Sterile Neutrino Searches at the FCC-eh

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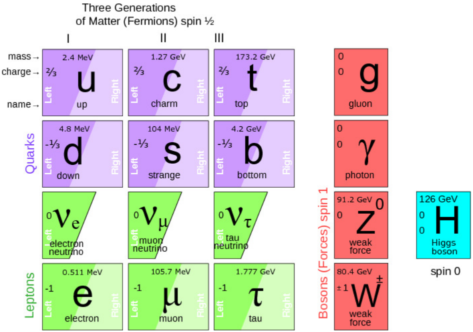
Based on S. Antusch, E. Cazzato, OF, 1612.02728

Motivation for sterile neutrinos



- Neutrino oscillations are evidence for new physics.
  $\Rightarrow$ *At least* two light neutrinos are massive.
- Sterile neutrinos for type I seesaw mechanism.
- Few studies on electron-proton collider phenomenology.

Present indirect constraints 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.:

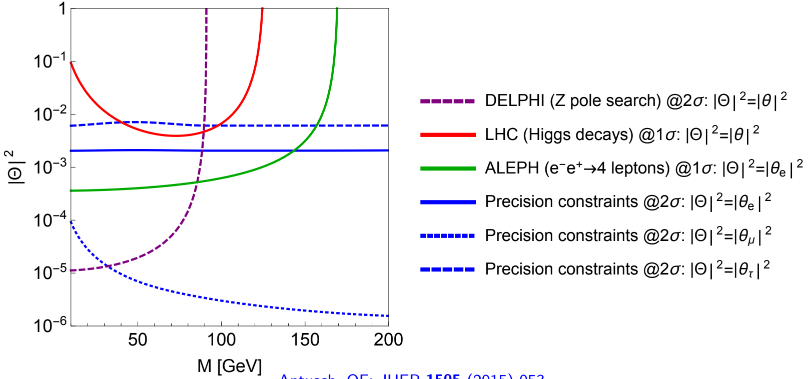
-0.0021	$\leq \varepsilon_{ee} \leq$	-0.0002	$\lvert\varepsilon_{e\mu}\rvert$	$<$	1.0×10^{-5}
-0.0004	$\leq \varepsilon_{\mu\mu} \leq$	0	$\lvert\varepsilon_{e\tau}\rvert$	$<$	2.1×10^{-3}
-0.0053	$\leq \varepsilon_{\tau\tau} \leq$	0	$\lvert\varepsilon_{\mu\tau}\rvert$	$<$	8.0×10^{-4}

Antusch, OF; JHEP 1410 (2014) 094

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

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

Present constraints including direct searches



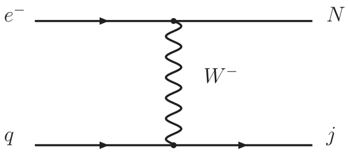
Antusch, OF; JHEP **1505** (2015) 053

- Z pole search: limits from Z branching ratios .

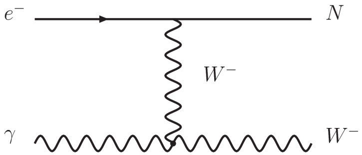
  Abreu *et al.* Z.Phys. C74 (1997) 57-71
- Higgs decays: Best constraints from $h \to \gamma\gamma$.
- Direct Search: $\delta\sigma_{\rm SM}^{WW} = 0.011_{stat} + 0.007_{syst}$

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

Heavy neutrino production at electron-proton colliders



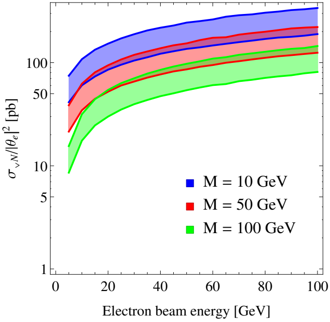
$\mathbf{W_t^{(q)}}$



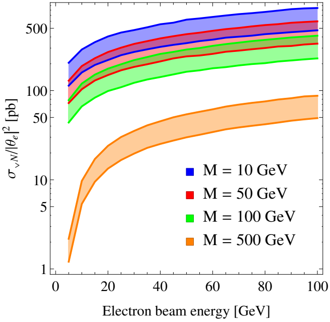
$\mathbf{W_t^{(\gamma)}}$

- 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



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).

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

Signatures from $\mathbf{W}_t^{(\gamma)}$

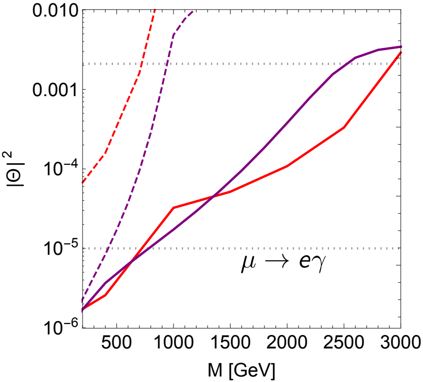
Name	Final State	$\lvert\theta_\alpha\rvert$ Dependency	LFV
lepton-quadrijet	$jjjj\ell_\alpha^-$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}$	✓
dilepton-dijet	$\ell_\alpha^-\ell_\beta^+\nu jj$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}$	✓
trilepton	$\ell_\alpha^-\ell_\beta^-\ell_\gamma^+\nu\nu$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}$	✓
quadrijet	$jjjj\nu$	$\lvert\theta_e\rvert^2$	×
electron-di-b-jet	$e^- b\bar{b}\nu\nu$	$\lvert\theta_e\rvert^2$	×
dijet	$jj\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×
monolepton	$\ell_\alpha^-\nu\nu\nu\nu$	$\lvert\theta_e\rvert^2$	×

- Additional signatures of LFV/LNV.
- Cross section suppressed by the small PDF of the photon.
- More efficient at higher center-of-mass energies.

Caveat:

- ⋆ For the following "first look" we confined ourselves to the parton level.
- ⋆ The analysis on the reconstructed level is about to begin.

First look at lepton-flavour-violating signatures at FCC-eh



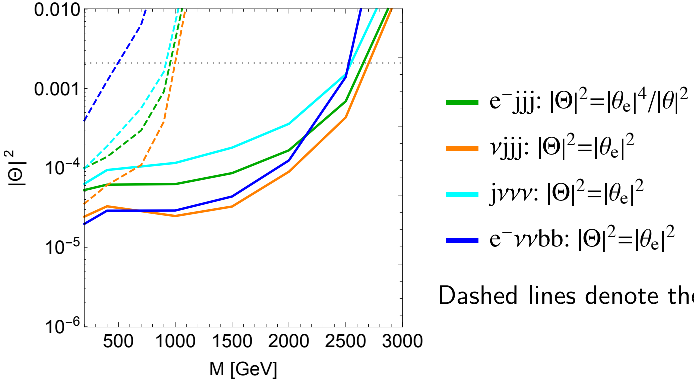
ℓ_α^-jjj ($\alpha=\mu,\tau$): $|\Theta|^2=|\theta_\alpha\theta_\tau|^2/|\theta|^2$

$\tau^-\mu^+$jν: $|\Theta|^2=|\theta_e\theta_\tau|^2/|\theta|^2$

Dashed lines denote the LHeC

- 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.

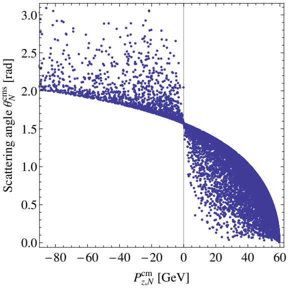
Lepton-flavour-conserving signatures at FCC-eh



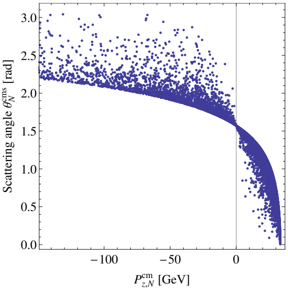
Dashed lines denote the LHeC

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

A glance at angular and momentum distributions



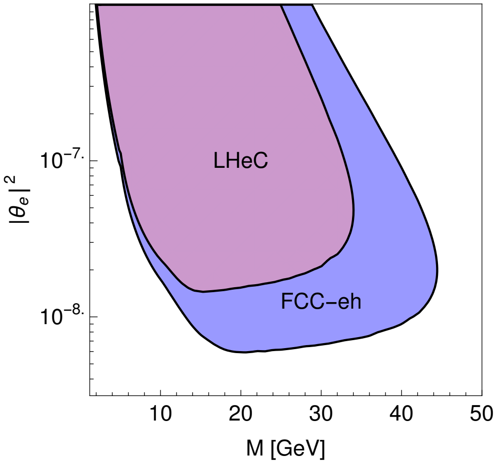
$M = 10$ GeV



$M = 80$ GeV

- Electron beams with 60 GeV and no polarisation.
- Simulated 10k events each for $M = 10, ..., 90$ GeV (WHIZARD).
- For a "first look": average Lorentz factor of 5.

Displaced vertex searches



- Displacements of 1 mm to 1 m are assumed free of background.
- Detector geometry not included.

Conclusions

- Electron-proton colliders produce heavy neutrinos via $|\theta_e|$.
- Present constraints limit active-sterile mixing to $\sim 10^{-3}$.
- Most sensitive searches for sterile neutrinos with masses
  - below m_W via displaced vertices.
  - above $\mathcal{O}(100)$ GeV via lepton-flavour violating signatures.
- Also lepton-number conserving signatures provide promising sensitivities.

$\Rightarrow$ Direct searches for sterile neutrinos at the FCC-eh have great prospects at testing sterile neutrinos with masses up to 3 TeV!

Personal opinion:

It is a wasted proton beam that does

not

collide with a lepton beam.