Theory of Neutrinos: A White Paper

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Abstract

During 2004, four divisions of the American Physical Society commissioned a study of neutrino physics to take stock of where the field is at the moment and where it is going in the near and far future. Several working groups looked at various aspects of this vast field. The summary was published as a main report entitled "The Neutrino Matrix" accompanied by short 50 page versions of the report of each working group. Theoretical research in this field has been quite extensive and touches many areas and the short 50 page report [1] provided only a brief summary and overview of few of the important points. The theory discussion group felt that it may be of value to the community to publish the entire study as a white paper and the result is the current article. After a brief overview of the present knowledge of neutrino masses and mixing and some popular ways to probe the new physics implied by recent data, the white paper summarizes what can be learned about physics beyond the Standard Model from the various proposed neutrino experiments. It also comments on the impact of the experiments on our understanding of the origin of the matter-antimatter asymmetry of the Universe and the basic nature of neutrino interactions as well as the existence of possible additional neutrinos. Extensive references to original literature are provided.

14 NuTeV Physics

The NuTeV experiment [498] at Fermilab has measured the ratios of neutral to charged current events in muon (anti)neutrino-nucleon scattering:

$$\begin{aligned} R_\nu &= \frac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu^- X)} = g_L^2 + r g_R^2 \,, \\ R_{\bar\nu} &= \frac{\sigma(\bar\nu_\mu N \to \bar\nu_\mu X)}{\sigma(\bar\nu_\mu N \to \mu^+ X)} = g_L^2 + \frac{g_R^2}{r} \,, \end{aligned} \tag{72}$$

where

$$r = \frac{\sigma(\bar\nu_\mu N \to \mu^+ X)}{\sigma(\nu_\mu N \to \mu^- X)} \sim \frac{1}{2} \,, \tag{73}$$

and has determined the parameters g_L^2 and g_R^2 [499] to be

$$\begin{aligned} g_L^2 &= 0.30005 \pm 0.00137 \,, \\ g_R^2 &= 0.03076 \pm 0.00110 \,. \end{aligned} \tag{74}$$

The Standard Model (SM) predictions of these parameters based on a global fit to non-NuTeV data, cited as $[g_L^2]_{\rm SM} = 0.3042$ and $[g_R^2]_{\rm SM} = 0.0301$ in Ref. [498], differ from the NuTeV result by 3σ in g_L^2. Alternatively, if the SM is fit to the NuTeV result, the preferred range of the Higgs mass is 660 GeV $< m_H$ (90% C.L.) [500], well above the value of $m_H \sim 90$ GeV preferred by the non-NuTeV global fit [501].

The significance of the NuTeV result remains controversial [502], and a critical examination of the initial analysis is ongoing. Several groups are evaluating potential theoretical uncertainties arising from purely Standard Model physics which might be comparable to or larger than the quoted experimental uncertainty of the NuTeV result. Candidate sources of large theoretical uncertainty include next-to-leading-order (NLO) QCD corrections [503], NLO electroweak corrections [504], and parton distribution functions (especially as involves assumptions about sea-quark asymmetries) [505]. The effect of the former has been estimated to be comparable in size to the NuTeV experimental uncertainty, while the latter two might give rise to effects comparable in size to the full NuTeV discrepancy with the Standard Model. Elucidation of the actual impact of these effects on the NuTeV result awaits a reanalysis of the NuTeV data. However, it remains a distinct possibility that the discrepancy with the Standard Model prediction is genuine and that its resolution lies in physics beyond the Standard Model. Indeed, as Chanowitz has emphasized [500], the precision electroweak data indicate new physics whether anomalous data are excluded from global fits (since the preferred Higgs mass is then well below the direct search limit) or included in the fits (in which case anomalous data themselves demand a new physics explanation).

Note that the NuTeV value for g_L^2 in Eq. (74) is *smaller* than its SM prediction. This is a reflection of the fact that the ratios R_ν and $R_{\bar\nu}$ were smaller than expected by the SM. (The g_R^2 term is smaller than the g_L^2 term by an order of magnitude and is insignificant.) 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. Two classes of models have been proposed which accomplish this task.

The first class comprises models which suppress R_ν and $R_{\bar{\nu}}$ with the introduction of 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 [502]. In order to preserve the excellent 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.

Ref. [502] proposes a model in which the Z' couples to $B - 3L_\mu$. This model must be fine-tuned to avoid Z-Z' mixing [506] which would disrupt, among other things, lepton universality at the Z-pole. Fitting the NuTeV anomaly requires

$$\frac{M_{Z'}}{g_{Z'}} \approx 3 \text{ TeV} . \tag{75}$$

Bounds from direct Z' searches at the Tevatron and LEP limit the possible range of $M_{Z'}$ to $M_{Z'} > 600\,\text{GeV}$ for $g_{Z'} \sim 1$, or $2\text{ GeV} < M_{Z'} < 10\,\text{GeV}$ for $g_{Z'} \sim 10^{-3}$.

The Z' in the model proposed in Ref. [507] does not couple the neutrinos and quarks directly, since the gauged charge is $L_\mu - L_\tau$. Rather, it is a tunable Z-Z' mixing in the model which is responsible for suppressing the neutral channel cross section. The same mixing violates lepton universality on the Z-pole and prevents the mechanism from completely mitigating the NuTeV anomaly. Z' masses in the range $60\,\text{GeV} < M_{Z'} < 72\,\text{GeV}$, or $M_{Z'} > 178\,\text{GeV}$ brings the theoretical value of g_L^2 within 1.6σ of the NuTeV value while keeping lepton universality violation within 2σ.

In general, models in this class are constrained strongly by lepton universality, because ν_ℓ is the $SU(2)_L$ partner of ℓ_L^-. New interactions which respect the $SU(2)_L$ gauge symmetry cannot affect neutrino couplings alone: they necessarily affect couplings of the charged leptons. Nevertheless, they provide possible explanations of the NuTeV anomaly, and predict a flavor-selective gauge boson in the several 100 GeV to TeV range, well within reach of the LHC.

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) [508–511]. For instance, if the $SU(2)_L$ active ν_μ is a linear combination of two mass eigenstates with mixing angle θ,

$$\nu_\mu = (\cos\theta)\nu_{\text{light}} + (\sin\theta)\nu_{\text{heavy}} , \tag{76}$$

then the $Z\nu_\mu\nu_\mu$ coupling is suppressed by a factor of $\cos^2\theta$ (assuming the heavy states are too massive to be created on-shell). Likewise, the $W\mu\nu_\mu$ coupling is suppressed by $\cos\theta$. Although both the numerators and denominators of R_ν and $R_{\bar{\nu}}$ are suppressed in such a model, the suppression of the numerators exceeds that of the denominators, and the ratios are therefore diminished. 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 $(1 - \varepsilon_\ell/2)$, and R_ν and $R_{\bar{\nu}}$ are suppressed by $(1 - \varepsilon_\mu)$.

The effect of such suppressions of the neutrino-gauge couplings is not limited to NuTeV observables alone. In addition to the obvious 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 muon decay constant G_μ:

$$G_F = G_\mu \left(1 + \frac{\varepsilon_e + \varepsilon_\mu}{2}\right) . \tag{77}$$

This shift in G_F will destroy the excellent agreement between the SM and Z-pole observables. However, since G_F always appears in the combination ρG_F in neutral current amplitudes, the agreement can be recovered by absorbing the shift in G_F into a shift in ρ, or equivalently, in the oblique correction parameter T [512]. Indeed, it was shown in Ref. [510], that 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 $\varepsilon = \varepsilon_e = \varepsilon_\mu = \varepsilon_\tau$, the best fit values given by

$$\begin{aligned} S &= -0.03 \pm 0.10 , \\ T &= -0.44 \pm 0.15 , \\ U &= 0.62 \pm 0.16 , \\ \varepsilon &= 0.0030 \pm 0.0010 , \end{aligned} \tag{78}$$

for a reference SM with $m_H = 115$ GeV. Therefore, for this class of models to work, neutrino mixing with heavy gauge singlet states must be accompanied by new physics contributions to S, T, and U. The values of S and T can be accommodated within the SM by simply increasing the Higgs mass to hundreds of GeV, but the W mass requires a large and positive U parameter which cannot be generated within the SM. Thus, the models are not complete until some mechanism is found which explains the W mass. But then, if the SM is fit to the W mass alone, the preferred Higgs mass is far below direct search limits [500], which could be an indication that the W mass requires new physics regardless of NuTeV.

At first blush, the preferred value of ε above is also problematic. This implies a large mixing angle, $\theta = 0.055 \pm 0.010$, if interpreted as due to mixing with a single heavy state. The commonly accepted seesaw mechanism [67–70] relates the mixing angle to the ratio of the neutrino masses:

$$\frac{m_{\text{light}}}{m_{\text{heavy}}} \approx \theta^2 . \tag{79}$$

Choosing $m_{\text{light}} \sim 0.1\,\text{eV}$ and $m_{\text{heavy}} \sim 100\,\text{GeV}$ ($m_{\text{heavy}} > M_Z$ is needed to suppress Γ_{inv}) we find the mixing angle orders of magnitude too small: $\theta \sim 10^{-6}$. However, this result does not mean that it is impossible to have a large enough mixing angle between the light and heavy states. As pointed out in Ref. [509], in models with more than one generation, the generic mass matrix includes enough degrees of freedom to allow us to adjust all the masses and mixings independently. Concrete examples of models with large mass hierarchies AND large mixing angles can be found in Refs. [511, 513]. What is sacrificed, however, is the traditional seesaw explanation of the small neutrino mass: i.e. since the Majorana mass M in the neutrino mass matrix should be of the order of the GUT scale, the neutrino mass $m_{\text{light}} \sim m^2/M$ is naturally suppressed if the Dirac mass m is comparable to that of the other fermions. An alternative mechanism is used in Ref. [511]. There, an intergenerational symmetry is imposed on the neutrino mass texture which reduces its rank, generating naturally light (massless) mass eigenstates.

Abandoning the seesaw mechanism also frees the masses of the heavy states from being fixed at the GUT scale. Indeed, in the model discussed in Ref. [511], the assumption that neutrinos and up-type quarks have a common Dirac mass implies that the masses of the heavy state could be a few TeV, well within the reach of the LHC. Without quark-lepton unification $m_{\rm heavy}$ could be even lighter, rendering them accessible to Tevatron Run II.

Because of the large mixing angles between the light and heavy states in this class of models, flavor changing processes mediated by the heavy states may be greatly enhanced [40,511,513,514]. As a result, stringent constraints can be placed on the models from the experimental limits on $\mu \to e\gamma$, $\tau \to \mu\gamma$, [145] μ-e conversion in nuclei [515,516], muonium-antimuonium oscillation [517, 518], etc. For instance, the MEGA limit on $\mu \to e\gamma$ leads to the constraint [511]

$$\varepsilon_e \varepsilon_\mu \approx 0 \; . \tag{80}$$

Therefore, lepton universality among the ε_ℓ must be broken maximally. Ref. [519] shows that it is possible to fit the Z-pole, NuTeV, and lepton universality data while satisfying this condition.

The MEG (Mu-E-Gamma) experiment at PSI [520] plans to improve upon the MEGA limit by about two orders of magnitude. The MECO (Muon on Electron COnversion) experiment at Brookhaven [521] aims to improve the limits on $\mu - e$ conversion in nuclei by three orders of magnitude. Further constraints can be obtained from muon $g-2$ [522,523], and the violation of CKM unitarity [524–526].

The NuTeV anomaly, even if it does not ultimately endure sustained scrutiny, stirs us to look past orthodoxies in our model-building (seesaw, SUSY, GUTs,...) and to ask broadly what is permitted by the data. The neutrino mixing solution is relatively conservative in its use of the neutrino sector to address the NuTeV question. Nonetheless, it makes interesting predictions about new particles at LHC, can be probed by a wide range of neutrino oscillation experiments, precision measurements and rare decay searches, and introduces an alternative to the seesaw paradigm. Whether this or another solution resolves the NuTeV anomaly, the NuTeV result serves to focus the imagination of the theorist on the opportunities presented by the experiments.