APA Design: Physics Motivation and Detector Performance

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APA Design Review

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- Brief refresher on LArTPC principle.
- Reminder of DUNE/protoDUNE LArTPC arrangement.
- APA Design Parameters
- Physics Motivations
- Detector Performance

Introduction

- This talk will provide an overview of the protoDUNE APA design.
- I will address the physics and detector performance aspects of the charge question: **"Does the APA design meet the requirements? Are the requirements/justifications sufficiently complete and clear?".** Lee Greenler's talk will address the engineering aspects of this charge question.
- I will present some information on anticipated detector performance, using available tools in LArSoft framework. Xin will have much more of the underlying technical details in his talk.

LArTPC Principle

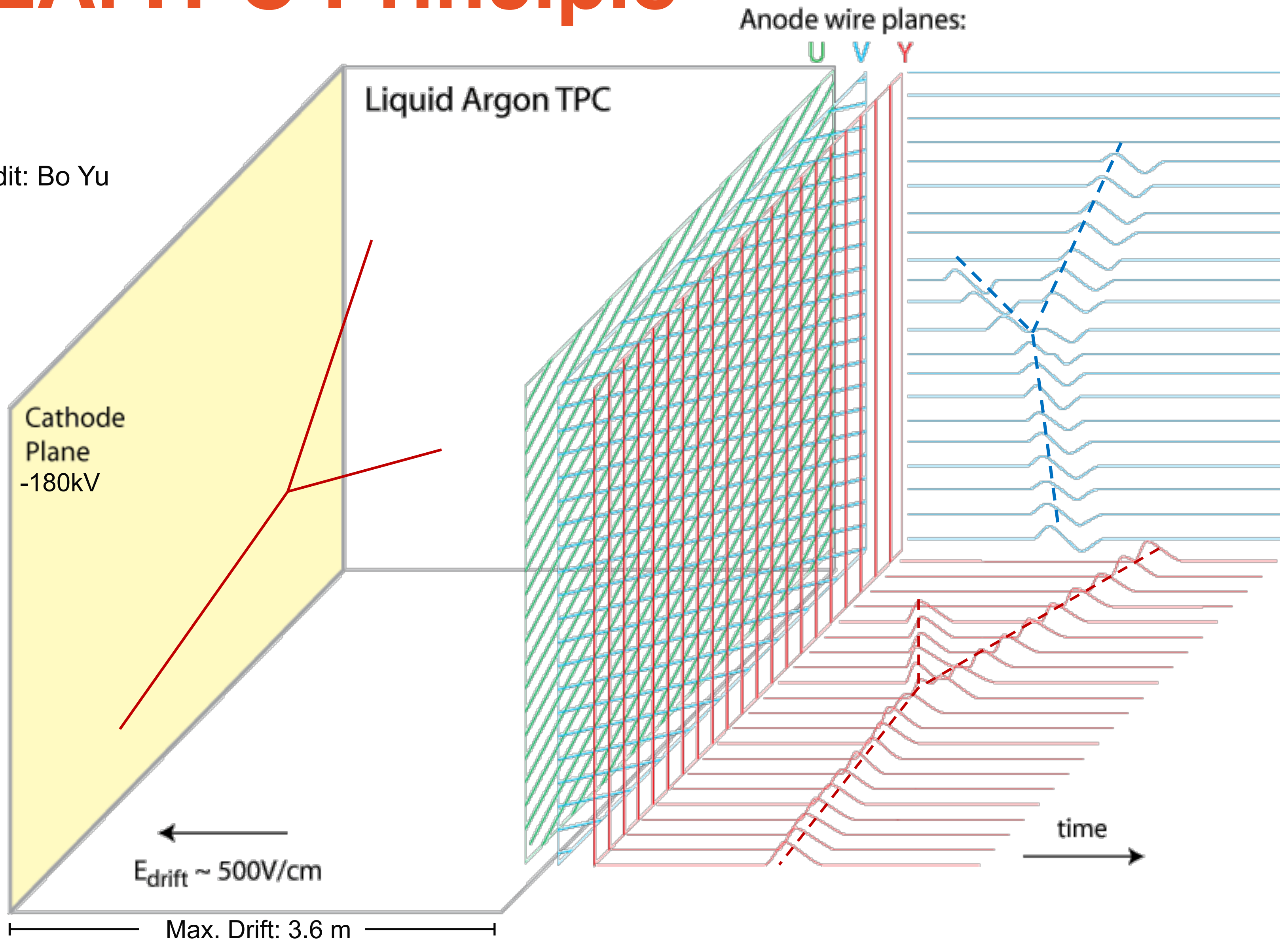
Why liquid argon (LAr)?

	He	Ne	Ar	Kr	Xe
Atomic Number	2	10	18	36	54
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165
Density [g/cm³]	0.125	1.2	1.4	2.4	3
Radiation Length [cm]	755.2	24	14	4.9	2.8
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175
Cost ($/kg)	52	330	5	330	1200

LAr combines abundant signal (ionization/scintillation), good dielectric, and low cost.

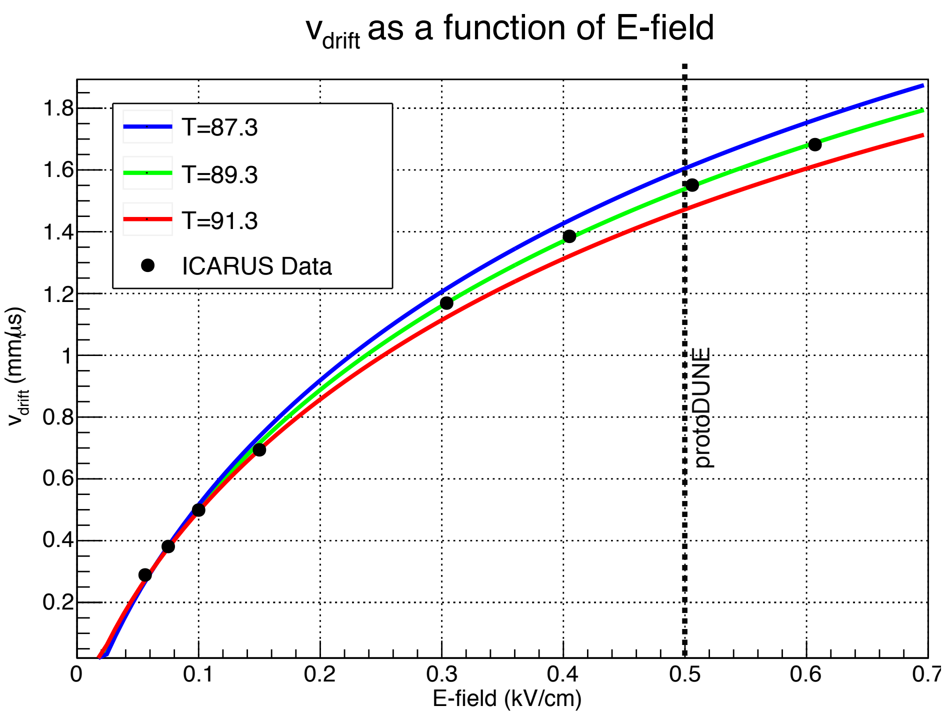
LArTPC Principle

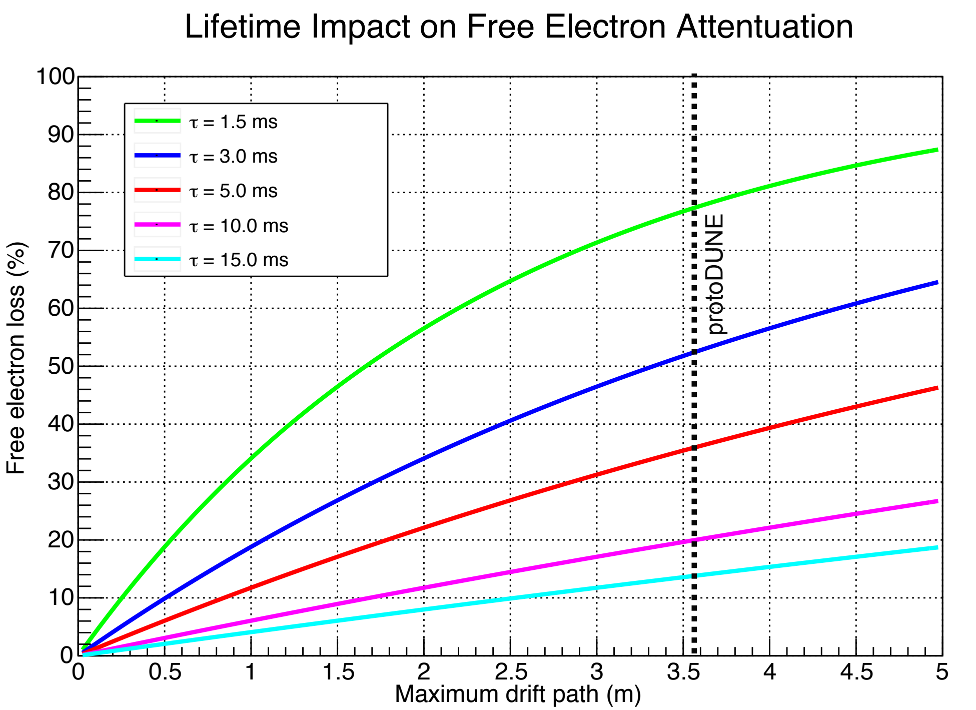
credit: Bo Yu



LArTPC Principle

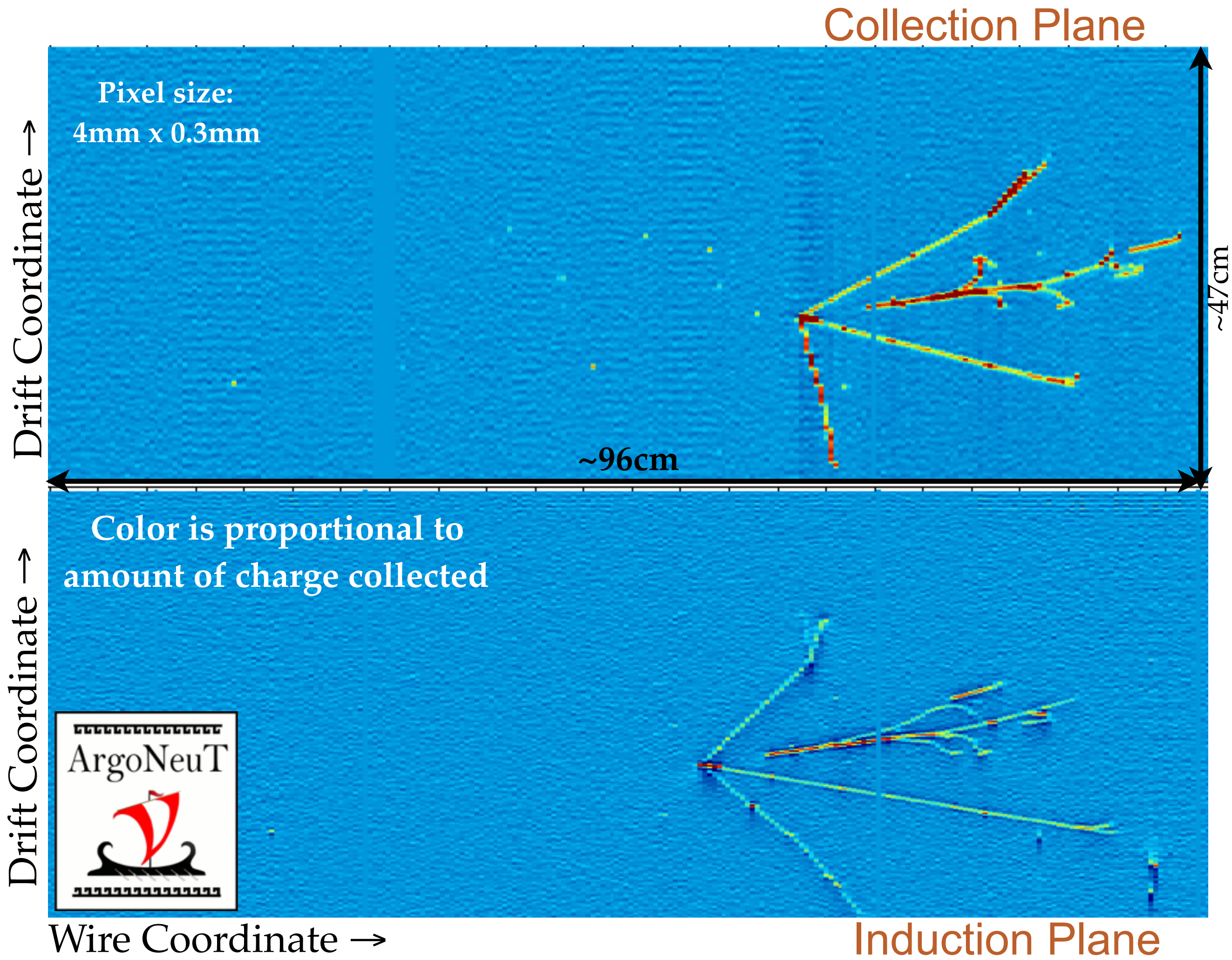
- At **operating field of 0.5 kV/cm**, drift velocity is ~1.6 mm/us.
- protoDUNE **max. drift length is 3.6 m**, which corresponds to 2.25 ms drift time.
- Want **electron lifetime >3 ms** to keep attenuation (i.e. charge loss) tractable.





LArTPC Principle

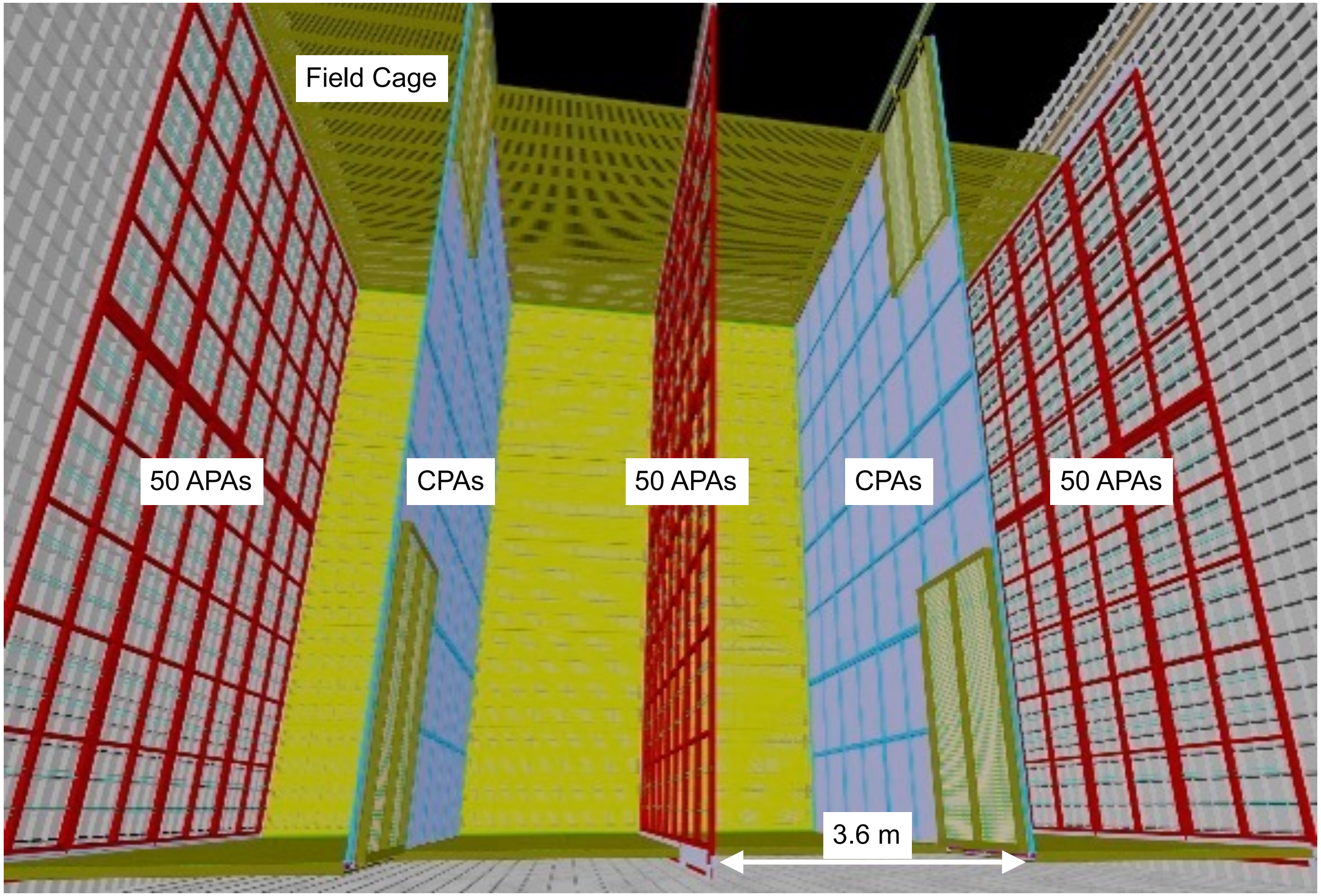
- Each instrumented plane provides a 2D image of the ionization present in the LArTPC.
- Analysis must combine data into 3D picture/ understanding of what occurred in the detector.
- Task made challenging by: dead wires, noisy wires, non-uniform drift-field, LAr impurities, long drift length, etc… see Xin's talk next.



DUNE Single-Phase TPC

- 10 kTon DUNE FD module features 150 **Anode Plane Assemblies (APAs)**, arranged in 3 rows of 50 double-stacked APAs.

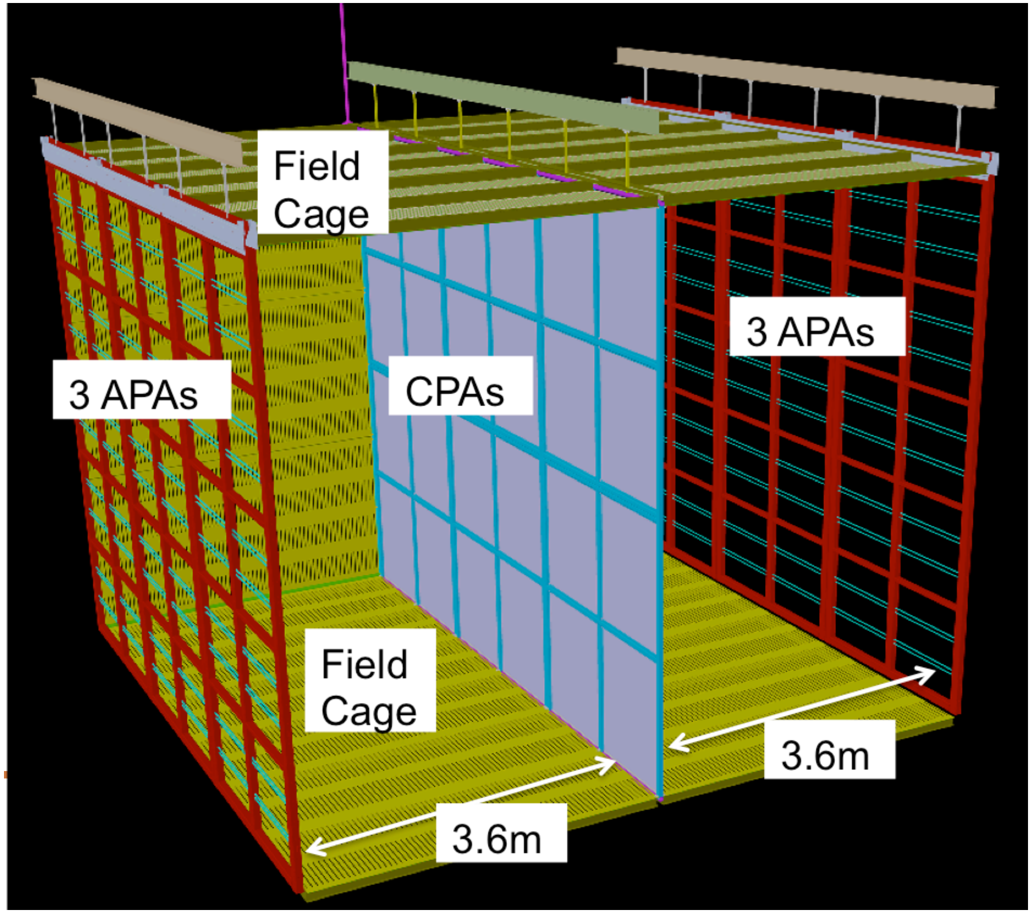
A portion of a 10kTon DUNE module



CPA = Cathode Plane Assembly

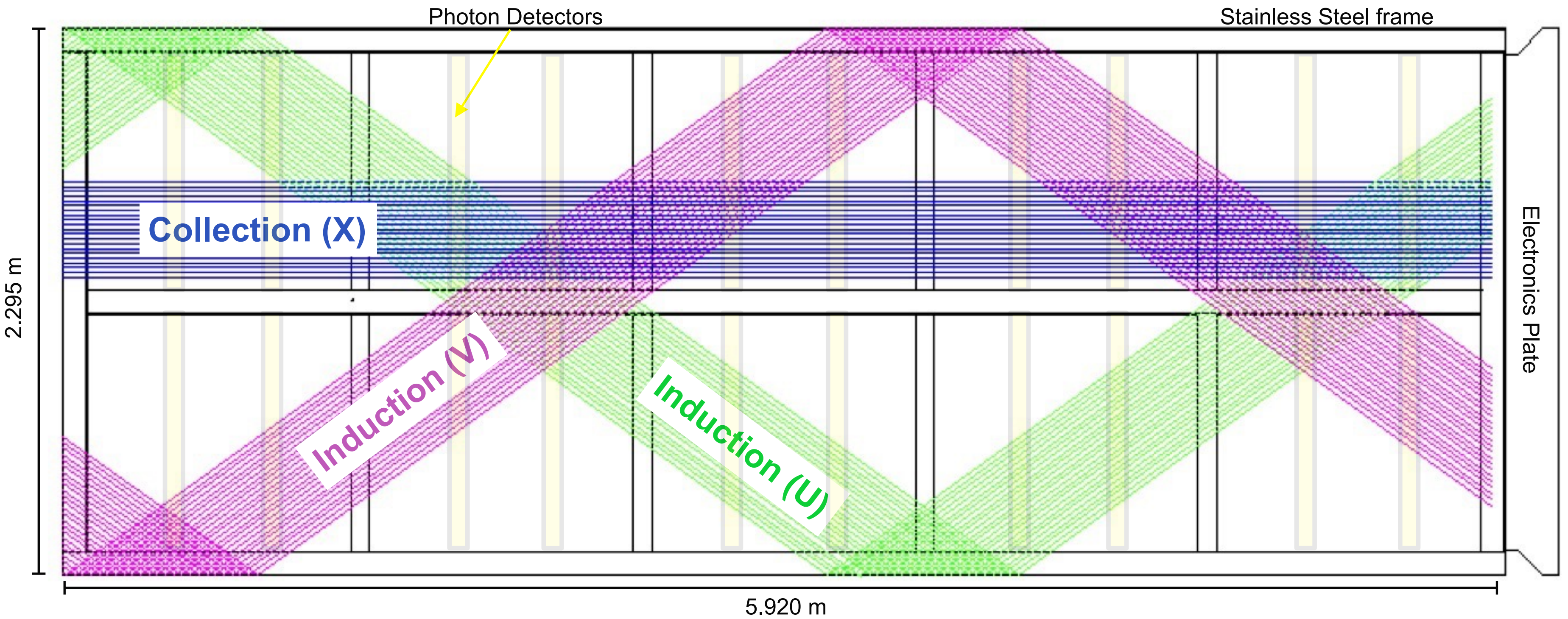
protoDUNE Single-Phase TPC

- protoDUNE will feature 6 full-sized DUNE APAs, arranged in 2 rows of 3 single-stacked APAs.



APA Design Parameters

- APAs are double-sided, including Induction plane wires that wrap in a helical fashion around long edge. A single Induction wire can thus sense signals from both sides of the APA.
- Design allows footprint taken up by electronics/cabling to be minimized, and allows APAs to tile the total active area of the detector.
- APAs sized to be assembled off-site and transported/installed underground.



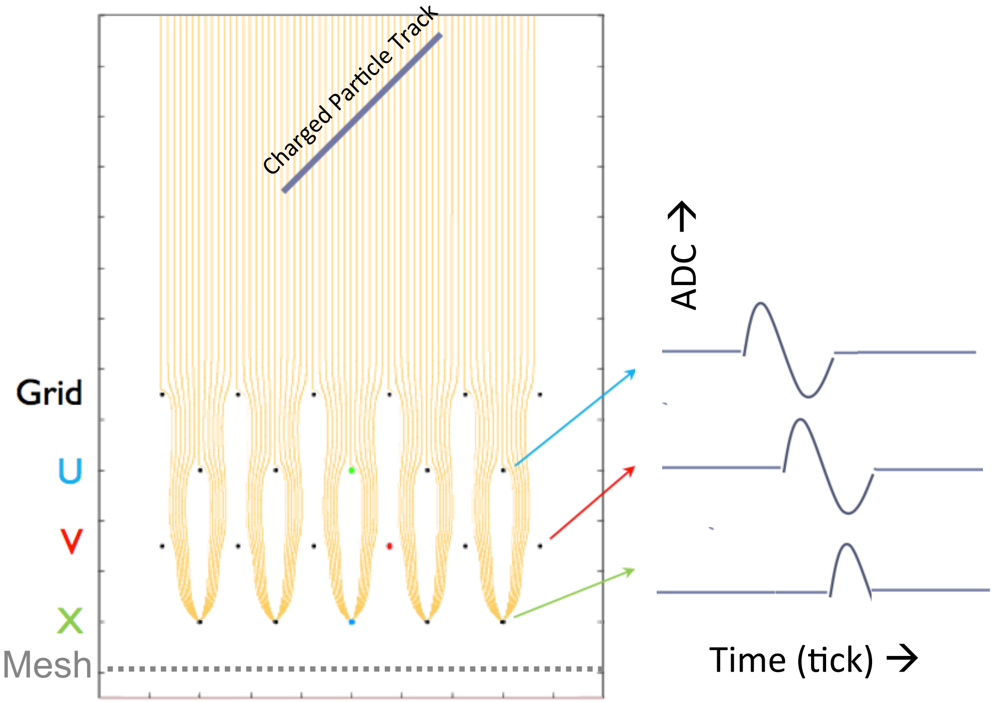
APA Design Parameters

Parameter	Value	Note
Active Height	5.920 m	Height of X wires.
Active Width	2.295 m	Distance between outermost X wires.
Wire Pitch (U,V)	4.67 mm	Chosen for particle ID and to keep integral number of readout boards
Wire angle w.r.t. vertical (U,V)	35.71 degrees	Based on reducing reconstruction ambiguity
Wire pitch (X)	4.79 mm	Chosen for particle ID and to keep integral number of readout boards
Wire angle w.r.t vertical (X)	0 degrees	Based on forward beam direction.

APA Design Parameters

Parameter	Value	Note
Wire Type	Copper Beryllium, 150um diameter.	Chosen for cost/solderability/ electrical properties
Wire Tension	5.0 N	Chosen to limit sag to <0.5mm, and stay below break-point of BeCu (~30 N)
Collection/Grid Wires/APA	960 (X), 960 (G)	Matches modularity of electronics
Induction Wires/APA	800 (U), 800 (V)	Matches modularity of electronics
Length of Longest Wire	7.3 m	Compatible with electronics noise requirements.
Longest Unsupported Wire Length	~1.2 m	To reduce possibility of touching wires.
Mesh layer	Yes (27 m^2 per APA).	Remove "reflection tracks", shield from noise.
Photon Detector slots	10	

APA Design Parameters



Anode Plane	Nominal Bias Voltage
Grid (G)	-665 V
Induction (U)	-370 V
Induction (V)	0 V
Collection (X)	820 V
Mesh (M)	0 V

Bruce Baller

Operating voltages are based on achieving >99% transparency for drifting ionization, and maintaining 500 V/cm drift field up to grid plane.

Physics Motivations

- **protoDUNE detector is a full-scale replica of DUNE FD to provide data-based input to design choices and physics performance.**
- protoDUNE is intended to provide comprehensive input on a DUNE-design LArTPC's capability for:
  - electron/photon separation
  - particle identification for all species ($\mu/\pi/K$/p/e/γ) across momentum range expected in DUNE beam.
  - low-E physics (< 100 MeV, e.g. SuperNova)
- Data will be used to tune simulations for DUNE.
- Analysis techniques developed for protoDUNE will be directly transferable to DUNE FD.

Physics Motivations

Physics Requirement (APA-centric)	Value
MIP Identification	100% efficiency anywhere in active detector volume.
Efficiency for charge reconstruction.	- >90% for >100 MeV of visible energy. - "High efficiency" for <100 MeV.
Vertex Resolution	(1.5 cm, 1.5 cm, 1.5 cm) to ensure <1% uncertainty of fiducial volume.
$\mu/\pi/K/p$ Identification	- Muons: <(18%) 5% momentum resolution (non)contained - Hadronic energy resolution for stopping hadrons: 1-5% - 90% efficiency for stub-finding (electron stubs >5 MeV momentum)
e/γ Identification/Separation	- <1% photon mis-ID, and >90% electron efficiency, in 0.2-6.0 GeV range -<5% electron energy scale uncertainty

Detector Performance

To meet Physics requirements, these detector parameter requirements are necessary.

Parameter (APA-centric)	Design Requirement	Note
Wire Tension	5.0 N [1.0 N]	Chosen to limit sag to <0.5mm, and stay below break-point of BeCu (~30 N)
APA Frame Planarity	5 mm	To maintain anode plane transparency.
Bias voltage	Must hold >100% of max. operating voltage.	Headroom in case anode voltages need to be adjusted.
S/N	>9:1	To allow MIP measurement with high-efficiency everywhere in TPC.
Wire pitch	~5 mm	To provide enough granularity for PID, particularly e/gamma separation.
Wire position tolerance	0.5 mm	To achieve reconstruction precision.
Induction Wire angle	35.71 degrees	To reduce Hit ambiguity during reconstruction.
Missing/unusable wires	<0.5% (~13 wires). No blocks of ≥3 in a row.	Missing wires impact anode field, and thus, reconstruction.

Detector Performance

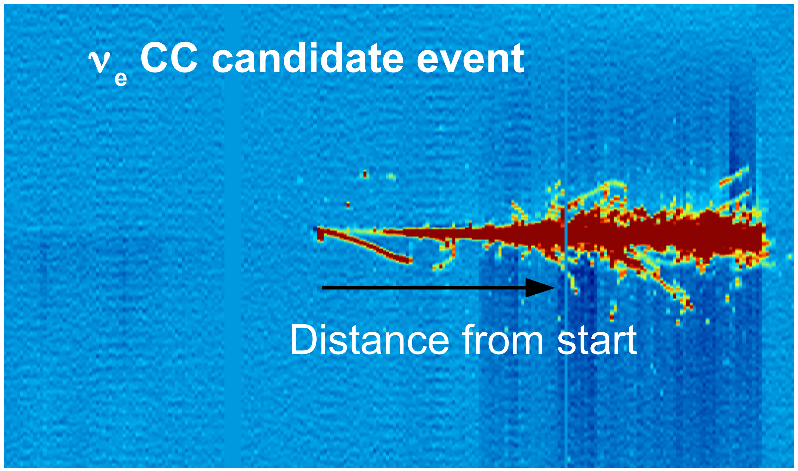
Other relevant parameters, not strictly APA-related.

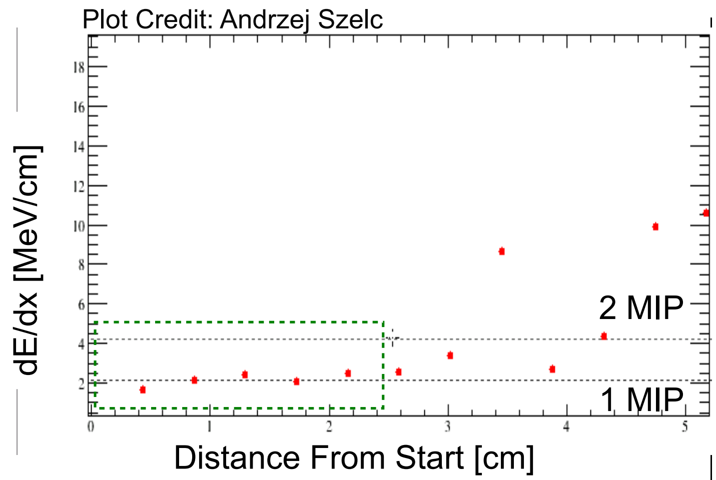
Parameter	Design Goal	Note
LAr purity (electron lifetime)	3 ms	To allow MIP measurements at longest drift; SuperNova events.
Drift field	500 V/cm	Leads to max. drift time of 2.25 ms for 3.6 m drift distance. Requires -180kV cathode voltage.
Electronics Noise	ENC<600 at 90 K.	To allow MIP measurement with high-efficiency.

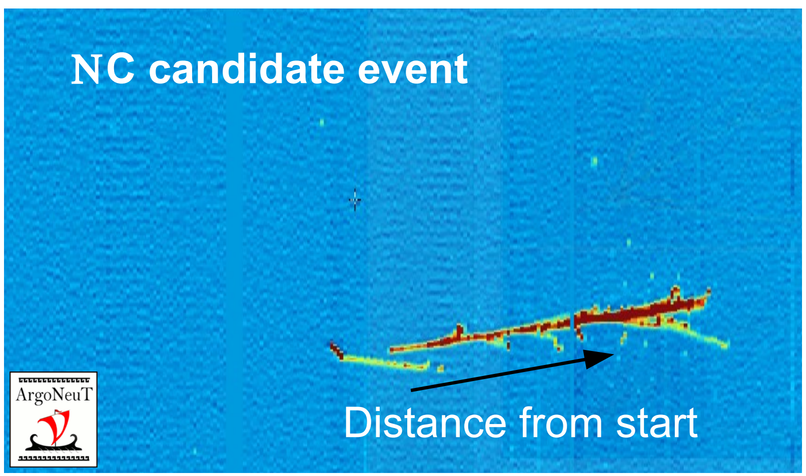
APAs, like rest of TPC, subject to requirements from Cleanliness and Electrical Grounding/Shielding.

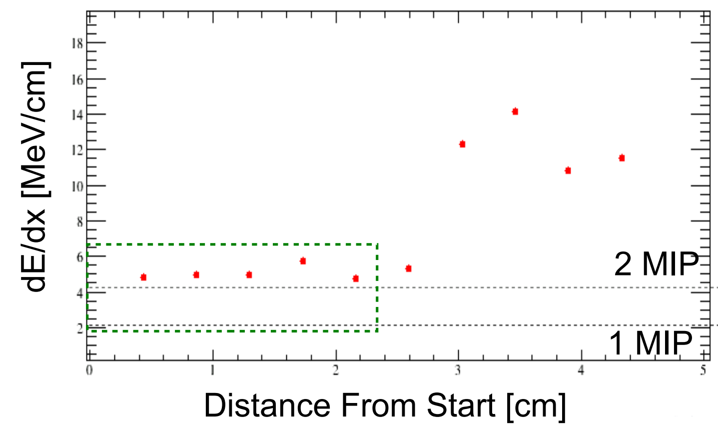
Detector Performance

- Critical for protoDUNE to demonstrate ability to identify electrons and reject photons.
- dE/dx profile in early stage of electromagnetic shower provides a handle for this.



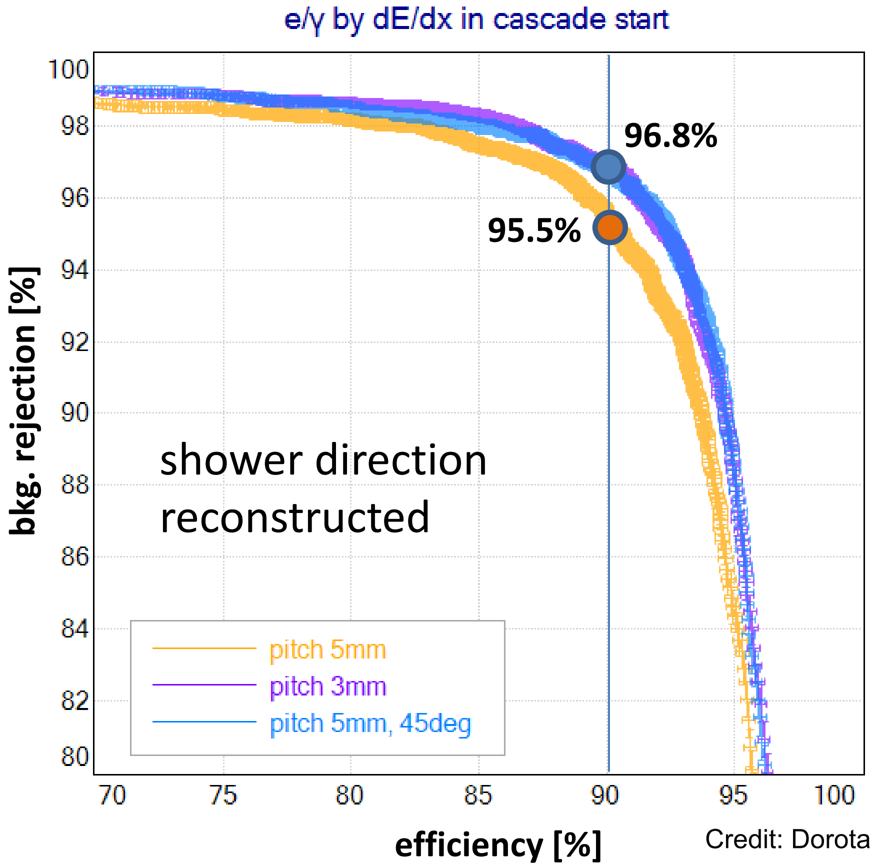


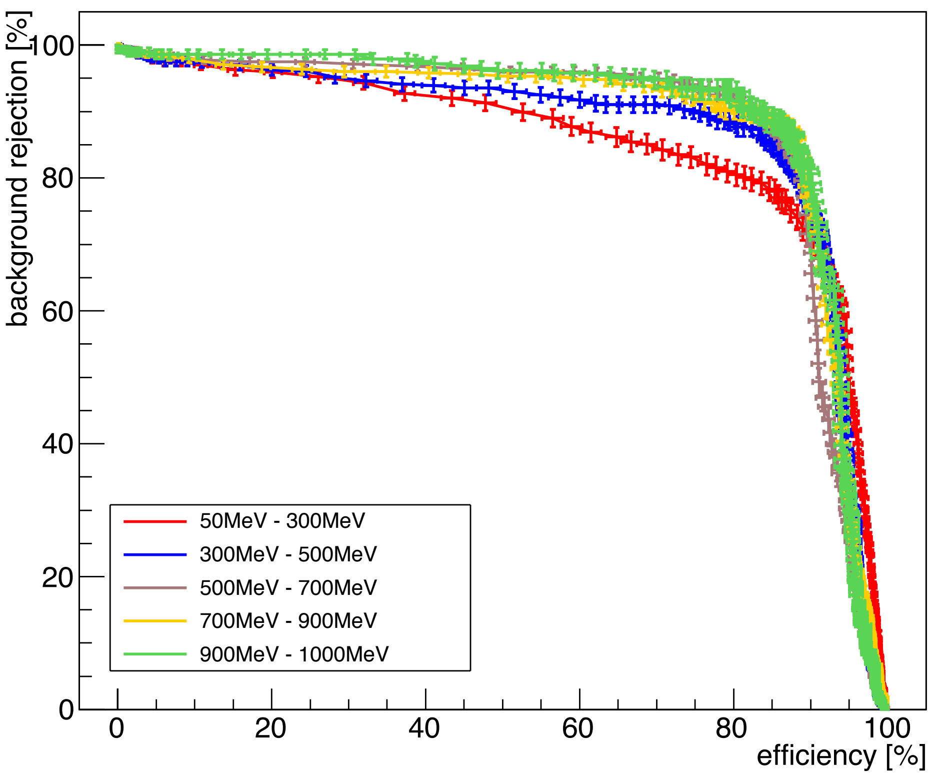




Detector Performance

- Goal is 90% ν_e efficiency and <1% NC mis-identification.
- Studies with single-particle MC and automated reconstructed, for three different values of wire pitch and Induction wire angle (5mm, 37 degrees), (5mm, 45 degrees), (3mm, 37 degrees) show these goals are almost met just using dE/dx. Folding in topology and other techniques will further reduce background.

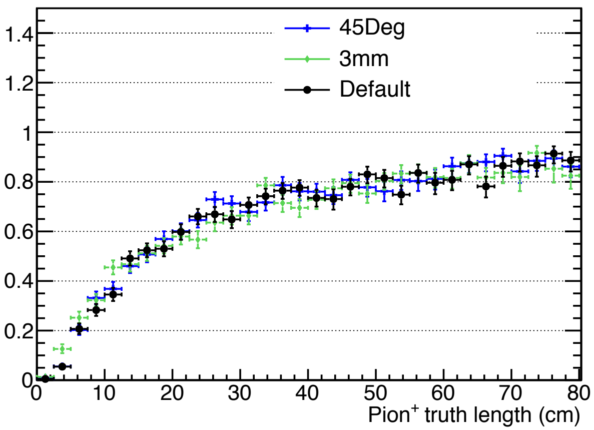


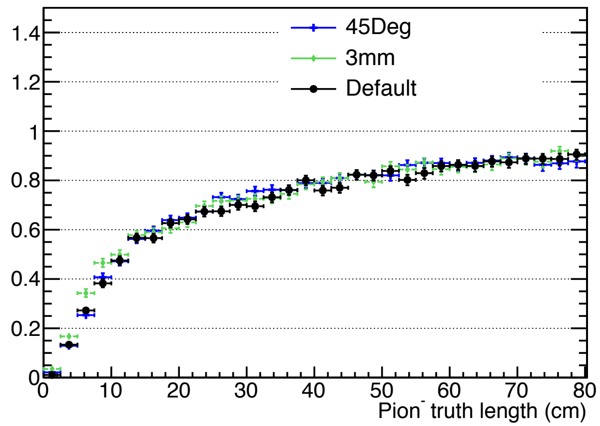


Credit: Dorota Stefan, Robert Sulej

Detector Performance

- Impact of wire pitch/angle on tracking efficiency of charged particles is also being studied.
- Very good efficiency for simulated neutrino (CC ν_μ) interactions, with lowest efficiency coming for very short tracks (<30cm).





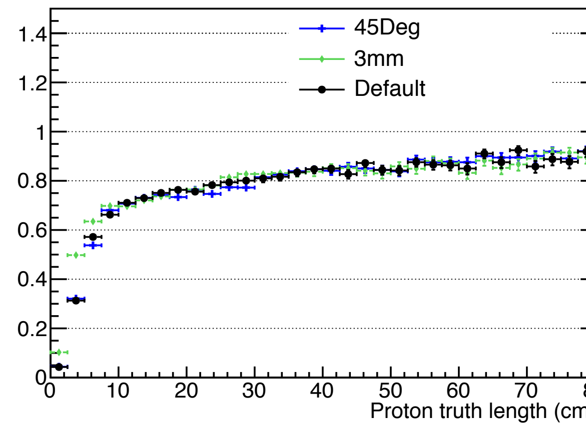


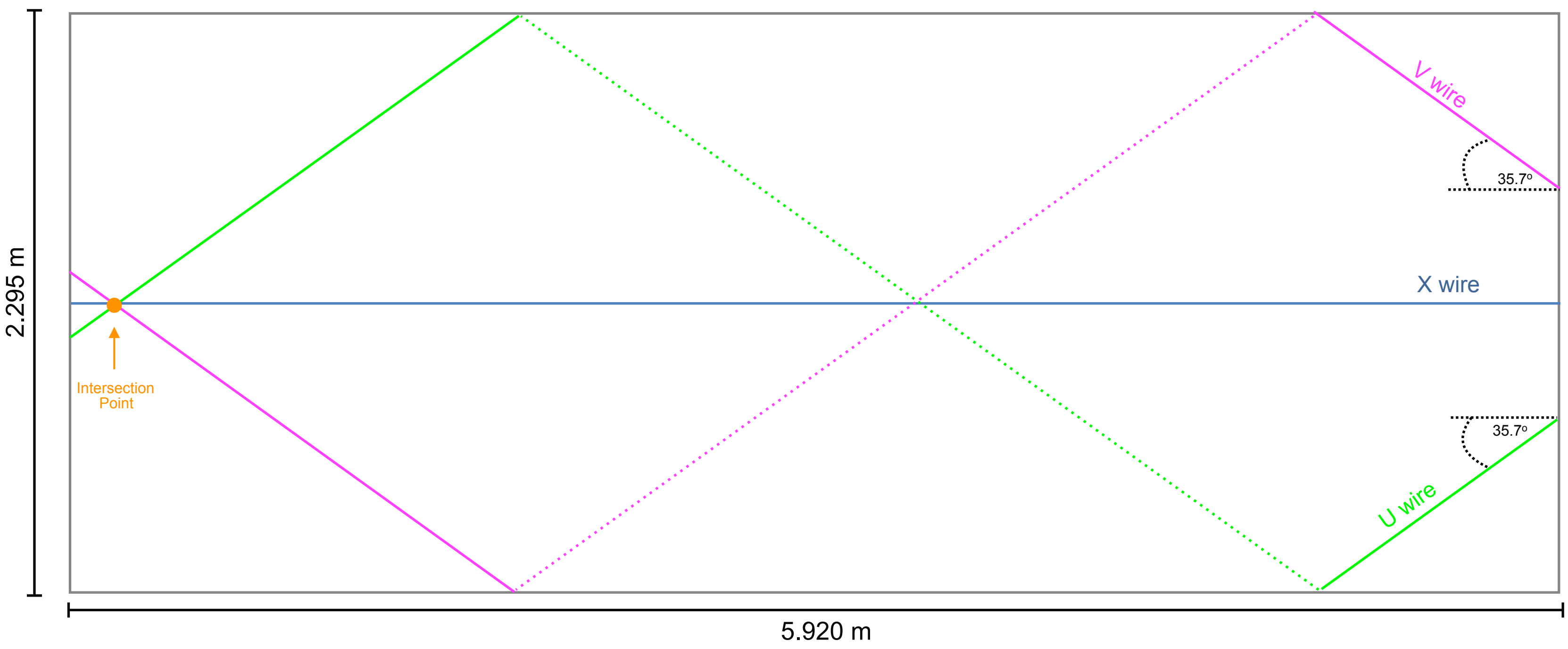
Table 1: Tracking Efficiencies for CC ν_μ events

	Default (%)	3mm (%)	45Deg (%)
Muon	98.2 ± 0.06	98.8 ± 0.05	98.1 ± 0.06
Proton	61.0 ± 0.26	64.1 ± 0.26	60.8 ± 0.26
Pion^+	66.5 ± 0.30	69.0 ± 0.30	68.1 ± 0.30
Pion^-	62.5 ± 0.50	63.0 ± 0.52	62.8 ± 0.51

Plot/Table Credit: Aaron Higuera

Detector Performance

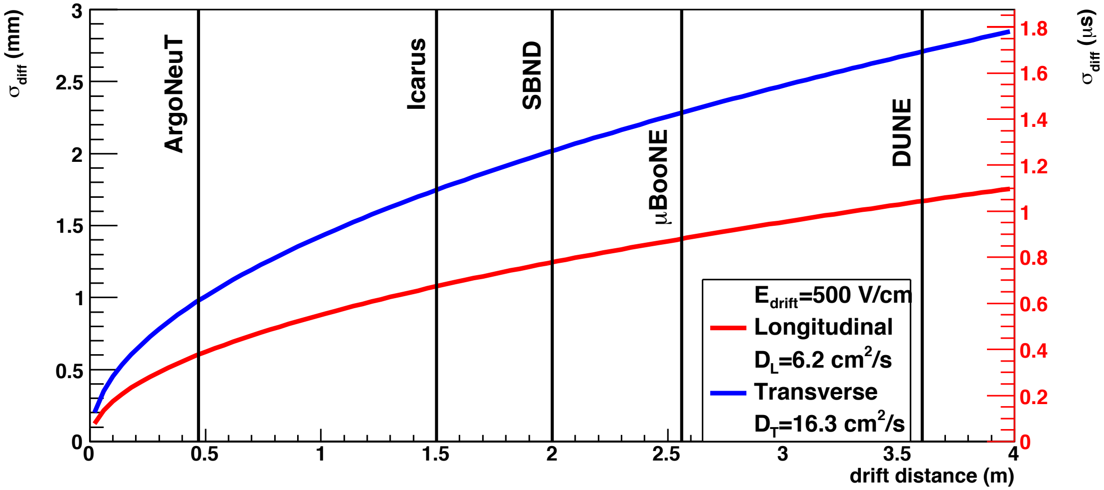
- Induction wire angle (35.7 degrees) chosen such that no wire crosses a Collection wire more than once.
- Triplets of U,V,X wires never intersect more than once.
- Hits still need "disambiguation" due to unknown location along a wire length, and combinatorics when multiple isochronic Hits present on different planes.



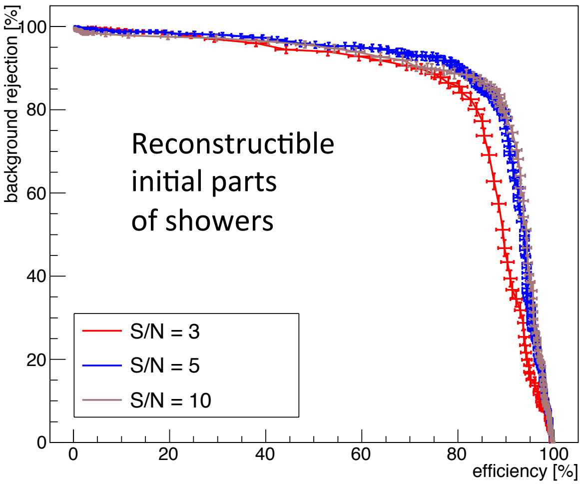
Detector Performance

- At longest drift distance (3.6 m), diffusion/electron-lifetime/wire-pitch all impact S/N and detector performance.
- APA design parameters chosen to allow MIP reconstruction at this distance.

Plot Credit: Michelle Stancari



Plot Credit: Dorota Stefan, Robert Sulej



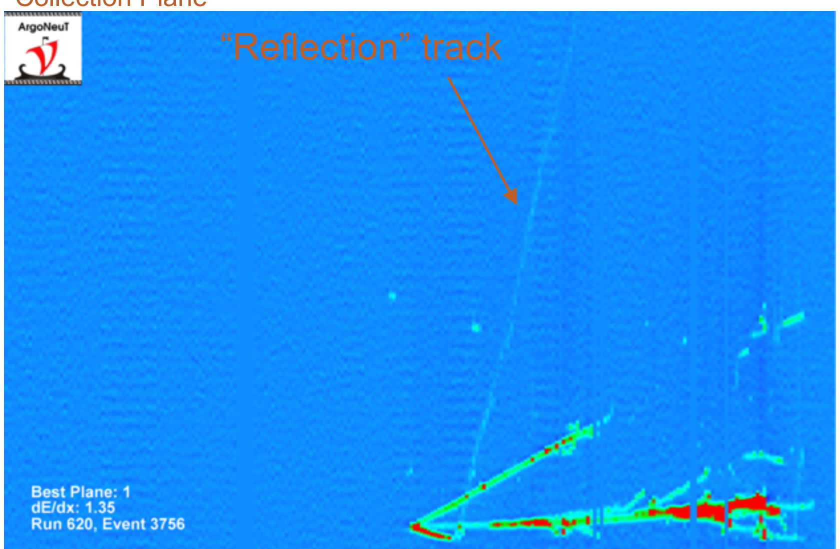
A bit pessimistic – isotropic event distribution

- Beam events will hit more collection wires in the initial parts of showers
- Extending algorithm to use the induction view for charge measurement will increase acceptance

Detector Performance

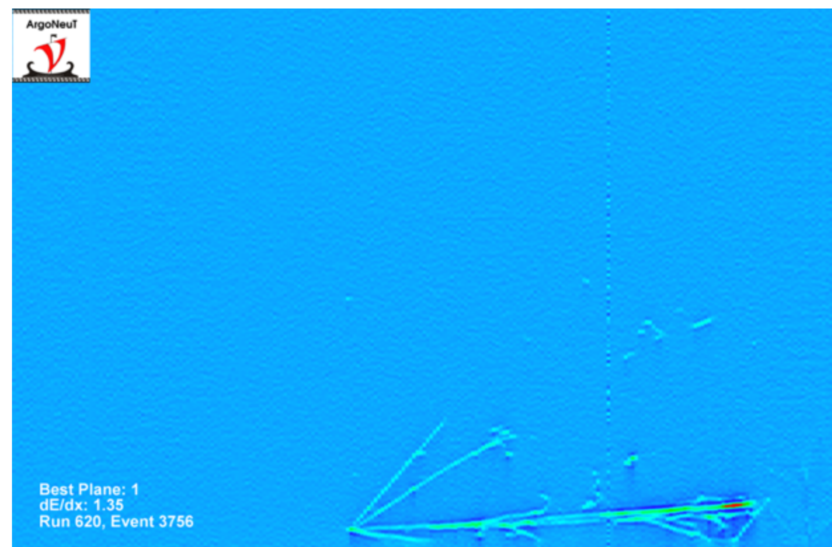
- **Why have mesh?**
- Particles passing through the Collection plane will deposit ionization “behind” the plane that will drift (in a non-uniform field) to the positively biased Collection wires. Leads to “reflection” tracks, which can confuse reconstruction.
- Grounded mesh block this charge and removes reflections.

Collection Plane



Track passing through collection plane.

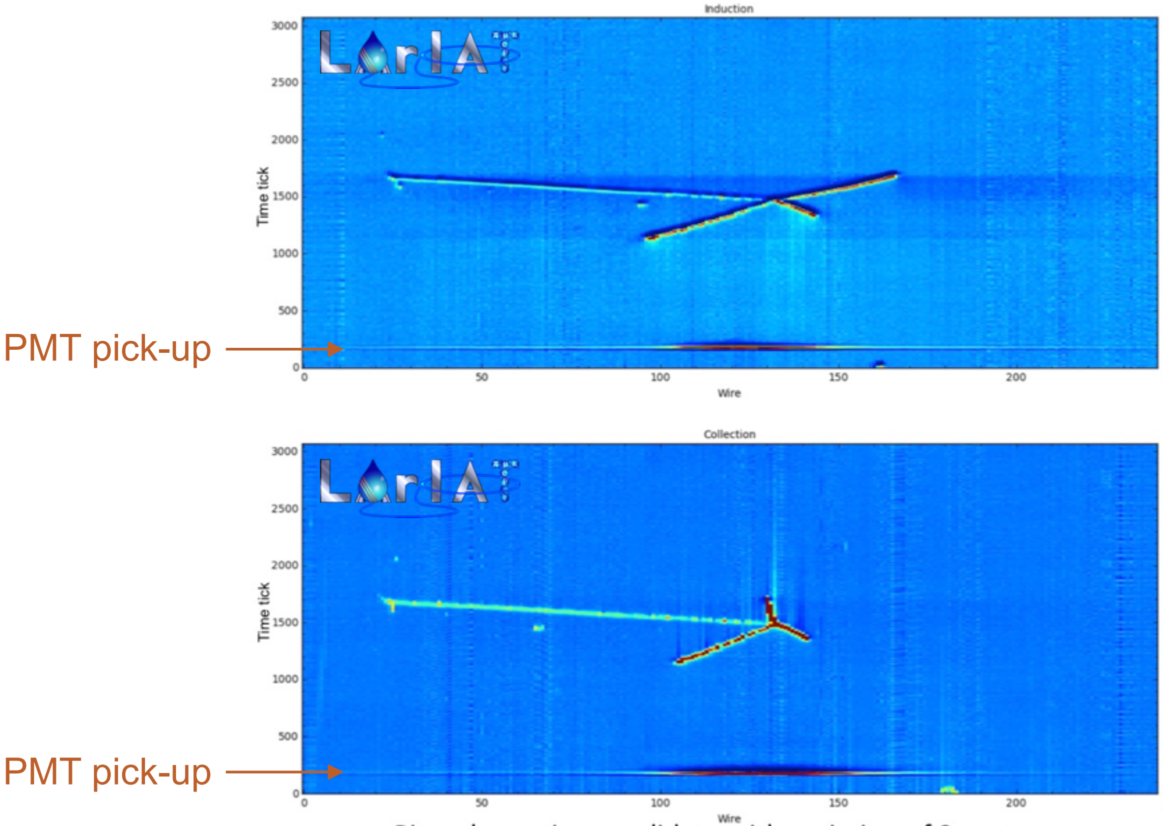
Induction Plane



Track passing through collection plane.

Detector Performance

- **Why have mesh?**
- PMTs behind anode planes have been observed to induce signals.
- protoDUNE not using PMTs…using scintillator bars + SiPMs.
- Mesh can shield any pickup noise that might otherwise be present.

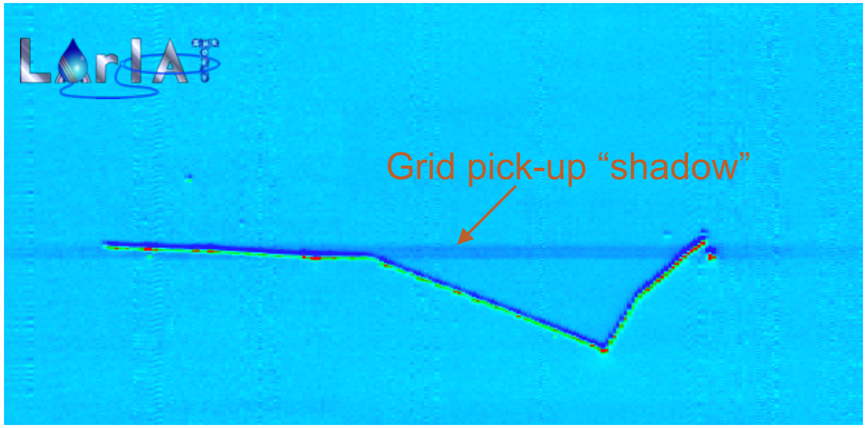


Pion absorption candidate with emission of 3 protons

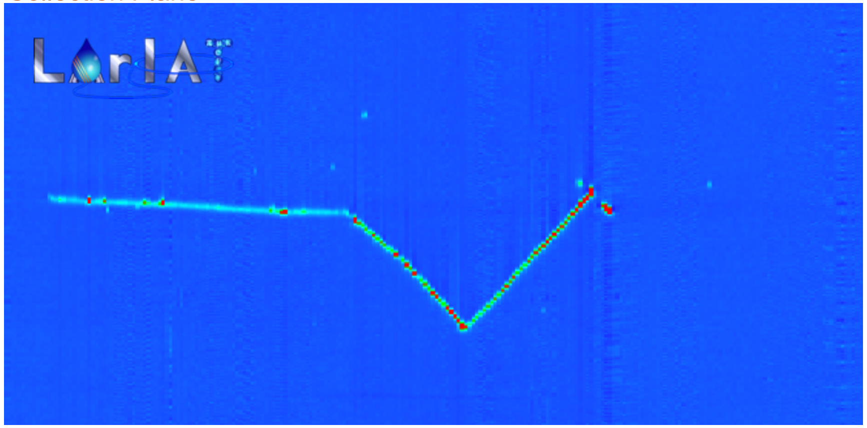
Detector Performance

- **Why have a grid?**
- Grid shields first instrumented Induction plane from drifting charge, leading to narrower pulses with higher S/N, improving reconstruction performance of that plane.
- Grid also shields instrumented planes from any noise originating from the cathode and high-voltage supply.
- Need to be careful…grid can induce signal on first Induction plane if not properly configured (see “shadow” in LArIAT image….fixed by reconfiguring RC filtering).

Induction Plane



Collection Plane



π^- double scatter and capture in LArIAT

Conclusions

- APA is designed to meet Physics goals for protoDUNE and DUNE.
- Design and understanding of performance builds heavily on extensive experience gained with previous LArTPCs.
- Data from protoDUNE will be invaluable in advancing understanding of detector performance, which will provide great benefit to the DUNE physics program.
- Construction and operation of protoDUNE will retire risks for DUNE.

Comparing LArTPC Anodes

- Anode design parameters for selected LArTPCs…

Experiment	Number of Wires	Number of Electronic Channels	Grid	Mesh	Wire	Notes
ArgoNeuT/LArIAT	706	480	x		BeCu	
35-ton	2496	2048	x	x	BeCu	
MicroBooNE	8256	8256			SS+Cu/Au	
SBND	11264*	11264		x	BeCu	*jumpered
protoDUNE	21120	15360	x	x	BeCu	
ICARUS	53248	53248		x*	SS	Mesh on PMTs
DUNE (10kTon)	528,000	384,000	x	x	BeCu	