Sterile Neutrino Searches at Future Colliders

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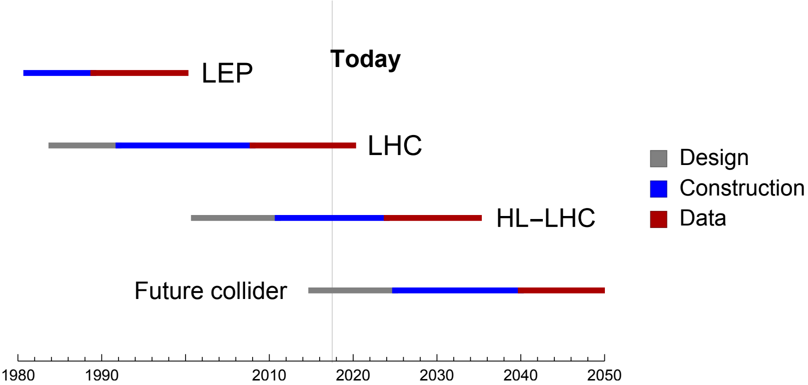
The Future Circular Collider project (CERN)

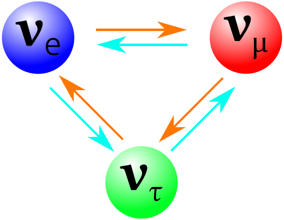
A note on future collider planning

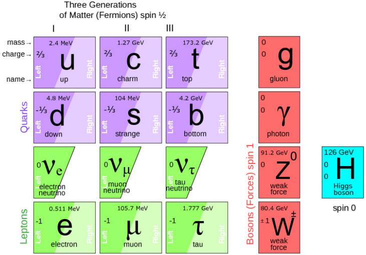
The LHC achieved record energy of 13 TeV not that long ago.



- LEP was conceived in 1975
- The LHC was conceived in '77 and influenced the LEP layout.
- FCC kickoff in 2014.

Neutrino oscillations & the Standard Model



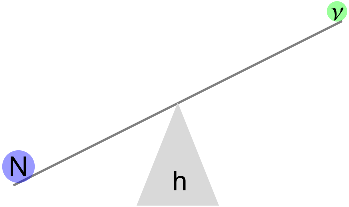


courtsy M. Shaposhnikov

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

⇒ Neutrino oscillations are evidence of 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.

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: $m_\nu = \frac{1}{2}\frac{v_{\rm EW}^2 |y_\nu|^2}{M_R}$.
- Analogously: “naïve” $(2\ \nu_L,\ 2\ \nu_R)$
- The effect of protective symmetries (no fine tuning):

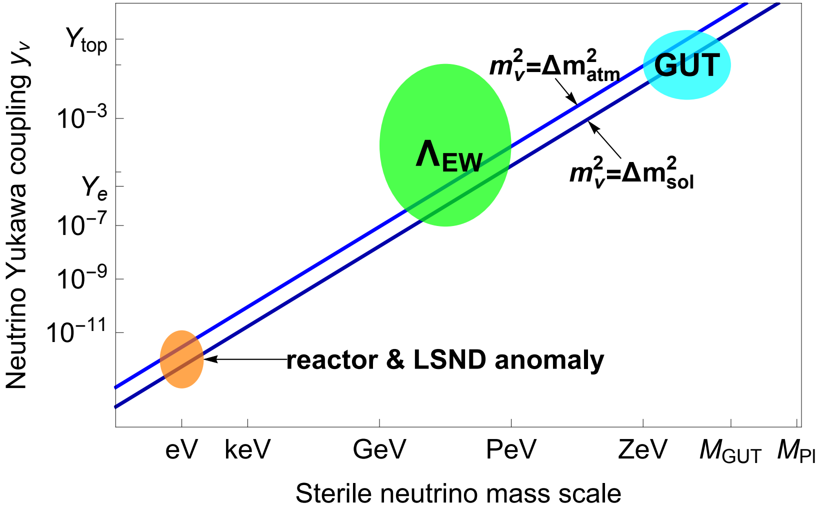
$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \qquad \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

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

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

$\Rightarrow$ Large y_ν can be compatible with neutrino oscillations if $\varepsilon \sim 0$.

The Big Picture



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

- Heavy neutrinos are mostly sterile, interactions via mixing.
- **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 $\equiv \nu_e, \nu_\mu, \nu_\tau$

Constraints on PMNS non-unitarity from precision data

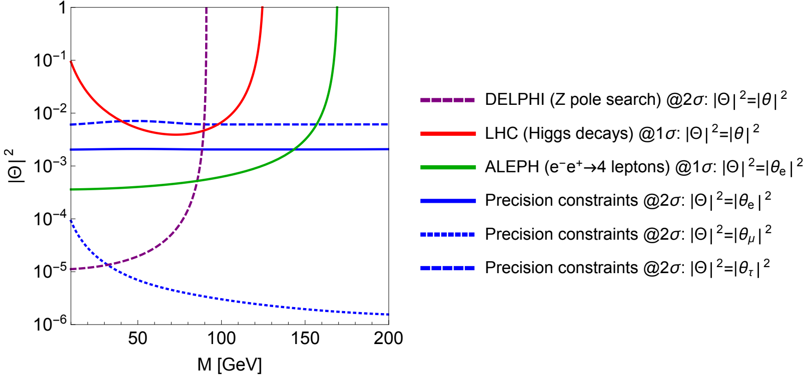
- Analysis of non-unitarity of the PMNS matrix.
- 34 precision observables:
  Electroweak Precision Observables (EWPO), lepton universality, charged lepton flavour violation, CKM unitarity
- Highest posterior density intervals at 90% Bayesian C.L.:

$$\boxed{\begin{array}{rcrlcl} -0.0021 & \leq \varepsilon_{ee} \leq & -0.0002 & |\varepsilon_{e\mu}| & < & 1.0 \times 10^{-5} \\ -0.0004 & \leq \varepsilon_{\mu\mu} \leq & 0 & |\varepsilon_{e\tau}| & < & 2.1 \times 10^{-3} \\ -0.0053 & \leq \varepsilon_{\tau\tau} \leq & 0 & |\varepsilon_{\mu\tau}| & < & 8.0 \times 10^{-4} \end{array}}$$

Antusch, OF; JHEP 1410 (2014) 094

- ⋆ Non-unitarity parameters: $\varepsilon_{\alpha\beta} = -\theta^*_\alpha \theta_\beta$.
- ⋆ Weak statistical preference for non-zero mixing for ε_{ee}.

Present Constraints (dominated by LEP & MEG)



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

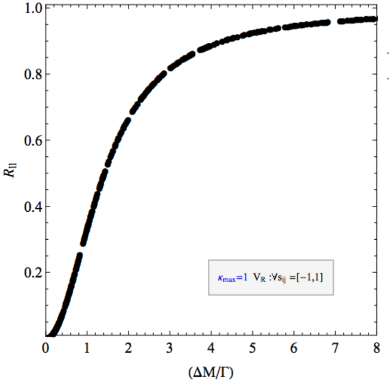
- Z pole search: limits from Z branching ratios.
  Abreu *et al.* Z.Phys. C74 (1997) 57-71
- Higgs decays: Best constraints from $h \to \gamma\gamma$.
- Direct Search: $\delta\sigma_{\mathrm{SM}}^{WW} = 0.011_{stat} + 0.007_{syst}$
  OPAL collaboration, Abbiendi **et al.** (2007)

Traditionally, searches for sterile neutrinos via Lepton Number Violating signatures

e.g. $\mu^{\pm}\mu^{\pm} + J$ at pp (SS dimuons) or $e^{+} + J$ at ep

However...

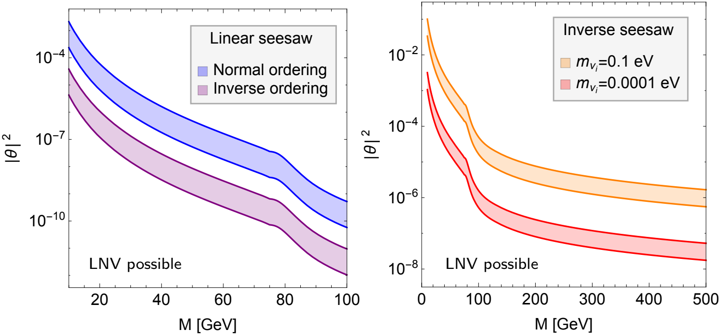
Lepton number violation and ΔM



Anamiati, Hirsch, Nardi; 1607.05641

- With $m'_D = \mu = 0$, no LNV in this class of models.
- $R_{\ell\ell}$ (=LNV/LNC) function of $|M_{N_1} - M_{N_2}| := \Delta M$ and Γ_N.
- For mass splitting $\sim$ decay width, $R_{\ell\ell} \in [0, 1]$.
- Zero mass splitting $\Rightarrow$ zero LNV.

Parameter space with LNV



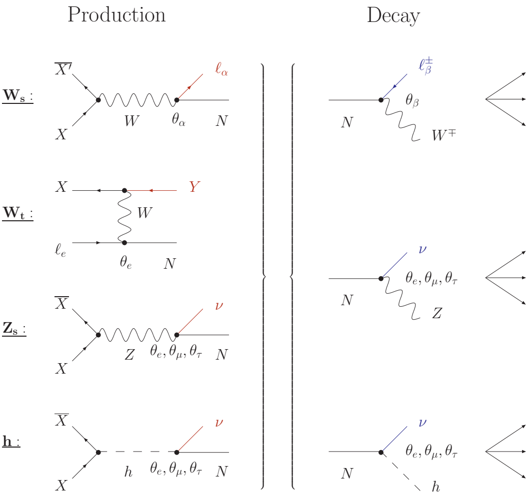
Antusch et al.; [1709.03797]

$$R_{\ell\ell} = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}$$

- The colored bands separate parameterspace w/ and w/o LNV.
- Upper contour: $R_{\ell\ell} = 0.1$, lower contour: $R_{\ell\ell} = 0.9$

$\Rightarrow$ No LNV for $M > 100$ GeV!

Schematizing sterile neutrino searches



pp : $\ell_\alpha \ell^\pm_\beta jj$, $\ell_\alpha \ell^\pm_\beta \ell^\mp_\gamma \nu$

e⁻e⁺, e⁻p : $Y \ell^\pm_\beta jj$, $Y \ell^\pm_\beta \ell^\mp_\gamma \nu$

e⁻e⁺, pp : $\nu \ell^\pm_\beta jj$, $\nu \ell^\pm_\beta \ell^\mp_\gamma \nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu\nu\nu$

e⁻e⁺, e⁻p : $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu\nu\nu$

e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu\nu\nu\nu$

pp : $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu VV$

e⁻e⁺, e⁻p : $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu VV$

e⁻e⁺, pp : $\nu\nu jj$, $\nu\nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu\nu VV$

S. Antusch, E. Cazzato, OF; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

Promising signatures at FCC-ee

- ⋆ **Displaced vertices:**
  - ▸ For $M < m_W$ and $|\theta|^2 \leq 10^{-5}$ heavy neutrinos are long lived.
  - ▸ Secondary vertex with visible displacement.

S. Antusch, E. Cazzato, OF; JHEP **1612**, 007 (2016)

- ⋆ **Indirect searches via EWPO:**
  - ▸ The mixing matrix of the three active neutrinos is non-unitary.
  - ▸ Modification of the theory prediction of precision observables.

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

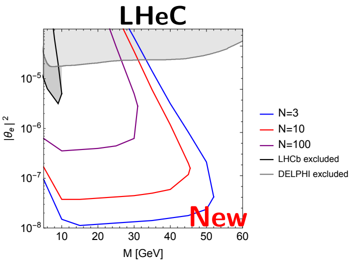
- ⋆ **Indirect searches via Higgs boson properties:**
  - ▸ Additional production mechanism at high energies.
  - ▸ New decay channel ⇒ modified branching ratios.

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

Promising signatures at colliders with proton beams

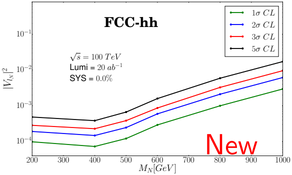
⋆ **Displaced vertices:**

- Possible at all FCC's.
- Easier at FCC-he compared to -hh.
- Best prospects for $M < m_W$.



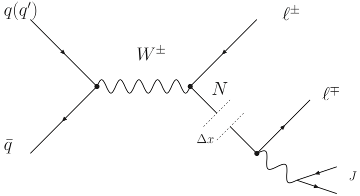
⋆ **Unambiguous LFV:**

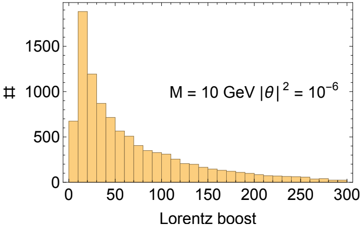
- Proton-proton: $\ell^\pm_\alpha \ell^\mp_\beta jj$, and $\ell^\pm_\alpha \ell^\mp_\beta \ell^\pm_\gamma$.
- Electron-proton: $\mu^- jjj$ and $\tau^- jjj$.
- Best prospects for $M \gg m_W$.

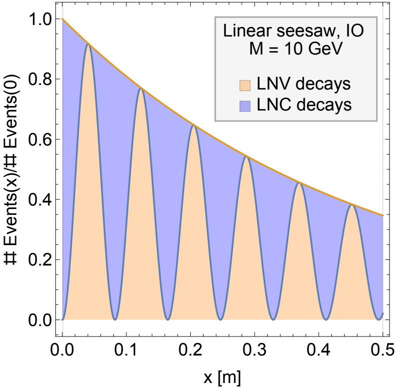


Antusch et al. [1805.11400]

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







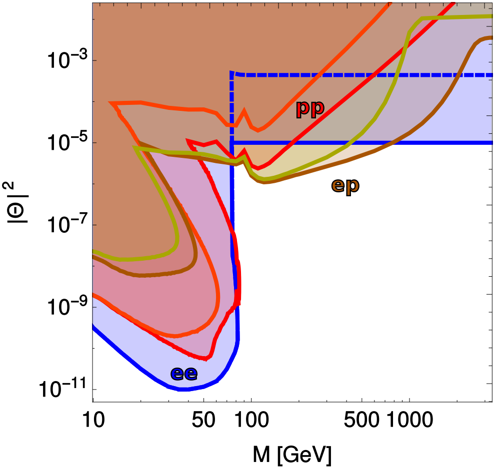
Antusch, Cazzato, Fischer; 1709.03797

- Oscillation from Δm_ν^2, can be $\sim$ mm.
- $M = \mathcal{O}(10)$ GeV and $|\theta|^2 \sim 10^{-6}$ yields displaced decays.
- Prompt lepton and displaced lepton are SS/OS as function of proper flight time

Overview of the estimated sensitivities

At one-sigma confidence level.

ep and pp at parton level



S. Antusch, E. Cazzato, OF; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

The combination of *ee* with *pp* and *ep* colliders provides complementary tests for symmetry protected sterile neutrinos.

Conclusions

- Sterile neutrinos are well motivated extensions of the SM.
- Symmetry protected seesaw scenarios allow for electroweak scale sterile neutrino masses and $\mathcal{O}(1)$ active-sterile mixings.
- Present constraints: active-sterile mixing $|\theta|^2 \leq 10^{-3}$.

- If HL-LHC finds no hints of sterile neutrinos, it may be:
  - ⋆ active-sterile mixing too small,
  - ⋆ masses above ~ 200 GeV.
- There is the exciting possibility to observe LNV oscillations.

$\Rightarrow$ The FCC has unique capabilities to go beyond the LHC

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
$[R_\ell]_{\mathrm{SM}}\,(1 - 0.15(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\mathrm{SM}}\,(1 + 0.03(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\mathrm{SM}}\,(1 - 0.06(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$\left[\sigma^0_{had}\right]_{\mathrm{SM}}\,(1 - 0.25(\varepsilon_{ee} + \varepsilon_{\mu\mu}) - 0.27\varepsilon_\tau)/\mathrm{nb}$	41.470(15)	41.541(37)
$[R_{inv}]_{\mathrm{SM}}\,(1 + 0.75(\varepsilon_{ee} + \varepsilon_{\mu\mu}) + 0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\mathrm{SM}}(1 - 0.11(\varepsilon_{ee} + \varepsilon_{\mu\mu}))/\mathrm{GeV}$	80.359(11)	80.385(15)
$[\Gamma_{\mathrm{lept}}]_{\mathrm{SM}}(1 - 0.59(\varepsilon_{ee} + \varepsilon_{\mu\mu}))/\mathrm{MeV}$	83.966(12)	83.984(86)
$[(s^{\ell,\mathrm{lep}}_{W,\mathrm{eff}})^2]_{\mathrm{SM}}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,\mathrm{had}}_{W,\mathrm{eff}})^2]_{\mathrm{SM}}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	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: $V_{ud} = 0.97427(15)$, $V_{ub} = 0.00351(15)$

$$|V_{ij}^{th}|^2 = |V_{ij}^{exp}|^2(1 + f^{\text{process}}(\varepsilon_{\alpha\alpha}))\ ,$$

$$|V_{ud}^{th}|^2 = |V_{ud}^{exp,\beta}|^2(NN^\dagger)_{\mu\mu}\ .$$

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 $\lvert\varepsilon_{\alpha\beta}\rvert$
$\mu \to e\gamma$	$2.4 \times 10^{-3} \lvert\varepsilon_{\mu e}\rvert^2$	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.