MICROBOONE: CAPABILITIES AND MEASUREMENTS

Kirsty Duffy, Fermi National Accelerator Laboratory

NuSTEC Workshop on Neutrino-Nucleus Pion Production in the Resonance Region
5th October 2019
**MicroBooNE:** a 170 ton Liquid Argon Time Projection Chamber (LArTPC)

2.5 x 2.3 x 10.4 m TPC volume
FERMILAB'S NEUTRINO BEAMS

Booster $\nu$ beam
MicroBooNE, SBN program

NuMI $\nu$ beam
NOvA, MINERvA, MINOS+

DUNE $\nu$ beam
(planned)

Booster Neutrino Beam (BNB): 463m

$>99\% \nu_\mu/\bar{\nu}_\mu$ at peak
$<E_\nu> = 850$ MeV

Image: G. Zeller
MicroBooNE main physics goals:

- Resolve anomalies from LSND/MiniBooNE
- Measure neutrino-Ar cross sections
- Exotic beam-dump/astrophysical neutrino signals
- LArTPC detector R&D for future experiments
MicroBooNE main physics goals:

- Resolve anomalies from LSND/MiniBooNE
- Measure neutrino-Ar cross sections
- Exotic beam-dump/astrophysical neutrino signals
- LArTPC detector R&D for future experiments
# SHORT-BASELINE NEUTRINOS AT FERMILAB

**Kirsty Duffy**

<table>
<thead>
<tr>
<th>MicroBooNE</th>
<th>Non-pion</th>
<th>Neutral pions</th>
<th>Charged pions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICARUS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MiniBooNE</td>
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<tr>
<td>MicroBooNE</td>
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<tr>
<td>SBND</td>
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**Booster Neutrino Beam (BNB)**
SHORT-BASELINE NEUTRINOS AT FERMILAB

Booster Neutrino Beam (BNB)

MicroBooNE

MiniBooNE

SBN Far Detector

SBN Near Detector

Booster Neutrino Beam

Non-pion

Neutral pions

Charged pions
LOW-ENERGY EXCESS: MINIBOONE

- Most recent result published in 2018:
  - $4.7\sigma$ excess of measured $\nu_e$ and $\bar{\nu}_e$ over prediction at low energies
    - $\rightarrow$ “Low Energy Excess” (LEE)

- Largest background from photons ($\pi^0$ or $\Delta \rightarrow N\gamma$) because MiniBooNE could not distinguish between $e^\pm$ and $\gamma$ (mineral oil Cherenkov detector)

Phys. Rev. Lett. 121, 221801
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Phys. Rev. Lett. 121, 221801
LOW-ENERGY EXCESS:
MICROBOONE

MicroBooNE (LArTPC) can
distinguish electrons from photons
→ resolve nature of MiniBooNE
low-energy excess

1) Shower start

\[ e^- \quad \gamma \]

LOW-ENERGY EXCESS: MICROBOONE

MicroBooNE (LArTPC) can distinguish electrons from photons → resolve nature of MiniBooNE low-energy excess

1) Shower start

\( e^- \)  

\( \gamma \)
LOW-ENERGY EXCESS: MICROBOOONE

**Signal channels**
- Electron-like $\rightarrow 1e1p$
- $\rightarrow 1eNp \ (N\geq1)$
- $\rightarrow 1e$
- Photon-like $\rightarrow 1\gamma0p$
- $\rightarrow 1\gamma1p$

**Sideband background constraints**

$\nu_\mu$ CC interactions $\rightarrow$ constrain neutrino flux and cross-section uncertainties (common between $\nu_e$ and $\nu_\mu$)

CC $\pi^0$, NC $\pi^0$ $\rightarrow$ constrain $\pi^0$ background
Resonant interactions form significant parts of the signal and backgrounds to MicroBooNE’s LEE analysis, in ways that are also strongly dependent on FSI

- **Signal**
  - $\text{CC}0\pi$ → large component ($\mathcal{O}(15\%)$, but model dependent) from resonant pion production with pion absorbed

- **Background**
  - **Neutral pions** (80% of background in $\gamma$-like signal)
    - → constrain with a sideband of our own data: $\text{CC}\pi^0$ and $\text{NC}\pi^0$ selections
    - Need models to describe the data well enough that our sideband will be valid
    - Cross-section measurements: $\text{CC}\pi^0$ (published, to be updated), $\text{NC}\pi^0$ (planned)
  - **Charged pions**
    - Inclusive $\nu_e$ searches $\to \text{NC}\pi^+$ background to $\nu_\mu$ CC0$\pi$ sideband
    - $\nu_e$ searches requiring a proton require a $\nu_\mu$ CC0$\pi$p sideband $\to \text{NC}\pi^p$ background ($\text{NC}\pi^+p$ suppressed). Current estimate $\mathcal{O}(\%)$, no current hope to constrain or measure in our data — will have to rely on model
EXTRA MOTIVATION: DUNE

- CC pion production will be an oscillation signal channel for DUNE (and many backgrounds similar to MicroBooNE LEE)

- → MicroBooNE measurements (on argon) will be an important input

- But watch out: different energies, different types of interactions
Cross-section measurements today:

- Measurements that aren’t specifically in the resonance region
- Measurements of neutral pions
- Measurements of charged pions
NOT-PION-SPECIFIC MEASUREMENTS
CC-INCLUSIVE

- Measure cross-section for **charged-current (CC) inclusive** muon neutrino interactions

Event selection summary:

- Identify neutrino interaction using topological/calorimetric information to reject cosmic tracks
- Identify muon candidate as longest track in event — $dE/dx$ must be consistent with a MIP

Figure from M. del Tutto
SELECTED EVENTS

Signal (CC-inclusive)
events: 50.4%

Estimate 25% resonant interactions
SELECTED EVENTS

Largest ever sample of neutrino interactions on argon

CROSS SECTION

- Unlike other cross section measurements we do not unfold to true muon momentum and angle
  - → unfolding introduces bias, inflates uncertainties
- Instead, present result in reconstructed muon momentum and angle
- Publish detector smearing and efficiency
  - → theoretical predictions can be forward folded (i.e. smeared by our known detector effects)
  - → produce a realistic prediction of what we expect to see in our detector
  - → directly compare to data
RESULTS

-1.00 \leq \cos(\theta_{\mu}^{\text{reco}}) < -0.50

MicroBooNE 1.6e20 POT

- GENIE v2.12.2 + Emp. MEC
- GENIE v3.00.04 G1810a0211a
- GiBUU 2019
- NuWro 19.02.1
- Data (Stat. $\pm$ Syst. Unc.)
Cross Section Measurement

-1.00 ≤ \(\cos(\theta^\text{reco})\) < -0.50

0.27 ≤ \(\cos(\theta^\text{reco})\) < 0.45

0.76 ≤ \(\cos(\theta^\text{reco})\) < 0.86

-0.50 ≤ \(\cos(\theta^\text{reco})\) < 0.00

0.45 ≤ \(\cos(\theta^\text{reco})\) < 0.62

0.86 ≤ \(\cos(\theta^\text{reco})\) < 0.94

0.00 ≤ \(\cos(\theta^\text{reco})\) < 0.27

0.62 ≤ \(\cos(\theta^\text{reco})\) < 0.76

0.94 ≤ \(\cos(\theta^\text{reco})\) < 1.00

MicroBooNE 1.6e20 POT

GENIE v2.12.2 + Emp. MEC
GENIE v3.00.04 G1810a0211a
GiBUU 2019
NuWro 19.02.1

Syst. Unc.) ⊕ Data (Stat.

MicroBooNE
Non-pion
Neutral pions
Charged pions

Kirsty Duffy

μBooNE
Tension reduced (smaller $\chi^2$) for GENIE v3, NuWro, and GiBUU compared to GENIE v2 (used for this analysis).

Large $\chi^2$ driven by high-momentum, forward-going bins (largely QE and MEC processes)uner for this analysis)

- GENIE v2+MEC: $\chi^2/N_{\text{bins}} = 245.9/42$
- GENIE v3: $\chi^2/N_{\text{bins}} = 108.8/42$
- GiBUU: $\chi^2/N_{\text{bins}} = 172.9/42$
- NuWro: $\chi^2/N_{\text{bins}} = 126.5/42$
CC-INCLUSIVE: COMPARISON TO GENIE MODELS

-1.00 ≤ cos(θμ reco) < -0.50
MicroBooNE 1.6e20 POT
-0.50 ≤ cos(θμ reco) < 0.00
0.00 ≤ cos(θμ reco) < 0.27

0.27 ≤ cos(θμ reco) < 0.45

0.45 ≤ cos(θμ reco) < 0.62

0.62 ≤ cos(θμ reco) < 0.76

0.76 ≤ cos(θμ reco) < 0.86

0.86 ≤ cos(θμ reco) < 0.94

0.94 ≤ cos(θμ reco) < 1.00
CC-INCLUSIVE: COMPARISON TO GENIE MODELS

Cross Section Measurement

$0 \leq \cos(\theta^\text{reco}_\mu) < 1$

$-1.00 \leq \cos(\theta^\text{reco}_\mu) < -0.50$

$-0.50 \leq \cos(\theta^\text{reco}_\mu) < 0.00$

$0.00 \leq \cos(\theta^\text{reco}_\mu) < 0.27$

$0.27 \leq \cos(\theta^\text{reco}_\mu) < 0.45$

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

$0.62 \leq \cos(\theta^\text{reco}_\mu) < 0.76$

$0.76 \leq \cos(\theta^\text{reco}_\mu) < 0.86$

$0.86 \leq \cos(\theta^\text{reco}_\mu) < 0.94$

$0.94 \leq \cos(\theta^\text{reco}_\mu) < 1.00$

Data (Stat. + Syst. Unc.)

Model

$\chi^2$/N_{bins}

GENIE v2+MEC

245.9/42

GENIE v3 (LFG, no RPA)

121.6/42

GENIE v3 (LFG, with RPA)

108.8/42

MicroBooNE 1.6e20 POT

GENIE v2.12.2 + Emp. MEC

GENIE v3.00.04 G18..., No RPA

GENIE v3.00.04 G1810a0211a

Syst. Unc.) ⊕ Data (Stat. Unc.)

Non-pion

Neutral pions

Charged pions
UPCOMING MEASUREMENTS

CC0π multi-proton measurements

- Pion-less measurements with protons are useful probes of nuclear effects
- Large disagreements between different (reasonable) models
- Because of FSI, on MicroBooNE → potentially large resonant contribution
SELECTING PROTONS

Compare dE/dx profile in last 30cm of track to proton Bethe-Bloch expectation

→ calculate $\chi^2$ to find tracks consistent with proton hypothesis
PROTON THRESHOLD

- LArTPCs have significantly lower thresholds than other detector technologies → measurement of lower-momentum protons than ever before

- Current MicroBooNE threshold 300 MeV/c
  → 47 MeV KE
  → 1.5 cm track

- Compare to other experiments:

**Current threshold limited by reconstruction** — expected to improve (ArgoNeuT: 21 MeV KE)
UPCOMING MEASUREMENTS

- CC0π2p, CC0πNp (N\geq 1)
- Selections described in MICROBOONE-NOTE-1056-PUB
- Further future: Single Transverse Variables
- All of these measurements will need to be interpreted using good resonance and FSI models
NEUTRAL PIONS

MicroBooNE
Non-pion
Neutral pions
Charged pions

$\pi^0$
\( \pi^0 \) IN MICROBOONE

- Photons (and electrons) produce showers in MicroBooNE

- Shower reconstruction is difficult: trade-off between completeness and purity (much more than track reconstruction) → direct impact on energy reconstruction

- Current approach: conservative to guard against cosmic charge being added to our showers

Low-energy photons appear more track like

→ low reconstruction efficiency

→ makes it difficult to identify both photons from a $\pi^0$

→ requiring that we reconstruct both $\pi^0$ photons limits statistics, and may sculpt phase space
Easier to select $\text{CC}\pi^0$ interactions than $\text{NC}\pi^0$ because muon gives us the interaction point

Excellent testing ground for shower energy and angle resolution → towards $\text{NC}\pi^0$ measurement

**Two-shower selection**
→ validate $\pi^0$ hypothesis by invariant diphoton mass

**Single-shower selection**
→ validate photon hypothesis
→ maximize statistics for cross section measurement
FINDING $\pi^0$s

Two-shower selection

- Select $\pi^0$ events by looking for two showers $\rightarrow$ two photons on top of CC-inclusive selection
- Convince ourselves that we really have found $\pi^0$s by calculating invariant mass of the two photons: if the photons come from a $\pi^0$ then should be $\sim \pi^0$ mass (135 MeV)
- Note: we do not cut on $\pi^0$ mass
CC$^{\pi^0}$: PHOTON CONVERSION

**Single-shower selection**

- Look at single photons passing CC-inclusive selection
- Measure mean conversion length to validate:
  1) that we have selected photons
  2) that we have the interaction vertex right
- ✔ Data agrees with simulation within uncertainties
CC$^\pi^0$ CROSS SECTION

- First ever CC$^\pi^0$ cross section measurement on argon
- Measurement in agreement with models within 1.2$\sigma$
- → current nuclear scaling consistent with our measurement

LOOKING FORWARD

- In the near future, plan to **update this measurement**:
  - Updated detector model and systematics
  - ~10x statistics
  - **Differential cross section** as a function of $\pi^0$ momentum and angle, muon momentum and angle
  - Main analyzer **Supraja Balasubramanian** (at this workshop!)
NC$\pi^0$: MEASUREMENTS ON ARGON

**NC$\pi^0$ ArgoNeuT measurement**

- ArgoNeuT: flux-integrated NC$\pi^0$ measurement [PRD 96, 012006 (2017)]

- Measure ratio of $\sigma(\text{NC}\pi^0)$ to $\sigma(\text{CC})$:
  - Good agreement with generators
  - Integrated result is slightly higher than previous results at lower energy
NC$\pi^0$: MEASUREMENTS ON ARGON

- Flux-integrated cross section measurement shows good agreement with generators

PRD 96, 012006 (2017)
**NCπ^0: MICROBOONE ANALYSIS**

- MicroBooNE photon-like LEE analysis will use π^0 sideband to constrain background.
- Have a fairly mature selection for two channels: 2\(\gamma 0p\), 2\(\gamma 1p\) (see A. Mogan, DPF 2019).
- Expect several hundred events in final selection with low background contamination: ~60% pure, currently largest background CCπ^0 (~45%).

**Signal Topologies**

- **2γ1p**
  - Vertex
  - Proton Track
  - Photon Showers

- **2γ0p**
  - Vertex
  - Photon Showers

A. Mogan, DPF 2019
Kirsty Duffy

**In progress**
(near future)

- **Run 5564**
- **Subrun 142**
- **Event 7127**

**March 23rd, 2016**

**MicroBooNE**

- **Non-pion**
- **Neutral pions**
- **Charged pions**
CHARGED PIONS
(I mostly mean $\pi^+$)

$\pi^\pm$
IDENTIFYING $\pi^+$

Separate charged pions from protons using deposited energy in track per unit length.
Separating **charged pions** from **muons** is harder → at our energies, dE/dx profile is $\sim$identical

So how can we distinguish charged pions from muons in a CC1π+ measurement?
OPTION 1: WE DON’T

- Simple selection: two tracks start at vertex, both inconsistent with being a proton → muon and charged pion candidates
- No further particle ID
- Limits the measurements you can make to just opening angle
- **We don’t plan to do this**
OPTION 2: TRACK LENGTH AND/OR CONTAINMENT

- We expect in CC1π⁺ interactions*:
  - >70% μ⁻ has higher momentum than π⁺
  - >90% π⁺ stops in detector

- We may consider this as a fallback if other methods don’t work (for reasons I’ll go into)

*GENIE v3.0.6, tune G18_10a_02_11a (Berger-Sehgal model, axial FF tuned to MiniBooNE)
OPTION 3: HADRONIC INTERACTIONS

MicroBooNE
Non-pion
Neutral pions
Charged pions

Slide source: Elena Gramellini, Fermilab Neutrino Seminar

LArIAT Data

Charge Exchange Candidate
LArIAT Data

π Prod Candidate
LArIAT Data

Elastic Scattering Candidate
LArIAT Data

Inelastic Scattering Candidate
LArIAT Data

Absorption Candidate (π -> 3p)
LArIAT Data

01/05/19
Kirsty Duffy

Elena Gramellini -- Fermilab
π⁺ INTERACTIONS

Roughly speaking, GENIE predicts π⁺ produced in MicroBooNE will fall in this energy range.
OPTION 3: HADRONIC INTERACTIONS

**LArIAT Data**

- Elastic Scattering Candidate
- Inelastic Scattering Candidate
- Charge Exchange Candidate
- \( \pi \) Prod Candidate
- Absorption Candidate (\( \pi \rightarrow 3p \))
OPTION 4: MICHEL ELECTRON

- GEANT4 predicts:
  - >90% of $\pi^+$ stop in detector
  - ~55% decay to produce a Michel electron (muon not visible) $\rightarrow$ ~50% with Michel electron > 5cm

- Look for $\pi^+$ by presence of Michel electron?
  - Pro: if we see a Michel electron, we know the pion has stopped $\rightarrow$ measure momentum using track length
  - Con: Efficiency loss of >50%

- Another con: **this isn’t a way to identify $\pi^+$ exclusively** — muons can also decay to produce Michel electrons! May be effective when combined with option 2 (track length), but model dependent? **We are considering this**
PUTTING IT ALL TOGETHER

Visible final states only ($\pi^+e^-$ length > 5 cm, proton momentum > 0.3 GeV/c)

According to GEANT simulation expect majority of what we see:

- $\pi^+$ stops, decays to visible Michel electron (with or without previously scattering)
- $\pi^+$ absorbed, produces one visible proton (with or without previously scattering)
- $\pi^+$ absorbed, produces multiple visible protons
- $\pi^+$ charge exchange: produces $\pi^0$ without previously scattering
RECONSTRUCTING $\pi^+$

- Charged pions can be difficult to reconstruct

  - Large amount of scattering: may be reconstructed as a shower, rather than a track

  - Secondary vertices often missed: pion and daughters can be merged

Figure from *Eur. Phys. J. C* (2018) 78: 82
A CATCH-22?

If a \( \pi^+ \) stops in the detector with a reconstructable Michel electron:

- ✔ We know the pion is at rest
- ✔ Can measure momentum accurately using length
- ✔ Likely fate for charged pions at MicroBooNE energies
- ✗ Cannot positively identify as a charged pion (i.e. not a muon)

If a \( \pi^+ \) interacts hadronically:

- ✔ Can positively identify as a charged pion (i.e. not a muon)
- ✗ More difficult to reconstruct correctly
- ✗ Cannot measure momentum accurately using length
- ✗ Less likely to happen at MicroBooNE energies (efficiency loss)
WHAT ABOUT $\pi^-$?

- I've focused on $\pi^+$ here because we plan to measure $\nu_\mu CC1 \pi^+$ production in MicroBooNE.

- $\pi^-$ are less of a focus for us, but will be more relevant for DUNE. They behave a little differently.

- Almost all $\pi^-$ are captured on Argon → can’t identify using scatters or Michel decays. Rely instead on looking for protons after absorption.

![Graph showing visible final states for different processes in MicroBooNE](image)
MEASUREMENTS ON ARGON

- ArgoNEUT: CC1 $\pi^\pm$ production Phys. Rev. D 98, 052002 (2018)

- Select two-track events: one matched to a track in MINOS (muon candidate)

- Select CC1 $\pi^\pm$ events using $dE/dx$ of pion candidate, event topology

- Overall purity 35.8% ($\nu$), 55.7% ($\bar{\nu}$)

- 337 selected $\nu$ events (285 $\bar{\nu}$)

Figure from T. Yang, NuInT 2017
MEASUREMENTS ON ARGON

$\nu_\mu$ CC $\pi^\pm$ ArgoNeuT measurement

MEASUREMENTS ON ARGON

$\nu_\mu$ CC $\pi^\pm$ ArgoNeuT measurement

**Resonant pion production model**
- GENIE, NEUT: Rein-Sehgal
- NuWro: $\Delta(1232)$ resonance only

**Nonresonant model**
- NEUT: Rein-Sehgal
- GENIE, NuWro: Bodek-Yang above resonance region, extrapolate smoothly to converge with resonance model at lower $W$

**FSI**
- NEUT, NuWro: Salcedo-Oset cascade
- GENIE: effective cascade model
- GiBUU: quantum-kinetic transport theory

**Paper conclusions**
- GiBUU: good agreement
- NuWro, NEUT: similar, higher than measured cross section
- GENIE: higher than other generators and measured cross sections (with reanalysis of bubble chamber data in EPJC (2016) 76: 474 points to GENIE’s nonresonant background prediction)

All predictions within 2\,$\sigma$ of measurement, except GENIE $\bar{\nu}$ (3.3\,$\sigma$)
MEASUREMENTS ON ARGON


- General agreement with Rein-Sehgal prediction (low statistics — select 24 $\nu$ and 30 $\bar{\nu}$ events, estimate $\sim 7 \pm 3$ signal events in each)
MICROBOONE ANALYSES

- **CC1 \( \pi^+ \) (inclusive) measurement**
  - Look for **one muon, one \( \pi^+ \), no showers (e/\( \gamma \)/\( \pi^0 \))**
  - (Preliminary) aim is for **differential measurement**: opening angle, muon momentum/angle, pion momentum/angle

- **CC-Coherent 1 \( \pi^+ \) measurement**
  - Look for **one muon, one \( \pi^+ \), no vertex activity**, very forward-going
  - Try to avoid cutting on \(|t| \) (squared 4-momentum transfer to nucleus) and measure — is that useful?
  - **CC1 \( \pi^+ \) will be significant background**: use above measurement and/or need good predictions

In progress (near future)
MICROBOONE ANALYSES

- **CClπ⁺1p**
  - More exclusive topology: reconstruct $\Delta^{++}$ resonance
  - **What interesting measurements can/should we make with this topology?**

- **CC-multiπ**
  - Interesting for DUNE, who will sit at RES-DIS transition region
  - May be difficult in MicroBooNE — expect very few DIS events at our energies
  - SBND may be able to make measurements (same flux, but $\sim30\times$ statistics) — **how interesting/necessary is that measurement?**
  - A question for you: **what other measurements would you like to see from MicroBooNE?**
SUMMARY

MicroBooNE needs to understand resonant interactions (and FSI) for the success of our own physics program: especially $\pi^0$ backgrounds and RES+FSI part of signal

Our measurements can help, as well as provide input to SBN/DUNE

- Current measurements: CCincl, CC$\pi^0$
- In progress: CC$2p$, CC$Np$ ($N>=1$), CC$\pi^0$ differential, NC$\pi^0$, CC$\pi^+$, CC-Coh$\pi^+$
- Coming later: CC$Np$ STV, CC$\pi^+1p$, CCmulti$\pi$

Appreciate input from the community on the most interesting measurements to make

What do we need to make precise measurements?

- Good predictions of $\pi-$Argon cross sections (FSI, interactions in detector)
- Good models for neutrino interactions (particularly CCQE, MEC, RES, FSI) with realistic and believable uncertainties
neutralino interacts with the argon inside the TPC volume and produces secondary particles

E = 273 V/cm
MicroBooNE

LIQUID ARGON TPC

(Anne Schukraft)

Liquid Argon TPC

Cathode

Anode

E = 273 V/cm

Secondary particles produce ionization electrons

ν

E = 500 V/cm

Ionization e⁻

Secondary particles produce ionization electrons

MicroBooNE Non-pion Neutral pions Charged pions

Kirsty Duffy 66
**LIQUID ARGON TPC**

(Electrons drift towards the anode)

*MicroBooNE*  
Non-pion  
Neutral pions  
Charged pions

These electrons drift towards the anode

**Cathode**

**Anode**

$E = 273\text{V/cm}$
LIQUID ARGON TPC

(Electrons arrive at anode)

Ionization $e^-$

Cathode

$E = 500 \text{ V/cm}$

$\nu$

$E = 273 \text{ V/cm}$

Electrons arrive at anode
LIQUID ARGON TPC

(Aanne Schukraft)

The pattern is recorded on a set of closely spaced wires

\[ E = 273 \text{V/cm} \]
LIQUID ARGON TPC

(Anne Schukraft)

Flash of scintillation light at time of neutrino interaction

Detected by PMTs behind Anode plane to get t0 → time of interaction → start time for electron drift

Nuclide interacts with the argon inside the TPC volume and produces secondary particles.

MicroBooNE
Non-pion  Neutral pions  Charged pions

E = 273 V/cm
LIQUID ARGON TPC

(E = 273V/cm)

Cathode

Ionization e-

wire planes

get a 3D picture
FERMILAB’S NEUTRINO BEAMS

Booster Neutrino Beam (BNB): 463m

- $>99\% \nu_\mu/\overline{\nu}_\mu$ at peak
- $\langle E_\nu \rangle = 850$ MeV

NuMI Neutrino Beam (NuMI): ~680m

- $8^\circ$ off axis $\rightarrow 5\% \nu_e$

Image: G. Zeller
COSMIC REJECTION

Large amount of cosmic contamination because of 2.3ms drift time

Figure from M. del Tutto

arXiv: 1905.09694
[hep-ex]
Accepted to PRL

Cross section results
COSMIC REJECTION

- **Check if in time with beam flash**

Figure from M. del Tutto

arXiv: 1905.09694
[hep-ex]
Accepted to PRL
COSMIC REJECTION

- Check if in time with beam flash
- Check if compatible with beam flash in terms of position and light intensity

Figure from M. del Tutto
COSMIC REJECTION

- Check if in time with beam flash
- Check if compatible with beam flash in terms of position and light intensity
- Check if track goes all the way through the detector

Figure from M. del Tutto

Neutrinos	MicroBooNE	Cross section results	What's next?

Accepted to PRL

Neutrinos MicroBooNE Cross section results What’s next?

arXiv: 1905.09694 [hep-ex] Accepted to PRL
COSMIC REJECTION

- Check if in time with beam flash
- Check if compatible with beam flash in terms of position and light intensity
- Check if track goes all the way through the detector
- Check if track is a cosmic crossing anode/cathode (known \( t_0 \))

Figure from M. del Tutto

arXiv: 1905.09694
[hep-ex]
Accepted to PRL

Neutrinos  MicroBooNE  Cross section results  What’s next?
COSMIC REJECTION

- Check if in time with beam flash
- Check if compatible with beam flash in terms of position and light intensity
- Check if track goes all the way through the detector
- Check if track is a cosmic crossing anode/cathode (known t0)
- Check for Bragg peak/decay electron indicating muon enters and stops

Figure from M. del Tutto

Accepted to PRL

Kirsty Duffy
SELECTING CC EVENTS

- Charged-current events selected by presence of muon
- Longest track in event is muon candidate → use $dQ/dx$ and track length to reject protons
## UNCERTAINTIES

Calculate uncertainty on total CC-inclusive cross section

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Relative uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam flux</td>
<td>12.4</td>
</tr>
<tr>
<td>Cross section modeling</td>
<td>3.9</td>
</tr>
<tr>
<td>Detector response</td>
<td>16.2</td>
</tr>
<tr>
<td>Dirt background</td>
<td>10.9</td>
</tr>
<tr>
<td>Cosmic ray background</td>
<td>4.2</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.2</td>
</tr>
<tr>
<td>Stat</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>23.8</td>
</tr>
</tbody>
</table>

- Flux uncertainty ~12%
- Inclusive measurement $\rightarrow$ not strongly dependent on cross section model
- Total uncertainty dominated by detector response

INDUCED CHARGE

- Detector response → 16% uncertainty on total cross section
- Largest single contribution: 13% due to modeling of **induced charge**
  - MC assumes drift electrons cause signal on only one wire
  - Not true! Nearby wires see **charge by induction**
  - Because of this, **detector response depends on track angle**
  - Easy to fix — include in simulation and reconstruction!

**Neutrinos**

**MicroBooNE**

**Cross section results**

**What’s next?**

Drifting electron

Charge **collected** on wire

\[ \varepsilon = -\frac{d\phi_B}{dt} = IR \]

Signal **induced** on neighbouring wires
-1.00 \leq \cos(\theta_{\mu}^{\text{reco}}) < -0.50

MicroBooNE 1.6e20 POT

-0.50 \leq \cos(\theta_{\mu}^{\text{reco}}) < 0.00

-1.00 \leq \cos(\theta_{\mu}^{\text{reco}}) < 0.00

0.00 \leq \cos(\theta_{\mu}^{\text{reco}}) < 0.27

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

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

0.62 \leq \cos(\theta_{\mu}^{\text{reco}}) < 0.76

0.76 \leq \cos(\theta_{\mu}^{\text{reco}}) < 0.86

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

0.94 \leq \cos(\theta_{\mu}^{\text{reco}}) < 1.00

GENIE v2.12.2 + Emp. MEC
GENIE Default CC QE
GENIE Default CC MEC
GENIE Default CC RES
GENIE Default CC DIS
Data (Stat. \oplus Syst. Unc.)
FINDING PI0S

- Measure electron and photon energies in the same way (energy of the shower)
- $\pi^0$ mass peak $\rightarrow$ shower energy resolution
- **Good news for DUNE!** LAr technology is already doing better than we thought we needed
NCPI0: MEASUREMENTS ON ARGON

- ArgoNeuT: flux-integrated NCπ^0 measurement PRD 96, 012006 (2017)

- Select events with:
  1) No tracks identified as μ± or e±
  2) Two showers, with dE/dx consistent with photon (identified by combination of automated reconstruction and hand-scanning)

- Final selection: 64% purity, 123 data events selected

- Confirm NCπ^0 hypothesis by reconstructing diphoton mass
OPTION 3: MCS

- Multiple Coulomb Scattering: charged particle traversing a medium undergoes electromagnetic scattering off atomic nuclei

- Previously used (in neutrino physics) in emulsion detectors (e.g. DONuT, OPERA) and ICARUS to determine particle momentum. Improved model implemented in MicroBooNE: JINST 12 P10010 (2017)

- RMS of scattering angle \( \sigma \) (perpendicular to beam direction) related to momentum \( p \):

\[
\sigma = \frac{S_2}{p\beta c} z_e \sqrt{\frac{l}{X_0}} \left[ 1 + c \cdot \ln \left( \frac{l}{X_0} \right) \right]
\]
OPTION 3: MCS

- MCS algorithm splits tracks into segments and measures scattering angles. Could we use that to distinguish $\pi^+$ from muons?

- We expect $\pi^+$ to scatter more:
  - Muons can scatter electromagnetically on Argon nuclei
  - Pions can scatter electromagnetically and hadronically on Argon nuclei

- May be a possibility, but current implementation does not provide enough separation:
  - Most reliable on long tracks — segment length: 14cm, ~radiation length
ARGONEUT CC1π±

- According to GENIE, ~50/50 RES/DIS interaction channel (figure from A. Mastbaum)