Tests of Non-Unitarity in Leptonic Mixing at the FCC-ee

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arXiv:1407.6607
JHEP 1410 (2014) 096

FCC-ee Physics workshop #8
Paris, 27-29 October 2014

Motivation & Outline

- Existence of massive neutral leptons (ν_R) is well motivated
- Affect many precision observables, in particular the EWPO
- Higgs boson discovery increases sensitivity of EWPO
- This talk:
  (i) Assumption: New physics at a scale $\Lambda > M_Z$
  (ii) Employ: Minimal Unitarity Violating scheme
  (iii) Present bounds
  (iv) **Future sensitivities at the FCC-ee**

Non-Unitarity of the Leptonic Mixing Matrix

Presence of massive right-handed neutrinos (ν_R):

$$\mathscr{L}_{\text{Theory}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{\nu_R}$$

Leads to mixing of the neutral states (ν_L, ν_R):

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

- $N \sim$ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- PMNS as submatrix in general **not** unitary

Minimal Unitarity Violation (MUV) Scheme

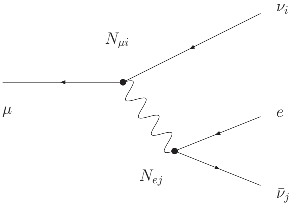
- For the formalism, see Backup I.
- Modification of the weak currents with neutrinos:

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

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

Theory Prediction for the EWPO

- Highest precision: M_Z, $\alpha(M_Z)$, G_F.



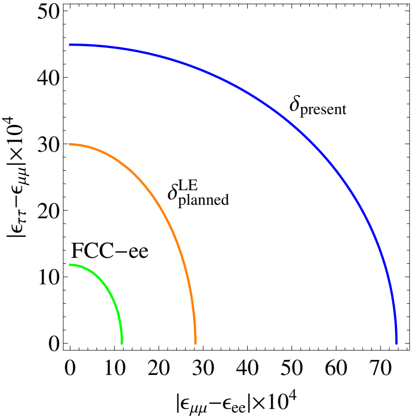
- Muon decay $\propto \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$
- Fermi constant $G_F \neq$ muon decay constant G_μ.
- Tree-level relation: $G_F = \frac{G_\mu}{\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}} = \frac{\alpha\pi}{\sqrt{2}s_W^2 c_W^2 m_Z^2}$
- Analogous: Observables involving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

Global Fit to Precision Data

- MUV theory prediction for 34 precision observables, see Backup II, III, IV, V.
- MCMC fit of six parameters $\varepsilon_{\alpha\beta}$, including correlations.
- Highest posterior density intervals at 90% Bayesian C.L.:

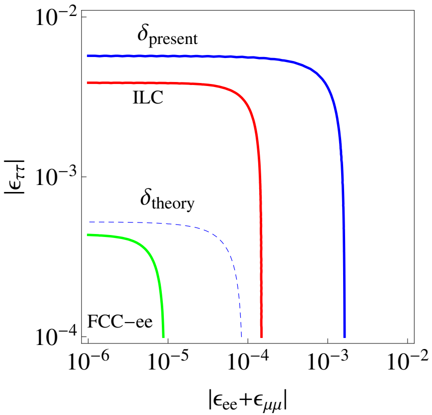
$$
\begin{array}{rcrcl}
-0.0021 & \leq \varepsilon_{ee} \leq & -0.0002 & |\varepsilon_{e\mu}| < & 1.0 \times 10^{-5} \\
-0.0004 & \leq \varepsilon_{\mu\mu} \leq & 0 & |\varepsilon_{e\tau}| < & 2.1 \times 10^{-3} \\
-0.0053 & \leq \varepsilon_{\tau\tau} \leq & 0 & |\varepsilon_{\mu\tau}| < & 8.0 \times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

Sensitivity to Non-Unitarity from Lepton Universality Tests



- Assumption: SM is true ($\varepsilon \equiv 0$ & $O^{exp} = O^{SM}$).
- Blue line: experimental constrains (present).
- Orange line: experimental sensitivity (planned). *MOLLER, TRIUMF, PSI, NA62, Tau/Charm factories*
- Green line: W decays at the FCC-ee.

Sensitivity to Non-Unitarity from EWPOs



- Non-unitarity of the EWPO only.
- Blue lines: theoretical and experimental constrains (present).
- Red/Green line: ILC/FCC-ee sensitivity, see Backup VI.
- $\varepsilon_{\alpha\beta} = -y^*_\alpha y_\beta v^2_{EW}/(2\, m^2_{\nu_R}) \Rightarrow$ Test m_{ν_R} up to $\sim$ 60 TeV.

Summary & Conclusions

- Minimal Unitarity Violation (MUV) scheme: Model independent description of non-unitary leptonic mixing.
- Global fit of MUV to precision data:
  (ia) Hints for non-unitarity at the 2σ level.
  (ib) What if present hints for non-unitarity are true?
  (See Backup VII.)
  (ii) Not conclusive, therefore used as constraints.
- Outlook on FCC-ee impact:
  (a) Dominant contribution to lepton universality measurements.
  (b) Particularly powerful probe of Non-Unitarity via EWPO.
  (c) Test of ν_R masses up to ~ 60 TeV.
  (d) Full exploitation: Work on theory uncertainties required.
  (e) ...
  (to be discussed next time).

Backup I - Minimal Unitarity Violation (MUV) 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 $\Rightarrow$ MUV $\neq$ SM.
- Theory prediction for observable O: separating tree- and loop-level:

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

- Theory prediction at leading order in the MUV parameters: $\delta^{tree}_{\rm MUV}$ is sufficient at the moment.
- The FCC-ee potential requires the $\delta\delta$ terms to be considered.

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)
$\left[\sigma^0_{had}\right]_{\rm SM}\,(1-0.25(\varepsilon_{ee}+\varepsilon_{\mu\mu})-0.27\varepsilon_\tau)/\mathrm{nb}$	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)
$[M_W]_{\rm SM}(1-0.11(\varepsilon_{ee}+\varepsilon_{\mu\mu}))/\mathrm{GeV}$	80.359(11)	80.385(15)
$[\Gamma_{\rm lept}]_{\rm SM}(1-0.59(\varepsilon_{ee}+\varepsilon_{\mu\mu}))/\mathrm{MeV}$	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
$R^{\ell}_{\mu e}$	$\frac{\Gamma(\tau \to \nu_\tau \mu \bar{\nu}_\mu)}{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}$	1.0018(14)
$R^{\ell}_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)}$	1.0006(21)
$R^{W}_{e\mu}$	$\frac{\Gamma(W \to e \bar{\nu}_e)}{\Gamma(W \to \mu \bar{\nu}_\mu)}$	1.0085(93)
$R^{W}_{\tau\mu}$	$\frac{\Gamma(W \to \tau \bar{\nu}_\tau)}{\Gamma(W \to \mu \bar{\nu}_e)}$	1.032(11)

	Process	Bound
$R^{\pi}_{\mu e}$	$\frac{\Gamma(\pi \to \mu \bar{\nu}_\mu)}{\Gamma(\pi \to e \bar{\nu}_e)}$	1.0021(16)
$R^{\pi}_{\tau\mu}$	$\frac{\Gamma(\tau \to \nu_\tau \pi)}{\Gamma(\pi \to \mu \bar{\nu}_\mu)}$	0.9956(31)
$R^{K}_{\tau\mu}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to \mu \bar{\nu}_\mu)}$	0.9852(72)
$R^{K}_{\tau e}$	$\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to e \bar{\nu}_e)}$	1.018(42)

Backup IV - CKM Unitarity Constraint

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

In the MUV scheme:

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

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

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	$f^{\rm process}(\varepsilon)$	$\lvert V_{us}\rvert$
$\frac{B(\tau\to K\nu)}{B(\tau\to\pi\nu)}$	$\varepsilon_{\mu\mu}$	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}	$\varepsilon_{\mu e} \geq 3.6 \times 10^{-7}$

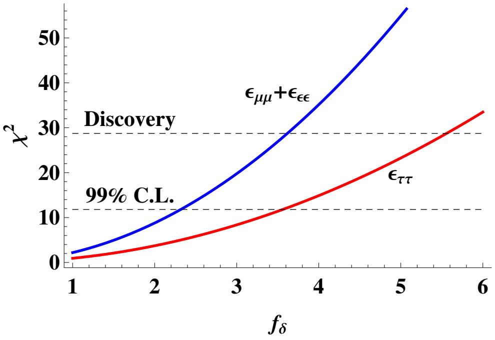
$\Rightarrow R_{\mu e}^{Ti}$ yields a sensitivity to m_{ν_R} up to 0.3 PeV.

Backup VI - Projected Precision of Future Colliders

Conservatively, we used the expected systematic uncertainty for the analysis. Using the statistical uncertainty yields more progressive sensitivities.

Observable	ILC	FCC-ee
R_ℓ	0.004	0.001
R_{inv}	0.01	0.002
R_b	0.0002	0.00002
M_W [MeV]	2.5	0.5
$s^{2,\ell}_{eff}$	1.3×10^{-5}	1×10^{-6}
σ^0_h [nb]	0.025	0.0025
Γ_ℓ [MeV]	0.042	0.0042
$Br(W \to \ell\nu)$	0.003	0.0003
Reference	1310.6708	1308.6176

Backup VII - Discovery of Non-Unitarity in EWPOs



- x-axis: Improvement factor reducing the experimental uncertainty.
- y-axis: χ^2 of the SM under the assumption that the present best fit values for ε are true.
- Exclusion of the SM at 5σ: $\chi^2 \simeq 30$ (two parameters).