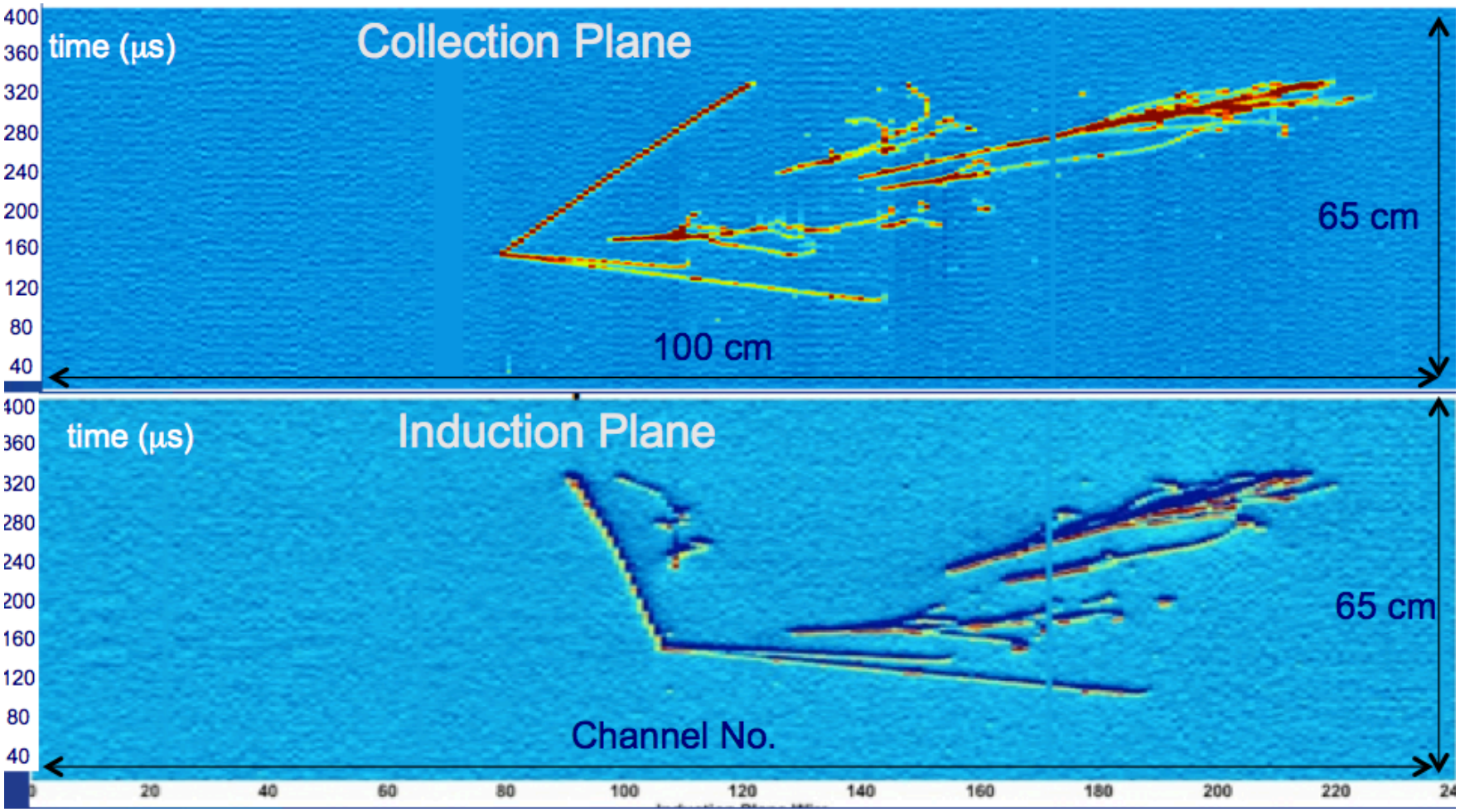
Liquid Argon Time Projection Chambers

Tingjun Yang
FNAL

9/26/13

Intensity Frontier Seminar

ArgoNeuT Event in NuMI Beam



3 tracks , 4 photon conversions,
many details

Outline

- LArTPC Basics
- History
- Technical details
  - Cryogenic vessels
  - LAr purity and monitors
  - TPC
- Physics reach
  - Neutrino physics
  - Other topics

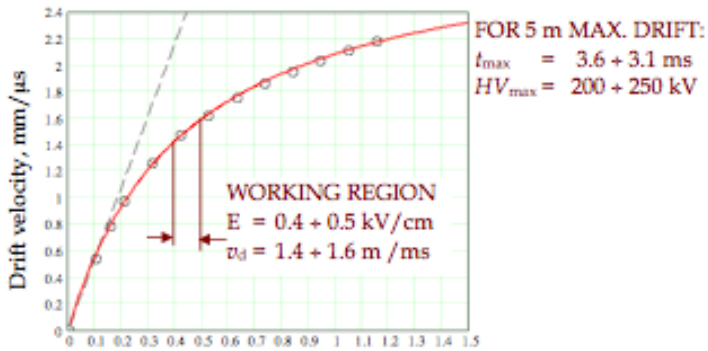
Nobel Liquids: Properties

- Ionization and scintillation light used for detection
- Low diffusion allows Ionization electrons to be drift over long distances in these liquids
- Excellent dielectric properties allow these liquids to accommodate very high-voltages
- Argon is relatively cheap and easy to obtain (1% of atmosphere)

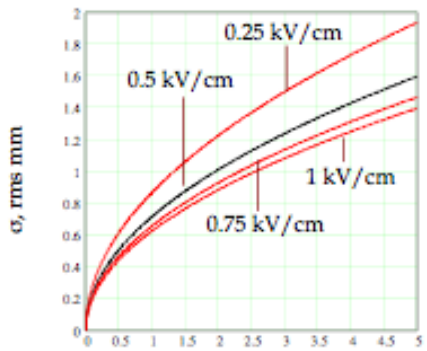
from Mitch Soderberg

	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
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation λ [nm]	80	78	128	150	175	
ppm in air	0	12	9500	1	0.1	

Drift velocity, diffusion, purity and attenuation



Drift velocity versus electric field in liquid argon



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$

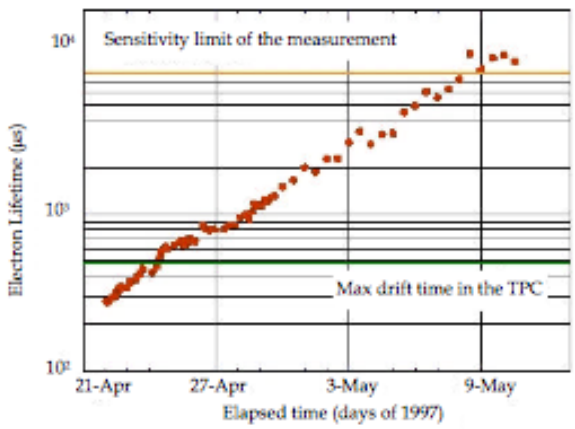
$D = 4.06\ \mathrm{cm^2/s}$

$\sigma_D = 0.9\ \mathrm{mm} \cdot \sqrt{T_D[\mathrm{ms}]}$

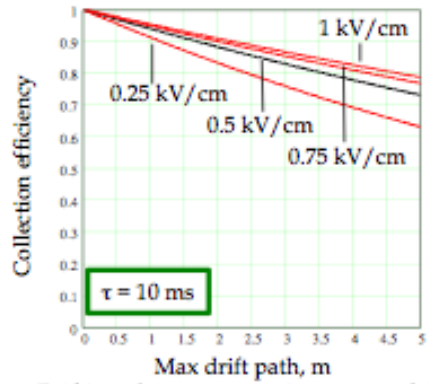
Longitudinal rms diffusion spread at 0.5 kV/cm

Average $\langle\sigma_D\rangle$ = 1.1 mm

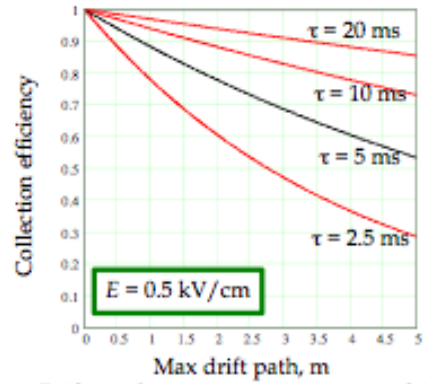
Maximum σ_{Dmax} = 1.6 mm



Purification rate for the 50L TPC



Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



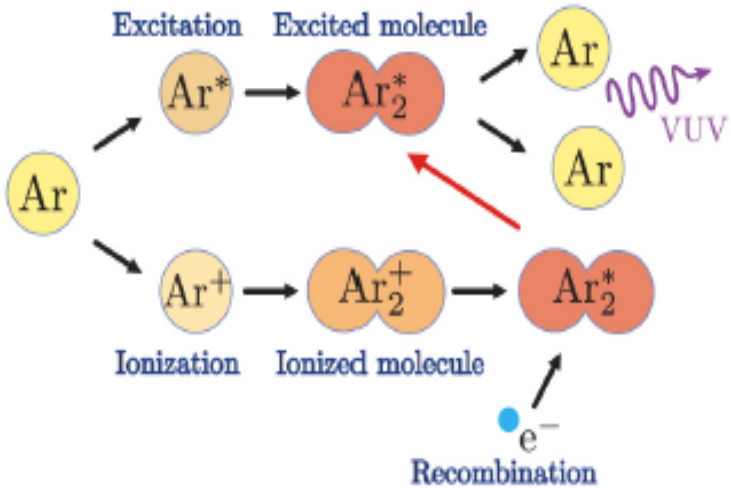
Drifting charge attenuation versus drift path at different electron lifetimes (E = 0.5 kV/cm)

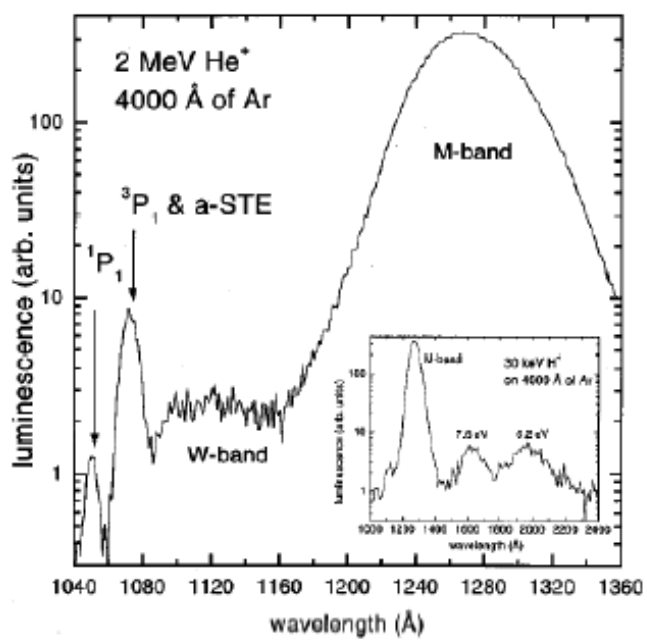
NuFact'01 – March 24-30, 2001 F. Sergiampietri LANNDD 22

- LAr ionization: W_e=23.6±0.5 eV - low detection thresholds and ~6k ionization electrons/mm/mip
- Electron affinity >0: does not attach electrons
- 1.6 mm/μs at 500V/cm; σ(mm)=$t^{1/2}$ (ms) 60; ppt O_2 -> 5 ms lifetime

S. Pordes

Light Production

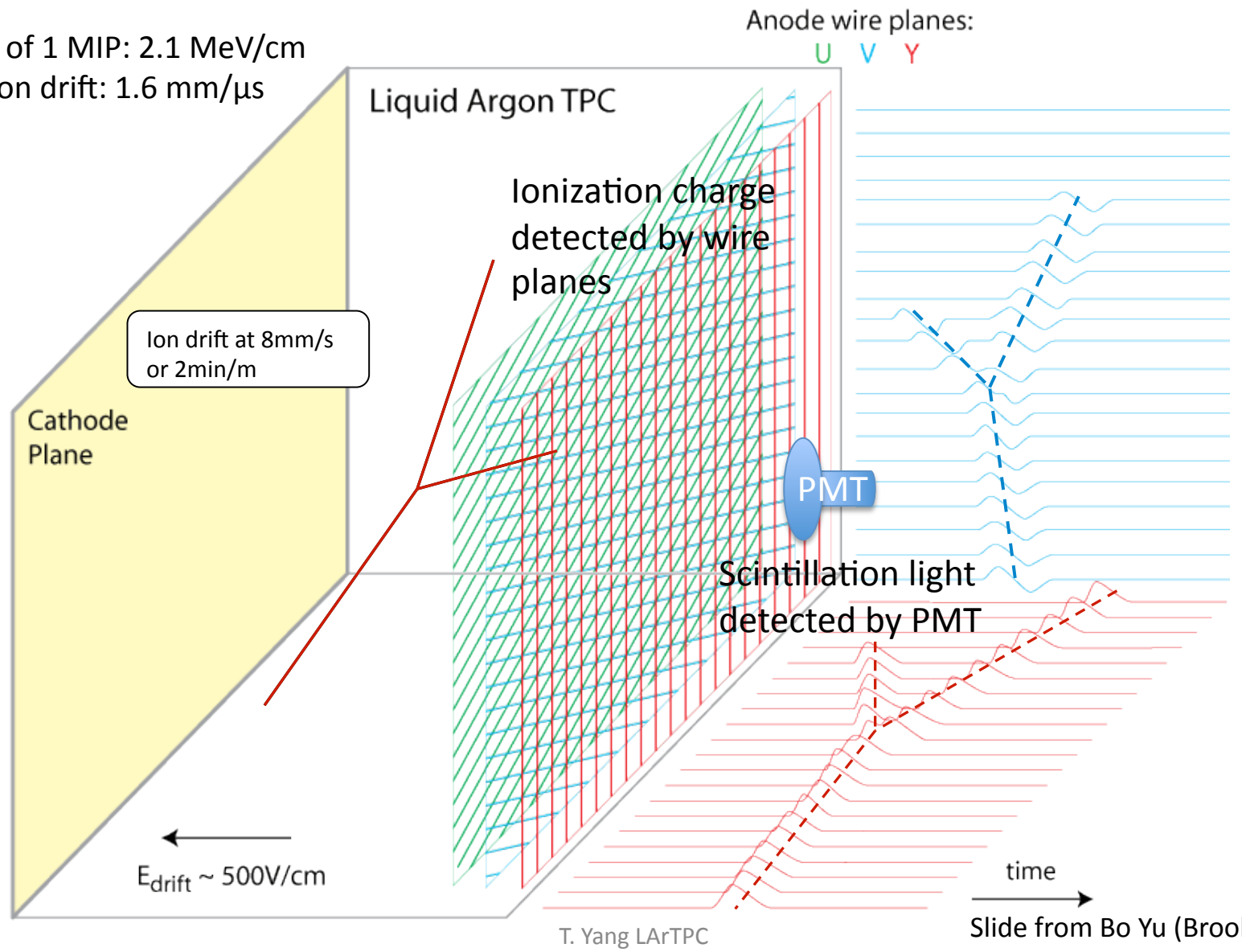




- LAr is an excellent scintillator: W_γ = 19.5 eV
- Singlet (t = 6 ns) and triplet (t = 1.6 μs) excimers both give spectrum peaked at λ=128nm (10 eV)
  - Ratio depends on ionization density
- Scintillation light provides trigger and t_0 (~ns)
  - ν beam window ~μs
  - Proton decay etc.

How does a LArTPC work?

dE/dx of 1 MIP: 2.1 MeV/cm
Electron drift: 1.6 mm/µs



Slide from Bo Yu (Brookhaven)

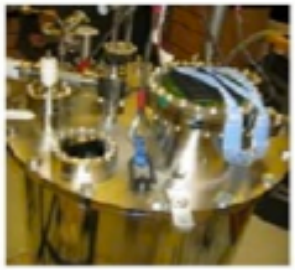
Development in Europe

- 1968 - Alvarez proposed the use of liquefied noble gases as detector media
- 1970's
  - LAr & LXe calorimeters in use, LAr TPC prototypes
  - Willis, Chen, Radeka, Gatti, Rubbia contributions
- 1977 – Carlo Rubbia proposed the LAr TPC
- 1985 – ICARUS (T600) proposal at Gran Sasso
  - 1993: Cosmic rays tracked with a 3 ton LAr TPC
  - 2010 – 2012: T600 exposed to CNGS ν beam
- Continuous development – ARGONTUBE (5m), GLACIER (100 kt LAr LEM)

ICARUS pioneer in LAr TPC technology, NIMA 527, 329 (1990)
The U.S. LAr TPC program uses ICARUS as a foundation

Development in the US

Yale TPC



Location: Yale University
Active volume: 0.002 ton
operational: 2007

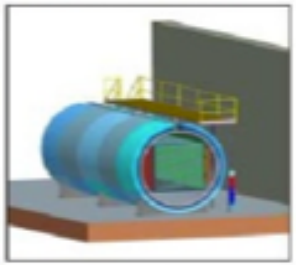
Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

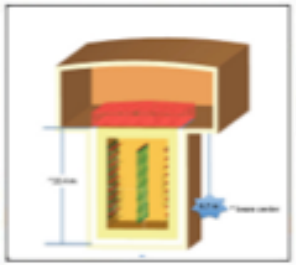
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: june 2009

MicroBooNE



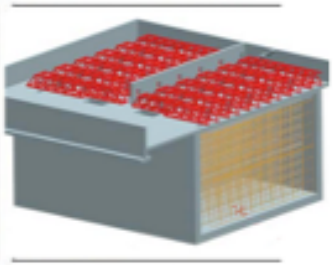
Location Fermilab
Active volume: 0.1 kton
Construction start: 2011

LAr1



Location: Fermilab
Active volume: 1 kton
Construction start: 2016?

LBNE



Location: Homestake
Active volume: 10 kton
Construction start 2020

Luke

Location: Fermilab
Purpose: materials test st
Operational: since 2008

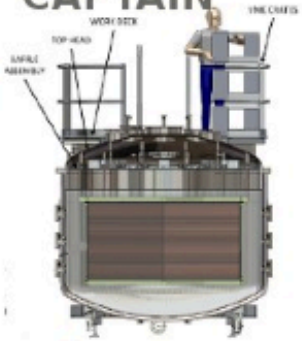
LAPD

Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LArIAT

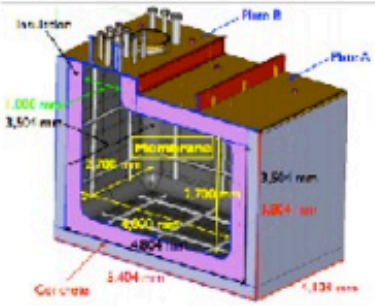
Location: Fermilab
Purpose: LArTPC calibration
Operational: 2014 (phase 1)

CAPTAIN



Location: LANL
Purpose: LArTPC calibration
Operational: 2014

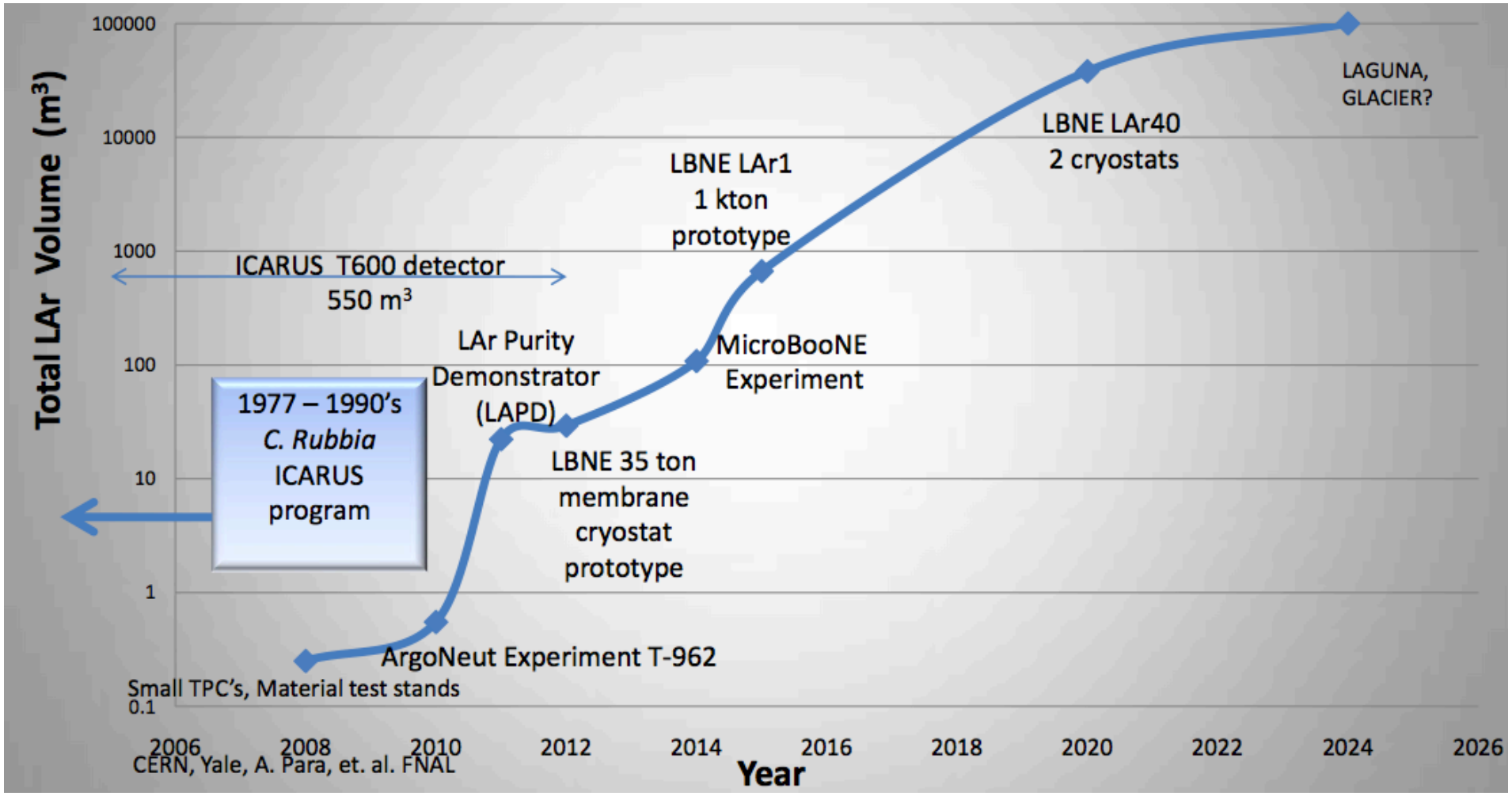
LBNE 35 Ton



Location: Fermilab
Purpose: purity demo
Operational: 2013

Details of many projects will be discussed as case studies.

Volume of LAr TPC Detectors with Time



Russ Rucinski, TIPP 2011

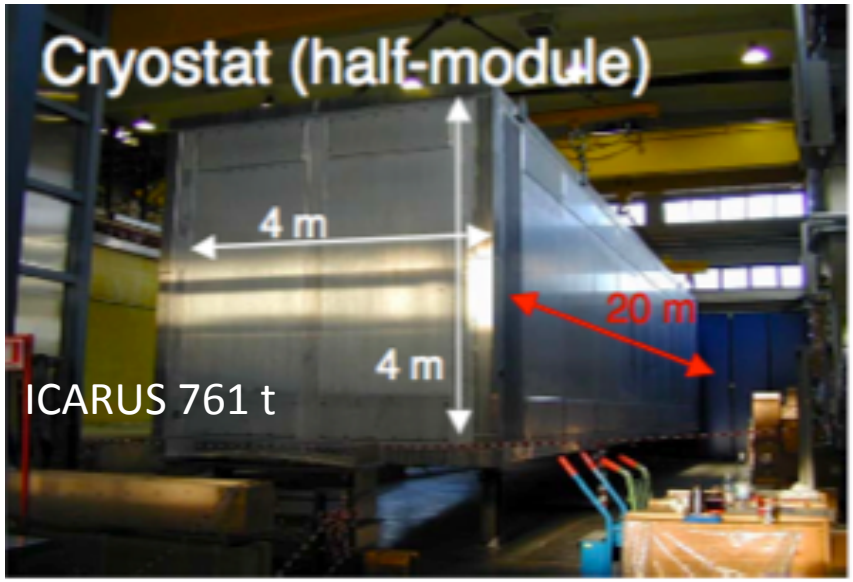
Technical Details

- Cryogenic vessels (cryostat)
- LAr purity and monitors
- TPC

Cryostat Requirements

- Sufficiently tight to maintain low impurity level
- Sufficiently low thermal loss
  - Passive insulation (vacuum/foam)
  - Active refrigeration (LN_2)
- Suitable for underground construction and operation
- Safety concerns
- Scalable

Cryostats

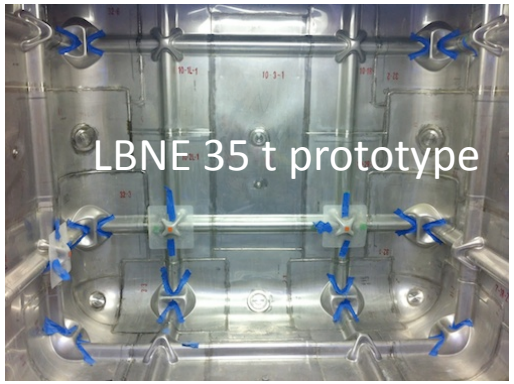

Cryostat (half-module)
4 m
20 m
4 m
ICARUS 761 t

CRYOSTAT
ArgoNeuT 0.76 t

LAPD 30 t

MicroBooNE 170 t

CAPTAIN 10 t


LBNE 35 t prototype

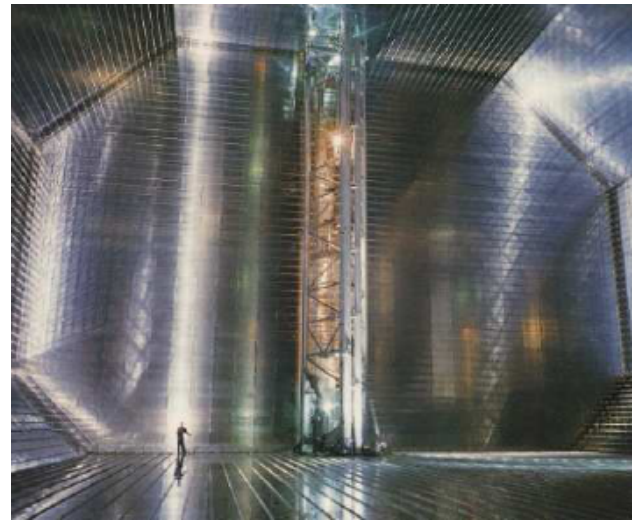
MicroBooNE Cryostat

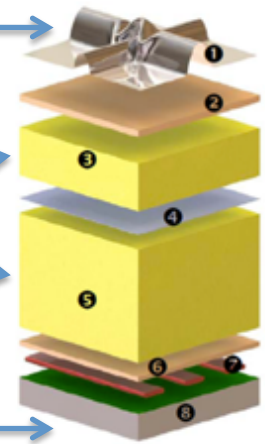
- MicroBooNE cryostat has a 150” diameter and is 40 ft long and 6/17” thick
- Will be insulated with foam on outside
- Will hold 170 t of LAr, fiducial volume of 60 t

Note: cryostat on its side

Membrane Cryostat

- One option for future large LAr vessels
  - Adopted by LBNE
- Design used in LNG (Liquefied Natural Gas) tankers
- Stainless steel membrane (2-3 mm) contains cryogenic liquid
- Foam insulated
- Surrounding rock/concrete provides mechanical support
  - Efficient use of the excavated cavern volume



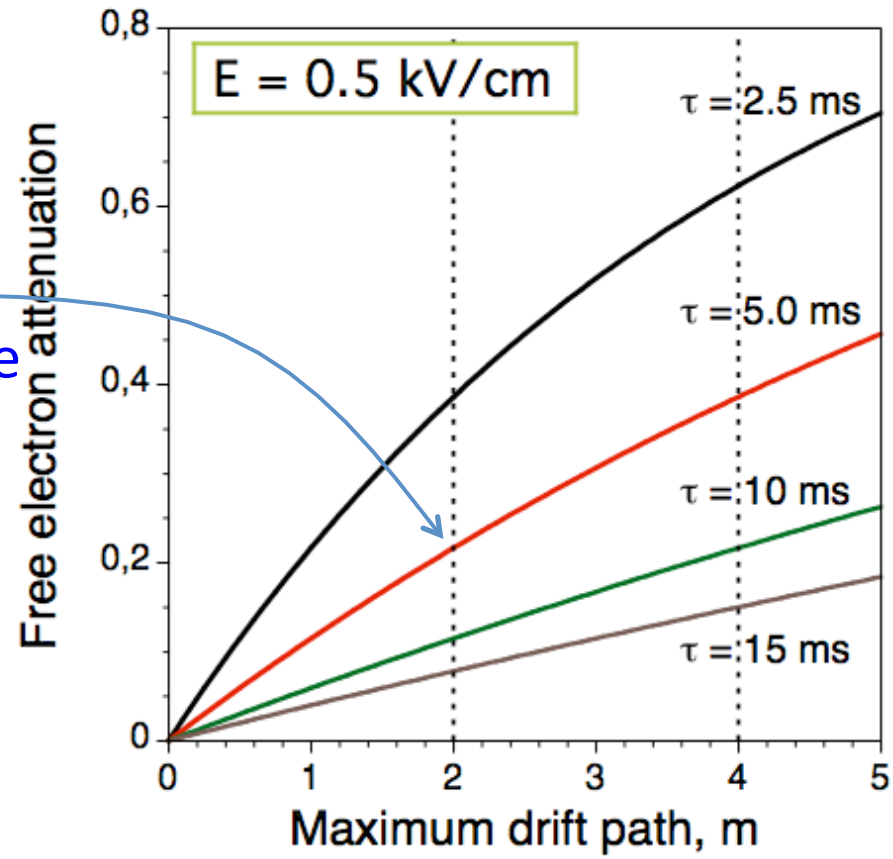


1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Concrete covered with moisture barrier

35 Ton Prototype at FNAL

Purity Requirement

- Electro-negative contaminants
  - Electron affinity <0
  - O_2 & water
- If 20% signal loss is OK for 2m drift
  - Need 5 ms electron lifetime ~60 ppt O_2 contamination
  - LAr supply typical 1 ppm
- N_2 < 1 ppm for light collection



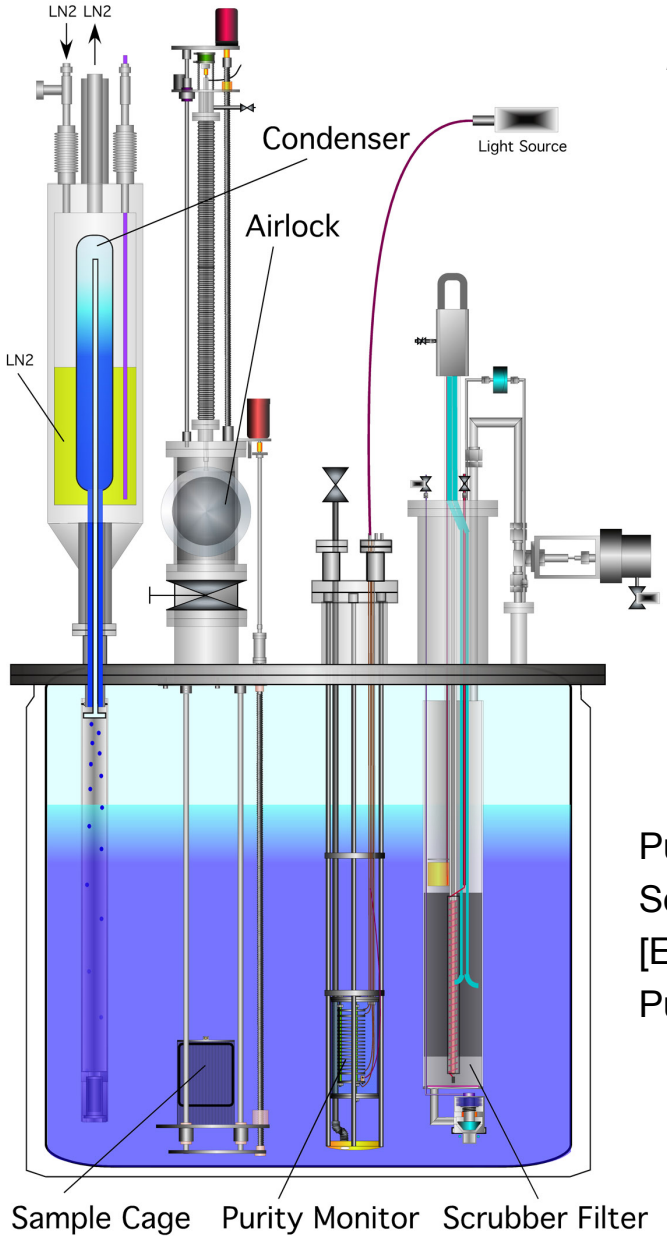
R&D Efforts at Fermilab

- Materials Test System (MTS)
  - Study materials effects on electron lifetime

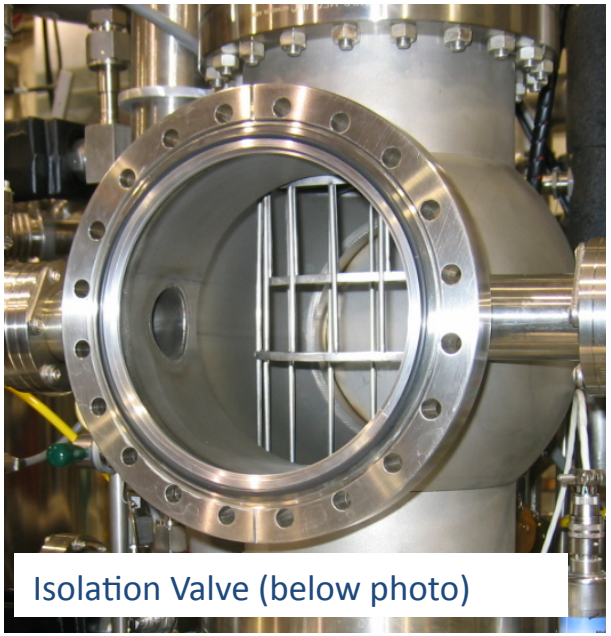
- Liquid Argon Purity Demonstrator (LAPD)
  - Achieve sufficient electron lifetime without evacuation

Test Cryostats and Infrastructure

Luke (Materials Test System)



insertion of materials without exposure to vacuum



Put materials in Sample Cage in the Argon Lock
Seal the Argon Lock (open in photograph).
[Evacuate the Argon Lock (or not).]
Purge with pure argon gas (available from the cryostat).

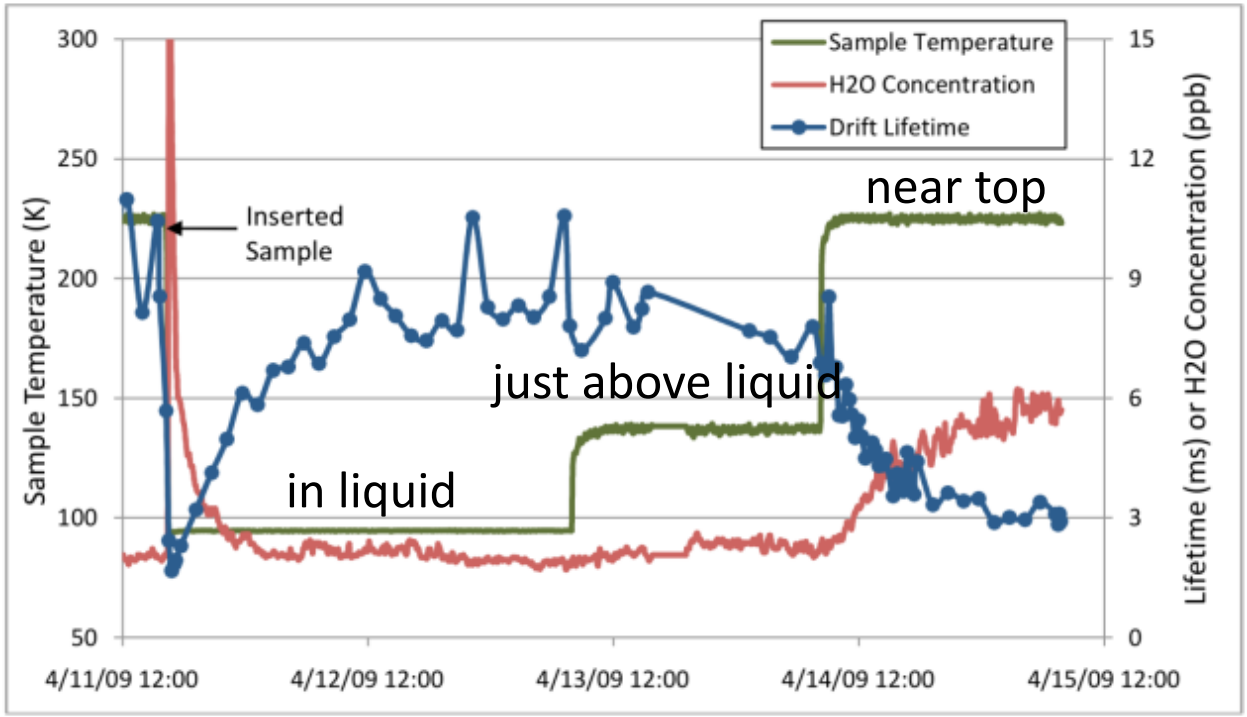
Summary of Results

Material	Sample Surface Area (cm^2)	Effect of Material on Electron Drift Lifetime (LT)			Comments
		94 K liquid	≈120 K vapor	≈225 K Vapor	
Red-X Corona Dope[a]	100	None	None	LT Reduced from 8 to 1 ms; recovery observed.	H_2O concentration not monitored.
Deactivated Rosin Flux[b]	200	None	Not Tested	LT reduced from 8 to 1.5 ms recovery observed	H_2O concentration not monitored.
FR4	1000	None	Not Tested	LT reduced from 8 to <1 ms	Outgassed enough H_2O at 225 K to saturate sintered metal return.
Taconic[c]	600	None	Not Tested	LT reduced.	Sample outgases water at 225 K.
Hitachi BE 67G[d]	300	None	Not Tested	LT reduced; recovery observed	Sample outgases water at 225K; outgassing reduced over time.
TacPreg[e]	200	None	None	LT reduced; recovery observed	Sample outgases water at 225 K; outgassing reduced over time.
FR4, y-plane wire endpoint for uBooNE	225	None	None	LT reduced from 8 to 3 ms	Sample outgases water at 225 K.
FR4, y-plane wire endpoint for uBooNE	225	None	None	None	Sample was evacuated in airlock prior to testing
FR4, y-plane wire cover for uBooNE	225	None	None	None	Sample was evacuated in airlock prior to testing
Devcon 5-min epoxy	100	None	None	LT reduced from 10 to 6 ms; some recovery observed	Sample outgases water at 225 K.

Nucl.Instrum.Meth. A608 (2009) 251-258
FERMILAB-PUB-09-355-E

Water Effects

FR-4 based circuit board – from Airlock *with purging only*



Significant change in H_20 reading and significant reduction in lifetime

Water is the dominant contaminant, not O_2, for lifetimes of 5 – 10 msec
Not a contaminant if the materials containing it are in LAr

Purification in a Massive LAr TPC

- Previous experiments (ICARUS, ArgoNeuT etc.) required evacuation of the tank as the first step
  - This becomes expensive for large tanks

- Liquid Argon Purity Demonstrator is designed to demonstrate sufficient electron lifetime can be achieved without initial evacuation of the tank.

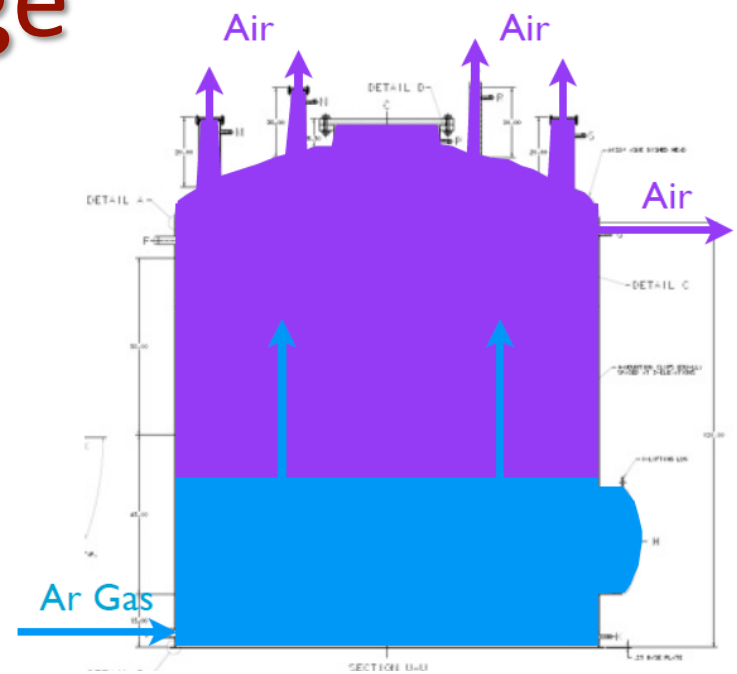
- Purification in 3 steps
  - Purge vessel with argon gas
  - Circulate argon gas through filter vessels
  - Introduce and circulate LAr through filter vessels

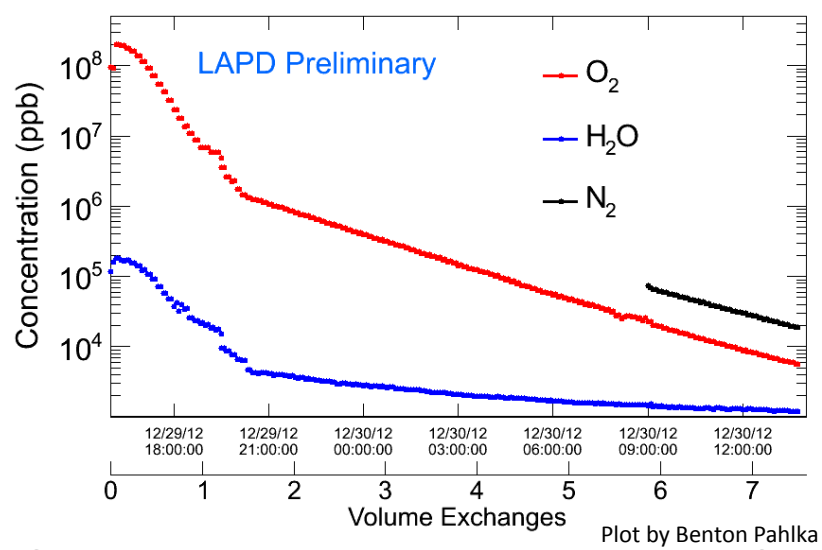
Liquid Argon Purity Demonstrator

- The Liquid Argon Purity Demonstrator (LAPD) serves as a workhorse test bed for liquid argon R&D at FNAL
- First large scale LAr system at FNAL, invaluable experience
- Demonstrated purification without evacuation of a 30 ton cryostat for the first time
- High electron lifetimes have been achieved, on the order of 5 ms

The Purge

- Pump room temperature argon gas into the tank
- Argon gas acts as a piston pushing ambient air out
  - O_2 from 21% to 6 ppm
  - N_2 from 78% to 18 ppm
  - H_2O from 200 ppm to 1.2 ppm
  - Measured using commercial gas analyzers

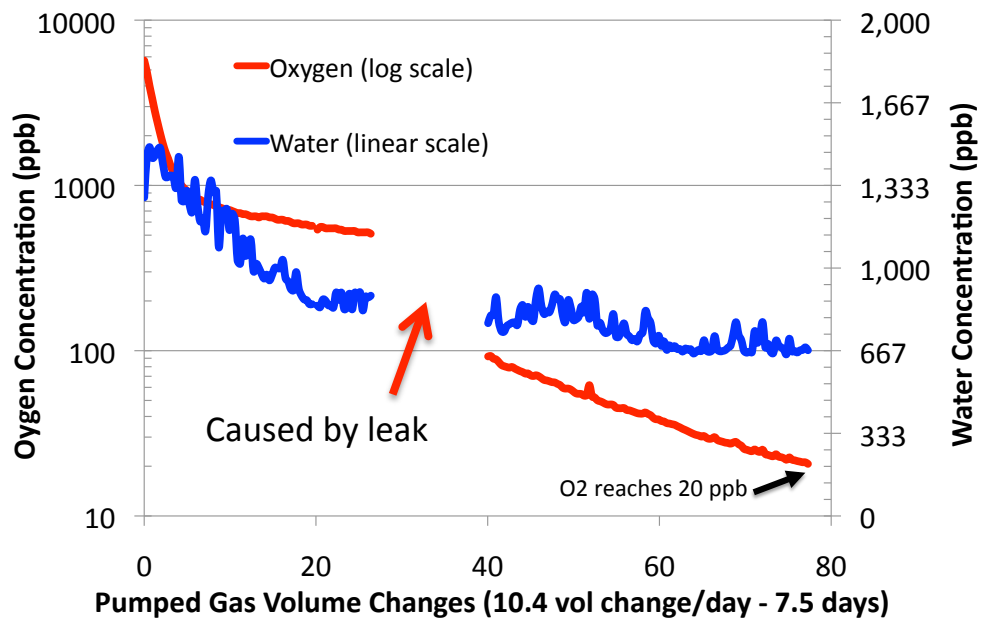




Plot by Benton Pahlka

Gas Recirculation

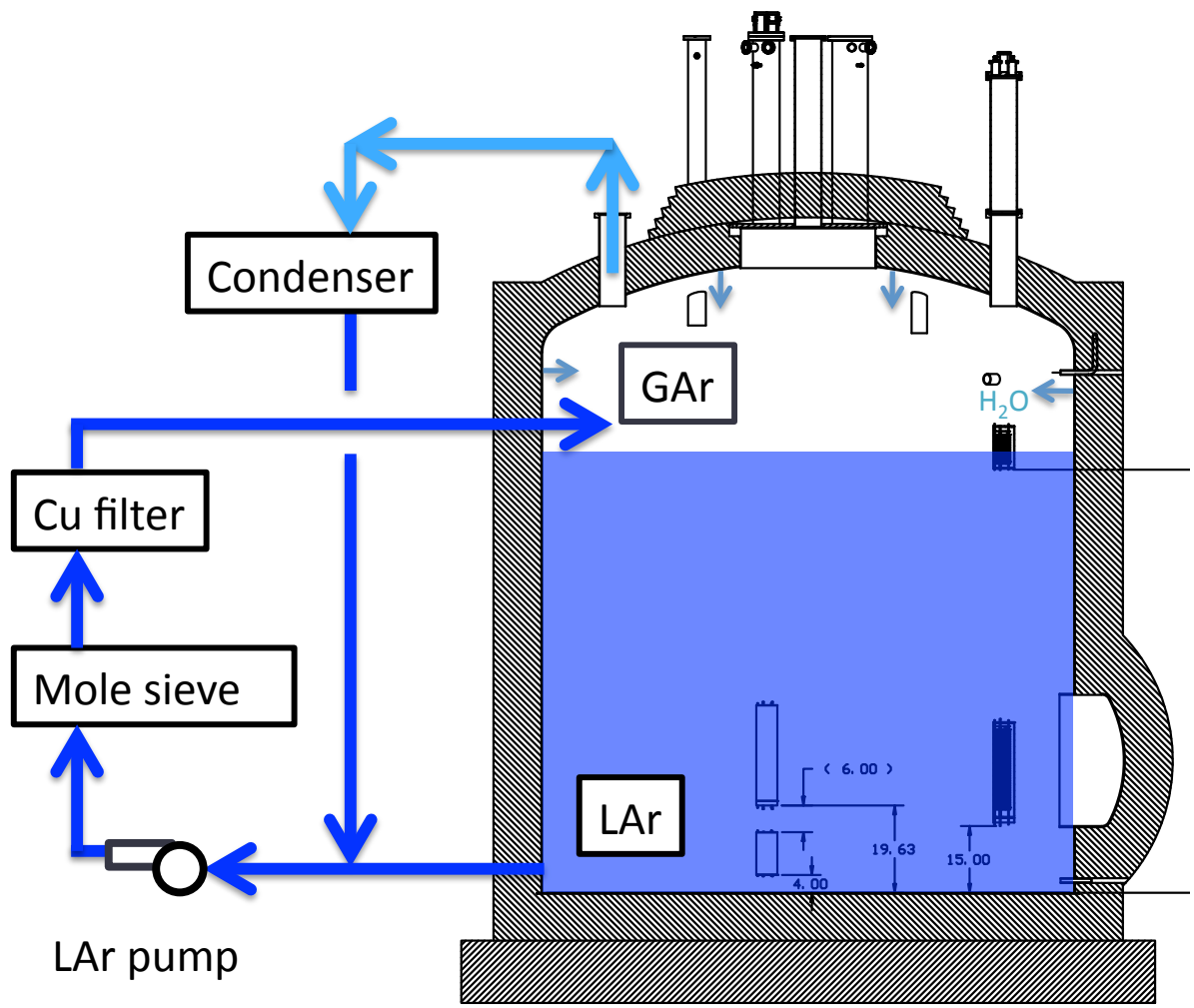
- Run gas through filters, same as for the liquid
- Useful for debugging
- Aim to bring H_2O outgassing rate to match filtration rate
- O_2 -> 20 ppb
- H_2O->667 ppb
- N_2->13 ppm



Plot by Terry Tope

Introduction of Liquid

- Molecular sieve removes H_2O
- Cu removes O_2
- LN_2 driven condenser reliquefy argon boil off
- Condensed LAr returns to the liquid pump
- Recirculation started at 2.42 vol change/day
- 1 millisecond electron lifetime achieved after 6.6 volume changes
- Stabilized at 5ms after 60 volume changes (60 ppt)



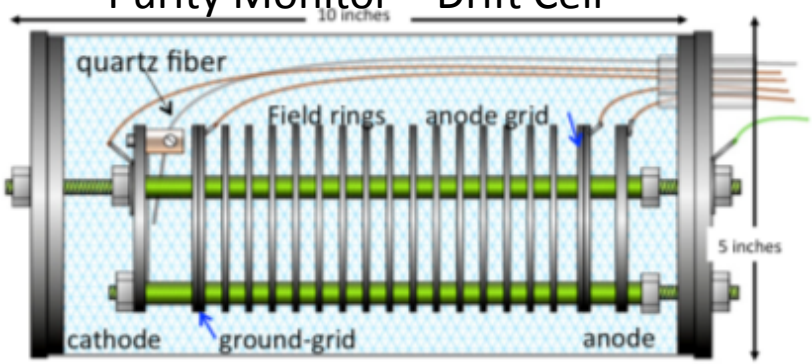
D0 LAr: <200 ppb O_2, 8 ppm N_2, tiny H_2O

Purity Monitors

NIMA 292, 580 (1990)

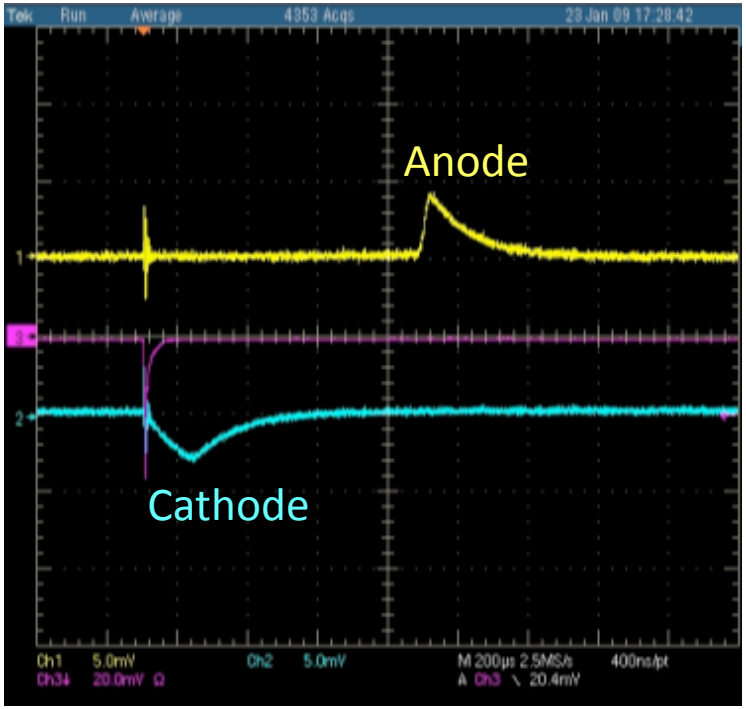
- Use purity monitors, consisting of a field cage, photocathode and anode

Purity Monitor – Drift Cell



- Measure electron signal loss from cathode to anode to find lifetime:

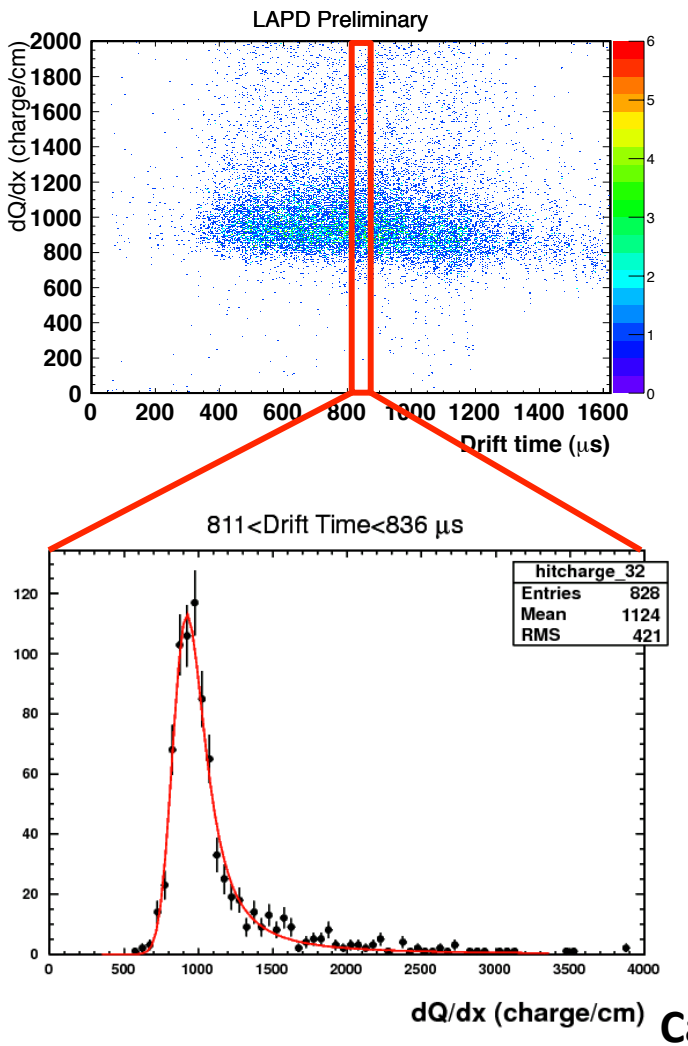
$$Q_{anode} = Q_{cathode} \times \exp(-t_{drift} / \tau)$$



PrM scope signal

- Observed lifetimes on the order of 5 ms

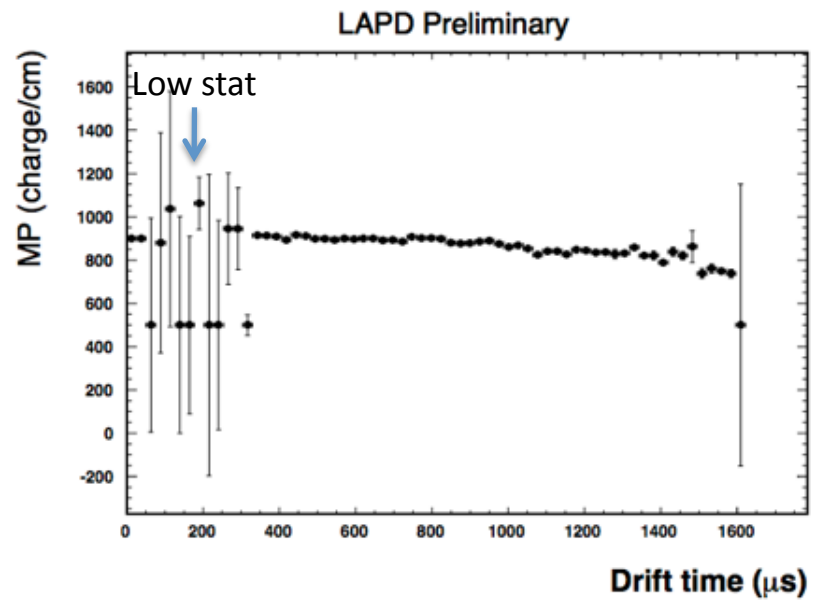
Measuring Purity with Muons



— Select single muon events between $50° < \theta < 70°$ and remove δ rays

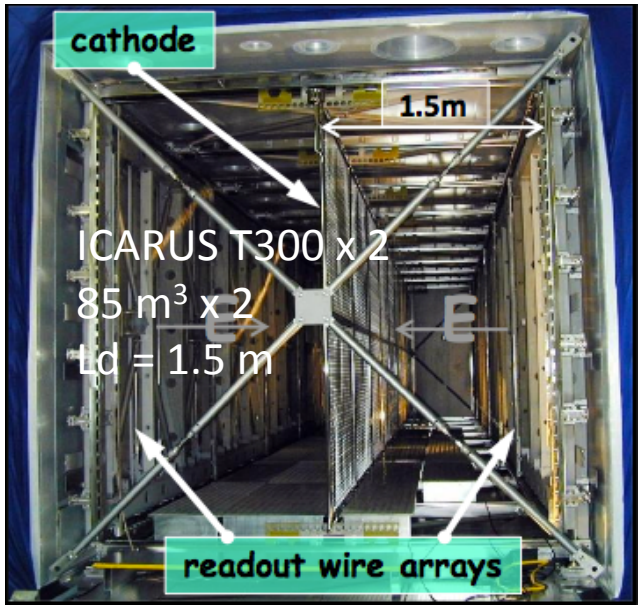
— Use dQ/dx of muon hits as a function of drift time to measure charge attenuation

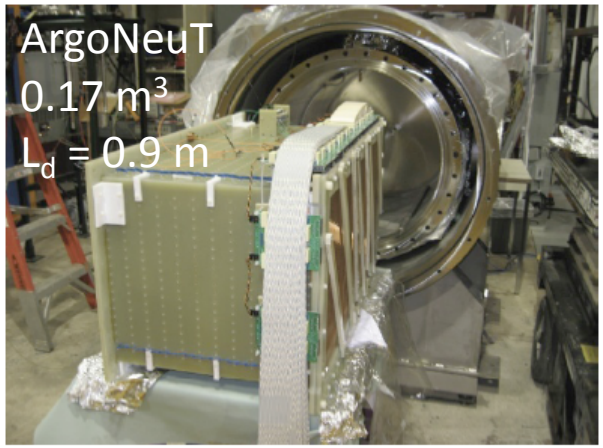
— Less than 20% attenuation over 1 m

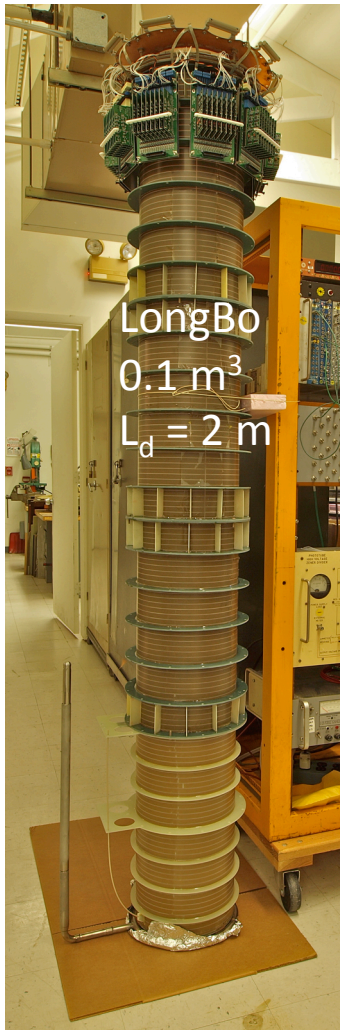


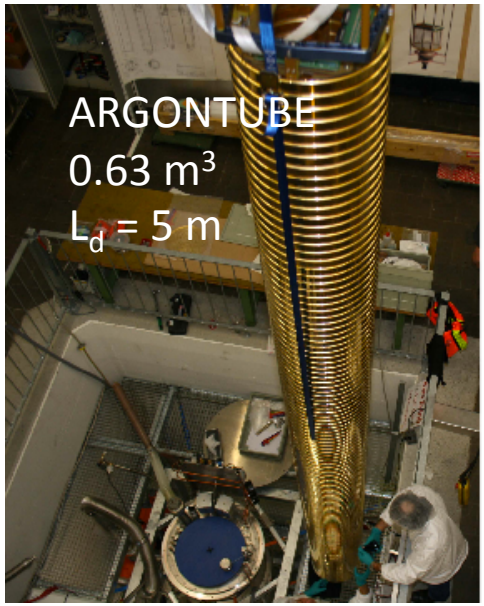
Can also use ν-induced muons(1205.6702) and UV laser (1304.6961).

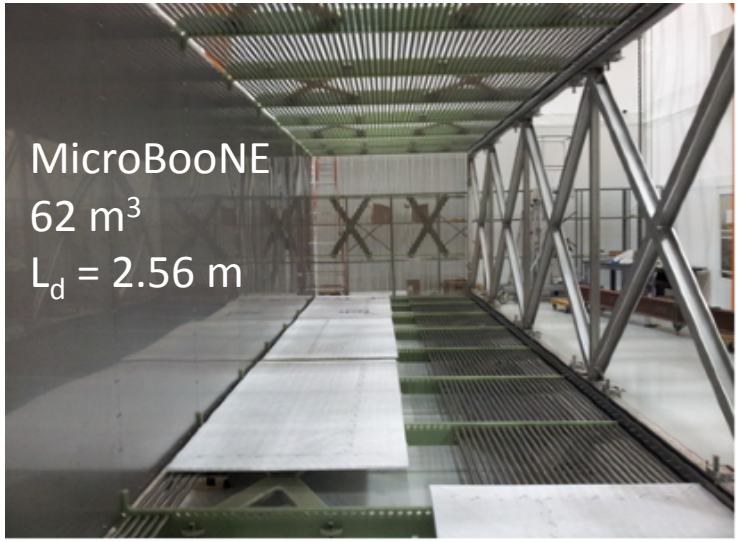
Time Projection Chambers





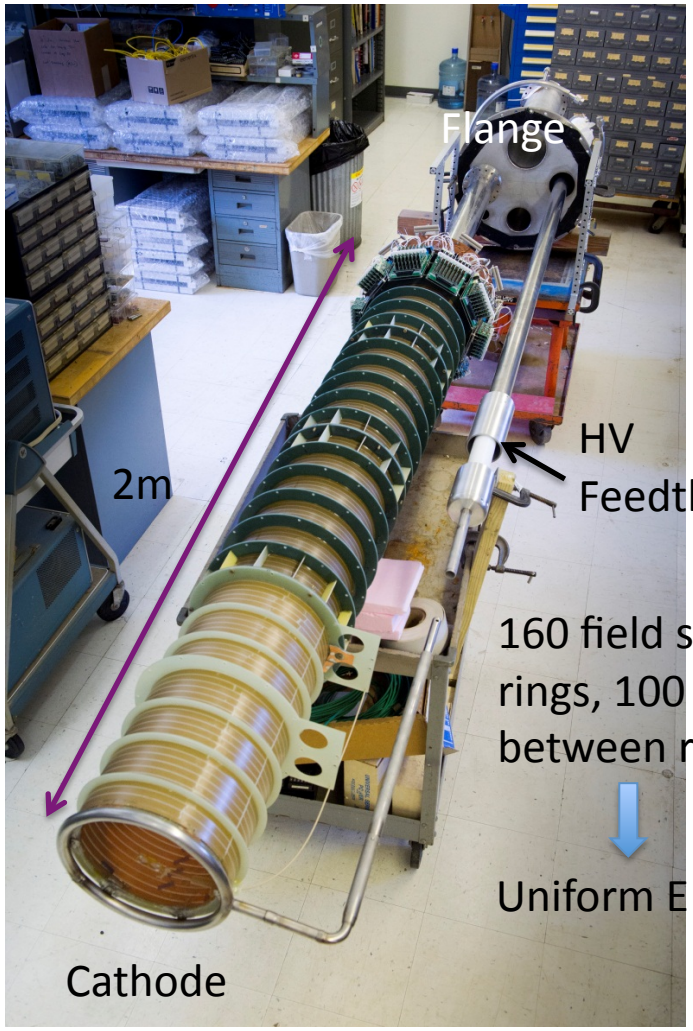


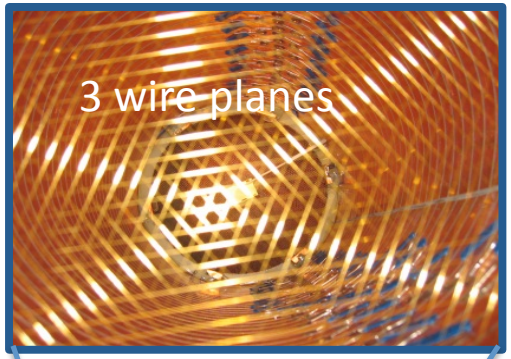


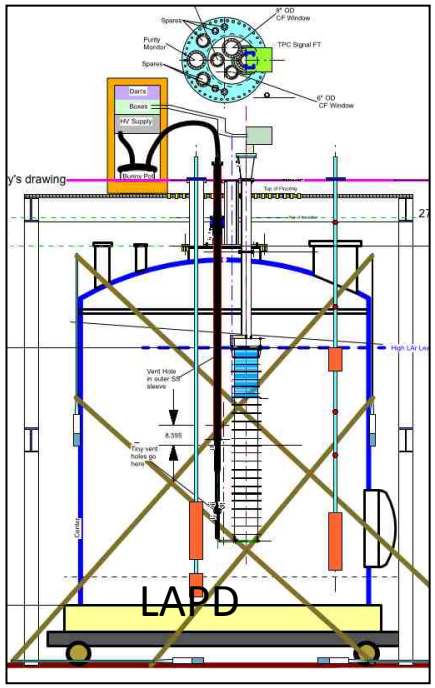


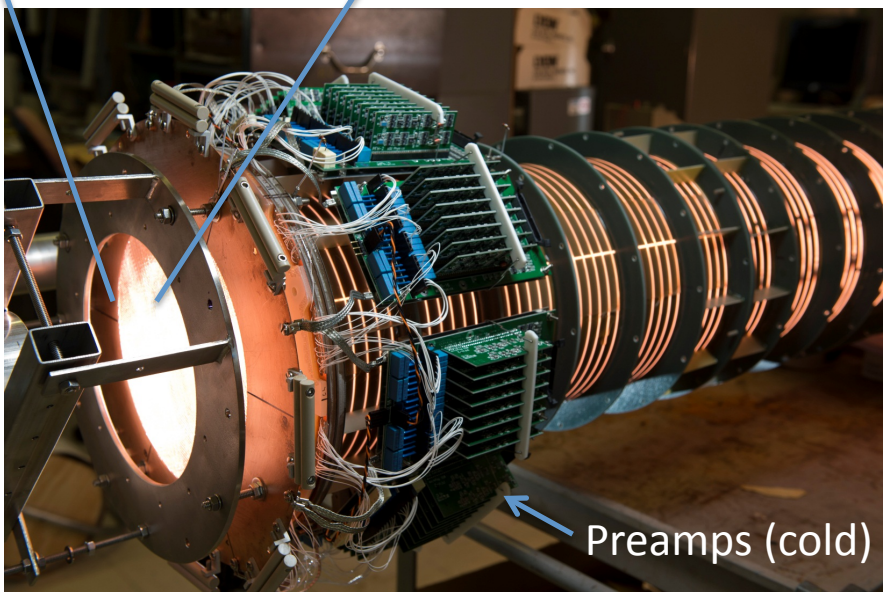
LongBo TPC in LAPD

MSU FNAL



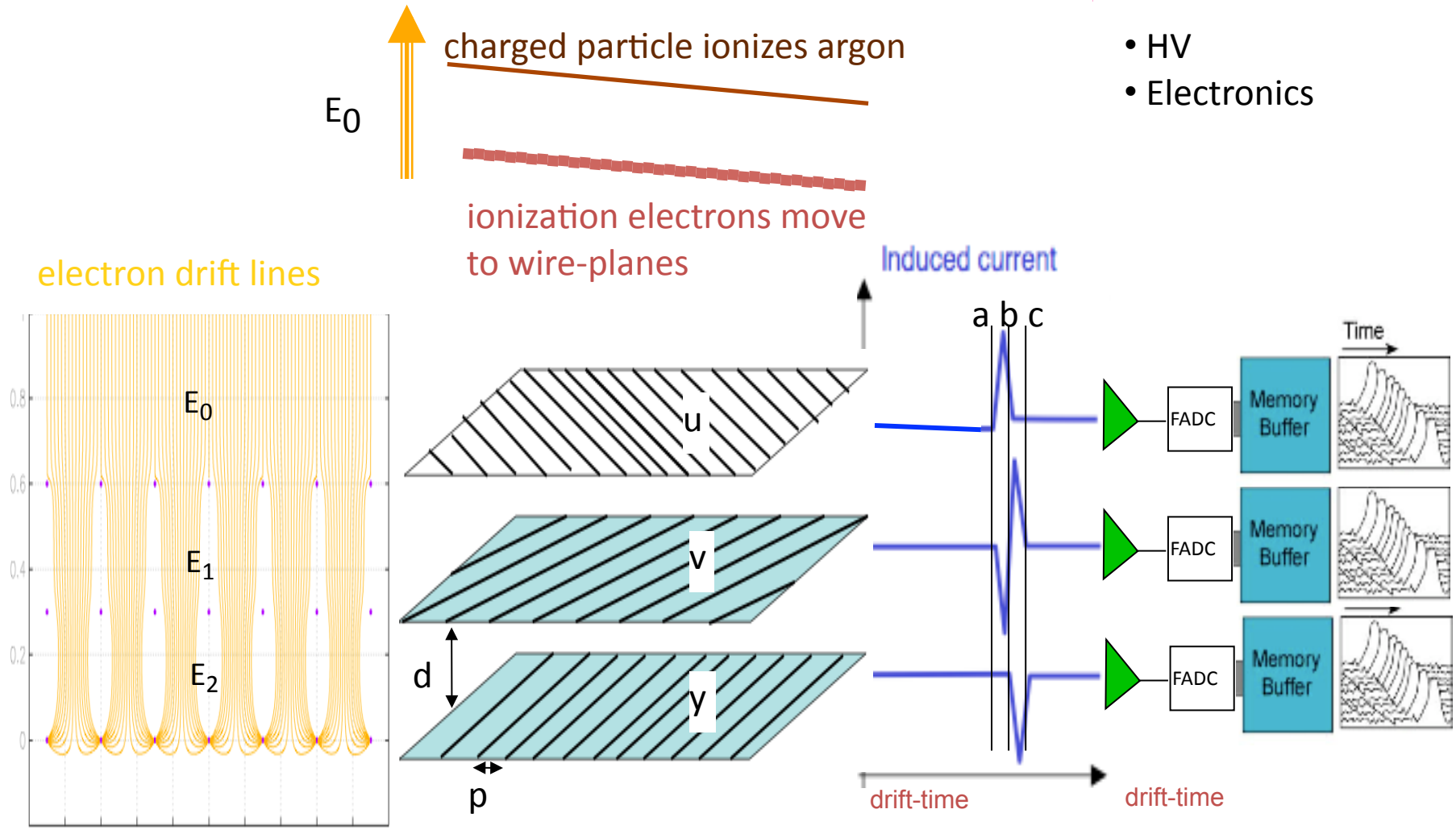






TPC schematic

- HV
- Electronics



$E_2 > E_1 > E_0$

Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191

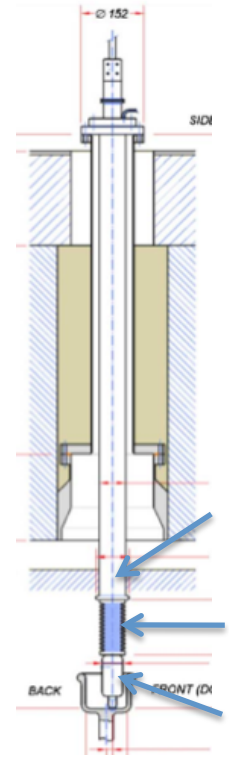
p~d~3-5 mm

Gatti, Padovini, Quartapelle,Greenlaw,Radeka IEEE Trans. NS-26 (2) (1979) 2910]

a = cross u
b = cross v
c = cross y

High Voltage Feedthrough

- HV provides a stable and uniform drift field over extended LAr volumes
- Higher HV
  - Shorter drift time
  - Less ionization electrons attenuation due to impurities
  - Lower recombination
  - Smaller diffusion
  - Require high bias voltage on wire planes to ensure transparency
- Typically 500 V/cm is used
- ICARUS achieved 150 kV
  - 75 kV is needed for 1.5 m drift
- ARGONTUBE developed a voltage multiplier based on Cockcroft-Walton circuit
  - 500 kV!



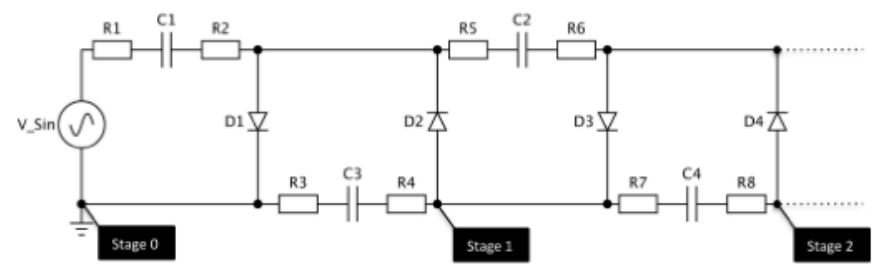
ICARUS HV Feedthrough

NIMA 527, 329 (1990)

Outer conductor

Insulation (with grooves)

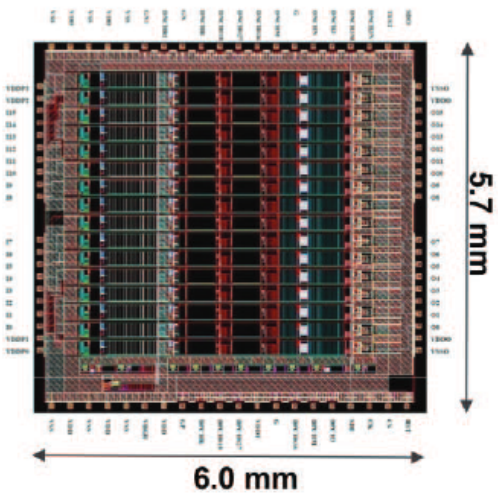
Inner conductor



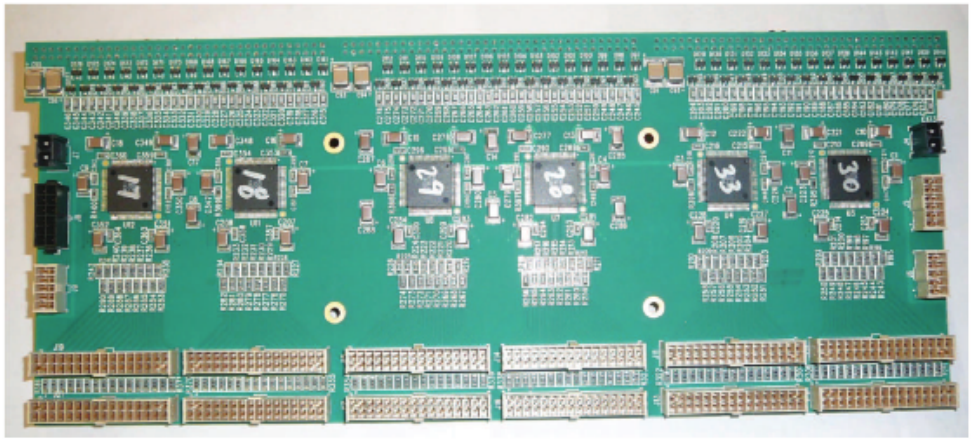
Cockcroft-Walton circuit for ARGONTUBE 1304.6961

Cold Electronics

- Traditional preamplifier with a junction field effect transistor (jFET) is located outside cryostat – warm electronics (1205.6747)
- Large detector (20m x 20m) → long cables to preamplifiers → large input capacitance → high noise → need for cold electronics
- MicroBooNE has developed a 180 nm CMOS ASIC (Application-Specific Integrated Circuit) to be operated in LAr in close proximity to the wire end: reduce cable length and noise
- Expect in future digitizers and multiplexers to also be inside cryogenic vessel=> demands low heat dissipation!



ASIC

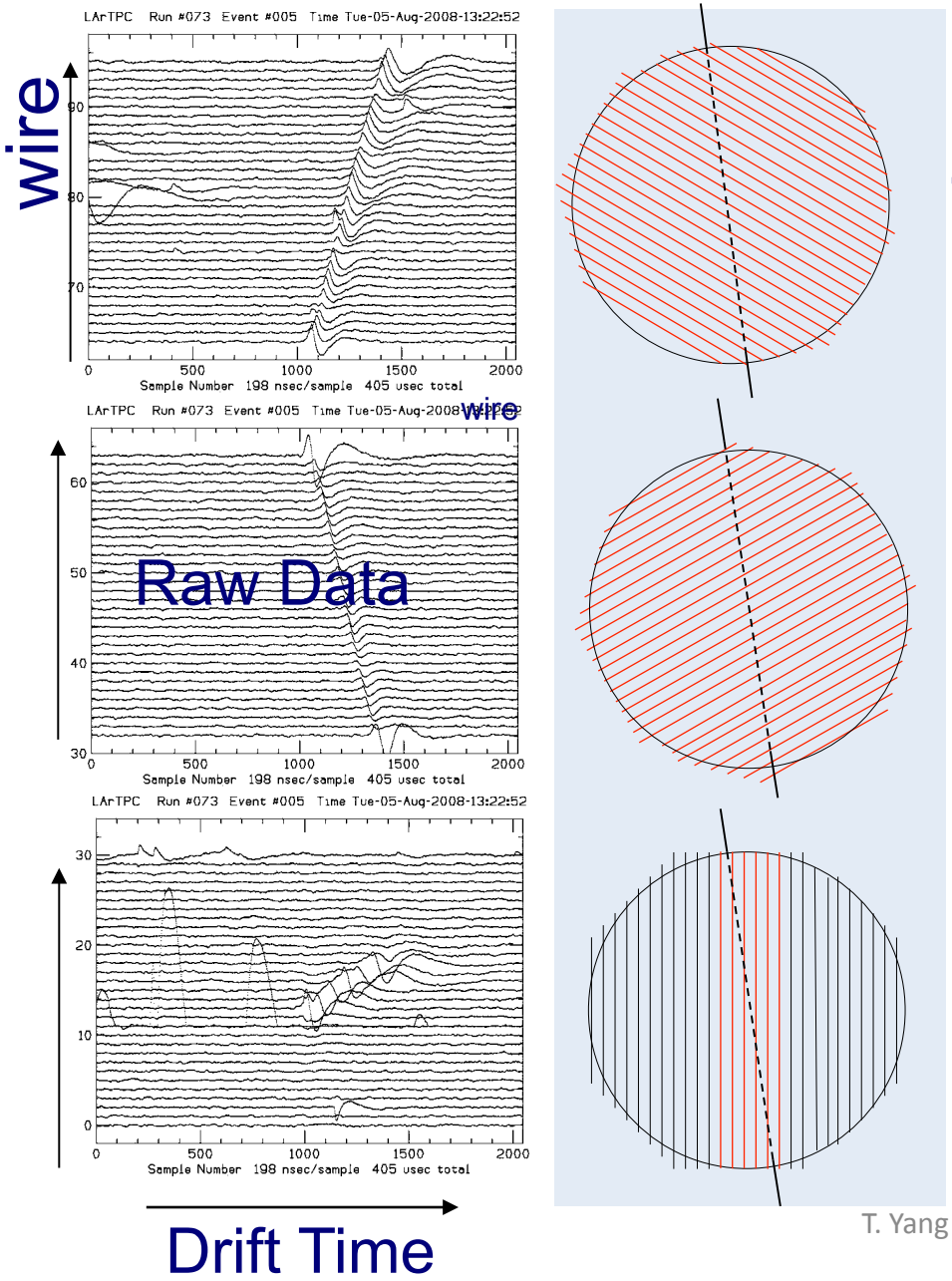


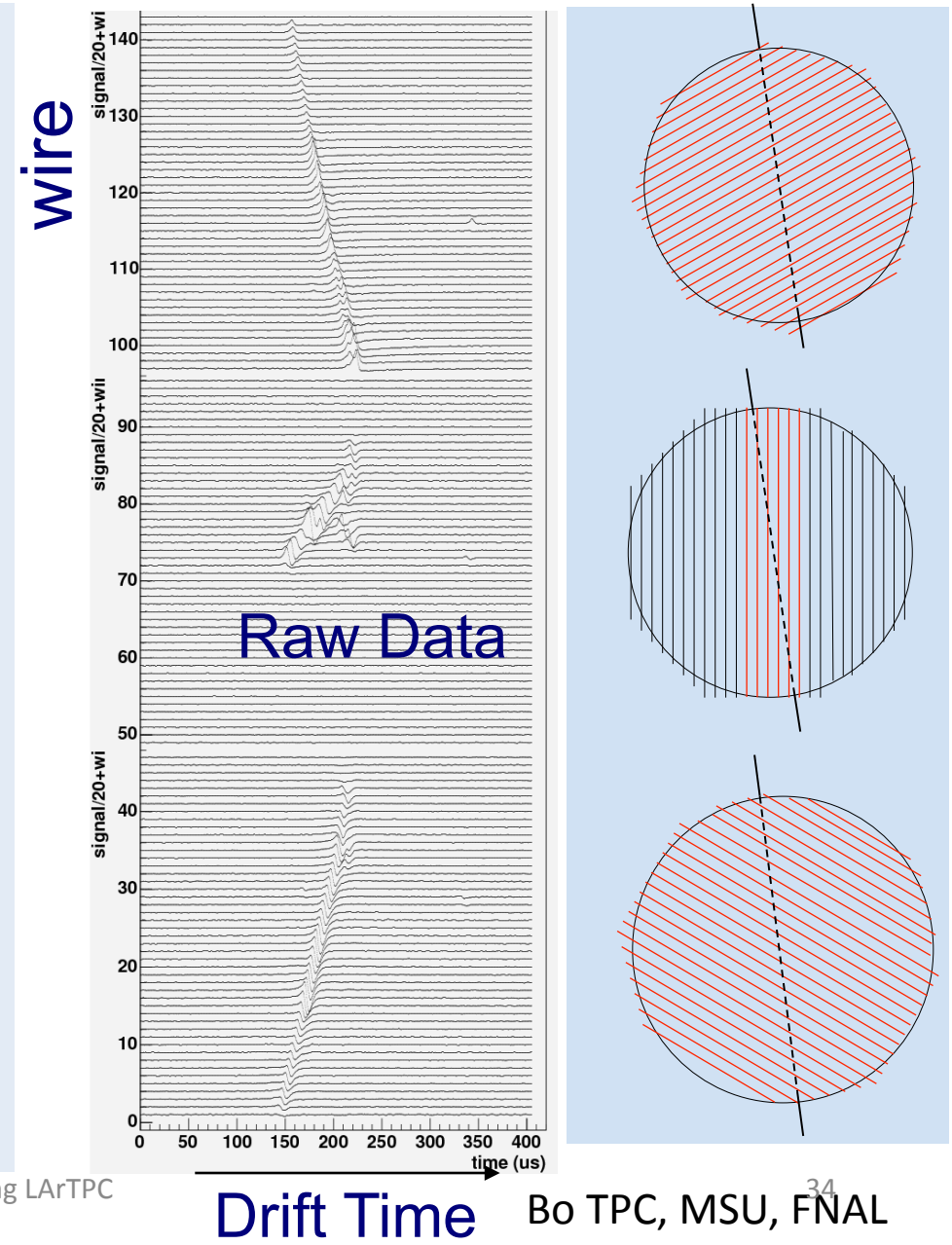
Motherboard with 12 ASIC

H. Chen, JINST 7:C12004 (2012)

Warm amps S/N = 15

Amps in liquid S/N >30



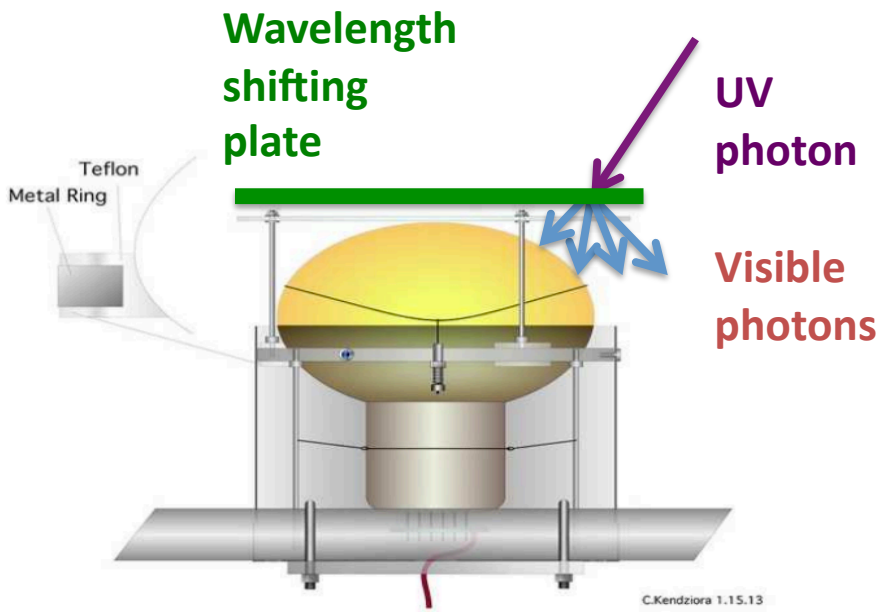


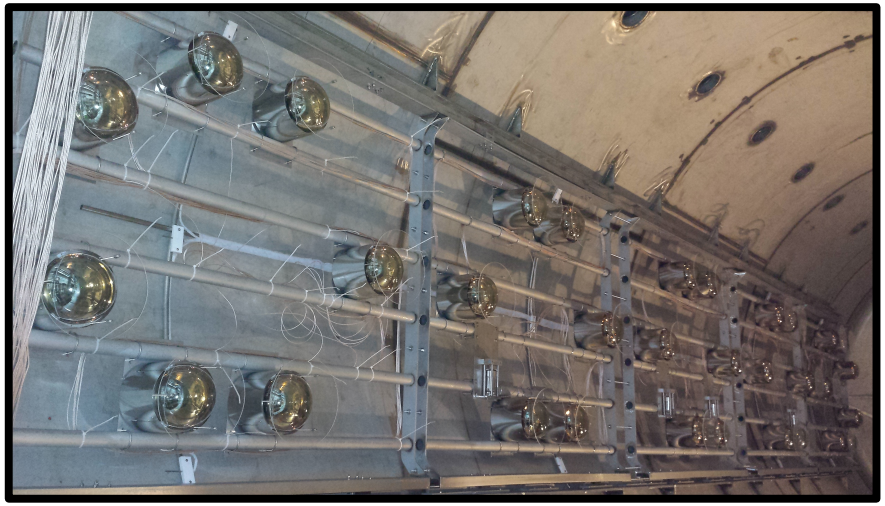
Bo TPC, MSU, FNAL

Scintillation Light Collection

- Scintillation light provides trigger and t0 measurements (~ns)

- MicroBooNE uses acrylic plates coated with a solution of tetraphenyl-butadiene (TPB) and polystyrene to shift the 128 nm LAr scintillation light to the visible region





MicroBooNE PMTs are installed.

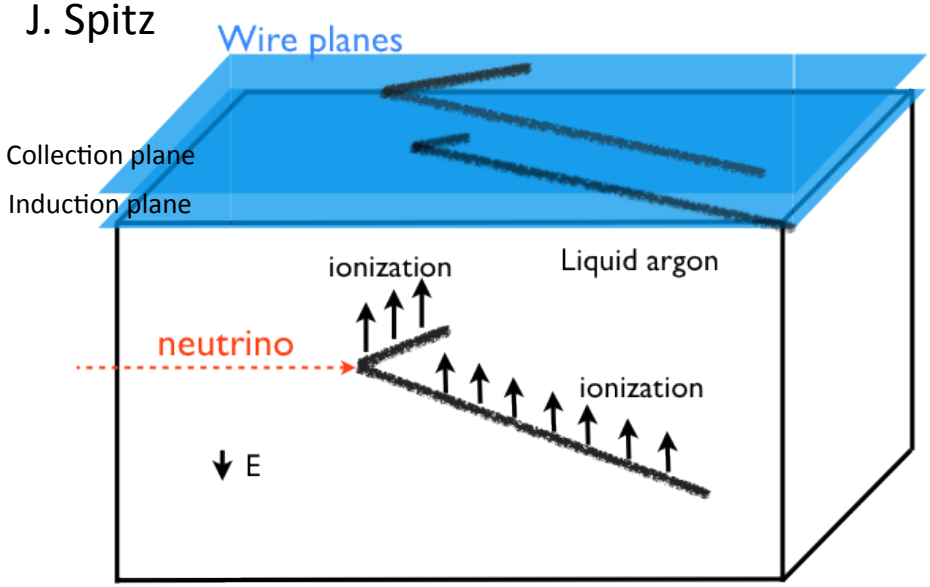
1304.0821, 1307.5256, 1308.3446
Ben Jones, talk at ICATPP 2013

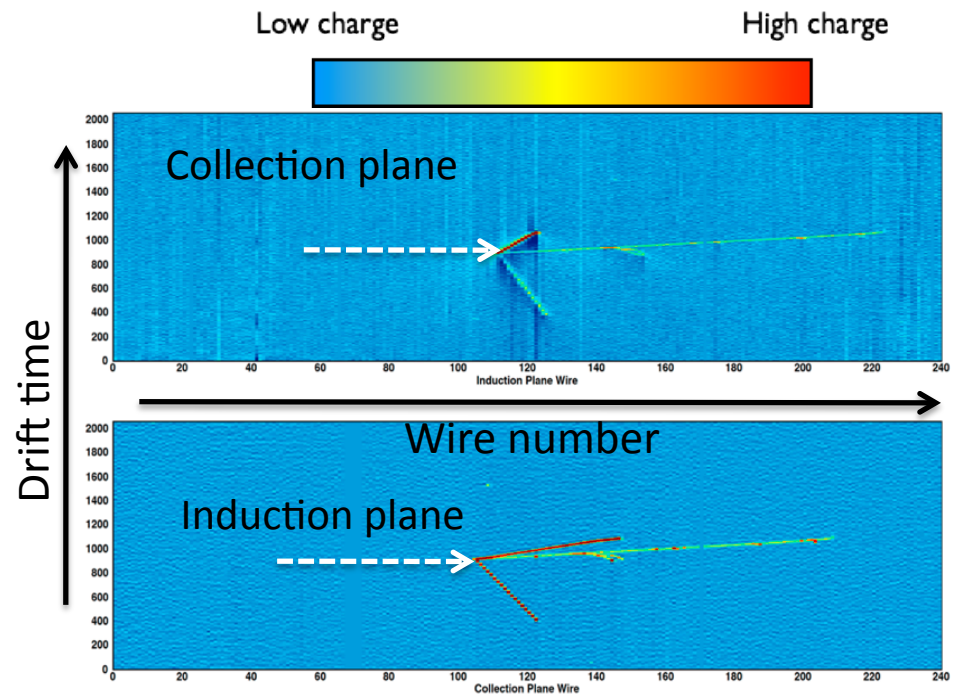
Physics Potential

- List of topics discussed here
  - Neutrino physics
    - Mainly results from ArgoNeuT
  - Search for proton decay
  - Search for dark matter
- Not covered
  - Supernova ν
  - …

Event Display

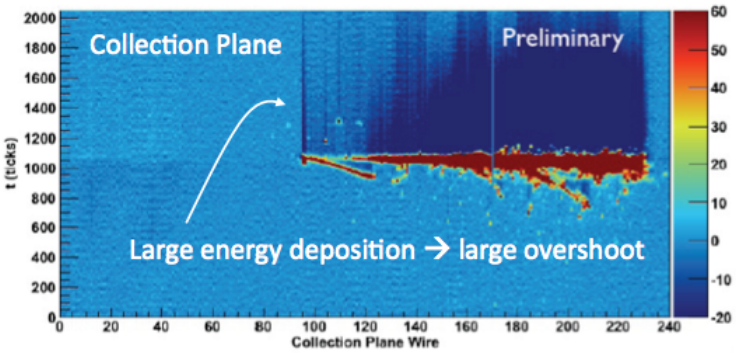
J. Spitz





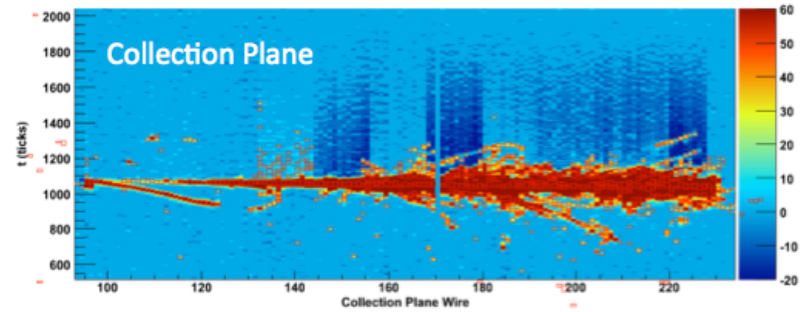
- ArgoNeuT TPC
- Two wire planes
- Drift time vs wire number on each plane
  - Match two views using common drift time to do 3D reconstruction
- Color represents signal amplitude

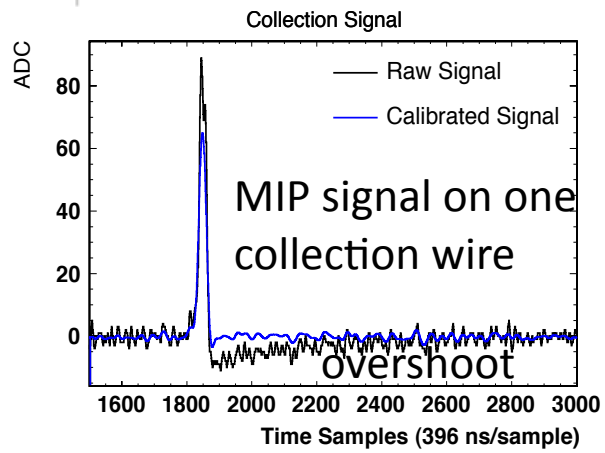
Waveform Transformation

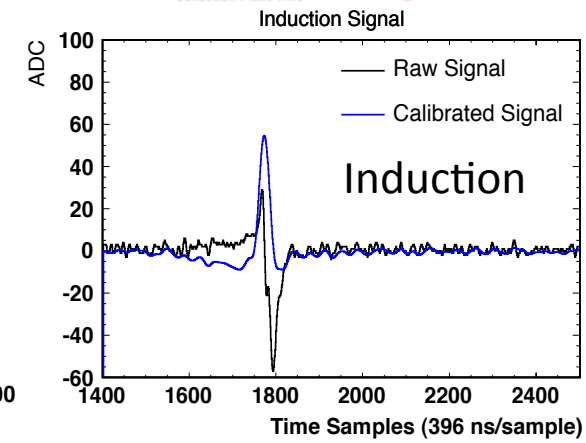


ArgoNeuT CCQE ν_e candiate

After deconvolution







De-convolution

Wire Signal = $\mathcal{F}^{-1}$ { Filter * $\mathcal{F}$(ADC) / ($\mathcal{F}$(Preamp) * $\mathcal{F}$(Shaper) * $\mathcal{F}$(Digitizer)) }

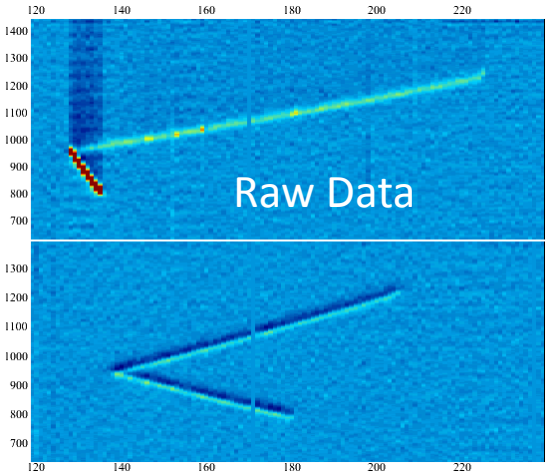
Band filter to remove coherent noise, etc

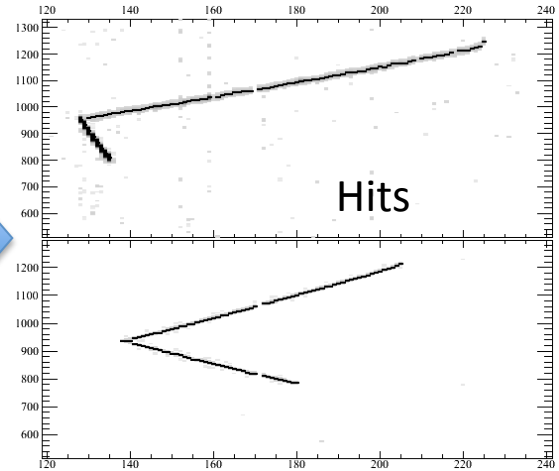
Remove electronics effects

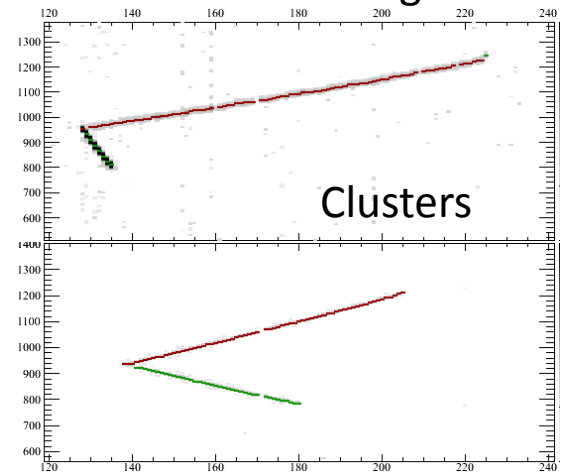
B. Baller, B. Page

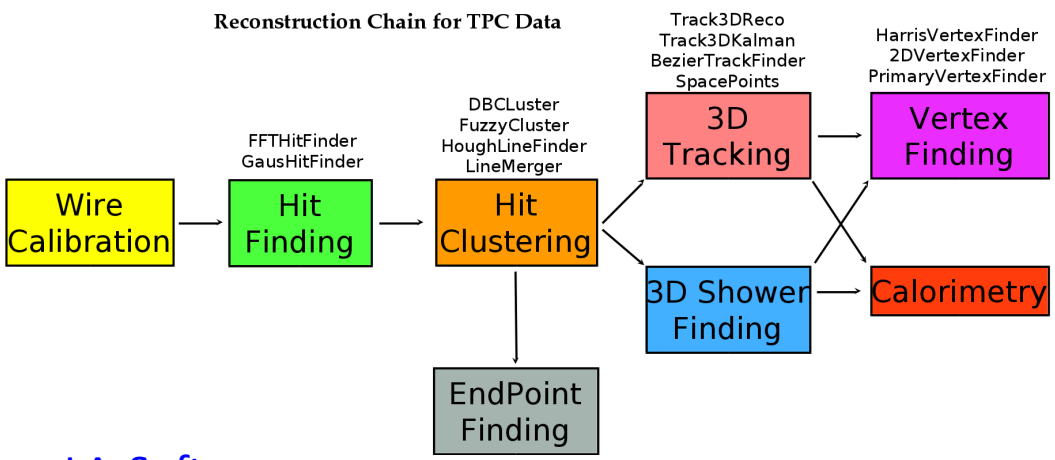
Track Reconstruction

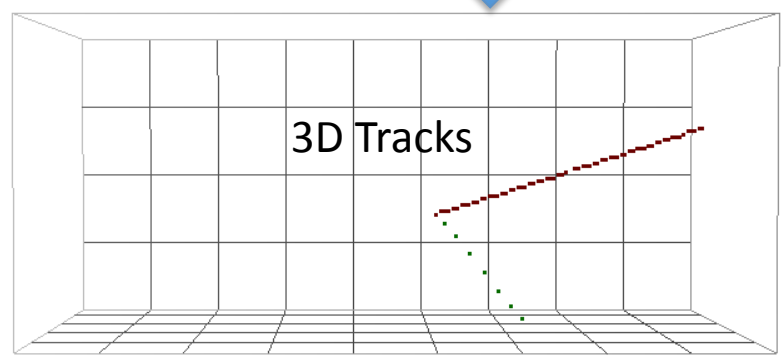
DBScan
Houghline









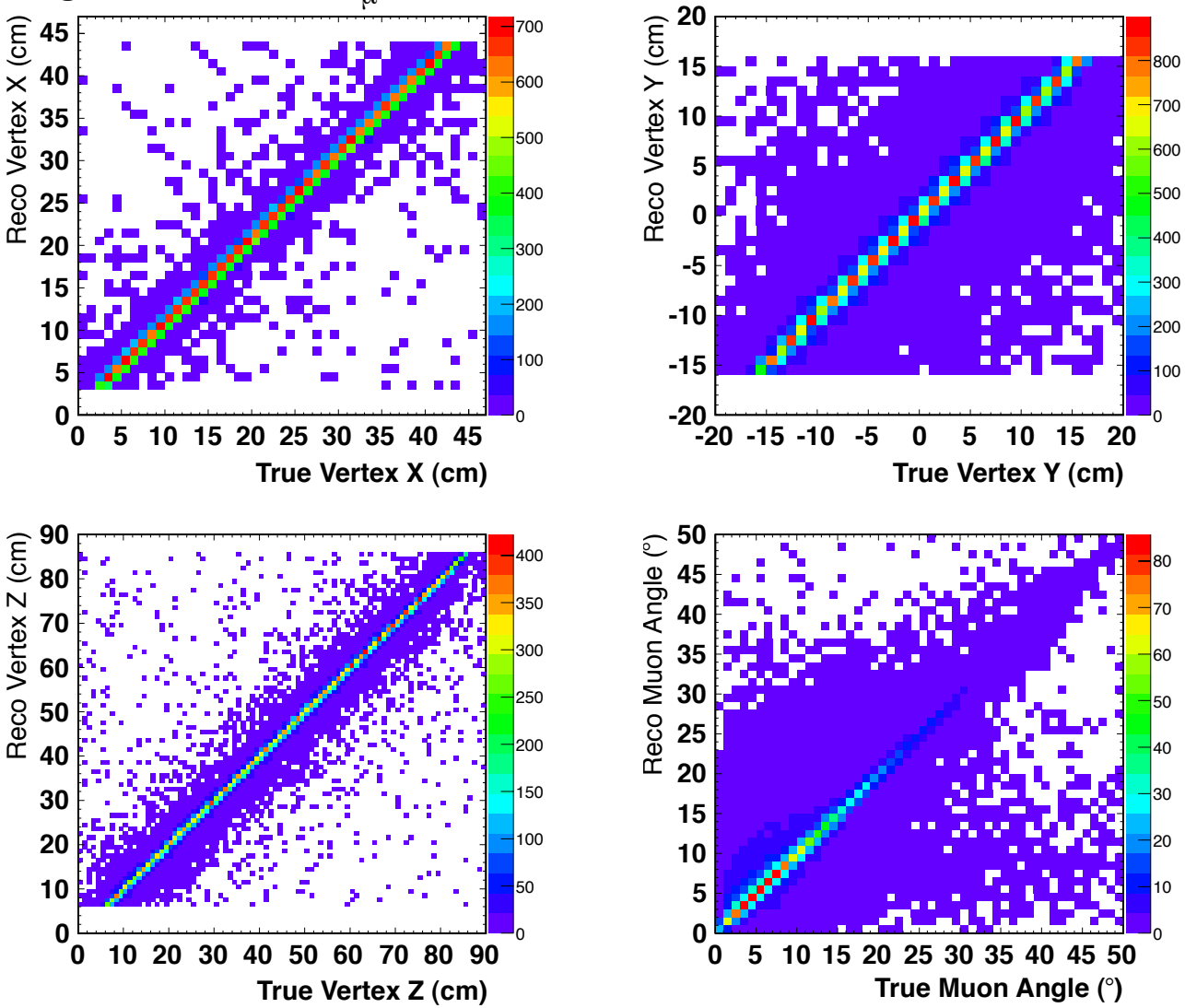


LArSoft
https://cdcvs.fnal.gov/redmine/projects/larsoftsvn

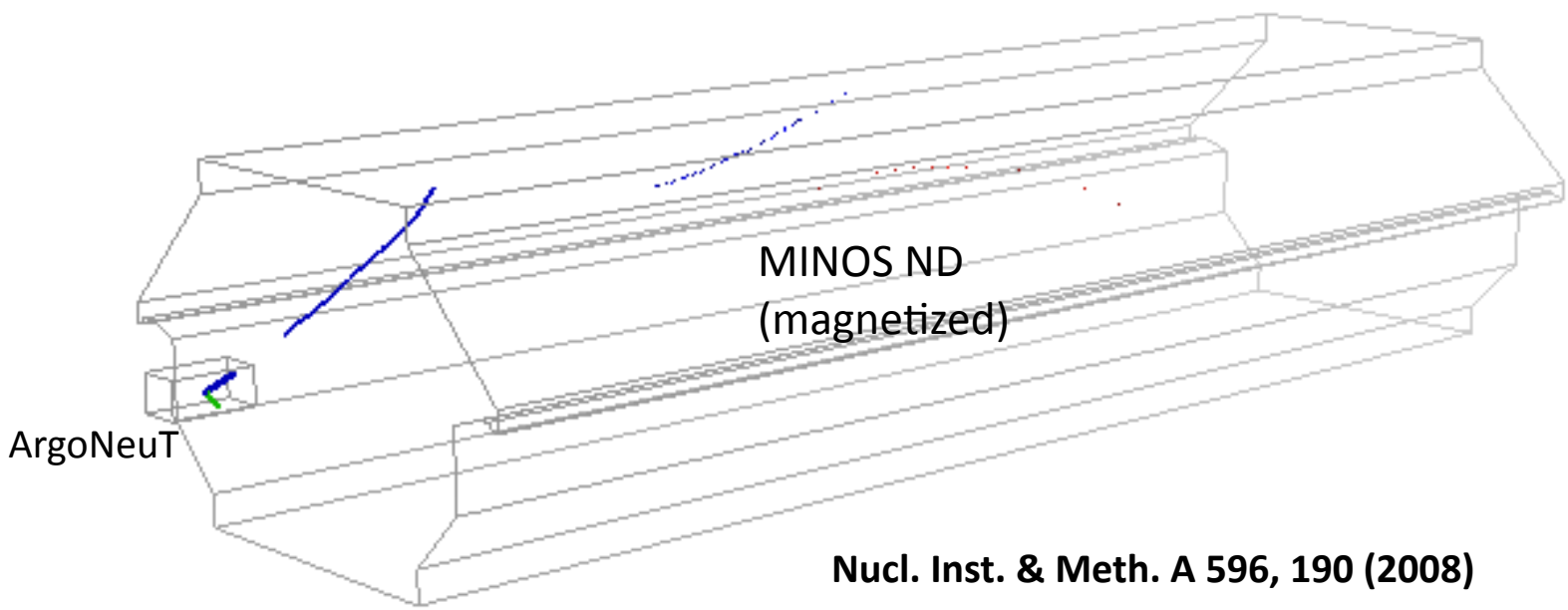
More sophisticated tracking algorithms are being developed for MicroBooNE

Vertex and muon angle reconstruction

ArgoNeuT MC, all ν_μ CC events



Muon Momentum Measurement (I)

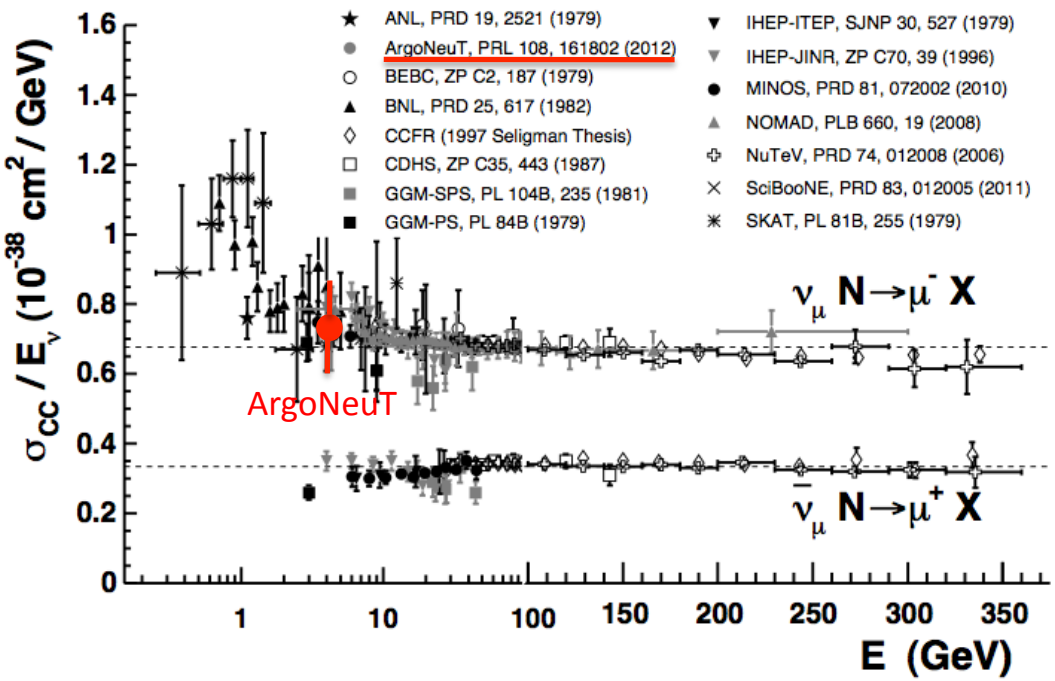


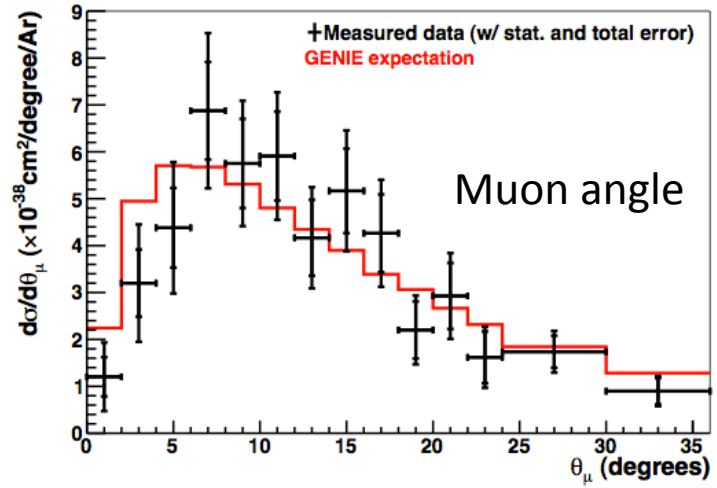
Nucl. Inst. & Meth. A 596, 190 (2008)

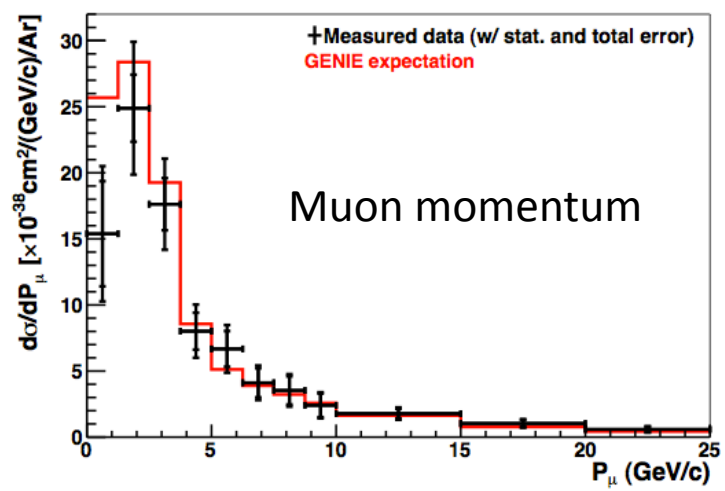
- ArgoNeuT was placed in front of the MINOS Near Detector
- MINOS ND is magnetized and can measure muon momentum and charge
- Match ArgoNeuT track with MINOS track to get the muon momentum and charge

ArgoNeuT Muon Neutrino Inclusive Charged Current Cross Sections (ν Mode - 8.5e18 POT)

"First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon " **PRL 108 (2012) 161802** (1111.0103)



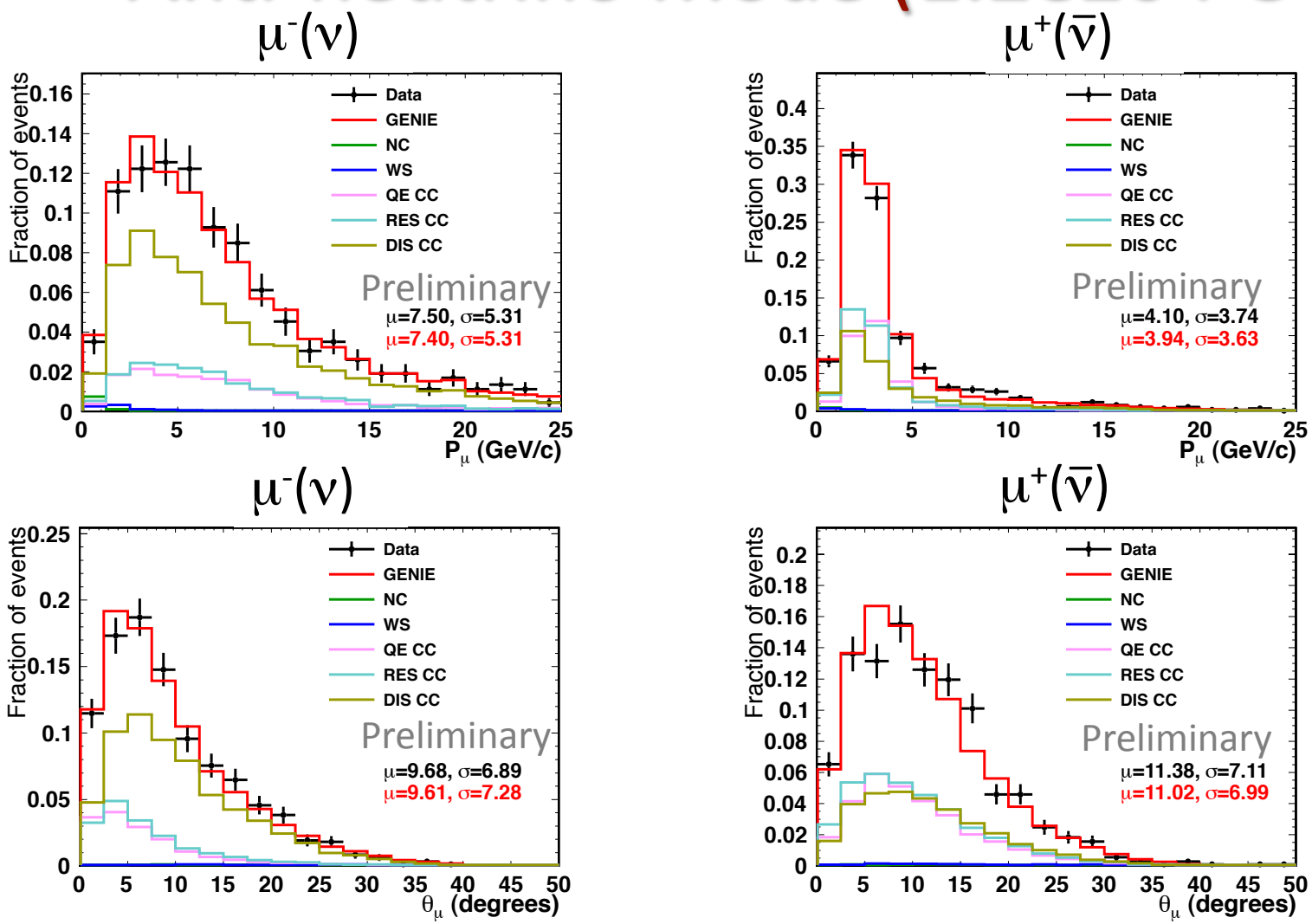




- Interaction vertex in fiducial volume
- Track matched to muon in MINOS ND
- Negatively charged muon in MINOS

T. Yang LArTPC

Anti-neutrino Mode (1.2e20 POT)

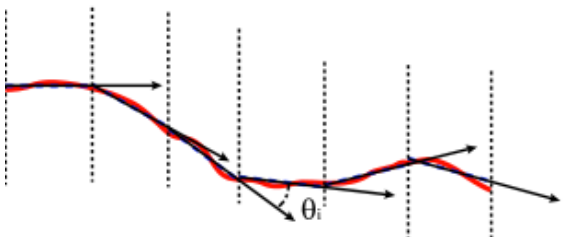


- Area normalized
- Need to improve flux prediction
- Paper in preparation

Muon Momentum Measurement (II)

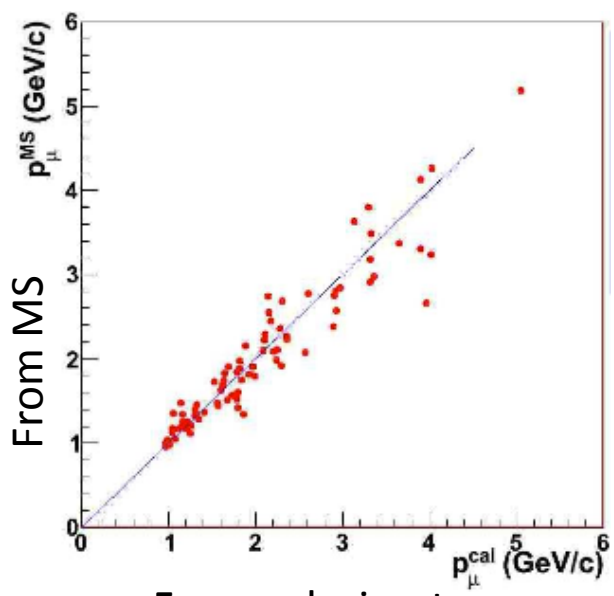
Measurement of muon momentum via multiple scattering

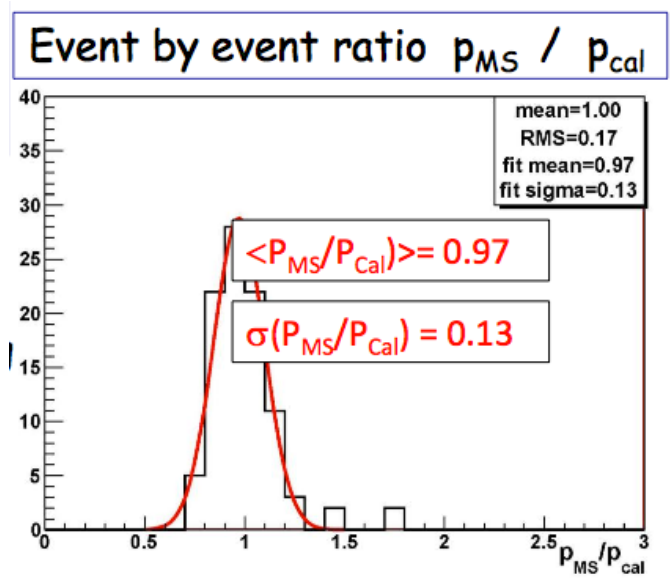
- In the T600 and in future LAr TPCs, a method to measure the momentum of escaping μ is needed in order to reconstruct ν_μ CC events
- Deflections due to Multiple Coulomb Scattering (MS) provide such a tool



The RMS of θ depends on *p* and on the meas. error σ

$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma_{noise}}{l^{3/2}}$$

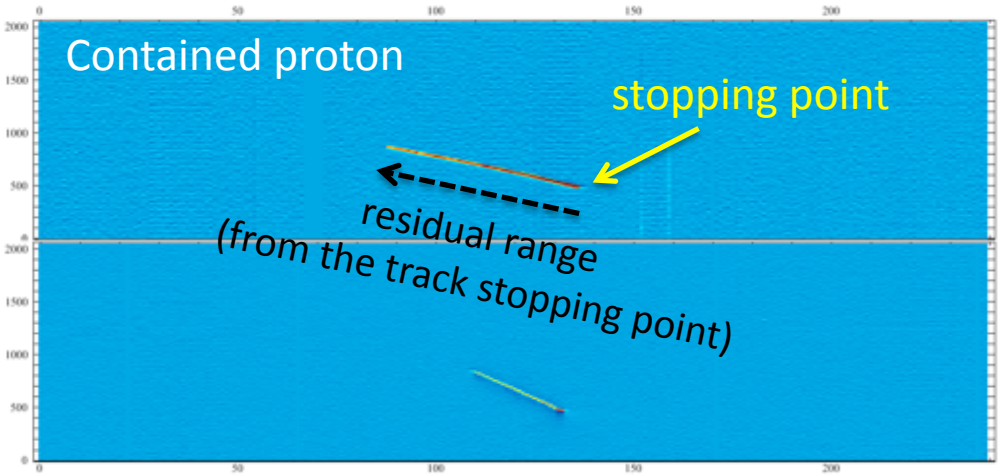




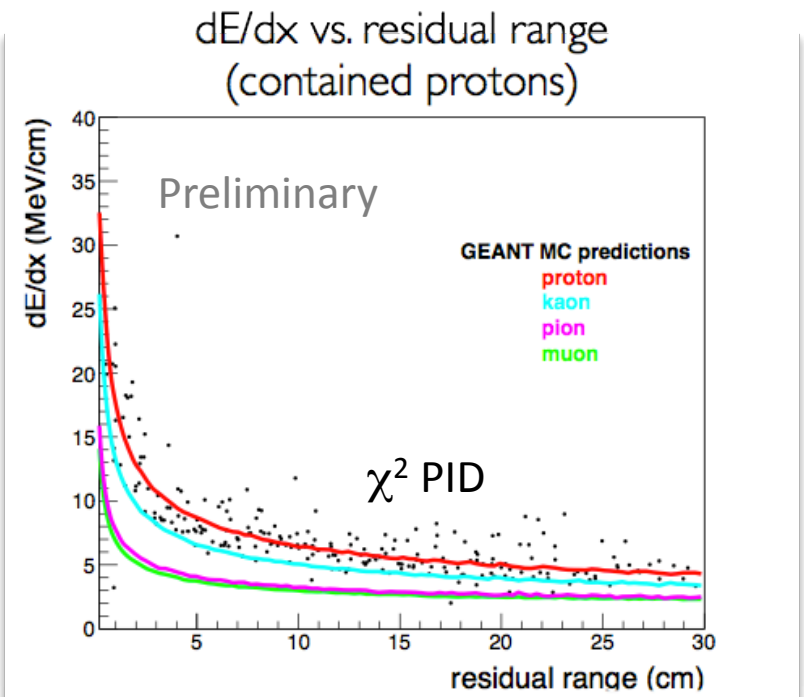
Muon p determination by MS is possible with a resolution ≈ 10% in the momentum range of interest for future LAr TPCs

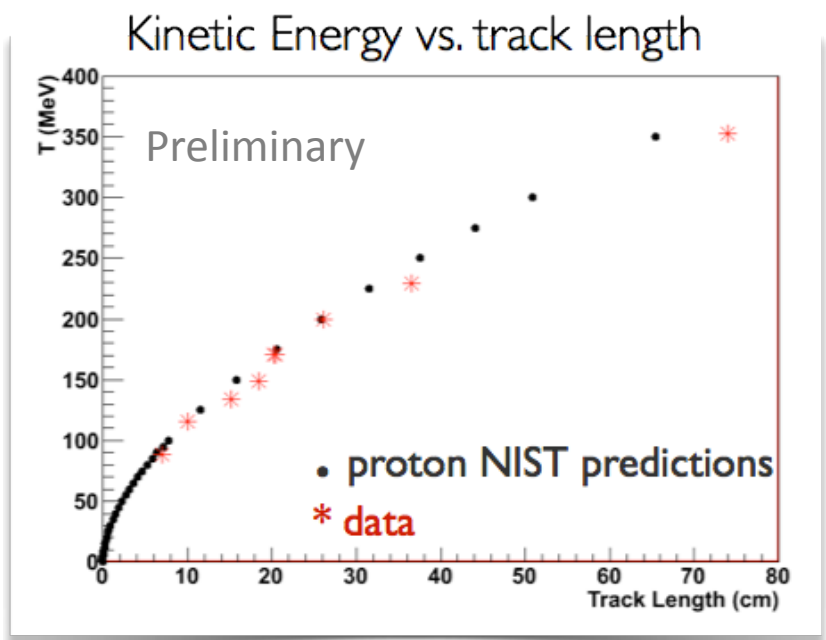
Paola Sala (ICARUS), NuFact 2013

Calorimetric ParticleID



- Wire space: 4 mm
- Measurement of:
  - dE/dx vs. residual range along the track
  - kinetic energy vs. track length

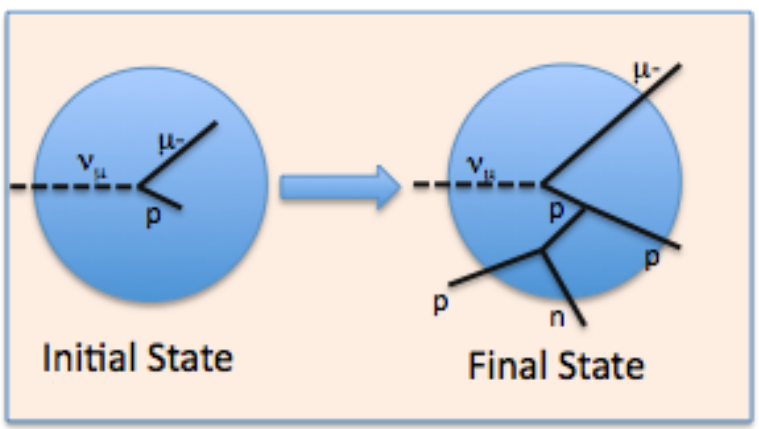


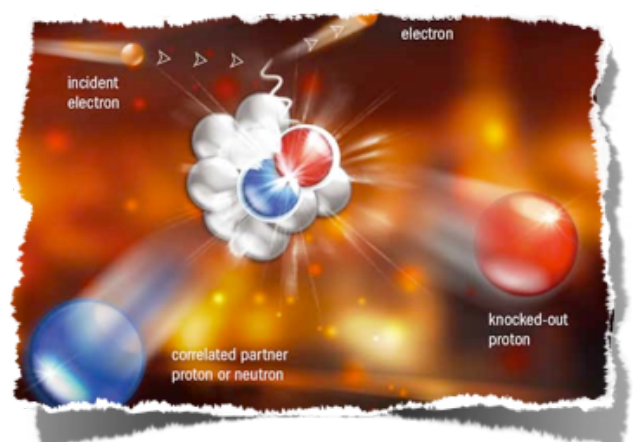


proton threshold:T_p>21 MeV

ν-Ar Interactions: Nuclear Effects

- Conventional measurement of exclusive channels: quasi-elastic (QE), resonance pion production (RES) etc.
- **Nuclear effects** play a key role in neutrino-nucleus interactions in nuclear targets.
- Due to ***intra-nuclear re-scattering (FSI)*** and possible effects of ***correlation between target nucleons***, <u>a genuine QE interaction can often be accompanied by additional particles (nucleons, de-excitation γ's and soft pions) in the Final State.</u>
- ArgoNeuT developed the first topological analysis
  - Cross section measurements based on final state topology (eg 1μ+Np+0π)





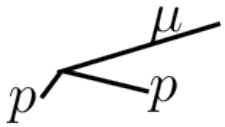
Multi-nucleon correlations

Short Range Correlation (SRC)

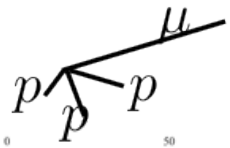
Event Topology

$1\mu + 0p$

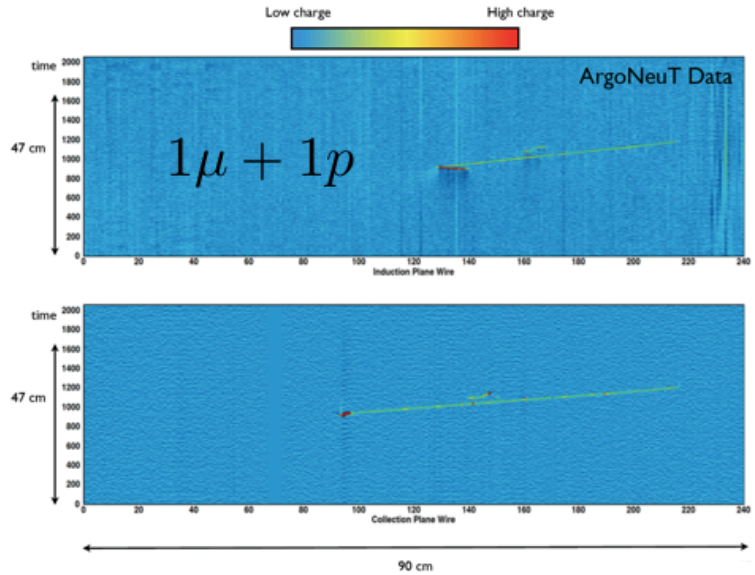
$1\mu + 1p$

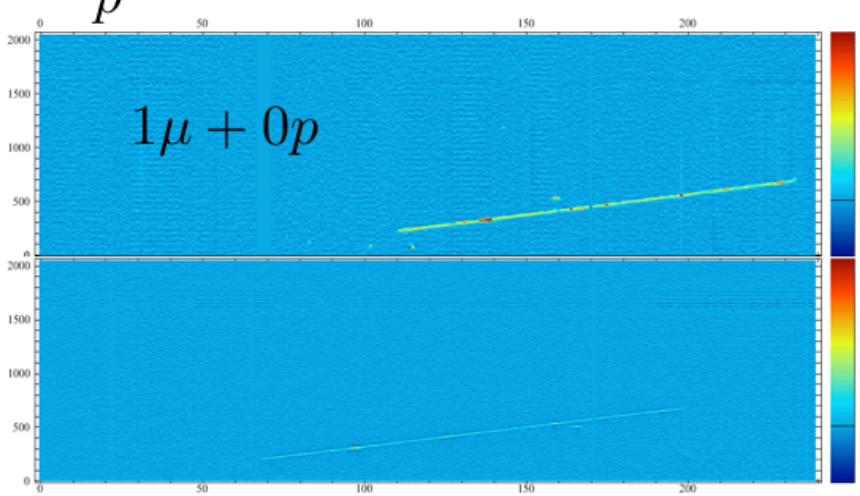


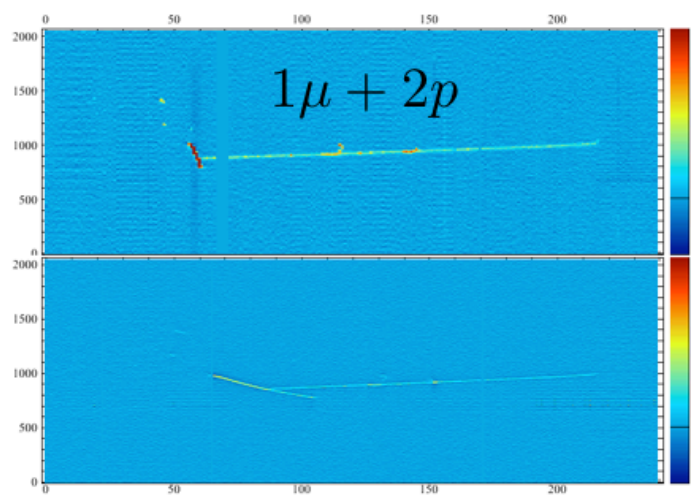
$1\mu + 2p$



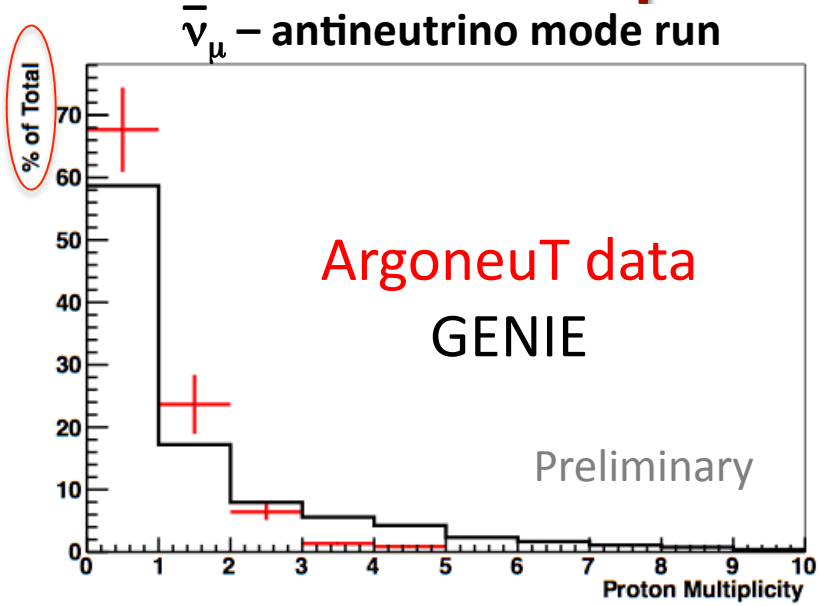
$1\mu + 3p$

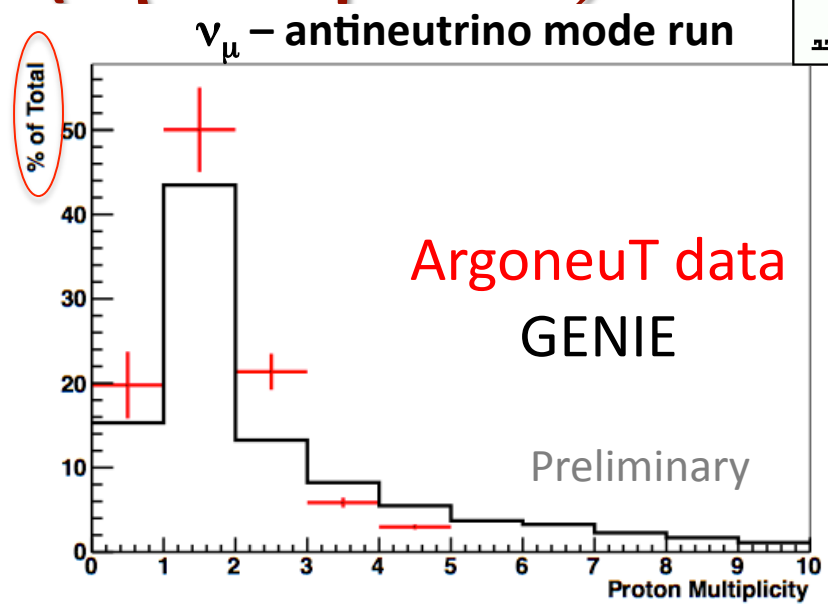




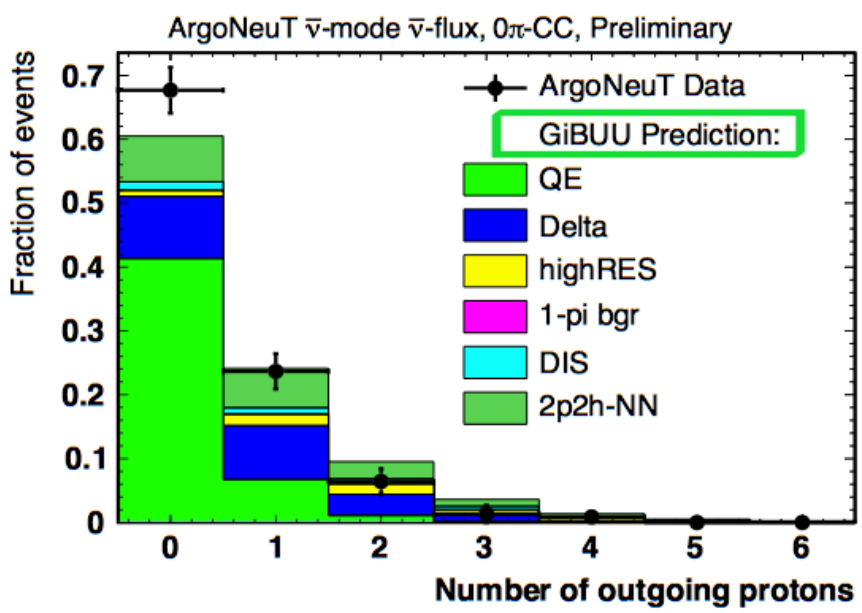


Proton Multiplicity (1μ+Np+0π)





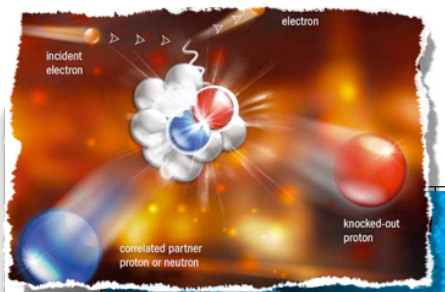
proton threshold:T_p>21 MeV

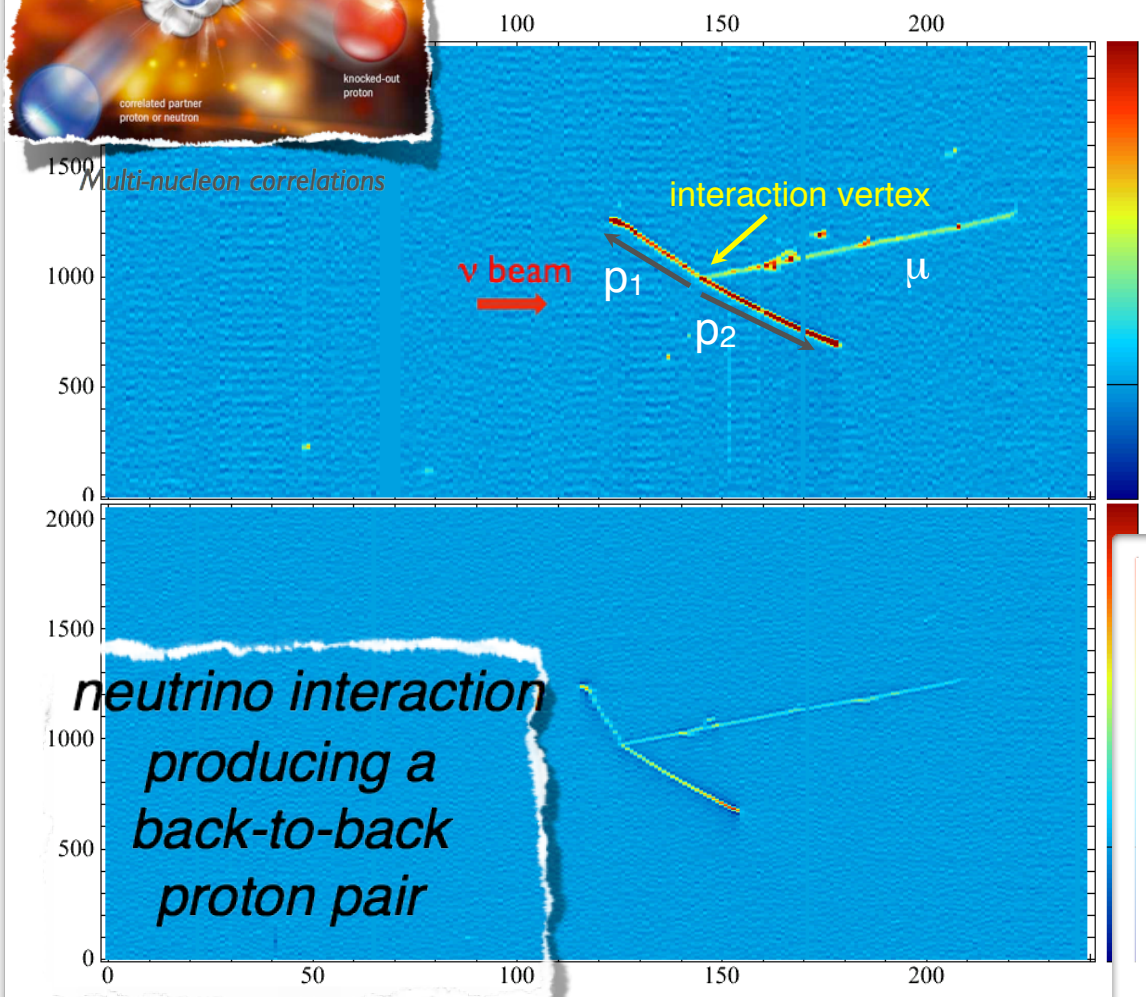


- Analysis steps
  - automated reconstruction
  - visual scanning
  - calorimetric reconstruction
    - Background (pion) removed

O. Palamara, K. Partyka

Back-to-back Proton Pair

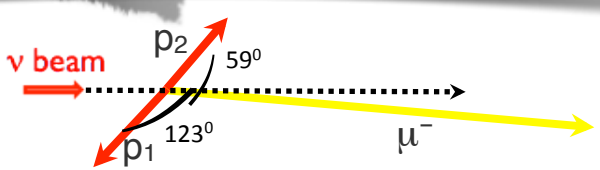




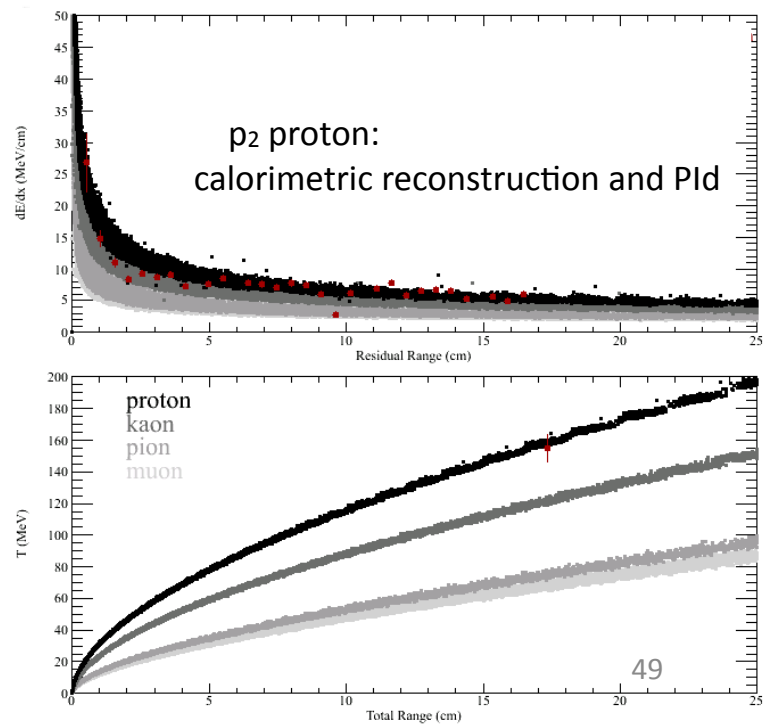
- p_1: $\theta_1 = 123^0$
  L_1=12 cm ----> p_1=513±31 MeV/c
- p_2: $\theta_2 = 59^0$
  L_2=17 cm ----> p_2=566±34 MeV/c

Angle between two protons $\gamma = 183^0$

Candidate for nucleon correlations effects



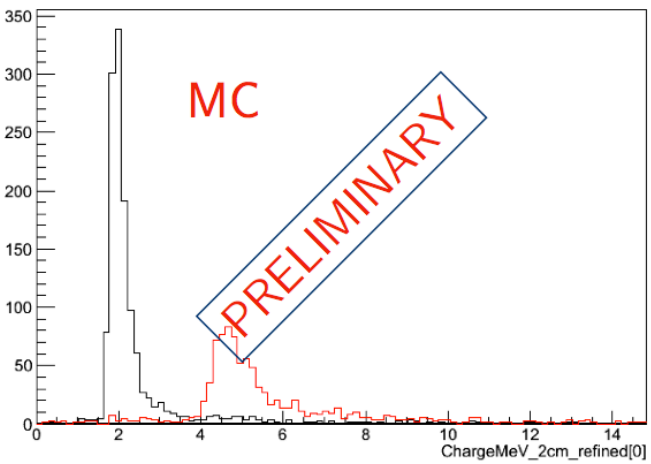
back-to-back protons

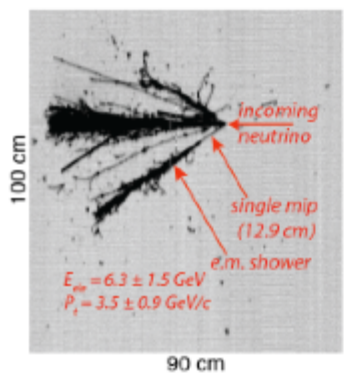


T. Yang LArTPC

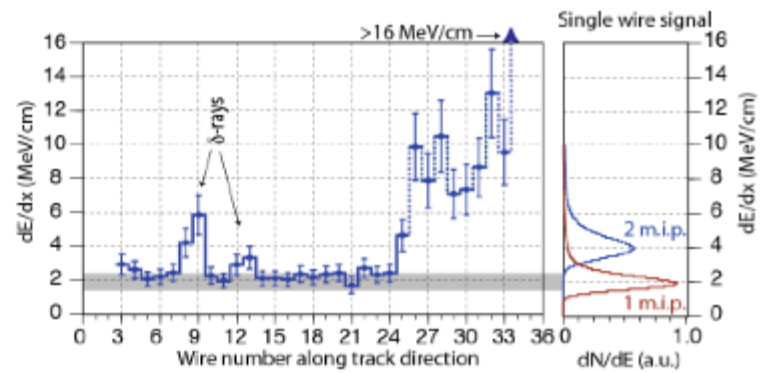
dE/dx e/γ ID

- Separating electrons from γs is important for future ν experiments
- e.g. understanding whether the MiniBooNE anomaly is an effect of oscillation or background
  - e/g separation
- Long baseline measurements e.g. CP violation etc.
  - ν_e appearance: e/π^0 separation
- The dE/dx at the beginning of a shower can be a powerful discrimination tool



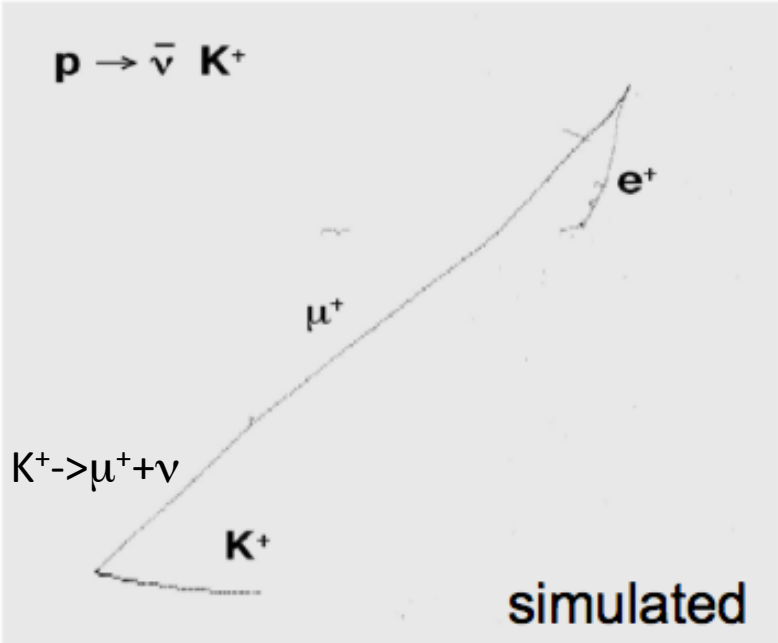


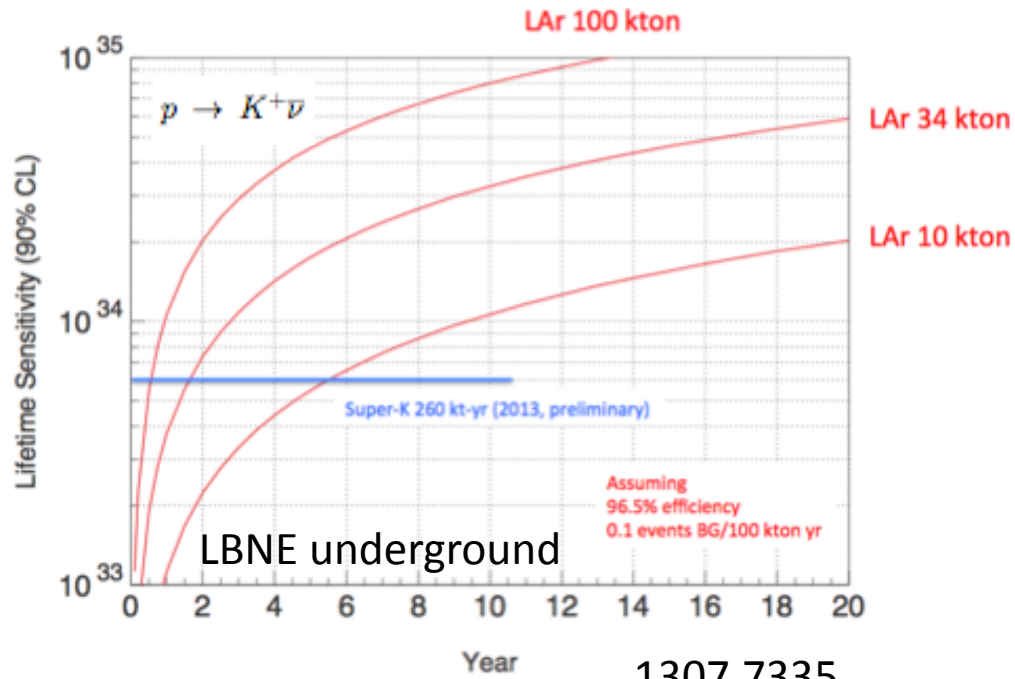
ICARUS ν_e CC candidate



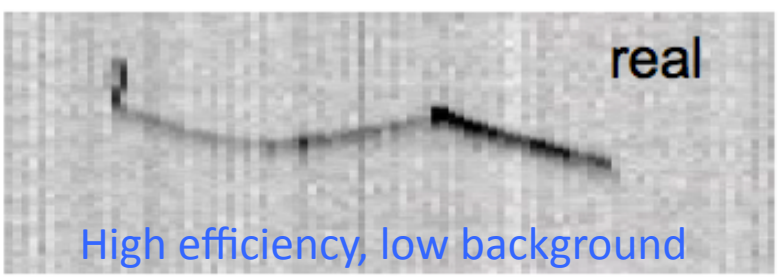
1307.4699

Proton Decay Sensitivity





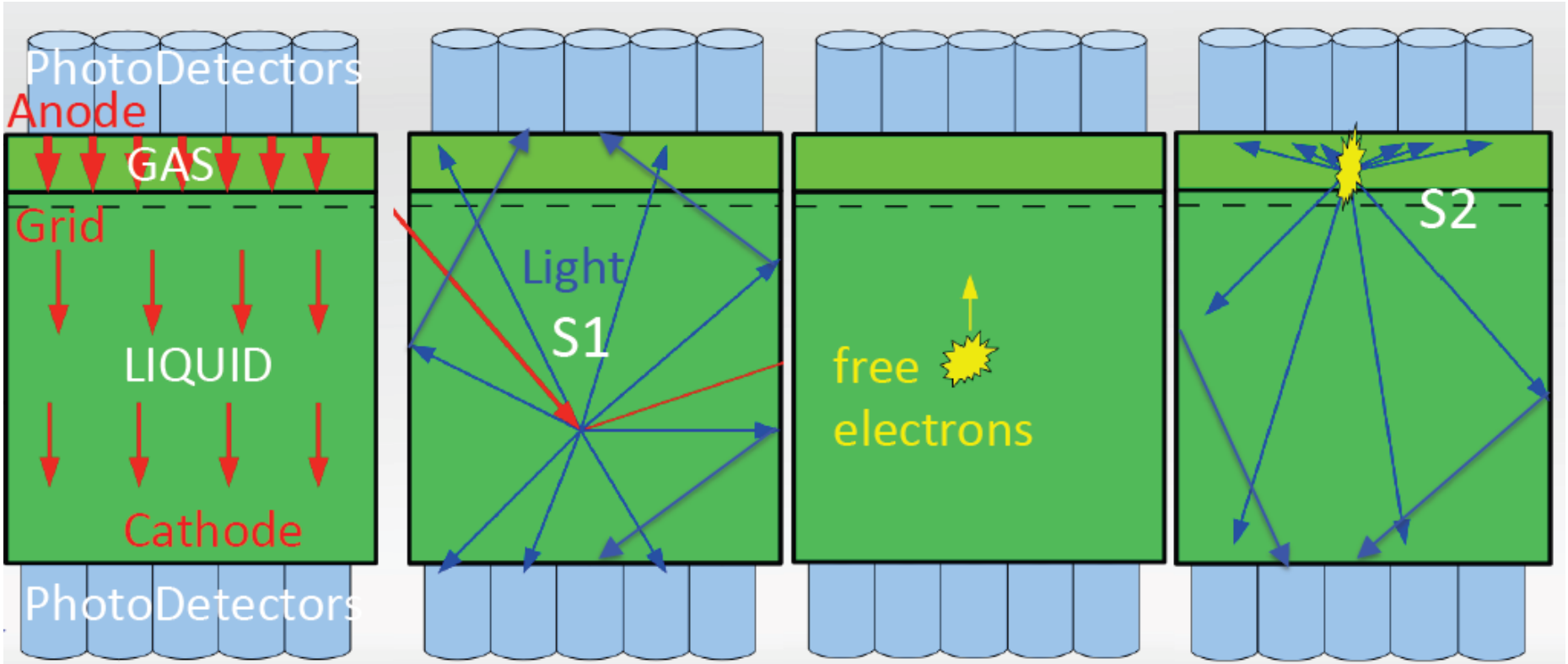
1307.7335



MicroBooNE can study entering K^0 background from cosmic ray interaction

There are two favored and benchmark decay modes:
$e^+\pi^0$ (gauge mediated) and $\bar{\nu}K^+$ (SUSY D=5)
good for water good for LAr

Dual Phase Electroluminescence TPC for Dark Matter Search



Liquid active volume with small drift field Gas multiplication volume

Primary interaction creates scintillation (S1)

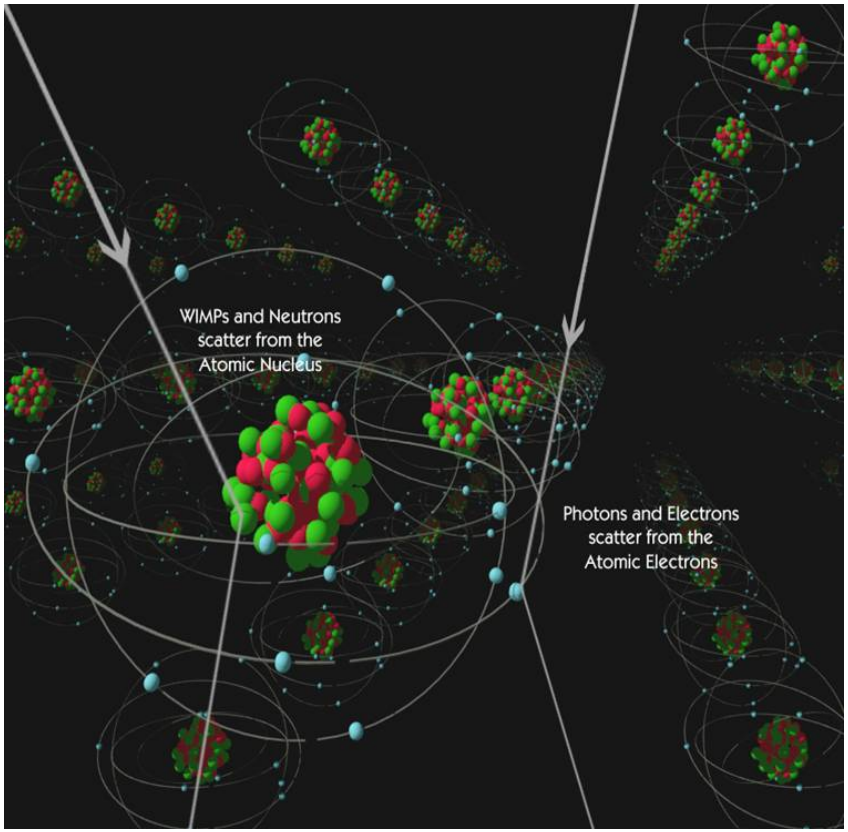
Ionized electrons drift toward gas region

High field in gas makes secondary scintillation (S2) (light-gain only)

Ben Loer, LArTPC R&D Workshop 2013

Why use a LArTPC for WIMP search?

- Nuclear recoils have high dE/dx compared to electrons
- High dE/dx => high ionization density => high ion recombination
- High dE/dx => higher singlet excitation
- Therefore:
  - NRs have faster scintillation pulses (S1) than ERs
  - NRs have lower ionization to scintillation ratio (S2/S1) than Ers
- DarkSide 1204.6218



Ben Loer, LArTPC R&D Workshop 2013

Conclusions

- LArTPC is a mature technique that has many applications in physics.

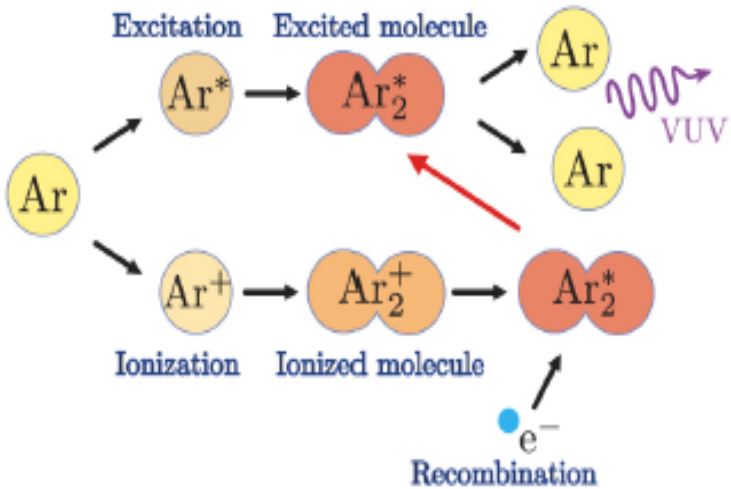
- Development of reconstruction is important for taking advantage of the detailed information provided by LArTPC.

Acknowledgement

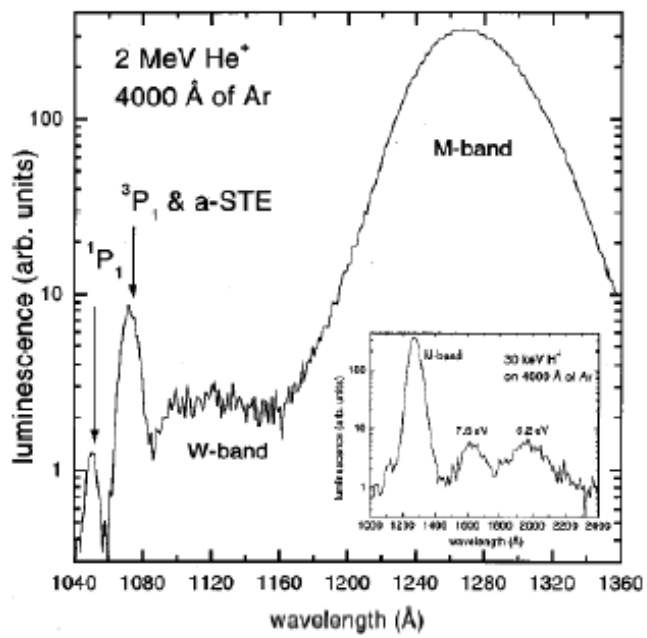
- Alberto Marchionni: arXiv:1307.6918
- Many thanks to Brian Rebel, Stephen Pordes, Ben Carls, Terry Tope, Michelle Stancari, Ornella Palamara, Mitch Soderberg, Bruce Baller and Carl Bromberg for useful suggestions and discussions.

Backup Slides

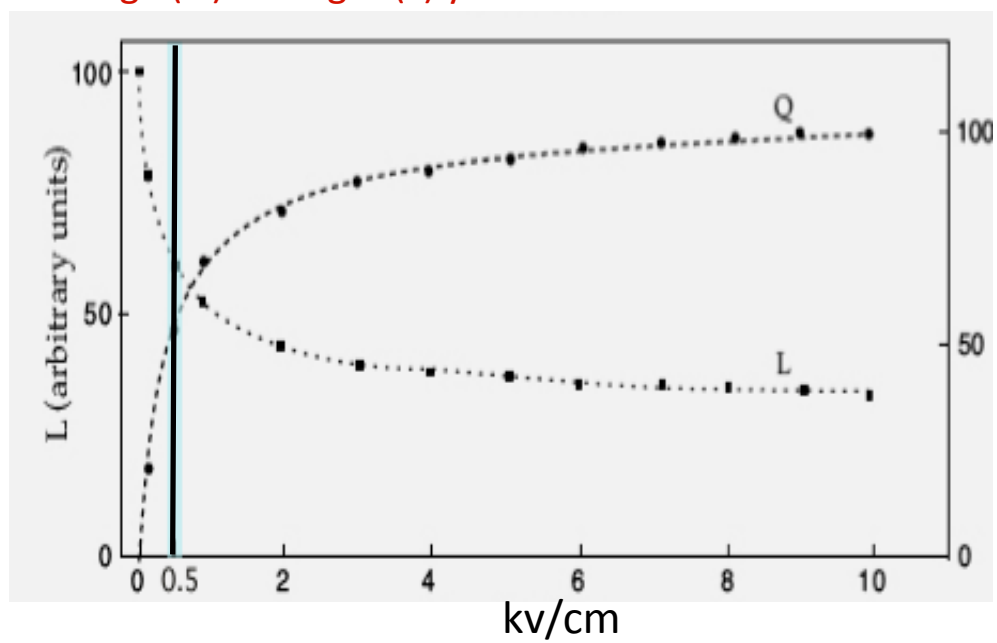
mechanism of light production



dE/dx = 2.1 MeV/cm
ρ= 1.4 g/cm^3



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



5000 e/mm and 2000 phot./mm at 0.5 kV/cm

S. Pordes

Time distribution of light* output from Liquid Argon for

γs, αs and neutrons

2 components:
τ(fast) = 7 ns
τ(slow) = 1600 ns

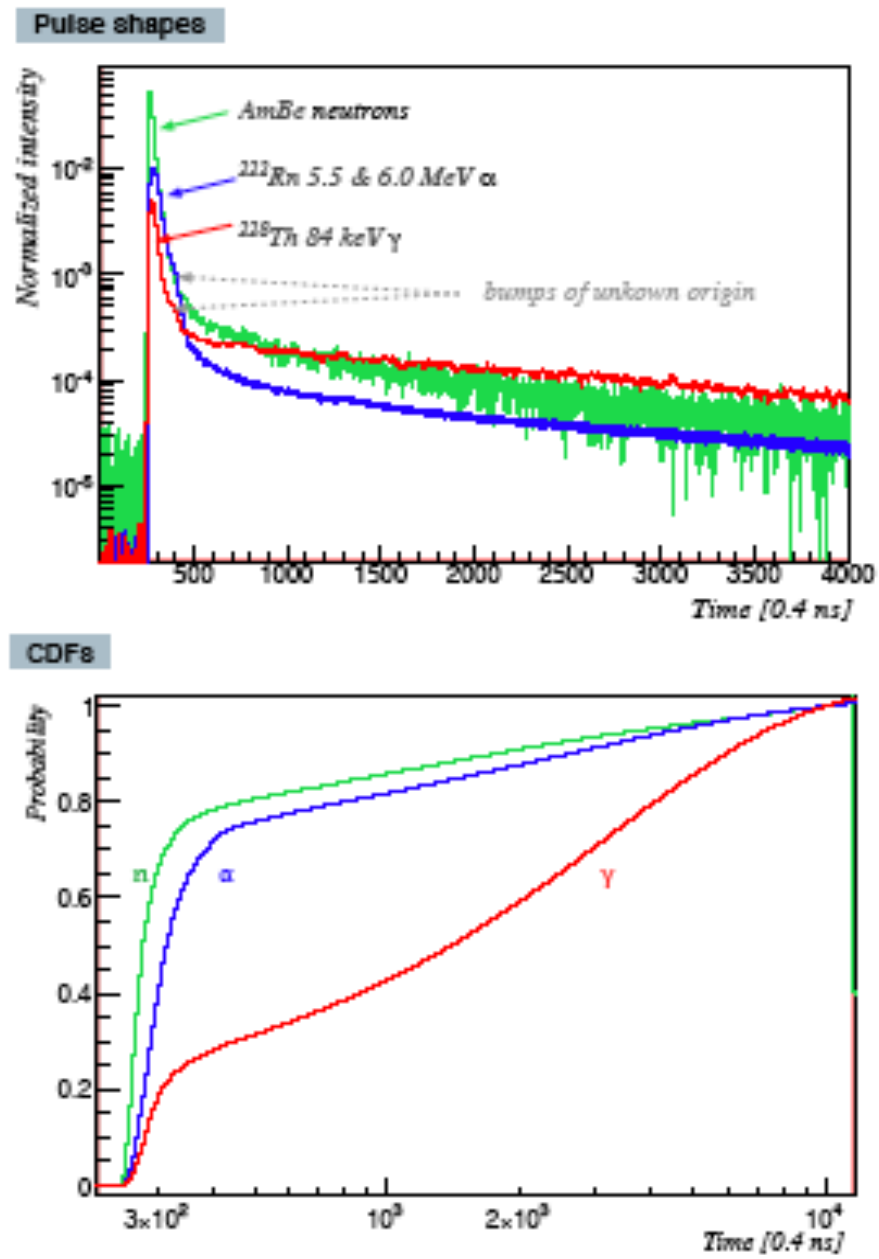
I(fast)/I(slow)

= 0.3(γ)

= 1.0(α)

= 3.0(neutrons)

*convolved with waveshifter and PMT response



from T. Pollman

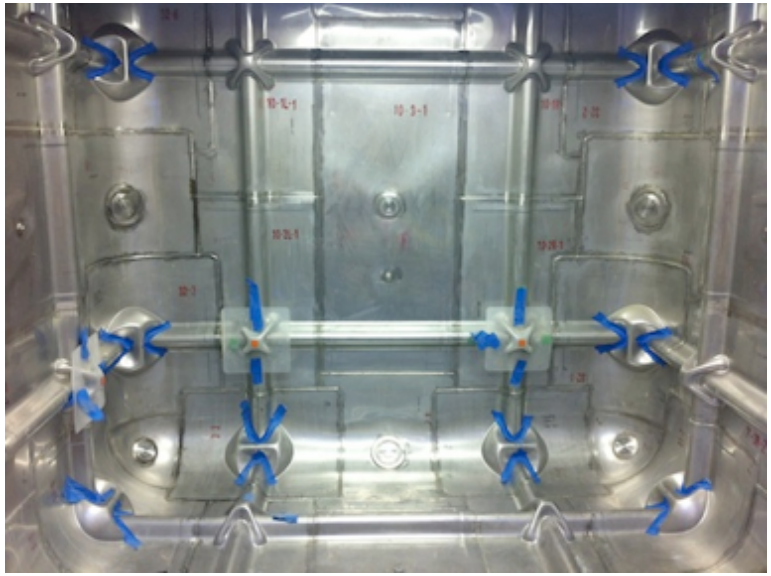
S. Pordes

Year(s)	Experiment or prototype	LAr Volume (m^3)	Total LAr Mass (tons)	Cryostat(s) Cost (x $1000)	Shape	Type	Insulation	Dimensions
2007 - present	Material Test Stand at FNAL	0.25	0.35	n/a	Cylinder, Vertical	commercial dewar	Vacuum	small
2009 - 2010	ArgoNeut Experiment T-962	0.55	0.76	$ 164K	Cylinder, Horizontal	pipe/plate	Vacuum	0.8 m x 1.3 m long
2011	LAr Purity Demonstrator (LAPD)	22.2	30.7	$ 140K	Cylinder, Vertical	plate shell	Foam, 0.3 m	3 m dia. x 3 m tall
2012	LBNE 35 ton membrane cryostat prototype	29.2	33.5	$ 600K	Rectangular	Membrane	Foam, 0.4 m	2.7 x 4.0 x 2.7 m high
2014	MicroBooNE Experiment	108	150	$ 1.0 M	Cylinder, Horizontal	1" thick plate	Foam, 0.4 m	4 m dia. x 12.2 m long
2003 - present	ICARUS T600 detector	550	761	?	Rectangular	Honeycomb panels	vacuum, LN2	2 vessels, 3.6 x 19.6 x 3.9 m high
2014	LBNE LAr1, 1 kton prototype	666	826	$ 4.0 M	Rectangular	Membrane	Foam, 1 m	7.1 x 10.2 x 9.2 m high
2020 ??	LBNE LAr40, in 2 cryostats	38,000	50,000	$ 90 M	Rectangular	Membrane	Foam, 1 m	2 vessels, 24 x 49 x 16 m high
2020 ??	LAGUNA	76,000	100,000	?	Cylinder, Vertical	?	?	?

Russ Rucinski, TIPP 2011

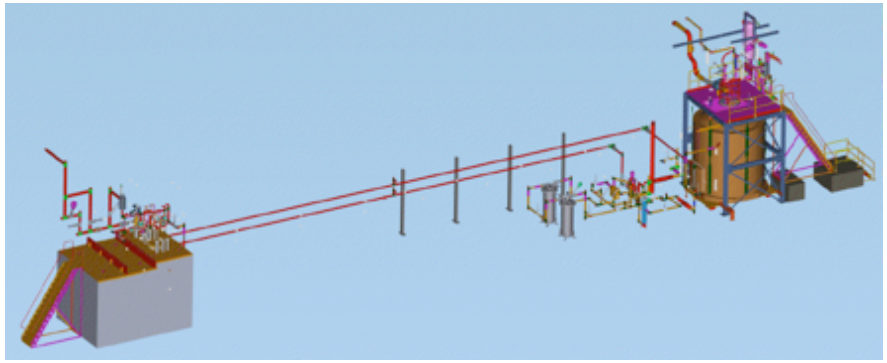
35 Ton Prototype

- A prototype of the membrane cryostat for LBNE exists right next to LAPD



- Capitalize on existing infrastructure at LAPD

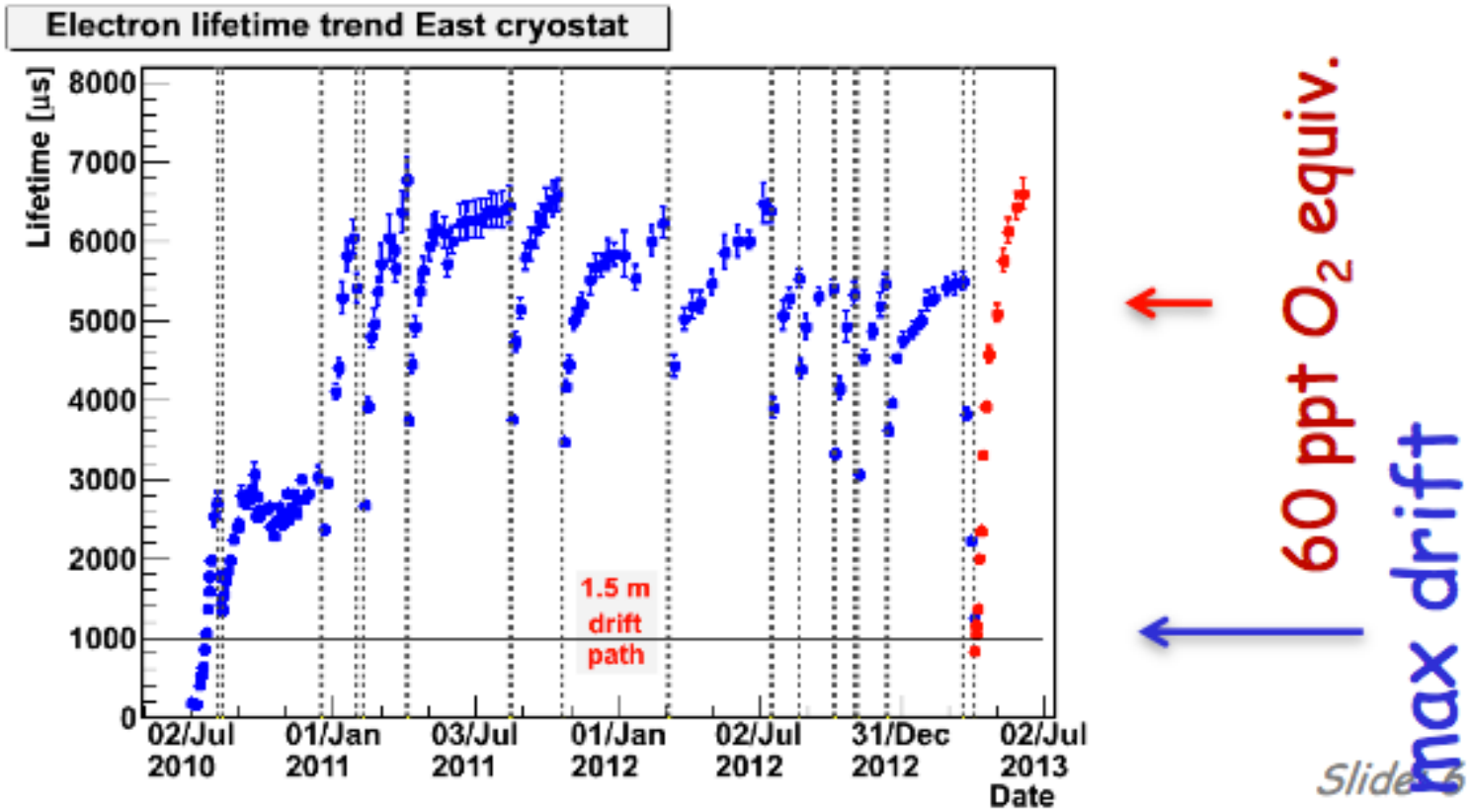
- Two runs in mind:
  - Phase 1 is to prove required purity can be achieved (> 1.4 ms)
  - Phase 2 will introduce two TPCs



ICARUS Purification Steps

- Use high vacuum standards in construction and cleaning
  - Is this needed?
- Evacuate the cryostat to < 10^{-3} mbar to remove contaminants
  - Expensive for a large cryostat
- Cool quickly and fill with LAr to minimize outgassing
  - Expensive for a large cryostat
- Re-liquefy gaseous argon (GAr) boil-off and purify before returning to the main volume
- Recirculate and purify the main LAr volume if there is significant contamination at filling or due to an upset condition

ICARUS Purification Experience



Paola Sala, NuFact 2013

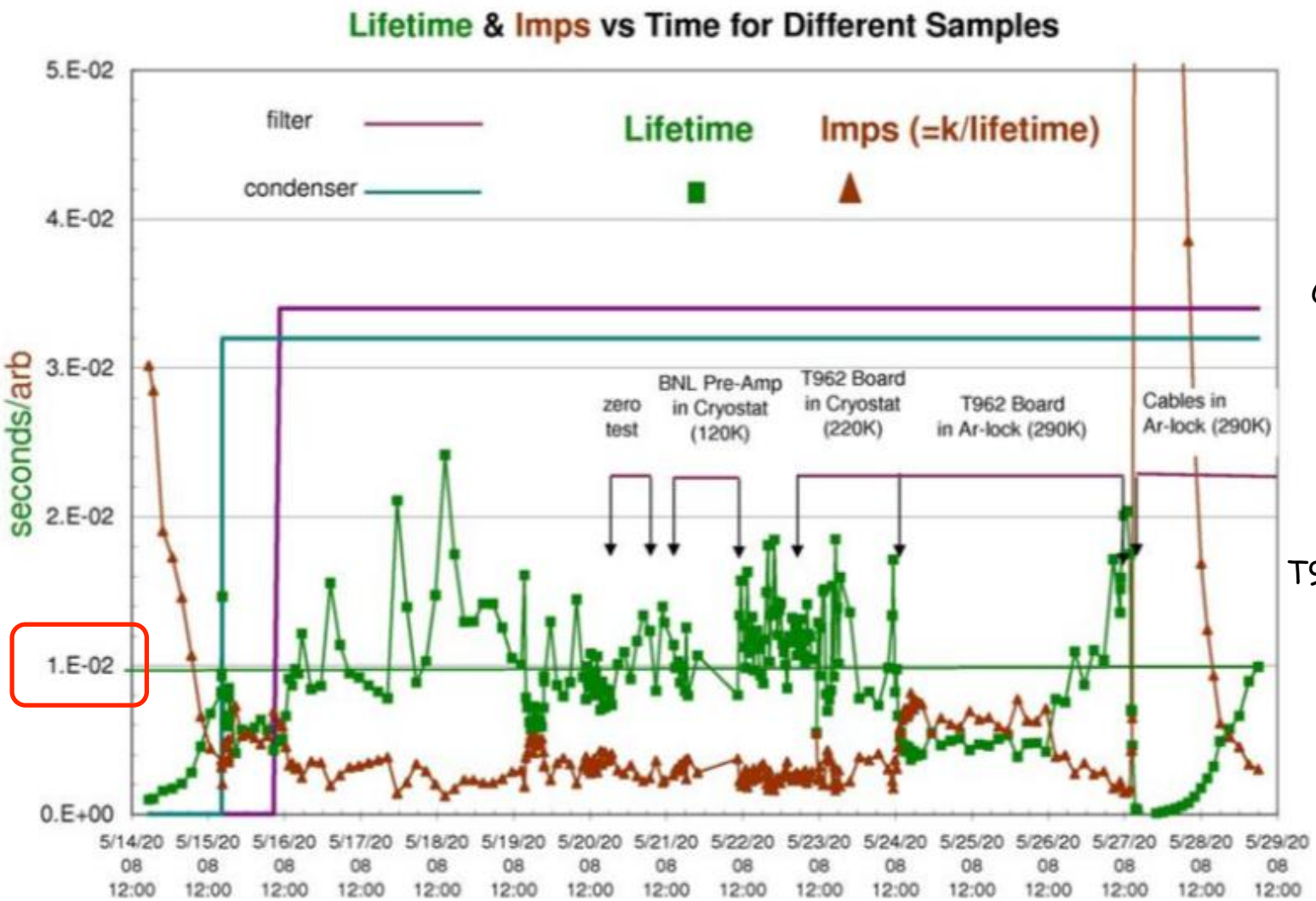
- LAr continuously filtered
- Electron lifetime > 5 ms for most of the runs.

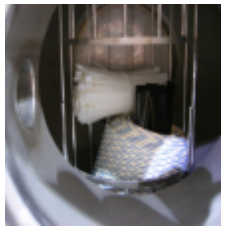
Materials Qualification

- No published results on materials effects on electron lifetime from ICARUS or other exps
  - Materials Test Stand

- ICARUS experience: pollution of the LAr is mainly due to outgassing of the inner surfaces in contact with the GAr, while contamination from objects immersed in the liquid is negligible
  - Materials Test Stand reached the same conclusion
  - Identified H2O to be the main contaminant

Materials Test Run





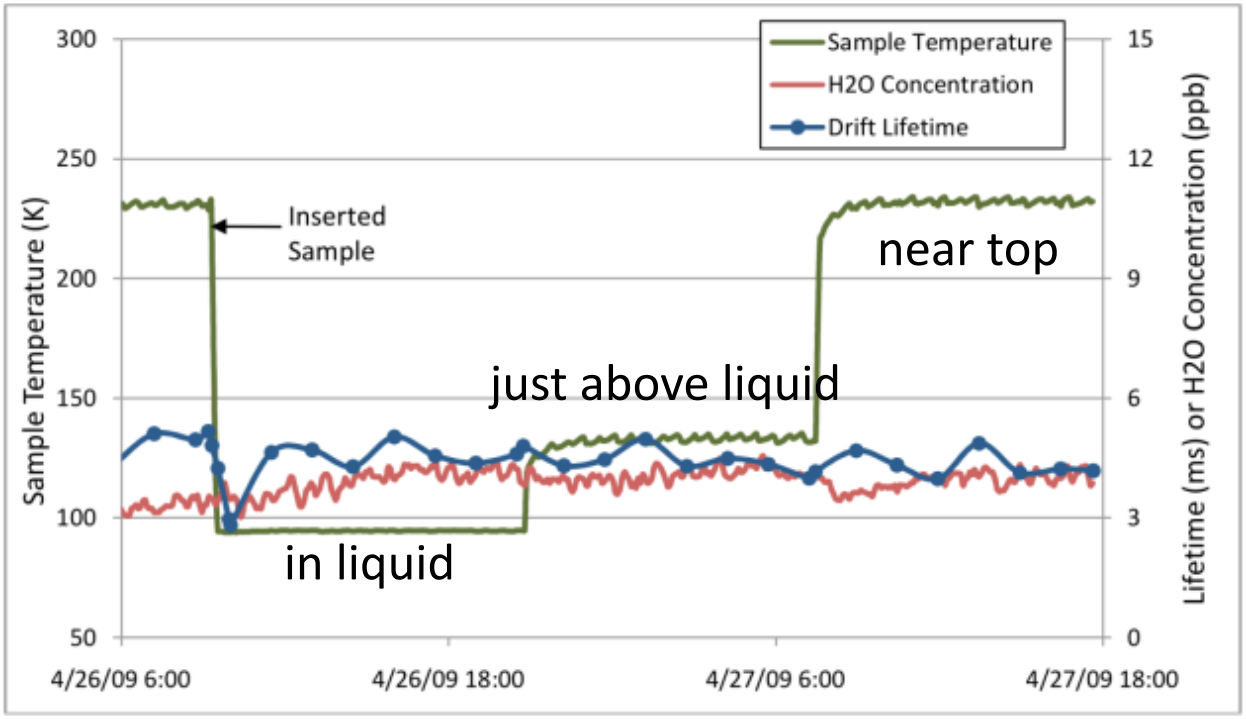
Cables & Cable ties

T962DecouplingBoard

Cold pre-amp

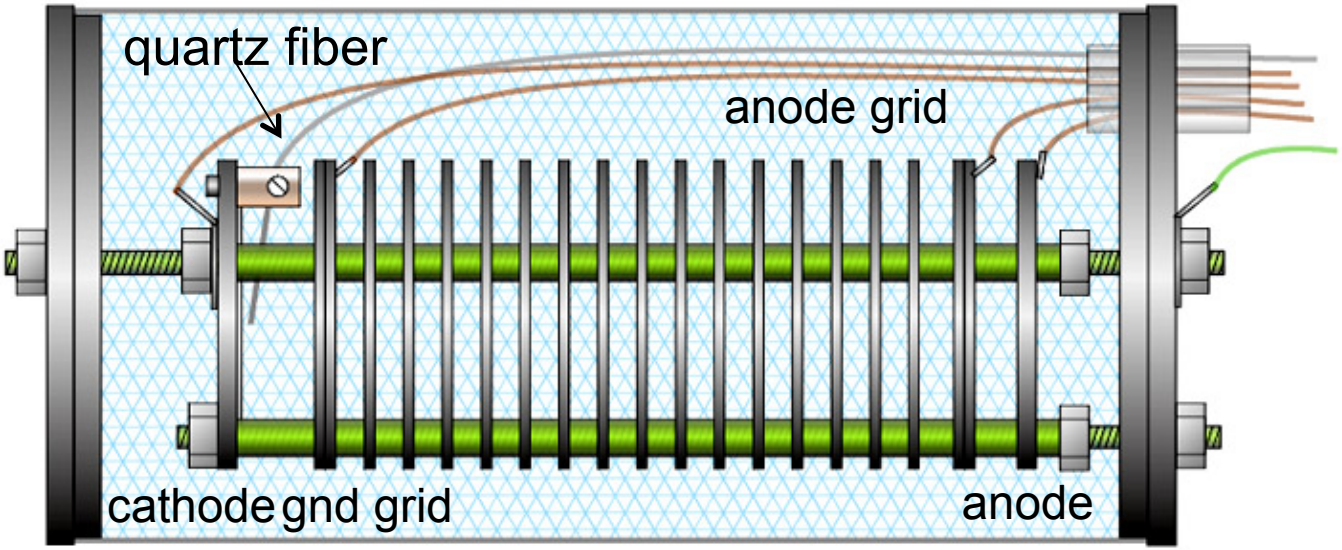
Water Effects - 2

FR-4 based circuit board – from Argonlock *with evacuation*

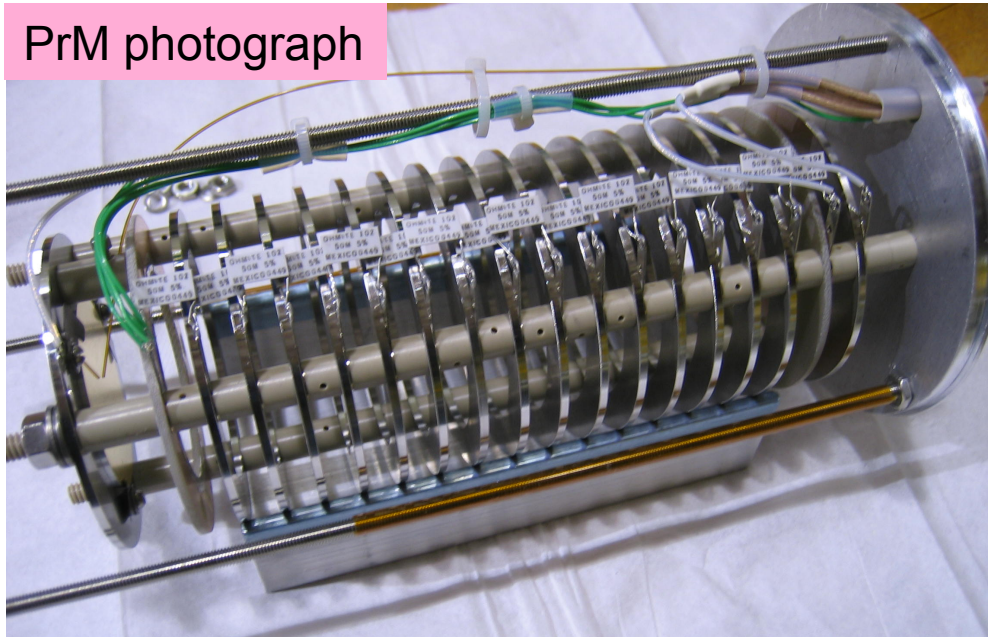


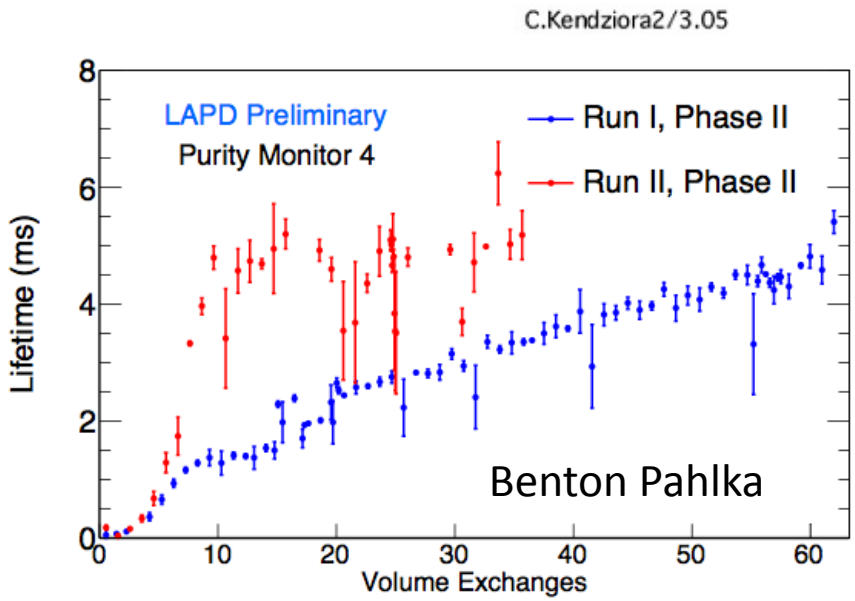
Little change in H_2O reading and little change in lifetime
Evacuation removes H_2O contaminant

PrM drawing



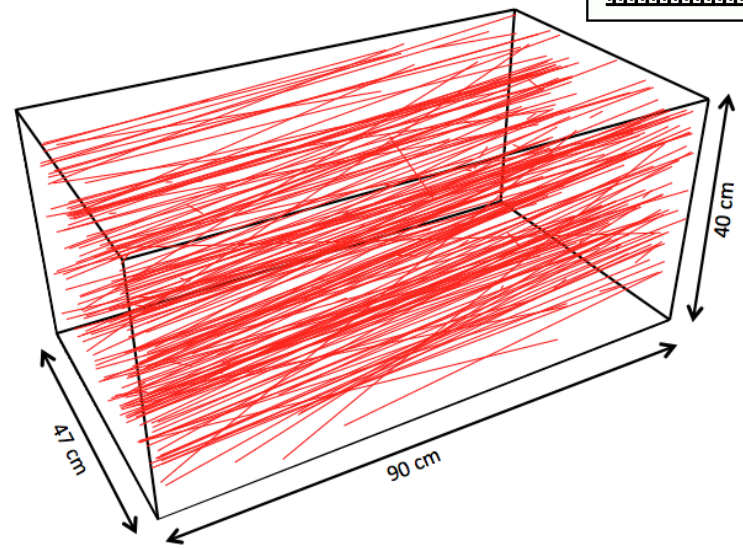
PrM photograph

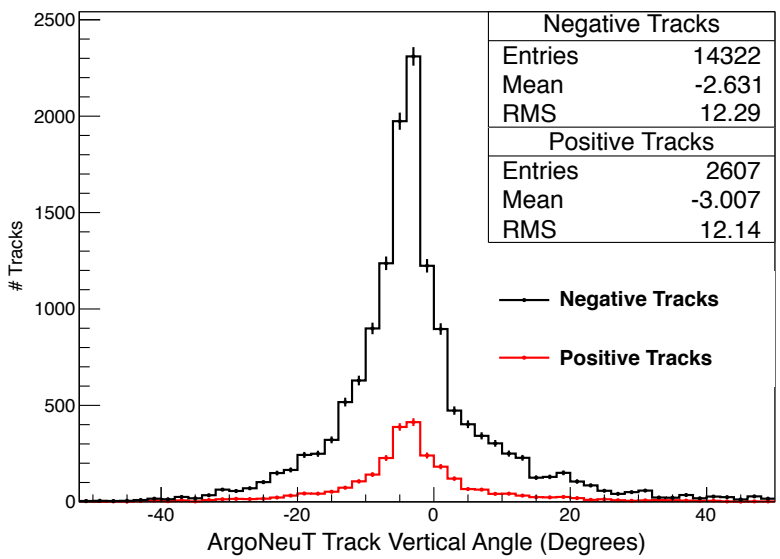


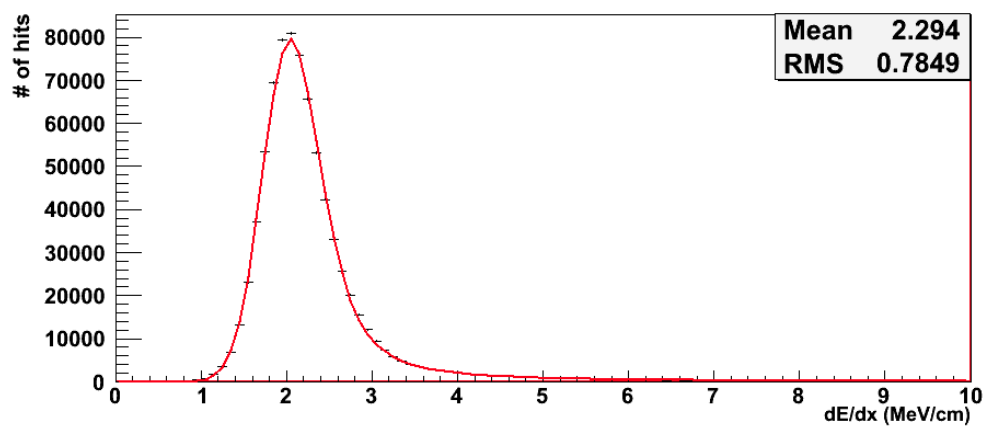


Detector Calibration with Through-going Muons

- A large sample of neutrino induced through-going muons are useful for detector calibration
- Test geometric and calorimetric reconstruction in the ArgoNeuT detector
- JINST 7 (2012) P10020; arXiv: 1205.6702



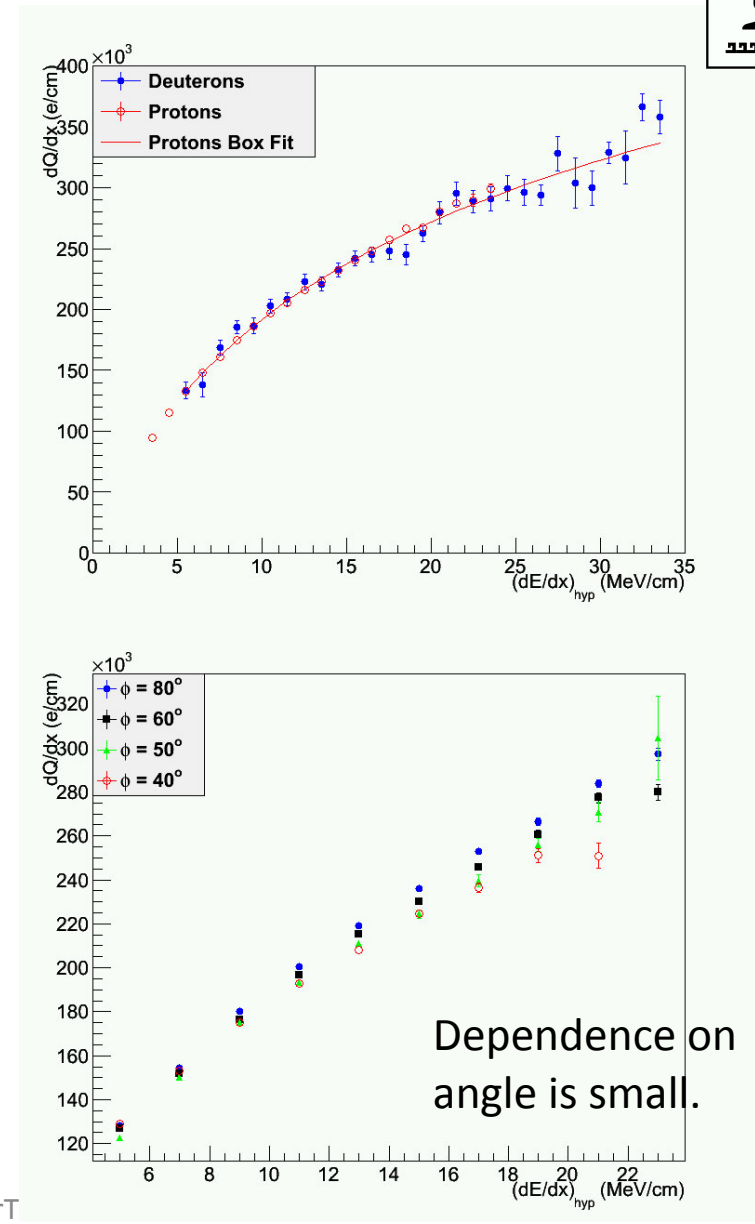




<dE/dx>=2.3±0.2 MeV/cm, in good agreement with theoretical expectations for $\langle E_\mu \rangle$=7.0 GeV

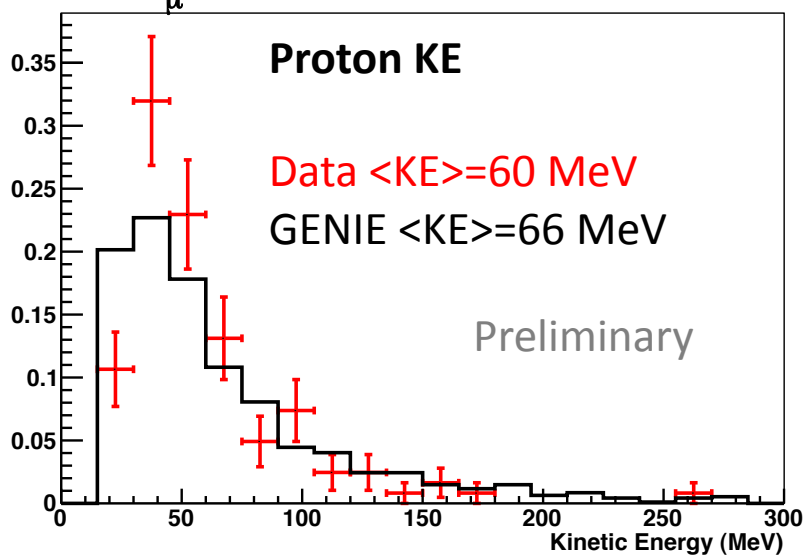
Recombination Studies

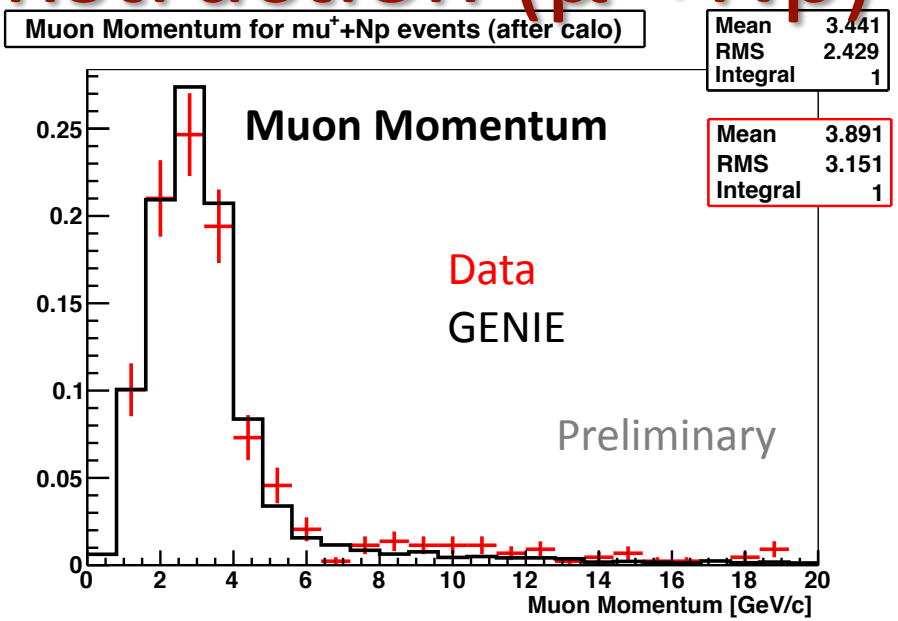
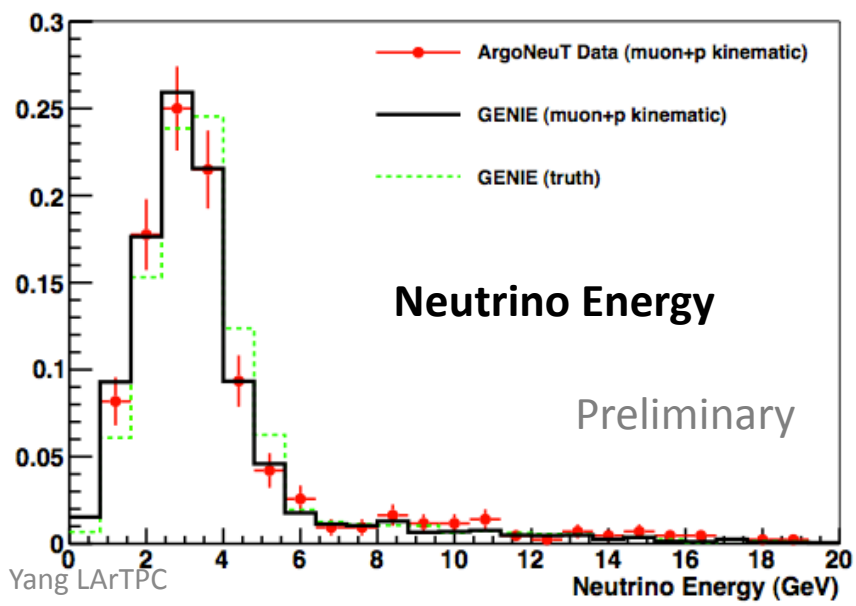
- Study the recombination of electron-ion pairs produced by ionizing tracks using stopping protons and deuterons
- Results in agreement with ICARUS with extended dE/dx range and smaller uncertainties
- Also study the dependence of recombination on the track angle
- *JINST* 8 (2013) P08005, arXiv: 1306.1712



Kinematics Reconstruction (μ^++Np)

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





- Neutrino Energy $E_\nu = E_\mu + \Sigma T_p$
- Not just muon information, model independent
- Other kinematic quantity reconstruction (Q^2 etc.) in progress