Update: Studies of neutrino energy reconstruction using electron scattering data

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Outline

1. **Introduction.**
2. **March 2019 status:**
   - Analysis review ongoing.
   - Looked at (e,e’), (e,e’p) events with zero detected pions and photons.
   - Reconstructed energies $E_{\text{Cal}}, E_{\text{QE}}$.
   - Subtraction for undetected $\pi^+, \pi^-$ and extra p complete.
   - Started subtraction for undetected $\gamma$.
3. **Status today:**
   - Completed subtraction for undetected $\pi^+, \pi^-, \gamma$ and extra p.
   - Modified e$^-$ momentum correction.
   - Analyzed the 1.1 GeV e2a data.
   - Determined binding energy values for $E_{\text{Rec}}$ calculations.
T2K experiment $L=295\text{km}$

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

$\theta_{23}$

$\Delta m_{23}^2$

#Observed / #Expected

Real vs. Reconstructed

Energy Reconstruction for QE reactions

(1) Cherenkov detectors:
- Detect: leptons & pions
- Miss: protons and neutrons

(2) Tracking detectors:
- Detect: Charged particles + $\pi^0$
- Miss: Neutrons and charged particles below threshold.

Use Lepton kinematics
Assuming QE interaction

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

- $\varepsilon$ - single nucleon separation energy
- M - nucleon mass
- $m_l$ - outgoing lepton mass
- $k_l$, $E_l$ - lepton three momentum, energy
- $\theta_l$ - lepton scattering angle

Use Final-State Calorimetry
Assuming low residual excitations

\[ E_{Cal} = E_l + \sum T_p + \varepsilon + \sum E_{\pi} \]

- $T_p$ - kinetic energy of knock out proton
- $E_{\pi}$ - energy of produced meson
E2a experiment

Targets:

CLAS: $^3\text{He}$, $^4\text{He}$, $^{12}\text{C}$, $^{56}\text{Fe}$
T2K: CH, H$_2$O
Minerva: $^3\text{He}$, $^4\text{He}$, C, Fe, H$_2$O
Microboone: Ar
Miniboone: mineral oil (C, H, O)
Nova: C$_6$H$_3$(CH$_3$)$_3$
DUNE: Ar

Neutrino expt. beam energies

- T2K off-axis: 1.1 GeV
- T2K on-axis: 2.2 GeV
- NOvA near detector: 4.4 GeV
- CLAS energies

Miniboone
MINERvA
QE Event Selection

As close to QE as one can get:
- Scattered electron,
- Knockout proton,
- Zero pion,
- Zero gammas in the EC.

Scale the $e^-$ scattering data with $1/\sigma_{\text{Mott}}$ to have 'neutrino like' data!
Want $0\pi (e,e')$ and $(e,e'p)$ events. Need to account for undetected $\pi, \gamma$ and extra protons.
Background Subtraction in (e,e’) analysis

Subtract for $\pi^\pm$ and $\gamma$:

Data Driven Correction:
1. Use measured (e,e’$\pi^\pm$/\gamma) events,
2. Rotate $\pi$ around q to determine its acceptance,
3. Subtract (e,e’) $\pi^\pm$/\gamma contributions,
4. Repeat for 2 $\pi^\pm$/\gamma, 3 $\pi^\pm$/\gamma.

4.46 GeV $^{56}$Fe

Counts

$N_{\pi^\pm/\gamma}$

$\pi^\pm$/\gamma multiplicity

0 1 2 3 4
Selecting non-radiation $\gamma$. 

$\gamma$ detected in EC

$\theta_{e-\gamma}$ [Deg.]

$\varphi_{\gamma} - \varphi_{e-}[\text{Deg.}]$

2 GeV $^{56}\text{Fe}$

radiation $\gamma$
(e, e') $\pi^\pm/\gamma$ subtraction

2.26 GeV

\[ \pi^\pm/\gamma \text{ subtraction} \]

\[ \nu = 0 \]

$4\text{He}$

$\pi$ detected in TOF+DC

$\gamma$ detected in EC

\[ \frac{N_\gamma}{N_{\pi^\pm}} = 0 \]
Background Subtraction in (e,e’p) analysis

Subtract for undetected $\pi^\pm, \gamma$ and multiple p.

Data Driven Correction:
1. Use measured (e,e’p$\pi^\pm/\gamma$) events,
2. Rotate $\pi$ around q to determine their acceptance,
3. Subtract (e,e’p)$\pi^\pm/\gamma$ contributions
4. Do the same for 2p, 3p, 2p+$\pi^\pm/\gamma$ etc

\[ e \rightarrow (e,e'p\pi^\pm/\gamma) \]

\[ q \]

\[ p \]

\[ \pi^\pm/\gamma \]

\[ 56\text{Fe} 4.4 \text{ GeV} \]

\[ N_p \]

\[ N_{\pi^\pm/\gamma} \]

\[ \begin{array}{cccccc}
0 & 0.24 & 0.08 & 0 & 0 & 0 \\
0 & 1.13 & 0.40 & 0.08 & 0 & 0 \\
0 & 4.43 & 1.86 & 0.40 & 0.06 & 0 \\
0 & 16.10 & 7.52 & 2.00 & 0.33 & 0.04 \\
0 & 23.70 & 15.86 & 4.83 & 0.92 & 0.12 \\
\end{array} \]

\[ \times 10^4 \]

Contributions accounted for

\[ 2p0\pi \]

\[ 1p0\pi \]

\[ 2p1\pi \]

\[ 1p1\pi \]

\[ 1p0\pi \]
$^{56}$Fe (e,e’p)

4.46 GeV

Subtraction converges

$N_{\pi^{\pm}/\gamma} = 0$

$N_p$

Uncorr.
No undet. 1p
1p $\pi^{\pm}/\gamma$
+ 2p
+ 3p
+ 4p
+ rest

$^{56}$Fe 4.4 GeV

Contributions accounted for

$N_{\pi^{\pm}/\gamma}$
Proton subtraction

Subtraction undet. $\pi^\pm, p$

$N_{\pi/\gamma} = 0$

$2.26 \text{ GeV}$

$4^4\text{He}$

$4.46 \text{ GeV}$

$^{56}\text{Fe}$

Weighted counts

$E_{\text{Cal}}[\text{GeV}]$
3He (e,e'pp)n

Problem: neutron peak in wrong location
$^{3}$He (e,e’pp)n

Solution: multiply $e^{-}$ momentum by a different factor $\alpha$ in each sector

$$MM^{2} = (P - P_{e})^{2} = M_{n}^{2}$$

$$P_{e}(\alpha p_{e}, \alpha p_{e} \hat{e}p)$$

$$P(E, \vec{P}) = P_{3He} + P_{Beam} - P_{p_{1}} - P_{p_{2}}$$

$$\alpha = \frac{-0.5(M_{n}^{2} - P^{2})}{Ep_{e} - \vec{P}p_{e}}$$

<table>
<thead>
<tr>
<th>e^{-} momentum correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries: 4396</td>
</tr>
<tr>
<td>Mean: 1.027</td>
</tr>
<tr>
<td>RMS: 0.04723</td>
</tr>
<tr>
<td>$\chi^{2}$/ndf: 8.373/13</td>
</tr>
<tr>
<td>Constant: 75.89 ± 3.63</td>
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<tr>
<td>Mean: 1.001 ± 0.000</td>
</tr>
<tr>
<td>Sigma: 0.00959 ± 0.00050</td>
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</tbody>
</table>
$^3$He (e,e'pp)n

**e⁻ momentum correction**

Same set of $\alpha$ factors at 2 and 4 GeV (Same magnetic filed)
Correcting for binding energy

\[ E_{Cal} = E_l + T_p + \varepsilon \]

\[ \varepsilon = E_{Bind}^A - E_{Bind}^{A-1} \]

\( \varepsilon(3\text{He}) = 5 \text{ MeV} \)
\( \varepsilon(4\text{He}) = 20 \text{ MeV} \)
\( \varepsilon(12\text{C}) = 16 \text{ MeV} \)
\( \varepsilon(56\text{Fe}) = 10 \text{ MeV} \)

Use these offsets to correct the binding energy used in \( E_{Cal} \) and \( E_{QE} \)

<table>
<thead>
<tr>
<th>Target</th>
<th>( E_{Cal} ) offset [2GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 3\text{He} )</td>
<td>4 MeV</td>
</tr>
<tr>
<td>( 4\text{He} )</td>
<td>5 MeV</td>
</tr>
<tr>
<td>( 12\text{C} )</td>
<td>5 MeV</td>
</tr>
<tr>
<td>( 56\text{Fe} )</td>
<td>11 MeV</td>
</tr>
</tbody>
</table>
Results
Large A dependence

2.26 GeV

$E_{Cal} = E_l + T_p + \varepsilon$

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

1. $E_{QE}$ has worse peak resolution than $E_{Cal}$.
2. Same tail for $E_{QE} + E_{Cal}$.
3. $^{56}\text{Fe}$ is predominantly tail.
4. $^{56}\text{Fe}$ is much worse than $^4\text{He}$.
Large E dependence

1.16 GeV

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

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

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

2.26 GeV

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

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

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

4.46 GeV

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

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

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

$^{12}\text{C}$

Better reconstruction at lower energies.
Agreement between the methods doesn’t imply correct energy reconstruction.
The fractional energy feed down is bigger at higher energies.

\[(e,e'p)\]
1. The first use of electron data to test neutrino energy reconstruction algorithms
   - select zero-pion events to enhance quasi-elastic signal
     - Subtract for undetected $\pi$ and extra $p$.
   - just using scattered lepton ($E_{QE}$)
     - used in Cherenkov-type neutrino detectors
   - total energy of electron plus proton ($E_{Cal}$)
     - used in calorimetric neutrino detectors
2. Only 0.1-0.66 of events reconstruct to within 5% of the beam energy
   - better for lighter nuclei
   - improved by a transverse momentum cut
3. Added 1GeV analysis.
4. Analysis complete.
5. Update note for committee.
6. Anticipate paper submission soon.

Summary

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Chris Marshal (LBL)
$^3$He $(e,e'pp)n$ moment correction

**1 GeV**

| h1_Wepp | Entries: 16062
| Mean: 1.052
| RMS: 0.1391
| $\chi^2$/ndf: 3.946/8
| Constant: 885.2 ± 13.5
| Mean: 0.9398 ± 0.0009
| Sigma: 0.02805 ± 0.0007 |

**4 GeV**

| h1_Wepp | Entries: 9145
| Mean: 1.004
| RMS: 0.09864
| $\chi^2$/ndf: 5.113/9
| Constant: 3.27 ± 53.65
| Mean: 0.0035 ± 0.9395
| Sigma: 0.00352 ± 0.03311 |

**2 GeV**

| h1_Wepp | Entries: 11965
| Mean: 0.9979
| RMS: 0.08879
| $\chi^2$/ndf: 8.229/4
| Constant: 452.8 ± 13.4
| Mean: 0.9398 ± 0.0005
| Sigma: 0.01712 ± 0.00063 |

**Same set of $\alpha$ factors at 2 and 4 GeV (Same magnetic filed)**
$^3\text{He} \,(e,e'pp)n$ e$^-$ momentum correction

Graphs showing the momentum correction for $^3\text{He} \,(e,e'pp)n$ at 2 GeV, 1 GeV, and 4 GeV, with the momentum transfer $M_n$ and the angle $\varphi$ in degrees as variables.
(e,e') $\pi^\pm/\gamma$ subtraction

$^{56}$Fe 4.46 GeV

$\pi^\pm$ subtraction

$\pi^\pm/\gamma$ subtraction

$\pi$ detected in TOF+DC
$\gamma$ detected in EC
$^{56}\text{Fe (e,e'p)}$

Proton subtraction

$4.46\text{ GeV}$

$N_{\pi/\gamma} = 0$

Subtraction undet. $\pi^\pm, p$

Subtract undetected $\pi^\pm/\gamma$ and $p$