
# ArgoNeuT physics results

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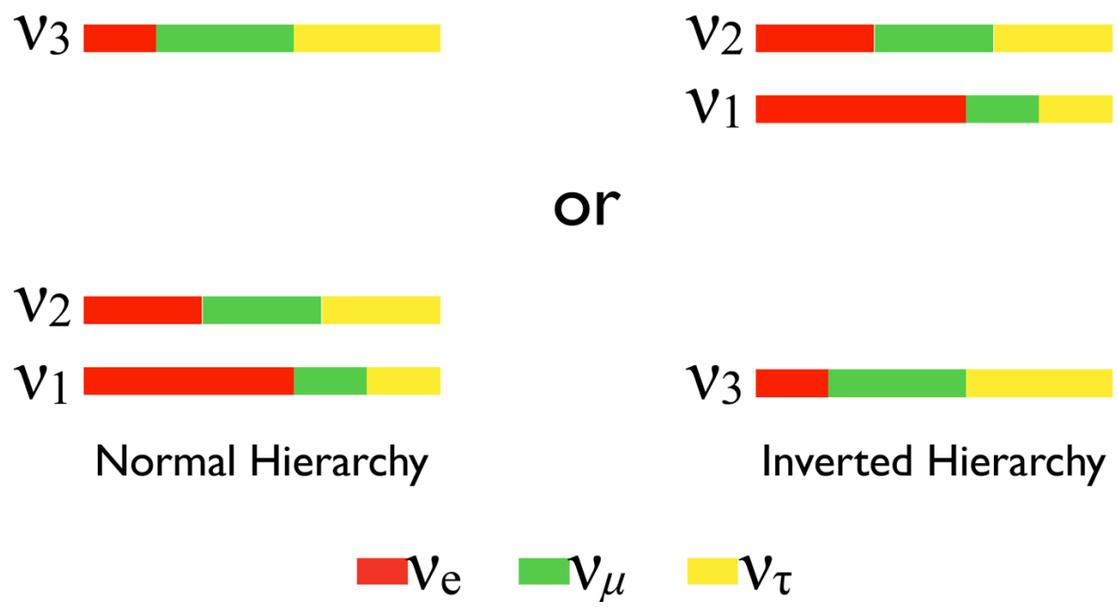
MIT

Wine & cheese 2/24/2012

# First-order goals of accelerator-based neutrino oscillation experiments

- Observe the $\nu_\mu \rightarrow \nu_e$ oscillation and measure the last mixing angle, $\theta_{13}$.
- Measure the CP violating phase, $\delta_{CP}$.
- Determine orientation of the mass hierarchy.

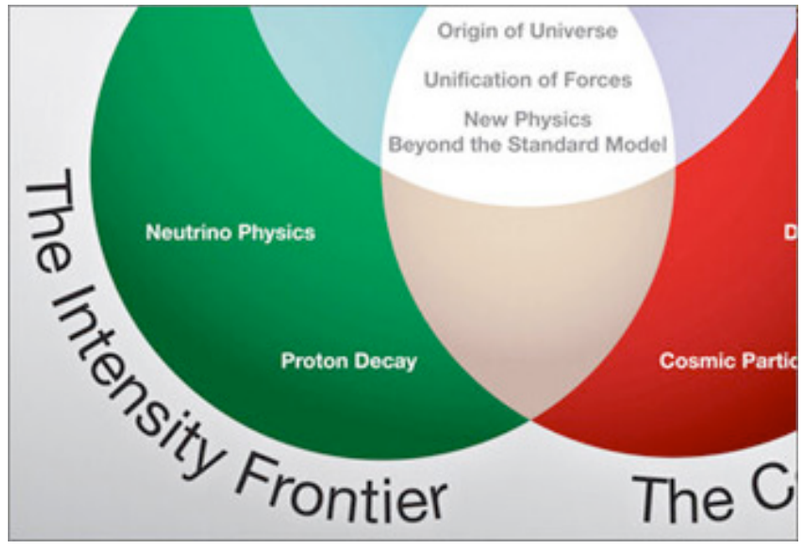


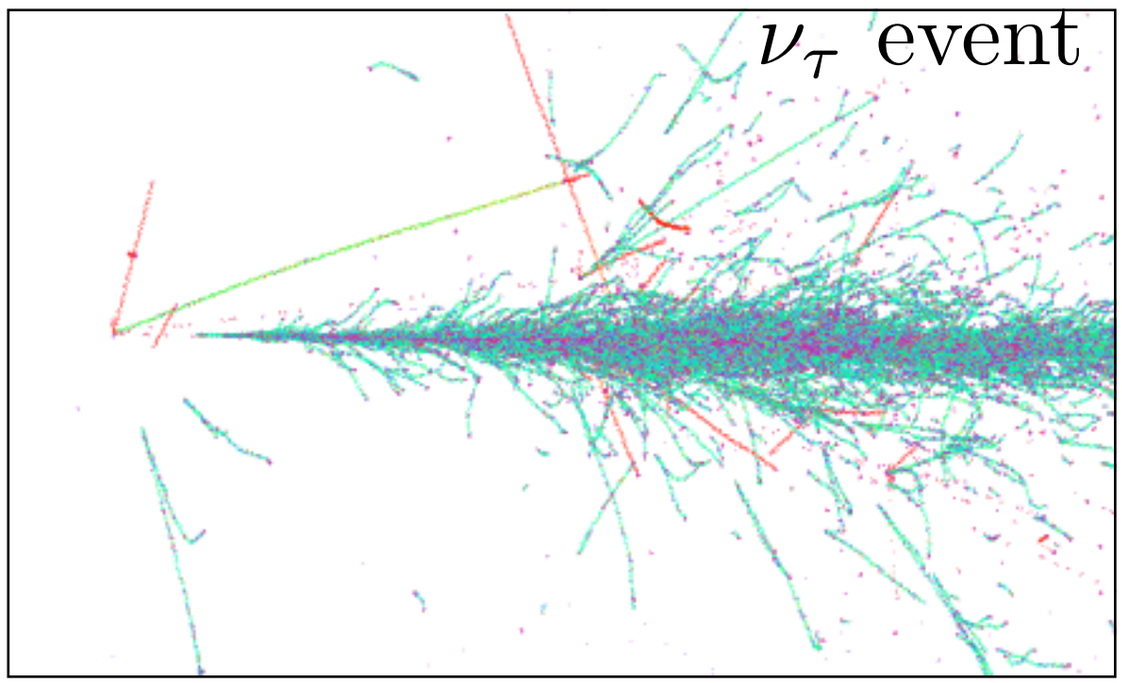

- Search for other (sterile?) neutrinos and exotic physics.

# More physics possibilities

(not a comprehensive list)

- Supernova burst and diffuse
- $\nu_\tau$
- Atmospheric $\nu$
- Proton decay
- Lorentz violation
- Cross sections and nuclear physics
  - Short range correlations, $\Delta s$, $M_A$

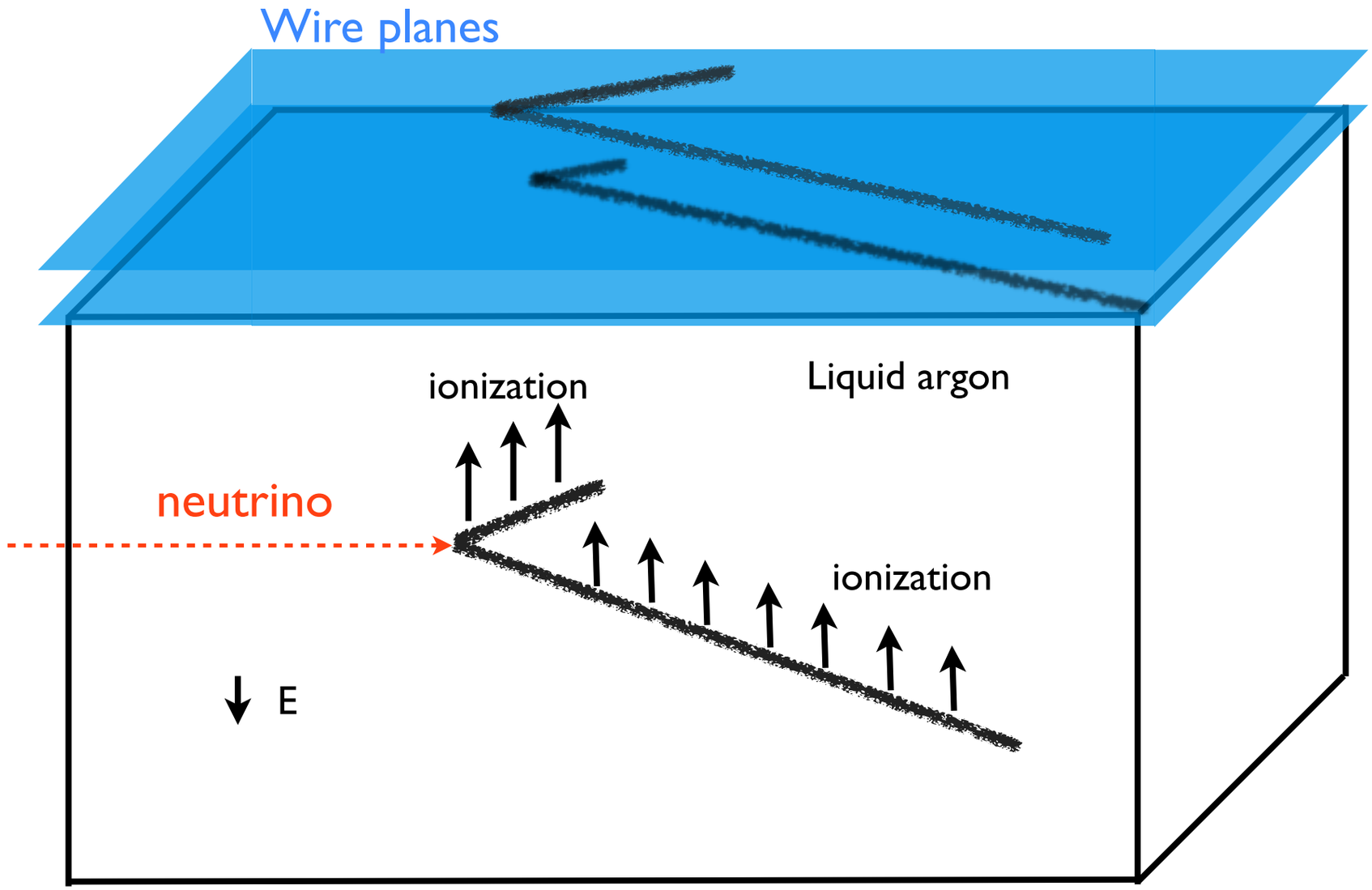


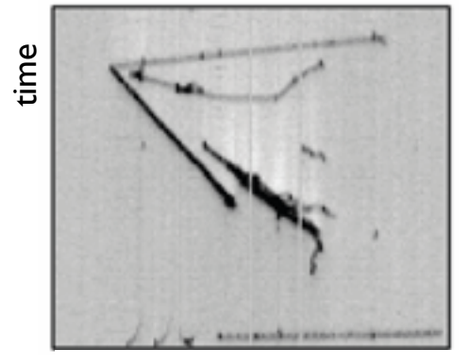
# A wish list

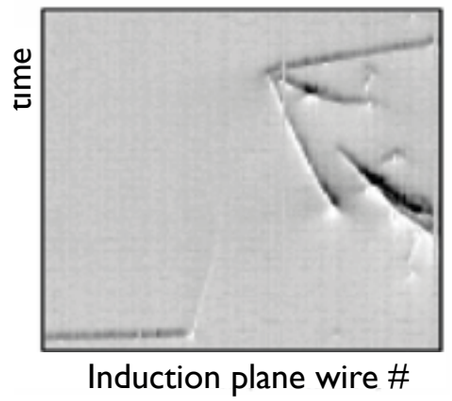
- Beam:
  - Intense, pure beam w/ a smartly chosen L/E to coincide with the parameter space of ($\Delta m^2, \theta$) that you want to explore.
- Detector(s):
  - High resolution 3D imaging
  - Precise calorimetric reconstruction
  - Fully active
  - Homogeneous volume
  - Low energy threshold
  - Particle ID (background suppression)
  - Big (scalable)

# The Liquid Argon Time Projection Chamber concept




Scintillation light is also available for detection!

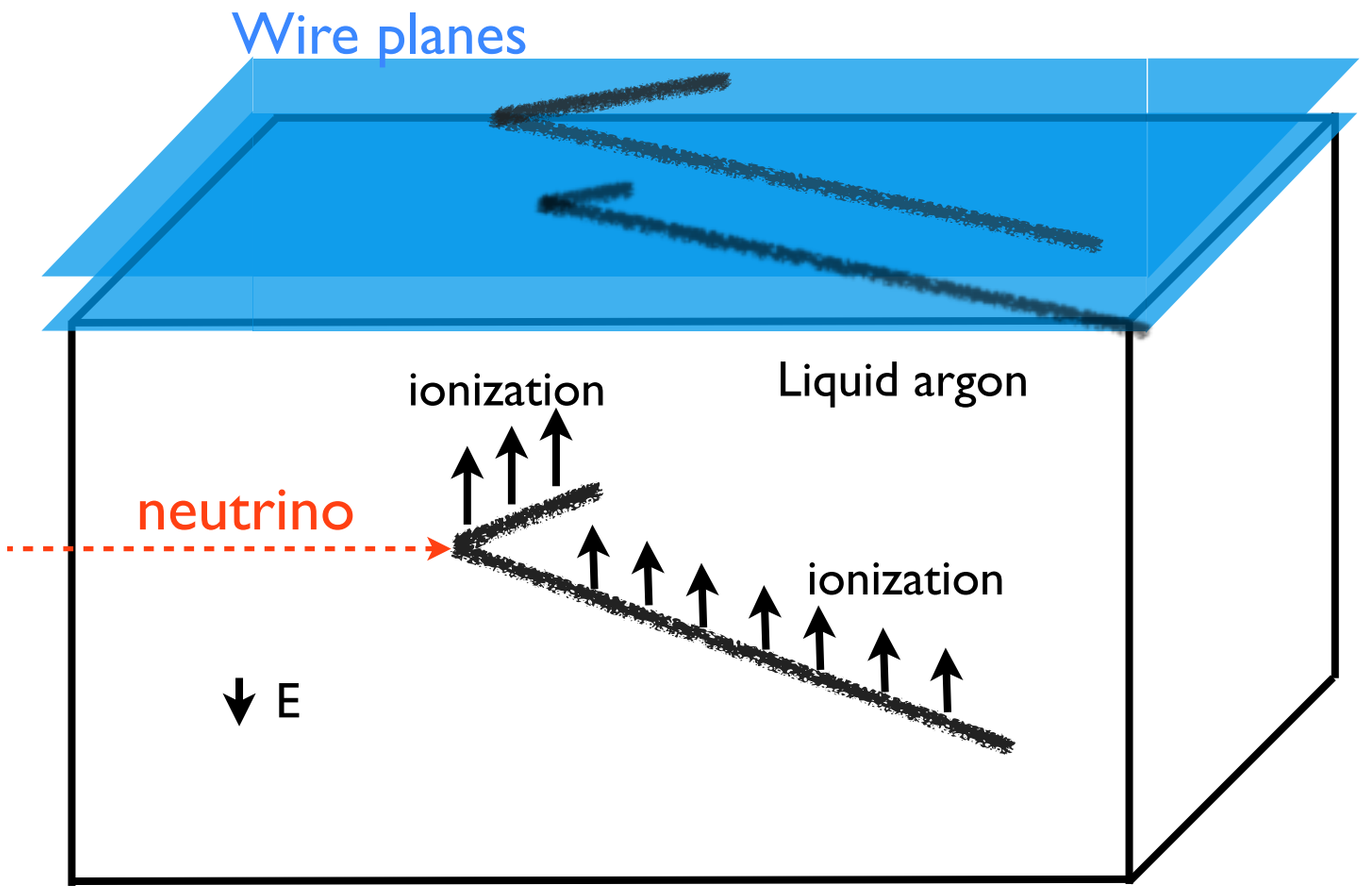



ICARUS (LArTPC pioneer)
50 L in WANF beam

Induction plane + collection plane + time
= 3D image of event (w/ calorimetric info)

# Advantages of a LArTPC




**Position resolution and topology**

-3D imaging w/ mm-scale resolution in a homogeneous and fully active detector.

**dE/dx**

-Vital to electron-neutrino tagging in appearance searches.

**Low energy threshold**

-Detection of particles with energy down to ~10 MeV.

**Always live and scalable**

Main technical challenge: obtaining and maintaining LAr purity so that the ionization trails can drift without attenuation.

# Why argon?

| |  | | | | |
|---|---|---|---|---|---|
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 |
| Density [g/cm$^3$] | 0.125 | 1.2 | 1.4 | 2.4 | 3.0 |
| Radiation Length [cm] | 755.2 | 24.0 | 14.0 | 4.9 | 2.8 |
| Scintillation [ $\gamma$ /MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 |
| dE/dx [MeV/cm] | 0.24 | 1.4 | 2.1 | 3.0 | 3.8 |
| Scintillation $\lambda$ [nm] | 80 | 78 | 128 | 150 | 175 |

Expensive

- Large ionization and scintillation yields offer two complementary methods for particle detection.
- Noble liquids also offer excellent dielectric properties for high voltage.

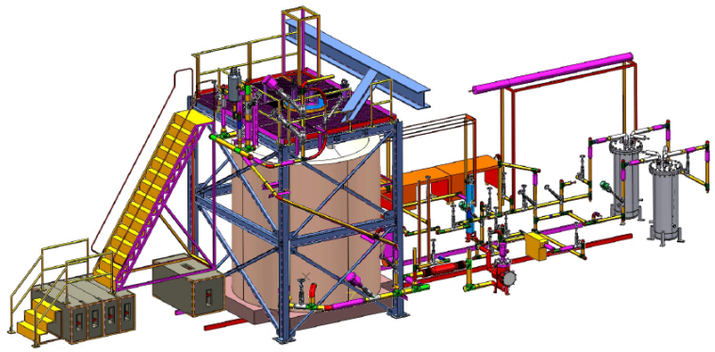
# LArTPCs at FNAL

The FNAL LArTPC program is fast moving from R&D to physics!

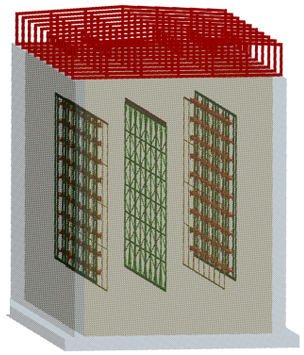
Materials Test Stand

Electronics Test Stand

Liquid Argon Purity Demonstrator



1 kiloton prototype



100% R&D

2007-

2008-

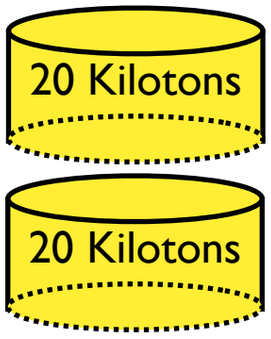
2012-

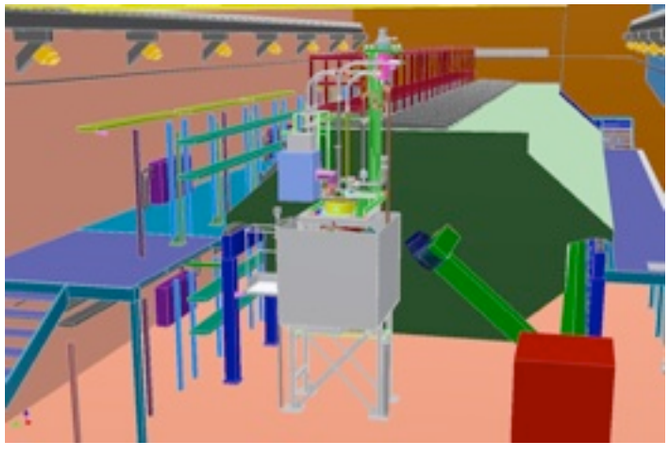
2013-

2014

100% Physics

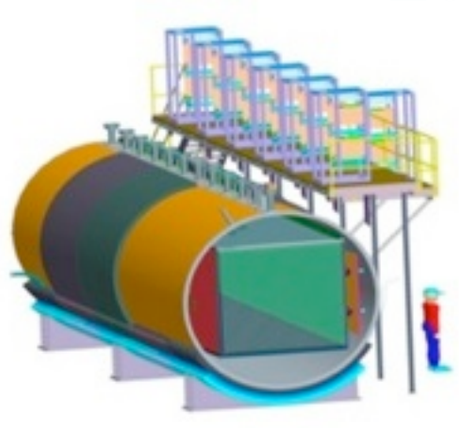
20??



## ArgoNeuT

Cross sections



## MicroBooNE

Cross sections

MiniBooNE anomalies

## LBNE

$\theta_{13}$ and $\delta_{CP}$

Proton decay

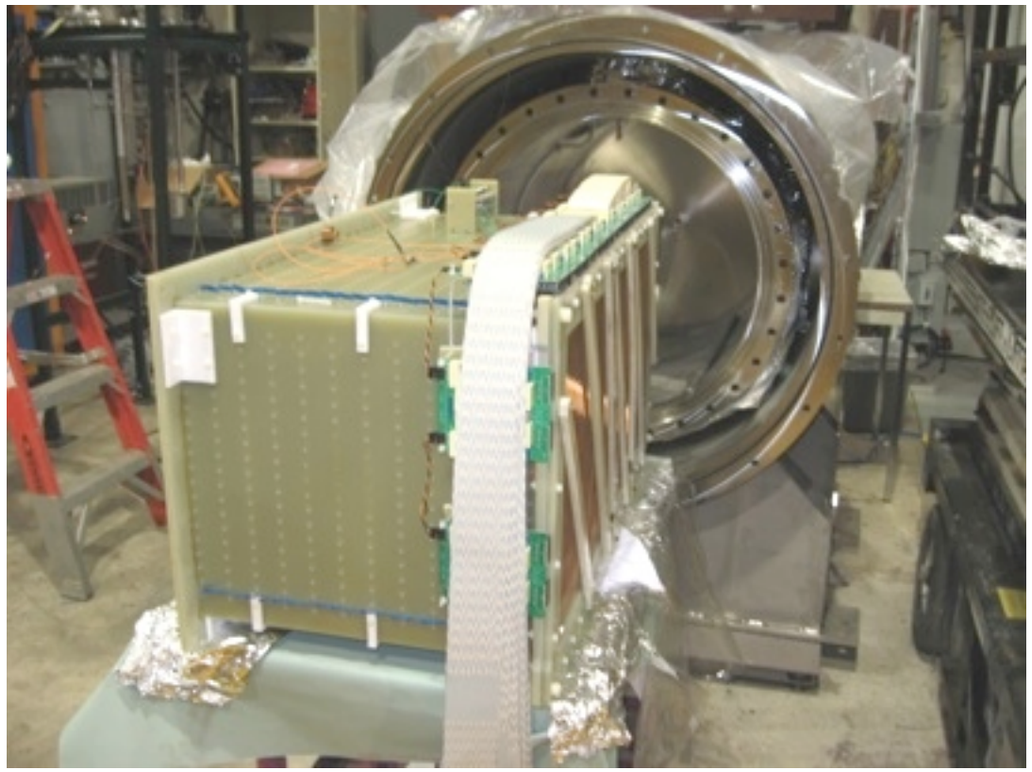
Supernova burst/diffuse

$\nu_\tau$ appearance

$\nu_\mu$ disappearance

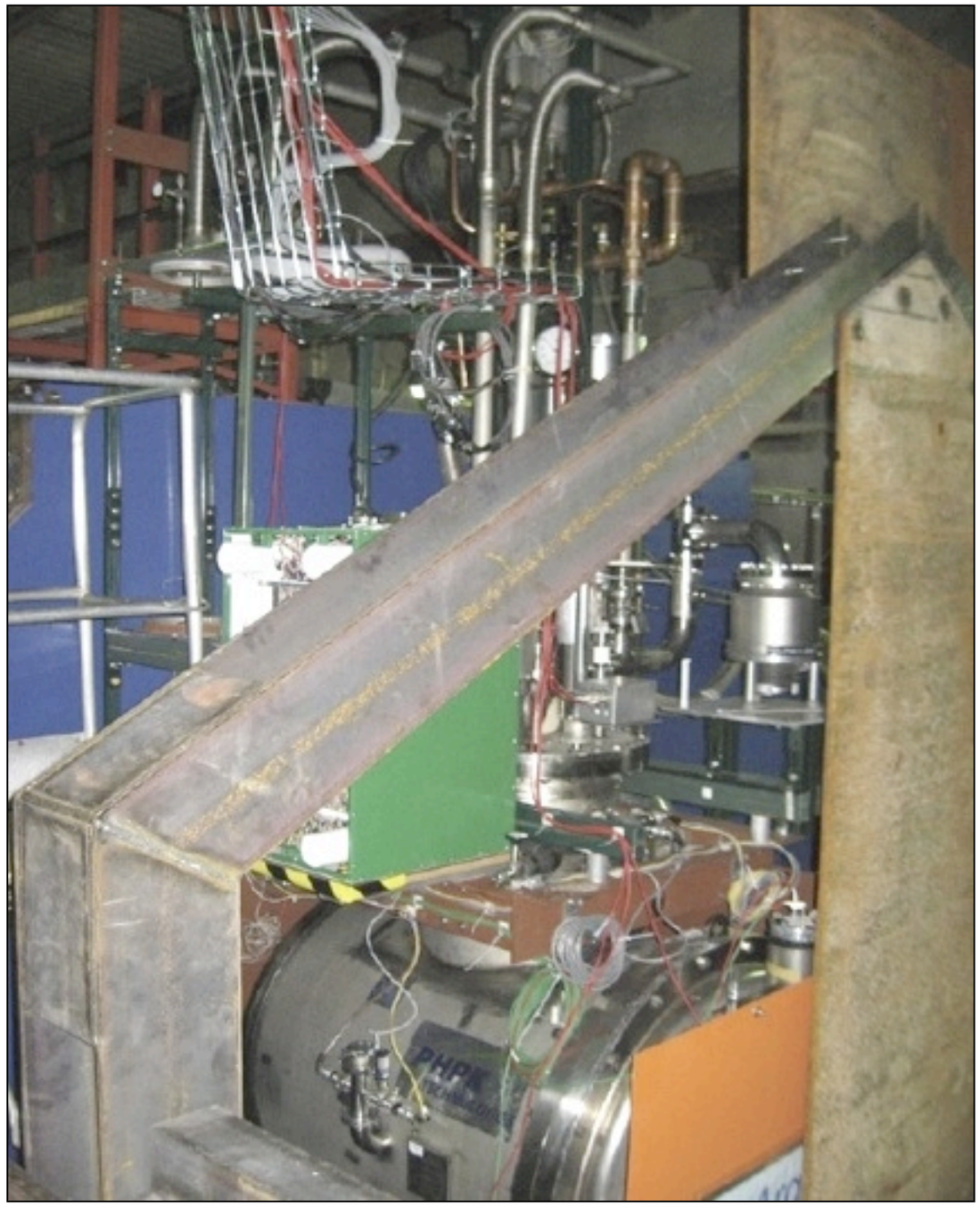
...

# ArgoNeuT TPC and cryostat



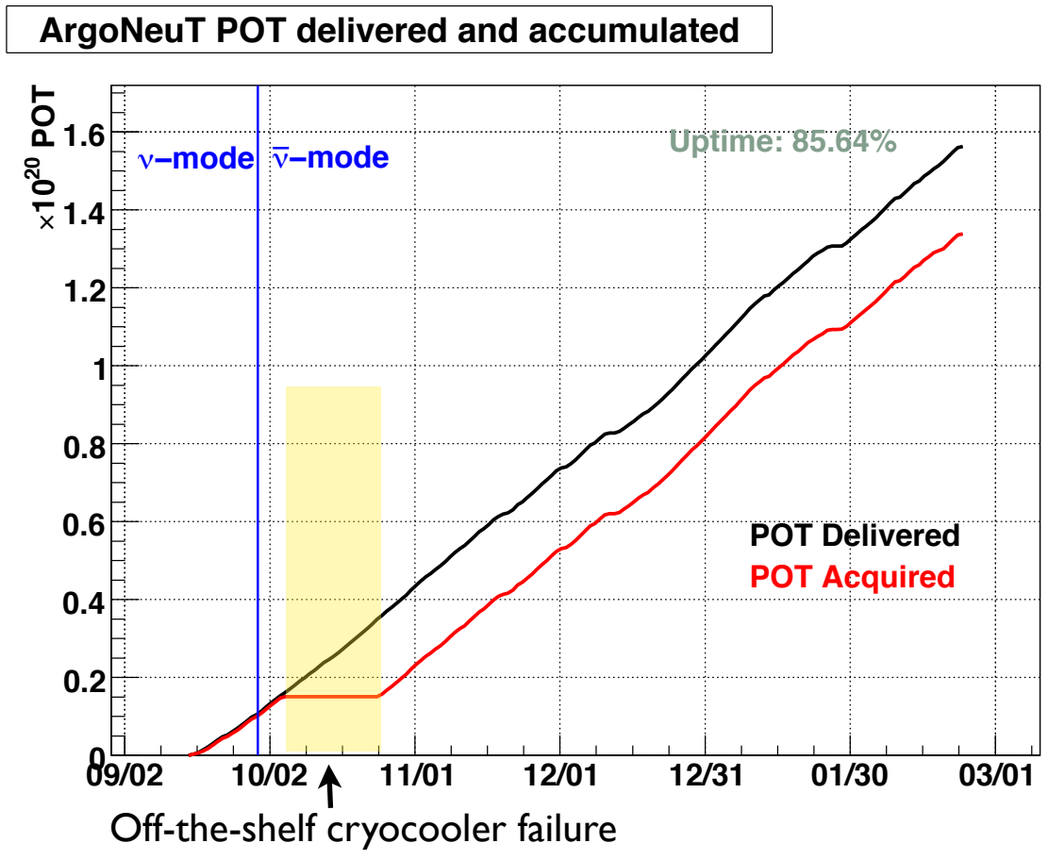
The TPC, about to enter the inner cryostat

| | |
|---|---|
| Cryostat Volume | 500 Liters |
| TPC Volume | 170 Liters |
| # Electronic Channels | 480 |
| Wire Pitch | 4 mm |
| Electronics Style (Temperature) | JFET (293 K) |
| Max. Drift Length | 47 cm |
| Light Collection | None |



The fully-instrumented detector in the beamline

# ArgoNeuT




- Goals:
  - Multiple neutrino cross section measurements.
  - Particle identification capabilities of LArTPCs will be demonstrated.
  - Developing automated reconstruction techniques, to be used for ArgoNeuT and future LArTPCs.
  - R&D for future LArTPCs.
    - Experience with LArTPC operations, obtaining and maintaining LAr purity, cryo, safety, ...

| Reaction | #events in AV (~1.35E20 POT) |
|---|---|
| $\nu_\mu$ CC | ~6600 |
| $\overline{\nu}_\mu$ CC | ~4900 |
| $\nu_\mu$ CCQE | ~600 |
| $\nu_e$ CC | ~130 |

(Before data quality cuts)

- ArgoNeuT (NSF/DOE) has completed its physics run, lasting from 9/14/2009-2/22/2010.
- Stable, shift-free operation for >5 months!
- The first 1000s of (anti-)neutrino LArTPC events collected in a low-energy (<4 GeV>) neutrino beam ever!

# Cryo-system


Nuclear Instruments and Methods in Physics Research A 605 (2009) 306–311

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A regenerable filter for liquid argon purification

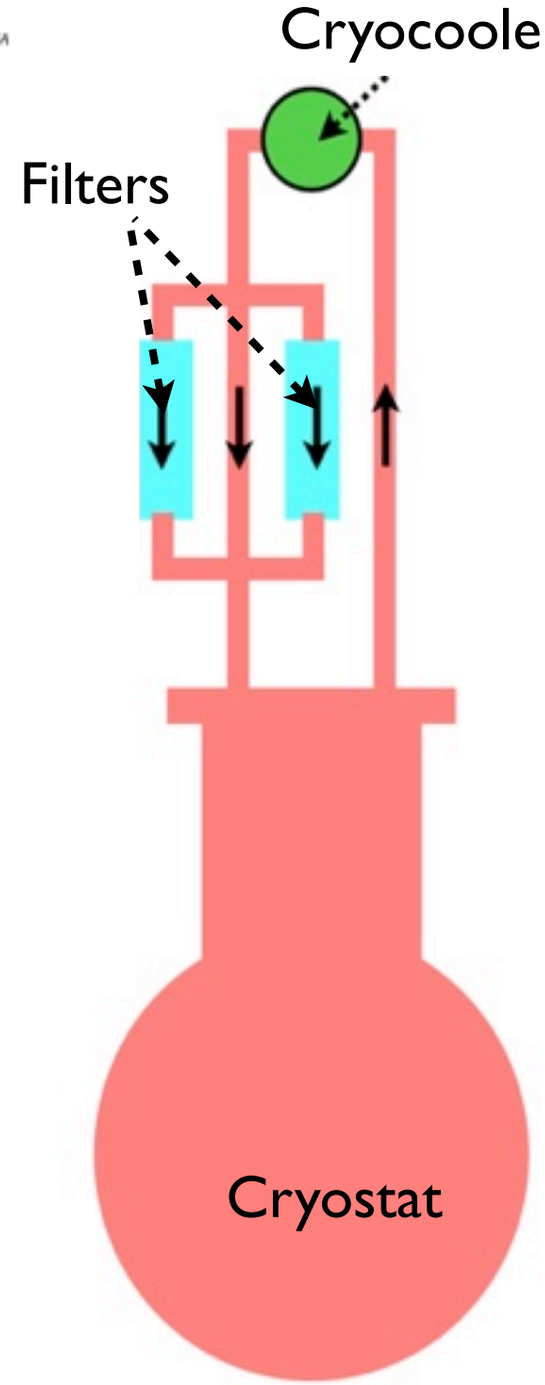
A. Curioni [b], B.T. Fleming [b], W. Jaskierny [a], C. Kendziora [a], J. Krider [a], S. Pordes [a], M. Soderberg [b], J. Spitz [b,*], T. Tope [a], T. Wongjirad [b]

[a] Particle Physics Division, Fermi National Accelerator Laboratory, Chicago, IL, USA
[b] Department of Physics, Yale University, New Haven, CT, USA

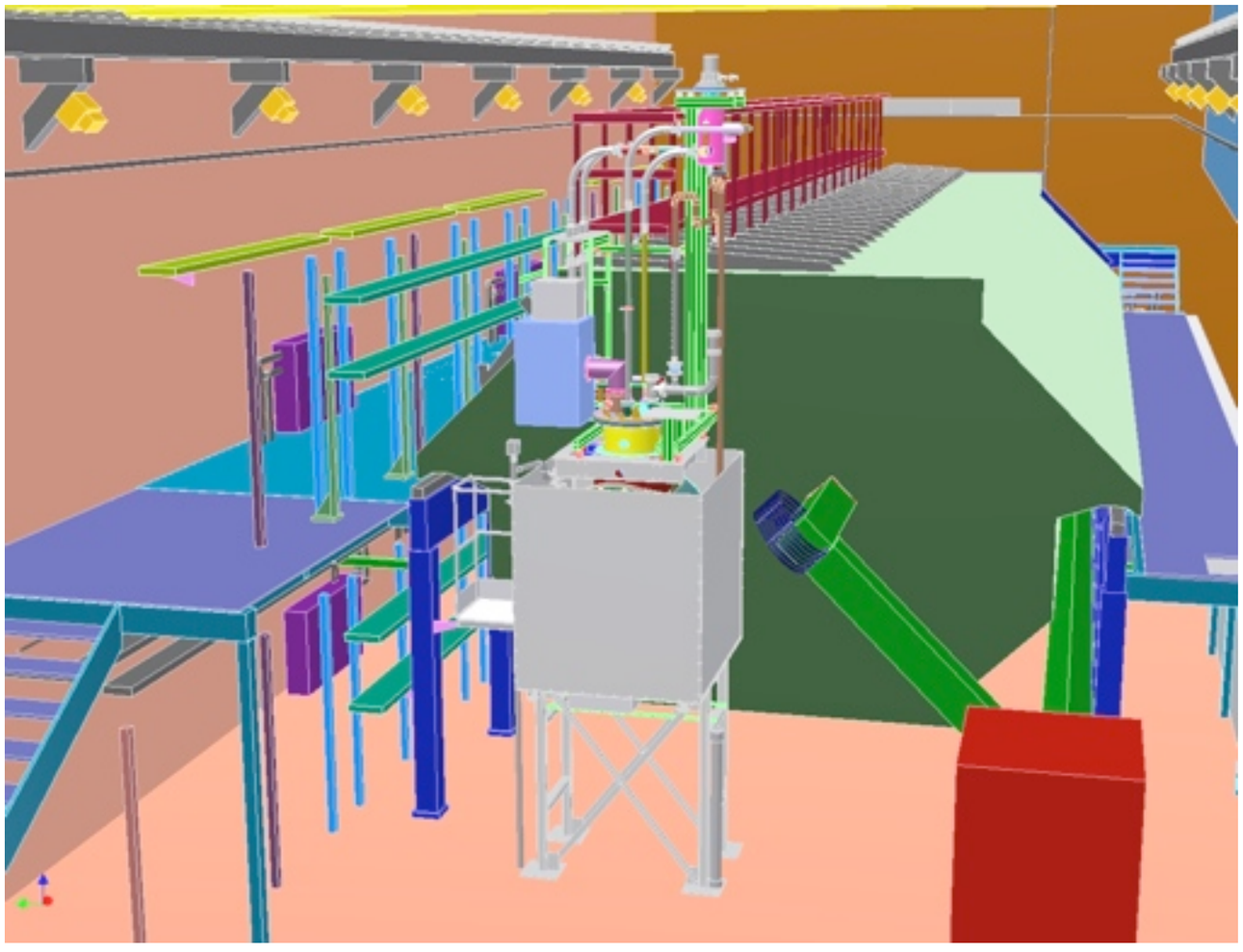
- Self contained system
- Recirculate argon through a copper-based filter.
- Cryocooler used to recondense boil-off gas.
- Multiple relief paths for safe running.

300W Cryocooler

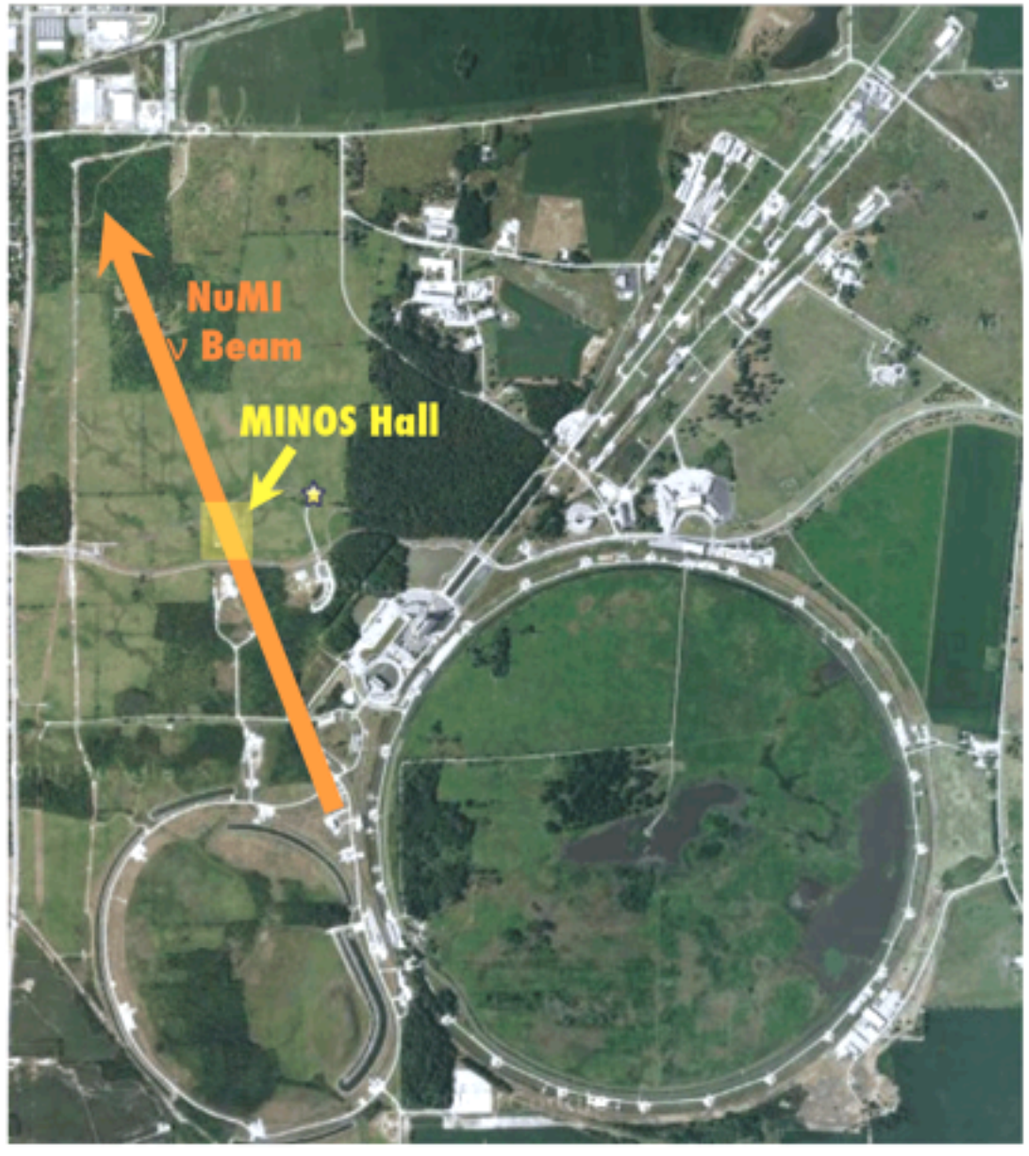

Vacuum-Jacketed Cryostat



# ArgoNeuT in the NuMI beam



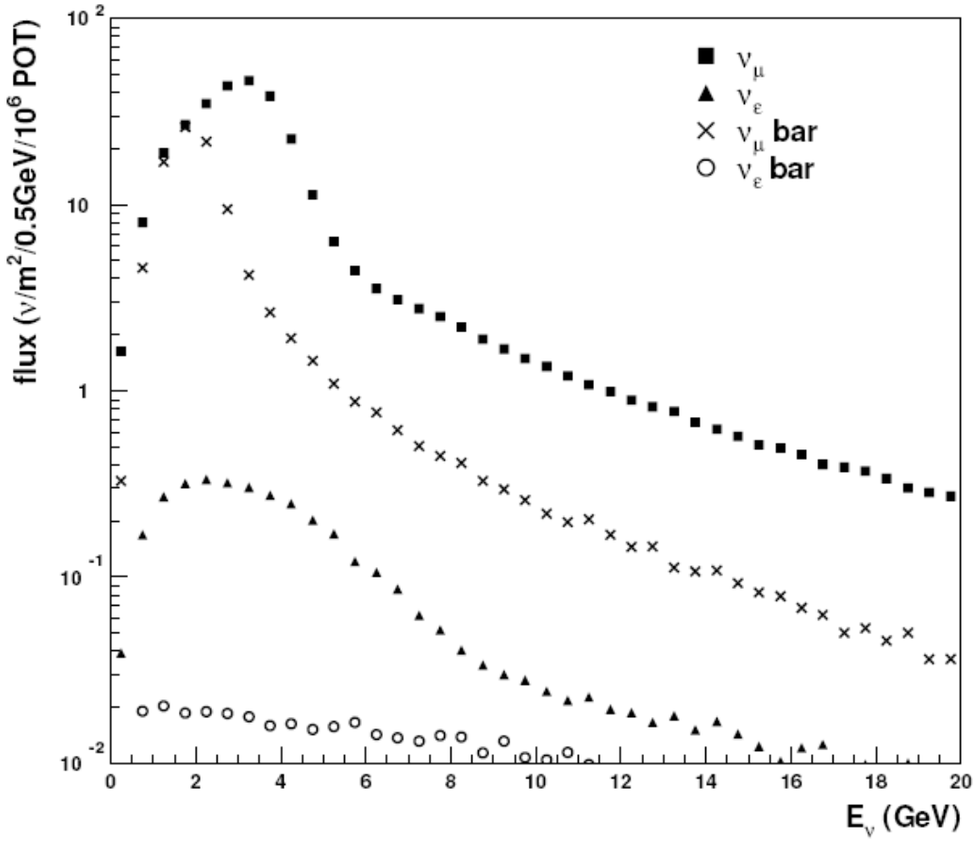
ArgoNeuT, just upstream of the MINOS near detector

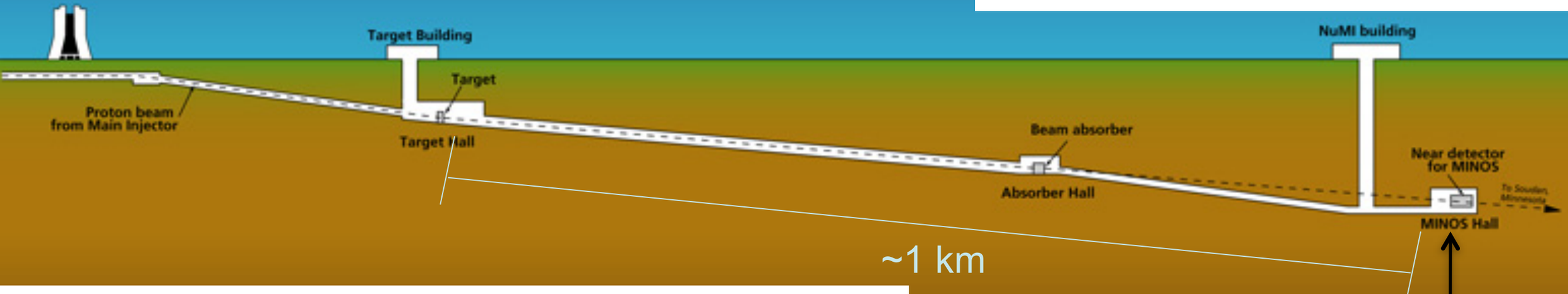


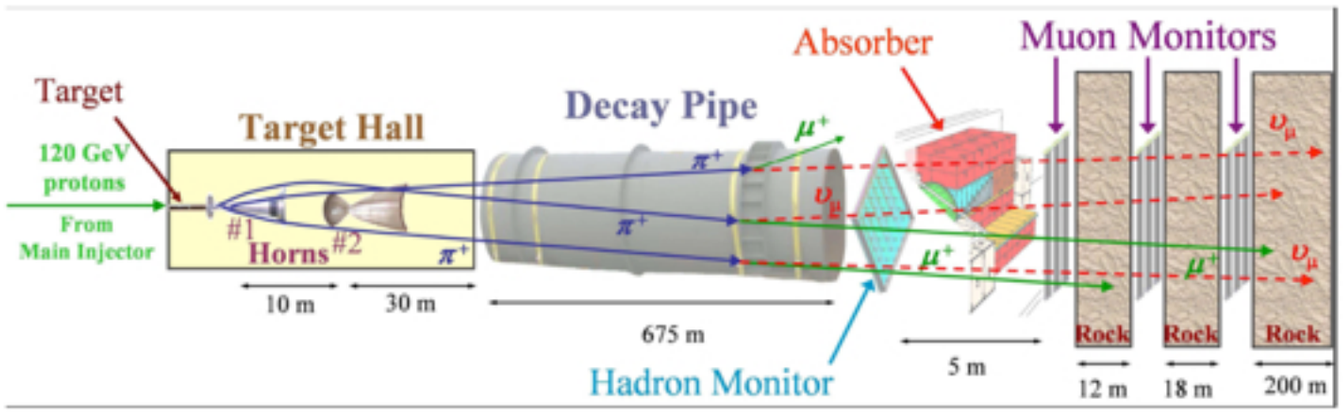

NuMI beamline at Fermilab

[MINOS Collaboration], Nucl. Instr. Meth. A **190**, 596 (2008)

# NuMI Tunnel Project



# A few ArgoNeuT photos

# Bringing ArgoNeuT underground

Fermilab *Today*

Wednesday, March 17, 2010

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**Calendar**

Have a safe day!

**Wednesday, March 17**
**3:30 p.m.**
DIRECTOR'S COFFEE BREAK - 2nd Flr X-Over
**4 p.m.**
Fermilab Colloquium - One West
Speaker: Thomas Levinson, Massachusetts Institute of Technology
Title: The Unknown Detective Career of...Isaac Newton?

**Thursday, March 18**
**2 p.m.**
Computing Techniques Seminar - FCC1
Speaker: Andrew

**Feature**

**ArgoNeuT detector, collaborators resurface**



ArgoNeuT Spokesperson Mitch Soderberg and graduate student Josh Spitz accompanied the ArgoNeuT detector to the MINOS hall.

**From the CMS Center**

**CMS comes on strong**

*Lothar Bauerdick, head of the CMS Center at Fermilab, wrote this week's column.*

Lothar Bauerdick

CMS has made good use of the time since the LHC pilot run last year, which started the LHC physics program with its first proton-proton collisions on Nov. 23. The machine delivered to CMS a luminosity of about 16 inverse microbarn at 900 GeV, and CMS recorded data with a high 87 percent efficiency. In terms of physics, this was a tiny amount of luminosity, but commissioning the detector and getting a first glimpse at physics data

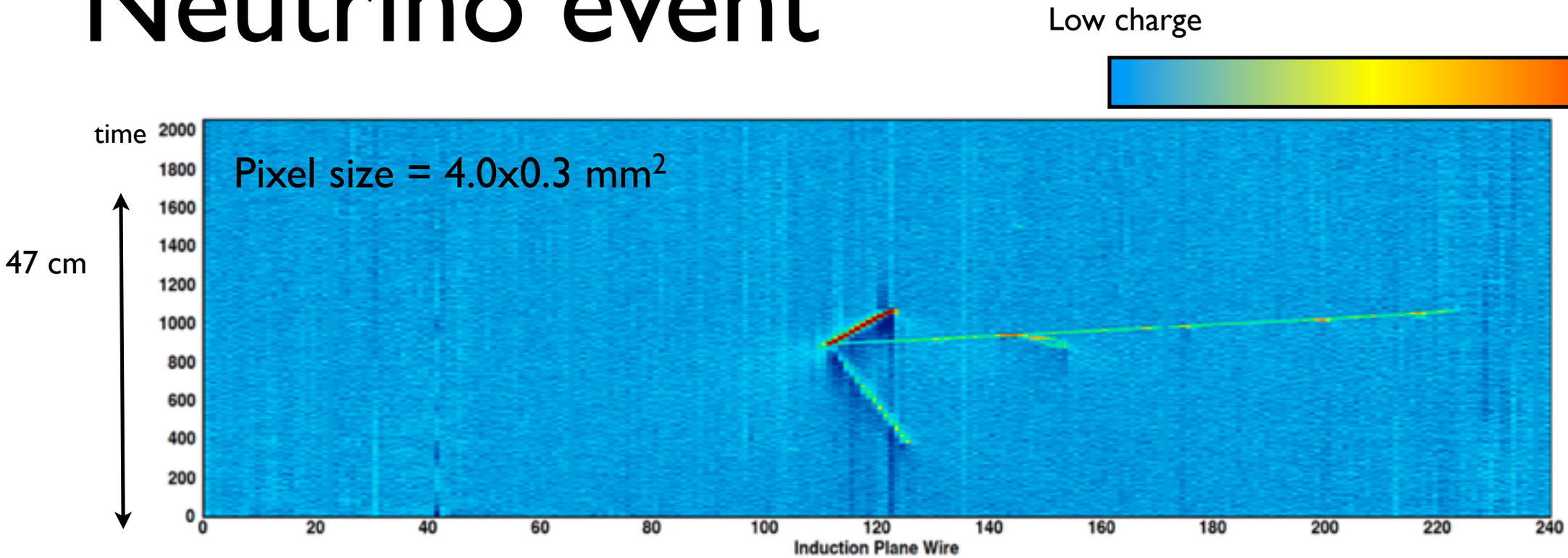
# Installation

# Filter regeneration

# Diagnosing the cryocooler failure

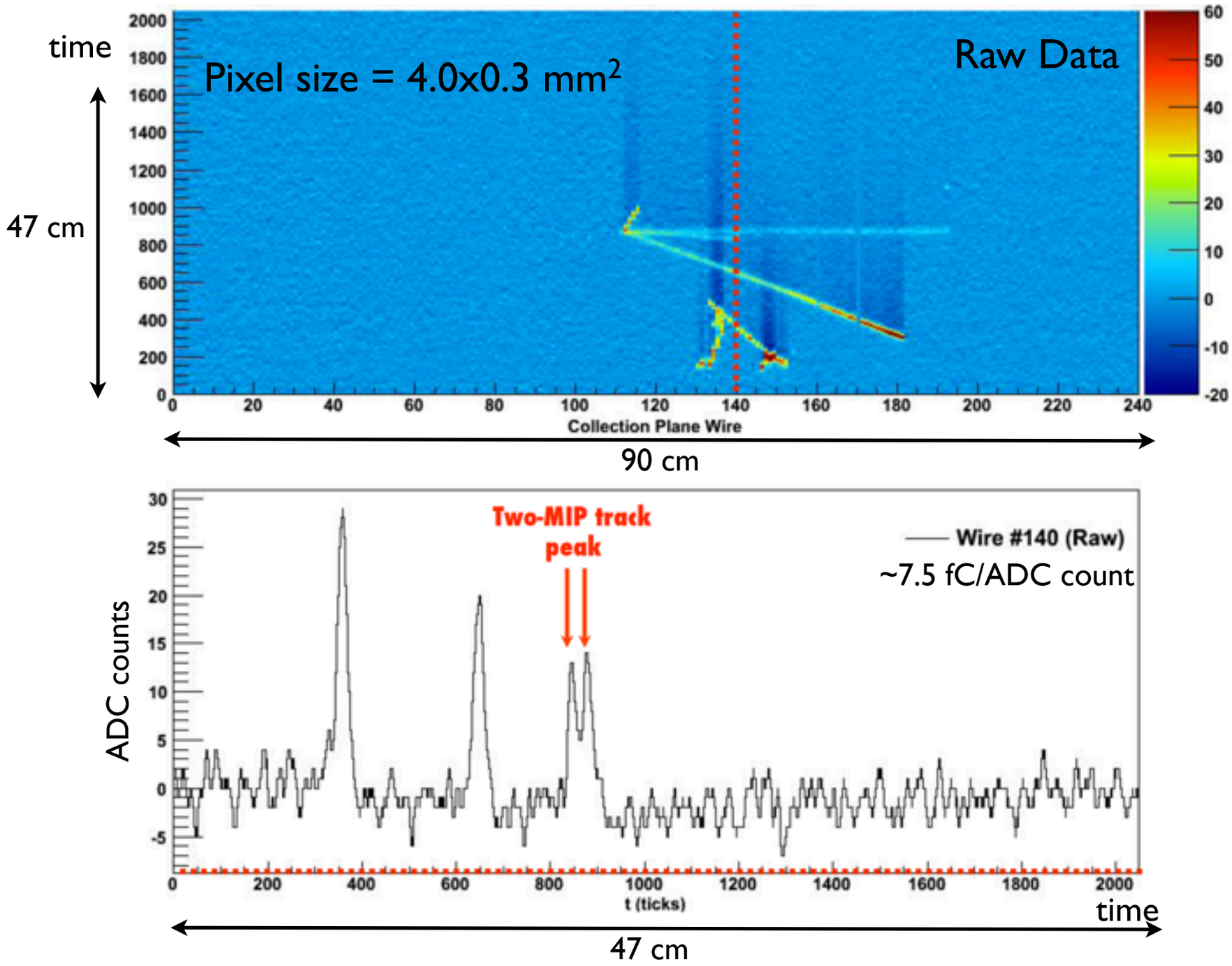
# The end of the physics run

# Neutrino event




- The detector provides two 2D-views of an event.
- The color scale is semi-indicative of the energy deposited along the track.

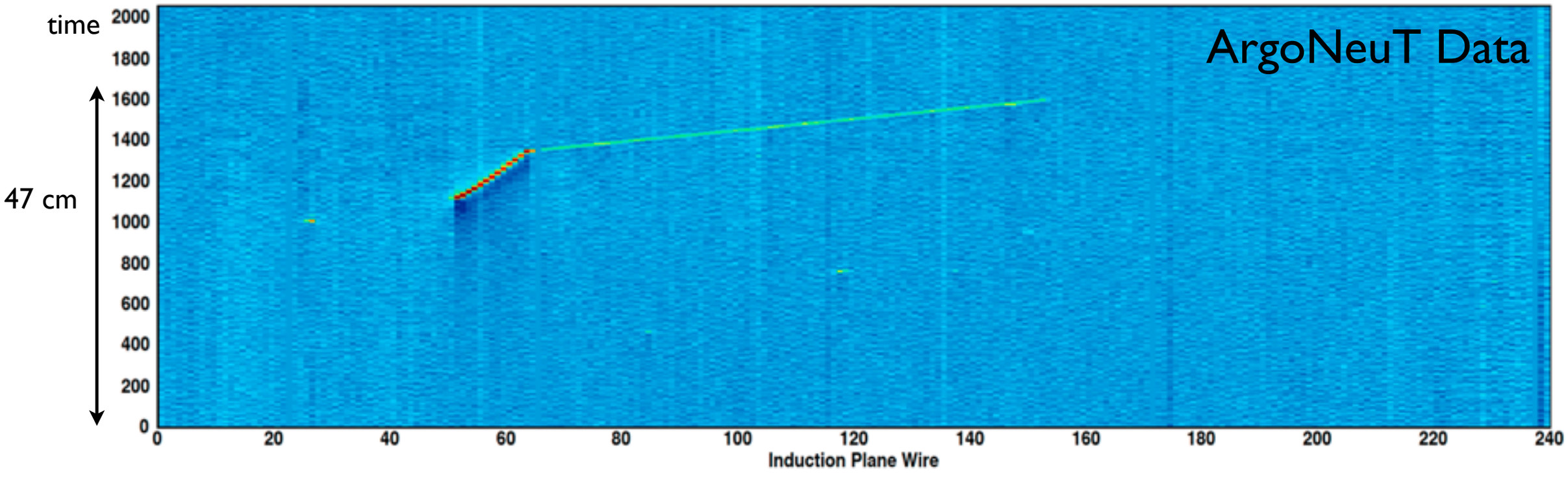
# Wire pulses

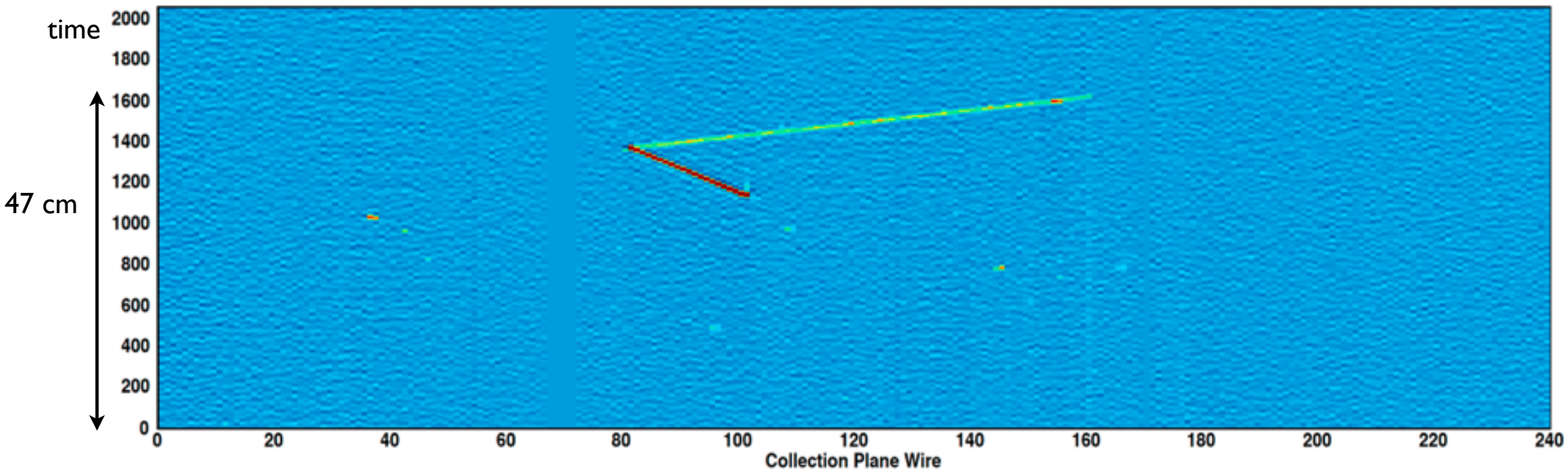



The actual wire pulses can be seen here in the "wire view".

Low charge

High charge

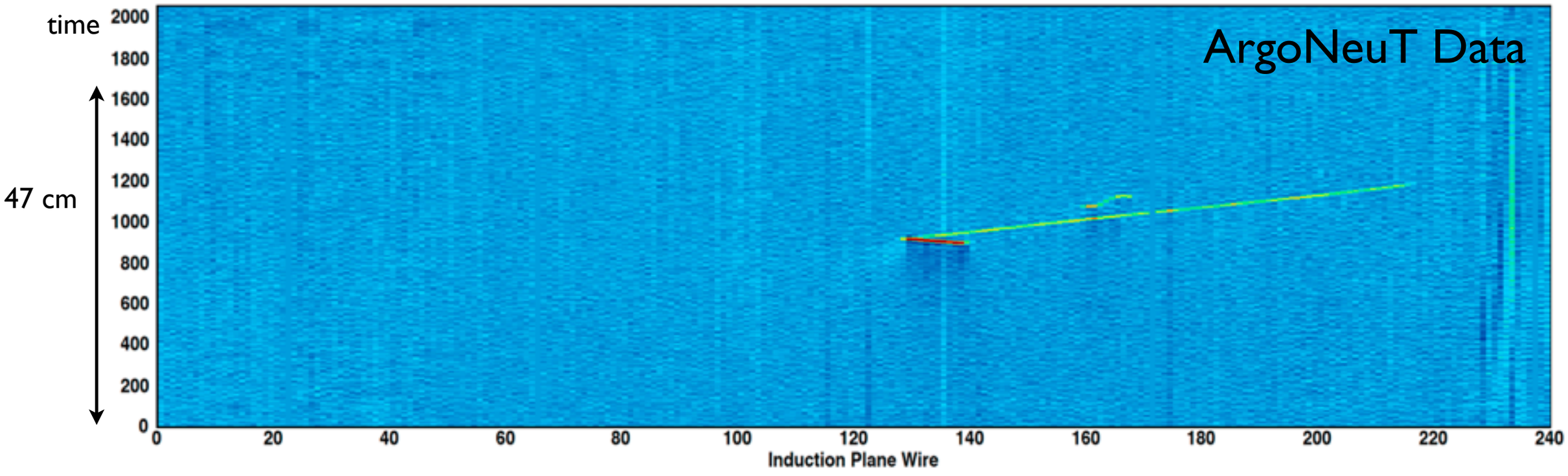


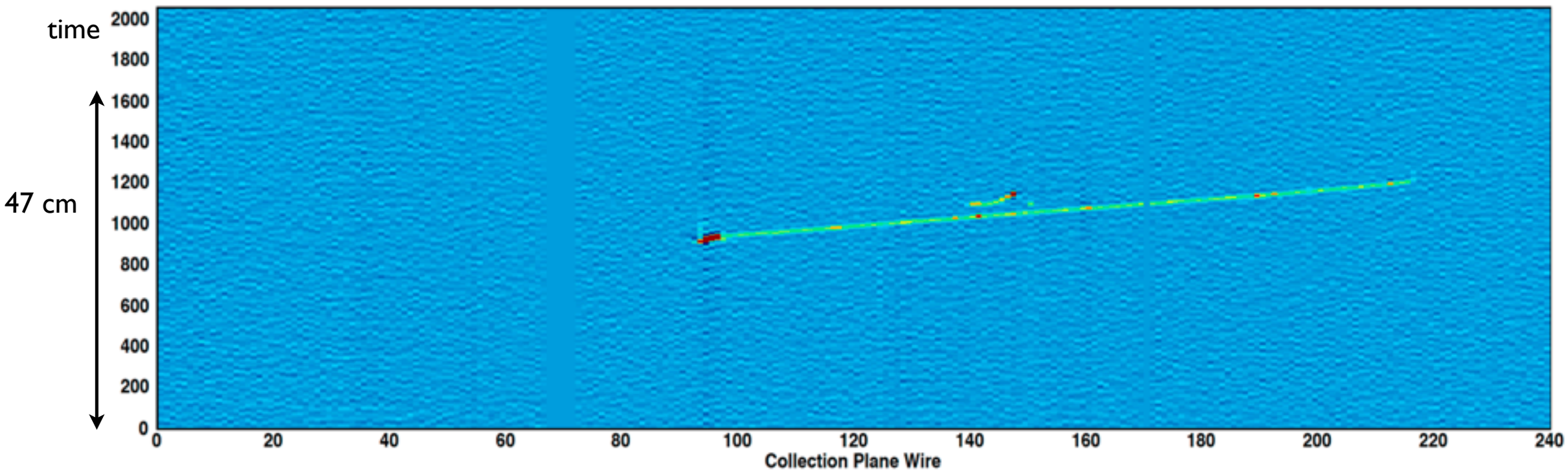




90 cm

Low charge

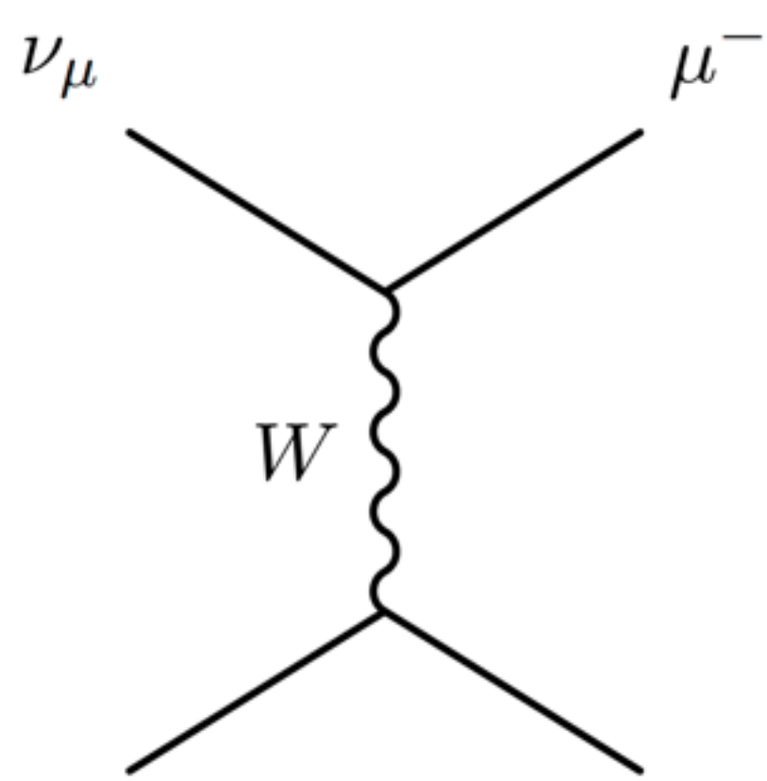
High charge



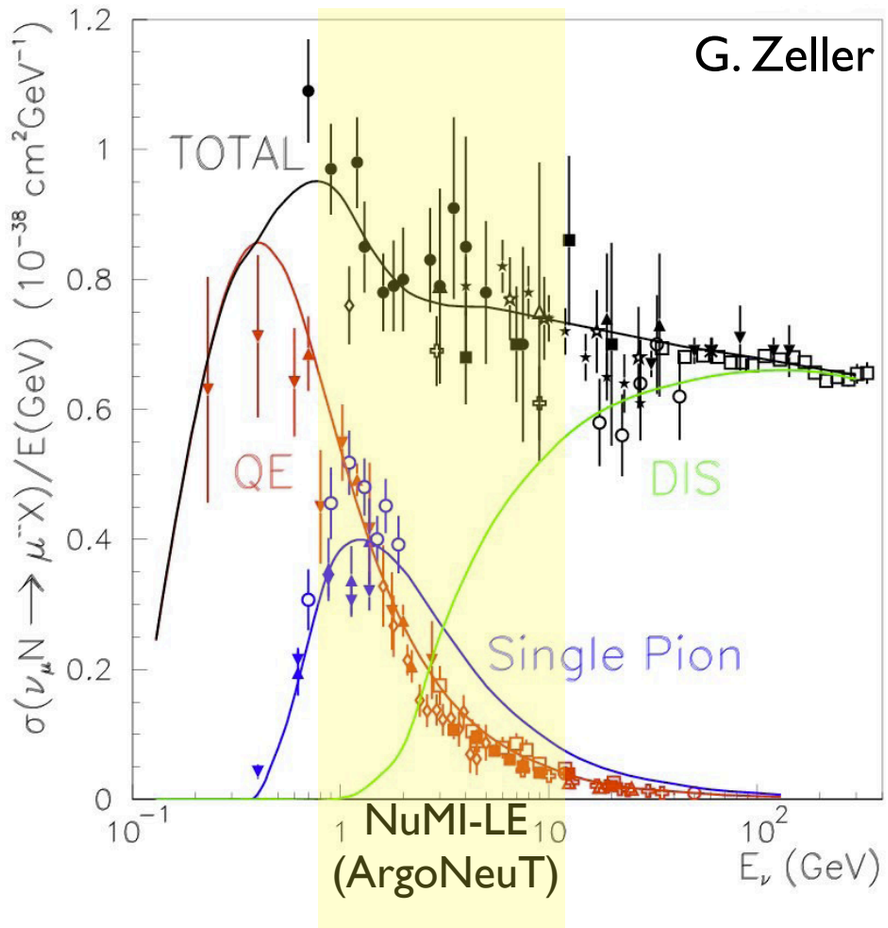

90 cm

# Muon neutrino charged current differential cross sections as measured by ArgoNeuT



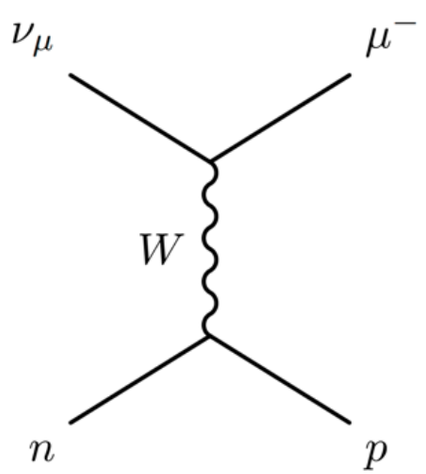
# The charged current cross section

- Measuring the inclusive charged current cross section does not require classification of the neutrino event beyond "it has a negative muon in the final state".
- All experiments can reconstruct the muon even if they have varying levels of blindness to the hadronic component of neutrino interactions.
  - CC-inclusive is a "standard candle".




CC Quasi-elastic

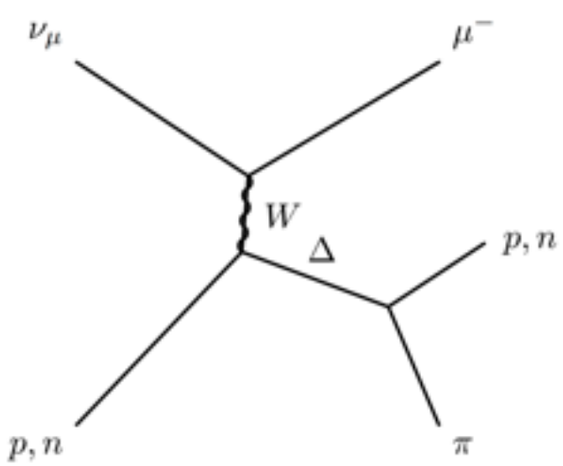
nucleon changes, but doesn't break up




+

CC Single pion

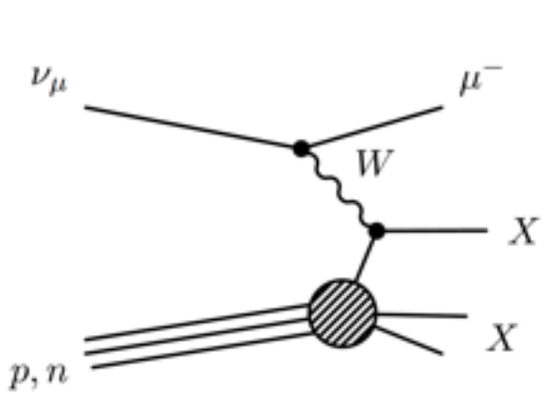
nucleon excites to resonance state




+

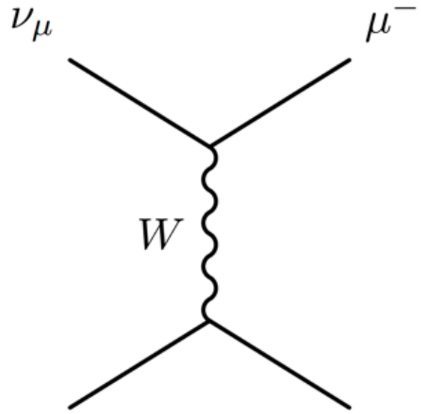
CC Deep Inelastic

nucleon breaks up




≈

Total CC



# Measuring a differential cross section

The differential cross sections reported here basically answer the question: What is the probability for a muon-neutrino charged current interaction to create an outgoing muon with a certain angle/momentum?

$u = \theta_\mu$ and $P_\mu$

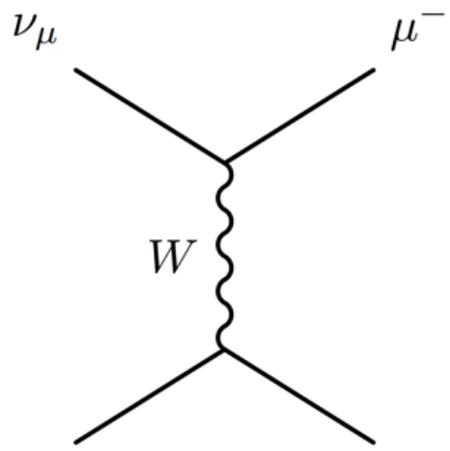
$$\frac{\partial\sigma(u_i)}{\partial u} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \epsilon_i N_{\text{targ}} \Phi}$$

$\Delta u_i$ = bin width

$\Phi$ = Integrated flux of neutrinos

$\epsilon_i$ = detection efficiency

$N_{\text{targ}}$ = Number of targets in volume



# Simulation and reconstruction

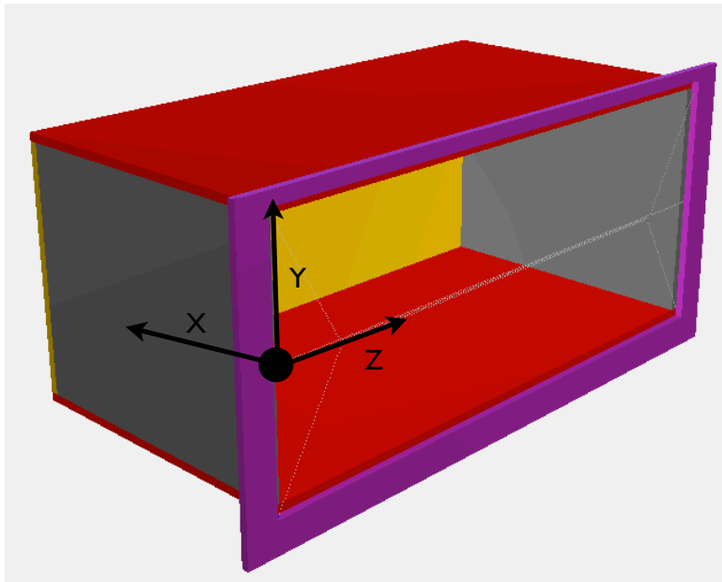
# Simulating neutrino events

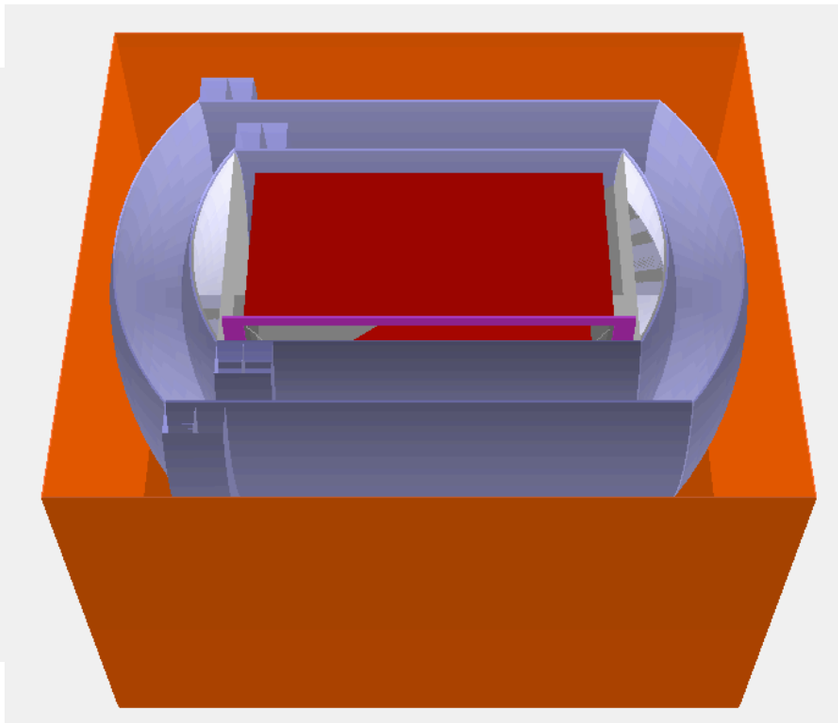
$$\frac{\partial\sigma(u_i)}{\partial u}_{(u=\theta_\mu \text{ and } P_\mu)} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \epsilon_i N_{\text{targ}} \Phi}$$

- Simulation is required in order to determine the background estimate and the detection efficiency.
- The simulation also helps to refine reconstruction techniques.

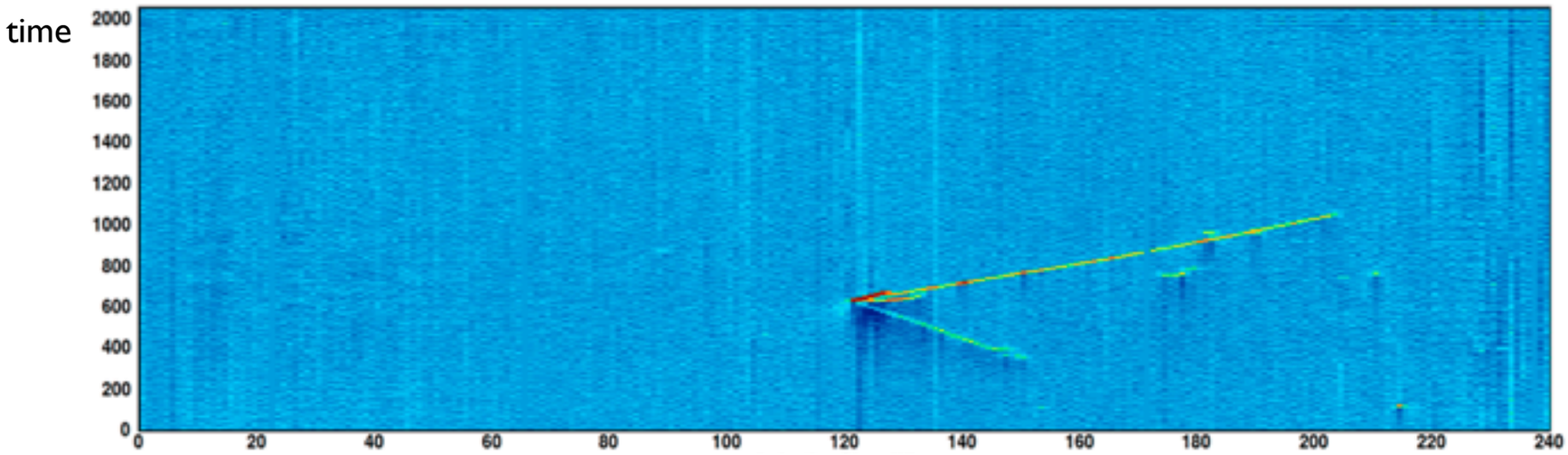
## What is simulated?

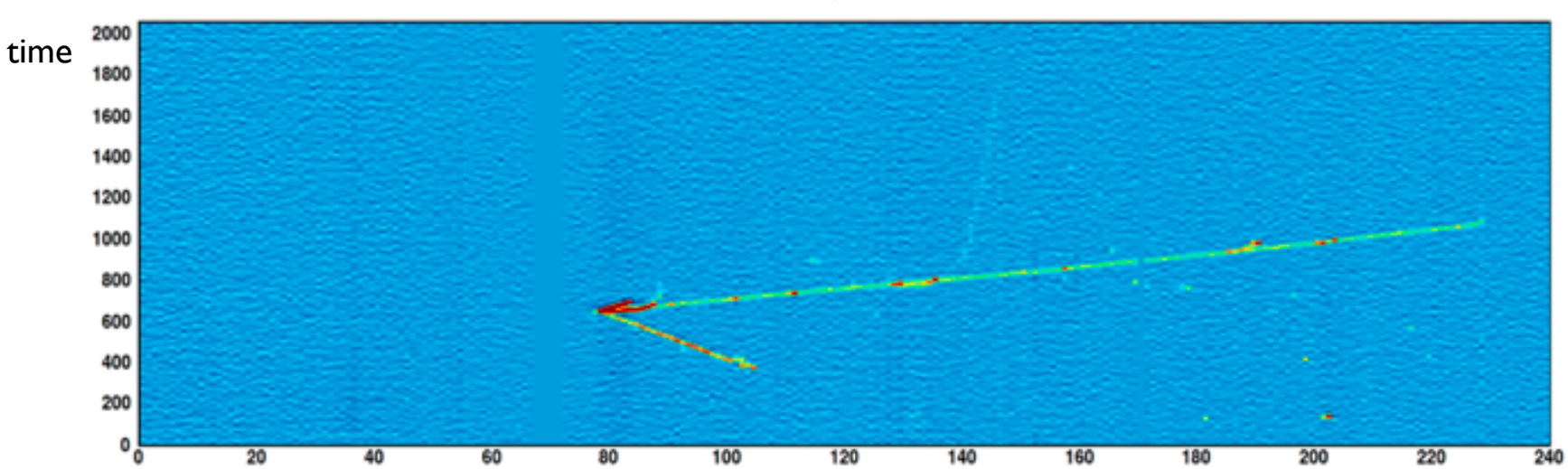
Detector geometry
MINOS
Neutrino event (GENIE)
Particle propagation (Geant4)
Wire signal creation
Electronics response
Electronics noise
LAr impurity, electron-recombination



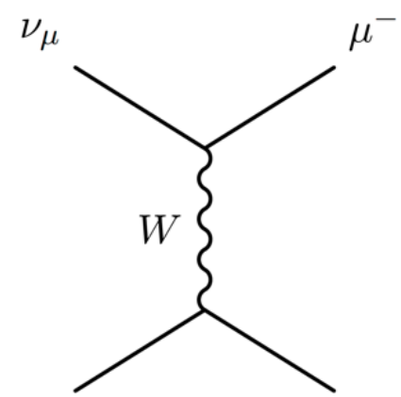
# How to reconstruct a LArTPC neutrino event?

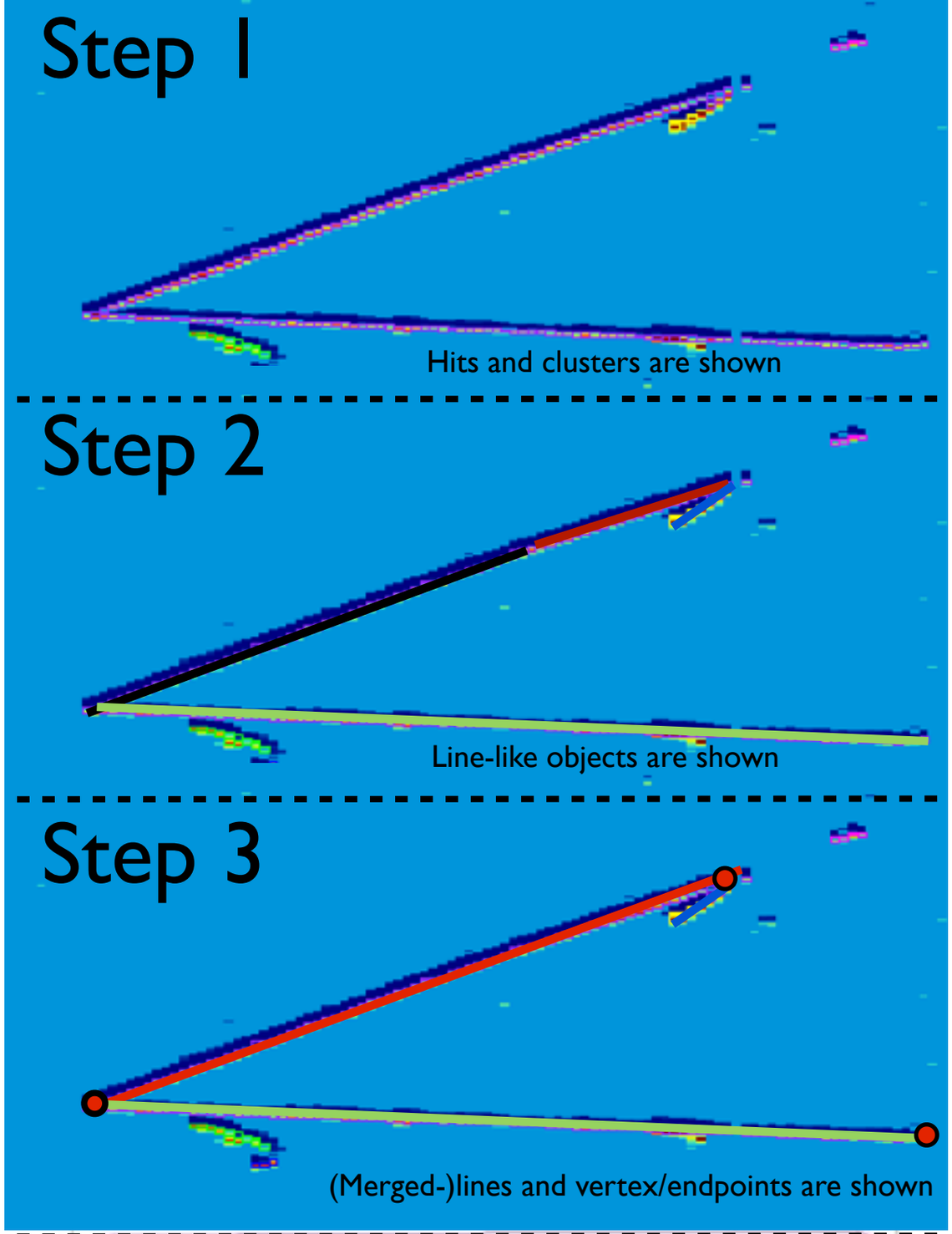



Most relevant items for this analysis:

-Did a neutrino event occur?
-Where is the neutrino interaction vertex?
-What are the initial direction cosines of the track(s)?
-Did the track(s) leave the TPC?
-What are the position and direction cosines of the track(s) as it leaves the TPC?






All steps are fully automated!

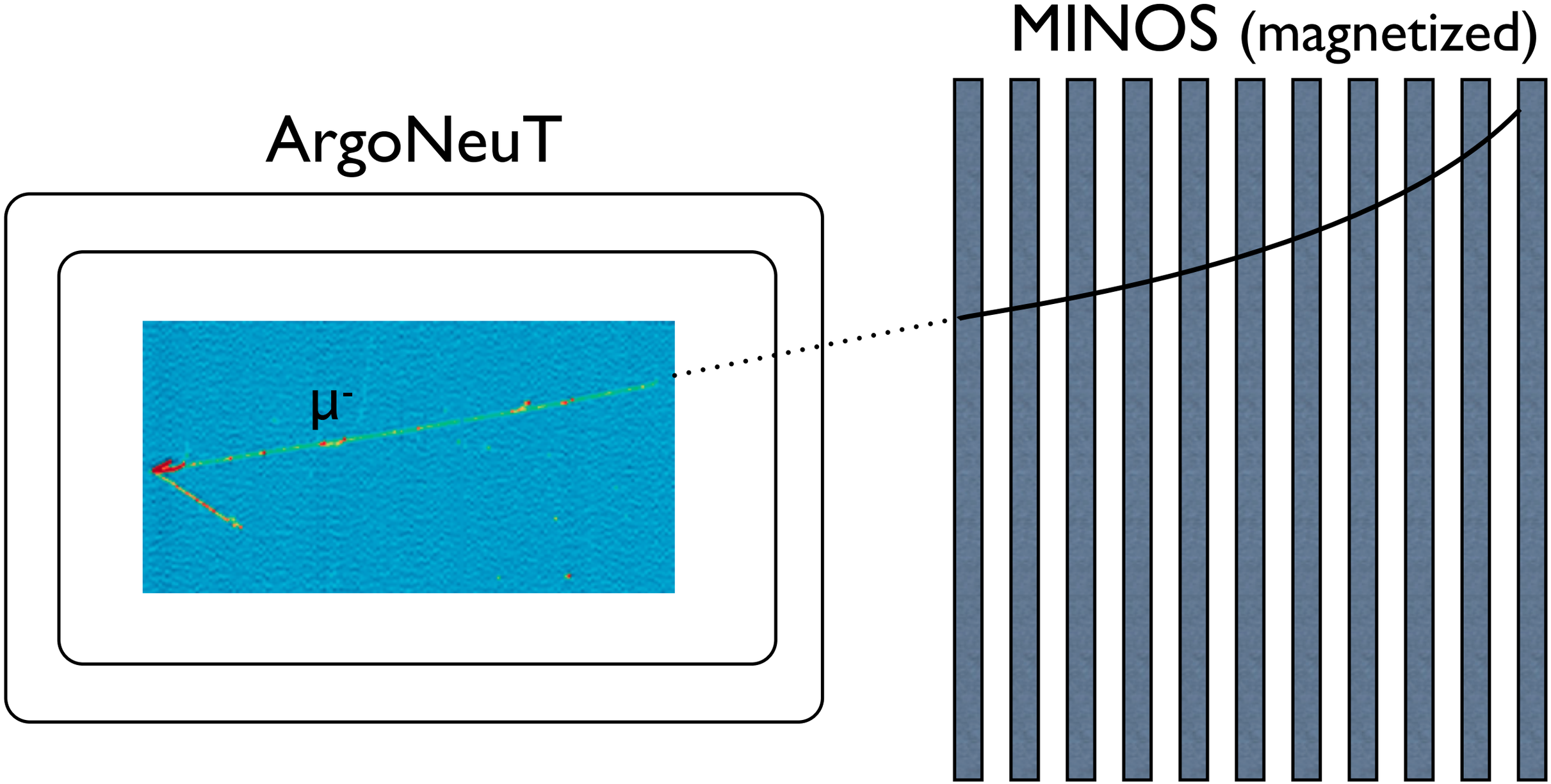
-Hit finding.
-Clustering of proximal hits.

-Line-finding, based on the Hough transform.

-Merging of near-parallel lines with shared endpoints.
-Vertex/endpoint finding.

-Three dimensional reconstruction, combining the line information from both planes.
-Track match to MINOS.

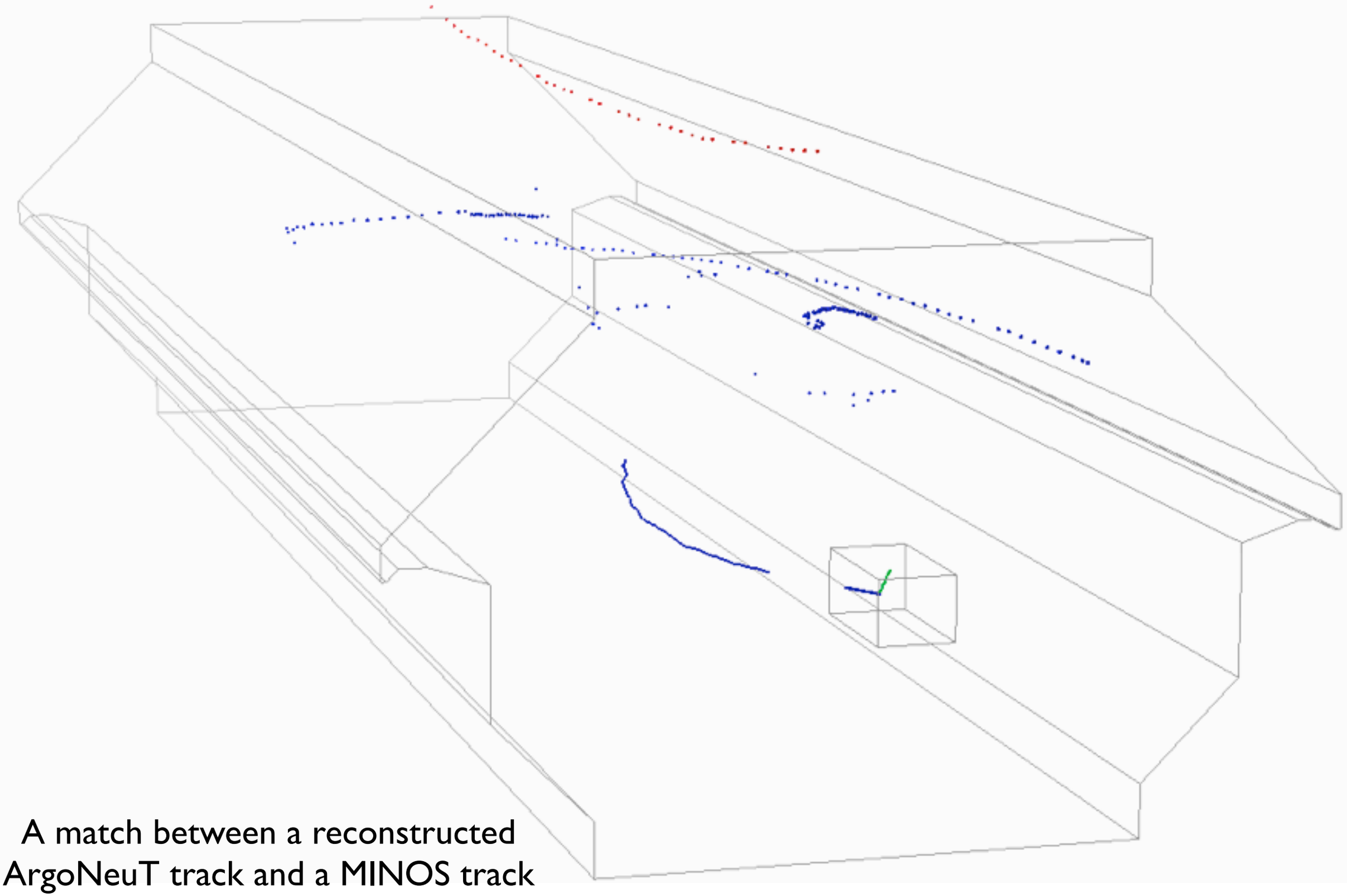
# Fully reconstructing muons




Track curvature is used for the muon momentum determination in the case that the muon is not contained in MINOS.

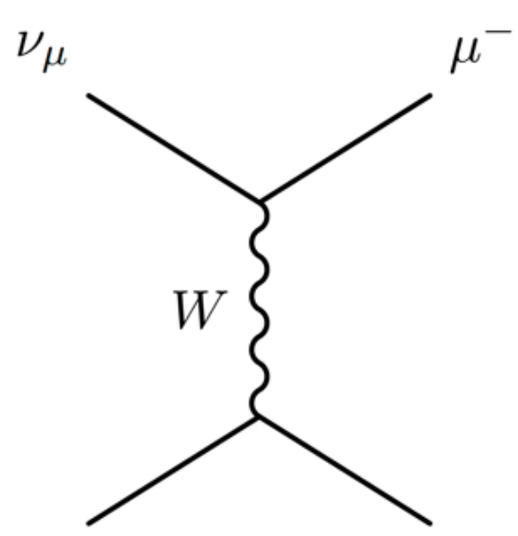
ArgoNeuT employs the downstream MINOS near detector to help reconstruct muons.

# ArgoNeuT+MINOS



A match between a reconstructed ArgoNeuT track and a MINOS track

# Charged current inclusive analysis

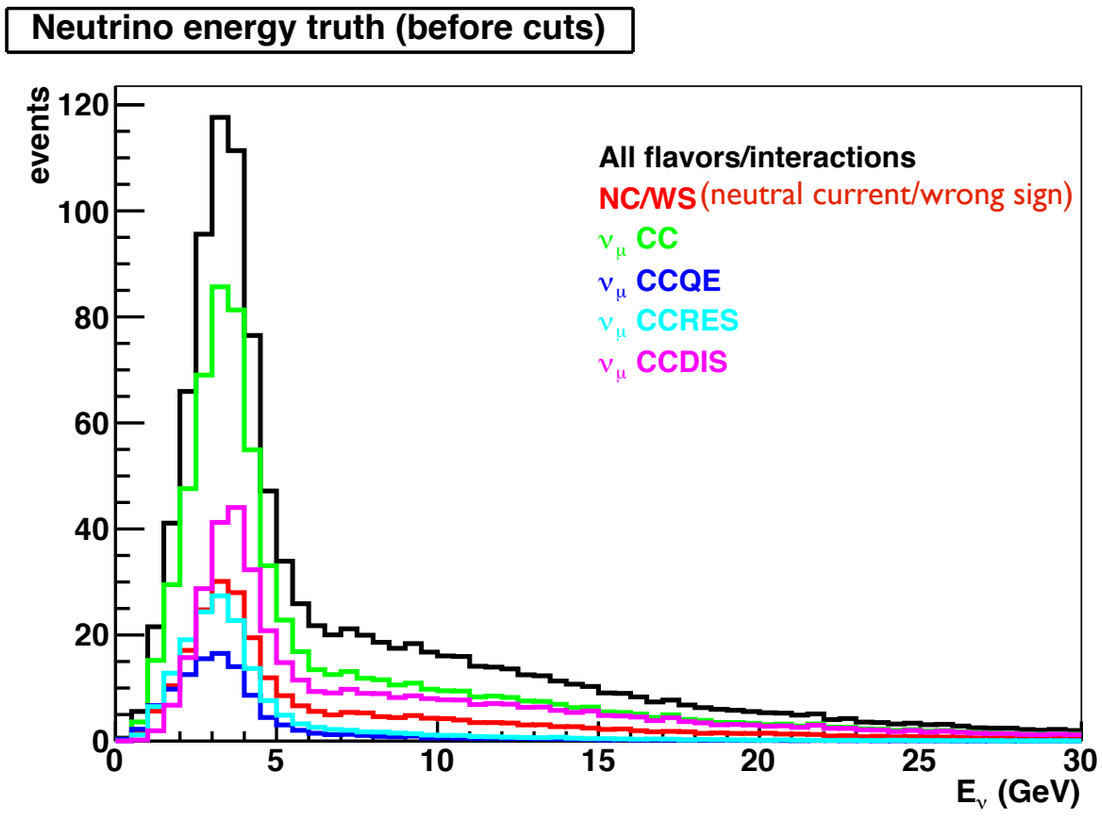


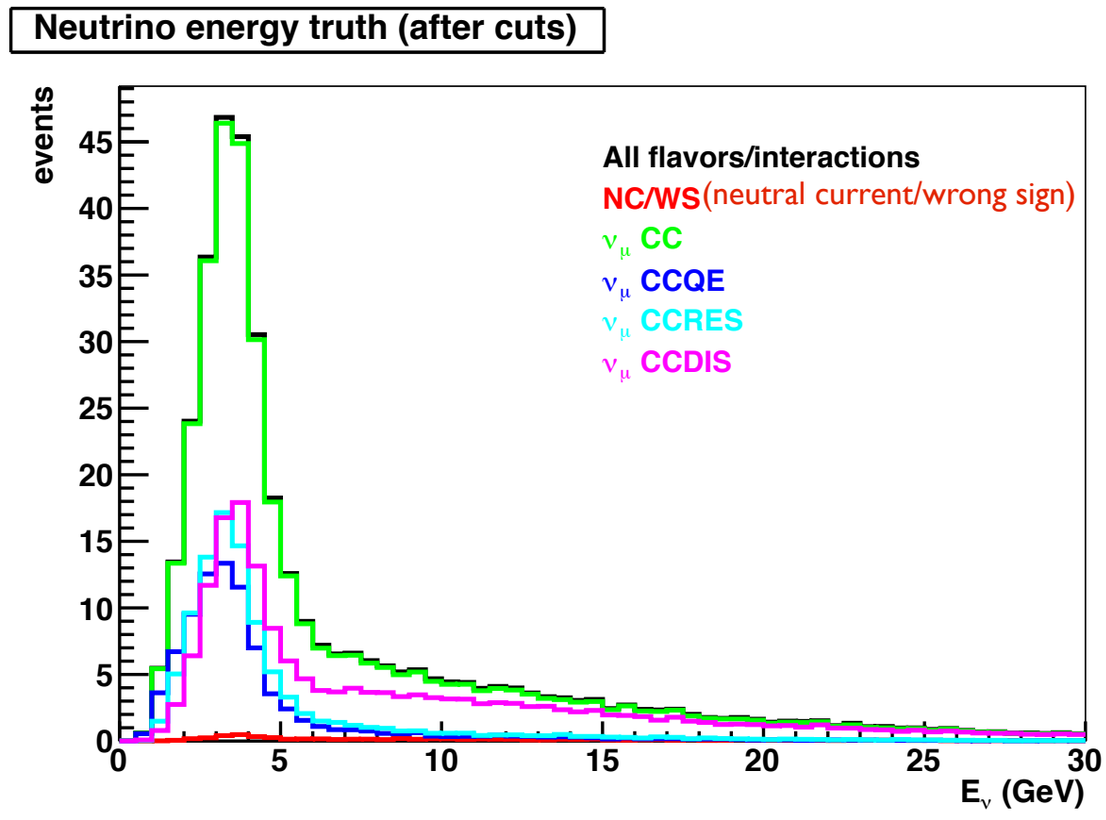
# Selection cuts

- The cuts employed in this analysis serve to increase signal ($\nu_\mu$ CC) and decrease background. The cuts are simple and straightforward.

| | |
|---|---|
| Fiducial volume requirements | 3 cm $<$ X $<$ 44 cm (3 cm from boundaries)<br>-16 cm $<$ Y $<$ 16 cm (4 cm from boundaries)<br>6 cm $<$ Z $<$ 86 cm [6(4) cm from up(down)stream boundary] |
| Matching requirements | $\theta <$ 0.4 rad<br>$\Delta r <$ 27 cm |
| MINOS requirement | q $<$ 0 |

- Require that the event originated inside the fiducial volume.
- Require that the ArgoNeuT track is well matched to a negatively charged track in MINOS.

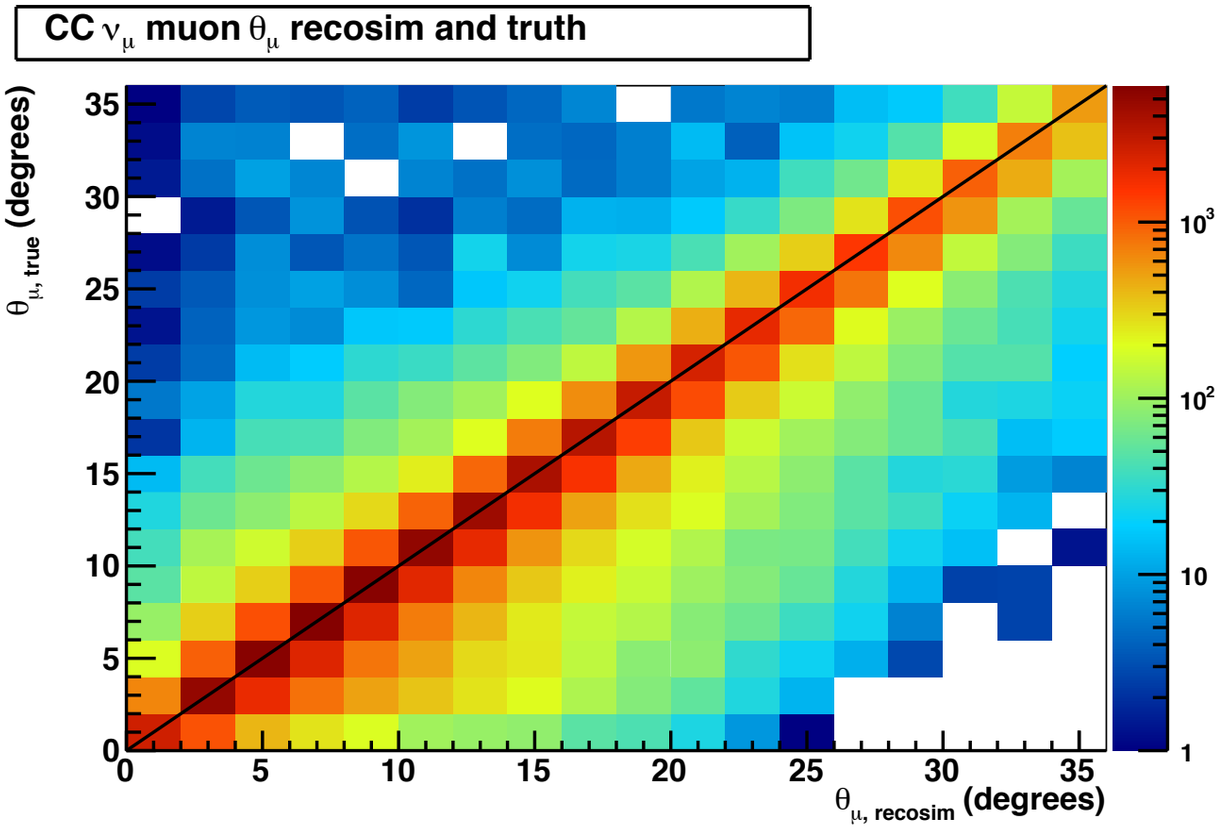


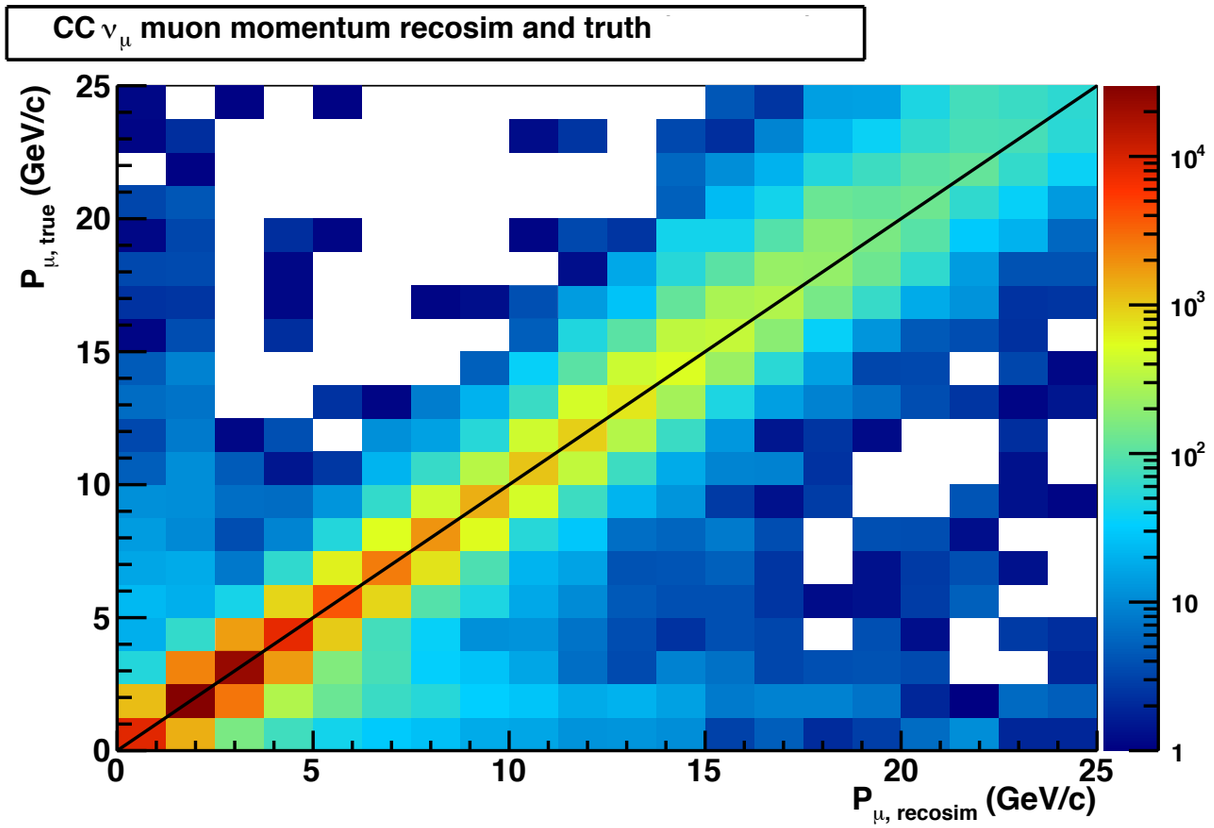



# Reconstructing neutrino events

- The reconstructed simulation and Monte Carlo truth distributions for the relevant variables ($\Theta_\mu$/$P_\mu$) agree well.
- The angular resolution is 1.0-1.5° and the momentum resolution is 5-10% across most of the measurement range.

$$\frac{\partial\sigma(u_i)}{\partial u}_{(u=\theta_\mu \text{ and } P_\mu)} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \epsilon_i N_{\text{targ}} \Phi}$$

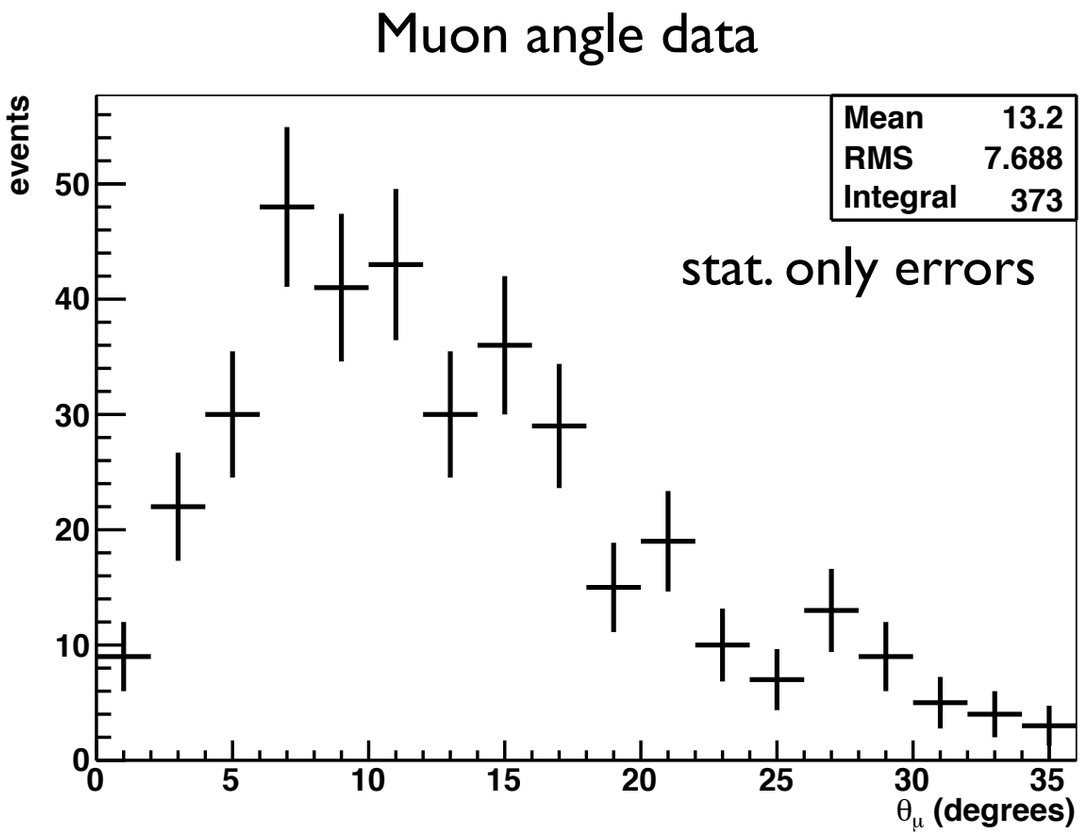


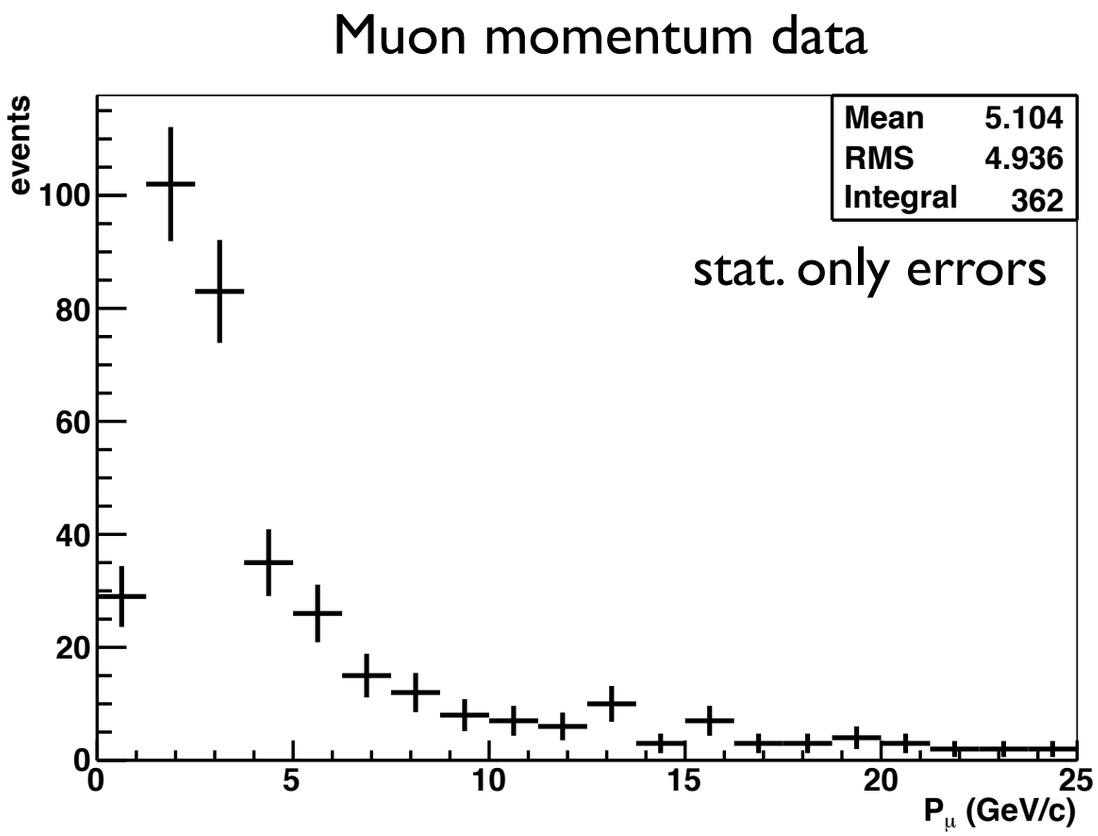



# The event sample

- The ArgoNeuT neutrino-mode sample is analyzed.
- Neutrino-mode represents about two weeks (9E18 protons on target) out of the 5.5 month physics run.
- ~380 events enter the sample after all cuts.

$$\frac{\partial\sigma(u_i)}{\partial u}_{(u=\theta_\mu \text{ and } P_\mu)} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \epsilon_i N_{\text{targ}} \Phi}$$

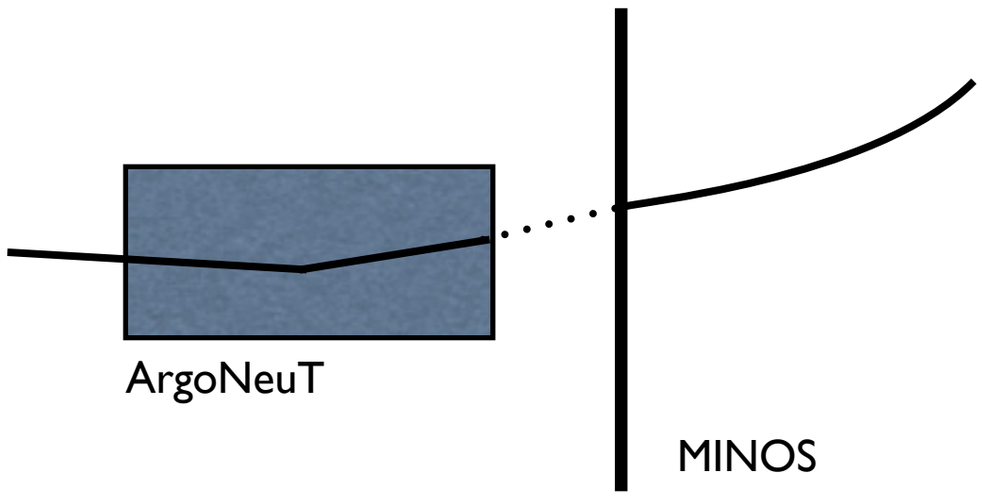


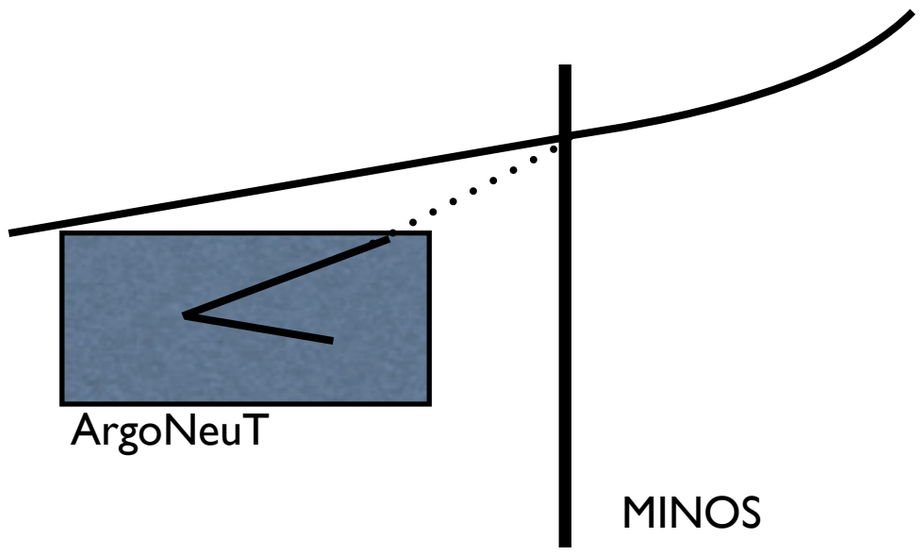
# Backgrounds

$$\frac{\partial\sigma(u_i)}{\partial u}_{(u=\theta_\mu \text{ and } P_\mu)} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \epsilon_i N_{\text{targ}} \Phi}$$

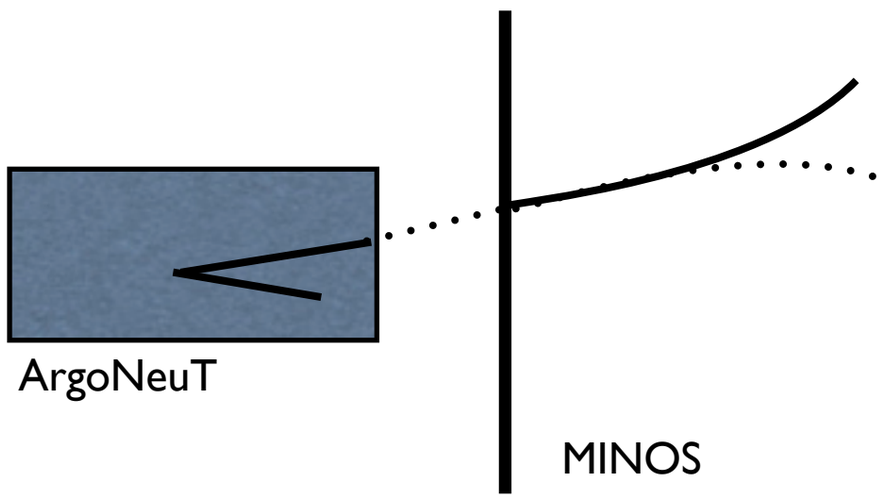
There are a number of backgrounds that can mimic a charged current muon neutrino event.




Through-going (TG) muon
(this background prediction comes
from an *in-situ* measurement)




Neutral current (NC) neutrino event
matched with a muon in MINOS




Wrong-sign (WS) anti-neutrino event
with charge mis-reconstructed

Efficiency/background summary

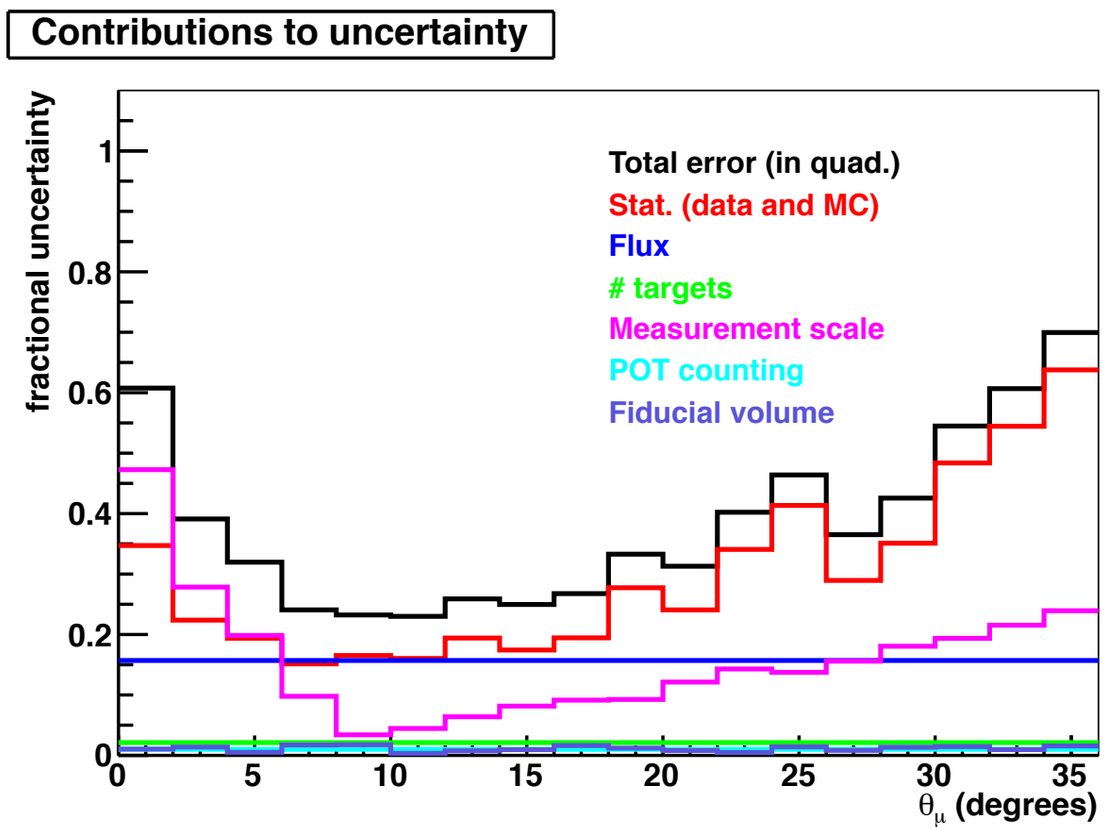
| | |
|---|---|
| Signal (CC $\nu_\mu$) reconstruction probability | 49.5% |
| Signal (CC $\nu_\mu$) purity | 95.4% |
| NC/WS background contamination | 2.2% |
| TG muon background contamination | 1.4% |
| NC match w/ TG muon background contamination | 1.0% |

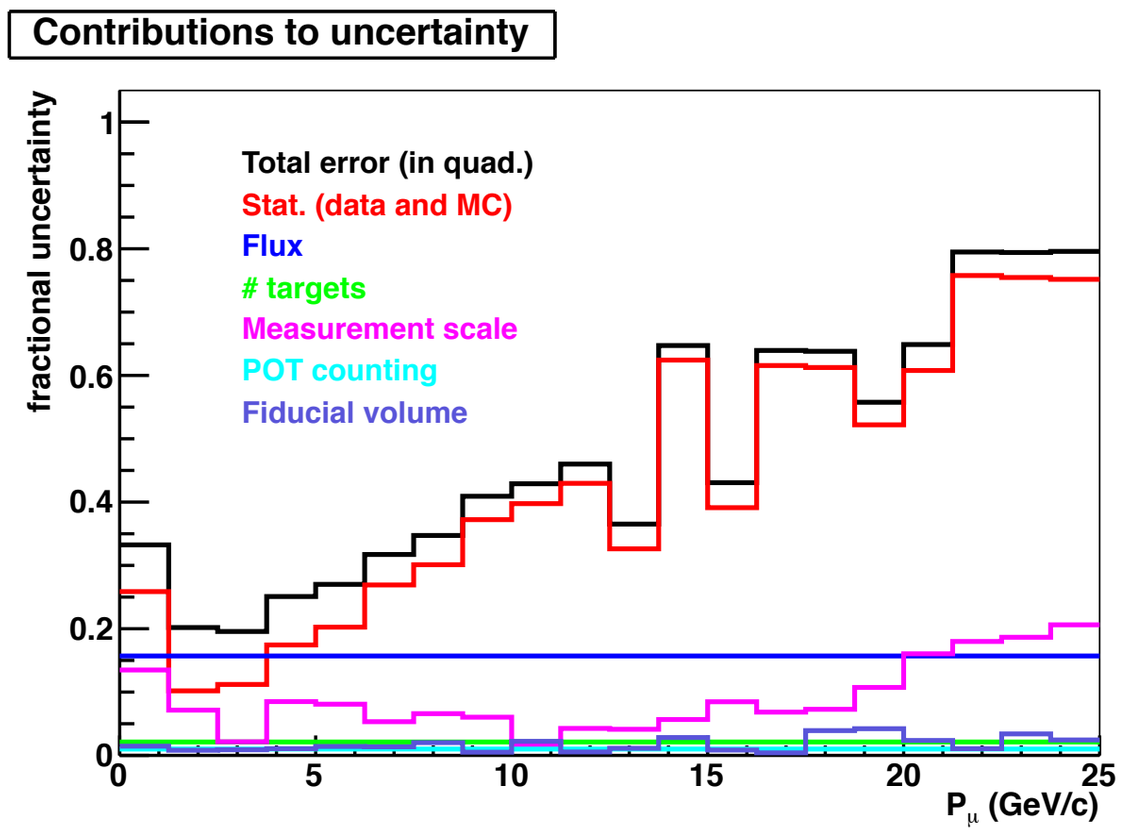
# Error accounting

- These results are dominated by statistical error for most of the measurement bins reported. Other significant contributions:
  - Neutrino flux
    - The flux uncertainty is taken directly from MINOS published results and communication with MINOS.
  - Measurement resolution/scale
    - Bin-migration effect of a measurement scale excursion.
    - The angular resolution is 1.0-1.5° and the momentum resolution is 5-10% across most of the measurement range.

$$\delta\left(\frac{\partial\sigma(u_i)}{\partial u}\right)_{(u=\theta_\mu \text{ and } P_\mu)}$$

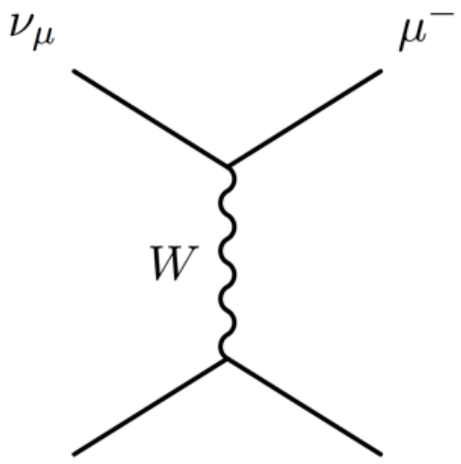
[MINOS collaboration], Phys. Rev. D **072002**, 81 (2010)



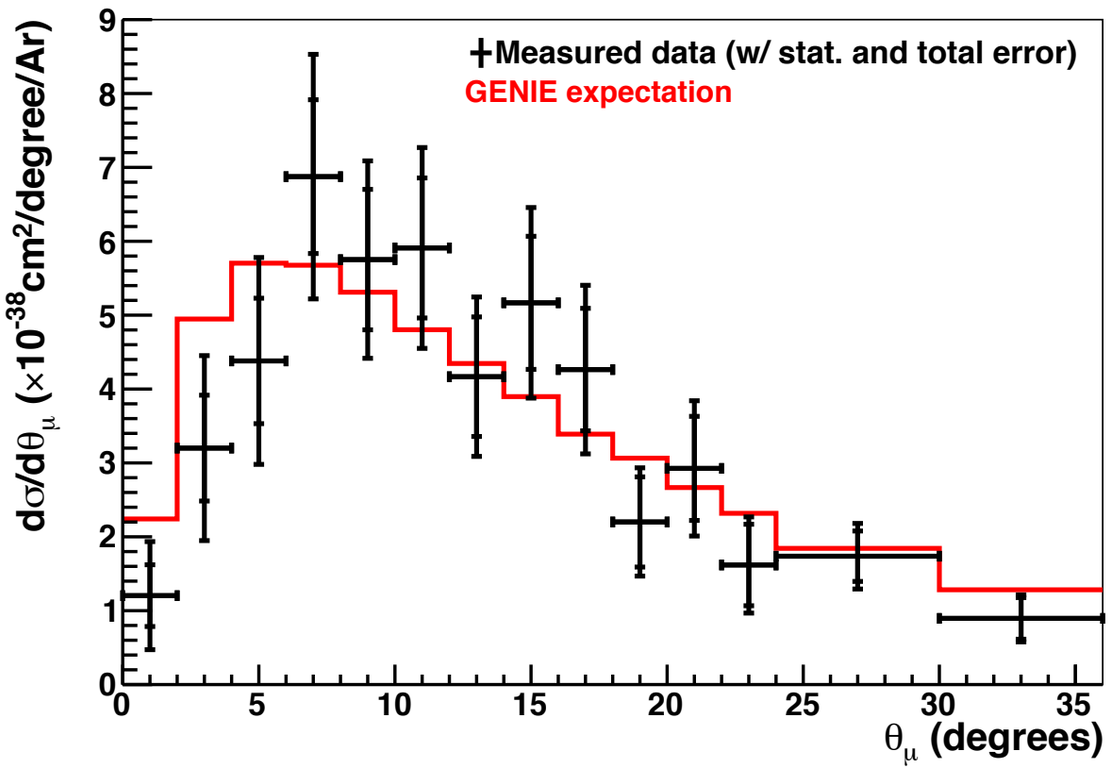
# Differential cross sections on argon

**arXiv:1111.0103, Submitted to PRL**

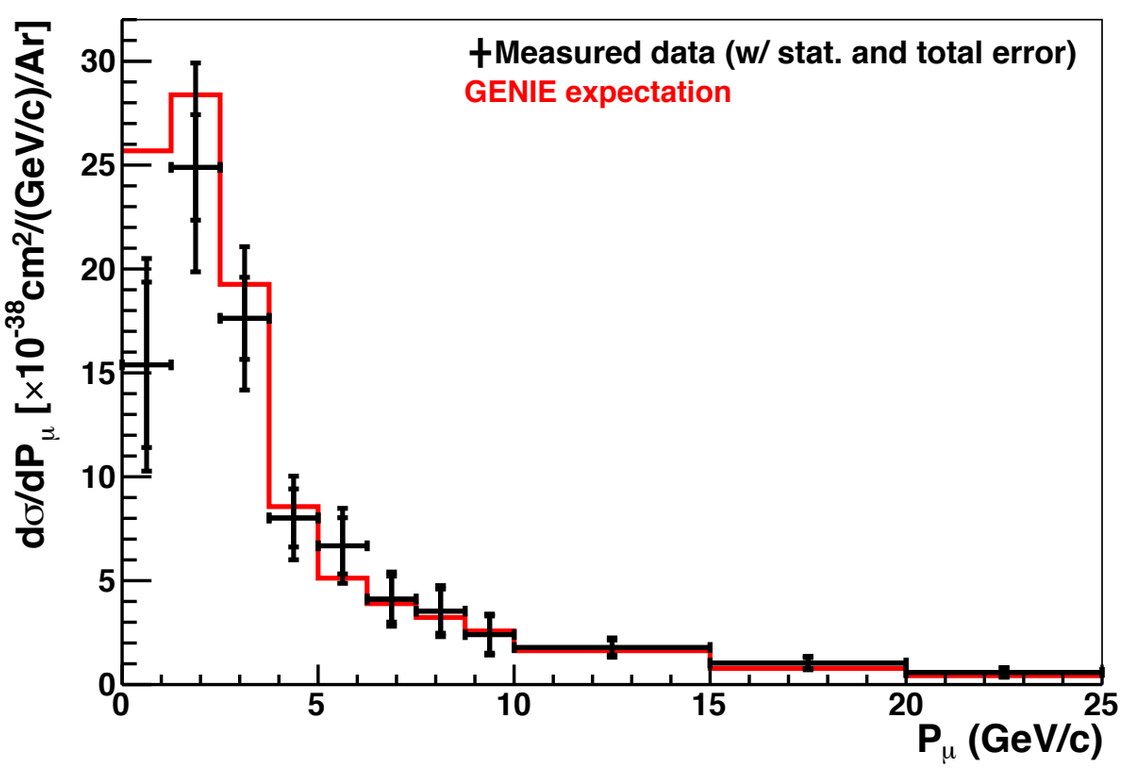



$$\underset{(u=\theta_\mu \text{ and } P_\mu)}{\frac{\partial\sigma(u_i)}{\partial u}} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \epsilon_i N_{\text{targ}} \Phi}$$

## CC $\nu_\mu$ on Ar



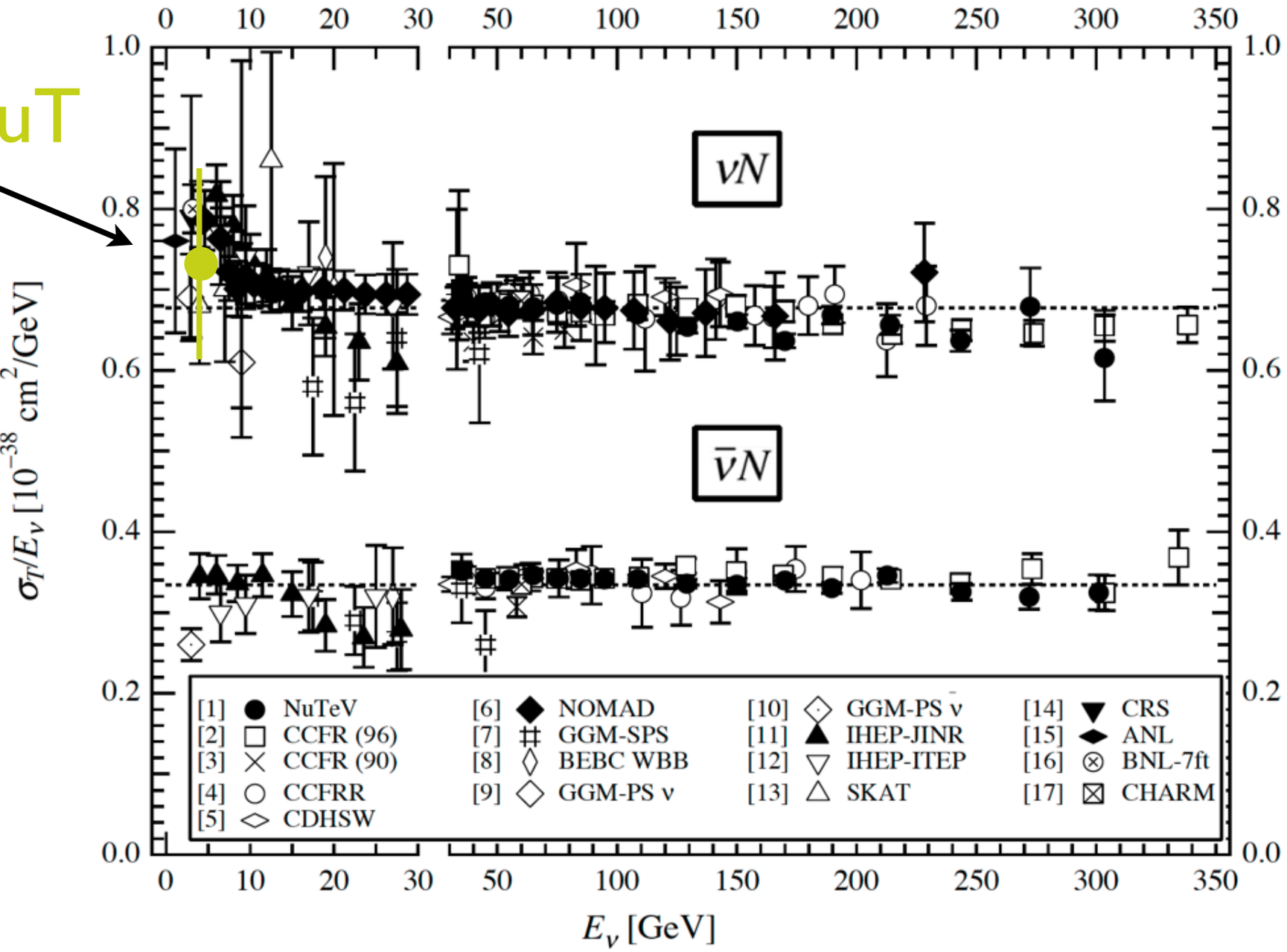

## CC $\nu_\mu$ on Ar



# Total cross section on argon

**arXiv:1111.0103, Submitted to PRL**

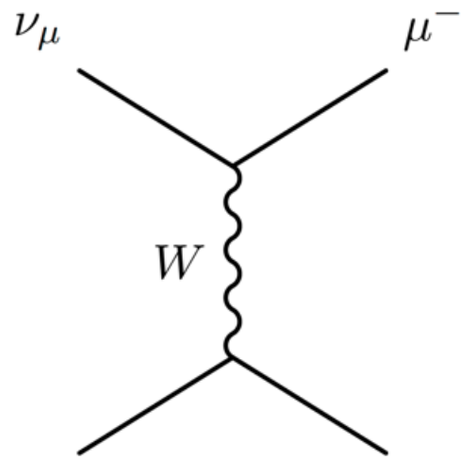
ArgoNeuT




$\sigma_{\rm tot}/E_\nu = (7.3 \pm 1.2) \times 10^{-39} \frac{\rm cm^2}{\rm GeV}$ per isoscalar nucleon at $\langle E_\nu \rangle = 4.3$ GeV

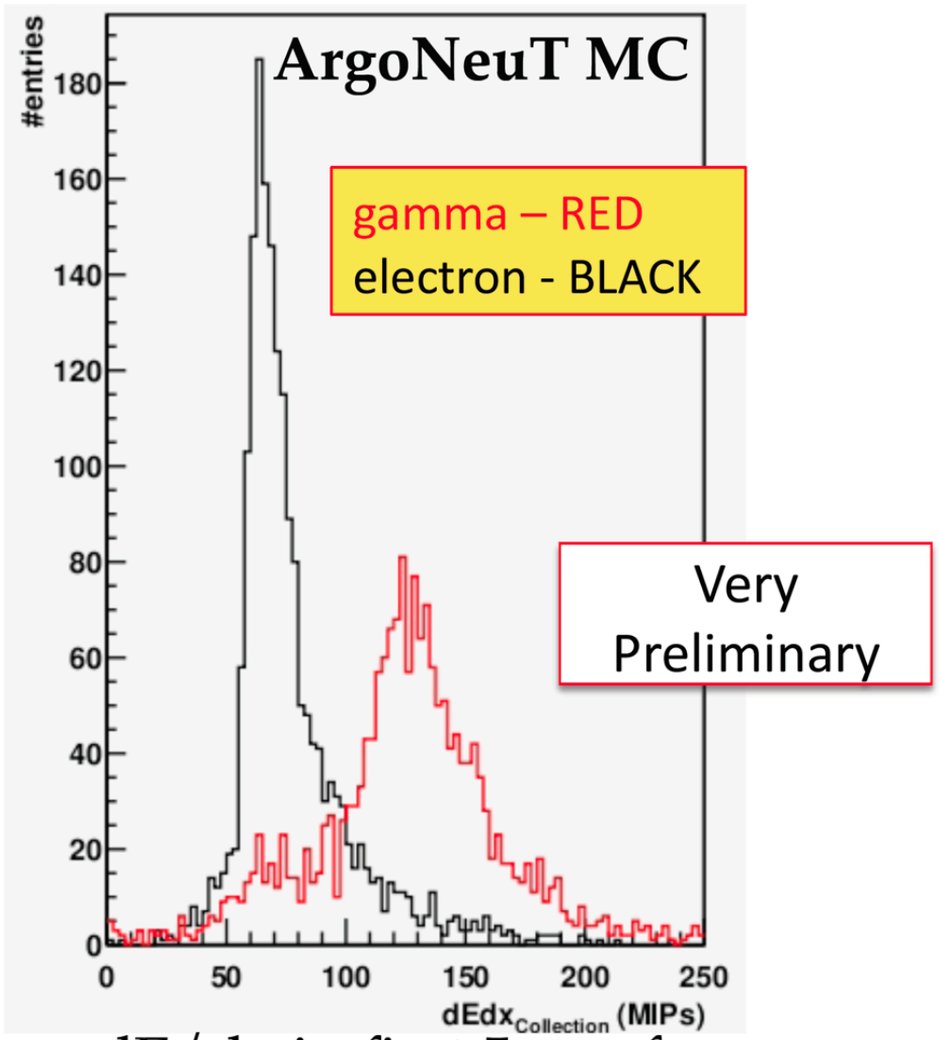
# These results represent the...

- First charged-current inclusive differential cross section measurement on argon.
- First charged-current inclusive total cross section measurement on argon.
- First ArgoNeuT physics measurement.
- First US LArTPC physics measurement.
- First physics measurement with a LArTPC in a low energy neutrino beam.



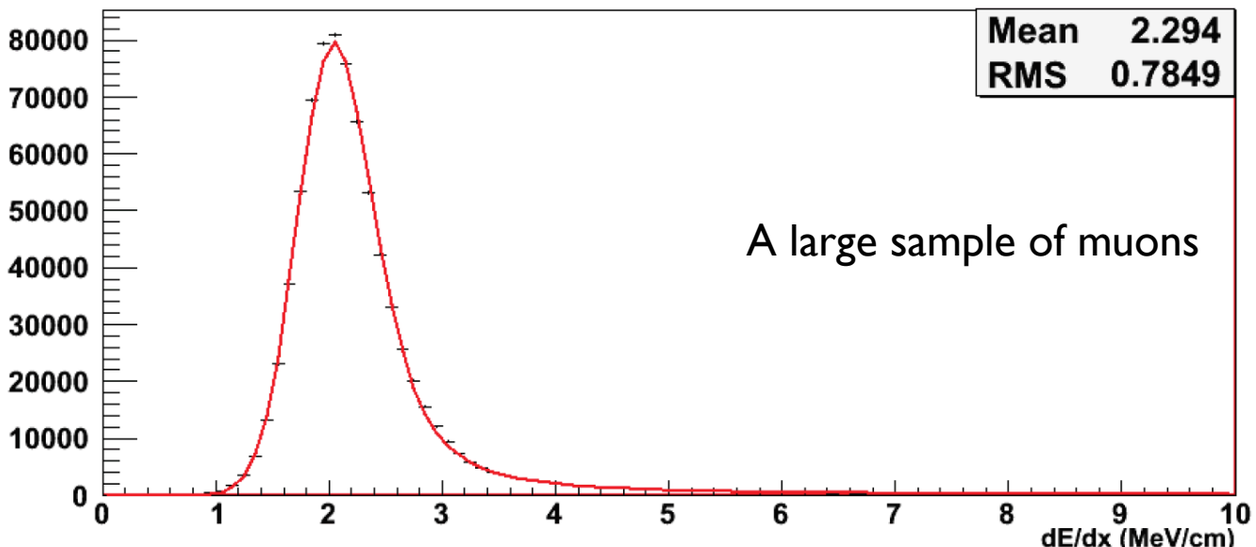
# Other ArgoNeuT work

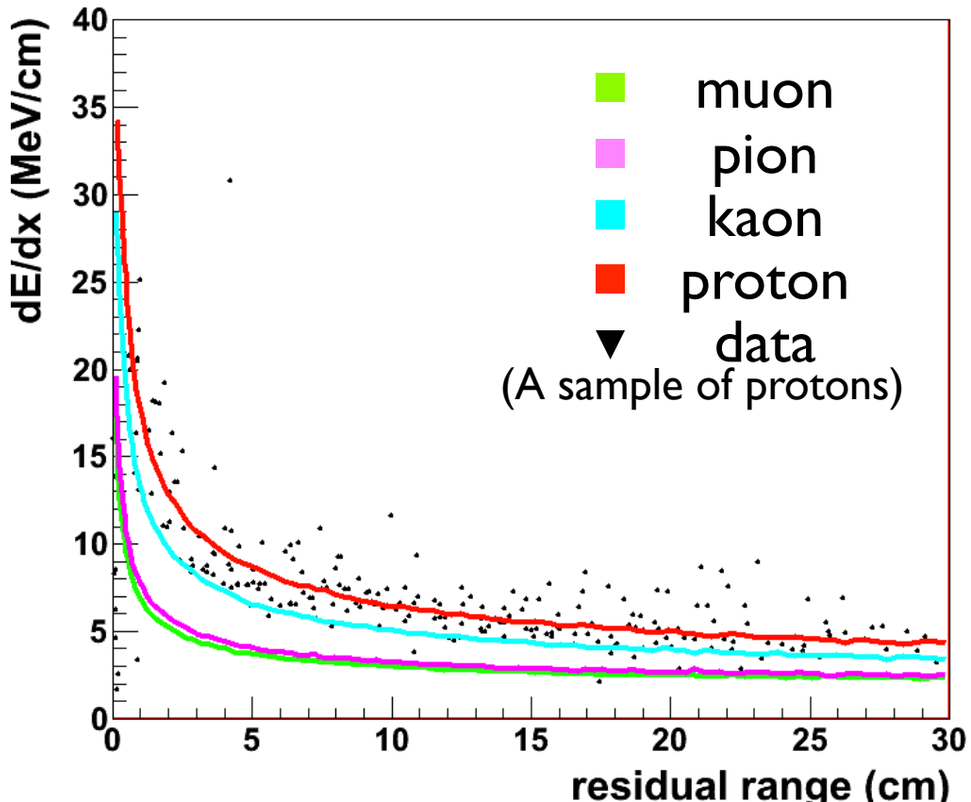
# Calorimetry




dE/dx in first 5cm of Simulated/Reconstructed Gamma/Electron showers.

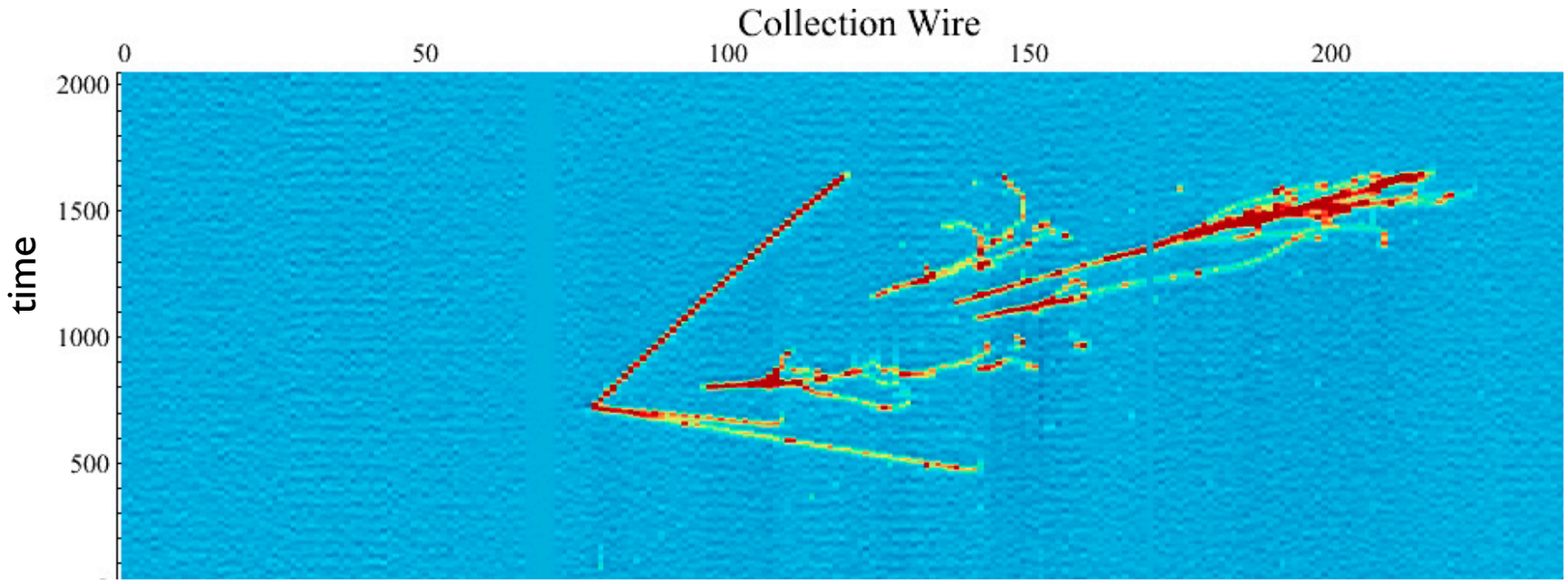
- Reconstructing the total energy and dE/dx of various particles is essential to future analyses.
- We can currently reconstruct the energy and dE/dx of muons and protons with high success.
- Demonstrating electron/gamma dE/dx-based identification is a priority.



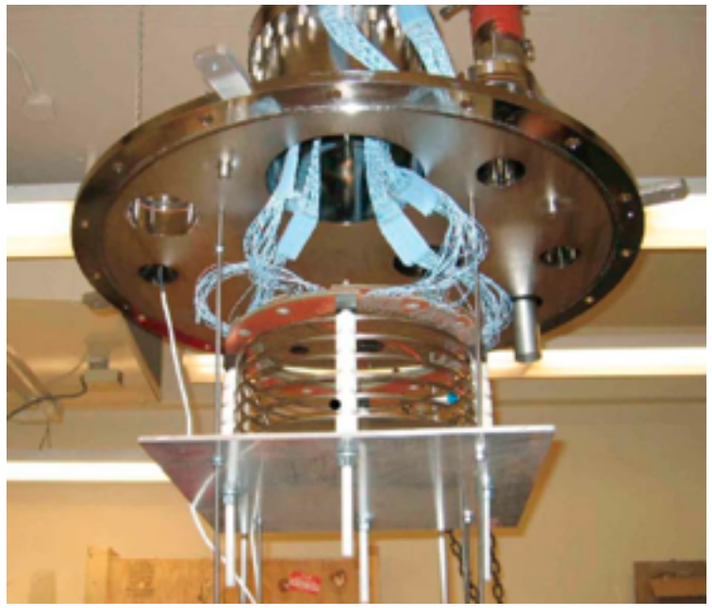



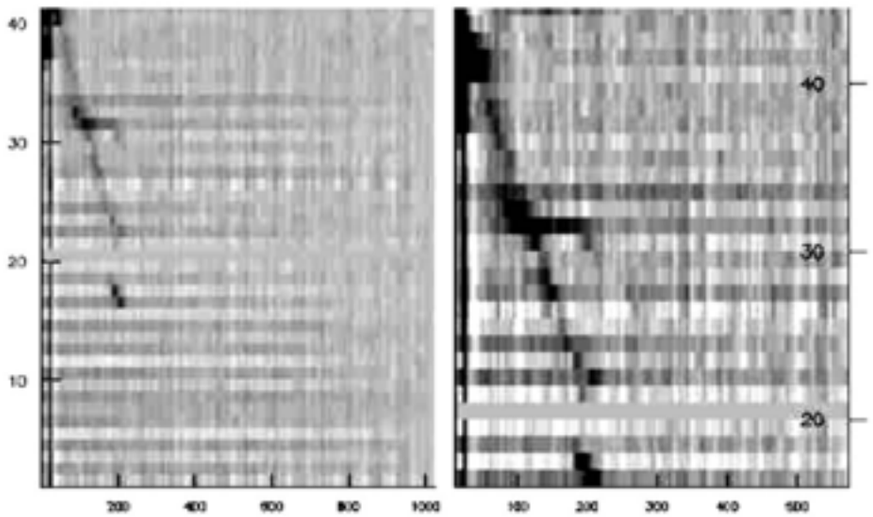
# Ongoing ArgoNeuT physics studies

- Neutrino/anti-neutrino charged current, quasi-elastic
- Characterizing the vertex activity associated with neutrino events
  - Neutrinos as a probe of short-range correlations between nucleons?
- Anti-neutrino charged current inclusive
- Neutrino-induced hyperon production
- Electron neutrinos
- Neutral current $\pi^0$

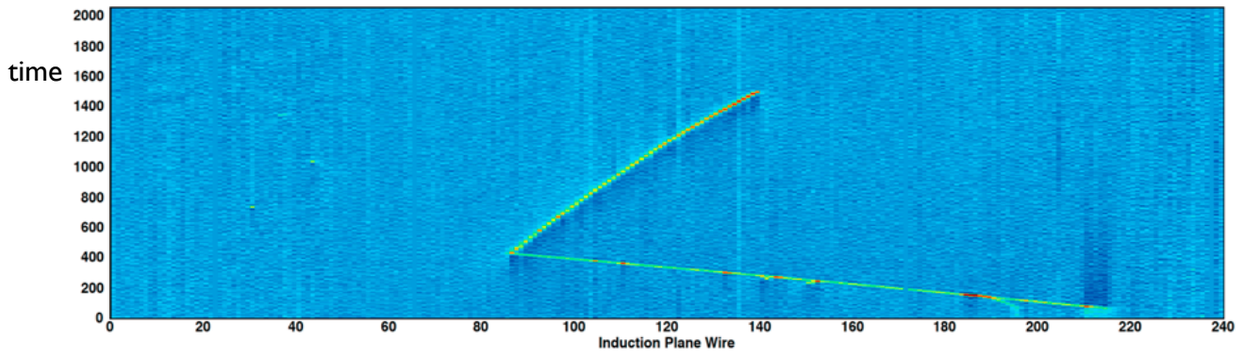


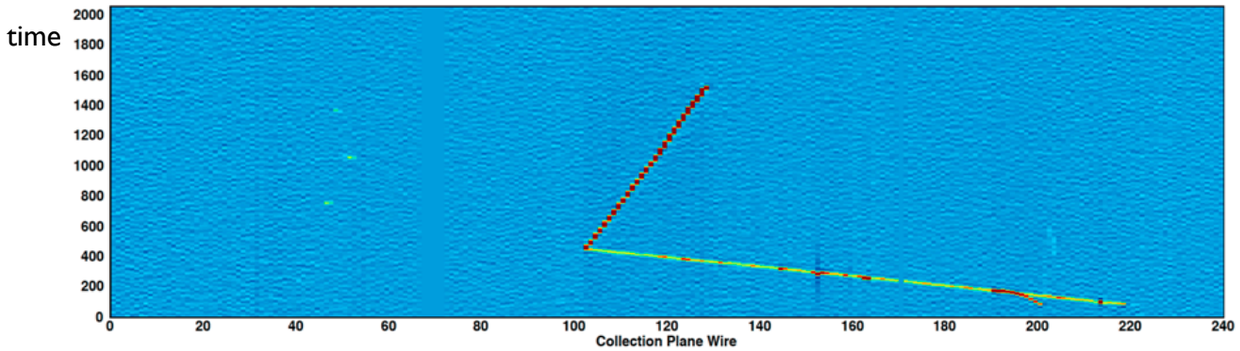
# Look how far we've come!



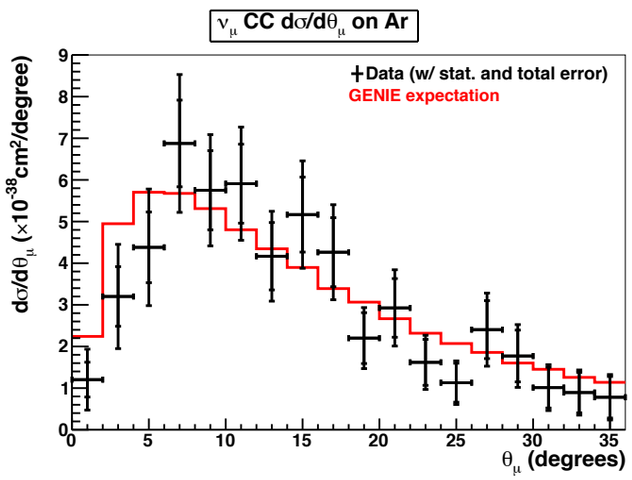


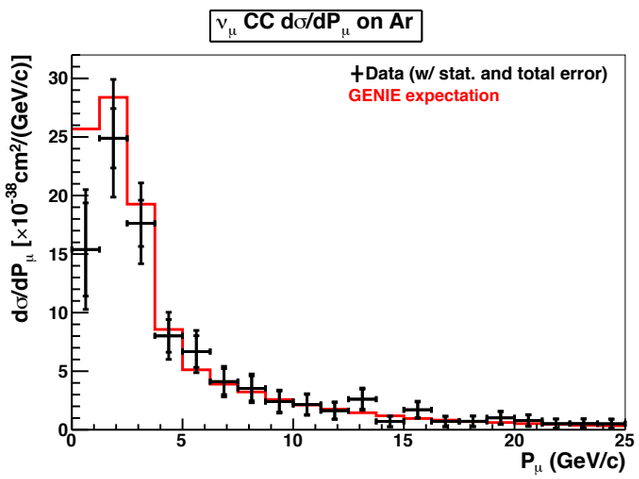
LArTPC tracks in US, Yale (2007)



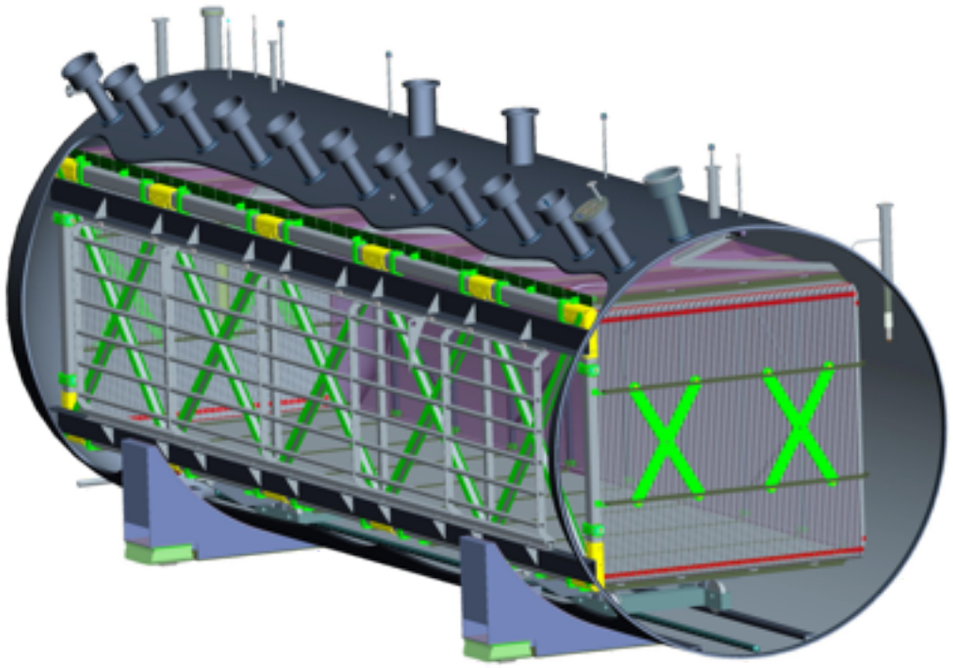

Neutrino detection w/ ArgoNeuT (2009)



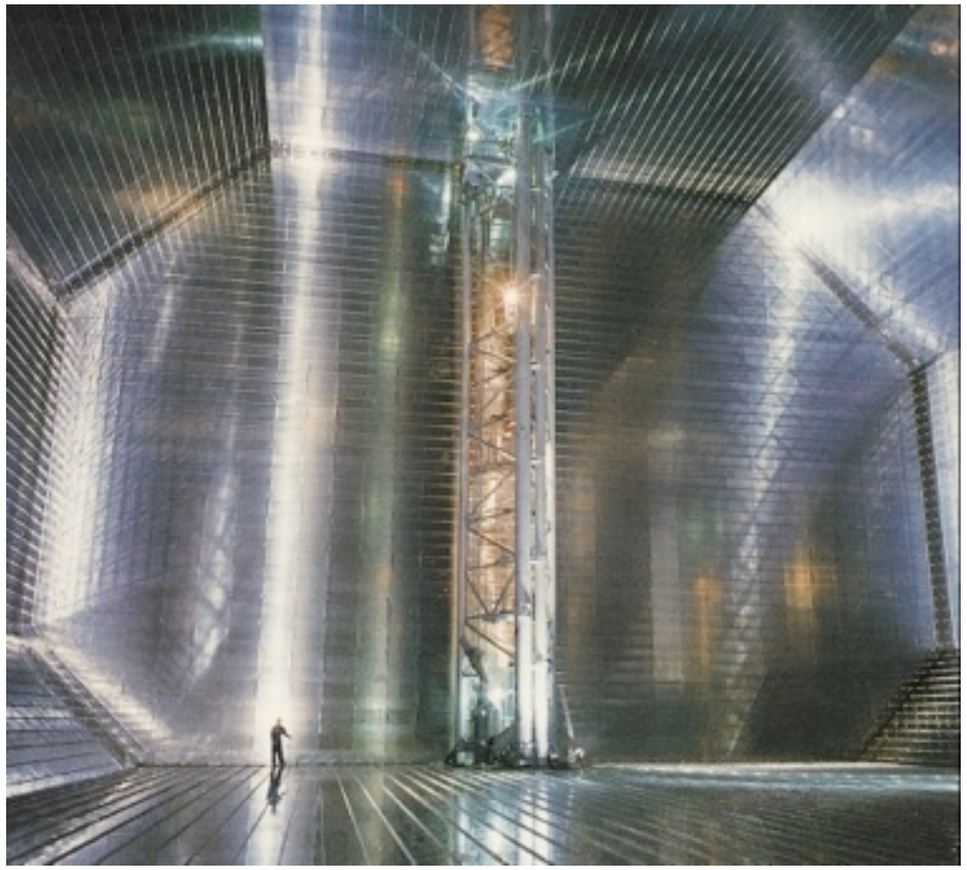




Physics w/ ArgoNeuT (2011)

# Look where we're going



MicroBooNE, starting in 2013
(TPC is 2.6x2.3x10.4 m)



Kiloton-scale LArTPC
(e.g. for LBNE)

$\theta_{13}$, leptonic CP violation, proton decay, mass hierarchy, tau neutrinos, maximal $\theta_{23}$, burst/diffuse supernova neutrinos, sterile neutrino(s), neutrino cross sections, nucleonic short range correlations, axial vector mass, strange spin component of the nucleon, non-standard neutrino interactions, ...

# Conclusion

- The first charged current inclusive differential cross sections on argon have been reported. The results agree well with the Monte Carlo expectations.
- The measured total cross section (at <4.3 GeV>) agrees well with the world's data.
- The reconstruction software applied for these measurements is fully automated. The software is shared between ArgoNeuT, MicroBooNE, LAr-1, and LBNE.
- ArgoNeuT is an R&D-oriented experiment that is also performing timely and relevant physics.
- All of this work is paving the way for a kiloton-scale LArTPC.

# Thanks to...

- MINOS collaboration, for providing an integral piece of this analysis.
- ICARUS collaboration, for pioneering LArTPC technology and sharing knowledge.
- MINERvA collaboration, for sharing knowledge.
- Accelerator division, for providing protons.
- Fermilab/NSF/DOE, for support.

# The international collaboration

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