Neutrino Interactions
Part 2: The Nucleus Strikes Back

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Summary so far

• The Weak Interaction
  o Point-like scattering is “easy” to calculate
  o Chirality is crucial for neutrino/anti-neutrino cross-section differences

• Neutrino-nucleon interactions
  o Separation into QE, RES and DIS
  o QE: almost calculable with some form (fudge) factors
  o RES: much more difficult, lots of diagrams to consider
  o DIS: easy for inclusive high $Q^2$, hard at low $Q^2$, hadronic side a total guess
  o RES-DIS transition is poorly understood but potentially important for DUNE

• Neutrino-nucleus interactions
  o Nuclear effects: there are lots of them, they can significantly alter the nucleon-level cross section
  o Lots of options for ground state modelling and how to build cross sections
  o Not all models can predict everything!
Overview

- The Weak Interaction
  - Historical Overview
  - Point-like scattering
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - Ground state modelling
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Where did it all go wrong? (Neutrino event generators)
  - Limitations of our simulations
- Don’t Panic! The future of neutrino interactions
The T2K Experiment
The T2K Experiment

Super Kamiokande

Near Detector

J-PARC

Mt. Noguchi-Goro 2924 m

Mt. Ikeno-Yama 1360 m

water equiv. 1700 m

295 km

Muon Neutrino beam
The T2K Experiment

Super Kamiokande

Near Detector

J-PARC

Mt. Ikeno-Yama 1360 m

Mt. Noguchi-Goro 2924 m

water equiv. 1700 m

Muon Neutrino beam

295 km

\[ \mu \] neutrino or anti-neutrino beam

Produce predominantly \( \nu_\mu \) neutrino or anti-neutrino beam
The T2K Experiment
The T2K Experiment

Super Kamiokande

Near Detector

J-PARC

Mt. Noguchi-Goro 2924 m

Mt. Ikeno-Yama 1360 m

water equiv. 1700 m

Muon Neutrino beam

295 km

Interaction cross section

Detector effects

Neutrino flux

\[ N_\mu(E_\nu) = \sigma(E_\nu) \Phi_\nu(E_\nu) \varepsilon(E_\nu) \]

Neutrino flux

Detected effects

Interaction cross section

Neutrino flux

\[ \nu \rightarrow l \]

\[ n \rightarrow p \]

\[ W \]

\[ 1 \]

\[ \frac{1}{E_\nu}(\text{GeV}) \]

Near Detector

ND280
The T2K Experiment

Super Kamiokande

Near Detector

J-PARC

Mt. Noguchi-Goro
2924 m

Mt. Ikeno-Yama
1360 m

water equiv.

1709 m

295 km

Muon Neutrino beam

$\Phi_\nu$ (A.U.)

$E_\nu$ (GeV)

Near Detector
ND280

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The T2K Experiment

Super Kamiokande

Near Detector

J-PARC

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water equiv. 1700 m

Muon Neutrino beam

295 km

$\Phi_{\nu}(A.U.)$

$E_{\nu}(\text{GeV})$

Osc. $\nu_\mu$

Osc. $\nu_\tau$

Osc. $\nu_e$

$\Phi_{\nu}(A.U.)$

$E_{\nu}(\text{GeV})$

$\nu_\mu$

Near Detector

ND280

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The T2K Experiment

Super Kamiokande

Near Detector

J-PARC

Muon Neutrino beam

Far Detector

Super-Kamiokande

Near Detector

ND280

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The T2K Experiment

Far Detector
Super-Kamiokande

\[ N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\varepsilon(E_\nu) \]

Near Detector
ND280

\[ N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\varepsilon(E_\nu) \]

Oscillation probability

PMNS Mixing
\[ \delta_{CP} \quad \theta_{13} \]
\[ \Delta m^2_{32} \quad \theta_{23} \]
Neutrino Interactions at T2K

\[ N_\ell(E_\nu) = P(\nu_\mu \rightarrow \nu_\ell)(E_\nu) \sigma(E_\nu) \Phi_\nu(E_\nu) \epsilon(E_\nu) \]

\( N_\ell(E_\nu) \) = Event rate
\( P(\nu_\mu \rightarrow \nu_\ell)(E_\nu) \) = Oscillation probability
\( \Phi_\nu(E_\nu) \) = Neutrino flux
\( \epsilon(E_\nu) \) = Detector efficiency
\( \sigma_\ell(E_\nu) \) = Interaction cross section

**CCQE**
(Charged-Current Quasi-Elastic)

**CC2p2h**
(2 particle, 2 hole)

\[ N_\ell(E_\nu) \]

\[ P(\nu_\mu \rightarrow \nu_\ell)(E_\nu) \]

\[ \sigma(E_\nu) \]

\[ \Phi_\nu(E_\nu) \]

\[ \epsilon(E_\nu) \]

\[ \sigma_\ell(E_\nu) \]
\( \nu \) oscillations need \( \nu \) cross sections

\[
N_\ell(E_\nu) = P(\nu_\mu \rightarrow \nu_\ell)(E_\nu) \sigma(E_\nu) \Phi_\nu(E_\nu) \epsilon(E_\nu)
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• Need to know \( \Phi \times \sigma \) in order to interpret \( N_\ell \) as \( P(\nu_\mu \rightarrow \nu_\ell) \)
\( \nu \) oscillations need \( \nu \) cross sections

\[
N_{\ell}(E_\nu) = P(\nu_\mu \to \nu_\ell)(E_\nu) \sigma(E_\nu) \Phi_\nu(E_\nu) \epsilon(E_\nu)
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- \( \sigma_\ell(E_\nu) \) = Interaction cross section

- Need to know \( \Phi \times \sigma \) in order to interpret \( N_{\ell} \) as \( P(\nu_\mu \to \nu_\ell) \)
- Near / far ratios don’t fully cancel this:
  - Dramatic change in \( E_\nu \) distribution
  - \( \nu_\mu \) at ND vs \( \nu_e \) at FD (for appearance)
  - Different ND/FD design, acceptance
\( \nu \) oscillations need \( \nu \) cross sections

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  - Dramatic change in \( E_\nu \) distribution
  - \( \nu_\mu \) at ND vs \( \nu_e \) at FD (for appearance)
  - Different ND/FD design, acceptance
- Not just counting experiments: Require a model to relate \( E_\nu^{\text{reco}} \) to \( E_\nu^{\text{true}} \)
Nuclear effects and $E_\nu$ (T2K/HK)

Proxy for $E_\nu$ from lepton kinematics is exact only for CCQE elastic scattering off a stationary nucleon.
Nuclear effects and $E_\nu$ (T2K/HK)

The motion of the nucleons inside the nucleus (Fermi motion) causes a smearing on $E_\nu$.

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}$$
Nuclear effects and $E_\nu$ (T2K/HK)

The motion of the nucleons inside the nucleus (Fermi motion) causes a **smearing** on $E_\nu$.

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**.

\[
E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}
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Nuclear effects and $E_\nu$ (T2K/HK)

The motion of the nucleons inside the nucleus (Fermi motion) causes a smearing on $E_\nu$.

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a bias.

Not a good proxy for non-CCQE events: 2p2h and CC1π with pion abs. FSI.

Final state interactions (FSI) can cause different interaction modes to have the same final state.

Interactions off a bound state of two nucleons can result in 2p2h final states.

\[
E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}
\]
Nuclear effects and $E_\nu$ (T2K/HK)

**CCQE (1p1h)**

- Interaction modes

**CCRES**

- Final state interactions (FSI) can cause different interaction modes to have the same final state.

- Interactions off a bound state of two nucleons can result in 2p2h final states.

**2p2h**

- 2p2h and pion abs. FSI cause further bias.

---

**First-order effects**

- Fermi motion causes a **smearing** on $E_\nu^{QE}$.
- Nuclear removal energy effects introduce a **bias**.

**Equation for $E_\nu$**

\[ E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)} \]
Neutrino interactions

Key challenge: estimating $E_{\nu}$
Nuclear effects and $E_\nu$ (SBN/DUNE/NOvA)

Calculation from calorimetry is exact only for interactions without neutrons and charged pions (ignore heavier mesons here) off a stationary nucleon. Usefulness is not restricted to QE-like interactions (no final state pions).

$$E_{\nu}^{\text{calo}} = E_\ell + E_{\text{had.}} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$
Nuclear effects and $E_\nu$ (SBN/DUNE/NOvA)

Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

$$E_{\nu}^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

All events without $n$ or $\pi^\pm$
Nuclear effects and $E_\nu$ (SBN/DUNE/NOvA)

Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

Charged pion masses also play a fairly small role

$E_{\nu \text{calo}} = E_\ell + E_{\text{had.}} = E_\ell + \sum T_p + \sum T_{\pi^\pm} + \sum E_\gamma$

All events without $n$ and $\pi^0 \rightarrow \gamma \gamma$
Nuclear effects and $E_\nu$ (SBN/DUNE/NOvA)

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Charged pion masses also play a fairly small role

Fraction of $E_\nu$ in Neutrons is critical

$E_{\nu}^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$
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$$E_{\nu}^{\text{calo}} = E_\ell + E_{\text{had.}} = E_\ell + \Sigma T_P + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

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Fraction of $E_\nu$ in Neutrons is critical – affected importantly by FSI (and more important for $\bar{\nu}$)
Nuclear effects and $E_\nu$ (SBN/DUNE/NOvA)

- Complex interaction topologies make $E_{\text{had}}$ tough to model.
- NOvA find strong data/simulation discrepancy at low $E_{\text{had}}$ (before applying a 2p2h modification).
- Covered by generous systematics, but this must be better understood for DUNE.
Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Ratio of $\nu_e$ to $\nu_\mu$ critical for future oscillation analyses
  - Measure $\nu_\mu$ at ND but need to know about $\nu_e$ to measure $\delta_{CP}$

- This is also subject to subtleties in the nuclear physics...

- If the outgoing nucleon exits the nucleus as a “plane wave” (no FSI):
  $\sigma(\nu_e) > \sigma(\nu_\mu)$

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INSS, CERN, August 2021
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  - Measure $\nu_\mu$ at ND but need to know about $\nu_e$ to measure $\delta_{CP}$

- This is also subject to subtleties in the nuclear physics…

- If the outgoing nucleon exits the nucleus as a “plane wave” (no FSI):
  $\sigma(\nu_e) > \sigma(\nu_\mu)$

- If the outgoing nucleon is distorted by the nuclear potential (FSI):
  $\sigma(\nu_e) < \sigma(\nu_\mu)$
Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Different models can predict quite different cross section ratios!
- Important for T2K/HK!

<table>
<thead>
<tr>
<th>Model</th>
<th>$E_\nu = 200$ MeV</th>
<th>$E_\nu = 600$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5°</td>
<td>60°</td>
</tr>
<tr>
<td>RFG (w/PB)</td>
<td>0.64</td>
<td>1.61</td>
</tr>
<tr>
<td>SF (full)</td>
<td>1.41</td>
<td>1.92</td>
</tr>
<tr>
<td>CRPA</td>
<td>~0.5</td>
<td>~1.4</td>
</tr>
</tbody>
</table>

Tabulated from Phys. Rev. C 96, 035501 and the left figure

These differences are predicted in regions that are relevant to T2K/HK oscillation analyses

Phys. Rev. Lett. 123, 052501 $\theta_l$ (degrees)
## What we need to know (a non exhaustive list!)

<table>
<thead>
<tr>
<th><strong>T2K/HK</strong>&lt;br&gt;(&quot;kinematic&quot; $E_\nu$ proxy)</th>
<th><strong>SBN/DUNE/NOvA</strong>&lt;br&gt;(&quot;calorimetric&quot; $E_\nu$ proxy)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Critical</strong>&lt;br&gt;</td>
<td><strong>Critical</strong>&lt;br&gt;</td>
</tr>
<tr>
<td>• Nuclear ground state: <em>Fermi motion</em> and &quot;binding energy&quot;</td>
<td>• Neutron production:</td>
</tr>
<tr>
<td>• $2p2h$ and <em>pion absorption FSI</em> contributions to $0\pi$ final states</td>
<td>• FSI</td>
</tr>
<tr>
<td></td>
<td>• $2p2h$</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>
What we need to know (a non exhaustive list!)

**T2K/HK**
(“kinematic” \(E_\nu\) proxy)

**Critical**
- Nuclear ground state: *Fermi motion* and “*binding energy*”
- *2p2h* and *pion absorption FSI* contributions to 0\(\pi\) final states

**Important**
- Impact of *nucleon FSI* on \(\sigma(\nu_e)/\sigma(\nu_\mu)\)
- Differences between interactions on Carbon and Oxygen

**SBN/DUNE/NOvA**
(“calorimetric” \(E_\nu\) proxy)

**Critical**
- Neutron production:
  - FSI
  - *2p2h*
  - DIS hadronisation

**Important**
- Charged pion multiplicities (e.g. from FSI)
- Nuclear ground state
- Differences between interactions on Carbon and Argon

---

Neutrino interaction modelling is crucial for all upcoming experiments, but different experiments have different priorities: *complimentary approaches!*
KEEP CALM
AND
MEASURE $d\sigma/dx$
Overview

- The Weak Interaction
  - Historical Overview
  - Point-like scattering
- Neutrino-nucleon interactions
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- Neutrino-nucleus interactions
  - Nuclear effects
  - Ground state modelling
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Where did it all go wrong? (Neutrino event generators)
  - Limitations of our simulations
- Don’t Panic! The future of neutrino interactions
What can we measure

**Interaction Modes**

- **CCQE** (1p1h)
- **CCRES**
- **2p2h**

**Interaction Topologies**

- **CC0π (CCQE-like)**
- **CC1π (CCRES-like)**
- **CC0π+Np (N>0)**

- Nuclear effects can hide the true interaction mode
- To minimise model dependence we measure interaction topologies

![Interaction modes in CC0π topology: (NEUT)](chart.png)

- CCRES 6.91%
- 2p2h 12.11%
- Other 0.38%
- CCQE 80.60%
ND280 and MINERvA

ND280 (Near detector for T2K)

Primary targets: CH, H$_2$O

- On Axis \( \sim 1.1 \) GeV
- Peak \( E_\nu \)
- Off Axis \( \sim 0.6 \) GeV

MINERvA

Primary targets: CH, Pb, Fe

- ME \( \sim 5.8 \) GeV
- Peak \( E_\nu \)
- LE \( \sim 3.2 \) GeV
NOvA and $\mu$BooNE

NOvA (Near detector)

Primary targets: “NOvA soup”
(Mostly C, H, Cl)

Peak $E_\nu$: $\sim 2$ GeV

$\mu$BooNE

Primary targets: Ar

Peak $E_\nu$: $\sim 0.6$ GeV
**CC0π measurements**

**Interaction Modes**
- **CCQE** (1p1h)
  - $\nu_\mu \rightarrow W^\pm \rightarrow n \rightarrow p$
- **CCRES**
  - $\nu_\mu \rightarrow W^\pm \rightarrow n \rightarrow \Delta^\pm \rightarrow n$
- **2p2h**

**Interaction Topologies**
- CC0π (CCQE-like)

- The thing we know “best”
- Dominant community focus for ~10 years
- Signal process for T2K/HK
Which observables?

Just the muon?
Our current models vs data

CC0π muon kinematics

Agreement is sort of okay (by our poor standards).
Forward Angles

- The very forward region is especially sensitive to interactions with low energy transfer ($\omega$)
- Things don’t look so good here …

---

**Graph 1:**
- O, $0.93 < \cos\theta_\mu < 1$
- T2K
- GENIE v3 SuSá v2 (103.5)
- NuWro SF (114.5)
- NEUT LFG (44.8)
- GiBUU (112.7)

**Graph 2:**
- $d^2\sigma/dp\,d\cos\theta_\mu$
- Muon momentum (GeV/c)
- MicroBooNE 1.6e20 POT
- GENIE v2.12.2 + Emp. MEC
- GENIE v3.00.04 G1810a021a
- GiBUU 2019
- NuWro 19.02.1
- Data (Stat. + Syst. Unc.)

**Graph 3:**
- $d\sigma/d\cos(\theta_{\text{rec}})$
- $\cos(\theta_{\text{rec}})$
What to measure?

Muon kinematics?

✓ Muon kinematics can be predicted directly from most theories

✗ But most theories predict very similar things in muon kinematics (apart from at forward angles)

✗ Differences are often normalisation changes: can be hidden under a flux error
Which observables?

Correlations between the muon and proton kinematics allow us to disentangle nuclear effects from neutrino energy.
Single Transverse Variables

\[ p^\nu \quad p^l \quad p^p \]

No nuclear Effects

\[ \nu_\mu + n \rightarrow \mu + p \]
Single Transverse Variables

\[ p_T^l = -p_T^p \]

No nuclear Effects
Single Transverse Variables

\[ p_T^l \neq -p_T^p \]

With Nuclear Effects
Single Transverse Variables

- Any deviation from $\delta p_T = 0$, $\delta \phi_T = 0$ is indicative of nuclear effects

• In the absence of other nuclear effects, $\delta p_T$ is the transverse projection of the Fermi motion.
• Since this motion is isotropic, $\delta p_T \rightarrow$ Fermi motion
In the absence of other nuclear effects, $\delta p_T$ is the transverse projection of the Fermi motion.

Since this motion is isotropic, $\delta p_T \rightarrow$ Fermi motion

Cross section beyond the Fermi surface must come from physics beyond RFG $\rightarrow$ 2p2h, FSI, SRCs …
Consider imbalance from only Fermi motion

Fermi motion is isotropic so no preferred $\delta \alpha_T$ direction
STV model discrimination - $\delta \alpha_T$

Deceleration of proton from FSI

$\delta \alpha_T$ = larger $\delta \alpha_T$

FSI causes $\delta \alpha_T$ to rise

LFG no FSI  CC0π

LFG w/ FSI CC0π
Current measurements

Phys. Rev. D 98, 032003
NuWro 11q

Phys. Rev. Lett. 121, 022504

\[ \frac{d\sigma}{d\delta p_T} \]

\[ \delta p_T \text{ (GeV)} \]
Current measurements

- The bulk of the distribution does not have the “Fermi-cliff” present in RFG models – rejection of RFG model
Current measurements

- The bulk of the distribution does not have the “Fermi-cliff” present in RFG models – **rejection of RFG model**
- SF appears important to fill in the “dip” region (SRCs extend the initial state nucleon momentum distribution)
Current measurements

- The bulk of the distribution does not have the “Fermi-cliff” present in RFG models – rejection of RFG model
- SF appears important to fill in the “dip” region (SRCs extend the initial state nucleon momentum distribution)
- None of the models are able to fully describe the results
Current measurements

- Can try altering 2p2h and FSI in the models
- Clear preference to need 2p2h, but models are still in poor agreement with the results
Current measurements

- This trend carries on when trying to describe most exclusive data.
What can we measure

**Interaction Modes**

- **CCQE (1p1h)**
  - $\nu_\mu \rightarrow n \rightarrow p$

- **CCRES**
  - $\nu_\mu \rightarrow n \rightarrow \Delta^+ \rightarrow n$

- **2p2h**
  - $\nu_\mu \rightarrow p\rightarrow p$

**Interaction Topologies**

- **CC1π (CCRES-like)**

• Key contributor to all experiments
• The thing we don’t understand well at all …
Pion production measurements

Similar story:

- Models generally able to predict lepton kinematics reasonably well
  - Even in the forward region!

(arXiv: 1803.08848)
Pion production measurements

Similar story:

- Models generally able to predict lepton kinematics reasonably well
  - Even in the forward region!

- But pion kinematics are poorly described across experiments

\[ \text{Phys. Rev. D 100, 072005} \]

\[ \text{Phys. Rev. D 101, 012007} \]
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  o Limitations of our simulations

• Don’t Panic! The future of neutrino interactions
The Generators

**GENIE**: very widely used. Large development team. Used as default simulations by most Fermilab neutrino experiments.

**NEUT**: used primarily by the SK, T2K and HK collaborations. Smaller development team – updated to fill needs of experiments.

**NuWro**: wide range of models available. Driven more by theory than by experimental requirements. Only a few developers. (Also called the WrOclaw Neutrino event Generator)

**GiBUU**: a full theory in its own right, predicting nu/e/hadron scattering. Different philosophy than the other generators. Hard to use as a primary input for experiments. One/two developers.
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Caveat: not everything I say applies to all models in all these generators. Too much to cover in one talk!
A generator’s view of $\nu N$ scattering
Fermi motion

- Start with a nucleon inside the nucleus, bound with some removal energy and moving with some Fermi motion.
Neutrino-nucleon interaction

- We have a nucleon, now let’s interact with it
Final state interactions

- We now have a nucleon inside the nucleus, it should probably bounce around a bit before it gets out: **Final State Interactions**
Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus
Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus

1. Step the particle through the nucleus a distance equal to its mean free path between interactions
Final state interactions

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3. Use MC methods to determine if it interacts or not, if it does choose a process according to its cross section

See e.g.: Phys. Rev. D 99, 052007
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4. Generate the interaction

5. Return to 1.
A generator’s view of $\nu N$ scattering
A generator’s view of $\nu N$ scattering

- Unfortunately we’ve seen things aren’t even this “simple”
What’s in CC0π?

CCQE

\[ n \rightarrow l \rightarrow W \rightarrow p \]
Recall: Inclusive scattering

Only predict lepton kinematics: inclusive model

All of the nuclear dynamics lives in here

$$\frac{d^2\sigma_{vl}}{d\Omega(\vec{k}')}dE'_l = \frac{\vec{k}'}{4\pi^2} G^2 L_{\mu\sigma} W^\mu\sigma$$

E.g. Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et Al, 2004

Need a nuclear model to calculate this, Nieves uses a “Local Fermi Gas”

Needs 6 “structure functions” built from 5 hadron tensor elements
Inclusive scattering in generators

Only predict lepton kinematics: inclusive model

\[ \frac{d^2 \sigma_{vl}}{d\Omega(\hat{k}')dE_l'} = \frac{|\vec{k}'|}{|\vec{k}|} \frac{G^2}{4\pi^2} L_{\mu\nu} W_{\mu\nu} \]

E.g. Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et Al, 2004

All of the nuclear dynamics lives in here

Need a nuclear model to calculate this, Nieves uses a “Local Fermi Gas”

This is what most older generator versions use (anything that uses RFG)

E.g.:
- Anything that isn’t SF in NEUT<5.4.0
- Anything in GENIE <3
- SuSAv2 in GENIE v3
- Any 2p2h model ...

\[
\begin{align*}
\frac{d^2 \sigma_{vl}}{d\Omega(\hat{k}')dE_l'} &= \frac{|\vec{k}'|E_l'G^2}{\pi^2} \left\{ \frac{2W_1}{\sin^2 \theta'\cos \theta'} + \frac{W_2}{\sin \theta'\cos \theta'} \right. \\
&\quad - \left. \frac{W_3}{2} \frac{E_{l'} + E_{l'}'}{M_i} \sin^2 \theta' + \frac{m_i^2}{E_{l'}(E_{l'} + |\vec{k}'|)} \right[ W_1 \cos \theta' \\
&\quad - \frac{W_4}{2} \cos \theta' + \frac{W_3}{2} \left( \frac{E_{l'} + |\vec{k}'|}{M_i} - \frac{E_{l'} + E_{l'}'}{M_i} \sin \theta' \cos \theta' \right) \\
&\quad + \frac{W_4}{2} \left( \frac{m_i^2}{M_i^2} \cos \theta' + \frac{2E_{l'}(E_{l'} + |\vec{k}'|)}{M_i^2} \sin^2 \theta' \right) \\
&\quad - W_5 \frac{E_{l'} + |\vec{k}'|}{2M_i} \right\}
\end{align*}
\]

(10)
Inclusive scattering in generators

Only predict lepton kinematics: inclusive model

CCQE

\[ \frac{d^2\sigma_{vl}}{d\Omega(k')} = \frac{|k'| G^2}{4\pi^2} L_{\mu\nu} W^{\mu\nu} \]

E.g. Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et Al, 2004

All of the nuclear dynamics lives in here

But then where does *insert generator name* get the nucleon kinematics from … ?

Is this reasonable?

Probably not

LFG

Inclusive interaction

FSI Cascade
Recall: Exclusive scattering

Exclusive model: can describe all final state particle kinematics

\[
\frac{d^5 \sigma_{\nu\ell}}{d\Omega(k')d\Omega(p_N)dE'} \sim L_{\mu\sigma} W^{\mu\sigma}
\]

E.g. Semi-inclusive charged-current neutrino-nucleus reactions, O. Moreno et Al, 2014

But now there’s 10 tensor elements …

\[
\eta^{s}_{\mu\nu} W^{s\mu\nu}_s \sim \hat{V}_{CC} W^{CC \text{semi}} + \hat{V}_{CL} W^{CL \text{semi}} + \hat{V}_{LL} W^{LL \text{semi}} + \hat{V}_T W^T_{\text{semi}} + \hat{V}_{TT} W^{TT \text{semi}} + \hat{V}_{TC} W^{TC \text{semi}} + \hat{V}_{TL} W^{TL \text{semi}}
\]

\[
\eta^{a}_{\mu\nu} W^{a\mu\nu}_a \sim \hat{V}_{T'} W^{T' \text{semi}} + \hat{V}_{TC'} W^{TC' \text{semi}} + \hat{V}_{TL'} W^{TL' \text{semi}}
\]

… and these become challenging to calculate

• Some models can do this, e.g. Relativistic Mean Field (RMF)
Exclusive scattering

Exclusive model: can describe all final state particle kinematics

All of the nuclear dynamics still lives in here

\[
\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)dE_{\ell}'} \sim L_{\mu\sigma} W^{\mu\sigma}
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... and these become challenging to calculate

- Some models can do this, e.g. Relativistic Mean Field (RMF)

No generator model does this
Recall: Factorization

Exclusive model: can describe all final state particle kinematics

If we assume the outgoing nucleon is non-relativistic and that there’s no FSI we can write the cross section like this:

\[
\frac{d^5 \sigma_{\nu \ell}}{d\Omega(\hat{k}')d\Omega(p_N)dE_{\ell}'} \sim S(E_m, p_m)L_{\mu \nu} W^{\mu \nu} \delta(\omega + M - E_m - E_{p'})
\]

“Spectral Function”

Single nucleon tensor contraction (no nuclear effects)

This doesn’t have to be the Benhar SF, it just needs to be a nuclear model predicting Fermi motion and removal energy.
Exclusive model: can describe all final state particle kinematics.

If we assume the outgoing nucleon is non-relativistic and that there’s no FSI we can write the cross section like this:

$$\frac{d^5 \sigma_{\nu \ell}}{d\Omega(k')d\Omega(p)dE_{\ell}'} \sim S(E_m, p_m)L_{\mu\nu}W^{\mu\nu}\delta(\omega + M - E_m - E_{p'})$$

This is what some newer generators use for CCQE – some limited predictive power for nucleon kinematics. An FSI cascade is added on top ad hoc but this only affects the nucleon. E.g.:

- SF in NEUT 5.4.x
- SF in NuWro
- Fermi-gas QE in GENIE v3 (I think!)
We’re finally getting somewhere?
Beyond the impulse approximation

- Most of our models start from the impulse approximation: we interact with a single nucleon inside the nucleus.
Beyond the impulse approximation

• Most of our models start from the impulse approximation: we interact with a single nucleon inside the nucleus

• But at low energy transfers this isn’t a great approximation
Beyond the impulse approximation

- To account for this we often apply an “RPA correction” to Fermi gas models which gives a strong suppression
Beyond the impulse approximation

- To account for this we often apply an “RPA correction” to Fermi gas models which gives a strong suppression.
- But more sophisticated approaches to breaking the IA don’t suggest the suppression should be so strong …
We’re finally getting somewhere?

(CAVEAT: If we restrict ourselves to high energy transfers)
Final state interactions (FSI) can cause different interaction modes to have the same final state.
Pion absorption FSI

Final state interactions (FSI) can cause different interaction modes to have the same final state

- No complete theory for pion absorption: have to use ad-hoc approaches to add nuclear effects to neutrino-nucleon models
Interactions off a bound state of two nucleons (mediated by Meson Exchange Currents) can result in 2p2h final states.
Interactions off a bound state of two nucleons (mediated by Meson Exchange Currents) can result in 2p2h final states

- No complete theory for outgoing nucleon kinematics for 2p2h: have to use ad-hoc approaches to add nuclear effects to neutrino-nucleon models
## Generator CCQE models

### CCQE Models in the Generators

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* NuWro includes an approximate technique for improving this, but it does not do reliable things to the outgoing nucleon kinematics

** Work in progress!!!
The impulse approximation is not so important.

Most are neutrino-nucleon models with nuclear effects added ad-hoc in a simple way.
  - Very little predictive power for hadron kinematics.

Even the neutrino-nucleon interaction models are hard to get right.

Inconsistent models for the RES and DIS interactions with a challenging transition region.
Let’s Recap

We describe intermediate muon kinematics in CC0π measurements quite well with most models

Expected?
Let’s Recap

We describe intermediate muon kinematics in CC0π measurements quite well with most models.

Expected?

Yes!

- Impulse approximation is reasonable
- Inclusive 2p2h models are reasonable
- The details of the hadron kinematics don’t matter so much
- The impact of FSI is small
Let’s Recap

We describe forward going muon kinematics in CC0π measurements badly most models

Expected?

Models with RPA do better here
Let’s Recap

We describe forward going muon kinematics in CC0π measurements badly most models

Expected?

Yes!

• Impulse approximation is not reliable, but most of our models use it

Models with RPA do better here

Makes sense!

• Provides some modelling of physics beyond the impulse approximation
We describe nucleon kinematics badly

SF models with do better here
Let’s Recap

We describe nucleon kinematics badly

Expected?

Yes!

• All of our models rely on ad-hoc model combinations to predict nucleon kinematics

SF models with do better here

Makes sense!

• Less approximations in predictions of nucleon kinematics
Summary so far

• Why do we care?
  o Understanding even the subtle details of neutrino interactions is crucial for precision measurements of neutrino oscillations
  o Much of this stems from the bias in $E_\nu$ reconstruction
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- Neutrino-nucleus interaction measurements
  - Measurements of only the outgoing lepton at intermediate kinematics: good, simulations mostly match the data
  - Measurements of anything else: not so good
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• Why do we care?
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  o Measurements of only the outgoing lepton at intermediate kinematics: good, simulations mostly match the data
  o Measurements of anything else: not so good

• Where did it all go wrong? (Neutrino event generators)
  o Generators predict anything you want them to, even when the underlying theory does not
  o Treat their predictions (and even provided uncertainties) with scepticism, they don’t cover everything
Overview

• The Weak Interaction
  o Historical Overview
  o Point-like scattering

• Neutrino-nucleon interactions
  o QE, RES and DIS

• Neutrino-nucleus interactions
  o Nuclear effects
  o Ground state modelling

• Why do we care?
  o Neutrino interactions for neutrino oscillations
  o Neutrino energy reconstruction

• Neutrino-nucleus interaction measurements
  o Inclusive successes and exclusive failures

• Where did it all go wrong? (Neutrino event generators)
  o Limitations of our simulations

• Don’t Panic! The future of neutrino interactions
How far we’ve come

**c. 2001** “Nuclear effects” is not in a neutrino physicist’s vocabulary

**c. 2010** “Most of our knowledge of neutrino cross sections in the 0.1-20 GeV energy range comes from early experiments ... conducted in the 1970s and 1980s”

Rev. Mod. Phys. 84, 1307

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![Rev. Mod. Phys. 84, 1307](image-url)

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Whilst it’s true that **our measurements have outstripped our models** in our generators, this is partially because **we have such rich measurements**!

It’s also true **we need to better understand neutrino interactions for DUNE and Hyper-K**, but **we do not need to have this tomorrow**!

However, **the measurements and theory developments have to start now**!
Undetectable, you say?

“I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do.” Wolfgang Pauli, 1930
Well, have I got $\nu_s$ for you!

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Wolfgang Pauli, 1930

Using these criteria, a sample of 4,105,696 interactions was selected. The simulation predicts an average selection efficiency of 64% in the $p_t-p_{||}$ phase space, where
Well, have I got $\nu_s$ for you!

L. Cremonesi

NOvA Preliminary

Data (Stat. + Syst.)
- GENIE 3.00.06*
- GiBUU 2019
- NEUT 5.4.0
- NuWro 2019

L. Cremonesi

NOvA Preliminary

NOvA Preliminary

arXiv: 2106.16210
Well, have I got $\nu_s$ for you!

World data c. 2013
A bright future for Argon

**Short Baseline Program:** Fermilab liquid Argon detectors in “Booster” beam (~0.8 GeV)

- **MicroBooNE:** already producing interesting results
- **ICARUS:** taking its first physics data
- **SBND:** enormous event rates coming soon (1M $\nu/y$)
More new ($\nu$) detectors

The SFGD:
- 2 M scintillator cubes
- 58,000 channels
- 2.1 tons target mass
More new ($\nu$) detectors

The SFGD:
- 2 M scintillator cubes
- 58,000 channels
- 2.1 tons target mass
New models, new constraints

- New models, successful in describing electron scattering data, are now being implemented in neutrino interaction simulations.

- Such models that describe $e^-$ and $\nu$ interactions in the same framework can be directly constrained by precision $e^-$ data.

- New theoretical efforts are allowing models to be more predictive.
New models, new constraints

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<tr>
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<td>Yes</td>
<td>No</td>
<td>Hybrid QM-Cascade??</td>
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Coming soon???
Electrons to the rescue!

- Generators are becoming more able to make neutrino and electron scattering predictions in the same framework.

- New data from CLAS (e-scattering): specifically to help better understand neutrino scattering.

Example:
- In CLAS we know $E_{e,initial}$.
- But can still reconstruct it as if it was a neutrino.
- See how well generators predict this.
- A great test of bias in neutrino scattering.
Summary

• A detailed understanding of neutrino-nucleus interactions is crucial for current and future experiments to realise their extraordinary goals (CP-violation, mass ordering, new BSM physics)

• This is a challenging task: neutrino interactions are complicated

• We’ve made enormous progress in the last 10 years, but still have some way to go

• New data from new detectors will be invaluable, offering dramatically improved probes of neutrino interactions

• Collaboration between theory and experimental communities will be crucial

• Expect plenty of exciting new results and a continued exponential growth of the field in the run up to DUNE & Hyper-K.
Thanks for listening!

"[Fermi’s theory of weak interactions] contains speculations too remote from reality to be of interest to the reader"
Backups
Neutrinos as probes of the weak force!

• Since neutrinos only interact via the weak force, they provide a great way of studying it

• **Weak neutral currents** were discovered by measuring neutrino interactions in the Gargamelle bubble chamber!
Parity, Helicity and Chirality

• The chiral properties of the weak interaction leads to differences in neutrino and antineutrino cross sections.

**Neutrino-electron Scattering**
\[ \nu_e + e^- \rightarrow e^- + \nu_e \]

**Antineutrino-electron Scattering**
\[ \bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_e \]

Assume massless leptons

\[
\frac{d\sigma_{\nu e}}{d\Omega} = \frac{G_F^2 s}{4\pi^2} \quad \sigma_{\nu e} = \frac{G_F^2 s}{\pi}
\]

\[
\frac{d\sigma_{\bar{\nu} q}}{d\Omega^*} = \frac{G_F^2}{16\pi^2} (1 + \cos \theta^*)^2 \hat{s}
\]

\[
\int (1 + \cos \theta^*)^2 d\Omega^* = \int (1 + \cos \theta^*)^2 d(\cos \theta^*)d\phi = 2\pi \int_{-1}^{+1} (1 + \cos \theta^*)^2 d(\cos \theta^*) = \frac{16\pi}{3}
\]

\[
\sigma_{\bar{\nu} q} = \frac{G_F^2 \hat{s}}{3\pi}
\]

\[
s = (p_1 + p_2)^2 = (p_3 + p_4)^2
\]
Joint measurements

Joint Carbon / Oxygen

Joint Carbon / Oxygen

Joint off-axis angles

Work in progress

- $\nu_\mu / \bar{\nu}_\mu$
- O, $0.6 < \cos\theta_\mu < 0.75$
- O, $0.93 < \cos\theta_\mu < 1$
- C, $0.6 < \cos\theta_\mu < 0.75$
- C, $0.93 < \cos\theta_\mu < 1$

Joint measurements

- $0.94 < \cos\theta_\mu^{\text{true}} < 0.98$
- $\chi^2 = 408.9(481.5)/116$
- $\chi^2 = 650.0(838.8)/116$

T2K

NuWro LFG+2p2h $\nu_\mu$

NuWro SF+2p2h $\bar{\nu}_\mu$

$\nu_\mu$, $\bar{\nu}_\mu$

- $p_\mu^{\text{true}}$ [GeV/c]
- $p_\mu^{\text{true}}$ [GeV/c]

Work in progress (55 DoF)

Stephen Dolan
INSS, CERN, August 2021

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What we need to know (a non exhaustive list!)

1. Relative CC0π contribution of CCQE and other processes
   • So we know how often we mis-reconstruct $E_\nu$

2. Initial state nucleon momentum and energy
   • So we know how wide (and biased) our CCQE $E_\nu$ reconstruction is

3. Differences in $\nu/\bar{\nu}$ cross sections
   • So we know when $\nu/\bar{\nu}$ differences correspond to CP-violation

4. Differences in carbon and oxygen cross sections
   • So we know how to extrapolate from our ND to our FD

5. Improved knowledge of the CC1π cross section
   • So we can better use new samples at SK and understand the largest background in the primary samples
Aside: should we do this for FG models?

Exclusive model: can describe all final state particle kinematics

If we assume the outgoing nucleon is non-relativistic and that there’s no FSI we can write the cross section like this:

$$\frac{d^5 \sigma_{\nu\ell}}{d\Omega(k')d\Omega(p_N)dE_{\ell}'} \sim S(E_m, p_m)L_{\mu \nu}W^{\mu \nu} \delta(\omega + M - E_m - E_{p'})$$

If SF = Valencia LFG ...

From the Nieves et. al. paper:
Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et al, 2004 [5,6]. One might think that the LFG description of the nucleus is poor, and that a proper finite nuclei treatment is necessary. For inclusive processes and nuclear excitation energies of at least 100 MeV or higher, the findings of Refs. [4,3,6] clearly contradict this conclusion. The reason is that in these circumstances one should sum up over several nuclear configurations, both in the discrete and in the continuum, and this inclusive sum is almost not sensitive to the details of the nuclear wave function, in sharp contrast to what happens in the case of exclusive processes where the final nucleus is left in a determined nuclear level. On the
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If SF = Valencia LFG …

From the Nieves et. al. paper:

Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et al, 2004 [5,6]. One might think that the LFG description of the nucleus is poor, and that a proper finite nuclei treatment is necessary. For **inclusive processes** and nuclear excitation energies of at least 100 MeV or higher, the findings of Refs. [4,3,6] clearly contradict this conclusion. The reason is that in these circumstances one should sum up over several nuclear configurations, both in the discrete and in the continuum, and this inclusive sum is almost not sensitive to the details of the nuclear wave function, in **sharp contrast to what happens in the case of exclusive processes** where the final nucleus is left in a determined nuclear level. On the
Beyond the impulse approximation

- Remember: these comparisons are to CC0π measurements, there are other contributions besides the CCQE
- Is it possible these are too strong?
Beyond the impulse approximation

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- Is it possible these are too strong?

- This remains a very open question!!!
It’s getting better - new models

... and also for the distribution of nn and np initial state pairs:

- Important implications for predicting available hadronic energy:

- NB: a lot of the variation here is actually also from the 1p1h model variation