Non-Unitarity in Leptonic Mixing

Constraints and Prospects

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to appear soon on the arXiv
(results preliminary)

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Motivation & Outline

- Existence of heavy neutral leptons (ν_R) is well motivated
- Discrepancies in Electroweak Precision Observables (EWPO)
- Higgs boson discovery increases sensitivity of EWPO to ν_R−mixing effects
- This talk:
  (i) Assumption: $m_{\nu_R} > M_Z$
  (ii) Present constraints
  (iii) Future sensitivities

Non-Unitarity of the Leptonic Mixing Matrix

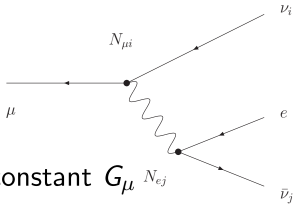
Heavy neutral leptons (ν_R) mix with SM neutral states ν_L:

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

- $N \sim$ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- PMNS as submatrix in general **not** unitary
- Modification of the weak currents involving neutrinos $\propto N$
- Parametrisation: $(NN^\dagger)_{\alpha\beta} = \mathbb{1}_{\alpha\beta} + \varepsilon_{\alpha\beta}$

Theory Prediction for Precision Observables

- All charged current processes modified
- Muon decay $\propto G_\mu \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$



- Fermi constant $G_F \neq$ muon decay constant G_μ
- Electroweak Precision Observables (EWPO):

$$G_F = \frac{G_\mu}{\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}} = \frac{\alpha\pi}{\sqrt{2} s_W^2 c_W^2 m_Z^2}$$

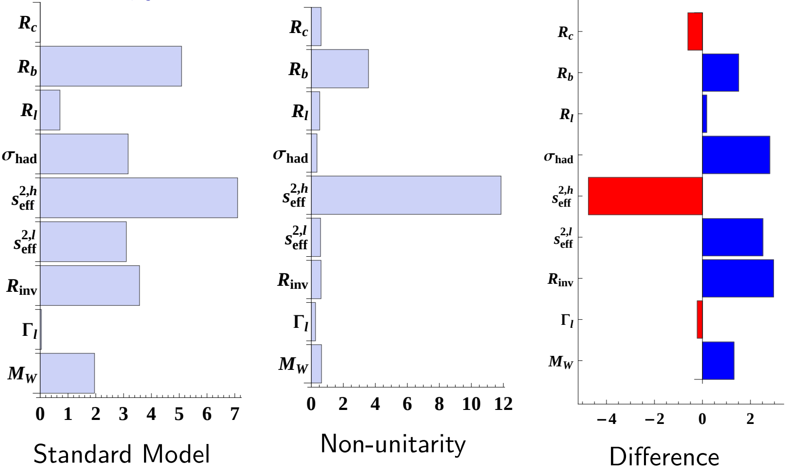
Statistical Analysis of Precision Data

- Global set of 34 precision observables:
  EWPO, lepton universality, CKM unitarity, rare decays, low energy parity violation
- Six non-unitarity parameters fitted by MCMC min. of χ^2
- 90% c.l. HPD intervals of best-fit parameter set ($\hat{\varepsilon}$):

-0.0022	$\leq \varepsilon_{ee} \leq$	-0.0003	$\lvert\varepsilon_{e\mu}\rvert$	$<$	4.2×10^{-6}
-0.00006	$\leq \varepsilon_{\mu\mu} \leq$	0	$\lvert\varepsilon_{e\tau}\rvert$	$<$	2.0×10^{-3}
-0.0056	$\leq \varepsilon_{\tau\tau} \leq$	0	$\lvert\varepsilon_{\mu\tau}\rvert$	$<$	6.9×10^{-4}

(preliminary)

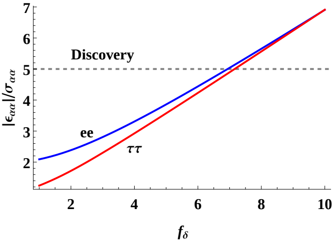
Individual $\Delta\chi^2$ for the Electroweak Precision Observables



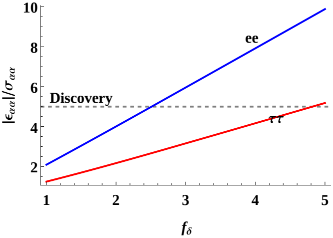
Fit w/o $s_{eff}^{2,h}$ is non-zero at 3.4σ, best fit value compatible.

Discovery Prospects for improved uncertainties

Intensity Frontier



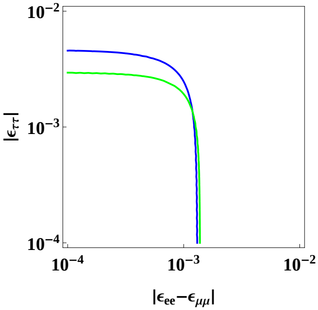
Energy Frontier



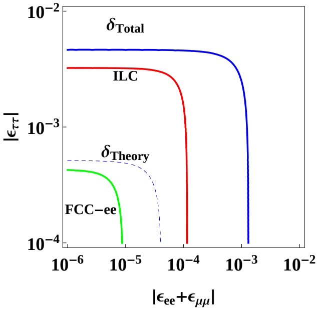
- Assumption: present best-fit parameter $\hat{\varepsilon}$ is true ($O^{exp} = O^{MUV}(\hat{\varepsilon})$)
- Uniform improvement of EWPO uncertainty: f_δ
- Modest experimental improvement $\Rightarrow$ discovery

Sensitivities of Future Experiments

Intensity Frontier



Energy Frontier



- Assumption: SM is true ($O^{exp} = O^{SM}$, $\varepsilon \equiv 0$)
- Constraints $\sim$ sensitivity of future measurements
- $\varepsilon_{\alpha\beta} \sim \mathcal{O}\left(v_{EW}^2/m_{\nu_R}^2\right) \Rightarrow$ Test m_{ν_R} up to $\sim$ 80 TeV

Conclusions

- Leptonic non-unitarity is well motivated.
- Model independent description is possible:
  Minimal Unitarity Violation scheme (MUV)
- Global fit to present data:
  - (i) Hints for non-unitarity at the 2 (3.4) σ level.
  - (ii) Not conclusive yet, use as constraints.
- Outlook on future sensitivities:
  - (a) Improvements on the intensity frontier as we/I speak.
  - (b) Future measurements of EWPO important.
  - (c) Test of ν_R masses up to ~ 80 TeV at FCC-ee.

Backup I

- 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

MUV prediction, linearized to 1st order	SM	Experiment
$[R_\ell]_{\rm SM}\,(1-0.15(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\rm SM}\,(1+0.03(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.21480(4)	0.21629(66)
$[R_c]_{\rm SM}\,(1-0.06(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.17227(4)	0.1721(30)
$\left[\sigma^0_{had}\right]_{\rm SM}\,(1-0.25(\varepsilon_{ee}+\varepsilon_{\mu\mu})-0.27\varepsilon_{\tau\tau})$	41.470(15)	41.541(37)
$[R_{inv}]_{\rm SM}\,(1+0.75(\varepsilon_{ee}+\varepsilon_{\mu\mu})+0.67\varepsilon_{\tau\tau})$	5.9721(2)	5.942(16)
$[M_W]_{\rm SM}(1-0.11(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	80.359(11)	80.385(15)
$[\Gamma_{\rm lept}]_{\rm SM}(1-0.59(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	83.966(12)	83.984(86)
$[s^{2,\ell}_{eff}]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[s^{2,{\rm had}}_{eff}]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$		0.23222(27)

Backup III - Lepton Universality

	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)
$R^{\ell}_{\tau e}$	$\frac{\Gamma(\tau \to \nu_\tau \mu \bar{\nu}_\mu)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)}$	1.0024(21)
$R^{\ell}_{\tau \mu}$	$\frac{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)}$	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)
$R^{W}_{\tau e}$	$\frac{\Gamma(W \to \tau \bar{\nu}_\tau)}{\Gamma(W \to e \bar{\nu}_e)}$	1.023(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: $V_{ud} = 0.97427(15)$, $V_{ub} = 0.00351(15)$

Mode	$V_{us} f_+(0)$
$K_L \to \pi e \nu$	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)
$f_+(0)$	0.959(5)

Mode	$\lvert V_{us} \rvert$
$\frac{B(\tau \to K\nu)}{B(\tau \to \pi\nu)}$	0.2262(13)
$\tau \to K\nu$	0.2214(22)
$\tau \to \ell, \tau \to s$	0.2173(22)

Backup V - Collider Precision

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
$s_{eff}^{2,\ell}$	1.3×10^{-5}	1×10^{-6}
σ_h^0 [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