Electron-scattering constraints for neutrino interactions and oscillations

A. Papadopoulou (apapadop@mit.edu)

For the e4ν collaboration

New Directions, March 15 2021
Absolute QE-Like $C(e,e'p)$ Cross Sections
Wealth of New Results...

- Many nuclei & beam energies
- \((e,e')\) & \((e,e'p)\)
- Energy reconstruction
- Single transverse variables
- Multiplicities
PHYSICS PROCESS

- Particles shoot out
- Interacts with the nucleus
- Neutrino comes in

Graph: Incident v Flux
PHYSICS PROCESS

Particles shoot out

Interacts with the nucleus

Neutrino comes in

Infer neutrino flux

Apply interaction model

Measure particles

Inferred v Flux

Incident v Flux

EXPERIMENTAL ANALYSIS

E$_{\nu}$ [GeV]
Improving Modeling Input

- $\nu$ near detector constraints

PRL 125, 201803 (2020)
Today

- $\nu$ near detector constraints
- Modelling development
  - $e$ & $\nu$ consistency

See talks by
Steven Gardiner & Marco Roda

Today

- Modelling development
- $\nu$ near detector constraints
- External Data

![Graph showing data and model comparison]
Why electrons?

• Very similar interactions
  Vector vs Vector + Axial-Vector
• Nuclear & FSI effects practically identical
• Monoenergetic electron beams
  → Benchmark ν event generators
Using GENIE v3:

- **SuSav2**: QE & MEC SuSav2 (GTEST19_10b_00_000)
  PRD 101, 033003 (2020)

- **G2018**: Rosenbluth QE & Empirical MEC (G18_10a_02_11a)
GENIE Reproduces Inclusive $e^-$ & $\nu$ Data

Fe($e,e')$; 0.961 GeV at 37.5°

G2018

Data

SuSav2 (Total)

QE

RES

MEC

DIS

$d^2\sigma/dΩdE$ [μb/sr/GeV]

Energy Transfer [GeV]

0

10

20

30

PRL 123, 131801 (2019)


0.45 $\leq \cos(θ^{ reco}) < 0.62$

G2018

MicroBooNE 1.6 x 10$^{20}$ POT

GENIE v2.12.2 + Emp. MEC

GENIE v3.0.6 G1810a0211a

GIBUU 2019

NuWro 19.02.1

Data (Stat. & Syst. Unc.)

$dp^{ reco}/dμ_\mu$ [10$^{-38}$ cm$^2$/GeV/n]

$dp^{ reco}/dμ_\mu$ [10$^{-38}$ cm$^2$/GeV/n]

μBooNE

0

0.5

1

1.5

2

2.5

$μ_\mu^{ reco}$ [GeV]
Issues To Be Further Investigated

\[ C(e,e') \text{: 3.595 GeV at 16}^\circ \]

Data

\[ \times 10^3 \]

\[ d^2\sigma/d\Omega dE \text{ [nb/sr/GeV]} \]

Energy Transfer [GeV]

\[ \times 10^{38} \text{ cm}^2/\text{GeV h} \]

PRL 123, 131801 (2019)

G2018

Similar $\nu$ & $e$ Distributions in Exclusive Reaction

$^{12}\text{C} @ 1.1 \text{ GeV}$

1 proton $> 300 \text{ MeV}/c$, no $\pi^{+/-} > 70 \text{ MeV}/c$, no $\gamma/\pi^0$; Electron scaled by $Q^4$

Using SuSav2 / GTEST19_10b_00_000 with $Q^2 > 0.1$
e4ν Data-Mining W/ CLAS6

- Large acceptance @ $\theta_e > 15^\circ$
- Charged particle threshold similar to $\nu$ tracking detectors
- Energies: 1, 2 & 4 GeV
- Targets: $^4$He, $^{12}$C, $^{56}$Fe
Playing The QE-like Neutrino Game

Strategy:
Select "clean" (e,e’p) events:
1 proton (> 300 MeV/c)
No π^± (> 150 MeV/c)
Scale by $\frac{\sigma_{\nu N}}{\sigma_{eN}} \propto Q^4$

Objectives
Study $\nu$ energy reconstruction
Benchmark $\nu$ event generators
Report absolute cross sections
Cross Section Extraction

• Subtract non-(e,e’p) backgrounds
• Scale counts by luminosity
• Correct for (e,e’p) acceptance & radiation

Systematic uncertainties on each correction above & difference between detector sectors
Absolute QE-Like $C(e,e'p)$ Cross Sections

\[ E_{cal} = E_l + T_p + \epsilon \]
A & E Dependence

$^{12}\text{C}$

\[
\frac{d\sigma}{dE_{\text{cal}}} = \left[ \text{ub} \right] \left[ \text{GeV} \right]
\]

1.159 GeV (x1/2)

2.257 GeV

4.453 GeV (x5)

Data

- SuSav2 (Total)
- $^{56}\text{Fe}$
- $\text{QE}$
- $\text{MEC}$
- $\text{RES}$
- $\text{DIS}$
- G2018

$E_{\text{cal}} = E_{\ell} + T_p + \epsilon$

$(e,e'p)_{1p0\pi}$ $E_{\text{cal}}$ [GeV]
• Data / MC disagreements
• Worse @ higher E
• Overestimation of RES & DIS
--- G2018:

- Peak offset.
- Binding energy issue?
- Overprediction of QE peak
SuSav2
- Correct peak location
- Issue with QE peak strength
QE Energy Reconstruction

- Relevant for T2K
- Overestimation of QE peak & RES tail

\[ E_{QE} = \frac{2M\epsilon + 2ME_\ell - m_l^2}{2(M - E_\ell + |k_l|\cos\theta_\ell)} \]
Transverse Missing Momentum

Overestimation of QE peak & RES tail
A & E Dependence

Data

- SuSav2 (Total)
  - QE
  - MEC
  - RES
  - DIS
- G2018

\[ \frac{d\sigma}{dp_T} \]
Angular A & E Dependence

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

\( ^{12}\text{C} \)

\( ^{56}\text{Fe} \)

\[ \delta\alpha_T = \arccos \frac{-\vec{p}_T^e \cdot \delta\vec{p}_T}{p_T^e \delta p_T} \]

Data

- SuSav2 (Total)
- QE
- MEC
- RES
- DIS

---G2018
Angular A & E Dependence

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

1.159 GeV
2.257 GeV
4.453 GeV (x2)

\[ ^{12}\text{C} \]

\[ \delta \varphi_T = \arccos \left( \frac{-\vec{p}_T^L \cdot \vec{p}_T^N}{p_T^L p_T^N} \right) \]

Data
- SuSav2 (Total)
- QE
- MEC
- RES
- DIS

\[ ^{56}\text{Fe} \]

\[ ^{1}\text{p}_0\pi \delta \varphi_T \text{ [deg]} \]
Energy Reconstruction In $P_T$ Slices

Multi-dimensional study
Detected Hadron Multiplicities

\[ \begin{align*}
12 \text{C} @ 2.2 \text{ GeV} \\
P_p > 300 \text{ MeV}/c \\
\pi^- \rightarrow 150 \text{ MeV}/c \\
\end{align*} \]

GENIE overpredicts hadron multiplicities

- SuSav2
- G2018
• Benchmarking $\nu$ models against wide phase-space electron data

• Data/MC disagreements even for QE-like topologies

• Need for more electron scattering datasets in relevant phase-space to constrain $\nu$ models

Potential impact on DUNE
Coming Fall ‘21: New Data W/ CLAS12

• Acceptance down to 5°
• x10 luminosity [$10^{35}$ cm$^{-2}$ s$^{-1}$]
• Targets $^2$D, $^4$He, $^{12}$C, $^{16}$O, $^{40}$Ar, $^{120}$Sn
• 1 - 7 GeV beam energies
• Better neutron & gamma detection

Support Letters

DUNE, ICENICUBE, Hyper-Kamiokande, T2K, NOvA, MINERvA, Fermilab, Gibeon, Genie, µBooNE
Thank you!
Thank you!

Joint theory & experimental effort

- New data with CLAS12 / ...
- More interaction channels (1p1π, 1π, NN, ...)
- Tuning efforts
- Implications on ν oscillation studies

[come join us! :]

\[ e^+ \nu + \text{fist} \Rightarrow ? \]
Parallel Efforts

ArTi (e,e’) & (e,e’p)
See talk by L. Jiang

See talk by L. Doria

See talk by A. Ankowski
Thank you!
Backup Slides
Energy Reconstruction

Cherenkov detectors
Assuming QE interaction
Using lepton kinematics
\[ E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)} \]

Tracking detectors
Calorimetric sum
Using all detected particles
\[ E_{cal} = E_l + T_p + \epsilon \]

nucleon separation energy \( \epsilon \sim 20 \text{ MeV} \)
Inclusive Electron Scattering C

SuSav2

G2018

Inclusive Electron Scattering C & Fe

SuSav2


SuSav2

G2018
GENIE v2 vs v3

PRD 102, 053001 (2020)

GENIE v2 vs v3

**v2**

560 MeV @ 60 deg

**v3**

$^12$C, 0.56 GeV, $\theta = 60^\circ$

**SuSav2**

**G2018**

Energy Transfer [GeV]

Energy Transfer [GeV]


PRD 102, 053001 (2020)
GENIE v2 vs v3

PRD 102, 053001 (2020)

GENIE v2 vs v3

$C(e, e')$

v2

\[
\frac{d^2\sigma}{d\Omega \, d\omega} \text{ (µb/sr GeV)}
\]

v3

$^{12}\text{C, 2.222 GeV, } \theta = 15.54^\circ$

PRD 102, 053001 (2020)

GENIE v2 vs v3

$v^2$

$Ar(e,e')$

(c)

$v^3$

SuSav2

$^{40}Ar$, 2.222 GeV, $\theta = 15.54^\circ$

G2018

$\frac{d^2\sigma}{d\Omega\,dE}$ [\mu b/sr/GeV]

Energy Transfer [GeV]

Energy Transfer [GeV]

PRD 102, 053001 (2020)

GENIE v2 vs v3

$\frac{d\sigma}{d\Omega\,d\omega}$ (µb/sr GeV)

$\frac{d^2\sigma}{dQ^2\,dE}$ (µb/sr/GeV)

PRD 102, 053001 (2020)

Mismodelling Impact On Mixing Parameters

Mismodelling Impact On Mixing Parameters

- DUNE oscillated far-detector spectrum
- Simulated with data-derived smearing matrices, reconstructed with model-derived ones

Inferred $\nu_e$ Flux vs $E_\nu$ [GeV]
Available Data Sets

- **Targets**
  - $^4$He, $^{12}$C, $^{56}$Fe

- **Energies**
  - 1, 2 & 4 GeV

Credit: L. Pickering
Nuclear Model Impact

QE Scattering

\[
\begin{array}{ccc}
\nu \text{ SuSav2} & \nu \text{ Nieves} & \nu \text{ Lwellyn-Smith} \\
\text{Relativistic MF} & \text{Local FG} & \text{Relativistic FG} \\
\hline
\text{e SuSav2} & \text{e Rosenbluth} & \text{e Rosenbluth} \\
\text{Relativistic MF} & \text{Local FG} & \text{Relativistic FG} \\
\end{array}
\]

Background Subtraction

Non-(e,e’p) interactions lead to multi-hadron final states
Gaps make them look like (e,e’p) events
Data Driven Correction

Non-(e,e’p) interactions lead to multi-hadron final states
Gaps make them look like (e,e’p) events

- Use measured (e,e’pπ) events
- Rotate p, π around q to determine π detection efficiency
- Subtract undetected (e,e’pπ)
- Repeat for higher hadron multiplicities
FIG. 13. Illustration the effect of FSI on $\delta \alpha_T$ on $^{12}C$ at 1.161 GeV for a QE selection with $Q^2 \geq 0.1 \text{GeV}^2/c^2$ requiring exactly one proton with $P_p \geq 300 \text{MeV}/c$, no charged pions with $P_\pi \geq 70 \text{MeV}/c$ and no neutral pions or photons of any momenta. The electron events have been scaled by $Q^4$. 
Migration Matrices: Data vs SuSav2
Migration Matrices: Data vs G2018
Electrons vs Neutrinos

Where are the remaining differences coming from?

\[
\frac{d^2\sigma^e}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4} \left[ \frac{1-y}{x} F_2^e(x, Q^2) + y^2 F_1^e(x, Q^2) \right].
\] (1)

Here \( F_1^e \) and \( F_2^e \) are the standard electromagnetic vector structure functions, \( Q^2 = q^2 - \omega^2 \) is the squared momentum transfer and \( q \) and \( \omega \) are the three-momentum and energy transfers, \( x = Q^2/(2m\omega) \) is the Bjorken scaling variable, \( m \) is the nucleon mass, \( y = \omega/E_e \) is the electron fractional energy loss, and \( \alpha \) is the fine structure constant. This formula is valid for \( Q^2 \gg m^2 \) where the electron-nucleon cross section is simplest. Cross sections at lower \( Q^2 \) have more complicated factors multiplying each of the two structure functions.

The corresponding inclusive charged current (CC) \((\nu, \nu^\pm)\) neutrino-nucleon cross section (where \( \nu^\pm \) is the outgoing charged lepton) has a similar form with the addition of third, axial, structure function:

\[
\frac{d^2\sigma^\nu}{dx dQ^2} = \frac{G_F^2}{2\pi} \left[ \frac{1-y}{x} F_2^\nu(x, Q^2) + y^2 F_1^\nu(x, Q^2) \right. \\
\left. -y(1-y/2) F_3^\nu(x, Q^2) \right].
\] (2)

Here \( F_1^\nu \) and \( F_2^\nu \) are the neutrino-nucleus vector structure functions, \( F_3^\nu \) is the axial structure function, and \( G_F \) is the Fermi constant. The parity-conserving structure functions, \( F_1^\nu \) and \( F_3^\nu \), both include a vector-vector term identical to \( F_1^e \) and \( F_2^e \), and an additional axial-axial term. See Refs. [4, 6, 7] for more detail.
<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QE</strong></td>
<td>SuSav2</td>
<td>SuSav2</td>
</tr>
<tr>
<td><strong>MEC</strong></td>
<td>SuSav2</td>
<td>SuSav2</td>
</tr>
<tr>
<td><strong>RES</strong></td>
<td>Berger-Sehgal</td>
<td>Berger-Sehgal</td>
</tr>
<tr>
<td><strong>DIS</strong></td>
<td>AGKY</td>
<td>AGKY</td>
</tr>
<tr>
<td><strong>FSI</strong></td>
<td>hN2018</td>
<td>hN2018</td>
</tr>
<tr>
<td><strong>Nuclear Model</strong></td>
<td>Relativistic Mean Field</td>
<td>Relativistic Mean Field</td>
</tr>
<tr>
<td></td>
<td>Electrons</td>
<td>Neutrinos</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td><strong>QE</strong></td>
<td>Rosenbluth</td>
<td>Nieves</td>
</tr>
<tr>
<td><strong>MEC</strong></td>
<td>Empirical</td>
<td>Nieves</td>
</tr>
<tr>
<td><strong>RES</strong></td>
<td>Berger-Sehgal</td>
<td>Berger-Sehgal</td>
</tr>
<tr>
<td><strong>DIS</strong></td>
<td>AGKY</td>
<td>AGKY</td>
</tr>
<tr>
<td><strong>FSI</strong></td>
<td>hA2018</td>
<td>hA2018</td>
</tr>
<tr>
<td><strong>Nuclear Model</strong></td>
<td>Local Fermi Gas</td>
<td>Local Fermi Gas</td>
</tr>
</tbody>
</table>
Closure Test

- Use GENIE files
- Filter specific topologies (e.g. $1p0\pi p + 1p1\pi$)
- Subtracted & True $1p0\pi$ are in good agreement

Ready to look at Data/MC comparisons!
\[ \delta \mathbf{p}_T = \mathbf{p}_T^\ell + \mathbf{p}_T^\nu, \]
\[ \delta \phi_T = \arccos \frac{-\mathbf{p}_T^\ell \cdot \mathbf{p}_T^N}{p_T^\ell p_T^N}, \text{ and} \]
\[ \delta \alpha_T = \arccos \frac{-\mathbf{p}_T^\ell \cdot \delta \mathbf{p}_T}{p_T^\ell \delta p_T}. \]
Well defined signal definition: Min $\theta_e$ Cut

@ 1.1 GeV: $\theta = 17 + 7 / P$
@ 2.2 GeV: $\theta = 16 + 10.5 / P$
@ 4.4 GeV: $\theta = 13.5 + 15 / P$

See backup for $p / \pi^{+/0}$ definitions

- We do not acceptance correct below min $\theta$
Well defined signal definition: Min $\theta_e$ Cut

@ 1.1 GeV: $\theta = 17 + 7 / P$
@ 2.2 GeV: $\theta = 16 + 10.5 / P$
@ 4.4 GeV: $\theta = 13.5 + 15 / P$

See backup for $p / \pi^{+/−}$ definitions

- We do not acceptance correct below min $\theta$
Min $\theta_p$ Cut = 12 deg

$^{12}\text{C} \ @ \ E = 4.461 \text{ GeV} \ (1\text{st Sector})$

Data

SuSav2
Min $\theta_{\pi^+}$ Cut = 12 deg

$^{12}$C @ $E = 4.461$ GeV (1st Sector)
@ 1.1 GeV: $\theta = 17 + 4 / P$

@ 2.2 GeV: $\theta = (P < 0.35) \times (25 + 7/P) + (P > 0.35) \times (16 + 10/P)$

@ 4.4 GeV: $\theta = (P < 0.35) \times (25 + 7/P) + (P > 0.35) \times (16 + 10/P)$
5.1 Statistical uncertainty due to the number of rotations

The statistical uncertainty due to the number of rotations contributes to the uncertainty of the obtained weights used for subtraction for undetected hadrons. This can be described by the uncertainty of probability in binomial distribution given by

$$\sigma = \frac{n}{N} \sqrt{\frac{1}{n} - \frac{1}{N}}$$  \hspace{1cm} (36)

$$\lim_{n \to 0} \sigma = \frac{\sqrt{n}}{N}$$ \hspace{1cm} (37)

$$\lim_{n \to N} \sigma = \frac{\sqrt{N - n}}{N}$$ \hspace{1cm} (38)

where $N$ is the total number of trials and $n$ is the number of successes, and is kept small with sufficient number of rotation (is not included in uncertainty calculation).
Systematics: pion electro-production angular cross section dependence

\[ \frac{d\sigma}{d\Omega_{\pi}}(W, Q^2, \theta_{\pi}, \phi_{\pi}) = A + B \cos \phi_{\pi} + C \cos 2\phi_{\pi} \]  \hspace{1cm} (43)

\[ A = (\sigma_T + \epsilon\sigma_L) \frac{p_{\pi}^*}{k_{\gamma}^*} \]  \hspace{1cm} (44)

\[ B = \sigma_{LT} \frac{p_{\pi}^*}{k_{\gamma}^*} \sin \theta_{\pi} \sqrt{2\epsilon(\epsilon + 1)} \]  \hspace{1cm} (45)

\[ C = \sigma_{TT} \frac{p_{\pi}^*}{k_{\gamma}^*} \sin^2 \theta_{\pi} \epsilon \]  \hspace{1cm} (46)

where \( p_{\pi}^* \), \( \theta_{\pi} \) and \( \phi_{\pi} \) are the absolute value of the three momentum, polar and azimuthal angles of the \( \pi^0 \) in the CM-frame, and \( k_{\gamma}^* = k_{\gamma}M/W \). \( \phi_{\pi} \) is shown in Fig. 181 and is the azimuthal angle between the hadronic and leptonic planes and \( \theta_{\pi} \) is the angle between the direction of the pion and the virtual photon. These expressions are taken from \( \pi^0 p \) electroproduction studies in [23], but they can also be used for charged pion production studies, like in our case.

When subtracting for undetected one pion events in inclusive analysis we have assumed that the second and third terms on the right side of the Eq. 43 are negligible compared to the first term, and so the dependence of the cross section on \( \phi_{\pi} \) can be neglected. To check if this assumptions is valid or not we have estimated the number of undetected 1 charged pion events with and without taking into account the \( \phi_{\pi} \) dependence of the cross section, and have found that both lead to similar results.

For this study we have used the values of exclusive structure functions \( \sigma_T + \epsilon\sigma_L \), \( \sigma_{TT} \) and \( \sigma_{LT} \) from [23] shown for \( \cos \theta_{\pi} = 0.1 \) and \( 0.4 \leq Q^2 \leq 1 \text{ GeV}^2 \). We have used the biggest provided absolute values \( \sigma_T + \epsilon\sigma_L = 30 \mu b \), \( \sigma_{TT} = -10 \mu b \) and \( \sigma_{LT} = -2 \mu b \) corresponding to \( Q^2 = 0.45 \text{ GeV}^2 \).
Figure 182: $E_{\text{QE}}$ 0 pi spectrum for $A(e, e')$ subtracted for undetected 1 charged pion events with (green) and without (red) accounting for $\phi_\pi$ dependence of the cross section at 4.4 GeV for $^{56}\text{Fe}$ target.
5.3 Systematic uncertainty due to photon identification cut

In order to separate photons from neutrons, we cut on the neutral particle velocity. The velocity distribution of neutral particles has a peak at $\beta = 1$ corresponding to photons and another at lower velocity corresponding to neutrons. To select photons we cut $2\sigma$ to the left of the photon peak and select the region above it. At 1.161 GeV we cut $3\sigma$ away from the photon peak as the neutron and photon peaks are well separated at this energy. The photon selection cuts for all the targets and beam energies are listed in Table.8.

In addition to the $\beta$ cut, we require the energy of the photons to be greater than 0.3 GeV. This additional PID cut applied on photon reduces the estimated photon contamination. Therefore we add a 3% systematic uncertainty to the photon subtraction.
### Systematics: Photon Identification Cut

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>Target</th>
<th>( \beta_{EC} )</th>
<th>Cuts on ( \beta_{EC} )</th>
<th>( \Delta t_{offset} ) for different sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 GeV</td>
<td>( ^3\text{He} )</td>
<td>0.89</td>
<td>-0.73</td>
<td>-0.81 -0.91 -0.94 -0.92 -0.81</td>
</tr>
<tr>
<td></td>
<td>( ^{12}\text{C} )</td>
<td>0.89</td>
<td>-0.71</td>
<td>-0.77 -0.87 -0.91 -0.89 -0.79</td>
</tr>
<tr>
<td>2.2 GeV</td>
<td>( ^3\text{He} )</td>
<td>0.93</td>
<td>-1.37</td>
<td>-1.42 -1.55 -1.53 -1.49 -1.44</td>
</tr>
<tr>
<td></td>
<td>( ^4\text{He} )</td>
<td>0.92</td>
<td>0.72</td>
<td>0.27 0.16 0.21 0.22 0.21</td>
</tr>
<tr>
<td></td>
<td>( ^{12}\text{C} )</td>
<td>0.92</td>
<td>0.50</td>
<td>0.39 0.29 0.29 0.32 0.33</td>
</tr>
<tr>
<td></td>
<td>( ^{56}\text{Fe} )</td>
<td>0.90</td>
<td>0.75</td>
<td>0.49 0.37 0.39 0.43 0.44</td>
</tr>
<tr>
<td>4.4 GeV</td>
<td>( ^3\text{He} )</td>
<td>0.92</td>
<td>-0.15</td>
<td>-0.26 -0.41 -0.29 -0.25 -0.23</td>
</tr>
<tr>
<td></td>
<td>( ^4\text{He} )</td>
<td>0.91</td>
<td>-0.01</td>
<td>-0.11 -0.23 -0.26 -0.21 -0.09</td>
</tr>
<tr>
<td></td>
<td>( ^{12}\text{C} )</td>
<td>0.92</td>
<td>-0.01</td>
<td>-0.11 -0.23 -0.27 -0.21 -0.08</td>
</tr>
<tr>
<td></td>
<td>( ^{56}\text{Fe} )</td>
<td>0.91</td>
<td>-0.49</td>
<td>-0.14 -0.32 -0.25 -0.17 -0.35</td>
</tr>
</tbody>
</table>

**Table 8:** The EC timing offsets for different sectors and the cuts applied on the velocity of neutral particles to select photons for all targets at 2.2 and 4.4 GeV.
5.4 Effect of fiducial cuts on undetected particle subtraction

If we were able to obtain the ideal fiducial cuts that describe perfectly the geometrical acceptance with flat detection efficiency for different particles, our energy reconstruction results would be independent of how tight or wide the geometrical acceptance is. This is however hard to achieve in real analysis. We have estimated the sensitivity of energy reconstruction results to the change in geometrical acceptance. We have obtained the reconstructed energy spectra after changing the original fiducial cuts for charged pions and photons in different CLAS sectors. We have moved the left and right sides of $\theta$ vs $\phi$ distribution outline inwards in $\phi$ by $3^\circ$. This results in the geometrical acceptance in each sector becoming narrower by $6^\circ$ in $\phi$. We have applied this change to the geometrical acceptances of charged pions and photons. We have then compared the reconstructed energy spectra obtained with original fiducial cuts to the ones obtained with modified tighter fiducial cuts. The plots for $E_{\text{calor}}$ energy reconstruction with different geometrical cuts are shown in Figure 5.4.
The systematic uncertainty due to the change in geometrical acceptence is the RMS of these two results obtained using the original and modified geometrical acceptences. The systematic uncertainty for each bin in reconstructed energy spectrum is calculated the same way as in the previous section and is given by the following formula:

\[
x^i_{\text{RMS}} = \sqrt{\frac{(x^i_1 - x^i_{\text{mean}})^2 + (x^i_2 - x^i_{\text{mean}})^2}{2}}
\]  

(50)

where \(x^i_{\text{mean}}\) is the mean bin content for bin \(i\) and is equal to \(x^i_{\text{mean}} = (x^i_1 + x^i_2)/2\), where \(x^i_1\) and \(x^i_2\) are the contents of the \(i\)th bin of the 1st and 2nd results.

The ratio of \(\sigma_{E_{\text{cal}}}\) systematic uncertainty distributions over the \(E_{\text{cal}}\) reconstructed energy spectra are shown on the right side of Figure 186. This uncertainty is the biggest at 4.4 GeV analysis and is below 4%. At 2.2 GeV analysis it is less than 1.2% and at 1.1 GeV it is less than 0.8%.
Systematics: Sector Dependence

Pinned Data, $^{12}\text{C} @ E = 1.161 \text{ GeV}$

- 1st
- 2nd
- 3rd
- 4th
- 5th
- 6th

SuSav2, $^{12}\text{C} @ E = 1.161 \text{ GeV}$

- 1st
- 2nd
- 3rd
- 4th
- 5th
- 6th

Normalized Yield

$E_{QE}$ [GeV]

$(e,e')_{0\pi}$
Systematics: Sector Dependence

Pinned Data/SuSav2, $^{12}$C @ E = 1.161 GeV

Ratio

$E^{QE}_{0\pi}$ vs $E^{QE}$ [GeV]

Double Ratio To 1st Sector

$E^{QE}_{0\pi}$ vs $E^{QE}$ [GeV]
Quantifying uncertainty by using unweighted variance & by subtracting variance from statistical uncertainty

- Playing this game across all nuclei & energies
- Division by $\sqrt{N_{\text{sectors}}}$
- Flat uncertainty of 6%

Full analysis
Single $\pi^+$ electroproduction on the proton in the first and second resonance regions at $0.25 \text{ GeV}^2 < Q^2 < 0.65 \text{ GeV}^2$

FIG. 12. The ratio of the measured elastic cross section to the parametrization of the world data [28]. The error bars represent the statistical uncertainty only. The solid line is from the fit of the data points to a constant.
1st e4ν Submission

Calorimetric energy reconstruction using the 1p0π channel

- Area normalized results
- No information with respect to absolute scale
- G2018 offset potentially due to binding energy issue

![Graph with data points and curves]
Step #2: Normalized Yield

Data

- Divide # events by integrated charge & target thickness to get xsec in $\mu$b
- Divide by bin width to get $\mu$b/GeV

Simulation

- Get GENIE total cross section for $E_e$ / target A & $Q^2 > Q^2_{\text{min}}$
- $\text{xsec} = (\text{Selected detected events} / \text{all generated events}) \times \text{total xsec} / \text{bin width}$

No corrections for CLAS acceptance or for bremsstrahlung radiation
Step #2: Normalized Yield

- Absolute scale comparison
- Small effect @ 1GeV

Data
- SuSav2 (Total)
- QE - MEC
- RES - DIS

-- G2018
Step #3a: Acceptance Correction

- Start from reco / true ratio w/o radiation to obtain acceptance correction

- Average on a bin-by-bin basis \( x = |\text{SuSav2} + G2018| / 2 \)

- Due to offset, G2018 Ecal predictions have been shifted by 10/25/36 MeV for 4He/12C/56Fe respectively
Step #3a: Example 12C @ 1.1 GeV

Use reco / true ratio to obtain acceptance correction
Step #3a: Acceptance Correction

Use average to apply acceptance correction
Step #3b: Radiation Correction

Use ratio of red / blue to correct for radiation
Acceptance Correction Factors

1.159 GeV

12C

2.257 GeV

4He

56Fe

4.453 GeV

(e,e'p)_{l0\pi} E_{cal} [GeV]
Step #4: Absolute Cross Sections

After both acceptance & radiation corrections, without systematics yet
Less than 50% of our selected events result in an $E_{\text{reco}}$ close to $E_{\text{beam}}$
On a bin-by-bin basis

\[ x = \frac{|\text{SuSav2} - \text{G2018}|}{\sqrt{12}} \]

Bin Entry = \( \frac{x}{\text{Average}} \times 100\% \)

Same recipe as for acceptance correction but, to avoid infinities, will use average (1 bin) around the peak and average(reco) / average(true) for correction factor
Example: Reco & True Spectra for 12C @ 1.1 GeV

Acceptance correction = True / Reco
Example: Acceptance Correction for $^{12}$C @ 1.1 GeV
All Nuclei & Energies

Fractional Contribution [%]

1.159 GeV

2.257 GeV

4.453 GeV

(e,e'p)_{1p0\pi} E_{\text{cal}} [GeV]
• Sector dependence
• Detector acceptance
• Photon identification cuts
• $\varphi_{q\pi}$ cross section dependence
• Number of rotations
# Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector acceptance</td>
<td></td>
</tr>
<tr>
<td>Identification cuts</td>
<td>2, 2.1, 4.7</td>
</tr>
<tr>
<td>$\phi_{q\pi}$ cross section dependence</td>
<td>(@ 1.1, 2.2, 4.4 GeV)</td>
</tr>
<tr>
<td>Number of rotations</td>
<td></td>
</tr>
<tr>
<td>Sector dependence</td>
<td>6</td>
</tr>
<tr>
<td>Acceptance correction</td>
<td>2-15</td>
</tr>
<tr>
<td>Overall normalization</td>
<td>3</td>
</tr>
<tr>
<td>Electron inefficiency</td>
<td>2</td>
</tr>
</tbody>
</table>

* See backup slides
Q4 Scaling Effect

Area Normalized

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

- $\nu$
- $e$
- $e$ (w/o Q4 scaling)
Schematic layout of the eP energy measurement system, showing the arrangement of its components, the polyethylene (CH2) target, the Cherenkov detectors, the silicon-strip detectors (SSD) for protons and electrons and the scintillator detectors, used for time-of-flight measurements.
MAMI Detector

Electron Beam:
- Energy: 600 MeV
- Current: > 20μA

Luminosity monitors:
- Förster probe (1-2 %)

Spectrometer A:
- Data taking
  - 65 kinematic points
- Angles:
  - 20 - 80° (7 configurations)
- Momentum:
  - 200 - 600 MeV/c (11 configurations)

Spectrometer B:
- Luminosity monitor (const. setting)
- Momentum: 600
- Angles: 50°

Spectrometer C:
- Not used