Theoretical Motivation for Electroweak Physics with Neutrinos

André de Gouvêa
Northwestern University

Outline

1. Introduction, Qualification;
2. The Physics of Neutrino – Charged Fermion Scattering;
4. Some TeV-Scale Examples. Interplay with LHC;
5. The Neutrino Coupling to the Z-Boson;
6. Concluding Thoughts.
Opening Remarks

I’ll discuss the physics of next-generation $\nu$ fixed target experiments, concentrating on

- testing the standard model of electroweak interactions;
- searching new TeV-scale physics.

The discussion presented here should apply qualitatively to most intense neutrino beams (which is why we are here) which can be aimed at the various near detectors.

Most quantitative results presented will refer to those presented or derived in the NuSOnG paper (arXiv:0803.0354 [hep-ph]). For more details, see the talk by Ingo Schienbein (next).

[See also plenary talk by Roberto Petti for other options, discussions]
Neutrino – Charged Fermion Scattering

Neutrino matter scattering provides a unique and clean environment to study purely weakly interacting processes. In the Standard Model, at low enough center of mass energies, $\nu_\mu + f$ elastic scattering is governed by the following effective Lagrangian.

$$\mathcal{L} = -2\sqrt{2}G_F \left( g^\nu_L \bar{\nu}_L \gamma_\mu \nu_L \right) \times \left[ g^f_L \bar{f}_L \gamma_\mu f_L + g^f_R \bar{f}_R \gamma_\mu f_R \right]$$

where (for $\nu \neq \nu_e$)

$$g^\nu_L = \sqrt{\rho} \left( +\frac{1}{2} \right) ,$$
$$g^f_L = \sqrt{\rho} \left( I_3^f - Q^f \sin^2 \theta_W \right) ,$$
$$g^f_R = \sqrt{\rho} \left( -Q^f \sin^2 \theta_W \right) .$$

At tree-level, $\rho = 1$. Loop corrections affect both $\rho$ and what we mean by $\sin^2 \theta_W$. 

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$\nu$ Electroweak Physics
One can interpret $\nu + f$ as measuring the Weinberg angle ... 

... but it measures $g^\nu_L g^f_L$ and $g^\nu_L g^f_R$ independently. Much more information.
Consider four NuSOOnG measurements:

1) \( \sigma(\nu, e) \),

2) \( \sigma(\bar{\nu}, e) \),

3) \( g_L^2 = (2g_L^\nu g_L^u)^2 + (2g_L^\nu g_L^d)^2 \)
   \( = \rho^2 \left( \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W \right) \),

4) \( g_R^2 = (2g_R^\nu g_R^u)^2 + (2g_R^\nu g_R^d)^2 \)
   \( = \rho^2 \left( \frac{5}{9} \sin^4 \theta_W \right) \).

fix \( \sin^2 \theta_W \), “measure” radiative corrections.

The \( \sigma(\nu, e) \) and \( g_L^2 \) measurements are the strongest with the initial run-plan.
Here, I’ll concentrate on $\nu_\mu + e$ elastic scattering.

- Another channel to study neutral currents with neutrinos (cf. NuTeV).

- Potential for significant improvements over world’s data sample – CHARM II had less than 6000 events, $\nu$ and $\bar{\nu}$ combined. $\Rightarrow$ NuSOnG capable of accumulating 75,000 events!

- This is a very, very clean process! (Among First Standard Model calculation, G. ’t Hooft, “Predictions For Neutrino - Electron Cross-Sections In Weinberg’s Model Of Weak Interactions,” Phys. Lett. B 37 (1971) 195.)

Important note: with large data samples, the key issue when it comes to performing precision measurements of $\nu + e$ elastic scattering is keeping systematic errors to a minimum $\rightarrow$ must know the neutrino flux very precisely!

“Easy” for NuFact, $\beta$-beams, requires “ratios” in the case of Superbeams.
NuTeV: $\nu q$ scattering ("PW") is $3\sigma$ off SM...

New Physics, e.g. nonuniversality? or "Standard Model"?

$u^p \neq d^n$

Pulls from Isospin Violation Models

$\delta \sin^2 \theta_W$

- Standard Model (zero shift)
- NuTeV Measurement (solid)

no model fully explains it...

An updated NuTeV analysis will be available spring/summer (?)
Directions of Effects not Considered
(length of arrows are arbitrary)

Shadowing (VMD) \( m_c \) Valence Isospin Violation

NuTeV Revisited, K. McFarland
Neutrino–Electron Elastic Scattering and New Physics

This is what one is able to measure:

\[ \frac{d\sigma}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi} \left[ (g_{V}^{\nu e} \pm g_{A}^{\nu e})^2 + (g_{V}^{\nu e} \mp g_{A}^{\nu e})^2 (1 - y)^2 \right], \]

in the limit \( m_e \ll E_\nu \), for \( y = \frac{T_e}{E_\nu} \) for the recoil electron. Sign ambiguity for neutrino and antineutrino scattering, respectively.

New “heavy” physics will modify the coefficients

\[ g_L^\nu g_L^e = g_{V}^{\nu e} + g_{A}^{\nu e} \]
\[ g_L^\nu g_R^e = g_{V}^{\nu e} - g_{A}^{\nu e} \]
Most general effective Lagrangian one can probe with $\nu_\mu + e$ scattering

$$L_{\text{NSI}}^e = \frac{\sqrt{2}}{\Lambda^2} \left[ \bar{\nu}_\alpha \gamma_\sigma P_L \nu_\mu \right] \left[ \cos \theta \bar{e} \gamma^\sigma P_L e + \sin \theta \bar{e} \gamma^\sigma P_R e \right].$$

$\Lambda =$ New Physics scale.

$\theta$ parameterizes “handedness” of the new physics. Note: signs matter.

Assumption 1: no scalar–scalar interaction, which involve right-handed neutrino fields (“suppressed” by neutrino and electron masses).

Assumption 2: charged current NOT modified. This is not true of specific models.
NSI reach for **neutrino-lepton scattering**

\[
\mathcal{L}^e_{\text{NSI}} = + \frac{\sqrt{2}}{\Lambda^2} \left[ \bar{\nu}_\alpha \gamma^\sigma P_L \nu_\mu \right] \left[ \cos \theta \bar{e} \gamma^\sigma P_L e + \sin \theta \bar{e} \gamma^\sigma P_R e \right]
\]

- **mass**
- **outgoing scale**
- **flavor**
- **Relative mixture of handedness**

\[ \Lambda \]

95% CL sensitivity

- if \( \alpha = \mu \) flavor \( \sim 4.5 \) TeV
- if \( \alpha \neq \mu \) flavor \( \sim 1.25 \) TeV
But we might see a signal!

Assume $\Lambda = 3.5$ TeV, $\theta = 2\pi/3$, $\alpha = \mu \ldots$
this is the 2$\sigma$ contour from NuSOnG.

Assume $\Lambda = 1$ TeV, $\theta = 4\pi/3$, $\alpha \neq \mu \ldots$
these are the 2$\sigma$ contours from NuSOnG.
How can we learn more about this “new physics”? We need information from other sources, including

- Neutrino quark scattering (same experiment!);
- Other TeV-sensitive experiments, including the LHC.

The types of new physics fall under different categories:

- They affect all “electroweak precision” observables in the same way (all loop-level effects that modify the $W$ and $Z$ boson propagators);
- They affect only neutrino neutral current measurements;
- They affect only neutrino-quark or neutrino-lepton measurements;
- ...
Modifying the Neutrino Coupling to the Heavy Gauge Bosons:

- neutrino mixing with heavy gauge-singlet leptons

\[ \nu = \nu_{\text{light}} \cos \theta + \nu_{\text{heavy}} \sin \theta \]
\[ \chi = -\nu_{\text{light}} \sin \theta + \nu_{\text{heavy}} \cos \theta \]
\[ Z_{\nu\nu} = Z\nu_{\text{light}}\nu_{\text{light}} \cos^2 \theta \]
\[ + 2Z\nu_{\text{light}}\nu_{\text{heavy}} \sin \theta \cos \theta \]
\[ + Z\nu_{\text{heavy}}\nu_{\text{heavy}} \sin^2 \theta \]
\[ W_{\ell\nu} = W_{\ell\nu_{\text{light}}} \cos \theta + W_{\ell\nu_{\text{heavy}}} \sin \theta \]
\[ Z\nu_{\ell\nu_{\ell}} (1 - \epsilon_{\ell}) \quad W_{\ell\nu_{\ell}} \left(1 - \frac{\epsilon_{\ell}}{2}\right) \]
includes “promised” improvements from $\tau$ data from BaBar and $\pi$ data from PINUE

WARNING: fit points to large $U \rightarrow$ other new physics

Fit with $S$, $T$, $\varepsilon_e$, and $\varepsilon_\mu$. [Loinaz et al, to appear]
NuSOnG still very relevant!

WARNING: fit points to large $U \to$ other new physics

Fit with $S, T, \varepsilon_e, \text{ and } \varepsilon_\mu$.  

[Loinaz et al, to appear]
What if The LHC Does not Find Any Evidence for TeV degrees of Freedom?

We May Still Run Into Surprises in the Neutrino Sector (Again!)
Another Example: The “Nature” of the $\nu - Z$-boson Coupling

In the Standard Model, the neutrino coupling to the $Z$-boson is purely left-handed. It is interesting to ask “how well do we know that?”

The most precise information we have regarding the neutrino–$Z$-boson coupling comes from the invisible $Z$-width at LEP. However, LEP does not measure $g_L^\nu$: it measures $(g_L^\nu)^2 + (g_R^\nu)^2$.

On the other hand, we know a lot about the nature of the neutrino $W$-boson coupling. That one is known to be purely left-handed.

This means that neutrino beam experiments measure only $g_L^\nu$: Complementary to LEP.
CHARM II – neutrino electron scattering – plays a fundamental role!
NuSOnG Improvement: could see new physics “easily”. What kind of new Physics is this?
Neutrino–Electron Scattering with Different Next-Generation Beams (Summary):

TABLE III: Results on the precision of parameter extraction, assuming a 100 ton detector located 100 m from the neutrino source. All limits are taken at 68% confidence. The bounds in parenthesis are computed assuming a worst case scenario of 5% systematic uncertainty. See text for details.

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Uncertainties % bkg, % flux</th>
<th>$\sin^2 \theta_W$ %</th>
<th>Magnetic moment $68%$</th>
<th>$Z'$ coupling $\epsilon$ $68%$</th>
<th>$\rho$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>1, 0.1</td>
<td>0.82</td>
<td>$4.8 \times 10^{-10} \mu_B$</td>
<td>$2.0 \times 10^{-3}$</td>
<td>1.1</td>
</tr>
<tr>
<td>$\mu^+ \nu$-factory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$50$GeV, $10^{20}$ $\text{decays/year}$ [22]</td>
<td>0(5), 0.1</td>
<td>0.14(6.64)</td>
<td>$2.5(10.1) \times 10^{-11} \mu_B$</td>
<td>6.9(13.1) $\times 10^{-4}$</td>
<td>0.09(1.2)</td>
</tr>
<tr>
<td>$\mu^- \nu$-factory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$50$GeV, $10^{20}$ $\text{decays/year}$ [22]</td>
<td>0(5), 0.05</td>
<td>0.04(8.62)</td>
<td>$3.1(12.4) \times 10^{-11} \mu_B$</td>
<td>3.3(8.7) $\times 10^{-4}$</td>
<td>0.06(0.93)</td>
</tr>
<tr>
<td>$\beta$-beam $\nu_e$ ($^{18}\text{Ne}$)</td>
<td>$\gamma = 500$, $1.1 \times 10^{18}$ $\text{decays/year}$ [1]</td>
<td>0(5), 0.1</td>
<td>0.34(7.60)</td>
<td>$3.0(6.6) \times 10^{-10} \mu_B$</td>
<td>9.8(16.3) $\times 10^{-4}$</td>
</tr>
<tr>
<td>$\beta$-beam $\bar{\nu}_e$ ($^{6}\text{He}$)</td>
<td>$\gamma = 500$, $2.9 \times 10^{18}$ $\text{decays/year}$ [1]</td>
<td>0(5), 0.1</td>
<td>0.22(5.72)</td>
<td>$2.6(6.7) \times 10^{-10} \mu_B$</td>
<td>7.7(14.2) $\times 10^{-4}$</td>
</tr>
<tr>
<td>Conventional</td>
<td>NuMI on-axis $3.7 \times 10^{20}$ POT</td>
<td>0(5), 3</td>
<td>0.48(9.92)</td>
<td>$1.8(6.6) \times 10^{-10} \mu_B$</td>
<td>2.7(6.4) $\times 10^{-3}$</td>
</tr>
</tbody>
</table>

[See AdG, J. Jenkins, PRD74, 033004 (2006)]
Summary and Conclusions

• A large, well-understood sample of $\nu + e$ ES events should prove to be a powerful tool for exploring TeV scale new physics.

• Any new physics result in $\nu$-matter–scattering should prove to be complementary to anything we may discover at the LHC – including only a standard model Higgs boson! Neutrino scattering will likely help elucidate the nature of the new physics discovered at the LHC.

• By measuring $\nu_\mu + e$ one can test most new physics interpretations of the NuTeV anomaly.

• Along with a record number of $\nu_\mu + e$ ES events, one also gets a record number of $\nu_\mu + q$ DIS events!

• Even if there is no new physics, Neutrino-matter scattering explores a different sector of the Standard Model and contributes significantly to electroweak precision observables and QCD. But remember: neutrinos have been (very) good to particle physics in the past!
Backup Slides . . .
[Example: SM $\nu_\mu + e$ elastic scattering at the loop-level]

**Oblique Shifts ($S$, $T$)**

\[
\sim \frac{1}{\Lambda^2} \left[ \bar{\nu}_L \gamma^a \nu_L \right] \left[ \cos \theta \ e_L \gamma_a e_L + \sin \theta \ e_R \gamma_a e_R \right]
\]

\[
\frac{1}{\Lambda^2} = 4\sqrt{2}G_F
\]

\[
\cos \theta = \frac{\alpha}{2} \left( g_L^e T + \frac{\tan^2 \theta_W}{4} [S - 2T] \right)
\]

\[
\sin \theta = \frac{\alpha}{2} \left( g_R^e T + \frac{\tan^2 \theta_W}{4} [S - 2T] \right)
\]
Summary:

New Heavy Physics

<table>
<thead>
<tr>
<th>Model</th>
<th>Contribution of NuSOnG Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Z' Choices: ((B - xL), (q - xu), (d + xu))</td>
<td>At the level of, and complementary to, LEP II bounds.</td>
</tr>
<tr>
<td>Extended Higgs Sector</td>
<td>At the level of, and complementary to (\tau) decay bounds.</td>
</tr>
<tr>
<td>R-parity Violating SUSY</td>
<td>Sensitivity to masses (\sim 2) TeV at 95% CL. Improves bounds on slepton couplings by (\sim 30%) and on some squark couplings by factors of 3-5.</td>
</tr>
<tr>
<td>Intergenerational Leptoquarks with non-degenerate masses</td>
<td>Accesses unique combinations of couplings. Also accesses coupling combinations explored by (\pi) decay bounds, at a similar level.</td>
</tr>
</tbody>
</table>

TABLE VI: Summary of NuSOnG’s contribution in the case of specific models
LHC:

- Highly enhanced $H \rightarrow ZZ$
- The Higgs mass, let's say 300 GeV
- Complex decay modes (e.g. 6W’s and 2 b’s)

And what it doesn’t…

- Measure mass of new quarks
- Observe new charged leptons (off mass shell Drell-Yan produced)
- Reconstruct the decay modes fully

A Chiral 4th generation ($\Delta S=0.2$) with isospin violation ($\Delta T=0.2$)

NuSOnG:

QCD explanation for NuTeV is found, allowing NuTeV to be corrected.
**Z’ Physics**

Note: Z’ couplings may depend heavily on the generation and field-type (quark versus lepton)

<table>
<thead>
<tr>
<th></th>
<th>$U(1)_{B-xL}$</th>
<th>$U(1)_{q+xu}$</th>
<th>$U(1)_{10+x\overline{5}}$</th>
<th>$U(1)_{d-xu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_{\mu L}, e_L$</td>
<td>$-x$</td>
<td>$-1$</td>
<td>$x/3$</td>
<td>$(-1+x)/3$</td>
</tr>
<tr>
<td>$e_R$</td>
<td>$-x$</td>
<td>$-(2+x)/3$</td>
<td>$-1/3$</td>
<td>$x/3$</td>
</tr>
</tbody>
</table>

TABLE VII: Charges of $\nu_{\mu L}, e_L, e_R$ under 4 phenomenologically viable classes of $U(1)^\prime$ symmetries. Each value of $x$ corresponds to a different $U(1)^\prime$ symmetry that is considered.

[Bounds competitive with LEP]
Reinforced NuTeV Anomaly: Modified Neutrino–Quark Interactions?

![Graph showing Modified Neutrino–Quark Interactions]