An example of synergy in BSM physics: Right-handed neutrinos

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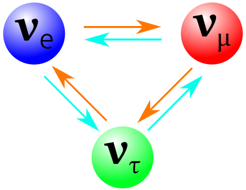
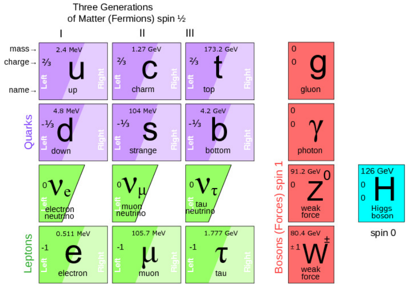
Motivation for sterile neutrinos





Shaposhnikov *et al.*

- Neutrino oscillations: *at least* two massive light neutrinos.
- No renormalisable way in the SM therefore;
  ⇒ evidence for new physics.
- Sterile neutrinos for type I seesaw mechanism.

The "naïve" type I seesaw

- The simplified version: $(1\ \nu_L,\ 1\ \nu_R)$
  - ⋆ Mass matrix $\sim \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$, with $m = y_\nu v_{\rm EW} \ll M$.
  - ⋆ Light neutrino mass: $m_\nu = \frac{1}{2}\frac{v_{\rm EW}^2 |y_\nu|^2}{M_R}$.
- More realistic case: $(2\ \nu_L,\ 2\ \nu_R)$

$$y_\nu \to \begin{pmatrix} y_\nu & 0 \\ 0 & y_\nu \end{pmatrix}, \qquad M \to \begin{pmatrix} M_R & 0 \\ 0 & M_R(1+\varepsilon) \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = \frac{v_{\rm EW}^2 y_\nu^2}{M_R}(1 + \delta_{i2}\varepsilon)$$

$\Rightarrow$ The m_{ν_i} fix a relation between y_ν and M_R.

The effect of protective symmetries

- Specific structures of the Yukawa and mass matrices can be realised by symmetries (no fine tuning).
- A $(2\ \nu_L,\ 2\ \nu_R)$ example:

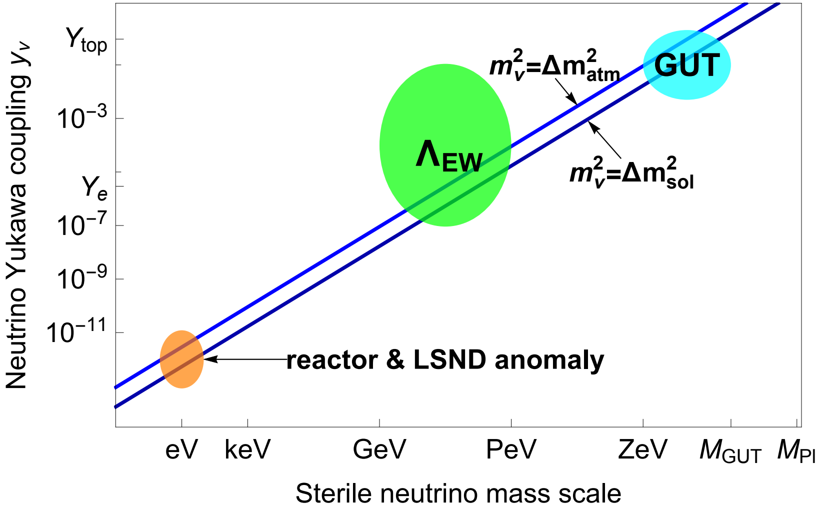
$$y_\nu \to \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \qquad M \to \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\rm EW}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

- "Symmetry violating" parameter ε controls magnitude of m_{ν_i}.

$\Rightarrow$ Large y_ν and $M_R \sim v_{\rm EW}$ can be compatible with small m_{ν_i}.

The Big Picture



Symmetry Protected Seesaw Scenario

Benchmark model for FCC studies, defined in Antusch, OF; JHEP **1505** (2015) 053.

Similar to e.g.: Mohapatra, Valle (1986); Shaposhnikov (2007); Gavela, Hambye, Hernandez (2009)

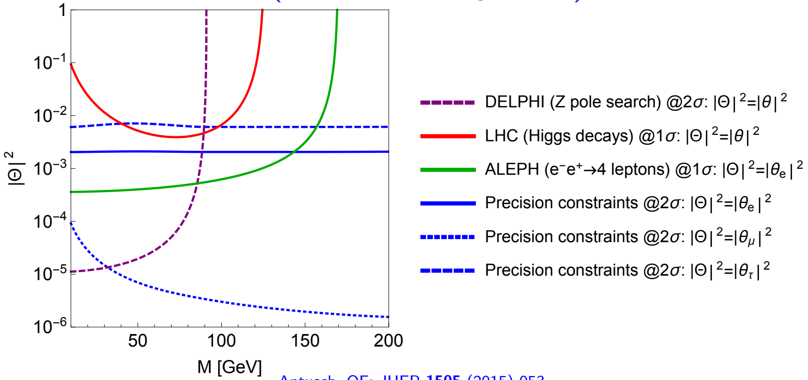
- Collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry, such that

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

- Further "decoupled" sterile neutrinos may exist.
- Active-sterile mixing: $\theta_\alpha = y_{\nu_\alpha}\frac{v_{\mathrm{EW}}}{\sqrt{2}\,M}$, $\theta^2 \equiv \sum_\alpha |\theta_\alpha|^2$
- The leptonic mixing matrix to leading order in θ_α:

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu 1} & \mathcal{N}_{\mu 2} & \mathcal{N}_{\mu 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau 1} & \mathcal{N}_{\tau 2} & \mathcal{N}_{\tau 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\mathrm{i}}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

Present Constraints (dominated by LEP)



Antusch, OF; JHEP **1505** (2015) 053

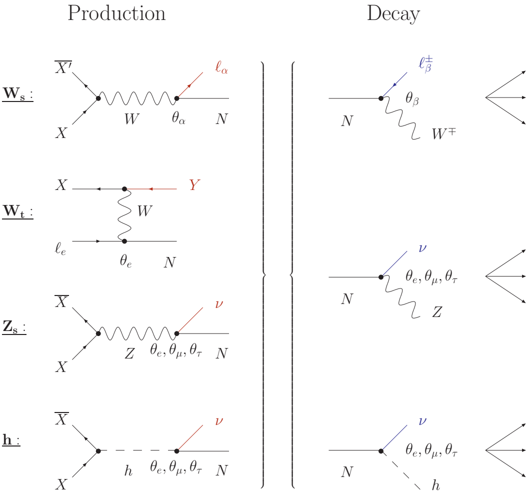
- Z pole search: limits from Z branching ratios .

  Abreu *et al.* Z.Phys. C74 (1997) 57-71

- Higgs decays: Best constraints from $h \to \gamma\gamma$.
- Direct Search: $\delta\sigma_{\mathrm{SM}}^{WW} = 0.011_{stat} + 0.007_{syst}$

  OPAL collaboration, Abbiendi **et al.** (2007)

Systematic assessment of signatures at the FCCs



Final States

- **pp** : $\ell_\alpha \ell_\beta^\pm jj$, $\ell_\alpha \ell_\beta^\pm \ell_\gamma^\mp \nu$
- $\mathbf{e^-e^+, e^-p}$: $Y \ell_\beta^\pm jj$, $Y \ell_\beta^\pm \ell_\gamma^\mp \nu$
- $\mathbf{e^-e^+, pp}$: $\nu \ell_\beta^\pm jj$, $\nu \ell_\beta^\pm \ell_\gamma^\mp \nu$

- **pp** : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu\nu\nu$
- $\mathbf{e^-e^+, e^-p}$: $Y \nu jj$, $Y \nu \ell_\beta^\pm \ell_\beta^\mp$, $Y \nu\nu\nu$
- $\mathbf{e^-e^+, pp}$: $\nu\nu jj$, $\nu\nu \ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu\nu\nu$

- **pp** : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell_\beta^\pm \ell_\beta^\mp$, $\ell_\alpha \nu VV$
- $\mathbf{e^-e^+, e^-p}$: $Y \nu jj$, $Y \nu \ell_\beta^\pm \ell_\beta^\mp$, $Y \nu VV$
- $\mathbf{e^-e^+, pp}$: $\nu\nu jj$, $\nu\nu \ell_\beta^\pm \ell_\beta^\mp$, $\nu\nu VV$

Antusch, Cazzato, OF; 1612.02728

Most promising search strategies for sterile neutrinos

FCC-ee:

- Displaced vertices (Z-pole) S. Antusch, E. Cazzato, OF; JHEP **1612** (2016) 007

  A. Blondel *et al.* [FCC-ee study Team], Nucl. Part. Phys. Proc. **273-275** 1883

- Electroweak precision measurements (mostly Z-pole)

  S. Antusch, OF; JHEP **1410** (2014) 094

- Higgs boson production and decay modes

FCC-hh:

- Displaced vertices
- Lepton-flavor violating di-leptons plus jets*
- Lepton-number violating di-leptons

FCC-eh:

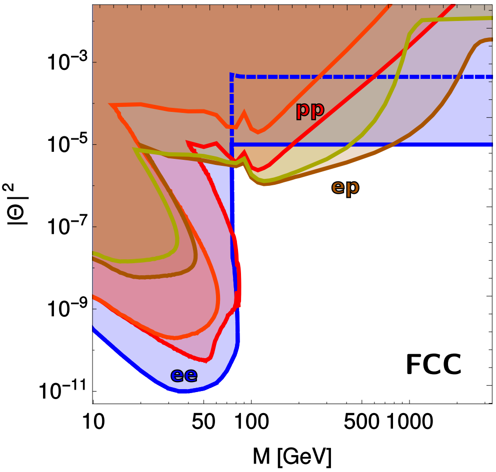
- Lepton-flavor violating lepton-trijet*
- Lepton-number violating antilepton-trijets

* S. Antusch, E. Cazzato, OF; 1612.02728

Sensitivities: summary

At one-sigma confidence level.

ep and pp at parton level



S. Antusch, E. Cazzato, OF; 1612.02728

The combination of *ee* with *pp* and *ep* colliders provides complementary tests for the neutrino mass mechanism.

Examples for work on right-handed neutrinos at FCC

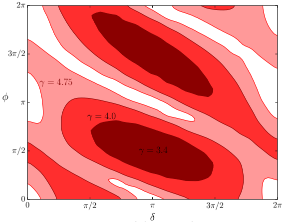
The Z-pole run at the FCC-ee (1)

General small breaking terms can yield small neutrino masses.

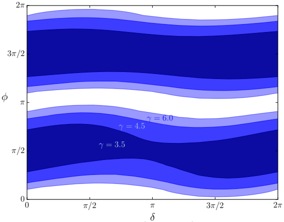
Gavela, Hambye, Hernandez; 0906.1461

Very predictive scenario (2l,2r): $U^2_{\alpha i}/U^2_{\beta i}$ with $\alpha, \beta = e, \mu, \tau$ fixed by the light neutrino masses, mixings and the CP phases (δ, Φ).

Hernandez, Kekic, Lopez-Pavon, Racker, Salvado; 1606.06719



normal hierarchy



inverse hierarchy

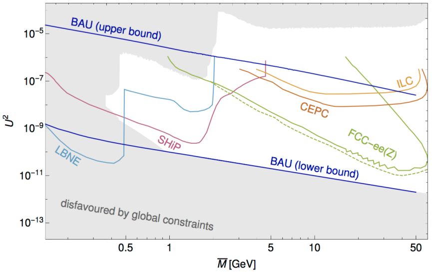
Caputo, Hernandez, Kekic, Lopez-Pavon, Salvado; 1611.05000

Fraction of the area of the regions (δ, Φ) where CP violating phases $\neq 0, \pi$ can be established at 5σ from Z-pole run

The Z-pole run at the FCC-ee (2)

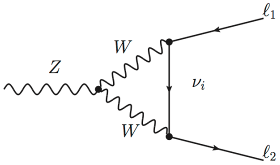
Lowscale Leptogenesis

- Baryon asymmetry generated from lepton-number violation
- Low-scale mechanism is driven from oscillations between sterile and active neutrinos



M. Drewes, B. Garbrecht, D. Gueter and J. Klaric; [1609.09069]

Exotic Z boson decays:



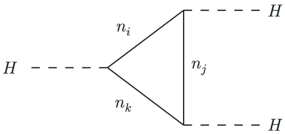
- Lepton-flavor violating decays $Z \to e\mu, e\tau, \mu\tau$
- Induced from sterile neutrinos at the loop level.

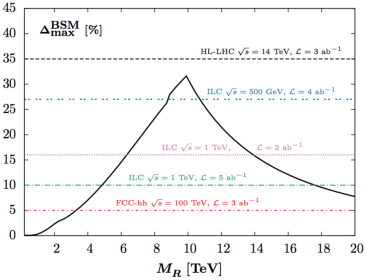
A. Abada, V. De Romeri, S. Monteil, J. Orloff and A. M. Teixeira; JHEP04(2015)051

Measuring the Higgs potential at the FCC-hh

"A new probe of low-scale seesaw models".

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





- FCC-hh can measure the triple Higgs coupling with high precision
- Sterile neutrinos contribute at the loop level

Related articles considering electron-proton colliders

- "Polarized window for left-right symmetry and a right-handed neutrino at the **Large Hadron-Electron Collider**,"

  S. Mondal, S. K. Rai; Phys. Rev. D **93** (2016) no.1, 011702

- "Probing the Heavy Neutrinos of Inverse Seesaw Model at the **LHeC**,"

  S. Mondal, S. K. Rai; Phys. Rev. D **94** (2016) no.3, 033008

- "Left-Right Symmetry and Lepton Number Violation at the **Large Hadron Electron Collider**,"

  M. Lindner, F. S. Queiroz, W. Rodejohann, C. E. Yaguna; JHEP **1606** (2016) 140

Synergy and Complementarity

FCC-ee:

- highest sensitivity for $M < m_W$; low mass regime.
  $\Rightarrow$ Test model predictions
- SM precision tests have high sensitivity; mass independent.
  $\Rightarrow$ Test heavy neutrinos up to ~ 60 TeV
  $\Rightarrow$ Not sensitivite to the number of neutrinos

FCC-hh and -eh:

- 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

- Right-handed neutrinos are well motivated BSM extensions.
- Symmetry protected seesaw scenarios allow for electroweak scale sterile neutrino masses and $\mathcal{O}(1)$ active-sterile mixings.
- Present constraints: active-sterile mixing $|\theta|^2 \leq 10^{-3}$.
- Ballpark: FCC sensitivity for active-sterile mixing $\mathcal{O}(10^{-5})$
- **Great prospects** for right-handed neutrino searches:
  - ⋆ **FCC-ee**: Electroweak precision observables.
  - ⋆ **FCC-hh**: Lepton-flavour violating dilepton-dijet.
  - ⋆ **FCC-eh**: Lepton-flavour violating lepton-trijet.
  - ⋆ **All**: Displaced vertex searches.
- **Synergy:** The combination of direct and indirect signatures at all FCCs will pin down the parameters and test model specific predictions.

$\Rightarrow$ Testing the origin of neutrino masses.

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		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)	$R^\pi_{\mu e}$	$\frac{\Gamma(\pi \to \mu \bar{\nu}_\mu)}{\Gamma(\pi \to e \bar{\nu}_e)}$	1.0021(16)
$R^\ell_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)}$	1.0006(21)	$R^\pi_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau \pi)}{\Gamma(\pi \to \mu \bar{\nu}_\mu)}$	0.9956(31)
$R^W_{e\mu}$	$\frac{\Gamma(W \to e \bar{\nu}_e)}{\Gamma(W \to \mu \bar{\nu}_\mu)}$	1.0085(93)	$R^K_{\tau\mu}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to \mu \bar{\nu}_\mu)}$	0.9852(72)
$R^W_{\tau\mu}$	$\frac{\Gamma(W \to \tau \bar{\nu}_\tau)}{\Gamma(W \to \mu \bar{\nu}_e)}$	1.032(11)	$R^K_{\tau e}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to e \bar{\nu}_e)}$	1.018(42)

Backup III - CKM unitarity constraint

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

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

For the kaon decay processes we have:

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

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	$f^{\text{process}}(\varepsilon)$	$\lvert V_{us}\rvert$
$\frac{B(\tau\to K\nu)}{B(\tau\to\pi\nu)}$	$\varepsilon_{\mu\mu}$	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 $\|\varepsilon_{\alpha\beta}\|$
$\mu \to e\gamma$	$2.4 \times 10^{-3}\|\varepsilon_{\mu e}\|^2$	5.7×10^{-13}	$\varepsilon_{\mu e} < 1.5 \times 10^{-5}$
$\tau \to e\gamma$	$4.3 \times 10^{-4}\|\varepsilon_{\tau e}\|^2$	1.5×10^{-8}	$\varepsilon_{\tau e} < 5.9 \times 10^{-3}$
$\tau \to \mu\gamma$	$4.1 \times 10^{-4}\|\varepsilon_{\tau\mu}\|^2$	1.8×10^{-8}	$\varepsilon_{\tau\mu} < 6.6 \times 10^{-3}$

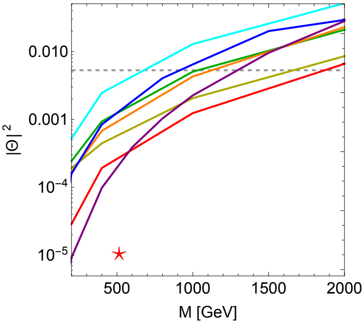
- Estimated sensitivities of planned experiments at 90% C.L.:

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

Backup V - state of the art analysis, pp

Background	cross section [fb]
ditop	3.1000349220E+07
Z+jj	1.2971836612E+08
$Z\,W^-$	1.3799375877E+05
$Z\,W^+$	1.7330162727E+05
$W\pm W^{\mp}Z$	4.3834221202E+06



For M = 500 GeV

N(mu) = N(e) =1

N(j) $\geq$ 2

no b-jet, tau

$p_T(j_1) > 140$ GeV,

$p_T(l_N) > 140$ GeV,

$p_T(l_W) > 120$ GeV

$MET < 40$ GeV

$H_T > 200$ GeV

$M(l_N l_W) > 250$ GeV

$50 < M(jj) < 110$ GeV

$M(jjl_N l_W) > 650$ GeV

$M(jjl_N) > 450$ GeV

$M(jjl_W) > 450$ GeV

$p_T(jj) > 140$ GeV

$p_T(jjl_N) > 160$ GeV

$p_T(jjl_W) > 160$ GeV

$\Rightarrow$ 5% signal efficiency remove all 10^8 background events.