Neutrino mass physics at lepton colliders

Oliver Fischer

University of Basel, Switzerland
soon: Karlsruhe Institute of Technology, Germany

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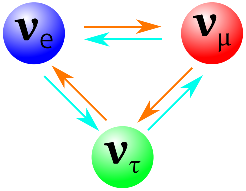
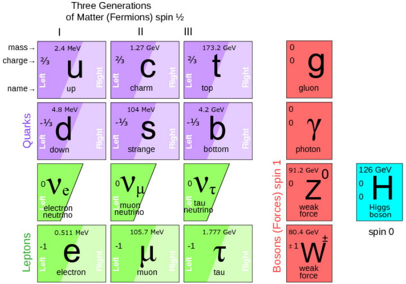
Motivation for sterile neutrinos





Shaposhnikov *et al.*

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

Type I seesaw

The "naïve" version:

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

The symmetry protected scenario:

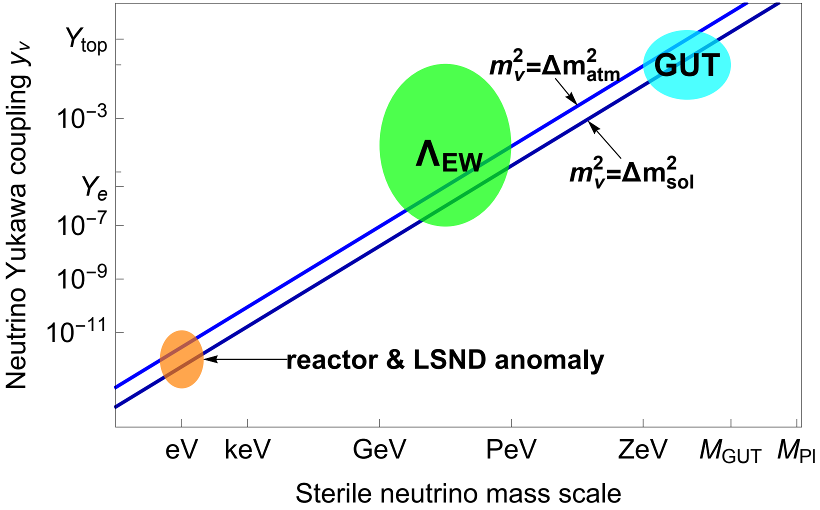
- Symmetry: for instance lepton number or $B - L$.
- A $(2\ \nu_L,\ 2\ \nu_R)$ example:

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

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

$\Rightarrow$ Large ratio of y_ν and M_R can be compatible with m_{ν_i}.

The Big Picture



Symmetry Protected Seesaw Scenario

Benchmark model for future collider 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:

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu1} & \mathcal{N}_{\mu2} & \mathcal{N}_{\mu3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau1} & \mathcal{N}_{\tau2} & \mathcal{N}_{\tau3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\mathrm{i}}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

Heavy neutrino interactions

- **Charged current** (CC):

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

- **Neutral current** (NC):

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

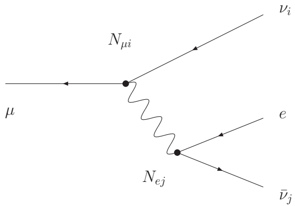
- Higgs boson **Yukawa** interaction:

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

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

Precision observables in seesaw scenarii

Input parameters: M_Z, $\alpha(M_Z)$, G_F.



The Fermi constant:

- Muon decay $\propto \left(NN^\dagger\right)_{ee}\left(NN^\dagger\right)_{\mu\mu}$
- Fermi constant $G_F \neq$ muon decay constant G_μ.
- Tree-level relation: $G_F = \frac{G_\mu}{\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}} = \frac{\alpha\pi}{\sqrt{2}s_W^2 c_W^2 m_Z^2}$
- Analogous: Observables involving weak decays.

$\Rightarrow$ Theory prediction for electroweak observables.

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

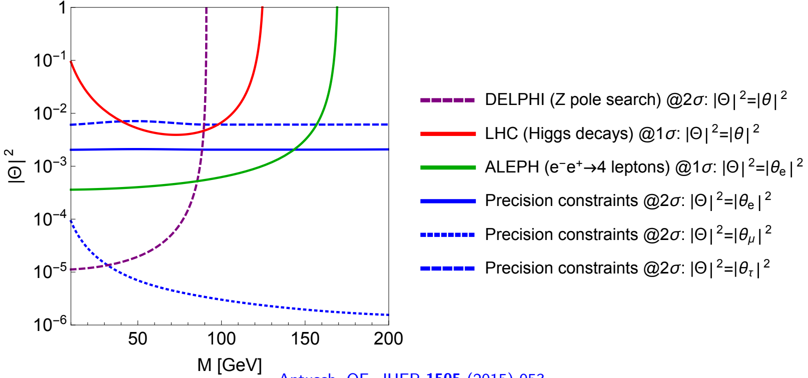
  Lots of details in the backup - please ask!
- Highest posterior density intervals at 90% Bayesian C.L.:

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

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)



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

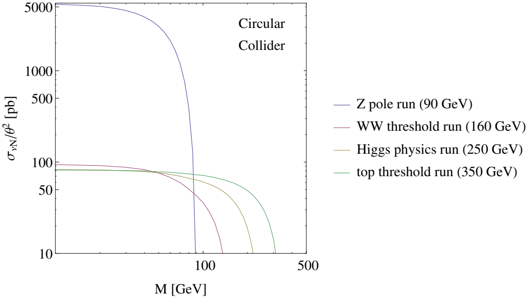
- Z pole search: limits from Z branching ratios .

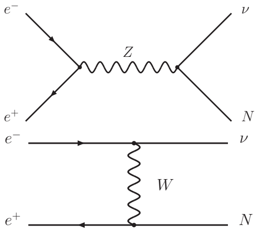
  Abreu *et al.* Z.Phys. C74 (1997) 57-71

- Higgs decays: Best constraints from $h \to \gamma\gamma$.
- WW production cross section: $\delta\sigma^{WW}_{\mathrm{SM}} = 0.011_{stat} + 0.007_{syst}$

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

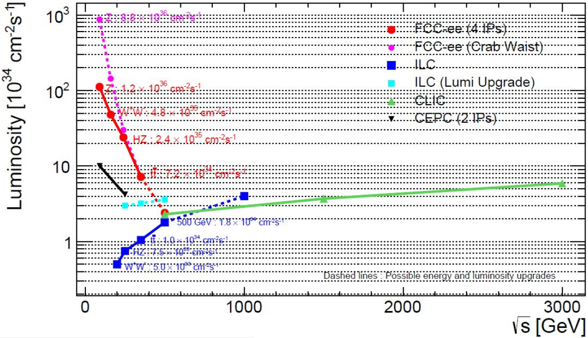
Heavy Neutrino Production in electron-positron collisions

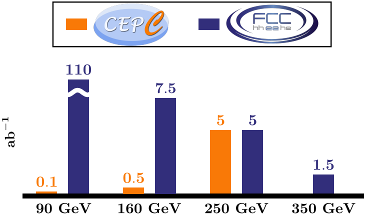


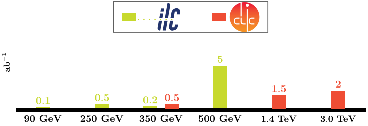


- Z pole: production via s-channel Z, sensitive to $|\theta|^2$.
- At higher energies: t-channel W, production sensitive to $|\theta_e|^2$.
- At Z pole very large instantaneous luminosities are feasible.

Luminosities at lepton colliders (old)







Signatures for direct searches

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

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.
- For masses below m_W lepton isolation becomes an issue.

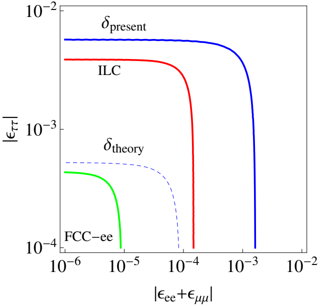
S. Dube, D. Gadkari and A. M. Thalapillil, arXiv:1707.00008 [hep-ph].

Indirect Signatures: Electroweak precision tests

Observable	LEP precision	from CEPC preCDR
M_W [MeV]	33	3
$\sin^2\theta_W^{\rm eff}$	0.07%	0.01%
R_b	0.3%	0.08%
R_c	0.3%	0.07%
R_{inv}	0.27%	8.9×10^{-4}
R_ℓ	0.1%	0.1%
Γ_ℓ	0.1%	0.1%
σ_h^0 [nb]	8.9×10^{-4}	1×10^{-4}

FCC-ee: much more ambitious;

ILC: no strong Z pole program.



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

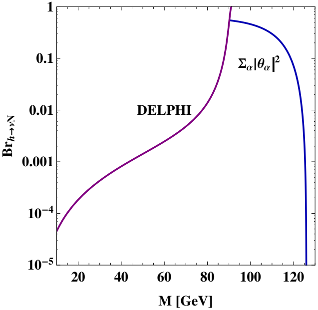
- Measuring the non-unitarity of the PMNS matrix.
- Improvement required: $\delta_{\rm theory}$ and $\delta_{\rm syst}$.
- Not included: lepton universality tests of W decays
- Not included: rare charged LFV ℓ decays

Indirect signatures: Higgs boson properties

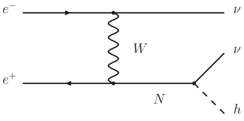
Higgs boson branching ratios:

- New decay channel $h \to \nu N$
- Large branching ratio possible, modified $\mathrm{Br}_{h\to\mathrm{SM}}$
- Precision $\mathrm{Br}_{h\to WW} \sim 10^{-3}$

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



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

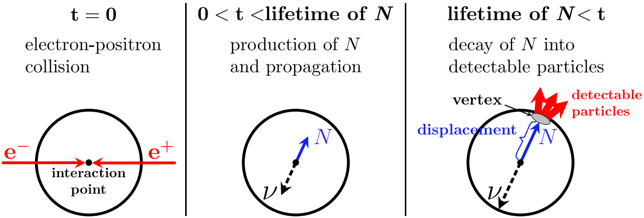


Higgs production:

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

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

Exotic signature: displaced vertices I



$t = 0$

electron-positron collision

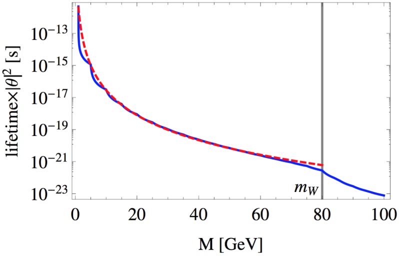
$0 < t <$ lifetime of N

production of N and propagation

lifetime of $N < t$

decay of N into detectable particles

- Lifetime $\sim \mathcal{O}(1 - 100)$ ps.
- Assumption: no SM background for displacements > 0.1 mm.
- Considered ILC detector SiD as benchmark.

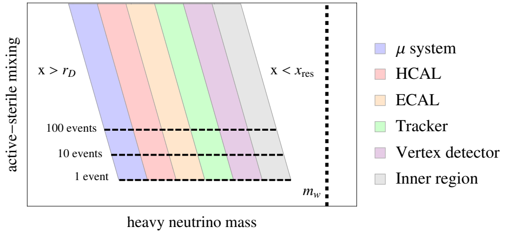


S. Antusch, E. Cazzato and OF, JHEP **1612**, 007 (2016)

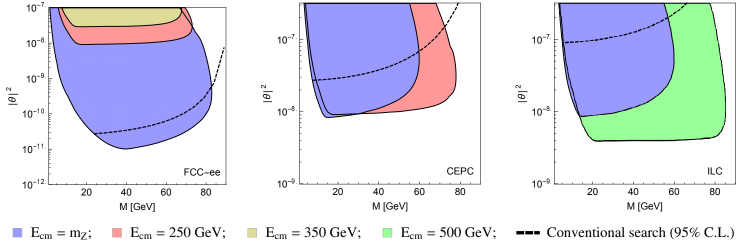
A. Blondel *et al.*, Nucl. Part. Phys. Proc. **273-275** (2016) 1883

Exotic signature: displaced vertices II

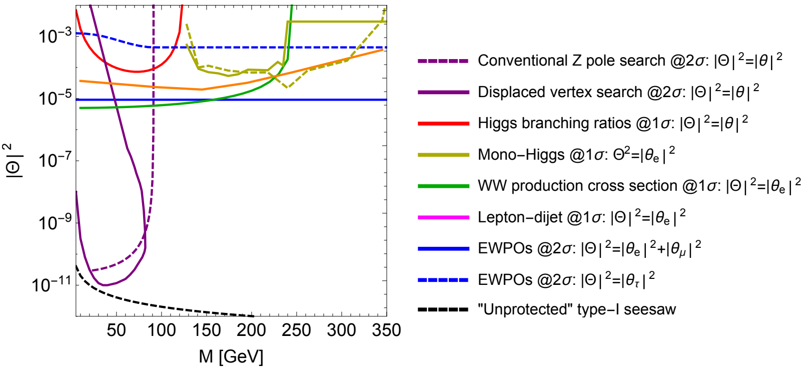
Schematic of the detector components' sensitivities:



Sensitivities:



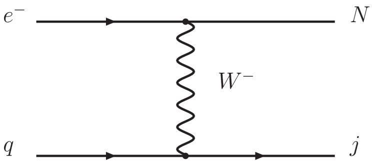
Summary: FCC-ee sensitivities



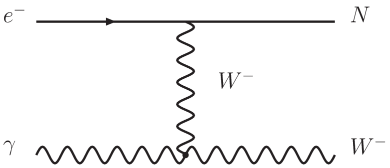
- Displaced vertex searches test $|\theta|^2 \sim 10^{-11}$ for $M \leq m_W$.
- EWPOs test $|\theta|^2 \sim 10^{-5}$ up to $M \sim 60$ TeV with $\mathcal{O}(1)$ Yukawa couplings.

Promising search strategies at electron-proton colliders

Heavy neutrino production at electron-proton colliders



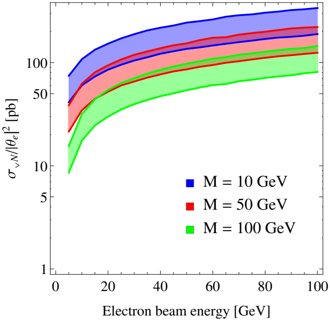
$\mathbf{W_t^{(q)}}$



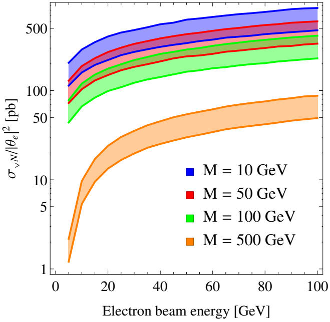
$\mathbf{W_t^{(\gamma)}}$

- Leading order production of heavy neutrino mass eigenstate.
- $\mathbf{W_t^{(q)}}$: dominant at lower center-of-mass energies.
- $\mathbf{W_t^{(\gamma)}}$: relevant for larger masses.

Production cross sections ($\mathbf{W_t^{(q)}}$)



LHeC



FCC-eh

For 60 GeV as benchmark for the electron beam E_e:

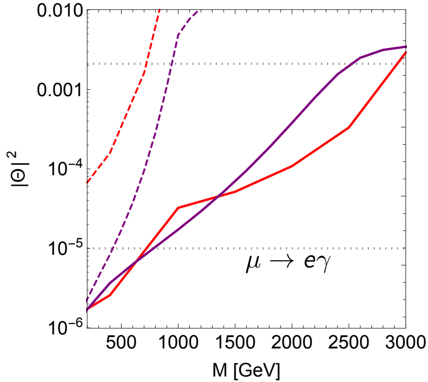
- $\sigma_{\nu N}$ increase of $\sim 30\%$ for $E_e \to 100$ GeV.
- Increased by $\sim 80\%$ when including polarisation.
- Consider 1 ab^{-1} (for FCC-eh and LHeC).

Signal channels from $\mathbf{W}_t^{(q)}$

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) signature for $\alpha \neq e$, $\beta \neq \alpha$, and $\gamma \neq \alpha, \beta$
- Unambiguous lepton-number-violating final states, e.g. e^+jjj.
- More (and more complex) signatures from $\mathbf{W}_\mathbf{t}^{(\gamma)}$.

Lepton-flavour-violating signatures



Dashed lines denote the LHeC

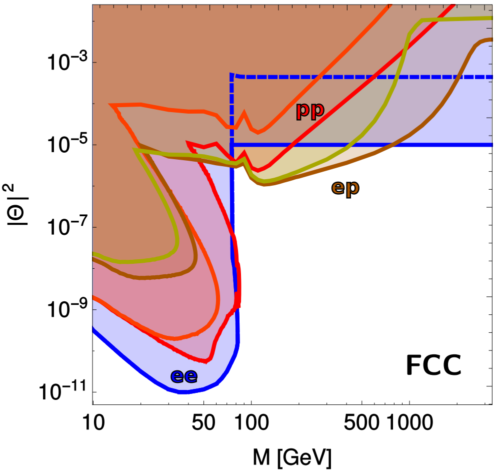
Antusch, Cazzato, OF; [1612.02728]

- Very sensitive tests of combinations $|\theta_e\theta_\alpha|$.
- Upper bounds:
  $|\theta_e\theta_\mu|$ from $\mu \to e\gamma$ (MEG); $|\theta_e\theta_\tau|$ from precision data.
- Requires $|\theta_\alpha| \gtrsim |\theta_e|$ for sizeable branching ratios.

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.

Summary

- Present constraints: active-sterile mixing $|\theta|^2 \leq 10^{-3}$.
- Search strategies at lepton colliders:
  - **Direct:** lepton-dijet, dilepton, dijets
  - **Higgs:** production and decay channels
  - **EWPO:** measurement of PMNS non-unitarity
  - **Displaced vertices:** best sensitivity for $M < m_W$
  - **pp/ep:** LFV dilepton-dijet/lepton-trijet & displaced vertices
- **Synergy:** The combination of direct and indirect signatures at ee/pp/ep will allow to test model specific predictions.

⇒ Testing the origin of neutrino masses.

Conclusion

- CEPC CDR writeup this year
- FCC-ee CDR writeup next year
- ILC & LHeC seeking additional physics motivation (neutrinos NOT included yet)

Extremely important input
for future collider projects!

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

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

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	$f^{\mathrm{process}}(\varepsilon)$	$\lvert V_{us}\rvert$
$\frac{B(\tau\to K\nu)}{B(\tau\to\pi\nu)}$	$\varepsilon_{\mu\mu}$	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.

Backup V - 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
$s_{eff}^{2,\ell}$	$1.3\ \times 10^{-5}$	$1\ \times 10^{-6}$	$2.3\ \times 10^{-5}$	$3.3\ \times 10^{-6}*$
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: $\delta_{\rm CEPC} = \delta_{\rm FCC-ee} \times \sqrt{10}$.