Neutrino experiments and lattice QCD

Gabriel N. Perdue (Fermilab)
Lattice QCD All Hand's Meeting
April 20, 2018
Introduction

• Goal: try to talk about things a lattice QCD practitioner would find interesting w.r.t. neutrino experiments. So, focus on aspects of the physics modeling, and explain how a few oscillation experiments experience these effects by examining their detector technologies at a high level.

- Disclaimer: I'm not a member of any of these collaborations - please do not regard my comments as official statements on the experiments, etc.

\[
\mathcal{M}_{\nu_{\mu} n \rightarrow \mu p}(p, p') = \langle \mu(p') | (V_{\mu} - A_{\mu}) | \nu(p) \rangle \langle p(q) | (V_{\mu} - A_{\mu}) | n(0) \rangle
\]

Figure by A. Meyer
Outline

• Brief motivation from a neutrino oscillation physics perspective
• How do neutrino experiments model neutrino-nucleus interactions?
  - MC Event Generators
    • Focus on GENIE due to author affiliations...
  - What are the major outstanding problems?
• What do neutrino experiments actually measure?
• How are we sensitive to problems with the interaction physics modeling?

M. Betancourt et al, "Comparisons and challenges of modern neutrino scattering experiments (TENSIONS2016 report)", in preparation
A very brief motivation

- U. Mosel, NuInt 2017: DUNE is “an impossible” experiment:
  - Flux not fully specified,
  - Beamline is over 1,000 km, diameter is over 1 km at Far Detector,
  - Cross sections are tiny ($10^{-11}$ mb) and plagued by numerous theory and experimental uncertainties,
  - Somehow we need to extract evidence of physics beyond the Standard Model!
- Control of cross section systematics is a critical piece - requires a multi-pronged effort involving theorists, experimenters, and Monté Carlo authors all working together.
  - No single measurement or calculation will solve it all!

We have ~10 years to get everything under control!
Framing the issue

**Charged Current**

Free Nucleon:
Parameterize
w/ Form Factors...

Nucleus:
What is the initial state?
What escapes the nucleus?

**Bare fermions:**
Graduate homework problem

**Neutral Current**

How do we get there?
The Basic Problem: we must interpret with *models*

\[ E_1, P_1 \]

\[ (Energy_1, \text{Probability}_1) \]

\[ E_2, P_2 \]

\[ E \sim E_1 P_1 + E_2 P_2 + E_3 P_3 + \ldots \]

\[ E_3, P_3 \]

(and so on…)

We must leverage every possible observable!

Need to integrate - we interpret results statistically using *event generators.*
Neutrino MC Event Generators

- The generator must simulate all the types and momenta of every particle that appears in the final state.
- Some generators (MadGraph, Pythia, etc.) are computation aids for theorists, but most neutrino event generators are not (GiBUU is somewhat different).
- This is because we lack a theoretical framework that is both complete and consistent.
- The ideal input theory would be internally consistent and provide fully-differential cross sections in the kinematics of every final state particle over all reaction mechanisms, energies, and targets.
  - But the experiments must go on! So we must stitch together an ensemble that is consistent with all the data.
Neutrino Simulations: A Three-Part Software Stack

Beaml ine (FLUKA/Geant)
+ Produces a flux prediction
+ Hadron production, focusing, etc.

Event Generator (GENIE)
+ Interaction Physics
+ Nuclear medium

Detector (Geant)
+ Final state radiation traversing matter

Detector (FLUKA/Geant)
+ Produces a flux prediction
+ Hadron production, focusing, etc.

(won't say much about Geant here...)

(won't say much about Geant here...)

π⁺ → μ⁺ + νµ

νµ + N → μ⁻ + X

νµ

μ⁺

μ⁻

X
Philosophy

• The kernel of GENIE's physics model is a free nucleon model, with corrections to account for bound state effects and final state particle propagation.

• Exclusive states are added together with no interference terms (generally) to build a global inclusive model. Two-body currents are tacked on as another piece of the cross section (so they are not exactly free nucleons, etc.).

- We are working on new models that blend one and two-body currents together with an interference term. These calculations often have their own, "built-in" ground state model that is, in general, different from the usual GENIE ground state and other calculations.

• Supposing we solve the interference terms problem, can this philosophy hold up?

![Diagram showing neutrino generation and interactions]
**Pieces (Usually)**

- Vertex selection
  - Simple nuclear density model
- Initial state nuclear model
  - Removal energy and momentum
    - RFG with Bodek-Ritchie tails.
    - New: Local Fermi Gas
    - New: Effective Spectral Function
    - Almost there: "Benhar" spectral function
    - Just started: Correlated Fermi Gas (MIT)
- Hard scattering process
  - Differential cross section formula to get event kinematics (x, y, Q2, W, t, etc.)
- Lepton kinematics
- Hadronic system
  - Propagation/transport (default is an "effective cascade")
    - Fast and re-weightable

**GROUND STATE**

**INITIAL STATE**

**FINAL STATE**
Pieces (Usually)

- Decays before and after propagation
- Remnant decay
  - Just started caring about this, really...
  - Current model is very simple
    - Working on adopting other codes (Geant4, INCL++, possibly GiBUU) to handle clustering, de-excitation, evaporation
    - May be a bridge to more sophisticated transport codes

- Sometimes models can't work this way - e.g., it really is better physics to include draws from the ground state nuclear model in the accept-reject loop for determining kinematics. But this slows the code down a lot and so we must think about when to apply that paradigm.
- Also, some calculations are integrated over very specific ground state models and we cannot factorize them.
Reaction Channel Menagerie: A Glossary

- Charged current: exchange a W boson; neutral current: exchange a Z (not shown) - no charged lepton in the final state for NC.
  - CCQE: Charged-Current Quasi-Elastic
  - CC \( \pi^\pm, \pi^0 \)
    - Coherent (no break-up) & Resonance Production
  - Deep Inelastic Scattering (DIS - scatter on a parton)

- **Our descriptive language is something of a historical accident.** These terms are really only proper when discussing scattering on free nucleons.
  - When scattering on nuclei, final state interactions (FSI) mix up the particles leaving the nucleus, making this sort of assignment impossible.
  - Modern language prefers specification by visible particles in the final state.
GENIE Cross Section Models

(mostly for reference)

• GENIE has a large collection of physics models - combined to create global models.
  - Many are fairly **primitive**, but for the most part they are **fast, re-weightable, and not awfully wrong**. In some corners of phase space, GENIE disagrees with data by as much as 50% but across many distributions it is within ~5%.

• The default nuclear model is the relativistic Fermi gas with Bodek and Ritchie high-momentum tails. GENIE also implements the Effective Spectral Function, and the Local Fermi Gas.

• The quasielastic process defaults to Llewellyn-Smith, but we also have the Nieves et al model. We offer dipole and z-expansion axial form factors.

• Excitation of nucleon resonances (decaying by meson emission) and coherent pion production are both described by models by Rein and Sehgal, but we offer a number of alternatives (Berger and Sehgal, different form factor models, etc.).
  - We also offer a diffractive pion production model (Rein).

• Models for neutrino-electron scattering and inverse muon decay are included and mostly complete (additional radiative corrections required for neutrino-electron scattering).

• We offer (non-default) a custom built and the Valencia 2p2h models.

• Bodek and Yang (2003) is used for nonresonant inelastic scattering.

• Other interesting exclusive states (QEL hyperon production, single Kaon production, etc.) are optional (making them default would lead to double counting in the hadronization model).
Electron and muon final states differ only in lepton mass - no other corrections are applied. (Same form factors, etc.)

There are essentially no radiative corrections.

Our resonant pion production model is not complete and does not account for interference terms with other single pion production modes. We also do not model non-resonant pion production well (essentially use our DIS model).

Neutrino-nucleon (especially antineutrino-nucleon) cross sections are not well known and will be VERY difficult to measure in the future.
What do we measure?

• Sliding scale across detector technologies - ranging from a "limited" picture (water Cherenkov) all the way through hyper-fine details (liquid Argon).
  - No implication of a hierarchy here - there are lots of pros and cons for each - the right choice is a function of beam energy, funds available, and physics goals.

• Reasonably universal themes:
  - **The neutrino energy is unknown!** And fluxes are constrained to the 5-10% level based on external data. Oscillation experiments can leverage their Near Detector to reduce this uncertainty, but residuals remain due to varying beam spectra at Near and Far sites.
  - **Leptons are fairly well-measured** (when correctly identified).
  - **The hadronic system is partially, or even largely, invisible.**
    • It is often possible to veto on exotic baryons or the presence of mesons, etc.
    • It is often possible to reconstruct a significant fraction of the hadronic system.
      - Low energy nucleons are problematic.
      - Neutrons are often invisible (they will sometimes kick out protons when the detector contains hydrogen, and they will capture on Gadolinium, etc.).
      - De-excitation and evaporation of the remnant nucleus is generally not observed, although this is changing in liquid Argon.
T2K FD

- Far detector Superkamiokande: 50 kiloton water Cherenkov detector.
- Good lepton flavor identification,
- Good pion veto,
- Hadronic recoil is difficult to measure - heavy nucleons are generally below threshold,
- No magnetic field,
- Target nucleus is Oxygen (Water).

mu-like (left): sharp ring

e-like (right): fuzzy ring
T2K ND

- High granularity, magnetized near detector complex for comprehensive cross section program on Carbon, Oxygen.
  - "P0D" contains water layers, scintillator, and absorbers.
  - TPC and segmented scintillator modules.
NA61/SHINE Data

INGRID/Beam monitor Data

External Cross-section Data

Flux Model

Cross-section Model

ND280 Detector Model

ND280 Data

Super-K Data

Super-K Detector Model

Oscillation Fit

Oscillation Parameters

Figure by K. Duffy
T2K and Lattice QCD

• Because T2K uses different target nuclei at their near and far detectors (for the most part; the near detector does contain water targets that they have begun to fold into the analysis), they need to build a detailed model of neutrino-nucleus interactions and constrain it with their near detector data.
  - Of course, the near and far detectors also have different acceptances and measure different details about the final state, etc.

• Quasi-elastic scattering is a dominant reaction mechanism at their energies, and their far detector does not measure recoil protons.

• Neutrino energy reconstruction uses lepton kinematics under the assumption of two-body scattering (one-body currents). This technique works even when there are two-body currents as long as the simulation models the distribution of those events. But even for one-body currents they benefit from tighter controls on the nucleon cross section.

• This means they are avid consumers of improved nucleon-level cross section modeling.
NOvA (NuMI Off-axis $\nu_e$ Appearance) is a neutrino oscillation experiment

- Baseline of 810 km
- NuMI, beam of mostly $\nu_\mu$
- 14 mrad off-axis from the beam
- Two functionally identical detectors

Oscillation channels accessible to NOvA:

- $\nu_\mu (\bar{\nu}_\mu)$ to $\nu_e (\bar{\nu}_e)$ (appearance)
- $\nu_\mu (\bar{\nu}_\mu)$ to $\nu_\mu (\bar{\nu}_\mu)$ (disappearance)

Figures:

- Far Detector (FD): 15m X 15m X 60m, 896 planes
- Near Detector (ND): 4m X 4m X 16m, 214 planes

- 14 kt, $\geq$ 344,000 channels
- On surface
- 810 km from source

- 0.3 kt, $\geq$ 20,000 channels
- 100 m below surface
- 1 km from the NuMI

Kanika Sachdev
March 2015

Kanika Sachdev 8/
500 microsecond readout “gate”: Detector on the surface.

Where’s the neutrino?
Apply a timing cut (still significant cosmic background)
Near-to-Far Extrapolation

1. ND Data $E_\nu$ Spectrum
2. ND Reco. $\rightarrow$ True $E_\nu$
3. FD / ND Event Ratio in True $E_\nu$ Bins
4. $P(\nu_x \rightarrow \nu_y)$
5. FD True $\rightarrow$ Reco. $E_\nu$
6. FD Oscillated Prediction

Figure by A. Mislivec
NOvA and Lattice QCD

- NOvA's energy reconstruction is calorimetric, so they are more sensitive to the way energy is shared between hadrons in the final state and less sensitive to effects that change lepton energy and angle.
  - Fraction of energy in neutrons,
  - Few high energy nucleons vs many low energy nucleons,
  - Charged to neutral pion ratios, etc.
- NOvA is at a higher energy than T2K, so quasielastics form a lower fraction of their total event budget, but it is still a very large fraction of their mix of events.
- QE and QE-like events tend to have better energy resolution in NOvA, so their weighted impact on the oscillation analysis is high.
- Pion production is extremely important for NOvA!

FIG. 8 (color online). The published and extracted ANL and BNL data are compared with other measurements of $\nu_\mu p \to \mu^- p\pi^+$ on hydrogen or deuterium targets [26–28]. Note that the ANL and BNL data have no invariant mass cut, whereas the other data sets have an invariant mass cut of $W \leq 2$ GeV.
1. Charged particles interact in Ar
   - Ionize argon
   - Produce scintillation light

2. Ionization
   - e- drift toward anode

3. Wire planes detect drift e-

TPC Working Principle

- Cathode @ 70 kV (plate)
- Electric Field ~270 V/cm
- Anode (wire plane)
- X = 2.5 m
- Y = 2.3 m
- Z = 10.4 m

Three Wire Planes

170 tons of liquid argon
- 50% inside the TPC

cosmic rate ~200 m\(^2\)s\(^{-1}\): ~8 muons per drift time

Drift Time = X position

Charge collected by wire plane

Scintillation Light detected by PMTs

32 eight-inch PMTs for scintillation light (fast)

Figures: Kazuhiro Terao, SLAC & Andy Furmanski, Manchester
(These are mostly ArgoNeut images)
Rampant speculation! - MicroBooNE and Lattice QCD

• We're eagerly awaiting results from MicroBooNE (but patiently waiting - they only started taking data recently).
• Like T2K, MicroBooNE should see the majority of its events as quasielastics, but like NOvA, their energy reconstruction will be calorimetric.
• Convincing evidence of a sterile neutrino will require excellent theoretical controls across the board.

![Diagram of Neutrino Experiments and Lattice QCD](image)

**Figure by M. Kirby**
Lattice QCD and neutrino experiments...

\[
\begin{align*}
F_{A}^{CC} & \quad F_{A}^{NC} \\
F_{P}^{CC} & \quad F_{P}^{NC}
\end{align*}
\]

A. Kronfeld

Importance to Neutrino Physics

\[
\begin{align*}
s\bar{s} & \text{ in } N \\
\langle NN | J | NN \rangle & \\
\nu N & \rightarrow N^*, \Delta, N\pi, \ldots
\end{align*}
\]

\[
\begin{align*}
NN & \text{ forces } \\
\pi N & \text{ forces }
\end{align*}
\]

Difficulty in lattice QCD
Conclusions

- A running theme in all three of the experiments highlighted today is that quasielastic events are a very large portion of their total cross section (and they are dominant at T2K and MicroBooNE).
- Pion production is crucial for today's program and that importance will only grow at DUNE, etc.
- Nucleon-level uncertainties are extremely important and neutrino-nucleon data will be extremely hard to come by!

The major challenges for this reaction channel are: (QE)

- improvement of our knowledge of the axial part of the nucleon–nucleon transition matrix elements via
  1. a new high-statistics hydrogen and/or deuterium cross section experiment; or
  2. lattice-QCD calculations of the nucleon form factors at the same level of quality and precision as for meson form factors used in quark-flavor physics;

You'll hear more about this in the next talk!
Experiments

We do not measure the probability directly - we measure a rate:

$$R(E_{\text{vis}}) = N \int dE \Phi_\alpha(E) \sigma_\beta(E, E_{\text{vis}}) \epsilon_\beta(E) P(\nu_\alpha \rightarrow \nu_\beta, E)$$

- $N =$ overall normalization (e.g., mass)
- $\Phi_\alpha =$ flux of $\nu_\alpha$
- $\sigma_\beta =$ cross section for $\nu_\beta$
- $\epsilon_\beta =$ detection efficiency for $\epsilon_\beta$
- NOTE: $\sigma_\beta \epsilon_\beta$ always appear together. Define:

$$\tilde{\sigma}_\beta = \sigma_\beta \epsilon_\beta$$
Problem & Solution

• How do we know the components of the integral?
• How can we even determine the ratios for flavor and helicity combinations?
• Even if we know the cross sections from theory, we don't know efficiency ratios.
• But, we can measure ratios if we use two detectors!

\[
\frac{R_{\alpha \to \alpha} \text{(Far)} L^2}{R_{\alpha \to \alpha} \text{(Near)}} = \frac{N_{\text{far}} \Phi_{\alpha} \tilde{\sigma}_{\alpha} P(\nu_{\alpha} \to \nu_{\alpha})}{N_{\text{near}} \Phi_{\alpha} \tilde{\sigma}_{\alpha}}
\]

\[
\frac{R_{\alpha \to \alpha} \text{(Far)} L^2}{R_{\alpha \to \alpha} \text{(Near)}} = \frac{N_{\text{far}}}{N_{\text{near}}} P(\nu_{\alpha} \to \nu_{\alpha})
\]
Measure "Near"/Far

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2 [1.27\Delta m^2_{32} (L/E)] \]

Fit Ratio

Extract Physics!

\[ \sim \Delta m^2_{32} \]

\[ \sim \sin^2 2\theta_{32} \]
But, another (harder) problem!

• The above equations were for a disappearance measurement. For appearance measurements:

\[
\frac{R_{\alpha \rightarrow \beta} (\text{Far}) L^2}{R_{\alpha \rightarrow \beta} (\text{Near})} = \frac{N_{\text{far}} \Phi_{\alpha} \tilde{\sigma}_{\beta} P(\nu_{\alpha} \rightarrow \nu_{\beta})}{N_{\text{near}} \Phi_{\alpha} \tilde{\sigma}_{\alpha}}
\]

\[
\frac{R_{\alpha \rightarrow \beta} (\text{Far}) L^2}{R_{\alpha \rightarrow \beta} (\text{Near})} = \frac{N_{\text{far}} \tilde{\sigma}_{\beta}}{N_{\text{near}} \tilde{\sigma}_{\alpha}} P(\nu_{\alpha} \rightarrow \nu_{\beta})
\]

• It is even worse than that, because the efficiencies and the cross sections will both change for antineutrinos.
But wait - because our beams aren't pure, we're saved, right?

• The oscillated flux is different for a given species, so energy-dependent effects never really cancel.
• You need independent, external measurements to constrain your cross section model. Using internal measurements only introduces a degree of circularity.
• If you are truly able to build identical near and far detectors, projecting your near detector measurement to the far detector to compute an expected spectrum is a powerful technique. But...
  - It is hard to build identical near and far detectors!
  - If nothing else, you typically want your far detector to be much, much larger than your near detector. Even assuming perfect calibration this has important consequences for the acceptance in both detectors.
  - Scaling the same technology in the same way is also challenging. Typically technologies that scale well for both small and large detectors involve making granularity sacrifices in the near detector.
Nucleon not at rest: Fermi Gas Model

- **Impulse approximation**: scatter off independent single nucleons summed (incoherently) over the nucleus.
- In the FGM, all the nucleons are non-interacting and all states are filled up to \( k_F \).
- The IA becomes problematic when the momentum transfer is *smaller* than \(~300\) MeV (think about the de Broglie wavelength and remember \( 1 \text{ fm} = 1/200 \text{ MeV} \)).

\[ ^{12}\text{C} \quad E_B = 25 \text{ MeV} \quad p_F = 220 \text{ MeV/c} \]

- It is nice to see this problem getting high-level attention.

---


Smith and Moniz, 1972, Nucl. Phys. B43, 605
Nucleon not at rest: Fermi Gas Model

- **Impulse approximation**: scatter off independent single nucleons summed (incoherently) over the nucleus.
- In the FGM, all the nucleons are non-interacting and all states are filled up to \( k_F \).
- The IA becomes problematic when the momentum transfer is *smaller* than \( \sim 300 \) MeV (think about the de Broglie wavelength and remember 1 fm = 1/200 MeV).

**You can’t use the Fermi Gas Model anymore!**

\[ \begin{array}{|c|c|c|}
\hline
^{12}\text{C} & E_B = 25 \text{ MeV} & p_F = 220 \text{ MeV/c} \\
\hline
\end{array} \]

Nucleons move freely within the nuclear volume in constant binding potential.

Global Fermi Gas

\[ p_F = \frac{\hbar}{r_0} \left( \frac{9\pi N}{4A} \right)^{1/3} \]

Local Fermi Gas

\[ p_F(r) = \hbar \left( \frac{3\pi^2 \rho(r) N}{A} \right)^{1/3} \]

Figure by T. Golan
QE Cross Section

\[
\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2 \theta_c}{8\pi E_\nu^2} \left[ A(Q^2) \pm B(Q^2) \frac{s-u}{M^2} + C(Q^2) \frac{(s-u)^2}{M^4} \right]
\]

• Early formalism by Llewellyn Smith.
• Vector and Axial-Vector Components.
  - Vector piece can be lifted from (“easier”) electron scattering data.
  - We have to measure the Axial piece.

• \(Q^2\) is the 4-momentum transfer (-\(q^2\)).

• \(s\) and \(u\) are Mandelstam variables.

• The lepton vertex is known; the nucleon structure is parameterized with 2 vector (\(F_1, F_2\)) and 1 axial-vector (\(F_A\)) form factors.
  - Form factors are \(f(Q^2)\) and encoded in \(A, B,\) and \(C\).

Form Factors

\[ A \approx \frac{t}{M^2} \left( |f_1V|^2 - |f_A|^2 \right) + \frac{t^2}{4M^2} \left( |f_1V|^2 + \xi^2 |f_2V|^2 + |f_A|^2 + 4\xi \text{Re} (f_1V f_2^*) \right) \]
\[ + \frac{t^3 \xi^2}{16M^6} |f_2V|^2 \]

\[ B \approx \frac{1}{M^2} \left( \text{Re} (f_1V f_A^*) + \xi \text{Re} (f_2V f_A^*) \right) t \]

\[ C = \frac{1}{4} \left( |f_1V|^2 + |f_A|^2 - \frac{\xi^2 |f_2V|^2}{4M^2} t \right) \]

\[ f_A (q^2) = \frac{f_A (0)}{\left(1 - \frac{q^2}{M_A^2}\right)^2} \]

\( f_A \) is the axial-vector form factor. We must measure this in \( \nu \)-scattering. The dipole has been dominant, but that is changing...

The **form factors** \( f \) contain parameterized information about the target (general shape of the form factors comes from symmetry arguments).

Not calculable from first principles, instead we measure them experimentally.
Lattice QCD and neutrino-nucleus scattering

- New neutrino-nucleon data will be hard to come by, making lattice contributions potentially critical.
- We have started to phase out the dipole form factor in favor of the model-independent z-expansion (lattice program ongoing to compute the elements of the z-expansion):

\[ z(t; t_0, t_c) = \frac{\sqrt{t_c - t} - \sqrt{t_c - t_0}}{\sqrt{t_c - t} + \sqrt{t_c - t_0}} \]

\[ F_A(z) = \sum_{n=0}^{\infty} a_n z^n \quad t_c = 9m_\pi^2 \]

- z-expansion: conformal mapping taking kinematically allowed region \((t = -Q^2)\) to \(|z| < 1\).

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

(Llewellyn-Smith, 1972)