MicroBooNE Cross Section Results

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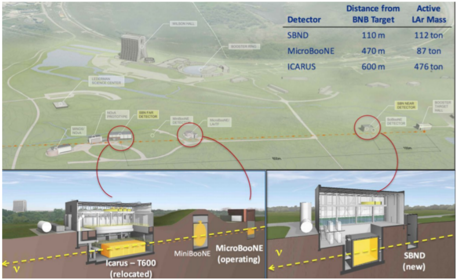
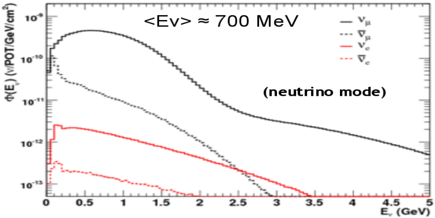
The SBN program at Fermilab:

- Three LArTPC detectors on same beamline:
  - SBND: Near detector, in installation stage, expected data taking in 2020.
  - **MicroBooNE:** running now, single detector data.

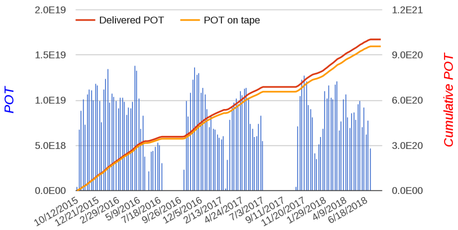
    Goal:
    - Investigate MiniBooNE low-energy excess
    - Cross section measurements of ν-Ar interaction
    - R&D for Deep Underground Neutrino Experiment(DUNE)
  - ICARUS: Far detector - moved from CERN to FNAL, expected data taking in 2019.
- ν-Ar cross section measurements.
- Sterile neutrino search.
- Crucial for understanding DUNE.

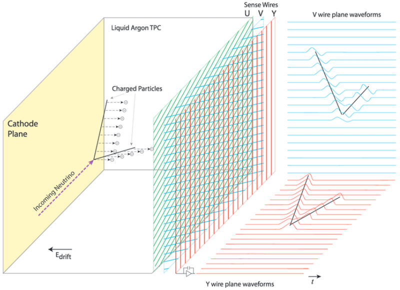




MicroBooNE Detector

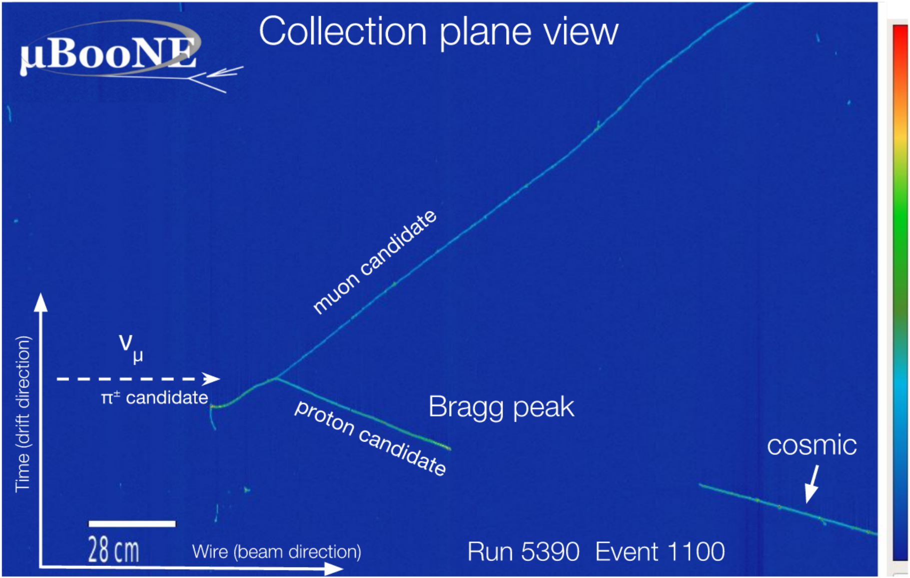
- Sits in BNB [1]
  - Pure source of ν_μ
  - Average Ev<1GeV
  - Benefits from 10+ years validation from MiniBooNE
  - 10^{21} POT delivered by the end of July 2018





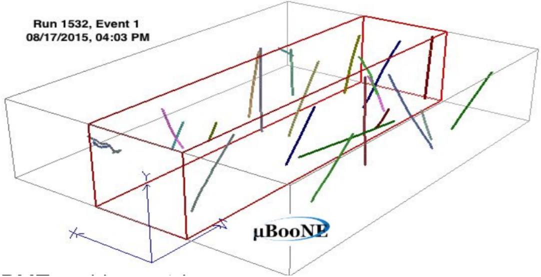
- Has three wire planes [5]:
  - 3mm wire spacing gives us impeccable spatial resolution
  - Final plane collects charge to give calorimetric measurements
- Triggered by an array of PMTs
- Collected beam data since October 2015

Candidate Neutrino Event Display



Cosmic in MicroBooNE

- Near surface location→
  Big Cosmic Backgrounds



- On-beam data: Coincidence of PMT signal with neutrino beam spill
- Off-beam data: Same PMT condition with fake beam spill

Challenge for MicroBooNE analysis:

1. 90% of the triggered events have only cosmic activity
2. Remaining 10% events have both cosmics and neutrinos are in same event($\sim$ 20 cosmics and 1 neutrino).
3. Half of the neutrino interactions occur outside the TPC

On-going and future Measurements

Charged particle multiplicity(submitted to PRD)

- Good for testing nuclear models, and provide broad constraints on reaction mechanisms, epecially FSI.

ν_μ **CC inclusive**

- Provides broad input on nuclear models for theory; Easy to compare with other experiment(clear signature)

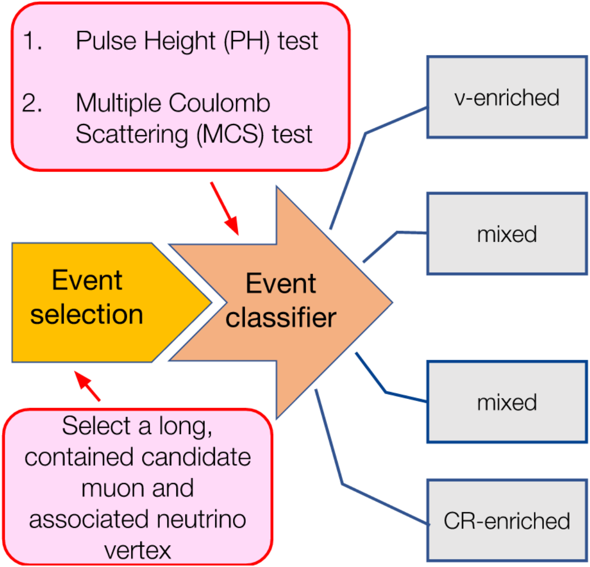
CC π^0 Cross Section

- For testing shower reconstruction performances and energy resolution

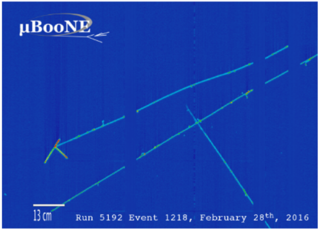
ν_μ **CCNp(N>0) Cross Section**

- Detailed test of nuclear models, CCQE and other reaction mechanism.
- Proton spectra with low threshold gives new insightes into FSI.
- Correlations between muon and protons provide more detailed information

Charged Particle Multiplicity(CPM)

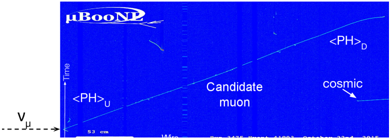


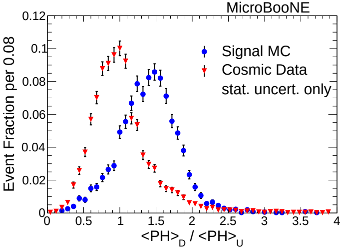
- Perform a likelihood fit using the number of events in each of these four categories to extract the number of neutrinos for CPM distribution [3].



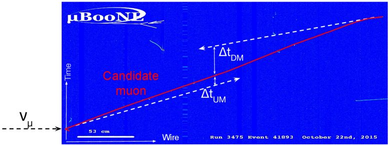
Charged Particle Multiplicity(CPM)

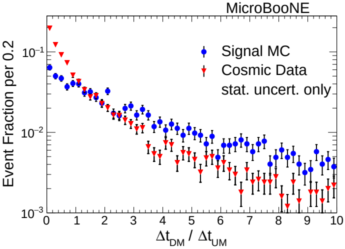
- Rate of energy loss increase along the track from upstream to downstream end.



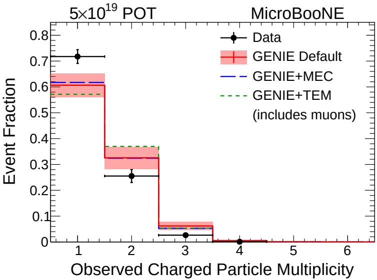


- Scattering is more pronounced along the downstream end of the track as the momentum decreases.





Charged Particle Multiplicity(CPM)

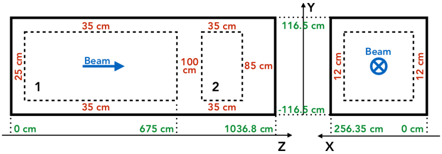


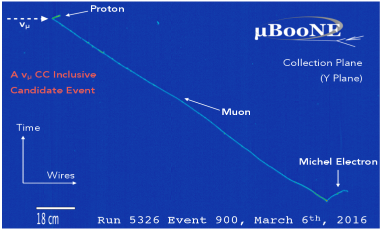
- Data favors lower multiplicity compared to all three simulations.
- Simulation agrees with data at the 2σ level.
- No efficiency correction and unfolding.
- MEC: Meson exchange current; TEM: Transverse enhancement model.

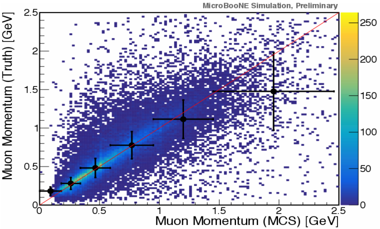
CC inclusive Event Selection and Cross Section Measurement

Event Selection:

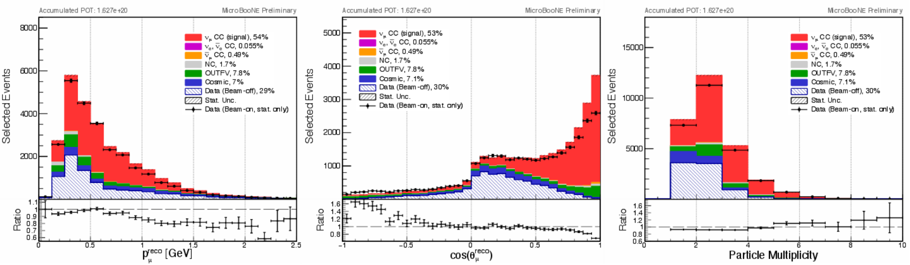
- Loose coincidence between scintillation light and beam(called flash) identifies neutrino events.
- A PMT-by-PMT matching is run between the flash and all reconstructed TPC interactions in order to select the best one(if any).
- Quality cuts ensure the event is well reconstructed.
- The candidate muon track must have a dQdx profile compatible with a minimum ionizing muon.
- The reconstructed vertex has to be in the fiducial Volume.







CC inclusive Event Selection and Cross Section Measurement

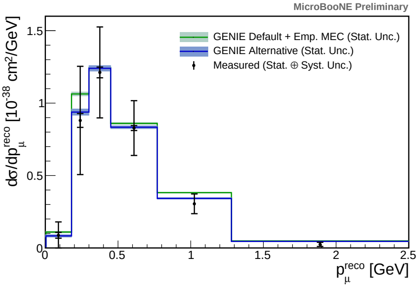


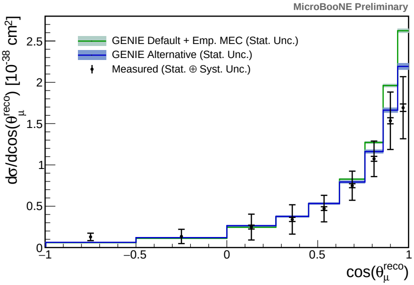
Error Source	Relative Unc.
Beam Flux	11.9%
Cross Section	3.6%
Detector Response	18.8 %
POT Counting	2%
Cosmic(out-of-time)	6.9%
Cosmic(in-time)	1.1%
Beam Timing Jitter	4%

- θ: angle w.r.t the beam line
- Particle Multiplicity: no. of reconstructed particles from the neutrino vertex.
- Data excess at $\cos(\theta)$<-0.5 is due to neutrino events interacting outside the cryostat. Currently not in the simulation, we are working on this.

The largest uncertainty comes from detector response due to the simulation of induced charge on neighboring wires, which will cause the migration of the deposited charge on one wire to the neighboring wires.

CC inclusive Event Selection and Cross Section Measurement





- Two GENIE models sets were used in the analysis: Default and Alternative.
- Differential cross sections with respect to muons momentum and $\cos\theta_\mu$ shows agreements in both these two model sets.
- Working on the double differential cross sections.

Model element	Default	Alternative
Nuclear Model	Bodek-Ritchie Fermi Gas	Local Fermi Gas
Quasi-elastic	Llevellyn-Smith	Nieves
MEC	Empirical	Nieves
Resonant	Rein-Sehgal	Berger-Sehgal
Coherent	Rein-Sehgal	Berger-Sehgal
FSI	hA	hA2014

MEC: Meson Exchange Current.
Nieves Model accounts for long range nuclear (RPA) correlations, final states interaction (FSI) and Coulomb corrections.

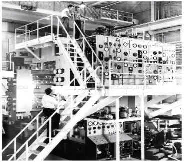
Published ν_μ CC1π^0 Measurements

(A = 1,2)

<u>Hydrogen</u>

BNL 7’

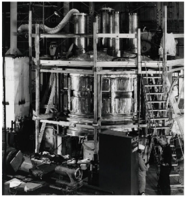
Phys. Rev. D 19, 2521 (1979)



ANL 12’

Phys. Rev. D 25, 1161 (1982)

Phys. Rev. D 34, 2554 (1986)



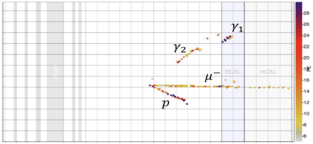
(A = 12)

<u>Carbon</u>

Minerva

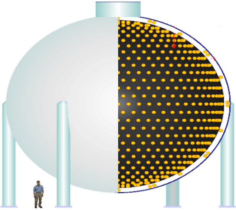
Physics Letters B 749, 130 (2015)

Phys. Rev. D96, 072003 (2017)



MiniBooNE

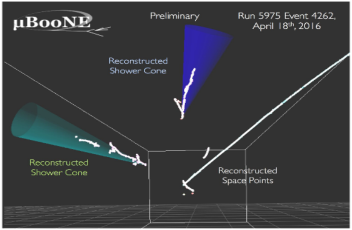
Phys. Rev. D 83, 052009 (2011)



(A = 40)

<u>Argon</u>

MicroBooNE



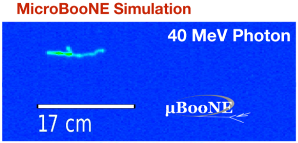
The final stage will be analyzing is

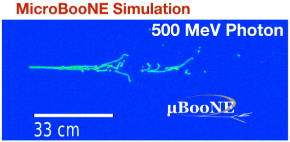
$$\nu_\mu + \mathbf{Ar} \rightarrow \mu + \mathbf{1}\pi^0 + \mathbf{X}$$

Scaling from Carbon to argon we expect pion obsorption effects ∼2x strong(default GENIE scales as $A^{2/3}$)

CC π^0 Cross Section Measurement

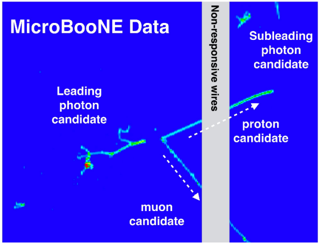
Challenging topology: Requires both track and low energy shower reconstruction:

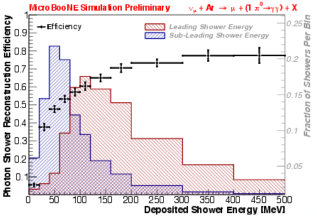




For shower reconstruction:

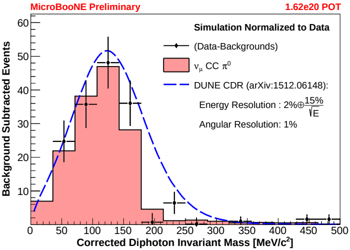
- Need guards against cosmic charge being added to our showers
  – Conservative approach sacrifices charge completeness to allow for charge purity.
- Remove track-like hits (local linearity)
- Remaining charge is clustered using OpenCV.
- First demonstration of fully automated shower reconstruction being used to analyze LArTPC





CC π^0 event selection and cross section measurement

- **Two shower selection**$\rightarrow$ Validate π^0 Hypothesis.

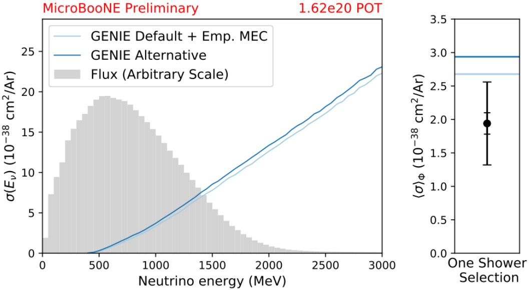


- We are achieving a better energy resolution in data than DUNE CDR assumes.

Signal shower selection$\rightarrow$ **Total Flux Integrated Cross section**

$$< \sigma^{\nu_\mu \, CC\pi^0} >_\Phi = (1.94 \pm 0.16[stat.] \pm 0.60[syst.]) \times 10^{-38} \frac{cm^2}{Ar}$$

Source	1σ Uncertainty
GENIE	17.2
Detector Simulation	21.1%
Flux	15.5%

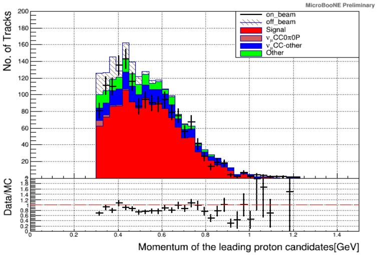


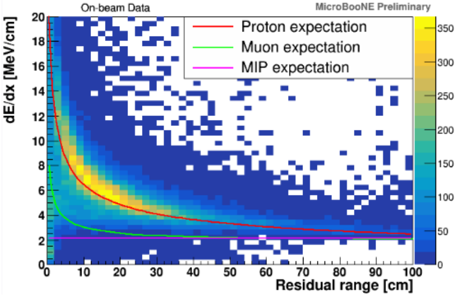
CC 0 pion N proton Analysis

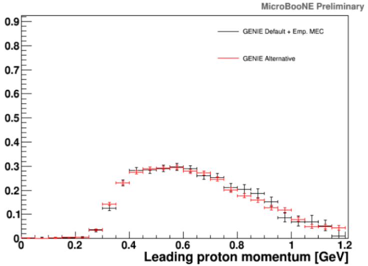
A future cross section measurement from MicroBooNE will be a ν_μ CC 0 pion with protons in the final state

- Tell us about nuclear physics:
  - final and initial state interactions
  - nucleon correlations
- Observing the hadronic side of the interaction is going to be crucial for precision cross section and oscillation measurements because hadrons carry a significant fraction of the initial neutrino energy.
- The thresholds of traditional experiments are around 100 MeV kinetic energy, for example in T2K (ARXIV:1802.05078) and MINERvA (JPSCP.12.010016). We can go down to lower thresholds with LArTPCs

CC 0 pion N proton analysis



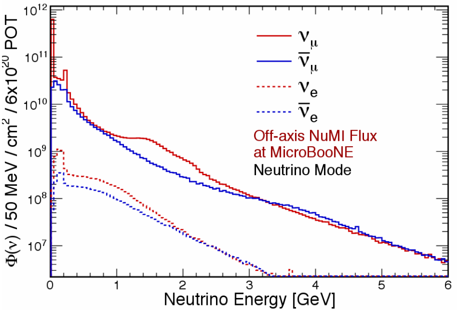




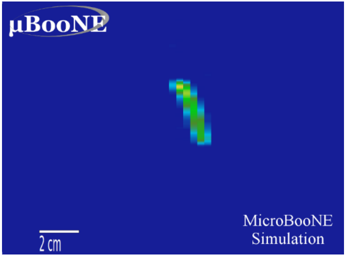
- Proton momentum threshold around 300 MeV/c - 2cm or 43 MeV kinetic energy.
- High energy proton inefficiency due to containment requirement and hadronic reinteractions

Other on-going physics analysis:

- ν_e cross section with NuMI
  — The figure below shows the NuMI flux distributions. A lot of ν_e compared to BNB is good for the ν_e cross section measurement.



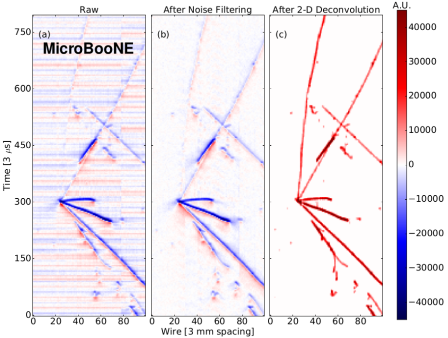
- NC-elastic
  - The signal for NC elastic scattering is a single proton track.
  - Used a gradient-boosted decision trees to identify protons based on reconstructed tracks.



- CC1pi/Coherent is in progress

Coming Soon

- All results shown here use first year of data
- newer data has:
  - Cosmic Tagger to improve the cosmic rejection.
  - Updated electronics boards that have better noise filtering, which will improve our noise filtering [2].
  - Large systematics dominated by dectector reponse - simulation and better handling (2D deconvolution [4]) of induced charge on the way!



Summary

- SBN at FNAL: MicroBooNE is taking data, ICARUS has arrived at FNAL, SBND under construction.
- First cross section results presented with 1.6e20 POT of data
- MicroBooNE has $\sim$ 1.00e21 POT still to analyse - very high statistics measurements expected in future!
- Many analysis improvements in development.

References

[1] A.-A. et al.
Neutrino flux prediction at miniboone.
Phys.Rev.D, 79(072002), 2009.

[2] C. et al.
Noise characterization and filtering in the microboone liquid argon tpc.
Journal of Instrumentation, 12:P08003, 2017.

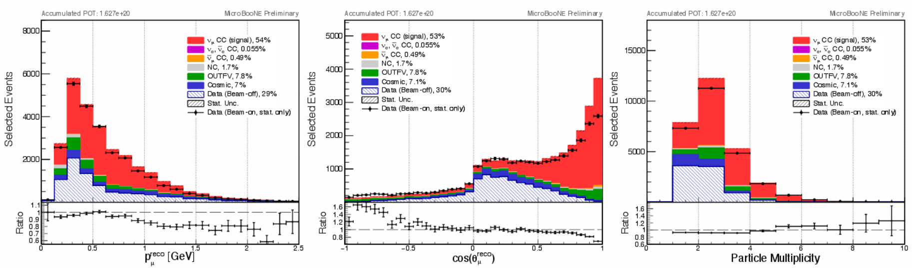
[3] C. et al.
Comparison of ν_μ-ar multiplicity distributions observed by microboone to genie model predictions.
arXiv:1805.06887, 2018.

[4] C. et al.
Ionization electron signal processing in single phase lartpcs.
Journal of Instrumentation, 13:P07006, 2018.

[5] R. et al.
Design and construction of the microboone detector.
Journal of Instrumentation, 12, 2017.

Backup Slides!

CC inclusive event selection and cross section measurement



Error Source	Method	Relative Unc.
Beam Flux	multism variations	11.9%
Cross Section	multism variations	3.6%
Detector Response	unism variations	18.8 %
POT Counting	Toroids resolution	2%
Cosmic(out-of-time)	MC+Data Overlay	6.9%
Cosmic(in-time)	Off-beam statistics	1.1%
Beam Timing Jitter	On- minus off-beam flashes	4%

The largest uncertainty comes from detector response due to the simulation of induced charge on neighboring wires, which will cause the migration of the deposited charge on one wire to the neighboring wires.

- θ: angle w.r.t the beam line
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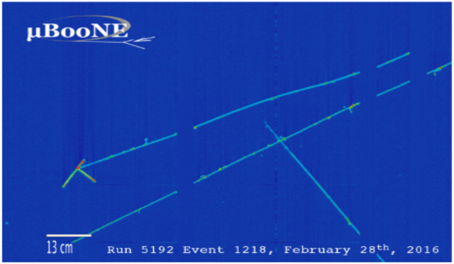
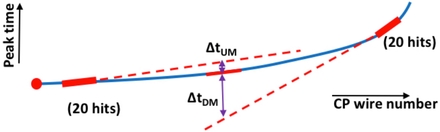
Charged Particle Multiplicity(CPM)





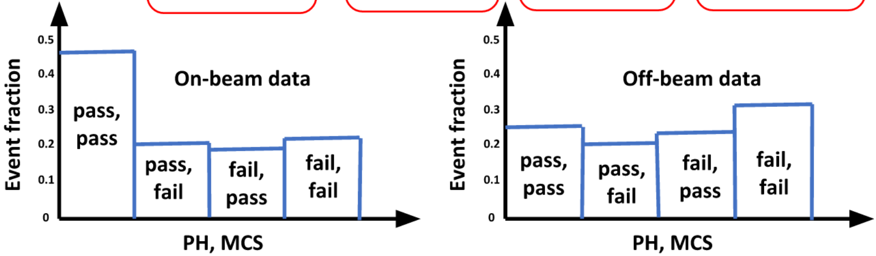
Event Selection:

- Requires an scintillator light detected within the 1.6μs beam window and the summed light collected by the PMT exceed 50PE.
- Requires an event with vertex locate within 80cm in z of the PMT-reconstructed position of an optical flash.
- Fiducial Volume Cut performed to the vertex(10cm from the border of the active volume in x and z, 20cm from the border of the active volume in y).
- Muon Candidate fully contained in FV.
- The longest track in an event starting 46 cm below the TPC top surface.
- Start of the longest track less than 3cm from vertex.
- Events with at least 80 collection plane hits.
- Truncated mean pulse height(PH) on collection plane $< PH >_{U}$ and Multiple Coulomb Scattering test(Δt_{UM}) were performed to further separate the signal and background.

The figure on the bottom left shows Δt_{UM} distribution which is used for the MCS test. It is defined as the difference between the hit time predicted at the geometric center on the track, to the time predicted at the geometric center of the track by the projection of L_U from the beginning of the track.

CPM: Signal extraction method

PH, MCS= (pass, pass) v-enriched | (pass, fail) mixed | (fail, pass) mixed | (fail, fail) CR-enriched

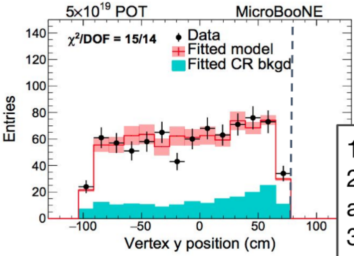


- To get to CPM, we perform likelihood fit multiplicity bin by bin to extract the number of on-beam neutrinos

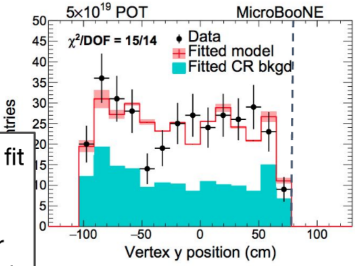
Nearly model independent method

CPM: Post-Fit Vertex Validation

ν-enriched sample

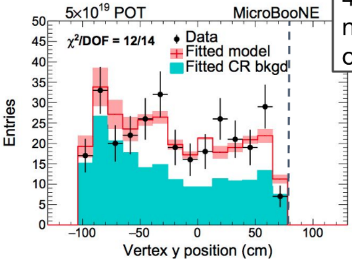


Mixed sample

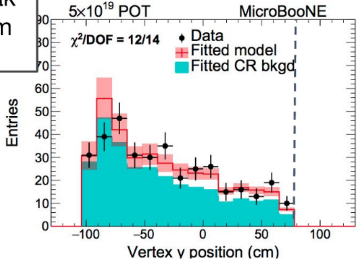


1. Validation of fit
2. Good shape agreement
3. Efficiency for selecting ν is flat
4. cosmics peak near the bottom of TPC

Mixed sample



CR-enriched sample



CPM: Post-Fit Vertex Validation

- The most comprehensive test of GENIE
  - 40 distributions in the paper
- Quantities
  - track/vertex positions (in x,y,z coordinates)
  - track length and angles (polar, azimuthal)
- All categories
  - ν-enriched distributions
  - Mixed distributions
  - CR-enriched distributions
- Multiplicities
  - All multiplicities
  - Multiplicity 1, 2, and 3 distributions
- Models
  - GENIE default
  - GENIE+MEC
  - GENIE+TEM

Some ν-enriched distributions are on the next slides

- **Good shape agreement in all distributions**
- **Can't distinguish GENIE models at this stage**

CPM paper:
https://arxiv.org/abs/1805.06887
Submitted to PRD

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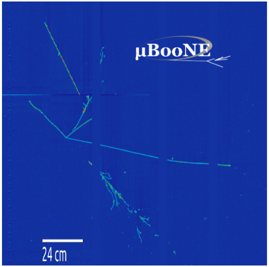
CC π^0 Cross Section Measurement



Shower Reconstruction:

Given that most subleading showers are with very low energy, we use events with at least one photon maximizes statistics in the calculation of the cross section.

Event Selection

- A ν_μ induced μ is selected if its deposited charge is consistent with the spatial distribution of light collected on the PMT array during the trigger and has a length, L, greater than 15 cm.
- one of the candidate muon track end points to be displaced less than 3 cm from a 3D reconstructed vertex.
- The vertex to be within a fiducial volume (10cm from the border of the active volume in x and z, 20cm from the border of the active volume in y).
- All other tracks with end-points within 3cm of the vertex are considered to have come from the candidate neutrino interaction point.
- Reject cosmic backgrounds by employing multiplicity-dependent cut(more details can be found in MicroBooNE-Note-1032-PUB).

Signle Shower Reconstruction

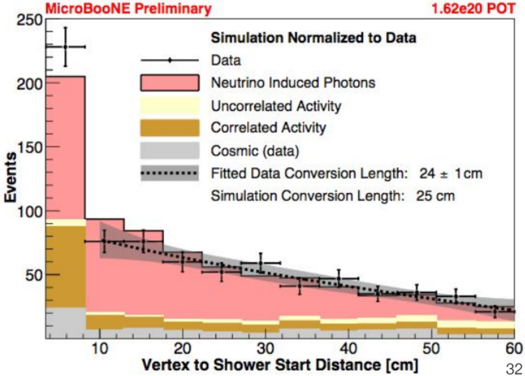
- Attempt to match reconstructed showers back to our interaction vertex:
  - Convert near the vertex
  - Backward projection has a small distance of closest approach to the vertex
- Use the mean free path length to validate our photon hypothesis
  - **Measured length in data and simulation agree within uncertainties**

One Shower Selection

Efficiency: 17%
Purity: 53%

771 Events

A. Hackenburg, Yale U., Ph.D. Thesis



J. Zennamo, Fermilab

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$\mathrm{CC}\pi^0$: ν_μ Interaction Model Uncertainties

- 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 independently varied $\pm 1\sigma$ and the cross section is remeasured

$$\langle \sigma^{\nu_\mu \mathrm{CC}\pi^0} \rangle_\Phi = \frac{N - B^C - B^{sim}}{\epsilon T \Phi}$$

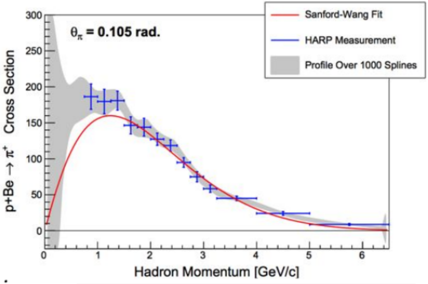
Backgrounds are modeled directly from GENIE simulation

Backgrounds are dominated by resonant events that GENIE assigns large uncertainties

Even though the efficiency is derived from the simulation it is less sensitive to these uncertainties

Together these are a 17% overall uncertainty

$CC\pi^0$: ν_μ Flux Uncertainties



Leverage the 10+ years of MiniBooNE work by using the flux uncertainties derived for their final analyses[1]

$$\langle \sigma^{\nu_\mu CC\pi^0} \rangle_\Phi = \frac{N - B^C - B^{sim}}{\epsilon T \Phi}$$

Normalization shifts impact background estimates which tend to come from higher energy neutrinos

Integrate over full flux range at the lowest energies the flux becomes very uncertain

Together these are a 16% overall uncertainty

$CC\pi^0$: ν_μ Detector Simulation Uncertainties

- Pursued a conservative estimate of many effects by creating separate MC sets with modified detector simulation
  - Microphysics of charge/light production and transport to readout
  - Simulated detector response
- Contribution from simulated cosmics also assigned an uncertainty

Future analyses will benefit from ongoing efforts to measure these in-situ and correct them via calibrations

$$\langle \sigma^{\nu_\mu CC\pi^0} \rangle_\Phi = \frac{N - B^C - B^{sim}}{\epsilon T \Phi}$$

Leads to more/fewer real photon backgrounds or mistakenly reconstructing tracks as showers

Certain variations impact track reconstruction modifying preselection efficiency

These tend to be second order

Together these are a 21% overall uncertainty

$CC\pi^0$: Flux-integrated Total Cross Section

With our validated single shower selection...

Data Events
Selected single shower events from on-beam data
N = 771 events

Cosmic Backgrounds
Background taken from off-beam data
B^c = 87 events

Neutrino Backgrounds
Backgrounds modeled by GENIE simulation
B^{sim} = 347 events

$$\langle \sigma^{\nu_\mu CC\pi^0} \rangle_\Phi = \frac{N - B^C - B^{sim}}{\epsilon T \Phi}$$

Signal Efficiency
Efficiency is estimated from simulation
ε = 17%

Number of Targets
We have measured contaminants to be <1ppm,

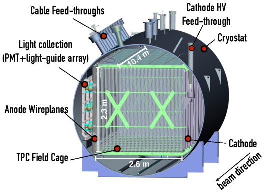
Treat full volume as pure argon

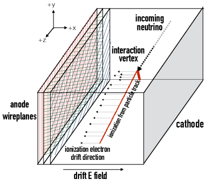
Integrated Flux
Integrate ν_μ flux over full range

MicroBooNE Detector

Physics goals:

- Investigate MiniBooNE low-energy excess
- Cross section measurements of ν-Argon interaction
- R&D for Deep Underground Neutrino Experiment(DUNE)





About MicroBooNE Detector

- LArTPC=Liquid Argon Time Projection Chamber-Non-evacuated liquid argon fill
- LArTPC with 85 ton active mass
- Near-surface operation, cosmic removal becomes very important.
- UV laser calibration system, improtant for space charge effect.
- 32 eight-inch PMTs for scintillation light (fast)
- 10.4 m $\times$ 2.6 m $\times$ 2.3 m TPC (Cathode Voltage:70 kV; E-field:273 V/cm)

Three anode wire planes

- 2 induction, 1 collection
- 3mm wire pitch
- 3mm wire plane spacing