Current Neutrino Experiments

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Fermilab Institutional Review
June 6-9, 2011

with help from:

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U.S. DEPARTMENT OF ENERGY

Fermilab

Introduction

Recently completed and on-going experiments in the Fermilab neutrino program have provided a wealth of neutrino interaction measurements, both for oscillation and neutrino cross sections.

- Booster Neutrino Beamline

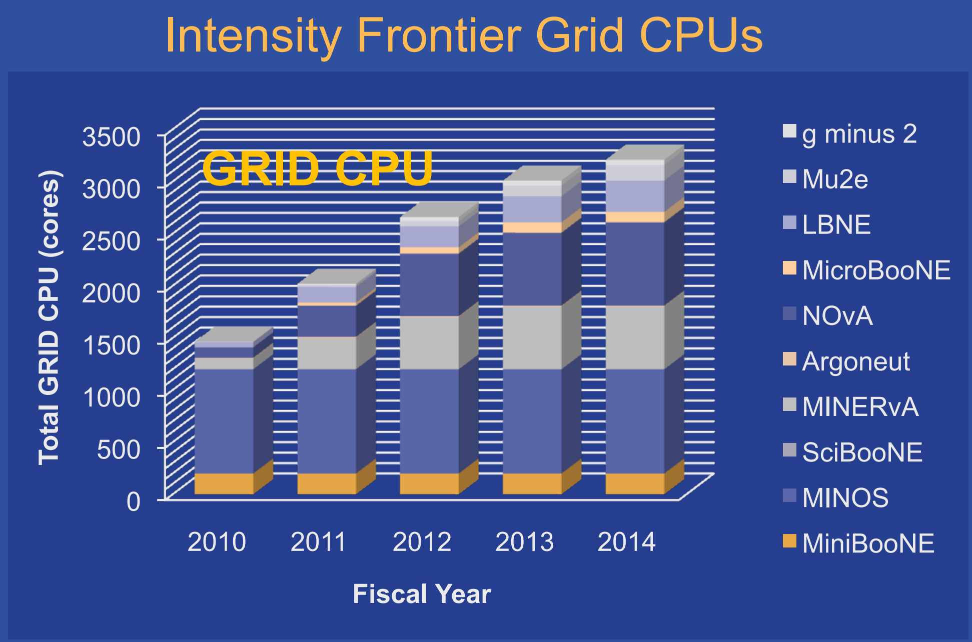
  SciBooNE, MiniBooNE,NOνA

- NuMI beamline

  MINERνA, MINOS, ArgoNeuT, NOνA

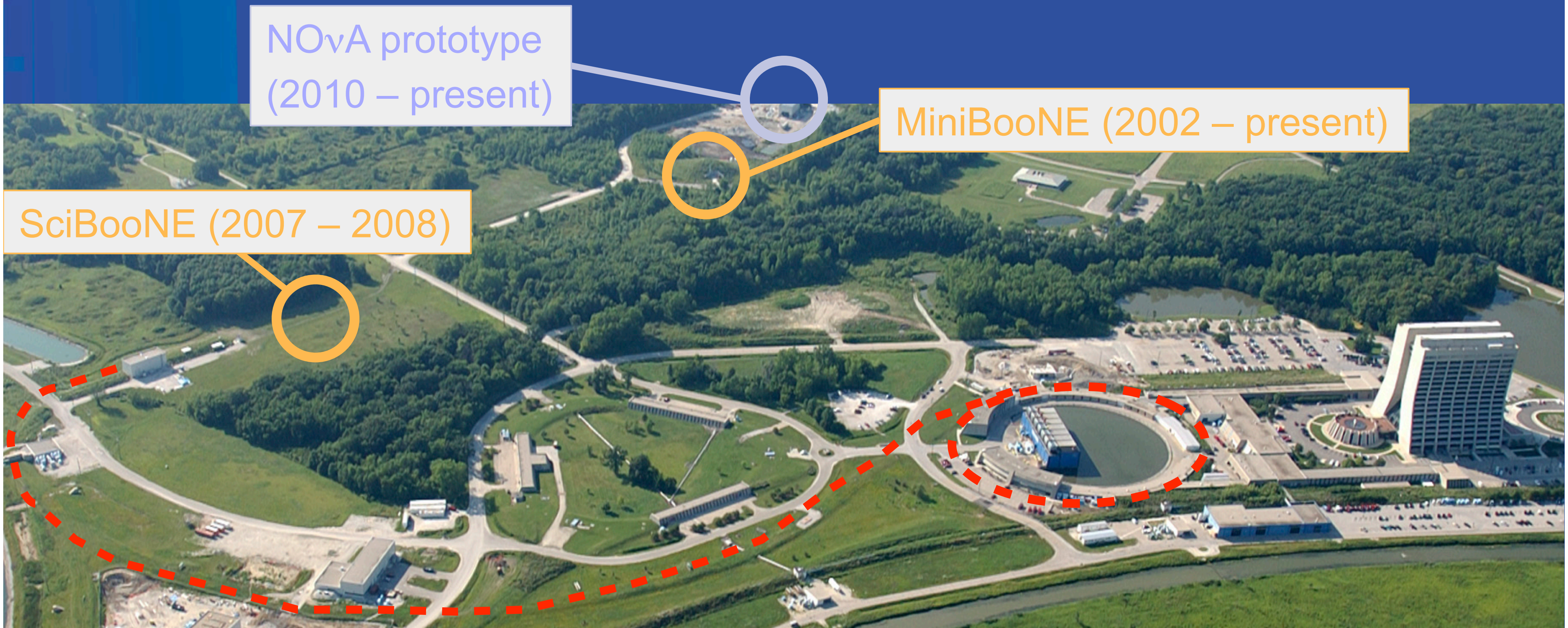
The entirety of the future neutrino program builds upon knowledge gained through operation of these experiments.

Computing Resources



- Computing usage by Intensity Frontier experiments steadily increasing
- None of the physics results shown today would have been possible without these resources

Booster Neutrino Beamline



MiniBooNE

- 54 collaborators (anti-ν run)
  15 institutions, 2 countries

- 11 FNAL personnel – ~3 FTEs
  - S. Brice (co-spokesperson $\bar{\nu}$ run)
  - C. Polly (analysis co-coordinator)
  - S. Zeller (analysis co-coordinator)
  - R. Stefanski (timing analysis, retired)
  - T. Kobilarcik (operations meeting coordinator, BNB expert)
  - D. Perevalov (RA, AEM presentations)
  - B. Brown, R. Ford, F. Garcia, B. Marsh, C. Moore (shifts)

MiniBooNE Physics Goals and Recent Publications

20 publications (8 in 2010-2011)

- ν_e and $\bar{\nu}_e$ appearance
  - "Event Excess in the MiniBooNE Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations," Phys. Rev. Lett. 105,181801 (2010)
- ν_μ and $\bar{\nu}_\mu$ disappearance
- ν_μ and $\bar{\nu}_\mu$ cross section measurements
  - "Measurement of neutrino-induced charged-current charged pion production cross sections on mineral oil at E_ν ~1 GeV," Phys. Rev. D83, 052007 (2011)
  - "Measurement of ν_μ-induced charged-current neutral pion production cross sections on mineral oil at E_ν from 0.5-2.0 GeV," Phys. Rev. D83, 052009 (2011)
  - "Measurement of the neutrino neutral-current elastic differential cross section," Phys. Rev. D82, 092005 (2010)
  - "First measurement of the muon neutrino charged current quasielastic double differential cross section," Phys. Rev. D81, 092005 (2010)
  - "Measurement of ν_μ and $\bar{\nu}_\mu$-induced neutral current single π^0 production cross sections on mineral oil at $E\nu$ ~1 GeV," Phys. Rev. D81, 013005 (2010)

MiniBooNE Physics Goals and Recent Publications

Additional measurements:

- Neutrino flux
  - "Measurement of the neutrino component of an anti-neutrino beam observed by a non-magnetized detector," arXiv:1102.1964, submitted to Phys. Rev. D
- Supernova search
  - "Search for core-collapse supernovae using the MiniBooNE neutrino detector," Phys. Rev. D81, 032001 (2010)

SciBooNE

- 63 collaborators
  18 institutions, 5 countries
- 9 FNAL personnel – <1 FTE
  - S. Brice
  - B. Brown
  - D. Finley
  - T. Kobilarcik
  - A. Russell
  - R. Stefanski (retired)
  - R. Tesarek (project manager)
  - H. White
  - S. Zeller

SciBooNE's World Tour

- Originally part of the K2K experiment at KEK in Japan (SciBar & EC)
- SciBar & EC shipped to Fermilab for SciBooNE project
  - MRD parts recycled from E-605, NuTeV, KTeV
  - Collaboration was awarded DOE Pollution Prevention Star (P2 Star) award for reusing existing materials
  - Fermilab was awarded DOE Pollution Prevention Environmental Stewardship Accomplishment award
- Now on its way to Mexico to become part of the Global Muon Detector Network at Sierra Negra!

SciBooNE Physics Goals and Recent Publications

5 publications (3 in 2010-2011)

- ν_μ and $\overline{\nu}_\mu$ cross section measurements
    - "Measurement of K^+ production cross section by 8 GeV protons using high energy neutrino interactions in the SciBooNE detector," arXiv:1105.2871, submitted to Phys. Rev. D (2011)
    - "Measurement of inclusive charged current interactions on carbon in a few-GeV neutrino beam," Phys. Rev. D83, 012005 (2011)
    - "Improved measurement of neutral current coherent π^0 production on carbon in a few-GeV neutrino beam," Phys. Rev. D81, 111102(R) (2010)
- Measure background processes for oscillation experiments (T2K)
- Act as MiniBooNE near detector

BNB Oscillation Summary

	SciBooNE	MiniBooNE
ν mode	0.99 x 10^{20} POT	6.5 x 10^{20} POT
$\bar{\nu}$ mode	1.53 x 10^{20} POT	8.7 x 10^{20} POT

Low energy excess (below 475 MeV)

- MB: 3σ ν_e-like excess in neutrino mode (128 ± 43 events)
  - Does not fit simple 2ν oscillation hypothesis
- MB: Negligible excess in anti-neutrino mode (18 ± 14 events)
  - Rules out some explanations of neutrino-mode excess

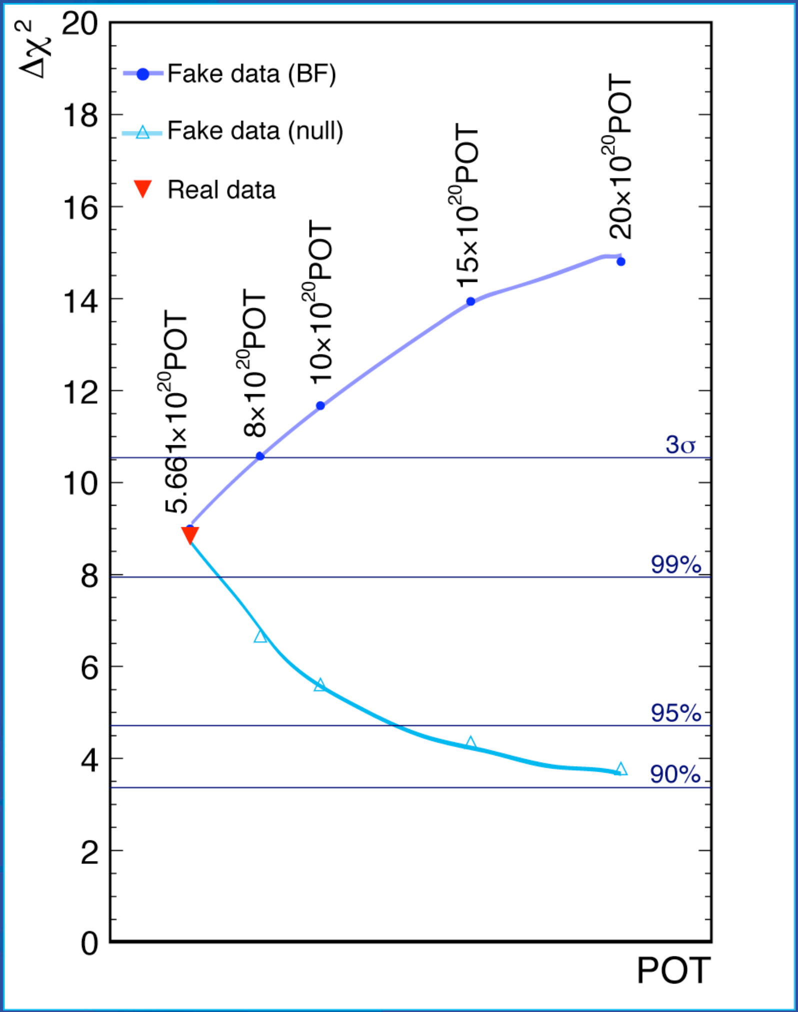
LSND-like signal (above 475 MeV)

- MB: No evidence of ν_e excess in neutrino mode
- MB: 2.7σ excess in anti-neutrino mode
  - Null hypothesis 0.5% probable, 2ν fit prefers LSND-like signal at 99.4% CL

ν_μ and $\bar{\nu}_\mu$ disappearance

- MB: No evidence in neutrino or anti-neutrino mode
- MB + SB: No evidence in neutrino mode
  - More precise anti-neutrino joint analysis underway

MiniBooNE: Expected sensitivity with additional $\bar{\nu}$ data



With 15 x 10^{20} POT $\bar{\nu}$ significance could grow to 3.7σ, or fall back to include null at 95% CL.

Analysis of 8.5 x 10^{20} POT will be released this summer.

Flux constraints

Comment from 2010 DOE S&T Review closeout report:

- Can SciBooNE say anything about the predicted antineutrino flux at MiniBooNE?

Flux constraints

Comment from 2010 DOE S&T Review closeout report:

- Can SciBooNE say anything about the predicted antineutrino flux at MiniBooNE?

SciBooNE measurement of ν from K^+ component of $\bar{\nu}$ beam

arXiv:1105.2871, submitted to Phys. Rev. D

TABLE VIII. K^+ fit results for the rate and production relative to the MC beam prediction for the neutrino, antineutrino and combined neutrino and antineutrino samples including the final χ^2/dof obtained from the K^+ production fit for NUANCE. Errors include statistical and systematic errors. The neutrino cross-section normalizations are held at the minimized values as listed in Table VII and are relative to the NUANCE predictions.

	ν-mode	$\bar{\nu}$-mode	Combined $\nu+\bar{\nu}$ mode
K^+ Prod.	0.89±0.13	0.54±0.33	0.85±0.12
K^+ Rate	0.94±0.12	0.54±0.31	0.88±0.11
χ^2/dof (Prod.)	47.8/45	18.5/27	67.3/79

Measure higher energy ν's (> 2 GeV) from "wrong-sign" parent:

Prediction of ν from K^+ in $\bar{\nu}$ beam over-estimated

Directly applicable to MiniBooNE

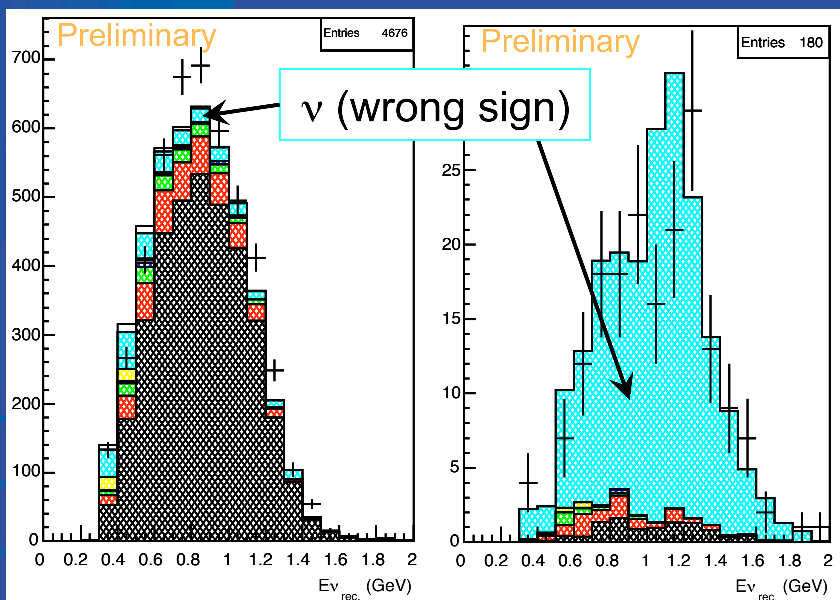
- Identical beam simulation
- Greatly reduces K^+ flux systematic errors

40% → 14%

Flux constraints

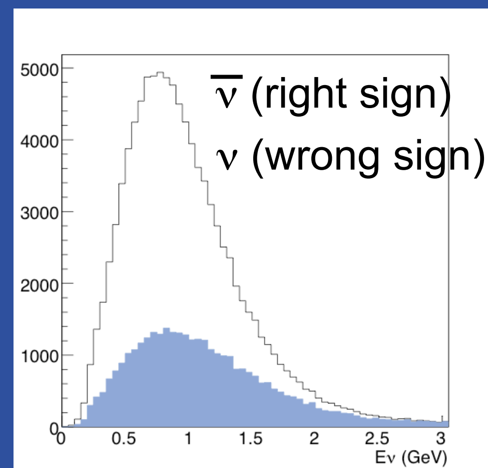
Comment from 2010 DOE S&T Review closeout report:

- Can SciBooNE say anything about the predicted antineutrino flux at MiniBooNE?



1-track w/o activity
~90% $\bar{\nu}$ purity

2-track QE-like
~90% ν purity



Wrong sign ~30% background in MRD-stopped sample

In progress:

Measuring wrong-sign component for lower energy neutrinos

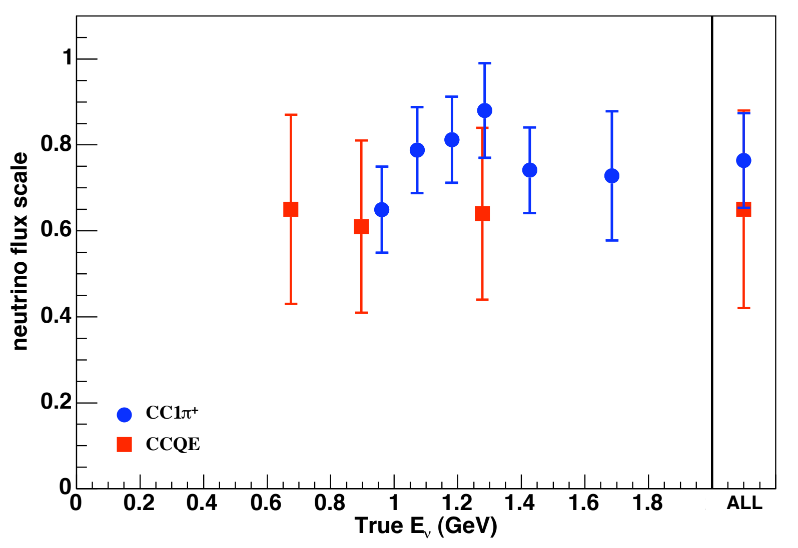
Fermilab

Flux constraints

~~Comment from 2010 DOE S&T Review closeout report:~~

- Can MiniBooNE say anything about the predicted antineutrino flux at MiniBooNE?

Measure the ν component of the $\bar{\nu}$ beam in MiniBooNE



arXiv:1102.1964, submitted to Phys. Rev. D

Two independent methods agree:

Prediction of ν flux component of predominately $\bar{\nu}$ beam is over-estimated.

- Constrains ν flux for region of angular acceptance HARP can't measure
- Novel technique for non-magnetized detectors

SciBooNE-MiniBooNE joint analysis

Comment from 2010 DOE S&T Review closeout report:

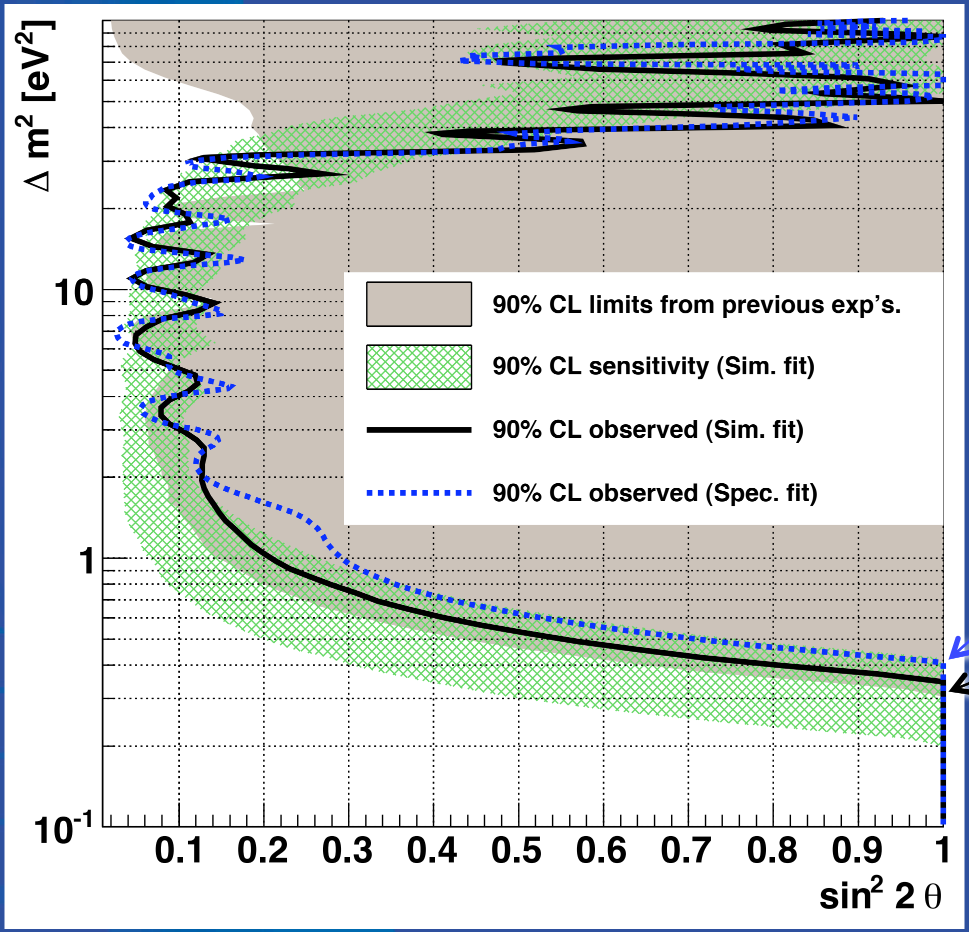
> ➢ We are particularly interested in seeing the joint SciBooNE–MiniBooNE analysis on neutrino disappearance.

- MiniBooNE-only results are limited by neutrino flux and neutrino interaction uncertainties
- Use CC ν_μ rate measured at SciBooNE to constrain MiniBooNE ν_μ rate and test for disappearance

Two methods

- Simultaneous oscillation fit of MB and SB data
- Correct MB energy spectrum to measured SB spectrum, then do oscillation fit to MB data only

Joint MiniBooNE-SciBooNE ν_μ disappearance



Both methods agree:

No disappearance at 90% CL

Spectrum fit

Simultaneous fit

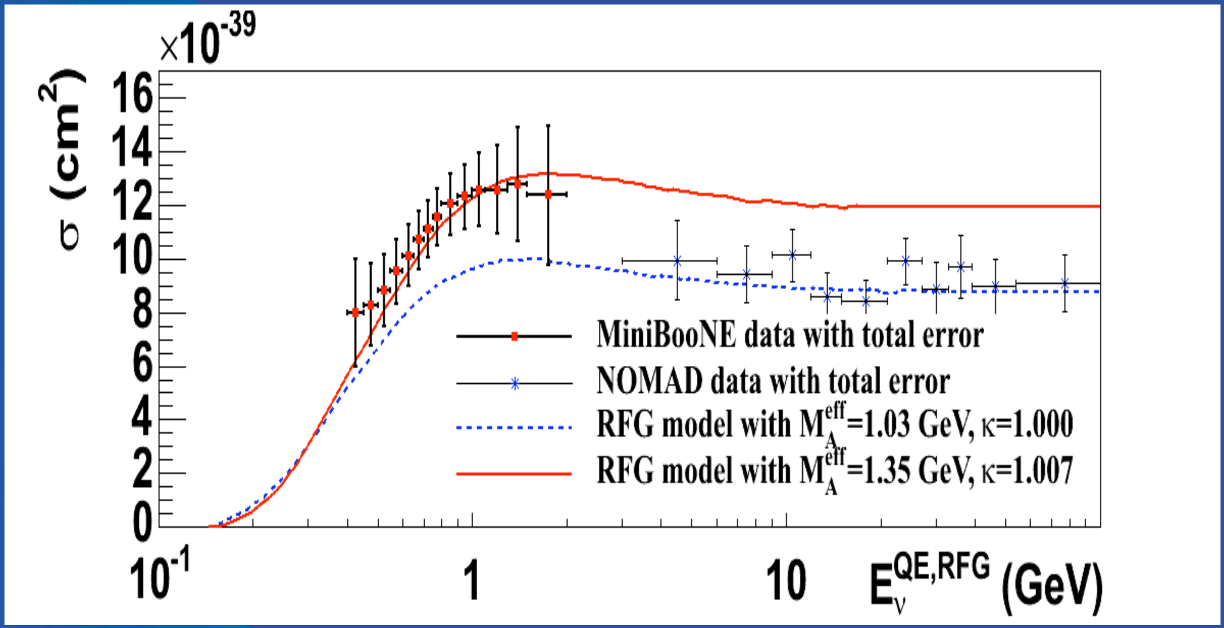
Truly collaborative effort!

In progress:

- Paper in approval process
- Joint $\bar{\nu}_\mu$ disapp. analysis

MiniBooNE Cross Sections

Neutrino cross sections are not well-known below ~2 GeV



MiniBooNE CC quasi-elastic cross section ~30% higher than “standard” QE prediction

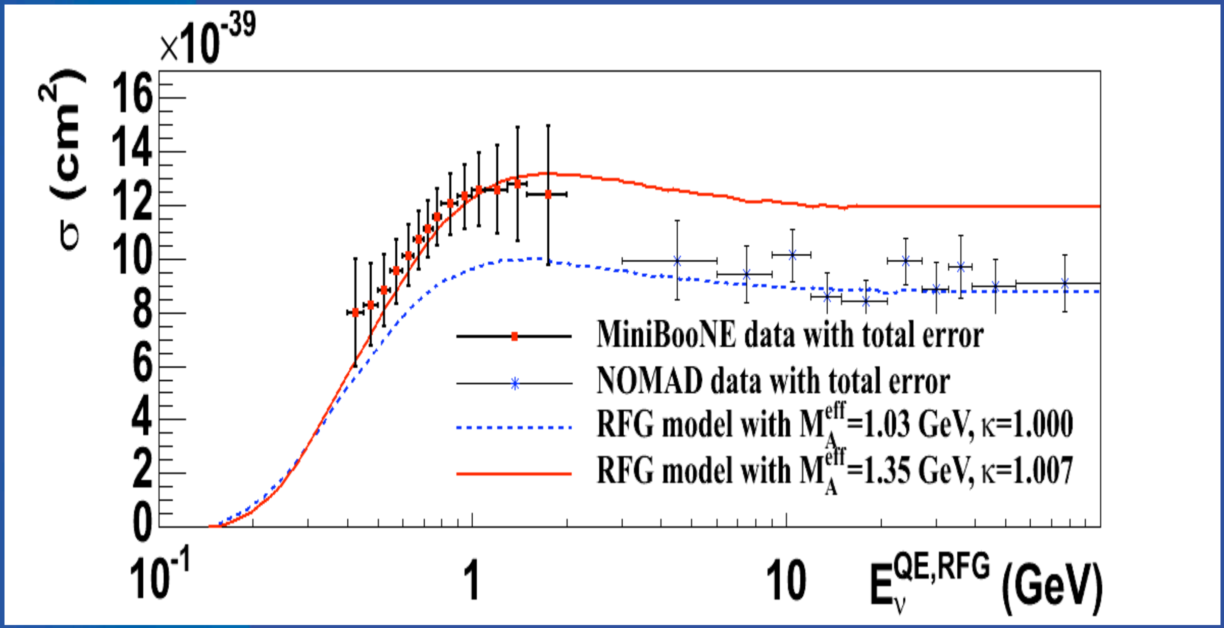
Possible explanation:

Extra contributions from multi-nucleon correlations in the nucleus.

Well-established effect in electron scattering… somehow forgotten when transferring knowledge to neutrino scattering.

MiniBooNE Cross Sections

Neutrino cross sections are not well-known below ~2 GeV



MiniBooNE CC quasi-elastic cross section ~30% higher than "standard" QE prediction

MINERνA, MINOS, ArgoNeuT

If discrepancy is due to extra nucleons, MINERνA, MINOS, and ArgoNeuT are all capable of detecting them, and they cover the gap between MiniBooNE and NOMAD data!

MiniBooNE/SciBooNE: What's Next…

MiniBooNE

- Analyzing 50% more $\bar{\nu}$ now, updated osc. results this summer
- $\bar{\nu}$ cross sections: QE, NC elastic (prelim. shown in March)

Published cross sections for 90% of ν data

Published 100% of oscillation data in ν mode

Focus now is really on $\bar{\nu}$

SciBooNE

- ν cross sections: QE, CC π^0 underway
- $\bar{\nu}$ cross sections: Coherent π^- underway

MiniBooNE + SciBooNE

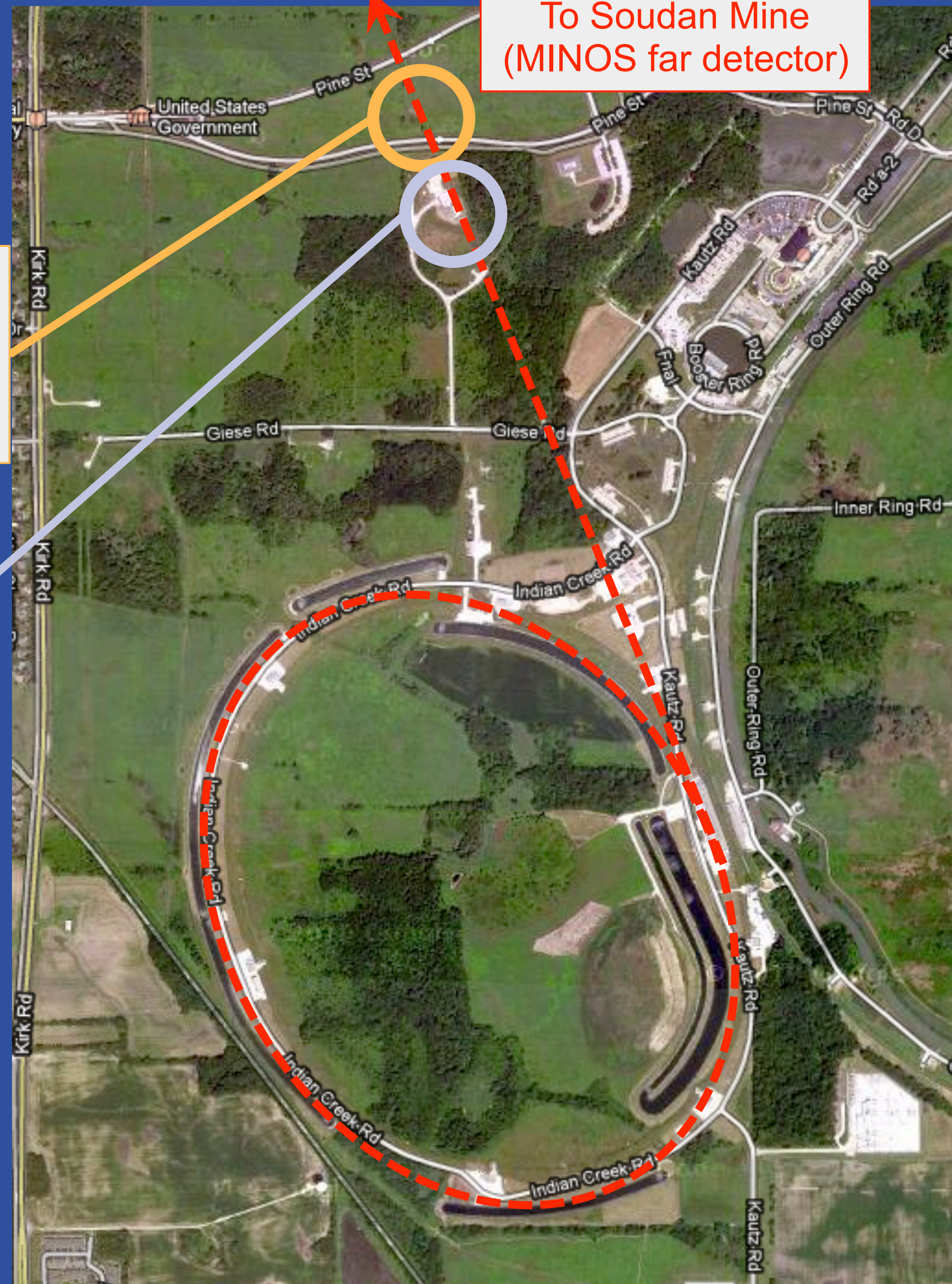
Joint $\bar{\nu}_\mu$ disappearance analysis underway

NuMI Beamline

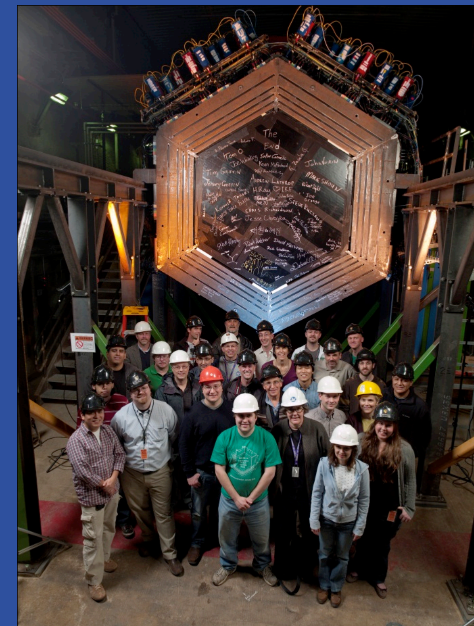
MINOS (2005 – present) near detector
ArgoNeuT (2009 – 2010)
MINERνA (2010 – present)

NOνA prototype
(2010 – present)

To Soudan Mine
(MINOS far detector)



MINERνA



- 80 collaborators
  23 institutions, 7 countries
- 5 FNAL physicists – ~4.5 FTEs
  - D. Harris (co-spokesperson, project manager)
  - J. Morfín (former co-spokesperson)
  - D. Schmitz (Lederman fellow, deputy analysis coordinator)
  - J. Osta (RA, testbeam, calorimetry reconstruction)
  - R. Snider (computing liaison)

Important technical contributors:

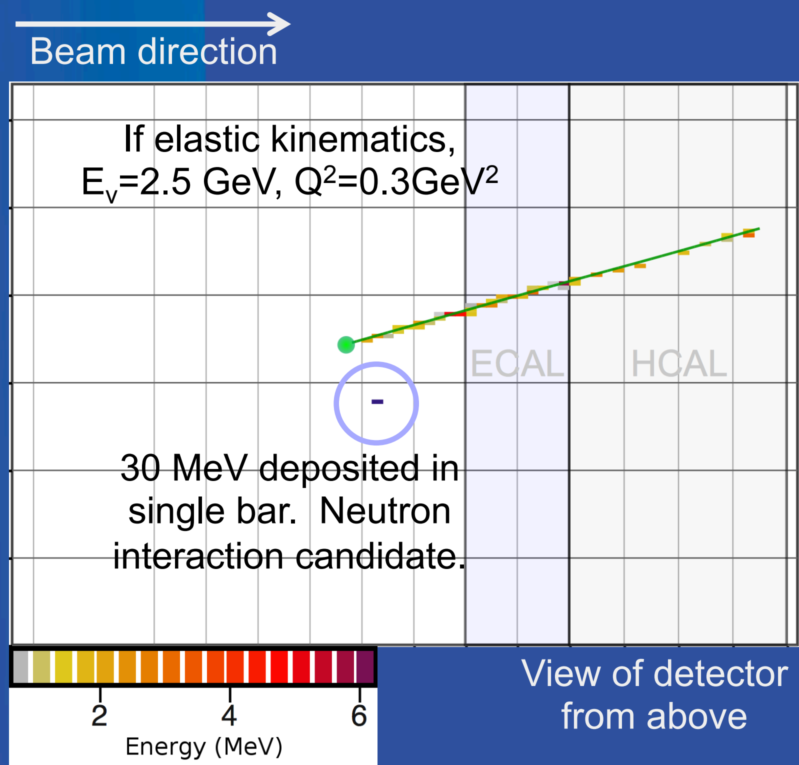
- D. Hahn (shift and safety coordinator)
- L. Bagby, R. DeMaat, J. Kilmer, A. Pla-Dalmau, P. Rubinov (active during project and installation, now “on call” experts)

D. Boehnlein, R. Stefanski (former shift coordinators, left last year)

MINERνA Physics Goals

- Precision ν–A cross section measurements at moderate energies, wide range of Q^2
- Exclusive final state and differential cross sections
- Form factors and structure functions
- Nuclear effects in a variety of targets
  - polystyrene (CH), C, Fe, Pb, He
- Provide measurements that will enable greater precision in oscillation experiments by minimizing systematic uncertainties

MINERνA: Quasi-Elastic Event Selection



View of detector
from above

- μ^+ must originate in MINERνA; analyze momentum in MINOS
- Neutron may or may not appear in detector

Two event samples:

Inclusive μ^+

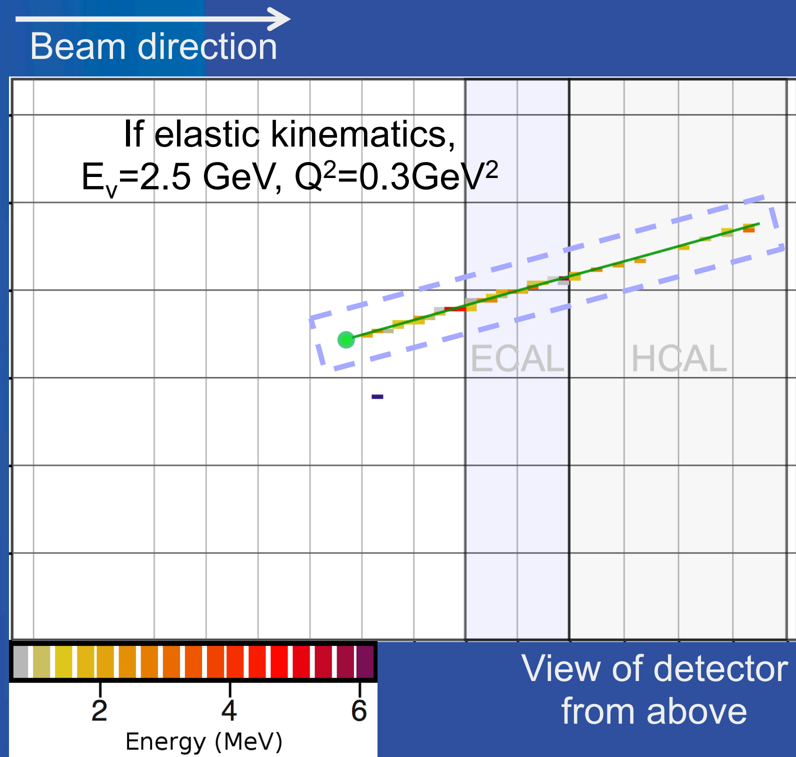
$\overline{\nu_\mu} p \rightarrow \mu^+ n$ candidates

This is a first pass at the analysis.

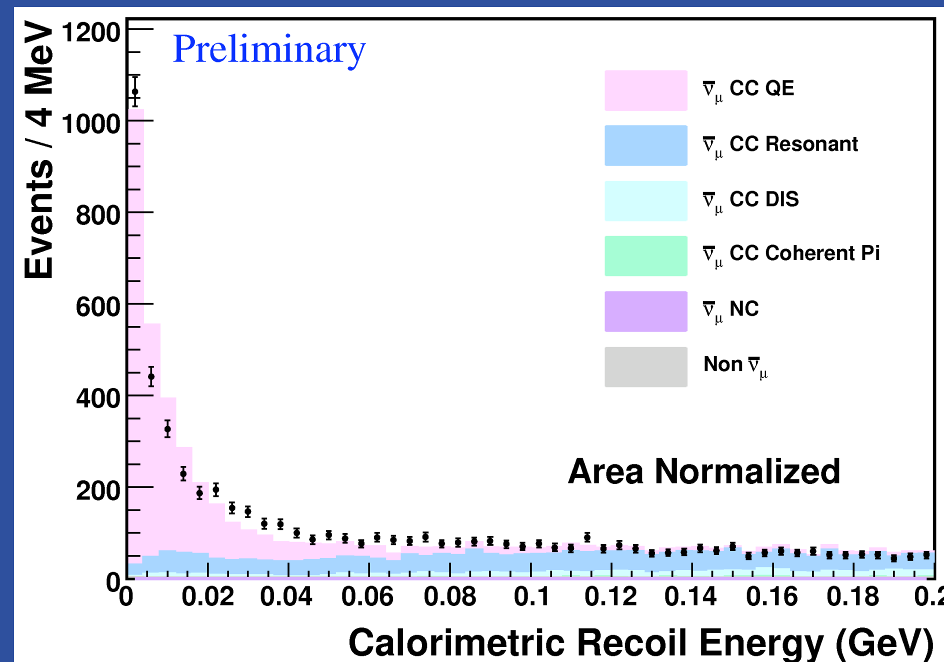
Other methods for selecting a clean event sample are in development (Michel veto, rejection of events with extra tracks, etc.)

$\overline{\nu}_\mu$ beam, partial detector: 0.4 x 10^{20} POT

MINERνA: Quasi-Elastic Recoil Selection



View of detector from above



- Sum calorimetric energy in detector, ignoring region within 5 cm of μ^+ track (to reduce contribution from δ-rays)
- QE events dominate at low recoil energy

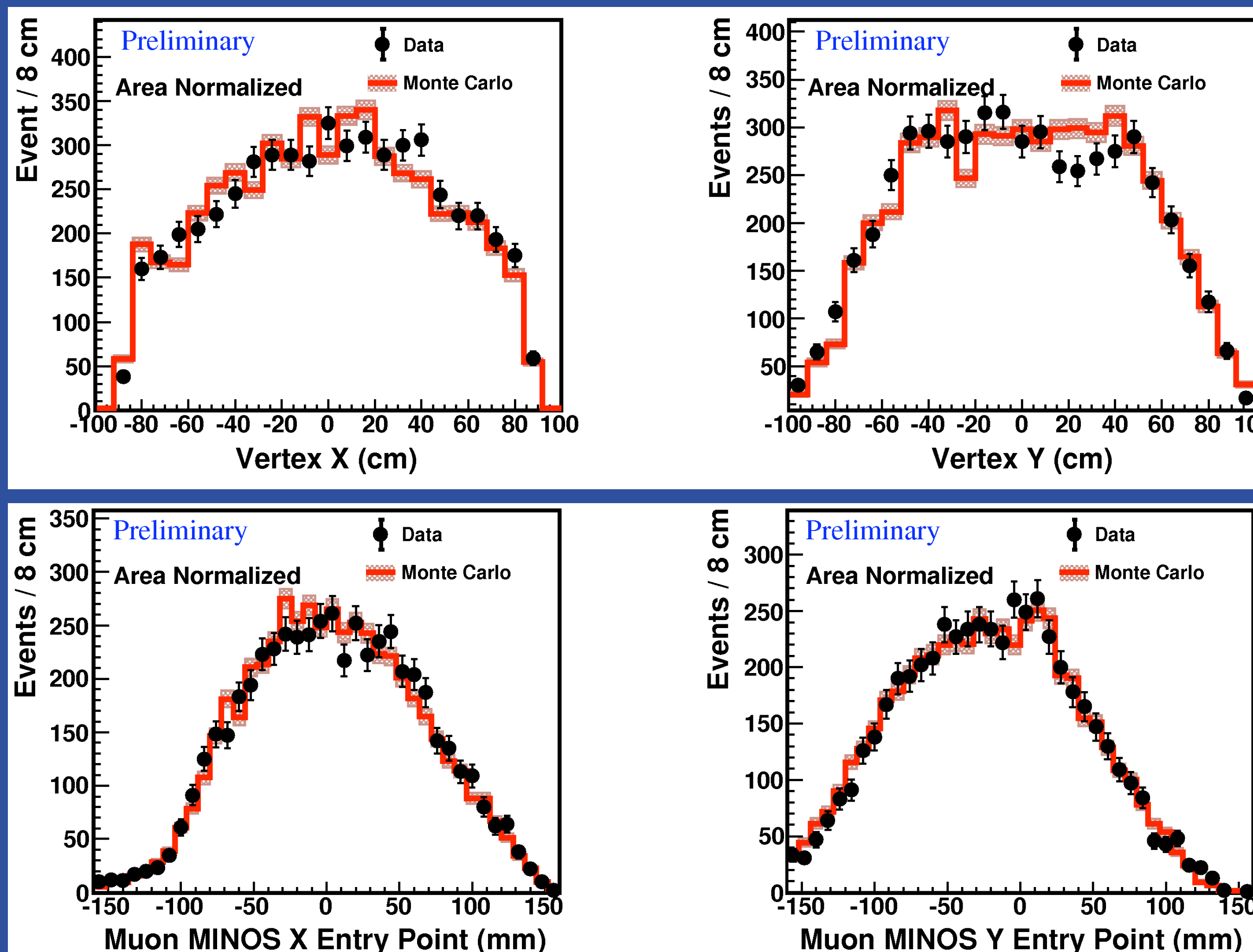
$\overline{\nu}_\mu$ beam, partial detector: 0.4 x 10^{20} POT

MINERνA Comparisons to Simulation

$$\overline{\nu_\mu} p \rightarrow \mu^+ n$$

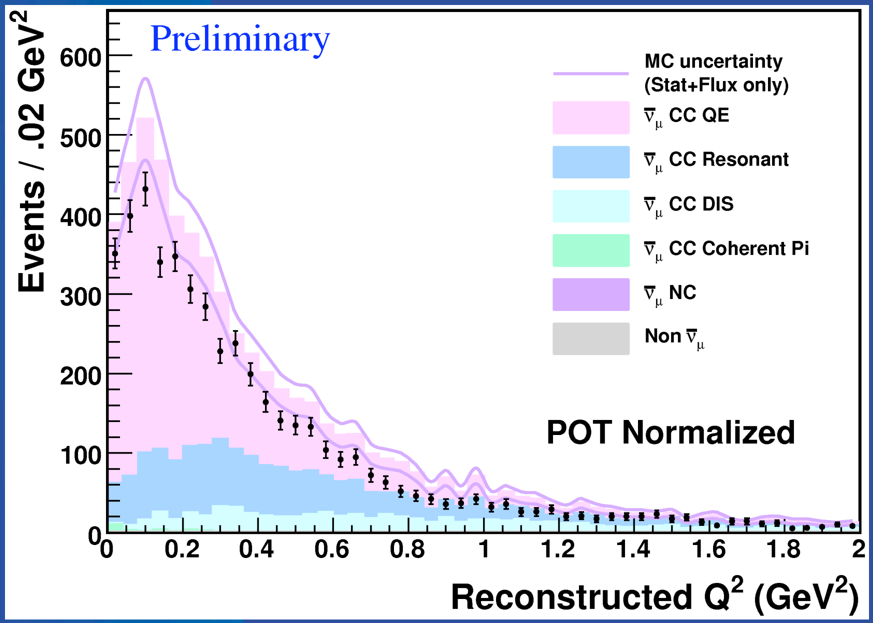
Event vertex in MINERνA

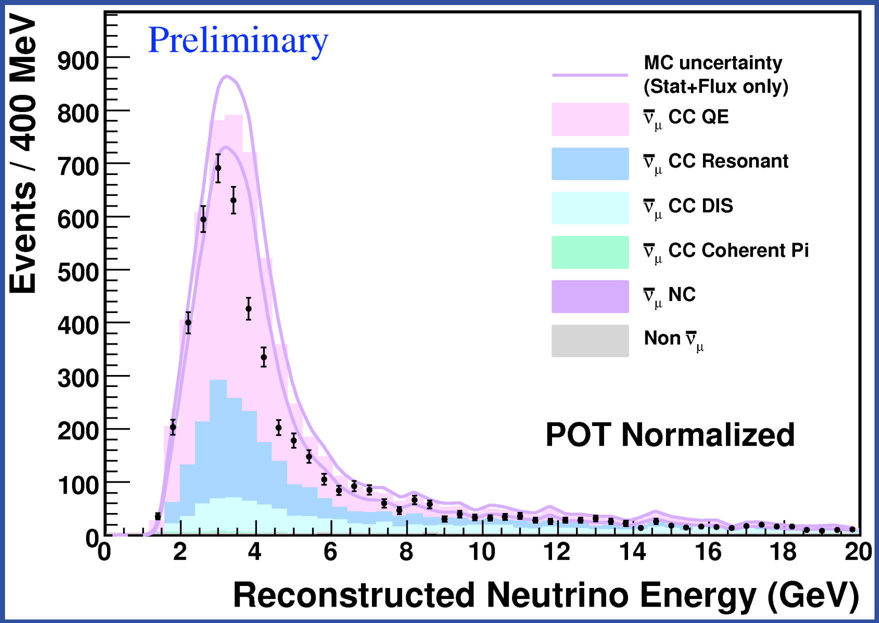
Muon entry in MINOS



Good agreement in spatial distributions across detectors

MINERνA: $\overline{\nu_\mu} p \rightarrow \mu^+ n$ Event Kinematics





Event deficit flat in Q^2, not flat in neutrino energy.

First look at QE physics from MINERνA!

Absolute normalization predictions include:

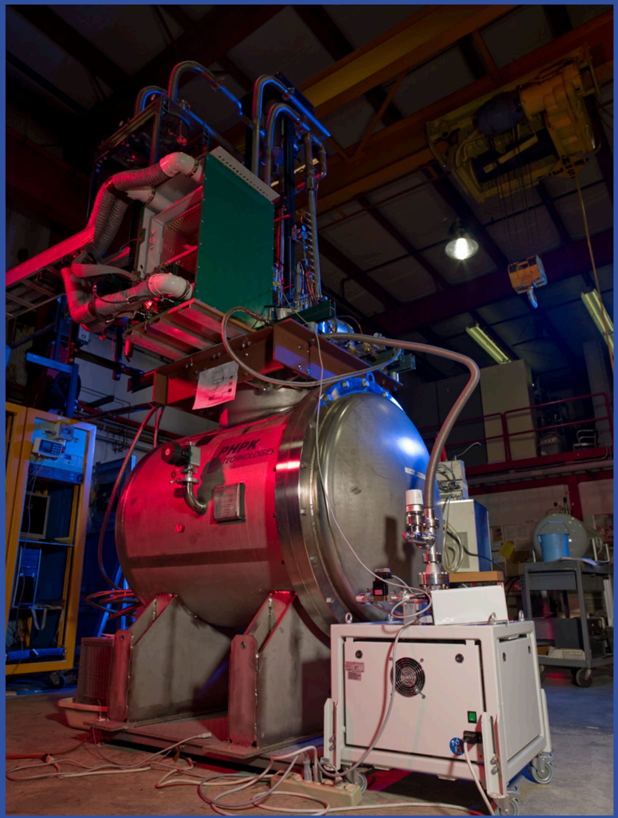
- Flux simulation
- GENIE 2.6.2
- MINERνA detector simulation

MINERνA: What's Next…

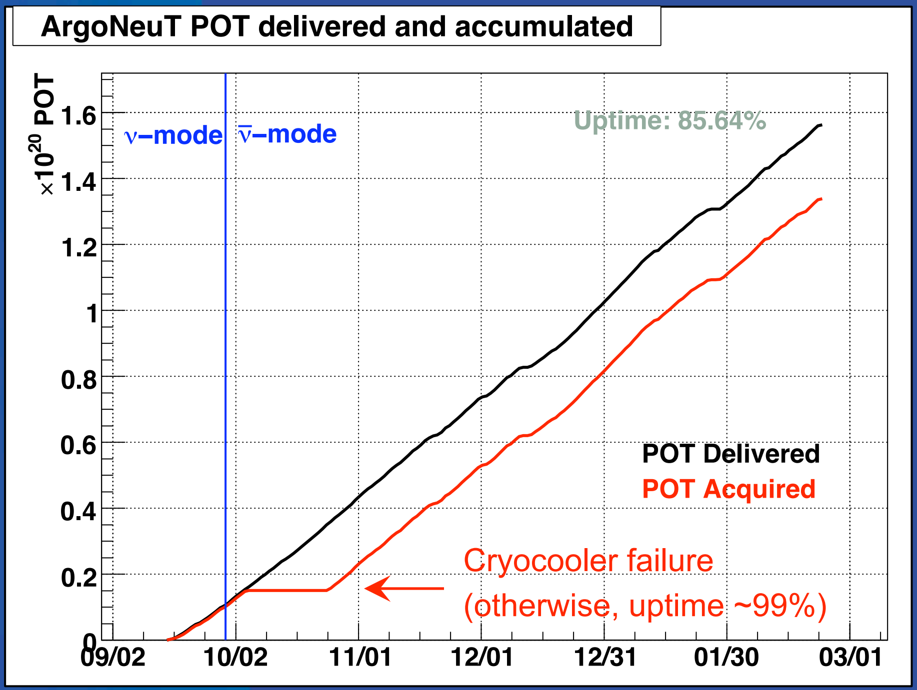
- Many other analyses currently underway
  - Inclusive CC events on nuclear targets
  - QE events in neutrino mode: nuclear targets and plastic
  - Flux tuning methodology
  - …many more! (These are the 3 most active areas now.)
- All of these analyses require different techniques that are being developed
  - pion (kinked) and proton (short) tracking
  - EM shower reconstruction
  - particle ID by dE/dx
  - stopping muons in MINERvA
  - Michel tagging
  - vertex reconstruction in passive targets

ArgoNeuT

- 30 collaborators
  9 institutions, 3 countries
- 6 FNAL personnel – ~1 FTEs
  - M. Soderberg (spokesperson)
  - B. Baller
  - C. James
  - R. Rameika
  - B. Rebel (Wilson Fellow, software coordinator)
  - S. Zeller



ArgoNeuT in the NuMI Beamline

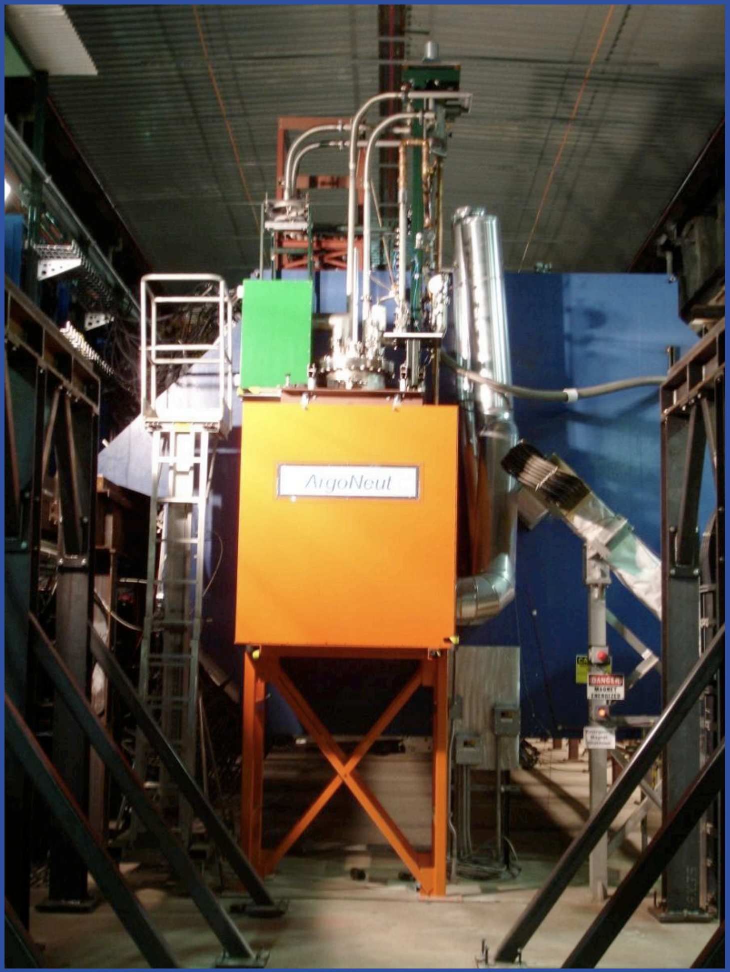


175 liter liquid argon TPC

Physics run: Sept. 2009 – Feb. 2010

Data collected: ~1.35 x 10^{20} P.O.T.

0.1 x 10^{20} ν-mode, 1.25 x 10^{20} $\bar{\nu}$-mode

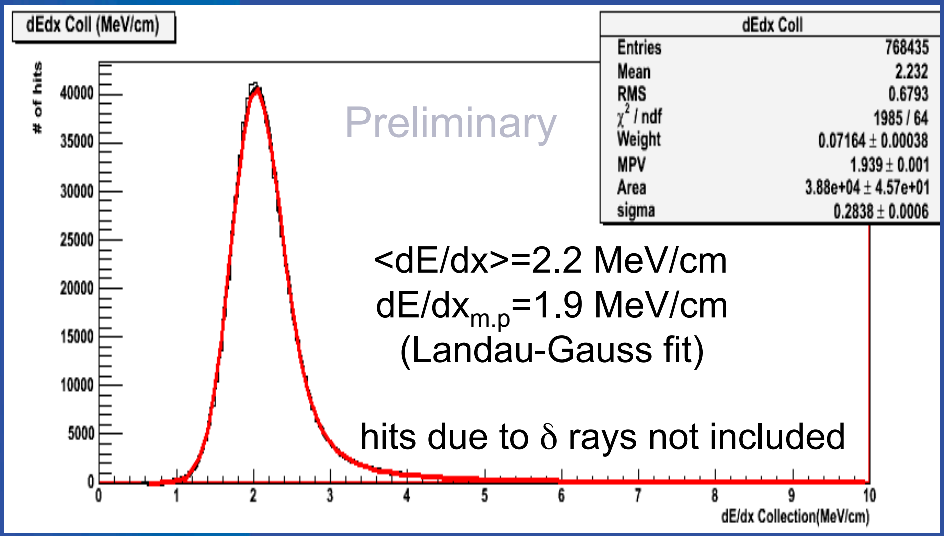


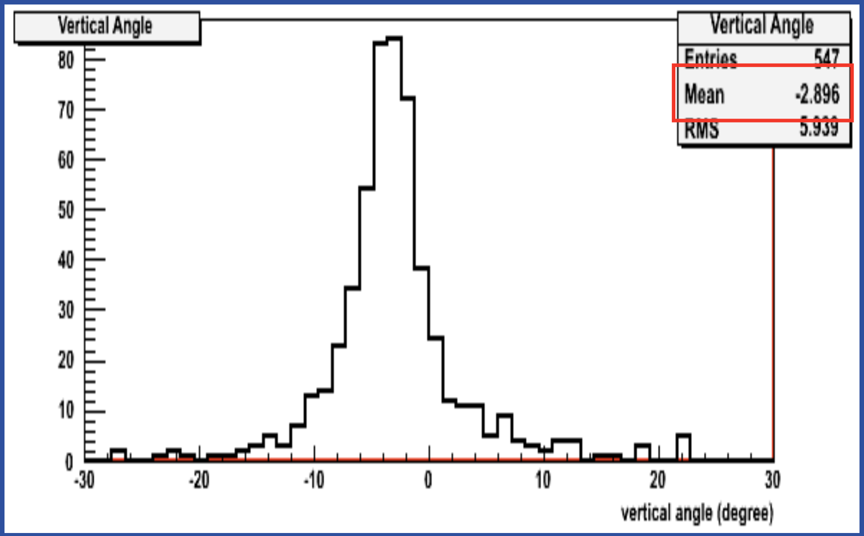
ArgoNeuT in the MINOS hall

ArgoNeuT Goals

- Experience building and running liquid argon TPCs
  - Development focused on scaling LArTPCs to sizes necessary for long baseline experiments
- Measure cross sections in the range 1 to 5 GeV
  - ν and $\bar{\nu}$ events accumulated
- Develop generalized simulation and reconstruction tools for LArTPCs

ArgoNeuT: LArTPC Reconstruction



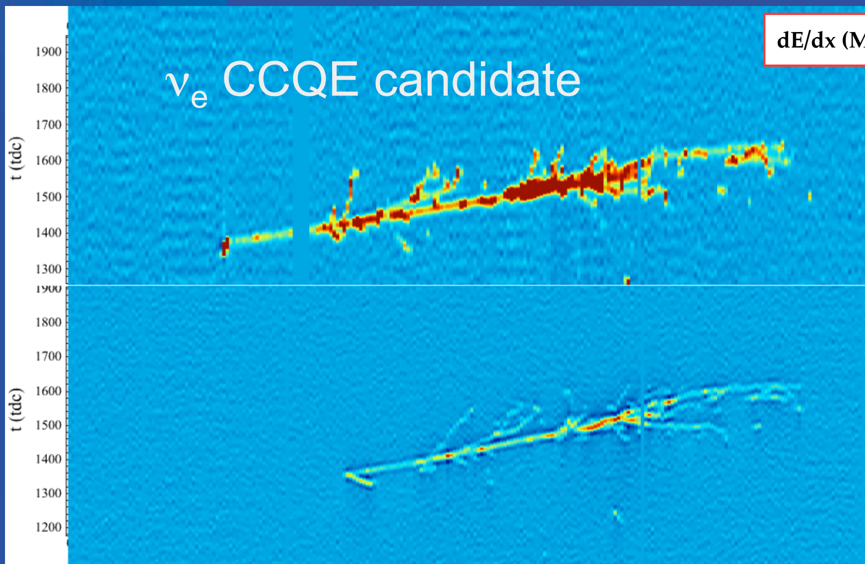


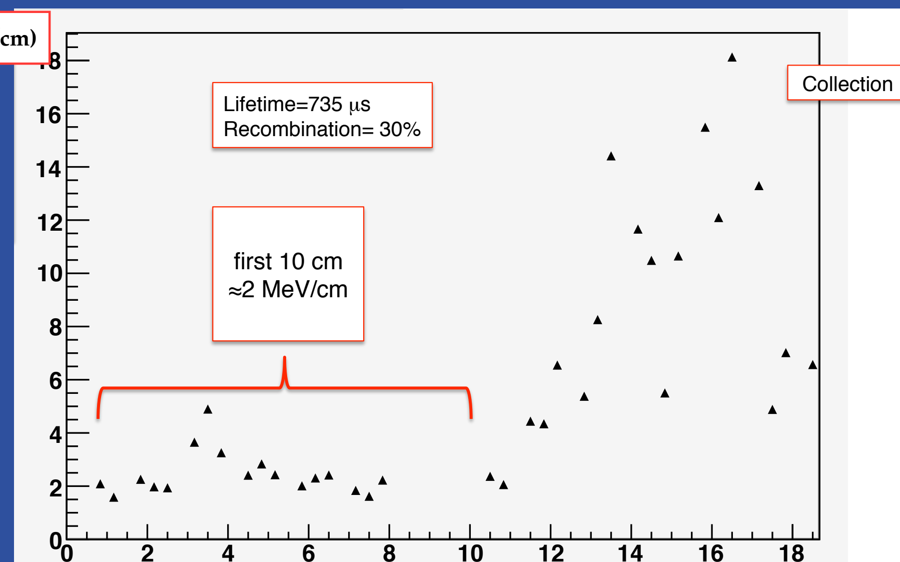
dE/dx, neutrino-induced muons

Vertical angle of muons (NuMI beam is -3°)

- ArgoNeuT data invaluable to development of full generalized reconstruction/simulation chain
- Useful for current and future LArTPC projects

ArgoNeuT: Shower Reconstruction





Development of 3D shower reconstruction tools in progress

Very important step for determining true signal & background capabilities of LArTPCs

Coming this summer…

DRAFT Analysis of a Large Sample of Muons with the ArgoNeuT Detector

M. Antonelllo[a], B. Baller[b], C. Bromberg[c], F. Cavanna[e], D. Edmunds[c], B. Fleming[f], C. James[b], K. Lang[g], P. Laurens[c], S. Linden[f], R. Mehdiyev[g], B. Page[c], O. Palamara[a], K. Partyka[f], G. Rameika[b], B. Rebel[b], M. Soderberg[b,d], J. Spitz[f], T. Wongjirad[f]

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[b] *Fermi National Accelerator Laboratory, Chicago, Illinois*
[c] *Michigan State University, East Lansing, Michigan 48824*
[d] *Syracuse University, Syracuse, New York 13039*
[e] *University of L'Aquila, L'Aquila, Italy*
[f] *Yale University, New Haven, Connecticut, USA*
[g] *The University of Texas at Austin, Austin, Texas 78712*

Abstract

ArgoNeuT has recently collected thousands of neutrino and anti-neutrino events in the NuMI beamline at Fermilab. The main physics thrust of the experiment is to measure neutrino cross sections in the 0.1-10 GeV energy range. Fully reconstructing the muon is imperative to measuring muon-neutrino charged current cross sections. This paper focuses on the complete kinematic reconstruction and identification of muons and line-like tracks in general with ArgoNeuT's automated reconstruction software. The various pattern recognition and characterization algorithms implemented in the software are described in detail with a focus on reconstructing neutrino-induced through-going muons, rather than neutrino events themselves. Along with being imperative to detector calibration, a high statistics sample of minimum ionizing, line-like tracks provides a means of measuring the electron drift velocity and lifetime in the liquid argon.

Keywords:

1. Introduction

Liquid Argon Time Projection Chambers (LArTPCs) are well suited for the study of neutrino interactions thanks to their unique combination of scalability, fine-grained tracking, and calorimetry. LArTPCs were proposed in the 1970s and have a long history of development in Europe [1, 2]. Until recently, only one LArTPC has ever been exposed to a neutrino beam [3]. There is considerable interest in developing this detector technology, with the goal of deploying a massive multi-kiloton LArTPC in a far-detector location as part of a long-baseline neutrino oscillation experiment and proton decay search, among other physics goals.

LArTPCs rely on the ability to drift ionization created in a neutrino interaction through a volume of highly purified liquid argon to a set of instrumented readout planes. The readout planes consist of finely spaced (mm-scale) wires, with neighboring planes oriented at varying angles to

Preprint submitted to Elsevier *March 21, 2011*

What's Next…

- Cross sections for CC QE-like ν and $\bar{\nu}$ from 1-5 GeV
  - Low statistics (but ICARUS 50-liter meas. with ~80 events)
- Initial focus: analyze ~2 weeks of ν-mode data
  - Study inclusive CC sample
  - Data/MC comparisons
- Start to look at $\bar{\nu}$ data this fall…

MINOS

- 126 collaborators
  29 institutions, 5 countries
- 18 FNAL personnel – ~7 FTEs
  - R. Plunkett (co-spokesperson)
  - B. Rebel (Wilson fellow, publications committee)
  - B. Pahlka (RA)
  - A. Kreymer, R. Hatcher (CD)
  - D. Torretta (DAQ)
  - R. Sharma (graduate student)
  - P. Adamson, S. Childress, J. Hylen, G. Koizumi, P. Lucas, C. Moore, B. Zwaska (beam)
  - G. Bock, D. Boehnlein, D. Bogert, C. James, D. Jensen (shifts)

MINOS Physics Goals and Recent Publications

24 publications (9 in 2010-2011)

- ν_μ disappearance

  "Measurement of the neutrino mass splitting and flavor mixing by MINOS," Phys. Rev. Lett. 106, 181801 (2011)

- $\bar{\nu}_\mu$ disappearance

  "First direct observation of muon antineutrino disappearance" arXiv:1104.0344, accepted for publication in Phys. Rev. Lett.

- ν_e appearance

  "New constraints on muon-neutrino to electron-neutrino transitions in MINOS," Phys. Rev. (Rapid Comm.) D82, 051102 (2010)

- Sterile neutrino search

  "Active to sterile neutrino mixing limits from neutral-current interactions in MINOS," arXiV:1104.3922, submitted to Phys. Rev. Lett.

  "Search for sterile neutrino mixing in the MINOS long-baseline experiment," Phys. Rev. D 81,052004 (2010)

MINOS Physics Goals and Recent Publications

Additional measurements:

- **Cross sections**

  "Neutrino and antineutrino inclusive charged-current cross section measurements with the MINOS near detector," Phys. Rev. D 81,072002 (2010)

- **Tests of Exotic Scenarios**

  "A search for Lorentz invariance and CPT violation with the MINOS far detector," Phys. Rev. Lett. 105, 151601 (2010)

- **Cosmic Ray Studies**

  "Measurement of the underground atmospheric muon charge ratio using the MINOS near detector," Phys. Rev. D83, 032011 (2011)

  "Measurement of the underground atmospheric muon charge ratio using the MINOS near detector," Phys. Rev. D 83, 032011 (2011)

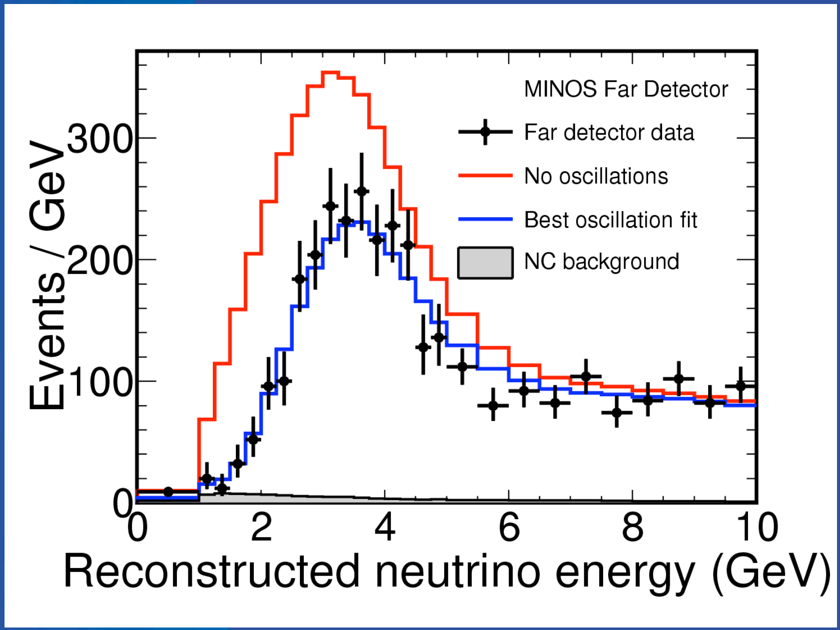
  "Observation in the MINOS far detector of the shadowing of cosmic rays by the sun and moon," Astropart. Phys. 34, 457-466 (2011)

  "The atmospheric charged kaon/pion ratio using seasonal variation methods," Astropart. Phys. 33, 140-145 (2010)

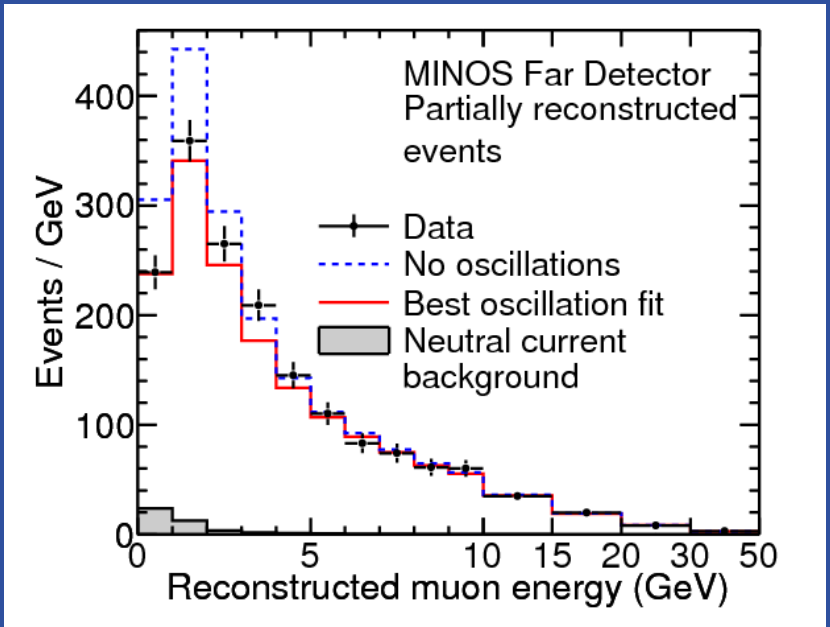
Phys. Rev. Lett. 106, 181801 (2011)

ν_μ dataset: 7.25 x 10^{20} POT

MINOS ν_μ disappearance



Fully reconstructed



Partially reconstructed

	Fully reconstructed	Partially reconstructed
Predicted (no osc.)	2451	2206
Observed at Far Detector	1986	2017

Fermilab

MINOS ν_μ disappearance

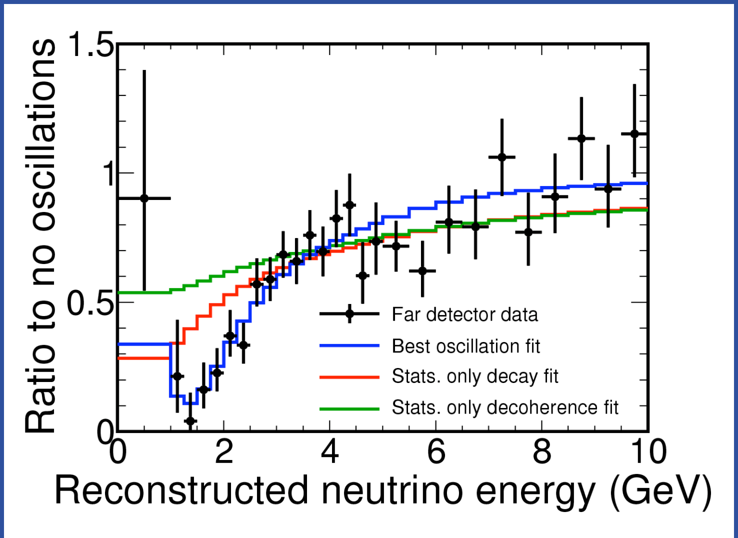
Pure decoherence disfavored at 9σ

Pure decay disfavored at 7σ

Best oscillation fit:

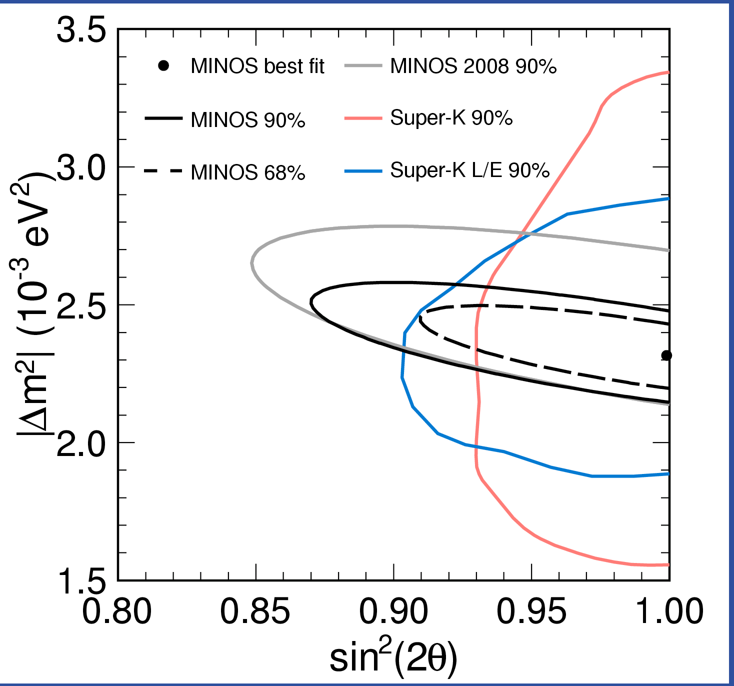
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\text{eV}^2$$

$$\sin^2(2\theta) > 0.90 \quad (90\% \text{ C.L.})$$



Dataset doubled from previous analysis:

3.4 x 10^{20} ⟶ 7.25 x 10^{20} POT



Improved analysis method

Most precise mass splitting measurement so far!

MINOS $\overline{\nu}_\mu$ disappearance

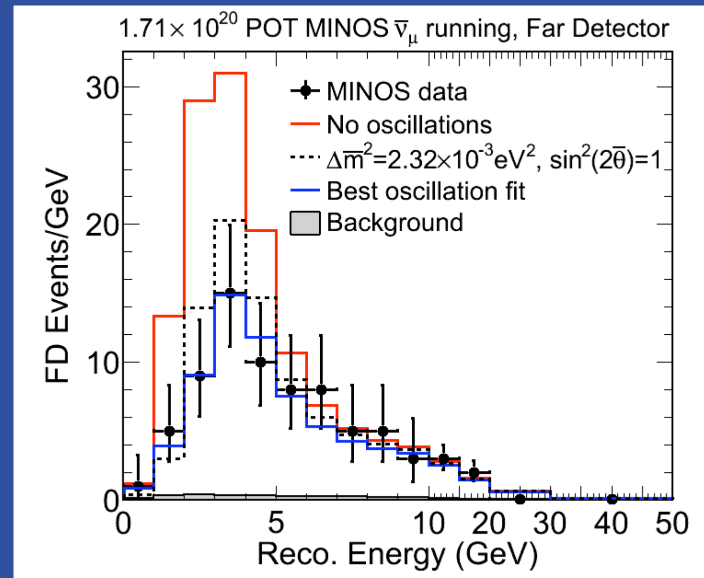
No oscillation disfavored at 6.3σ

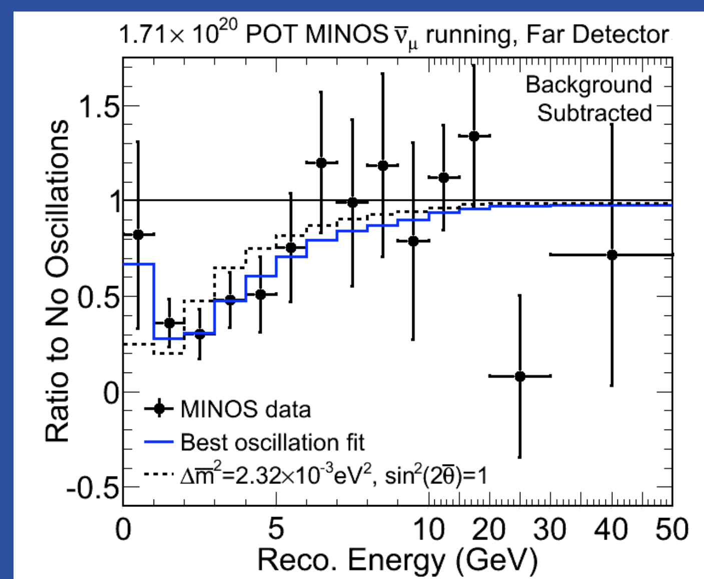
Best oscillation fit:

$$|\overline{\Delta m^2}| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\left(2\overline{\theta}\right) > 0.86^{+0.11}_{-0.12}$$

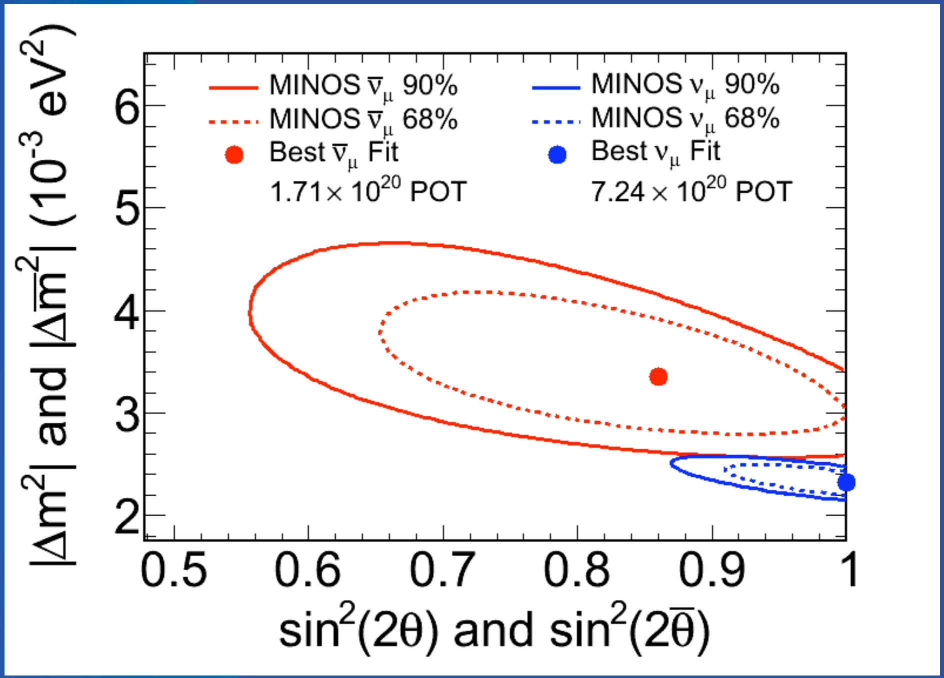
Predicted (no osc.)	156
Observed at Far Detector	97





First direct observation of muon antineutrino disappearance.

MINOS: Neutrinos *vs.* Antineutrinos



Best oscillation fit ($\overline{\nu_\mu}$):

$$|\overline{\Delta m^2}| = 3.36^{+0.46}_{-0.40} \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.86^{+0.11}_{-0.12}$$

Best oscillation fit (ν_μ):

$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.90 \quad (90\% \text{ C.L.})$$

Nearly independent measurements:

- Less than 3% contamination of ν_μ in $\overline{\nu_\mu}$ sample (and of $\overline{\nu_\mu}$ in ν_μ sample)

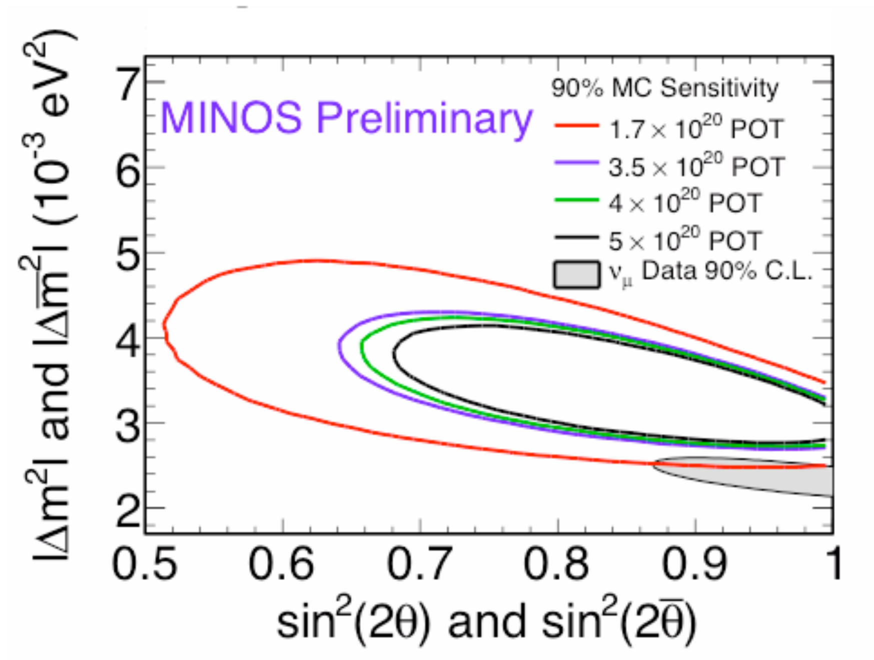
~2% probability of common parameters

MINOS Future Sensitivity

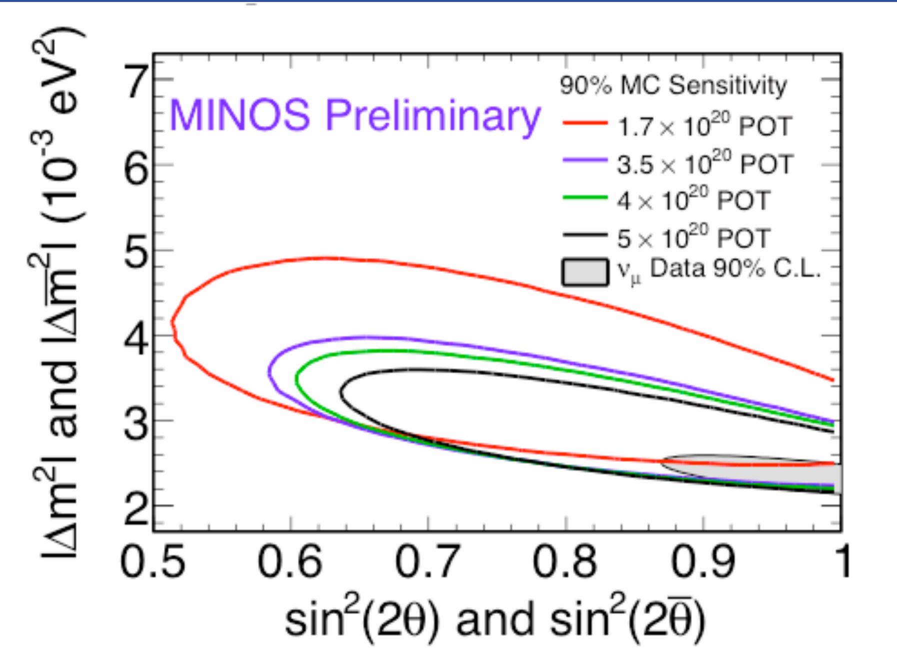
Comment from 2010 DOE S&T Review closeout report:

- With approximately double the anti-neutrino statistics, it would be interesting to estimate the expected sensitivity for measuring a neutrino vs. anti-neutrino differences. This may be an important number to understand for future planning.

Assuming additional data have same $\overline{\nu}_\mu$ parameters

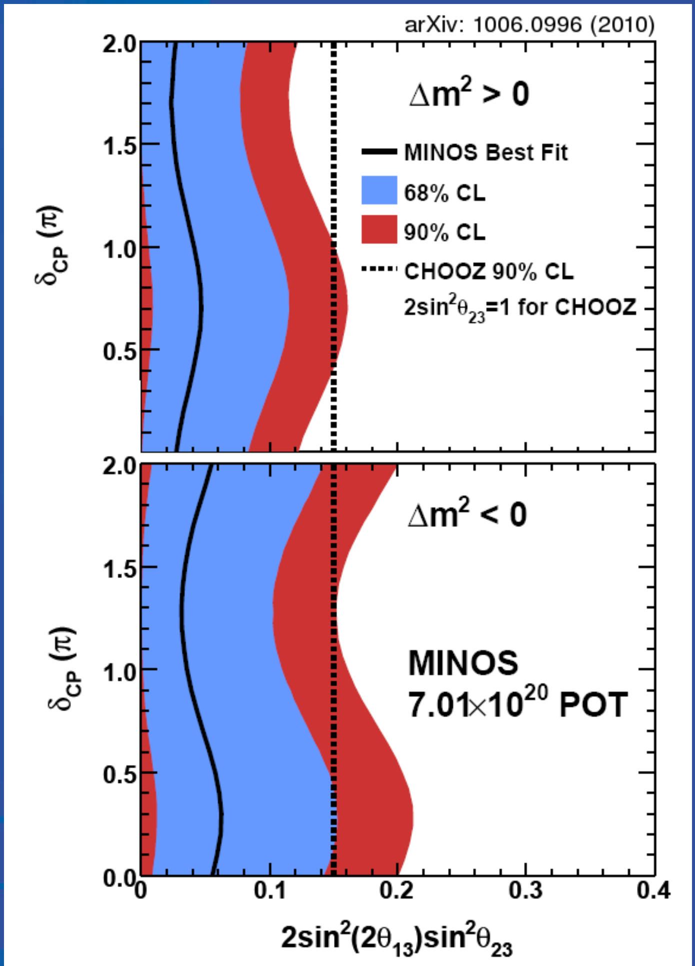


Assuming additional data have CC ν_μ parameters



Phys. Rev. (Rapid Comm.) D82, 051102 (2010)

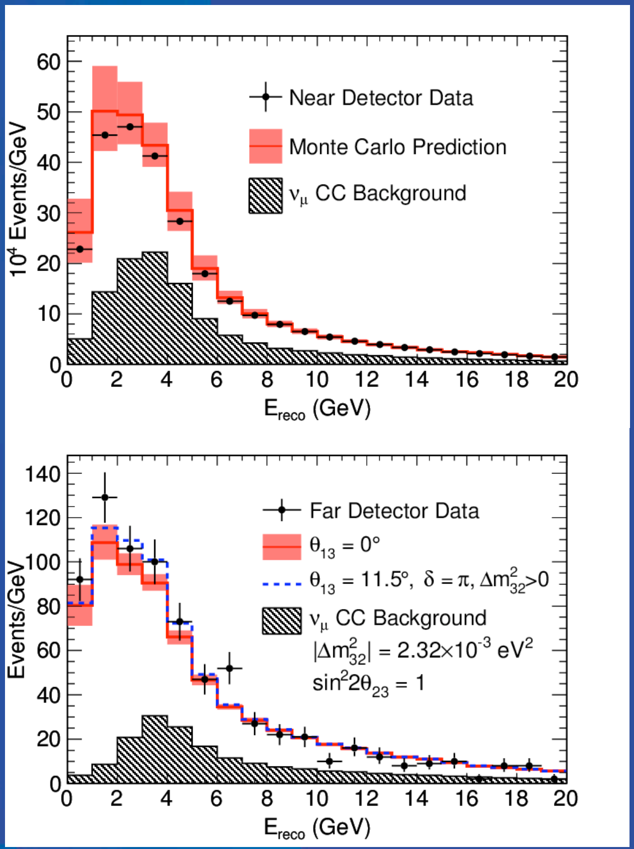
MINOS ν_e appearance

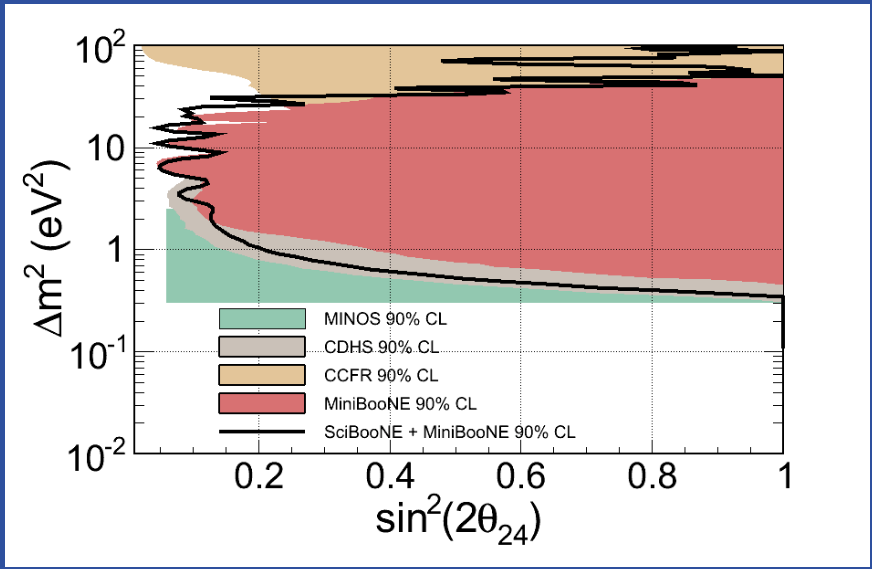


- Strongest limit for all but a small portion of δ_{CP} in the case of normal hierarchy.
- Analysis with new ν_e event selection and improved analysis techniques underway for 8.2 x 10^{20} POT.

ν_μ dataset: 7.1 x 10^{20} POT

MINOS: Sterile ν mixing limits from NC events





Predicted (for std. 3 flavor osc.)	757
Observed at Far Detector	802

$$f_s \equiv \frac{P_{\nu_\mu\to\nu_s}}{1-P_{\nu_\mu\to\nu_s}} < 0.22 \;\; (0.40) \text{ at } 90\% \text{ C.L. without (with) } \nu_e \text{ appearance}$$

World’s most stringent limit on sterile neutrino fraction.

Fermilab

MINOS: What's Next…

- Updated $\bar{\nu}_\mu$ results soon
- ν_e appearance
  - Improved analysis technique, new event selection
  - Analysis of 8.2 x 10^{20} POT available in ~1 month
- Additional cross section measurements
- Updated atmospheric neutrino results
- Further symmetry tests and exotic model exclusions
- MINOS+
  - Discussed in next talk (M. Soderberg)

Conclusions

Many new results from the Fermilab neutrino program this year

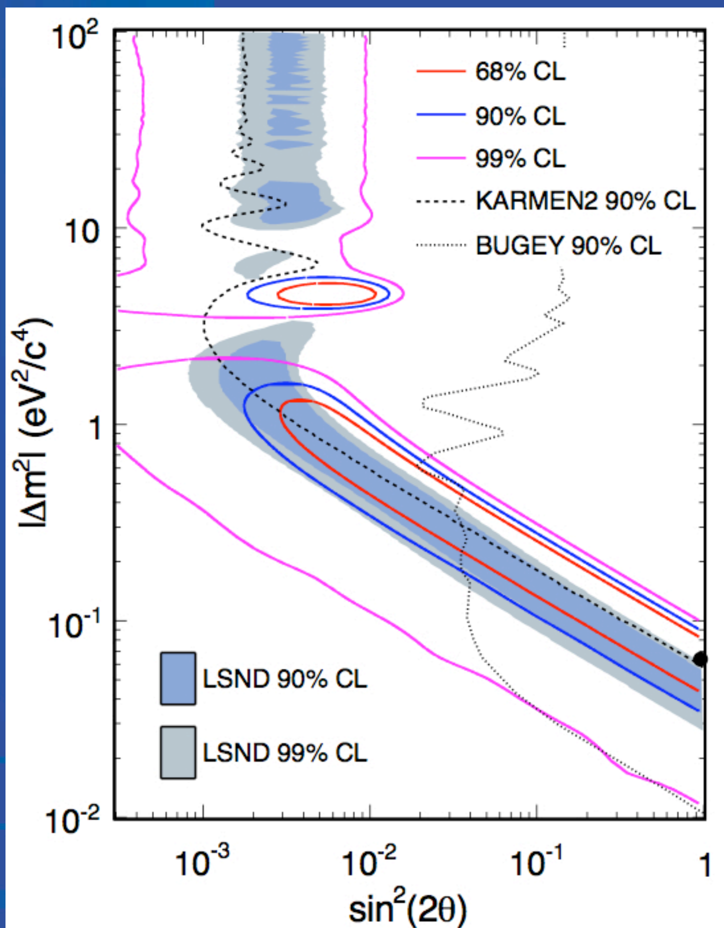
- Renewed interest in nuclear effects and neutrino cross sections by theorists, resulting directly from MiniBooNE "QE" measurement
  - SciBooNE, MINERνA, ArgoNeuT can help!
- Differences in ν and $\bar{\nu}$ not yet clear
  - MINOS summer update (ν_μ *vs.* $\bar{\nu}_\mu$ disappearance)
  - MiniBooNE summer update ($\bar{\nu}_e$ appearance)
- MINERνA and ArgoNeuT
  - Great advances in reconstruction software and analysis tools
  - Preliminary QE analysis from MINERνA, many others in progress

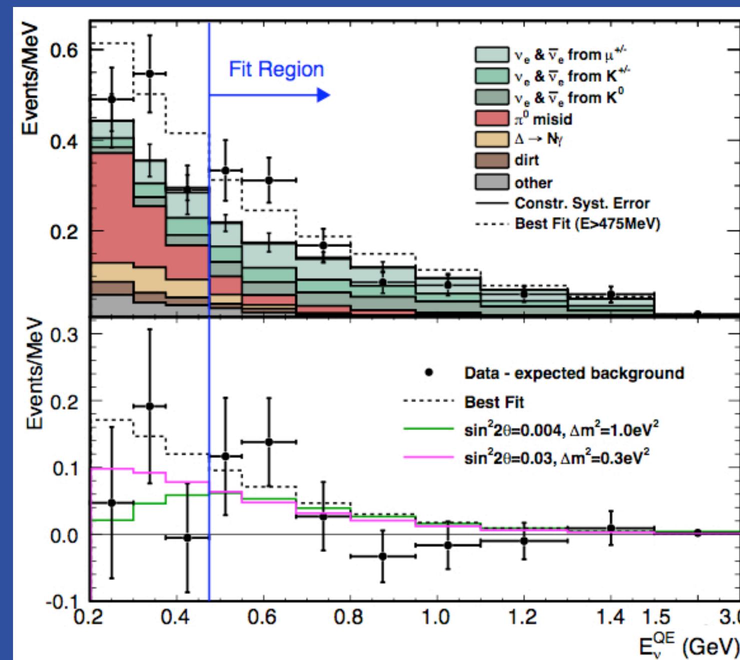
Many new puzzles in neutrino physics!

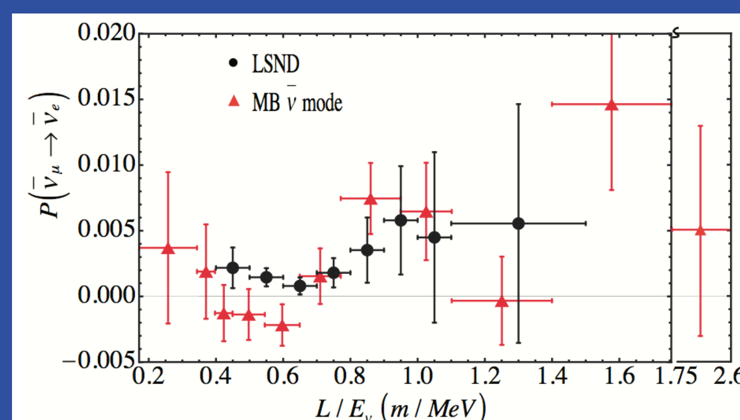
Fermilab experiments will continue to play a strong role in the global neutrino program.

Extra

MiniBooNE Anti-neutrino Results

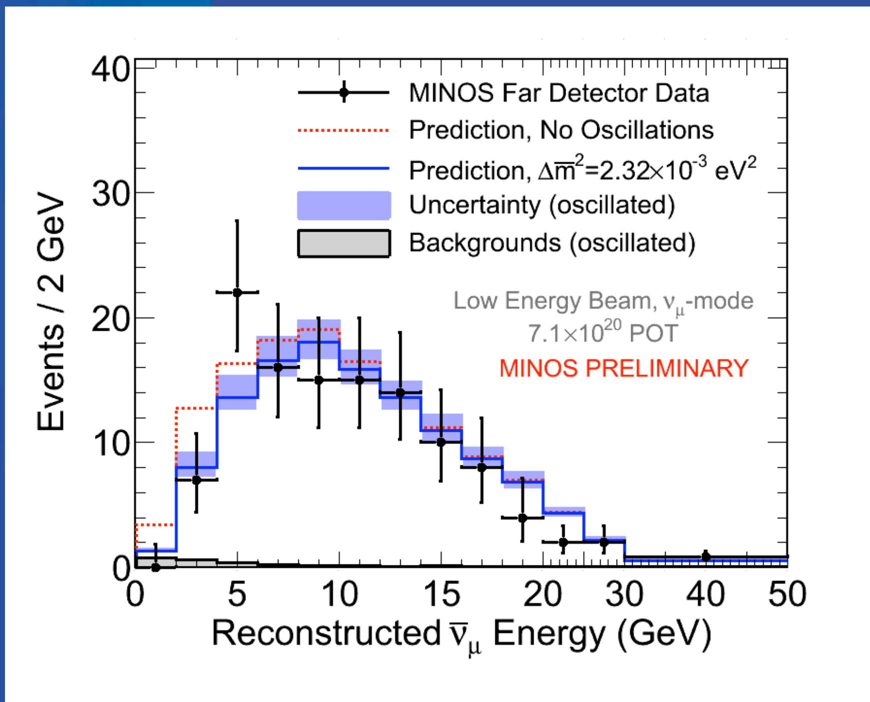


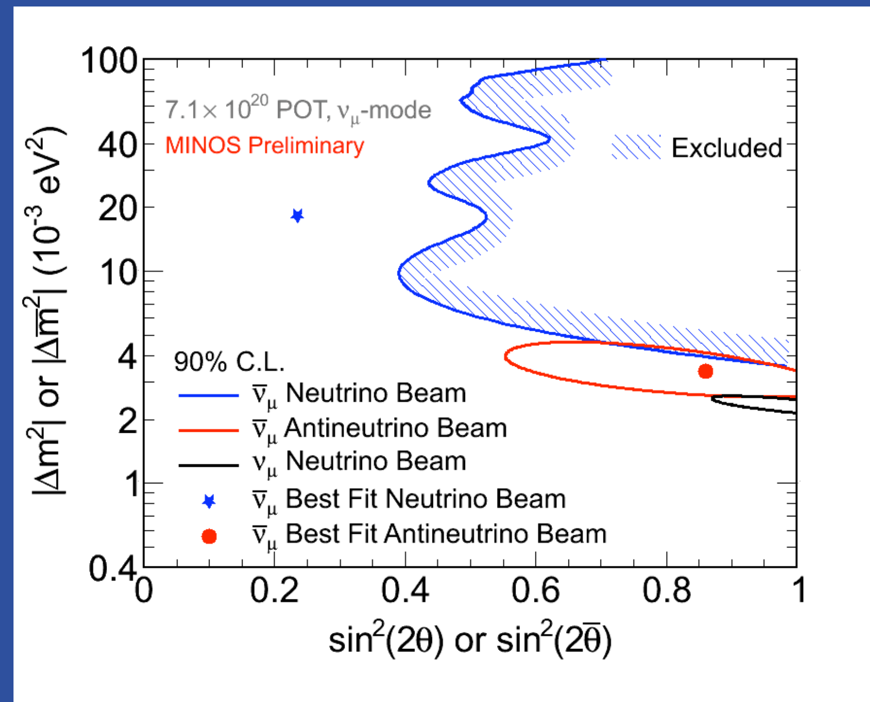




Fermilab

MINOS: Another handle on $\overline{\nu}_\mu$ oscillations





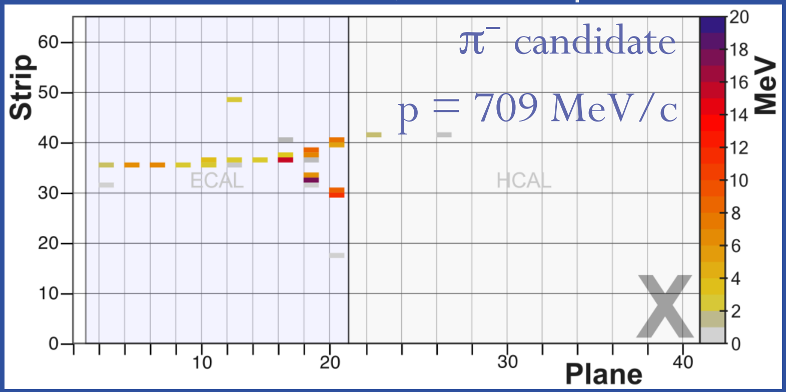
Anti-ν_μ selected from ν_μ beam

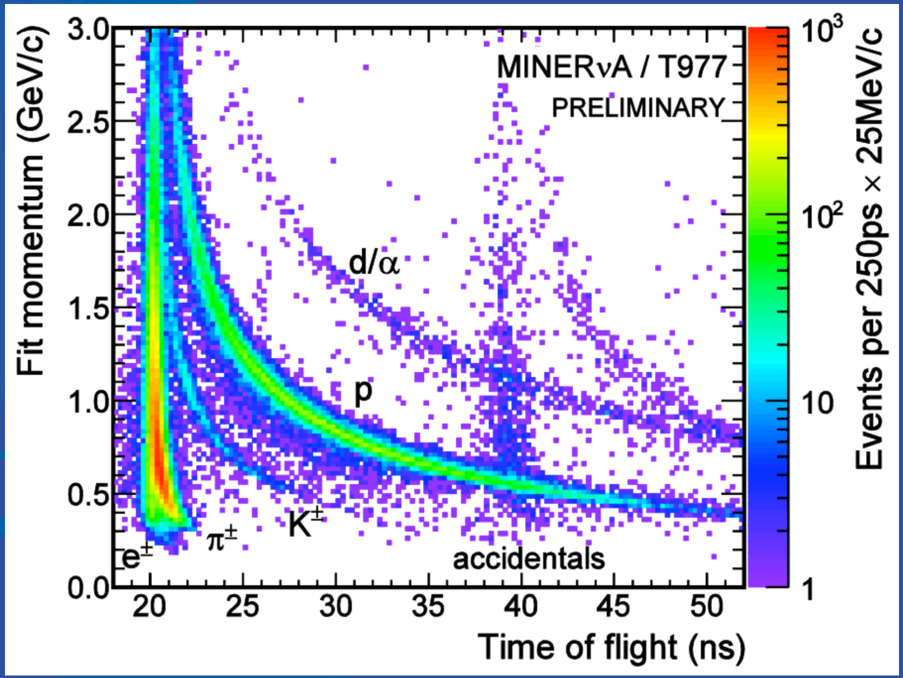
Predicted (no osc.)	150
Observed at Far Detector	130

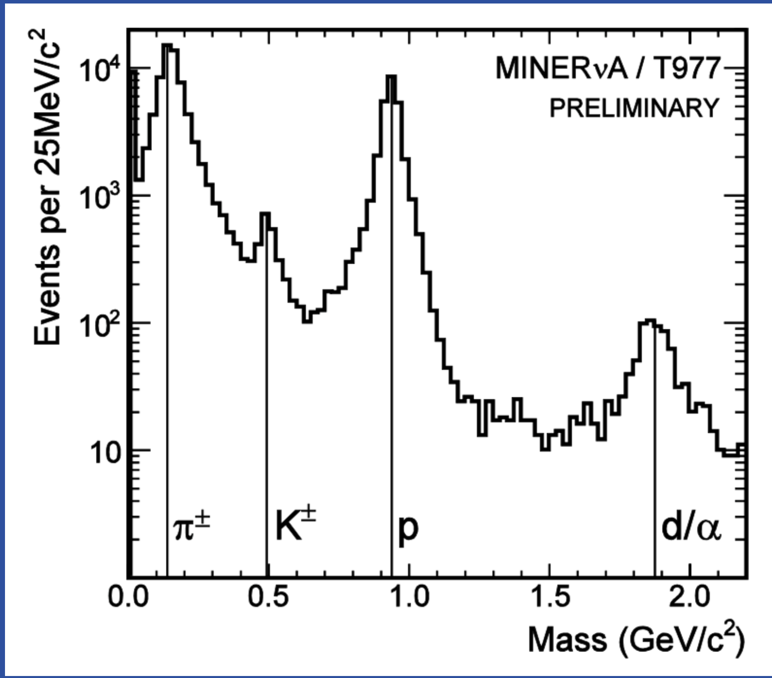
MINERνA Testbeam Activities

- FNAL M-Test beam:
  - p, π, K, μ (0.4-1.2 GeV) sent to 40-plane MINERνA replica
  - June/July, 2010
- Two configurations to study tracker, ECAL, HCAL performance

Beam data,107k accepted events

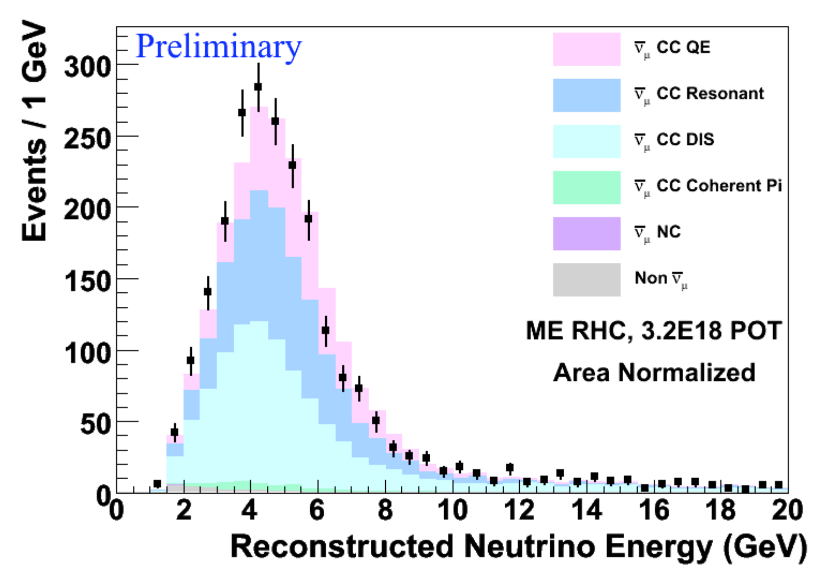






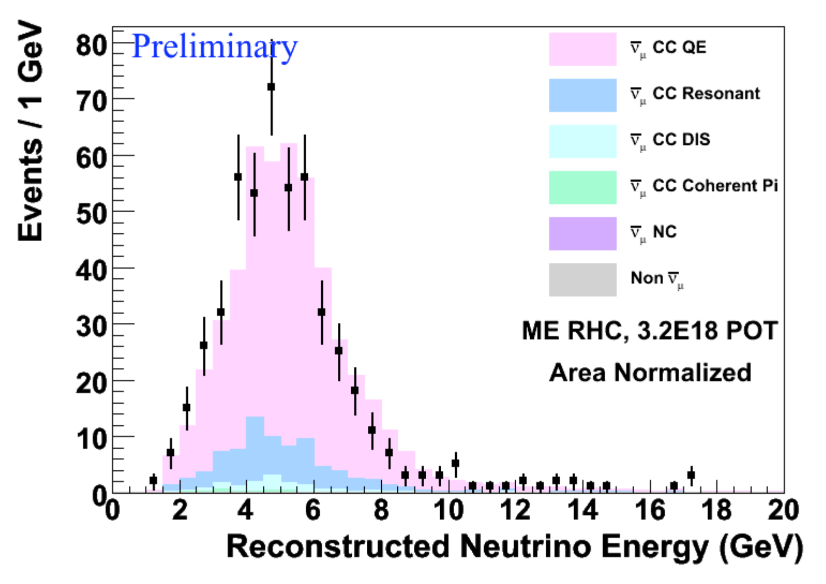
Fermilab

MINERνA CCQE in Special Runs



CC candidates

(before recoil cut)

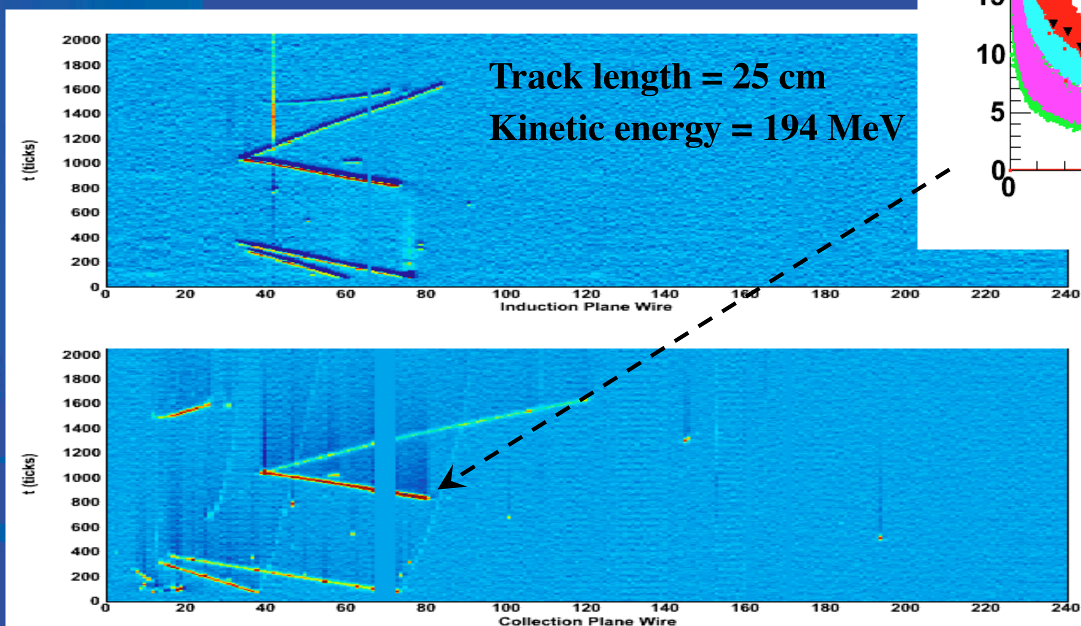


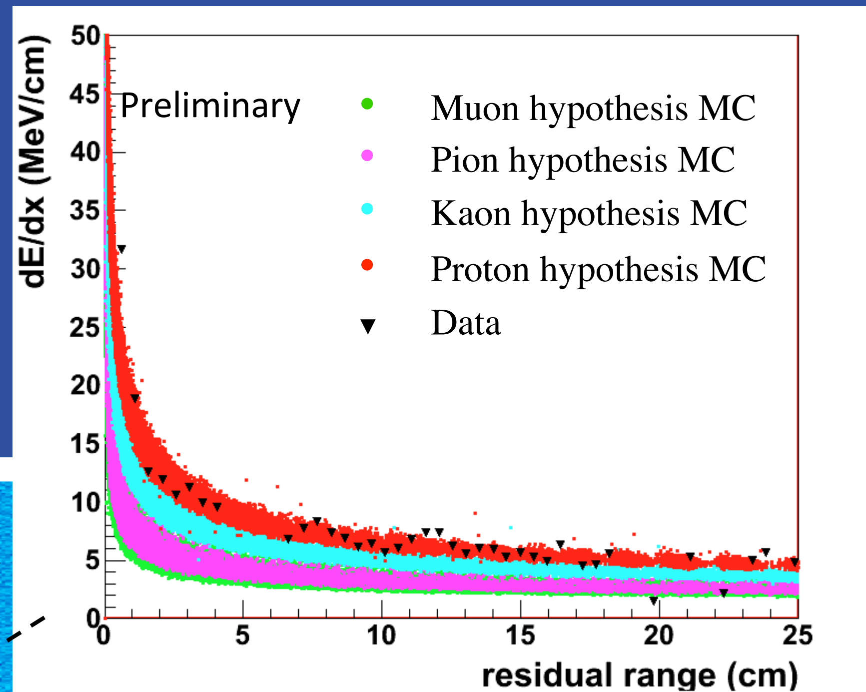
CCQE candidates

(after recoil cut)

Fermilab

ArgoNeuT: Calorimetry

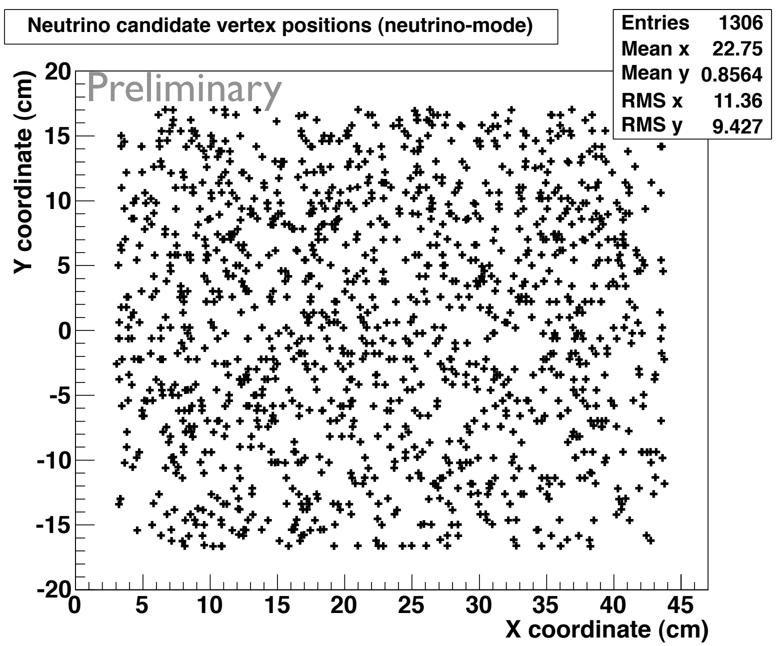




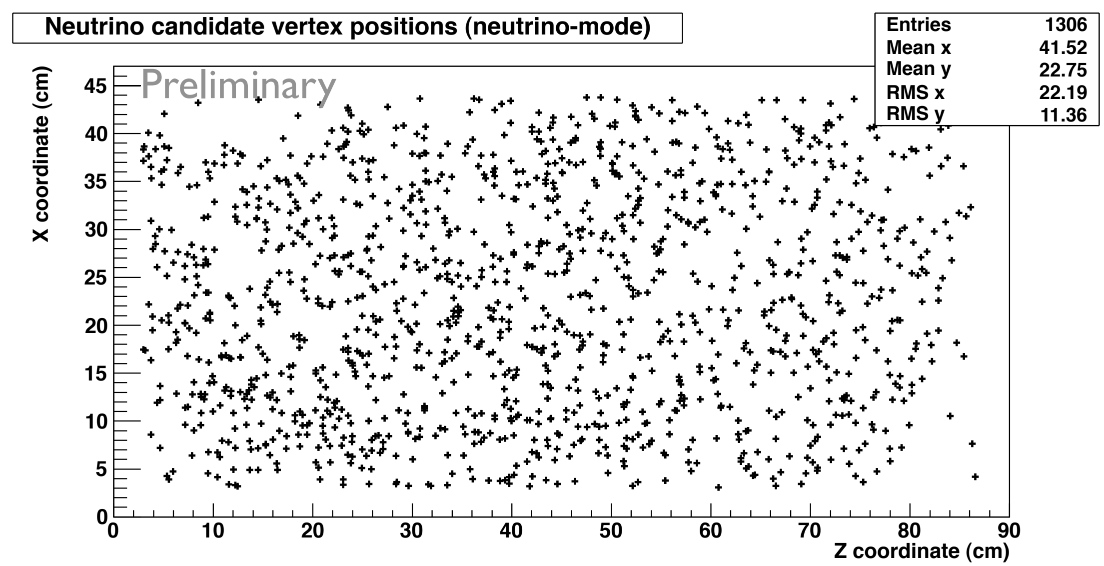
ArgoNeuT Neutrino Data

- Combination of software and eye-scan to identify neutrino candidates
- Identify 3D tracks and match to corresponding MINOS information, allowing full muon reconstruction (available soon)

Vertex position, neutrino candidates



Beam view



Top view

Computing Resources

None of the physics results shown today would have been possible without the efforts of CD:

- Framework for reconstruction and analysis code
- Database implementation/migration
- GRID submissions for simulations
- Many others…