Measurements of Neutrino Interactions

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Why?

- Interactions are only weak, so measurements can probe character of weak interaction.
  - E.g., neutral current discovery in neutrino interactions.
- Weak response of target may be of interest.
  - E.g. parity-violating structure functions.
- Neutrino interactions enable oscillation experiments.
  - An oscillation experiment must measure neutrino flavor and $\frac{L}{E_v}$.
- The last has led to a renaissance of interest in the past decade as we aim for precise oscillation experiments.
Short baseline oscillation experiments have enough rate to also measure neutrino interactions: LSND, MiniBooNE, MicroBooNE.

Oscillation experiments have near detectors which measure interactions with varying degrees of effort: K2K, MINOS, T2K, NOvA, SBN.

A few dedicated experiments: SciBooNE, MINERvA, ANNIE.
Who? Where? and When?

- Cerenkov experiments: can be massive, high thresholds, few samples: LSND, MiniBooNE, K2K, ANNIE.
- Segmented scintillator: small(ish), lower thresholds, good timing: K2K, MINOS, SciBooNE, MINERvA, T2K, NOvA.
- Liquid argon TPCs: small(ish), very low thresholds, slow: MicroBooNE, SBN.
• Motivation and Background for Experiments
• Selected results:
  ▪ Elastic Scattering on Electrons
  ▪ Lepton kinematics of nearly elastic events
  ▪ Lepton and recoil
  ▪ Transverse balance
  ▪ Coherent and Inelastic
• Summary and Outlook
Motivation
“Neutrino flavor and $\frac{L}{E_\nu}$”: implications

- Oscillation experiments need neutrino flavor and $\frac{L}{E_\nu}$.
  - If a neutrinos arrive with unknown flavor and energy, we must infer these from the final state.
  - Measurements are made with charged-current reactions.

Why are neutral current reactions (mostly) not useful?

[Diagram of electron, neutrino, W boson, and charged current reactions]
“Neutrino flavor and $L/E_\nu$”: when nature is kind

• Experiments at reactors, e.g., Reines and Cowan (1955) or Daya Bay/RENO/Double Chooz
  ▪ Constant source of neutrinos, so backgrounds are high.
  ▪ Coincidence technique… positron & neutron detected. $\bar{\nu}p \rightarrow e^+n$

• This reaction has a calculable interaction cross-section because
  ▪ It is on free nucleons.
  ▪ Momentum transferred to nucleon is low and therefore “static” properties suffice.

• Bonus… you know the energy of the neutrino from the positron energy!

$$\langle E_e \rangle = \frac{2E_\nu M_p - M_n^2 + M_p^2 + M_\bar{\nu}^2}{2(E_\nu + M_p)} \approx E_\nu - 1.3 \text{ MeV}$$

Variation of energy is small, ~1/2% at 4 MeV, since recoiling neutron is heavy compared to momentum transfer.

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“Neutrino flavor and $\frac{L}{E_\nu}$”: when nature is cruel

- Not everyone is so lucky. Consider the analogous problem of 10s to 100s MeV neutrinos striking argon.
- In the low energy region, 1-100 MeV the nuclear structure is critical for energy reconstruction

**Reconstructing true neutrino energy:**

$Q$ is determined by measuring de-excitation gammas and nucleons

$$E_\nu = E_e + Q + K_{\text{recoil}}$$

... but detector may not see all energy, e.g., neutrons

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Excitation of $^{40}$K

At least 25 transitions have been observed indirectly

Figures from S. Gardiner, NuINT17

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Significant difference means model for unseen energy is uncertain.

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Must be supplemented by theory at higher energies

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Protons and neutrons and photons, oh my!

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$\nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K}^* + e^-$

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“Neutrino flavor and $L/E_\nu$”: when nature is cruel

- Remember the DUNE example from Alex’s lecture.
  - Need models of composition of final state to reconstruct energy.

![Diagram of neutrino interactions](image)

### Hadronic energy for 4 GeV neutrinos by reaction type

![Plot of hadronic energy](image)

### Stochastic fluctuations of hadronic energy.

![Plot of resolutions](image)

### Resolutions (caution: not Gaussian!)

**Resolutions**
- CDR-like
- Charge
- Best rec

**Hadronic energy for 4 GeV neutrinos by reaction type**

- QE
- DIS
- MEC
- RES

**Fraction of hadronic energy**

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<td>10</td>
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See arXiv:1811.06159, PRD 2019

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Shirley Li
SLAC postdoc

21 August 2019
Selected Results

Should have mentioned… I’m a MINERvA and T2K collaborator, which also happen to be the experiments that are most rapidly publishing right now. And I’m biased. So, I’ll “select” a heavy dose of those results.
Elastic Scattering from Electrons
Neutrino-Electron Elastic Scattering

Fundamental process: $\bar{v}e$ scattering

$$\frac{d\sigma}{dT_e} = \frac{2G_F^2 m_e}{\pi} \left[ c_L^2 + c_R^2 (1 - y)^2 - c_L c_R \frac{m_e}{E_\nu} y \right]$$

- Here, $y = T_e / E_\nu$ (the inelasticity parameter)
- The total cross section is
  $$\sigma = \frac{2G_F^2 m_e E_\nu}{\pi} \left[ c_L^2 + \frac{1}{3} c_R^2 - \frac{1}{2} c_L c_R \frac{m_e}{E_\nu} \right]$$
- Let’s examine this a bit

One of the few reactions you are encouraged to calculate in “baby QFT” courses!
Neutrino-Electron Elastic Scattering

• Electron-Z$^0$ coupling
  - (LH $e^-$): $-1/2 + \sin^2\theta_W$
  - (RH $e^-$): $\sin^2\theta_W$

\[ \sigma \propto \frac{G_F^2 S}{\pi} \left( \frac{1}{4} - \sin^2 \theta_W + \sin^4 \theta_W \right) \]

\[ \sigma \propto \frac{G_F^2 S}{\pi} \left( \sin^4 \theta_W \right) \]

One of the few reactions you are encouraged to calculate in “baby QFT” courses!

\[ \sigma_{TOT} = \frac{G_F^2 S}{\pi} \left( \frac{1}{4} - \sin^2 \theta_W + \frac{4}{3} \sin^4 \theta_W \right) \]

\[ = 1.4 \times 10^{-42} \text{ cm}^2 / \text{GeV} \cdot E_{\nu} (\text{GeV}) \]

This reaction is nearly unique among neutrino reactions in being predicted to high (~½%) precision.
6 GeV (“Medium Energy”) Flux from Neutrino-Electron Scattering

- Experimentally, a forward going energetic electron with nothing else in event.
- Backgrounds are primarily from $\nu_e$ interactions and photons from $\pi^0$ decays.

![Graph showing electron-like ionization and forward energy distribution](image)

- Data points and categories for different interactions:
  - $\nu_\mu e$: 939
  - $\nu_e e$: 68
  - $\nu_e$ CCQE: 78
  - $\nu_e$ others: 172
  - $\nu_\mu$ others: 481
  - $\nu_\mu$ cc: 274
  - COH $\pi^0$: 458
  - DFR $\pi^0$: 26

- Forward electron-like ionization and energy distribution with categories:
  - $\nu_\mu e$: 862
  - $\nu_e e$: 62
  - $\nu_e$ CCQE: 64
  - $\nu_e$ others: 30
  - $\nu_\mu$ others: 430
  - $\nu_\mu$ cc: 212
  - COH $\pi^0$: 126
  - DFR $\pi^0$: 481

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arXiv:1906.00111
6 GeV ("Medium Energy") Flux from Neutrino-Electron Scattering

- 1021 events in data with a predicted background of 212. S/N~4 for a process that is 0.02% of total interaction rate.

![Diagram showing flux uncertainties and events](image-url)
Leptons in “mostly elastic” scattering
What does “mostly elastic” mean?

- Let’s start from a “simple” experiment, electrons scattering from a nucleus at fixed angle.
- On a free nucleon at fixed angle, $2\rightarrow 2$ kinematics tells you that the energy transfer is also fixed. In this example, it would be fixed at ~110 MeV.
- So why a smeared out peak at the right?
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\[ e^- + ^{12}\text{C} \rightarrow e^- + \text{X} \]

E. Moniz et al, PRL 26, 445 (1971)
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- **Why is the peak shifted from 110 MeV?**

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Energy loss of lepton
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- What are all the events at ~250 MeV? Hint: can they contain pions in the final state?

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• What are all the events at $\sim 250$ MeV? Hint: can they contain pions in the final state?

Initial state nucleons can be in a correlated state. Or final state nucleons can exchange momentum in hard scattering. “Multinucleon” effects.
Precise MINERvA $\nu$ pionless events (CC0$\pi$)

$\frac{d^2\sigma_{GCC}^{0\pi}}{dp_T dp_\parallel} \nu$

Double-differential cross section - neutrino mode

MINERvA Data

GENIE 2.8.4 with MINERvA tune (RPA, 2p2h)

GENIE 2.8.4 (out of the box)

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PreciseT2K’s CC0π?

- MINERvA tune over corrects the effect.
- However, higher energy MINERvA only is sensitive to terms in the cross-section that are constant with energy.
- But T2K sees a significant contribution from 1/E terms.
- Apply only to the constant energy part, and get better agreement. But that’s a model. 😞

Scaled MINERvA tune, compared to data from Phys. Rev. D93, 112012 (2016)

Patrick Stowell’s thesis
Interpretation is Tricky. Historical (but recent) example

- MiniBooNE observed a large discrepancy in lepton kinematics in its “CCQE” events vs $Q^2$.
  - Attributed to axial form factor and Pauli blocking, just an event distortion in $Q^2$.
  - Now we understand this is, at least in part, due to multinucleon production w/ different energy-momentum transfer relationship.
- MiniBooNE’s attribution of the different to form factors meant misreconstructing $E_\nu$ in the oscillation analysis.
- Lesson: need multiple observables to diagnose an incorrect deconvolution.

$F_A(Q^2) = F_A(0)/(1+Q^2/M_A^2)^2$

Nominal model

Lepton and Recoil Energy
If we had a monochromatic neutrino beam, like electron scattering...

To do this in neutrino scattering, we have to use the final state observed energy since we don’t know incoming neutrino energy.
Since we don’t know neutrino energy...

• Must determine neutrino energy from the final state energy.
• If that is known,
  ▪ Neutrino direction fixed
  ▪ Outgoing lepton is well measured.
• MINERvA uses calorimetry for all but the final state lepton
  ▪ Don’t measure energy transfer, $q_0$, but a related quantity dependent on the details of the final state, “available energy”

$$ E_{\text{avail}} \equiv (\text{Proton and } \pi^\pm \text{ KE}) + (E \text{ of other particles except neutrons}) $$

Figure courtesy P. Rodrigues
• Nieves 2p2h & RPA model added to GENIE prediction used by MINERvA.

• But it doesn’t provide enough strength at moderate \(|q_3|\).
Leptons in “mostly elastic” scattering, revisited
MINERvA $\nu$ pionless events (CC0$\pi$)

- What if we take tune to inclusive data and feed it back to predict muon distributions in an exclusive channel?

\[
d^{2}\sigma^{0\pi}_{CC} \frac{d\sigma}{dp_{T}dp_{\parallel}} \nu
\]

\[
d^2\sigma_{DD} \frac{dp_{T}dp_{\parallel}}{dE}\frac{dF}{dp_{T}dp_{\parallel}}\frac{dG}{dp_{T}dp_{\parallel}}
\]

[Image of a graph showing double-differential cross sections for different pion momenta ranges.]
**MINERvA $\nu$ pionless events (CC0$\pi$)**

- Tuned vs untuned in an exclusive channel

\[
\frac{d^2\sigma_{CC}^{0\pi}}{dp_T dp_\parallel} \vphantom{\frac{\text{MINERvA Data}}{\text{GENIE 2.8.4}}}
\]

![Graph showing the ratio of tuned to default GENIE for different pionless CC events](image)

**Comparison**

- MINERvA Data
- MnvGENIE v1
- GENIE 2.8.4
- GENIE+RPA+2p2h

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*arXiv:1811.02774*
Apply to T2K’s CC0π?

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Transverse Balance in Quasielastic Scattering

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Transverse Balance in CC0\(\pi\)

- One very useful probe is the transverse balance of the leading proton and the lepton in CC0\(\pi\) events.
- In the absence of nuclear effects and extra particles in the final state, they are balanced.
- If energy of recoiling nucleus is known, can reconstruct momentum of target nucleon.


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Initial State and Final State in CC0π

- MINERvA 2p2h tune helps! But by studying reconstructed neutron momentum and transverse variables in CC0π events, we have evidence for deficiencies in the initial and final state models (and tune?).

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Transverse Variables and Binding Energy

- Transverse balance projected into the reaction plane is directly biased by binding energy.

Peak shift from GENIE’s default binding energy to correction proposed by Arie Bodek in arXiv:1801.07975

As it turns out, there is a similar shift near the peak. (Features in tail also.)
Coherent, Inelastic
Not this kind of newsworthy Coherent...
How are single pions produced?

- Many competing production mechanisms.

\[ \text{Resonant pion production} \]

\[ \text{Non-resonant pion production} \]

\[ \text{Interference at low } Q^2 \text{ on hydrogen} \]

\[ \text{Interference may be large effect} \]

\[ \text{Dominant} \]

\[ \text{Sub-leading} \]

\[ \text{Coherent inelastic} \]

\[ \text{Diffractive} \text{ (on hydrogen)} \]
Coherent pion production

• MINERvA’s coherent pion production results show some preference for Berger-Sehgal rather than GENIE’s Rein-Sehgal prediction.
  ▪ NEUT R-S prediction was poor at low pion energy.
  ▪ Used to be a puzzle since experiments “didn’t see” expected coherent pions!
  ▪ T2K reduced uncertainties after MINERvA’s results.
Coherent pion production

- MINERvA’s coherent pion production results show some preference for Berger-Sehgal rather than GENIE’s Rein-Sehgal prediction.
- Berger-Sehgal has been implemented in GENIE.
Summary/Outlook
**Pion Production needs a makeover...**

- Nucleon neutrino data is disturbingly imprecise.
- Models of final state interactions are not reliable.
- So when we make a measurement of neutrino pion production on nuclei, it is difficult to interpret.

![Diagram](image)

**Invariant Mass calculated with proton and $\pi^0$ 4-momenta**

![Graph](image)

Data on nuclei

Understanding

Final State Interactions

Data on nucleons

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Incoherent pion production observations

- MINERvA sees a strong deficit of pion production at low $Q^2$ in several channels.
  - MINOS has also seen a low $Q^2$ suppression in “resonance region”.
- MINERvA also sees a shift in the pion spectra to slightly lower values, which look to be consistent with a shift in the $\Delta(1232)$ peak.
  - Maybe resonant-non resonant interference that is absent from model?

\[ W_{\text{exp}} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2} \]
Why this deep dive? A.k.a., conclusions…

- Program of future experiments, e.g., DUNE and Hyper-K is going to require improved understanding of nuclear effects in inelastic (pion production) events.
- This is analogous to what I’ve described in “more elastic” events.
  - Harder in the sense of more degrees of freedom in the model.
  - Less demanding in the sense that less of the neutrino energy goes into each individual particle in higher multiplicity events.
- There are other challenges I haven’t touched on. My favorites…
  - Uncertainties in using $\nu_\mu/\bar{\nu}_\mu$ events to predict $\nu_e/\bar{\nu}_e$ interactions.
  - Detection of neutrons to directly validate missing energy models.
- As Alex said also, there is much work to do!
- Fortunately, we have a lot of data and new experiments to do it.