



# Final State Nucleon Reconstruction in LArTPC

Tingjun Yang (FNAL)

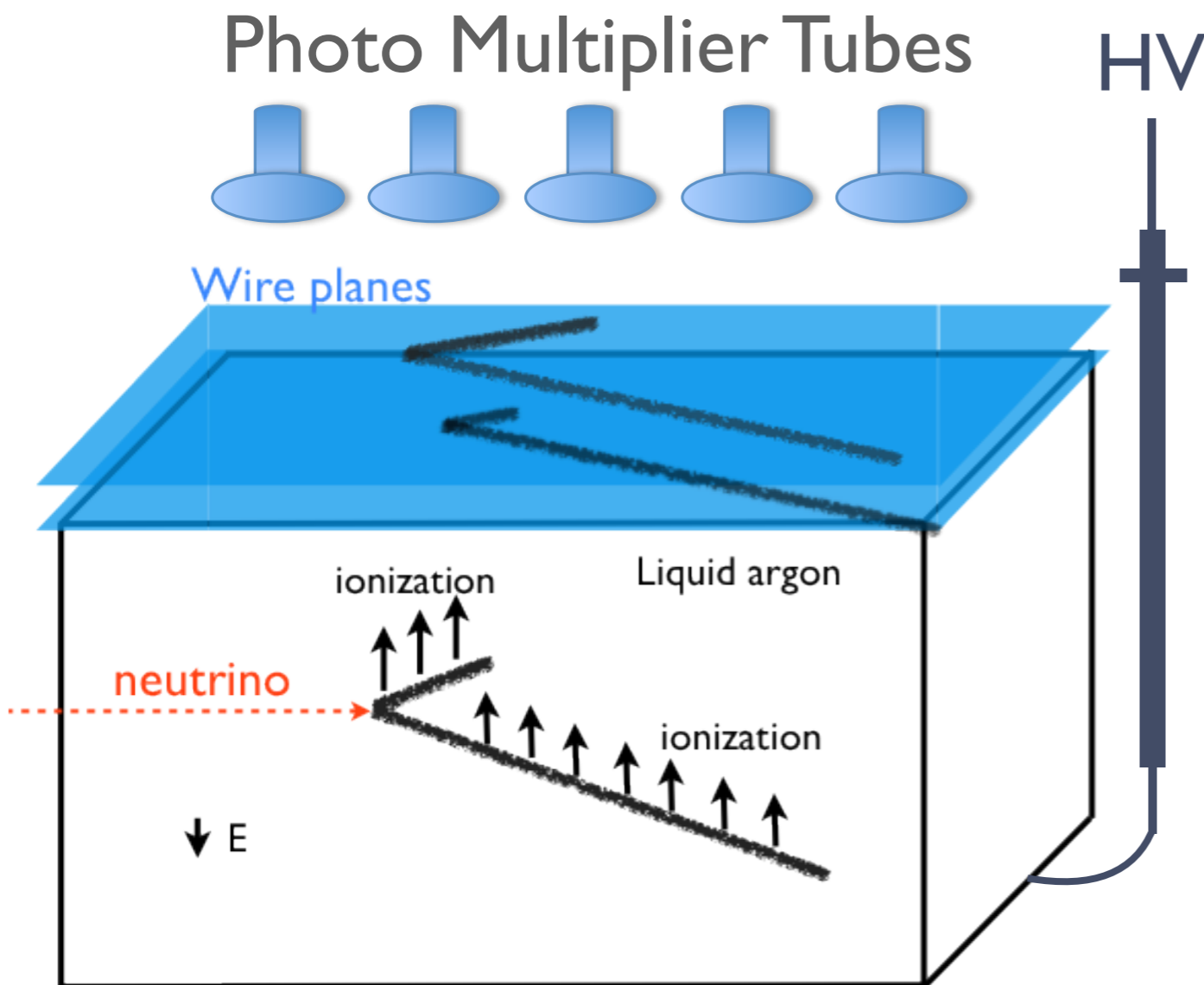
January 19, 2017

# Outline

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- LArTPC introduction.
- Experiences from LArTPC experiments on final state nucleon reconstruction.
  - ArgoNeuT
  - MicroBooNE
  - LArIAT
  - SBND

# LArTPC concept



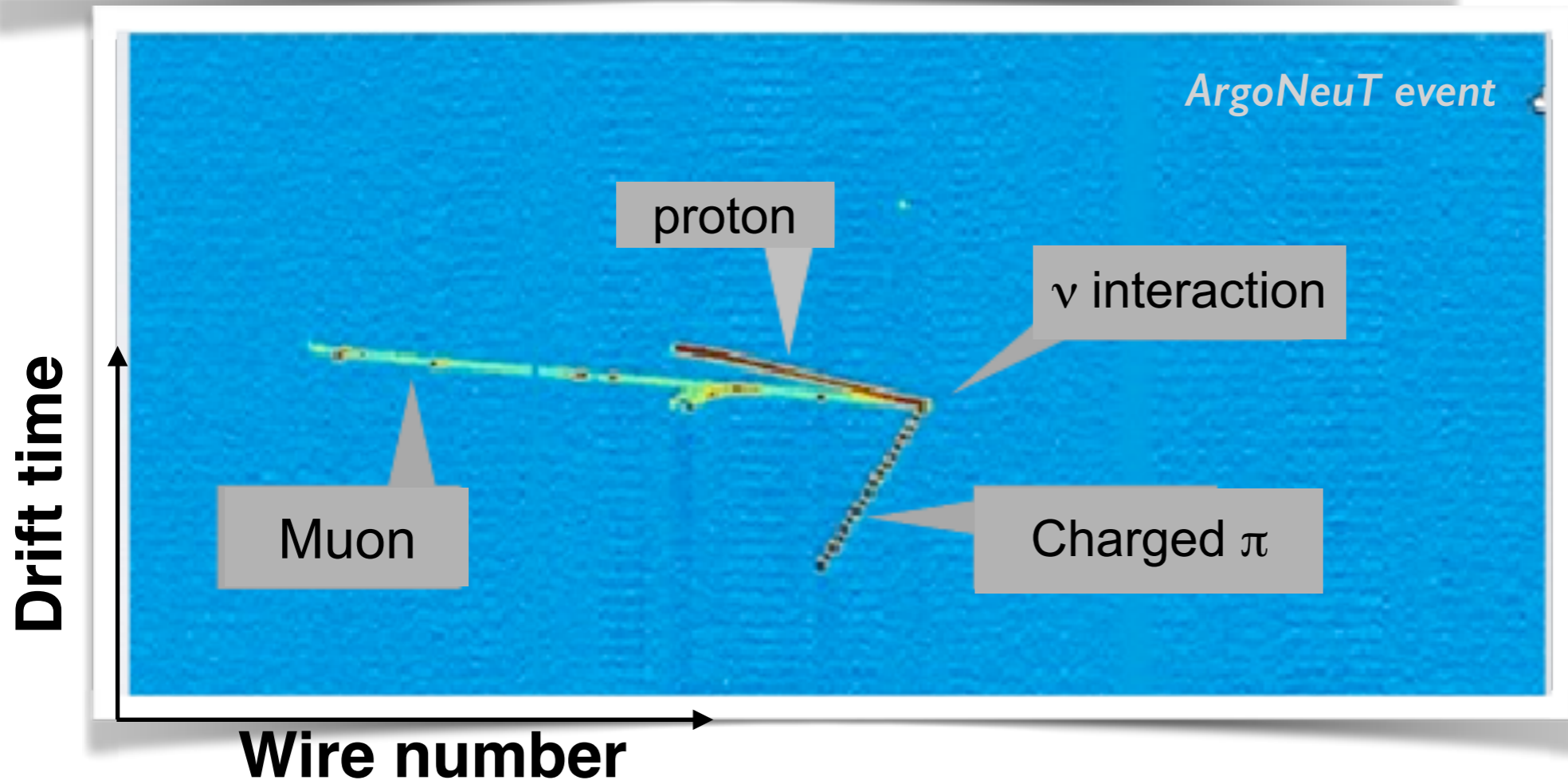
- High voltage provides electric field.
- Ionization electrons drifted by electric field and read out by wire planes.
- Scintillation light recorded by PMT provides trigger information.

# LAr TPC and Exclusive topologies

## LAr TPC detectors

- provide *full 3D imaging, precise calorimetric energy reconstruction and efficient particle identification* and
- allow for **Exclusive Topology recognition/reconstruction** and **Nuclear Effects exploration** from detailed studies of the **hadronic** part of the final states.

***LAr TPC is an Ideal detector for Few-GeV  $\nu$  scattering measurements***



# ArgoNeuT experiment in the NUMI Beam

## First LAr TPC in a neutrino beam in the US

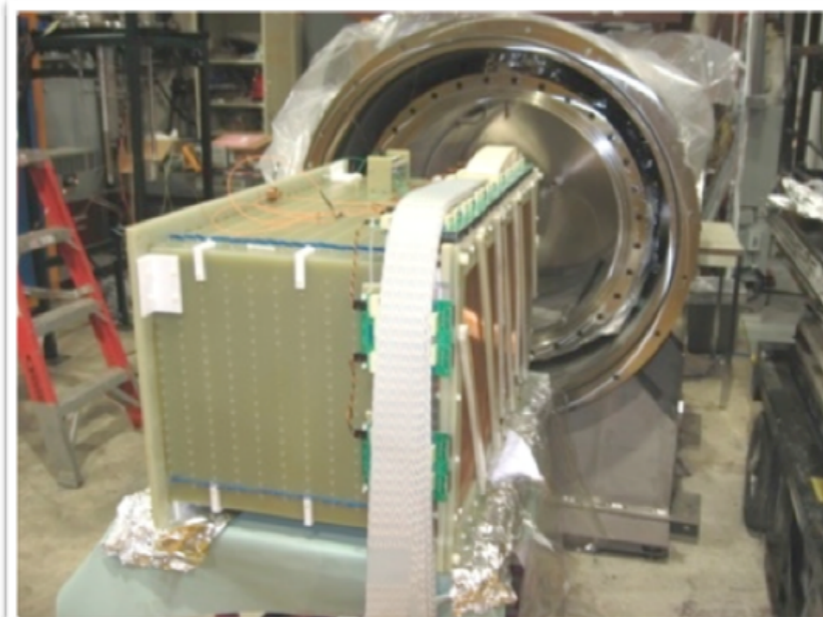
First LArTPC in a low (1-10 GeV) energy neutrino beam

Acquired  $1.35 \times 10^{20}$  POT, mainly in  $\bar{\nu}_\mu$  mode

240 kg active volume

LAr TPC

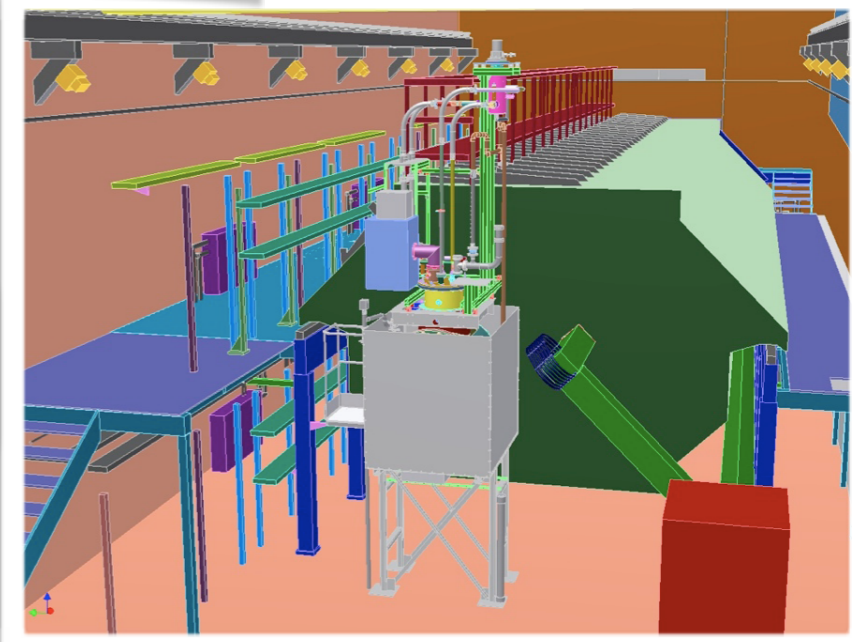
$47 \times 40 \times 90$  cm<sup>3</sup>, 2 readout planes,  
480 wires, 4 mm spacing,  
no light detection system



*C. Anderson et al., JINST 7 (2012) P10019*

MINOS ND as muon spectrometer  
for ArgoNeuT events\*

*\*ArgoNeuT Coll. is grateful to MINOS Coll. for providing the  
muon reconstruction*

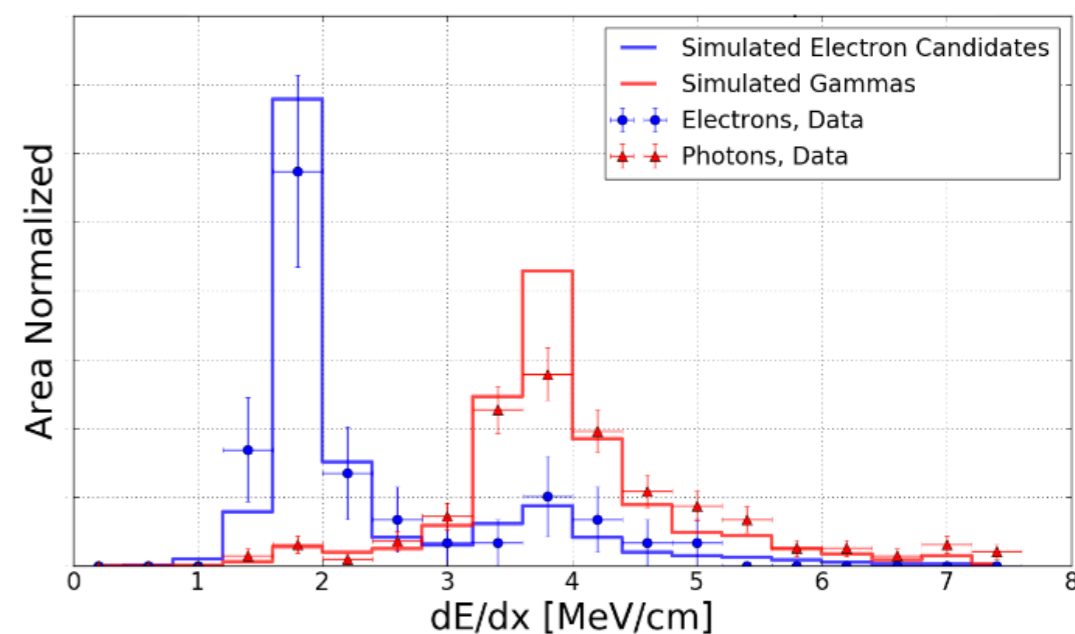


Designed as test experiment  
but obtaining physics results!

~7000 CC events  
collected

***Largest data sample of  
[low energy]  
neutrino interactions in  
LArTPC***

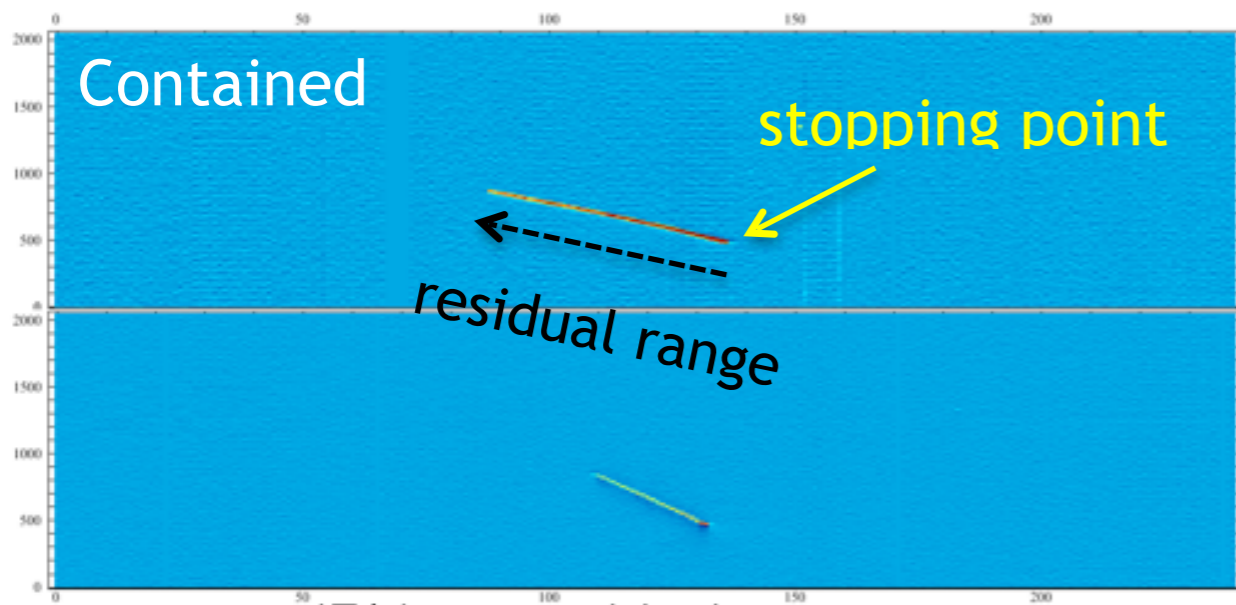
**New result:**  
**Electron neutrinos in LArTPC**



<https://arxiv.org/abs/1610.04102>

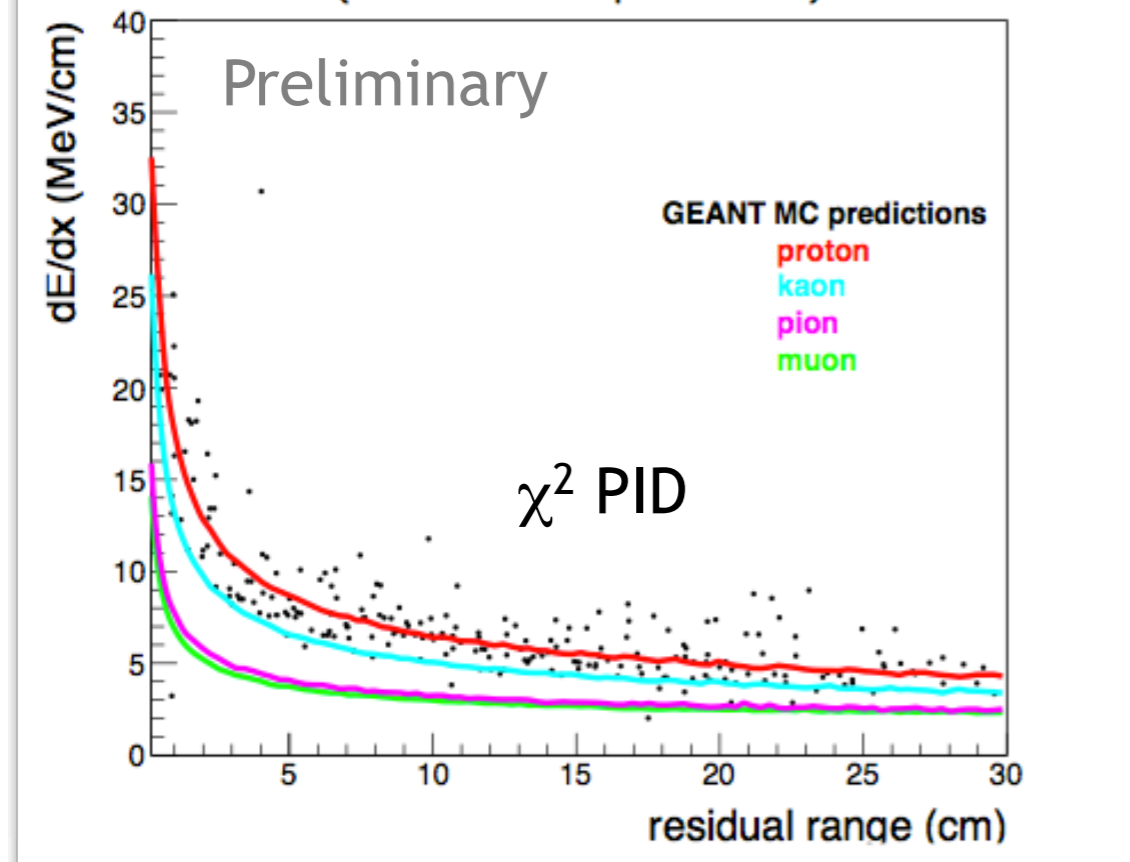
Publications so far:  $\nu$ -Ar cross sections measurements, LAr TPC calibration techniques and studies of nuclear effects in  $\nu$ -Ar interactions

# Calorimetric ParticleID

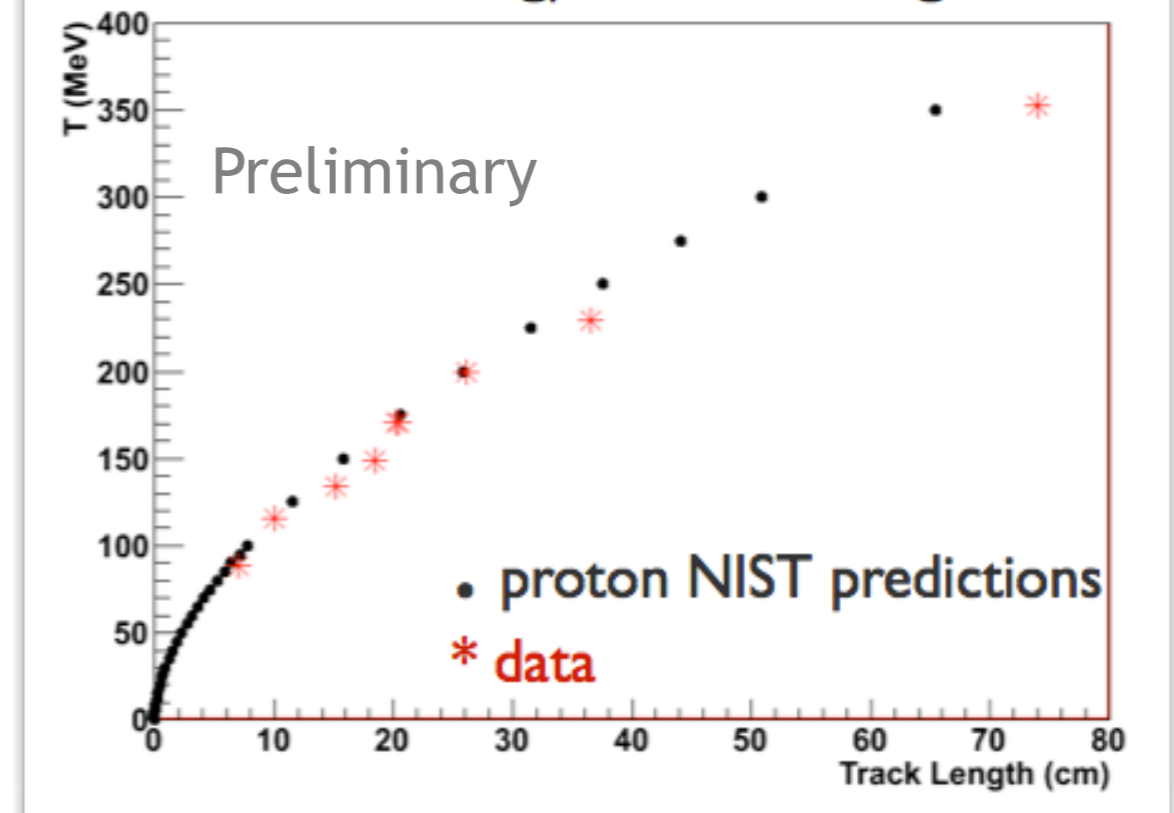


- Measurement of:
  - $dE/dx$  vs. residual range along the track
  - kinetic energy vs. track length

$dE/dx$  vs. residual range  
(contained protons)



Kinetic Energy vs. track length



*proton threshold:  $T_p > 21$  MeV (2 wires)*

# Looking for pion-less final states

*Select events with:*

- **1 muon** with the correct sign,
- **no pion** (10 MeV Kinetic energy threshold) and
- **any # of nucleons [proton(s)]**, fully contained in the Fiducial Volume (for PID) and above the energy threshold and any # of neutrons (undetected)]

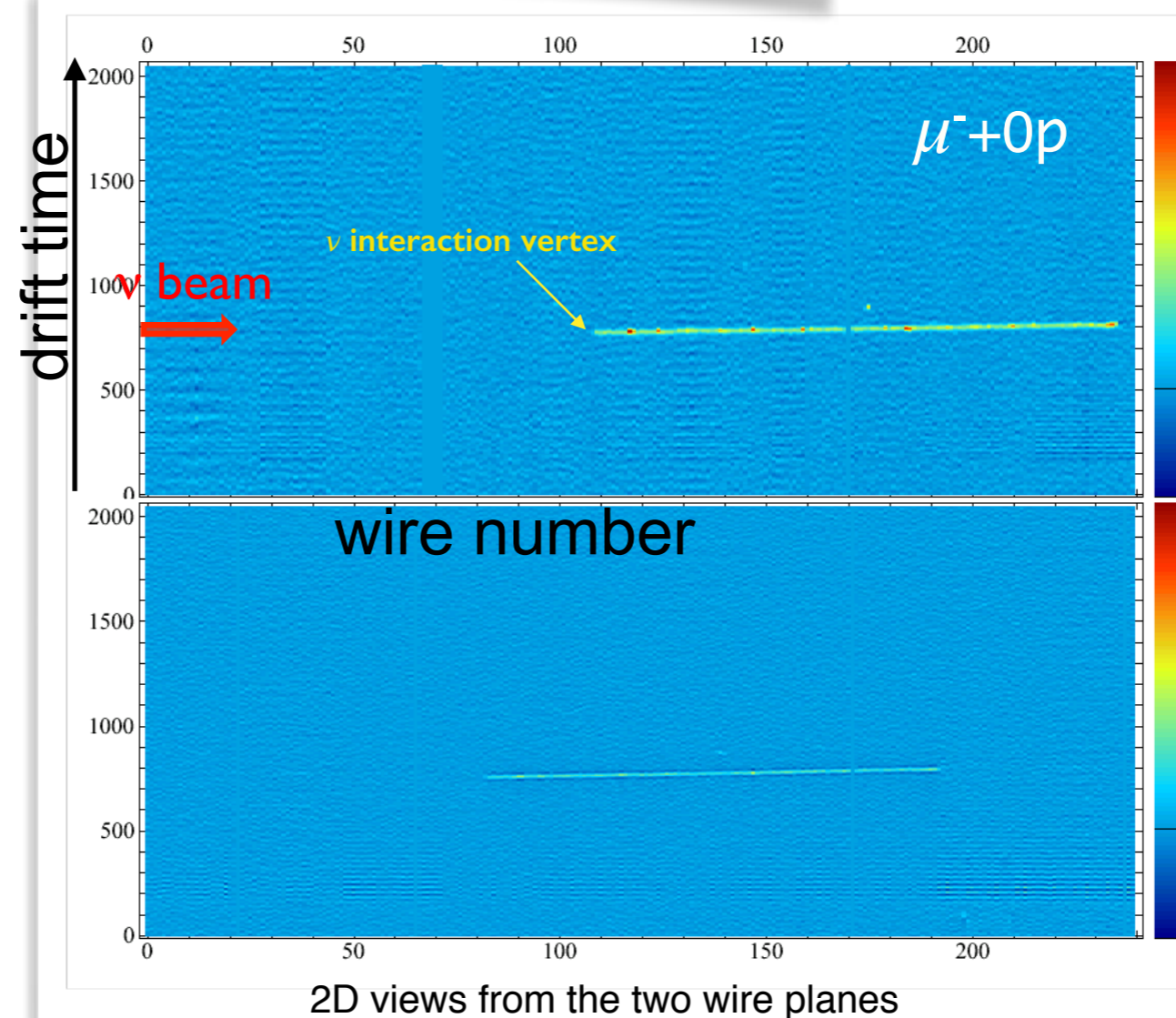
- Selection cuts (fully **automated reconstruction**)
- **Automated reconstruction** of the **muon** (geometrical and calorimetry)
- **Semi-automated** reconstruction of the **proton(s)** at the interaction vertex: **Visual Scanning** (hit selection) and **automated reconstruction** (geometrical, calorimetry and PiD).
  - Efficiency of the automated reconstruction, detector acceptance, proton containment and backgrounds estimated from  $\nu_\mu$  CC 0 pion GENIE MC events.
  - Overall efficiency/acceptance for the  $(\mu+Np)$  sample is estimated to be  $\sim 50\%$  (neutrinos) and  $\sim 70\%$  (antineutrinos), **dominated by** the requirement of proton containment in the FV.

# Looking for pion-less final states

- Proton/pion separation through **energy deposition vs range** measurement
- Measurements of **proton multiplicity** at the neutrino interaction vertex and **reconstruction of proton(s) kinematics**

*LAr TPC is an Ideal detector for Few-GeV  $\nu$  scattering measurements*

*Low proton energy threshold  
(21 MeV Kinetic energy - ArgoNeuT)*



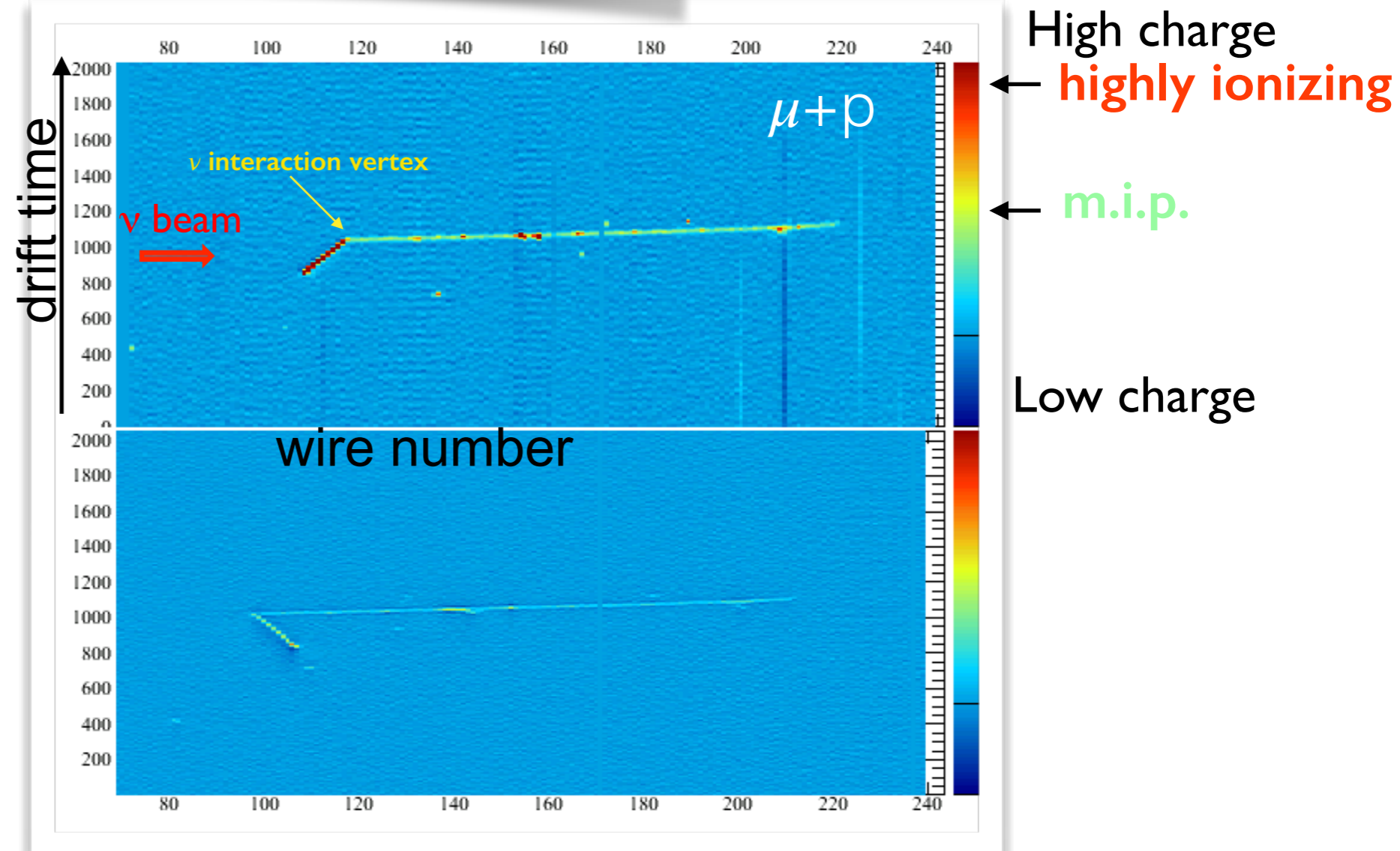
High charge  
← highly ionizing  
← m.i.p.  
Low charge

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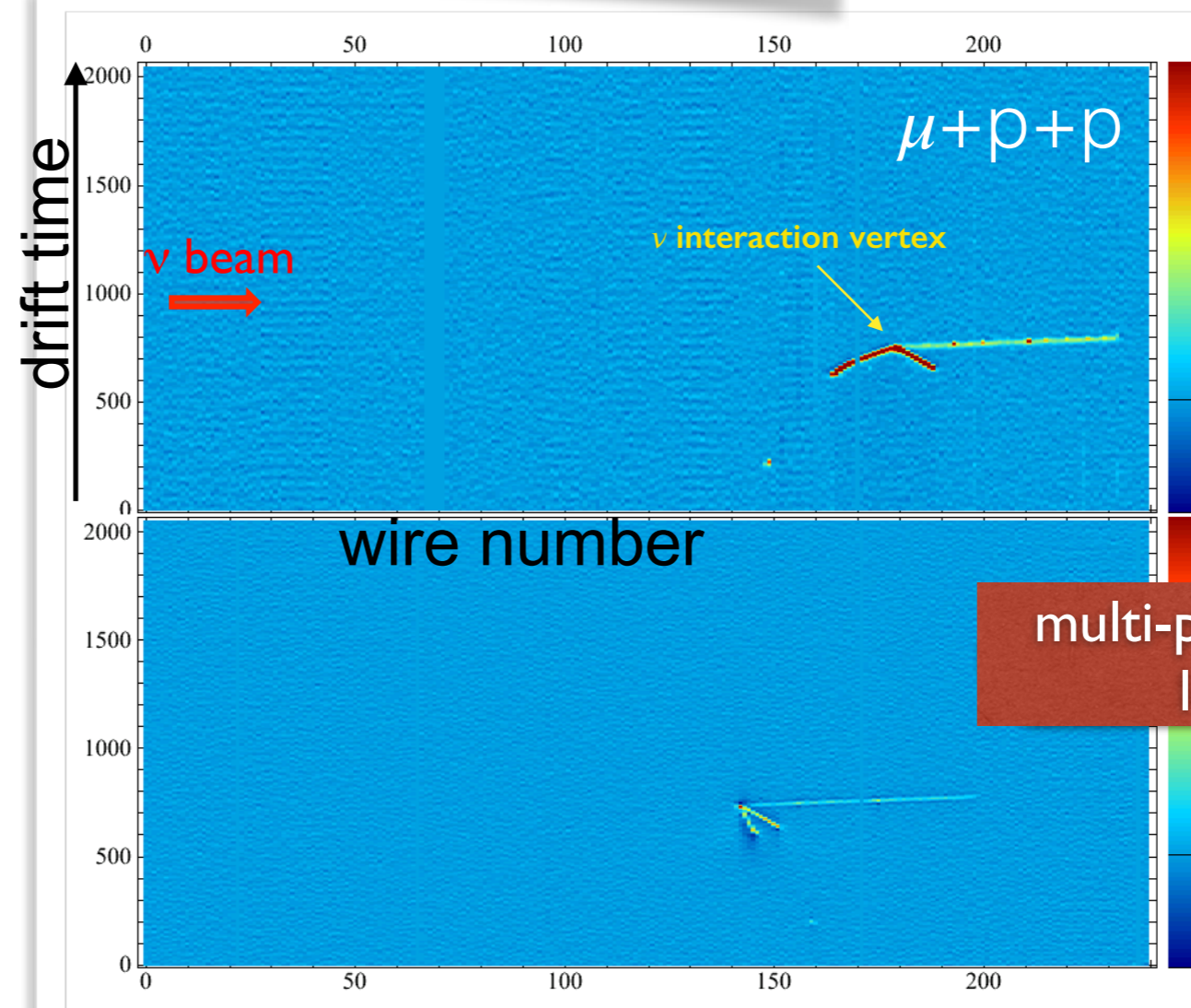


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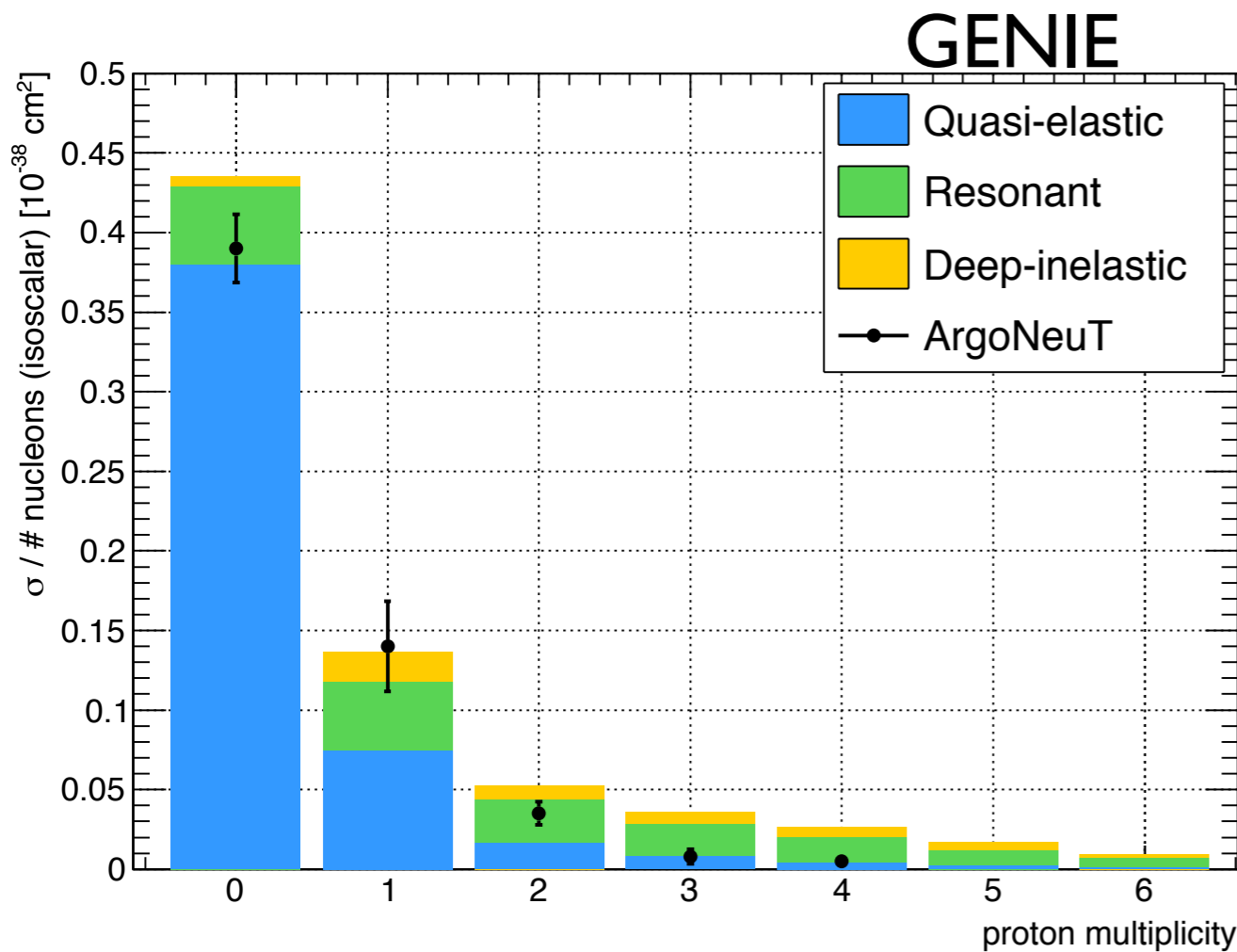
High charge  
← **highly ionizing**

← **m.i.p.**

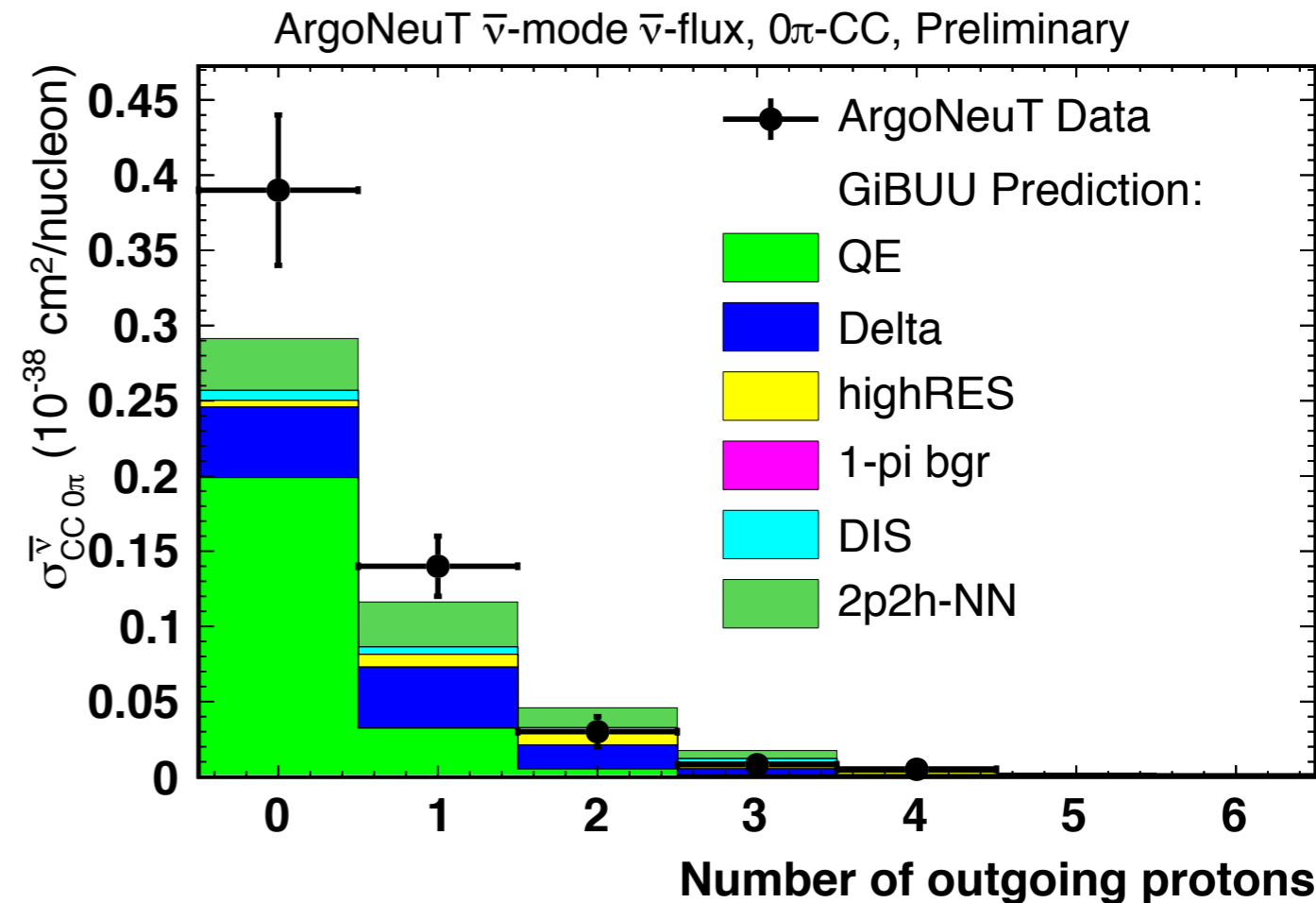
Low charge

multi-p accompanying the  
leading muon

# Exclusive neutrino cross sections Comparison with GENIE



$$\sigma_{CC0\pi} = 0.71 \text{ cm}^2/\text{nucleon}$$



$$\sigma_{0\pi}^{\bar{\nu}} = 0.48 \text{ } 10^{-38} \text{ cm}^2/\text{nucleon}$$

**GENIE MC**

**GiBUU**

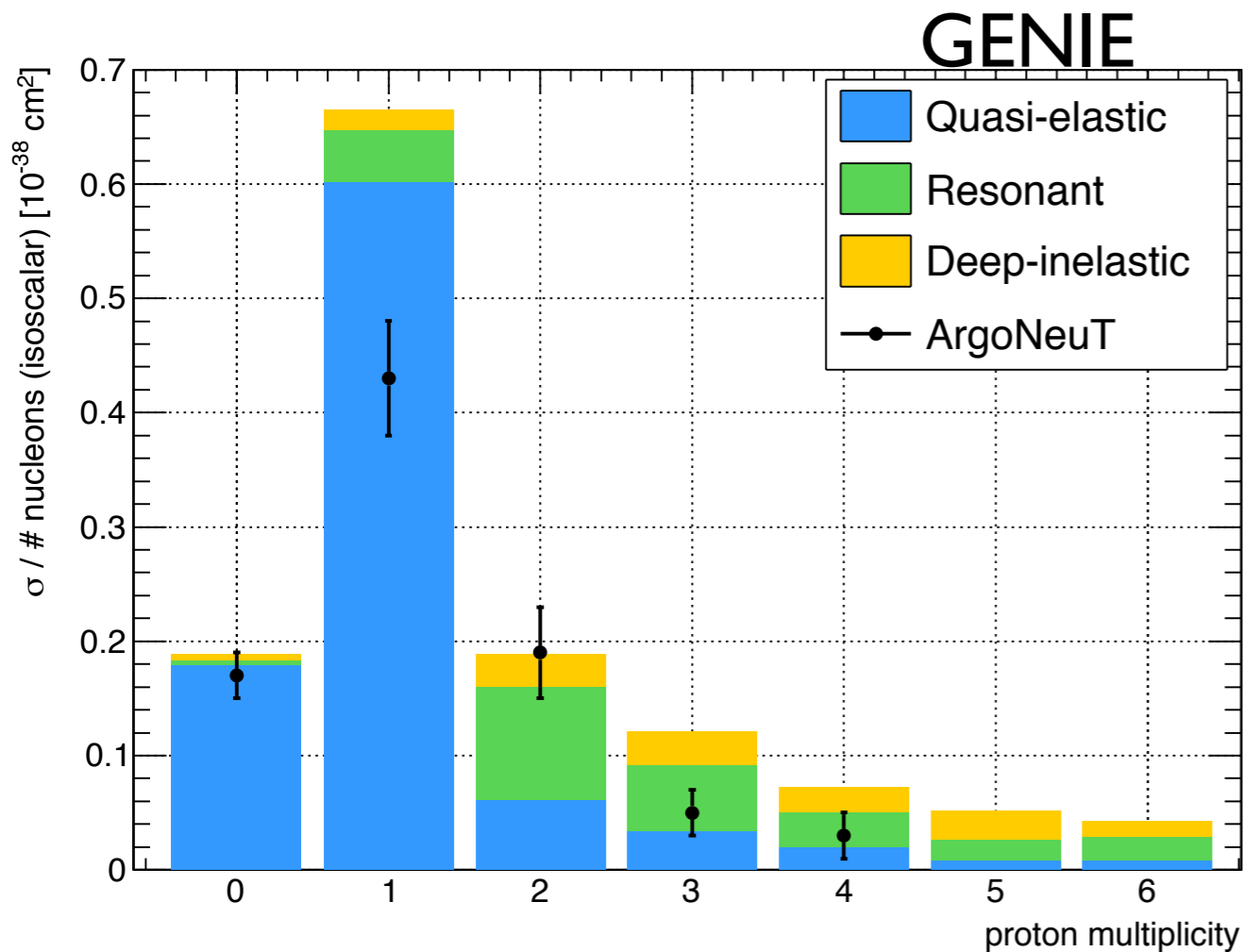
$$\sigma_{CC0\pi}^{\bar{\nu}} = 0.58 \pm 0.03(\text{stat.}) \pm 0.06(\text{syst.}) 10^{-38} \text{ cm}^2/\text{nucleon}$$

**ArgoNeuT data**

GENIE: 22% higher than data, large difference at high multiplicity

GiBBU: 17% lower than data, large difference at 0p

# Exclusive neutrino cross sections Comparison with GENIE



Comparison with GiBUU and  
NUWRO not yet available

$$\sigma_{CC0\pi} = 1.42 \text{ cm}^2/\text{nucleon}$$

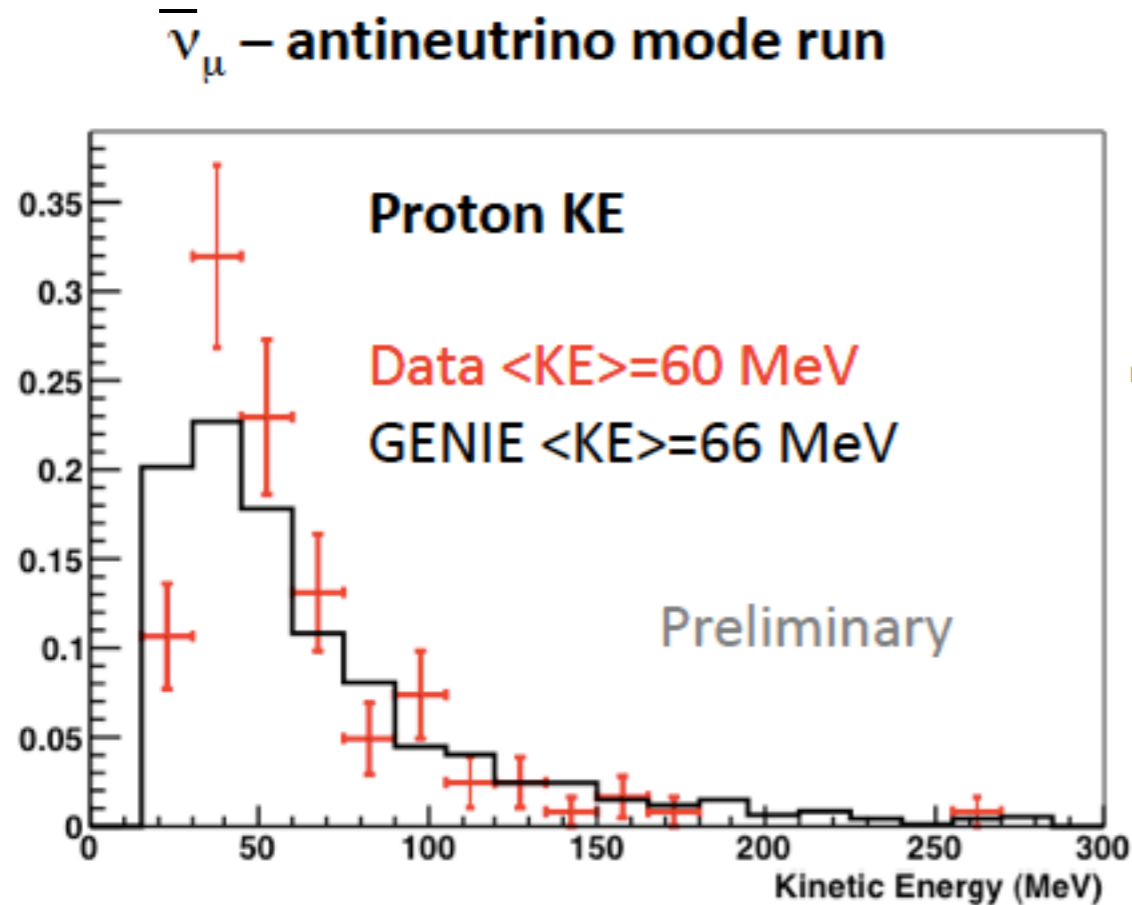
**GENIE MC**

$$\sigma_{CC0\pi}^{\nu} = 0.87 \pm 0.08(\text{stat.}) \pm 0.004(\text{syst.}) 10^{-38} \text{ cm}^2/\text{nucleon}$$

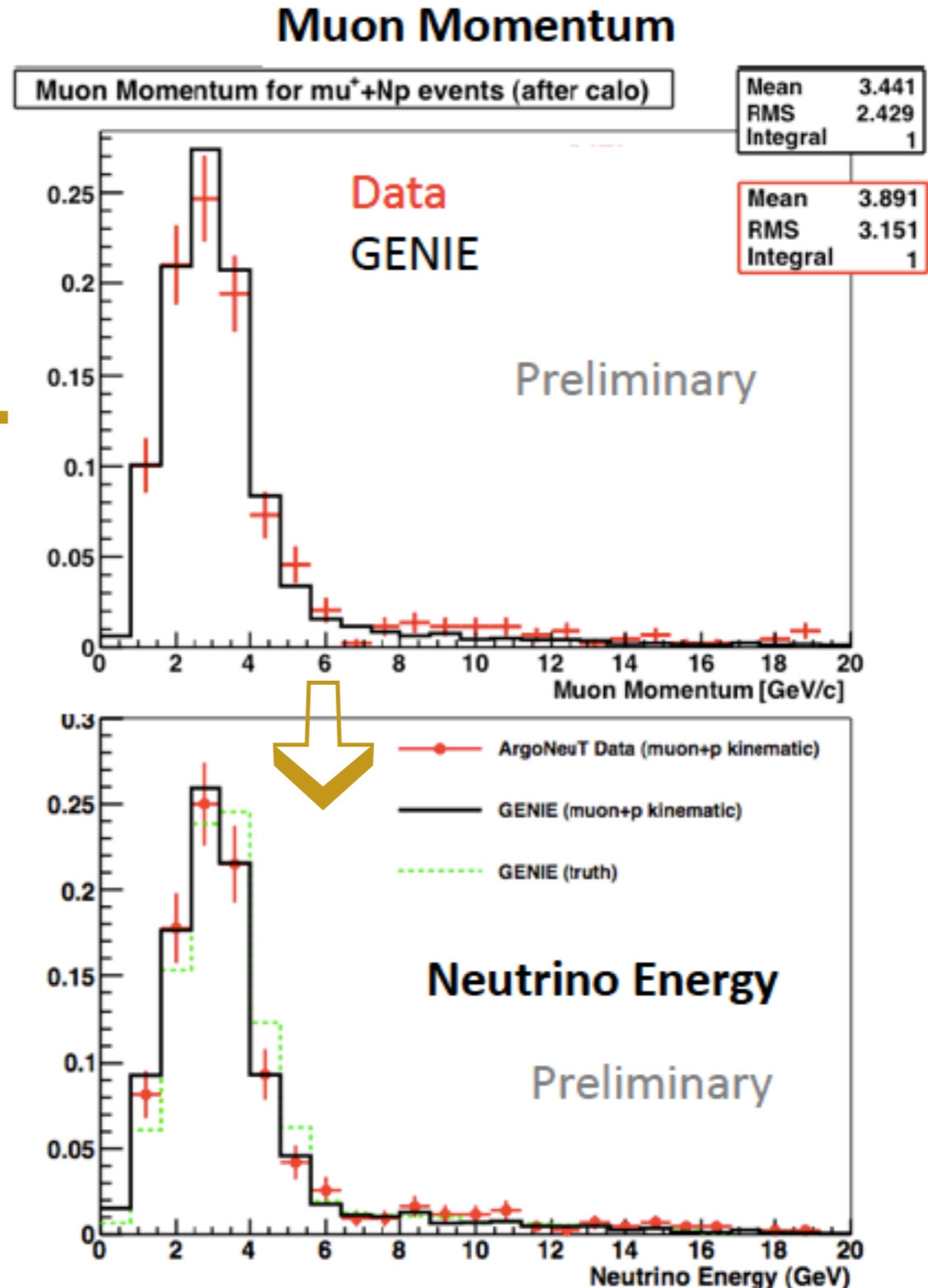
**ArgoNeuT data**

**GENIE: 64% higher than data, large difference at 1p and at high multiplicity**

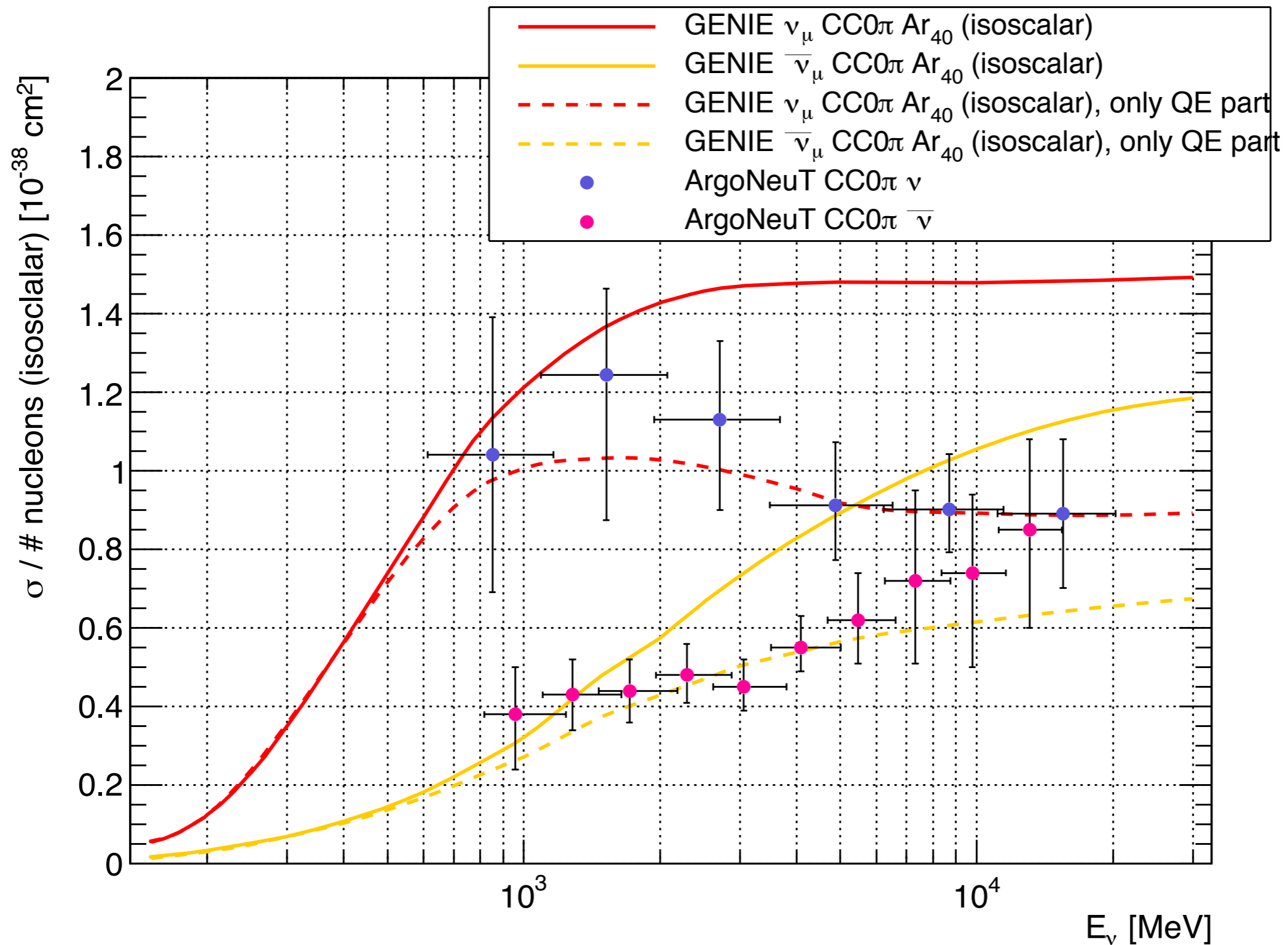
# Neutrino Energy Reconstruction



+



# Neutrino/Antineutrino cross sections comparison with GENIE

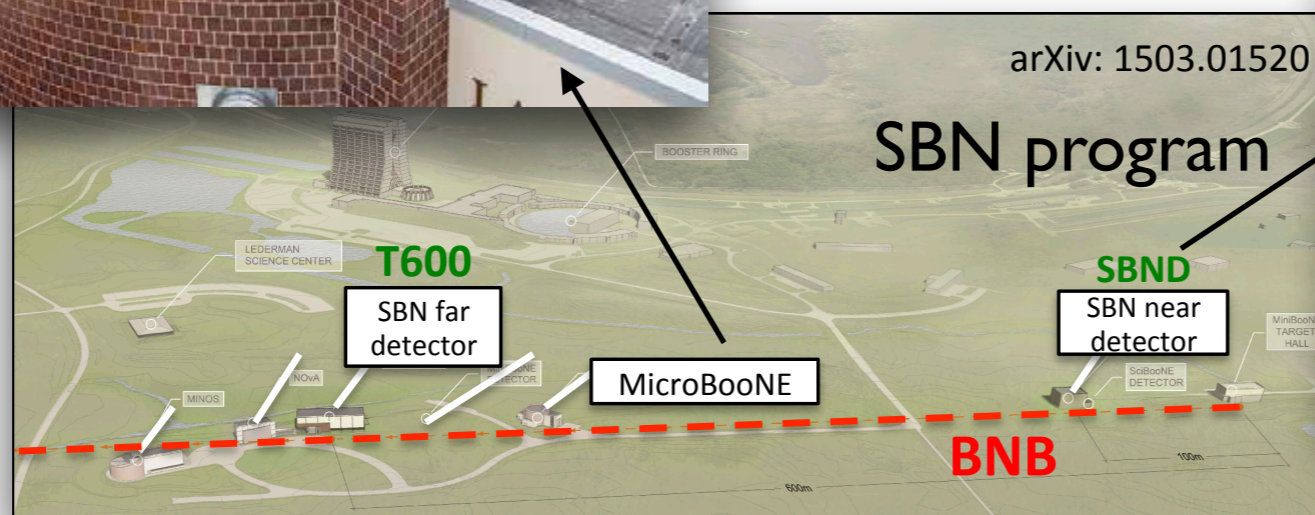


The statistics from ArgoNeuT events is very limited  
(~ 5 months run on the NuMI beam with a 240 Kg active volume LArTPC)

Current and Future LArTPC experiments: MicroBooNE and SBND  
(on the BNB beam @ FNAL, CC 0 pion dominant)

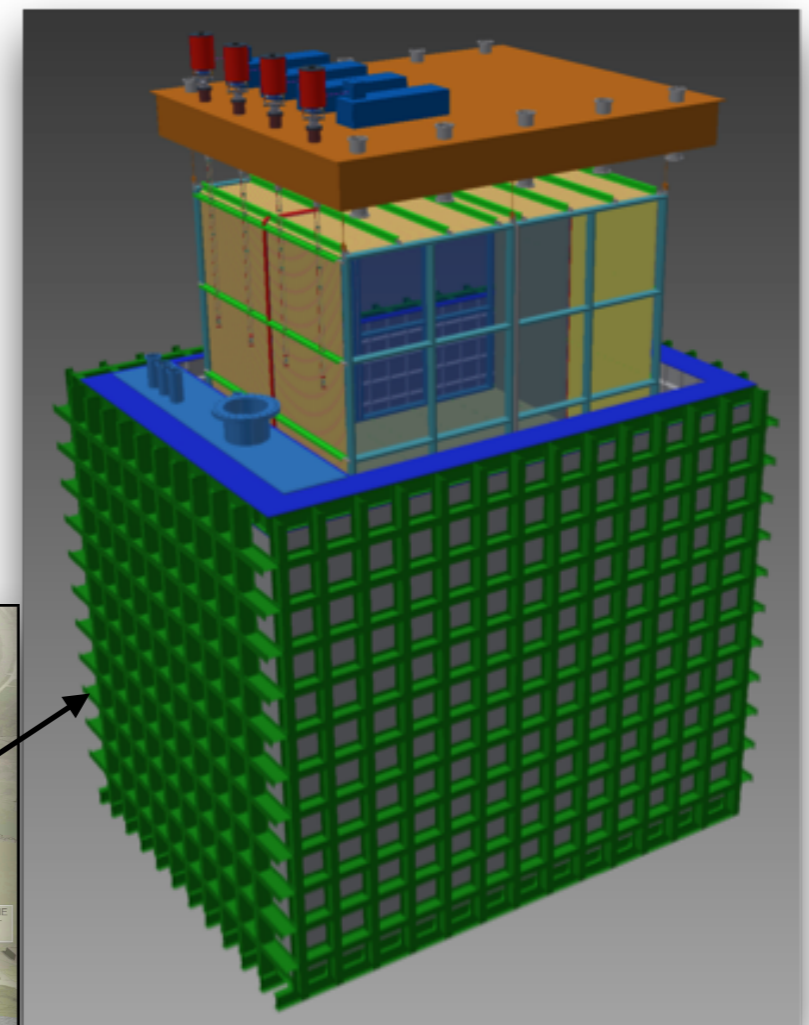
## **MicroBooNE** (*data taking phase*)

6.6  $10^{20}$  POT exposure (~3 years)  
of MicroBooNE (87 t):  
~100000 CC 0-pion events

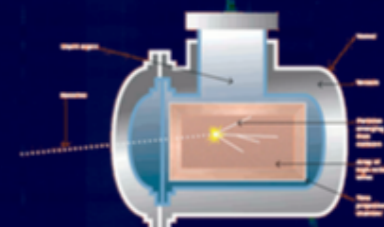
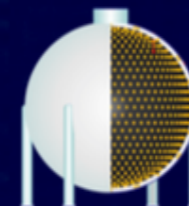
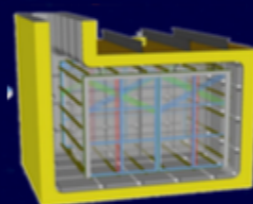
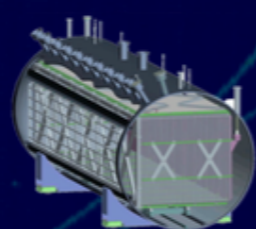


## **SBND**

1.2  $10^{20}$  POT exposure (~1 year)  
of SBND (112 t):  
CC 0-pion event sample 6-7x larger  
than MicroBooNE



# Event rates



$\nu_\mu$  rates only

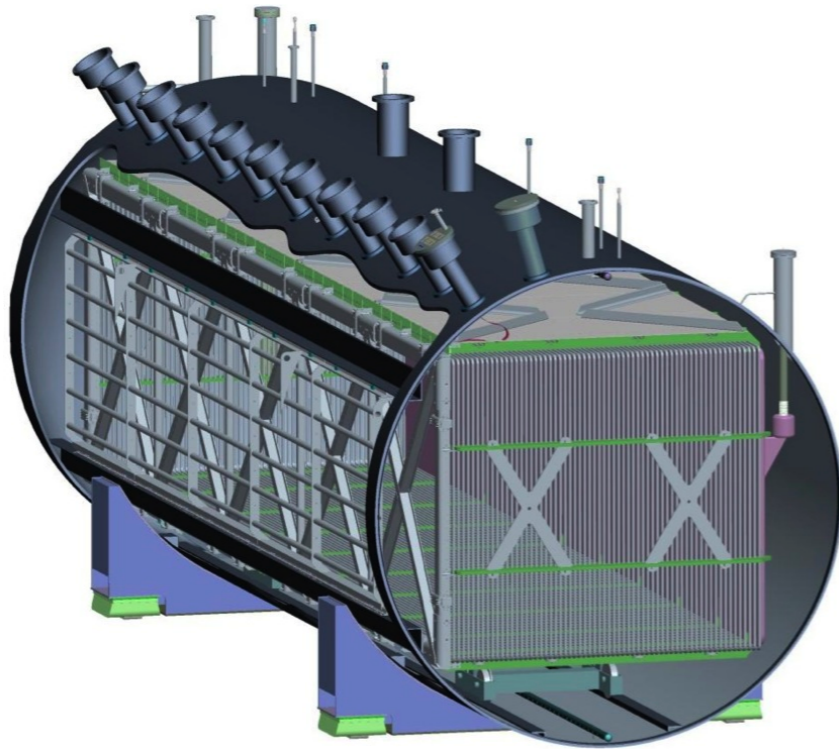
|                              | MicroBooNE<br>6.6 x 10 <sup>20</sup> POT<br>(3 years) | SBND<br>6.6 x 10 <sup>20</sup> POT<br>(3 years) | MiniBooNE<br>~ 6 x 10 <sup>20</sup> POT | ArgoNeuT<br>1.2 x 10 <sup>20</sup> POT<br>(5 months) |
|------------------------------|---|---|---|--|
|                              | EXPECTED  |   | SELECTED                                |  |
| CC inclusive                 | 175k  |   |   | ~3k ( $\nu_\mu$ and $\bar{\nu}_\mu$ )                |
| CC 0 $\pi$                   | 112k  | 3500k   | 146k                                    | ~1k ( $\nu_\mu$ and $\bar{\nu}_\mu$ )                |
| 1 $\mu$ + 2p                 | 12k   | 360k  |   | 30 ( $\nu_\mu$ and $\bar{\nu}_\mu$ )                 |
| NC single $\pi^0$            | 11k   | 358k  | 21k                                     | ~150 ( $\nu_\mu$ and $\bar{\nu}_\mu$ )               |
| NC elastic                   | 17k   |   | 95k                                     |  |
| CC coherent $\pi$ production |   | 19k   |   | ~15 ( $\nu_\mu$ and $\bar{\nu}_\mu$ )                |
| CC $\nu_e$                   |   | 37k   |   |  |

BNB

NuMI

A. Schukraft - Fermilab

# MicroBooNE



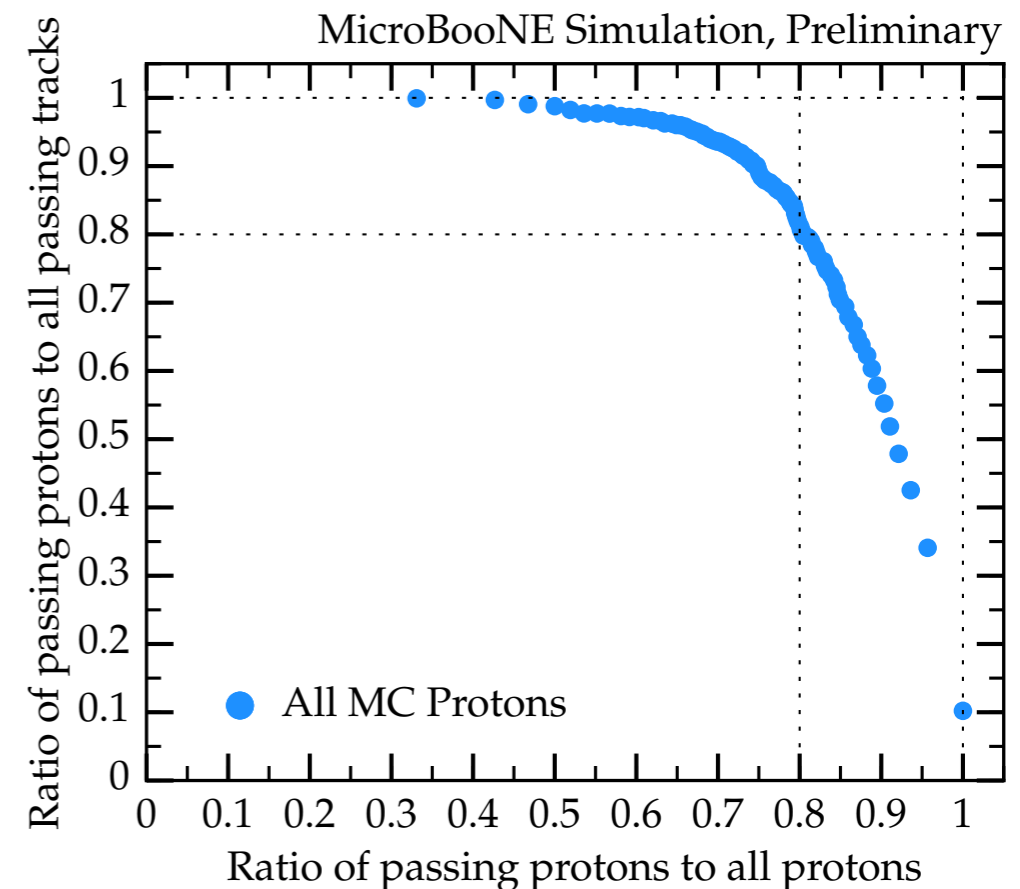
- 470 m downstream of BNB target
- 170 tons of LAr (89 tons active)
- $10 \times 2.5 \times 2.3 \text{ m}^3$
- 3 planes of  $\sim 3000$  wires each
- 3 mm wire spacing
- 32 PMTs to detect scintillation light

- Installed in LArTF completed summer 2015
- Commissioned and started taking neutrino data fall 2015
- MicroBooNE has collected  $5E20$  protons on Target in the BNB to date
  - $\sim 130K$  CC neutrino events.



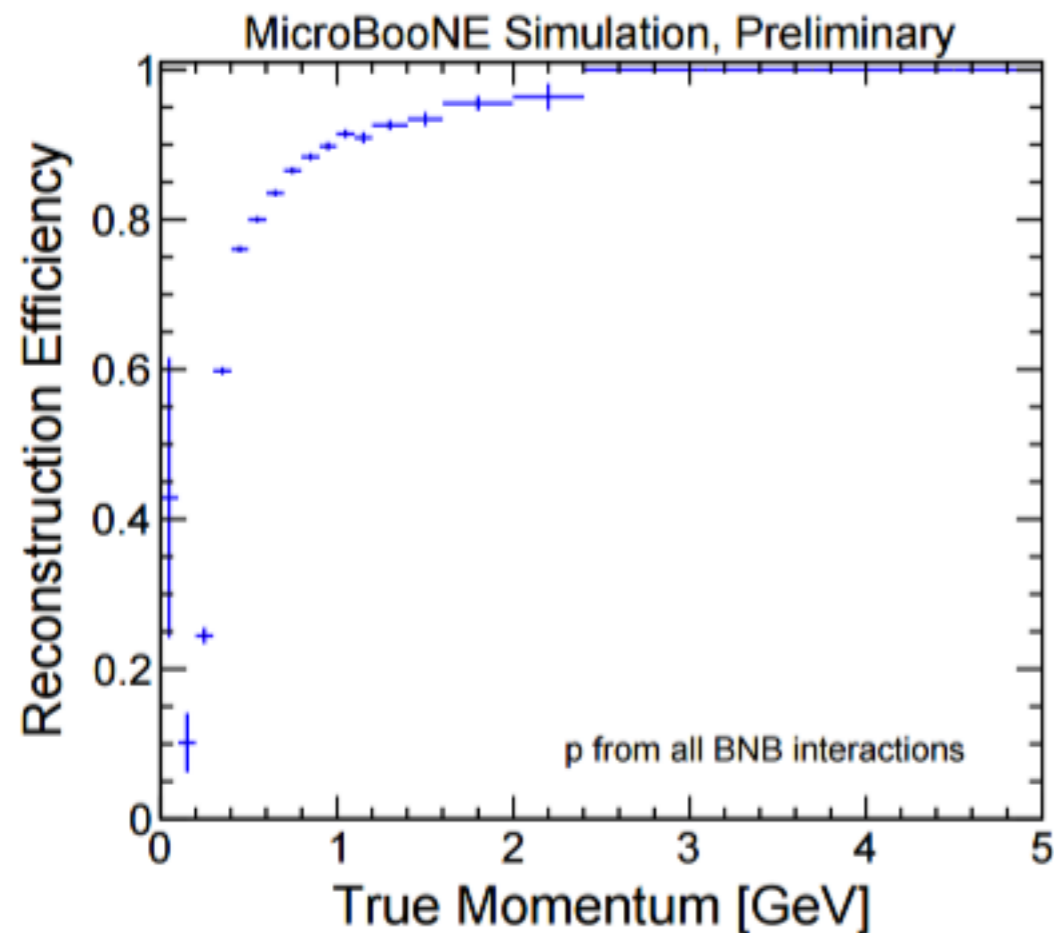
# Proton Track ID in MicroBooNE

- The current proton track ID in MicroBooNE is based on **fully automated reconstruction**.
  - Start with all reconstructed tracks.
  - Train boosted decision tree classifier on reconstructed track features: **geometric**, **calorimetric** and **optical** information.
- Important for NC elastic scattering and nuclear effect measurements.
  - 70% BNB CC neutrino events are predicted to be 0pi events.

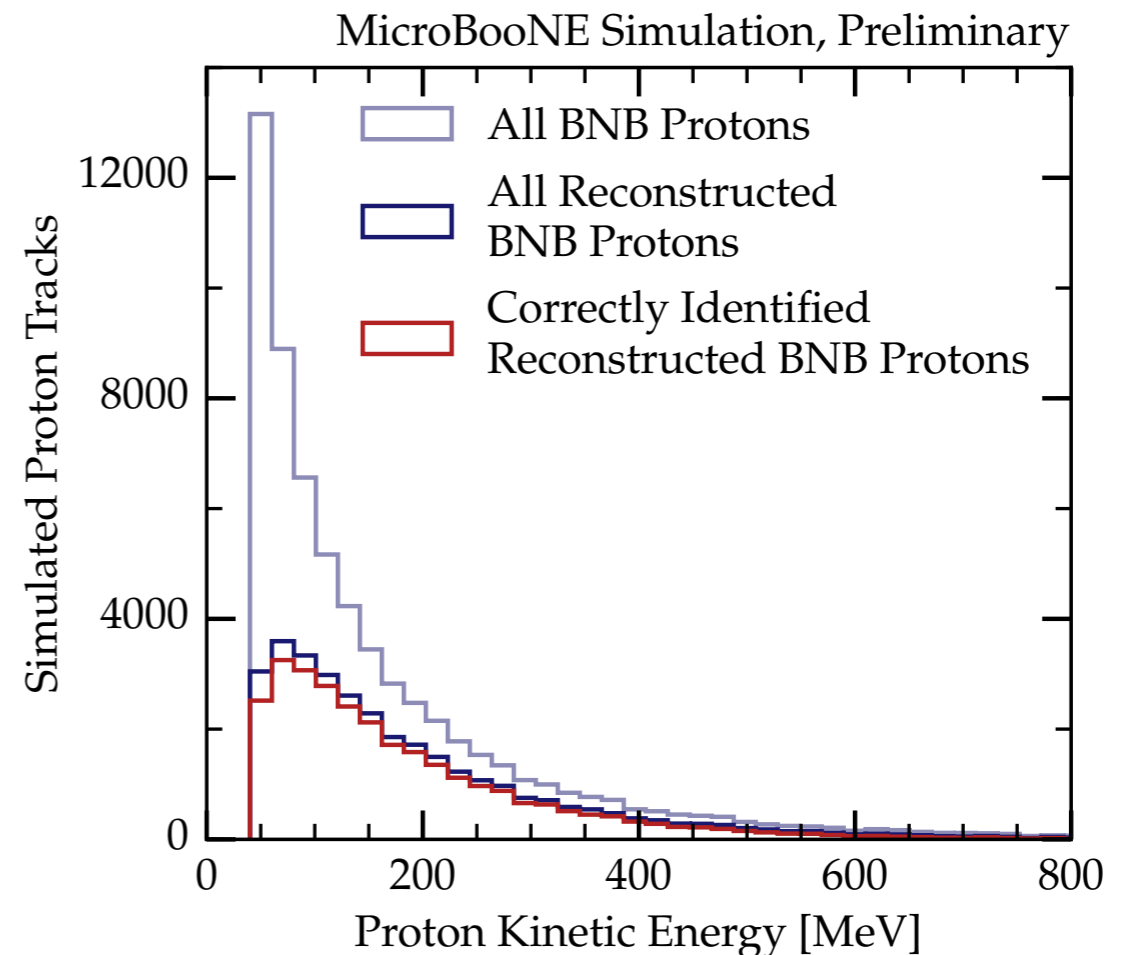


MICROBOONE-NOTE-1025-PUB

# Proton ID Performance



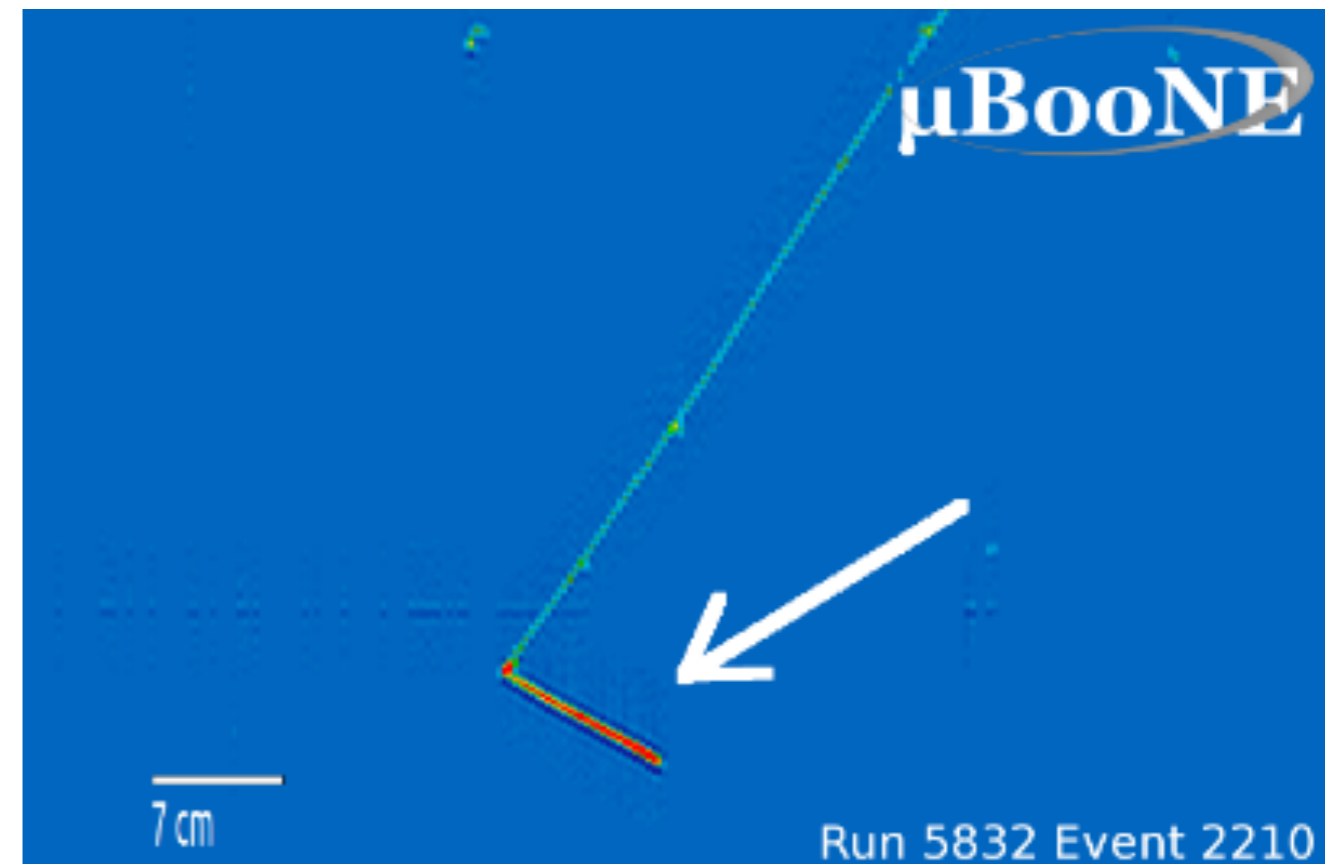
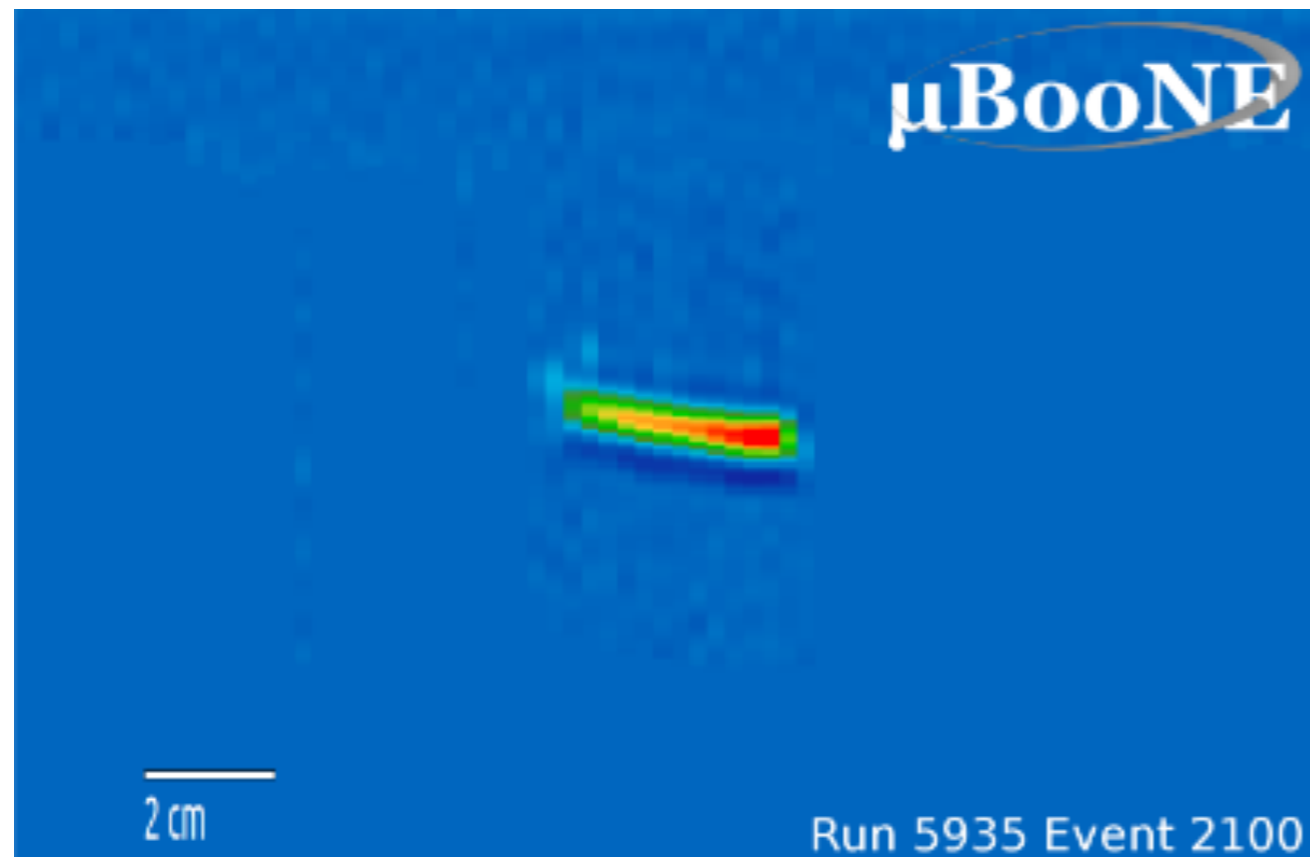
MICROBOONE-NOTE-1015-PUB



MICROBOONE-NOTE-1025-PUB

- The challenge is to reconstruct protons as tracks.
- Proton ID efficiency is high (88%) once a track is reconstructed.

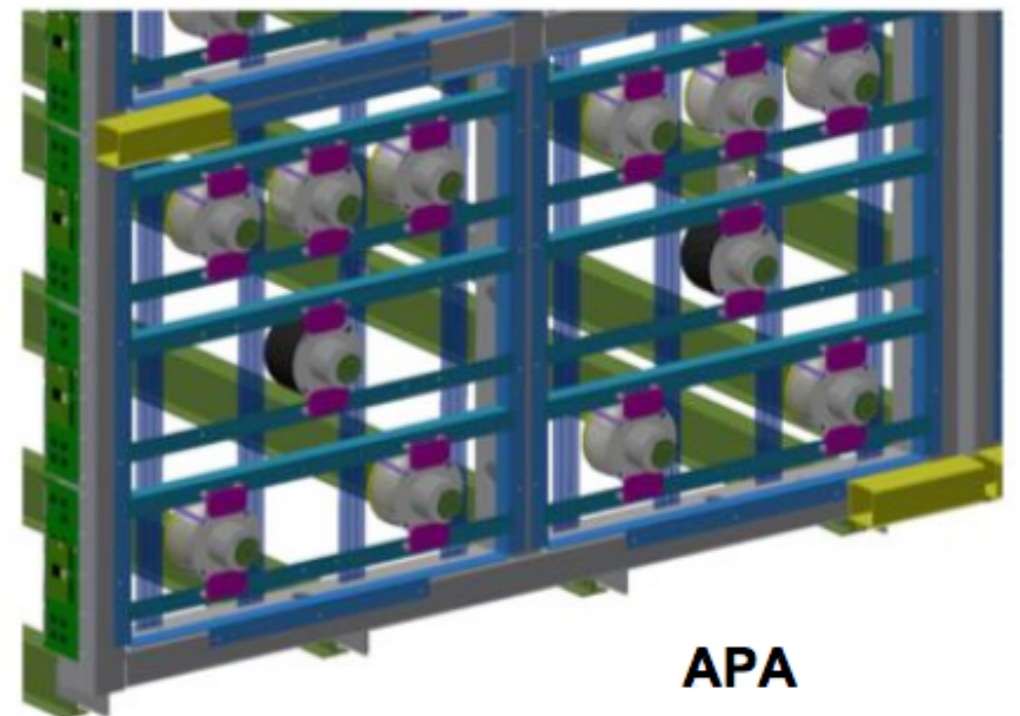
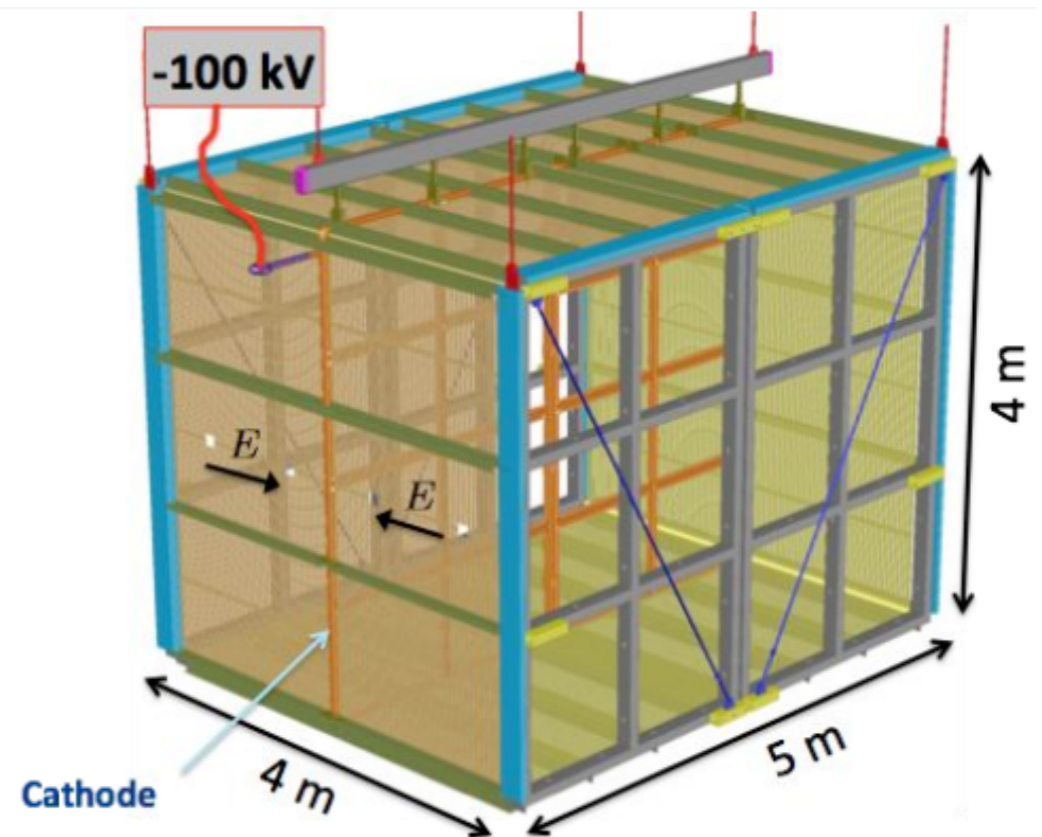
# Selected data events



- A big step forward with full automated reconstruction and event selection.
- Large statistics for many interesting studies.
- Nex step is to improve tracking efficiency.

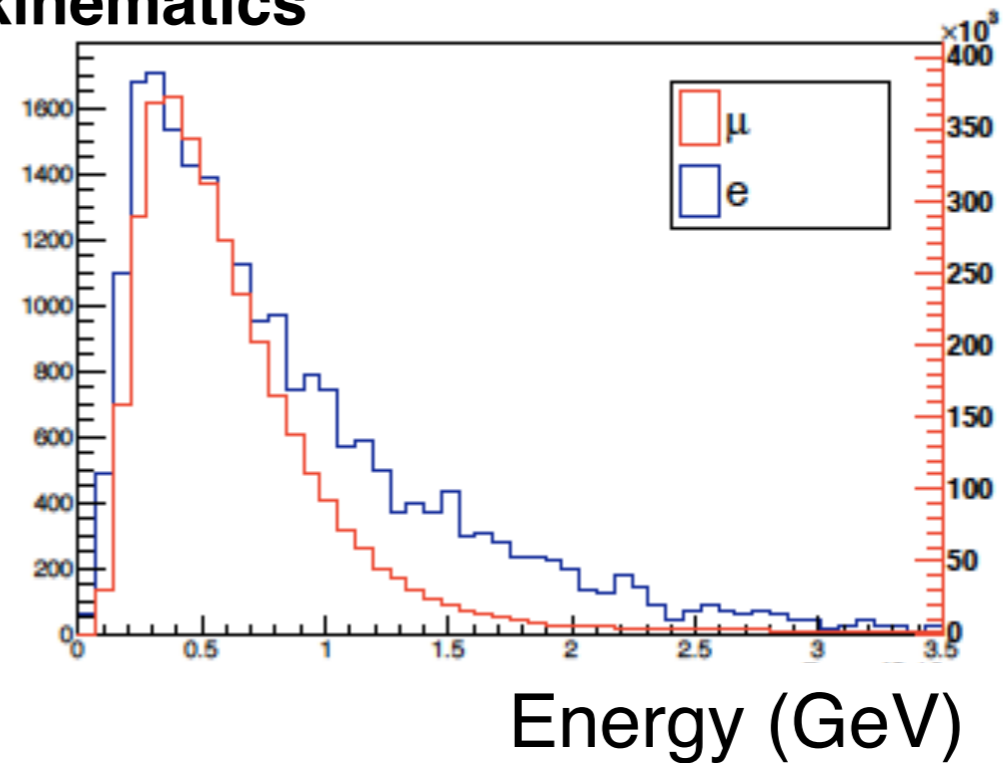
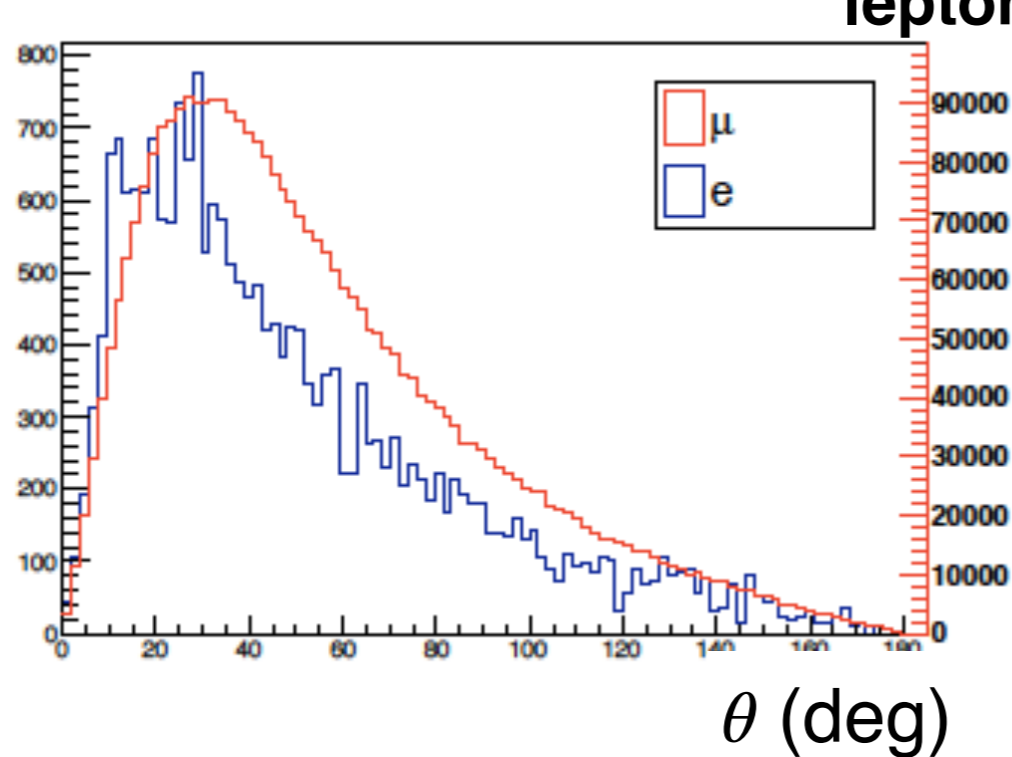
# SBND

- ND for SBN program and neutrino-Ar cross section measurements.
- 260 tons LAr (112 tons active)
- Membrane cryostat
- Two TPCs
  - 2 m drift distance
  - 3 wire planes (vert,  $\pm 60^\circ$ )
  - 3 mm wire spacing
- 120 8" PMTs coated with TPB
- Laser calibration system
- External cosmic ray tracker (nearly full coverage)
- 30x MicroBooNE's statistics before the detector is bigger and much closer to the neutrino source.

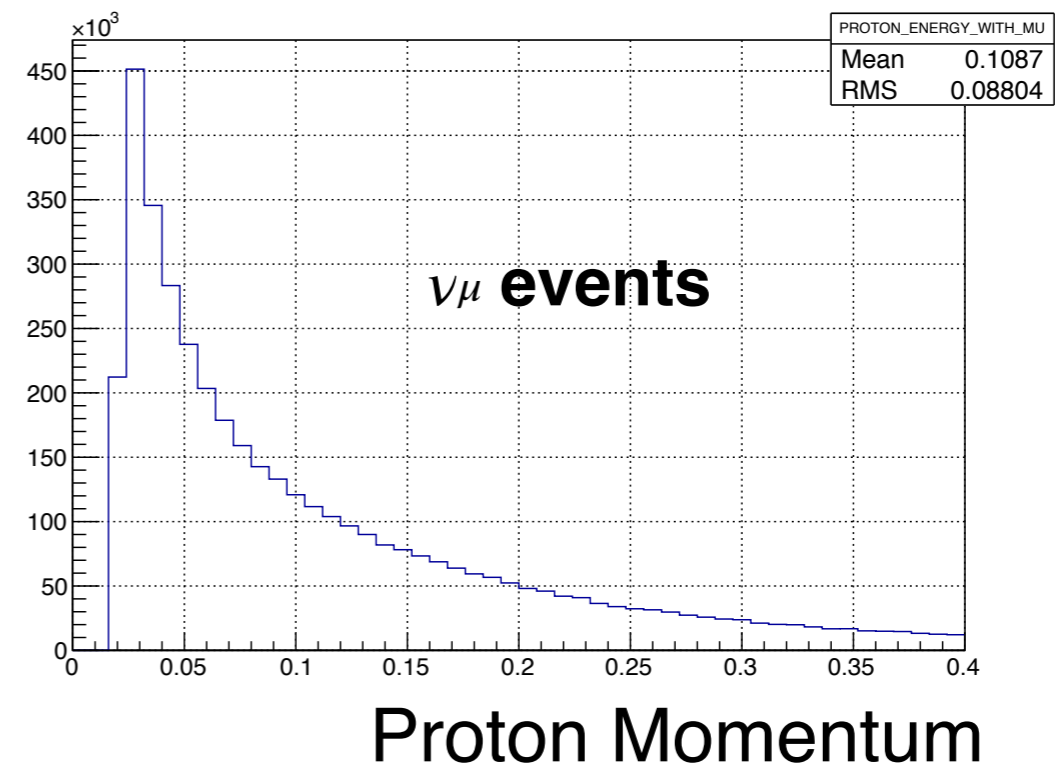
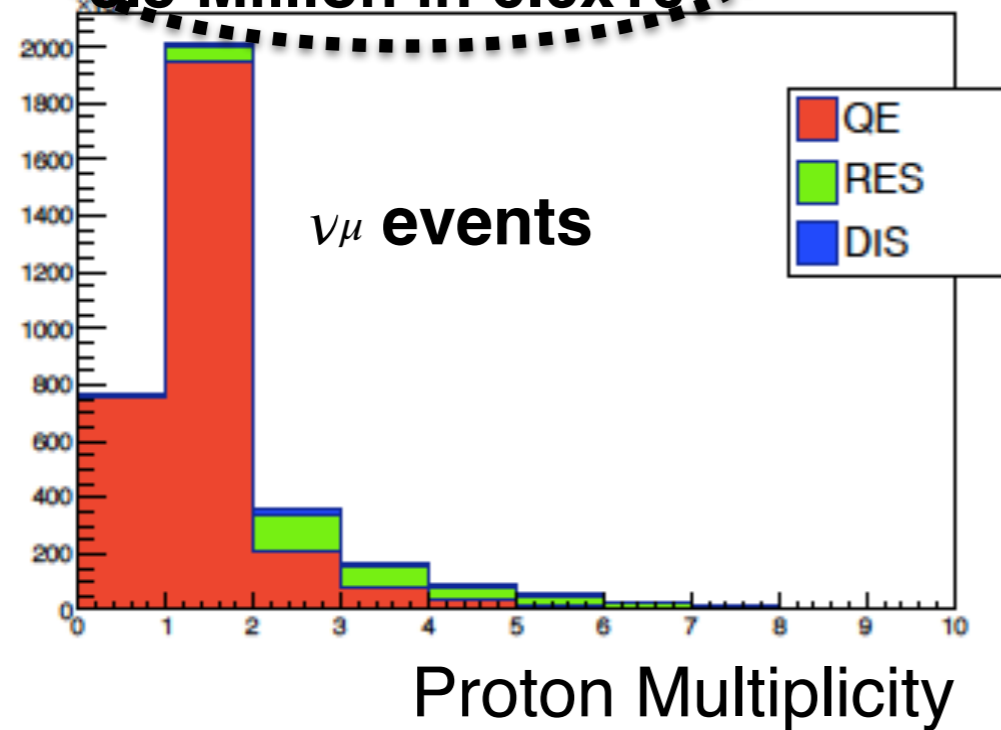


# CC $0\pi$ events

## lepton kinematics



$\nu_\mu$  events:  
3.5 Million in  $6.6 \times 10^{20}$

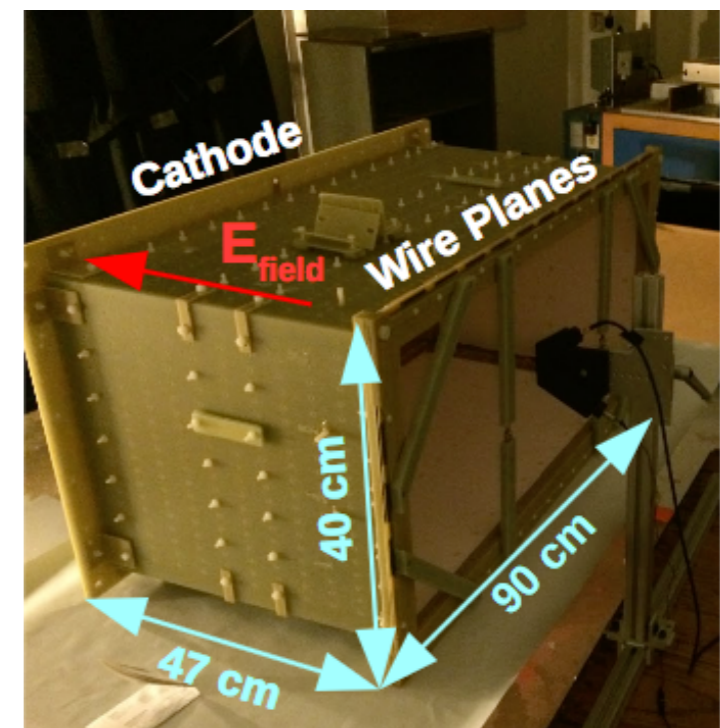
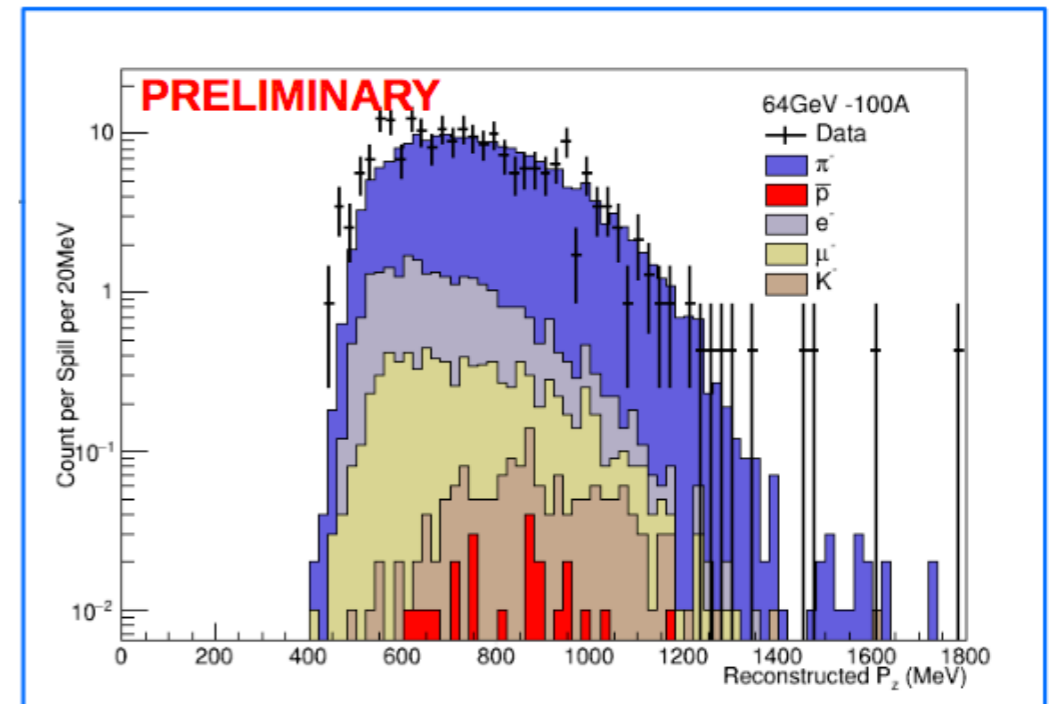


- High statistics measurement of  $\nu_\mu$  and  $\nu_e$  CC  $0\pi$  pion events will allow to quantify nuclear effects in neutrino-Ar scattering.

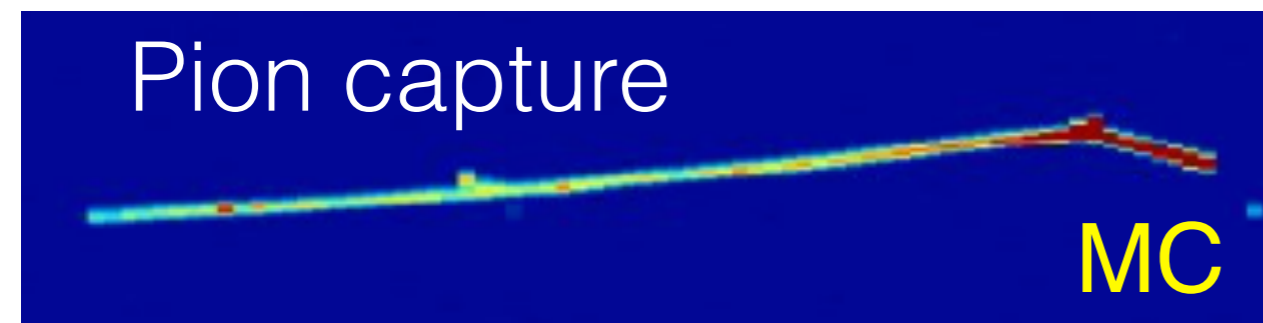
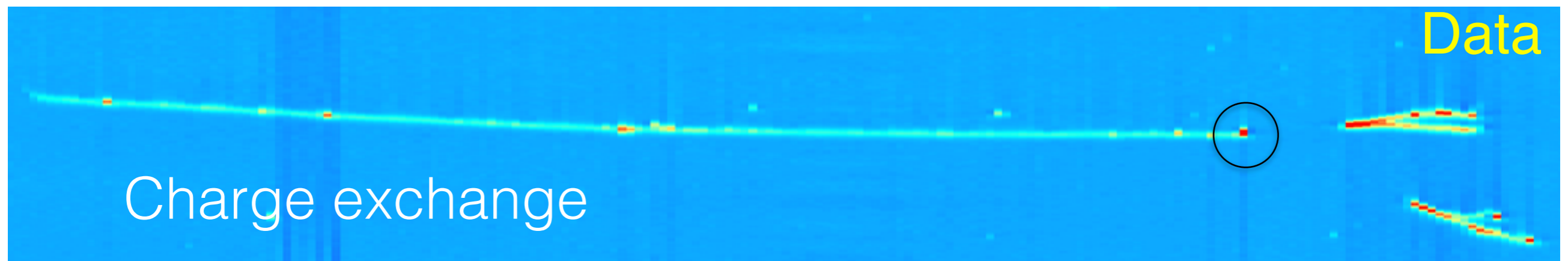
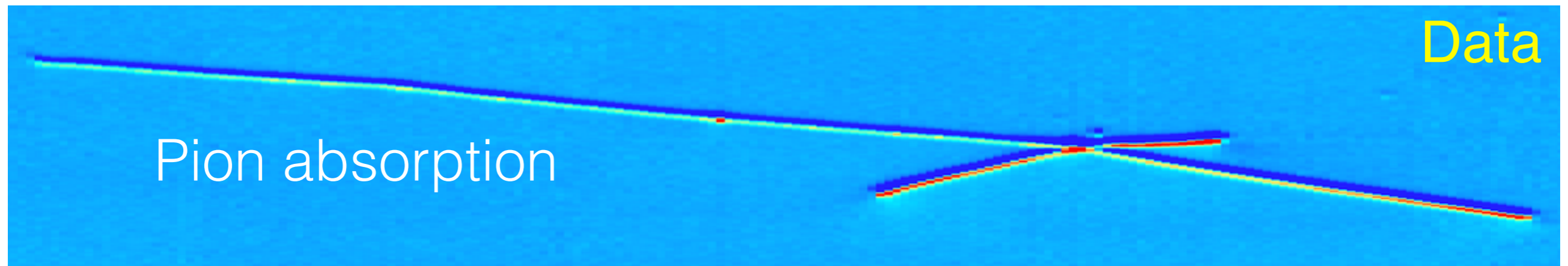
# LArIAT

- A LArTPC in Fermilab Test Beam Facility (FTBF)
  - Measure charged pion interaction with LAr
- Refurbished ArgoNeuT TPC and cryostat.
- 240 kg active volume
- 90 cm x 40 cm x 47 cm (drift) TPC
- 2 wire planes, 4mm wire spacing
- Cold readout electronics
  - Same BNL ASIC as MicroBooNE, on a different motherboard designed at MSU.
- Light collection system: 2 standard PMTs + 3 SiPM + wavelength shifting reflector foils

LArIAT Tertiary Beam Particle Momenta



# Protons induced by pions



- Many interesting physics topics involve final state protons!

# Conclusions

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- Final state protons play an important role in the neutrino cross section measurements
  - Nuclear effects and FSI
  - ArgoNeuT pioneered the measurements of final state protons in LArTPC
  - MicroBooNE and SBND will continue to measure final state protons with larger statistics and improved reconstruction techniques
- LArIAT will measure final state protons through charged pion interactions with LAr
  - Improve understanding of pion cross sections - important for neutrino-Ar FSI
  - Tune reconstruction of final state protons using data