Sterile Neutrinos at Future Colliders

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Motivation

- The Standard Model (SM) does not include ν–masses.

$\Rightarrow$ Theory extension necessary!

- Most popular: ν_R ("sterile" or "right-handed" neutrinos).

$\Rightarrow$ ν_R affects low energy precision observables.

$\Rightarrow$ Probe sterile neutrino extensions of the SM.

Seesaw and Minimal Unitary Violation 1

arXiv:1407.6607

- Seesaw extension of the SM:

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{1}{2}\overline{\nu_{\rm R}^{I}} M^{N}_{IJ} \nu_{\rm R}^{cJ} - (Y_N)_{I\alpha} \overline{\nu_{\rm R}^{I}} \widetilde{\phi}^\dagger L^\alpha + {\rm H.c.}$$

- Effective theory: Minimal Unitarity Violation (MUV) scheme

$$\mathscr{L}_{\rm MUV} = \mathscr{L}_{\rm SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6}\,.$$

  - Dim 5 operator $\equiv$ Weinberg operator: generates light neutrino masses after EW symmetry breaking

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, L_\beta\right) + {\rm H.c.}\,,$$

  - Mass matrix for light neutrinos (seesaw formula):

$$(m_\nu)_{\alpha\beta} = -\frac{v_{\rm EW}^2}{2} c^{d=5}_{\alpha\beta} = -\frac{v_{\rm EW}^2}{2} (Y_N^T)_{\alpha I} (M_N)^{-1}_{IJ} (Y_N)_{J\beta}\,.$$

$\Rightarrow$ Leptonic mixing

What is leptonic mixing?

- Diagonalisation of a mass matrix $\mathcal{M} \Rightarrow$ mass Eigenstates.
- Mass Eigenstates $\neq$ flavour Eigenstates.
- Analogously to CKM quark mixing.
- Leptonic mixing can be expressed by the PMNS matrix U.
- PMNS matrix is unitary: $UU^\dagger = 1$

Seesaw and Minimal Unitary Violation 2

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- Dim 6 operator: contribution to the kinetic term of the light neutrino after EW symmetry breaking
  $\delta\mathcal{L}^{d=6} = c^{d=6}_{\alpha\beta} \left(\overline{L}_\alpha \tilde{\phi}\right) i\partial\!\!\!/ \left(\tilde{\phi}^\dagger L_\beta\right)$

- Kinetic term of the neutrinos:
  $\mathscr{L}_{\mathrm{kin},\nu} = i\,\overline{\nu}_\alpha\,\partial\!\!\!/\,(1 + \frac{v_{\mathrm{EW}}^2}{2} c^{d=6})_{\alpha\beta}\,\nu_\beta = i\,\overline{\nu}_\alpha\,\partial\!\!\!/\,(NN^\dagger)^{-1}_{\alpha\beta}\,\nu_\beta\,.$

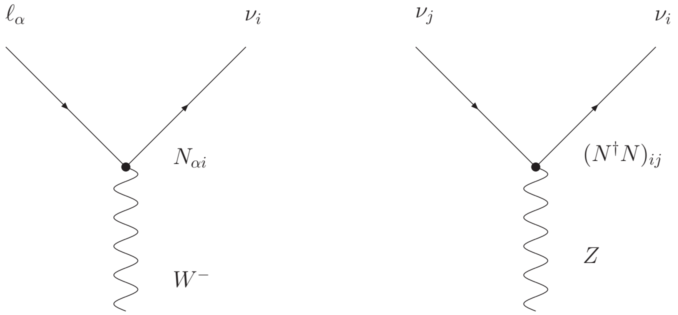
$\Rightarrow$ Performing the canonical normalisation of $\mathscr{L}_{\mathrm{kin},\nu}$: induces a **non**-unitary leptonic mixing matrix N.

$\Rightarrow$ Identify contribution from dim 6 operator as the deviation from unitarity.

What is non-unitarity in this context?

- Non-unitarity in leptonic mixing: $UU^\dagger = 1 \quad \longrightarrow \quad NN^\dagger \neq 1$
- Parametrize the deviation from unitarity ("1") by
  $(NN^\dagger)_{\alpha\beta} = 1_{\alpha\beta} + \varepsilon_{\alpha\beta} \qquad$ for $\alpha, \beta \in \{e, \mu, \tau\}$
- Six non-unitarity parameters: ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$, $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$, $\varepsilon_{\mu\tau}$

Modified Weak Currents



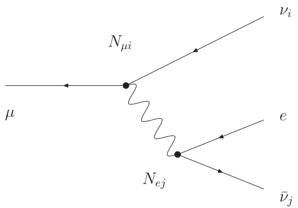
$$\left(J^{\mu,\pm}\right)_{\alpha i} = \ell_\alpha \gamma^\mu \nu_i \, N_{\alpha i} \,, \qquad \left(J^{\mu,0}\right)_{ij} = \nu_i \gamma^\mu \nu_j \, \left(N^\dagger N\right)_{ij}$$

Observable Consequences

Input parameters:

- Fermi constant: $G_F = 1.1663787(6) \times 10^{-5}\text{GeV}^{-2}$
- Fine-structure constant: $\alpha(m_z)^{-1} = 127.944(14)$
- Z pole mass: $m_Z = 91.1875(21)\text{GeV}$

Fermi constant with non-unitarity:



- Fermi constant $G_F \neq$ muon decay constant G_μ.
- Tree-level relation: $G_\mu^2 = G_F^2 (NN^\dagger)_{\mu\mu}(NN^\dagger)_{ee}$

EWPO Modifications with Leptonic Non-Unitarity

Electroweak Precision Observables (EWPO):

Weak mixing angle θ_W:

- SM tree-level relation: $\sin^2(\theta_W)\cos^2(\theta_W) = \frac{\alpha(m_Z)\pi}{\sqrt{2}G_F m_Z^2}$

- With non-unitarity:

$$\sin^2(\theta_W) = \frac{1}{2}\left[1 - \sqrt{1 - \frac{2\sqrt{2}\alpha\pi}{G_\mu m_Z^2}\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}}\right]$$

$\Rightarrow$ Obtain leading order expression in non-unitarity parameters $\varepsilon_{\alpha\beta}$.

EWPO Modifications with Leptonic Non-Unitarity

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Non-Unitarity
$[R_\ell]_{\rm SM}\,(1-0.15\,\varepsilon_+)$
$[R_b]_{\rm SM}\,(1+0.03\,\varepsilon_+)$
$[R_c]_{\rm SM}\,(1-0.06\,\varepsilon_+)$
$\left[\sigma^0_{had}\right]_{\rm SM}\,(1-0.25\,\varepsilon_+-0.27\varepsilon_{\tau\tau})$
$[R_{inv}]_{\rm SM}\,(1+0.75\,\varepsilon_++0.67\varepsilon_{\tau\tau})$
$[M_W]_{\rm SM}(1-0.11\,\varepsilon_+)$
$[\Gamma_{\rm lept}]_{\rm SM}(1-0.59\,\varepsilon_+)$
$[(s_{W,\rm eff}^{\ell,\rm lep})^2]_{\rm SM}(1+0.71\,\varepsilon_+)$
$[(s_{W,\rm eff}^{\ell,\rm had})^2]_{\rm SM}(1+0.71\,\varepsilon_+)$

$$\varepsilon_+ = \varepsilon_{ee} + \varepsilon_{\mu\mu}$$

Modification to the EWPO in the MUV scheme, to leading order in non-unitarity parameters $\varepsilon_{\alpha\beta}$.

Global Fit to Precision Data

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⇒ Highest posterior density intervals at 90% Bayesian C.L.:

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

⇒ Hints for non-unitarity at the 2σ level.

Sensitivity to Non-Unitarity from EWPO at Future Colliders

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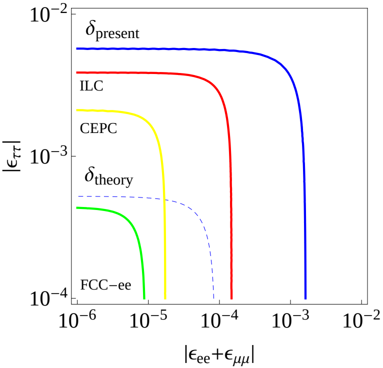
- theoretical and experimental constrains (present).
- **I**nternational **L**inear **C**ollider in Japan?
- **C**ircular **E**lectron **P**ositron **C**ollider in China
- **F**uture **C**ircular **C**ollider by CERN



⇒ Future machines will turn hint into a discovery!

Summary

- Non-unitarity of the leptonic mixing matrix at low energies is a generic signal of extensions of the SM with "sterile" or "right-handed" neutrinos.
- Very powerful probe of non-unitarity via EWPOs.
- Global fit of non-unitarity to precision data:
  - Hints for non-unitarity at the 2σ level.
  - If true we will certainly find it with the next lepton machine!

Precision for Discovery!