Electron-scattering constraints for neutrino-nucleus interactions

Lawrence Weinstein
Old Dominion University
APS April Meeting
Denver, CO, April 2019
Collaboration

- Old Dominion University
- MIT
- Jefferson Lab
- Tel Aviv U
- Michigan State
- FermiLab
- Pitt
- York University, UK

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Afroditi Papdopolou (MIT)
Adi Ashkenazi (MIT)
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Outline

• Why electrons?
  – Nuclear Physics

• Current work
  – Jefferson Lab data analysis
  – Genie improvements

• Future plans
Measuring Neutrino Oscillations

T2K experiment L=295km

\[ P(\nu_\mu \rightarrow \nu_\mu) = \sin^2 (2\theta_{23}) \times \sin^2 \left( \frac{\Delta m^2_{32} L}{4E_\nu} \right) \]

Event Generators and Neutrino Oscillations

Measure neutrino-nucleus reaction products in detector
- Reconstruct incident neutrino energy for each event
From the measured incident neutrino energy distribution
- Use a neutrino event generator (GENIE, NUWRO, GiBUU ...) to determine the actual neutrino beam energy distribution

- Create events with GiBUU
- Reconstruct events with GiBUU and GENIE.

=> Incorrect neutrino-nucleus interaction modeling will bias the extracted oscillation parameters
Event Generators and Neutrino Oscillations

How do we reconstruct:
• The energy of each incident neutrino
• The number of incident neutrinos from the neutrino-nucleus reaction products measured in the detectors?

How can we validate these reconstructions?

=> Incorrect neutrino-nucleus interaction modeling will bias the extracted oscillation parameters
Event Generators and Neutrino Oscillations

How do we reconstruct:
- The energy of each incident neutrino
- The number of incident neutrinos from the neutrino-nucleus reaction products measured in the detectors?

How can we validate these reconstructions?

If they don’t work for electrons, they won’t work for neutrinos!
Why electrons?

• Known incident energy
• High intensity
• Similar interaction with nuclei
  – Single boson exchange
  – CC Weak current [vector plus axial]
    • \( j_{\mu}^{\pm} = \bar{u} \frac{-ig_{w}}{2\sqrt{2}} (\gamma_{\mu} - \gamma_{\mu} \gamma^{5}) u \)
  – EM current [vector]
    • \( j_{\mu}^{em} = \bar{u} \gamma_{\mu} u \)
• Similar nuclear physics
Nuclear Physics

\[
\frac{d\sigma}{d\omega}
\]

Elastic
Giant resonance
Quasielastic
Dip
\(\Delta\)
\(N^*\)
DEEP INELASTIC "EMC"

\(\frac{Q^2}{2A}\)
\(\frac{Q^2}{2m}\)
\(\frac{Q^2}{2m} + 300\ \text{MeV}\)

\(\omega\) or \(v\)

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What neutrino expts want
Nuclear Physics

What we get (even for 0pi)

- Resonance
- Meson Exchange Currents
- Short Range Correlations
- Final State Interactions
How do reaction mechanisms appear in $A(e,e'p)$?

Single nucleon knockout

Undetected 2\textsuperscript{nd} nucleon

Undetected pion

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From QE to “dip”

C(e,e’p)

\[
\omega = 0.2 \text{ GeV} \\
x \sim 2
\]

\[
\omega = 0.2 \\
x \sim 1
\]

\[
\omega = 0.2 \\
\text{dip}
\]

\[x = \frac{Q^2}{2m\omega}\]

R. Lourie, PRL 56, 2364 (1986)
L. Weinstein, PRL 64, 1646 (1990)
S. Penn, unpublished
C(e,e’p)

\[ q = 400 \text{ MeV/c} \]
\[ \omega = 275 \text{ MeV/c} \]

\[ q = 473 \text{ MeV/c} \]
\[ \omega = 382 \text{ MeV/c} \]

\[ \Delta \rightarrow \pi p \]

\[ \Delta N \rightarrow pN \text{ or } 2p2h \]

Baghaei, PRC 39, 177 (1989)

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What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State
Responsible for the high momentum part of the Nuclear WF
Two-body currents are not Correlations
(but everything adds coherently)
2N currents enhance correlations

Central correlations only

Central + tensor corr

MEC and correlations add coherently
→ 2p2h

Corr + MEC

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O(e,e’p) Ryckebusch
NP A672 (2000) 285
Physics Summary

• Electron scattering:
  – Monochromatic beam
  – Vector current only
  – Can choose kinematics to minimize “uninteresting” reaction mechanisms
  – Calculate cross sections after the fact

• Neutrino interactions
  – Continuous mixed beams
  – Vector plus axial current
  – Must include all reaction mechanisms
    • MEC, IC, correlations, Delta, ...
    • FSI (not discussed here)
  – Need good models in event generators
Jefferson Lab data

CLAS6: 1996-2015
### CLAS6 Data (million events)

<table>
<thead>
<tr>
<th></th>
<th>1.1 GeV (e,e’p)</th>
<th>2.2 GeV (e,e’p)</th>
<th>2.2 GeV (e,e’p)</th>
<th>4.4 GeV (e,e’)</th>
<th>4.4 GeV (e,e’p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3He</td>
<td>Not done</td>
<td>24</td>
<td>9</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>4He</td>
<td>Not done</td>
<td>46</td>
<td>17</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>12C</td>
<td>Not done</td>
<td>30</td>
<td>11</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>56Fe</td>
<td>Not done</td>
<td>1</td>
<td>0.5</td>
<td>0.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

E2a data only.
E2b has more 4.6 GeV 3He and 56Fe
Eg2 has 5 GeV d, C, Al, Fe, and Pb
Reconstructing the initial energy

• Choose 0π events to enhance the QE sample
  – Subtract undetected pions and photons
• Weight by $1/\sigma_{\text{Mott}}$ to account for photon propagator
• Reconstruct the incident lepton energy:

\[- E_{\text{QE}} = \frac{2M_N\epsilon + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l \cos \theta_l)}\]

• $\epsilon$: nucleon separation energy, $M_N$ nucleon mass
• $\{m_l, E_l, k_l, \theta_l\}$ scattered lepton mass, energy, momentum and angle
  • broadened by nucleon fermi motion

\[- E_{\text{cal}} = E_e + T_p + \epsilon \quad \text{[for (e,e’p)]}\]
CLAS6 coverage

$p_{\text{min}} \approx 300 \text{ MeV/c}$

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$p_{\text{min}} \approx 150 \text{ MeV/c}$
Background Subtraction

Want $0\pi$ event sample
(e,e') background: undetected pions (and photons)
(e,e'p) background: undetected pions and extra protons

Data Driven Correction:
1. Use measured (e,e'pπ) events,
2. Rotate $\pi$ around $q$ to determine its acceptance,
3. Subtract (e,e'pπ) contributions
Background Subtraction

Want 0π event sample
(e,e’) background: undetected pions (and photons)
(e,e’p) background: undetected pions and extra protons

Data Driven Correction:
1. Use measured (e,e’pπ) events,
2. Rotate π around q to determine its acceptance,
3. Subtract (e,e’pπ) contributions
4. Do the same for 2p, 3p, 2p+ π etc.
Background Subtraction

Want 0\pi event sample
(e,e') background: undetected pions (and photons)
(e,e'p) background: undetected pions and extra protons

Data Driven Correction:
1. Use measured (e,e'p\pi) events,
2. Rotate \pi around q to
determine its acceptance,
3. Subtract (e,e'p\pi) contributions
4. Do the same for 2p, 3p, 2p+ \pi etc.
• \gamma subtraction in progress

![Graph showing proton and pion multiplicity distributions](image)
Energy Reconstruction: A dependence

2.26 GeV beam

Zero pion events

Even 0pi events have a LOT of non-QE events

Much bigger in Fe than $^4$He

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Preliminary
Energy Reconstruction: E dependence

1.16 GeV

$E_{\text{Cal}}(e,e'p)$

$E_{\text{QE}}(e,e')$

$E_{\text{QE}}(e,e'p)$

12C

Non-QE events increase with E

2.26 GeV

3.16 GeV

$E_{\text{Cal}}(e,e'p)$

$E_{\text{QE}}(e,e')$

$E_{\text{QE}}(e,e'p)$

4.46 GeV

$E_{\text{Cal}}(e,e'p)$

$E_{\text{QE}}(e,e')$

$E_{\text{QE}}(e,e'p)$
Can we select QE events?

2.2 GeV $^{56}$Fe

$P_{\text{miss}}^\perp = P_{e^-}^\perp + P_p^\perp \approx P_{\text{init}}^\perp$

$E_{QE}[\text{GeV}]$

$P_{\text{miss}}^\perp [\text{GeV} / c]$
$P_{\text{miss}}$ slices

$E_{QE}$

$E_{Cal}$

$^4\text{He}$

0-0.2

0.2-0.4

$>0.4$

$^{12}\text{C}$

$^{56}\text{Fe}$

$E_{QE}[\text{GeV}]$

$E_{Calor}[\text{GeV}]$
We’re Also Improving Genie

\[ C(e,e') \] 560 MeV \( \theta = 60^\circ \)

Before (default)

After

Still big discrepancies in “dip region”

See M. Betancourt’s talk, session J
We’re Also Improving Genie

1. Corrected lots of errors in electron GENIE
2. Made electron-GENIE more similar to neutrino-GENIE
   1. Lewellyn-Smith cross section for electrons
3. MEC/2p2h
4. Resonance
   1. Replaced old calculation with GSL Minimizer (now gives correct peak location)
   2. Switched to Berger-Seghal model
5. Nucleon momentum distributions
   1. Switched to Local Fermi Gas Model
   2. Implemented Correlated Fermi Gas with high-momentum tail
6. Added radiative effects

Beginning work on NuWro and GiBUU. Consulting with the relevant experts on each code.
0π Data vs Genie: everywhere

GENIE  C(e,e'p) 2.26 GeV  Data

Data vs Genie: everywhere

\( C(e,e'p) \) @ \( E = 2.261 \text{ GeV} \) (hA2018_RadCorr)

\( Q^2 (\text{GeV}^2) \)

\( x_B = 1.2 \)

\( x_B = 0.8 \)

No RadCorr  RadCorr  Data

No RadCorr  RadCorr  Data

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Preliminary
$0\pi$ Data vs Genie: QE Peak

$C(e,e'p)\ 2.26\ GeV,\ 0.8 < x < 1.2$

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**Legend:**
- **Data**
- **MC-Data**
- **RadCorr**
- **No RadCorr**

**Graphs:**
- **$Q^2$ vs Energy Transfer**
- **Energy Transfer vs $P_{miss}$**

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Data vs Genie: $E_{beam}$ Reconstruction

\[ E_{QE} = \frac{2ME_l + 2M\varepsilon - m_l^2}{2(M - E_l + |k_l|\cos\theta)} \]

![Graphs showing comparisons between GENIE and Data for different $p_\perp$ intervals](image)

Peaks in same location
Data vs Genie: $E_{\text{beam}}$ Reconstruction

\[ E_{\text{cal}} = E_l + \sum E_p + \epsilon + \sum E_\pi \]

**GENIE**

- $p_\perp < 0.2 \text{ GeV/c}$
- $0.2 < p_\perp < 0.4$
- $p_\perp > 0.4$

**Data**

- $p_\perp < 0.2 \text{ GeV/c}$
- $0.2 < p_\perp < 0.4$
- $p_\perp > 0.4$

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Preliminary
Data vs Genie: $E_{beam}$ Reconstruction

<table>
<thead>
<tr>
<th></th>
<th>e$^-$ Data</th>
<th>$e$ GENIE</th>
<th>$\nu$ GENIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 2.2 GeV</td>
<td>25%</td>
<td>67%</td>
<td>66%</td>
</tr>
<tr>
<td>Fe 4.4 GeV</td>
<td>16%</td>
<td>68%</td>
<td>66%</td>
</tr>
</tbody>
</table>

Fraction of Fe($e, e'p$) and Fe($\nu, \mu^-p$) events with $E_{Cal}$ within 5% of $E_{beam}$

Errors affect both $\theta_{23}$ and $\Delta m_{23}^2$
Apply CLAS data to DUNE Oscillation

- Proof of principle to show potential impact
- Threw events with $\nu A$ Genie
  - Reconstructed with $\nu A$ Neut or $eA$ data
- Compared $E_{\text{rec}}$ for $eA$ to $E_{\text{rec}}$ for $\nu A$
- Used 2.26 GeV $eA$ $E_{\text{rec}}$ for all incident energies

(DChris Marshall, LBNL)
CLAS12

• forward detector (8 – 40°)
  – Toroidal magnetic field
  – $\frac{\delta p}{p} \sim 0.5\text{—}1\%$
  – Neutrons:
    • 50% effi for $p > 1$ GeV/c
    • $\frac{\delta p}{p} \sim 10\text{—}15\%$ for 1 GeV/c

• Hermetic central detector (40 – 135°)
  – 5 T solenoidal field
  – Neutron effi $\sim 10\text{—}15\%$
  – Neutron $\frac{\delta p}{p}$: 60 ps @ 0.3 m

• 45 beam days approved with an A rating for
  • 1.1, 2.2, 4.4, and 6.6 GeV beam energies
  • $d$, He, C, O, Ar, Sn and SRC targets
Goals

• We provide event yields and detector acceptance maps
  – Many beam energies
  – Many targets
  – Many event topologies

• Let experts use these to tune generators and understand energy reconstruction

• Neutrino community input is welcome
• Nuclear physics is complicated!
• Electron scattering can contribute dramatically to neutrino experiments
  – Similar physics
  – Lots of data available
  – Lots more to come
• Neutrino community input is welcome

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Backup slides
Mott weighting

\[ Q^2 \ (\text{GeV}/c)^2 \]

- $^{12}\text{C} \ 4.4 \text{ GeV weighted}$
- $^{12}\text{C} \ 4.4 \text{ GeV}$
- $^{12}\text{C} \ 2.2 \text{ GeV weighted}$
- $^{12}\text{C} \ 2.2 \text{ GeV}$
E2a $^3$He 2.261 GeV

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Number of events with pions and protons

- Proton multiplicity $^3$He
- Charged pion multiplicity $^3$He
$p_{\text{miss}}$ slices

$E_{\text{kin}}$

$E_{\text{cal}}$

$^3\text{He}$

$^4\text{He}$

$^{12}\text{C}$

$^{56}\text{Fe}$

$p_{\text{miss}}^\perp < 0.2$

$0.2 - 0.4$

$p_{\text{miss}}^\perp > 0.4$ MeV/c

$p_{\text{miss}}^\perp < 0.2$

$0.2 - 0.4$

$p_{\text{miss}}^\perp > 0.4$ MeV/c

$p_{\text{miss}}^\perp < 0.2$

$0.2 - 0.4$

$p_{\text{miss}}^\perp > 0.4$ MeV/c

$p_{\text{miss}}^\perp < 0.2$

$> 0.4$

$0.2 - 0.4$

$p_{\text{miss}}^\perp > 0.4$ MeV/c
Similarity of electron and neutrino GENIE

2.2 GeV Fe, zero-pion, QE

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How Quasielastic is the \((e,e')\) QE peak?

\[
\frac{d\sigma}{d\Omega dv} = \sigma M \frac{E'}{E} \left[ \frac{Q^4}{q^4} R_L(Q^2,\nu) + \left( \frac{Q^2}{2q^2} + \tan^2 \frac{\theta}{2} \right) R_T(Q^2,\nu) \right]
\]

- \(C(e,e')\)
- \(|q|=0.4 \text{ GeV/c}\)

Fermi gas model

\(y = \text{minimum initial nucleon momentum} = mv/q - q/2\) (nonrelativistic only!)

\(f = \text{reduced response function}\)

\[
\begin{align*}
\mathcal{L}(Q^2,\omega) &\propto \frac{R_L(Q^2,\omega)}{\tilde{G}_E^2(Q^2)} \\
\mathcal{T}(Q^2,\omega) &\propto \frac{R_T(Q^2,\omega)}{\tilde{G}_M^2(Q^2)}
\end{align*}
\]

- \(L\) scales
- \(T\) scales
- \(T \neq L!!\)

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P. Barreau et al, NPA 402, 515 (1983)
Finn et al, PRC 29, 2230 (1984)
Extra Transverse even at the QE peak

$^{12}\text{C}(e,e'p)$
$q = 0.4 \text{ GeV}$ and $x = 1$

extra transverse strength starting at the 2N KO threshold

decreases with $Q^2$

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Ulmer et al, PRL 59, 2259 (1987);
The ideal electron experiment

• Identify contributing reaction mechanisms over a wide kinematic range
  – Full acceptance for all charged hadrons
  – High efficiency for neutrals
    • Neutrons
    • $\pi^0$

• Lots of targets
  – Neutrino detector materials: C, O, Ar, Fe
  – More nuclei to constrain models

• Enough beam energies to cover the full range of interesting momentum transfers
Why momentum transfer and not beam energy?

• The scattering cross section depends primarily on energy and momentum transfer

• For (e,e’p):

\[
\frac{d^6 \sigma}{d \Omega_e d \Omega_p d E_p d \omega} = \sigma_{\text{Mott}} [ \nu_L R_L + \nu_T R_T + \nu_{LT} R_{LT} \cos \phi_{pq} + \nu_{TT} R_{TT} \cos 2\phi_{pq} ]
\]

– Kinematic factors \( \nu_i \) depend on \( \{ Q^2, \omega, \theta_e \} \)
– Response functions \( R_i \) depend on \( \{ Q^2, \omega, \theta_{pq} \} \)
– Only beam energy dependence comes from \( \theta_e \)

• Need to account for boson propagator \( \propto \frac{1}{Q^2 + M^2} \)

– \( \propto \frac{1}{M^2} \) for W exchange
– \( \propto \frac{1}{Q^2} \) for photon exchange (Mott Cross section)
How to use electron data for neutrino measurements

• Tune vector models in generators to data
  – Span a wide enough range in $Q^2$ and $A$ to constrain models well
  – Constrain final state interaction (outgoing particle rescattering) models

• Tune remaining model elements to near detector data

• Guide event selection for “enhanced QE” samples, “Res” samples, etc

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GENIE Development

Standard Candle → Inclusive Analysis on $^{12}\text{C}$

$E = 0.961 \text{ GeV} & \theta = 37.5^\circ$

- Data
- Total
- QE
- MEC
- RES
- Other

Improved

Default
$^{56}\text{Fe } (e,e'p)$

$N_\pi = 0$ and $N_\pi / y = 0$

Proton subtraction converges

$5.6\text{ Fe } 4.4\text{ GeV}$

Subtraction converges
We’re Also Improving Genie

1. Corrected expression for Mott cross section in QE
2. MEC/2p2h
   1. Added boost back to lab frame
   2. Corrected mass for cluster of particles
   3. Corrected Form Factors
3. Resonance
   1. Replaced old calculation with GSL Minimizer (now gives correct peak location)
   2. Switched to Berger-Seghal model
   3. Used corrected coupling constant for EM interactions
4. Nucleon momentum distributions
   1. Switched to Local Fermi Gas Model

Beginning work on NuWro and GiBUU.
Consulting with the relevant experts on each code.