Sterile Neutrinos at Future Lepton Colliders

based on arXiv:1502.05915 and arXiv:1407.6607

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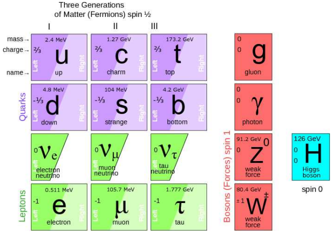
Motivation for sterile neutrinos

- Neutrino oscillations require *at least* two massive light/active SM neutrinos.
- One of the most attractive ways to introduce massive neutrinos is the addition of gauge singlet fermions – "sterile neutrinos".
- Symmetry protected seesaw allows for (sub) TeV masses **and** large active-sterile neutrino mixings.



Courtesy Marco Drewes

⇒ Observable effects via non-unitarity of the leptonic mixing matrix and direct tests at colliders.

Outline: how to test heavy sterile neutrinos

- Sterile Neutrino Mass (M) $>$ Electroweak scale (Λ_{EW}): Search possible via non-unitarity of the effective leptonic mixing matrix.
    - ⋆ Indirect effect on precision observables.
    - ⋆ Emphasis: Electroweak Precision Observables (EWPO).
- $M \sim \Lambda_{\mathrm{EW}}$: Sterile neutrino production at particle colliders possible.
    - ⋆ Indirect effect on low energy precision observables and a modified effect on EWPO.
    - ⋆ Direct searches: N decays at the Z pole, at and beyond the W threshold and Higgs boson decay properties.
- This talk (after a brief introduction to future lepton colliders) presents the state-of-the art present bounds and future sensitivities for active-sterile neutrino mixing:
    - ⋆ Part 1: for $M > \Lambda_{\mathrm{EW}}$.
    - ⋆ Part 2: for $M \sim \Lambda_{\mathrm{EW}}$.

Future electron positron colliders

CERN Future Circular Collider (FCC-ee, FCC-hh, FCC-eh)

- Presently Establishing feasibility of the project.
- Circumference: 80 to 100 km.
- Ambitious goals in precision and energy reach.

China Circular Electron-Positron Collider

- Completed conceptual design reports (CDR)
- Project including the Super Proton-Proton Collider.
- Circumference: 50 to 80 km.

Japan International Linear Collider (ILC)

- Completed technical design reports (TDR).
- R&D program running for a decade.
- Kitakami mountains (Iwate & Miyagi prefectures), Japan.

Part I:
$M > \Lambda_{\mathrm{EW}}$ (electroweak scale)

Non-unitarity of the leptonic mixing matrix

Generic type-I seesaw extension of the Standard Model:

$$\mathscr{L}_{\text{seesaw}} = y_\alpha \overline{N_R}\widetilde{\phi}^\dagger L^\alpha + M\,\overline{N_R^c}N_R + \text{H.c.}$$

$\Rightarrow$ Mixing matrix for the neutral fermions:

$$\mathcal{U} = \begin{pmatrix} \begin{pmatrix} & \mathcal{N} & \end{pmatrix} & \cdots \\ \vdots & \ddots \end{pmatrix} \qquad \text{with} \qquad \mathcal{U}^\dagger\mathcal{U} = \mathbb{1}$$

- $\mathcal{N}$ is the leptonic mixing matrix
  $\sim$ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- PMNS as submatrix in general **not** unitary ($\mathcal{N}\mathcal{N}^\dagger \neq \mathbb{1}$).

Minimal Unitarity Violation (MUV) scheme

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon (2006)

- Brief description of the formalism in Backup I.
- Effective field theory treatment for energies below M.
- Modification of the weak currents with neutrinos:

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

- Corresponding observables are $\propto \mathcal{N}\mathcal{N}^\dagger \sim \mathcal{N}^\dagger\mathcal{N}$
- Parametrisation: $(\mathcal{N}\mathcal{N}^\dagger)_{\alpha\beta} = \mathbb{1}_{\alpha\beta} + \varepsilon_{\alpha\beta}$

Present constraints

Antusch, Fischer (2014)

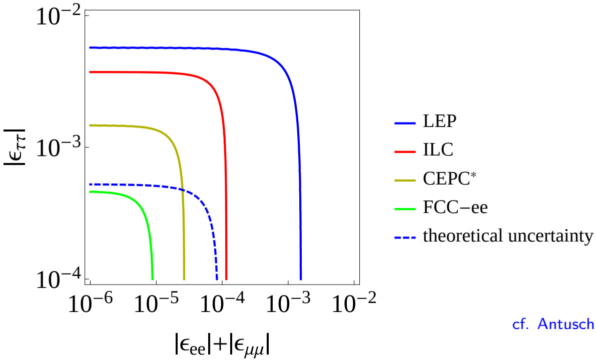
- MUV theory prediction for 34 precision observables: EWPO, lepton universality, charged lepton flavour violation, CKM unitarity
- See Backup II, III, IV, V for a complete list.
- Markov chain monte carlo fit, including correlations.
- Highest posterior density intervals at 90% Bayesian C.L.*:

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

⇒ In the following we will only use this as constraints.

* This talk: 90% C.L. if not stated otherwise.

Improved sensitivity from future colliders



cf. Antusch, Fischer (2014)

- Considering exclusively EWPO (precision in Backup VIII).

⇒ For $y_\alpha = \mathcal{O}(1)$, the FCC-ee can test M up to $\sim$ 60 TeV.

⇒ Needs improved theoretical uncertainties (challenge).

Part II:

$M \sim \Lambda_{\mathrm{EW}}$ (electroweak scale)

Low scale seesaw scenario

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

Kersten, Smirnov (2007)

- Assumption: collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry, such that

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

- The leptonic mixing matrix to leading order in the active-sterile mixing parameters:

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

Disclaimer: Further sterile neutrinos may exist and contribute to the active neutrinos' masses when the protective symmetry gets broken.

Interactions between heavy neutrinos and the SM

- **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):

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

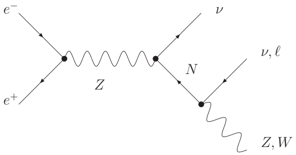
- Higgs boson **Yukawa** interaction:

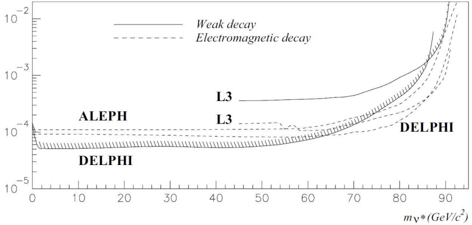
$$\mathscr{L}_{\mathrm{Yukawa}} = \sum_{i=1}^{3} \xi_{\alpha 2}\,\frac{\sqrt{2}\,M}{v_{\mathrm{EW}}}\,\nu_i\,\phi^0\,\left(\overline{N}_1 + \overline{N}_2\right)$$

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

Next: Important processes to search for sterile neutrinos at present and future colliders

Sterile neutrino searches @ the Z pole



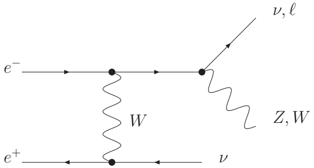


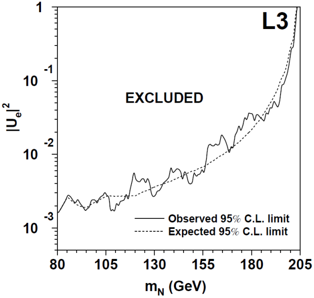
DELPHI collaboration, Abreu **et al.** (1997)

- Search for $Z \to \nu\, N$ in Z–pole data at LEP.
- Exclusion contour at 95% confidence level:

$$\theta^2 = \sum_{\alpha=e,\mu,\tau} |\theta_\alpha|^2 \leq \frac{1.1 \times 10^{-5}}{\frac{1}{2}\left(1-\mu_Z^2\right)^2\left(2+\mu_Z^2\right)}\,, \qquad \mu_Z = \frac{M}{m_Z}\,.$$

Searches in 4ℓ final states for $\sqrt{s} \geq 2\, m_W$





L3 collaboration, Achard **et al.** (2001)

- N decay contributes to 4ℓ final states.
- Experimental uncertainty from the Aleph measurement of the WW production cross section.

$$\frac{n_{WW}^{Aleph}}{n_{WW}^{\mathrm{SM}}} = 0.995 \pm 0.011_{stat} \pm 0.007_{syst}$$

ALEPH collaboration, Heister **et al.** (2004)

Constraints from processes involving the Higgs boson

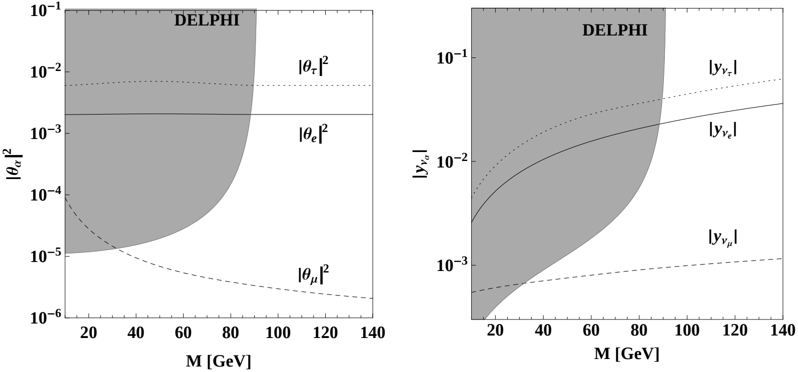
For studies on Higgs decays to sterile neutrinos at the LHC, see e.g.: Bhupal Dev, Franceschini, Mohapatra (2012);
Cely, Ibarra, Molinaro, Petcov (2013)

- Most constraining process at the LHC: $h \to \gamma\gamma$.
- Present constraint: $Br_{h\to\gamma\gamma} = 1.15(27) \times Br^{\mathrm{SM}}_{h\to\gamma\gamma}$
- $h \to \nu\, N \Rightarrow$ reduction of the SM branching ratios:

$$r = \frac{\Gamma_{h,\,\mathrm{SM}}}{\Gamma_{h,\,\mathrm{SM}} + \Gamma_{h\to\nu N}}$$

- Relevant processes for future colliders:
  - ⋆ h decay into WW
  - ⋆ Higgs production from N decays
  - ⋆ $e^+e^- \to h + \not{E}_{(T)}$

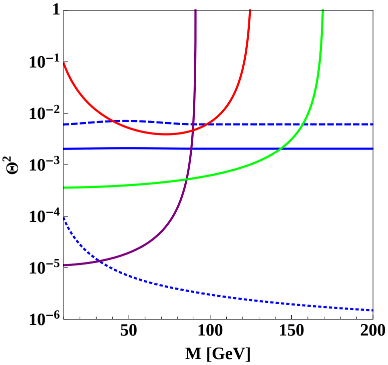
Present indirect constraints from precision data

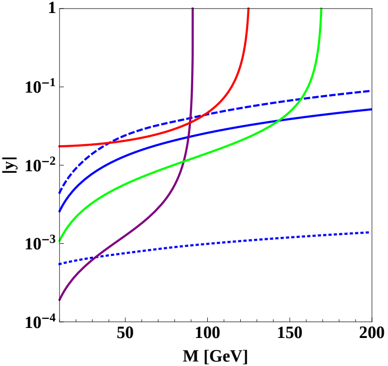


Antusch, Fischer (2015)

- For observables used, see Backup II, III, IV, V.
- Some EWPOs obtain dependency on M: R_{inv}, σ^0_{had}, $R_{\ell,b,v}$.
- Charged lepton flavour violation constraints relaxed for decreasing M.

Combination of present bounds





Direct searches

▬ Delphi (Z pole searches) @2σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$

▬ LHC (Higgs decays*) @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$

▬ Aleph ($e^+e^- \to 4$ leptons) @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

Other (global fit)

▬ $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

┅ $|y|=|y_{\nu_\mu}|$, $\Theta^2=|\theta_\mu|^2$

╍ $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$

Antusch, Fischer (2015)

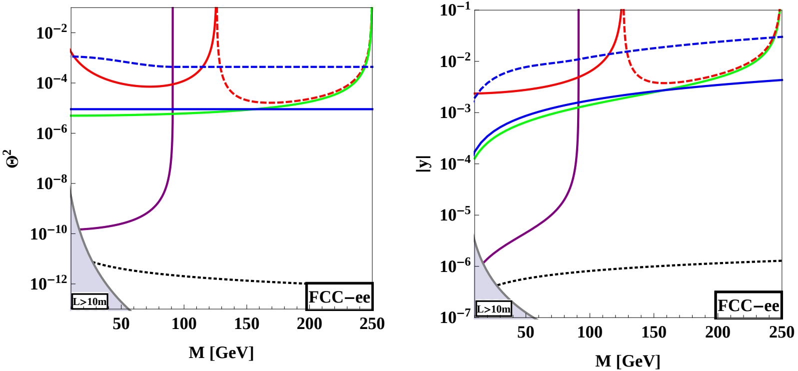
$*$ Currently dominated by $h \to \gamma\gamma$.

Improvements in precision at future lepton colliders

All processes discussed so far could be measured much more precisely at future lepton colliders (e.g. at the FCC-ee: 10^{12} Z bosons, 10^{8} W bosons, 10^{6} Higgs bosons and top quarks):

- Estimated precision for ILC, CEPC and FCC-ee for the EWPO, see Backup VIII.
- Estimated precision for Higgs boson production and decay, see Backup IX.
- Estimated improvement of lepton universality, see Backup IX.
- Top, W and Higgs mass measurements can improve parametric theory uncertainty.

Prospects of sensitivity at the FCC-ee (CEPC and ILC in the backup)



Direct searches

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━ Higgs → WW @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$

╍ $e^+e^- \to h + E_{T,\mathrm{miss}}$ @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$

━ $e^+e^- \to$ 4 leptons* @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

Other

━ Precision constraints: $|y|=\sqrt{|y_{\nu_e}|^2+|y_{\nu_\mu}|^2}$, $\Theta^2=|\theta_e|^2+|\theta_\mu|^2$

╍ Precision constraints: $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$

╍ Unprotected type−I seesaw

Antusch, Fischer (2015)

∗ Preliminary estimate using statistical uncertainty only.

Summary and conclusions

- Sterile neutrinos are well motivated extensions of the SM.
- Symmetry protected scenarios allow for electroweak scale sterile neutrino masses and $\mathcal{O}(1)$ active-sterile mixings.
- For $M >$ TeV, model independent constraints are possible via the MUV scheme.
  - ⋆ We presented state-of-the-art constraints.
  - ⋆ Discussed sensitivities of future lepton colliders (FCC-ee up to $M \sim 60$ TeV).
- For $M \sim \Lambda_{\mathrm{EW}}$:
  - ⋆ we presented first estimates for searches of sterile neutrino decay products at future lepton colliders.
  - ⋆ The most sensitive search is given at the Z pole which can test θ^2 down to 10^{-10}.
  - ⋆ The different search channels provide complementary information on the sterile neutrino parameters.

Thank you for your attention.

Backup I - MUV scheme formalism

- Lepton number violating mass operator:

$$\delta\mathscr{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta}\, (\overline{L^c}_\alpha \tilde{\phi}^*)(\tilde{\phi}^\dagger\, L_\beta)$$

- Lepton number conserving "kinetic" operator:

$$\delta\mathscr{L}^{d=6} = c^{d=6}_{\alpha\beta}\, (\overline{L}_\alpha \tilde{\phi}) i\partial\!\!\!/ (\tilde{\phi}^\dagger L_\beta)$$

- Mass-mixing & kinetic terms ⇒ MUV $\neq$ SM.
- Theory prediction for observable O: separating tree- and loop-level:

$$\begin{aligned} O_{\mathrm{MUV}} &= O^{\mathrm{tree}}_{\mathrm{MUV}} + \delta O^{\mathrm{loop}}_{\mathrm{MUV}} \\ &= O^{\mathrm{tree}}_{\mathrm{SM}}(1+\delta^{\mathrm{tree}}_{\mathrm{MUV}}) + \delta O^{\mathrm{loop}}_{\mathrm{SM}}(1+\delta^{\mathrm{loop}}_{\mathrm{MUV}})\,, \\ &= O_{\mathrm{SM}} + O^{\mathrm{tree}}_{\mathrm{SM}}\,\delta^{\mathrm{tree}}_{\mathrm{MUV}} + \delta O^{\mathrm{loop}}_{\mathrm{SM}}\delta^{\mathrm{loop}}_{\mathrm{MUV}} \\ &= O_{\mathrm{SM}} + (O_{\mathrm{SM}} - \delta O^{\mathrm{loop}}_{\mathrm{SM}})\,\delta^{\mathrm{tree}}_{\mathrm{MUV}} + \delta O^{\mathrm{loop}}_{\mathrm{SM}}\,\delta^{\mathrm{loop}}_{\mathrm{MUV}} \\ &= O_{\mathrm{SM}}(1+\delta^{\mathrm{tree}}_{\mathrm{MUV}}) + \ldots\,, \end{aligned}$$

- Theory prediction at leading order in the MUV parameters: $\delta^{tree}_{\mathrm{MUV}}$ is sufficient at the moment.

Backup II - EWPO

Experimental results and SM predictions for the EWPO, and the modification in the MUV scheme, to first order in $\varepsilon_{\alpha\alpha}$.

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)

Backup III - lepton universality

MUV prediction:

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

	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 IV - CKM unitarity constraint

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

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)

In the MUV scheme:

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

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

For the kaon decay processes we have:

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

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

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 V - lepton flavour violation

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

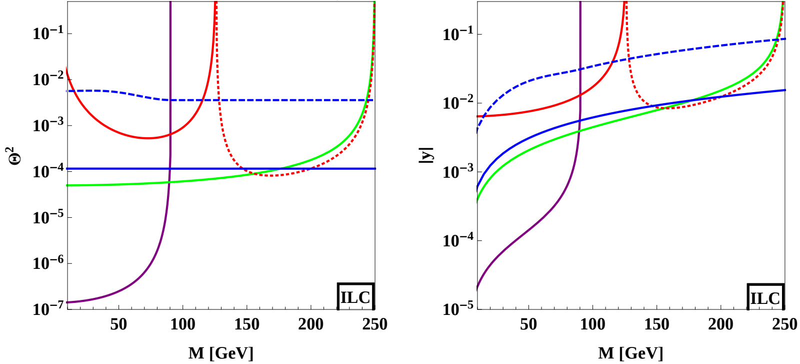
Process	MUV Prediction	Bound	Constraint on $\lvert\varepsilon_{\alpha\beta}\rvert$
$\mu \to e\gamma$	$2.4 \times 10^{-3} \lvert\varepsilon_{\mu e}\rvert^2$	5.7×10^{-13}	$\varepsilon_{\mu e} < 1.5 \times 10^{-5}$
$\tau \to e\gamma$	$4.3 \times 10^{-4} \lvert\varepsilon_{\tau e}\rvert^2$	1.5×10^{-8}	$\varepsilon_{\tau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

Backup VI - ILC summary plot



Direct searches

▬ Z pole search @2σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$

▬ Higgs → WW @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$

╍ $e^+e^-\to h + E_{T,\text{miss}}$ @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$

▬ $e^+e^-\to$ 4 leptons* @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

Other

▬ Precision constraints: $|y|=\sqrt{|y_{\nu_e}|^2+|y_{\nu_\mu}|^2}$, $\Theta^2=|\theta_e|^2+|\theta_\mu|^2$

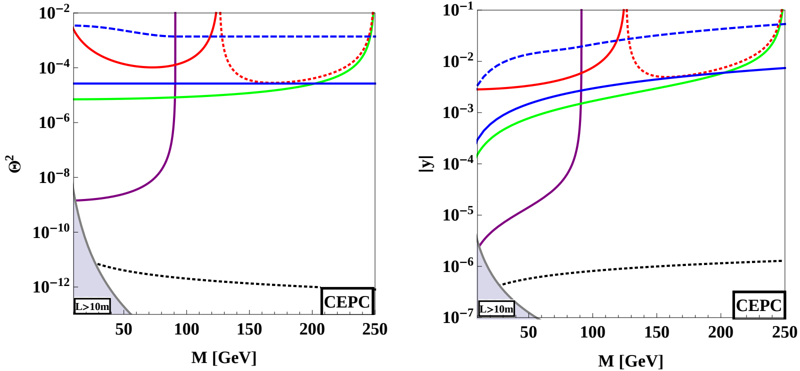
╍ Precision constraints: $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$

╍ Unprotected type−I seesaw

Antusch, Fischer (2015)

∗ Preliminary estimate using statistical uncertainty only.

Backup VII - CEPC summary plot



Direct searches

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━ $e^+e^- \to$ 4 leptons* @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

Other

━ Precision constraints: $|y|=\sqrt{|y_{\nu_e}|^2+|y_{\nu_\mu}|^2}$, $\Theta^2=|\theta_e|^2+|\theta_\mu|^2$

╍ Precision constraints: $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$

┅ Unprotected type−I seesaw

Antusch, Fischer (2015)

∗ Preliminary estimate using statistical uncertainty only.

Backup VIII - precision estimates for EWPOs

Observable	ILC	FCC-ee	CEPC	CEPC*
R_ℓ	0.004	0.001	0.01	0.003*
R_{inv}	0.01	0.002	0.012	0.006*
R_b	0.0002	0.00002	0.00017	0.00007*
M_W [MeV]	2.5	0.5	0.5	0.5
$s_{eff}^{2,\ell}$	1.3×10^{-5}	1×10^{-6}	2.3×10^{-5}	$3.3 \times 10^{-6*}$
σ_h^0 [nb]	0.025	0.0025	n.a.	0.008*
Γ_ℓ [MeV]	0.042	0.0042	n.a.	0.014*
Reference	1310.6708	1308.6176	Ruan (2014)†	scaled*

- † Private communication.
- ∗ Assumption: CEPC produces 10^{11} Z bosons, compared to the 10^{12} Z bosons @FCC-ee.

⇒ Uncertainties scaled: $\delta_{\text{CEPC}} = \delta_{\text{FCC-ee}} \times \sqrt{10}$.

Backup IX - precision estimates for Higgs and W properties

Precision for one year of data taking and one detector (we consider 10 years of data taking with two detectors):

Branching ratio	ILC [%]	CEPC [%]	FCC-ee [%]
$\delta Br_{h\to WW}$	6.4	1.3	0.9
$\delta Br_{h\to ZZ}$	19	5.1	3.1
$\delta Br_{h\to\gamma\gamma}$	35	8	3.0
Reference	1310.6708	1411.5606	1308.6176

Expected W boson yield:

	Aleph	ILC	CEPC	FCC-ee
$\#W$'s prod.	10^4	10^7	10^8	2×10^8
$\delta_{\mathrm{stat.}}$	0.011	3×10^{-4}	10^{-4}	7×10^{-4}
$\delta_{\mathrm{syst.}}$	0.007	n.a.	n.a.	n.a.

At the moment it seems $\delta_{\mathrm{syst.}} \sim \delta_{theo.} \sim 10^{-3}$ is realistic.

(Not considered in the analysis.