Precision neutrino physics

European Strategy for Future Neutrino Physics

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Neutrino are optimal windows into the exotic -dark- sectors

* Can mix with new neutral fermions, heavy or light

* Interactions not obscured by strong and e.m. ones

What are the main physics goals in ν physics?

- To determine the absolute scale of masses
- To determine whether they are Majorana

* To discover Leptonic CP-violation

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* To discover Leptonic CP-violation

What is the relation of the these putative discoveries to the matter-antimatter asymmetry of the universe?

Can leptogenesis be “proved”?

The short, and rather accurate answer

NO

Nevertheless, a positive discovery of ***both***
2 last points

would constitute a very compelling argument
in favour of leptogenesis

What are the main physics goals in ν physics?

- To determine the absolute scale of masses

  (Tritium…., cosmo?)

- To determine whether they are Dirac Majorana

  (neutrinoless $\beta\beta$ decay, degenerate or inverse hierarchy)

- To discover Leptonic CP-violation

  (in ν_μ-ν_e oscillations at superbeams, betabeams….
  neutrino factory)

Go for those discoveries!

Entering the era of precision neutrino oscillation physics

~ % level

ν_μ<---->ν_e golden channel...

Neutrino masses indicate new physics beyond the SM

Maybe new physics could also appear in neutrino couplings ?

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?

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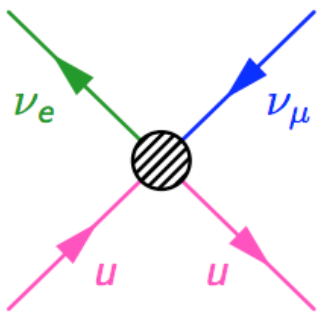
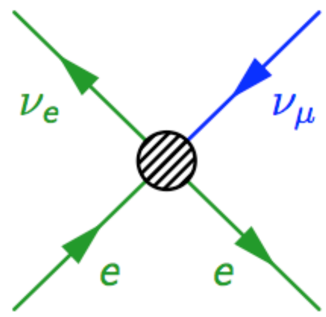
Maybe new physics could appear in Non Standard neutrino Interactions?

i.e. NSI





Neutrino masses indicate new physics beyond the SM

?

Maybe new physics could appear in Non Standard neutrino Interactions?

Or other exotic neutrino couplings….

Or rare lepton decays….

Two cases:

Heavy new scales (M > v)

Light new scales (M << v)

Heavy new scale $M > v$

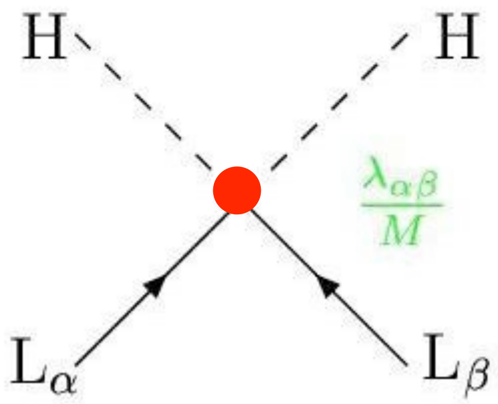
$$\mathcal{L} = \mathcal{L}_{SM} + c^{d=5} \frac{O^{d=5}}{M} + c^{d=6} \frac{O^{d=6}}{M^2} + \ldots\ldots$$

ν masses beyond the SM

The Weinberg operator

Dimension 5 operator:

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



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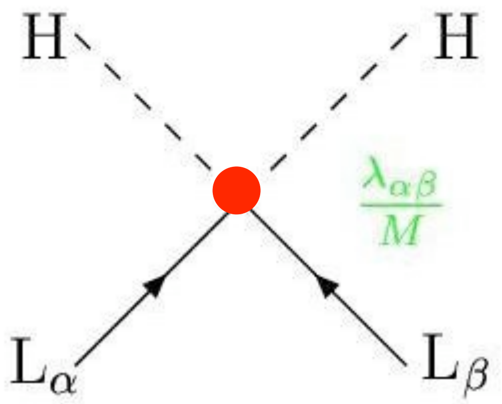

It's unique → very special role of ν masses:
lowest-order effect of higher energy physics

ν masses beyond the SM

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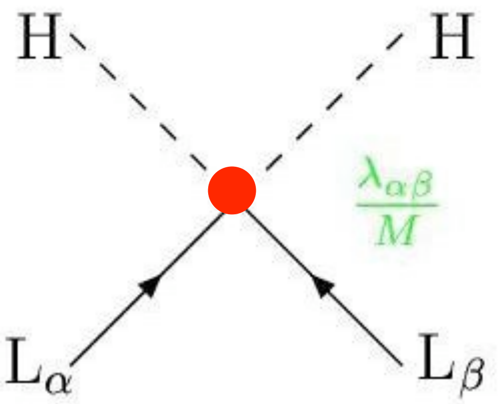

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This mass term violates lepton number (B-L)
→ Majorana neutrinos

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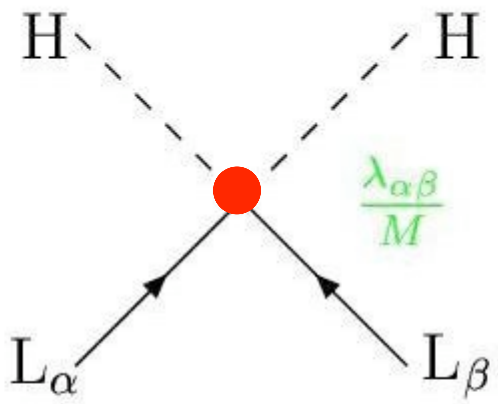

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This mass term violates lepton number (B-L)
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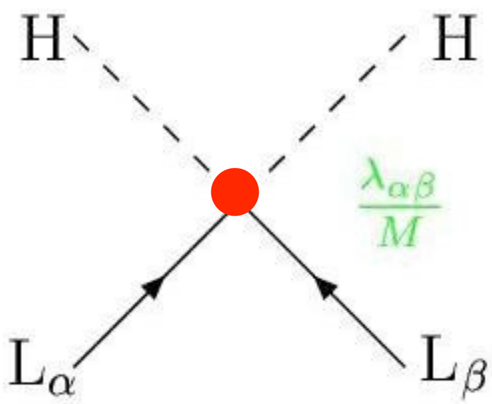
$O^{d=5}$ *is common to all models of Majorana* ν*s*

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



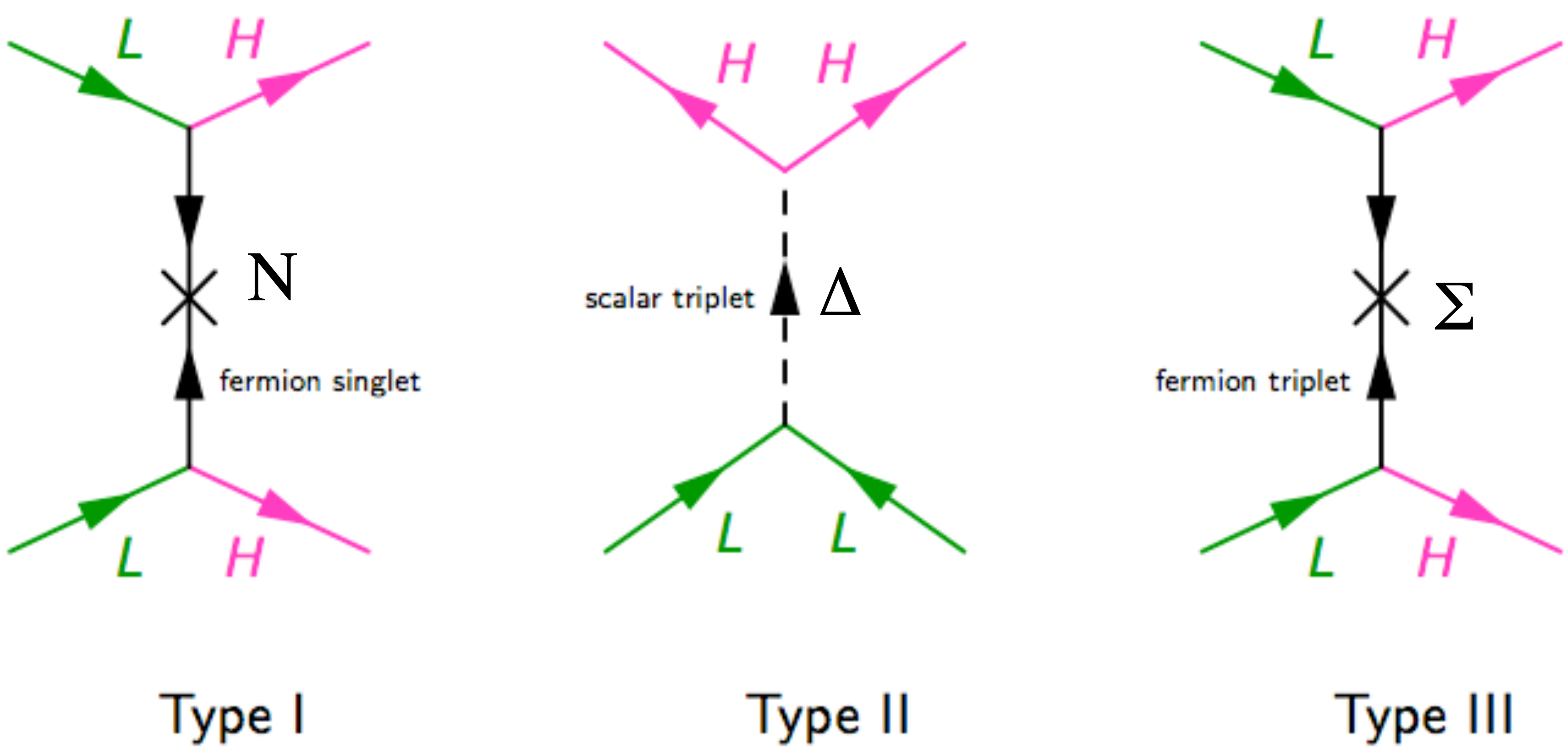
2 x 2 = 1 + 3

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

3 generic types (Ma)

The Seesaw models

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



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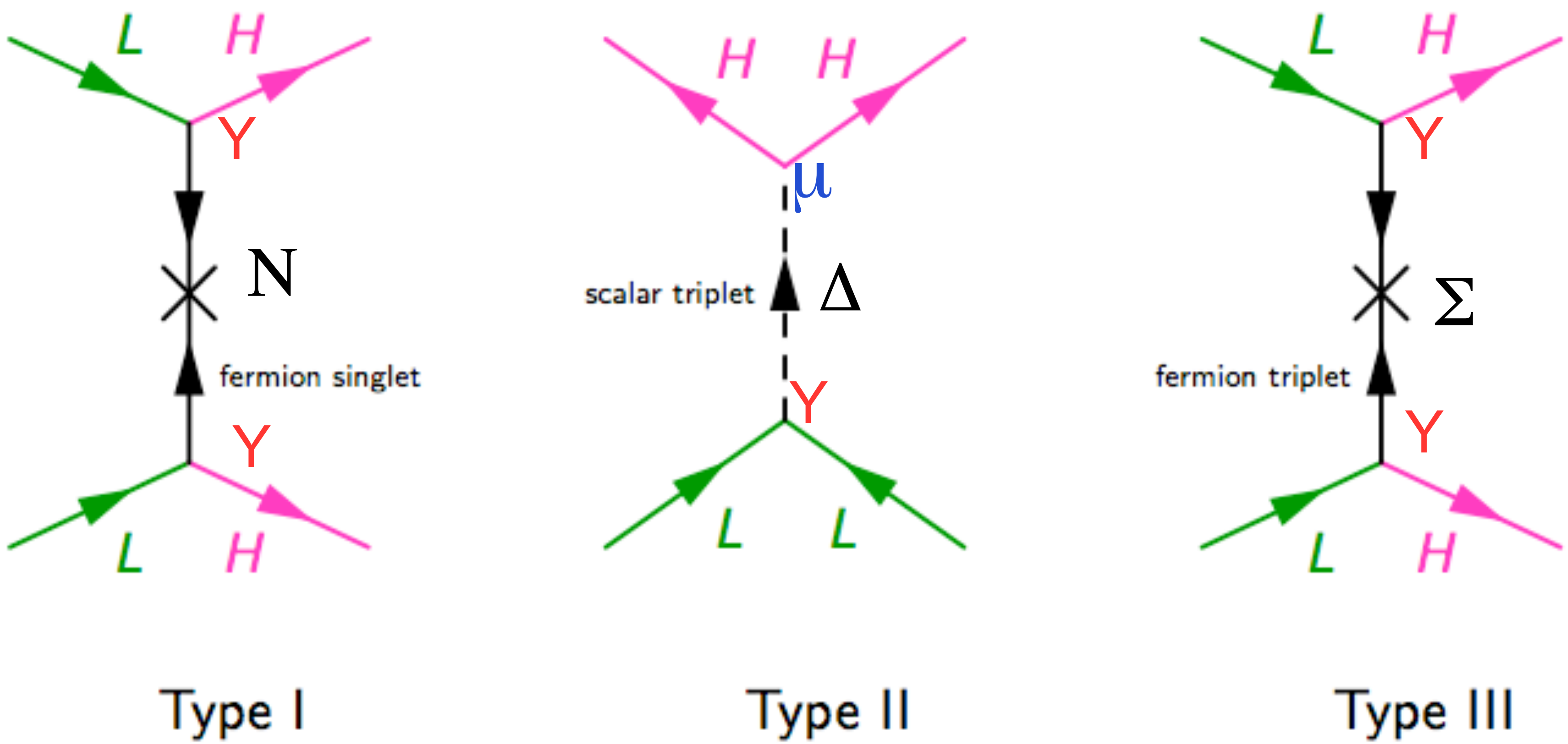

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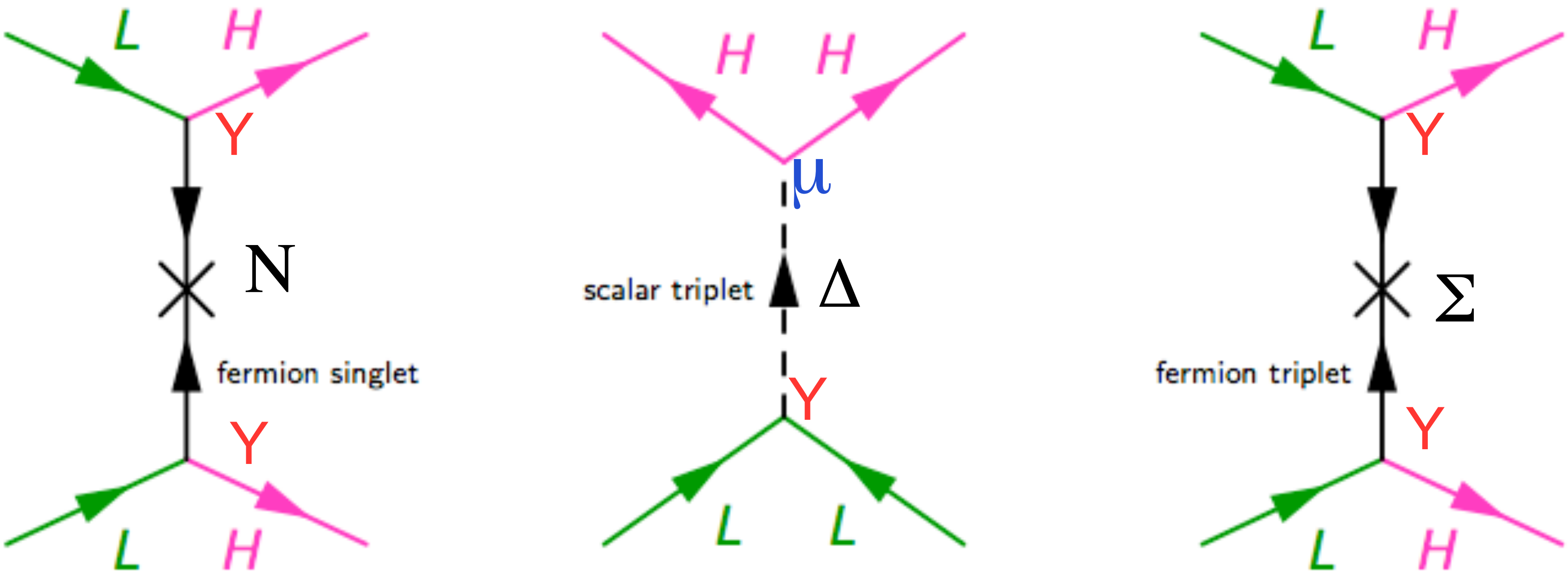

Type I

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

Type II

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

Type III

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

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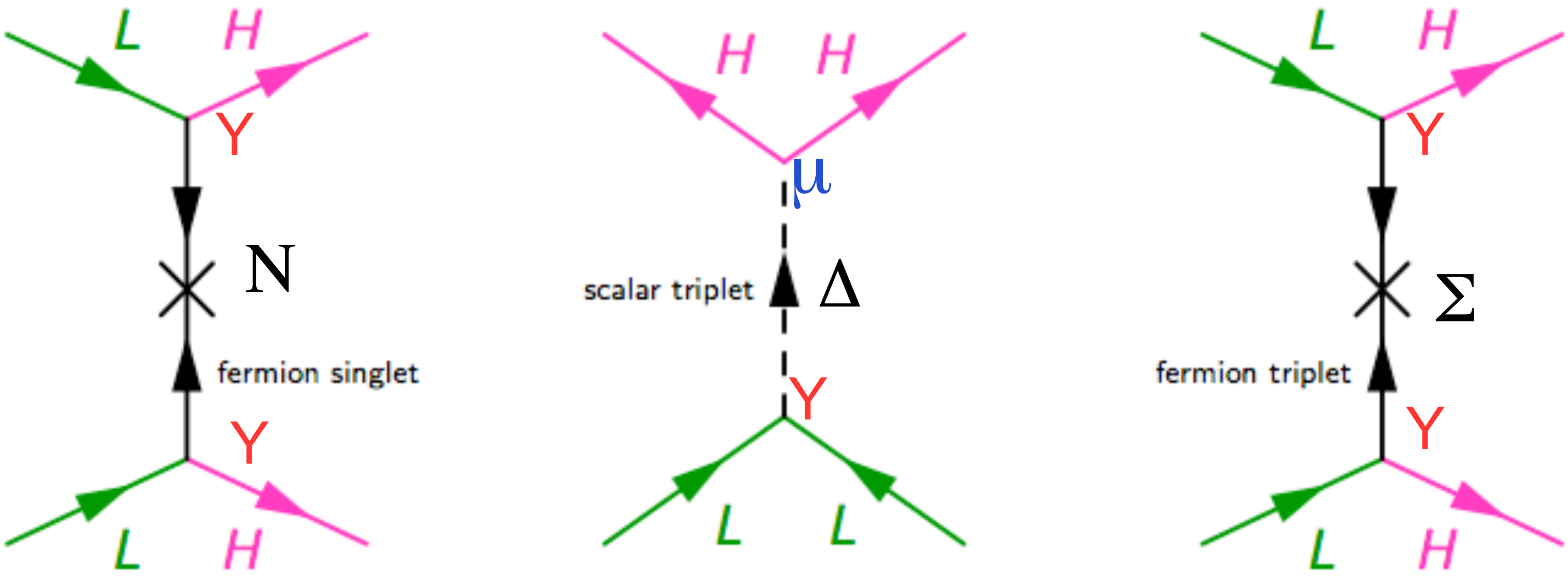


Type I | Type II | Type III

Heavy fermion singlet N_R
Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic

Heavy scalar triplet Δ
Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle

Heavy fermion triplet Σ_R
Ma, Roy, Senjanovic, Hambye et al.,

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

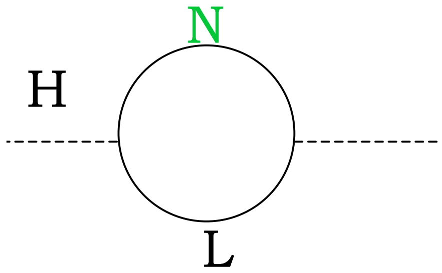
Which are the new exotic couplings,

that is, d=6 operators, in Seesaws?

Observable effects?

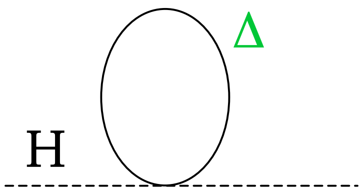
Obviously requires scale near the TeV

M~1 TeV is suggested by electroweak hierarchy problem



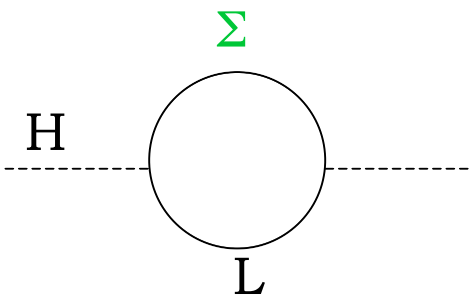
$$\delta m_H^2 = -\frac{Y_N^\dagger Y_N}{16\pi^2}\left[2\Lambda^2 + 2M_N^2 \log\frac{M_N^2}{\Lambda^2}\right]$$

(Vissani)



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

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



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

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)	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N^\dagger \frac{1}{\vert M_N\vert^2} Y_N$	$\left(\overline{L}\widetilde{H}\right) i\partial\!\!\!/ \left(\widetilde{H}^\dagger L\right)$
Fermionic Triplet (type III)	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	$Y_\Sigma^\dagger \frac{1}{\vert M_\Sigma\vert^2} Y_\Sigma$	$\left(\overline{L}\vec{\tau}\widetilde{H}\right) iD\!\!\!\!/ \left(\widetilde{H}^\dagger \vec{\tau} L\right)$
Scalar Triplet (type II)	$4Y_\Delta \frac{\mu_\Delta}{\vert M_\Delta\vert^2}$	$Y_\Delta^\dagger \frac{1}{2\vert M_\Delta\vert^2} Y_\Delta$	$\left(\overline{\widetilde{L}}\vec{\tau}L\right)\left(\overline{L}\vec{\tau}\widetilde{L}\right)$
		$\frac{\vert\mu_\Delta\vert^2}{\vert M_\Delta\vert^4}$	$\left(H^\dagger\vec{\tau}\widetilde{H}\right)\left(\overleftarrow{D_\mu}\overrightarrow{D^\mu}\right)\left(\widetilde{H}^\dagger\vec{\tau}H\right)$
		$-2\left(\lambda_3+\lambda_5\right)\frac{\vert\mu_\Delta\vert^2}{\vert M_\Delta\vert^4}$	$\left(H^\dagger H\right)^3$

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

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

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

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

For all scalar and fermionic Seesaw models, present bounds:

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

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

or stronger

Fermionic seesaws ---> Non unitarity

The complete theory of ν masses is unitary.

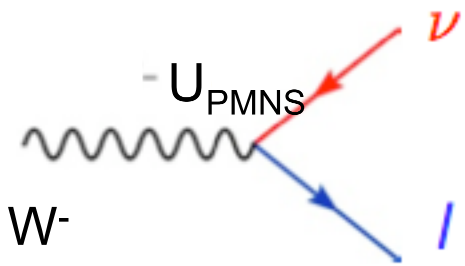
i.e, a neutrino mass matrix larger than 3x3

All fermionic Seesaws exhibit non-unitary mixing

In fact, ot is a quite general characteristic of new physics, well beyond the Seesaw scenarios:

A non-unitary mixing matrix arises when leptons mix with heavy fermions

i.e. In charged currents



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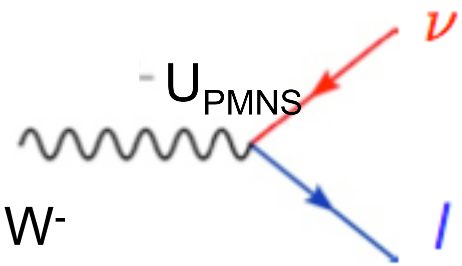

U_{PMNS} --------> N (non-unitary)

Langacker+London

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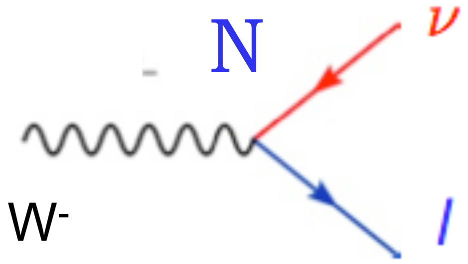


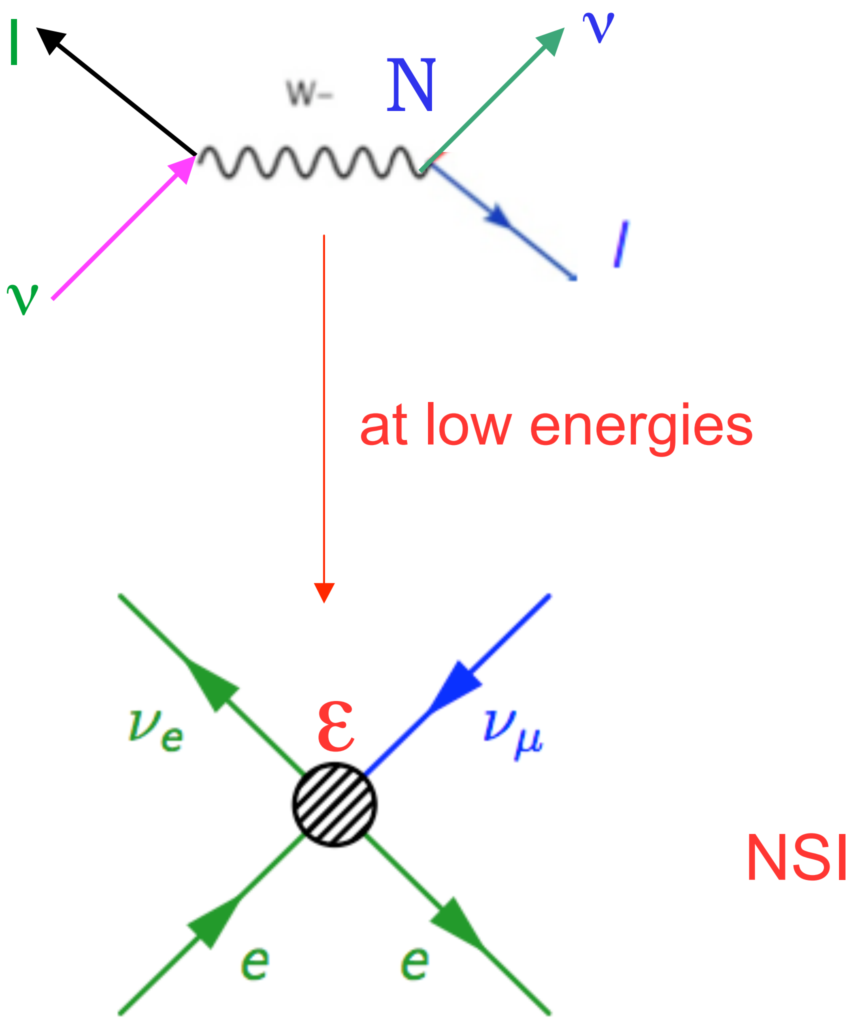
U_{PMNS} --------> N (non-unitary)

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

$$(|NN^\dagger| - 1)_{\alpha\beta} = |\ \varepsilon\ |_{\alpha\beta} = -v^2 \left| \frac{Y^+ Y}{M^2} \right|_{\alpha\beta}$$

Langacker+London

i.e.



All fermionic Seesaws exhibit non-unitary mixing

Unitarity constraints on (NN^{+}) from:

* All ν oscillation + near detector data

+

* Weak decays...

* W decays

* Invisible Z width

* Universality tests

* Rare lepton decays

→ $|N|$ is unitary at the % level

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

i.e. for heavy singlet neutrinos

$$|\varepsilon|_{\alpha\beta} = \frac{v^2}{2}|c_{\alpha\beta}^{d=6,kin}| < \begin{pmatrix} 4.0\cdot 10^{-3} & 1.2\cdot 10^{-4} & 3.2\cdot 10^{-3} \\ 1.2\cdot 10^{-4} & 1.6\cdot 10^{-3} & 2.1\cdot 10^{-3} \\ 3.2\cdot 10^{-3} & 2.1\cdot 10^{-3} & 5.3\cdot 10^{-3} \end{pmatrix}$$

Antusch, Baumann, Fdez-Martinez 08

Future bounds on $\varepsilon_{\alpha\beta}$

$\nu_e \longleftrightarrow \nu_\mu$: $\mu \rightarrow eee$, $\mu \rightarrow e\gamma$ ($\sim 10^{-5}$MEG), $\mu - e$ conversion
(PRISM/PRIME)

$\nu_e \longleftrightarrow \nu_\tau$
$\nu_\mu \longleftrightarrow \nu_\tau$ } τ *channels at ν factory* ~10-3…..

… or simpler?:

$\nu_e \longleftrightarrow \nu_\tau$ with betabeams ? (Agarwalla,Huber,Link) disappearance

$\nu_\mu \longleftrightarrow \nu_\tau$ even easier??

A simple proposal for $\nu_\mu \leftrightarrow \nu_\tau$:

MINSIS

Adam Para

(Main Injector Non Standard Interactions Search)

http://www-off-axis.fnal.gov/MINSIS/

- Emulsion near detector at the NuMI beam

ν_τ appearance

can achieve $\varepsilon_{\mu\tau} < 10^{-3}$ in ~ 5 years

(over Chorus-Nomad $\varepsilon_{\mu\tau} < 10^{-2}$)

PRELIMINARY

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Adam Para +….. A. de Gouvea, E. Fernandez-Martinez, M.B.G., P. Hernandez, J. Kopp, O. Mena, A. Nelson, S. Parke, T.Ota, JJ….

PRELIMINARY

Can we measure the phases of N ?

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

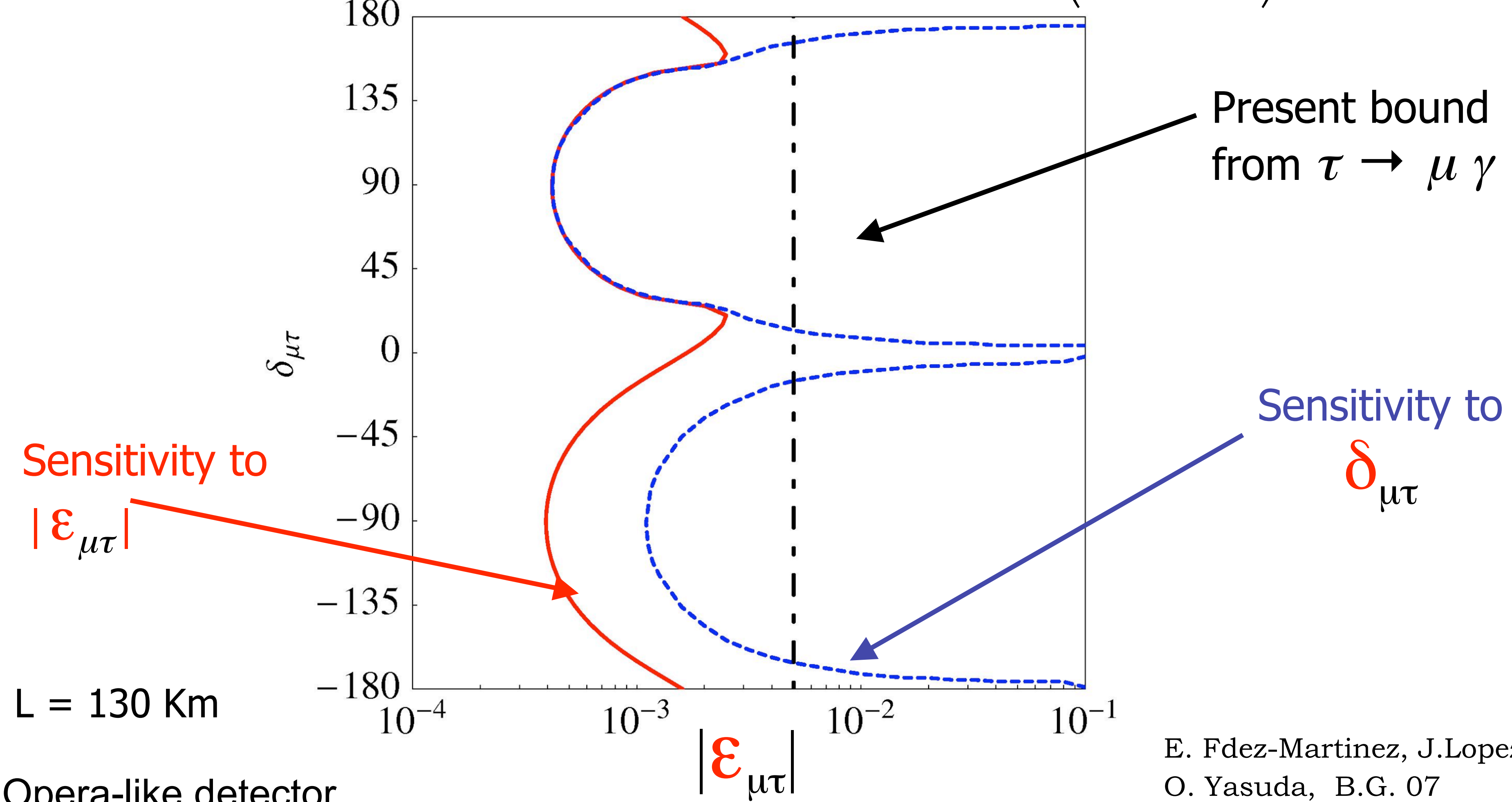
➡ New CP-violation signals
even in the two-family approximation

E. Fdez-Martinez, J.Lopez, O. Yasuda, B.G. 07

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

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



L = 130 Km

Opera-like detector

E. Fdez-Martinez, J.Lopez, O. Yasuda, B.G. 07

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

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

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

* Antusch et al.--> $\varepsilon_{e\tau}$ from the golden channel $\nu_e - \nu_\mu$ at ~ 1000 km

Could d=6 be stronger than d=5 ?

* Two independent scales in d=5, d=6 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

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

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

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

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

Minimal Flavour Violation

The global Flavour symmetry of the SM: without Yukawas

$$G = SU(3)_{Q_L} \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

$$Q_u \to L_u Q_u \,, \quad d_R \to R_d d_R \,, \ldots \quad .$$

Minimal Flavour Violation

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

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

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Quark sector

$$\mathcal{L} = \mathcal{L}_{SM} + c^{d=6} \frac{O^{d=6}}{\Lambda_{fl}^{2}} + \ldots\ldots$$

(D'Ambrosio, Cirigliano, Isidori, Grinstein, Wise….Buras….)

Predictive !

Minimal Flavour Violation

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Quark sector $\quad \mathcal{L} = \mathcal{L}_{SM} + c^{d=6} \dfrac{O^{d=6}}{\Lambda_{fl}^2} + \ldots\ldots$

(D'Ambrosio, Cirigliano, Isidori, Grinstein, Wise….Buras….)

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

A rationale for the MFV ansatz?

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

• Inspired in "condensate" flavour physics a la Froggat-Nielsen (Yukawas ~ $<\Psi\Psi>^n/\Lambda_{fl}$), rather than in susy-like options

•It makes you think on the relation between scales:
electroweak vs. flavour vs lepton number scales

What happens in the presence of neutrino masses?

Cirigliano, Isidori, Grinstein, Wise

In the lepton sector

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

$c^i_{d=5}$: Λ_{LN}

$c^i_{d=6}$: $\Lambda_{flavour}$

Delicate:

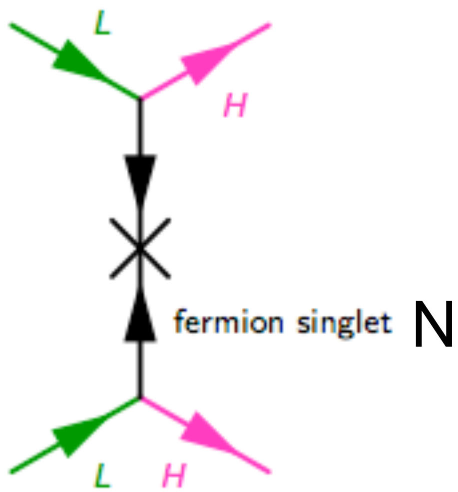
* Majorana masses are model dependent : $c^{d=5}(Y_e, ?)$, $c^{d=6}(Y_e, ?)$

* Requires to separate lepton number from flavour origin

An unsuccessful model: simplest type I

Standard Seesaw (Type I) doesn't work

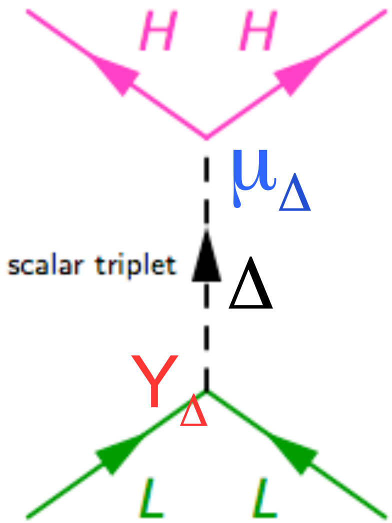
$$\mathscr{L} = \cdots - Y_N \bar{N} \phi^\dagger L_L - \Lambda_{LN} \bar{N}^c N \ldots$$



- 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], B.G. 09

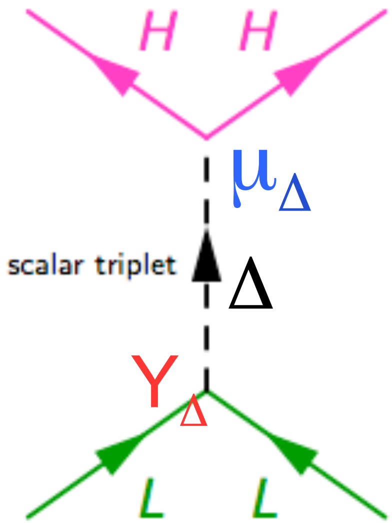
A successful model: Scalar-triplet Seesaw (type II)



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

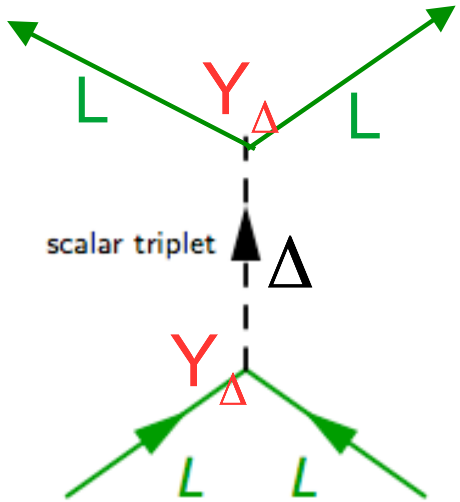
$$+\, Y_{\Delta}^{\alpha\beta}\,\overline{\widetilde{\mathrm{L}}}\,(\tau\cdot\Delta)\,\mathrm{L} + \mu_{\Delta}\widetilde{\phi}^{\dagger}(\tau\cdot\Delta)^{\dagger}\phi + \ldots$$

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



$\Lambda_{fl} = M_\Delta$

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

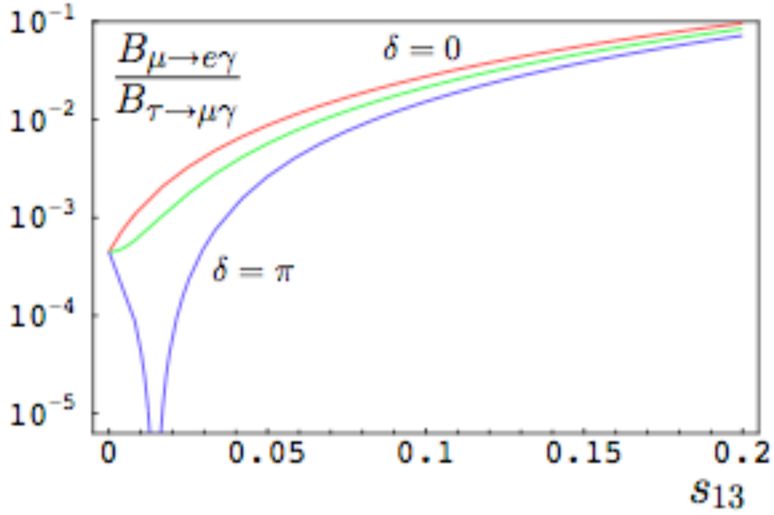


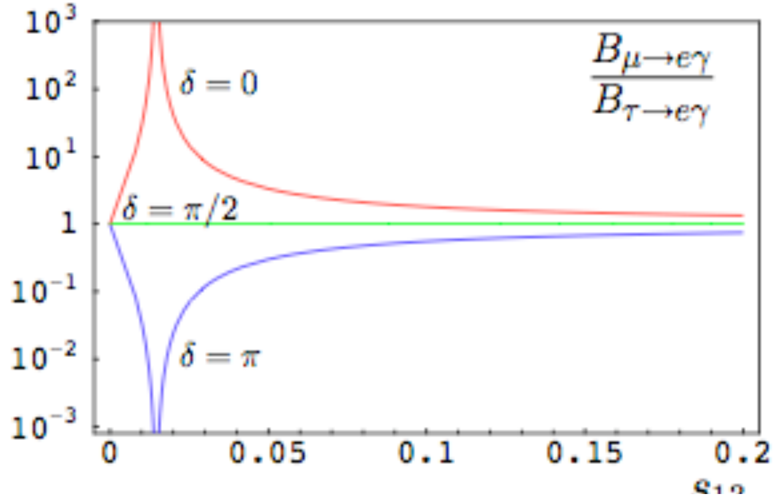
$$\mathscr{L}_\Delta = \cdots + (D_\mu \Delta)^\dagger (D^\mu \Delta) - M_\Delta^2 \, \Delta^\dagger \Delta + +$$

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

Correlations among
weak processes, i.e.

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





* Neutrino masses OK
* Measurable flavour OK
* Predictivity OK

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise, hep-ph/0507001.
M. B. Gavela, T. Hambye, P. Hernández, D.H., 0906.146

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

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

$$\mathscr{L}_{M_\nu} = \begin{pmatrix} 0 & Y_N^T v & 0 \\ Y_N v & 0 & \Lambda^T \\ 0 & \Lambda & 0 \end{pmatrix}$$

Successful fermionic-mediated Seesaws:

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

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

Lepton number conserved

U(1)

$\Lambda_{fl} = \Lambda$

$\Lambda_{LN} = \infty$

Wyler+Wolfenstein; Mohapatra+Valle; Branco+Grimus+Lavoura….

Successful fermionic-mediated Seesaw:

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

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

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

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

Lepton number violated by any of those 3 entries

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

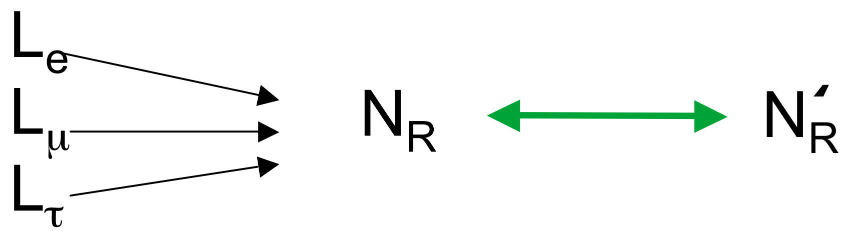
Wyler,Wolfenstein; Mohapatra,Valle, Branco,Grimus,Lavoura,Malinsky, Romao…

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

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

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

μ' is irrelevant (at tree-level)



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

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

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

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

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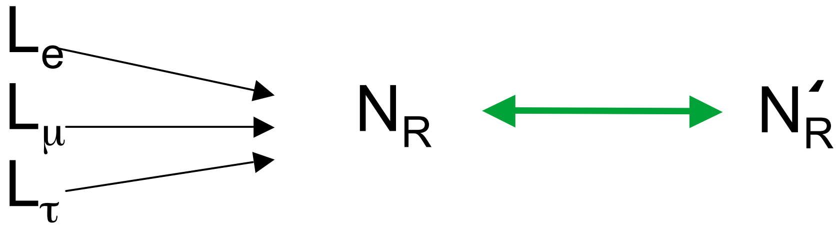

-- one massless neutrino

-- just one low-energy Majorana phase

arguably the sumplest model of neutrino mass

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

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

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

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

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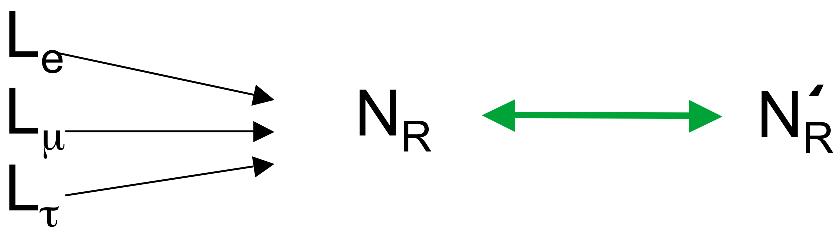

FUNDAMENTAL

	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.

- A normalization factor apart, Yukawas are determined from the U_{PMNS} and neutrino masses!

Hambye, Hernandez^2, B.G. 09

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

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

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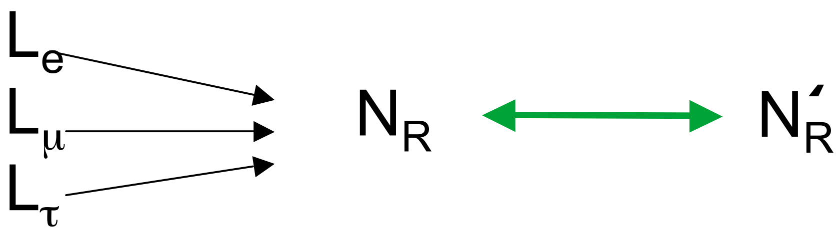


i.e.

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

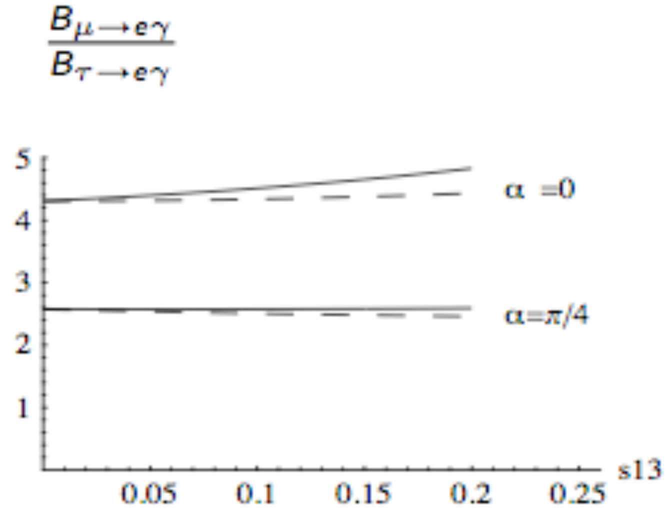
Normal hierarchy

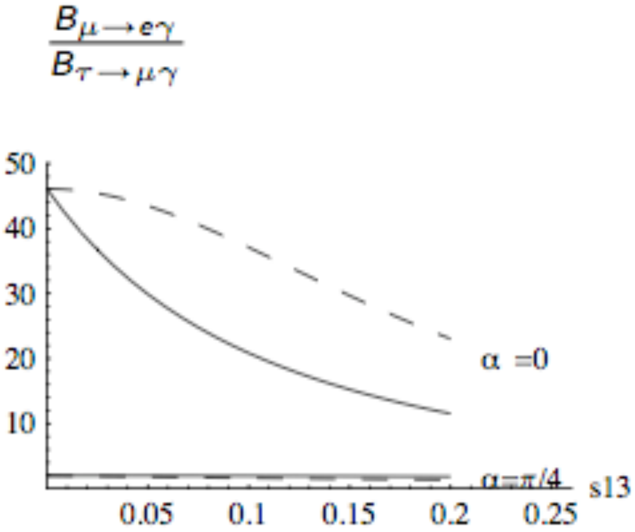
- A normalization factor apart, Yukawas are determined from the U_{PMNS} and neutrino masses!

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

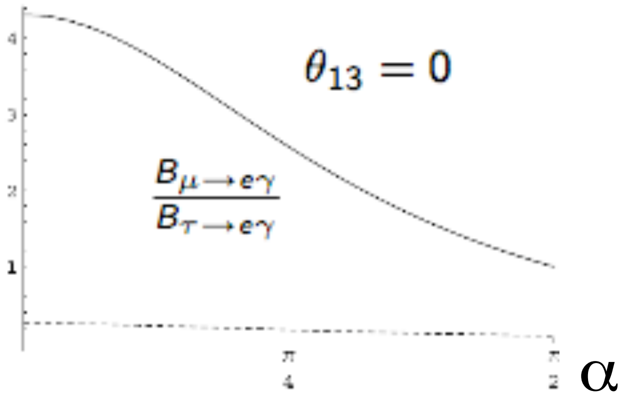
NORMAL HIERARCHY

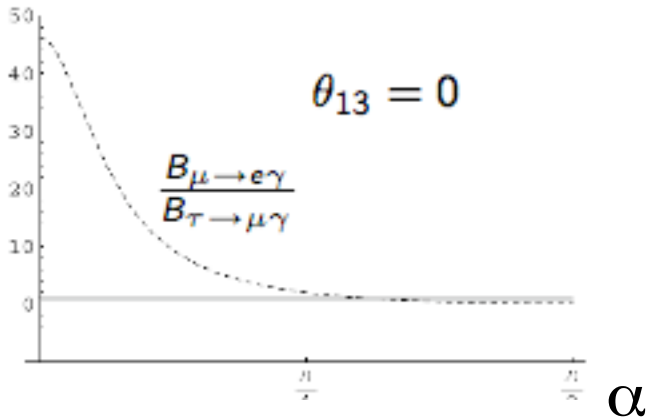
INVERTED HIERARCHY





Strong dependence on the Majorana phase!





Light new scales $M << v$

Most bounds on non-unitarity do NOT apply (i.e. M < GeV)

Can oscillation experiments detect/bound light sterile νs?

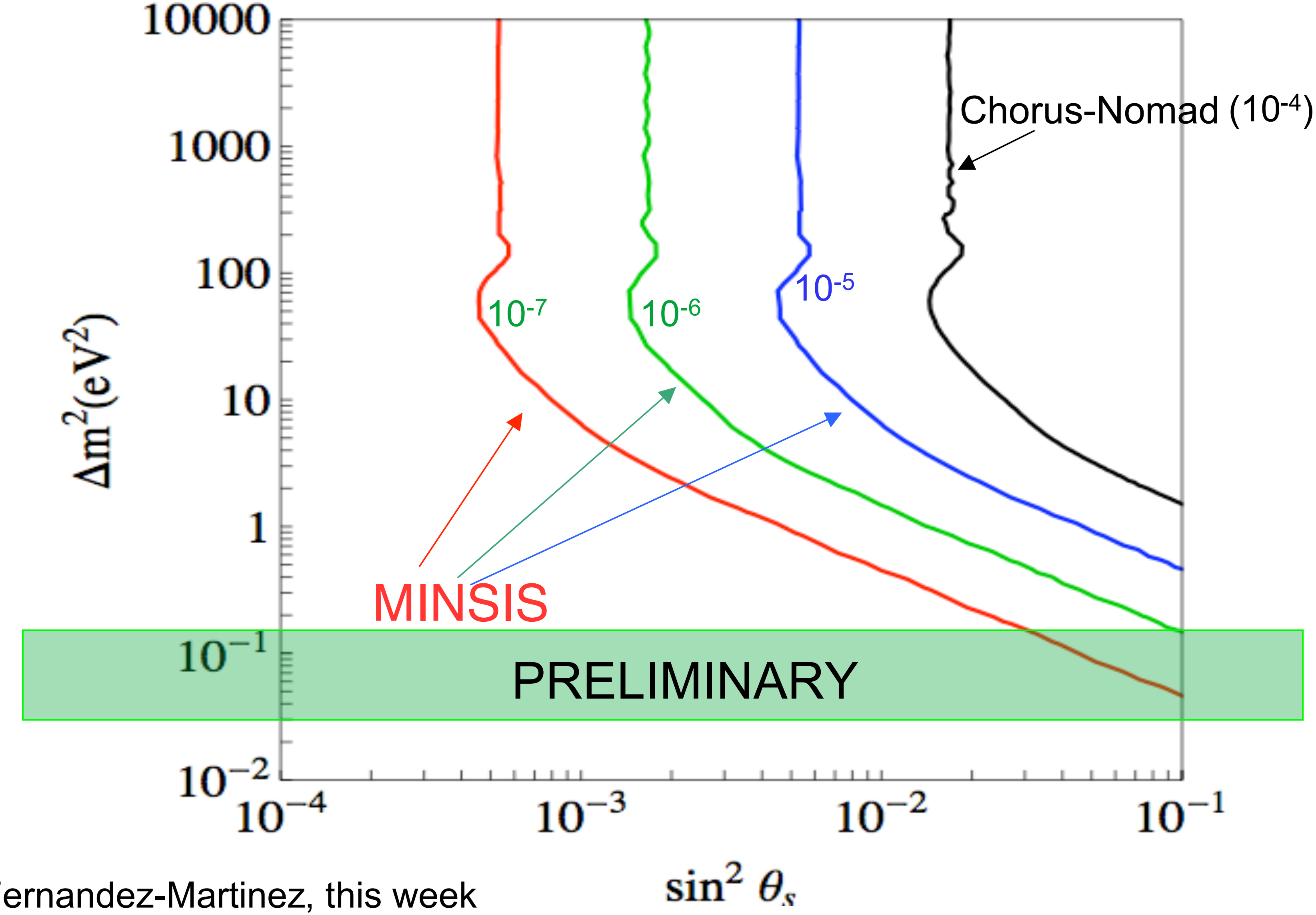
Yes, mainly with near detectors

* Disappearance i.e. MINOS

* Appearance i.e. MINSIS

i.e for a mixing 3-sterile θ_s

$$P(\nu_\mu - \nu_\tau) = \cos^2(\theta_{12}) \, . \, \sin^4(\theta_s) \, . \, \sin^2(\Delta m^2 \, L/4E)$$



E. Fernandez-Martinez, this week

Conclusions

* The guideline is clear: m_ν + Majorana + θ_{13}–>CP

• The seesaw mechanism induces:
non-unitary mixing matrix; new CP channels; rare decays.

Difficult signals, but they should be there if:
--- M ~TeV (also at LHC)
--- Yukawas near ~O(1)

* Near/short distance detectors are called for

$\nu_e \leftrightarrow \nu_\tau$: from ν factory (*and/or betabeams ? …*)

$\nu_\mu \leftrightarrow \nu_\tau$: from present beams ? (*and/or ν factory…*)
and may shed light on TeV seesaws… or light sterile νs

Back-up slides

N elements from oscillations only

- **KamLAND+CHOOZ+Atmospheric+K2K**

+ Near detectors: MINOS, NOMAD, BUGEY, KARMEN

without unitarity
OSCILLATIONS

$$|\varepsilon| = \begin{pmatrix} <0.025 & <0.05 & <.34 \\ <0.05 & <-0.05 & <0.013 \\ <0.09 & <0.013 & ? \end{pmatrix}$$

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 $c^{d=6}$

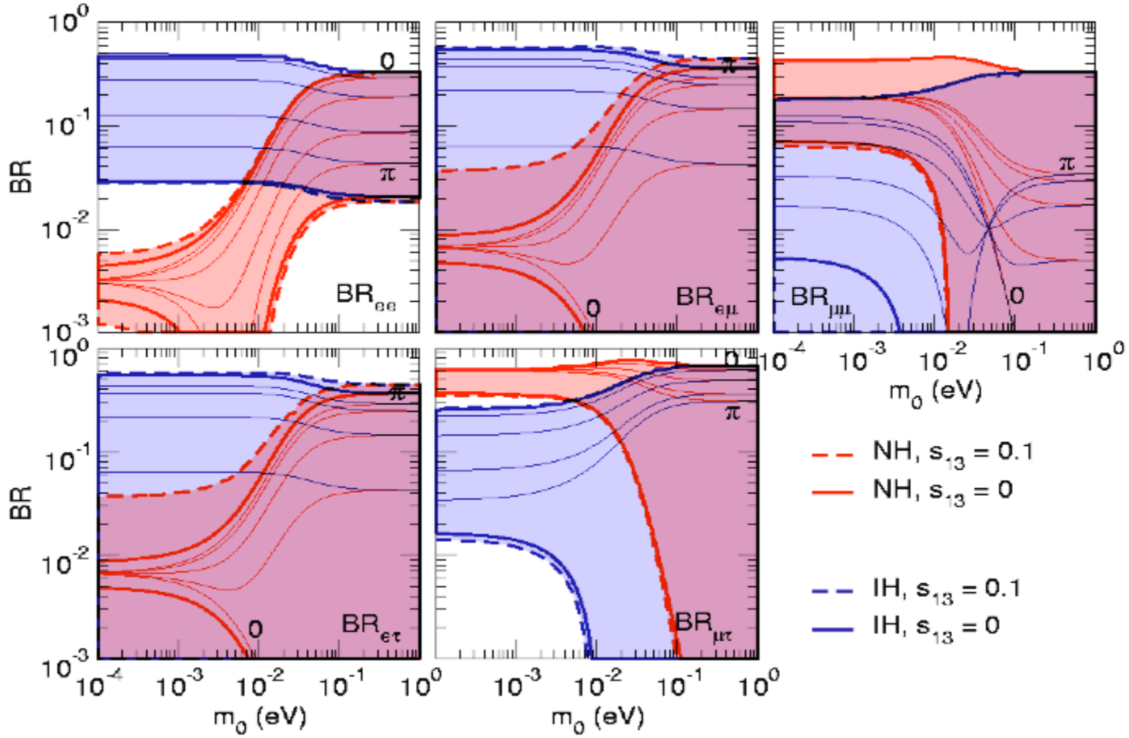
Combined bounds		
Process	Yukawa	Bound $\left(\times \left(\frac{M_\Delta}{1\,\text{TeV}}\right)^4\right)$
$\mu \to e\gamma$	$\left\lvert {Y_\Delta}^\dagger_{\mu\mu} {Y_\Delta}_{\mu e} + {Y_\Delta}^\dagger_{\tau\mu} {Y_\Delta}_{\tau e} \right\rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\left\lvert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

M_Δ ~ TeV: direct searches at LHC ?

See-saw II:Pair-production of charged triplet scalars

$pp \to \Delta^{++} \Delta^{--} \to l^+ l^+ l^- l^-$

Flavour structure one-to-one to m_ν ! $BR(\Delta^{++} \to l_\alpha^+ l_\beta^+) \sim |M_{\alpha\beta}|^2$



Han et al;Garayoa, Schwetz; Kadastik,et al ; Akeroyd, et al; Fileviez et al

Normal hierarchy:

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

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

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

Inverted hierarchy:

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

Hence, measuring U_{PMNS}, and ν masses determines EVERYTHING!!

$$B_{\mu \to e\gamma} \propto |Y_{N_e} Y_{N_\mu}|^2 , \quad |m_{ee}|_{IH} \simeq |s_{12}^2 e^{-2i\alpha} - c_{12}^2 e^{2i\alpha}|$$