# The MicroBooNE & ArgoNeuT Experiments and the Future of Liquid Argon Time Projection Chambers

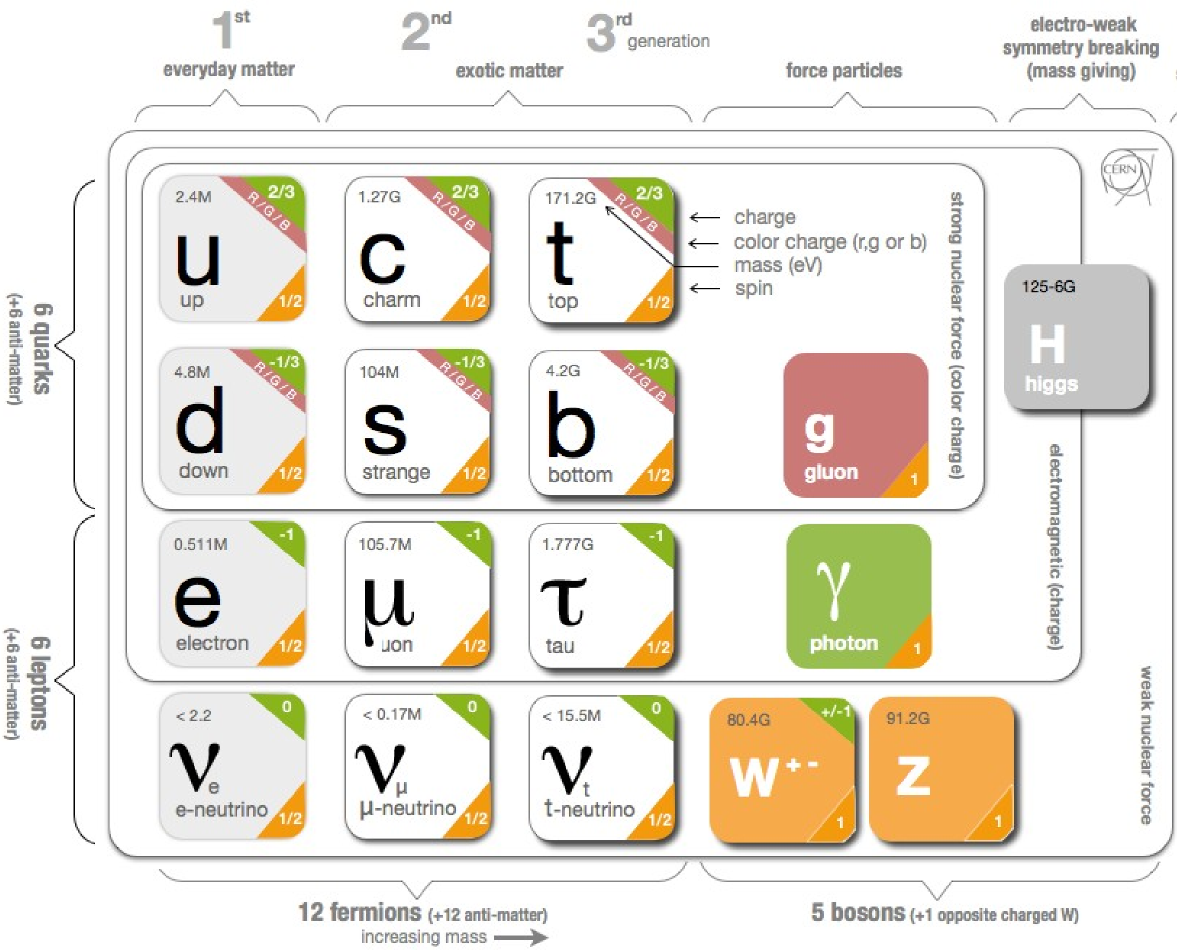
**Jonathan Asaadi**

**Syracuse University**

# Outline

- **Overview of Neutrino Physics**
  - Standard Model (SM) → ν–SM
  - Neutrino Oscillations
- **Liquid Argon Time Projection Chambers (LArTPC's)**
  - Quick primer on neutrino detectors
  - Overview of how LArTPC's work
- **The ArgoNeuT** *(**Argo**n **Neu**trino **T**eststand)* **Experiment**
  - Published Analysis
  - Ongoing Analysis
- **MicroBooNE** *(**Micro-Boo**ster **N**eutrino **E**xperiment)*
  - Physics Motivation
  - Current Status
- **Future Experiments**
  - LAr1-ND *(**L**iquid **Ar**gon **1**kton **N**ear **D**etector)*
  - LArIAT *(**L**iquid **Ar**gon **I**n **A** **T**estbeam)*
  - LBNE *(**L**ong **B**aseline **N**eutrino **E**xperiment)*

# Standard Model




With the discovery of the Higgs (or Higgs like) boson in 2012 we have a very elegant and nearly complete model of the fundamental particles that make up the universe

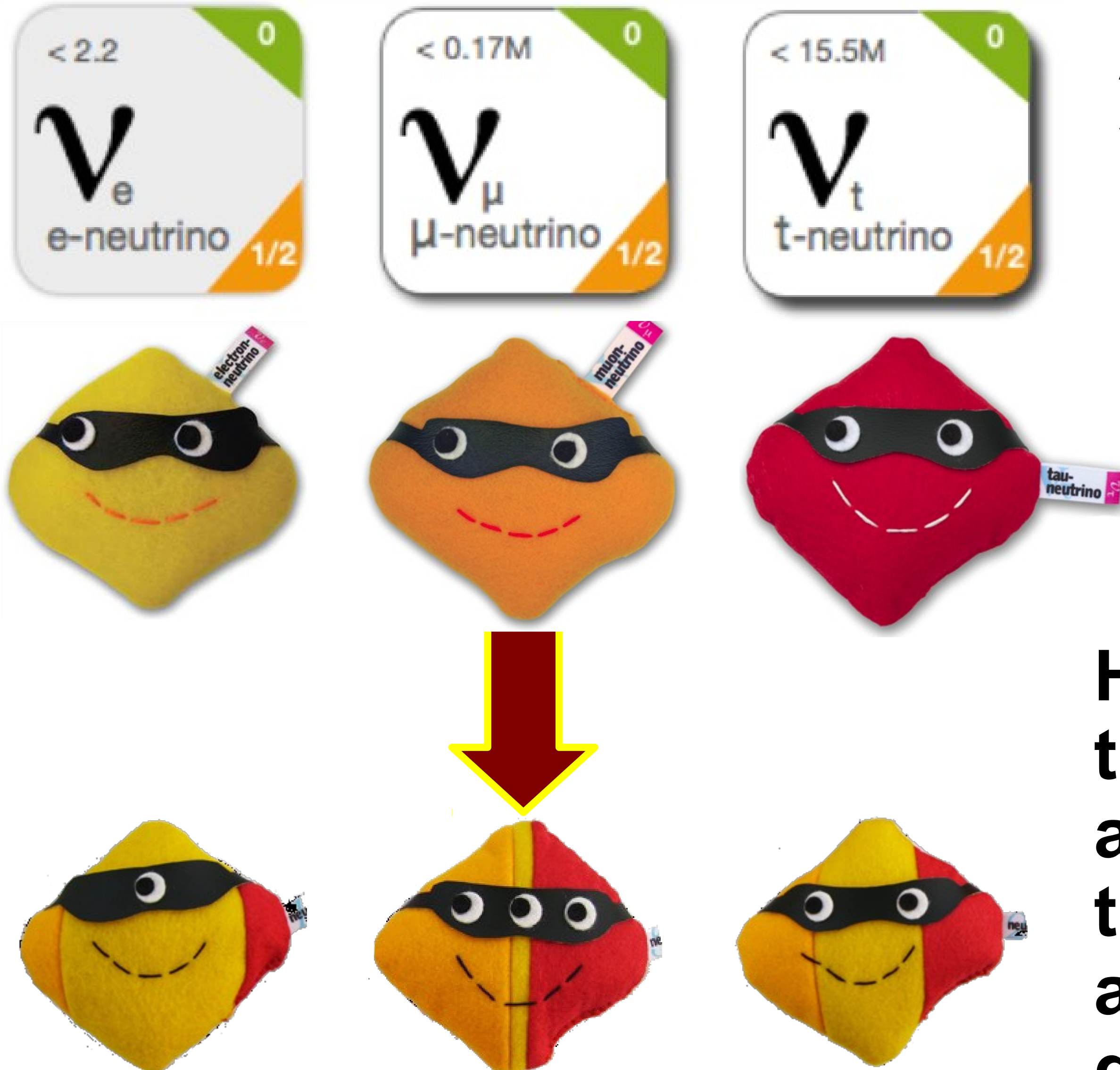
However, we do have a few clues to physics beyond the Standard Model

What is the nature of the **Higgs Boson**?

What is the **majority of the matter** in the universe?

**What is the nature of neutrinos?**

# ν-Standard Model

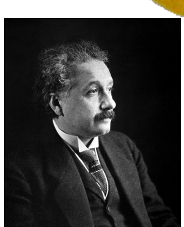



**As recent as 1998 our view of neutrinos was simple:**

1) 3 Flavors
2) Interact via Weak Force
3) Massless

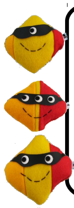
**However, we observed that neutrinos flavors mix and neutrinos can change their flavors (oscillate) after propagating some distance**

→ **This implies neutrinos have mass!**



***N.B. Neutrino oscillation is observed as the particle travels (meaning over time)...relativity tells us that only things with mass have a sense of time***

# Neutrino Oscillation Physics



$$\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = U \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

w

Oscillations can be understood by writing the mass states( ) in terms of the flavor states ( ) related through a mixing matrix

$c_{ij} = \cos(\theta_{ij})$

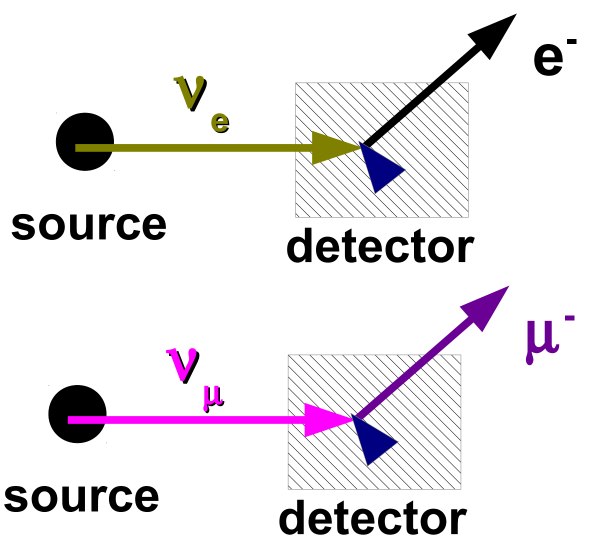
$s_{ij} = \sin(\theta_{ij})$

$\delta = \text{CP phase}$

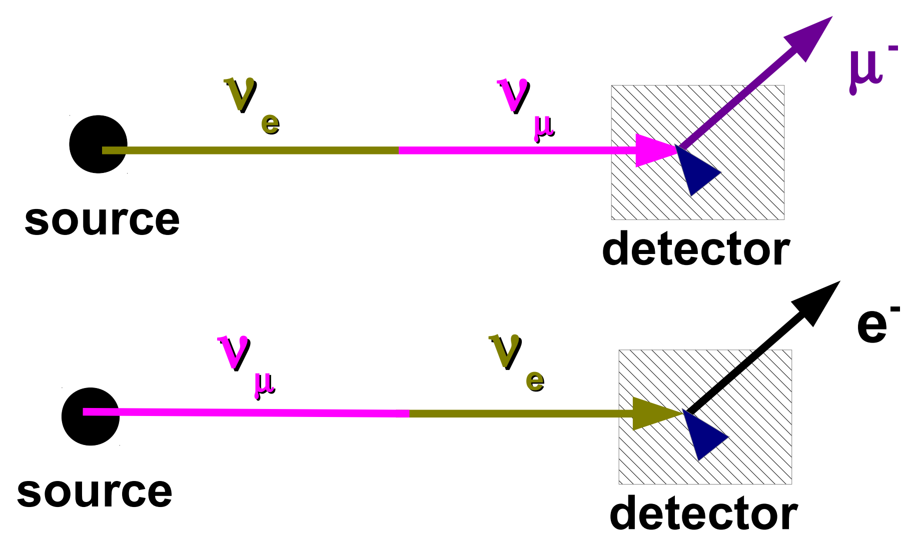
**Oscillations parametrized by 3 angles and 1 phase**

## What this means experimentally

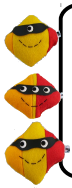
### For very short distances




### For longer distances



# Neutrino Oscillation Physics



$$\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = U \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} \quad \text{where} \quad U = \begin{pmatrix} U_{e1} & U_{\mu 1} & U_{\tau 1} \\ U_{e2} & U_{\mu 2} & U_{\tau 2} \\ U_{e3} & U_{\mu 3} & U_{\tau 3} \end{pmatrix}$$

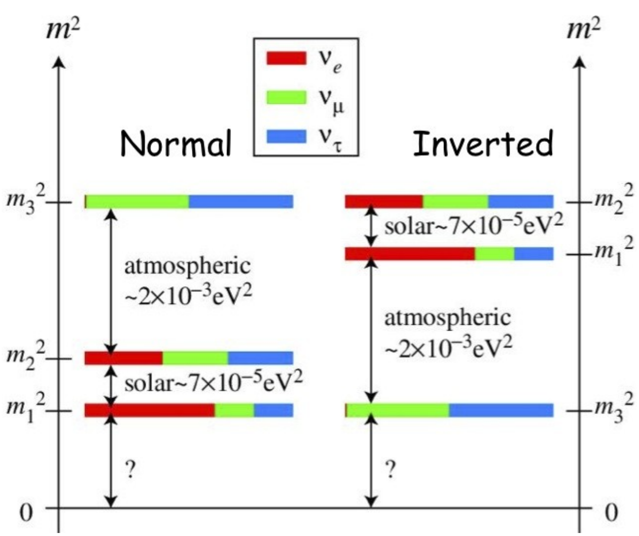
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij})$
$s_{ij} = \sin(\theta_{ij})$
$\delta$ = CP phase

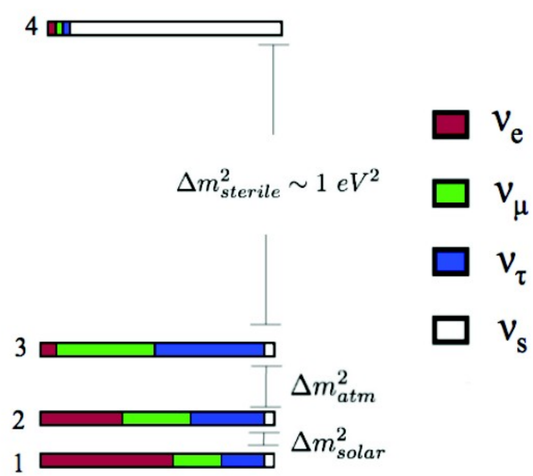
**As of 2012 we now have measured the three angles** ($\theta_{12} \sim 34^\circ$, $\theta_{13} \sim 9^\circ$, $\theta_{23} \sim 45^\circ$)

## Still lots of unanswered questions

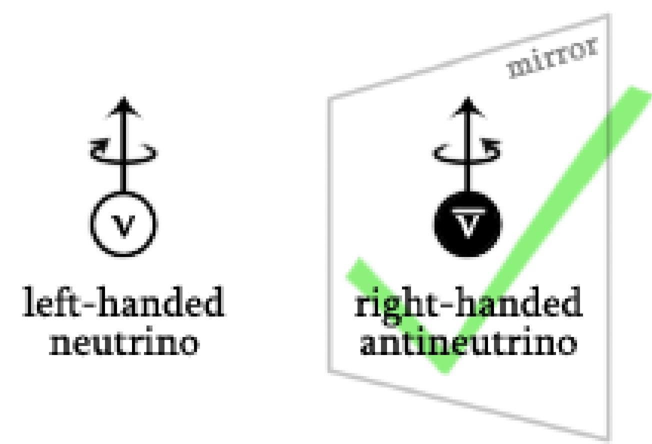
**Mass Hierarchy?**



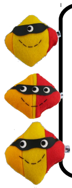

**Sterile Neutrinos?**




**CP Violation?**



# Neutrino Oscillation Physics



$$\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = U \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

where $U = \begin{pmatrix} U_{e1} & U_{\mu 1} & U_{\tau 1}\\ U_{e2} & U_{\mu 2} & U_{\tau 2}\\ U_{e3} & U_{\mu 3} & U_{\tau 3}\end{pmatrix}$

$$U = \begin{pmatrix} 1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

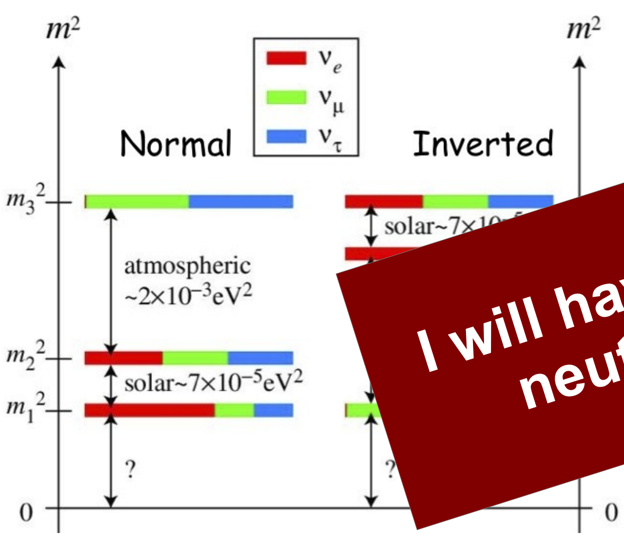
$c_{ij} = \cos(\theta_{ij})$
$s_{ij} = \sin(\theta_{ij})$
$\delta$ = CP phase

**As of 2012 we now have measured the three angles**

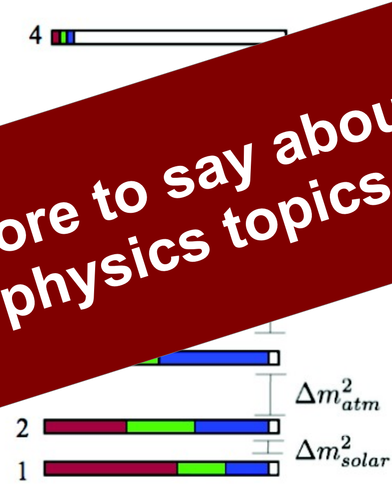
$(\theta_{12} \sim 34^\circ, \theta_{13} \sim 9^\circ, \theta_{23} \sim 45^\circ)$

## Still lots of unanswered questions

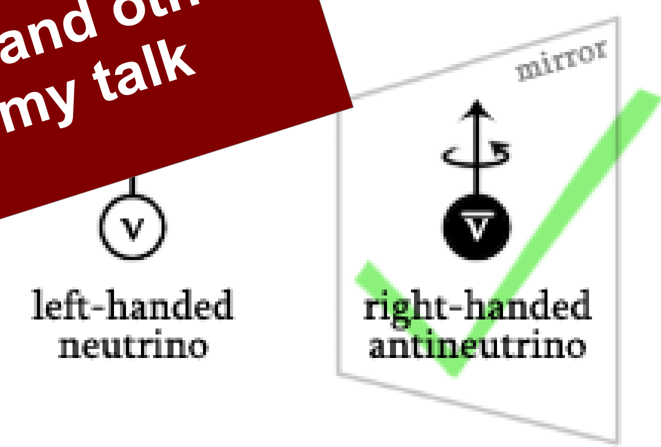
**Mass Hierarchy?**




**Sterile Neutrinos?**

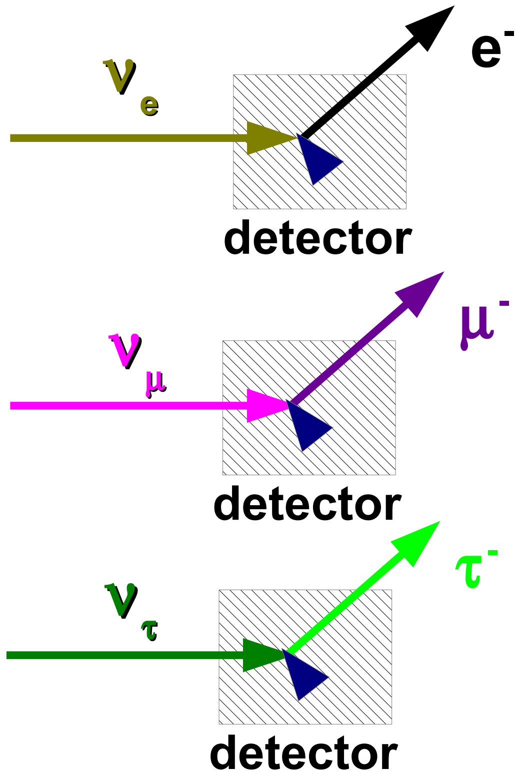



**olation?**




**I will have more to say about these and other neutrino physics topics later in my talk**

# Neutrino Detectors




Since neutrinos only interact via the weak force a basic strategy for a neutrino detector is to be:

**1) Big**

*Put a large number of nuclei in the path of the neutrino*

**2) Dense**

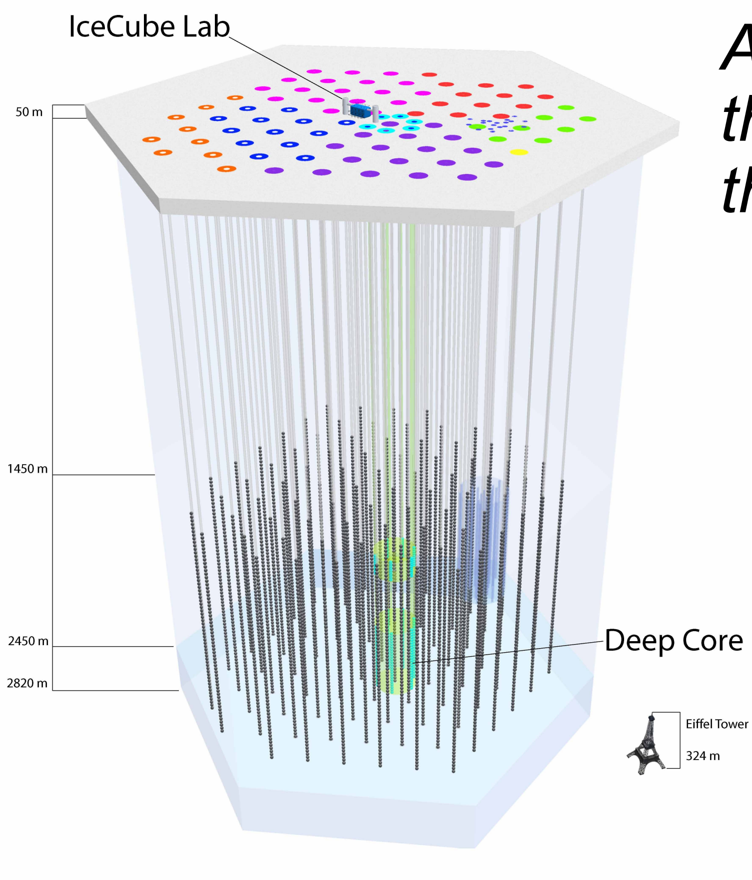
*Pack in as many nuclei to increase your interaction rate*

**3) Sensitive to neutrino interactions**

*Neutrino interactions produce charged particles and light*

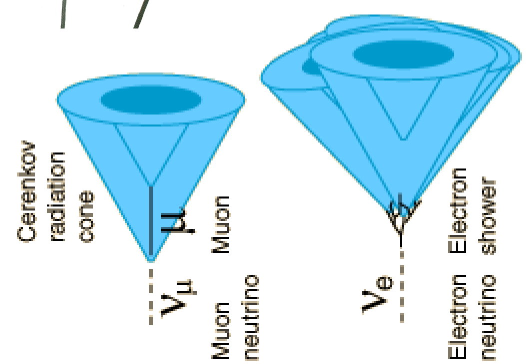
→ *We want to collect information about what type of charged particle was produced (particle identification) to identify the incident neutrino flavor*

# Neutrino Detectors




*An example where everyone else in the room is likely more of an expert than me.... :-)*

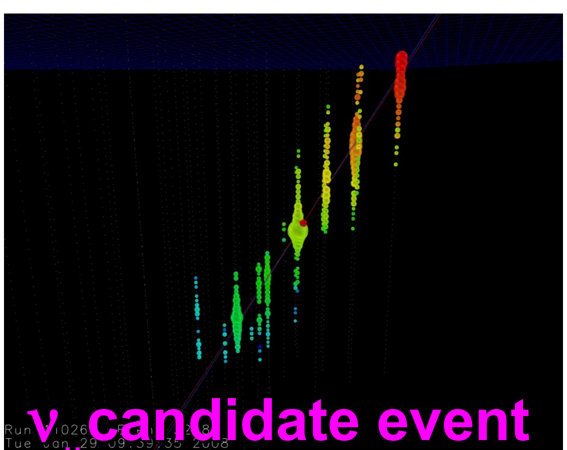
Digital optical modules detect Chernkov radiation created by the charged particle traveling through the ice

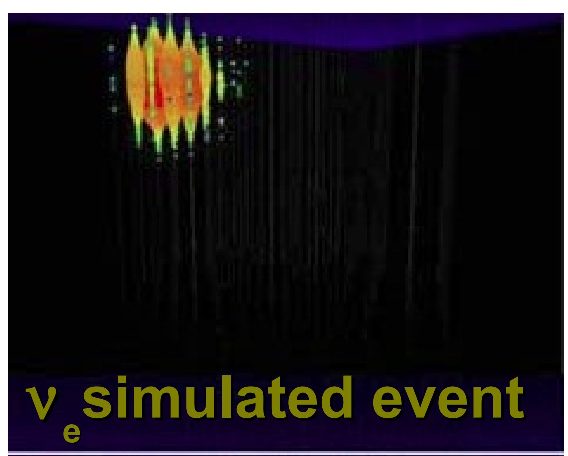



## Big
**(Frankly they don't come much bigger....)**

## Dense
**(Not the most dense material)**

## Sensitive
**(Very sensitive to high energy muon neutrinos...less sensitive to electrons and taus)**

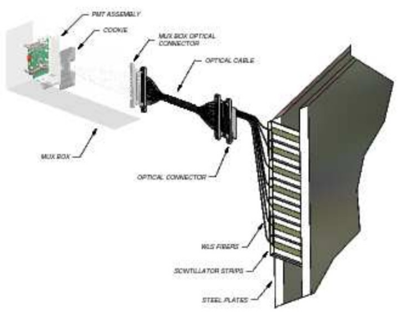


# Neutrino Detectors


**Dense**
(You don't get much more dense than steel)

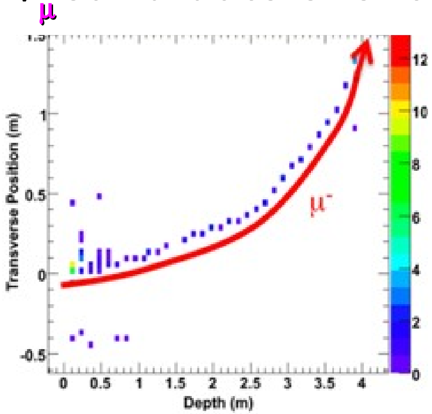
**Big**
(Difficult to get too much bigger...heavy and expensive)



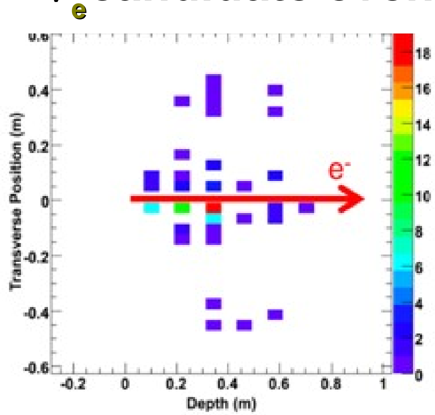
**Steel Scintillator panels**

**Sensitive**
(Limited granularity and detail of the interaction)

$\nu_\mu$ candidate event




$\nu_e$ candidate event



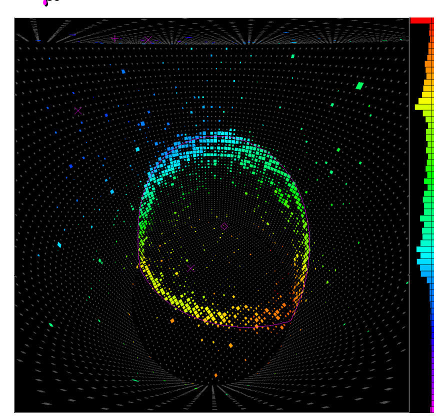

**Dense**
(Not the most dense thing we've got)

**Big**
(The detector scales to larger sizes "easily"...water is cheap)

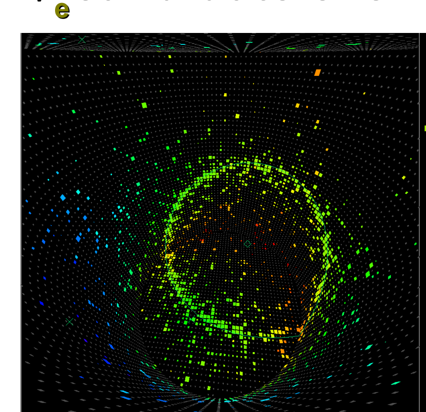
**Sensitive**
(Known detector technology and quite good at seeing interactions...but again limited granularity)


Water Cherenkov Detector

$\nu_\mu$ candidate event



$\nu_e$ candidate event



# Argon Detectors

**Nobel liquids are also considered for use in neutrino detectors because they have many attractive properties:**

1) Ionization charge that won't recombine easily
2) Scintillation light
3) Good dielectric properties (doesn't breakdown easily at high voltage)

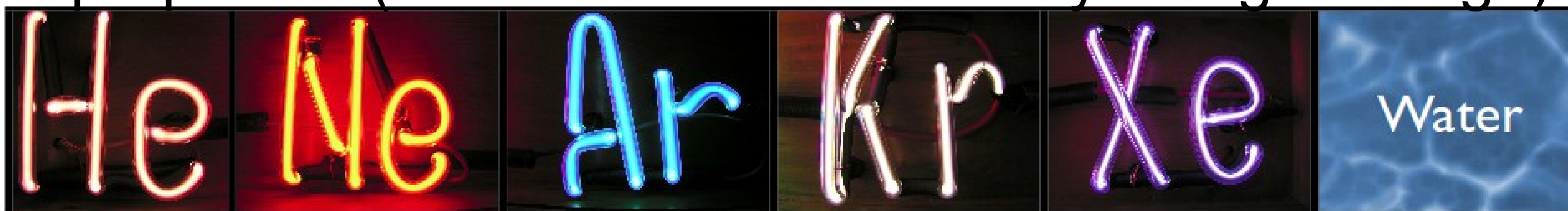
| | He | Ne | Ar | Kr | Xe | Water |
|---|---|---|---|---|---|---|
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 | 373 |
| Density [g/$cm^3$] | 0.125 | 1.2 | 1.4 | 2.4 | 3.0 | 1 |
| Radiation Length [cm] | 755.2 | 24.0 | 14.0 | 4.9 | 2.8 | 36.1 |
| dE/dx [MeV/cm] | 0.24 | 1.4 | 2.1 | 3.0 | 3.8 | 1.9 |
| Scintillation [$\gamma$ /MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 | |
| Scintillation $\lambda$ [nm] | 80 | 78 | 128 | 150 | 175 | |

***Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!***

# Argon Detectors

**Nobel liquids are also considered for use in neutrino detectors because they have many attractive properties:**

1) Ionization charge that won't recombine easily
2) Scintillation light
3) Good dielectric properties (doesn't breakdown easily at high voltage)




| | He | Ne | Ar | Kr | Xe | Water |
|---|---|---|---|---|---|---|
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 | 373 |
| [redacted] | | | | | | |
| Scintillation λ [nm] | 80 | 78 | 128 | 150 | 175 | |

**Argon is abundant**
**(9300 ppm (~1%) in the atmosphere)**
**Inexpensive and easy to obtain**
**Can be cooled using liquid nitrogen**
**(also inexpensive)**

***Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!***

# Argon Detectors

**Nobel liquids are also considered for use in neutrino detectors because they have many attractive properties:**

1) Ionization charge that won't recombine easily
2) Scintillation light
3) Good dielectric properties (doesn't breakdown easily at high voltage)

| | He | Ne | Ar | Kr | Xe | Water |
|---|---|---|---|---|---|---|
| Boiling Point [K] @ 1atm | 4.2 | ~ $500 / L | 87.3 | ~ $700 / L | 165.0 | 373 |
| Density [g/cm³] | ~ $10 / L | [illegible] | ~ $2 / L | [illegible] | ~ $3000 / L | 1 |
| Radiation Length [cm] | 755.2 | 24.0 | 14.0 | 4.9 | 2.8 | 36.1 |
| dE/dx [MeV/cm] | 0.24 | 1.4 | 2.1 | 3.0 | 3.8 | 1.9 |
| Scintillation [γ /MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 | |
| Scintillation λ [nm] | 80 | 78 | 128 | 150 | 175 | |

*Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!*

# Argon Detectors

**Nobel liquids are also considered for use in neutrino detectors because they have many attractive properties:**

1) Ionization charge that won't recombine easily
2) Scintillation light
3) Good dielectric properties (doesn't breakdown easily at high voltage)

| | He | Ne | Ar | Kr | Xe | Water |
|---|---|---|---|---|---|---|
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 | 373 |
| Density [g/cm³] | 0.125 | 1.2 | 1.4 | 2.4 | 3.0 | 1 |
| [redacted] | | | | | | |
| Scintillation [γ /MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 | |
| Scintillation λ [nm] | 80 | 78 | 128 | 150 | 175 | |

**Argon is dense**

**(almost one and a half times more dense than water)**

***Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!***

# Argon Detectors

**Nobel liquids are also considered for use in neutrino detectors because they have many attractive properties:**

1) Ionization charge that won't recombine easily
2) Scintillation light
3) Good dielectric properties (doesn't breakdown easily at high voltage)

| | He | Ne | Ar | Kr | Xe | Water |
|---|---|---|---|---|---|---|
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 | 373 |
| Density [g/cm³] | 0.125 | 1.2 | 1.4 | 2.4 | 3.0 | 1 |
| Radiation Length [cm] | 755.2 | 24.0 | 14.0 | 4.9 | 2.8 | 36.1 |
| dE/dx [MeV/cm] | 0.24 | 1.4 | 2.1 | 3.0 | 3.8 | 1.9 |

[redacted]

**Argon ionizes easily**
**(55,000 electrons / cm)**

*Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!*

# Argon Detectors

**Nobel liquids are also considered for use in neutrino detectors because they have many attractive properties:**

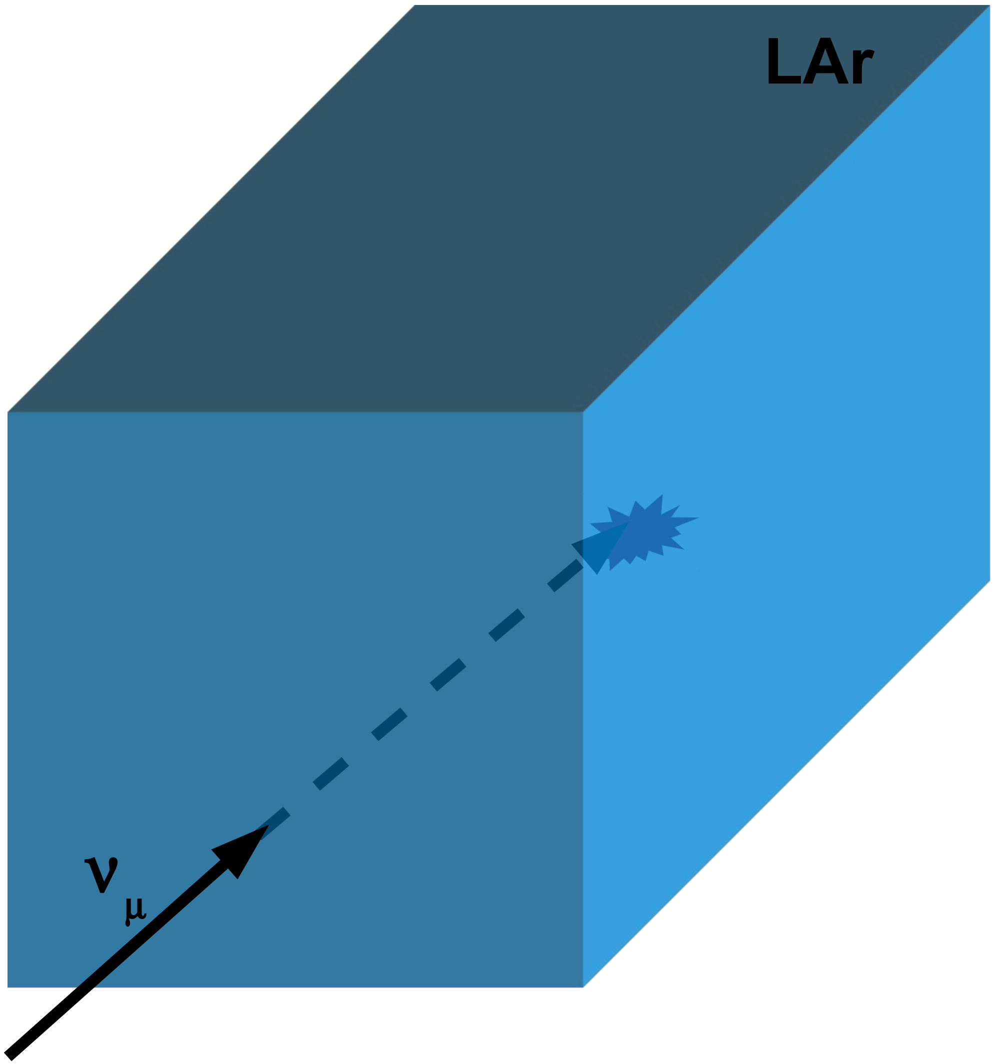
1) Ionization charge that won't recombine easily
2) Scintillation light
3) Good dielectric properties (doesn't breakdown easily at high voltage)

| | He | Ne | Ar | Kr | Xe | Water |
|---|---|---|---|---|---|---|
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120.0 | 165.0 | 373 |
| Density [$g/cm^3$] | 0.125 | 1.2 | 1.4 | 2.4 | 3.0 | 1 |
| Radiation Length [cm] | 755.2 | 24.0 | 14.0 | 4.9 | 2.8 | 36.1 |
| dE/dx [MeV/cm] | 0.24 | 1.4 | 2.1 | 3.0 | 3.8 | 1.9 |
| Scintillation [$\gamma$ /MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 | |
| Scintillation $\lambda$ [nm] | 80 | 78 | 128 | 150 | 175 | |

**Produces lots of scintillation light**

**(and is transparent to the light it produces)**

# Neutrino interactions in Liquid Argon

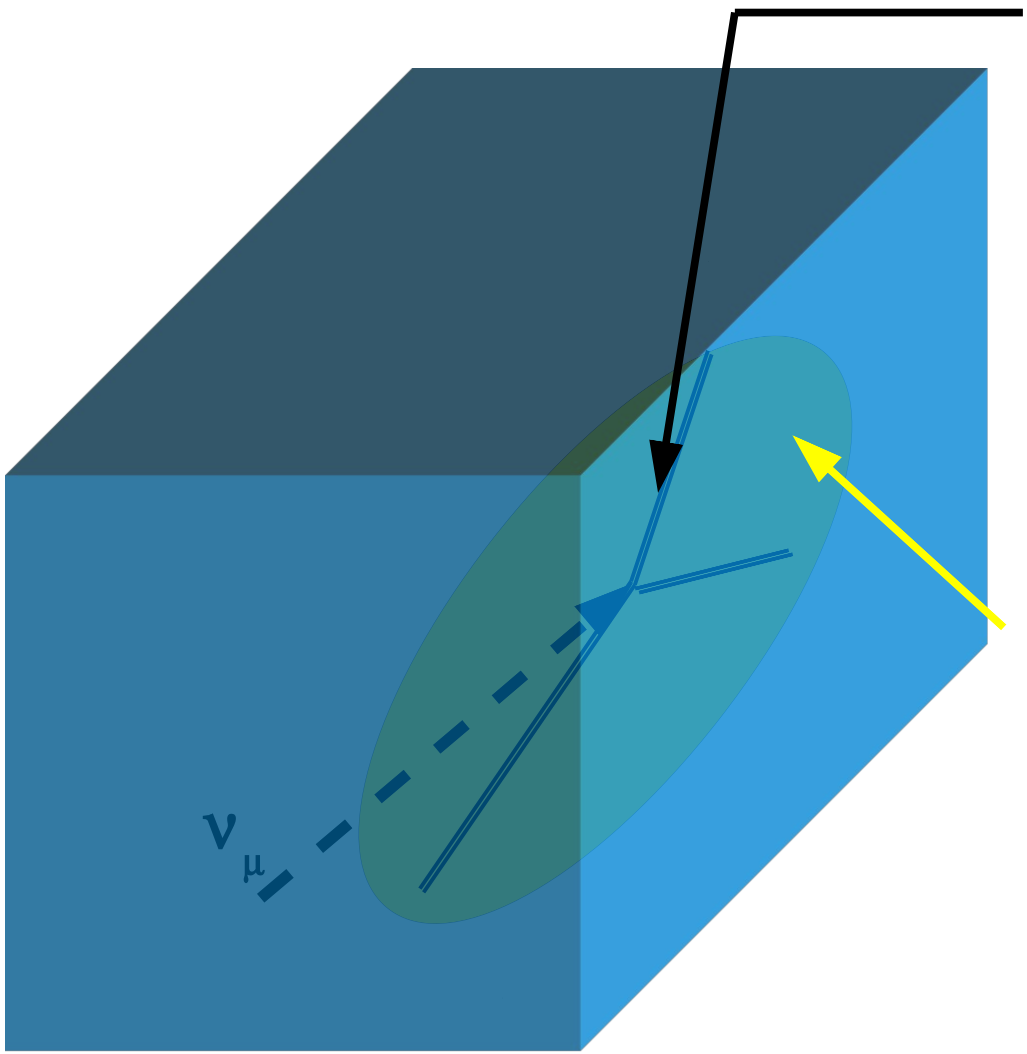



**To better understand how a liquid argon (LAr) neutrino detector works we'll look at some of the details of what a neutrino-Argon ($\nu$-Ar) nucleus interaction looks like**

**Process starts by firing a beam of neutrinos into the volume of LAr and wait for an interaction**

→ *I'll have more to say later about how we keep and cool a large volume of liquid argon*

# Neutrino interactions in Liquid Argon




**In the ν-Ar interaction the charged particles produced ionize the argon as they move through the volume**

**Additionally, the interaction causes scintillation light to be produced isotropically**

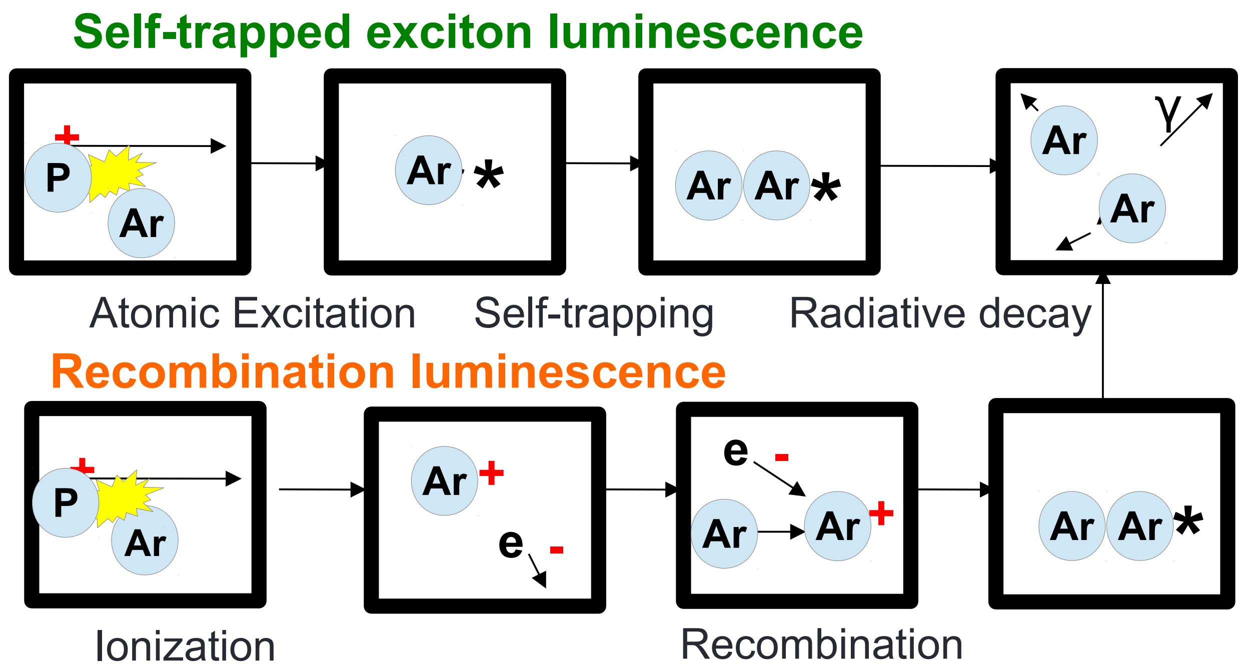
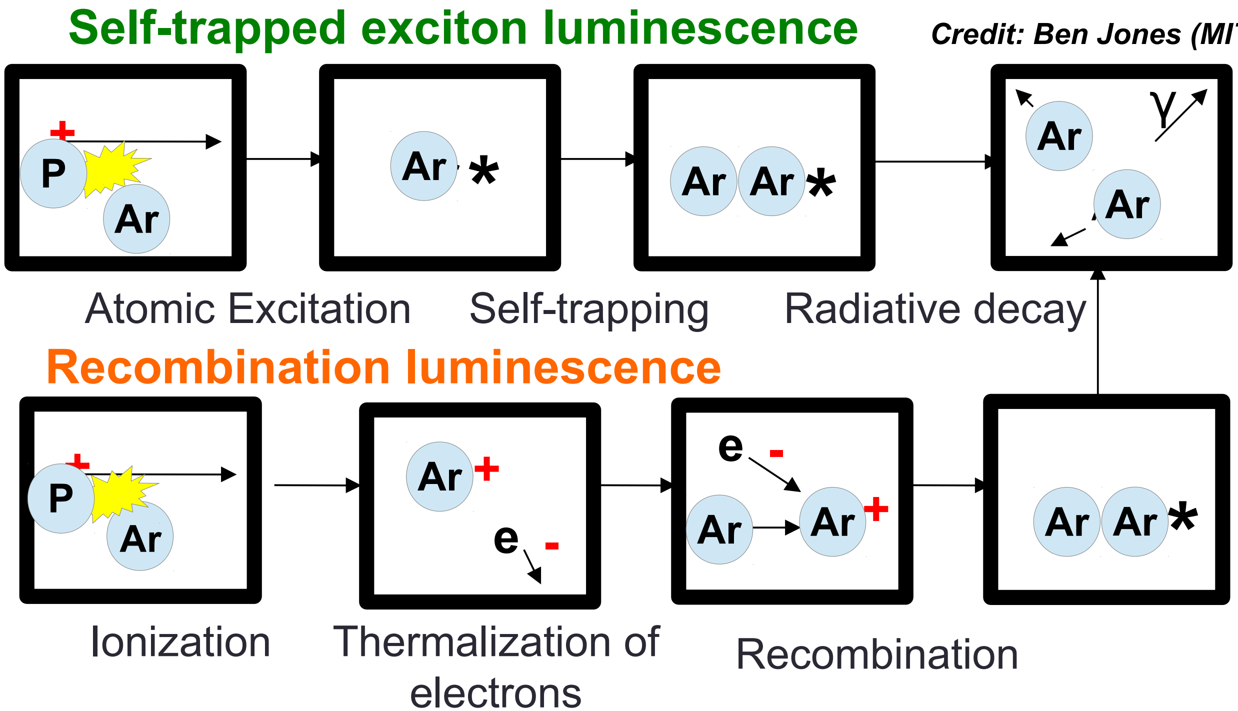


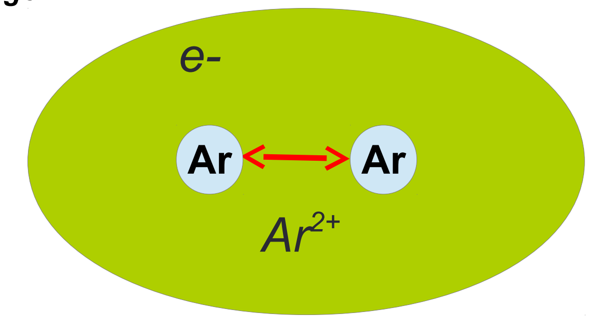

*Image Credit: Ben Jones (MIT)*
*→ If you want to learn a great deal about scintillation light in Liquid Argon Ben gives a great seminar!*

- **In liquid argon there are two important scintillation methods**
  - Self trapped exciton luminescence
  - Recombination luminescence

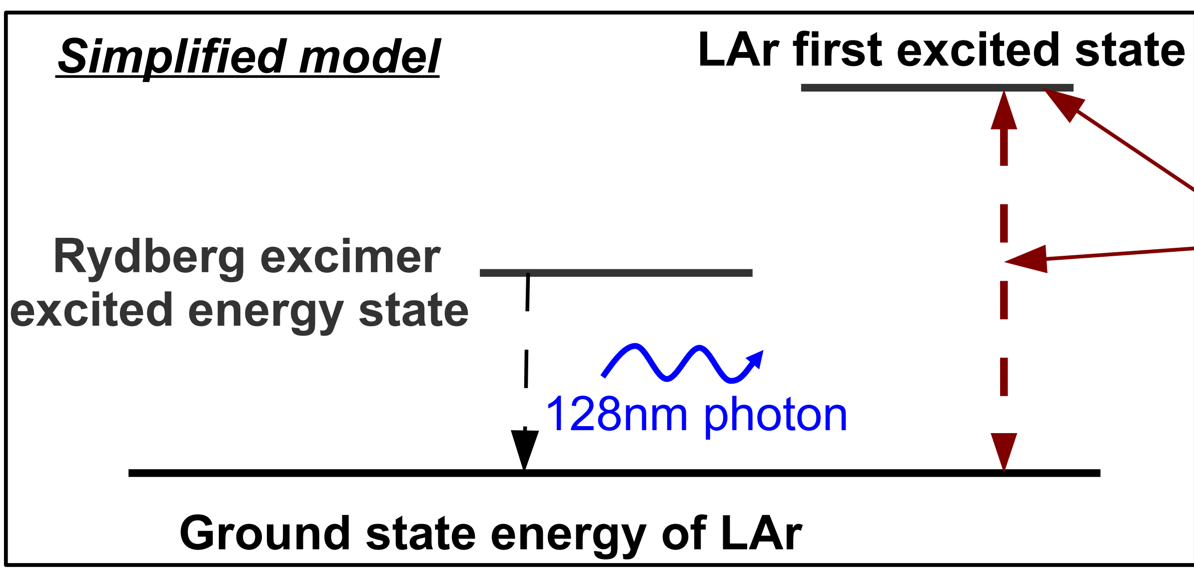
# Interesting aside about scintiallation light

Credit: Ben Jones (MIT) for image



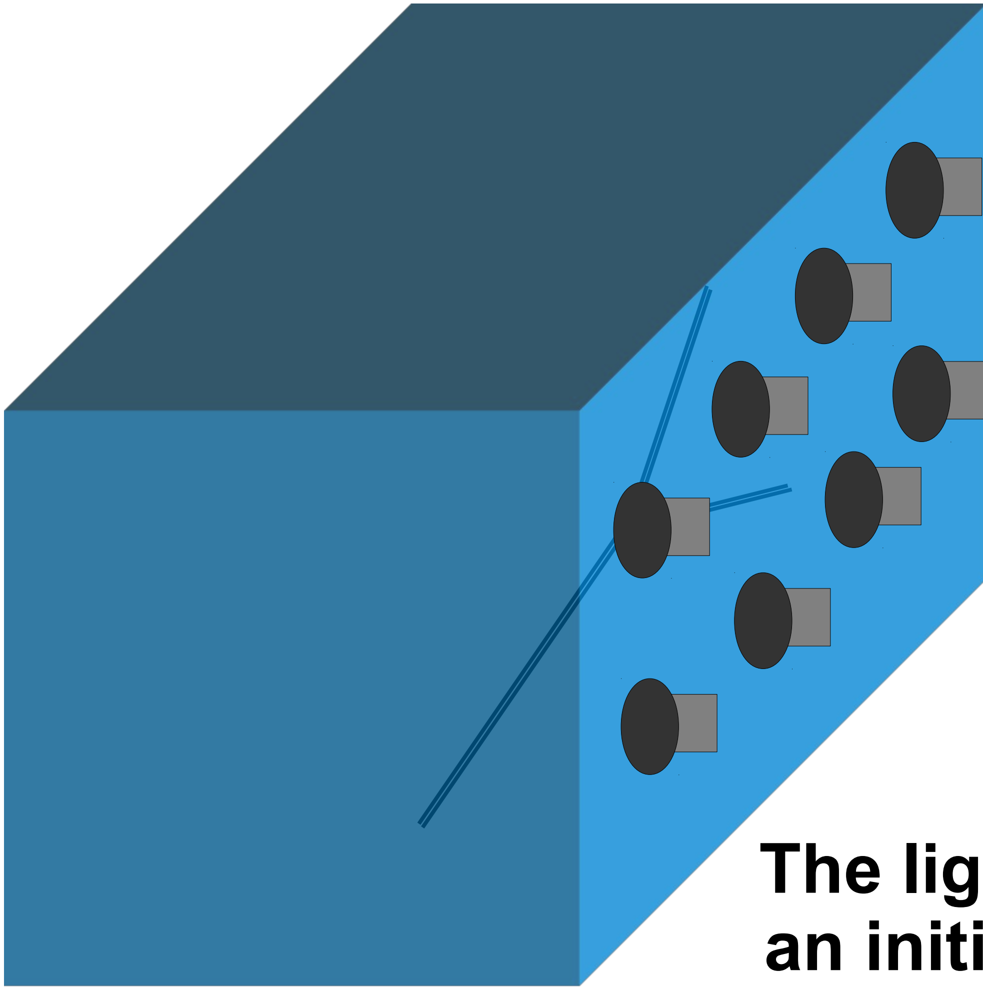




**Excimer state formed during this process is a Rydberg state: $Ar^{2+}$ with a bound electron**

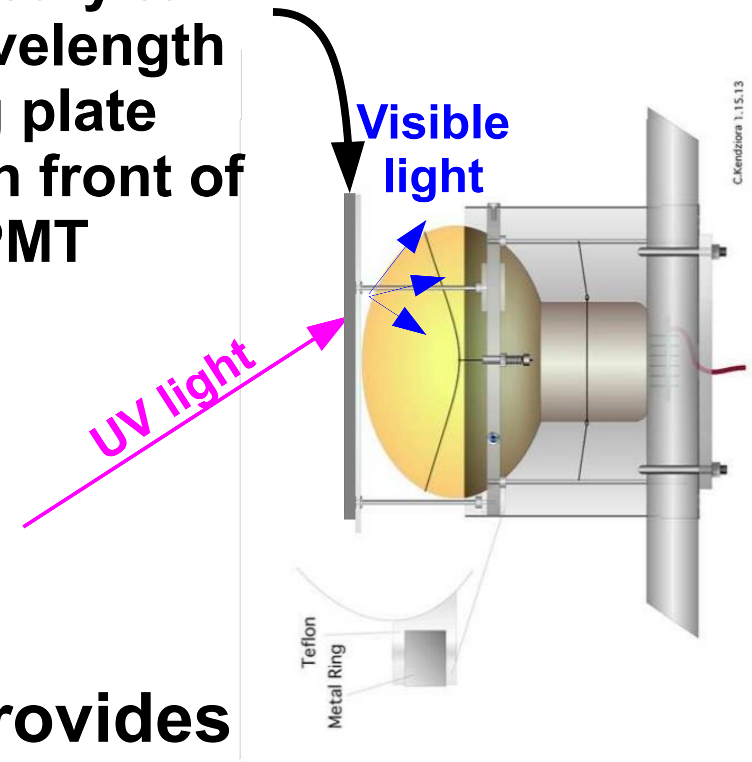



***This difference between the energy levels is why LAr is transparent to the scintillation light it produces***

# Neutrino interactions in Liquid Argon



**In order to detect the scintillation light using PMT's it is necessary to utilize wavelength shifting plate mounted in front of the PMT**




*Credit: Ben Jones (MIT) for image*

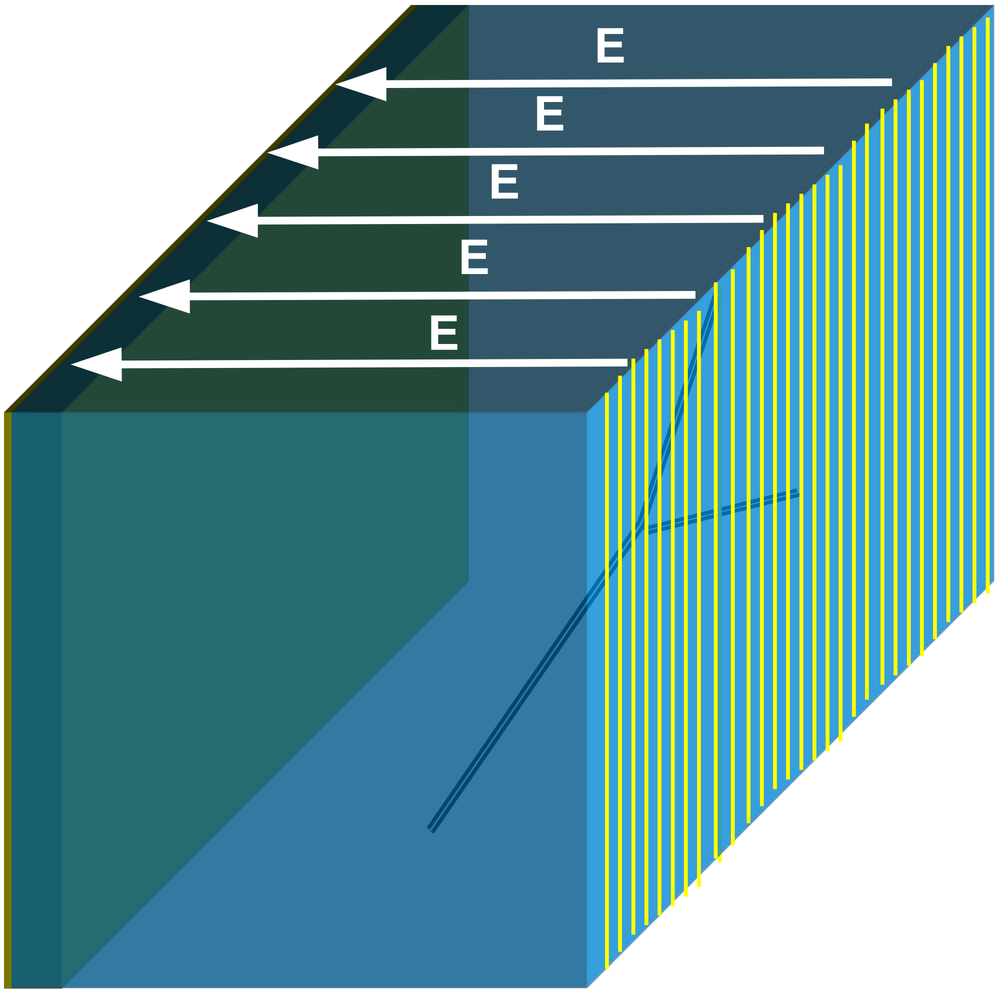
**The light pulse provides an initial time ($t_0$) for the neutrino event**

***<u>Details can be found in these papers (done by others)</u>***

**Testing of cryogenic photomultiplier tubes for the MicroBooNE experiement** JINST 8 T07005

**Environmental effects on TPB wavelength-shifting coatings** JINST 7 P07007

# Neutrino interactions in Liquid Argon




We apply a uniform electric field to drift the ionization charge
***(drift times on the order of $\mu$s)***

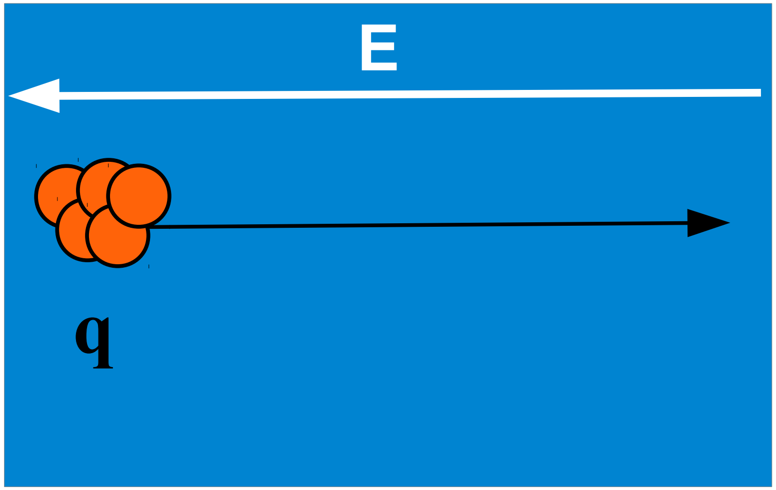
We collect this charge on a series of wires
***(Don't just put one set of wires, I just didn't want to draw them all)***

What you read off of your wires is the amount of charge and the drift time of the ionization “projected” back into the volume of liquid argon

**Hence the name Liquid Argon Time Projection Chamber**

# Aside about ion drift

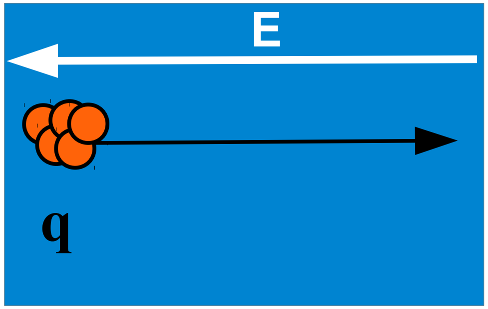
**When drifting your electrons through the argon you encounter a lot of interesting physics that impacts your measurement**




- Ion Drift Velocity
- Ion Diffusion
- Ion Recombination

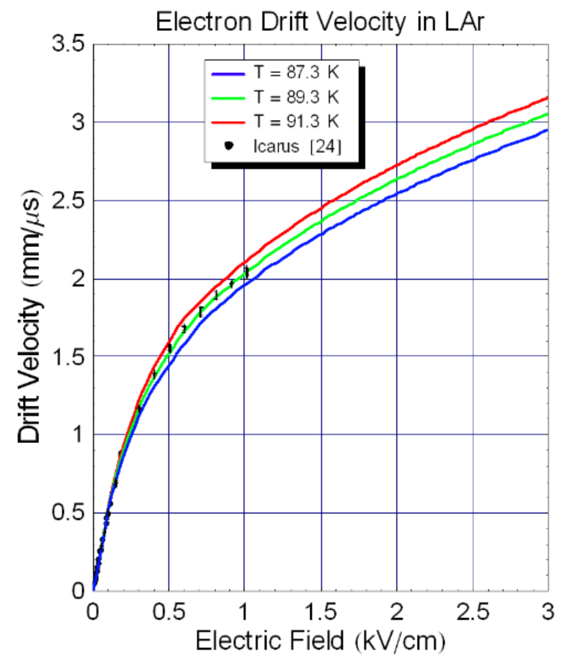
# Aside about ion drift

- ## Ion Drift Velocity



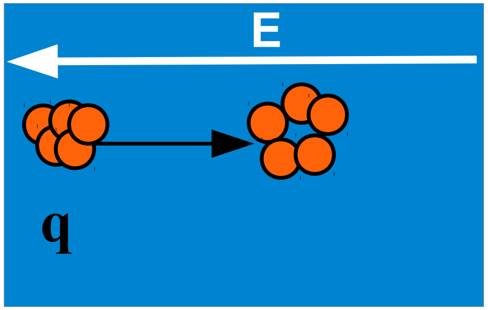

**The drift velocity is an empirically modeled function depending on temperature (T) and electric field (E) in the argon**

W. Walkowiak, NIM A 449 (20




$$v_d(T,|E|) = (P_1(T-T_0)+1)(P_3|E|\ln(1+P_4/|E|)+P_5|E|^{P_6})+P_2(T-T_0)$$

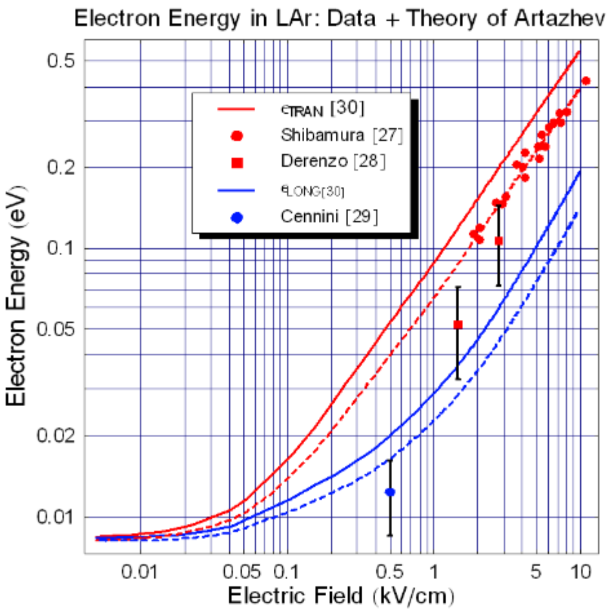
- ## Ion Diffusion




**The ion diffusion (RMS spread) is related to the drift distance (Δz), the electric field (E), and the electron mobility in argon**

S. Amoruso NIM **A516** (2004) 68

W. Walkowiak, NIM A449 (2000) 228



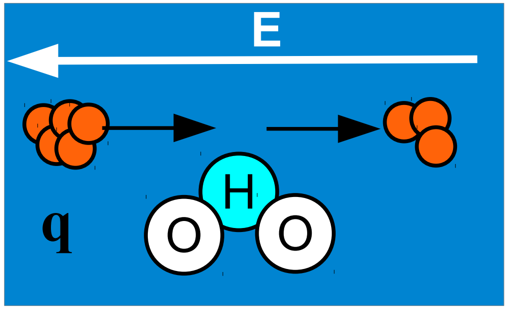

$$\sigma_{T(L)} = \sqrt{\frac{2\,\varepsilon_{T(L)}\,\Delta z}{E}}$$

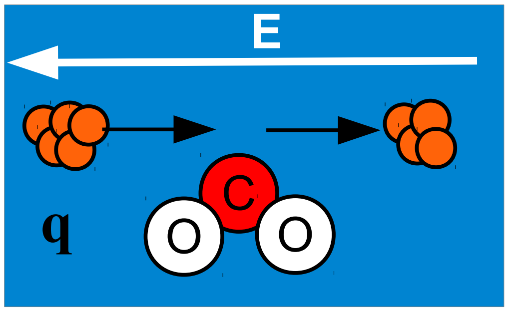
$$D = \mu\,\varepsilon$$

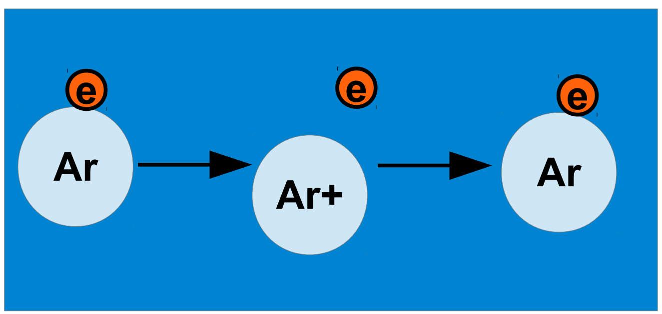
**Note: What I measure is the electron energy (ε) and I get the diffusion constant using the relationship with the electron mobility**

# Aside about ion drift

- **Ion Recombination**



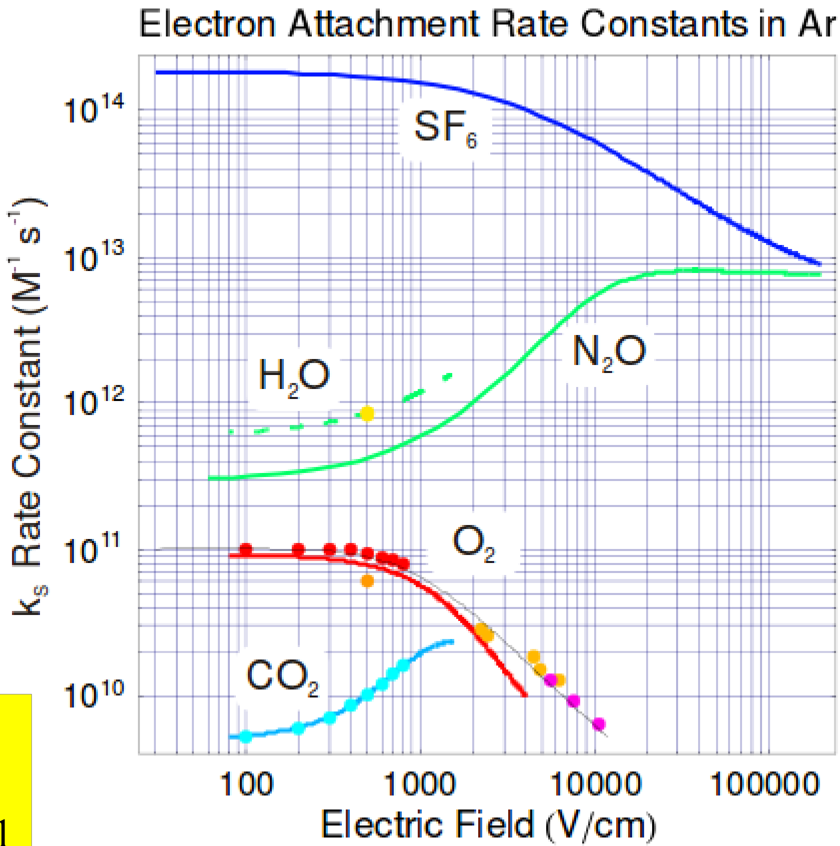




**Ion recombination is also a complicated affair depending on various types of impurity, its concentration, and the electric field**

$$Q(t) = Q_0 e^{t/\tau_a}$$

$$\text{where } \tau_a = (k_s n_s)^{-1}$$

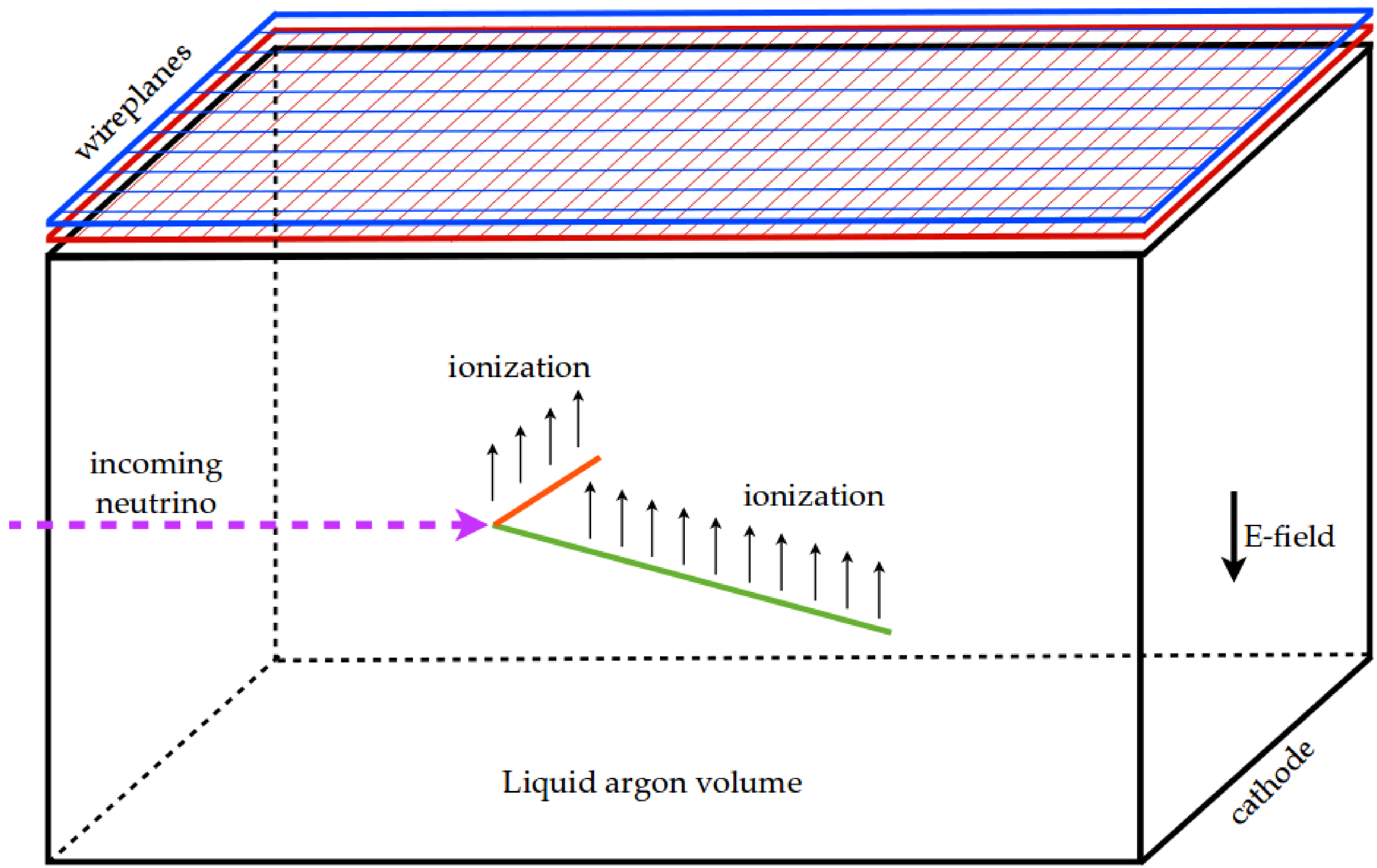



**Q(t)** is the charge collected as a function of time

$\mathbf{k_s}$ is the electron attachment rate at a constant molar concentration (which itself has a dependence on the electric field)

$\mathbf{n_s}$ is the molar solute concentration in LAr

# Aside about charge collection




**Now that we have our ionization charge drifting, there is some physics we should consider in the charge collection**

# Aside about charge collection

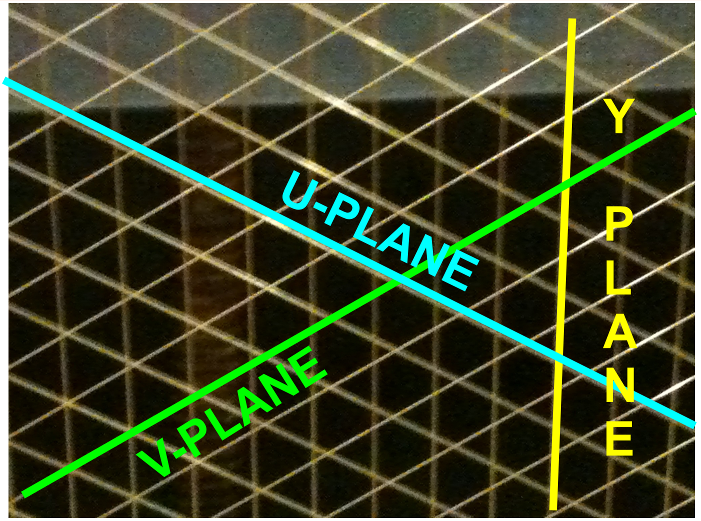



*Image from: B. Yu*

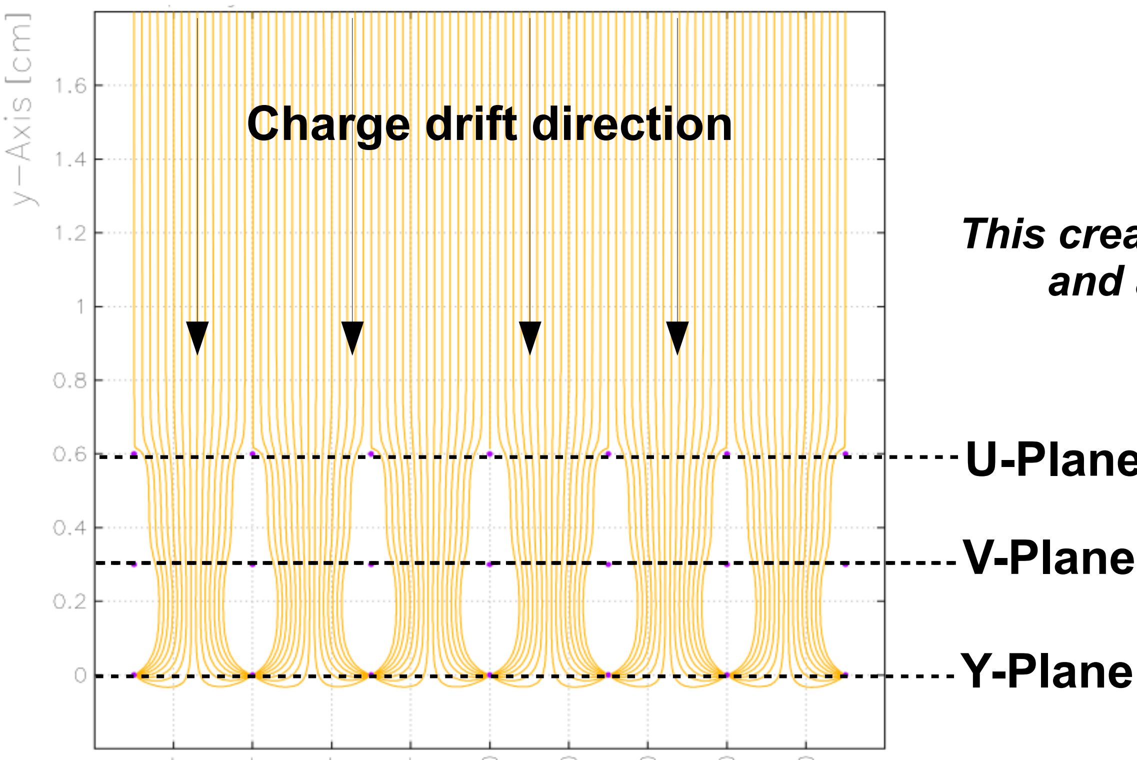
The wire planes act like an electrostatic grid

The set-up of the wire planes (spacing and bias voltages) are such that the first plane(s) are transparent to the charge (induction planes) and the last plane collects the drifting charge (collection plane)

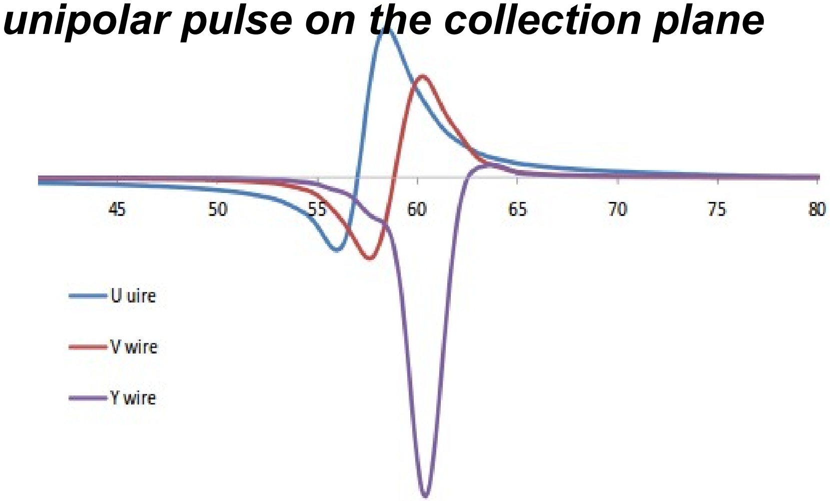
**100% Transparency Condition:** $$\frac{E_2}{E_1} = \frac{(1+\rho)}{(1-\rho)}$$

where $\rho = \frac{(2\pi r)}{d}$

where $r$ = wire radius and $d$ = wire pitch



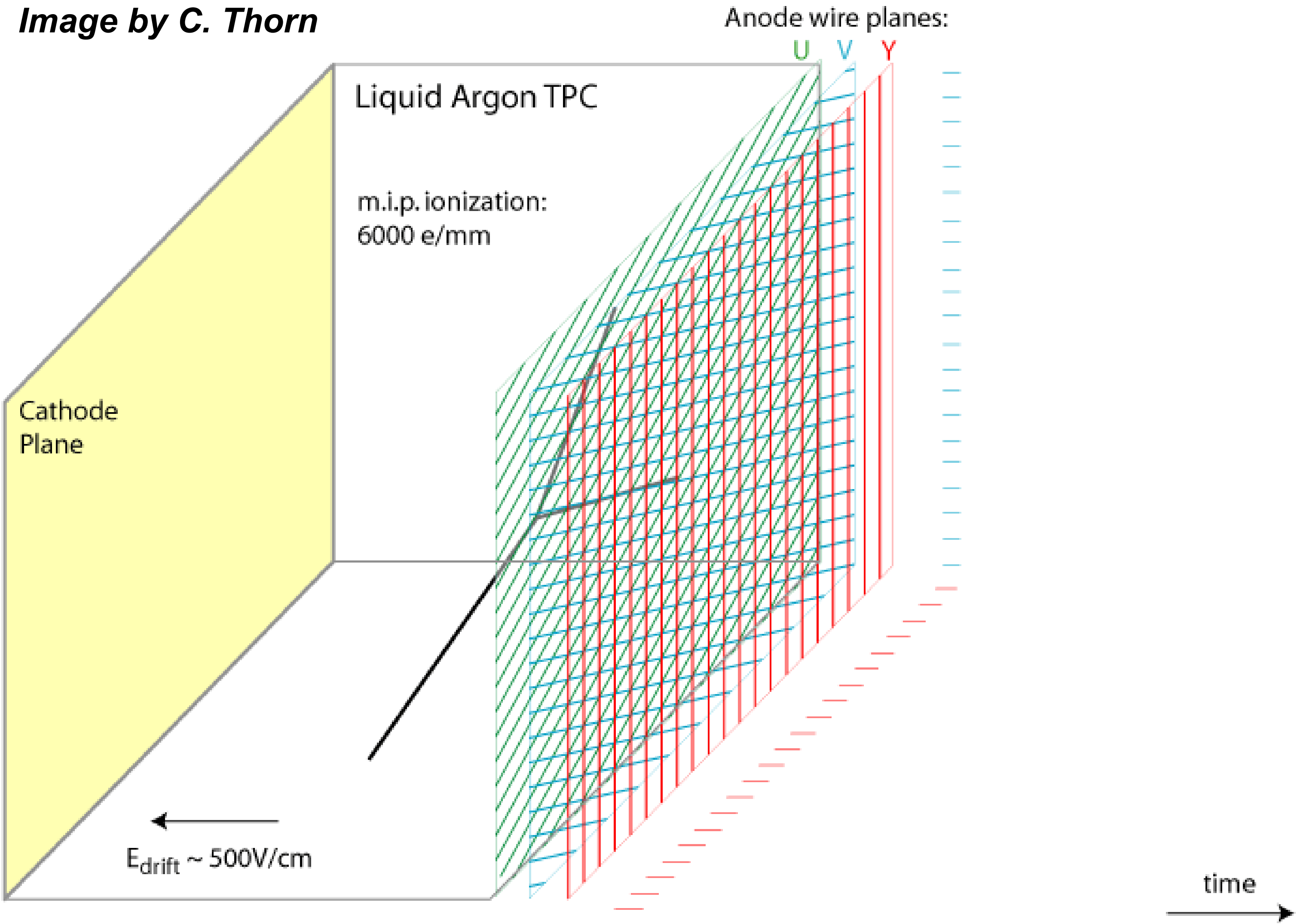

***This creates a bi-polar pulse on the induction planes and a unipolar pulse on the collection plane***




1.) Design of Grid Ionization Chambers, O. Bunemann, T.E. Cranshaw, and J.A. Harvey; Canadian Journal of Research, 27, 191-206, (1949)

# Liquid Argon Time Projection Chamber

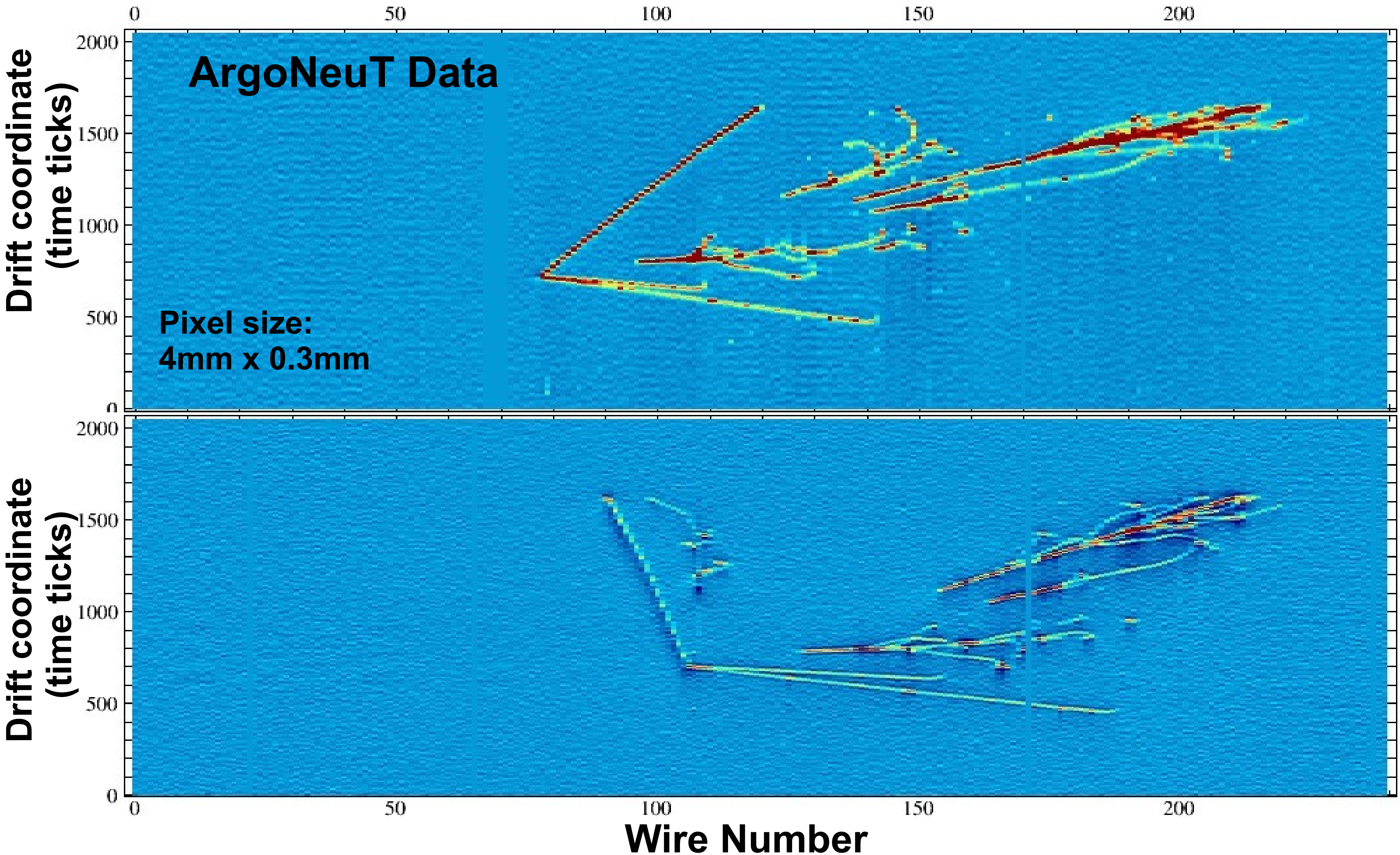
*Image by C. Thorn*



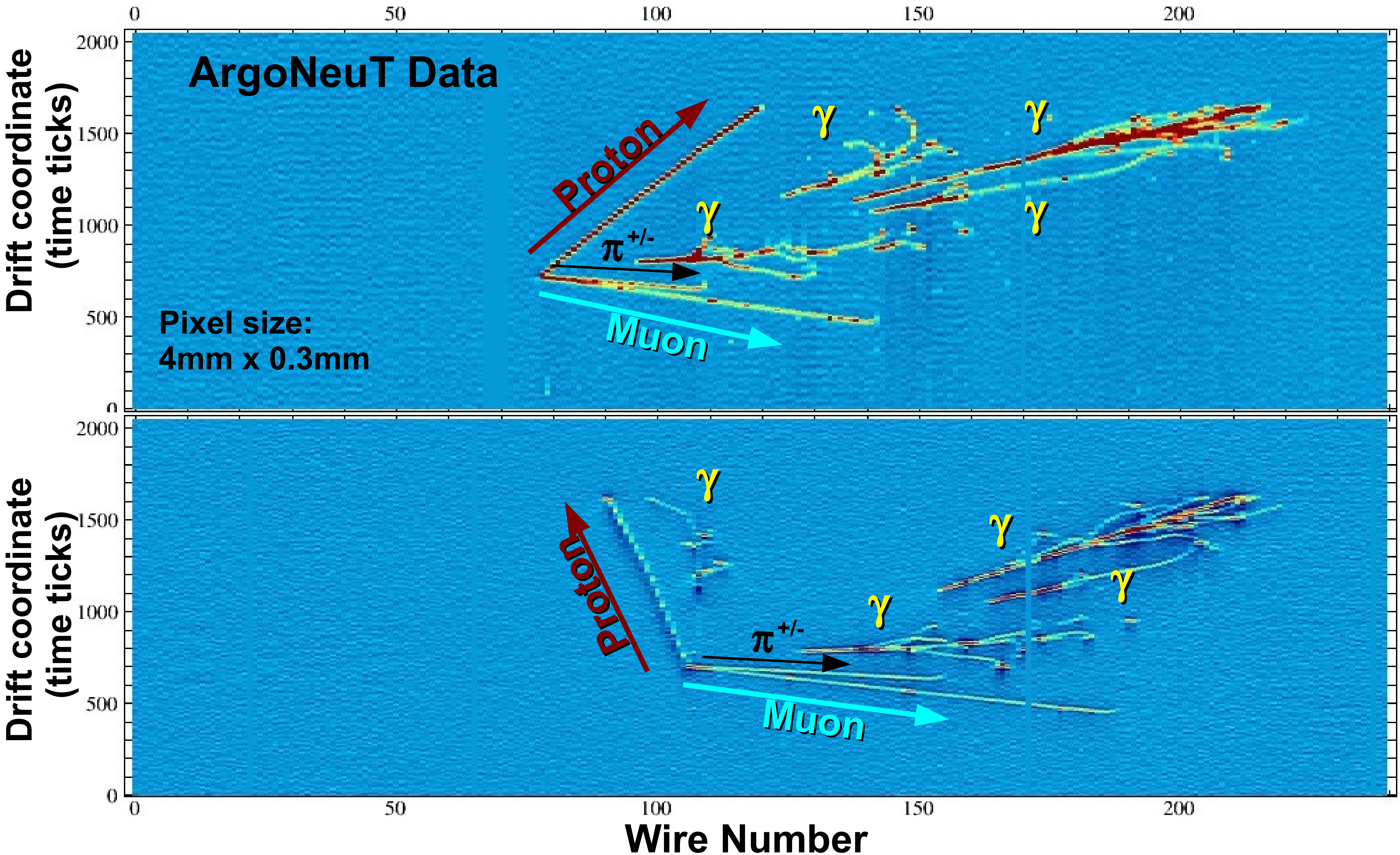

**The wires placed at the end of the drift provide a 2-d view of the ν-Ar interaction**

**Using multiple wire planes with different angles allows us to perform 3-d event reconstruction!**

# Liquid Argon Time Projection Chamber



# Liquid Argon Time Projection Chamber

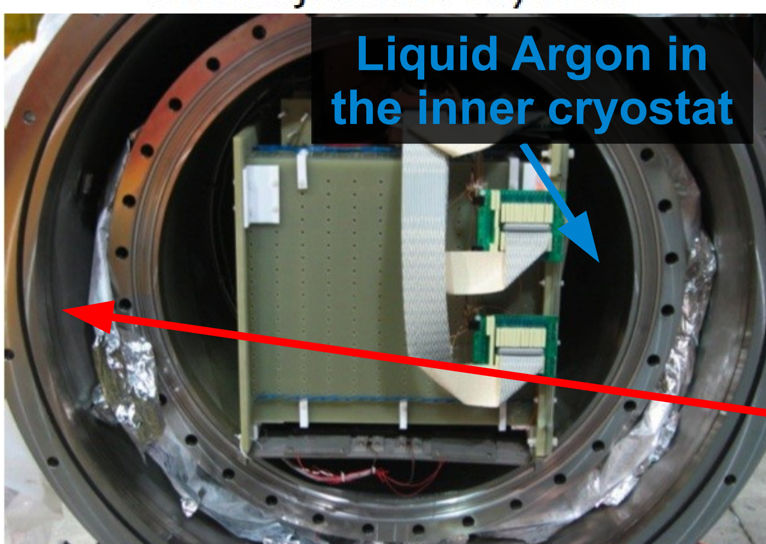


# LArTPC's: Cryostats

Argon has to be kept near 87 Kelvin in order to stay in the liquid phase
(so you can't just put it in any old pot!)

**You need a vessel that is insulated to keep the Argon cold!**

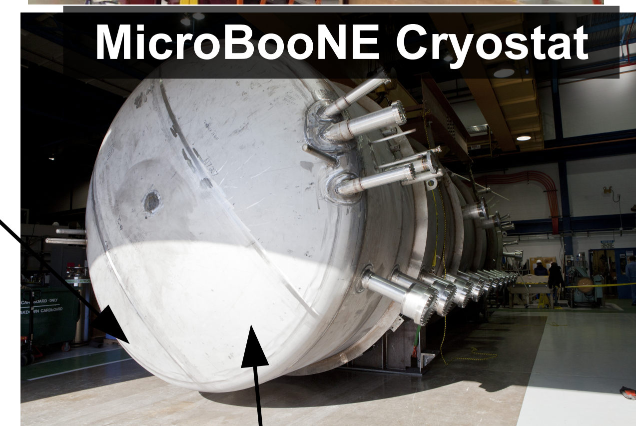

Vacuum-Jacketed Cryostat

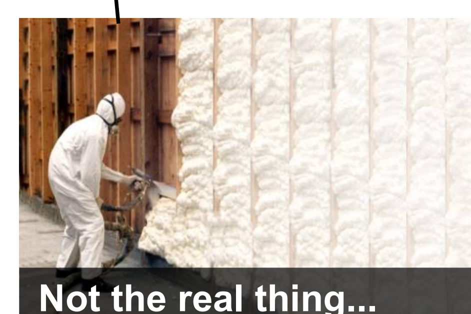



**Vacuum between the inner and outer cryostat acts like an insulator**

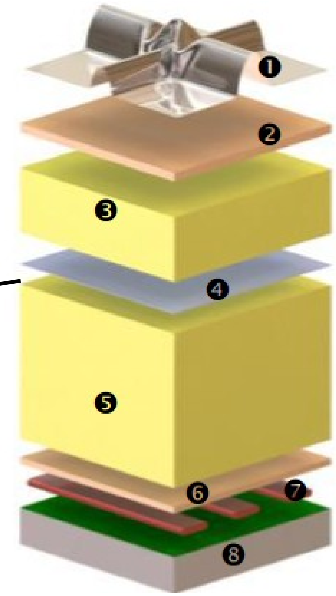
**Liquid Argon inside the cryostat**


**Then we spray the outside with insulating foam ~6" thick**

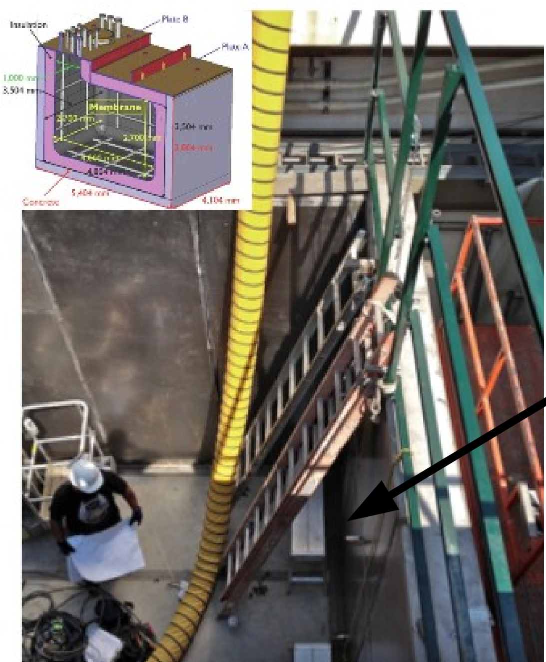


# LArTPC's: Cryostats

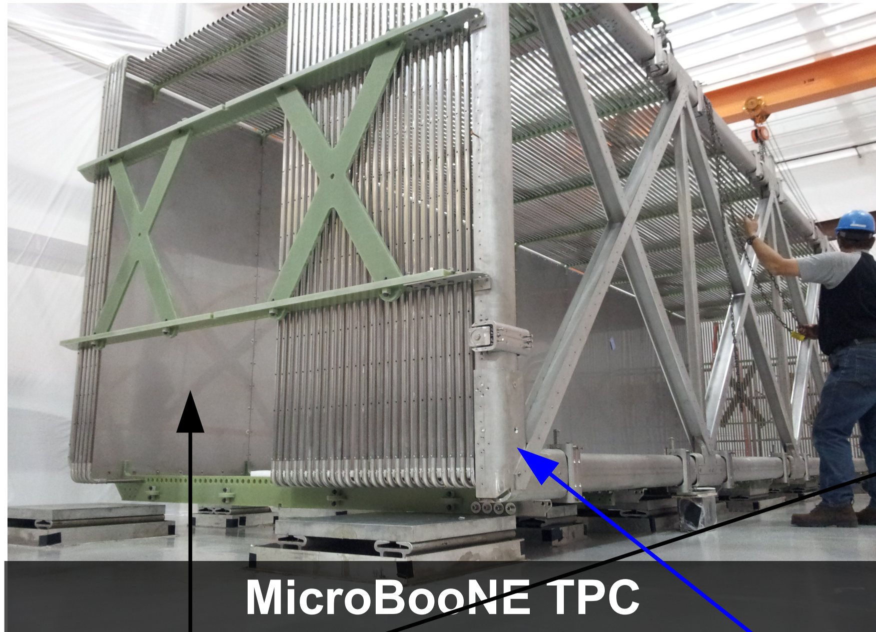
1) Stainless steel primary membrane (LAr inside here)
2)Plywood board
3) Polyurethane foam
4)Secondary barrier
5) Polyurethane foam
6) Plywood board
7) Bearing mastic
8)Concrete

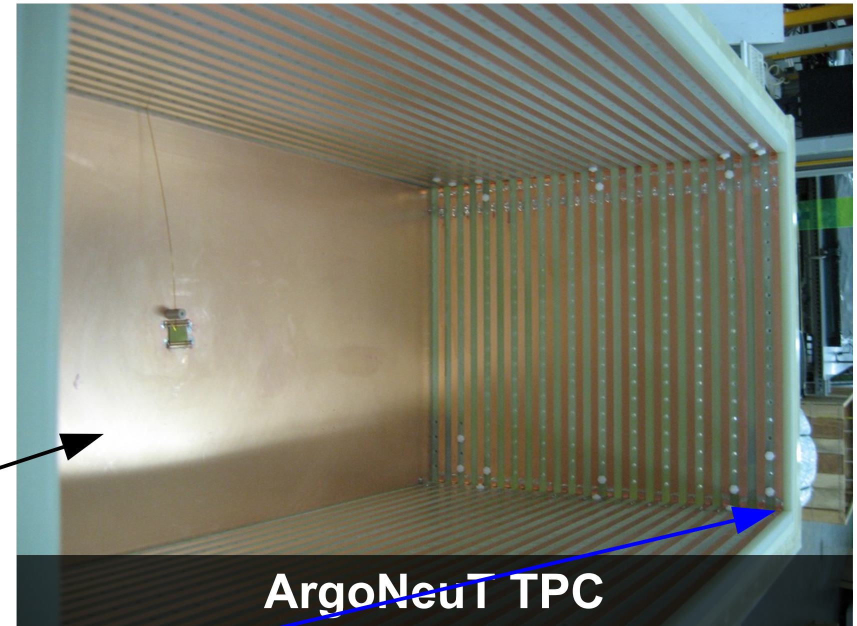


**In order to go even bigger we will use a membrane cryostat borrowing experience from industry (used to ship liquid natural gas)**

***35 ton membrane cryostat constructed at Fermilab as a demonstrator***

# LArTPC's: Field Cage



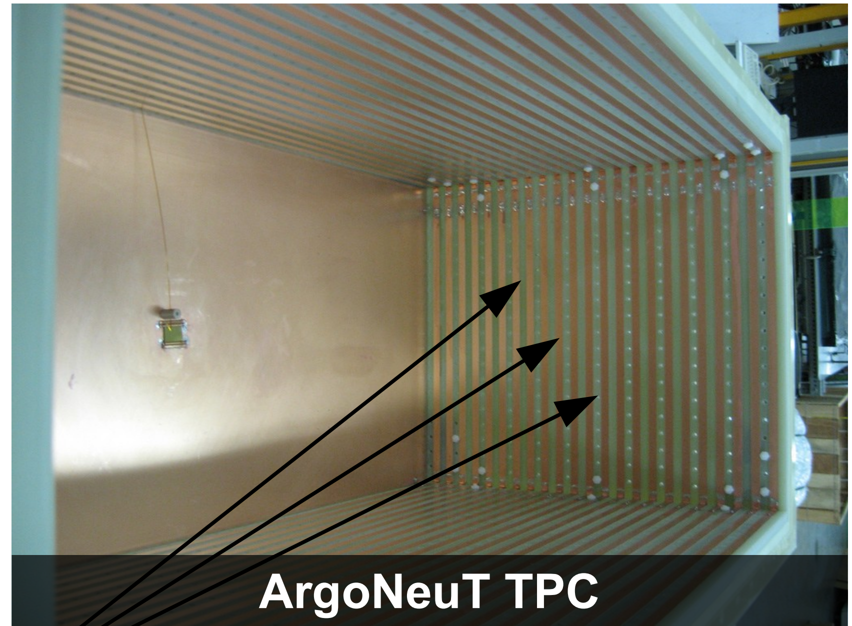

Cathode (High Voltage) Anode (Ground)

**The goal is to get the maximum amount of charge drifted from the interaction to the anode side (where the wires are)**

**<u>This can be obtained if you have a uniform electric field insidethe TPC</u>**

**To achieve this uniform field we start with a flat cathode plane that we bring to high voltage**

# LArTPC's: Field Cage


**Then we will have the field cage running in continuous bands around the TPC spaced uniformly a few centimeters apart**

By attaching a series of resistors from one field cage to the next, we slowly step up the electric field from the cathode side to the anode side while maintaining a field that is very uniform

Unfortunately I haven't even really scratched the surface of all the interesting aspects, challenges, and research that goes into LArTPC's

→ **Purity**
- How pure do we need the LAr to be (answer is really pure)
- How do we achieve this purity (cryogenic filters & recirculation)
- How to fill a large volume with pure LAr without pumping out a huge vacuum
- How do we monitor the purity

→ **Cryogenics**
- How do we re-condense argon that has boiled off to a gas
- How do we circulate a liquid at 87°K
- How do we monitor the cryogenic system

→ **Electron Mobility and Recombination**
- The electron drift distance is effected by the purity of the LAr
- How do electrons re-combine with the positive ions in the event

→ **High Voltage**
- Challenges of extremely high fields in LAr
- Causes of breakdown of materials in LAr
- 2 day conference last week at FNAL

→ **Light Detection**
- There was literally a 3 day long conference dedicated to this At Fermilab, so yeah there is a lot here!

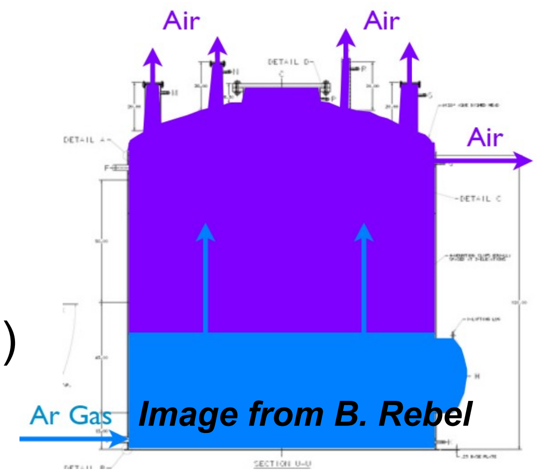
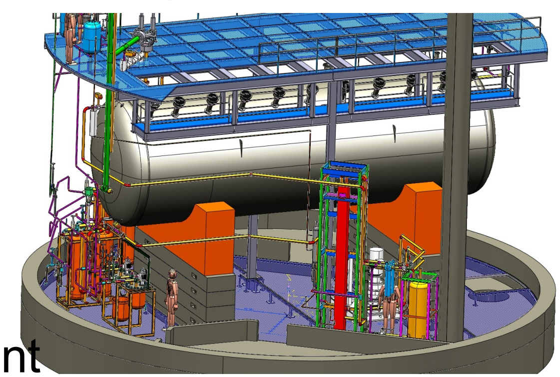


*Image from B. Rebel*

*Image from J. Raaf*


# Liquid Argon Time Project Chamber

Unfortunately I haven't even really scratched the surface of all the interesting aspects, challenges, and research th... goes into LArTPC's

→ **Purity**
- How pure do we need the LAr to be...
- How do we achieve this purity...
- How to fill a large volum...
  a huge vacuum
- How do we...

→ **Cryog...**

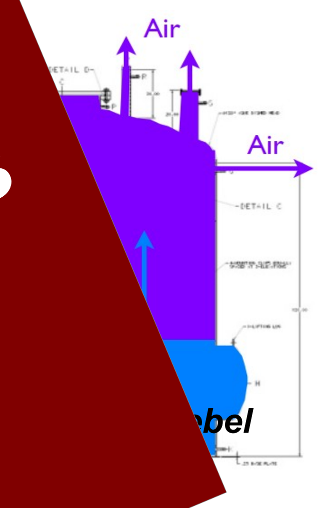
...e purity of the LAr
...e positive ions in the event

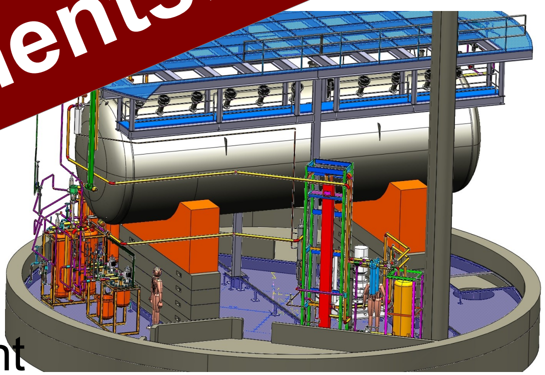
→ ...
...ly high fields in LAr
...down of materials in LAr

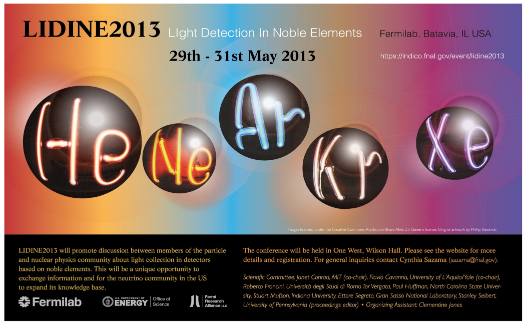
→ **Li... ...ction**
- ...re was literally a 3 day long conference dedicated to this
  At Fermilab, so yeah there is a lot here!

**You will just have to invite me back for another seminar to learn about all this interesting research**

**For now, on to the experiments!**

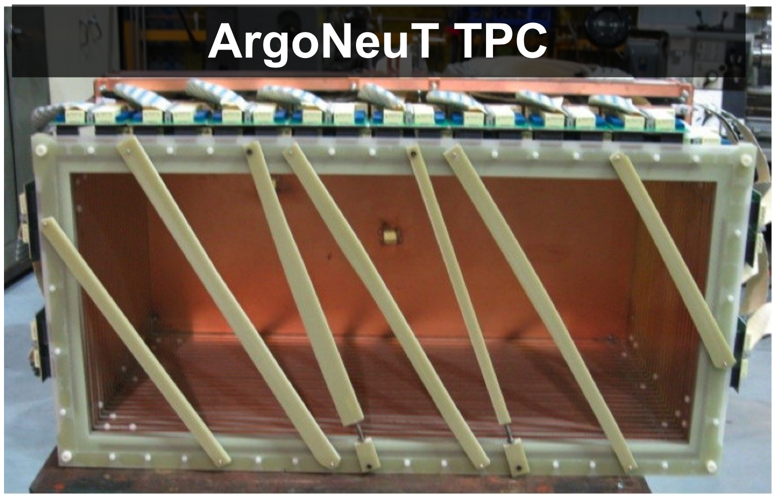


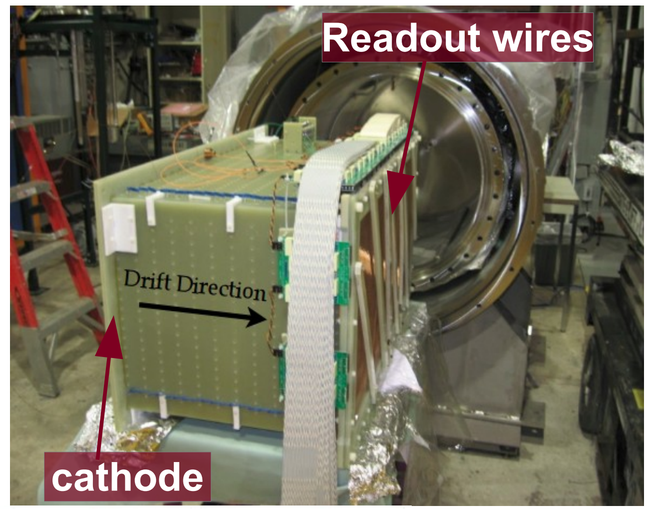





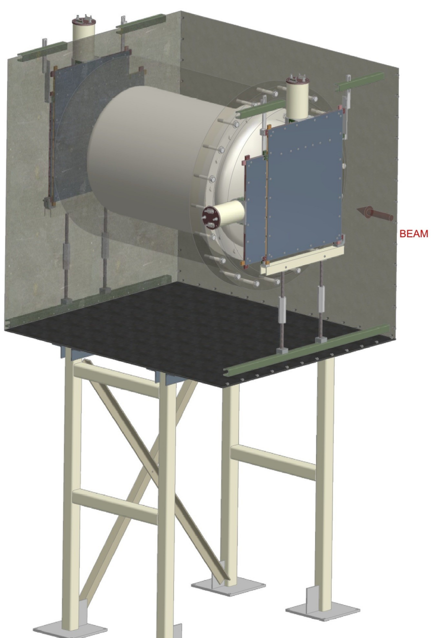
# ArgoNeuT
## *(Argon Neutrino Teststand)*

**ArgoNeuT was the first Liquid Argon TPC in a neutrino beam in the U.S.**



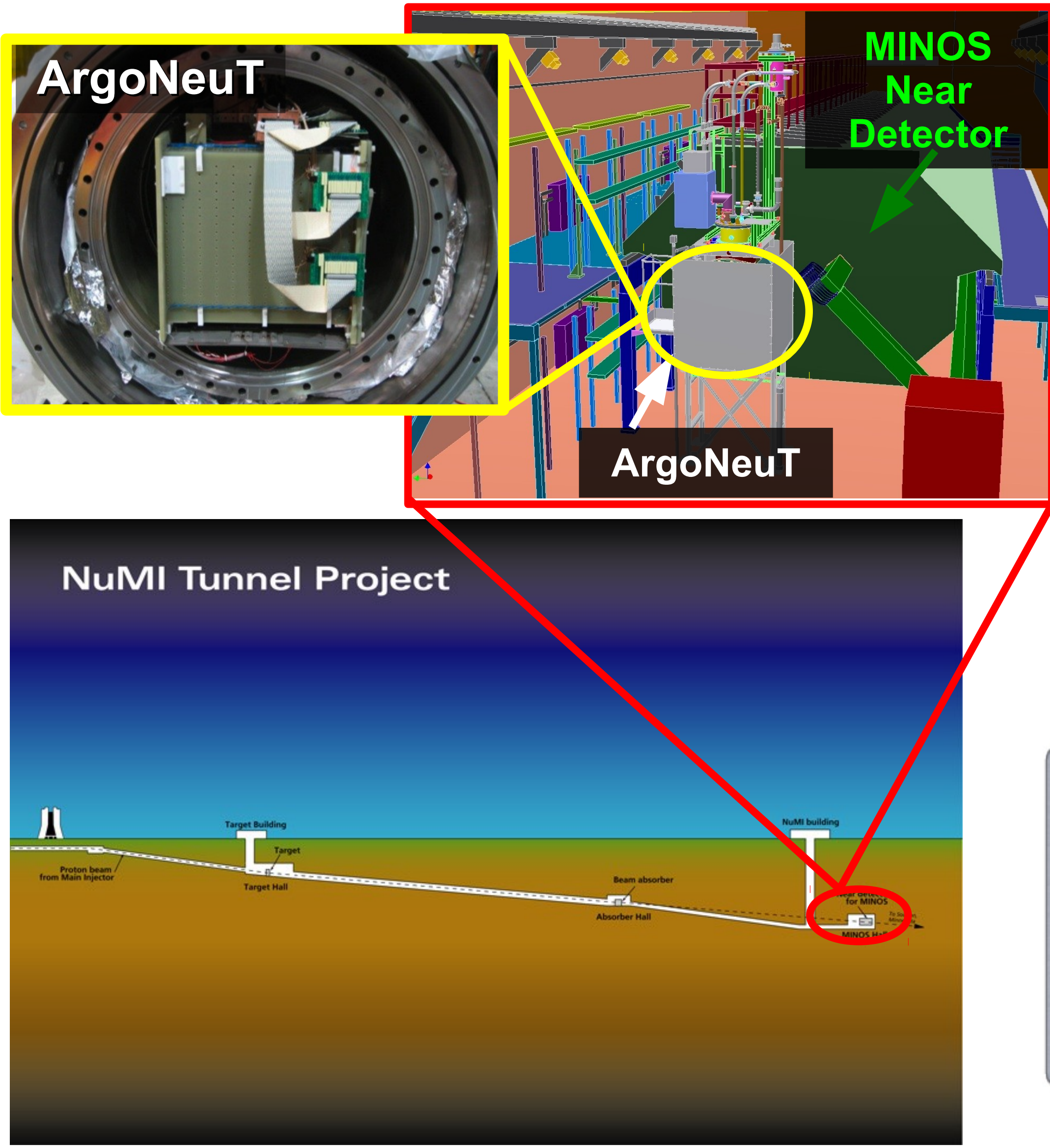





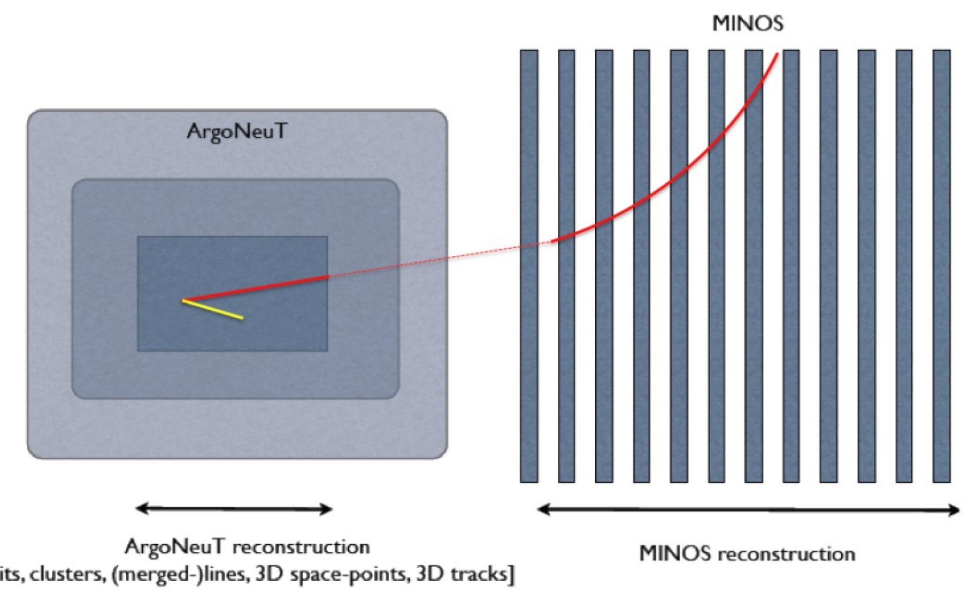



# ArgoNeuT
## (Argon Neutrino Teststand)

MINOS TDR: NUMI-L-337, FERMILAB-DESIGN-1998-02

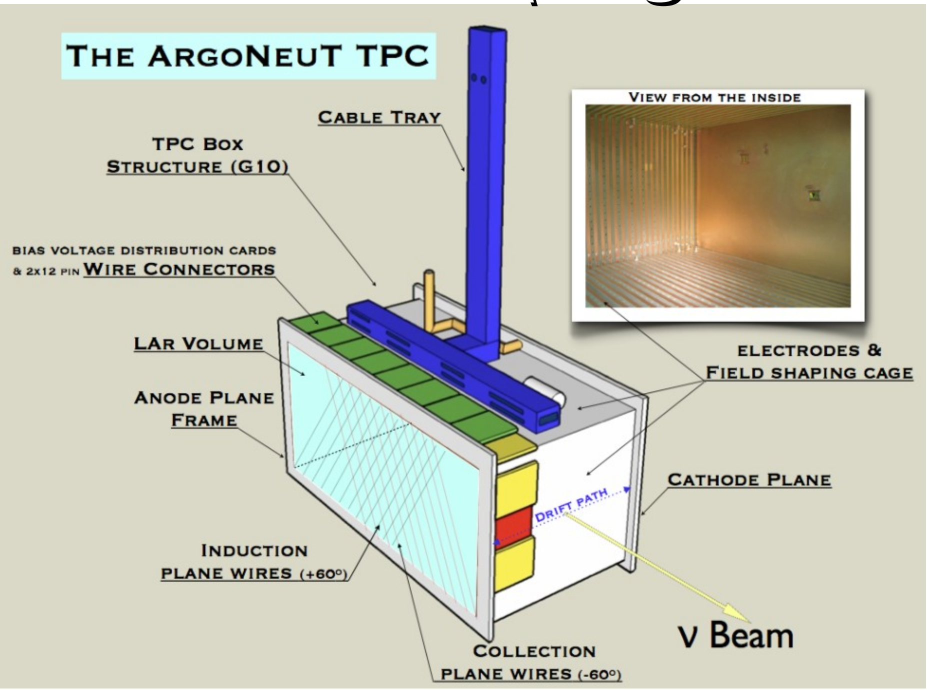



- **ArgoNeuT**
  - Located in the NuMI (Neutrinos from the Main Injector) beam at Fermilab
  - Utilized the MINOS near detector as a muon spectrometer (sign & momentum determination)



# ArgoNeuT

## (Argon Neutrino Teststand)




| | |
|---|---|
| TPC dimensions | $40\ h \times 47\ w \times 90\ l$ cm$^3$ |
| TPC (active) volume | 170 liters |
| Max. Drift Length (TPC width) | $\ell_d = 470$ mm |
| # of wire-planes | 3 (2 instrumented - I, C) |
| Interplane gaps width | $\ell_g = 4$ mm |
| Wire pitch (normal to wire direction) | $\delta s = 4$ mm (all planes) |
| Wire Type | Be-Cu Alloy #25, diam. 152 $\mu$m |
| # of wires (total)<br>Shield plane (S)<br>Induction plane (I)<br>Collection plane (C) | 705<br>225 (non-instrumented)<br>240 (instrumented - w-index: $n_w^I$)<br>240 (instrumented - w-index: $n_w^C$) |
| Wire Orientation (w.r.t. horizontal) | $90^o$, $+60^o$, $-60^o$ (S, I, C) |
| Non-destructive Configuration<br>Drift volume<br>S-I gap<br>I-C gap | EF nominal (Transparency Ratio)<br>$E_d = 500$ V/cm<br>$E_{g1}$=700 V/cm ($r_T = 1.4$)<br>$E_{g2}$=900 V/cm ($r_T = 1.3$) |
| Drift Velocity (at nominal field) | 1.59 mm/$\mu$s |
| Max. Drift Time (at nominal field) | $t_d = 295\ \mu$s |

## Cliffnotes

0.26 Tons (active mass)

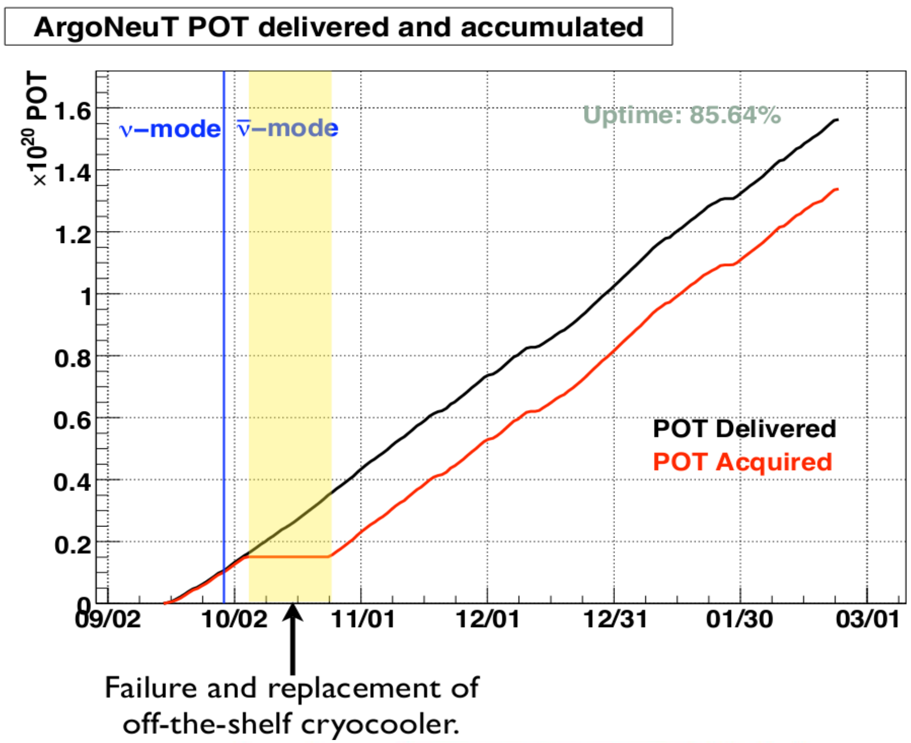
0.40 m tall x 0.47 m wide (drift length) x 0.90 m long

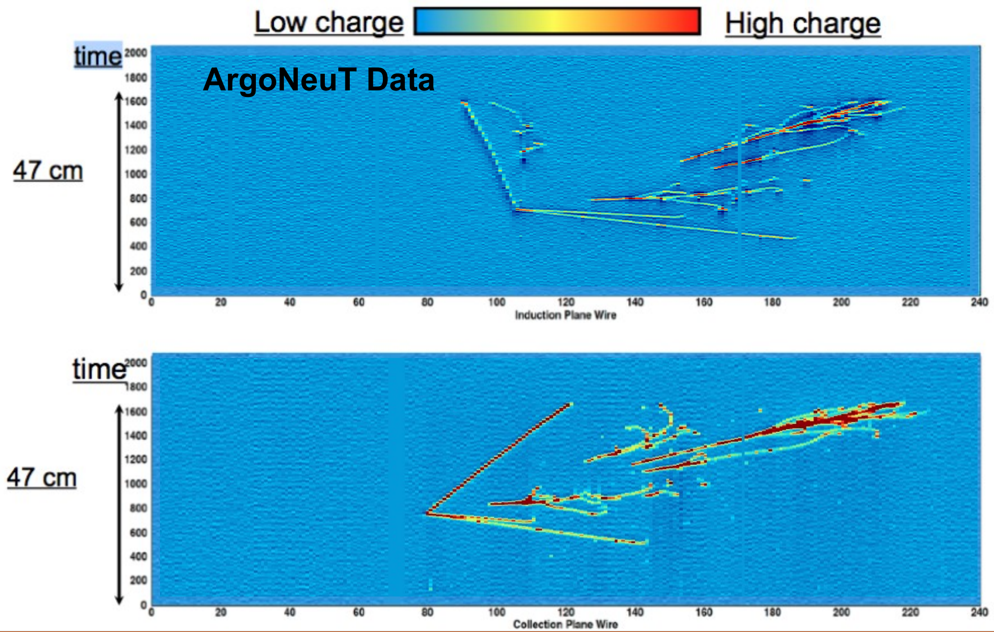
480 wires (4mm pitch) *(Oriented +/- 30° w.r.t vertical)*

No light detection system

***ArgoNeuT TDR: JINST 7 P10019 (2012)***

# ArgoNeuT: Overview



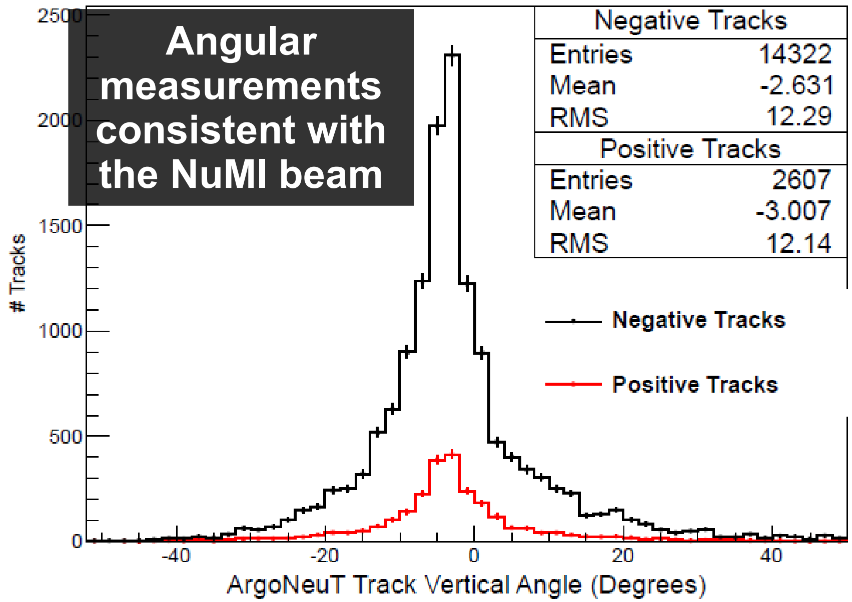



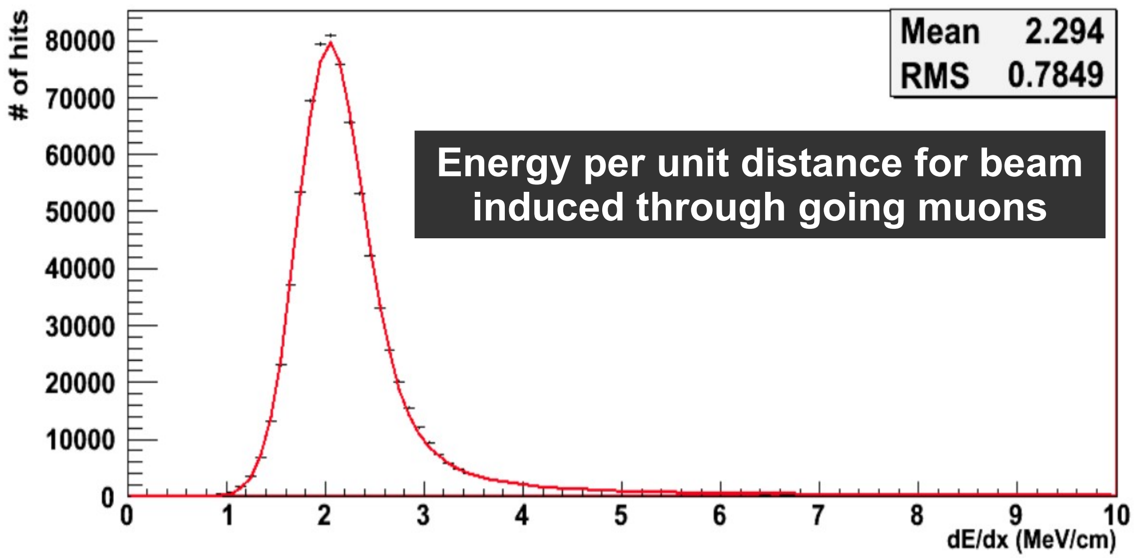

- **ArgoNeuT took data from 09/2009 – 02/2010**
  - 2 weeks in Neutrino mode ($0.085 \times 10^{20}$ POT)
  - 4 months in Antineutrino mode ($1.2 \times 10^{20}$ POT)
- **Collected high quality neutrino data in the range of 0.1→20 GeV**
  - Measure ν-Ar cross-sections
  - Study calibration of LAr detectors
  - Study nuclear effects
    - Final state interactions (FSI)
    - Nucleon/Nucleon Correlation
  - Develop automated reconstruction techniques

# ArgoNeuT's Published Results

# Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector

*JINST 7 P10020 (2012)*



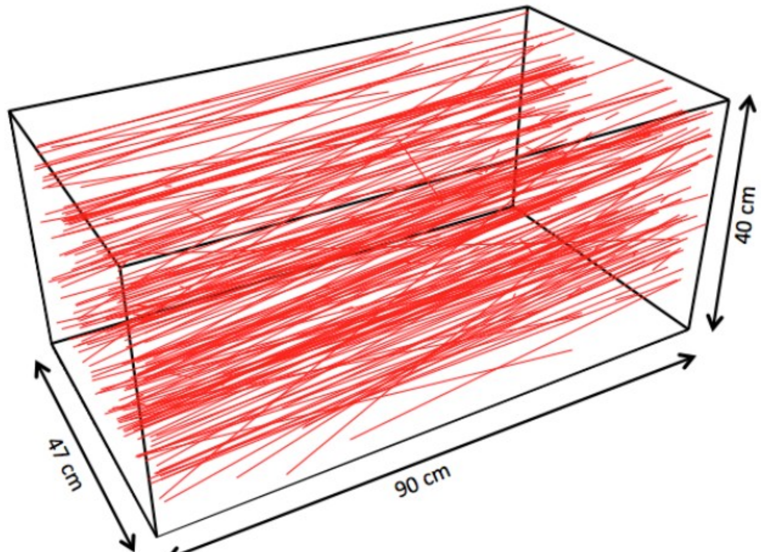




## Paper released from ArgoNeuT

***Analysis only used 2 weeks of neutrino data***

**Demonstrates geometric and calorimetric reconstruction capabilities**

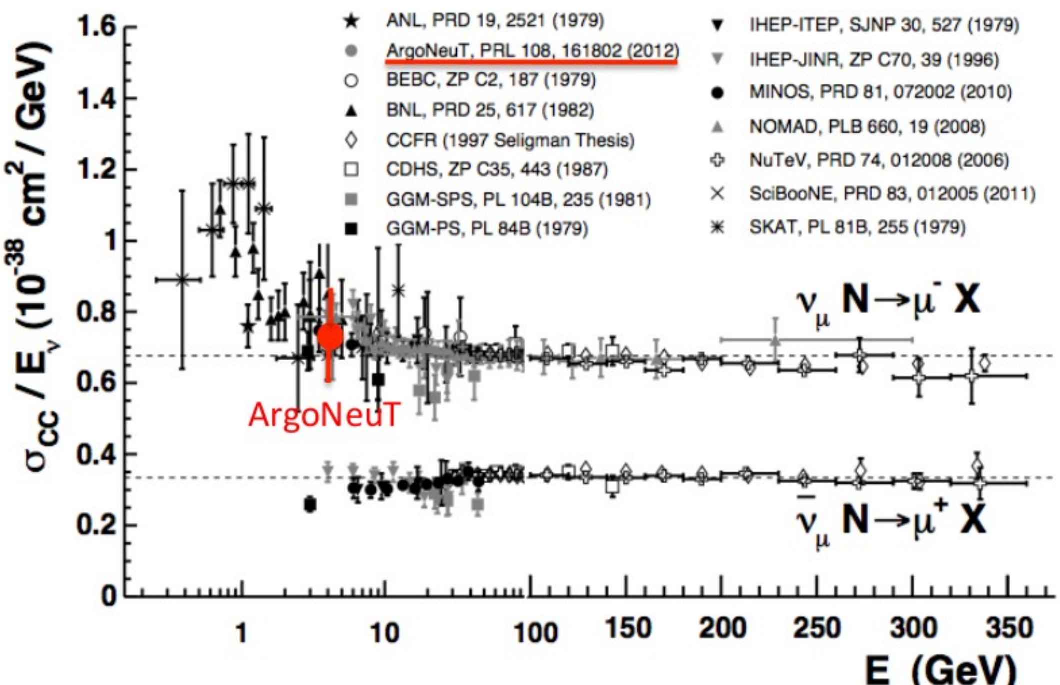
**Provides calibration input into charge-current analyses**

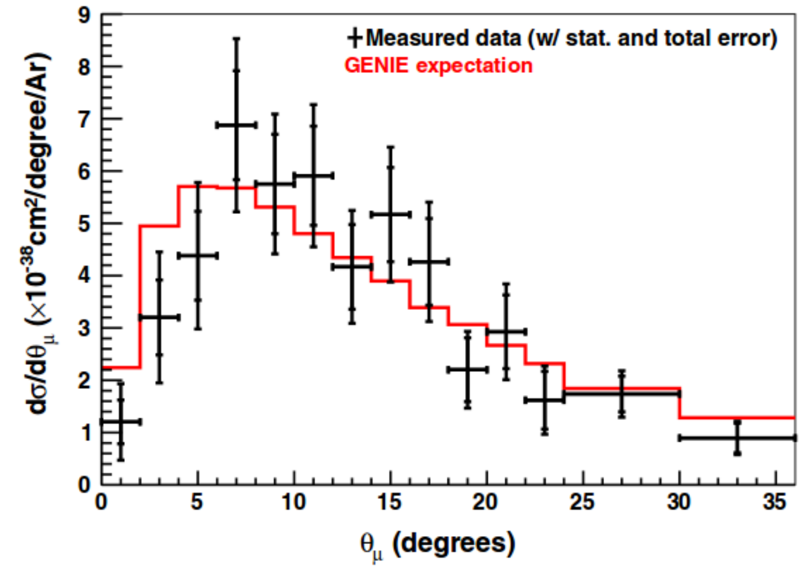


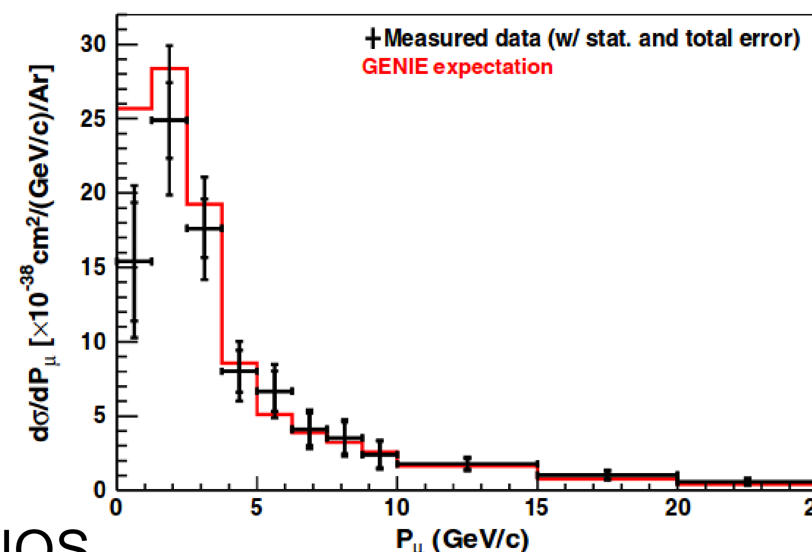

Reconstructed through-going muons

# Inclusive $\nu_\mu$ Charged Current Differential Cross-section

*PRL 108, 161802 (2012)*




## First neutrino cross-section measurement done on Argon!

***Analysis only used 2 weeks of neutrino data***

## Straightforward analysis

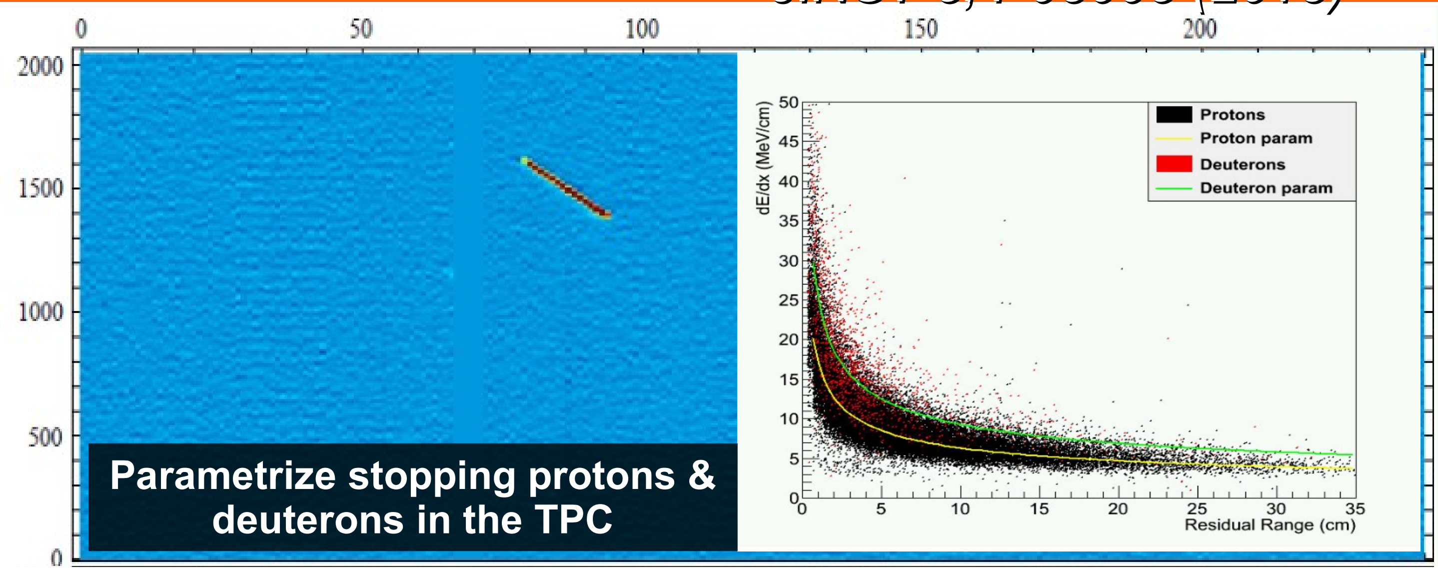
→ Interaction vertex in the fiducial volume

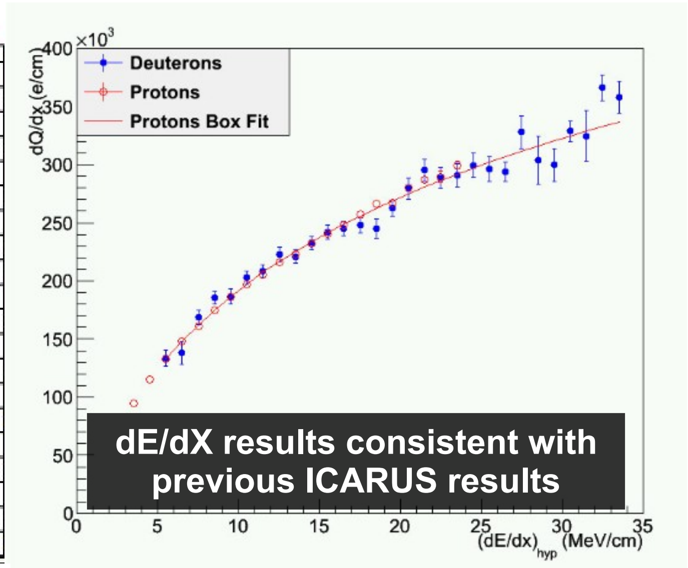
→ Reconstructed track which is matched to MINOS

→ Use MINOS for sign determination (choose $\mu^-$) and momentum measurement

# A study of electron recombination using highly ionizing particles in the ArgoNeuT Liquid Argon TPC

*JINST 8, P08005 (2013)*



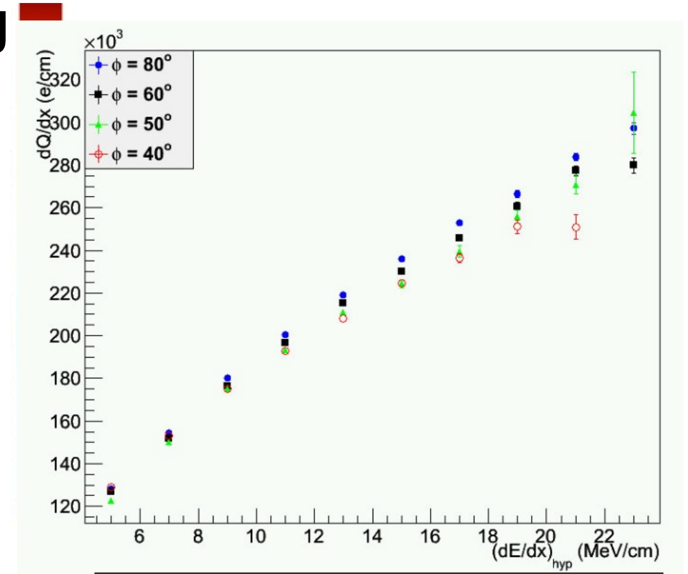

**Study the electron-ion recombination effects using contained proton/deuteron tracks found in ArgoNeuT**

**Small angular dependence of recombination**

→ Collected charge is reduced by 5%-10% at small angle (w.r.t. to Electric Field)

→ This is less than the 25% loss predicted by the Jaffe Columnar theory and simulations.

**dE/dx results extended beyond the ICARUS result with smaller uncertainties**

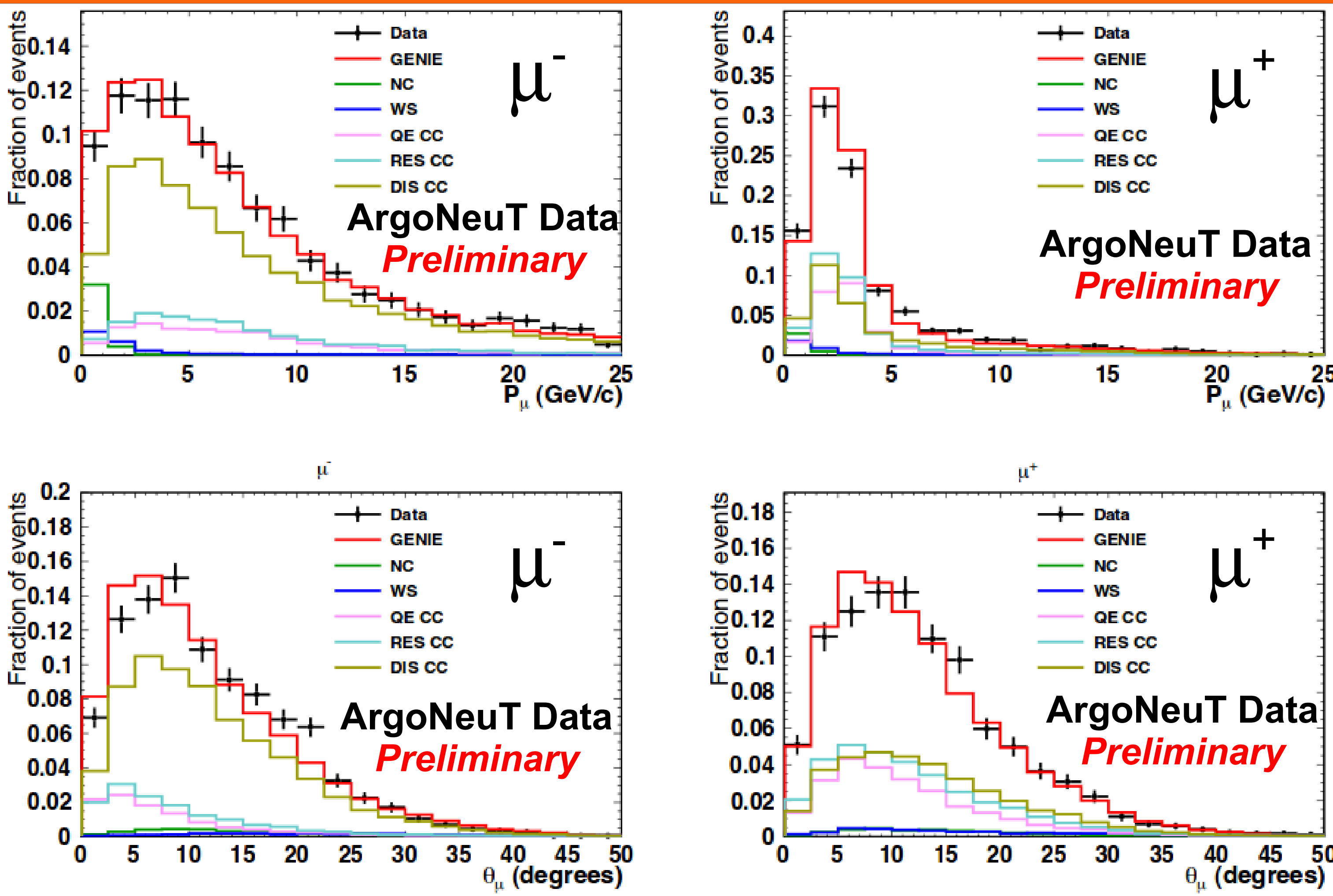



**Small angular dependence on recombination observed**

# ArgoNeuT Analyses in Progress

# Inclusive $\bar{\nu}_\mu$ Charged Current Differential Cross-section

*Paper in preparation*




**Similar analysis to what was done in neutrino mode**

→ Interaction vertex

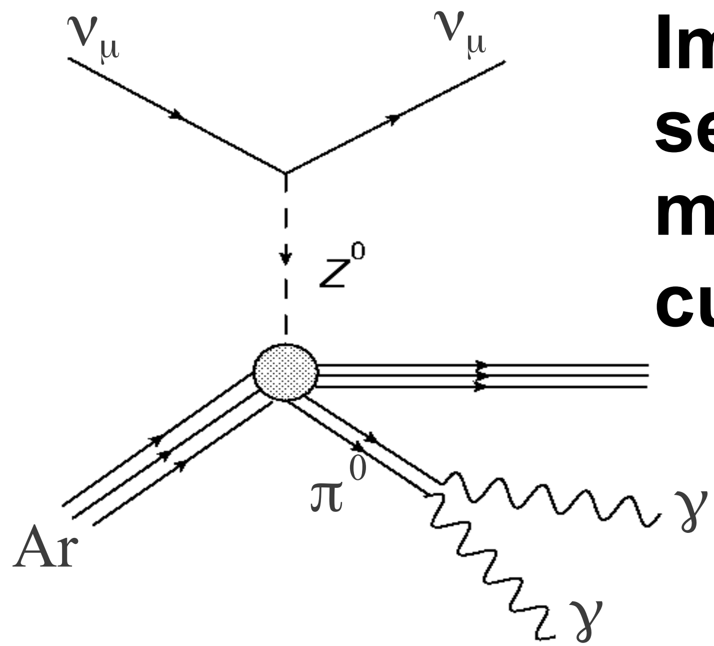
→ Track matched to MINOS

→ Use MINOS for sign determination (choose $\mu^+$ or $\mu^-$) and momentum measurement

**→ 8 times the data available in anti-neutrino mode**

**→ Beam composition allows you to select both neutrino ($\mu^-$) and anti-neutrino ($\mu^+$) interactions**

**→ Working on final flux normalizations and uncertainties**



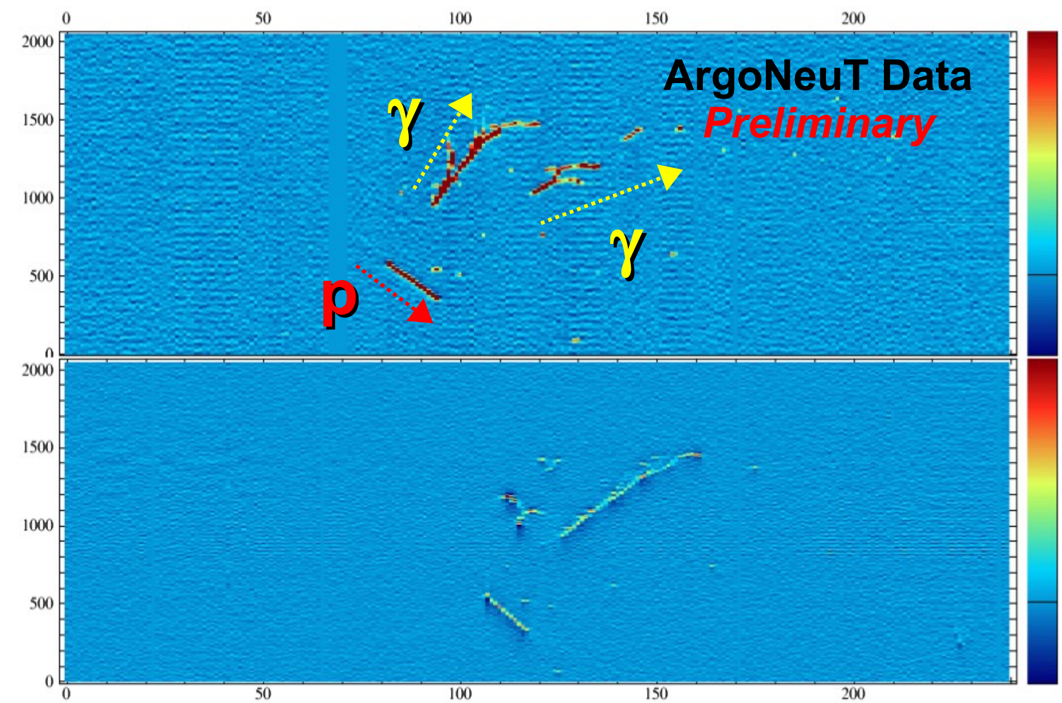

**Important channel for both oscillation searches and cross-section measurements comes from neutral current $\pi^0$ production.**

→ Particularly insidious background for $\nu_e$ appearance searches

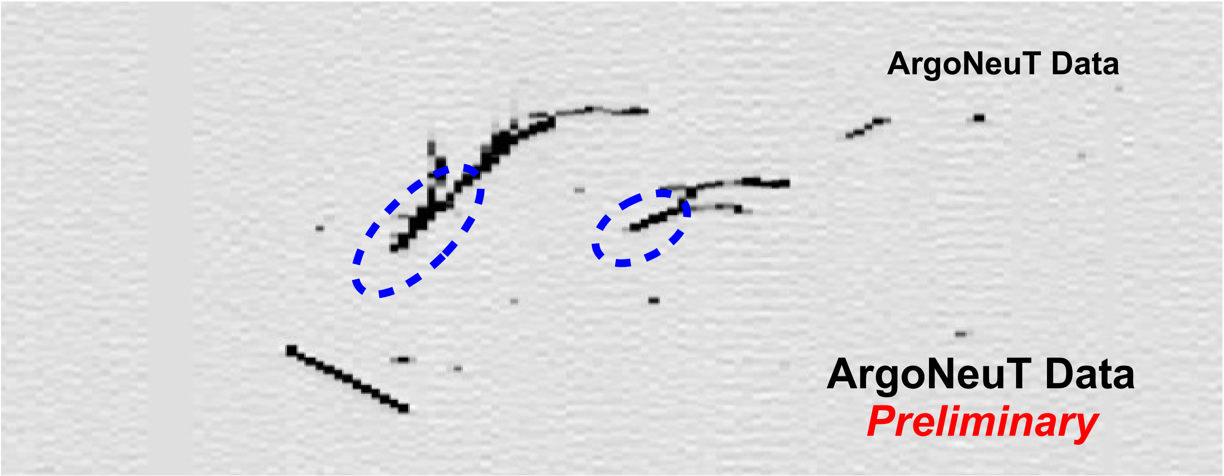
→ Notoriously difficult topology to reconstruct in LAr

**The ArgoNeuT detector is to small to contain the majority of photon showers produced from $\pi^0$'s**

→ However, we are exploring how to utilize this data and look for NC $\pi^0$ production

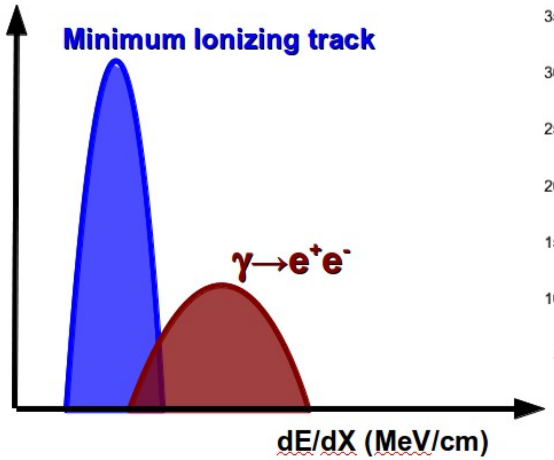


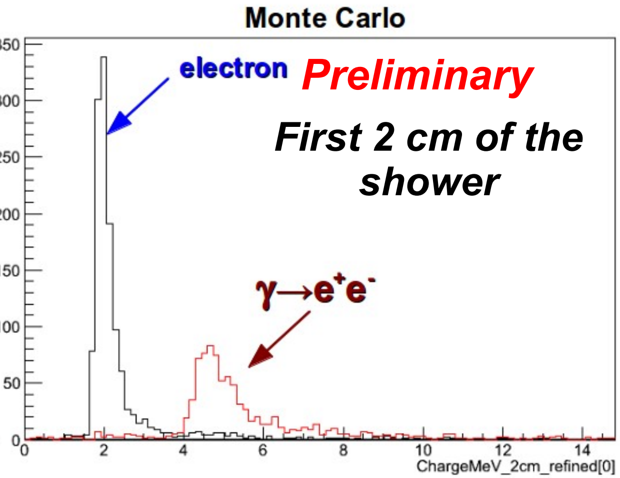
**Break the clusters into smaller "track-like" segments and reconstruct the shower's "track-segments" and analyze the dE/dX profile of the track segments**




**Example of how we expect the dE/dX profiles to look like**

→ Method utilized in e/γ separation studies




**Begin by selecting a sample of events likely to be neutral current**

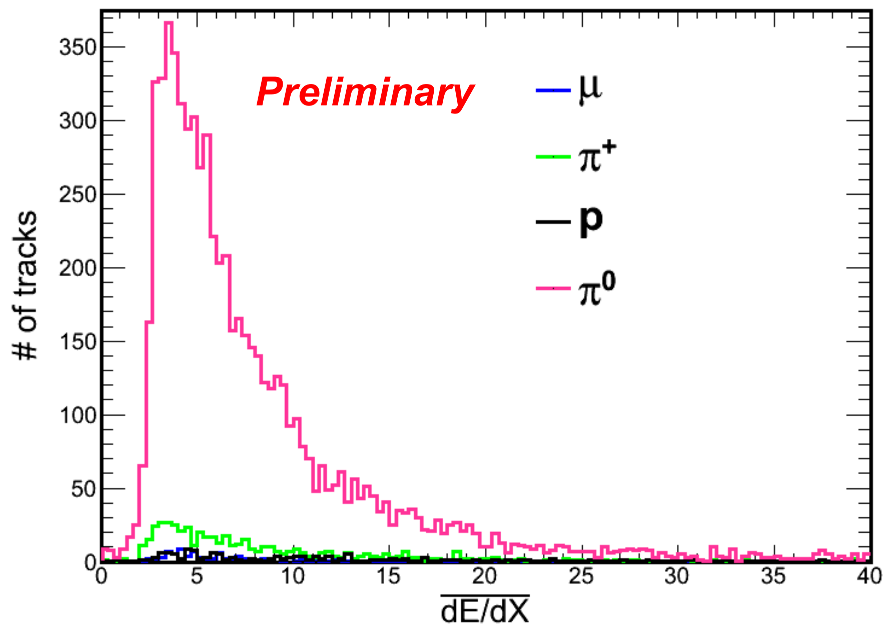
→ Require no track matched to MINOS

→ Require at least to clusters of energy found in each wire plane

→ Require a reconstructed vertex in the detector

# Neutral Current $\pi^0$ analysis

Candidate neutral current $\pi^0$ events should have **two highly ionizing "track-segments" consistent with dE/dX profile for a photon pointed back to a common point**




***Looking at the dE/dX of these "track-segments" in MC and data show early promise of potential event discrimination***

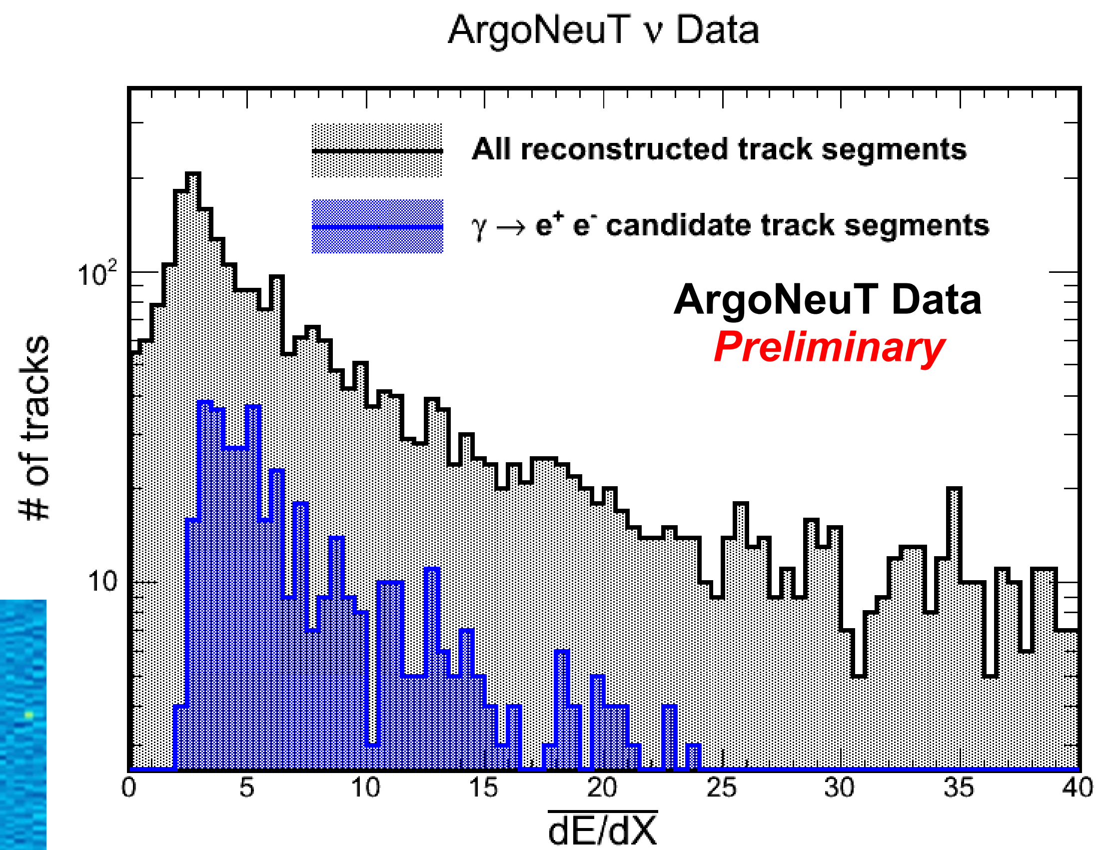
**$\gamma \rightarrow e^+e^-$ candidate track segment requirement**

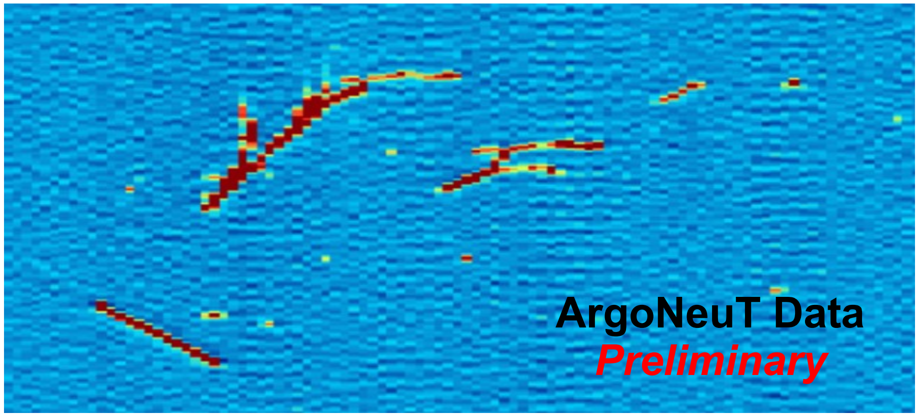
- Greater than 75% of the hits must have a dE/dX > 3.5 MeV/cm ***(not minimum ionizing)***
- Track pairs spatially separated ***(looking for photon candidate)***
- Track particle ID not consistent with proton, muon, pion hypothesis ***(not minimum ionizing)***

# Neutral Current $\pi^0$ analysis

Preliminary look at Neutrino mode data applying our selection looks promising

→ Events with two $\gamma \rightarrow e^+e^-$ track segments in the event are still under investigation

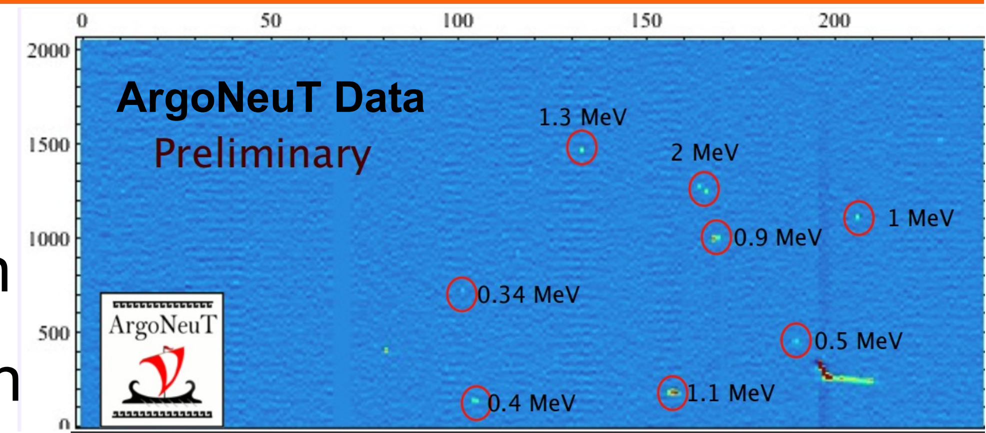


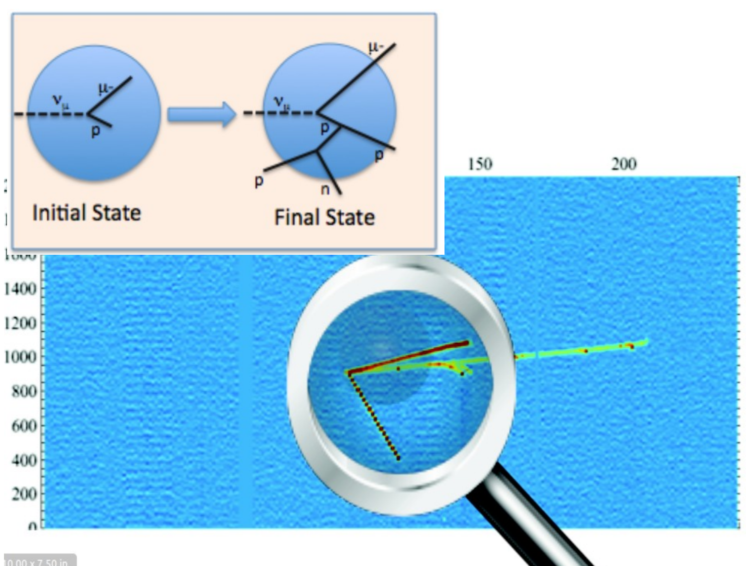

**More detailed reconstruction studies of these events in progress...updates coming soon!**

# Other ongoing analyses....

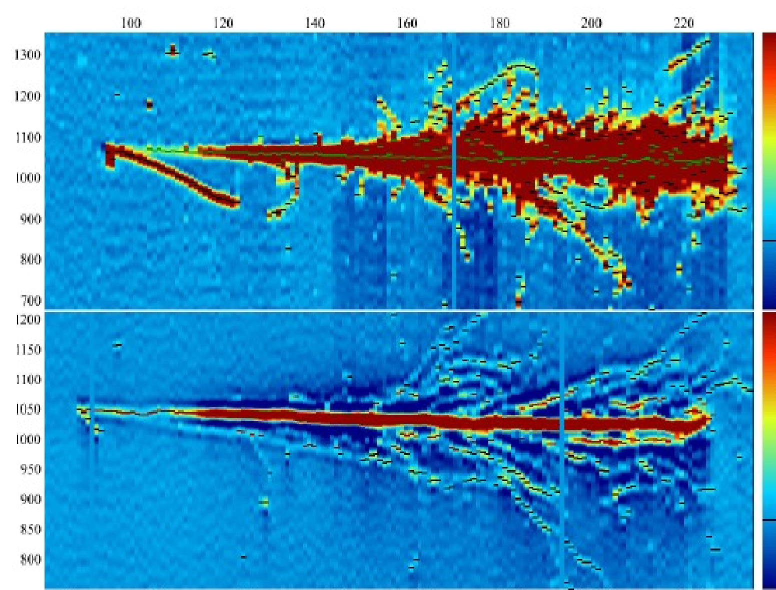
- Nuclear de-excitation photons
- Coherent pion production
- Electron neutrino event identification
- dE/dX electron / photon identification
- Search for neutral hyperon production
- Nuclear Final State Interactions



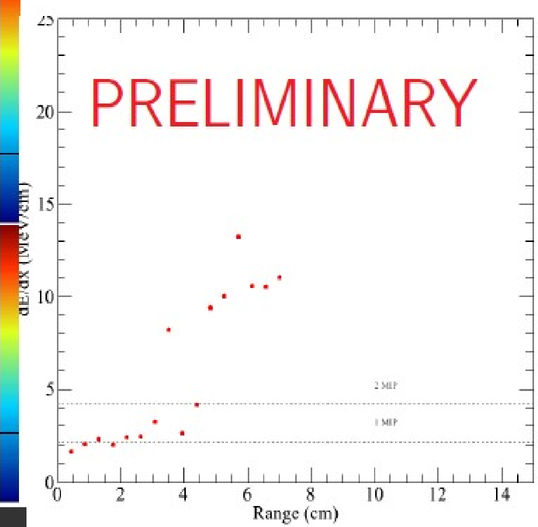

De-excitation gamma candidate event



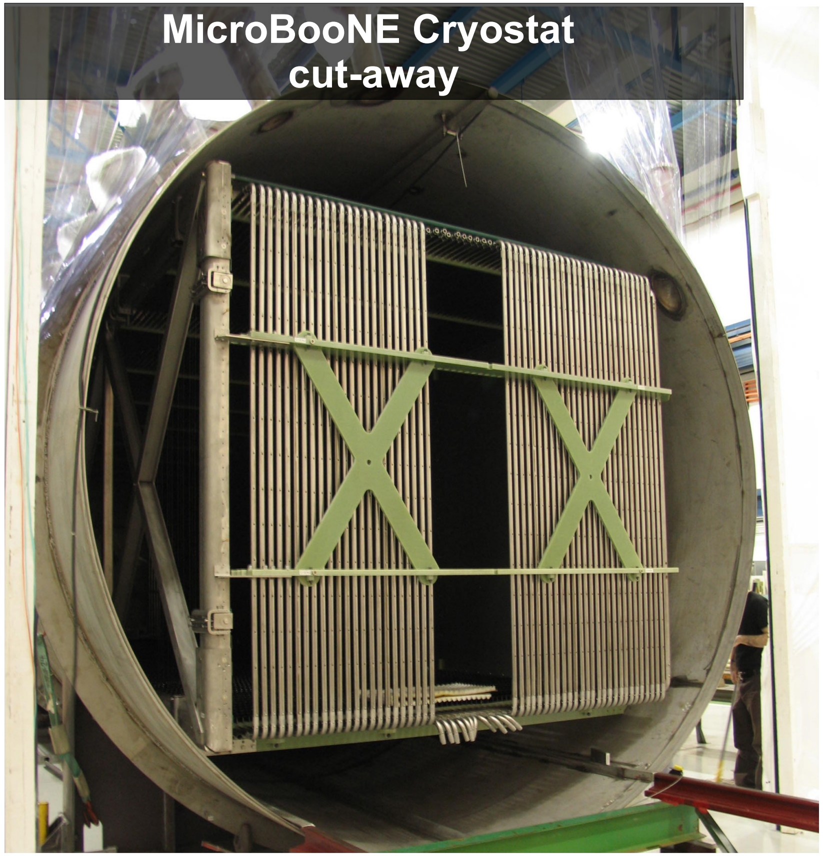

Study of Final State Interactions



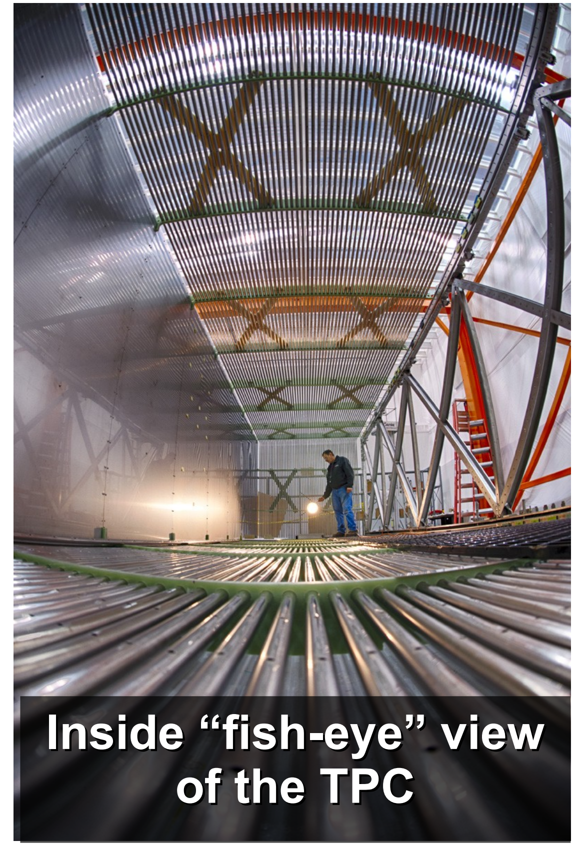
Electron neutrino candidate event



# MicroBooNE



MicroBooNE Cryostat cut-away



Inside "fish-eye" view of the TPC

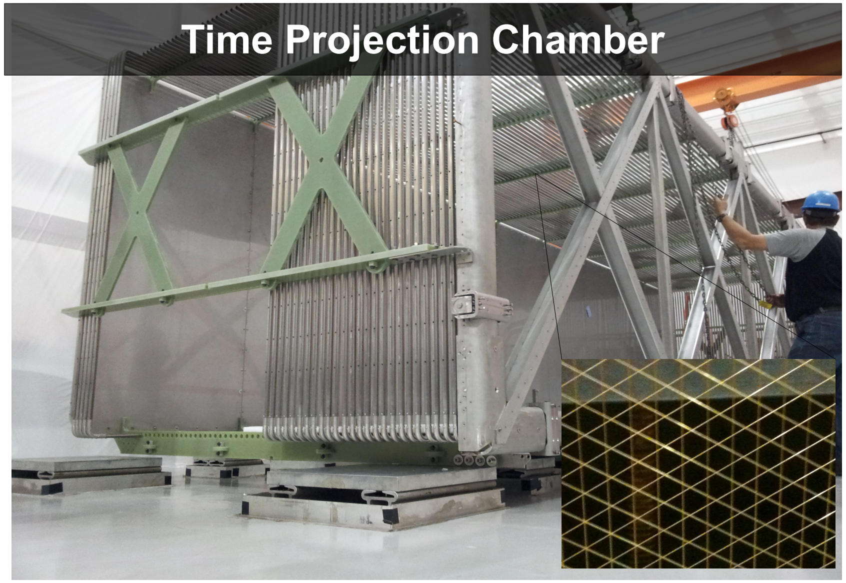
MICROBOONE

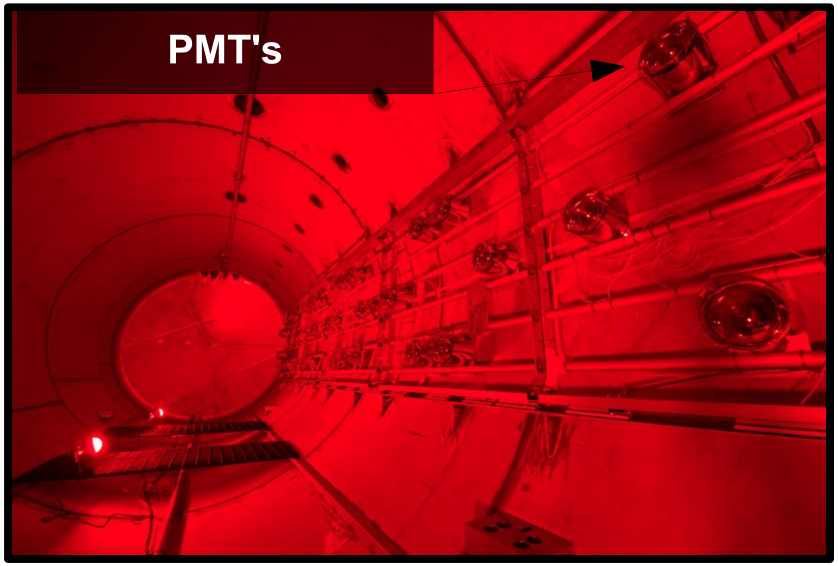
**MicroBooNE is finishing construction now and will be operational in early 2014**

MICROBOONE

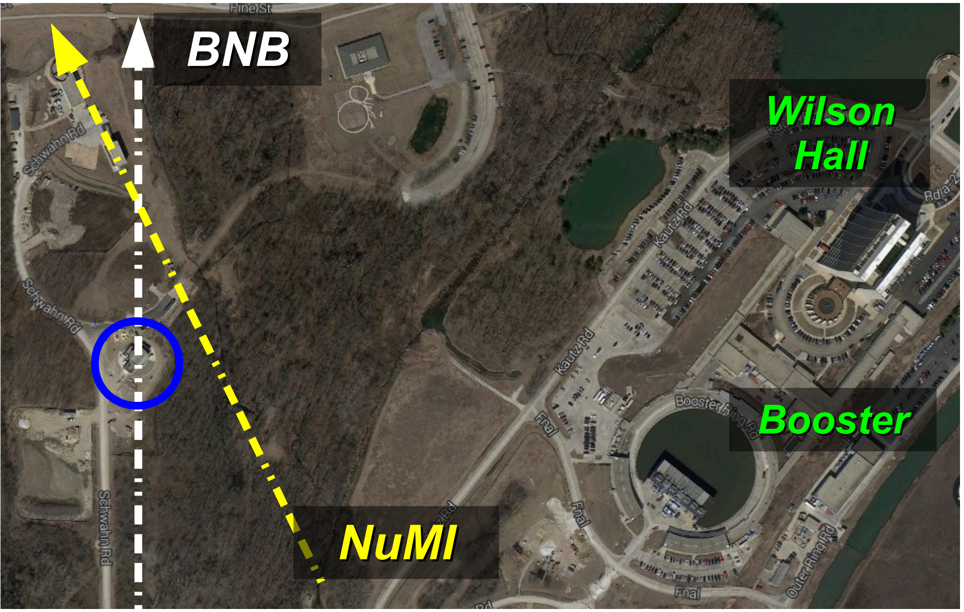
# MicroBooNE: Overview

- **MicroBooNE is a 170 ton (total volume) LArTPC**
- **TPC Dimensions:**
  - 10.3 m long x 2.3 m tall x 2.5 m wide (drift distance)
  - 80 ton active mass
- **8256 wire channels**
  - 3456 Collection channels
    - Wires oriented w.r.t. the vertical
  - 4800 Induction channels
    - Wires oriented +/- 60$^0$
- **32 8" cryogenic PMT's**
  - Provides event $t_0$ as well as cosmic ray removal
- **UV Laser Calibration System**



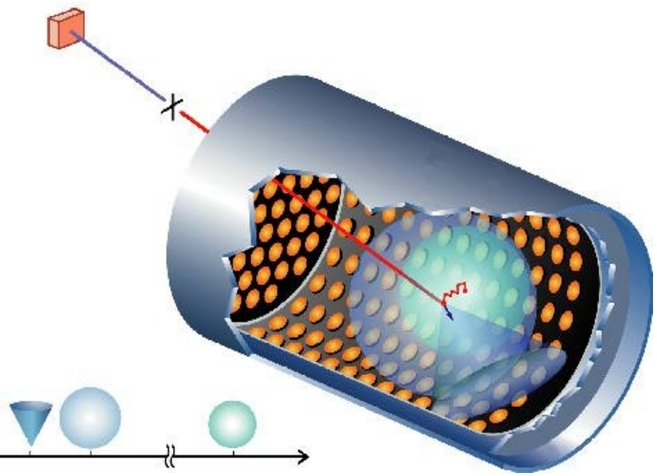
# MicroBooNE: Overview

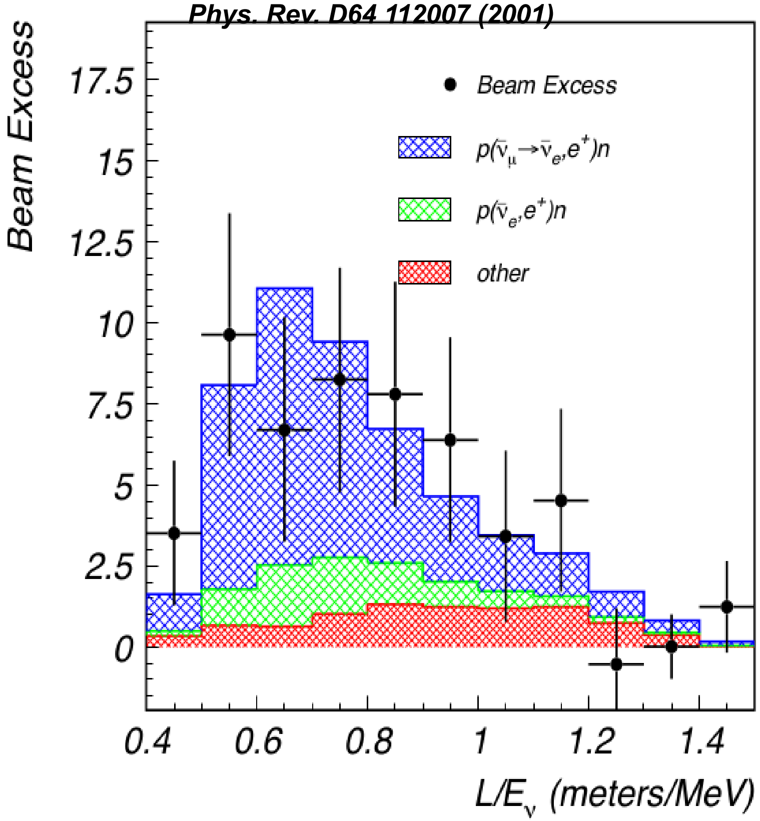




- **MicroBooNE will be located at Fermilab's Liquid Argon Test Facility (LArTF)**
  - Will see the Booster Neutrino Beam (BNB) and off-axis Neutrinos from the Main Injector (NuMI) beam
  - Two beams provide both a low energy and high energy source of neutrinos
    - Booster beam is created from 8 GeV protons on a beryllium target
      - Mean neutrino energy → < 1 GeV
    - NuMI beam created from 120 GeV protons on a carbon target
      - Mean neutrino energy → ~ 2-20 GeV

# MicroBooNE: Physics Motivation



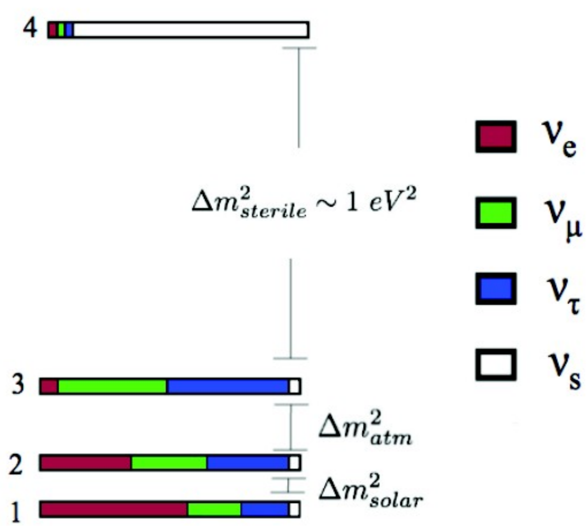



**Liquid Scintillator Neutrino Detector (LSND) observes an excess of events (3.8σ above background) in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance search**

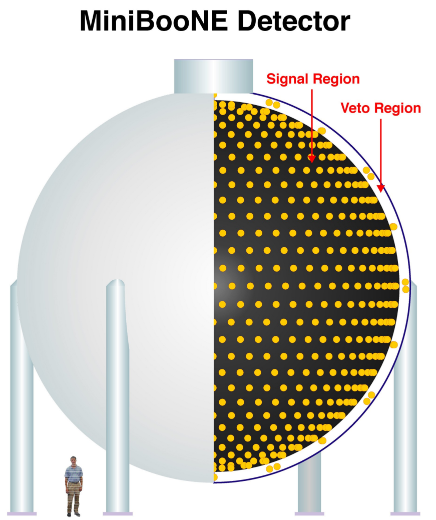
→ Much disputed result

→ Could be evidence for new Physics? (Sterile Neutrinos)

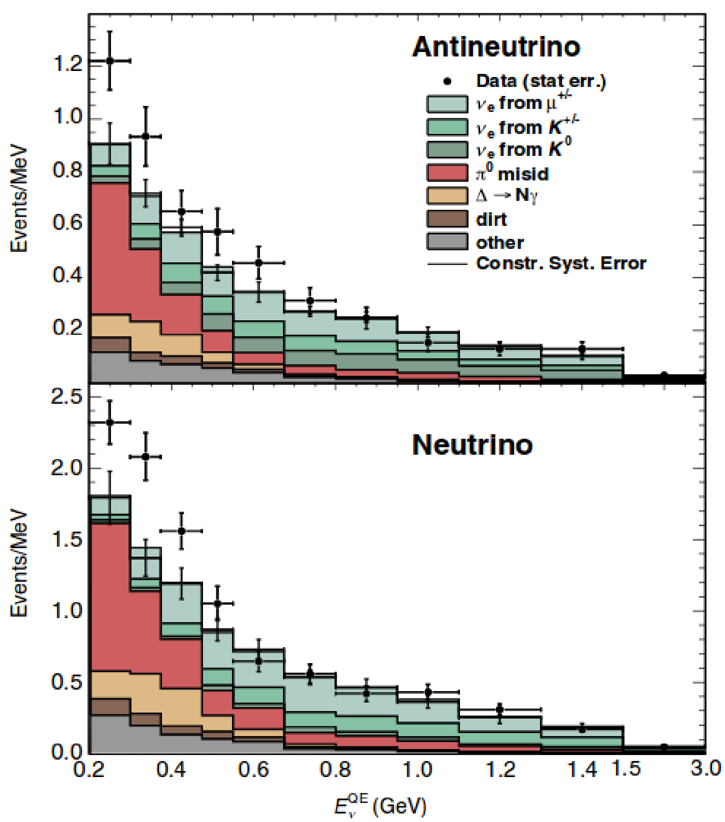
→ Experimental setup defined L/E (this determines your oscillation probability)



# MicroBooNE: Physics Motivation




*Phys Rev Lett. 110, 16180 (2013)*



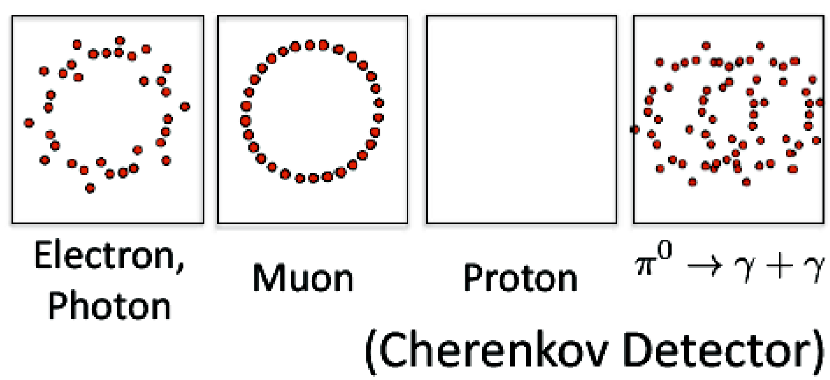

**Mini-Booster Neutrino Experiment (MiniBooNE) at Fermilab runs at a similar L/E and sees a slightly different excess in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ appearance search**

→ Effect dominates at low energy

- *Between 0.2 – 0.5 GeV*

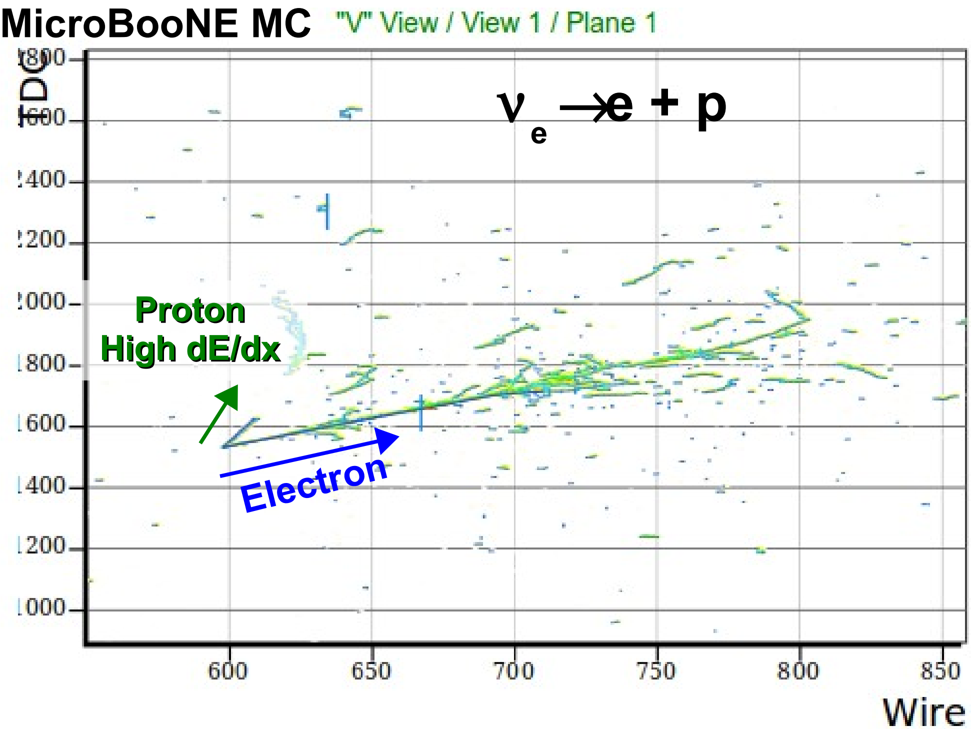
→ Insidious backgrounds dominate

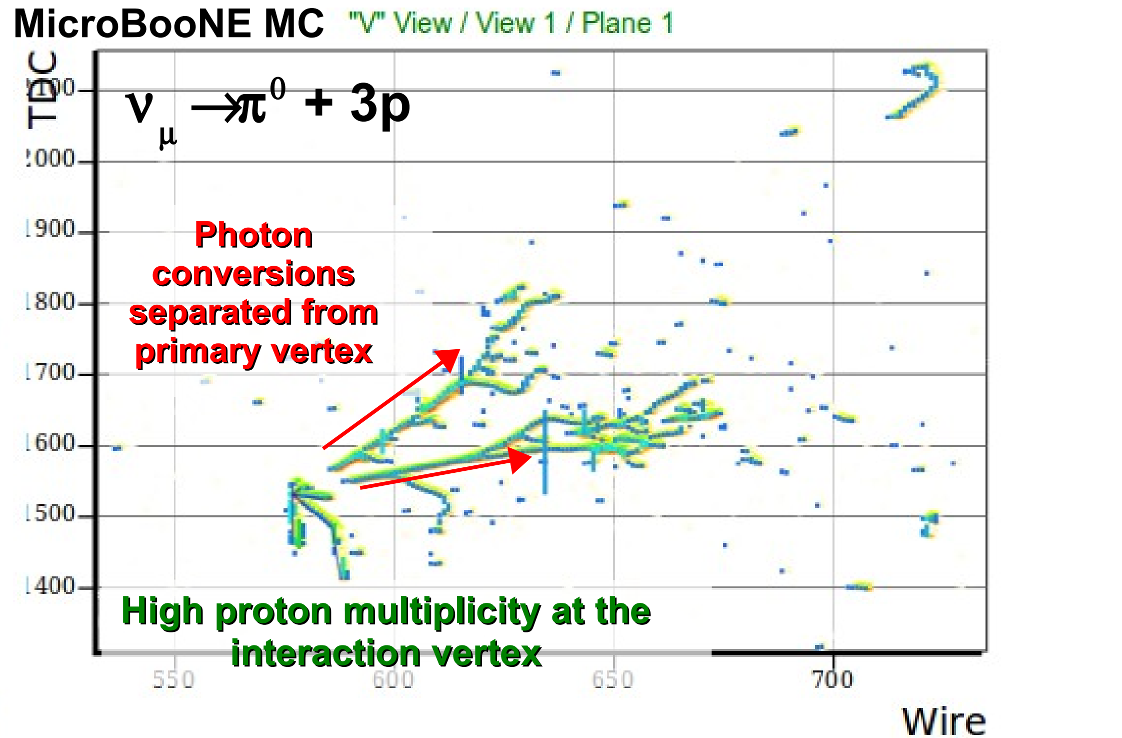
→ Can be *tough to distinguish* $\pi^0 \rightarrow \gamma\gamma$ *from* $e^-$ *signature in a cherenkov detector*

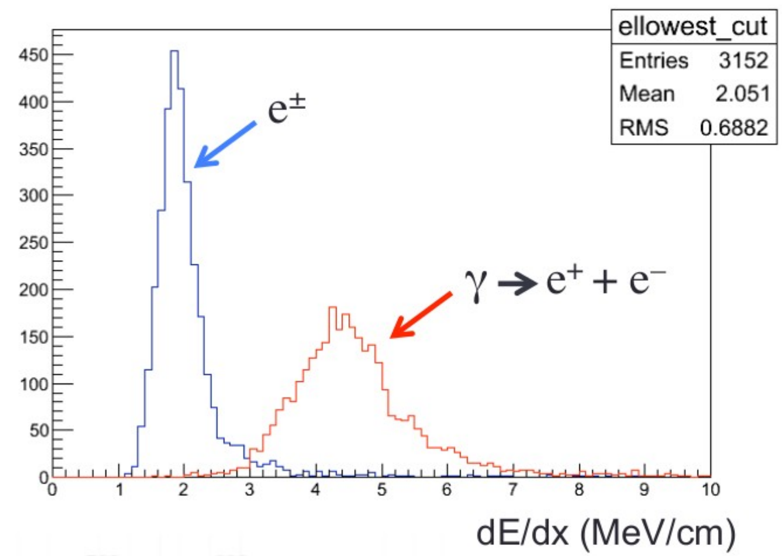



**e/γ seperation is a specialty of LAr detectors!**

# MicroBooNE: Physics Motivation

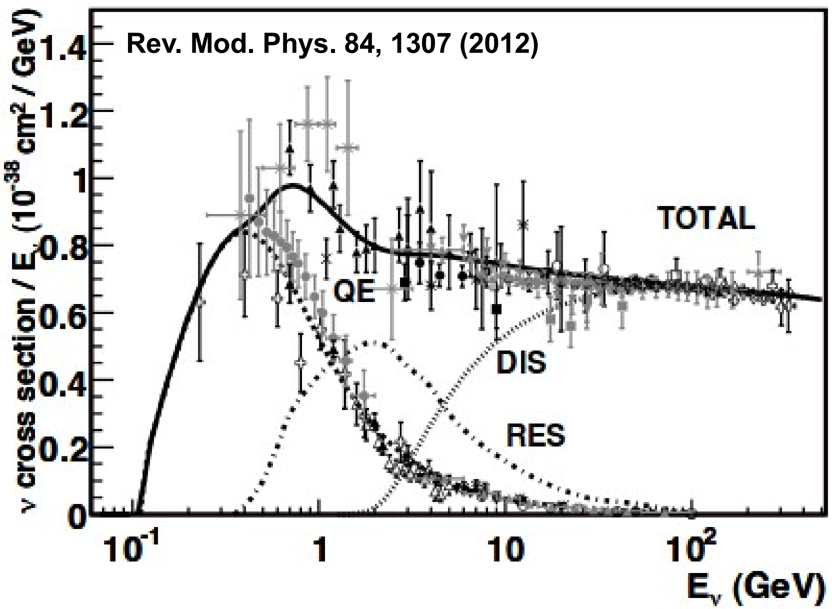


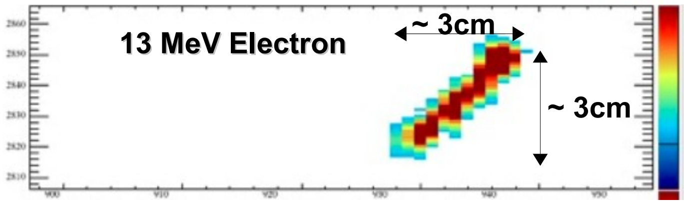



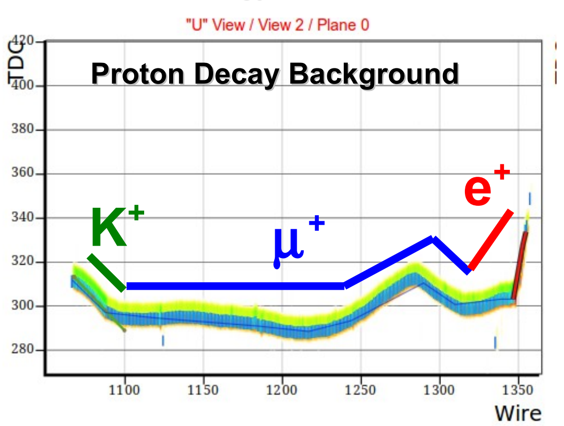

***Liquid Argon TPC's offer the ability to distinguish background ($\pi^0 \rightarrow \gamma\gamma$) from signal ($\nu_e$ appearance) and address both of these anomalies***

***MicroBooNE can do more than just oscillation physics!***



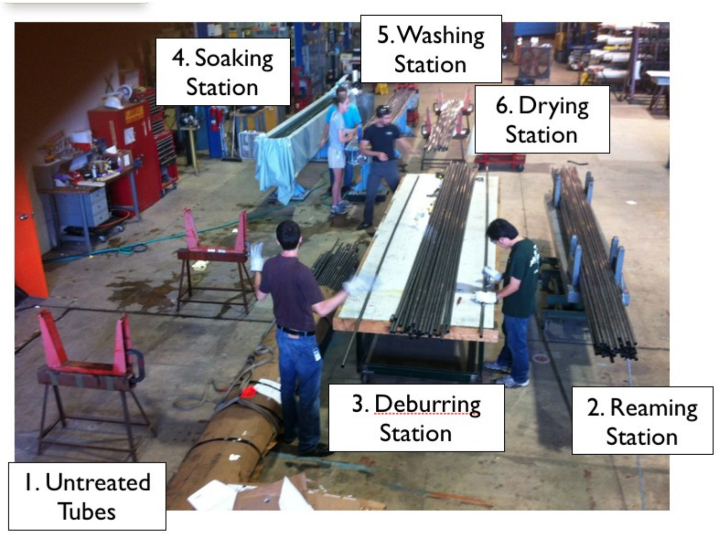




Low energy electron



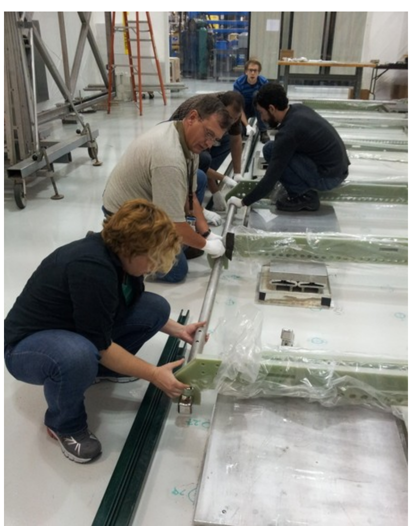

- **Cross-section physics**
  - Understanding low energy cross-sections crucial to many oscillation searches
    - *MicroBooNE will provide powerful insight*
    - *E.g. nuclear models of final state interactions*
      ***(See ArgoNeuT analysis mentioned earlier)***
  - Well understood cross-sections also a must for next generation long-baseline experiments
- **R&D physics**
  - MicroBooNE will also provide a testing ground for many physics R&D subjects
    - Supernova
      - Low energy electron reconstruction
    - Proton decay backgrounds
      - Study Kaon decays as background to "golden" channel $p \rightarrow K^+ \nu_\mu$

# MicroBooNE: Construction
## TPC



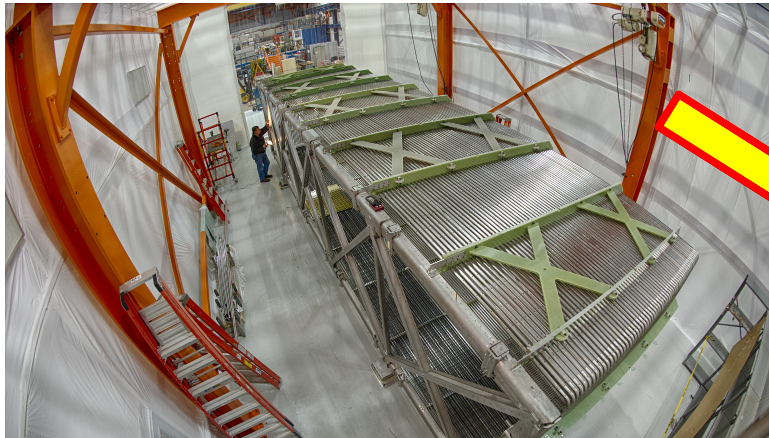

In the summer of 2012 we received our parts and diagrams for construction and went about leading teams to clean, transport, and assemble all the components of the TPC

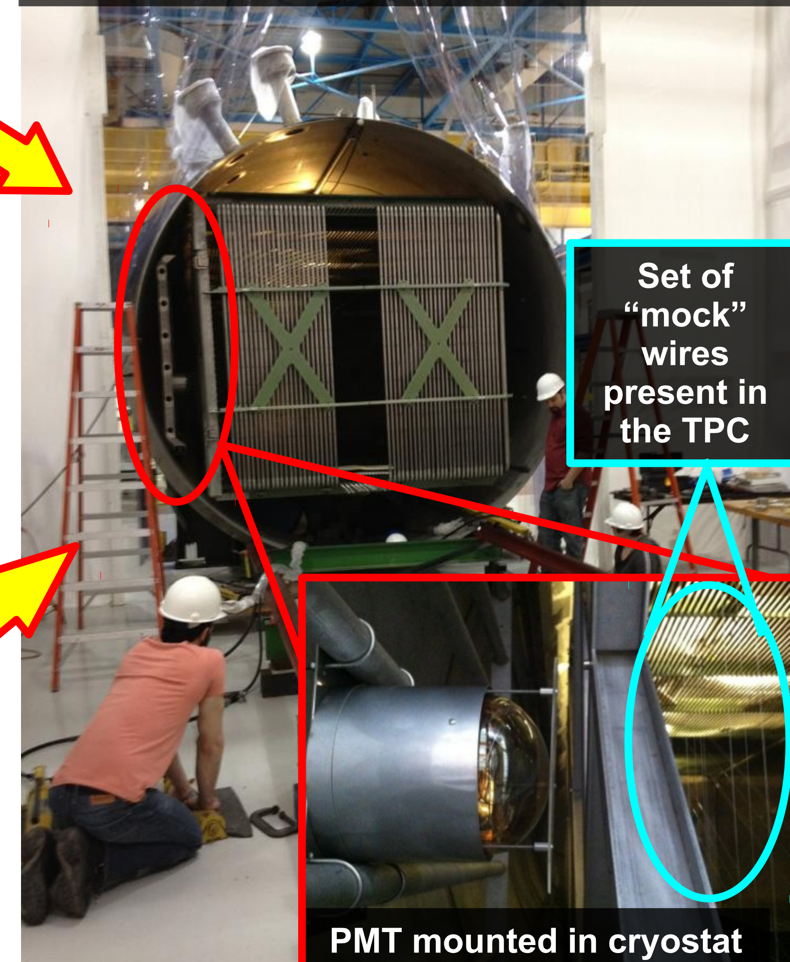
***(With an infinite amount of support from Fermilab technicians!)***



# MicroBooNE: Current Status
## TPC & Cryostat

**Major construction of the MicroBooNE TPC completed early in 2013**


Birds eye view of constructed TPC

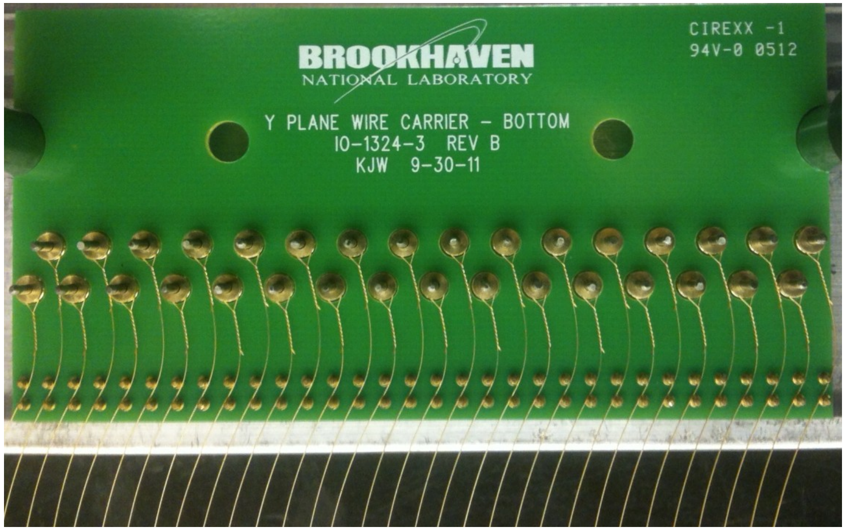
TPC & cryostat during test fit


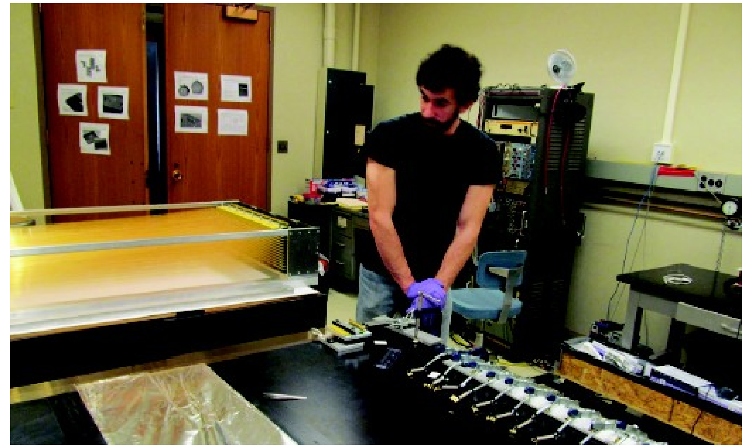


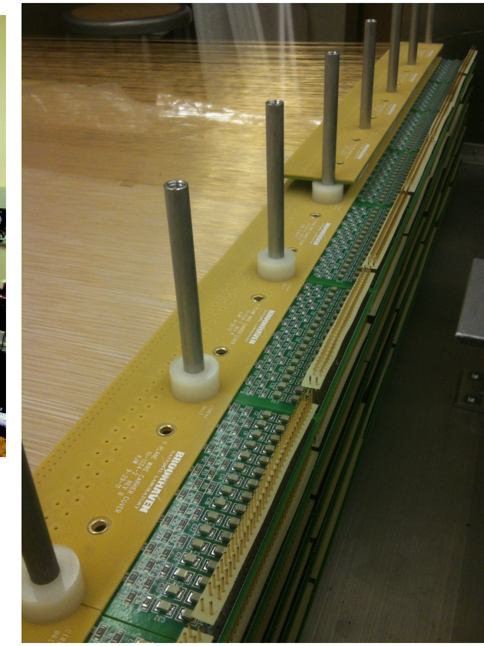

MicroBooNE cryostat arriving at Fermilab

**With the arrival of the cryostat we performed a test fit of the TPC with test wires and PMT's present**

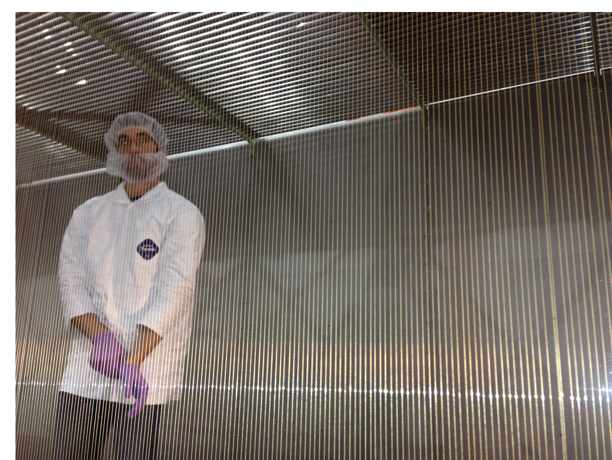
# MicroBooNE: Construction
## Wires





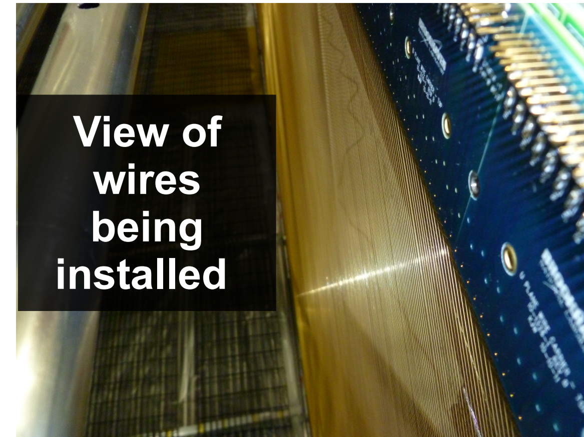
All 8256 MicroBooNE wires (150 micron stainless steel core with a gold flash cover) were individually wound, tested, and placed on wire carrier boards before being installed in the MicroBooNE TPC

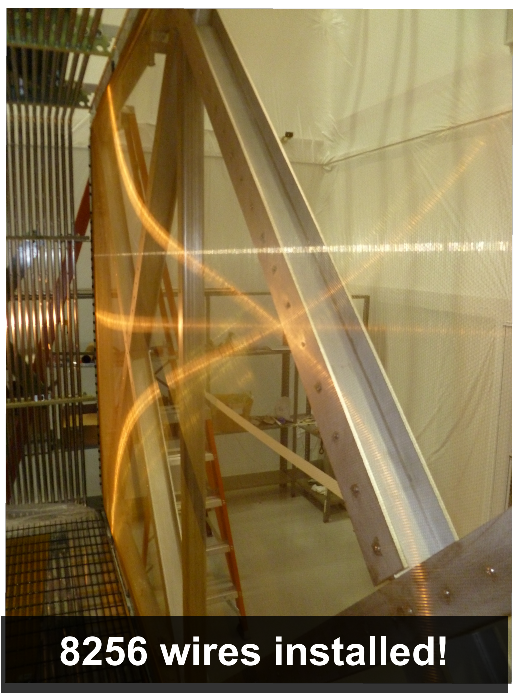


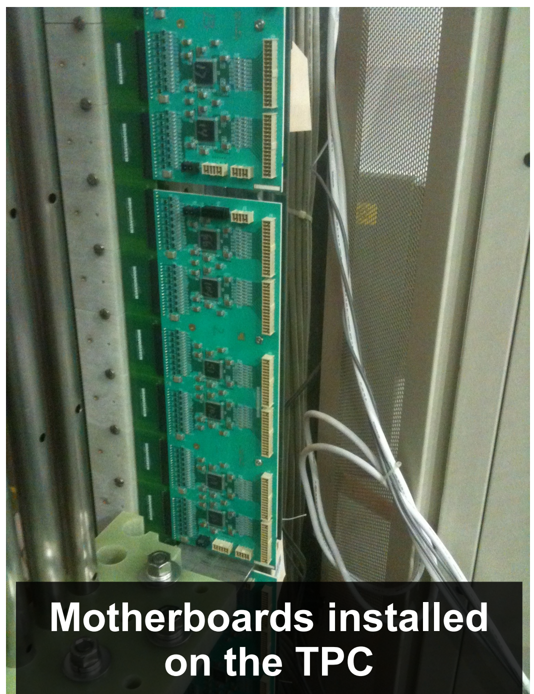
# MicroBooNE: Current Status
## Wire & Electronics Installation

**Following a successful test fit, installation of the TPC wires and cold electronics was able to go forward**

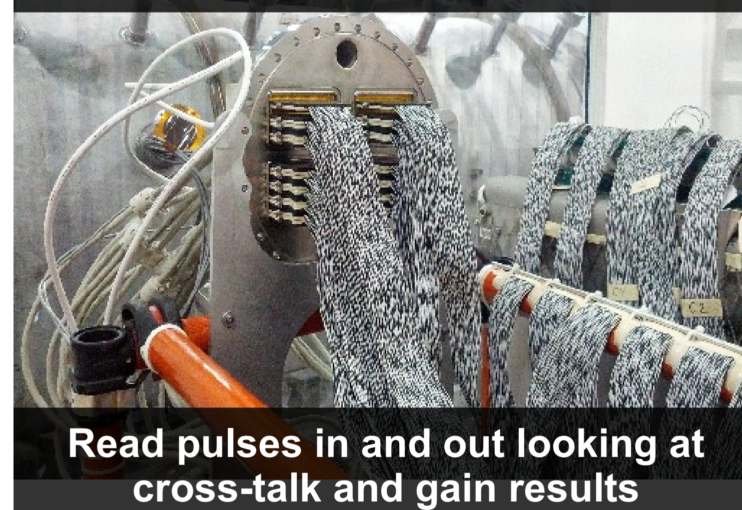

Wire installation team


View of wires being installed


8256 wires installed!


Motherboards installed on the TPC

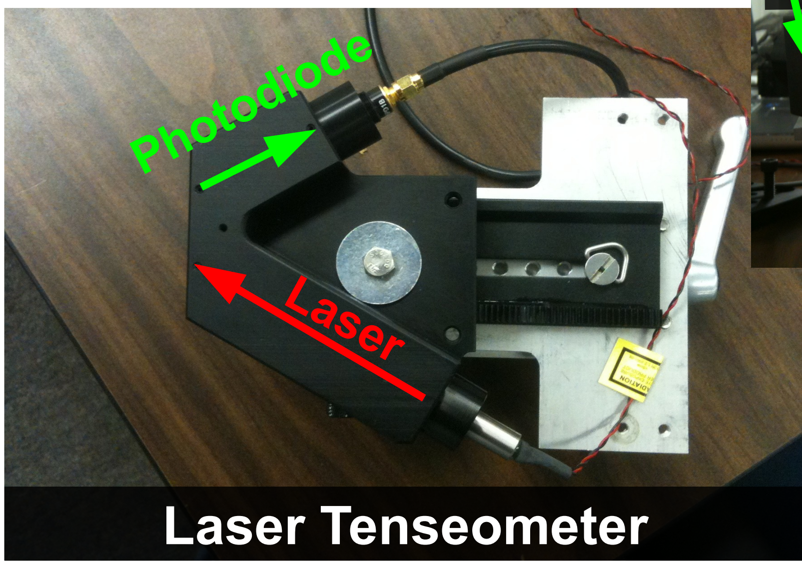
Able to test one complete feedthrough at a time

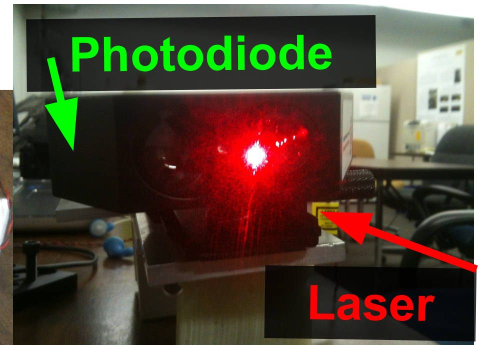

Read pulses in and out looking at cross-talk and gain results

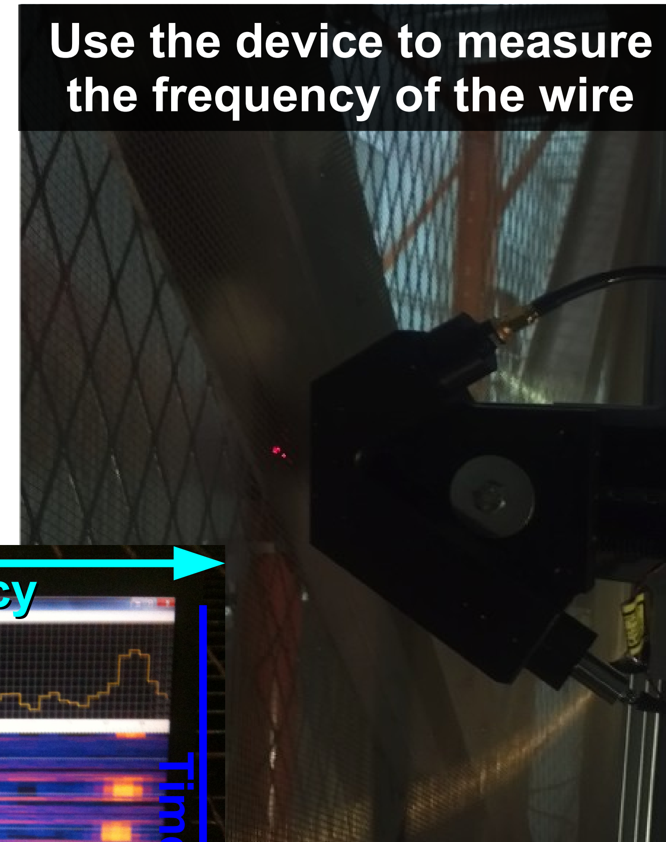
**Preliminary tests are able to exercise the data acquisition system and verify the successful installation of all TPC wires**

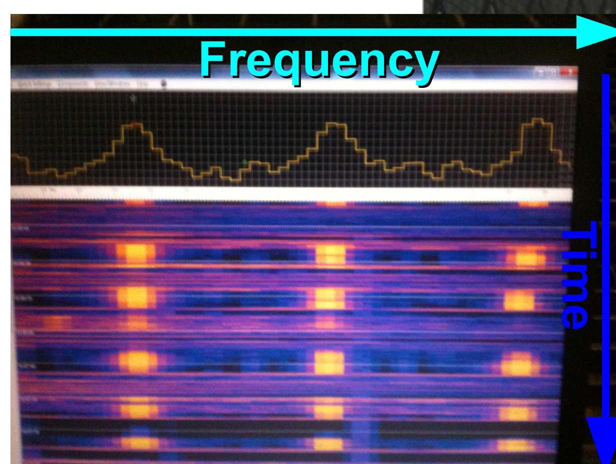
# Wire Tension Measurements

- **One place where UW Madison Physical Science Laboratory has already contributed to MicroBooNE!**



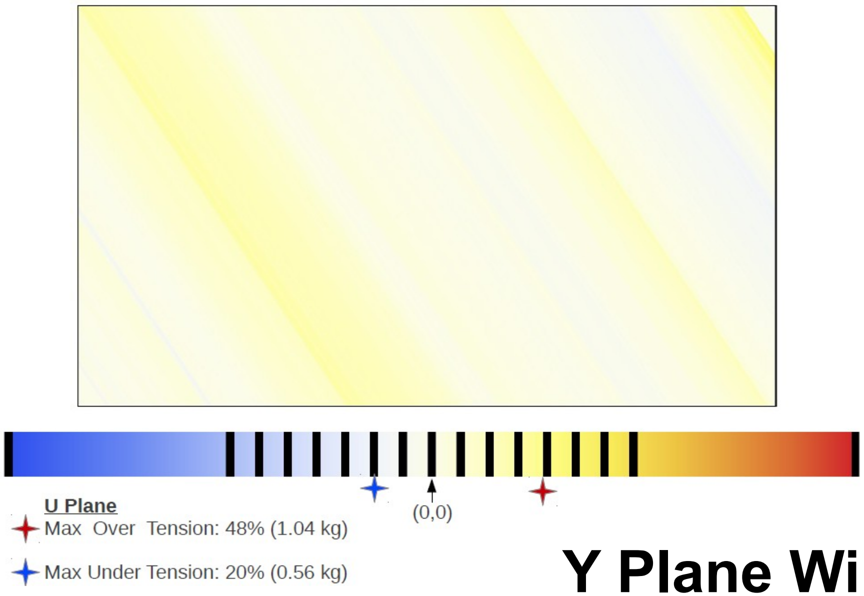




$$f = \frac{1}{2L}\sqrt{\frac{T}{\rho}}$$

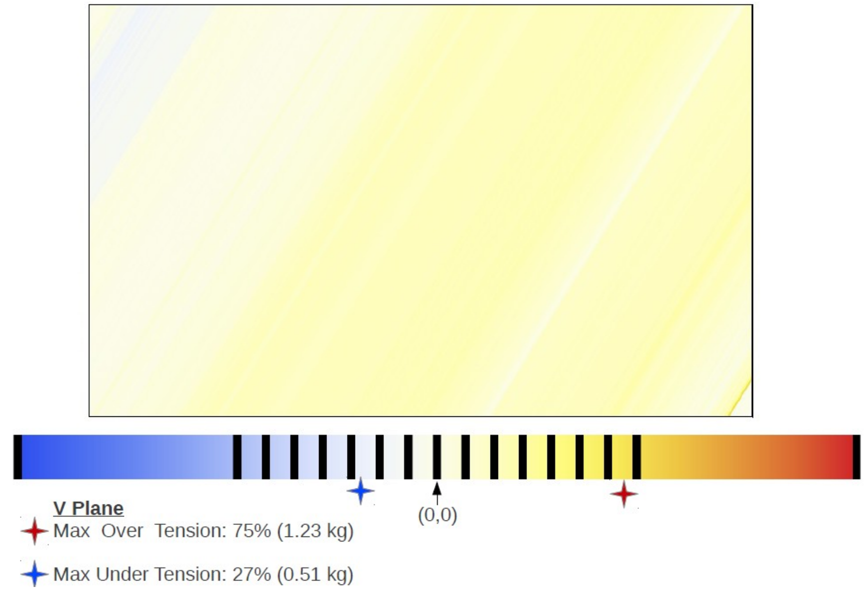
L = Length of the wire
T = Tension of the wire
ρ = density of the wire (0.00014 kg/m)

# MicroBooNE: Current Status
## Wire Tension Measurements

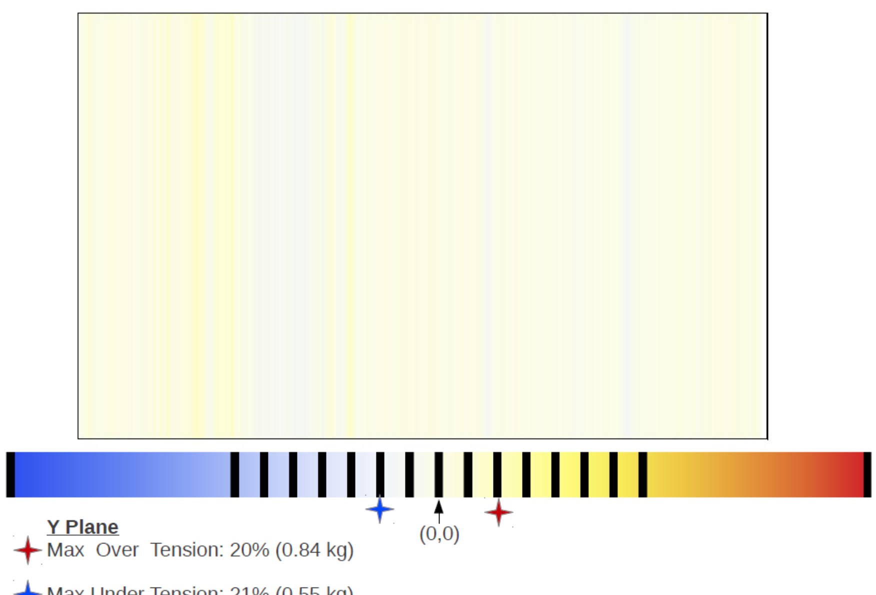
### U Plane Wires




### V Plane Wires




### Y Plane Wires




**Results look great!**

**Each line on here represents an individual wire measurement made by a dedicated (and patient) team**

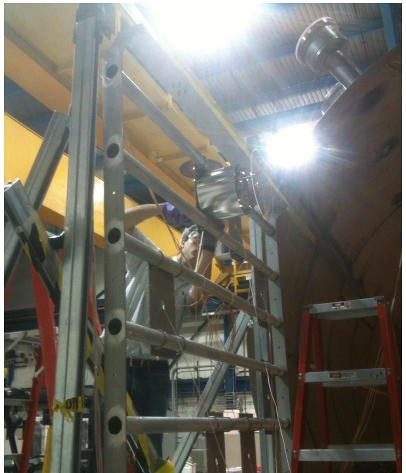
**Scales show maximum allowed deviation within our safety factors**

# MicroBooNE: Current Status

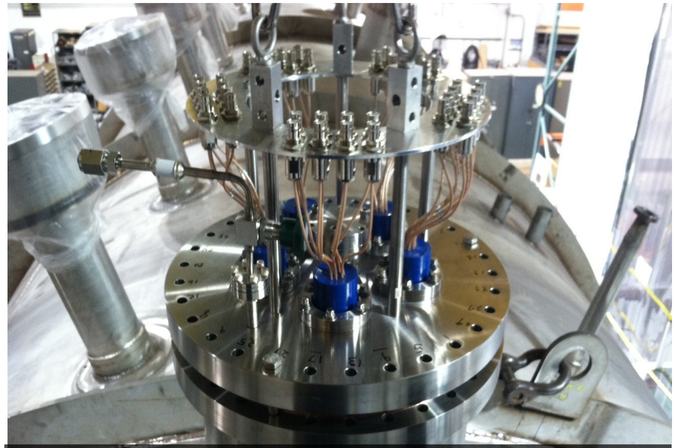
## PMT Installation


PMTs being prepared for installation


PMT cables being soldered


PMT being installed on mounting rack


The PMT Group

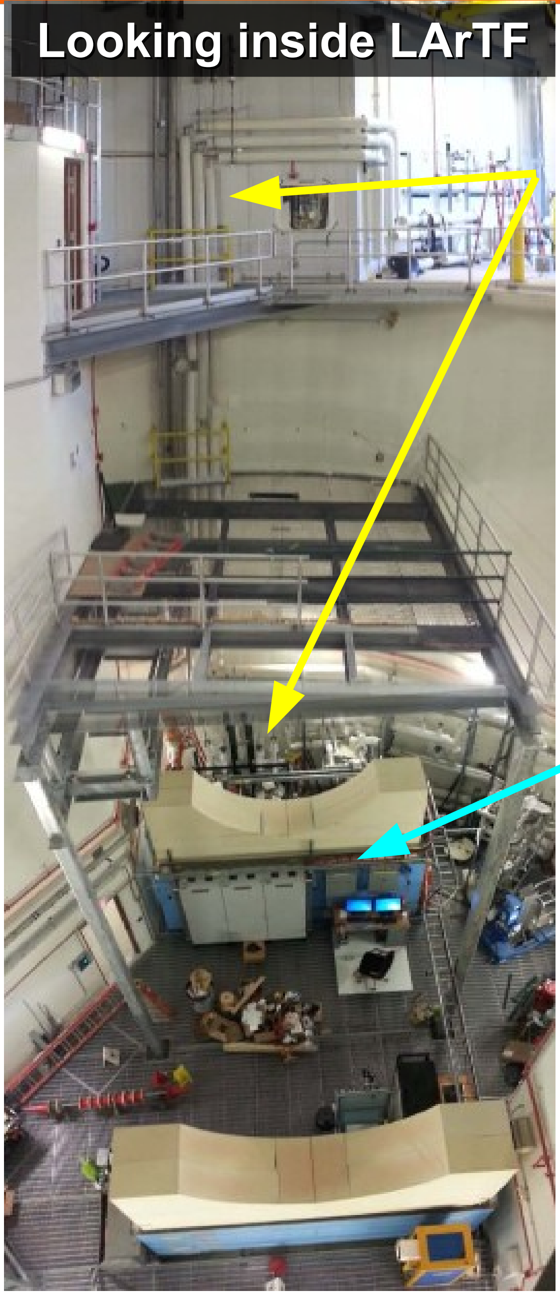

PMT flange and cables installed on the MicroBooNE cryostat


First rack installed


All 32 PMTs installed inside the cryostat (covered with dark bags for protection)

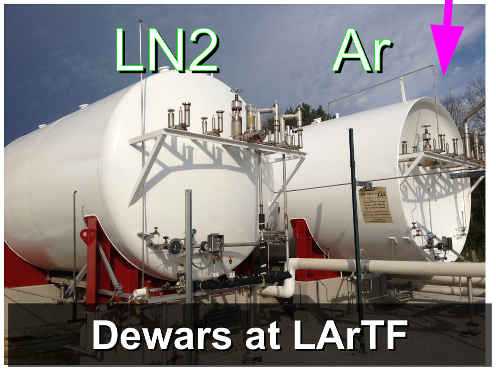
**First complete subsystem installed in the cryostat!**

# MicroBooNE: Current Status
## Cryogenics and LArTF




Installation of cryogenic piping and vent lines leading into experiment cavern


**Cryogenic installation proceeding at LArTF**


WHAT NEXT?

# A Staged Multi-LArTPC SBL Program at FNAL

*LAr1 was originally conceived as a 1 kton fiducial volume far detector for MicroBooNE to address the MiniBooNE antineutrino anomaly.*
*Recently reconsidering LAr1 as a phased short-baseline program.*


**Phase 1:**

LAr1-ND as Near Detector to MicroBooNE*
Run ~2016-2017
Estimated ~100 collaborators

*MicroBooNE begins running in 2014

**Phase 2:**

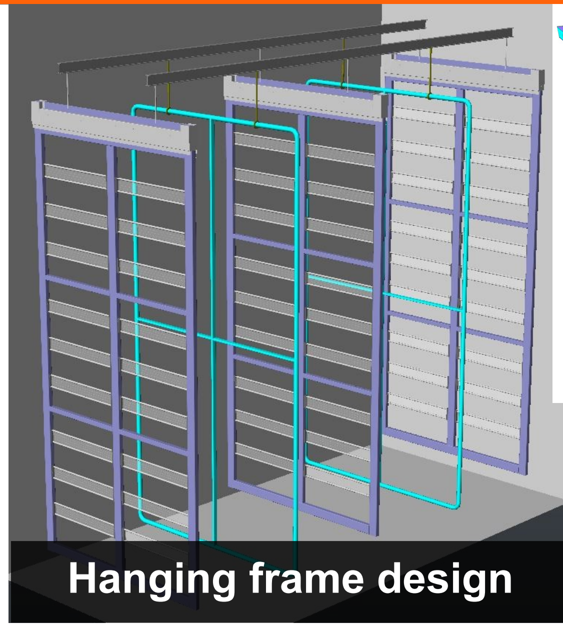
1 kton-scale Far Detector to complete 3 detector configuration
Run ~2020-
Estimated 100-150 collaborators

*Overall, the design philosophy of the LAr1(ND) detectors is to serve as a development step toward LBNE both for hardware and software development (as a next step beyond current LAPD, 35 ton etc. prototypes), while functioning as a physics experiment* 13

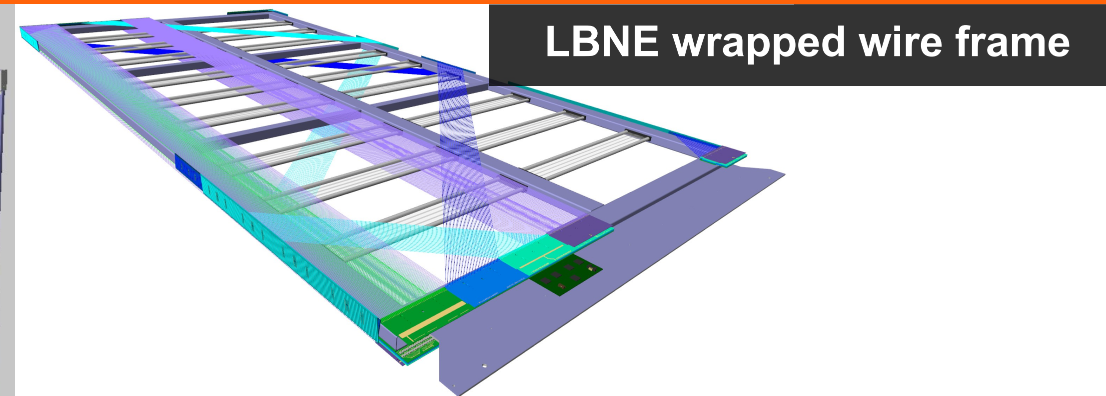
***Slide taken from Dave Schmitz talk at P5 Face to Face meeting***

# LAr1-Near Detector

SciBooNE Hall

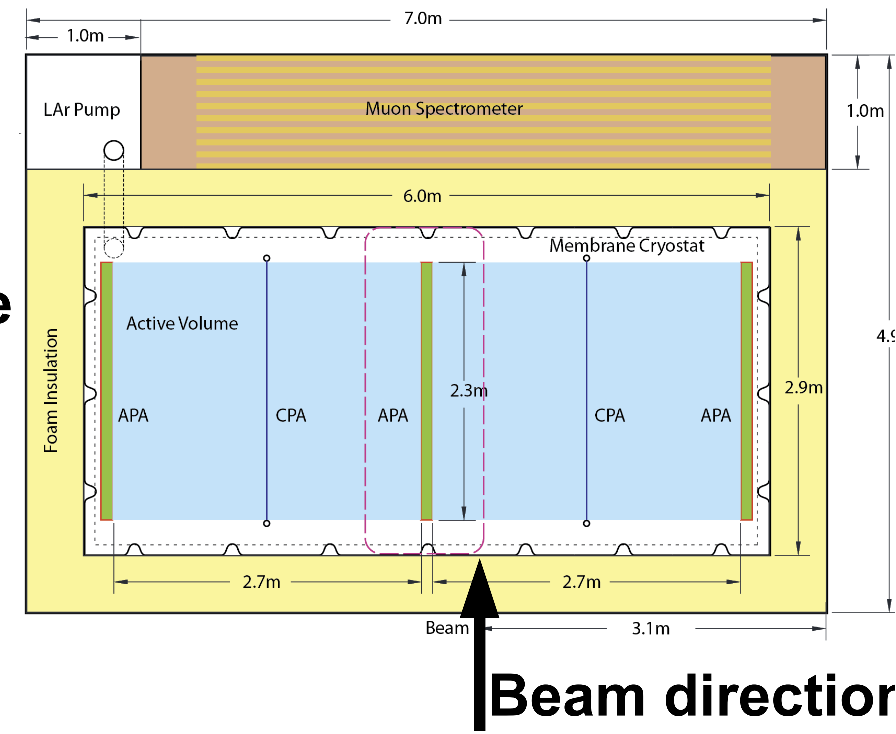


Hanging frame design



LBNE wrapped wire frame

View from above




Beam direction

**Run a 40 ton LArTPC near detector in the existing SciBooNE hall 100 meters from the target in conjuction with MicroBooNE**

→ High statistics cross-sections

→ Near/Far configuration with LAr detectors

→ Utilize LBNE-like designs for TPC and cryostat

**arXiv.org > physics > arXiv:1309.7987**

**Physics > Instrumentation and Detectors**

**LAr1-ND: Testing Neutrino Anomalies with Multiple LArTPC Detectors at Fermilab**

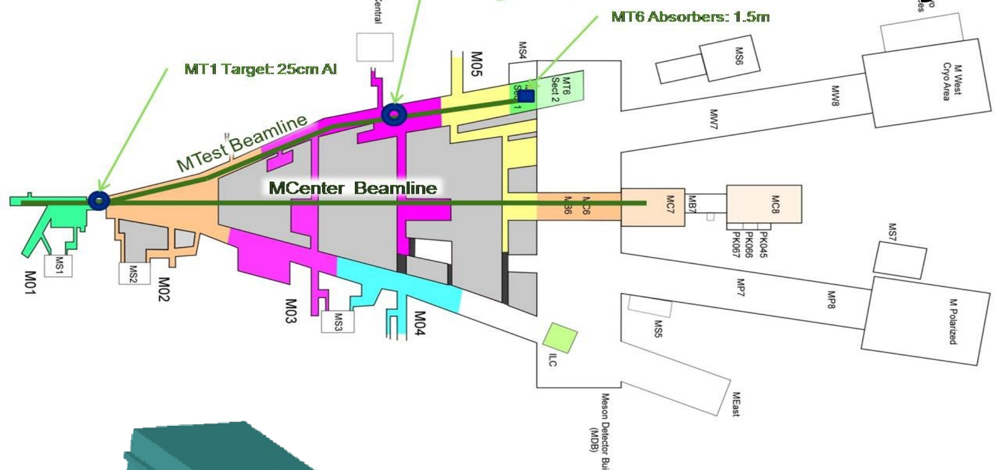
C. Adams, C. Andreopoulos, J. Asaadi, B. Baller, M. Bishai, L. Camilleri, F. Cavanna, H. Chen, E. Church, D. Cianci, G. Collin, J. Conrad, A. Ereditato, B. Fleming, W.M. Foreman, G. Garvey, R. Guenette, C. Ignarra, B. Jones, G. Karagiorgi, W. Ketchum, I. Kreslo, D. Lissauer, W.C. Louis, K. Mavrokoridis, N. McCauley, G.B. Mills, O. Palamara, Z. Pavlovic, X. Qian, L. Qiuguang, R. Rameika, D.W. Schmitz, M. Shaevitz, M. Soderberg, J. Spitz, A.M. Szelc, C.E. Taylor, K. Terao, M. Thomson, C. Thorn, M. Toups, C. Touramanis, T. Strauss, R.G. Van De Water, C.R. von Rohr, M. Weber, B. Yu, G. Zeller, J. Zennamo

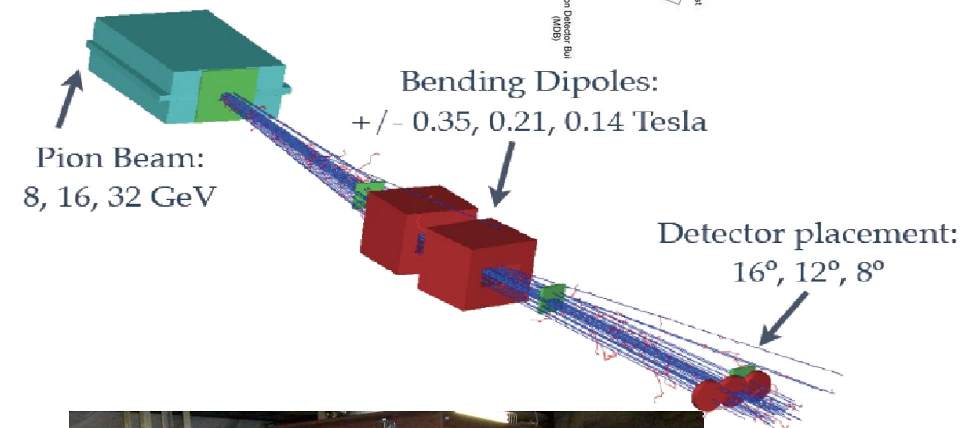
# LArIAT

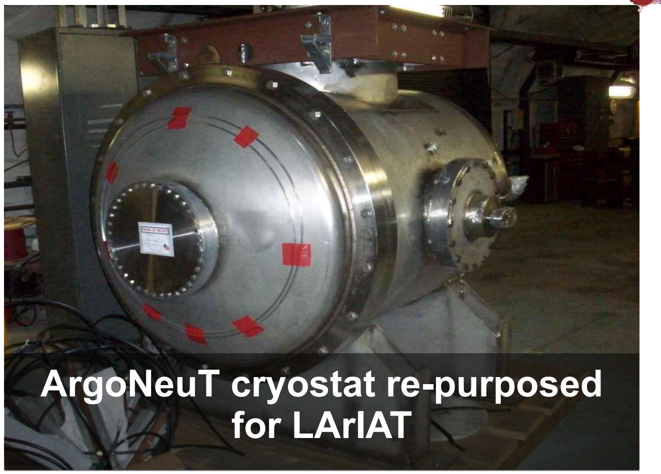
## *Liquid Argon In A Testbeam*

- **LArIAT's Vision**
  - To build a long term test beam facility for LArTPC's at FNAL
  - Study LArTPC's response using a range of particles of known momentum
  - Provide detailed calibration information for LAr technologies

**Fermilab Test Beam Facility**

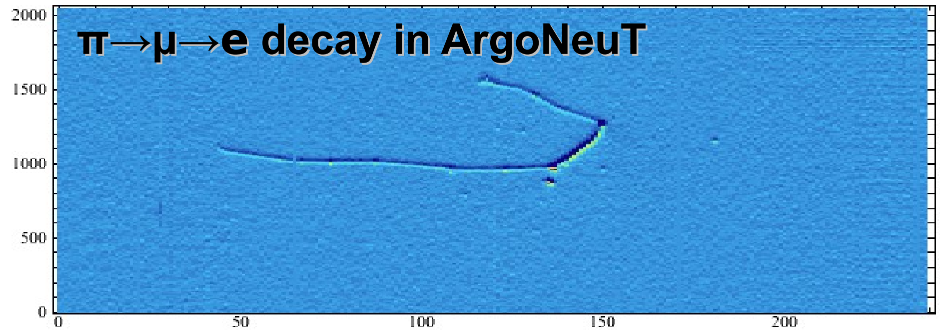


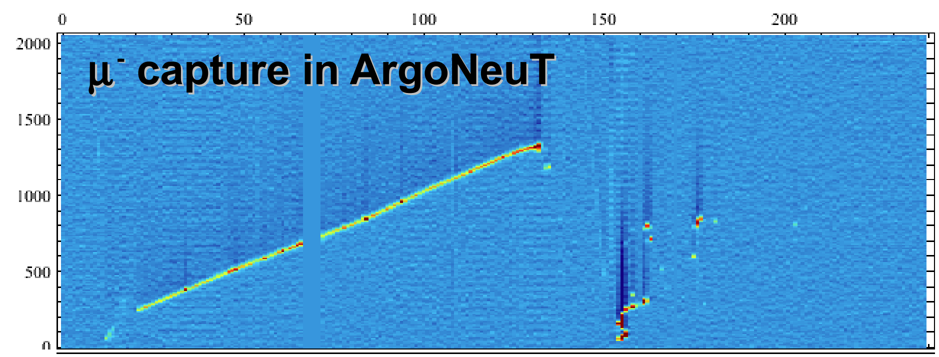



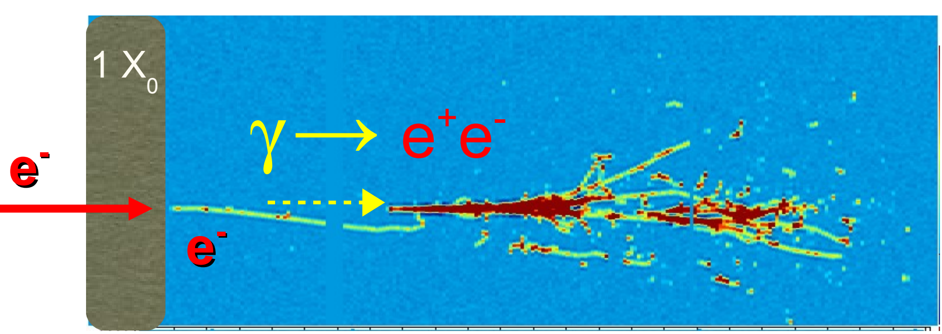


ArgoNeuT cryostat re-purposed for LArIAT

# LArIAT

## *Liquid Argon In A Testbeam*



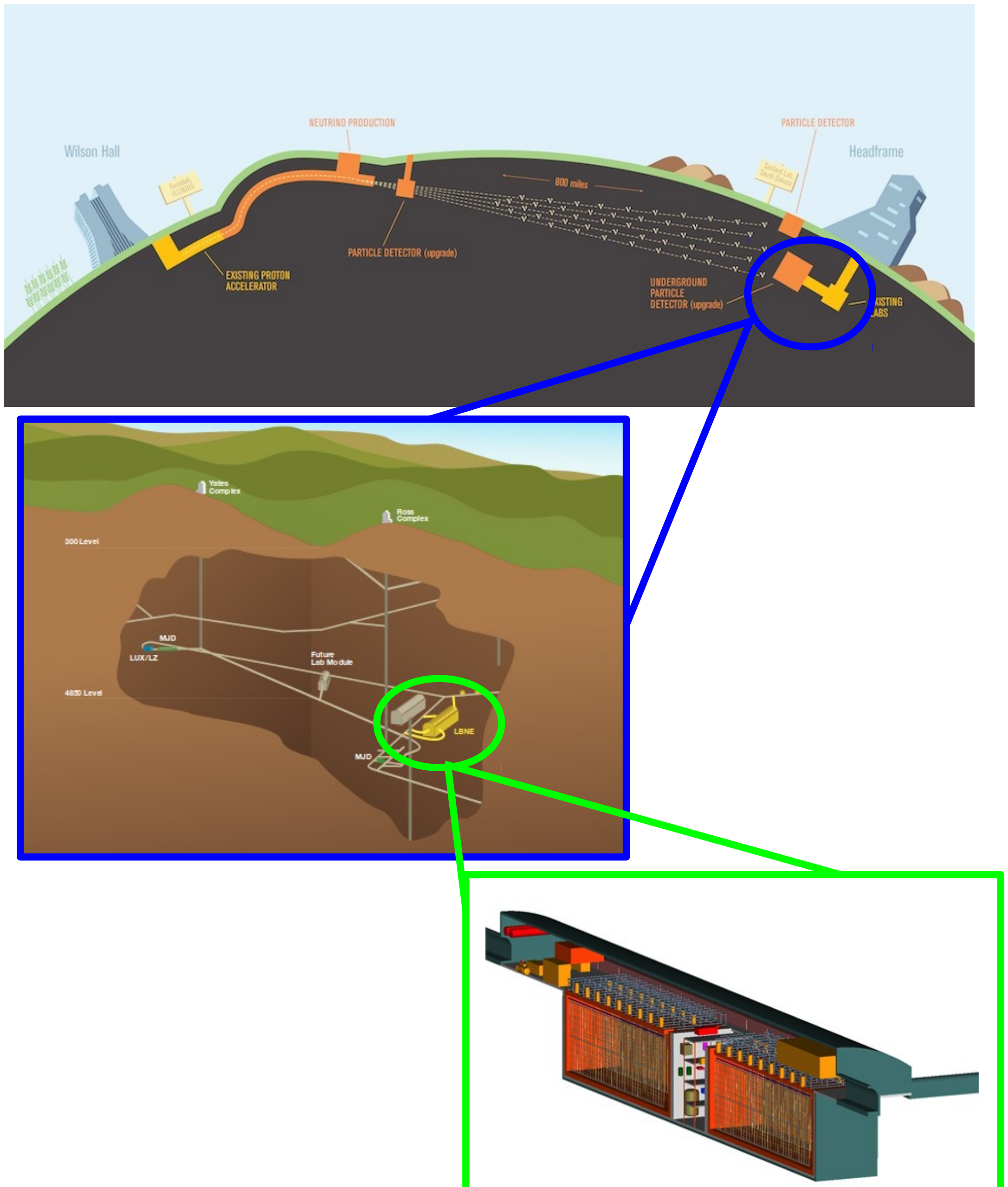




- **Physics with LArIAT**
- **Charge sign determination** (w/o a magnetic field) can be obtained for particles which stop inside a LArTPC using statistical analysis
  - $\mu^+$ decay only with an $e^+$ emission of a known energy spectrum
  - $\mu^-$ capture on a nuclei (~ 75%, followed by a γ/n emission) or decay (~25%)
- LArIAT's large electron (e) tagged event sample will **experimentally measure** separation efficiency and sample purity for e-induced vs. photon (γ)-induced showers in a liquid argon TPC

**Plus lots more that I don't have time to talk about**
**http://intensityfrontier.fnal.gov/lariat.html**

# LBNE

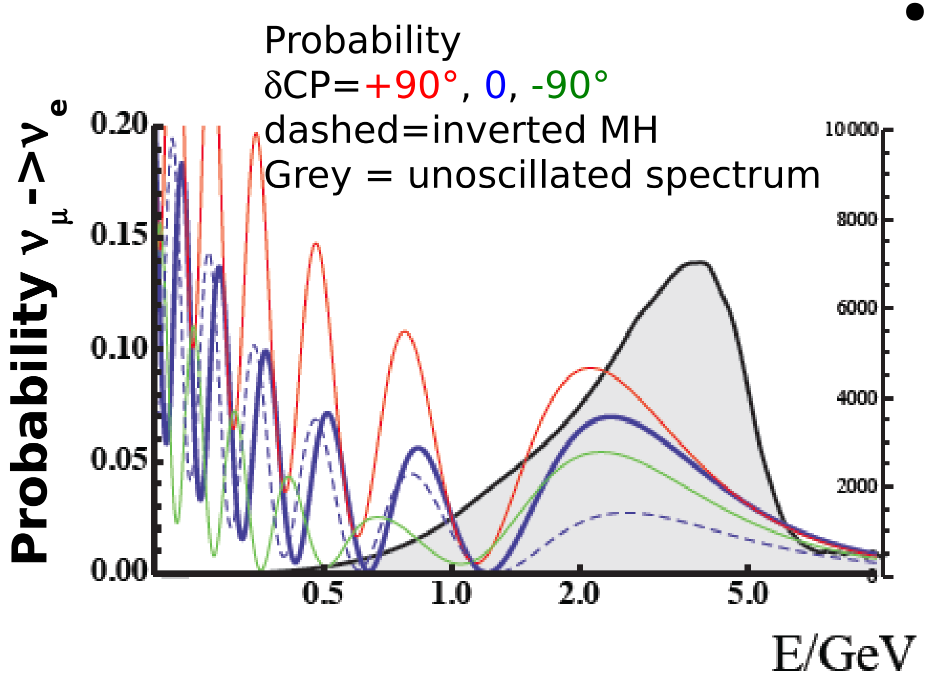
## *Long Baseline Neutrino Experiment*

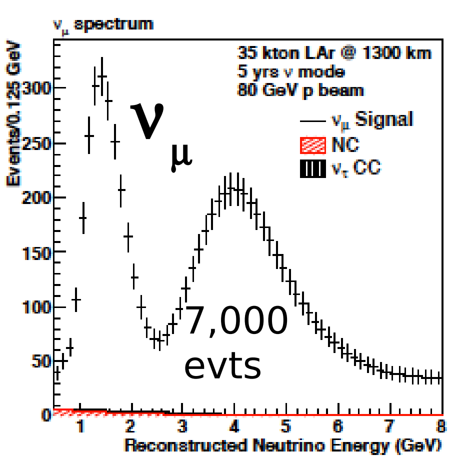


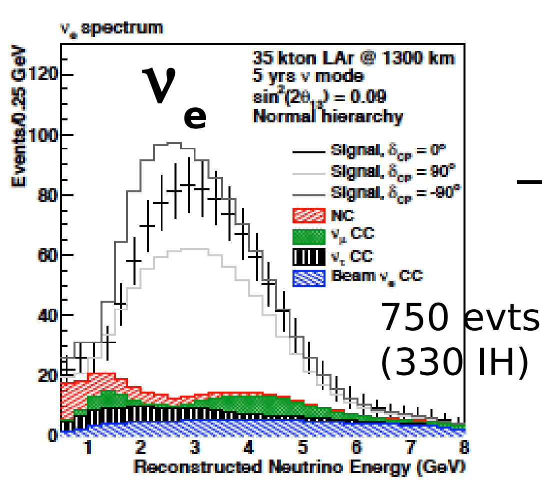

- **Long Baseline Neutrino Experiment is the next major neutrino experiment proposed**
  - Build a large scale (34 kTon) LArTPC deep underground
  - Build it at a baseline that optimizes the oscillation parameters to probe CP violation and the mass hierarchy
  - Build  it deep underground to maximize your sensitivity and allow you to do more physics
  - Shoot a powerful beam of neutrinos at it

# LBNE

## *Long Baseline Neutrino Experiment*



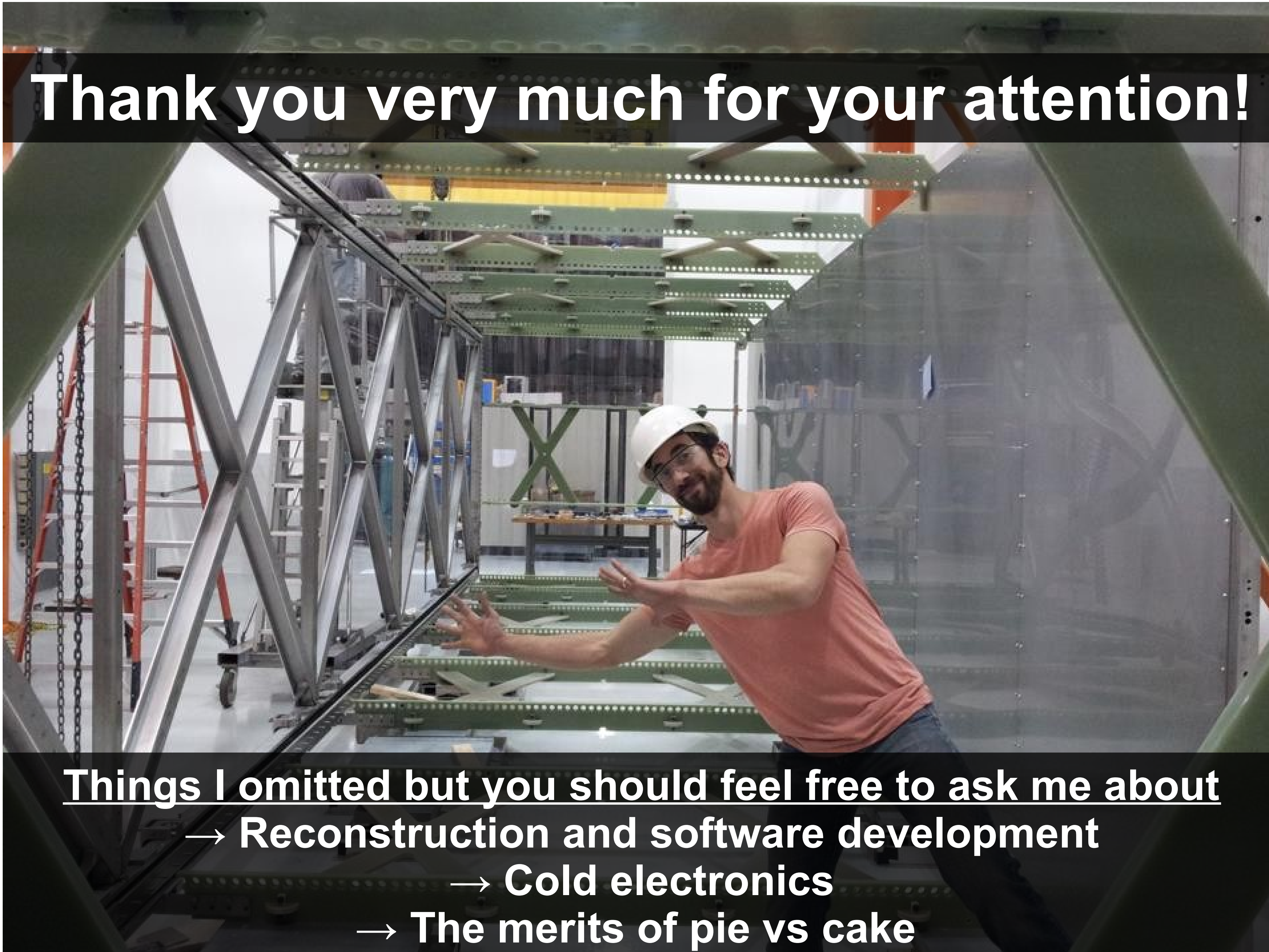




- **LBNE's strategy**
  - Have a pure beam of $\nu_\mu$ with an energy spectrum matched to the oscillation at the far site distance
  - Measure the spectrum of $\nu_\mu$ and $\nu_e$ at the far site
  - Utilize these measurements to extract the CP phase, mass hierarchy, and a dizzying array of other physics quantities
  - Additionally utilize the fact you are underground to look for proton decay and supernova neutrinos

# Conclusions

- Liquid Argon Time Projection Chambers are an exciting technology for the study of neutrino interactions!
- The ArgoNeuT experiment continues to squeeze all the information it can out of its successful run in the NuMI beam
- MicroBooNE is in the final stages of construction and should start taking date in 2014
- There is a bright and growing future in LArTPC technology with many experiments continuing to push the envelope

# Thank you very much for your attention!



<u>Things I omitted but you should feel free to ask me about</u>

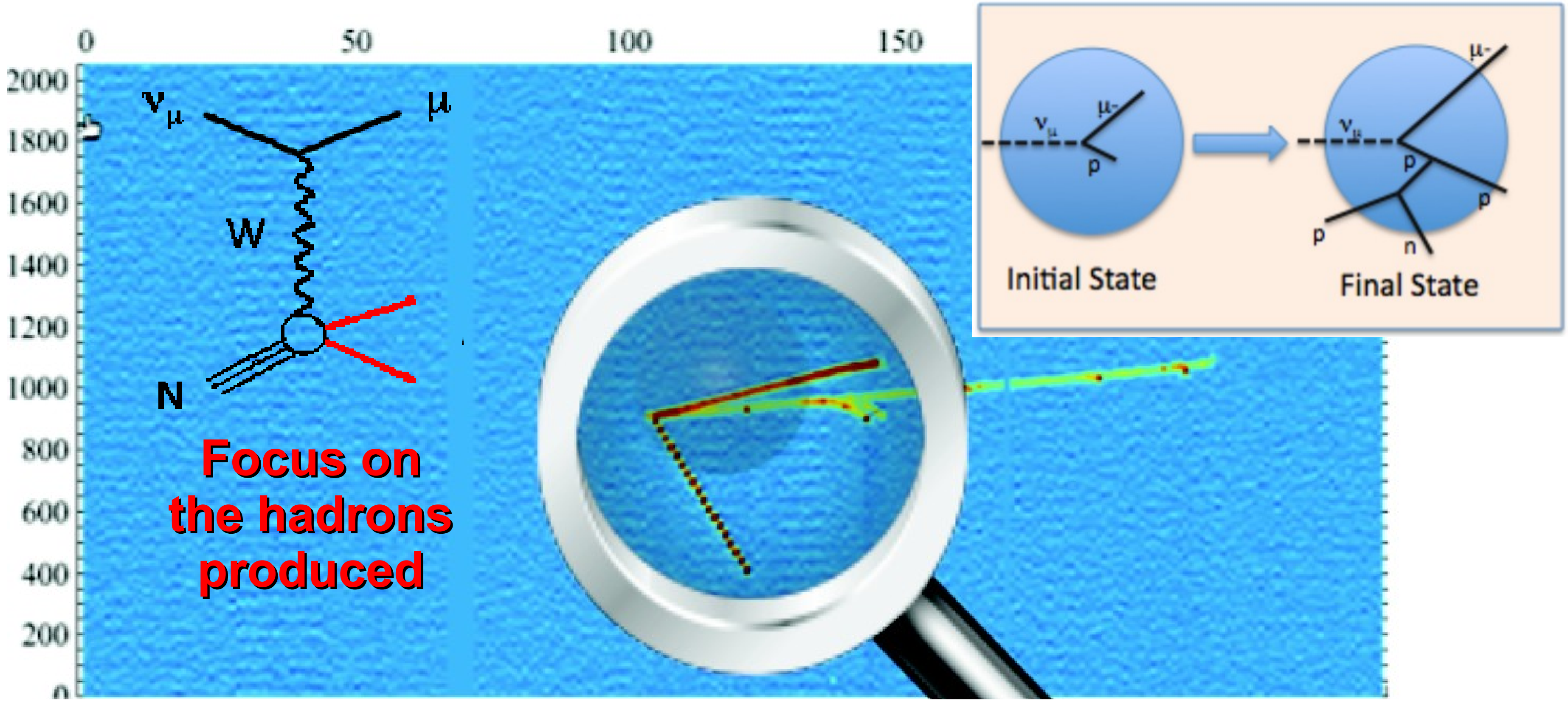
→ Reconstruction and software development

→ Cold electronics

→ The merits of pie vs cake

# Study of Nuclear Final State Interactions (FSI)

*Paper in preparation*




Nuclear effects play an important role in neutrino-nucleus scattering

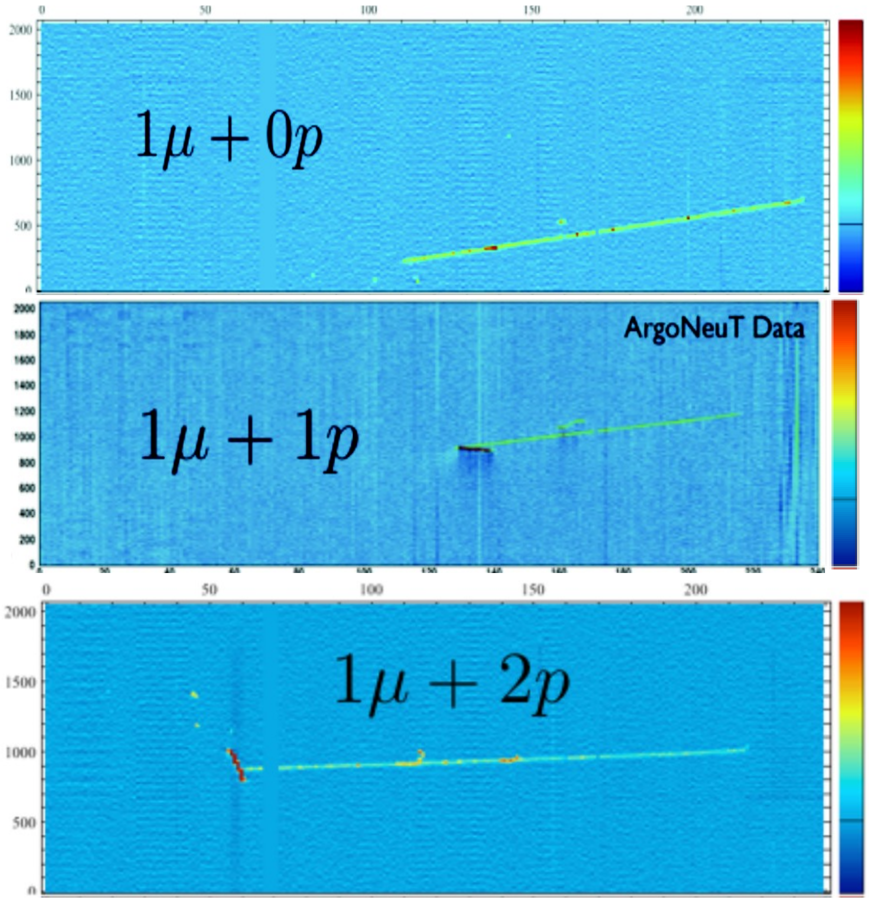
Intra-nuclear scattering and nucleon-nucleon correlations can cause quasi-elastic events to be accompanied by additional final state particles

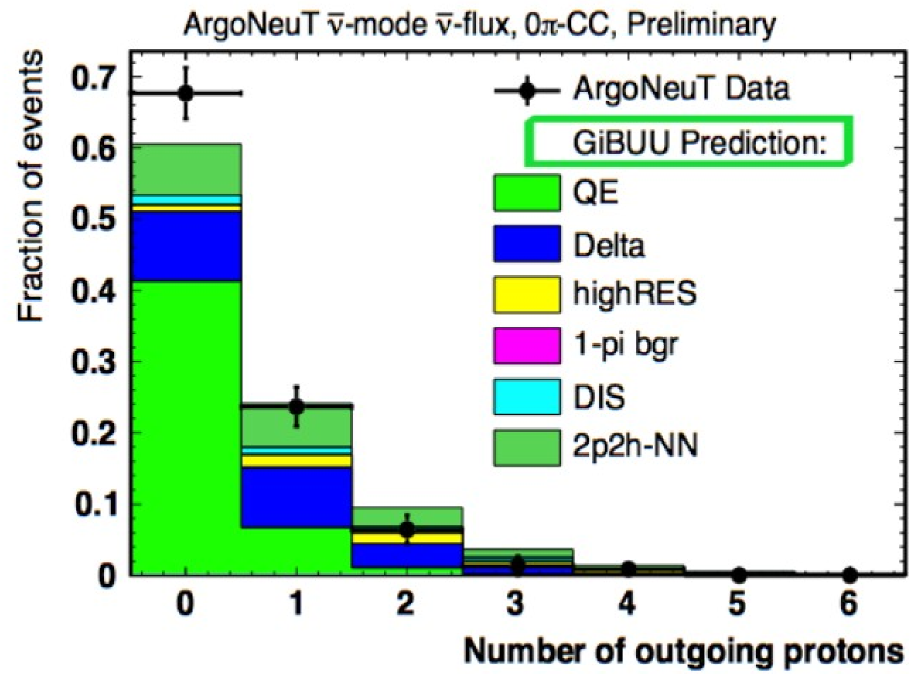
ArgoNeuT is able to **observe and reconstruct** these final state particles

Allows classification of events based on **final state topology**

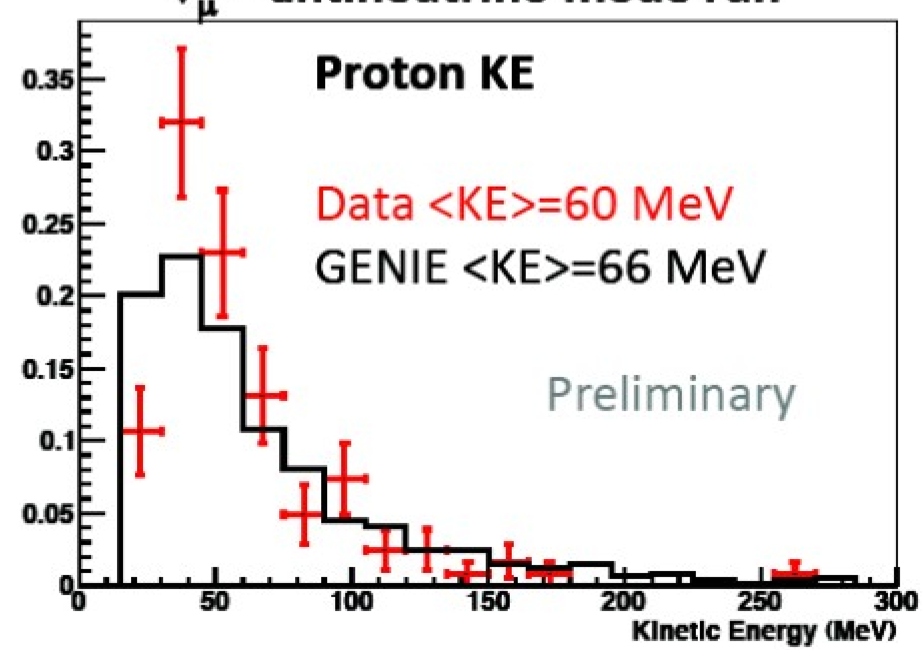
# Study of Nuclear Final State Interactions (FSI)

*Paper in preparation*




$\bar{\nu}_\mu$ – antineutrino mode run

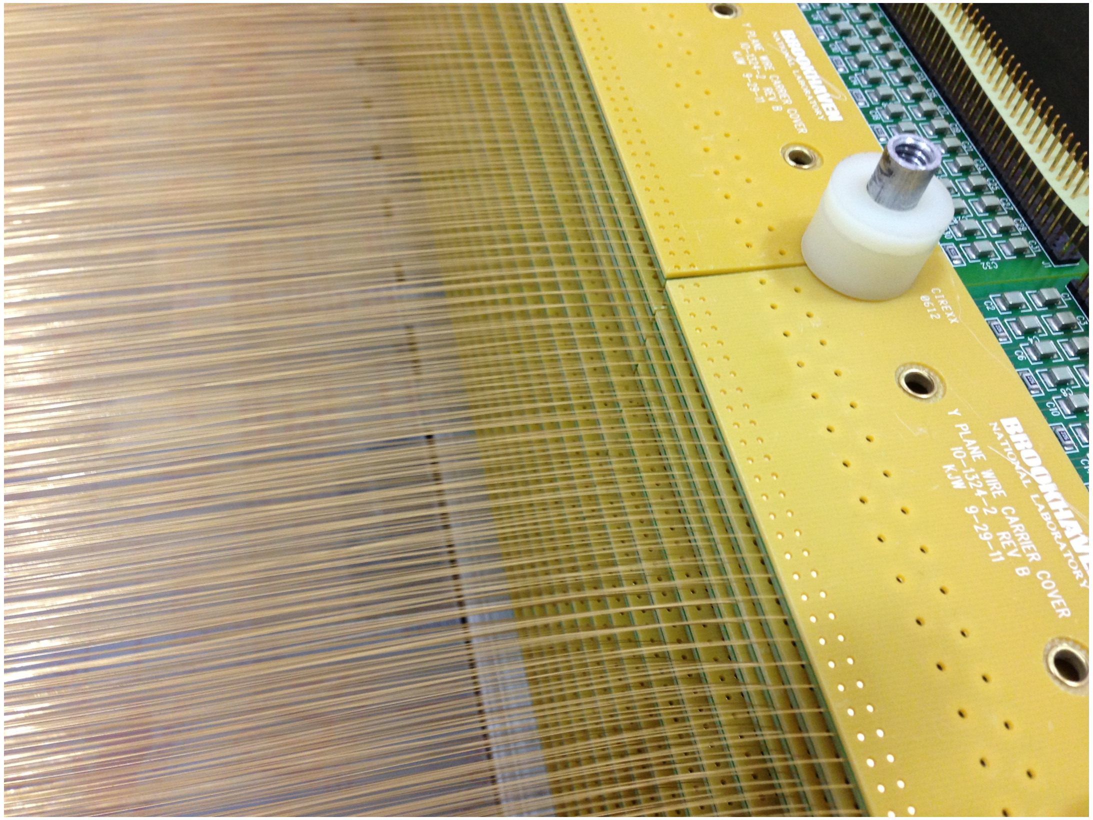



Measurements of **proton multiplicity** and **proton kinematics** in these multiple proton final states provides powerful insight into FSI

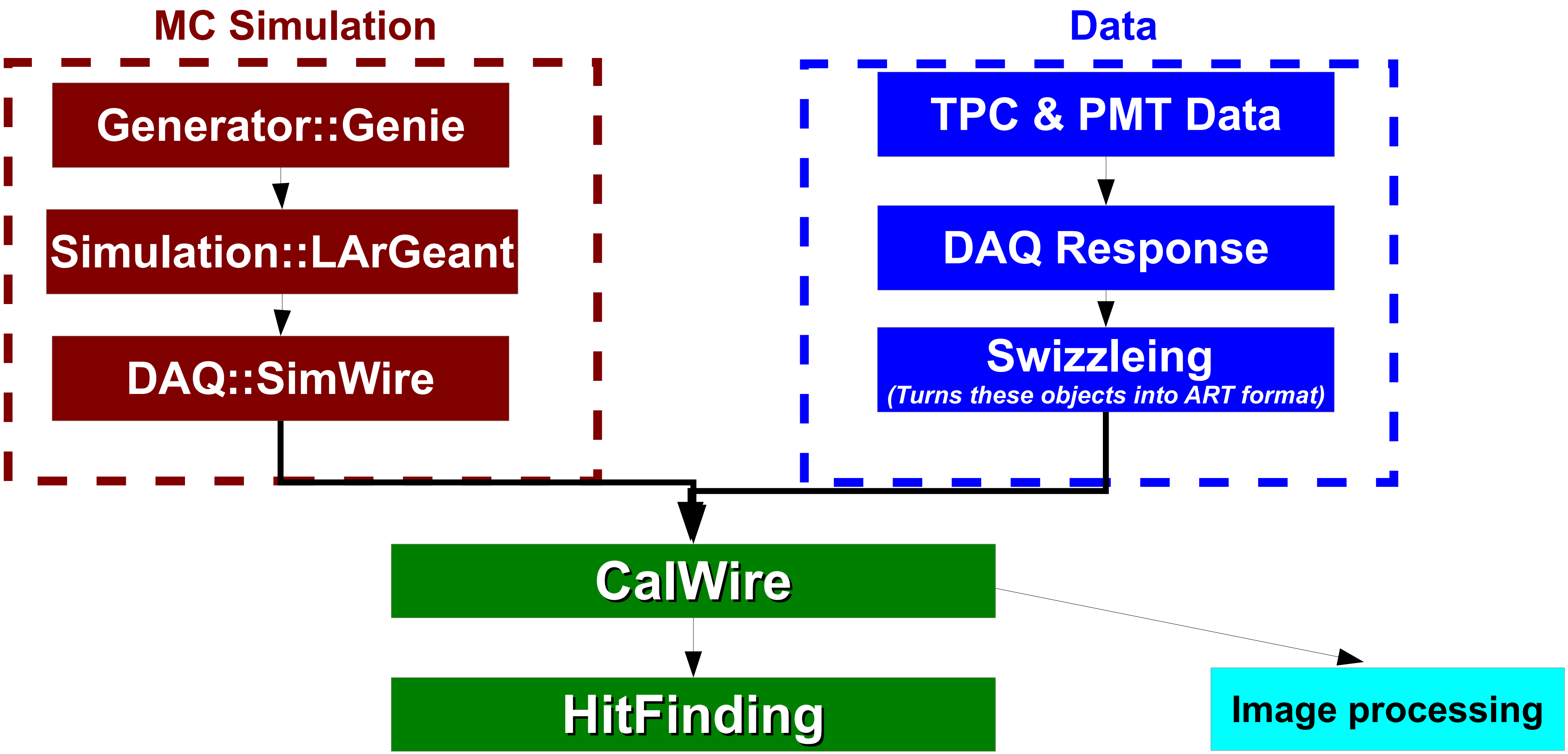
→ LAr experiments will be able to discriminate various FSI models based on data

# Wires and Hits

Jonathan Asaadi
Overview of MicroBooNE Reconstruction



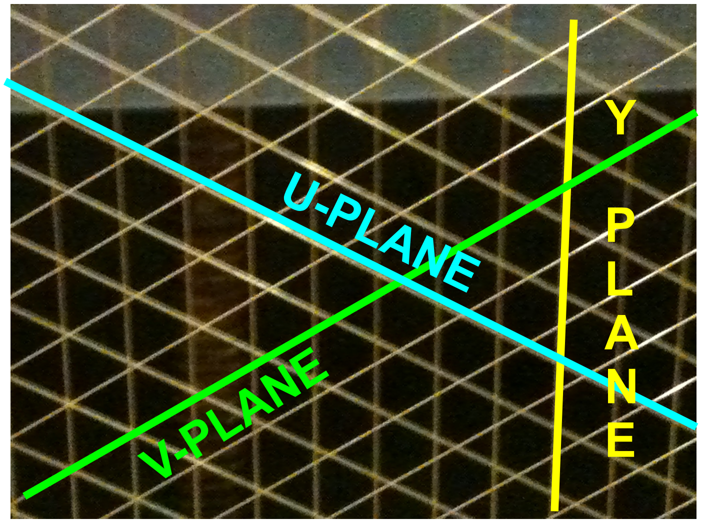
# Following the TPC reconstruction chain



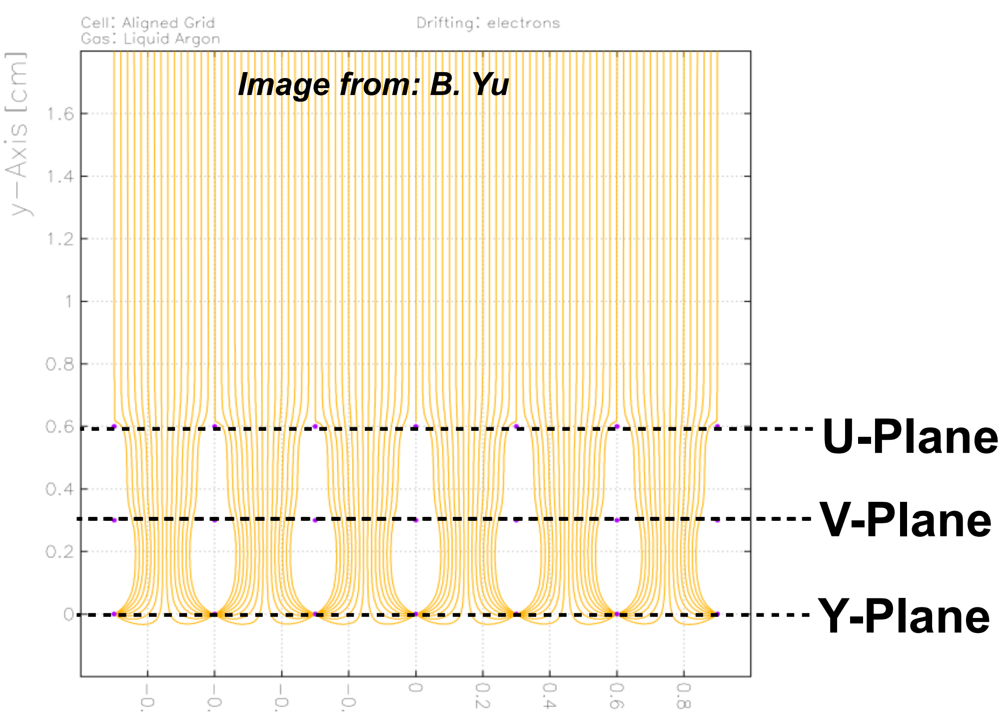

*Not talking about these off shoots here*

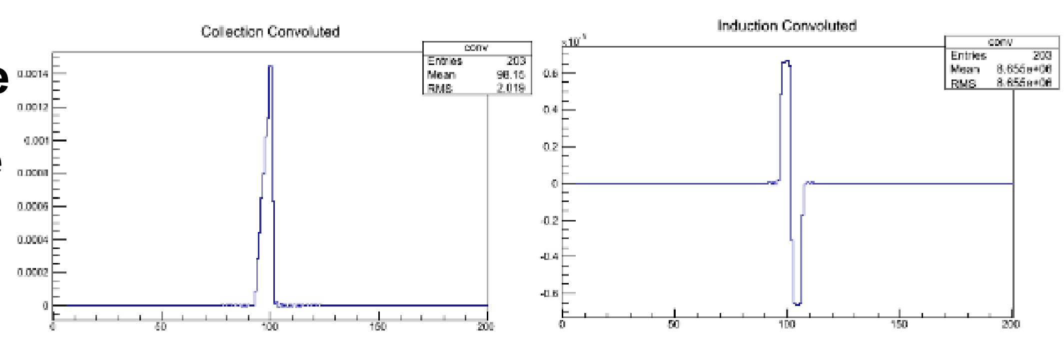
# CalWire

***Note: I am not an expert on this package***

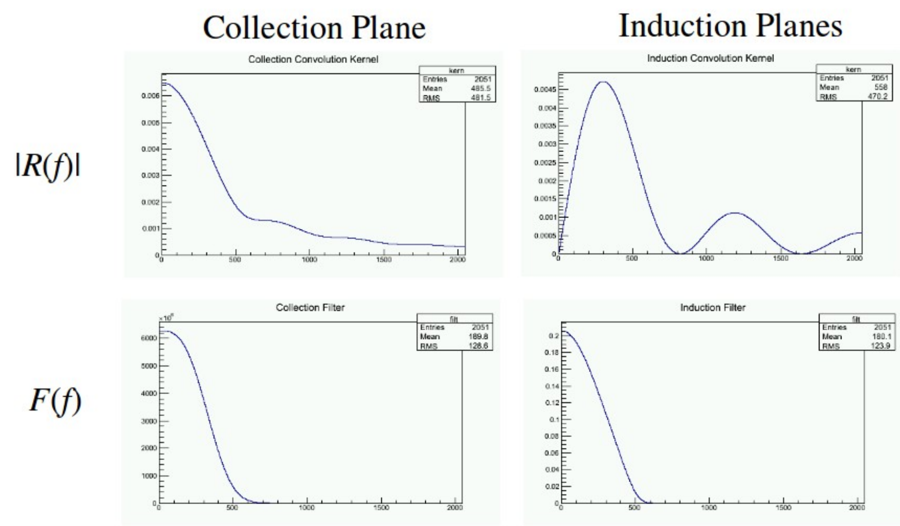


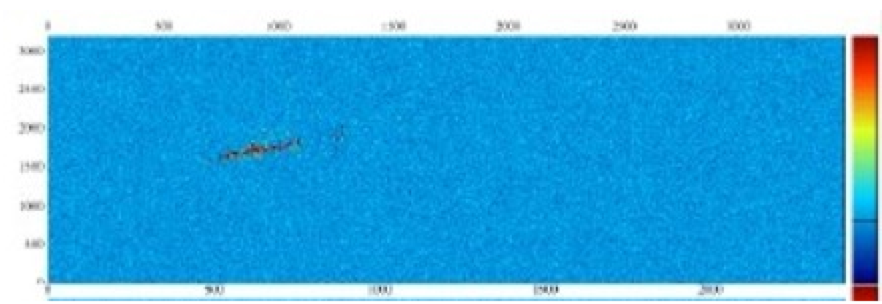

- **Our 3-plane configuration means we have two induction planes and one collection plane**
  - This causes our induction planes to have a bipolar pulse and the collection plane to have unipolar pulse
  - To get rid of the bipolar shape we have to deconvolve these shapes and obtain unipolar signals.



- **Issues I am not covering in this talk**
  - When <u>simulating</u> signals we need to include “realistic” signal & noise
  - This implies including filter functions, response functions, etc...
  - All of this happens in DAQ::Simwire
  - See A. Szelc & H. Greenlee for these details



# CalWire

*Note: I am not an expert on this package*

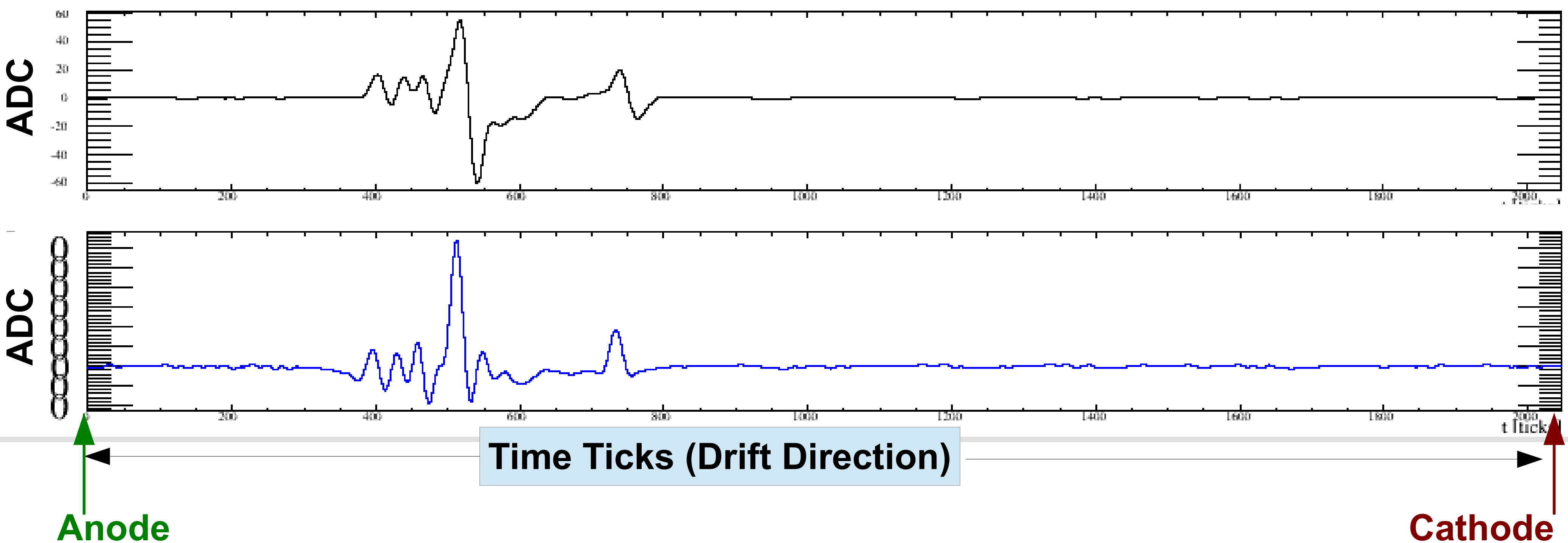
- **What we want to get out here is a proxy for the initial charge (as seen by the wires) in terms of ADC counts without detector effects**
  - Remove field shape effects
  - Remove electronics response
- **CalWire Steps:**
  - Take in RawDigit (loop over all the wires)
  - Uncompress the data
  - Add or subtract any pedestal
  - Use the signal shaping service to deconvolve the signal
    - This is where we remove detector effects
  - Save the wires onto the event

# CalWire

## *Note: I am not an expert on this package*

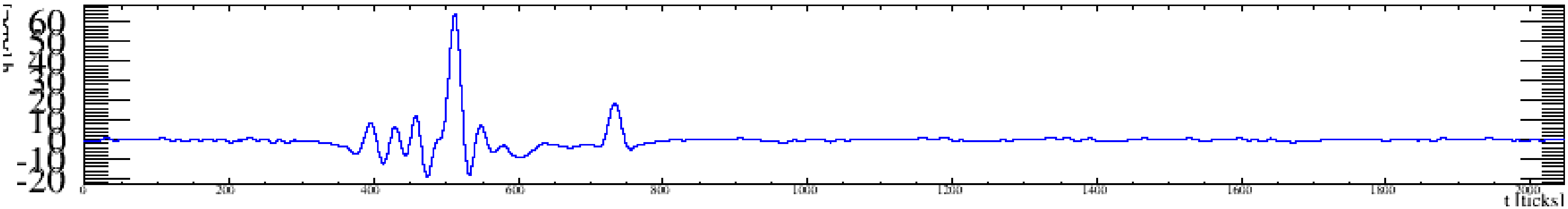
```
public:
    Wire(std::vector<float> siglist,
         art::Ptr<raw::RawDigit> &rawdigit);

    // Get Methods
    const std::vector<float>&  Signal()     const;
    size_t                     NSignal()    const;
    art::Ptr<raw::RawDigit>    RawDigit()   const;
    geo::View_t                View()       const;
    geo::SigType_t             SignalType() const;
    uint32_t                   Channel()    const;
```

- Signal(): Calibrated signal waveform
- RawDigit(): Vector to the index of the raw digit for this wire
- View(): Which view (plane) is the signal in
- SignalType(): Collection or Induction
- Channel(): Channel number



# HitFinding

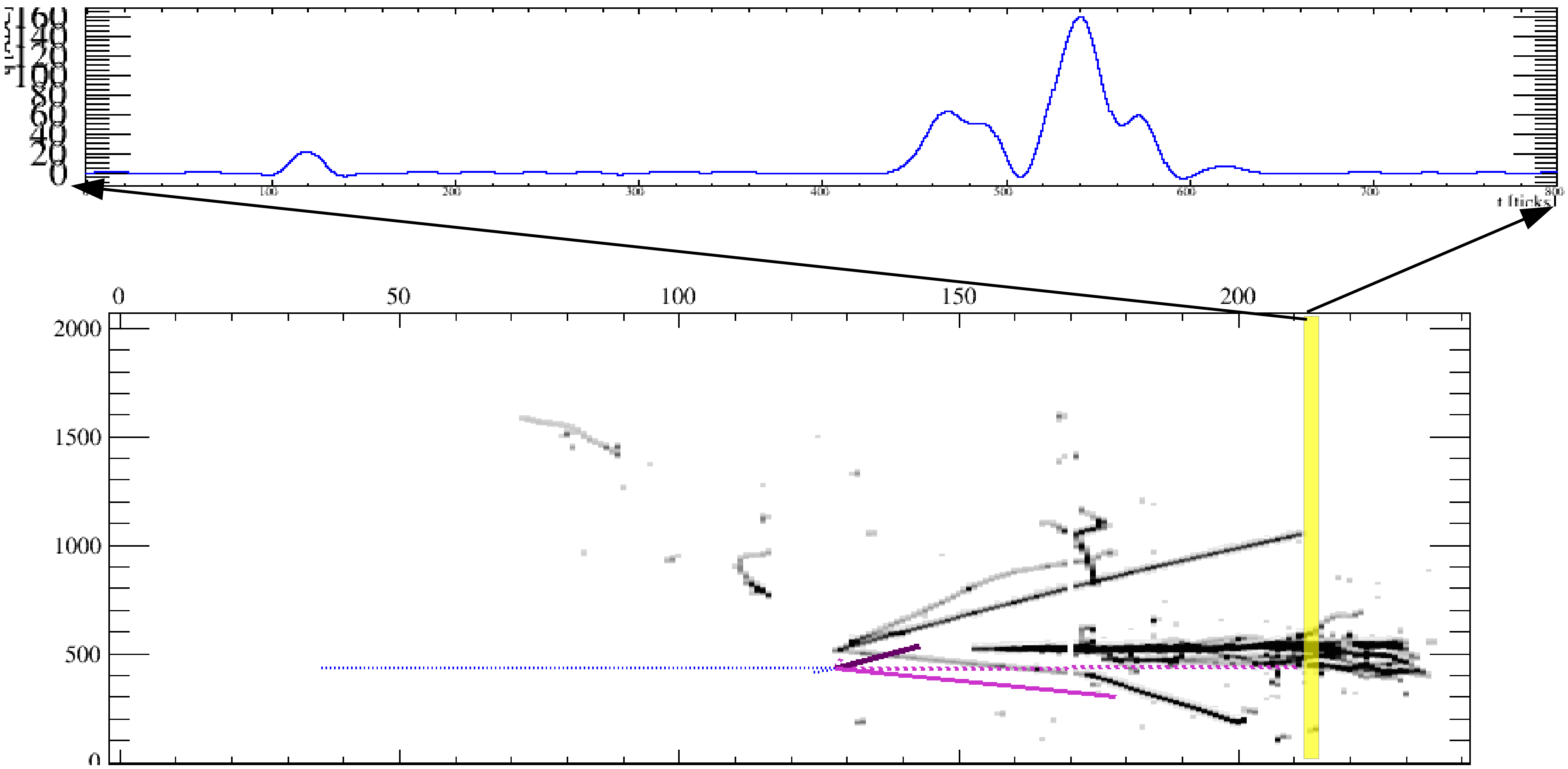
- **The basic idea of hit finding is to “walk” along each wire and look for “bumps” that correspond to charge passing by or being collected on the wire**
  - The bumps characteristics tells you about the charge that created it
  - To first order, the “bump” is characterized by a Gaussian
    - Amplitude, mean, width
    - Can also report back about the pulse that created the bump
      - Start time, End time, number of peaks in the pulse, etc



# HitFinding

- **As of today there are 4 hit finding algorithms in LArSoft**
  - FFTHitFinder, GausHitFinder, CCHitFinder, RFFHitFinder
  - Each one handles things slightly different from the other
    - CCHitFinder (ClusterCrawler Hit Finder) and RFFHitFinder (Real Frickin Fast Hit Finder) are big speed improvements as well as slightly different algorithms
    - FFTHitFinder and GausHitFinder are similar in method with tweaks for various improvements
  - I'm going to focus on the basics used in FFT, Gaus and CC Hit finder
    - I'll leave the details to the authors and Reco meetings

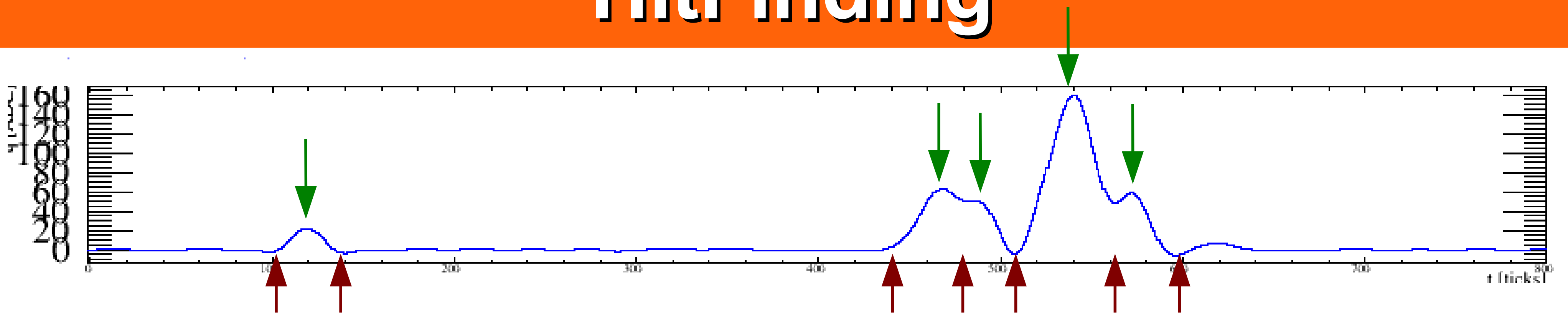
# HitFinding




**Let's start with a slightly complicated looking series of pulses coming from this event**

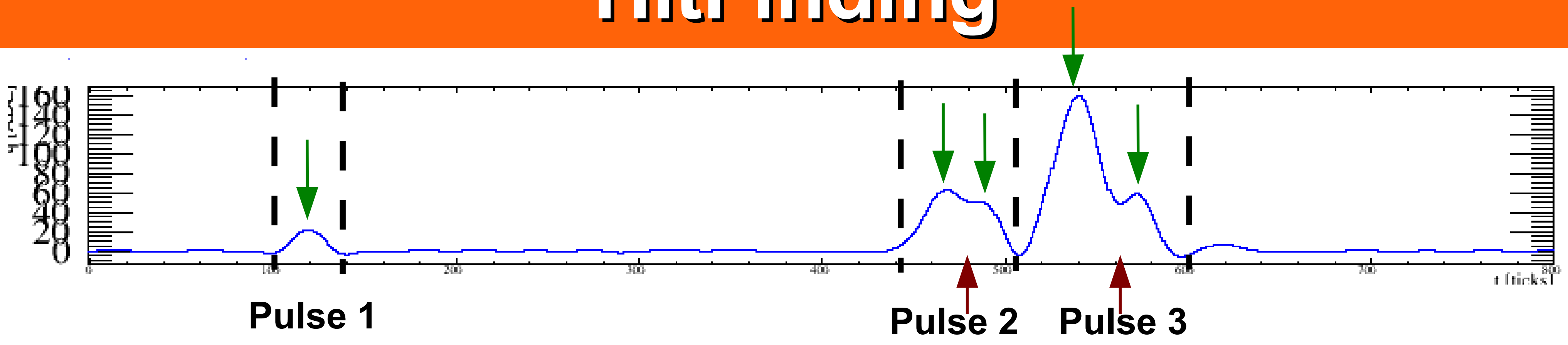
***(Focused on the highlighted wire)***

# HitFinding



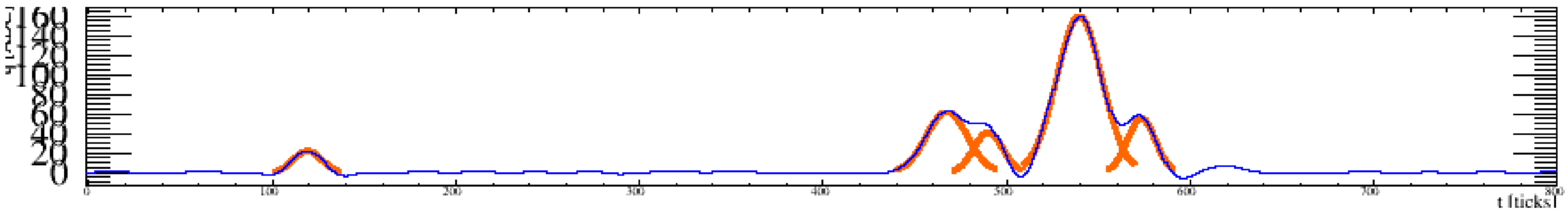

- **First thing is we walk along the wire and find all the local maxima and minima**
  - Whether or not a point goes above “threshold” or we find an inflection point is a matter of tuning in the algorithm
  - As of today we require 6 ADC's for the induction plane and 11 ADC's for the collection plane

# HitFinding




- **Now we group these maxima and minima into "pulses" of consecutive hits**
  - Group them into consecutive hits if:
    - 1) We are less than the maximum number of consecutive peaks (configurable....right now set to 3 peaks)
    - 2) The height of the dip is greater than threshold/2
    - 3) There is no gap between them
    - 4) We aren't at the end of the wire

# HitFinding




- **Finally fit the pulses with N Gaussians where N is the number of peaks in a pulse**
  - Each Gaussian represents a single hit
    - Even if it came from a pulse with multiple peaks
    - The fact that it came from a pulse with multiple peaks is saved as the "multiplicity" of the hit
  - Gaussian fits are constrained based on configurable hit widths and amplitudes
  - Results are saved as Hit objects on the event

# HitFinding

```
public:
    Hit(art::Ptr<recob::Wire> &wire,
        geo::WireID wid,
        double startTime, double sigmaStartTime,
        double endTime,   double sigmaEndTime,
        double peakTime,  double sigmaPeakTime,
        double totcharge, double sigmaTotCharge,
        double maxcharge, double sigmaMaxCharge,
        int    multiplicity,
        double goodnessOfFit);

    Hit(art::Ptr<raw::RawDigit> rawdigit,
        geo::View_t view,
        geo::SigType_t signaltype,
        geo::WireID wid,
        double startTime, double sigmaStartTime,
        double endTime,   double sigmaEndTime,
        double peakTime,  double sigmaPeakTime,
        double totcharge, double sigmaTotCharge,
        double maxcharge, double sigmaMaxCharge,
        int    multiplicity,
        double goodnessOfFit);
```

Wire information

Start time of the hit (and error)

End time of the hit (and error)

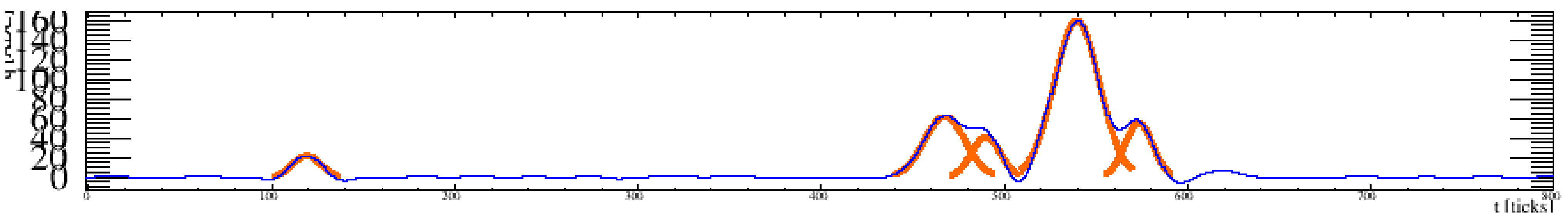
Peak time of the hit (and error)

**Total amount of "charge" in the hit**

**(Really this is the total number of ADC counts)**

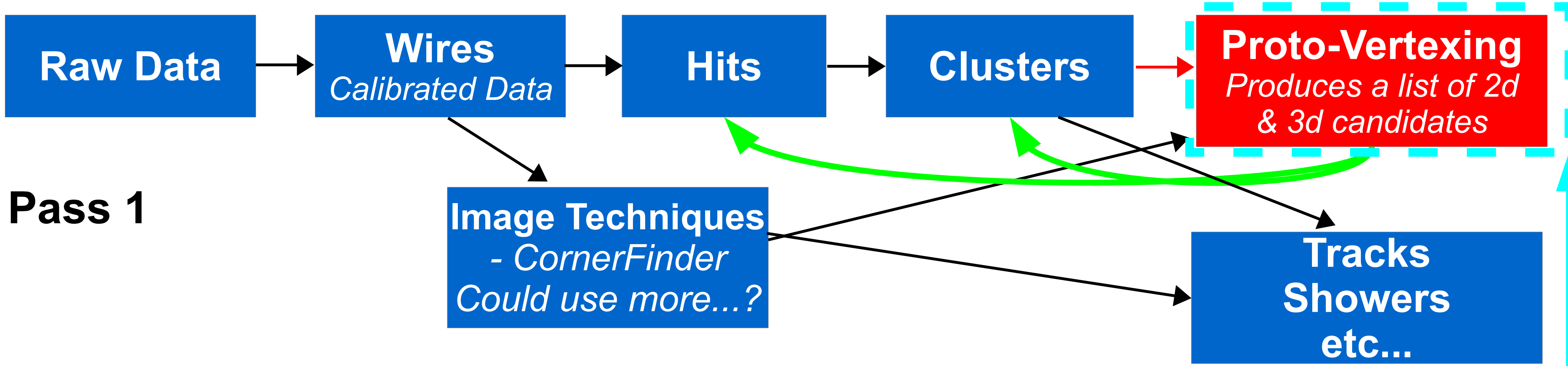
Multiplicity (number of peaks in a pulse)

$\chi^2$ / NDF (For GausHitFinder if this is > 15 we don't even save the hit...configurable)



# Reconstruction

*(How I imagine it could be)*




→ **= simple feed forward technique** (like we do now)

→ **= new link in the chain** (i.e. FeatureVertexFinder)

→ **= feed back to previous algorithms**

■ **= Existing algorithm**

■ **= New algorithm**

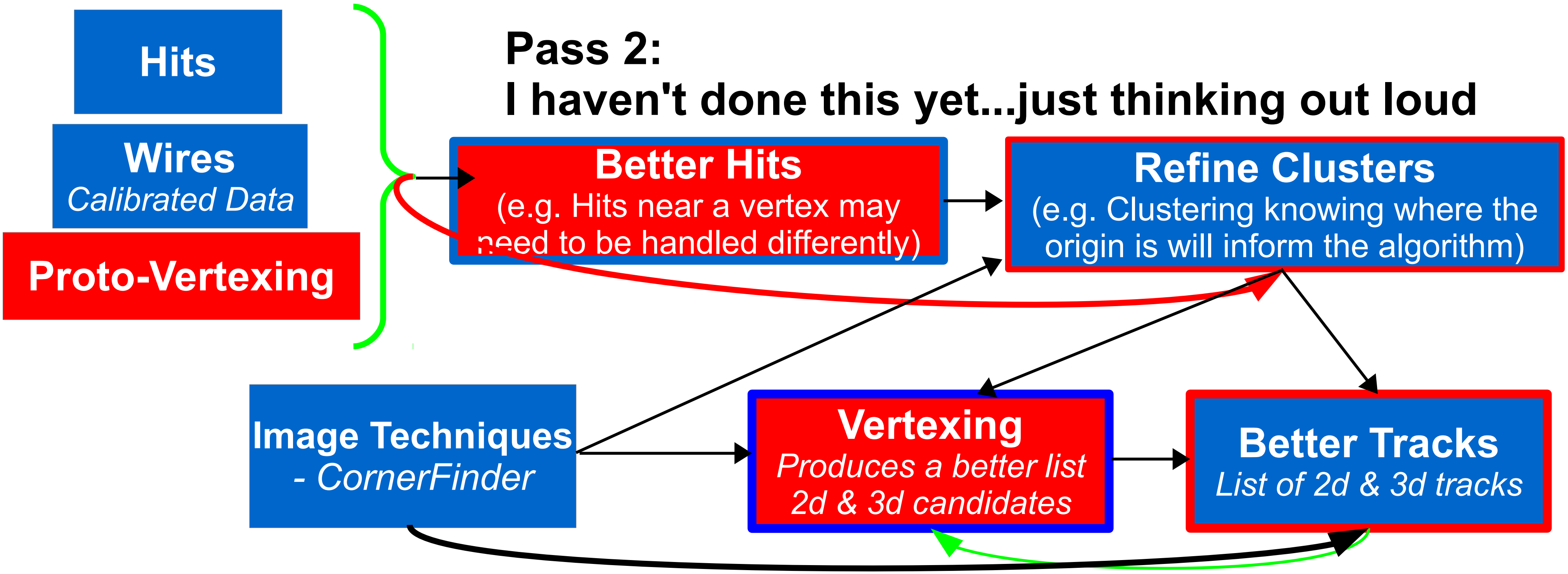
**During our first pass we do much of what we do now (i.e. make simple objects based on available information) However, since many of these object can be used to inform/improve reconstruction algorithms, we identify those links and re-run reconstruction using this information as input!**

**Most of this talk will focus on this new module**

# Reconstruction

*(How I imagine it could be)*

**Pass 2:**
**I haven't done this yet...just thinking out loud**




→ = **simple feed forward technique** (like we do now)

→ = **new link in the chain** (i.e. FeatureVertexFinder)

→ = **feed back to previous algorithms**

■ = **Existing algorithm**

■ = **New algorithm**

= **modify / improve existing algorithm**

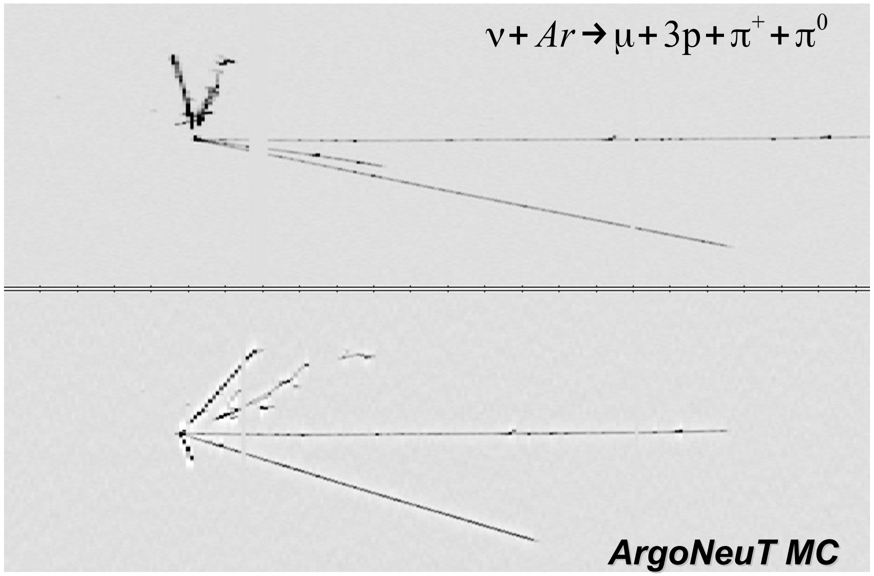
**Obviously this web can get complicated in a hurry...but hopefully the idea is clear**

**A first step in this (in my opinion) is trying to find vertex candidates**

# Feature Vertex Finder

***Easiest method is to show how module works is to step through an example MC event***

**Step 1:** Start with a wire information




**Step 2:** Run the event through a generic reconstruction chain up to 2-d clusters *(keep CalWire)*

- HitFinder (GausHitFinder)
- 2-d Cluster (dbCluster)
- 2-d LineFinding (HoughLineFinder)
- 2-d LineFinding (LineMerger)

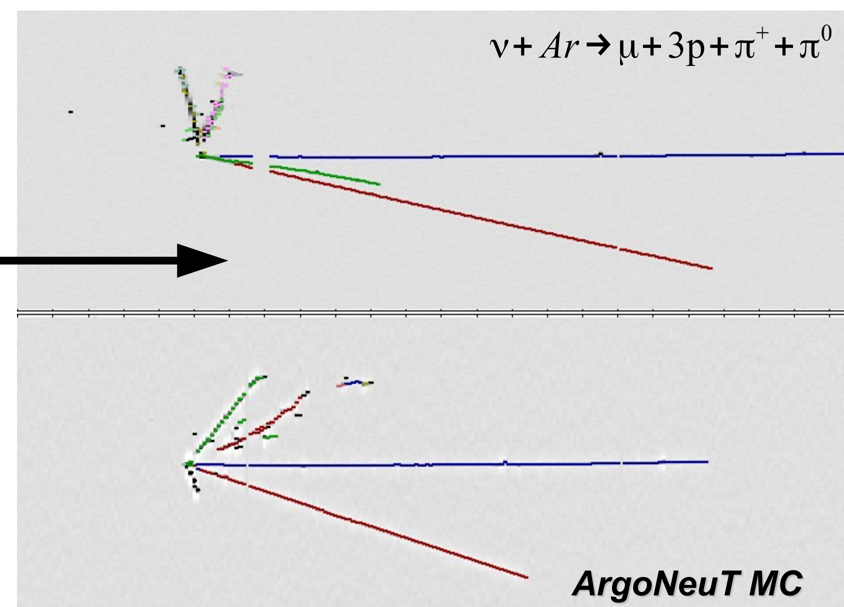
***Note: These are just 2-d Cluster modules*** (2-d LineFinding (HoughLineFinder), 2-d LineFinding (LineMerger))

**What I am showing here are reconstructed hits and the 2d-Clusters from LineMerger**

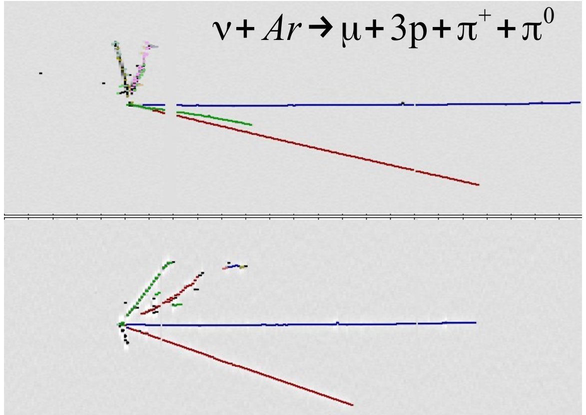
→ In principal you could have used any 2-d cluster module

→ I chose linemerger because it seemed to give me sensible clusters for finding a vertex

**At this point in the reco chain I run FeatureVertexFinder**

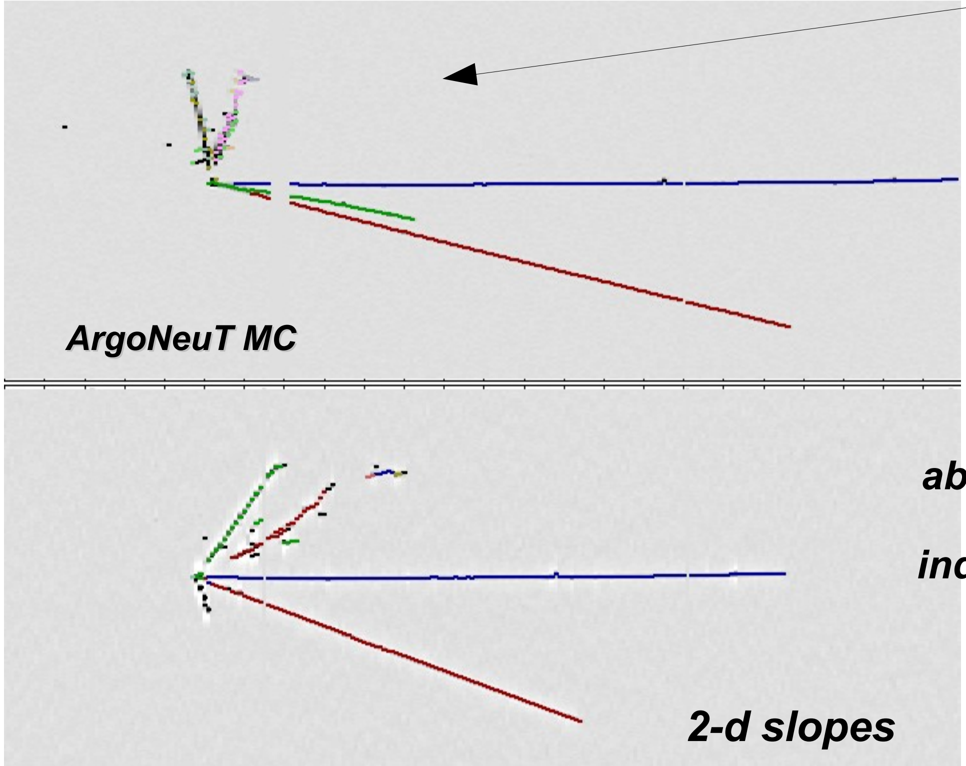


# Feature Vertex Finder

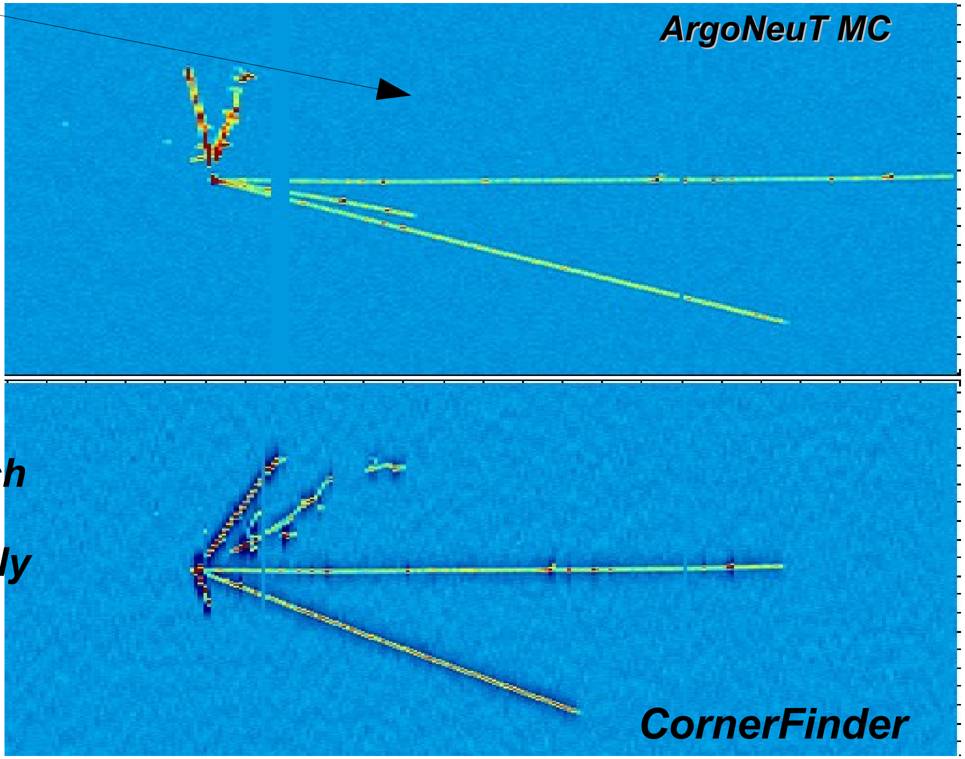



**At this point FeatureVertexFinder looks at the event in two ways**

1) 2d- Cluster slopes and intercepts
2) 2-d Image Finding using ConerFindingAlg

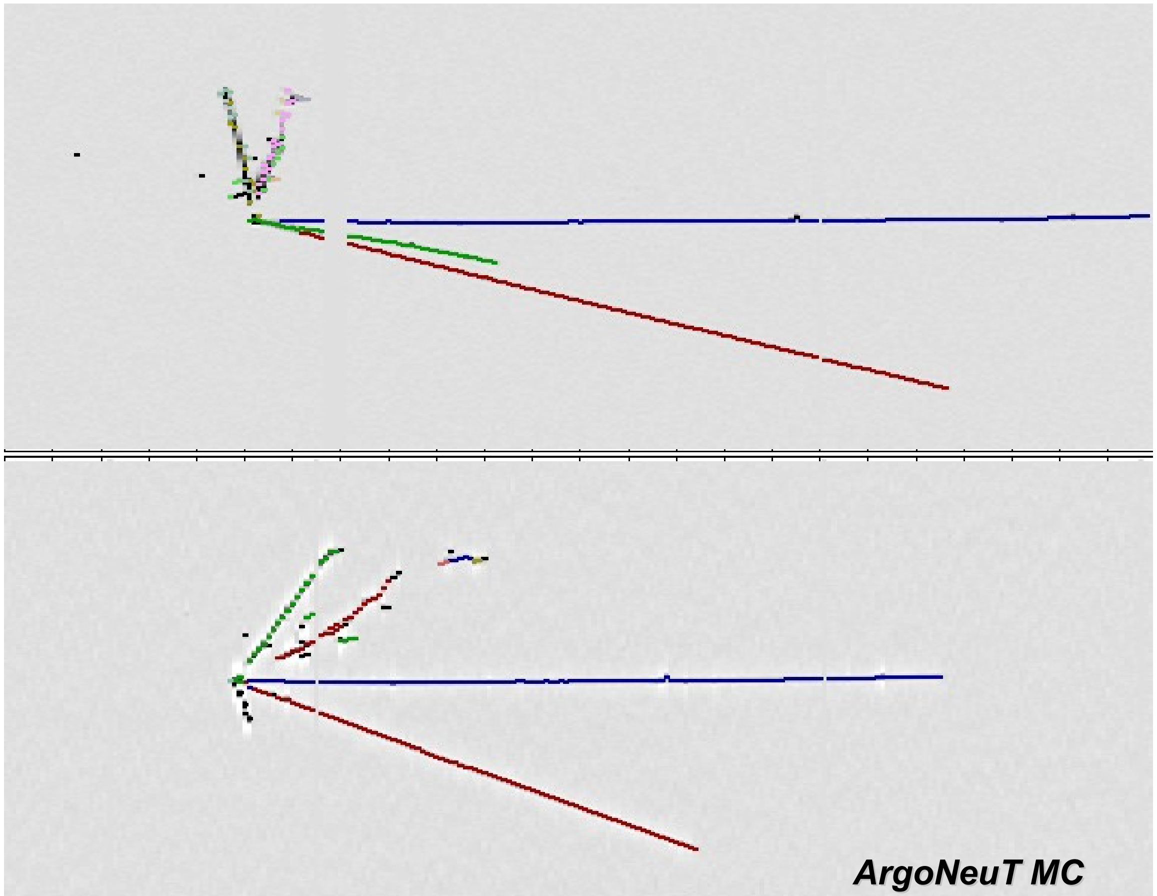



*I'll talk about each way individually*



# Feature Vertex Finder

## *2-d Slopes*

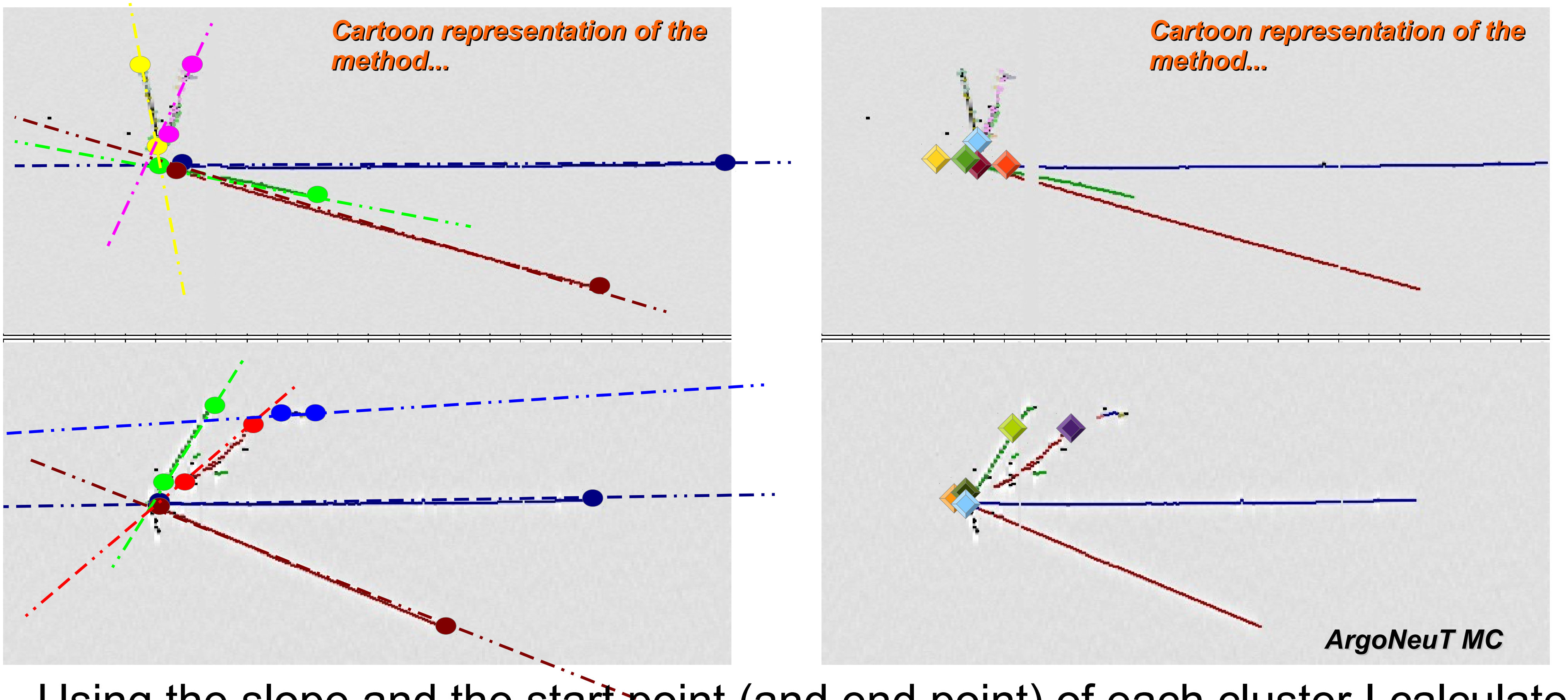



- For every cluster I take the hits for that cluster and fit a 1st order polynomial to the hits (pol1) and save the slope
  - I use a fit instead of the reco cluster slope (dTdW = delta Time / delta Wire) because not every cluster module calculates this
- I also save the start and end position (wire and time) for each cluster
  - I do this since I expect the clustering algorithms (at this point) to get the actual start and end position switched sometimes

Now I search for **2-d vertex candidates** in each plane

# Feature Vertex Finder

## *2-d Slopes*



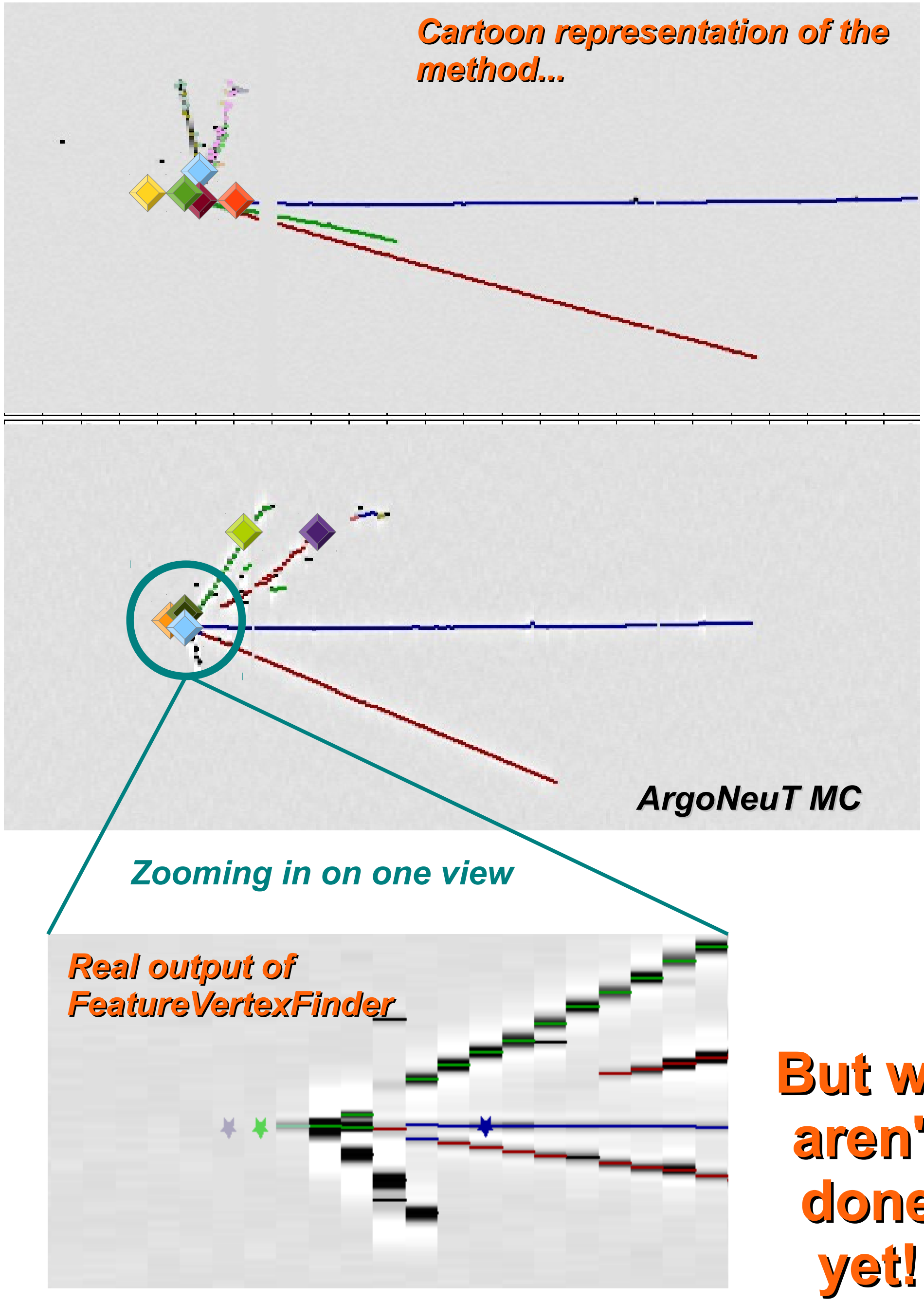

Using the slope and the start point (and end point) of each cluster I calculate all the intersection points in each plane between all the lines

***Greater details in the backup slides...***

Now with a long list of 2-d vertex candidates (wire & time) in each plane I look for **3-d cluster vertex candidates**

# Feature Vertex Finder

## *Matching between views*

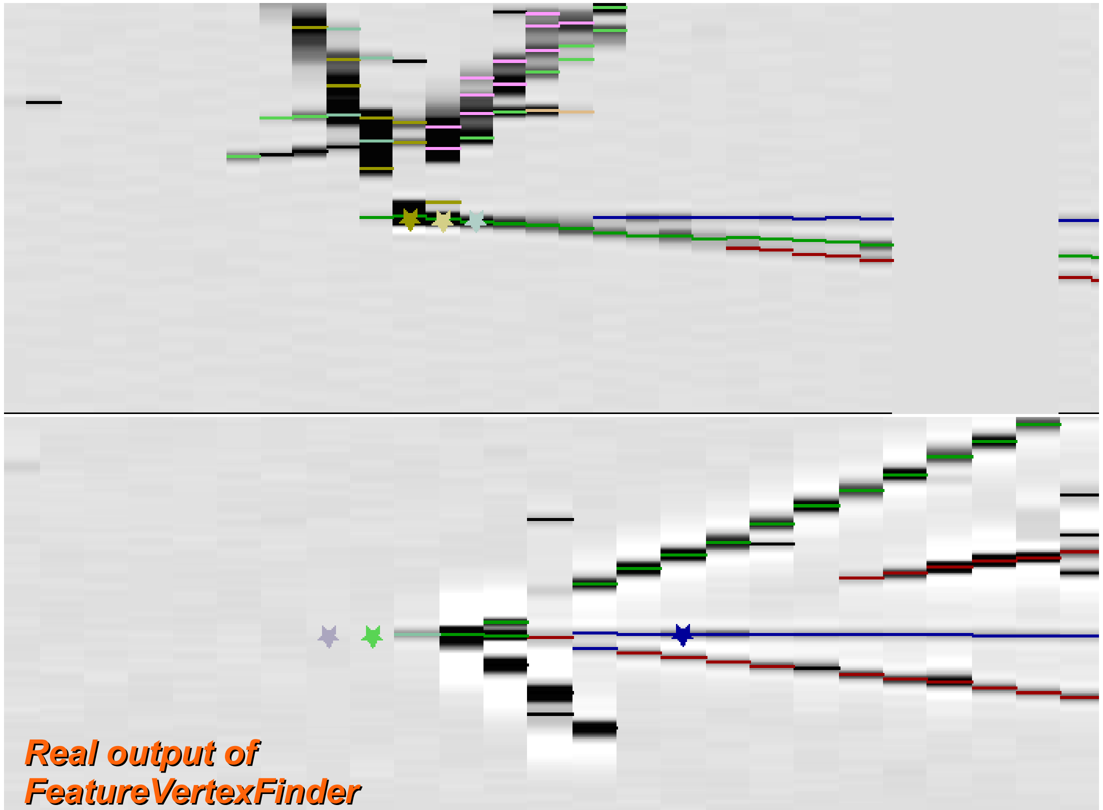



**But we aren't done yet!**

- I loop over each 2-d vertex candidates (channel$_1$ and time$_1$) and look to see if there is a corresponding 2-d vertex candidate (channel$_2$ and time$_2$) in a different view and see if the channels intersect *(ChannelsIntersect(C1,C2,Y,Z) )*.
  - This gives me a Y and Z coordinate for my potential **3-d cluster vertex**
- Finally I require that the time difference between the two vertex candidates (*abs(time1-time2)*) is within 1.5 times the expected offset between planes (*TimeOffsetV, TimeOffsetU, TimeOffsetZ*)
- If the vertex satisfies both these conditions (*ChannelsIntersect and 1.5TimeOffset*) I then calculate the vertex X coordinate (*TickstoX*)
  - So now I have a **3d cluster vertex** and a **2-d cluster vertex** (in each plane)

# Feature Vertex Finder

## *Vertex Strength*

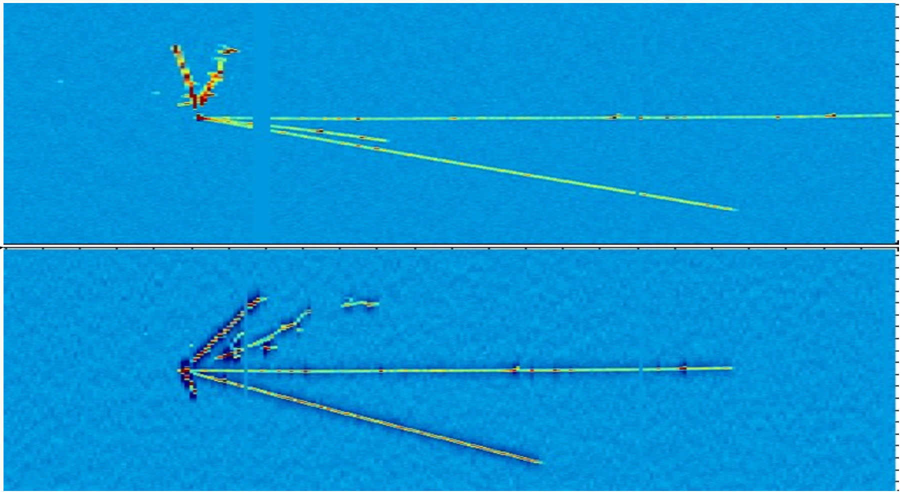



Recall that I have done this process for both startpoints and endpoints for every cluster

This means I have to do some bookkeeping to make sure I remove duplicate entries ***(details in the backups)***

Now I need to assess how strong of a candidate each found 3d/2d vertex found

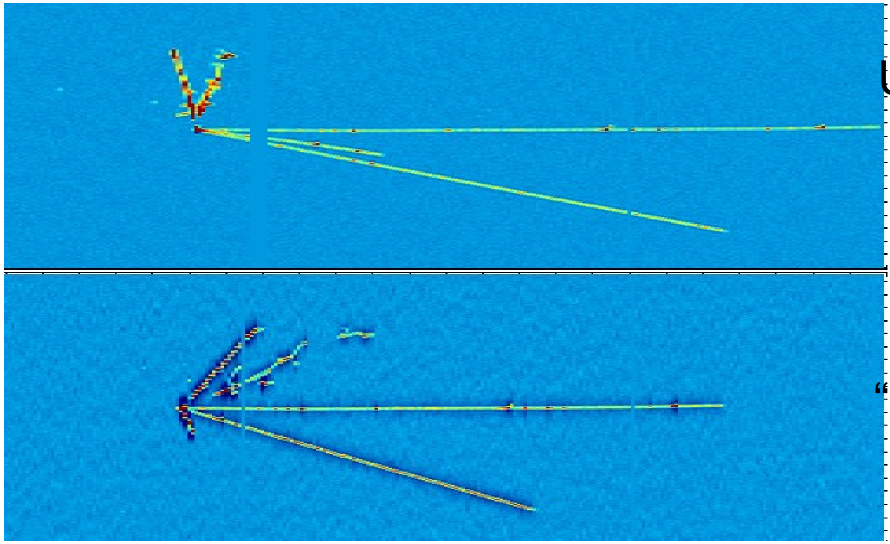
**To do this I come back to the image techniques employed in CornerFinderAlg**



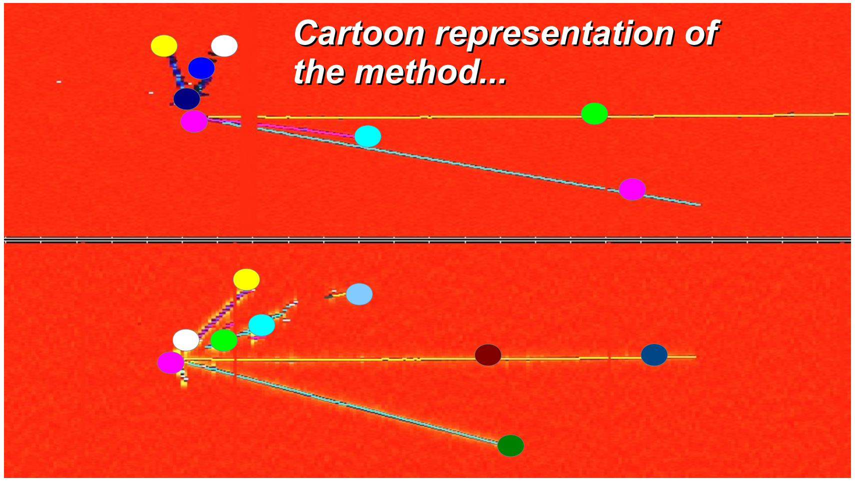
# Feature Vertex Finder

## *CornerFinder*

***Lots more details about the CornerFinder have been given by W. Ketchum and can be found***
***https://cdcvs.fnal.gov/redmine/attachments/download/9953/CornerFinderIntro.pdf &***
***https://indico.fnal.gov/getFile.py/access?contribId=1&resId=0&materialId=slides&confId=6845***
***and another example of it being used by B. Jones for tracks can be found***
***https://indico.fnal.gov/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=6845***



Using the image techniques described elsewhere ***(see back-up slides)*** I find the 2-d "corner features" in each plane




This technique finds **lots** of 2d corner points (wire & time) in each plane

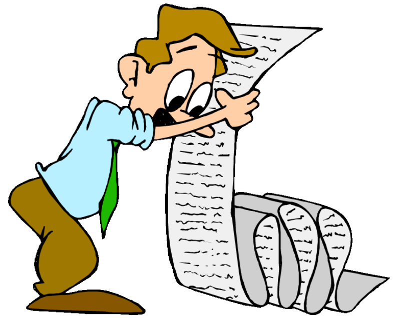
Now I loop over all the corner points in each plane and similar to before keep only the corner points that match in Wire and Time
***(note: I also record the 3d matched feature points strength as defined by the CornerFinderAlg...this is important for later)***

This gives me a list of 2d/3d corner point vertices (x, y, z)

# Feature Vertex Finder

## *A tale of two lists*

2d/3d Corner Verticies



2d/3d Cluster Verticies

- Now what I have is two lists of 2d/3d vertex candidates found from two different methods
  - What comes next depends on the length of the cluster vertex list and the proximity in centimeters (in x, y, z) of the verticies from the different lists

***Nitty gritty details can be found in the back-up slides, but everything follows this rough prescription***

**0) All vertex candidates start with a strength equal to zero**

**1) Loop over the cluster vertex list and merge a 3d vertex that is within 1.5 cm of another vertex in x, y, and z (has to satisfy all three spatial directions)**

→ *When you merge two vertex candidates +1 to the vertex strength*

→ *Merging right now is the dumb (x+y)/2...needs to be improved*

**2) Take the merged cluster vertex list and compare it to the corner vertex list.**

→ *If there is a corner vertex within 3 cm in x, y, and z of the cluster vertex add +1 to the strength*

→ *I do not merge these vertex candidates...I just use them to add weight to the found cluster vertex*

**3a) If you have > 0 proto-verticies, record all of them**

→ *EndPoint2d (TimeTick, geo::WireID, strength, Vtx #, View, Total Charge not used)*

→ *Vertex ( xyz, Vtx #)*

**3b) If you have exactly 0 vertex candidates use a bail/recover method**

→ *More on the next slide*

# Feature Vertex Finder

## *Bailout*


So if somehow after looking for a cluster vertex and/or a corner vertex we still haven't found at least one 3d proto-vertex we employ a series of bail out tactics

***Note: All these verticies will have strength 0 or 1***

**Bail Out Strategy 1:**

Take the start point and end point of the longest cluster in each plane and try to match this 2d point to a corresponding 3d corner point projected down into the plane (if it matches to many 3d feature points use the strongest 3d feature point).

→ If you find a match take the strongest point and construct a 2d/3d proto-vertex from the 3d feature point (this way I can have a point in all planes that is consistent) ***strength 1***

**Bail Out Strategy 2 (only used if strategy 1 fails):**

Take the strongest 3d feature point found and project it down into 2d

→ Take this point and construct a 2d/3d proto-vertex ***strength 0***

**Bail Out Strategy 3 (only used if strategy 1 & 2 fails):**

Take the start point of the longest cluster in each plane as the 2d vertex (regardless of if they match between views)

→ Use geometry to find the nearest 3d point between the planes ***strength 0***

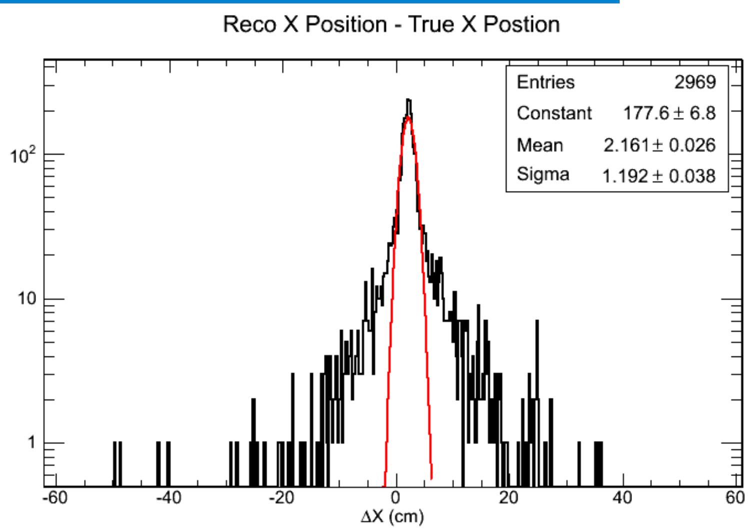
# Preliminary Performance Plots

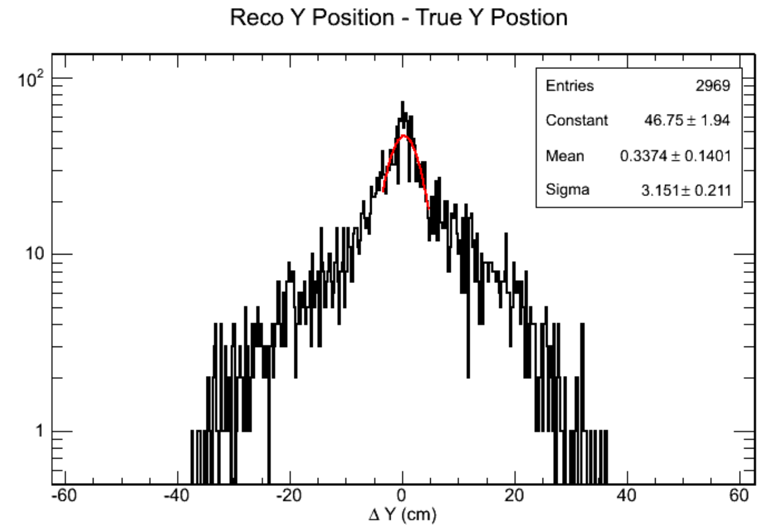
**How well does FeatureVertexFinder do?**

**→ Look at 400 genie events generated in ArgoNeuT**

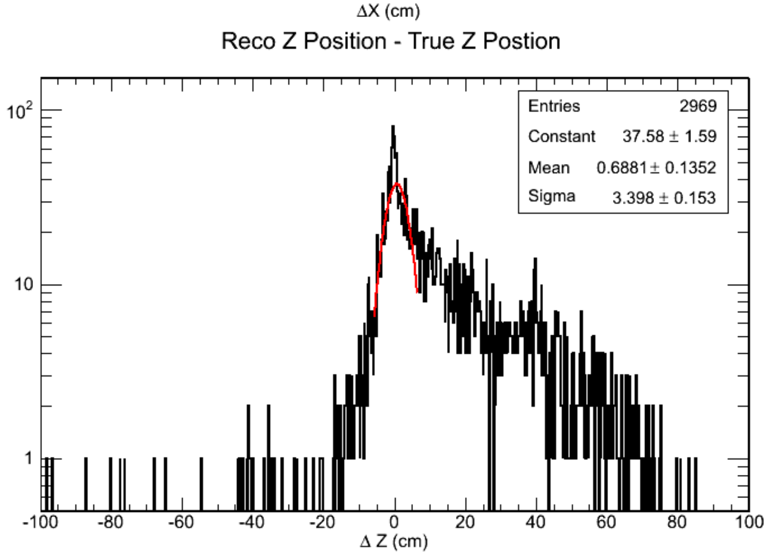
- Reconstructed: GausHitFinder → dBCluster→HoughLineFinder→**LineMerger**

**All reconstructed verticies**




**See backup slides for more plots from the "all reconstructed" sample**

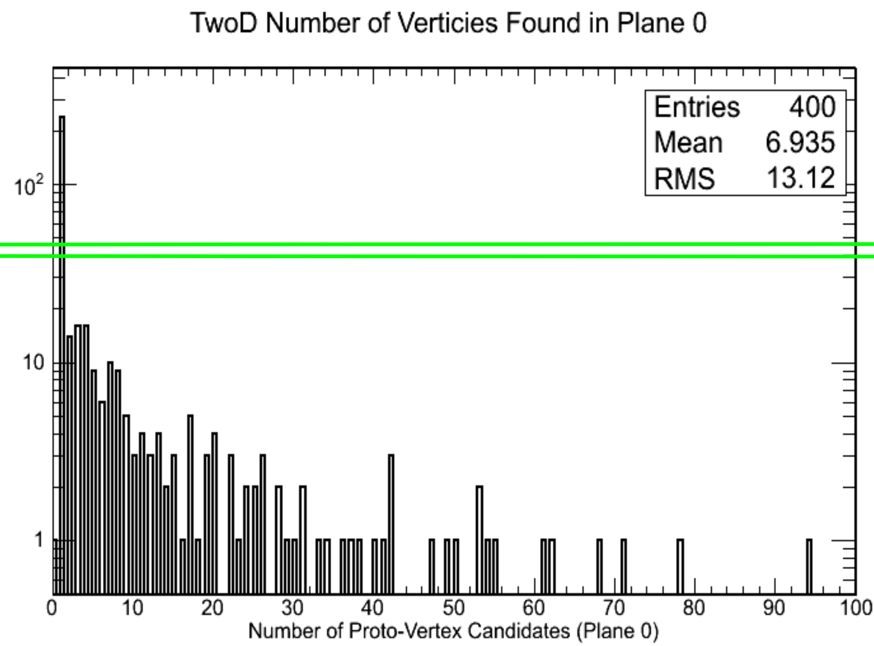



**Question**: Why do things look so bad?

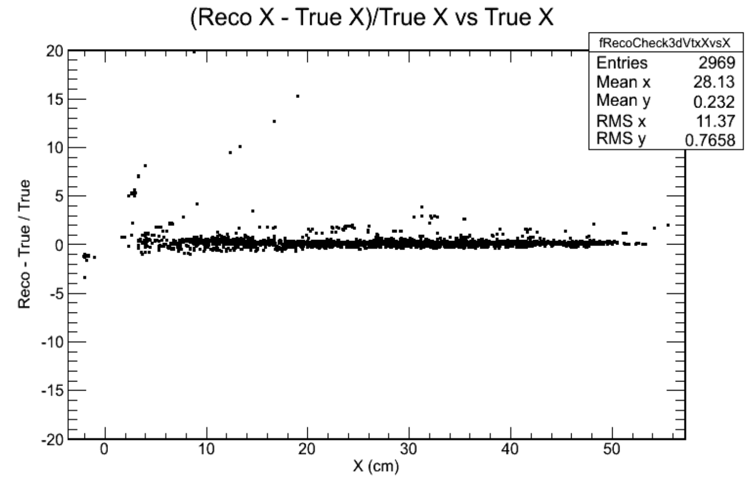
**Answer**: Remember that this is for all reconstructed proto-vertex candidates

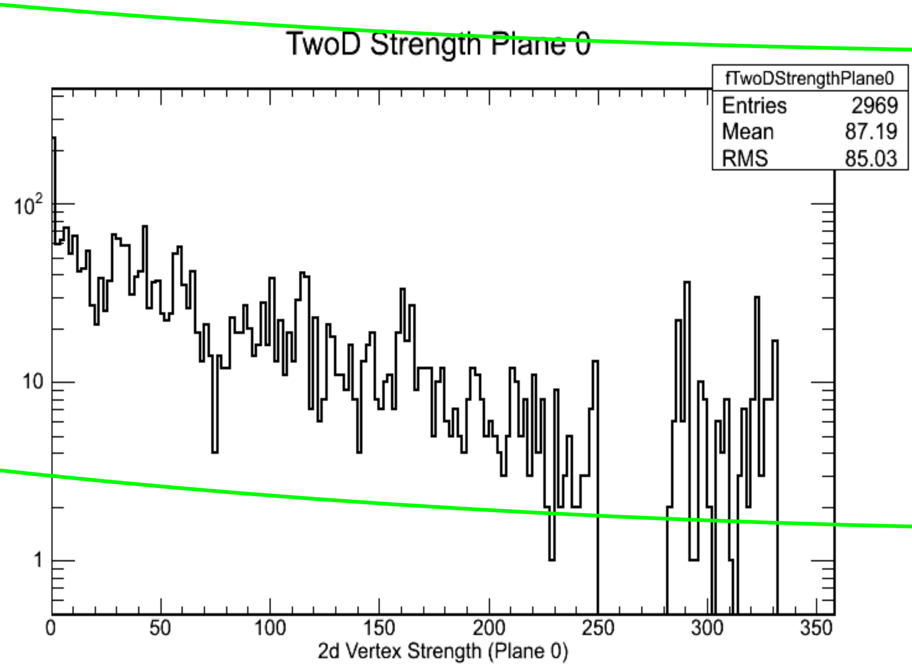
(~ 7.5 candidates per event for this sample)

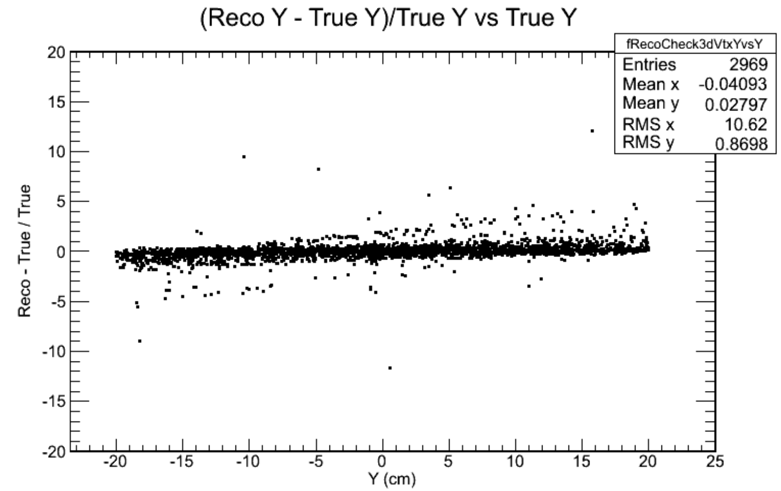
# Preliminary Performance Plots

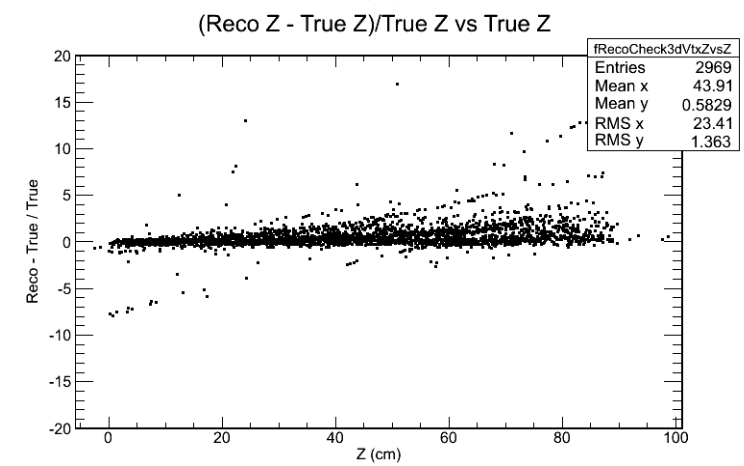



**Actually, not all that bad...**



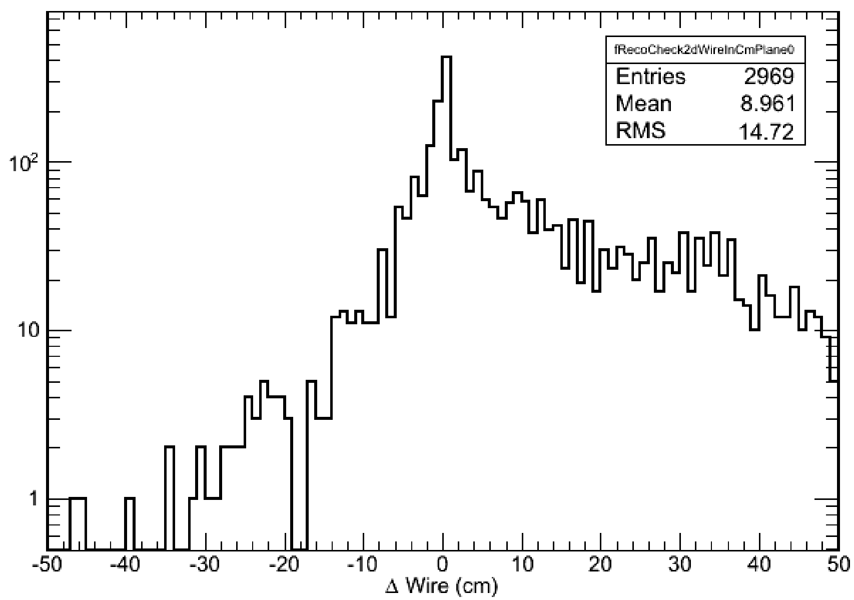



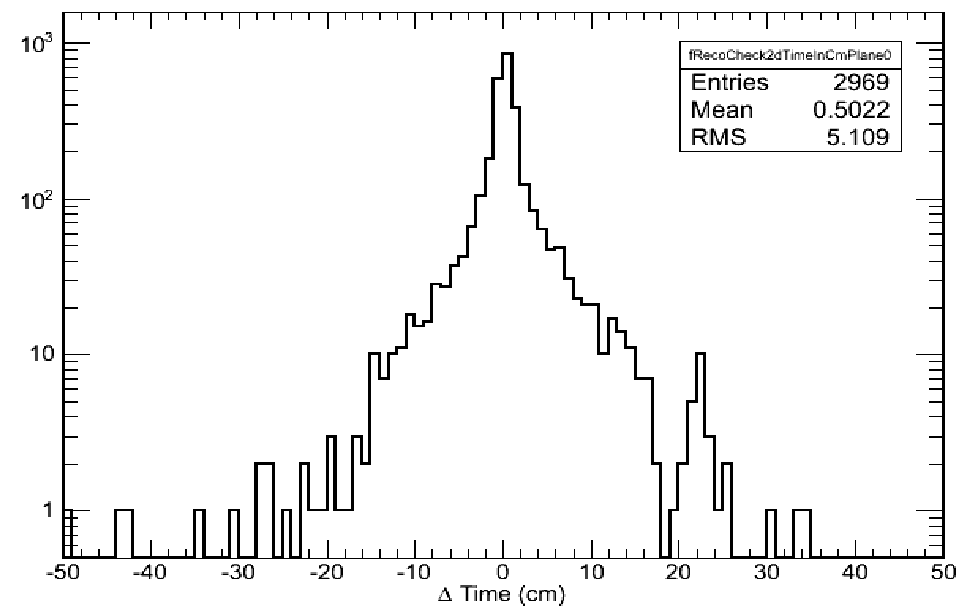



# Preliminary Performance Plots

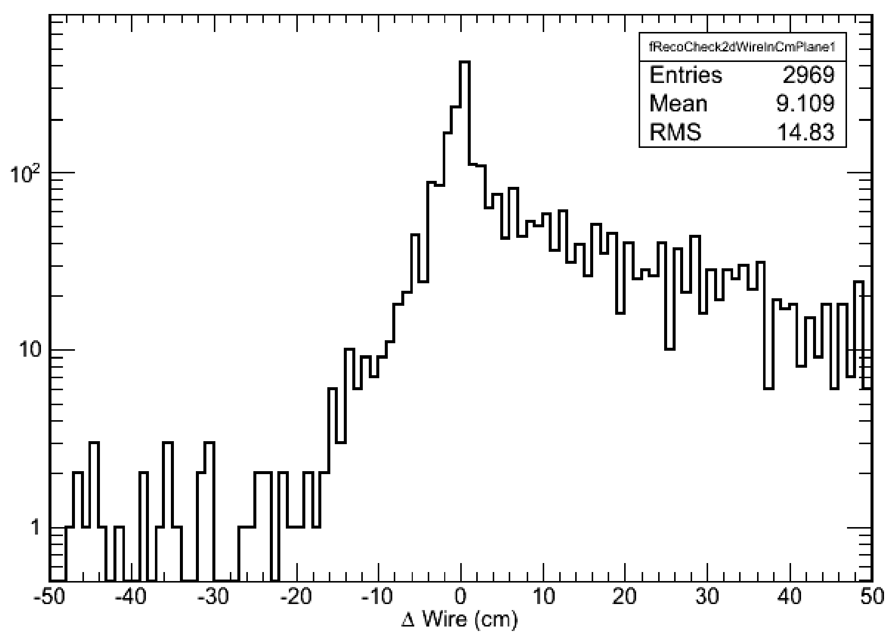
Reco Wire in CM - True Wire in CM Plane 0



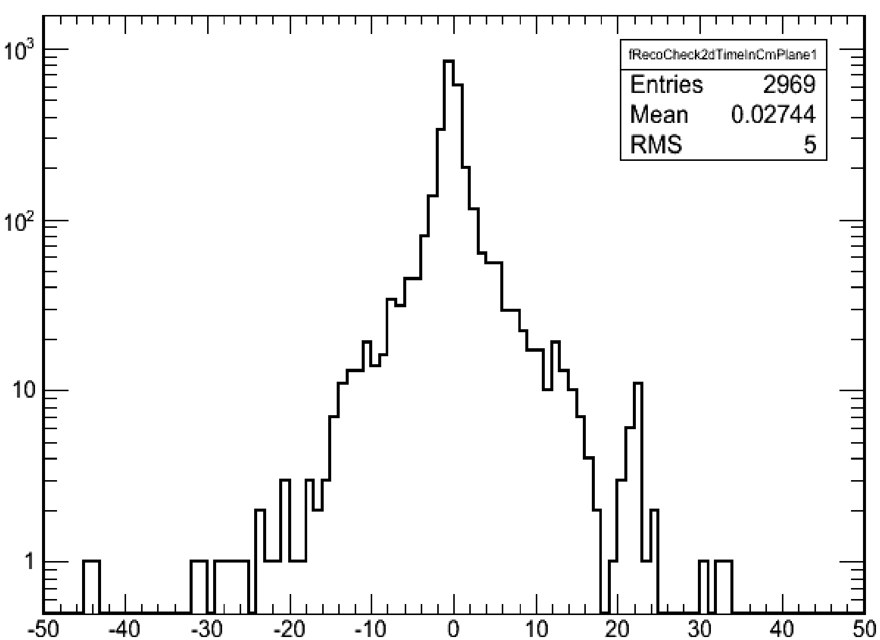

Reco Time in CM - True Time in CM Plane 0




Reco Wire in CM - True Wire in CM Plane 1

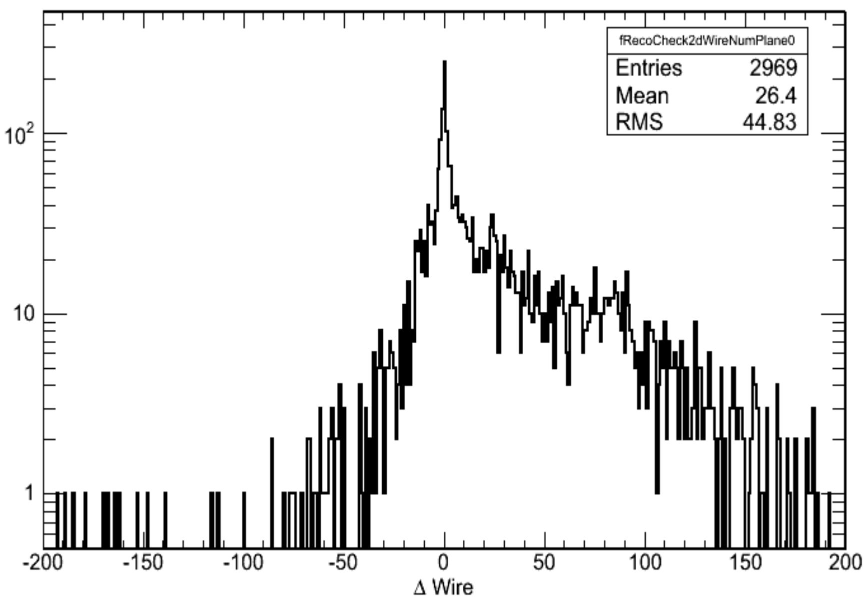



Reco Time in CM - True Time in CM Plane 1

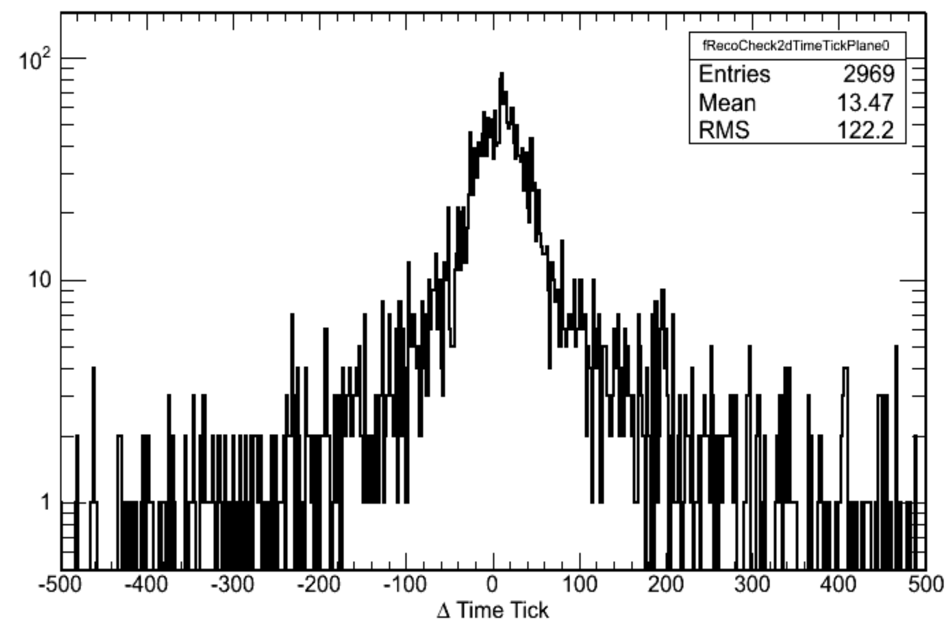


# Preliminary Performance Plots

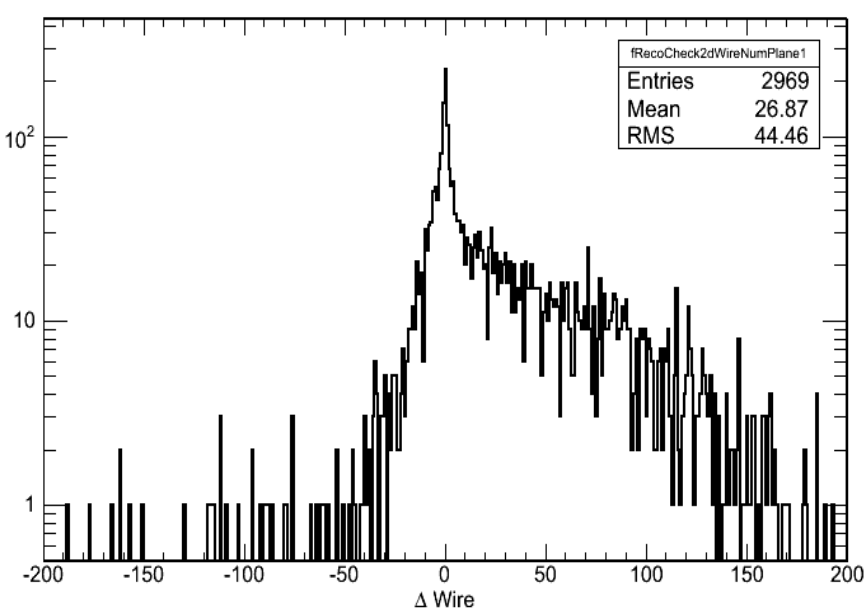
Reco Wire Number - True Wire Number Plane 0



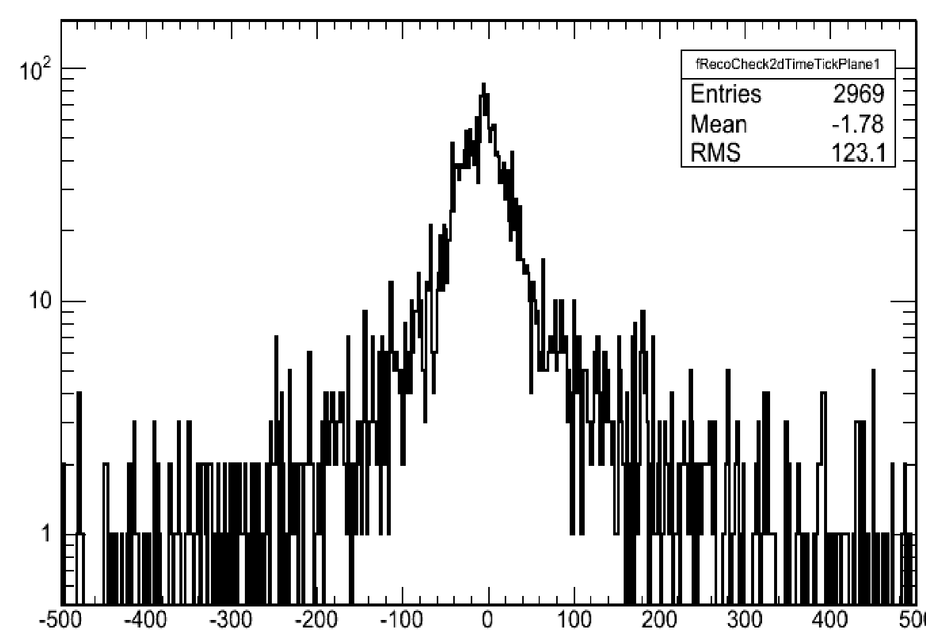

Reco Time Tick - True Time Tick Plane 0



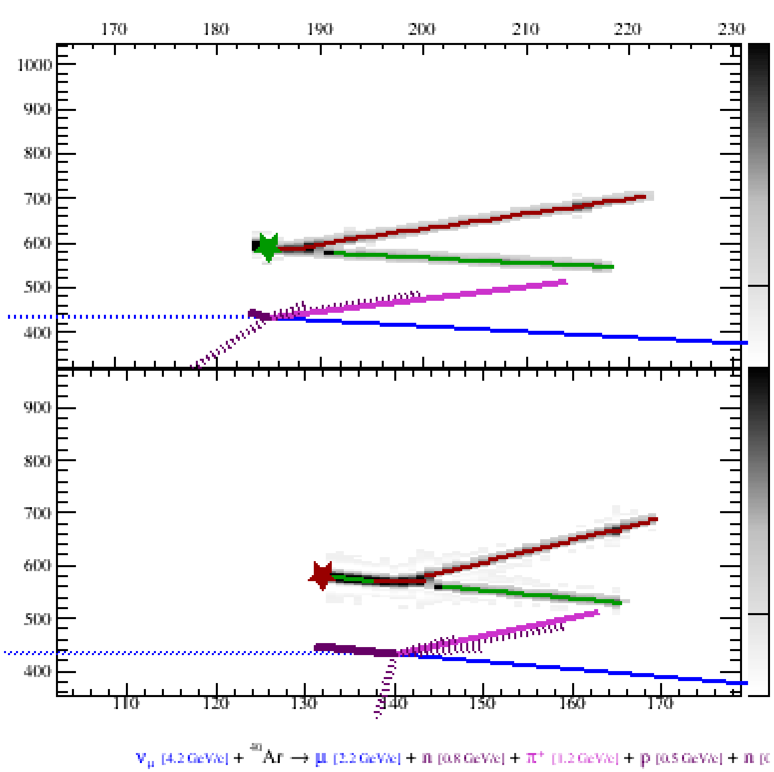

Reco Wire Number - True Wire Number Plane 1



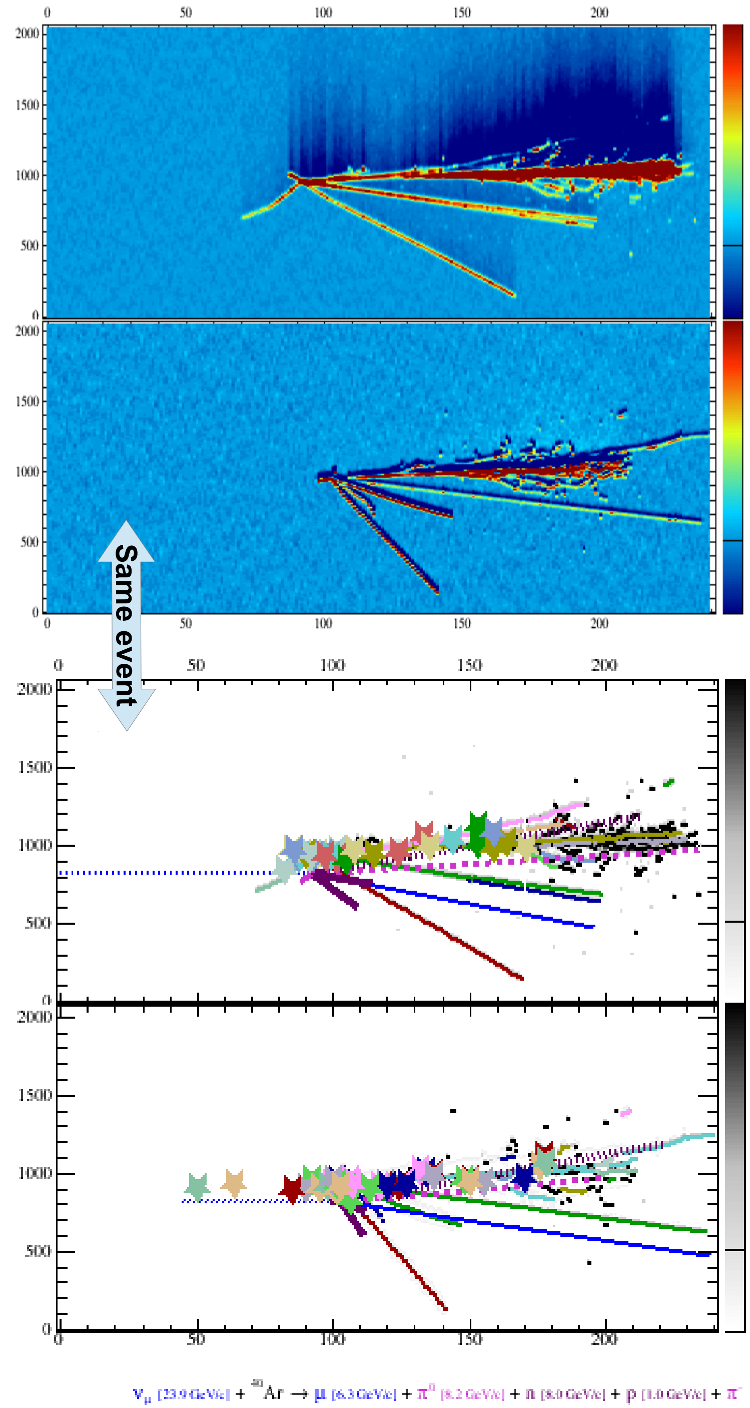

Reco Time Tick - True Time Tick Plane 1



# Taste of everything we find...



It's true that we do find the primary vertex in nice simple events like this one




But there are also events like this where we find **lots** of proto-verticies

Don't want to throw away this information
→ Some of this is a function of what clustering algorithm you chose

→There is information in this that tells we likely have a shower in this event