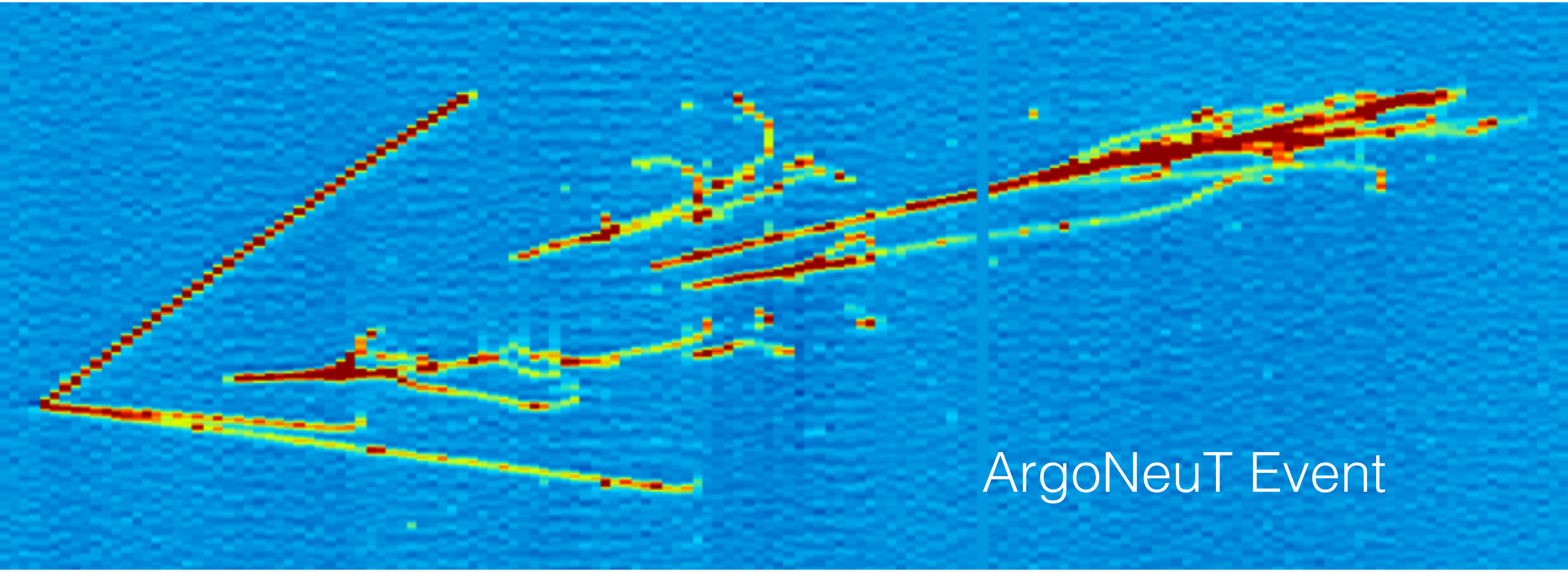


Requirements for Neutrino Experiments

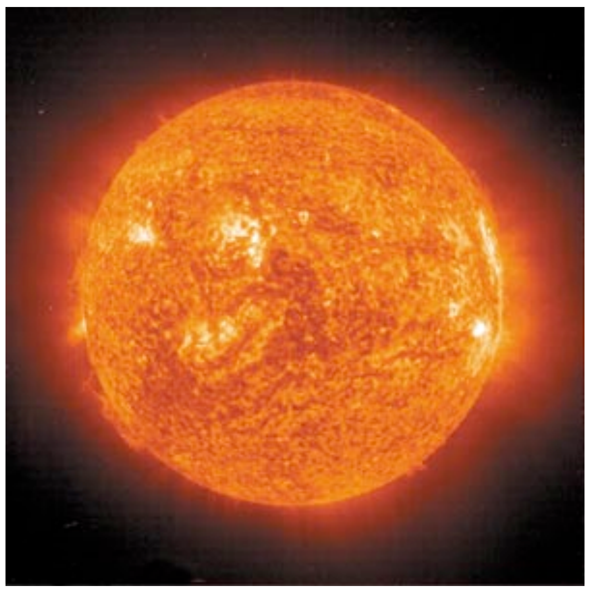
Tingjun Yang
FNAL

LArTPC14, July 7, 2014

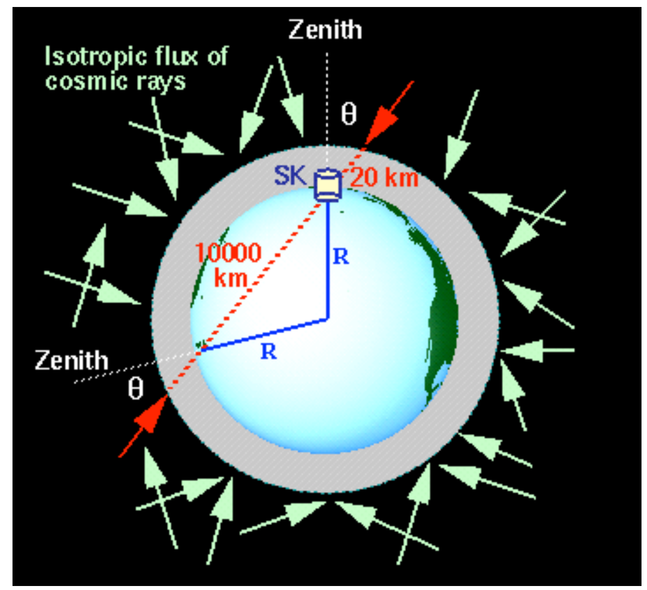
Outline

- Neutrino physics and liquid argon TPC (LArTPC).
- Physics requirements for LArTPC:
  - ✓ Big volume.
  - ✓ High resolution.
    - ★ Particle identification (e/π^0 separation, $\pi^\pm$/p separation)
    - ★ Energy/momentum measurements (range, multiple scattering, calorimetry, B-field).

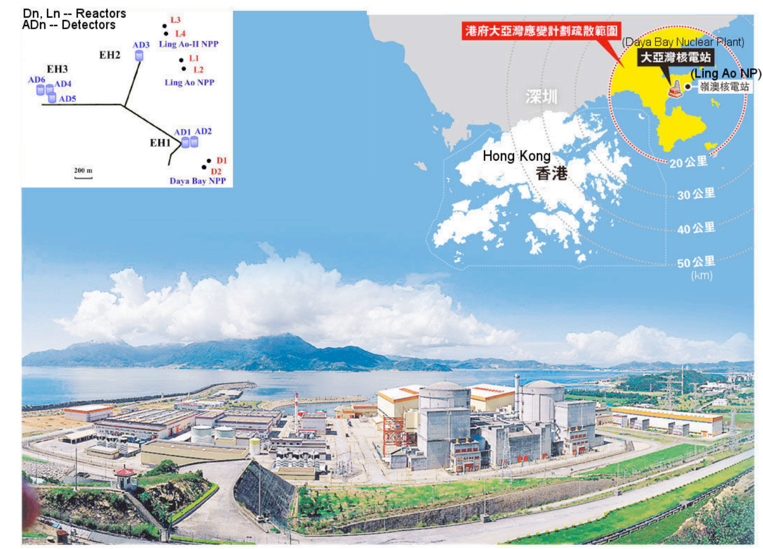
Neutrinos are everywhere



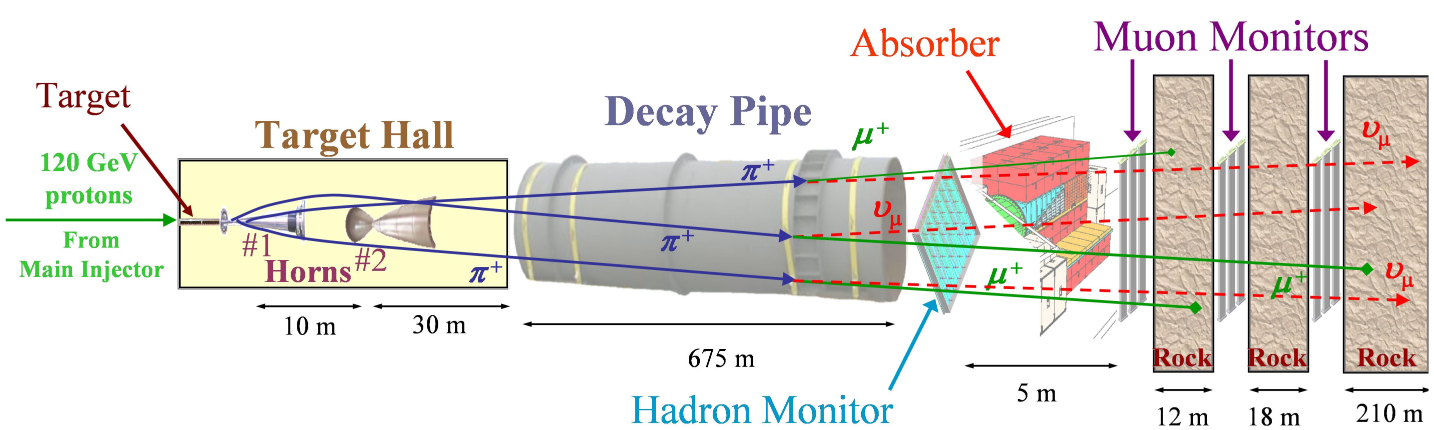
Billions solar ν/sec/cm²



Millions atmospheric ν/sec/cm²



Reactor neutrinos



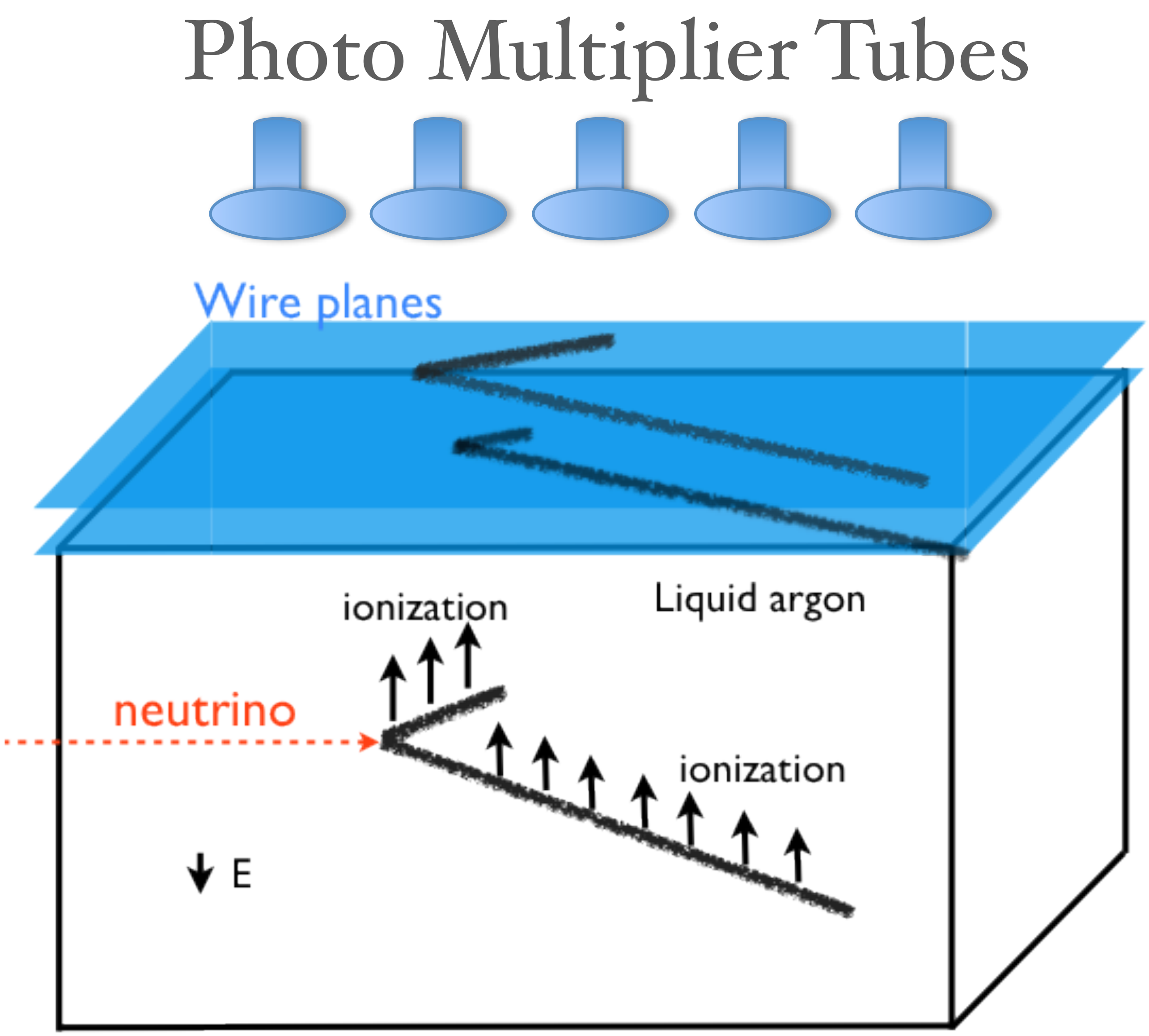
Accelerator neutrinos

Neutrinos can help us understand many profound puzzles in physics and cosmology.

Main questions in neutrino physics

- Most of them can be answered by measuring $\nu_\mu \rightarrow \nu_e$ transitions.
  - Short baseline: search for **sterile neutrinos**
  - Long baseline: matter effects resolve **mass hierarchy**, neutrinos vs antineutrinos: measure **CP violation**
- Detector requirements
  - **Massive**: large statistics
  - **Good granularity**: e/π^0 separation
- Liquid argon TPC (LArTPC) can achieve both large mass and good granularity

LArTPC concept



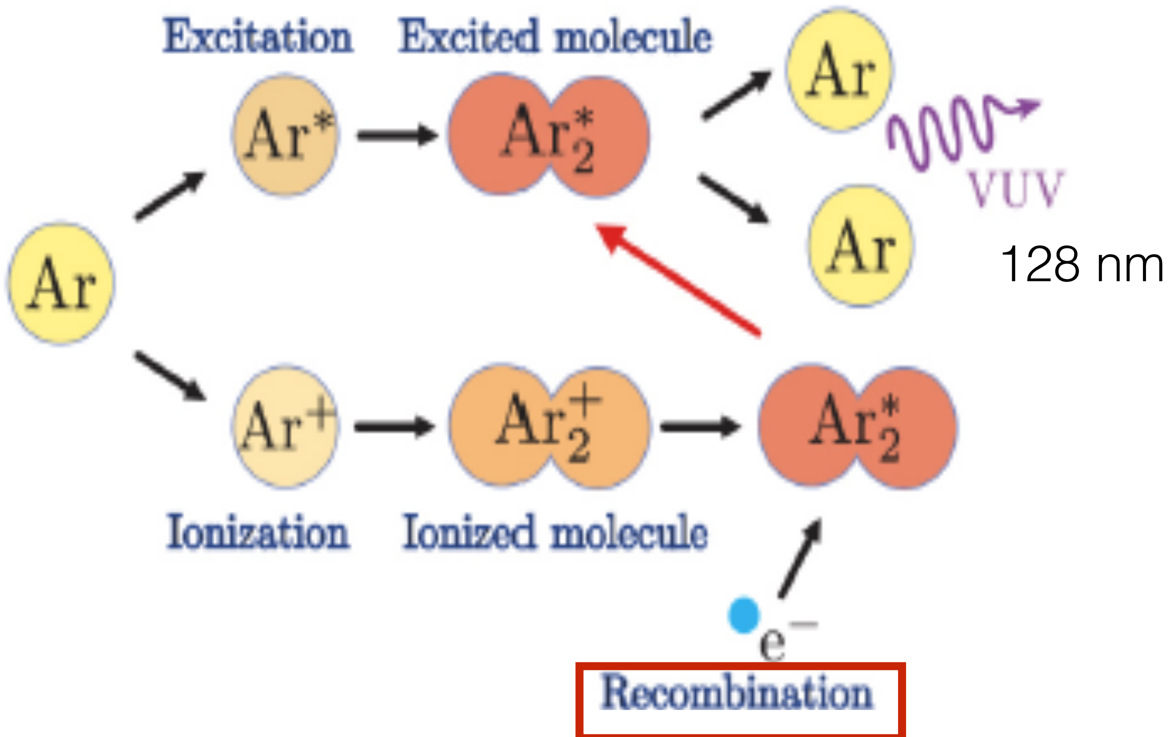
- Ionization electrons drifted by electric field and read out by wire planes.
- High voltage provides electric field.
- Scintillation light recorded by PMT provides trigger information.
- Requires high-purity liquid argon.

Choice of Argon

- Lots of ionization & scintillation light
- When purified (<0.1ppb), long ionization drift distances
- Excellent dielectric properties (very large voltages)
- Dense noble liquids - ν good target
- Relatively cheap (1% of atmosphere).

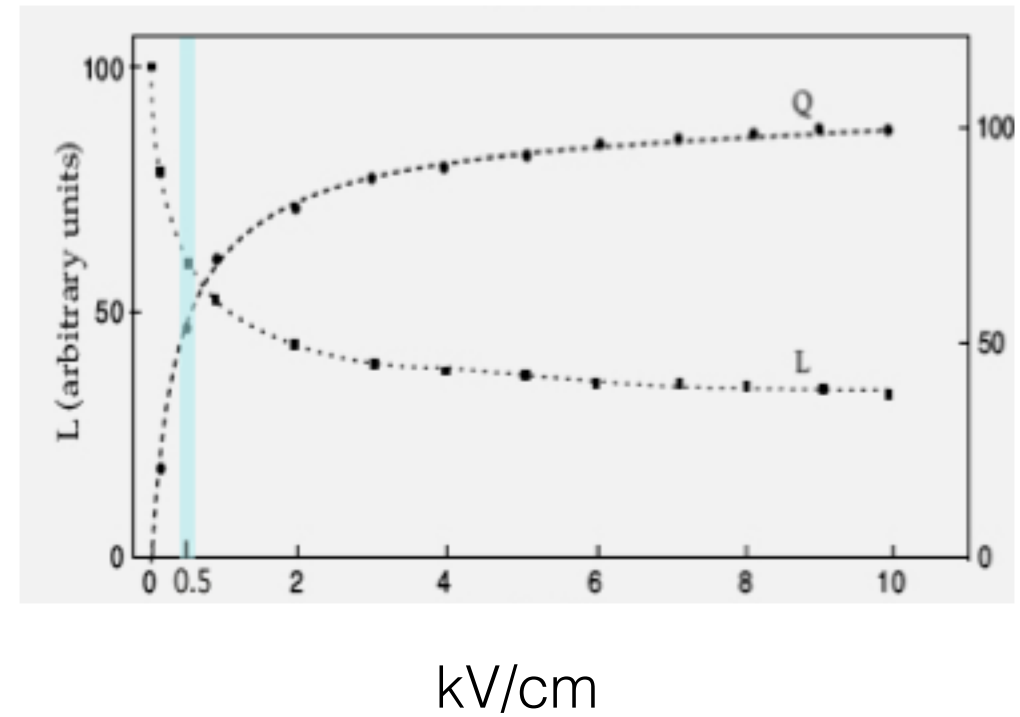
M. Soderberg	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165	373
Density [g/cm	0.125	1.2	1.4	2.4	3	1
Radiation Length [cm]	755.2	24	14	4.9	2.8	36.1
Interaction Length [cm]	568	82.2	85.7	61.8	58.3	83.3
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

mechanism of light production

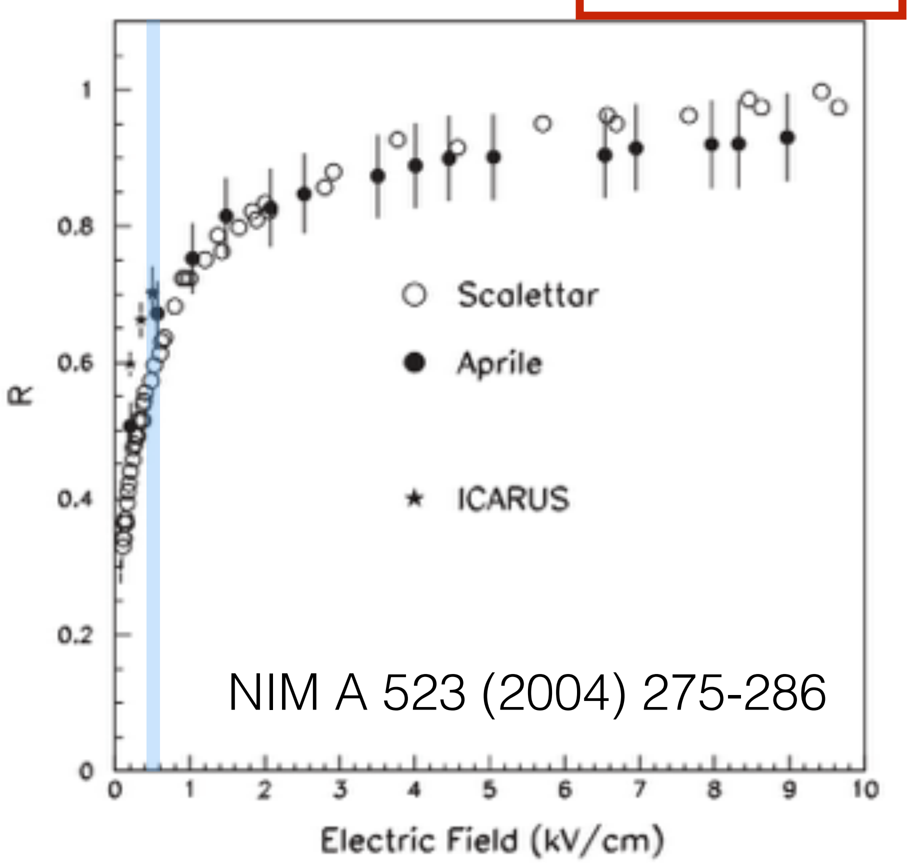


dE/dx = 2.1 MeV/cm for MIP
Ionization: W_e = 23.6 eV
Scintillator: W_γ = 19.5 eV

charge (Q) and light (L) yield vs electric field



5000 e/mm and 5000 phot./mm at 0.5 kV/cm



v_d=1.6 mm/μs at 0.5kV/cm
Diffusion ~ 1 mm over 2 m
60 ppt O_2 -> 5 ms electron lifetime

Recombination factor R=collected charge/initial charge = 0.65 at 0.5 kV/cm for MIP.

Multi-kt LArTPC

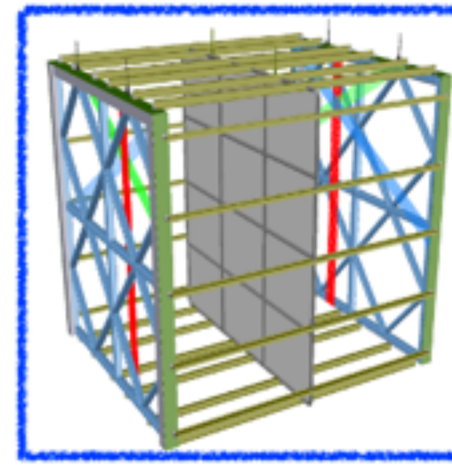
- Neutrino interaction rate is low: need large detector to accumulate high statistics data.
- **Long drift distance** ~ 2 m:
  - Demands 100 kV to produce high electric field (0.5 kV/cm) to drift electrons and suppress recombination, diffusion. Need to understand dielectric strength of LAr.
  - HV session tomorrow.
- **Large volume cryostat**: remove impurities (O_2, H_2O, N_2) to suppress signal attenuation.
  - 5 ms electron lifetime (60 ppt O_2 concentration) leads to 20% attenuation over 2 m.
  - Purification without initial evacuation - see Michelle's talk on LAPD
- **Cold electronics**: reduce cable length and improve signal/noise - electronics session tomorrow.
- **Optical system**: record scintillation light to provide trigger information - optical system session today.
- **Detector calibration**: laser system and cosmic muons - calibration session tomorrow.
- **Magnetic field**: facilitate μ+/μ- separation and momentum measurement, discussion tomorrow.

US based LAr programs

Bo TPC
0.02 ton

ArgoNeuT
0.3 ton

MicroBooNE
0.1 kilo-ton



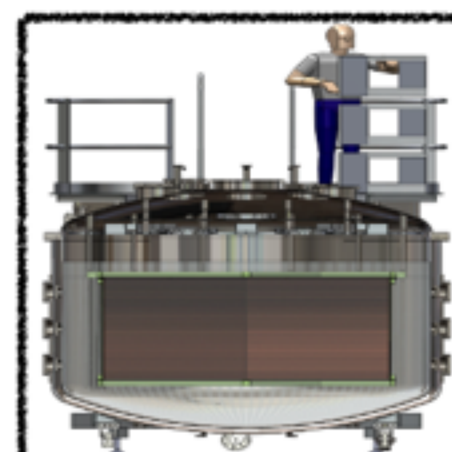
SBN
0.05 + 0.6 kilo-ton

LBNE Far Detector
34 kilo-ton

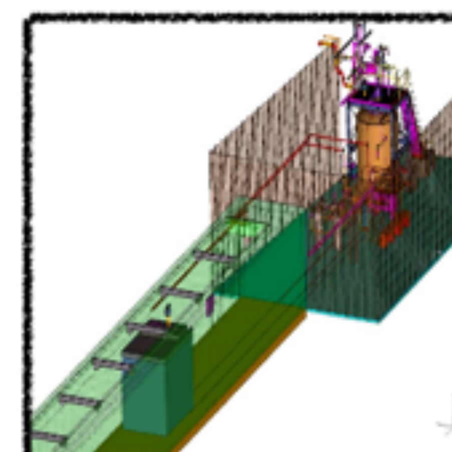
LUKE
(Material Test Stand)

LAPD
Purity Demonstrator

LArIAT
TPC Calibration



CAPTAIN
TPC Calibration



LBNE 35 ton
Purity Demonstrator

courtesy of Kazu Terao

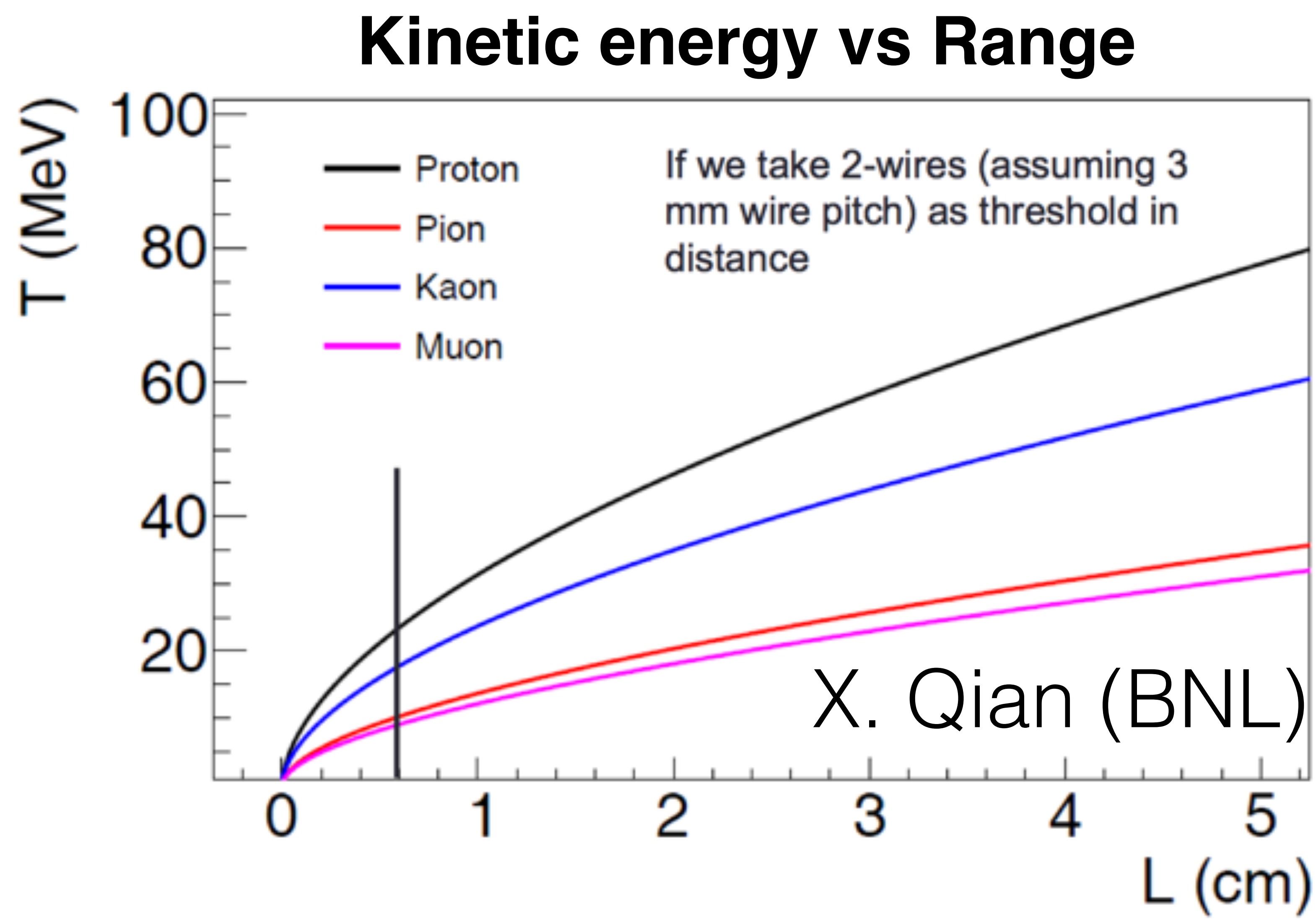
Physics reach of LArTPC

- Look for $\nu_\mu \rightarrow \nu_e$ signals at long baseline (LBNF).
  - Measure neutrino mass hierarchy and CP violation.
  - **Good e/π^0 separation.**
- Look for $\nu_\mu \rightarrow \nu_e$ signals at short baseline (MicroBooNE, SBN).
  - Search for sterile neutrinos.
  - **Good e/γ separation.**
- Neutrino cross section measurements (ArgoNeuT et al.)
  - **Low threshold. Good $\pi^\pm$/p separation.**
- Supernova neutrinos, proton decay, new physics.

Wire spacing

- Wire spacing determines the detector resolution.
- Smaller wire spacing leads to higher sampling frequency and higher resolution, better particle ID.
- The decision of wire spacing has to take into account diffusion (~1 mm over 2 m), cross talk and cost.
- Most experiments use a few mm spacing:
    - 3 mm - MicroBooNE/ICARUS
    - 4 mm - ArgoNeuT
    - 5 mm - LBNE

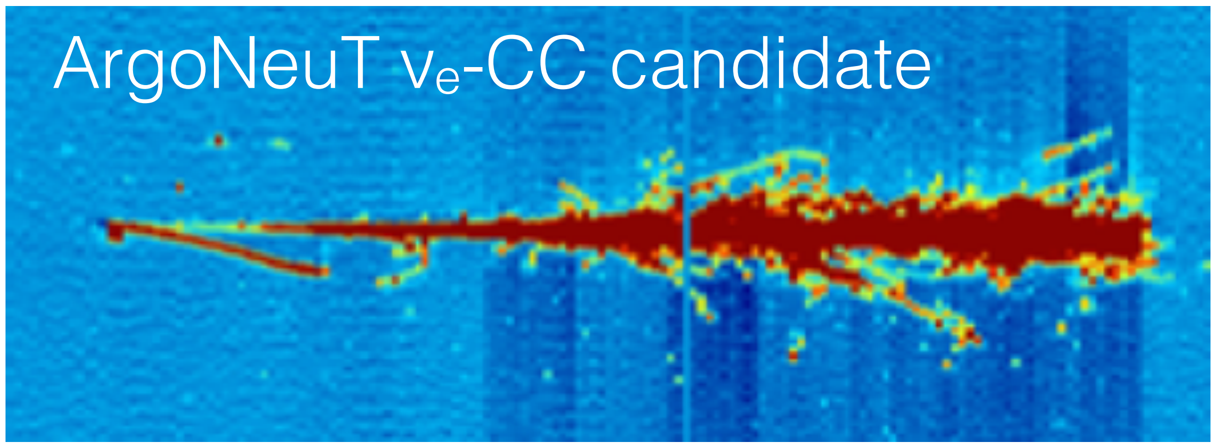
Threshold to reconstruct tracks

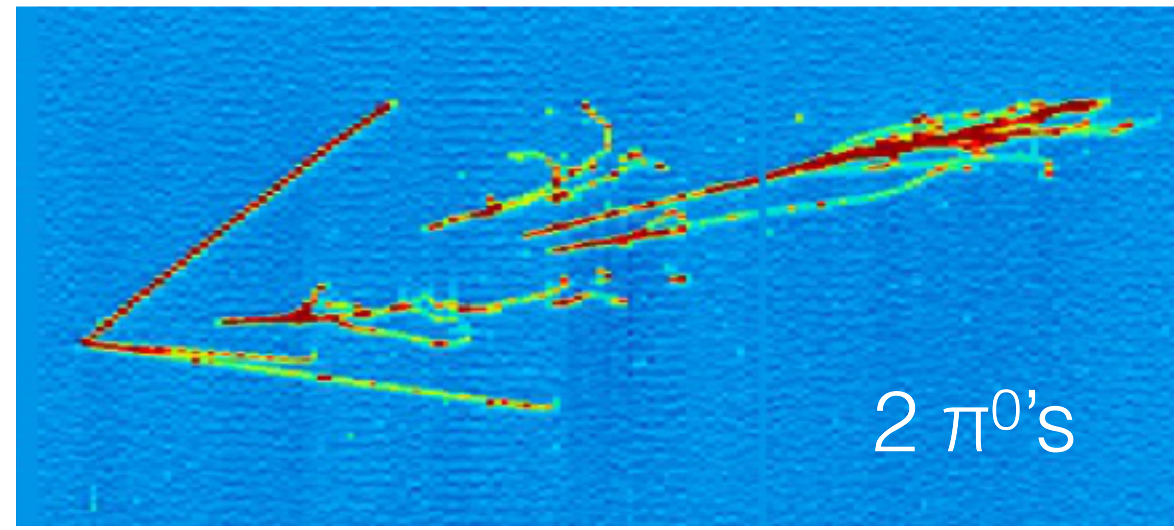


Particle	Proton	Pion	Kaon	Muon
Threshold	22 MeV	10 MeV	17 MeV	10 MeV

Low threshold also makes it possible to detector supernova neutrinos (10-30 MeV ν_e's)

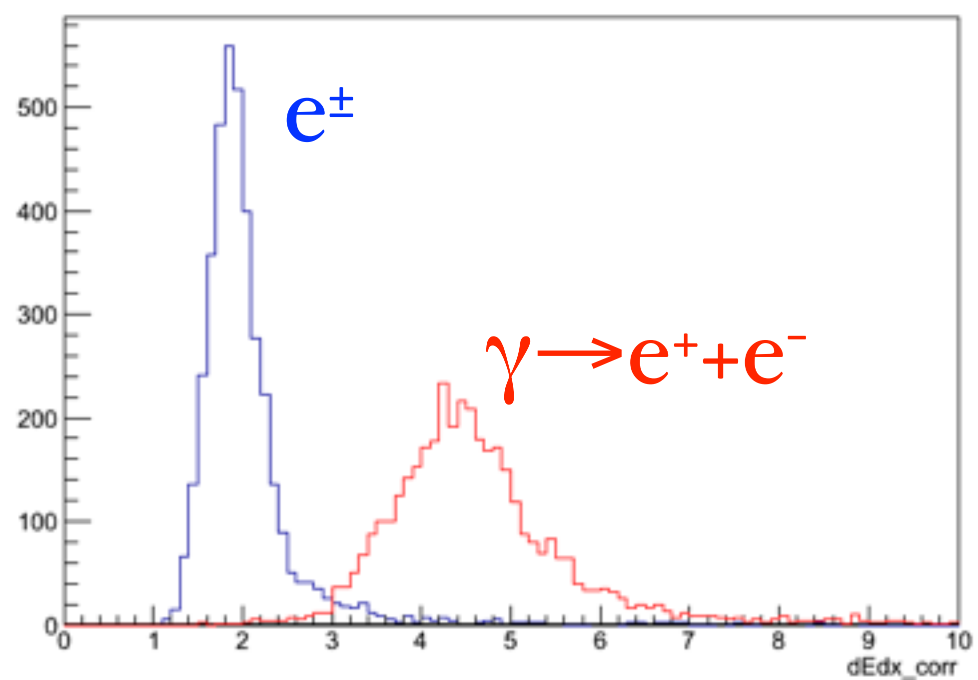
e/π^0 separation





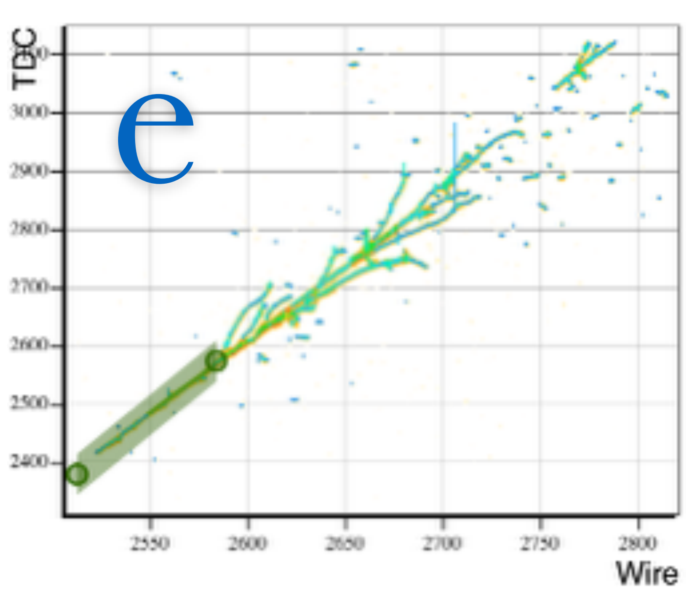
- Photon conversion length is $9/7X_0$ = 18 cm in LAr.
  - Sampling frequency is 0.036 X_0 for 5 mm wire spacing (NOvA: 0.15 X_0).
- Topology information (gaps near vertex) is useful in rejecting π^0 background.
- Main background comes from events when two photons overlap or one photon is not converted. dE/dx information is helpful in rejecting those backgrounds.
- LBNE estimates 80% signal efficiency and 1% background mis-ID rate in their sensitivity studies for ν_e appearance (arXiv:1307.7335).

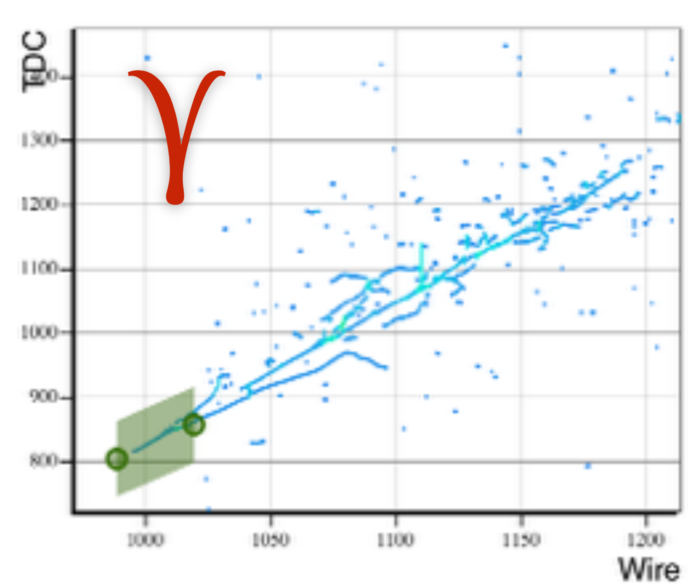
e/single-γ separation

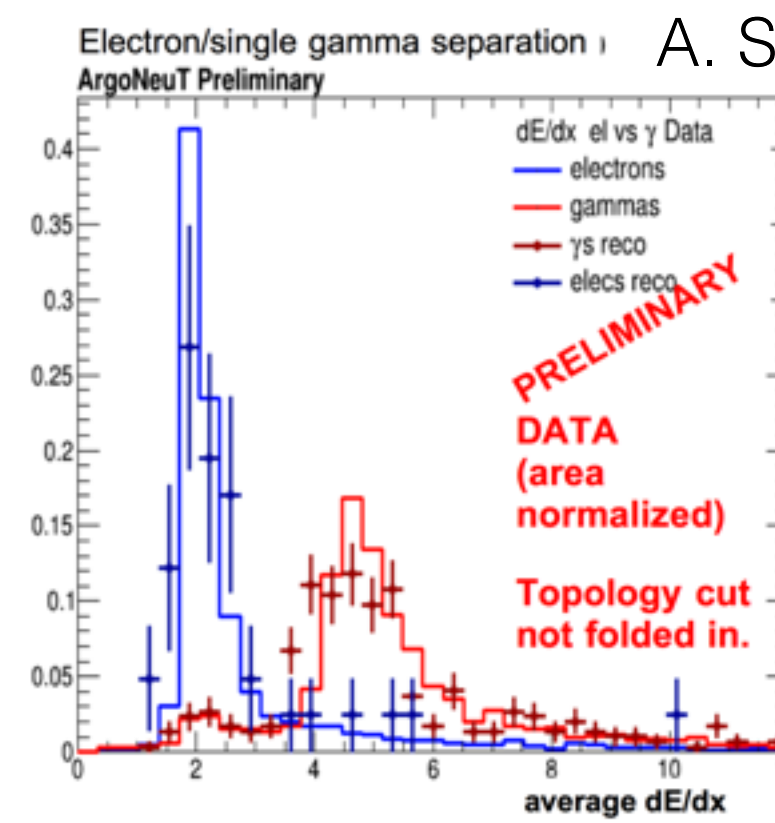


Radiation length X_0 = 14 cm
dE/dx at shower vertex distinguishes
e (1 MIP) from e^+e^- (2 MIPs)

MicrobooNE is expected to resolve MiniBooNE low-E anomaly with high significance (>4σ)







A. Szelc

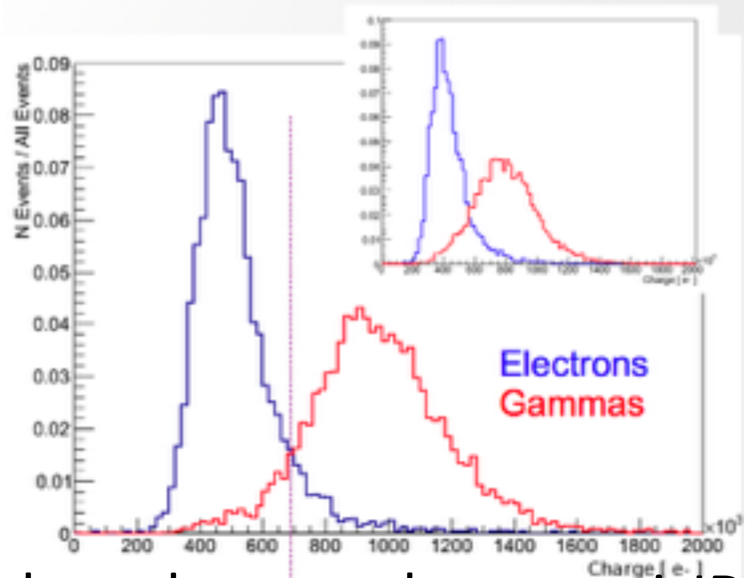
LBNE e/γ Separation Status

M. Szydagis,
D. Coelho (UC Davis)

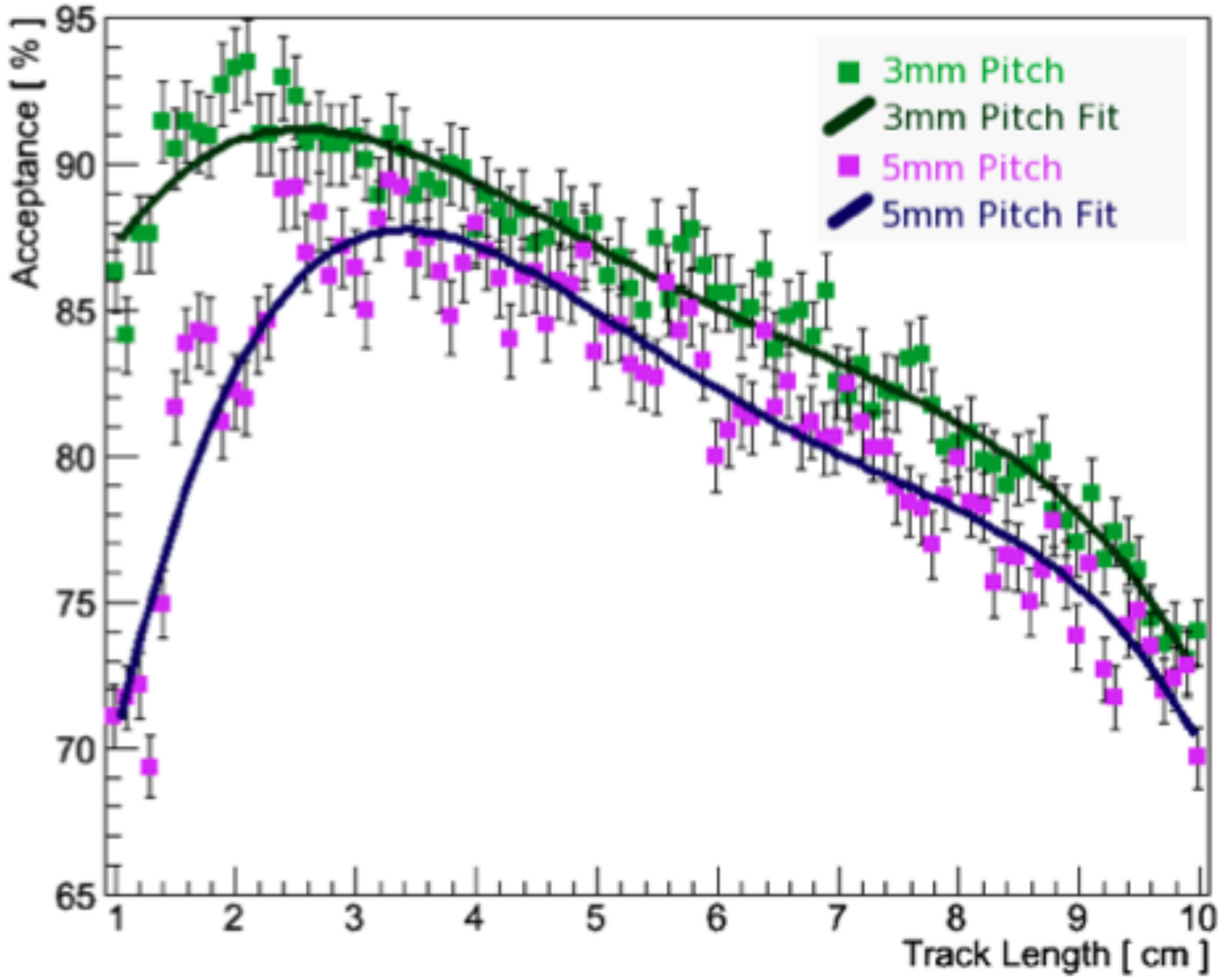
Currently using just the reconstructed charge in the first part of the shower (labeled "track length") below

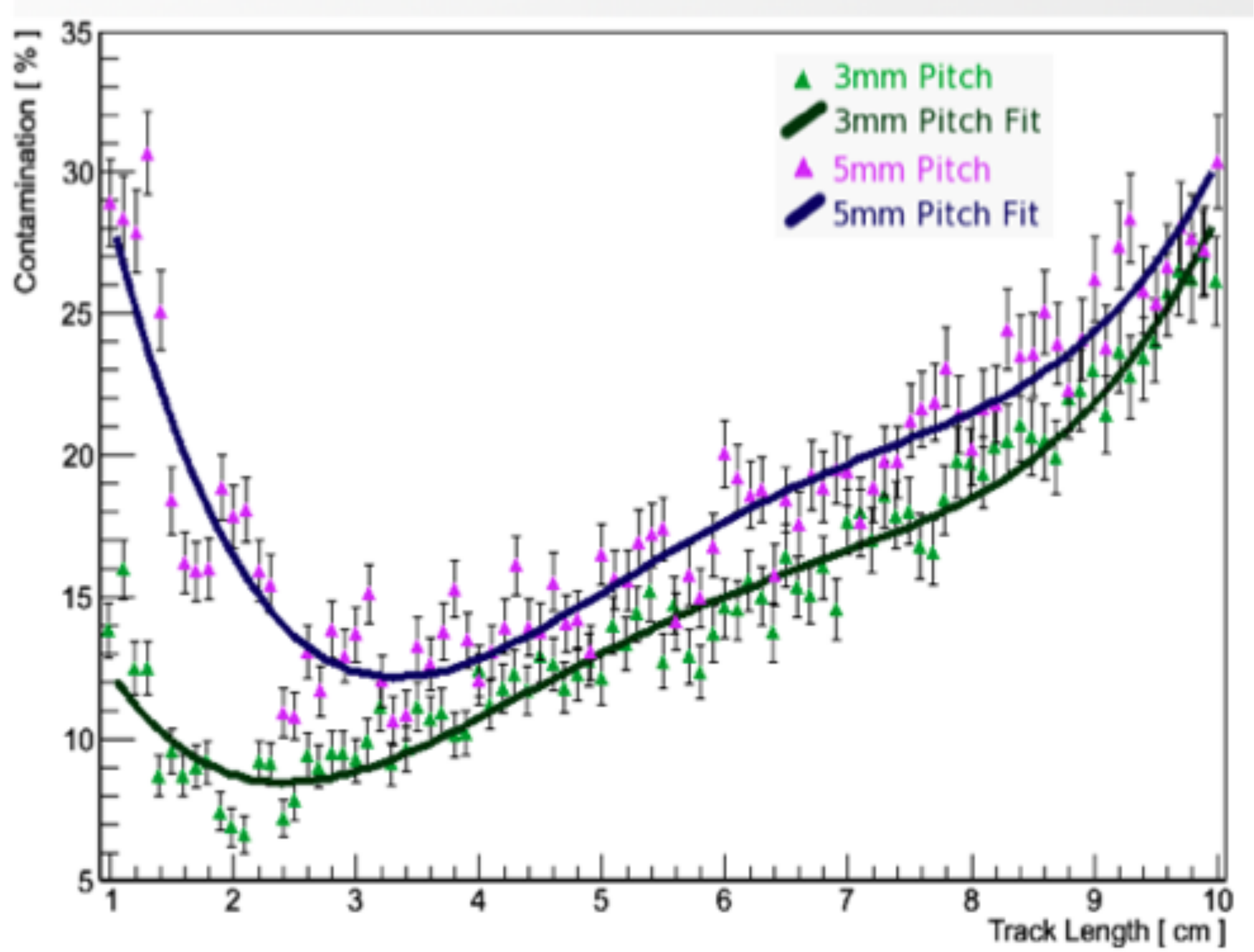
Measured charge in the first part of an EM shower used to tell one MIP from two

Working on displaced vertex reconstruction and other discriminants



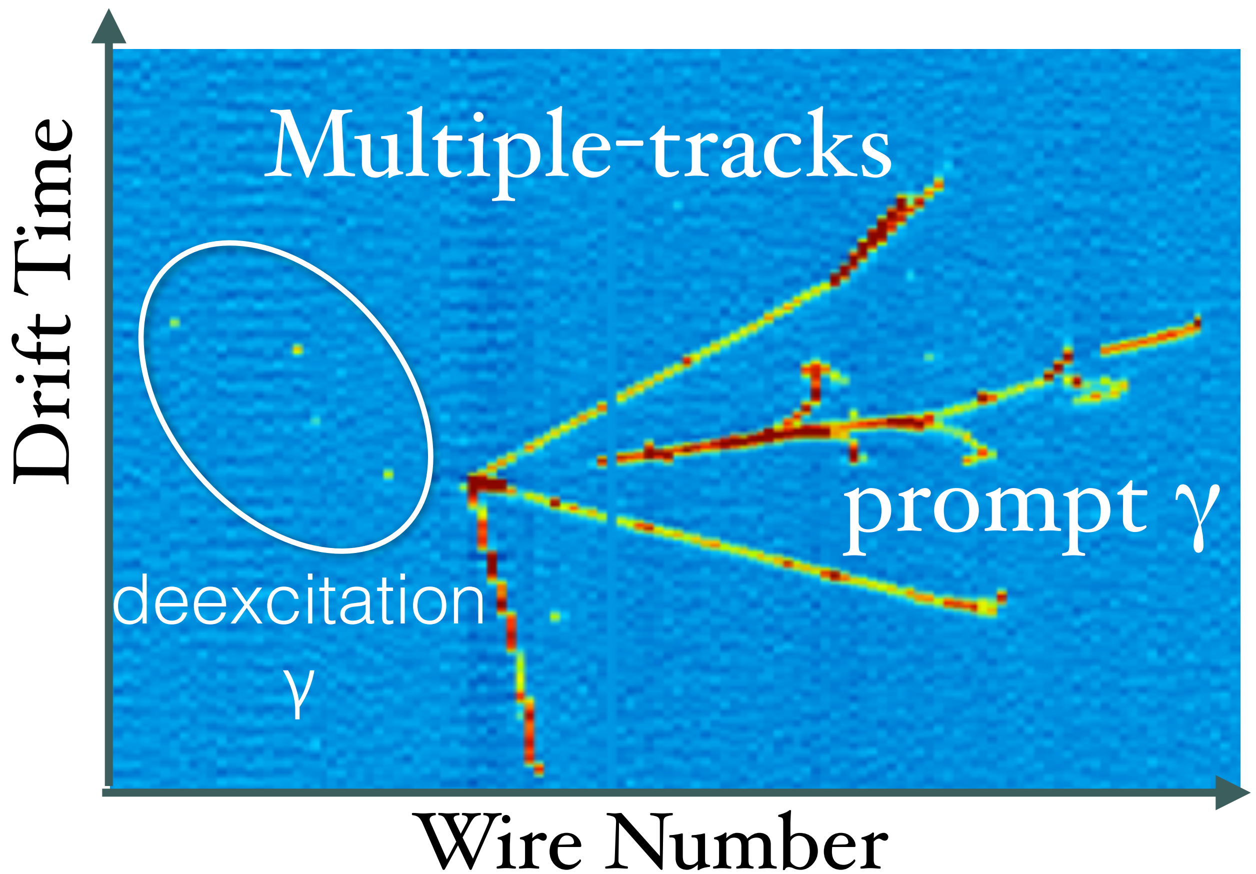
Fraction of selected events that are misID photons (assuming equal e and photon parent distribution)

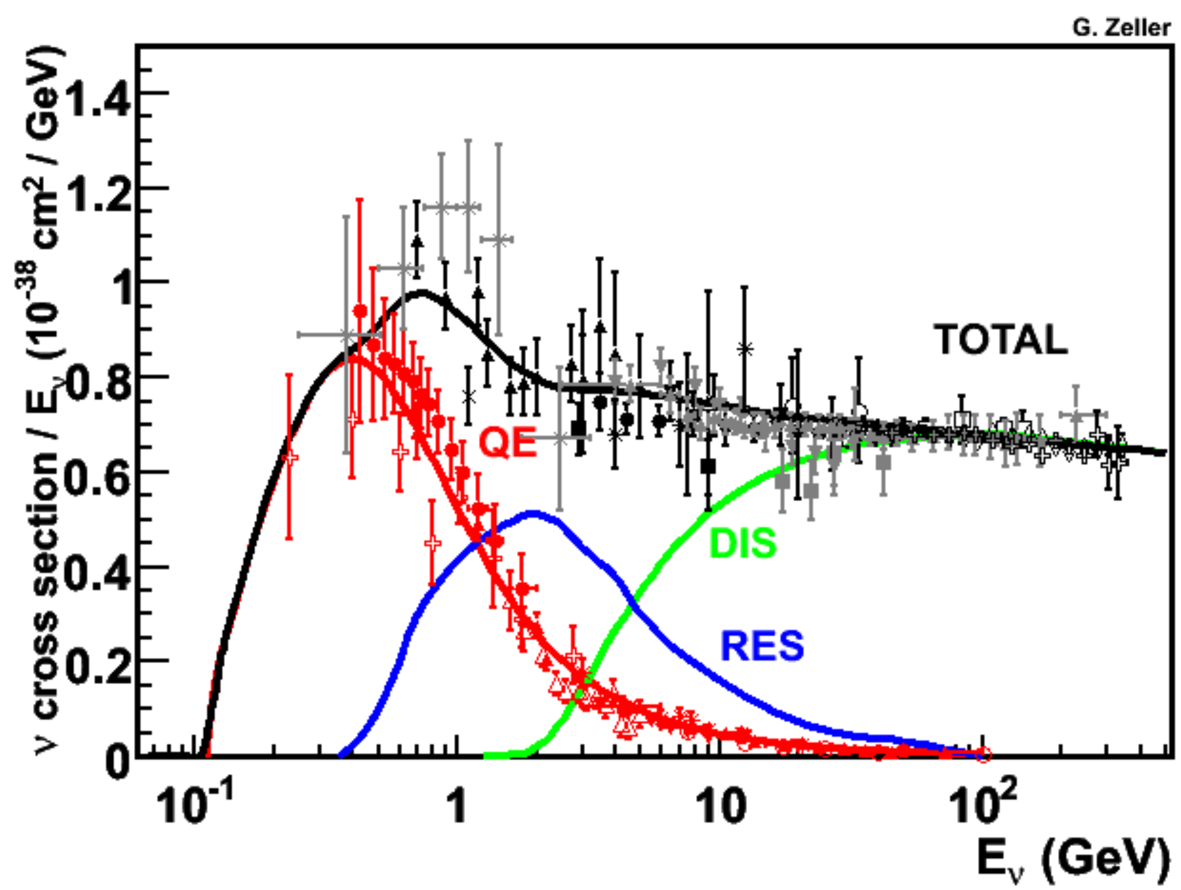




Low-E neutrino cross section measurements

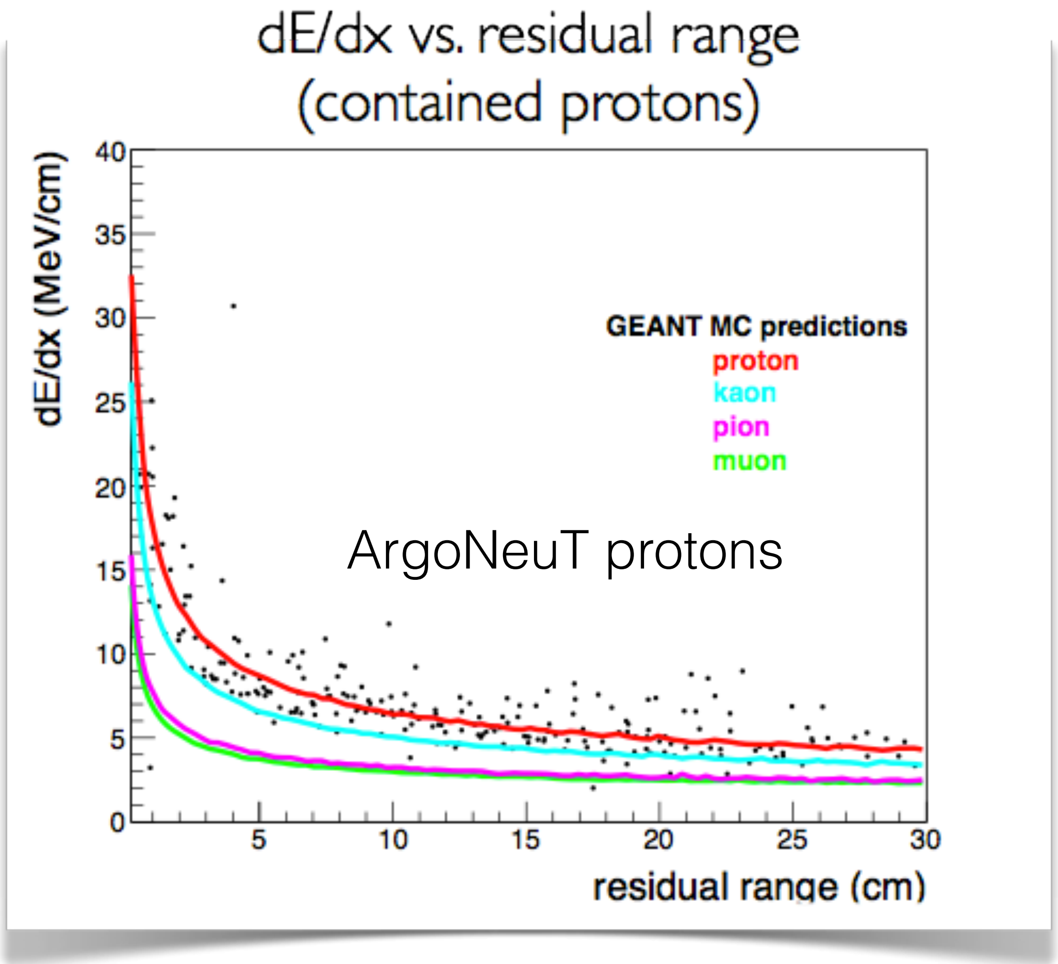
ArgoNeuT data

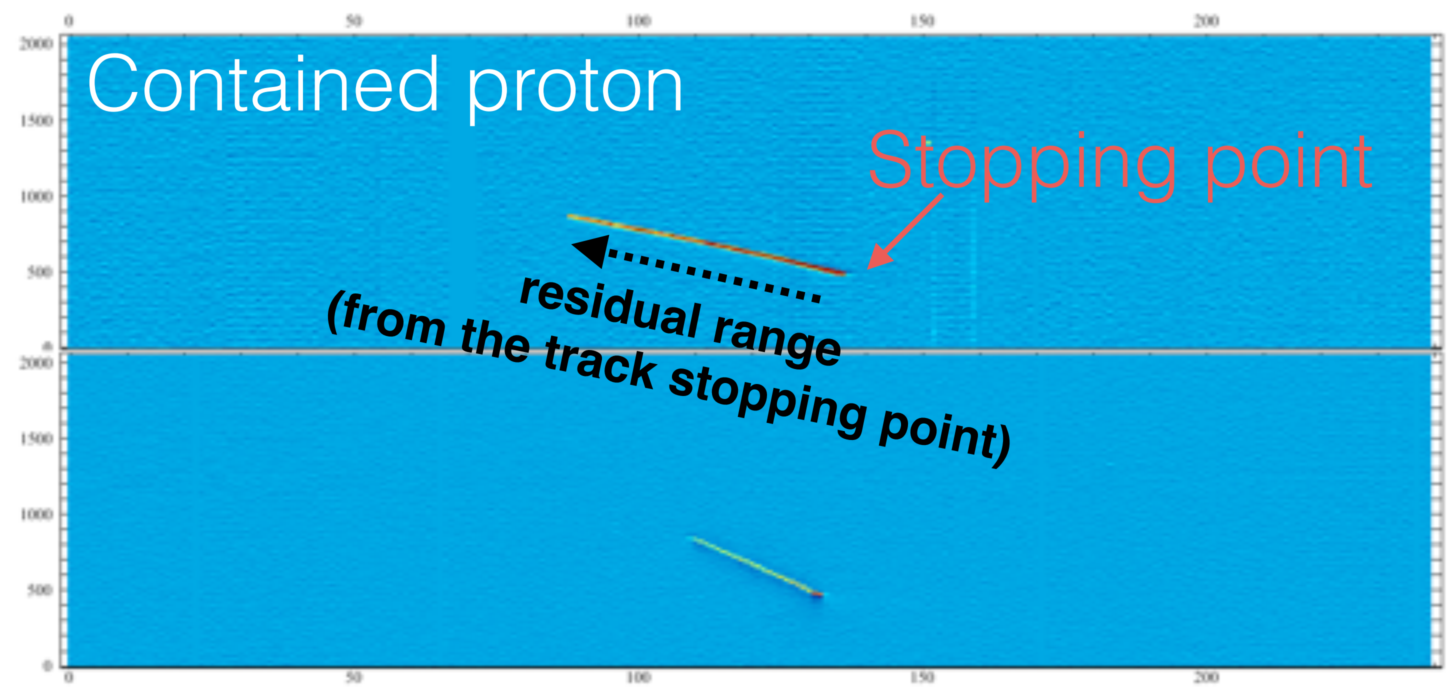




- High-resolution LArTPC provides detailed information on neutrino-Ar interactions.
    - Ideal for study of neutrino cross sections and nuclear effects.

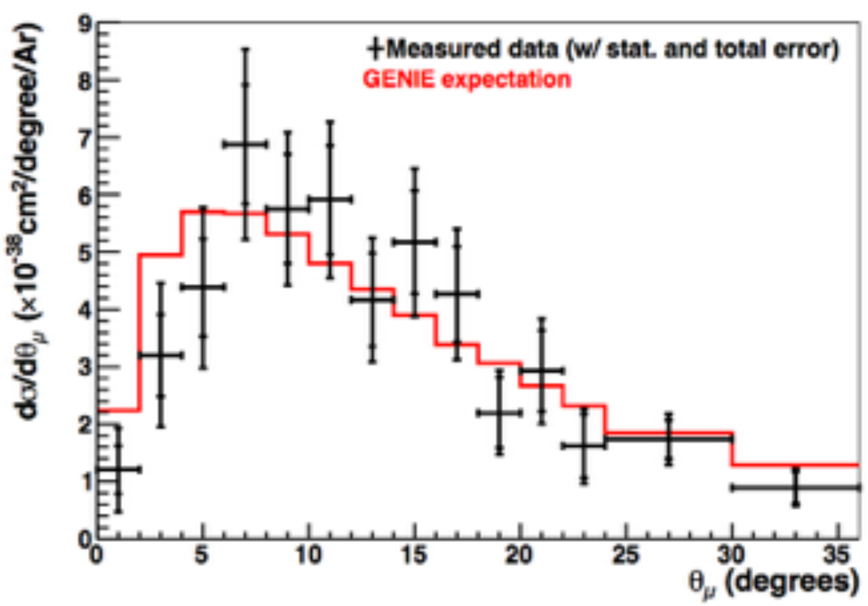
Calorimetry and PID



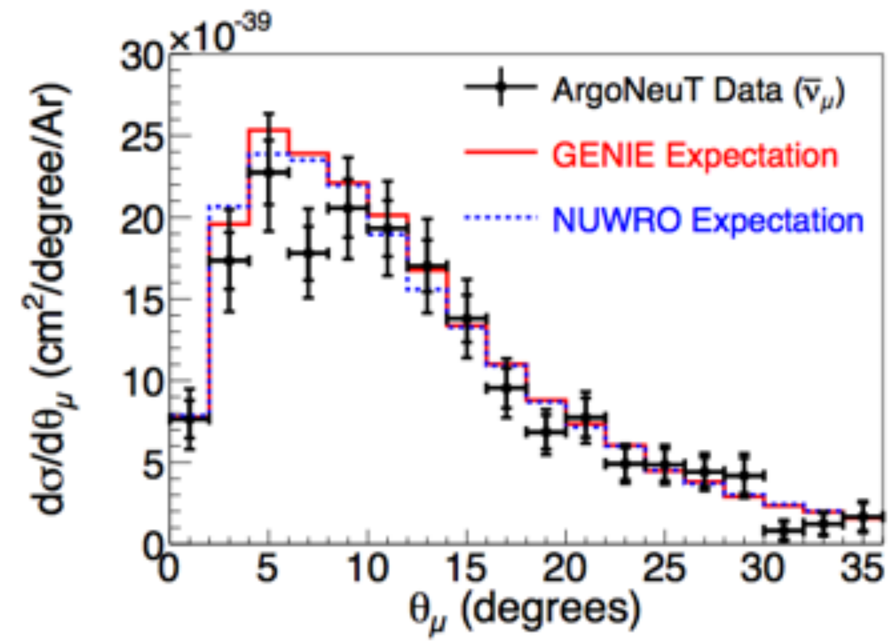


- dE/dx vs residual range for particle ID.
- 10% resolution on dE/dx provides good separation between protons and charged pions.
  - Physics: ionization, recombination, diffusion
  - Detector: Attenuation corrections, electronics response and noise
  - Reconstruction

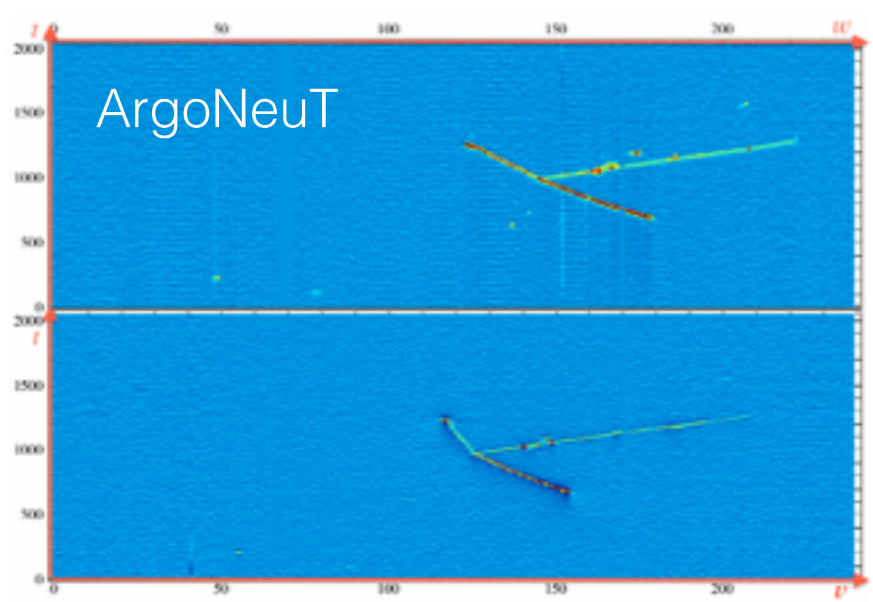
Cross section measurements



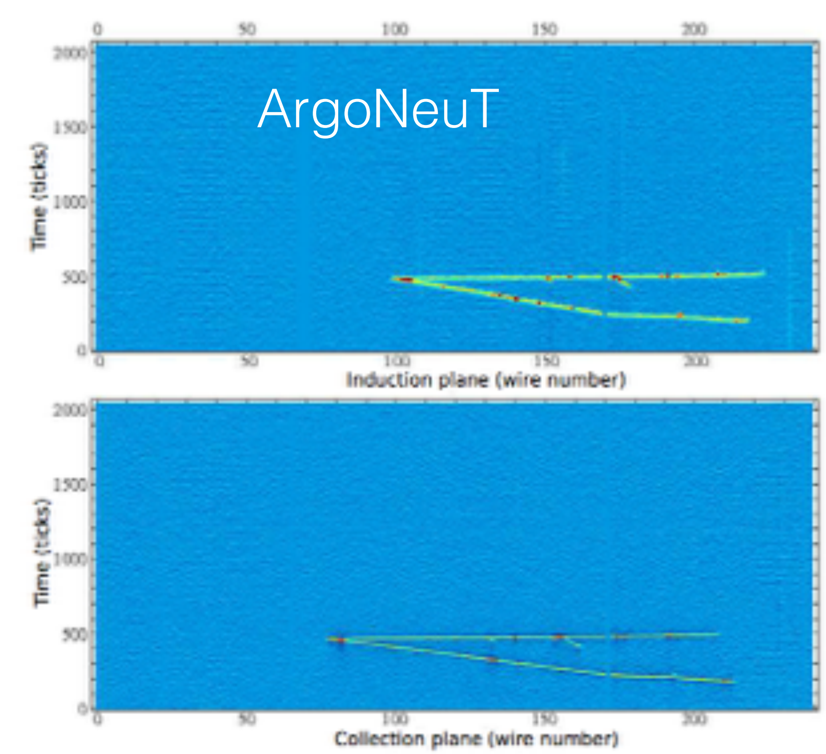
CC-inclusive, neutrino beam
1111.0103, PRL **108**, 161802, (2012)



CC-inclusive, antineutrino beam
1404.4809, PRD **89**, 112003 (2014)



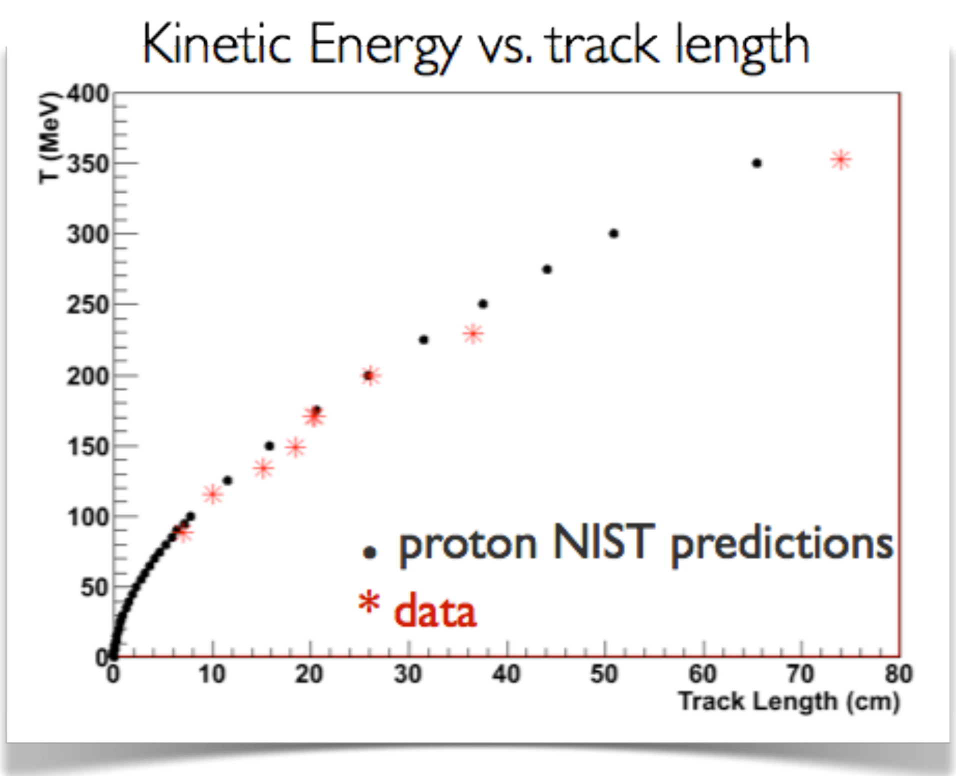
muon+back-to-back protons
1405.4261, accepted by PRD

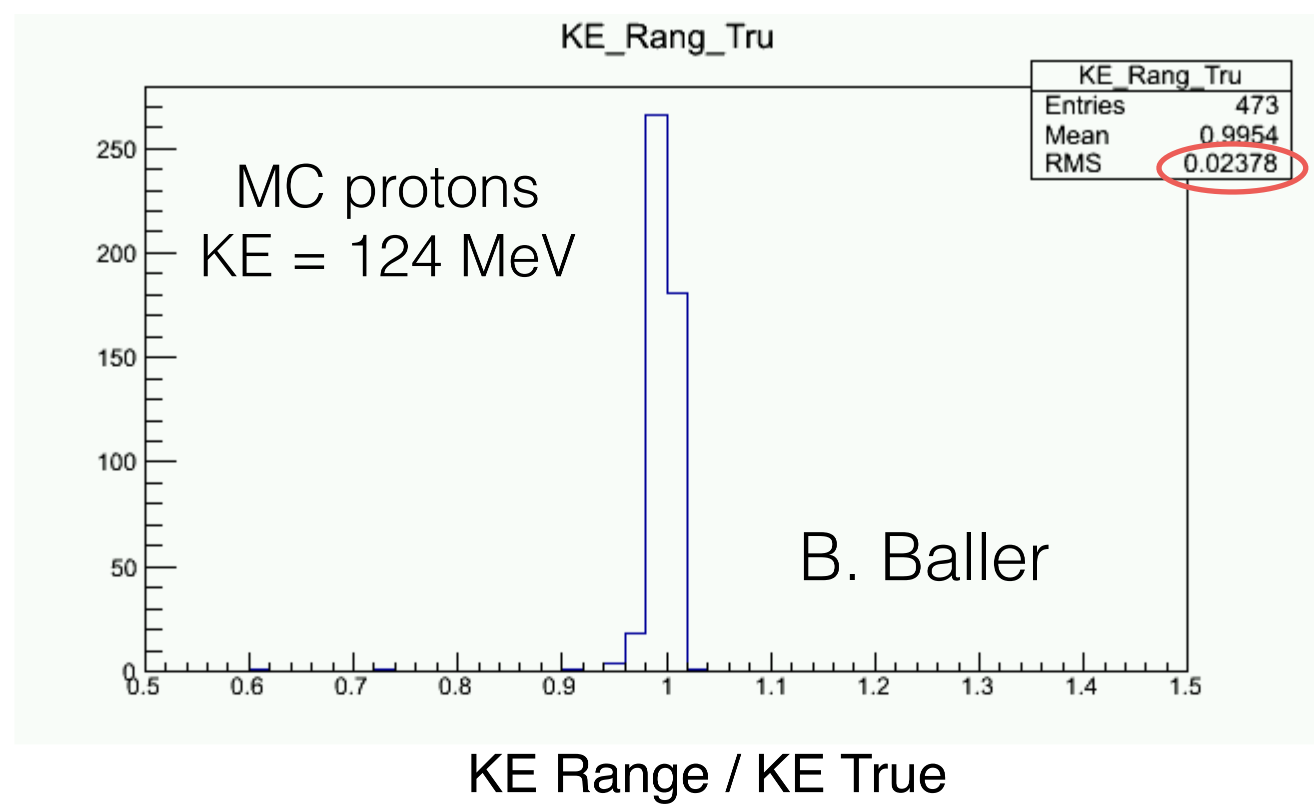


CC-coherent pion production
to be submitted soon

Momentum measurement

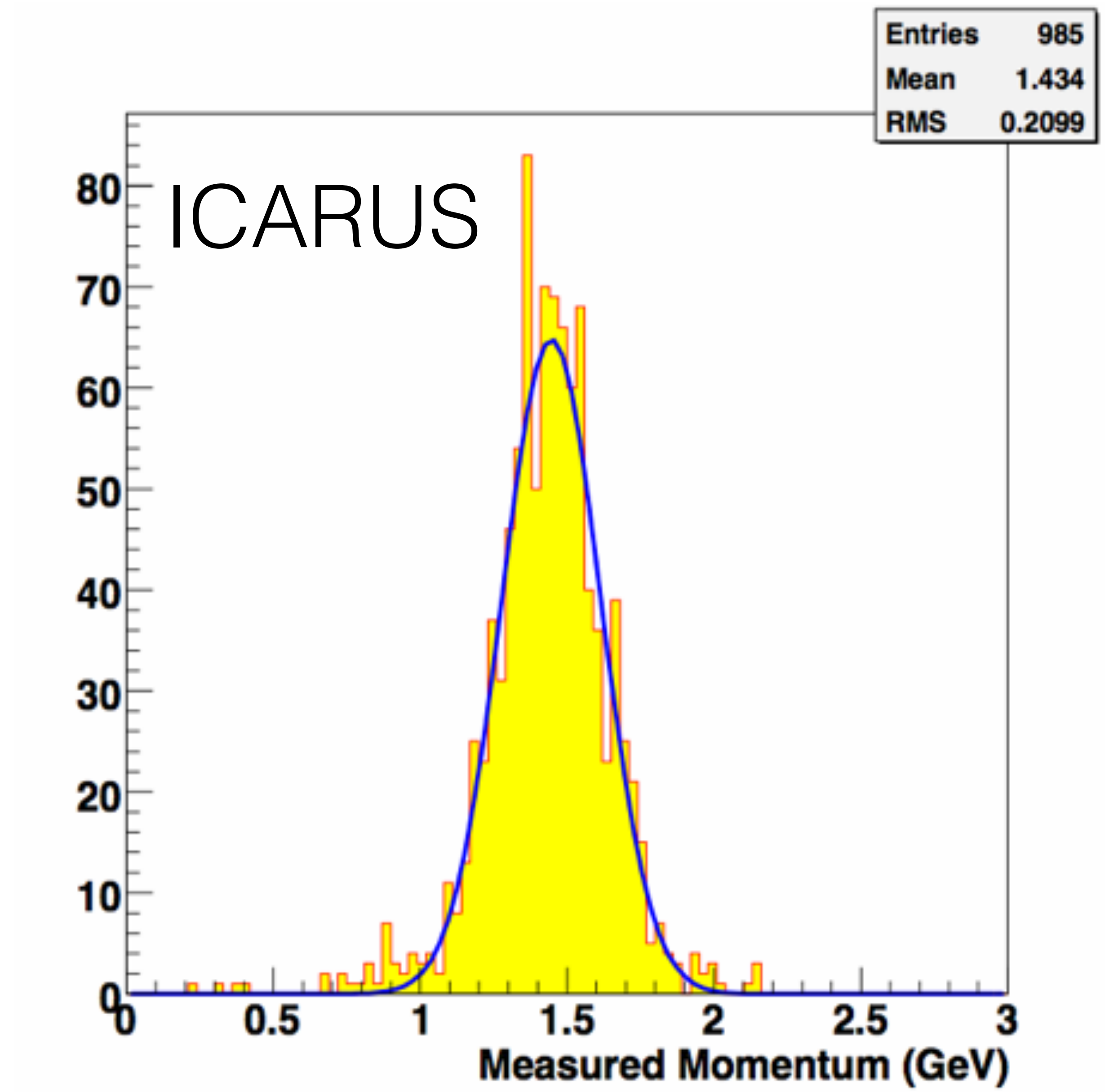
- For contained tracks, momentum can be measured by the track range.
- ArgoNeuT has shown the resolute is 2% for proton kinetic energy measured from range.





Multiple scattering

- In case of exiting muons, the energy calculation becomes even more difficult if you don't have a muon ranger behind your detector.
- Kalman tracking methods are able to reconstruct energies with a precision of 20% using multiple scattering. Eur.Phys.J.C48:667-676,2006
- A magnetic field would help.



Simulated 1.5 GeV muons.

R&D development

- Understanding LArTPC response to charged particles, photons and neutrons.
    - **LArIAT** and **CAPTAIN** are working towards that.
- Detector optimization
    - Wire spacing.
    - Studies of wrapped wires for LBNE.
    - Best way to use optical system to trigger signal and remove background.
- Software development is critical for getting physics results from LArTPCs.
    - Software session today.

Conclusions

- The next generation of neutrino experiments have the potential to discover new physics.
- LArTPCs are ideal detectors for searching for new physics in the neutrino sector because of their high resolution.
- The current work on LArTPC R&D is crucial for the planned experiments to succeed.