Heavy neutrino discovery prospects at FCC

Oliver Fischer

Karlsruher Institut für Technologie

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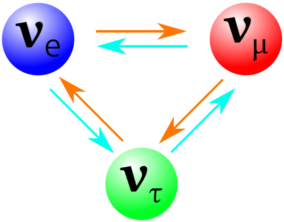
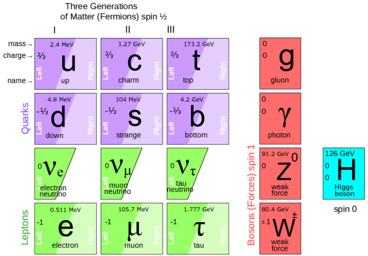
Neutrino oscillations & the Standard Model



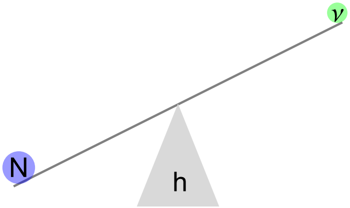


courtsy M. Shaposhnikov

- 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.

Neutrino masses with right-handed neutrinos



- Fermionic singlets, speak: “Right-handed” or “sterile” neutrinos → seesaw mechanism.
- Two mass-differences ⇒ *at least* two sterile neutrinos.
- New mass scale, a priori unrelated to the known ones.
- May be connected to e.g. Dark Matter and Baryogenesis.

Symmetry Protected Seesaw Scenario

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

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

- 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 included.
- The mass matrix:

$$\mathcal{M}_\nu = -\frac{1}{2} \begin{pmatrix} 0 & \frac{y_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{s}} & 0 \\ \frac{y_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{s}} & 0 & M \\ 0 & M & 0 \end{pmatrix} + \text{ H.c.}$$

Neutrino mixing

- Active-sterile mixing: $\theta_\alpha = y_{\nu_\alpha} \frac{v_{\rm EW}}{\sqrt{2}M}$, $\theta^2 \equiv \sum_\alpha |\theta_\alpha|^2$
- The leptonic mixing matrix to leading order in θ_α:

$$\mathcal{U} = \left(\begin{array}{cc} \mathcal{N} & \theta \\ \tilde{\theta} & \mathcal{W} \end{array} \right)$$

- $\mathcal{N} \sim$ PMNS as submatrix in general **not** unitary ($\mathcal{N}\mathcal{N}^\dagger \neq \mathbb{1}$).
- Modification of the weak currents with light neutrinos:

$$\left(J^{\mu\,,\pm}\right)_{\alpha i} = \ell_\alpha \gamma^\mu \nu_i \, \mathcal{N}_{\alpha i} \,, \qquad \left(J^{\mu,\,0}\right)_{ij} = \nu_i \gamma^\mu \nu_j \, \left(\mathcal{N}^\dagger \mathcal{N}\right)_{ij}$$

Constraints on PMNS non-unitarity from precision data

- Analysis of non-unitarity of the PMNS matrix.

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon; JHEP **0610** (2006) 084

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

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

Antusch, OF; JHEP 1410 (2014) 094
Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon; JHEP **1608** (2016) 033
Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, Lucente; JHEP **1510** (2015) 130

⋆ Non-unitarity parameters: $\varepsilon_{\alpha\beta} = -\theta^*_\alpha \theta_\beta$.

⋆ Weak statistical preference for non-zero mixing for ε_{ee}.

Heavy neutrino interactions

- **Charged current** (CC):

$$j_\mu^{\pm} = \frac{g}{2}\,\theta_\alpha\,\bar{\ell}_\alpha\,\gamma_\mu\,(-\mathrm{i}N_1 + N_2)$$

- **Neutral current** (NC):

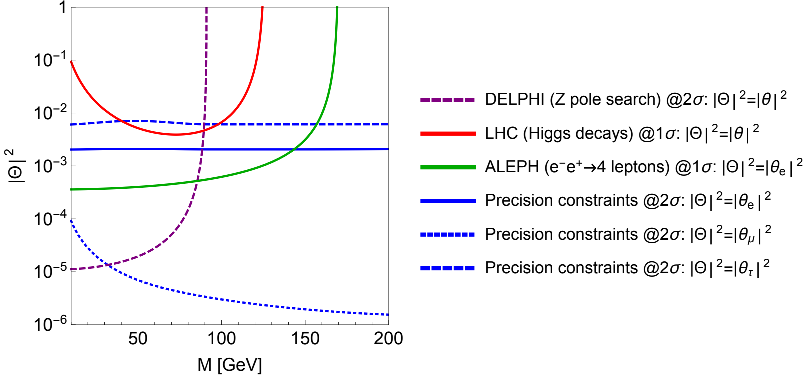
$$j_\mu^0 = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_\mu\,N_2 \;+ (\bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_\mu\,\xi_{\alpha 2}\,N_2 \;+\; \text{H.c})\right]$$

- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\mathrm{Yukawa}} = \sum_{i=1}^{3} \xi_{\alpha 2}\frac{\sqrt{2}\,M}{v_{\mathrm{EW}}}\nu_i\phi^0\left(\overline{N}_1 + \overline{N}_2\right)$$

- With the mixing parameters: $\xi_{\alpha 1} = (-\mathrm{i})\,\mathcal{N}^*_{\alpha\beta}\frac{\theta_\beta}{\sqrt{2}}$, $\xi_{\alpha 2} = \mathrm{i}\,\xi_{\alpha 1}$

Present Constraints (dominated by LEP & MEG)



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

- Z pole search: limits from Z branching ratios.

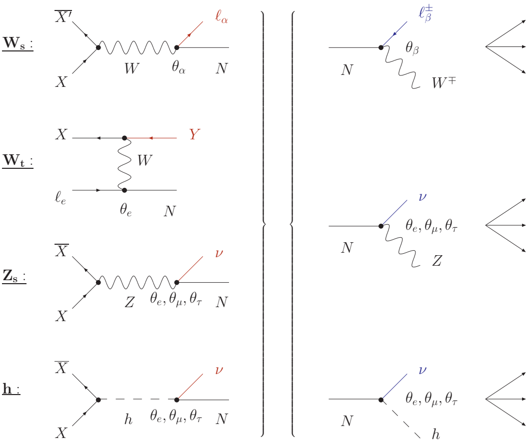
  Abreu *et al.* Z.Phys. C74 (1997) 57-71

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

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

Schematizing sterile neutrino searches

Production | Decay | Final States



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

Signatures for direct searches at FCC-ee

Name	Final State	$\vert\theta\vert$, Z pole	$\vert\theta\vert$, $\sqrt{s} > m_Z$
lepton-dijet	$\ell_\alpha \nu jj$	$\vert\theta_\alpha\vert^2$	$\frac{\vert\theta_e\theta_\alpha\vert^2}{\theta^2}$
mixed flavour dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$\vert\theta_\alpha\vert^2$	$\frac{\vert\theta_e\theta_\alpha\vert^2}{\theta^2}$
same flavour dilepton	$\ell_\alpha \ell_\alpha \nu\nu$	$\vert\theta\vert^2$	$\vert\theta_e\vert^2$
dijet	$\nu\nu jj$	$\vert\theta\vert^2$	$\vert\theta_e\vert^2$
invisible	$\nu\nu\nu\nu$	$\vert\theta\vert^2$	$\vert\theta_e\vert^2$

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

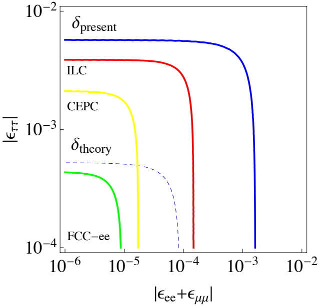
- Measurement of LNV not straightforward.
- The dependency on the active-sterile mixing is determined by the center-of-mass energy, i.e. by the physics run.
- Displaced vertices → See talk by Stefan Antusch.

Blondel et al., Antusch et al.,...

Electroweak precision tests at FCC-ee

Relative precision in percent:

observable	ILC	CEPC	FCC-ee
MW	0.003	0.0006	0.0006
Gammal	0.05	0.1	0.005
Rinv	0.17	0.18	0.03
s2l	0.006	0.01	0.0004
sigmah	0.06	0.09	0.006
Rl	0.02	0.05	0.005
Rb	0.09	0.08	0.009
Rc	0.5	1.7	0.05



Antusch, OF; JHEP 1410 (2014) 094

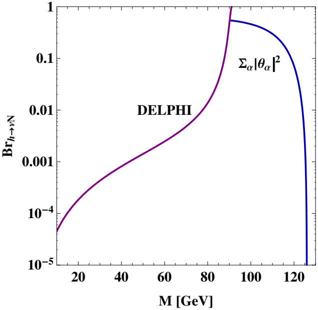
- Measuring the non-unitarity of the PMNS matrix.
- Further improvement: δ_{theory} and $\delta_{\text{syst.}}$
- Not included: lepton universality tests of W decays

Indirect signatures: Higgs boson properties

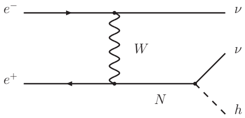
Higgs boson branching ratios:

- New decay channel $h \to \nu N$
- Large branching ratio possible, modified $\mathrm{Br}_{h\to\mathrm{SM}}$
- "Higgs Measurement at e^+e^- Circular Colliders"

M. Ruan, Nucl. Part. Phys. Proc. **273-275**, 857 (2016)



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



Higgs production:

- Additional production mechanism at high energies.
- Enhanced mono-Higgs production cross section.

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

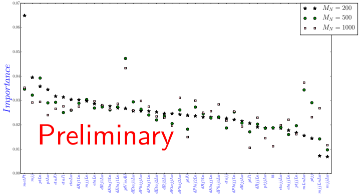
Signatures for direct searches at FCC-hh

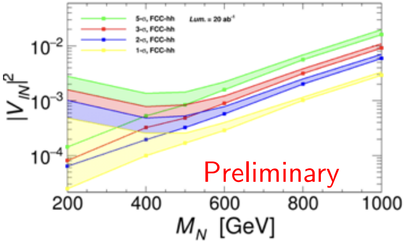
Name	Final State	Channel [production,decay]	$\lvert\theta_\alpha\rvert$ dependency	LNV/LFV
dilepton-dijet	$\ell_\alpha \ell_\beta jj$	$[\mathbf{W_s}, W]$	$\frac{\lvert\theta_\alpha\theta_\beta\rvert^2}{\theta^2}$	✓/✓
trilepton	$\ell_\alpha \ell_\beta \ell_\gamma \nu$	$[\mathbf{W_s}, \{W, Z(h)\}]$	$\left\{ \frac{\lvert\theta_\alpha\theta_\beta\rvert^{2\,(*)}}{\theta^2}, \lvert\theta_\alpha\rvert^{2(*)} \right\}$	×/✓
lepton-dijet	$\ell_\alpha \nu jj$	$[\mathbf{W_s}, Z(h)]$, $[\mathbf{Z_s}, W]$	$\lvert\theta_\alpha\rvert^2$	×
dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$[\mathbf{Z_s}, \{W, Z(h)\}]$	$\left\{ \lvert\theta_\alpha\rvert^{2(*)}, \lvert\theta\rvert^{2(*)} \right\}$	×
mono-lepton	$\ell_\alpha \nu\nu\nu$	$[\mathbf{W_s}, Z]$	$\lvert\theta_\alpha\rvert^2$	×
dijet	$\nu\nu jj$	$[\mathbf{Z_s}, Z(h)]$	$\lvert\theta\rvert^2$	×

- Checkmark in “LNV/LFV” column indicates existence of unambiguous signal for LNV and/or LFV
- Displaced vertices → See talk by S. Antusch.

Lepton flavor violating signatures for FCC-hh

List of observables and relative importance:





Unambiguous signal for lepton flavor violation: $pp \to \ell_\alpha \ell_\beta jj$

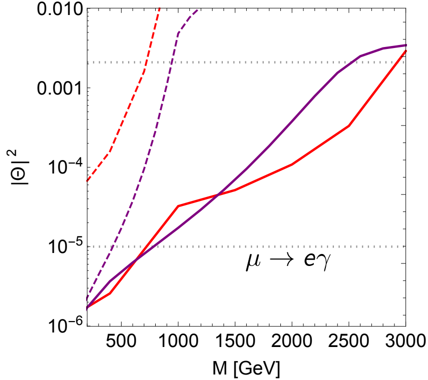
- Dilepton dijet, $\ell_\alpha^\pm \ell_\beta^\mp jj$ (also trilepton $\ell_\alpha^\pm \ell_\beta^\mp \ell_\gamma^\pm$).
- Production via all mixing angles $|\theta_\alpha|$, $\alpha = e, \mu, \tau$.
- Analysis with many backgrounds, fast simulation, TMVA.
- Recover results from previous analysis.

Signatures for FCC-eh

Name	Final State	$\lvert\theta_\alpha\rvert$ Dependency	LFV
lepton-trijet	$jjj\ell_\alpha^-$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓
jet-dilepton	$j\ell_\alpha^-\ell_\beta^+\nu$	$\frac{\lvert\theta_e\theta_\alpha\rvert^{2\,(*)}}{\theta^2}$	✓
trijet	$jjj\nu$	$\lvert\theta_e\rvert^2$	×
monojet	$j\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

- LFV (and LNV) for $\alpha \neq e$, $\beta \neq \alpha$, and $\gamma \neq \alpha, \beta$
- Unambiguous lepton-number-violating final states, e.g. e^+jjj.

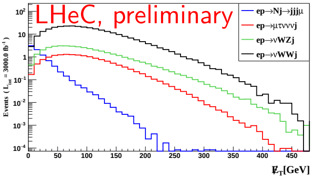
Sensitivities from lepton-flavour-violating signatures



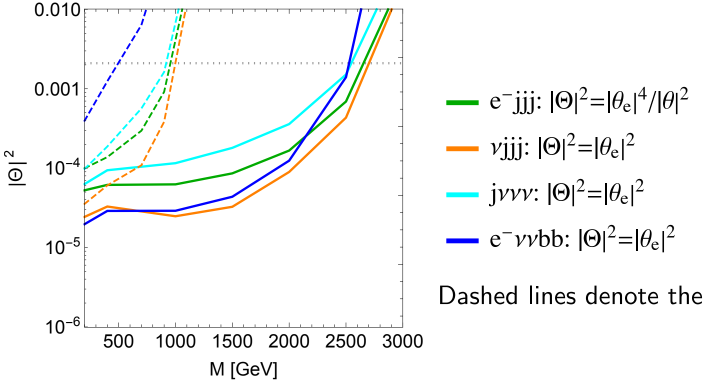
Dashed lines denote the LHeC results from parton level analysis

Analysis, fast simulation, cut based:

- signal efficiency $\mathcal{O}(1)$
- backgrounds less than 1 event
- Recover parton level sensitivity



Lepton-flavour-conserving signatures at FCC-eh



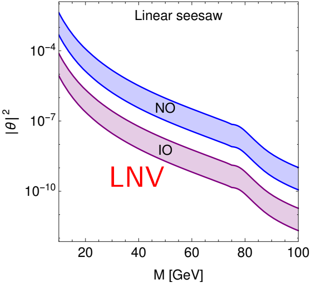
Dashed lines denote the LHeC

- Sensitive to $|\theta_e|$ or $|\theta_e| \times \mathrm{Br} N \rightarrow e^- W^+$.
- "Conservative" sensitivity for $|\theta_\alpha| \ll |\theta_e|$.

Lepton-number violation at colliders with proton beams

⋆ **Unambiguous final states:**

- FCC-hh: $\ell^\pm_\alpha \ell^\pm_\beta + X$, no MET.
- FCC-eh: $\ell^+ + X$, no MET.
- LNV strongly suppressed for $M \gtrsim m_W$.



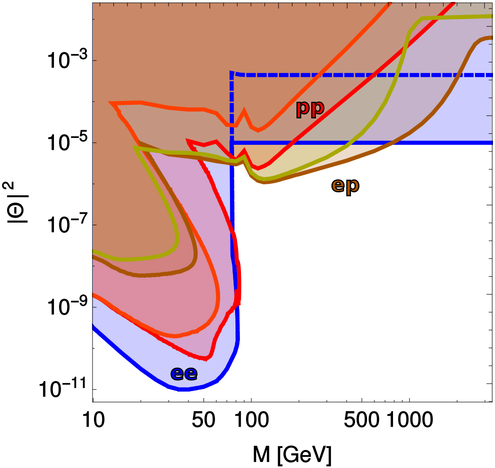
⋆ **Heavy neutrino-antineutrino oscillations:**

see talk by S. Antusch.

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 $|\theta|^2 \leq 10^{-3}$.

- The FCC modes provide different (complementary information).
- Global fits may help to pin down model parameters and distinguish different realisations of the seesaw mechanism.

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		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.