Searching for massive neutrinos

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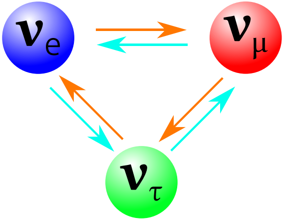
An incomplete history of neutrino experiments

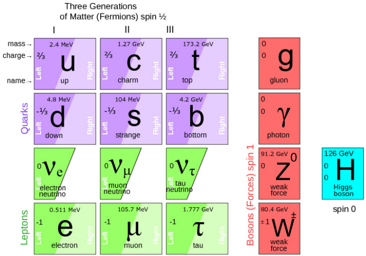
1931	Pauli presents hypothetical neutral particle.
1934	Fermi Theory of weak interactions, coins the term "neutrino".
1956	Experimental discovery via a reactor and a water tank.
1962	Detection of muon neutrinos at AGS.
1968	Detection of solar neutrinos.
1987	Supernova neutrinos at Kamiokande.
1990	Atmospheric neutrino anomaly, Kamiokande and IMB.
1991	2.9840 ± 0.0082 lepton generations from LEP.

Credit: https://icecube.wisc.edu/outreach/neutrinos

21^{st}	Many great experiments planned and running to study neutrino parameters.

Neutrino masses & the Standard Model





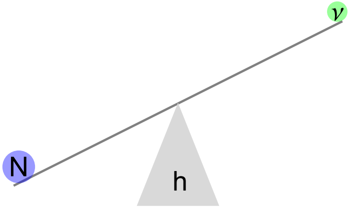
courtsy M. Shaposhnikov

We measure neutrino parameters, but:

- No right-handed neutrinos in the Standard Model (SM).
- No mass matrix, no mixing of the neutrino flavour states.

⇒ Neutrino oscillations are evidence for physics beyond the SM.

The Seesaw mechanism with right-handed neutrinos



- Economic extension: a number of Fermionic singlets, speak: “Right-handed” or “sterile” neutrinos.
- Two mass-differences ⇒ *at least* two sterile neutrinos.
- New mass scale, a priori unrelated to the known ones.
- Many constraints from experiments on all energy scales.
- May be connected to e.g. Dark Matter and Baryogenesis.

Lowscale seesaw

Benchmark model, defined in Antusch, OF; JHEP **1505** (2015) 053

Similar to e.g.: Mohapatra, Valle (1986); Malinsky, Romao Valle (2005); Shaposhnikov (2007);

- Lowscale seesaw Lagrangian, two sterile neutrinos N_i with protective symmetry:

$$\mathscr{L}_N = -\frac{1}{2}\overline{N_R^1} M (N_R^2)^c - y_{\nu_\alpha} \overline{N_R^1} \widetilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

- The mass matrix after electroweak symmetry breaking:

$$M_\nu = \begin{pmatrix} 0 & m_D & m_D' \\ (m_D)^T & 0 & M \\ (m_D')^T & M & \mu \end{pmatrix},$$

- Perturbations $\Rightarrow m_\nu$ and HNL mass splitting (ΔM)
- m_D': Linear seesaw, $\Delta M^{\mathrm{NO}} = 0.0416\,\mathrm{eV}$, $\Delta M^{\mathrm{IO}} = 0.000753\,\mathrm{eV}$
- μ: inverse seesaw, $\Delta M \sim \frac{m_{\nu_i}}{|\theta|^2}$.

Heavy neutrino interactions

Diagonalisation of the mass matrix yields heavy (mostly sterile) neutrinos N and light (mostly active) neutrinos ν.

- **Charged current** (CC):

$$j_\mu^{\pm} = \frac{g}{2}\, \theta_\alpha\, \bar{\ell}_\alpha\, \gamma_\mu N$$

- **Neutral current** (NC):

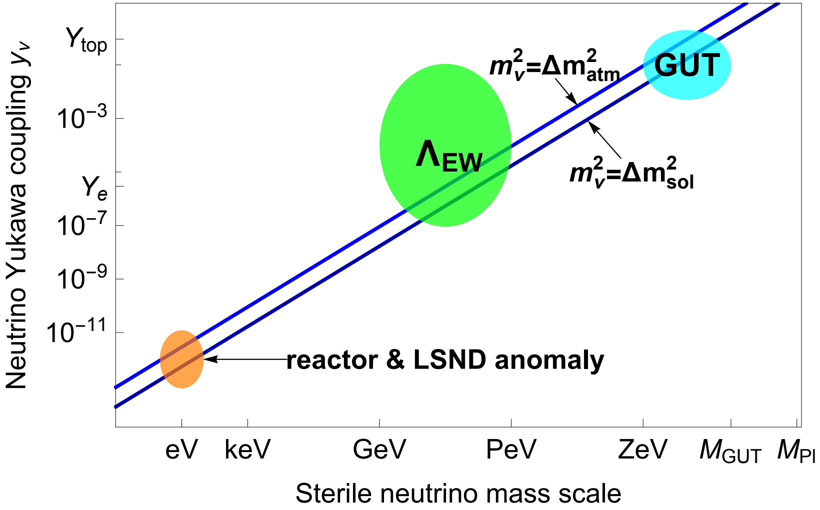
$$j_\mu^{0} = \bar{\nu}_\alpha\, \gamma_\mu\, \theta_\alpha\, N$$

- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\mathrm{Yukawa}} = \sum_{\alpha=e,\mu,\tau} \theta_\alpha \frac{\sqrt{2}\, M}{v_{\mathrm{EW}}} \nu_\alpha \phi^0 \overline{N}$$

- Simplification: light neutrino mass eigenstates $\equiv \nu_e, \nu_\mu, \nu_\tau$

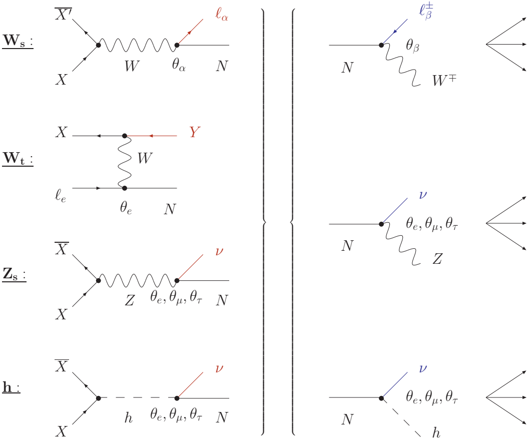
The Big Picture



How can we search for massive neutrinos at the FCC?

Schematizing sterile neutrino searches at FCC

Production Decay Final States



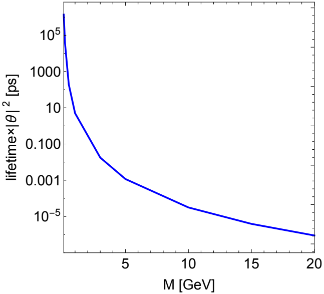
pp : $\ell_\alpha \ell^\pm_\beta jj$, $\ell_\alpha \ell^\pm_\beta \ell^\mp_\gamma \nu$
$\mathbf{e^-e^+, e^-p}$: $Y \ell^\pm_\beta jj$, $Y \ell^\pm_\beta \ell^\mp_\gamma \nu$
$\mathbf{e^-e^+, pp}$: $\nu \ell^\pm_\beta jj$, $\nu \ell^\pm_\beta \ell^\mp_\gamma \nu$

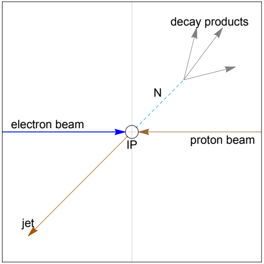
pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu\nu\nu$
$\mathbf{e^-e^+, e^-p}$: $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu\nu\nu$
$\mathbf{e^-e^+, pp}$: $\nu\nu jj$, $\nu\nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu\nu\nu\nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu VV$
$\mathbf{e^-e^+, e^-p}$: $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu VV$
$\mathbf{e^-e^+, pp}$: $\nu\nu jj$, $\nu\nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu\nu VV$

S. Antusch *et al.*; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

Displaced vertex searches





Example: FCC-he

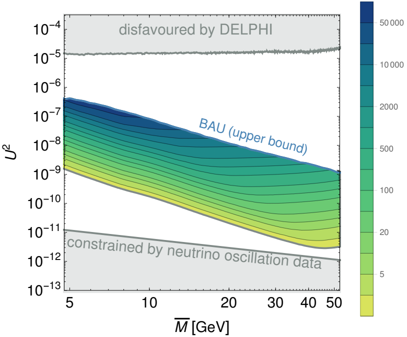
- $M < m_W$ and $|\theta|^2 < 10^{-5}$ leads to macroscopic lifetimes.
- Displacement: measurement of primary (production) vertex.
- Secondary vertex with "large" displacement
  - ee&he: A few times tracking resolution: $\mathcal{O}(10)\mu$m,
  - hh: Beyond background, detector noise, pileup: $\mathcal{O}(10)$ cm.

$\Rightarrow$ Unique signal, can be combined with external detectors (e.g. MATHUSLA).

D. Curtin *et al.*.

Displaced vertex searches at FCC-ee

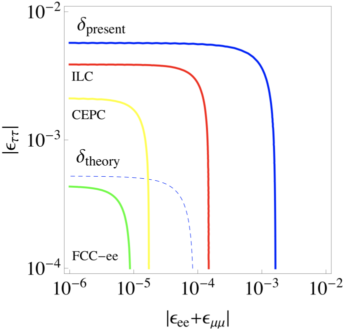
A. Blondel *et al.*; Nucl. Part. Phys. Proc. **273-275** (2016) 1883   S. Antusch *et al.*; JHEP **1612**, 007 (2016)



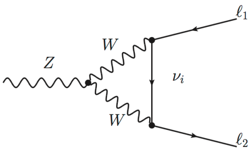
Antusch, Cazzato, Drewes, Fischer, Garbrecht, Gueter, Klaric; JHEP **1809** (2018) 124

- Ratios of θ_α measurable with high accuracy.
- Test minimal type I seesaw hypothesis.
- Together with ΔM also tests the compatibility with leptogenesis.

Indirect searches in electroweak precision data



Antusch, OF; JHEP 1410 (2014) 094

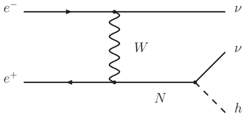


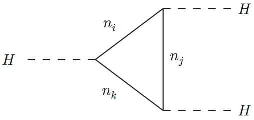
Exotic lepton flavor violating Z boson decays

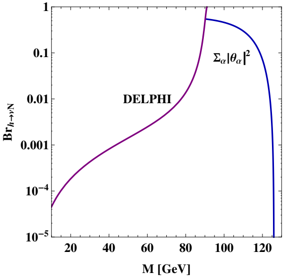
A. Abada *et al.*; JHEP04 (2015) 051

- The mixing matrix of the three active neutrinos is non-unitary.
- Modification of the theory prediction of precision observables.
- Present constraints include:
  EWPO, lepton universality, charged LFV, CKM unitarity
- Constraints dominated by LEP and MEG, $\theta^*_\alpha \theta_\beta = \mathcal{O}(10^{-3})$.

Indirect searches via Higgs boson properties





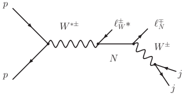


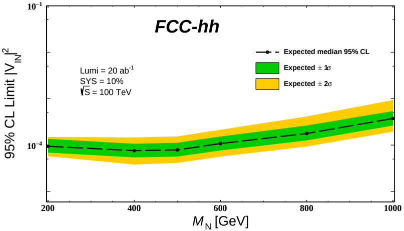
S. Antusch, OF; JHEP **1604** (2016) 189

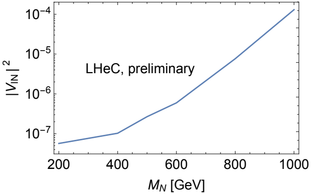
- Additional mono-Higgs production mechanism.
- New Higgs decay channels:
  - Modification of Higgs branching ratios;
  - New exotic decay channels: $h \to \nu N$, $N \to SM$;
  - New invisible decay channels.
- N contribution to the triple Higgs coupling.

J. Baglio and C. Weiland; JHEP **1704**, 038 (2017)

Promising signatures at colliders with proton beams





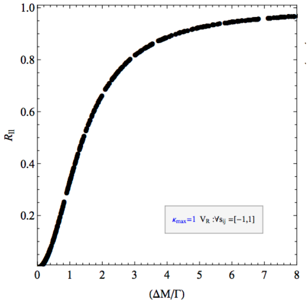


S. Antusch, E. Cazzato, O. Fischer, A. Hammad and K. Wang, JHEP **1810** (2018) 067

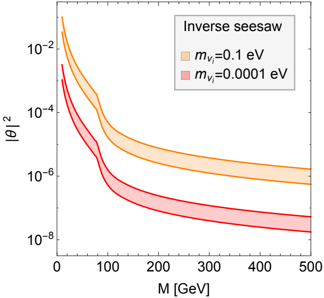
- Unambiguous signature: lepton **flavor** violation.
- Proton-proton: $\ell^{\pm}_{\alpha}\ell^{\mp}_{\beta}jj$, and $\ell^{\pm}_{\alpha}\ell^{\mp}_{\beta}\ell^{\pm}_{\gamma}$.
- Electron-proton: $\mu^{-}jjj$ and $\tau^{-}jjj$ (better prospects than pp).
- Traditionally also searches for lepton **number** violation: e.g. $\mu^{\pm}\mu^{\pm} + J$ at pp (SS dimuons) or $e^{+} + J$ at ep

D. Alva, T. Han, R. Ruiz; JHEP **1502**, 072 (2015)

A note on lepton number violation



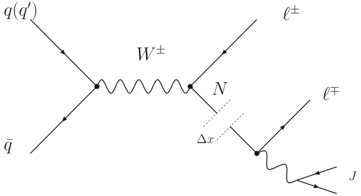
Anamiati, Hirsch, Nardi; 1607.05641

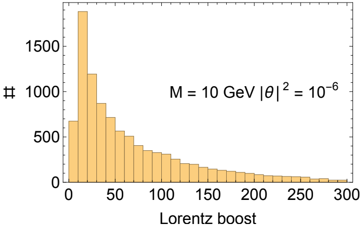


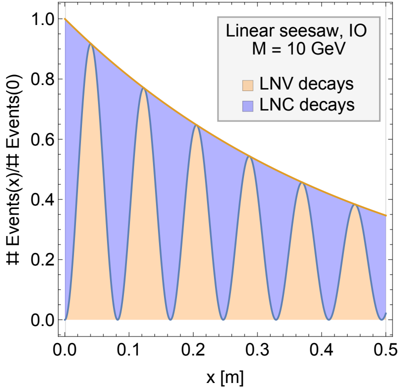
S. Antusch *et al.* arXiv:1709.03797

- In the symmetric limit no LNV in this class of models.
- $R_{\ell\ell}$ (=LNV/LNC) $\sim$ heavy neutrino mass splitting and Γ_N.
- For mass splitting $\sim$ decay width, $R_{\ell\ell} \in [0,1]$.
- LNV heavy neutrinos with $M = \mathcal{O}(100)$ GeV
  $\Leftrightarrow$ Non-minimal model.

Heavy neutrino-antineutrino oscillations @ FCC-hh & -he







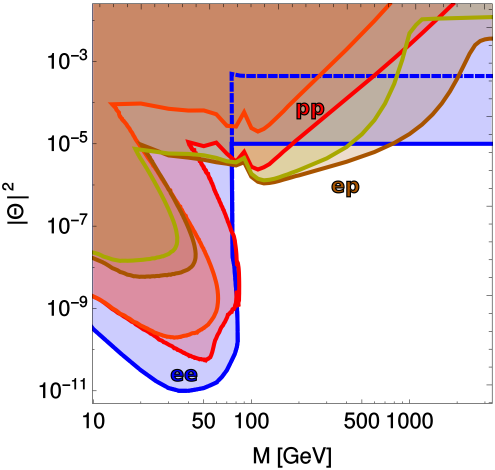
Antusch *et al.*; 1709.03797

- Oscillation length can be $\sim$ mm (proper frame).
- Prompt lepton and displaced lepton are SS/OS as function of proper flight time.
- Measurement of oscillation $\Rightarrow$ mass splitting ΔM.

Overview of the estimated sensitivities

At one-sigma confidence level.

ep and pp at parton level



S. Antusch *et al.*; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

Synergy and Complementarity

FCC-ee:

- highest sensitivity for $M < m_W$; low mass regime.
  $\Rightarrow$ Test model predictions (seesaw, leptogenesis).
- SM precision tests have high sensitivity; mass independent.
  $\Rightarrow$ Test heavy neutrinos up to $\sim$ 60 TeV.
  $\Rightarrow$ Not sensitive to the model details.

FCC-hh and -he:

- Direct test of lepton-flavor (and -number) violation.
  $\Rightarrow$ Number of heavy neutrino generations and their masses
- Indirect test via measurement of Higgs potential.
- Sensitive to high mass regime

Conclusions

- Neutrino oscillations: evidence for **physics beyond the SM**.
- Symmetry protected type I seesaw: electroweak scale massive neutrinos with “large” interactions.
- FCC has unique prospects of testing model predictions.

- Many theories for light neutrino masses and mixings exist:
  - Type II seesaw with scalar (Higgs) $SU(2)_L$ triplets,
  - Type III seesaw with fermion $SU(2)_L$ triplets,
  - Theories with extended gauge sectors, e.g. $U(1)_{B-L}$, left-right symmetry

⇒ **Neutrino mass physics** should be a **benchmark** for future collider studies!

Thank you for your attention.

Backup I - EWPO

Experimental results and SM predictions for the EWPO, and the modification*, to first order in the "non-unitarity" parameters $\varepsilon_{\alpha\alpha} = \theta^*_\alpha \theta_\beta$. (formulae for $M \gg m_Z$)

Prediction in MUV	SM Prediction	Experiment
$[R_\ell]_{\rm SM}\,(1 - 0.15(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\rm SM}\,(1 + 0.03(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\rm SM}\,(1 - 0.06(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$\left[\sigma^0_{had}\right]_{\rm SM}\,(1 - 0.25(\varepsilon_{ee} + \varepsilon_{\mu\mu}) - 0.27\varepsilon_\tau)/\text{nb}$	41.470(15)	41.541(37)
$[R_{inv}]_{\rm SM}\,(1 + 0.75(\varepsilon_{ee} + \varepsilon_{\mu\mu}) + 0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\rm SM}(1 - 0.11(\varepsilon_{ee} + \varepsilon_{\mu\mu}))/\text{GeV}$	80.359(11)	80.385(15)
$[\Gamma_{\rm lept}]_{\rm SM}(1 - 0.59(\varepsilon_{ee} + \varepsilon_{\mu\mu}))/\text{MeV}$	83.966(12)	83.984(86)
$[(s^{\ell,\rm lep}_{W,\rm eff})^2]_{\rm SM}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,\rm had}_{W,\rm eff})^2]_{\rm SM}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23222(27)

* Minimal Unitarity Violation scheme: Antusch *et al.*; JHEP **0610** (2006) 084.

Backup II - lepton universality

Modification due to sterile neutrinos (formulae for $M \gg m_Z$):

$$R_{\alpha\beta} = \sqrt{\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}} \simeq 1 + \frac{1}{2}\left(\varepsilon_{\alpha\alpha} - \varepsilon_{\beta\beta}\right) .$$

	Process	Bound
$R^{\ell}_{\mu e}$	$\frac{\Gamma(\tau \to \nu_\tau \mu \bar{\nu}_\mu)}{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}$	1.0018(14)
$R^{\ell}_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)}$	1.0006(21)
$R^{W}_{e\mu}$	$\frac{\Gamma(W \to e \bar{\nu}_e)}{\Gamma(W \to \mu \bar{\nu}_\mu)}$	1.0085(93)
$R^{W}_{\tau\mu}$	$\frac{\Gamma(W \to \tau \bar{\nu}_\tau)}{\Gamma(W \to \mu \bar{\nu}_e)}$	1.032(11)

	Process	Bound
$R^{\pi}_{\mu e}$	$\frac{\Gamma(\pi \to \mu \bar{\nu}_\mu)}{\Gamma(\pi \to e \bar{\nu}_e)}$	1.0021(16)
$R^{\pi}_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau \pi)}{\Gamma(\pi \to \mu \bar{\nu}_\mu)}$	0.9956(31)
$R^{K}_{\tau\mu}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to \mu \bar{\nu}_\mu)}$	0.9852(72)
$R^{K}_{\tau e}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to e \bar{\nu}_e)}$	1.018(42)

Backup III - CKM unitarity constraint

Current world averages: $V_{ud} = 0.97427(15)$, $V_{ub} = 0.00351(15)$

$$|V^{th}_{ij}|^2 = |V^{exp}_{ij}|^2(1 + f^{\rm process}(\varepsilon_{\alpha\alpha})) \ ,$$
$$|V^{th}_{ud}|^2 = |V^{exp,\beta}_{ud}|^2(NN^\dagger)_{\mu\mu} \ .$$

For the kaon decay processes we have:

$$|V^{th}_{us}|^2 = |V^{exp,K\to e}_{us}|^2(NN^\dagger)_{\mu\mu} \ ,$$
$$|V^{th}_{us}|^2 = |V^{exp,K\to \mu}_{us}|^2(NN^\dagger)_{ee} \ .$$

Process	$V_{us}f_+(0)$
$K_L \to \pi e \nu$	0.2163(6)
$K_L \to \pi \mu \nu$	0.2166(6)
$K_S \to \pi e \nu$	0.2155(13)
$K^\pm \to \pi e \nu$	0.2160(11)
$K^\pm \to \pi \mu \nu$	0.2158(14)
Average	0.2163(5)

Processes involving tau leptons:

Process	$f^{\rm process}(\varepsilon)$	$\lvert V_{us}\rvert$
$\frac{B(\tau\to K\nu)}{B(\tau\to\pi\nu)}$	$\varepsilon_{\mu\mu}$	0.2262(13)
$\tau \to K\nu$	$\varepsilon_{ee} + \varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}$	0.2214(22)
$\tau \to \ell,\ \tau \to s$	$0.2\varepsilon_{ee} - 0.9\varepsilon_{\mu\mu} - 0.2\varepsilon_{\tau\tau}$	0.2173(22)

Backup IV - lepton flavour violation

- Present experimental limits at 90% C.L.:

Process	MUV Prediction	Bound	Constraint on $\lvert\varepsilon_{\alpha\beta}\rvert$
$\mu \to e\gamma$	$2.4 \times 10^{-3}\lvert\varepsilon_{\mu e}\rvert^2$	5.7×10^{-13}	$\varepsilon_{\mu e} < 1.5 \times 10^{-5}$
$\tau \to e\gamma$	$4.3 \times 10^{-4}\lvert\varepsilon_{\tau e}\rvert^2$	1.5×10^{-8}	$\varepsilon_{\tau e} < 5.9 \times 10^{-3}$
$\tau \to \mu\gamma$	$4.1 \times 10^{-4}\lvert\varepsilon_{\tau\mu}\rvert^2$	1.8×10^{-8}	$\varepsilon_{\tau\mu} < 6.6 \times 10^{-3}$

- Estimated sensitivities of planned experiments at 90% C.L.:

Process	MUV Prediction	Bound	Sensitivity
$Br_{\tau e}$	$4.3 \times 10^{-4}\lvert\varepsilon_{\tau e}\rvert^2$	10^{-9}	$\varepsilon_{\tau e} \geq 1.5 \times 10^{-3}$
$Br_{\tau\mu}$	$4.1 \times 10^{-4}\lvert\varepsilon_{\tau\mu}\rvert^2$	10^{-9}	$\varepsilon_{\tau\mu} \geq 1.6 \times 10^{-3}$
$Br_{\mu eee}$	$1.8 \times 10^{-5}\lvert\varepsilon_{\mu e}\rvert^2$	10^{-16}	$\varepsilon_{\mu e} \geq 2.4 \times 10^{-6}$
$R_{\mu e}^{Ti}$	$1.5 \times 10^{-5}\lvert\varepsilon_{\mu e}\rvert^2$	2×10^{-18}	$\varepsilon_{\mu e} \geq 3.6 \times 10^{-7}$

$\Rightarrow R_{\mu e}^{Ti}$ yields a sensitivity to m_{ν_R} up to 0.3 PeV.