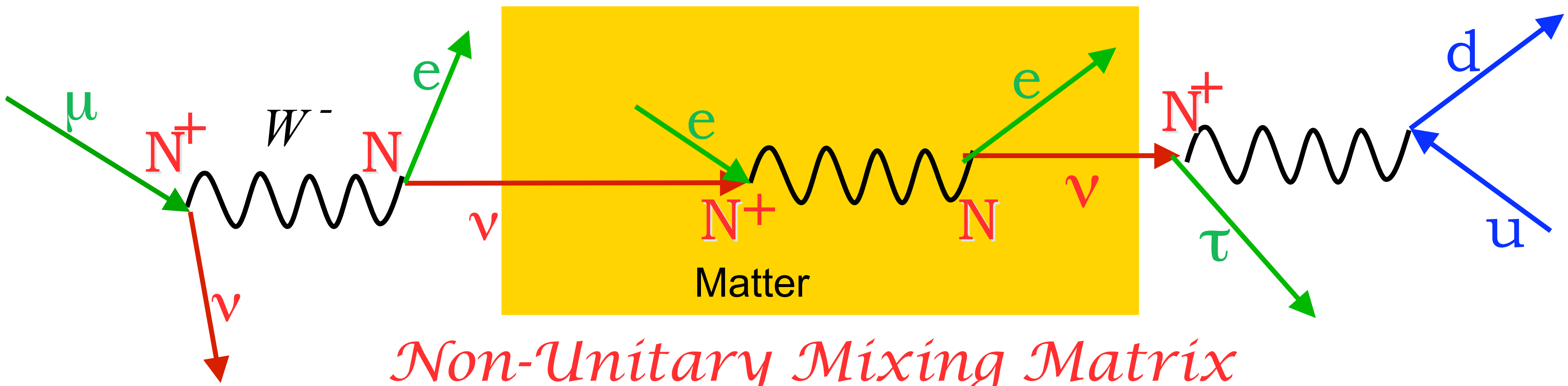
Back-up slides

YES! These effects ARE non-standard neutrino interactions



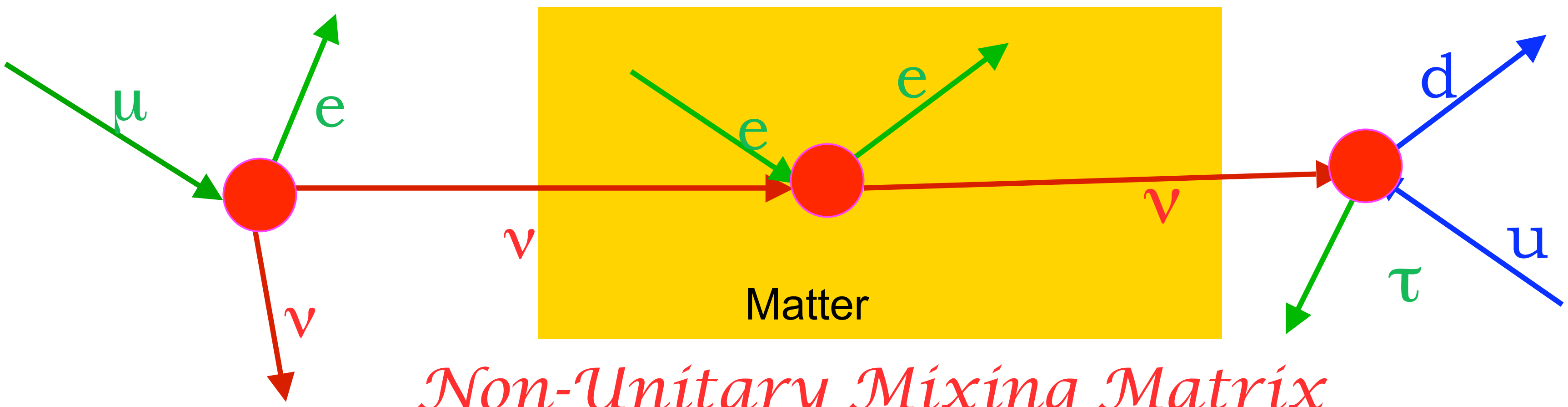
Standard scenario

YES! These effects ARE non-standard neutrino interactions



Non-Unitary Mixing Matrix

YES! These effects ARE non-standard neutrino interactions…



Non-Unitary Mixing Matrix

…affecting <u>simultneously</u> *<u>production, propagation and detection</u>*.

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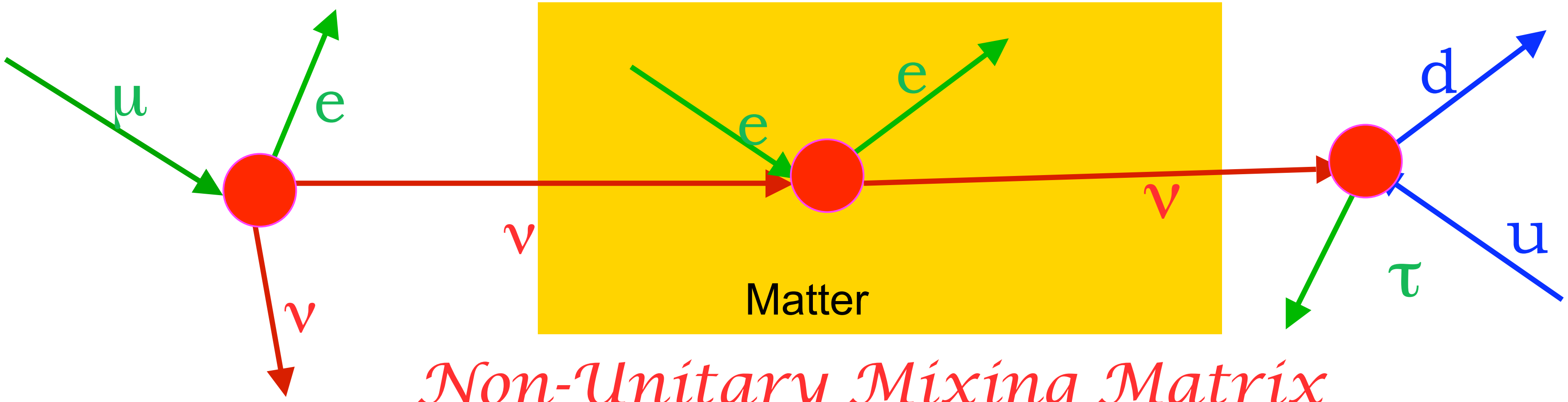
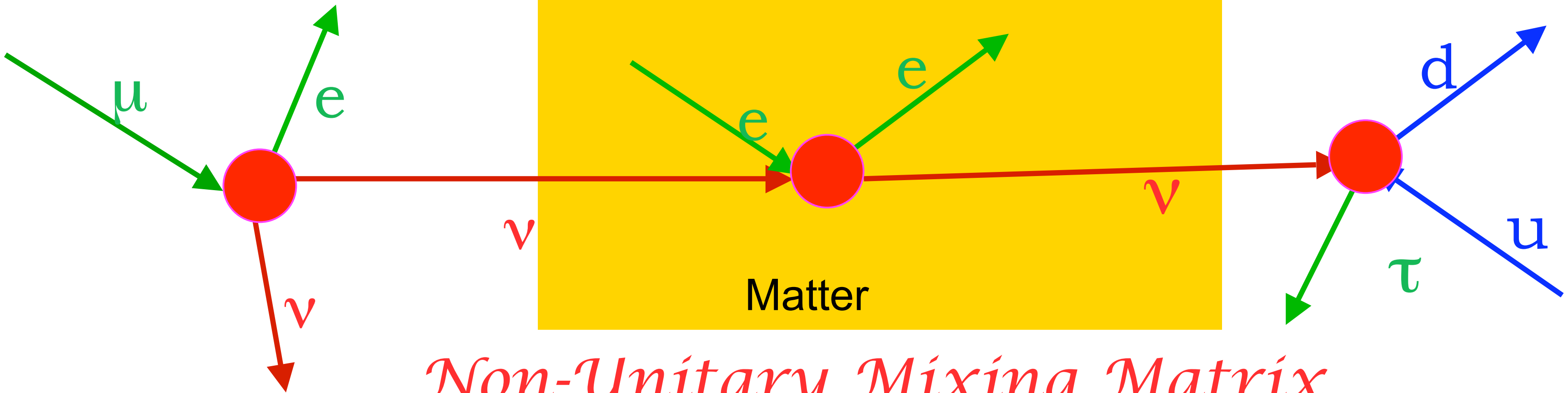


Non-Unitary Mixing Matrix

…affecting <u>simultneously</u> *production, propagation and detection.*

These NSI are a generic signature
of fermionic Seesaws

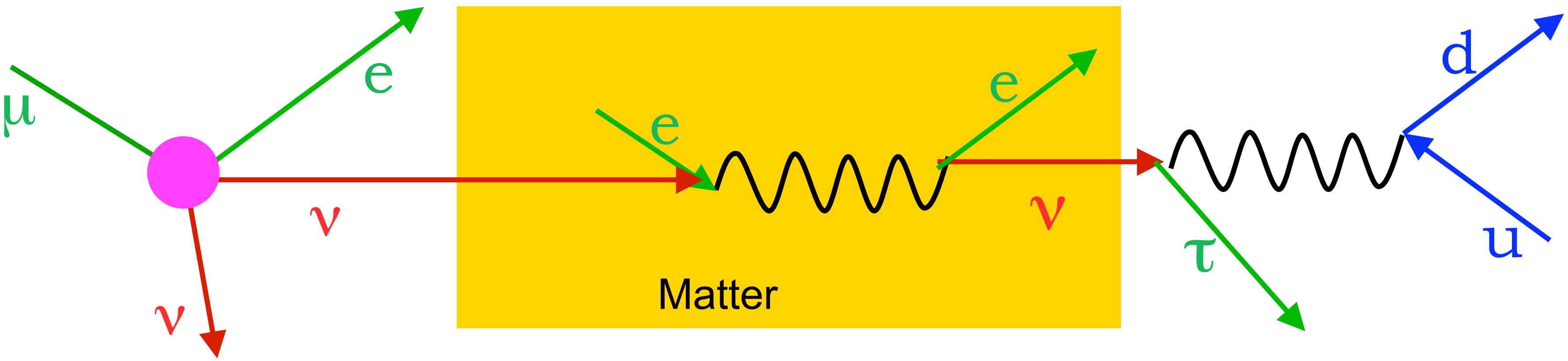
YES! These effects ARE non-standard neutrino interactions…



Non-Unitary Mixing Matrix

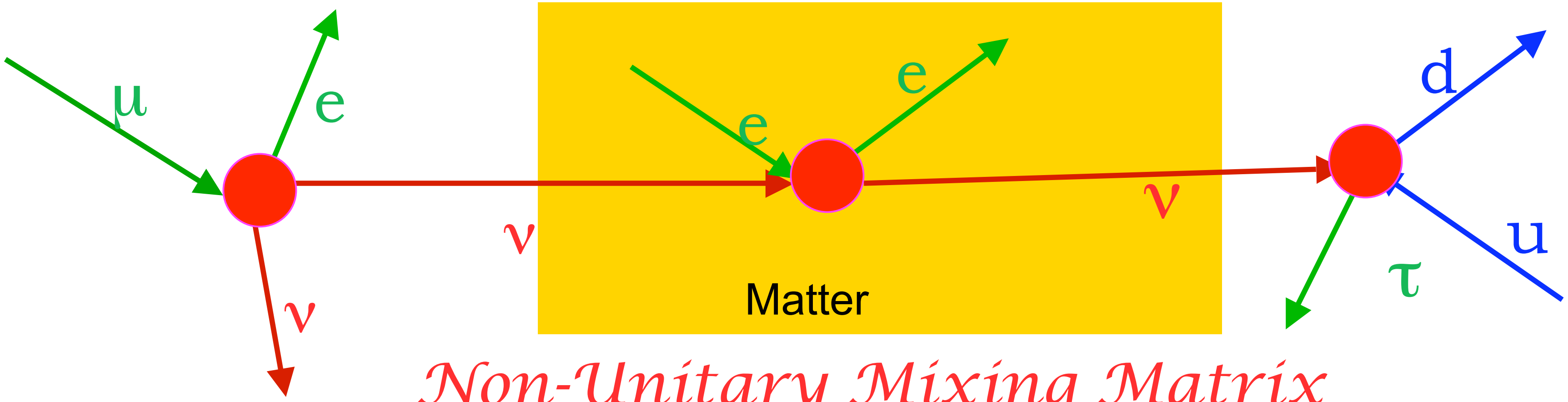
…affecting simultneously *production, propagation and detection.*

To be compared with popular non-standard interactions, with either:



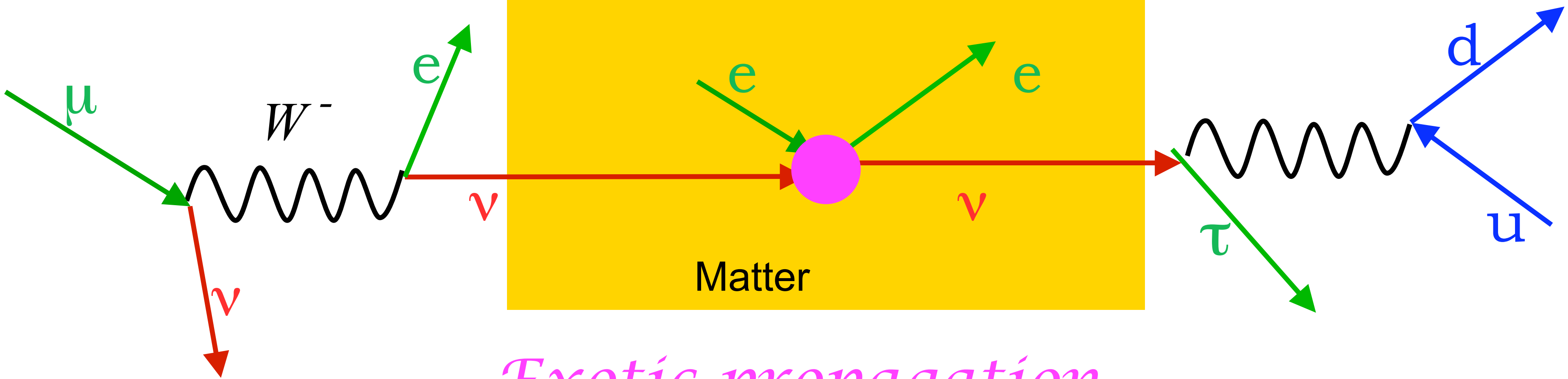
Exotic production

YES! These effects ARE non-standard neutrino interactions…



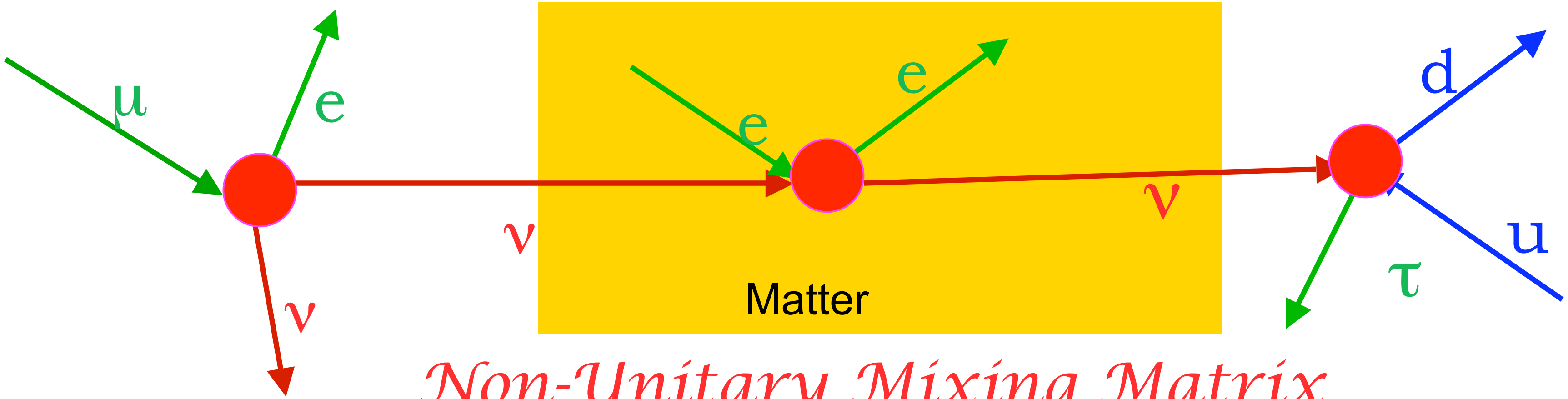
Non-Unitary Mixing Matrix

…affecting simultneously *production, propagation and detection.*



Exotic propagation

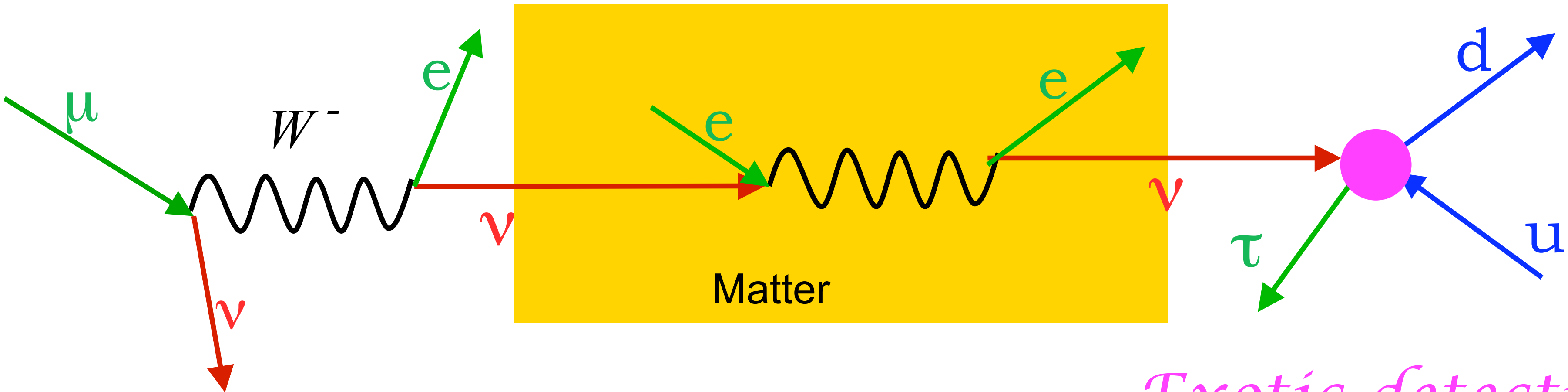
YES! These effects ARE non-standard neutrino interactions…



Non-Unitary Mixing Matrix

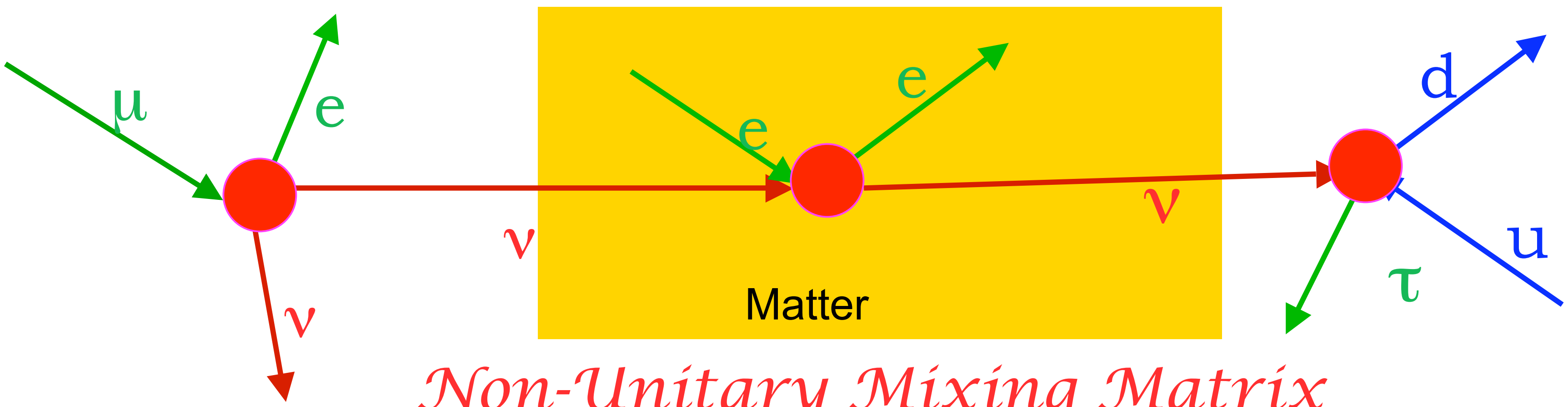
…affecting simultneously *production, propagation and detection.*

To be compared with popular non-standard interactions, with either:



Exotic detection

YES! These effects ARE non-standard neutrino interactions…



Non-Unitary Mixing Matrix

…affecting simultneously *production, propagation and detection.*

These NSI are a generic signature
of fermionic Seesaws

➡ New CP-violation signals
even in the two-family approximation

E. Fdez-Martinez, J.Lopez, O. Yasuda, M.B.G.

i.e. $P(\nu_\mu \dashrightarrow \nu_\tau) \neq P(\overline{\nu_\mu} \dashrightarrow \overline{\nu_\tau})$

➡ Increased sensitivity to the moduli $|N|$
in future Neutrino Factories

Can we measure the phases of N ?

E. Fdez-Martinez, J.Lopez, O. Yasuda, M.B.G.

If we parametrize $N \approx (1 + \varepsilon)\, U_{PMNS}$ with $\varepsilon = -\frac{v^2}{4}\, c^{d=6}$

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

If L/E small

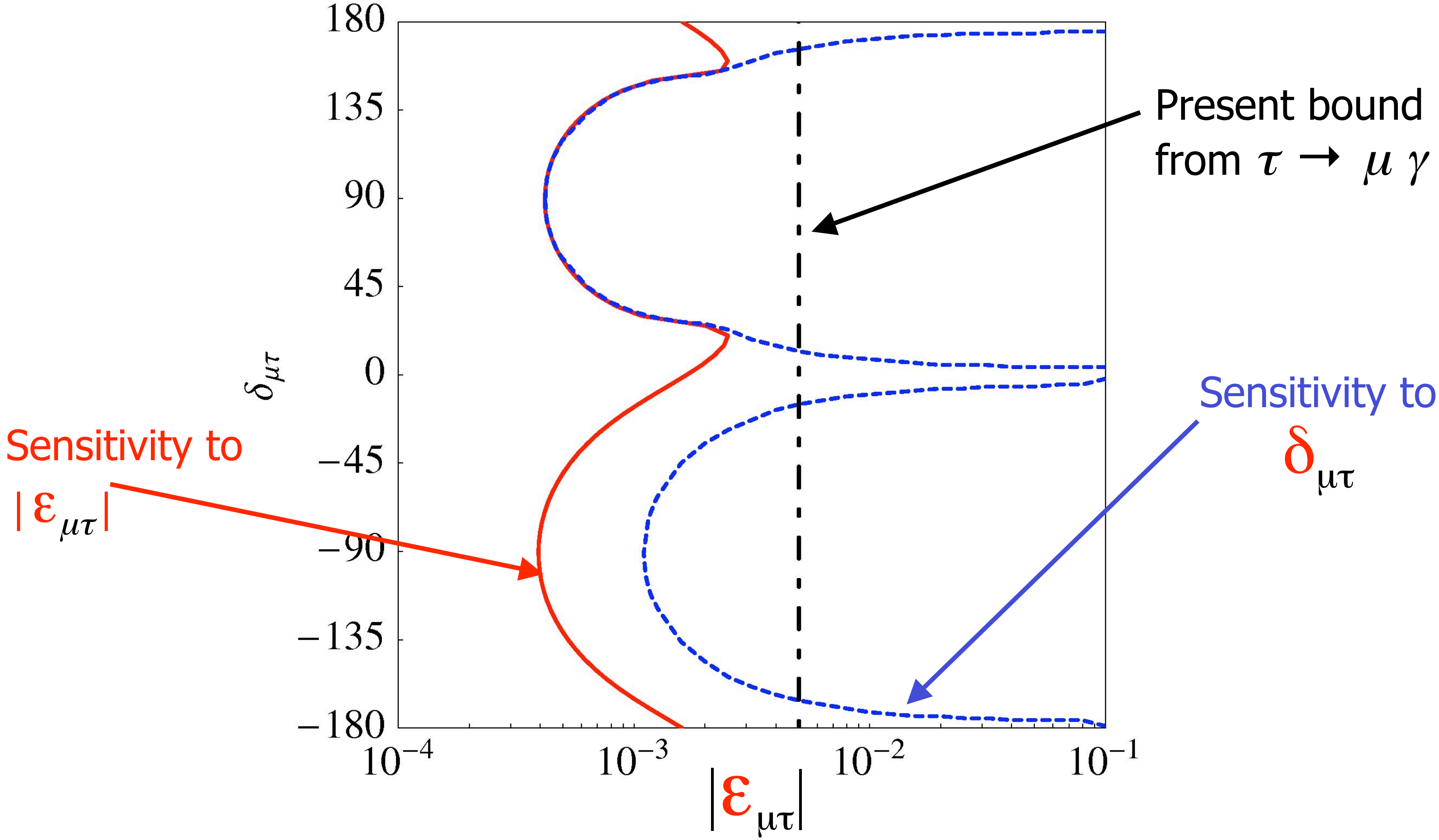
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) - 2\,\mathrm{Im}(\varepsilon_{\alpha\beta})\,\sin(2\theta)\sin\left(\frac{\Delta m^2 L}{2E}\right) + 4|\varepsilon_{\alpha\beta}|^2$$

SM

CP violating interference

Zero dist. effect

Measuring non-unitary phases

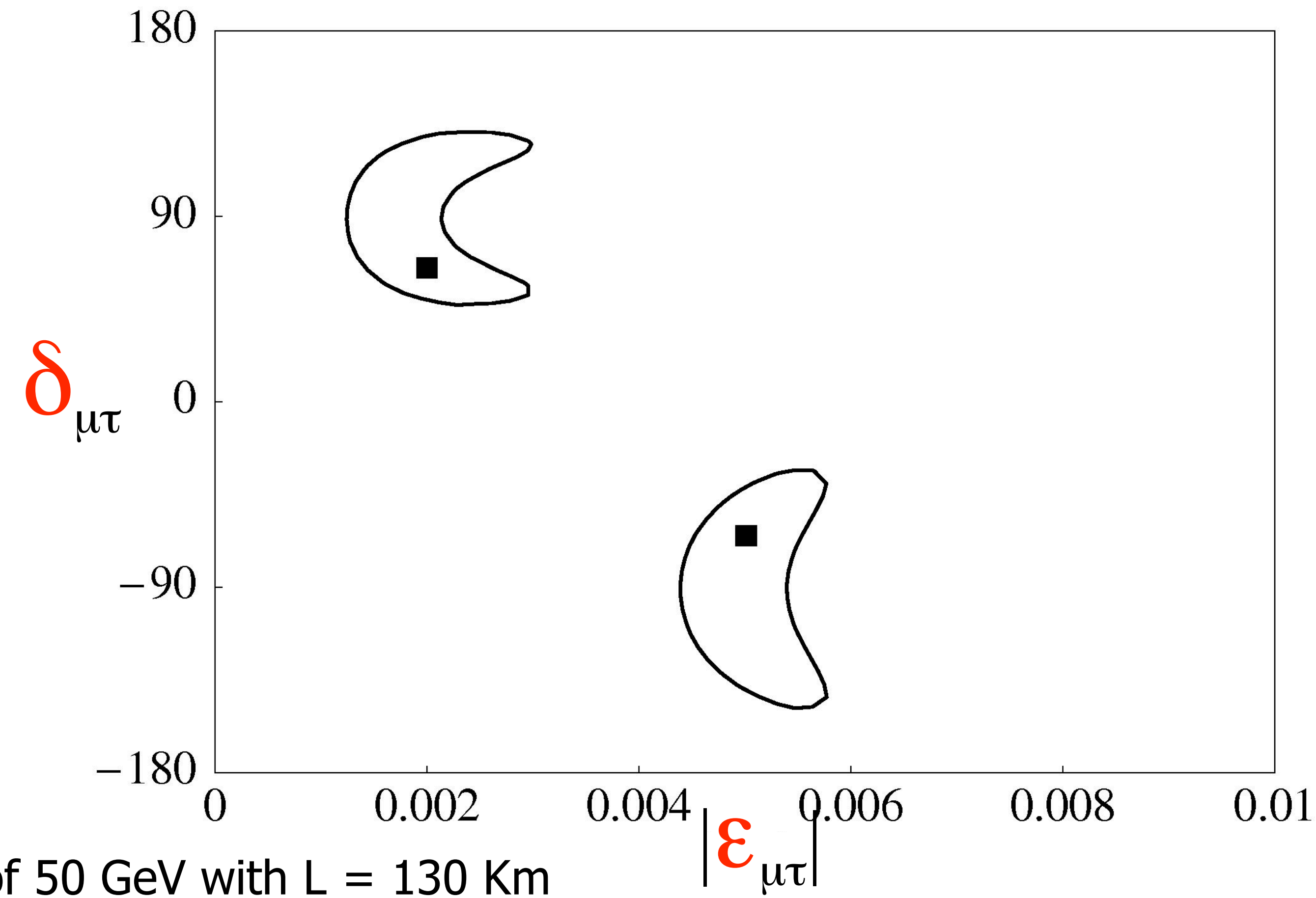


For non-trivial $\delta_{\mu\tau}$, one order of magnitude improvement for $|N|$

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

$$P_{\mu\tau} - P_{\bar{\mu}\bar{\tau}} = -4\,\mathrm{Im}(\varepsilon_{\mu\tau})\sin(2\theta_{23})\sin\left(\frac{\Delta m_{23}^2 L}{2E}\right)$$

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



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

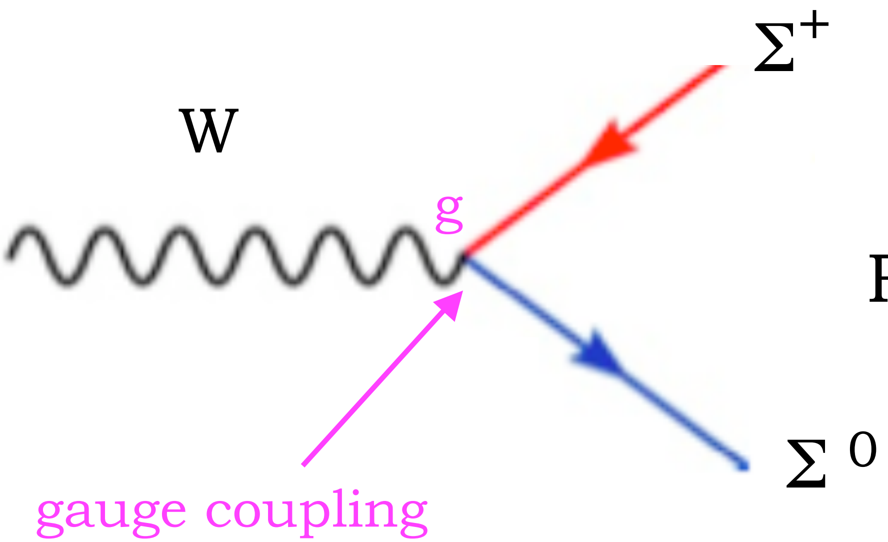
Good prospect for $\nu_\mu - \nu_\tau$ channel at near detector -O(100 km)

* Recently: Goswami+ Ota; Altarelli+Meloni, Tang+Winter at nufact

- Also today!
  Antusch et al.--> impact of e-tau non-unitary contribution to the golden channel in standard nufact setup, detector at ~ 1000 km

Fermion-triplet seesaws:

similar - although richer! - analysis



(Abada et al. 07))

For $M \approx TeV \;\rightarrow\; |Y| < 10^{-2}$

➡ For the Triplet-fermion Seesaws (type III):

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

(Abada et al 07)

Scalar triplet seesaw

Bounds on $c^{d=6}$

Process	Constraint on	Bound $(\times (\frac{M_\Delta}{1\,\mathrm{TeV}})^2)$
M_W	$\lvert Y_{\Delta\mu e}\rvert^2$	$< 7.3 \times 10^{-2}$
$\mu^- \to e^+e^-e^-$	$\lvert Y_{\Delta\mu e}\rvert\lvert Y_{\Delta ee}\rvert$	$< 1.2 \times 10^{-5}$
$\tau^- \to e^+e^-e^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta ee}\rvert$	$< 1.3 \times 10^{-2}$
$\tau^- \to \mu^+\mu^-\mu^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta\mu\mu}\rvert$	$< 1.2 \times 10^{-2}$
$\tau^- \to \mu^+e^-e^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta ee}\rvert$	$< 9.3 \times 10^{-3}$
$\tau^- \to e^+\mu^-\mu^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta\mu\mu}\rvert$	$< 1.0 \times 10^{-2}$
$\tau^- \to \mu^+\mu^-e^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta\mu e}\rvert$	$< 1.8 \times 10^{-2}$
$\tau^- \to e^+e^-\mu^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta\mu e}\rvert$	$< 1.7 \times 10^{-2}$
$\mu \to e\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^\dagger_{l\mu} Y_{\Delta el}\rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^\dagger_{l\tau} Y_{\Delta el}\rvert$	< 1.05
$\tau \to \mu\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^\dagger_{l\tau} Y_{\Delta \mu l}\rvert$	$< 8.4 \times 10^{-1}$

Scalar triplet seesaw

Combined bounds on $c^{d=6}$

Combined bounds		
Process	Yukawa	Bound $\left(\times\left(\frac{M_\Delta}{1\,\mathrm{TeV}}\right)^4\right)$
$\mu \to e\gamma$	$\left\lvert {Y_\Delta}^\dagger_{\mu\mu} {Y_\Delta}_{\mu e} + {Y_\Delta}^\dagger_{\tau\mu} {Y_\Delta}_{\tau e} \right\rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\left\lvert {Y_\Delta}^\dagger_{\tau\tau} {Y_\Delta}_{\tau e} \right\rvert$	< 1.05
$\tau \to \mu\gamma$	$\left\lvert {Y_\Delta}^\dagger_{\tau\tau} {Y_\Delta}_{\tau\mu} \right\rvert$	$< 8.4 \times 10^{-1}$

Obervable non-standard interactions from

$$\boxed{Y_\Delta^{+} Y_\Delta / M^2 \; (\bar{L}_\alpha L_\beta)\; (\bar{L}_\gamma L_\delta)}$$ in scalar triplet seesaw ???

Barely so ! (Malisnky Ohlsson and Zhang 08):

--- Require Yukawa couplings are almost diagonal--> *degenerate neutrino spectrum*

--- Not excluded are

$\mu^- \dashrightarrow e^- \nu_e \bar{\nu}_\mu \ldots$ *Wrong sign muons at near detector*

No ν **masses** in the SM

because the SM *accidentally* preserves B-L

i.e. Adding singlet neutrino fields N_R

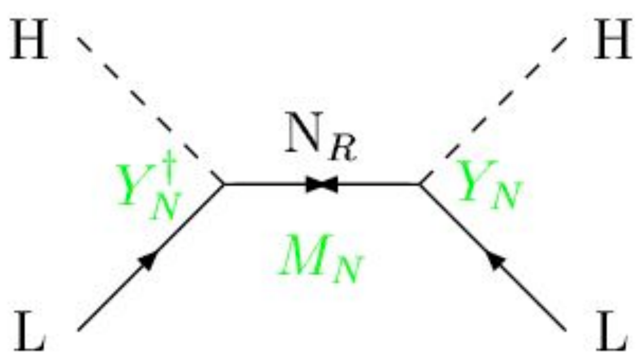
- right-handed $N_R \rightarrow$ $Y_N \, \tilde{H} \, \bar{L} \, N_R + h.c. \;\longrightarrow\; m_D \bar{\nu}_L \, N_R + h.c.$

Would require $Y_N \sim 10^{-12}$!!! Why νs are so light???

Why N_R does not acquire large Majorana mass?

$$\delta\mathcal{L} \sim M \, (N_R N_R)$$

OK with gauge invariance



Seesaw model

Which allows $Y_N \sim 1$ --> $M \sim M_{Gut}$

$\mathcal{N}$ elements from oscillations & decays

MUV

without unitarity
OSCILLATIONS
+DECAYS

$$|N| = \begin{pmatrix} .75 - .89 & .45 - .65 & <.20 \\ .19 - .55 & .42 - .74 & .57 - .82 \\ .13 - .56 & .36 - .75 & .54 - .82 \end{pmatrix}$$

Antusch, Biggio, Fernández-Martínez,
López-Pavón, M.B.G. 06

3σ

with unitarity
OSCILLATIONS

$$|U| = \begin{pmatrix} .79 - .88 & .47 - .61 & < .20 \\ .19 - .52 & .42 - .73 & .58 - .82 \\ .20 - .53 & .44 - .74 & .56 - .81 \end{pmatrix}$$

M. C. Gonzalez Garcia hep-ph/0410030