

Phenomenology of Not-so-heavy Neutral Leptons: The NuTeV Anomaly, Lepton Universality, and Non-Universal Neutrino-Gauge Couplings

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The NuTeV experiment [1] at Fermilab has determined the effective neutrino-nucleon coupling parameters g_L^2 and g_R^2 from muon (anti)neutrino-nucleon scattering:

$$\begin{aligned} g_L^2 &= 0.30005 \pm 0.00137, \\ g_R^2 &= 0.03076 \pm 0.00110. \end{aligned} \quad (1)$$

The Standard Model (SM) predictions of these parameters based on a global fit to non-NuTeV data, cited as $[g_L^2]_{\text{SM}} = 0.3042$ and $[g_R^2]_{\text{SM}} = 0.0301$ in Ref. [1], differ from the NuTeV result by 3σ in g_L^2 .

The NuTeV value for g_L^2 in Eq. (1) is *smaller* than its SM prediction, reflecting the fact that the ratios $R_\nu = \sigma(\nu_\mu N \rightarrow \nu_\mu X)/\sigma(\nu_\mu N \rightarrow \mu^- X)$ and $R_{\bar{\nu}} = \sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)/\sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)$ were smaller than expected by the SM. Thus, possible *new* physics explanations of the NuTeV anomaly would be those that suppress the neutral current cross sections over the charged current cross sections, or enhance the charged current cross sections over the neutral current cross sections. To this end, two classes of models have been devised.

Models of the first class suppress R_ν and $R_{\bar{\nu}}$ through new neutrino-quark interactions, mediated by leptoquarks or extra $U(1)$ gauge bosons (Z' 's), which interfere either destructively with the Z -exchange amplitude, or constructively with the W -exchange amplitude [2]. To maintain agreement between the SM and non-NuTeV data, the new interactions must selectively interfere with the $\nu_\mu N$ ($\bar{\nu}_\mu N$) scattering process, but little else. This severely restricts the types of interactions that may be introduced.

Models of the second class suppress the $Z\nu\nu$ coupling by mixing the neutrino with heavy gauge singlet states (neutrissimos, *i.e.* right-handed neutrinos) [3, 4, 5]. For instance, if the $SU(2)_L$ active ν is a linear combination of two mass eigenstates with mixing angle θ ,

$$\nu = \nu_{\text{light}} \cos \theta + \nu_{\text{heavy}} \sin \theta, \quad (2)$$

then $Z\nu\nu$ is suppressed by $\cos^2 \theta$, and $W\ell\nu$ is suppressed by $\cos \theta$. More generally, if the $Z\nu_\ell\nu_\ell$ coupling ($\ell = e, \mu, \tau$) is suppressed by a factor of $(1 - \varepsilon_\ell)$, then the $W\ell\nu_\ell$ coupling is suppressed by $(1 - \varepsilon_\ell/2)$.

Such suppressions of the neutrino-gauge couplings affect not only NuTeV observables. In addition to the suppression of the Z invisible width by a factor of $[1 - (2/3)(\varepsilon_e + \varepsilon_\mu + \varepsilon_\tau)]$, all SM observables will be affected through the Fermi constant G_F which is no longer equal to the the muon decay constant G_μ :

$$G_F = G_\mu \left(1 + \frac{\varepsilon_e + \varepsilon_\mu}{2} \right). \quad (3)$$

This shift in G_F would destroy the agreement between the SM and Z -pole observables. But, since G_F always appears in the combination ρG_F in neutral current amplitudes, agreement can be recovered by absorbing the shift in G_F into a shift in ρ , or equivalently, in the oblique correction parameter T [6]. The Z -pole, NuTeV, and W mass data can all be fit with the oblique correction parameters S, T, U , and a flavor universal suppression parameter $\varepsilon = \varepsilon_e = \varepsilon_\mu = \varepsilon_\tau$, with best fit value $\varepsilon = 0.0030 \pm 0.0010$. [4].

This value of ε implies a large mixing angle, $\theta = 0.055 \pm 0.010$, if interpreted as due to mixing with a single heavy state. The traditional seesaw mechanism ties θ to the ratio of neutrino masses:

$$\frac{m_{\text{light}}}{m_{\text{heavy}}} \approx \theta^2. \quad (4)$$

With $m_{\text{light}} \sim 0.1 \text{ eV}$ and $m_{\text{heavy}} \sim 100 \text{ GeV}$ (we need $m_{\text{heavy}} > M_Z$ to suppress Γ_{inv}) the mixing angle is orders of magnitude too small: $\theta \sim 10^{-6}$.

By contrast, models with intergenerational mixing have additional degrees of freedom which permit them to evade these constraints by decoupling masses and mixing angles [3, 5]. In these models, intergenerational symmetries imposed on the neutrino mass texture are the source of the naturally light mass eigenstates. No longer fixed at the GUT scale, heavy states might be relatively light (not-so-heavy), the current experimental lower bound being just above the Z mass [7], and well within reach of near-future collider experiments.

Large mixing angles between heavy and light states may enhance the rate of flavor-changing processes mediated by heavy states. Hence, stringent constraints can be placed on these models by limits on lepton flavor violation. For instance, assuming $m_{\text{heavy}} \gg M_W$, the MEGA limit on $\mu \rightarrow e\gamma$ [8] leads to the constraint [5] $\varepsilon_e \varepsilon_\mu < 10^{-8}$. This is clearly incompatible with $\varepsilon_e = \varepsilon_\mu = 0.003$ and implies rather $\varepsilon_e \approx 0$ or $\varepsilon_\mu \approx 0$.

Such a pattern of ε_ℓ will generically induce violations of lepton universality in charged-current processes. The fit to lepton universality violating parameters $\Delta_{e\tau} \equiv \varepsilon_e - \varepsilon_\tau$ and $\Delta_{\mu\tau} \equiv \varepsilon_\mu - \varepsilon_\tau$ to data from W, K, π, τ , and μ decays is shown in Fig. 1. Best-fit values are:

$$\begin{aligned} \Delta_{e\tau} &= 0.0039 \pm 0.0040, \\ \Delta_{\mu\tau} &= 0.0017 \pm 0.0038. \end{aligned} \quad (5)$$

Unfortunately, the quality of the fit is unimpressive ($\chi^2/\text{d.o.f.} = 8.4/5$). In addition, the internal consistency of the data determining some of the branching ratios entering the fit, especially $B(\tau \rightarrow \pi\nu_\tau)$, is poor. Thus,

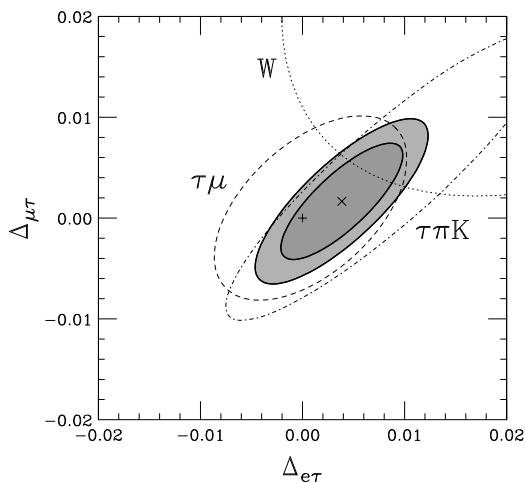


FIG. 1: The limits on $\Delta_{e\tau}$ and $\Delta_{\mu\tau}$ from various decays.

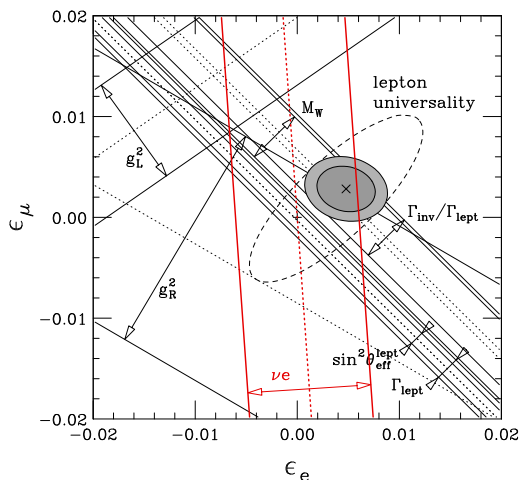


FIG. 2: Limits on ϵ_e and ϵ_μ . The 1σ bands are shown for each observable ignoring correlations. The shaded areas are the 68% (dark gray) and 90% (light gray) confidence contours including correlations. The red band illustrates the potential impact of a proposed reactor measurement of the $\bar{\nu}_e e e$ cross section.

definitive bounds on lepton universality await additional data.

Fits to ϵ_ℓ and S, T, U using both electroweak data and the best-available lepton universality constraints indicate that the data are compatible with several patterns of neutrino-gauge coupling suppression. The result of a five-parameter fit to S, T, U, ϵ_e , and ϵ_μ is shown in Fig. 2 [9]. Among the models analyzed in Ref. [9], the model with $\epsilon_e \neq 0, \epsilon_\mu = \epsilon_\tau = 0$ best accommodates both the fit data and the MEGA constraint, with best-fit values

$$\begin{aligned} S &= -0.04 \pm 0.10, \\ T &= -0.46 \pm 0.15, \\ U &= 0.52 \pm 0.16, \\ \epsilon_e &= 0.0051 \pm 0.001, \end{aligned} \quad (6)$$

for a reference SM with $m_H = 115$ GeV.

Further experimental constraints to neutrino-neutrino mixing models are expected in the near future. For instance, a proposed improved reactor measurement of the $\bar{\nu}_e e e$ cross section would provide a very clean and direct measurement of ϵ_e [10] and could significantly improve the current bound. The potential bound from a measurement at the 1.3% level is illustrated by the red band in Fig. 2, and even more precise measurements are contemplated. The consistency of the charged-current lepton universality constraints from various decays is currently poor but should improve with additional data. Searches for lepton flavor violation at MEG, MECO, and elsewhere are underway.

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