CLFV and the origin of neutrino masses

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Based for a large part on a collaboration with: A. Abada, R. Alonso, C. Biggio, F. Bonnet, X. Chu, M. Dhen, B. Gavela, D. Hernandez, P. Hernandez

CLFV-Lecce 06/05/2013

Neutrino masses: seesaw models

neutrino oscillations → neutrinos have a mass

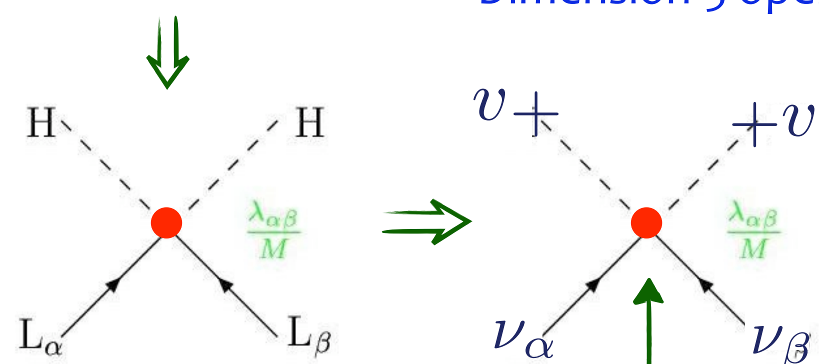
→ require new fields beyond the Standard Model

→ e.g. heavy

→ Seesaw models: neutrino masses from the tree level exchange of heavy fields

→ induces a $\mathcal{L} \ni \frac{\lambda}{M}(LLHH)$ interaction

"Dimension-5 operator"



$$m_\nu = \frac{\lambda}{M} v^2$$

Majorana mass

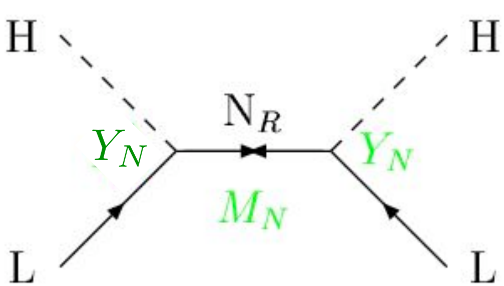
The 3 seesaw models

→ i.e. tree level ways to generate the neutrino masses, i.e. the LLHH dim-5 interact.

Right-handed singlet: (type-I seesaw)

$$N_{R_i}$$

$$\mathcal{L} \ni -Y_{N_{ij}} \bar{N}_i L_j H - \frac{m_{N_i}}{2} \overline{N_i^c} N_i + h.c.$$



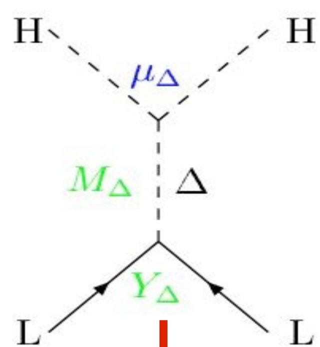
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida;Glashow; Mohapatra, Senjanovic

Scalar triplet: (type-II seesaw)

$$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$$

$$\mathcal{L} \ni -Y_\Delta \Delta L_i L_j - \mu_\Delta \Delta H H + h.c.$$



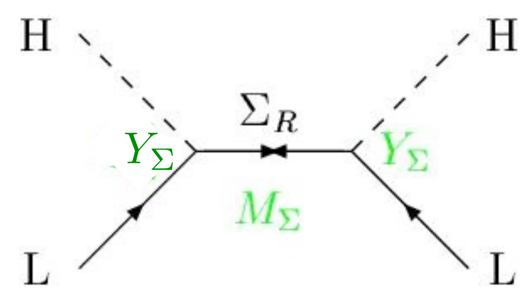
$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet: (type-III seesaw)

$$\Sigma_i \equiv (\Sigma_i^+, \Sigma_i^0, \Sigma_i^-)$$

$$\mathcal{L} \ni -Y_{\Sigma_{ij}} \bar{\Sigma}_i L_j H - \frac{m_{\Sigma_i}}{2} \overline{\Sigma_i^c} \Sigma_i + h.c.$$



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

Foot, Lew, He, Joshi; Ma; Ma, Roy;T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

How to distinguish experimentally the 3 seesaw models??

not possible only from the ν masses (i.e. not from neutrino oscillation experim., $0\nu 2\beta$,...)

⇓

same unique LLHH operator for all 3 models ← any observed ν mass matrix could be accounted for in any of the 3 seesaw models

we need : - either to be able to produce the heavy states at colliders

- and/or to distinguish them from CLFV processes

- and/or make extra assumptions, SUSY, GUT, flavour symmetry, ...

⇒ This talk: CLFV in seesaw models

Two different sources of CLFV in seesaw models

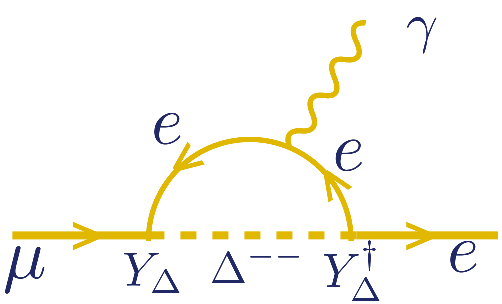
The L violating source: directly from the neutrino masses ← whatever they come from

→ $$Br(\mu \to e\gamma) \sim \frac{3}{32}\frac{\alpha}{\pi}\frac{m_\nu^4}{m_W^4} \sim 10^{-54}\,!$$

for example in type-II model it comes from $m_\nu \propto Y_\Delta \mu_\Delta$

$Y_\Delta \mu_\Delta$: L-violating coupl. combination

The L conserving source: from a L conserving combination of seesaw couplings



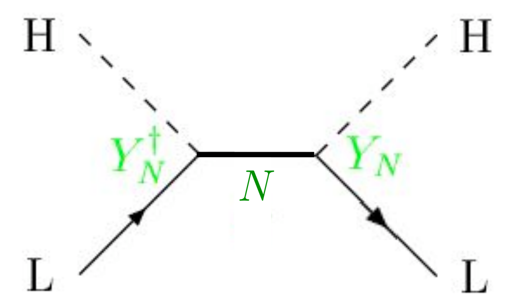
Δ^{--}: for example in type-II model

→ $$Br(\mu \to e\gamma) \sim \frac{1}{192}\frac{\alpha}{\pi}\frac{1}{G_F^2}(Y_\Delta Y_\Delta^\dagger)^2\frac{1}{m_\Delta^4}$$

$Y_\Delta Y_\Delta^\dagger$: L-conserving coupl. combination

Building blocks for CLFV: dimension 6 operators

- Type-I: $\mathcal{L}^{d=6} = Y_N^\dagger \frac{1}{M_N^2} Y_N \, (\bar{L}H) \, \partial\!\!\!/ (H^\dagger L)$

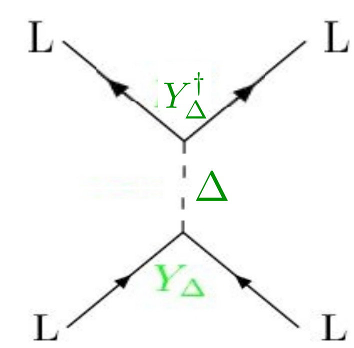


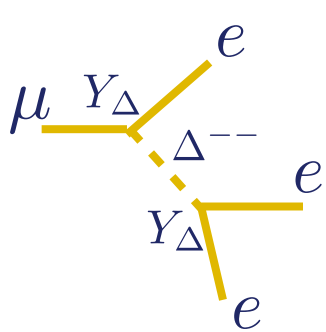
Broncano, Gavela, Jenkins '02

- Type-III: $\mathcal{L}^{d=6} = Y_\Sigma^\dagger \frac{1}{M_\Sigma^2} Y_\Sigma \, (\bar{L}H) \, D\!\!\!\!/ (H^\dagger L)$
- Type-II: $\mathcal{L}^{d=6} = Y_\Delta^\dagger \frac{1}{M_\Delta^2} Y_\Delta \, (\bar{L}L) \, (\bar{L}L)$

$$+ \frac{\mu_\Delta^2}{M_\Delta^4} (H^\dagger H)^3$$

$$+ \lambda_i \frac{\mu_\Delta^2}{M_\Delta^4} (H\tau H) D_\mu D^\mu (H\tau H)$$





Observable CLFV from seesaw models through L-conserving contribution: not impossible at all!

but 2 conditions nevertheless:

- Seesaw scale must be low: up to $m_{N,\Delta,\Sigma} \sim 100 - 1000\,\mathrm{TeV}$
- L-conserving entries must be much larger than L-violating entries:

approximate lepton number conservation

for example in type II model: $Y_\Delta Y_\Delta^\dagger >> Y_\Delta \mu_\Delta / m_\Delta \;\leftrightarrow\; Y_\Delta >> \mu_\Delta / m_\Delta$

in type-I seesaw model: $Y_{N_{ij}} Y^\dagger_{N_{ik}} >> Y_{N_{ij}} Y^T_{N_{ik}}$

L-conserving combination — L-violating combination

in type-III seesaw model: $Y_{\Sigma_{ij}} Y^\dagger_{\Sigma_{ik}} >> Y_{\Sigma_{ij}} Y^T_{\Sigma_{ik}}$

Type-I (and type-III) seesaw: approximate L?

example with n N_1 and n N_2: $L_{N_1} = +1\,,\; L_{N_2} = -1$

$$
\begin{array}{c} \\ \nu_L \\ N_1 \\ N_2 \end{array}
\begin{array}{c}
\begin{array}{ccc} \nu_L & N_1 & N_2 \end{array} \\
\begin{pmatrix} 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}
\end{array}
$$

if Y_N is large, M_N not too high:

large CLFV

Type-I (and type-III) seesaw: approximate L?

example with n N_1 and n N_2: $L_{N_1} = +1\,,\; L_{N_2} = -1$

$$\begin{array}{c} \\ \nu_L \\ N_1 \\ N_2 \end{array} \begin{array}{c} \begin{array}{ccc} \nu_L & N_1 & N_2 \end{array} \\ \begin{pmatrix} 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix} \end{array}$$

soft L breaking: $\mu << M_N$

"inverse seesaw" as in
Mohapatra, Valle '86
Gonzalez-Garcia, Valle '89
Branco, Grimus, Lavoura '89
Kersten, Smirnov '07
Abada, Biggio, Bonnet, Gavela, T.H. '07

if Y_N is large, M_N not too high:

large CLFV with small neutrino masses: $m_\nu = Y_N^T \frac{\mu}{M_N^2} Y_N v^2$

L is approximately conserved

Type-I (and type-III) seesaw: approximate L?

example with n N_1 and n N_2: $L_{N_1} = +1\,,\ L_{N_2} = -1$

hard L breaking: $Y'_N << Y_N$

$$
\begin{array}{c} \\ \nu_L \\ N_1 \\ N_2 \end{array}
\begin{array}{c}
\begin{array}{ccc} \nu_L & N_1 & N_2 \end{array} \\
\left(\begin{array}{ccc}
0 & Y_N \frac{v}{\sqrt{2}} & Y'_N \frac{v}{\sqrt{2}} \\
Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\
0 & M_N & 0
\end{array} \right)
\end{array}
$$

Grimus, Lavoura 94';
TH, Gavela, Hernandez, Hernandez 09',
Blanchet, Asaka 08',
Kersten, Smirnov '07
Abada, Biggio, Bonnet, Gavela, T.H. '07

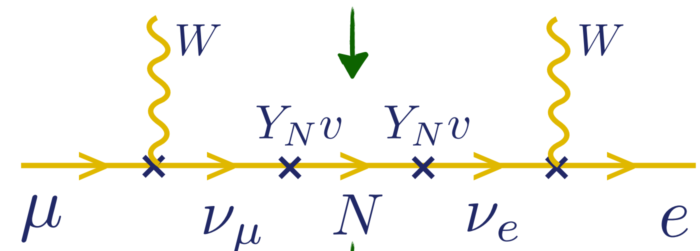
if Y_N is large, M_N not too high:

large CLFV with small neutrino masses: $m_\nu = -(Y'^T_N \frac{1}{M_N} Y_N + Y^T_N \frac{1}{M_N} Y'_N) v^2$

L is approximately conserved

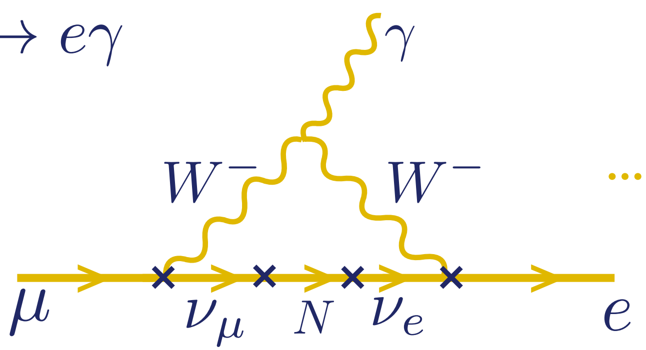
Phenomenology of type-I seesaw CLFV

crucial property for CLFV in type-I seesaw: flavour mixing only at the level of neutral states



all CLFV are loop processes

$\mu \to e\gamma$



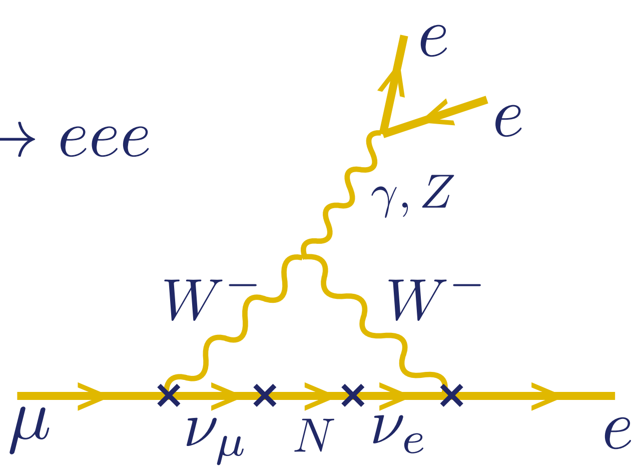
$$\Rightarrow \Gamma(\mu \to e\gamma) = \sum_{N_i} \frac{|Y_{N_{ie}} Y^\dagger_{N_{i\mu}}|^2}{m^4_{N_i}} \cdot [\, c + c' \log(m^2_{N_i}/m^2_W)\,]^2$$

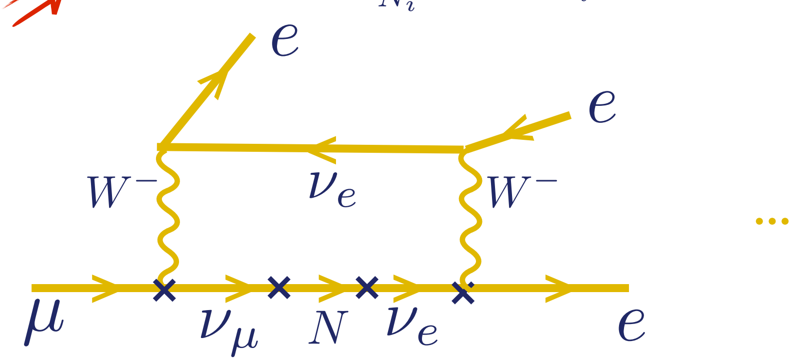
Minkowski 77'; Marciano, Sanda 77'; Cheng, Li 80'; Lim, Inami 82'

$$\Gamma(\mu \to eee) = \sum_{N_i} \frac{|Y_{N_{ie}} Y^\dagger_{N_{i\mu}}|^2}{m^4_{N_i}} \cdot [\, d + d' \log(m^2_{N_i}/m^2_W)\,]^2$$

...; Ilakovac, Pilaftsis 95'

$\mu \to eee$

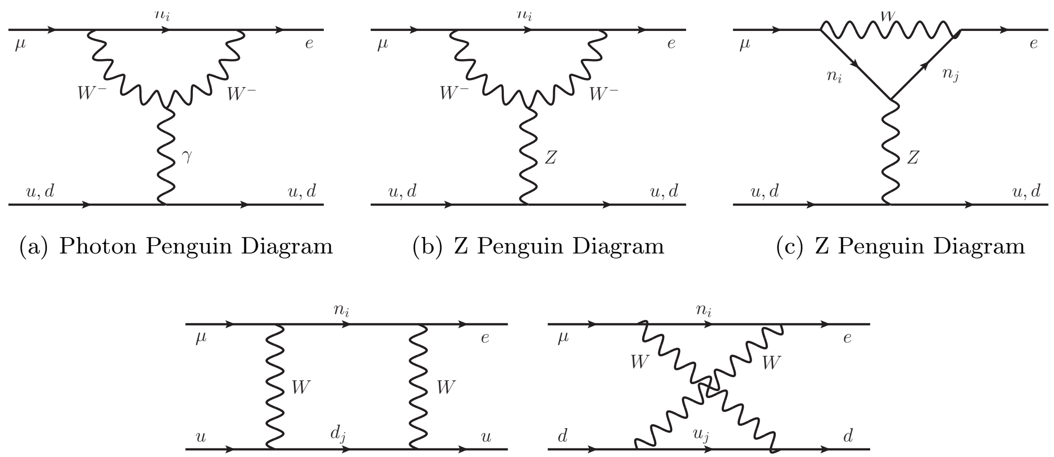




$\Rightarrow$ $\Gamma(\mu \to eee)/\Gamma(\mu \to e\gamma)$ can vary a lot depending on parameters, e.g. of order $10^{-1} - 10^{-2}$

Phenomenology of type-I seesaw CLFV

$\mu \to e$ conversion in atomic nuclei



(a) Photon Penguin Diagram (b) Z Penguin Diagram (c) Z Penguin Diagram

(d) Box Diagram (e) Box Diagram

new full calculation:

$$R^N_{\mu\to e} = \sum_{N_i} \frac{|Y_{N_{ie}} Y^\dagger_{N_{i\mu}}|^2}{m^4_{N_i}} \cdot [\, b^N + b'^N \log(m^2_{N_i}/m^2_W)\,]^2$$

see analytic result in Alonso, Dhen, Gavela, TH, JHEP 2013

Quasi-degenerate right-handed neutrino case

$m_{N_1} \sim m_{N_2} \sim ... \equiv m_N$: the natural situation to have observable CLFV rates

situation of approximately conserving L frameworks

Ratio of 2 CLFV processes involving a same flavour transition: all the Yukawa coupling dependence cancels out!

Chu, Dhen, TH 12'

Alonso, Dhen, Gavela, TH 13'

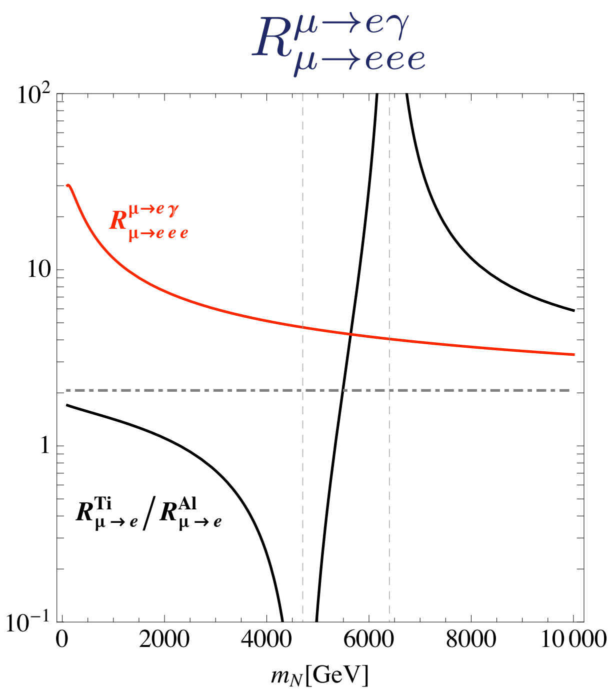
$$R^{\mu\to e\gamma}_{\mu\to eee} = \frac{\Gamma(\mu\to e\gamma)}{\Gamma(\mu\to eee)} = \Big(\frac{c + c' \log[m_N^2/m_W^2]}{d + d' \log[m_N^2/m_W^2]}\Big)^2$$

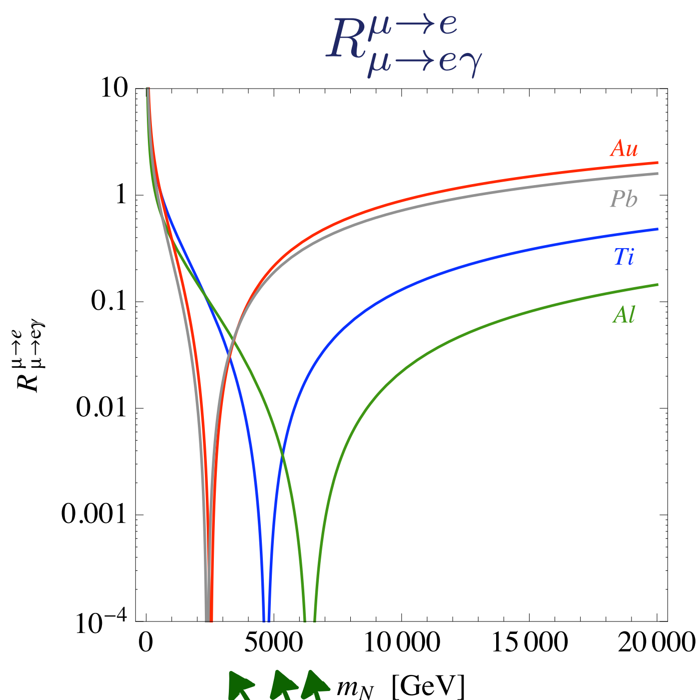
$$R^{\mu\to e,N}_{\mu\to e\gamma} = \frac{R^N_{\mu\to e}}{\Gamma(\mu\to e\gamma)} = \Big(\frac{b^N + b'^N \log[m_N^2/m_W^2]}{c + c' \log[m_N^2/m_W^2]}\Big)^2$$

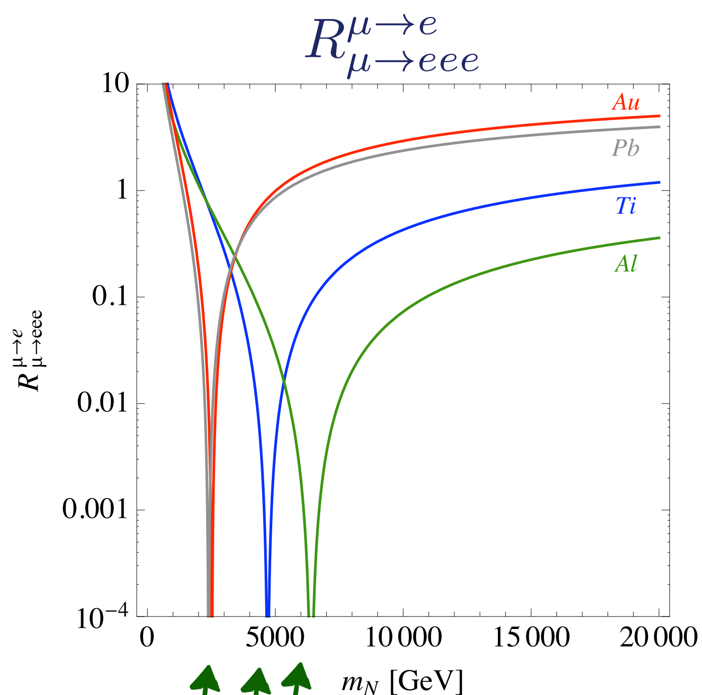
depends only on m_N !

Quasi-degenerate right-handed neutrino case

Chu, Dhen, TH 12'   Alonso, Dhen, Gavela, TH 13'







every $\mu \to e$ conversion rates vanishes for a specific value of m_N

⟹ measurement of ratio(s): determination of the seesaw scale (or exclusion of the scenario)

Upper bounds on Yukawa couplings and future sensitivities

$Br(\mu \to e\gamma) < 5.7 \cdot 10^{-13}$ (MEG)

$Br(\mu \to eee) < 10^{-12}$ $(SINDRUM)$

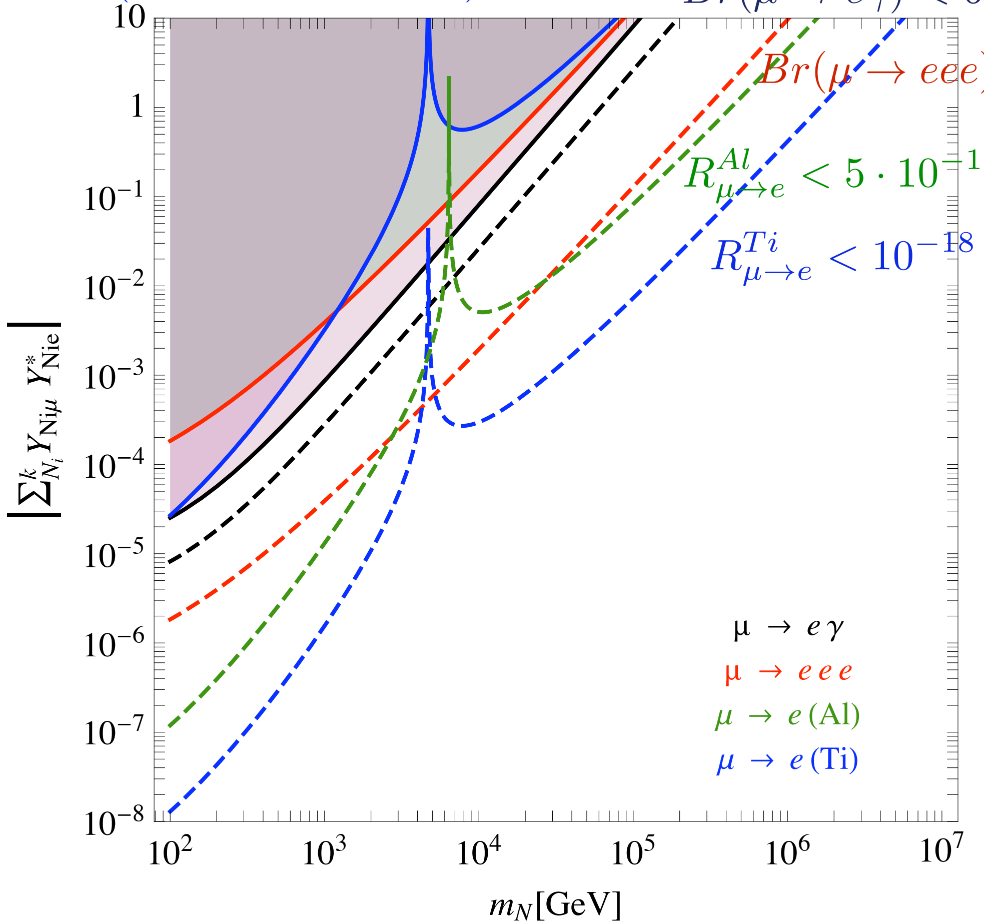
$R^{Ti}_{\mu \to e} < 4.3 \cdot 10^{-12}$ $(SINDRUM-II)$

$Br(\mu \to e\gamma) < 6 \cdot 10^{-14}$ $(MEG-future)$

$Br(\mu \to eee) < 10^{-16}$ $(Mu3e-future)$

$R^{Al}_{\mu \to e} < 5 \cdot 10^{-17}$ $(Mu2e-future)$

$R^{Ti}_{\mu \to e} < 10^{-18}$ $(Comet/Prism, ... - future)$



Alonso, Dhen, Gavela, TH 13'

Seesaw scale future sensitivities (Type-I)

→ assuming perturbative couplings:

$$m_N \lesssim 6000\,\mathrm{TeV} \cdot \left(\frac{10^{-18}}{R^{Ti}_{\mu\to e}}\right)^{\frac{1}{4}},$$

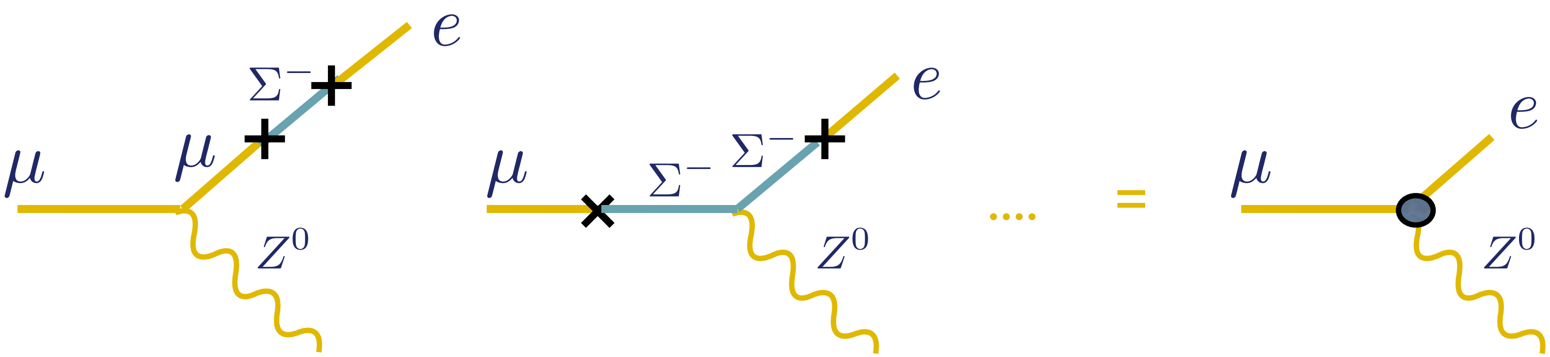
$$m_N \lesssim 1000\,\mathrm{TeV} \cdot \left(\frac{10^{-16}}{R^{Al}_{\mu\to e}}\right)^{\frac{1}{4}},$$

$$m_N \lesssim 300\,\mathrm{TeV} \cdot \left(\frac{10^{-14}}{Br(\mu \to e\gamma)}\right)^{\frac{1}{4}},$$

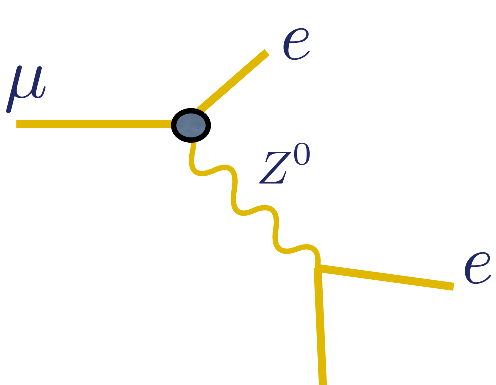
$$m_N \lesssim 1000\,\mathrm{TeV} \cdot \left(\frac{10^{-16}}{Br(\mu \to eee)}\right)^{\frac{1}{4}}.$$

Phenomenology of type-III seesaw CLFV

crucial property for CLFV in type-III seesaw: flavour mixing directly at the level of charged states



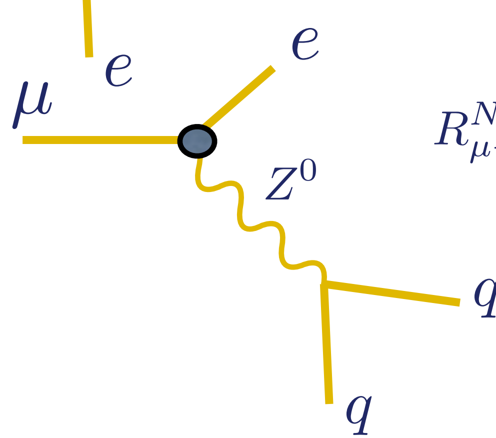
⟹ $\mu \to eee$: tree level



$$\Gamma(\mu \to eee) = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^{\dagger}_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot d^2$$

Abada, Biggio, Bonnet, Gavela, TH 07', 08'

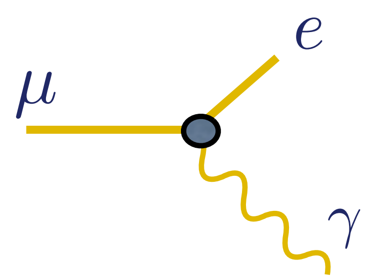
$\mu \to e$ conversion : tree level



$$R^N_{\mu \to e} = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^{\dagger}_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot (b^N)^2$$

Phenomenology of type-III seesaw CLFV

$\mu \to e\gamma$: still at one loop because no



but no log: $\Gamma(\mu \to e\gamma) = \sum_{\Sigma_i} \frac{|Y_{\Sigma_{ie}} Y^{\dagger}_{\Sigma_{i\mu}}|^2}{m^4_{\Sigma_i}} \cdot c^2$

Abada, Biggio, Bonnet, Gavela, TH 07'

⇒ ratios of 2 processes with same flavour transition: totally fixed!

$$
\begin{aligned}
Br(\mu \to e\gamma) &= 1.3 \cdot 10^{-3} \cdot Br(\mu \to eee) = 3.1 \cdot 10^{-4} \cdot R^{\mu \to e}_{Ti} \\
Br(\tau \to \mu\gamma) &= 1.3 \cdot 10^{-3} \cdot Br(\tau \to \mu\mu\mu) = 2.1 \cdot 10^{-3} \cdot Br(\tau^- \to e^- e^+ \mu^-) \\
Br(\tau \to e\gamma) &= 1.3 \cdot 10^{-3} \cdot Br(\tau \to eee) = 2.1 \cdot 10^{-3} \cdot Br(\tau^- \to \mu^- \mu^+ e^-)
\end{aligned}
$$

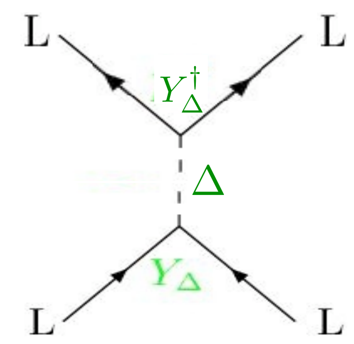
$$Br(\mu \to e\gamma) < 5.7 \cdot 10^{-13} : Y_\Sigma \lesssim 10^{-2} \cdot (m_\Sigma / 1\,\mathrm{TeV})$$

$$Br(\mu \to eee) < 10^{-12} : Y_\Sigma \lesssim 2 \cdot 10^{-3} \cdot (m_\Sigma / 1\,\mathrm{TeV})$$

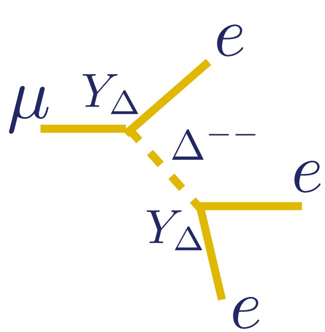
$$R^{Ti}_{\mu \to e} < 4.3 \cdot 10^{-12} : \quad Y_\Sigma \lesssim 3 \cdot 10^{-4} \cdot (m_\Sigma / 1\,\mathrm{TeV})$$

Phenomenology of type-II seesaw CLFV

crucial property for CLFV in type-III seesaw: flavour mixing directly at the level of charged states in processes involving two charged lepton lines



$\mu \to eee$: at tree level



Leontaris, Tamvakis, Vergados 85'; Bernabeu, Pich, Santamaria 86'; Bilenky, Petcov 87'; ...

$\mu \to e$ conversion : at one loop

Raidal, Santamaria 98'; Ma, Raidal, Sarkar 01'; Dinh, Ibarra, Molinaro, Petcov 12'; ...

$\mu \to e\gamma$: at one loop

Petcov 82'; Han, Zhang 06'; del Aguila, Aguilar-Saavedra, Pittau 07'; Dinh, Ibarra, Molinaro, Petcov 12'; ...

Bounds on type-II seesaw couplings from CLFV

Process	Constraint on	Bound $(\times(\frac{M_\Delta}{1\,\mathrm{TeV}})^2)$
M_W	$\lvert Y_{\Delta\mu e}\rvert^2$	$< 7.3\times10^{-2}$
$\mu^-\to e^+e^-e^-$	$\lvert Y_{\Delta\mu e}\rvert\lvert Y_{\Delta ee}\rvert$	$< 1.2\times10^{-5}$
$\tau^-\to e^+e^-e^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta ee}\rvert$	$< 1.3\times10^{-2}$
$\tau^-\to\mu^+\mu^-\mu^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta\mu\mu}\rvert$	$< 1.2\times10^{-2}$
$\tau^-\to\mu^+e^-e^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta ee}\rvert$	$< 9.3\times10^{-3}$
$\tau^-\to e^+\mu^-\mu^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta\mu\mu}\rvert$	$< 1.0\times10^{-2}$
$\tau^-\to\mu^+\mu^-e^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta\mu e}\rvert$	$< 1.8\times10^{-2}$
$\tau^-\to e^+e^-\mu^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta\mu e}\rvert$	$< 1.7\times10^{-2}$
$\mu\to e\gamma$	$\lvert\Sigma_{l=e,\mu,\tau}Y_{\Delta^\dagger_{l\mu}}Y_{\Delta el}\rvert$	$< 1.0\times10^{-3}$
$\tau\to e\gamma$	$\lvert\Sigma_{l=e,\mu,\tau}Y_{\Delta^\dagger_{l\tau}}Y_{\Delta el}\rvert$	< 1.05
$\tau\to\mu\gamma$	$\lvert\Sigma_{l=e,\mu,\tau}Y_{\Delta^\dagger_{l\tau}}Y_{\Delta\mu l}\rvert$	$< 8.4\times10^{-1}$

Abada, Biggio, Bonnet, Gavela, T.H. '07

Partly from: Barger et al '82; Pal '83; Bernabeu et al '84, '86; Bilenky, Petcov'87; Gunion et al '89, '06; Swartz '89; Mohapatra '92

$$R^{Ti}_{\mu\to e}:\ \Big|\sum_{l=e,\mu,\tau} Y_{\Delta^\dagger_{l\mu}}Y_{\Delta_{el}}\Big| < 1.0\times10^{-2}$$

...; Dinh, Ibarra, Molinaro, Petcov 12'; ...

Summary

- CLFV in seesaw models: not necessarily suppressed as neutrino masses

  dim-6 operators for CLFV do conserve L unlike the neutrino mass dim-5 one

  observable CLFV rates if seesaw scale low and lepton number is approximately conserved

  ↪ "natural" in type-II, possible in type-I and III

- Each seesaw model leads to a characteristic CLFV phenomenology

  - type-I: ratios of 2 same flavour transition processes depend only on seesaw scale

  - type-III: ratios of 2 same flavour transition processes is totally fixed $\frac{Br(\mu \to e\gamma)}{Br(\mu \to eee)} = 1.3 \cdot 10^{-3}$

  - type-II: $l \to lll$ processes are the most sensitive

Backup

MFV in type-I model? The simplest realization

B. Gavela, D. Hernandez and P. Hernandez, JHEP 09'

There exists a particularly minimal and predictive MFV type-I seesaw model!

A model with 2 right-handed neutrinos: $L_{N_1} = +1\,,\ L_{N_2} = -1$

$$\begin{array}{c|ccc} & \nu_L & N_1 & N_2 \\ \hline \nu_L & 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ N_1 & Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ N_2 & 0 & M_N & 0 \end{array} \quad \Longrightarrow \quad c_{d=6} = Y_N^\dagger \frac{1}{M_N^2} Y_N$$

hard L breaking

$$\begin{array}{c|ccc} & \nu_L & N_1 & N_2 \\ \hline \nu_L & 0 & Y_N \frac{v}{\sqrt{2}} & Y'_N \frac{v}{\sqrt{2}} \\ N_1 & Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ N_2 & Y'_N \frac{v}{\sqrt{2}} & M_N & 0 \end{array} \quad \Longrightarrow \quad \begin{aligned} c_{d=5} &= -\frac{m_\nu}{v^2} \\ &= (Y'^T_N \frac{1}{M_N} Y_N + Y^T_N \frac{1}{M_N} Y'_N) \end{aligned}$$

separation of scales: $\Lambda_F \sim M_N \longleftrightarrow \Lambda_{LN} \sim M_N / Y'$

Definition of Minimal Flavour Violation in lepton sector

- 1) The flavour structure of the dim-6 coefficients fixed by the dim-5 one
- 2) Large flavour violation with small L violation: a hierarchy between L-viol. scale Λ_{LN} and flavour-viol. scale Λ_F: $\Lambda_{LN} >> \Lambda_F$

→ a practical definition of MFV for leptons

see also Cirigliano, Grinstein, Isidori, Wise 05'

The simplest MFV type-I model

counting of parameters:

M_N	$\rightarrow$ 1 real + 1 phase	$\rightarrow$	1 real	$\leftarrow$ 1 normalizat.
Y_N	$\rightarrow$ 3 real + 3 phases	$\rightarrow$	3 real	$\leftarrow$ 1 normalizat. + 2 flavour param.
Y'_N	$\rightarrow$ 3 real + 3 phases	$\rightarrow$	3 real + 2 phases	$\leftarrow$ 1 normalizat. + 2 flavour param. + 2 phases

rephasing N_1, N_2 and the 3 L_i

to be compared with the $m_{\nu ij}$ matrix from 2 N's:

m_{ν_i}	$\rightarrow$ 2 real ν masses	$\leftarrow$ 1 normalizat. + 1 flavour param.
θ_{ij}	$\rightarrow$ 3 real mixing angles	$\leftarrow$ 3 flavour param.
$\delta\,,\alpha_1$	$\rightarrow$ 1 CKM + 1 Majorana phase	$\leftarrow$ 2 phases

$\Longrightarrow$ the full flavour structure of the model can be reconstructed from $m_{\nu ij}$!

$\Longrightarrow$ the full flavour structure of dim-6 effects can be reconstructed!

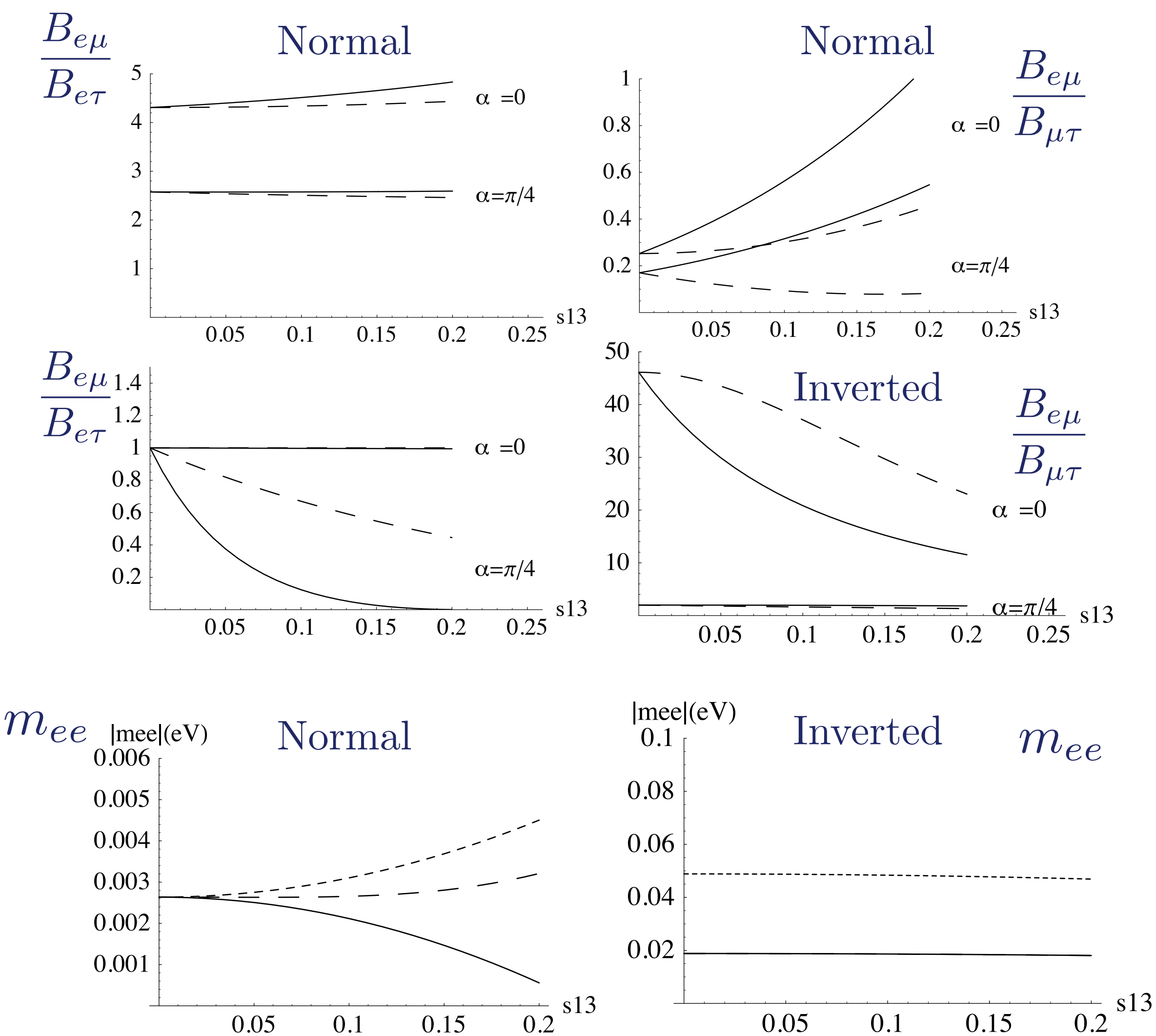
Predictions

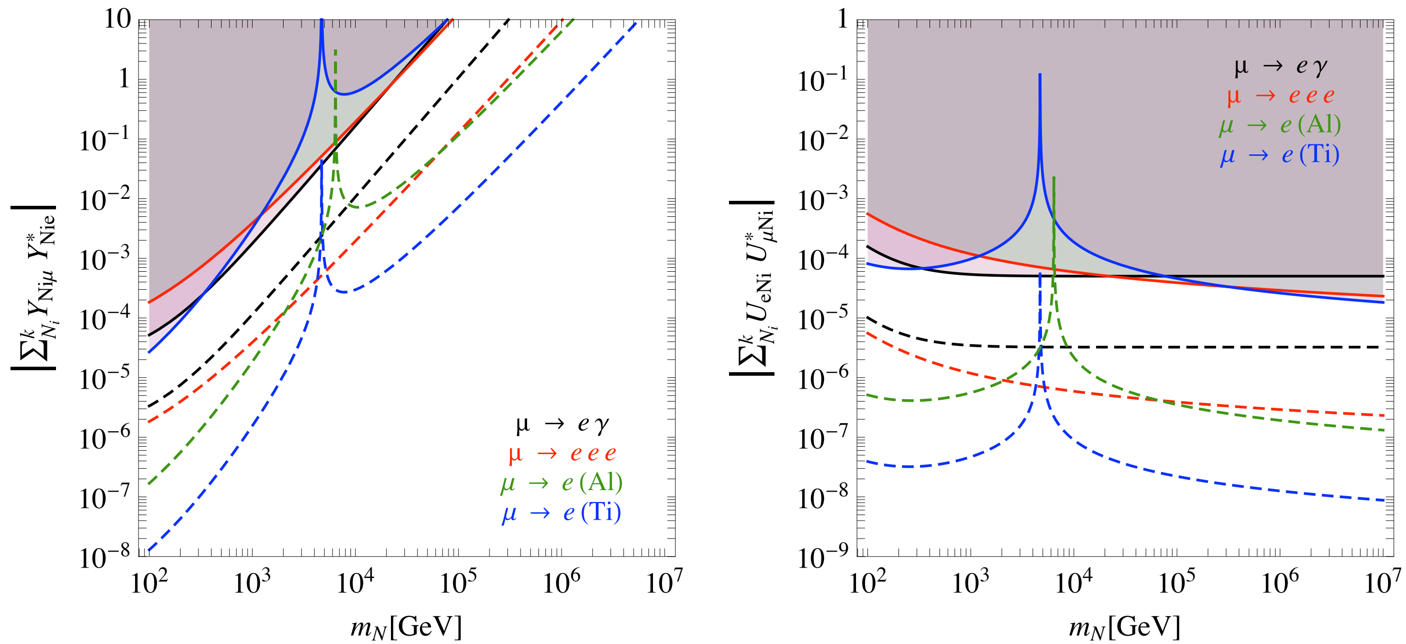
in terms of the 3 unknown parameters of $m_{\nu ij}$: $\theta_{13},\ \delta,\ \alpha$

$$B_{e\mu} \equiv \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu_\mu\bar{\nu}_e)}$$

$$B_{e\tau} \equiv \frac{\Gamma(\tau \to \mu\gamma)}{\Gamma(\tau \to e\nu_\tau\bar{\nu}_e)}$$

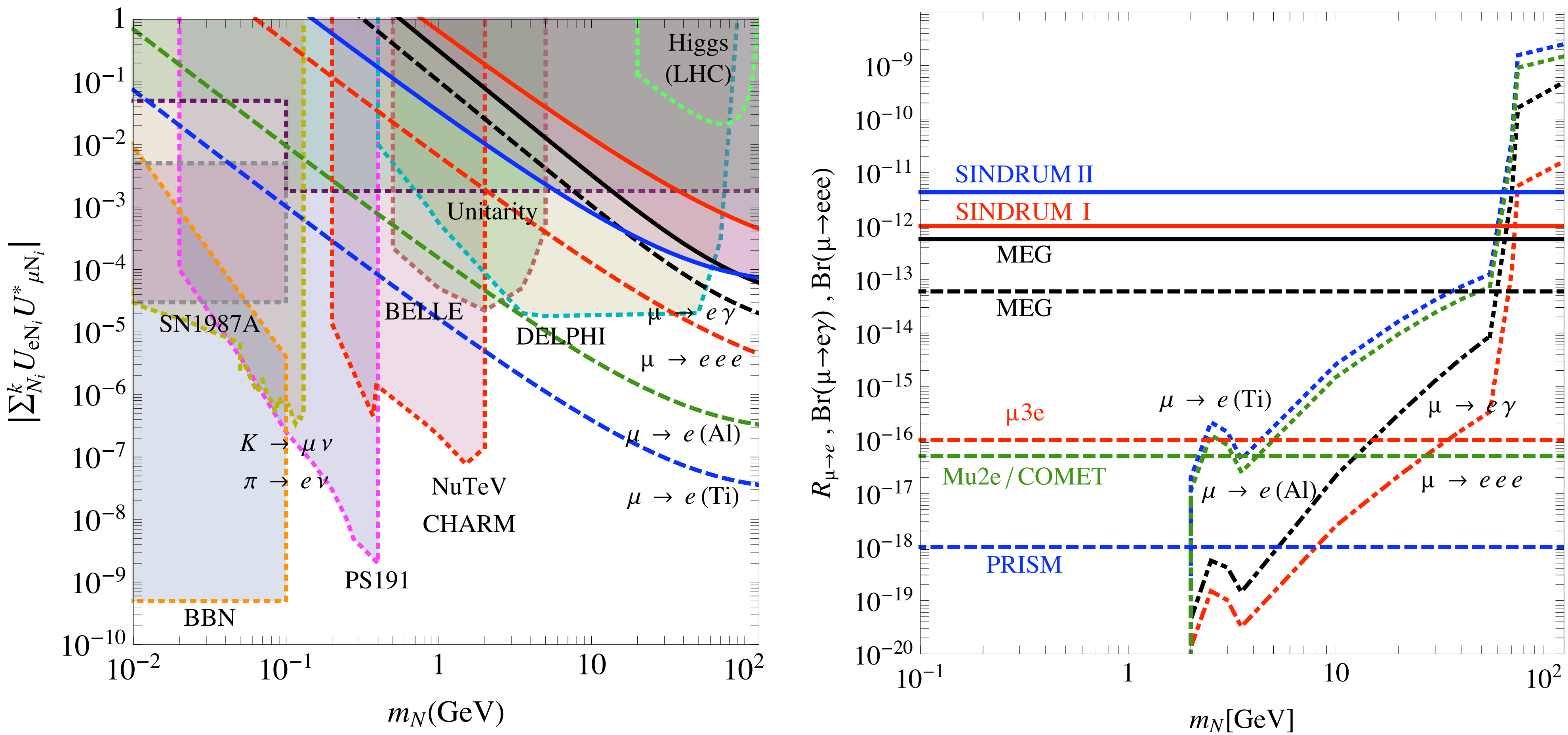
$$B_{\mu\tau} \equiv \frac{\Gamma(\tau \to \mu\gamma)}{\Gamma(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}$$





(a) Present bounds and future sensitivity to Yukawas as a function of the right-handed mass

(b) Present bounds and future sensitivity to heavy-light mixing as a function of the right-handed mass



Higgs
(LHC)
Unitarity
SN1987A
BELLE
DELPHI
μ → e γ
μ → e e e
μ → e (Al)
μ → e (Ti)
K → μ ν
π → e ν
NuTeV
CHARM
PS191
BBN
m_N(GeV)
SINDRUM II
SINDRUM I
MEG
MEG
μ3e
Mu2e / COMET
PRISM
μ → e (Ti)
μ → e γ
μ → e (Al)
μ → e e e
m_N[GeV]

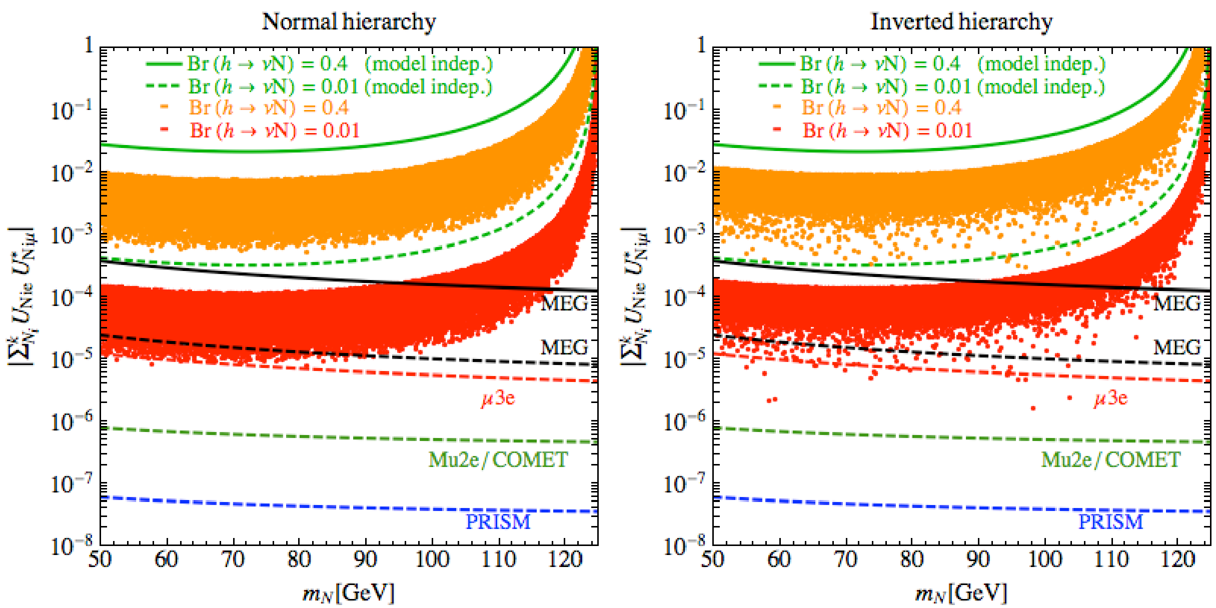


Figure 7. Bounds on $|\Sigma_i U_{eN_i} U^*_{\mu N_i}|$ from LHC Higgs decay data and comparison with flavour violation searches. The contraints from LHC data are illustrated for a sensitivity of $Br(h \to \nu N) < 0.4$, and a future one improved to the % level [80]. For these values, isolated green curves are the absolute bounds for a generic seesaw model. Bands in orange and red show instead the variation with the unknown values of the Dirac and Majorana CP phases, for the approximately L conserving scenario in Ref. [44], for normal (lelft panel) and inverted (right panel) hierarchy. The present (black) and future (dashed black) MEG sensitivities and the expected one for conversion in Titanium (blue), in Aluminium (green) and $\mu \to eee$ (red) are shown for comparison.