Neutrino Responses and the Long Baseline Program

- Review of existing plans: FermiLab to DUSEL
- INT program critiques: challenge of event reconstruction with a broadband beam experiment
- Possible contributions by our TC

[Summary of program discussions from long-baseline workshops: sides borrowed from Wilson, Svoboda, Conrad, Zeller, Mosel, Sobczyk: see their talks for much more detail]
- FermiLab to DUSEL baseline plus the goal of seeing more than one oscillation defines beam energy

- present guidance is 700 kW broad-band beam, on axis, water or argon detector, using a new beamline to DUSEL and FermiLab’s main injector (produces 120 GeV protons, energy might be lowered)

- matter effects (hierarchy) and CP phase; 5 years of $\nu$ then $\bar{\nu}$ running
- distinguish hierarchy through matter effects imprinted on oscillations

- Fermilab – Homestake (South Dakota) = 1300 km
- Wide Band Low Energy Beam – information from both 1\textsuperscript{st} & 2\textsuperscript{nd} maxima?
- All neutrino parameters measured in the same detector complex
- second goal is the determination of the Dirac CP phase: size of effects scales with $\theta_{13}$

- collaboration focused on beam optimization, detector choices, background rejection
projected LB sensitivities

\[ \theta_{13} \]

\[ \text{MH} \]

\[ \text{CPV} \]

\[ 3\sigma \]

(36.5+36.5)\times10^{20} \text{ POT}
### far detector options under consideration

<table>
<thead>
<tr>
<th>Technology</th>
<th>Depth</th>
<th>Detail</th>
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<tbody>
<tr>
<td>Three x 100 kton* WC</td>
<td>4850’</td>
<td>15% pmt(^\d) coverage</td>
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<td>300’/800’</td>
<td>30% pmt(^\d) coverage</td>
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<td>Three x 17 kton* LAr TPC</td>
<td>4850’</td>
<td>Scintillation photon trigger</td>
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<td>300’/800’</td>
<td>No photon trigger</td>
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<tr>
<td>Two x 100 kton* WC AND One x 17 kton* LAr TPC</td>
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* fiducial volume  † 10 inch High-QE PMT’s
NuMI/HOMESTAKE

New tunnel starts near end of Carrier Tunnel

Extraction uses upstream portion of NuMI line

Homestake/DUSEL Neutrino Beam
- spectrum optimization (lower energies) sacrifices rate, perhaps now unfavored (700kW)

- running main injector @ 60 GeV -- 4 GeV peak, broader;
  run at 120 GeV, 0.5 degrees off axis -- 2.5 GeV peak, narrower
The oscillation of muon-flavor to electron-flavor at the atmospheric $\Delta m^2$ may show CP-violation dependence!

in a vacuum...

$$ P \left( \frac{\nu_\mu}{\bar{\nu}_\mu} \rightarrow \frac{\nu_e}{\bar{\nu}_e} \right) = \begin{pmatrix} \sin^2 \theta_{23} \sin^2 2\theta_{13} & \sin^2 \Delta_{31} \\ \mp \sin \delta \left( \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \right) \sin \Delta_{31} \sin \Delta_{21} \\ + \cos \delta \left( \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \right) \sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21} \\ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \end{pmatrix}.$$ 

We want to see if $\delta$ is nonzero

- terms depending on mixing angles
- terms depending on mass splittings

$$ \Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu $$

Janet Conrad
And the ground is made of matter (electrons) not antimatter (positrons).

Forward scattering affects neutrinos differently than antineutrinos.

\[ P_{\text{osc}} \left( \nu_\alpha \rightarrow \nu_\beta \right) \]

\[ P_{\text{osc}} \left( \bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta \right) \]

- underlying physics task difficult because of parameter degeneracies: e.g., CP violation and matter effects intertwined because a comparison of \( \nu \) and \( \bar{\nu} \) appearance channels

This slides the “allowed ring” off the diagonal

This a type of CP violation, but not what we are looking for!

- CP parameter

\( \theta \)

\( \delta \)

\( \pi \)

\( \text{CP} \)

\( \text{CP + matter,} \)
Other problems…

Long Baseline experiments are usually low in antineutrino statistics!

A combination of style of beam and cross section… and the backgrounds are larger compared to signal, but the larger difficult is the energy-dependent backgrounds that must be properly subtracted to determine the imprint of the oscillations.

but the larger difficult is the energy-dependent backgrounds that must be properly subtracted to determine the imprint of the oscillations.
Expectation for inverted hierarchy:

\[ \sin^2 2\theta_{13} = 0.04 \]

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**Thursday, August 26, 2010**
If we know the mass hierarchy, then this is how well LBNE can do in 10 years of running (e.g. without Project X).

10 years of running (e.g. without Project X)
- after background subtractions, quasi-elastic kinematics used to reconstruct initiating energy of the neutrino, necessary for connecting to an oscillation probability

- e.g., MiniBOONE, where the free parameters are a Fermi gas binding energy and a mass in the axial form factor

- collaborations recognize they need some help: nuclear response is typically 60% QE and 40% resonance production, with a water detector missing the produced \( \pi_0 \)s and missing energy from nucleons evaporating from the nucleus, and with 40% of the \( \pi \)s reabsorbed in the target
Theory: Mosel and Sobczyk presentations

- basic theory challenges
  - reconstructing neutrino energy from final-state observables, as it is not known a priori: unobserved pions and evaporation nucleons from nuclear targets
  - assumption of quasi-free kinematics to determine neutrino energy
  - “medium effects,” which are the full set of nuclear corrections that would renormalize vector and axial-vector responses in a complex target

- Mosel event generator
  - initial event is a neutrino interacting with one bound nucleon in a Fermi sea, with final states blocked
  - reaction products then propagated through nucleus
  - validity of the propagation model by testing generator against electron scattering or any other process that produces an equivalent initial event

- Label: Giessen Boltzmann-Uehling-Uhlenbeck Project -- mesons and baryons propagating in mean fields and scattering through input cross sections
Neutrino nucleon cross section

Note: $10^{-38} \text{ cm}^2 = 10^{-11} \text{ mb}$
Quasielastic scattering

\[
J_{QE}^\mu = \left( \gamma^\mu - \frac{q^\mu}{q^2} \right) F_1^V + \frac{i}{2M_N} \sigma^{\mu\alpha} q_\alpha F_2^V \\
+ \gamma^\mu \gamma_5 F_A + \frac{q^\mu \gamma_5}{M_N} F_P
\]

**vector form factors**
- vector FF ↔ EM FF via CVC
- BBBA07 parametrization for EM FF

**axial form factors**
- \( F_A \leftrightarrow F_P \) and \( F_A(0) \) via PCAC
- dipol ansatz for \( F_A \) with \( M_A = 1 \) GeV:

\[
F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}
\]

\[\nu_\mu \ n \rightarrow \mu^- \ p\]

5% error in \( M_A \)

ν_\mu n → μ^- p

- Barish, PRD 16 (1977)
- Mann, PRL 31 (1973)

INT 08/10
Axial Formfactor of the Nucleon

Recent Data give significantly larger values for $M_A$
- old neutrino data agree with electro-pion prod. data

- **K2K SciFi** ($^{12}$C, $Q^2 > 0.2$)
  - $M_A = 1.14 \pm 0.11$ GeV

- **K2K SciBar** ($H_2O$, $Q^2 > 0.2$)
  - $M_A = 1.20 \pm 0.12$ GeV

- **MiniBooNE** ($^{12}$C, $Q^2 > 0.25$)
  - $M_A = 1.25 \pm 0.12$ GeV

**MiniBooNE @NUFACT09:**
- $M_A = 1.35$ GeV

One difference:
- all old data use H (or D) as target
- all new data use nuclei (C, O, Fe) as target

INT 08/10
Pion production

- 13 resonances with $W < 2$ GeV, non-resonant single-pion background
- Pion production dominated by $P_{33}(1232)$ resonance:

$$J^{\alpha\mu}_{\Delta} = \left[ \frac{C_3^V}{M_N} (g^{\alpha\mu} q - q^{\alpha} \gamma^{\mu}) + \frac{C_4^V}{M_N^2} (g^{\alpha\mu} q \cdot p' - q^{\alpha} p'^{\mu}) + \frac{C_5^V}{M_N^2} (g^{\alpha\mu} q \cdot p - q^{\alpha} p^{\mu}) \right] \gamma^5$$

$$+ \frac{C_3^A}{M_N} (g^{\alpha\mu} q - q^{\alpha} \gamma^{\mu}) + \frac{C_4^A}{M_N^2} (g^{\alpha\mu} q \cdot p' - q^{\alpha} p'^{\mu}) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2} q^{\alpha} q^{\mu}$$

- $C^V$ from electron data (MAID analysis with CVC)
- $C^A$ from fit to neutrino data (experiments on hydrogen/deuterium)

Brookhaven data

10 % error in $C_5^A(0)$

Argonne data

discrepancy between data sets

$\Rightarrow$ uncertainty in axial form factor

data:
PRD 25, 1161 (1982), PRD 34, 2554 (1986)
Resonance excitation: Formfactors

- **vector form factors**
  - vector form factors $C_i^V \leftrightarrow$ EM form factors $C_i^{EM} \leftrightarrow$ helicity amplitudes
    Fogli et al. NPB160 (1979), Alvarez-Ruso et al. PRC57 (1998), Lalakulich et al. PRD71 (2006), ...
  - helicity amplitudes from **MAID analysis**

- **axial form factors**
  - axial coupling strength $\leftrightarrow$ PCAC
  - dipole ansatz for all resonances except $P_{33}(1232)$
  - refit of axial form factor required for $P_{33}(1232)$ (data!), Adler model sets 3 of the 4 formfactors for the $\Delta$, only $C_5^A$ reasonably well determined
Pion production through $\Delta$

New V, old A

New V, new A

Argonne Data

$\nu_\mu \, p \rightarrow \mu^- \, \pi^+ \, p$

$\frac{d\sigma}{dQ^2} \left[ 10^{-38} \text{ cm}^2/\text{GeV}^2 \right]$

$Q^2 \left[ \text{GeV}^2 \right]$

averaged over ANL flux, $W < 1.4 \text{ GeV}$

INT 08/10
Modelling the nuclear initial state

- **Initial-state interaction (ISI)**
  - impulse approximation
  - Fermi motion, Pauli blocking
  - self energies (mean-field potential and collisional broadening), spectral functions
  - medium-modified $\nu N$ cross sections
Free primary interaction cross sections, cross sections boosted to restframe of moving nucleon in local Fermigas
- no off-shell dependence, but include spectral functions for baryons and mesons (binding + collision broadening)

Cross sections taken from
- Electro- and Photoproduction for vector couplings
- Axial couplings modeled with PCAC

Pauli-principle included

Shadowing by geometrical factor \( (Q^2, \nu) \) included
Model Ingredients: ISI

- Hole spectral function (local TF)
  Local Thomas-Fermi Particles in mean-field potential.

\[ P_h(\vec{p}, E) \sim \int d^3r \left[ \Theta(p_F(r) - p) \delta(E + T_p + V(r)) \right] \]

- Particle spectral function: collisional broadening

\[ P_p(\vec{p}, E) \sim \frac{-\Im \Sigma(\vec{p}, E)}{(p^2 - M_0^2 - \Re \Sigma(\vec{p}, E))^2 + (\Im \Sigma(\vec{p}, E))^2} \]

- Inclusive cross section

\[ d\sigma^{lA \rightarrow l'X}_{tot} = g \int dE \int \frac{d^3p}{(2\pi)^3} P_h(\vec{p}, E) \frac{k \cdot p}{k^0 p^0} d\sigma^{lN}_{tot} P_{PB}(\vec{p}, E) \]
Medium modifications of the inclusive cross section

- All cross sections Fermi smeared
- $\Delta$ cross section is further modified in the nuclear medium:
  - $\pi$ decay might be Pauli blocked: decrease of the free width $\Gamma \rightarrow \Gamma_P$
  - additional "decay" channels in the medium: collisional width $\Gamma_{\text{coll}}$
    - $\Delta N \rightarrow NN$ "pion-less decay"
    - $\Delta NN \rightarrow NNN$
    - $\Delta N \rightarrow \pi NN$
    - $\Delta N \rightarrow \Delta N$

overall effect: increase of the width

$\Gamma \rightarrow \Gamma_{\text{med}} = \Gamma_P + \Gamma_{\text{coll}}$

collisional broadening
Model validation: incl. electron scattering

Perfect agreement at QE peak for higher energies

PRC 79, 034601 (2009)
This kind of approach has more in common with experimental event generators than with some of the first-principles QM microscopic techniques used in few-body systems.

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<thead>
<tr>
<th>Theory</th>
<th>Experiment</th>
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<tbody>
<tr>
<td>GiBUU</td>
<td>Neut (K2K, SciBooNE, T2K)</td>
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<tr>
<td>NuWRO</td>
<td>Nuance (SK, Minos, MiniBooNE)</td>
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<tr>
<td></td>
<td>GENIE/Neugen (Minos, Minerva, T2K, Nova)</td>
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<td>FLUKA (ICARUS)</td>
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</tbody>
</table>

QE: Smith-Moniz Fermi gas -- kinematics, spectral function, ...
RES: how many? interferences? nonresonant contributions? decay angular distributions?
DIS: hadronization model
COH: coherent pion production
Nuclear effects: e.g., GiBUU blocking, mean fields, resonance broadening ...
Sobczyk summary (but see talk on line)

compared specific features of these event generators
  - pion production on 16O: pionless and single-pion final states probabilities differing by ±25%
  - input spectral function (nucleon initial-state momentum distribution): FG vs. functions taken from electron scattering parameterizations
    - recognized shortcoming, yet just a bit on work (GENIE, NUANCE tests) have been done
    - neutrino energy reconstruction: impacts of systematic 22 MeV shifts
  - inappropriate use of impulse approximation
    - simple momentum counting rules shows that exchange currents and related corrections important at 500 MeV/c
  - “extra” QE contribution: discussed introduction of initial-state correlations to account for axial form factor masses significantly above accepted world average (2p2h RPA corrections of Martini, Ericson, et al.)
  - coherent pion production identified experimentally through use of the ancient Rein-Sehgal model
  - cascade code validation for critical channels, such as single π0
    - large absorption corrections
    - “data” presented in which large theoretical subtractions have already been made
Our collaboration

- we all have more interesting problems to work on

- however, the investment in this physics could reach $2B, and the current generation of experiments is already showing various anomalies

- one could pose two problems
  - can we construct a “challenge problem” that either validates existing event generators, or demonstrates they are not up to the tasks ahead?

  - can we construct a formalism that is sufficiently simple that it can be plugged into existing event generators, but sufficiently faithful to the underlying physics that accuracy is preserved?
Question for Joe:

Could we construct a challenge problem based on GFMC calculations for 4He?

- define the (likely more limited) kinematic region where GFMC might be reliable
- calculate electron scattering “data”
- calculate near-detector un-oscillated “data”
- pick a set of blind oscillation parameters: known ones consistent with current errors, unknown ones ($\theta_{13}$, $\delta_{\text{CP}}$, hierarchy)
- present the data to the experimentalists, ask them to identify the underlying parameter choice

Worry: the resonance production difficulties (e.g., quality of pQCD or conventional nuclear physics descriptions of deuteron photodisintegration)
If they fail: can we provide them with a representation of the response function that will allow them to do the analysis successfully, assuming a broad-band beam?

Won’t repeat the discussion given at our last meeting and in our proposal

\[ S_n(q, \omega) = |c|^2 \sum_{i=1}^{n} \delta(\omega - E_i) |\hat{\phi}_{E_i}(1, q)|^2 \]

This representation arises naturally from response function reconstructions based on the Lanczos algorithm: systematically extracts the lowest moments (in the distribution over energy) from the exact response matrix

Must be defined in terms of the observed final states. Could define “quasielastic” as anything with an observed energetic nucleon.

Then the \((E_i - Q)\) represent the “missing energy” from unobserved pions, evaporation nucleons, etc.

The associated “form factor” is an integration over all unobserved channels.

One could represent the GFMC results in this way: a series of successively more accurate representations as \(n\) is incremented.