Electron-scattering constraints for neutrino interactions and oscillations

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For the e4ν collaboration
Neutrino Oscillation Experiments

Source \( \nu_\alpha \) → Near Detector → Detect \( \nu_\alpha \) → Distance L → Far Detector → Detect \( \nu_\beta \)
Neutrino Oscillation Experiments

Near Detector
Detect $\nu_\alpha$

Far Detector
Detect $\nu_\beta$

Distance $L$

$N(E_{\text{rec}}) \sim \Phi(L,E_{\nu,\text{true}}) \sigma(E_{\nu,\text{true}}) \varepsilon(E_{\nu,\text{true}}) P(\nu_\alpha \rightarrow \nu_\beta)$

Neutrino Flux Prediction
Neutrino Cross Section Model
Selection efficiency

$\propto L / E_{\nu,\text{true}}$
High Precision Measurements

Before any oscillation parameter extraction, need for good handle of

- cross section predictions for signal & background events
- accuracy of energy reconstruction $E_{\text{rec}}$

\[ N(E_{\text{rec}}) \sim \Phi(L,E_{\nu,\text{true}}) \sigma(E_{\nu,\text{true}}) \varepsilon(E_{\nu,\text{true}}) P(\nu_\alpha \rightarrow \nu_\beta) \]
PHYSICS PROCESS

Particles shoot out

Interacts with the nucleus

Neutrino comes in

Incident v Flux

0 2 4 6 8 10
PHYSICS PROCESS

Particles shoot out

Interacts with the nucleus

Neutrino comes in

\[ \pi^+ \]
\[ \pi^0 \]
\[ p \]
\[ n \]
\[ \nu \]
\[ \mu \]

Apply interaction model

Infer neutrino flux

Infered \( v \) Flux

[Graph showing incident and inferred flux vs. energy in GeV]

EXPERIMENTAL ANALYSIS
Improving Modeling Input

• $\nu$ near detector constraints
Improving Modeling Input

- $\nu$ near detector constraints
- Modelling development

![Graph showing energy transfer vs. area normalized](arXiv:2009.07228 [nucl-th])
Today

- Modelling development
- $\nu$ near detector constraints

- External Data

![Diagram](image-url)
And a Wealth of New Results...

- Many nuclei & beam energies
- \((e,e')\) & \((e,e'p)\)
- Energy reconstruction
- Single transverse variables
- Multiplicities
Why electrons?

• Very similar interactions
  Vector vs Vector + Axial-Vector
• Nuclear & FSI effects practically identical
• Monoenergetic electron beams
  → Benchmark $\nu$ event generators
• 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
Energy Reconstruction

Cherenkov detectors
Assuming QE interaction
Using lepton kinematics

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

nucleon separation energy \( \epsilon \sim 20 \text{ MeV} \)

Tracking detectors
Calorimetric sum
Using all detected particles

\[ E_{cal} = E_l + T_p + \epsilon \]
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 $\sigma_{\nu N} / \sigma_{eN} \propto Q^4$

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

Hall A@ JLab

H(e,e’p) @ 4.32 GeV
Absolute QE-Like C(e,e’p) Cross Sections

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

\[ \frac{d\sigma}{dE_{cal}} \]  

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

\[ \frac{\text{ub}}{\text{GeV}} \]  

1.159 GeV (x1/2)  

2.257 GeV  

4.453 GeV (x5)  

† Data  

- SuSav2 (Total)  

- QE  

- MEC  

- RES  

- DIS  

- G2018  

\[ E_{cal} = E_{l} + T_{p} + \epsilon \]
• 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

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

2.257 GeV

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

- Overestimation of QE peak & RES tail
Energy Reconstruction In $P_T$ Slices

Multi-dimensional study
Detected Hadron Multiplicities

$^{12}$C @ 2.2 GeV

$P_p > 300$ MeV/c

$P_{\pi} > 150$ MeV/c

MC overpredicts hadron multiplicities
e4ν Wrap Up

- Benchmarking ν 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 ν models

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

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

Support
Letters
Thank you!

[come join us! :)]
Thank you!

Joint theory & experimental effort

• New data with CLAS12 / ...
• More interaction channels (1p1\(\pi\), 1\(\pi\), NN, ...) 
• Tuning efforts
• Implications on \(\nu\) oscillation studies
Thank you!
Backup Slides
Inclusive $e^+\nu$ Cross Section

$(e,e')^{12}\text{C}$ 1.161 GeV, $\theta = 37.5^\circ$

![Graph showing the cross section data and various models: Data, QE, G2018, RES, MEC, DIS.](image)
Inclusive Electron Scattering C
GENIE Reproduces Inclusive $e^-$ & $\nu$ Data

$\frac{d^2\sigma}{d\Omega \, dE} \left[ \text{[mb/sr/GeV]} \right]$  

- Fe($e,e'$): 0.961 GeV at 37.5°
- Data
- SuSav2 (Total)
- QE
- RES
- MEC
- DIS

$0.45 \leq \cos(\theta_{\text{reco}}^{\mu}) < 0.62$

MicroBooNE $1.6 \times 10^{20}$ POT
- GENIE v2.12.2 + Emp. MEC
- GENIE v3.0.6 G1810a0211a
- GIBUU 2019
- NuWro 19.02.1
- Data (Stat. $\oplus$ Syst. Unc.)

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PRL 123, 131801 (2019)
Similar $\nu \& e$ Distributions in Exclusive Reaction

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

Using SuSav2 / GTEST19_10b_00_000 with $Q^2 > 0.1$
Issues To Be Further Investigated

\[ \frac{d^2 \sigma}{d \Omega dE} \text{ [nb/sr/GeV]} \times 10^3 \]

C(e,e'): 3.595 GeV at 16°
SuSav2 (Total)

Data

QE
RES
MEC
DIS

Energy Transfer [GeV]

\[ 0.5, 1, 1.5 \]

\[ 0, 2, 4 \]

\[ 0 \text{ to } 3 \text{ cm}^2/\text{GeV h} \]

\[ 0.86 \leq \cos(\theta_{\mu}^{\text{reco}}) < 0.94 \]

G2018

MicroBooNE 1.6 \times 10^{20} \text{ POT}

GENIE v2.12.2 + Emp. MEC

GENIE v3.0.6 G1810a0211a

GiBUU 2019

NuWro 2019

Data (Stat. + Syst. Unc.)

\[ \frac{d^2 \sigma}{dp_{\mu}^{\text{reco}} d\cos(\theta_{\mu}^{\text{reco}})} \text{ [10^{-38} GeV cm^2/GeV h]} \]

\[ 0 \text{ to } 3 \text{ GeV} \]

\[ 0 \text{ to } 3 \text{ GeV} \]

\[ 0.5, 1, 1.5, 2, 2.5 \]

\[ \mu\text{BooNE} \]


PRL 123, 131801 (2019)
GENIE v2 vs v3

PRD 102, 053001 (2020)
Deuterium GENIE v2 vs v3

v2

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

\[ \omega \text{ (GeV)} \]

5.500 GeV @ 41.00°

total

QE
res
DIS

(a)

+50%

+30%

+10%

-10%

v3

G2018

\[ \frac{d^2 \sigma}{d \Omega \ d E} \text{ (nb/sr/GeV)} \]

\[ E \text{ (GeV)} \]

2H(e,e'): 5.5 GeV at 41°

Data

QE
RES

MEC
DIS

SuSav2

SuSav2 (Total)

PRD 102, 053001 (2020)
Deuterium GENIE v2 vs v3

v2

SuSav2

v3

G2018

PRD 102, 053001 (2020)
Proton GENIE v2 vs v3

v2

v3

G2018

1H(e,e'): 5.5 GeV at 41°

Data

QE

RES

MEC

DIS

PRD 102, 053001 (2020)
Proton GENIE v2 vs v3

v2

\[ \frac{d^2 \sigma}{d \Omega \, dE} \] (nb/sr GeV)

v3

G2018

1H(e,e'): 3.245 GeV at 26.98°

\[ \frac{d^2 \sigma}{d \Omega \, dE} \] (nb/sr GeV)
Proton GENIE v2 vs v3

v2

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

\( \omega (\text{GeV}) \)

v3

\[ \frac{d^2\sigma}{dQ dE} (\text{nb/sr/GeV}) \]

Energy Transfer [GeV]

H(e,e'): 2.445 GeV at 20°

Data

QE

RES

MEC

DIS

G2018 (Total)

G2018

PRD 102, 053001 (2020)
GENIE v2 vs v3

v2

519 MeV @ 60 deg

(a)

v3

SuSav2

C(e,e'): 0.519 GeV at 60°

Data

SuSav2 (Total)

QE

RES

MEC

DIS

G2018

C(e,e'): 0.519 GeV at 60°

Data

QE

RES

MEC

DIS

PRD 102, 053001 (2020)
GENIE v2 vs v3

v2

620 MeV @ 60 deg

SuSav2

C(e,e'): 0.62 GeV at 60°

G2018

C(e,e'): 0.62 GeV at 60°
GENIE v2 vs v3

v2
680 MeV @ 60 deg

v3
SuSav2

C(e,e'): 0.68 GeV at 60º

v3
G2018

C(e,e'): 0.68 GeV at 60º
GENIE v2 vs v3

PRD 102, 053001 (2020)

GENIE v2 vs v3

v2

$v^2$

C($e, e'$)

(a)

d$^2\sigma/d\Omega d\omega$ (µb/sr GeV)

- total
- QE
- MEC
- res
- DIS

v3

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

Energy Transfer [GeV]

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

Energy Transfer [GeV]
GENIE v2 vs v3

$v2$

$Ar(e, e')$

(c)

$v3$

SuSav2

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

G2018

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

PRD 102, 053001 (2020)

GENIE v2 vs v3

PRD 102, 053001 (2020)

Mismodelling Impact On Mixing Parameters

SuSav2
- DIS (32%)
- RES (37%)
- MEC (7%)
- QE (22%)

G2018
- DIS (29%)
- RES (39%)
- MEC (6%)
- QE (24%)

G18_02a
- DIS (33%)
- RES (38%)
- MEC (5%)
- QE (21%)

\( \frac{d\sigma}{dE_{\nu}} \times 10^{-38} \text{ cm}^2 \text{ GeV Ar}^{-1} \)

Mismodelling Impact On Mixing Parameters

DUNE oscillated far-detector spectrum

Simulated with data-derived smearing matrices, reconstructed with model-derived ones
Available Data Sets

• Targets
  $^4\text{He}$, $^{12}\text{C}$, $^{56}\text{Fe}$

• Energies
  1, 2 & 4 GeV

Credit: L. Pickering
Nuclear Model Impact

QE Scattering

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 $^{12}\text{C}$ 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

![Graphs showing migration matrices for Data vs G2018]
Electrons vs Neutrinos

Where are the remaining differences coming from?

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

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, \( x = Q^2/(2m_\nu) \) 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) \((\nu, \ell^\pm)\) neutrino-nucleon cross section (where \( \ell^\pm \) is the outgoing charged lepton) has a similar form with the addition of third, axial, structure function:

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

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 \( F_2^\nu \), 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.
Model Configurations

Using GENIE v3:

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

- **G2018**: Rosenbluth QE & Empirical MEC (G18_10a_02_11a)
<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Neutrinos</th>
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</thead>
<tbody>
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<td>QE</td>
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<td>Berger-Sehgal</td>
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<tr>
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<td><strong>Nuclear Model</strong></td>
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<tr>
<td>Nuclear Model</td>
<td>Local Fermi Gas</td>
<td>Local Fermi Gas</td>
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</tbody>
</table>
Closure Test

- Use GENIE files
- Filter specific topologies (e.g. 1p0πp + 1p1π)
- Subtracted & True 1p0π are in good agreement

Ready to look at Data/MC comparisons!
Single Transverse Variables (STV)

\[ \delta \vec{p}_T = \vec{p}_T^\ell + \vec{p}_T^{\perp}, \]
\[ \delta \phi_T = \arccos \frac{-\vec{p}_T^\ell \cdot \vec{p}_T^N}{p_T^\ell p_T^N}, \text{ and} \]
\[ \delta \alpha_T = \arccos \frac{-\vec{p}_T^\ell \cdot \delta \vec{p}_T}{p_T^\ell \delta p_T}. \]
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/π$^+/-$ 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 $p / \pi^{\pm/-}$ definitions

- We do not acceptance correct below min $\theta$

$^{12}$C @ E = 2.261 GeV
Min $\theta_p$ Cut = 12 deg

$^{12}\text{C} \ @ \ E = 4.461 \text{ GeV} \ (1\text{st Sector})$
Min $\theta_{\pi^+}$ Cut = 12 deg

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

Data

SuSav2
Min $\theta_{\pi^-}$ Cut

@ 1.1 GeV: $\theta = 17 + 4 / P$

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

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

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

(43)

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

(44)

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

(45)

\[
C = \sigma_{TT} \frac{p_\pi^*}{k_\gamma^*} \sin^2 \theta_\pi \epsilon
\]

(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 \( \pi^0p \) 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 \( 0.4 \leq Q^2 \leq 1 \) GeV². 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 \( Q^2 = 0.45 \) GeV².
Figure 182: $E_{QE}$ 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 $^{56}$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>Cuts on $\beta_{EC}$</th>
<th>$\Delta t_{\text{offset}}$ for different sectors</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>$1$</td>
<td>$2$</td>
</tr>
<tr>
<td>1.1 GeV</td>
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<td>0.91</td>
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</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 vs $x$ are shown on the left side of Figure 5.4.
Systematics: Fiducial cuts on undetected particle subtraction

The systematic uncertainty due to the change in geometrical acceptance is the RMS of these two results obtained using the original and modified geometrical acceptances. 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:

$$x_{\text{RMS}}^i = \sqrt{\frac{(x_{1i}^i - x_{\text{mean}}^i)^2 + (x_{2i}^i - x_{\text{mean}}^i)^2}{2}}$$  \hspace{1cm} (50)

where $x_{\text{mean}}^i$ is the mean bin content for bin $i$ and is equal to $x_{\text{mean}}^i = (x_1^i + x_2^i)/2$, where $x_1^i$ and $x_2^i$ 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

Normalized Yield

$(e,e')_{0\pi} E^{QE} [\text{GeV}]$

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

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

Normalized Yield

$(e,e')_{0\pi} E^{QE} [\text{GeV}]$
Systematics: Sector Dependence
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 showing weighted events vs. C(e,e'p)_{1p0π} vs. E^{cal} [GeV] with data points and four curves representing different components: SuSav2 (Total), QE, MEC, RES, DIS, and G2018.](image)
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 & $Q^2 > Q_{2\text{min}}$
• $xsec = (\text{Selected detected events} / \text{all generated events}) \times \text{total xsec} / \text{bin width}$

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 $x = \frac{|\text{SUSav2} + \text{G2018}|}{2}$
- Due to offset, G2018 Ecal predictions have been shifted by $10/25/36$ MeV for $4\text{He}/12\text{C}/56\text{Fe}$ 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

Acceptance Correction

$^{12}\text{C}$

$^{4}\text{He}$

$^{56}\text{Fe}$

$^{1.159}\text{GeV}$

$^{2.257}\text{GeV}$

$^{4.453}\text{GeV}$

$(e,e'p)_{1p0\pi} E_{cal} \ [\text{GeV}]$
Step #4: Absolute Cross Sections

After both acceptance & radiation corrections, without systematics yet
### Energy Reconstruction Accuracy

<table>
<thead>
<tr>
<th>Peak Fraction (%)</th>
<th>1.161 GeV</th>
<th>2.261 GeV</th>
<th>4.461 GeV</th>
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<tbody>
<tr>
<td><strong>^4He</strong></td>
<td></td>
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</tr>
<tr>
<td>Data</td>
<td>-</td>
<td>41</td>
<td>38</td>
</tr>
<tr>
<td>SuSav2</td>
<td>-</td>
<td>45</td>
<td>22</td>
</tr>
<tr>
<td>G2018</td>
<td>-</td>
<td>39</td>
<td>24</td>
</tr>
<tr>
<td><strong>^12C</strong></td>
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</tr>
<tr>
<td>Data</td>
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<td>31</td>
<td>32</td>
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<tr>
<td>SuSav2</td>
<td>44</td>
<td>27</td>
<td>12</td>
</tr>
<tr>
<td>G2018</td>
<td>51</td>
<td>37</td>
<td>23</td>
</tr>
<tr>
<td><strong>^56Fe</strong></td>
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<tr>
<td>Data</td>
<td>-</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>SuSav2</td>
<td>-</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>G2018</td>
<td>-</td>
<td>30</td>
<td>19</td>
</tr>
</tbody>
</table>

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 = \( x / \text{Average} \times 100\% \)

Same recipe as for acceptance correction but, to avoid infinities, will use average (1 bin) around the peak and \( \frac{\text{average(reco)}}{\text{average(true)}} \) 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

![Graph showing acceptance correction vs. $(e,e'p)_{1p0\pi}$ and $E^{cal}$ vs. [GeV]]
$E_{QE}$ All Nuclei & Energies

$^12C \frac{d\sigma}{dE_{QE}}$ [ub/GeV]

1.159 GeV (x1/2) | 2.257 GeV | 4.453 GeV (x5)

Data

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

$(e,e')_{0\pi} E_{QE}$ [GeV]
A & E Dependence

$^{12}_{\text{C}}\, \frac{\text{d} \sigma}{\text{d}p_T}\, \frac{\text{ub}}{\text{GeV/c}}$ for $1.159\, \text{GeV}$, $2.257\, \text{GeV}$, and $4.453\, \text{GeV}$ (x4)

Data

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

$^{56}_{\text{Fe}}\, \frac{\text{d} \sigma}{\text{d}p_T}\, \frac{\text{ub}}{\text{GeV/c}}$ for $(e,e'p)_{l\pi^0}$ and $P_T [\text{GeV/c}]$
Angular A & E Dependence

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

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

1.159 GeV

2.257 GeV

4.453 GeV (x2)

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

Data

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

\[ \delta\varphi_T = \arccos \frac{-\vec{p}_T^f \cdot \vec{p}_T^N}{p_T^f p_T^N} \]

\[ (e,e'p)_{1p0\pi} \delta\varphi_T \text{ [deg]} \]
Systematics

• Sector dependence
• Detector acceptance
• Photon identification cuts
• $\phi_{q\pi}$ cross section dependence
• Number of rotations
<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
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<td>Detector acceptance</td>
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<td>Identification cuts</td>
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<td>$\varphi_{q\pi}$</td>
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<td>cross section dependence</td>
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<tr>
<td>Number of rotations</td>
<td>2, 2.1, 4.7</td>
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<td>Sector dependence</td>
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<td>Acceptance correction</td>
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<td>Overall normalization</td>
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<tr>
<td>Electron inefficiency</td>
<td>2</td>
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</tbody>
</table>

* See backup slides
Q4 Scaling Effect

![Graph showing area normalized against Q^2 (GeV^2/c^2)]

- ν
- 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

**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

**Luminosity monitors:**
- Förster probe (1-2 %)
Parallel Efforts

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

See talk by L. Doria

See talk by A. Ankowski