Muon-Neutrino Charged-Current Inclusive Cross Section at MicroBooNE

Marco Del Tutto
representing the MicroBooNE collaboration

NUINT2018
16th October 2018
This afternoon’s agenda

Previous Talk by Anne S.:
- MicroBooNE detector
- Data samples
- Cosmic rejection
- Reconstruction
- Systematics

This Talk:
- $\nu_\mu$ CC cross-section measurement
**Introduction**

**Inclusive** sample, all $\nu_\mu$ CC topologies:

- One of the first channels that will be addressed by the MicroBooNE cross-section program
- Simple: looking for a long muon track
- We have an automated reconstruction and event selection

**Inclusive measurements are valuable:**

- High purity and efficiency.
- Not sensitive to hadron uncertainties.
- Test different channel predictions from models.
- Interesting physics measurement on argon, provide input for theory.
- $\nu_e$ rate constraint in MicroBooNE through correlation with neutrino parents.
- Provide a pre-selection to study other specific channels (proton kinematics, ...).
Introduction

Simulated $\nu_\mu$ CC events

[Image: Simulated POT: 8.80576e+20, Scaled to POT: 1.627e+20 MicroBooNE Simulation, Preliminary]

[Legend: QE, 45%; MEC, 20%; RES, 27%; COH, 0.33%; DIS, 7.6%; Stat. Unc.]

[Graph: Generated Signal Events vs True Neutrino Energy [GeV]]

GENIE v2_12_2

MicroBooNE

Ar

MiniBooNE

CH$_2$

MINERvA

CH

T2K

CH

NOvA

CH

Fermilab

Neutrino Source

MicroBooNE Detector

 Booster Neutrino Beam Line 470 m

Marco Del Tutto
16th October 2018
Introduction

**Inclusive** sample, all $\nu_\mu$ CC topologies:

- CC 0 pion
- CC 1 pion
- CC multi-track
- ...

**Main analysis characteristics:**

- First $\nu_\mu$ CC cross section on Ar at **low neutrino energies**
- **Full angular coverage**
- **Full momentum coverage** by using multiple Coulomb scattering (MCS) for momentum reconstruction (includes both contained and exiting tracks)
- First differential cross section measurement from MicroBooNE
Neutrino flux at MicroBooNE is simulated using the framework built by the MiniBooNE collaboration \( (\text{Phys. Rev. D 83 052009, 2011}) \)

Neutrino interactions on argon are simulated with the GENIE event generator \( (v2\_12\_2) \)

Particles exiting from the neutrino interaction are passed to a custom implementation of Geant4 in LArSoft

Cosmic rays (CRs) in events with no neutrino interactions are measured directly in data

Other CR backgrounds are modelled with CORSIKA
We compare out measurement with two sets of models available in GENIE

Neutrino interactions on argon are simulated with the GENIE event generator (v2_12_2)

<table>
<thead>
<tr>
<th>Model Element</th>
<th>Default GENIE + Emp. MEC</th>
<th>GENIE Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Model</td>
<td>Bodek-Ritchie Fermi Gas [1]</td>
<td>Local Fermi Gas [2, 3]</td>
</tr>
</tbody>
</table>

References:

Event Selection

- Cosmic Rejection
- Reconstruct TPC tracks under neutrino hypothesis (using the Pandora toolkit for multi-algorithm pattern recognition)
- Require optical activity (flash > 50PE) in time with neutrino beam
- Pick TPC reconstructed interaction that is matched with the flash (if any)
- TPC interaction must have at least 1 track (multiple Coulomb scattering is used to remove broken tracks)
- Muon consistency (using track truncated mean dQ/dx)
- Reconstructed vertex has to be in the fiducial volume

Event is selected
Several algorithms mitigate the cosmic background (see talk by Anne Schukraft).

A track is tagged as cosmic if:

- It is through-going in the detector.
- It is not compatible with the neutrino beam time (that lasts for only $1.6 \mu s$ compared to the $4.8 \text{ ms}$ readout window).
- The track is a cosmic crossing the anode or cathode plane (for which we can reconstruct the $t_0$).
- It is not compatible with the flash in the neutrino beam spill in terms of spatial position and light intensity.

![Diagram of reconstructed tracks before and after cosmic tagging.](attachment:cosmic tagging diagram.png)
Event Selection - PMT-TPC matching

Optical Activity Reconstructed as a Flash

Beam Spill

Neutrinos arrive during this time

TPC Reconstructed Interaction

Using Pandora toolkit:

We **match** the **flash** in the beam spill with every reconstructed **TPC interaction**.

The interaction that best matches with the flash is kept as **neutrino candidate**.
Event Selection - PMT-TPC matching

Optical Activity Reconstructed as a Flash

We match the flash in the beam spill with every reconstructed TPC interaction.

The interaction that best matches with the flash is kept as neutrino candidate.
Event Selection - Quality Cuts

A series of quality cuts ensure the event is well reconstructed.

We make use of:

- **Multiple Coulomb Scattering** (MCS) to identify well reconstructed tracks
- **track dQ/dx v.s. track length** for a MIP consistency check

MCS is also used for momentum estimation
(see talk by Anne Schukraft)

\[
\sigma_o^{HL} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[ 1 + \epsilon \times \ln \left( \frac{\ell}{X_0} \right) \right]
\]


**Muon/Proton Separation**
using truncated mean dQ/dx

\[
\text{Candidate Track } < \frac{dQ}{dx} >_{\text{trunc}} [e^-/cm]
\]
Event Selection - Performances

Purity and efficiency for every selection cut

MicroBooNE Simulation, Preliminary

Efficiency for different GENIE interaction modes

MicroBooNE Simulation, Preliminary

Overall efficiency x acceptance: 55%
Overall purity: 53%

All interaction modes are selected with roughly the same efficiency, making this analysis really inclusive.
There is a negligible contribution from CC coherent pion production events not plotted.

νμ CC selected events in 1.6 x 10^{20} POT: ~15000
Distributions of selected events

More plots available in our public note:

MICROBOONE-NOTE-1045-PUB

**Reconstructed muon momentum.**
Full momentum coverage thanks to MCS used for momentum reconstruction: allows to include exiting tracks.

**Cosine of the muon $\theta$ angle.**
$\theta$ is the angle w.r.t. the neutrino beam line.
Full angular acceptance.

**Number of reconstructed particles from the neutrino vertex (including muon).**
This selection can be used for more exclusive channels.
Cross-Section Measurement

Final goal: double-differential cross section in muon angle and momentum:

\[
\frac{d^2 \sigma}{(dp_{\mu,i}^{\text{reco}})(d \cos \theta_{\mu,j}^{\text{reco}})} = \frac{N_{ij} - B_{ij}}{\tilde{\epsilon}_{ij} \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot \Delta p_{\mu,i} \cdot \Delta \cos \theta_{\mu,j}}
\]

We are currently working on finalising this measurement, and here we will only present the two single-differential cross sections:

\[
\left\langle \frac{d\sigma}{dp_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot (\Delta p_{\mu})_i}
\]

\[
\left\langle \frac{d\sigma}{d \cos \theta_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot (\Delta \cos \theta_{\mu})_i}
\]

- \(N_i\) number of selected events in reconstructed bin \(i\) (data)
- \(B_i\) number of background events in reconstructed bin \(i\) (MC and cosmic data)
- \(\tilde{\epsilon}_i\) overall efficiency (selection eff. x acceptance) in reconstructed bin \(i\) (MC)
- \(N_{\text{target}}\) number of target nucleons
- \(\Phi\) muon neutrino flux (integrated over all energies)
Cross-Section Measurement

\[
\langle \frac{d\sigma}{dp_{\mu}^{\text{reco}}} \rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot (\Delta p_{\mu})_i}
\]

\[
\langle \frac{d\sigma}{d\cos\theta_{\mu}^{\text{reco}}} \rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot (\Delta \cos\theta_{\mu})_i}
\]

Flux integrated cross section:
- detector dependent
- less model bias

Number of targets:
- temperature and pressure are constantly monitored to measure the number of targets
- we have measured contaminants < 1ppm
- we treat the full volume as pure argon

with 68% of the values falling into the energy range of: [325,1325] MeV
Cross-Section Measurement

\[
\left\langle \frac{d\sigma}{dp_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{c}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_{\mu})_i}
\]

\[
\left\langle \frac{d\sigma}{d \cos \theta_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{c}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta \cos \theta_\mu)_i}
\]

Background estimation:

\[
B_i = B_i^{\text{sim}} + B_i^{\text{beam-off}}
\]

Hashed histogram (cosmic only events)

Main MC backgrounds:

- **Blue histogram**: cosmics selected even if a neutrino interaction is also present in the event

- **Green histogram**: events happening outside the fiducial volume
  
  (Red: signal events)

Reconstructed momentum of the muon candidate track

Accumulated POT: 1.627e+20

MicroBooNE Preliminary

- $\nu_\mu$, CC (signal), 54%
- $\nu_\mu$, $\bar{\nu}_\mu$, CC, 0.055%
- $\nu_\tau$, CC, 0.49%
- NC, 1.7%
- Cosmic, 7%
- OUTFV, 7.8%
- Data (Beam-off), 29%
- Stat. Unc.
- Data (Beam-on, stat. only)
Cross-Section Measurement

\[
\left\langle \frac{d\sigma}{dp_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i}
\]

\[
\left\langle \frac{d\sigma}{d\cos \theta_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta \cos \theta_\mu)_i}
\]

Background estimation:

\[ B_i = B_i^{\text{sim}} + B_i^{\text{beam-off}} \]

<table>
<thead>
<tr>
<th>Signal and Background Composition [%]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_\mu ) CC in FV (signal)</td>
<td>53.20</td>
</tr>
<tr>
<td>Cosmic in BNB</td>
<td>7.06</td>
</tr>
<tr>
<td>OUTFV</td>
<td>7.75</td>
</tr>
<tr>
<td>NC</td>
<td>1.65</td>
</tr>
<tr>
<td>( \bar{\nu}_\mu )</td>
<td>0.49</td>
</tr>
<tr>
<td>( \nu_e ) and ( \bar{\nu}_e )</td>
<td>0.06</td>
</tr>
<tr>
<td>Cosmic Only (data)</td>
<td>30.01</td>
</tr>
</tbody>
</table>

Reconstructed momentum of the muon candidate track

Accumulated POT: 1.627e+20

MicroBooNE Preliminary

![Graph showing reconstructed momentum of the muon candidate track](image)
Cross-Section Measurement

\[
\left\langle \frac{d\sigma}{dp_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot (\Delta p_{\mu})_i}
\]

\[
\left\langle \frac{d\sigma}{d \cos \theta_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot (\Delta \cos \theta_{\mu})_i}
\]

**Efficiency**

only statistical uncertainties shown here

systematic effects shown in following slides

![Efficiency plot 1](image1)

![Efficiency plot 2](image2)
Cross-Section Measurement

\[
\left\langle \frac{d\sigma}{dp_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{e}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_{\mu})_i}
\]

\[
\left\langle \frac{d\sigma}{d\cos\theta_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{e}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta \cos\theta_{\mu})_i}
\]

**Forward Folding**

- We are not going to unfold the measurement to true muon momentum and true muon angle
- Final result will be in reconstructed muon momentum and angle
- Unfolding introduces biases that inflate the uncertainties
- Our efficiency needs to be forward folded to be as a function of reconstructed variables
- A smearing matrix is constructed to achieve this
- The smearing matrix will be published alongside with the measurement
Forward Folding

- We are going to keep the distributions as a function of reconstructed quantities.
- We convert the efficiency as a function of true momentum/angle, in an efficiency as a function of reconstructed momentum/angle.
- We do this by constructing a smearing matrix $S$.

\[ N^\text{reco}_i = \sum_j S_{ij} N^\text{true}_j \quad \text{\(S_{ij} = P(\text{observed in bin } i \mid \text{true value in bin } j)\)} \]
Forward Folding

- We are going to keep the distributions as a function of reconstructed quantities.
- We convert the efficiency as a function of true momentum/angle, in an efficiency as a function of reconstructed momentum/angle.
- We do this by constructing a smearing matrix $S$.

\[
N_{\text{reco}}^i = \sum_j S_{ij} N_{\text{true}}^j \quad S_{ij} = P(\text{observed in bin } i \mid \text{true value in bin } j)
\]

\[
\left\langle \frac{d\sigma}{dp_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot (\Delta p_{\mu})_i}
\]

\[
\left\langle \frac{d\sigma}{d \cos \theta_{\mu}^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_{\mu}} \cdot (\Delta \cos \theta_{\mu})_i}
\]

The efficiency in reconstructed bin $i$ is given by:

\[
\tilde{\epsilon}_i = \frac{\sum_j S_{ij} N_{j}^{\text{sel}}}{\sum_j S_{ij} N_{j}^{\text{gen}}}
\]

The smearing matrix $S$ will be published with the cross section measurement to allow testing other generators/predictions.
How are the Systematics Estimated?

The goal is to evaluate three systematic covariance matrices in order to get to the full systematic covariance matrix:

\[ E^{\text{syst}} = E^{\text{flux}} + E^{\text{xsec}} + E^{\text{detector}} \]

- Generating several MC replicas, each one called a "universe".
- Parameters in the models are varied accordingly within their uncertainties.
- Done through event reweighing. Requires only one MC run.

- Changing one detector parameter at a time according to its uncertainty.
- Each parameter variation corresponds to a MC run.
- The difference between the central value cross section and the cross section calculated with the new MC runs gives an indication of the systematic uncertainty on the cross section.
How are the Systematics Estimated?

**Central Value**

\[
\left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu} \cdot (\Delta x_\mu)_i}
\]

**Universe s**

\[
\left\langle \frac{d\sigma^s}{dx_\mu} \right\rangle_i = \frac{N_i - B^s_i}{\tilde{\epsilon}^s_i \cdot N_{\text{target}} \cdot \Phi^s_{\nu} \cdot (\Delta x_\mu)_i}
\]

Reminder:

- \(N_i\): from data (doesn’t change)
- \(B_i\): from MC (changes in every universe)

Background events, efficiency and smearing matrix change in every universe

The covariance matrix is calculated as:

\[
E_{ij} = \frac{1}{N_s} \sum_{s=0}^{N_s} \left( \left\langle \frac{d\sigma^s}{dx_\mu} \right\rangle_i - \left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_i \right) \left( \left\langle \frac{d\sigma^s}{dx_\mu} \right\rangle_j - \left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_j \right)
\]

\[\tilde{\epsilon}^s_i = \frac{\sum_{j=1}^{M} S^s_{ij} N_{s,\text{sel}}^j}{\sum_{j=1}^{M} S^s_{ij} N_{s,\text{gen}}^j}\]
Neutrino Flux Uncertainties

We use the final flux simulation and flux uncertainties from the MiniBooNE collaboration (PRD 79, 072002, 2009)

MICROBOONE-NOTE-1031-PUB

Neutrino Flux Relative Uncertainty on Total Cross Section: 12%

![Graph showing neutrino flux re-weighting only and flux re-weighting only for p+Be → π+]
GENIE provides a set of uncertainties that go with their default models

- These uncertainties are tuned to cover differences between the models and neutrino and pion scattering data
- Over 35 parameters within the models are varied according to their uncertainties to generate several MC replicas by event reweighing.

Cross Section Model Relative Uncertainty on Total Cross Section: 4%
Cross Section Uncertainties: Future

1. We are currently using GENIE model set which
   • does not include RPA
   • includes an empirical MEC model, which is currently not reweighable

   Need to assess systematic uncertainties related to these two limitations. Currently comparing the baseline model to an alternative model set (Nieves et al. for quasi elastic interactions).
   We treat ratios of this model (“Valencia”) to our baseline model (“default”) in exclusive interaction channels as an uncertainty on the cross section.

2. Further inspection of non-reweighable GENIE uncertainties

3. In the process of binding alternate generators to MicroBooNE software framework to study impact of models not in GENIE
Detector Systematics

We generated MC samples for each one of these detector parameters and recalculated the cross section for each: $\sigma^m$. The uncertainty has then been evaluated as:

$$E_{ij}^{\text{det}} = \sum_m \left( \sigma_i^{\text{cv}} - \sigma_j^m \right) \left( \sigma_j^{\text{cv}} - \sigma_j^m \right)$$

### Systematic Sample

<table>
<thead>
<tr>
<th>Systematic Sample</th>
<th>Relative Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced Charge Effect</td>
<td>15.0</td>
</tr>
<tr>
<td>Wire Noise</td>
<td>6.4</td>
</tr>
<tr>
<td>TPC Visibility</td>
<td>4.3</td>
</tr>
<tr>
<td>Improved Light Yield Model</td>
<td>3.7</td>
</tr>
<tr>
<td>Space Charge Effect</td>
<td>2.7</td>
</tr>
<tr>
<td>Remove Channels Prone to Saturating</td>
<td>2.1</td>
</tr>
<tr>
<td>Remove Misconfigured Channels</td>
<td>2.1</td>
</tr>
<tr>
<td>Transverse Diffusion</td>
<td>2.1</td>
</tr>
<tr>
<td>PE Noise</td>
<td>2.1</td>
</tr>
<tr>
<td>Wire Response</td>
<td>1.4</td>
</tr>
<tr>
<td>Longitudinal Diffusion</td>
<td>1.4</td>
</tr>
<tr>
<td>Electron Recombination</td>
<td>1.3</td>
</tr>
<tr>
<td>Electron Lifetime</td>
<td>1.2</td>
</tr>
</tbody>
</table>
### Detector Systematics

Dominant contribution by the **induced charge effect**. This is the charge induced on the neighbouring wires. Currently not in the default MicroBooNE simulation. In the process of incorporating this effect into the MicroBooNE simulation.

<table>
<thead>
<tr>
<th>Systematic Sample</th>
<th>Relative Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced Charge Effect</td>
<td>15.0</td>
</tr>
<tr>
<td>Wire Noise</td>
<td>6.4</td>
</tr>
<tr>
<td>TPC Visibility</td>
<td>4.3</td>
</tr>
<tr>
<td>Improved Light Yield Model</td>
<td>3.7</td>
</tr>
<tr>
<td>Space Charge Effect</td>
<td>2.7</td>
</tr>
<tr>
<td>Remove Channels Prone to Saturating</td>
<td>2.1</td>
</tr>
<tr>
<td>Remove Misconfigured Channels</td>
<td>2.1</td>
</tr>
<tr>
<td>Transverse Diffusion</td>
<td>2.1</td>
</tr>
<tr>
<td>PE Noise</td>
<td>2.1</td>
</tr>
<tr>
<td>Wire Response</td>
<td>1.4</td>
</tr>
<tr>
<td>Longitudinal Diffusion</td>
<td>1.4</td>
</tr>
<tr>
<td>Electron Recombination</td>
<td>1.3</td>
</tr>
<tr>
<td>Electron Lifetime</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Detector Systematics

After the induced charge effect we have **Wire Noise** and **TPC Visibility**.

Both these effects we’ll be reduced once we switch to a data driven model of the detector.

This will be accomplished by using cosmic data overlaid with simulated neutrino interactions.

<table>
<thead>
<tr>
<th>Systematic Sample</th>
<th>Relative Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced Charge Effect</td>
<td>15.0</td>
</tr>
<tr>
<td>Wire Noise</td>
<td>6.4</td>
</tr>
<tr>
<td>TPC Visibility</td>
<td>4.3</td>
</tr>
<tr>
<td>Improved Light Yield Model</td>
<td>3.7</td>
</tr>
<tr>
<td>Space Charge Effect</td>
<td>2.7</td>
</tr>
<tr>
<td>Remove Channels Prone to Saturating</td>
<td>2.1</td>
</tr>
<tr>
<td>Remove Misconfigured Channels</td>
<td>2.1</td>
</tr>
<tr>
<td>Transverse Diffusion</td>
<td>2.1</td>
</tr>
<tr>
<td>PE Noise</td>
<td>2.1</td>
</tr>
<tr>
<td>Wire Response</td>
<td>1.4</td>
</tr>
<tr>
<td>Longitudinal Diffusion</td>
<td>1.4</td>
</tr>
<tr>
<td>Electron Recombination</td>
<td>1.3</td>
</tr>
<tr>
<td>Electron Lifetime</td>
<td>1.2</td>
</tr>
</tbody>
</table>
## Summary of Systematics

More information are available in our public note:

**MICROBOONE-NOTE-1045-PUB**

The table shows a summary of the systematics uncertainties and the size of them for the total cross section.

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Method</th>
<th>Estimated Relative Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Flux</td>
<td>Estimated with multisim variations</td>
<td>12%</td>
</tr>
<tr>
<td>Cross Section Modeling</td>
<td>Estimated with multisim variations</td>
<td>4%</td>
</tr>
<tr>
<td>Detector Response</td>
<td>Estimated with unisim variations</td>
<td>19%</td>
</tr>
<tr>
<td>POT Counting</td>
<td>Toroids Resolution</td>
<td>2%</td>
</tr>
<tr>
<td>Cosmics (in-time)</td>
<td>Estimated from data-driven cosmic model</td>
<td>7%</td>
</tr>
<tr>
<td>Cosmics (out-of-time)</td>
<td>Estimated from off-beam statistics</td>
<td>1%</td>
</tr>
<tr>
<td>Beam Timing Jitter</td>
<td>Estimated from on- minus off-beam flashes</td>
<td>4%</td>
</tr>
</tbody>
</table>

★ Described previously

★★ It will be reduced when we’ll switch to a neutrino simulation with cosmic data overlaid

★★★ It will go away in the next analysis iteration, as the beam jitter is taken into account during event selection
Cross Section Measurement

The final single-differential $\nu_\mu$ CC inclusive cross section on argon

Model Element | Default GENIE + Emp. MEC | GENIE Alternative
---|---|---
Nuclear Model | Bodek-Ritchie Fermi Gas | Local Fermi Gas
Quasi-elastic | Llewellyn-Smith | Nieves
Meson-exchange Currents | Empirical | Nieves
Resonant | Rein-Seghal | Berger-Seghal
Coherent | Rein-Seghal | Berger-Seghal
FSI | hA | hA2014
The final single-differential $\nu_\mu$ CC inclusive cross section on argon

- We start exploring differences between models
- Results will be even more useful with the double-differential cross section
- This analysis is still missing DIRT background (interactions outside the cryostat) and a few (minor) systematic uncertainties.
Conclusions

We have presented the first $\nu_\mu$ CC inclusive differential cross section from MicroBooNE

This analysis:

- is the first $\nu_\mu$ CC inclusive cross section on argon at low neutrino energies (other measurement from ArgoNeuT is at higher energies)
- is the first differential cross section from MicroBooNE
- has full angular coverage
- for the first time uses MCS for momentum reconstruction, which allows the selection of exiting tracks and so there is no momentum cut-off.
- Public note: MICROBOONE-NOTE-1045-PUB (http://microboone.fnal.gov/public-notes/)

We are finalising the double differential cross-section
Back-up
How are the Systematics Estimated?

A covariance matrix can then be calculated as:

$$E_{ij} = \frac{1}{N_s} \sum_{s=0}^{N_s} \left( \left< \frac{d\sigma^s}{dx_\mu} \right>_i - \left< \frac{d\sigma^{cv}}{dx_\mu} \right>_i \right) \left( \left< \frac{d\sigma^s}{dx_\mu} \right>_j - \left< \frac{d\sigma^{cv}}{dx_\mu} \right>_j \right)$$
Existing $\nu_\mu$ CC Inclusive Measurements

V. CONCLUSIONS

Whether the strange quarks in the nucleon sea contribute negatively or not at all to the spin of the nucleon is an open question. Elastic neutrino-proton scattering offers a unique way to determine $\nu_\mu p \rightarrow \nu_\mu p$ that is independent of the assumptions required by previous measurements.

The MicroBooNE liquid argon TPC can detect low-$Q^2$ NC elastic events and is currently taking neutrino data at Fermilab. Automated event reconstruction and selection methods are being developed to analyze the large amount of high-resolution neutrino events in MicroBooNE.

---

**Event Selection**

Cosmic-oriented reco.  
Flashes, tracks, vertices  
Objects  
Muon candidate  
Neutrino candidate

### Cosmic Removal

In order to remove cosmics, tracks are tagged and removed if they are:
1. trough-going  
2. not compatible with the beam flash  
3. identified as anode/cathode piercing  
4. identified as stopping muons

### Flash in beam window

A 50 total PE cut is applied to the flash in the beam spill. This ensures there is activity during beam spill time.

### Create “TPC objects”

TPCObjects represent interactions in the TPC (cosmics or neutrinos). They are constructed using Pandora particle hierarchy.

### “Flash-object-matching”

A TPCObject-to-flash matching is run between the beam flash and all the TPCObjects in the event. Only the one with the best match is kept.

### Minimum track/vertex quality

The TPCObject must have at least one track and STD of the hits residuals has to be small.

### Muon quality

Multiple coulomb scattering momentum v.s. range momentum is used for a quality check and to remove broken tracks.

### Select the muon candidate track

dQ/dx v.s. track length is used for a muon consistency check. This allows to remove candidates where a proton is selected instead of a muon.

### Pick the neutrino object

If the TPCObject survived all previous cuts and has the reconstructed vertex inside the fiducial volume, is selected as a neutrino candidate interaction.