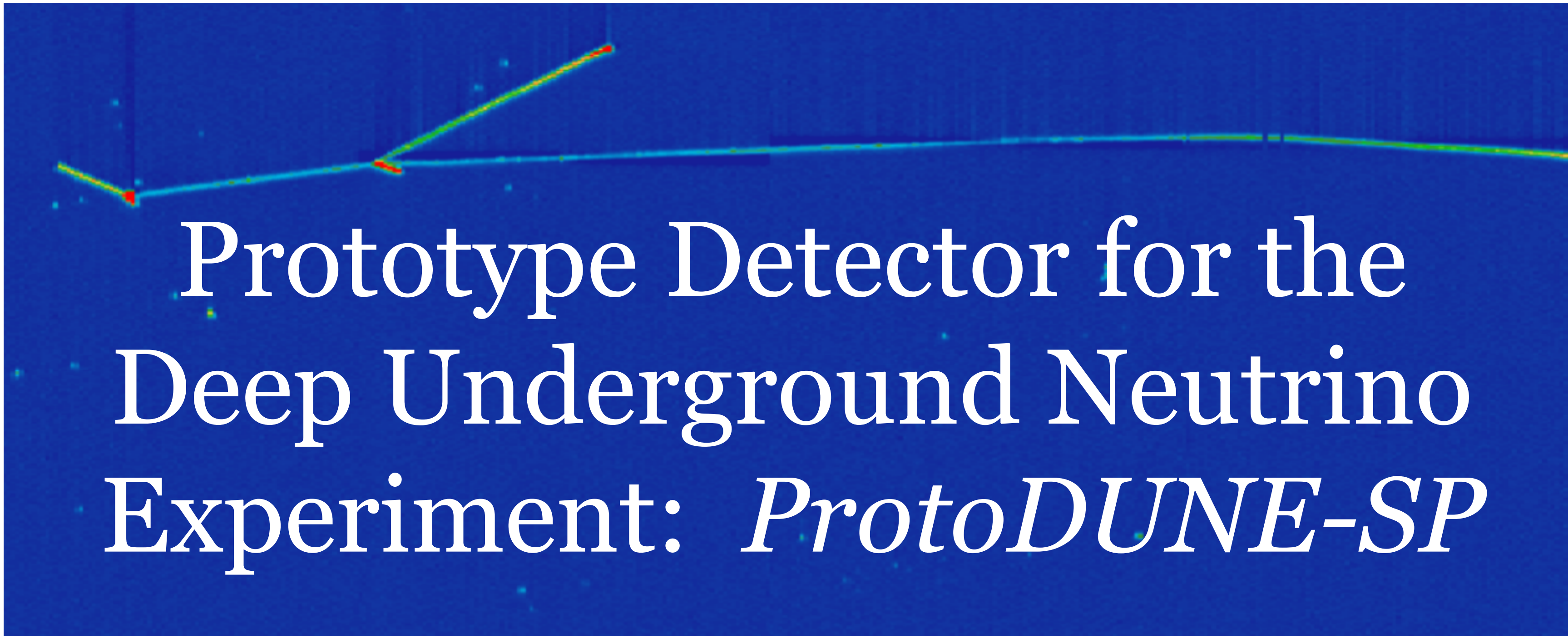


Prototype Detector for the Deep Underground Neutrino Experiment: *ProtoDUNE-SP*

Michael Mooney

Colorado State University

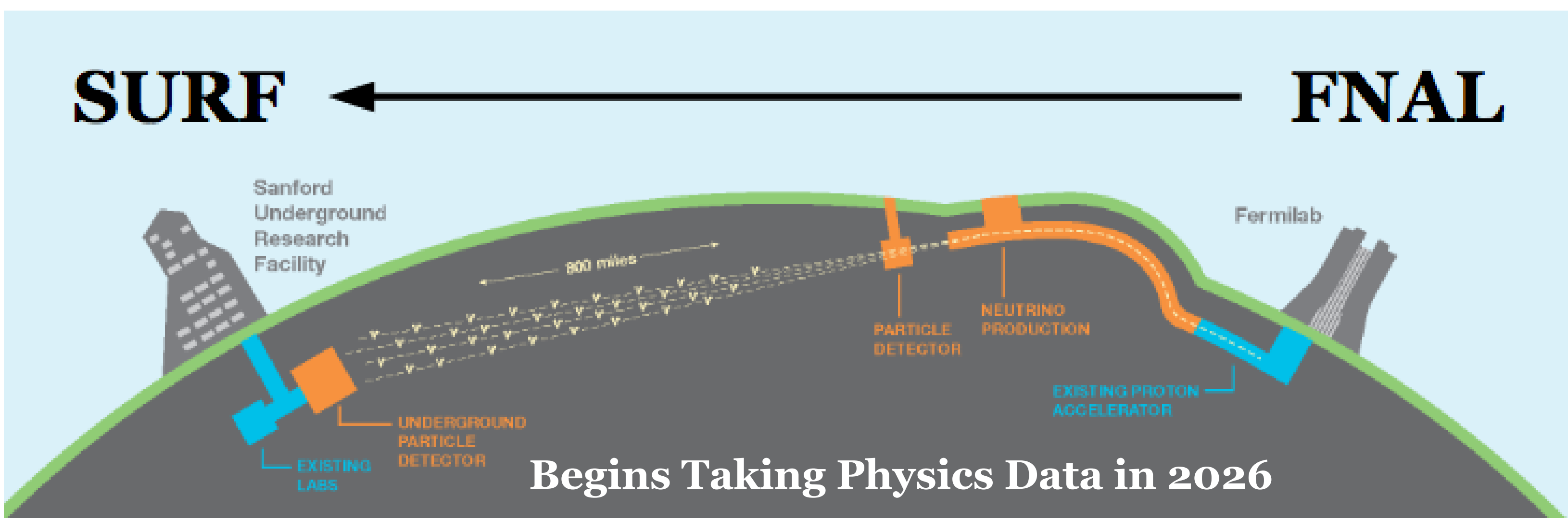
APS Four Corners Meeting

October 11th, 2019

Introducing DUNE

- “Deep Underground Neutrino Experiment”
  - 1300 km baseline
  - Large (40 kt) LArTPC far detector and near detector (w/ LAr component)
  - Far detector 1.5 km underground
  - Wide-band, on-axis beam

- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - **Ordering of ν masses**
    - $\boldsymbol{\delta_{CP}}$, θ_{23}, θ_{13}
  - Nucleon decay
  - Supernova burst neutrinos
  - Solar neutrinos



DUNE Collaboration

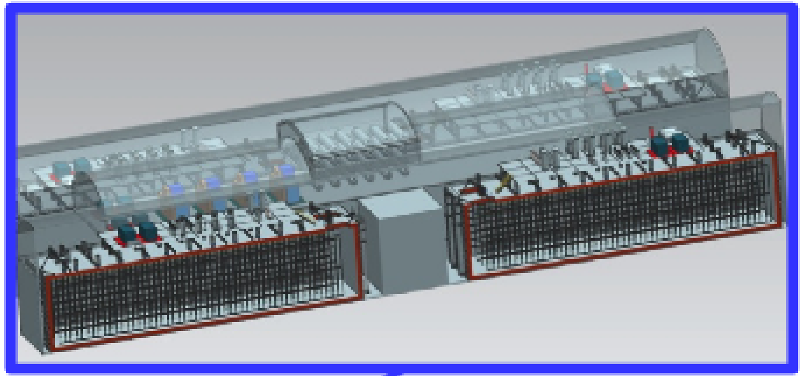
- Over 1000 collaborators from 175 institutions in 32 countries!

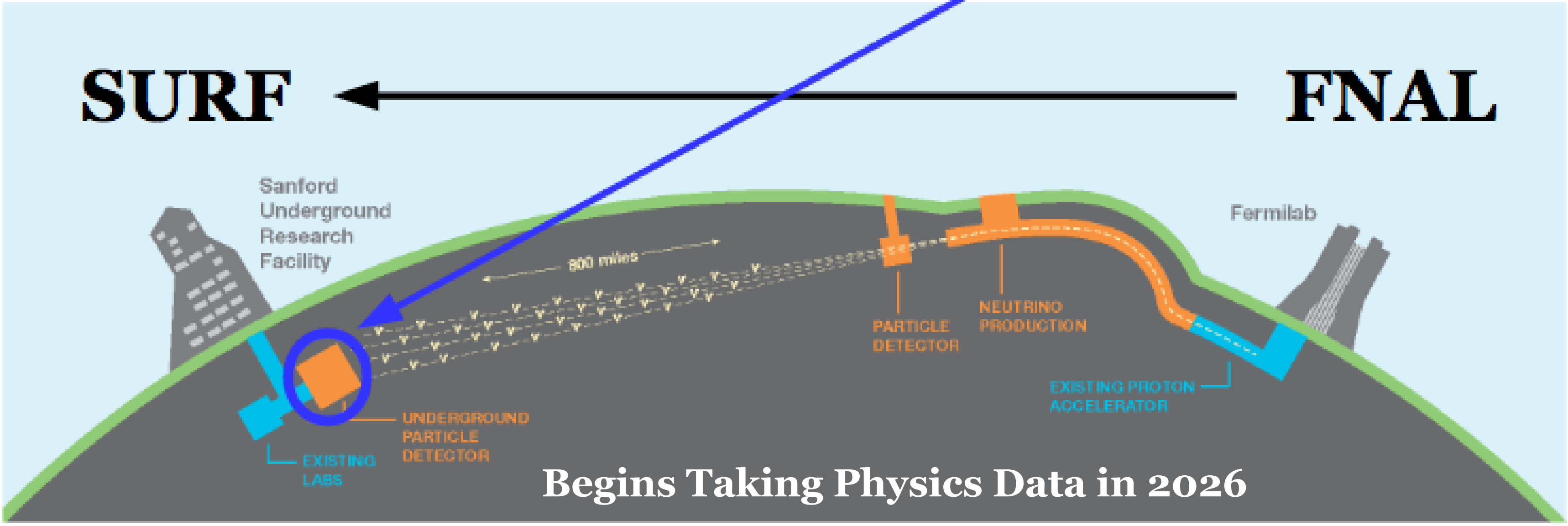
May 2018 Collaboration Meeting

DUNE Far Detector

The DUNE Far Detector:

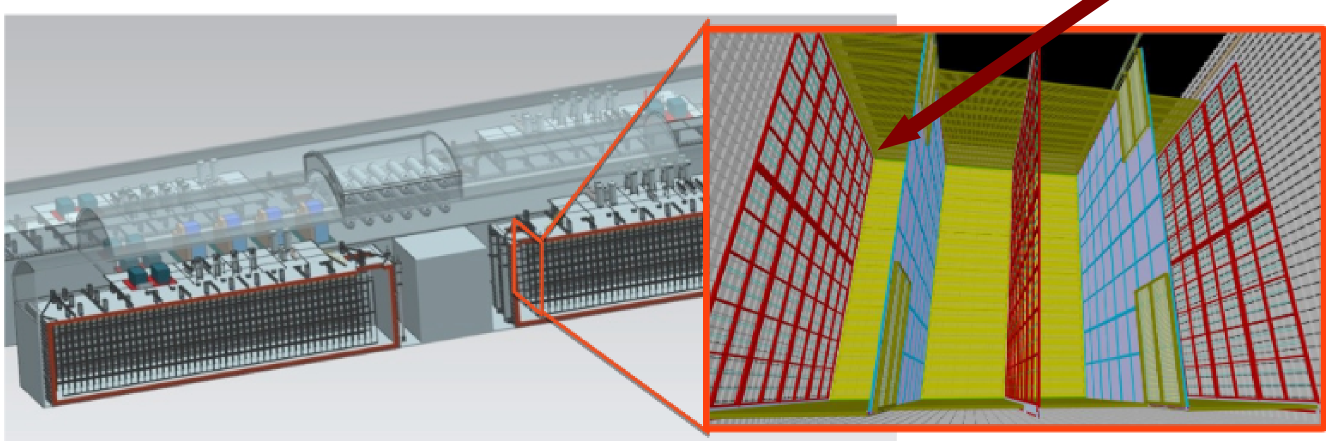
A Giant LArTPC Detector

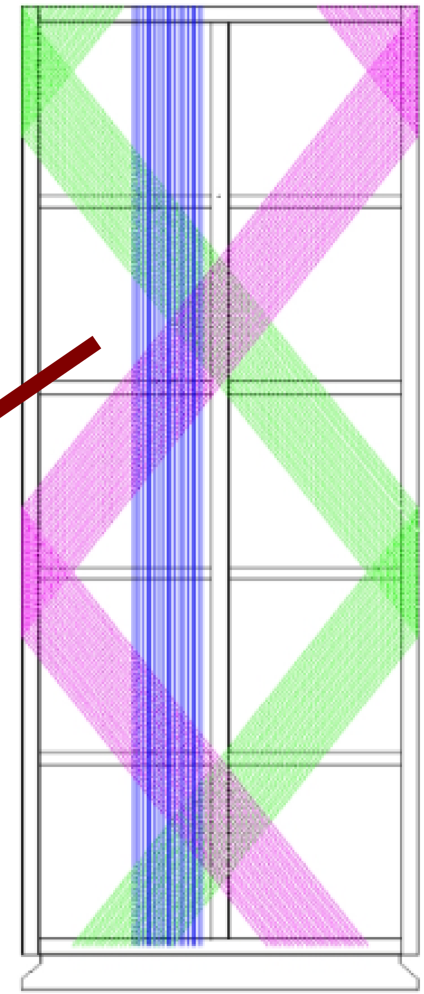




Far Detector LArTPC

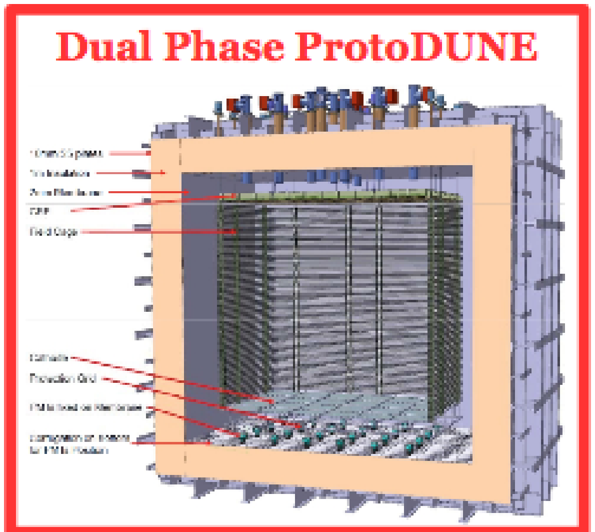
- Two far detector (FD) designs being considered: single phase (LAr) and dual phase (LAr + GAr)
- Single phase FD uses modular drift cells (scalable)
  - Suspended Anode and Cathode Plane Assemblies (APAs and CPAs), **3.6 m drift**, **500 V/cm field**
  - **Wrapped wire** to reduce number of readout channels needed and cabling complexity
- Four 10-kt modules deployed in stages

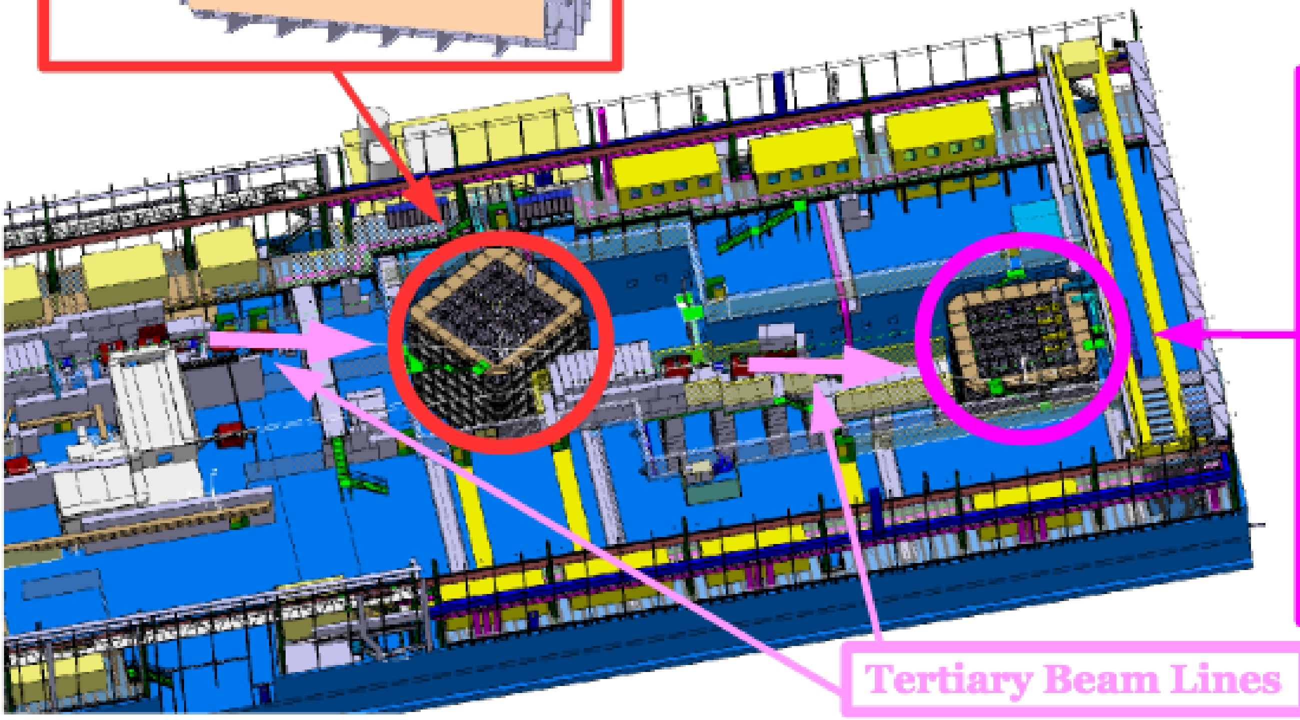


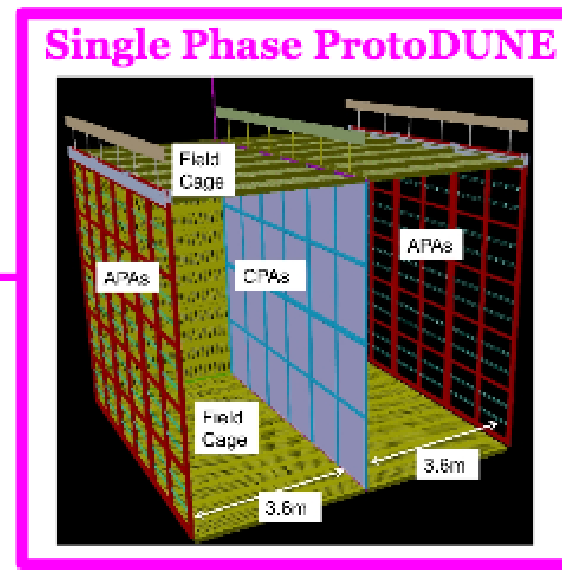


ProtoDUNEs

- Two ~6×6×6 m³ "ProtoDUNEs" in charged test beam at CERN (one per FD design)
- Test of component installation, commissioning, and performance
- ProtoDUNE-SP operating since September 2018; ProtoDUNE-DP in 2019







ProtoDUNEs

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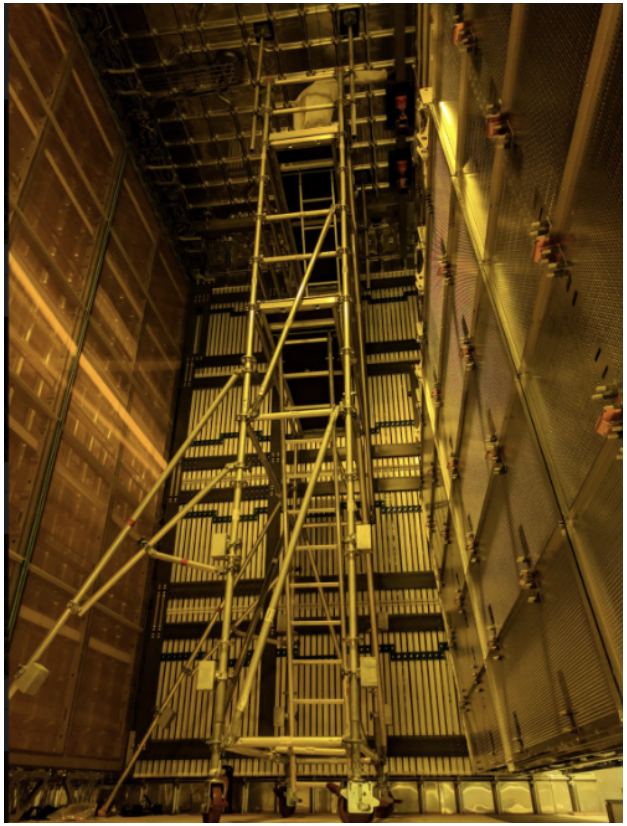
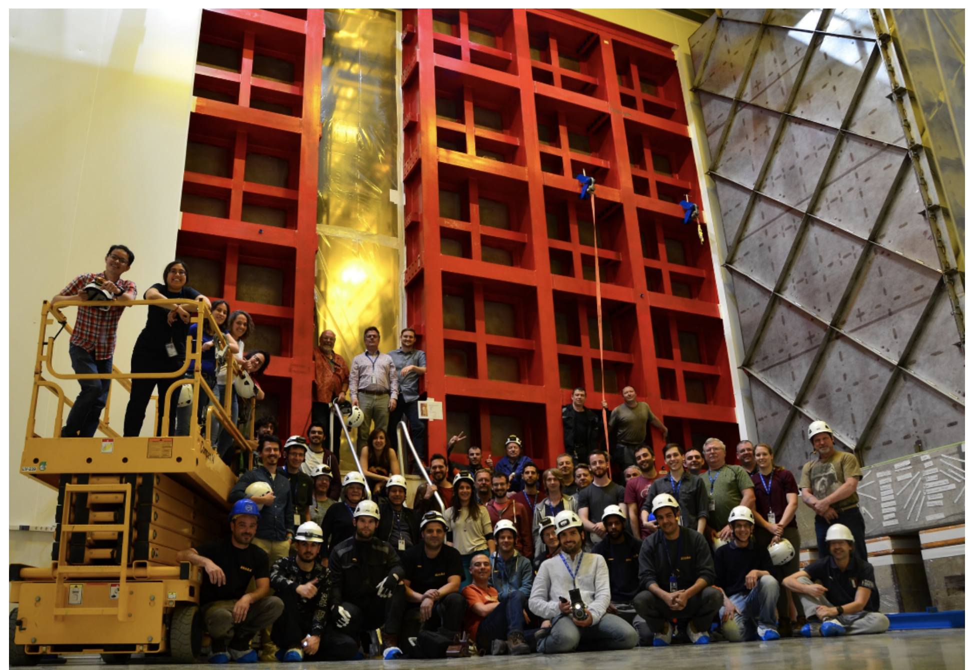
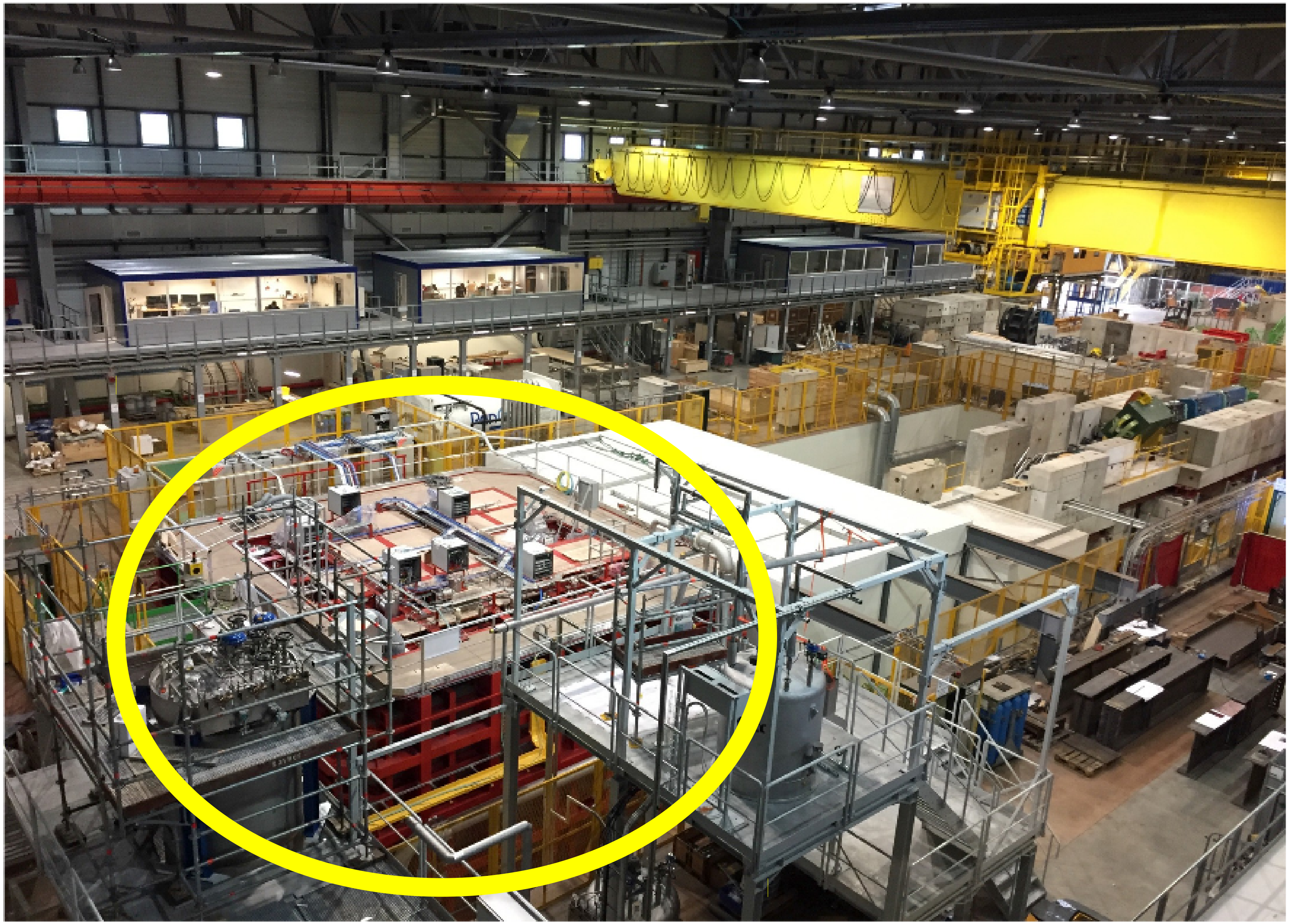


Inside ProtoDUNE-SP



ProtoDUNE-SP Prior to Closing of Temporary Construction Opening

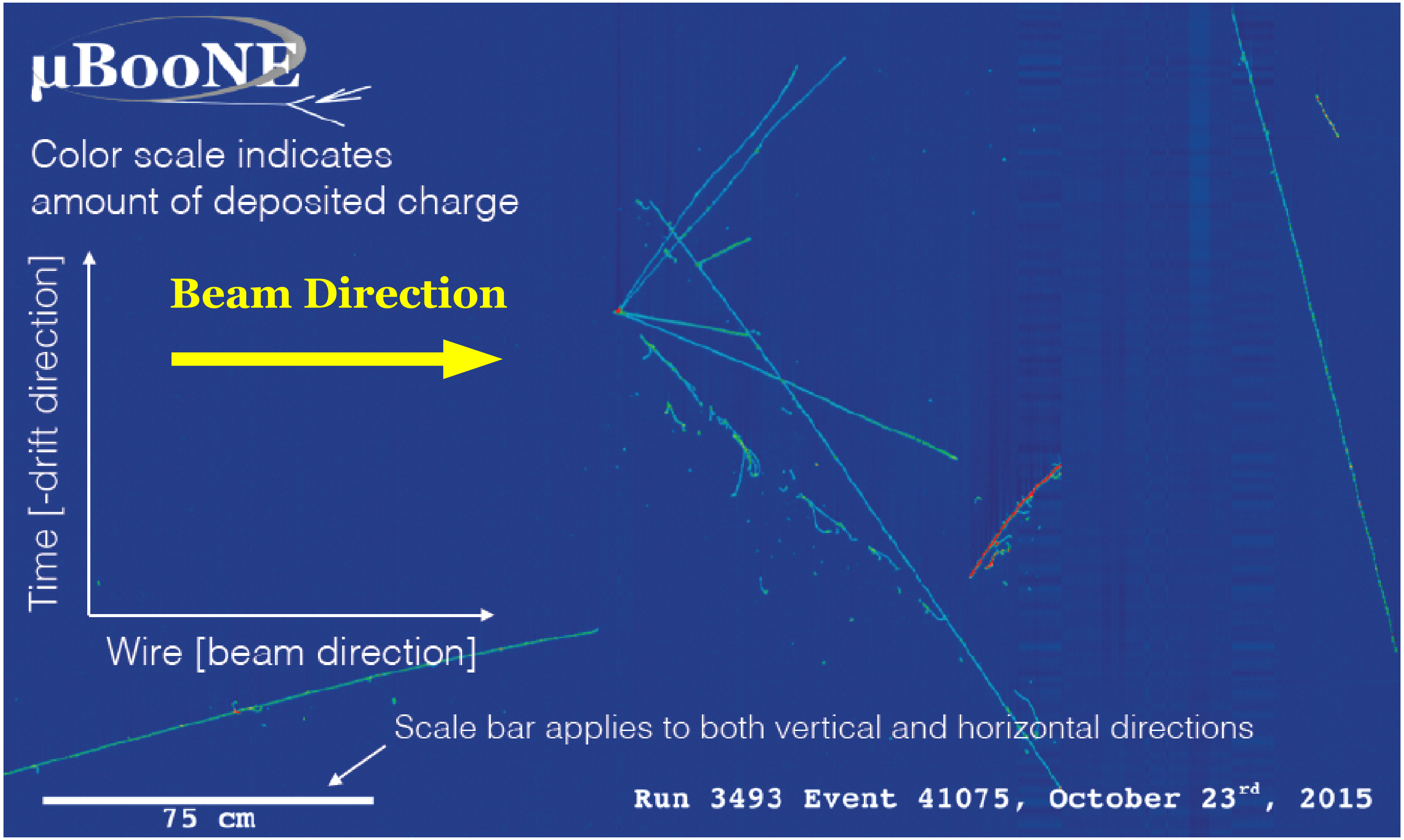
ProtoDUNE-SP From Above



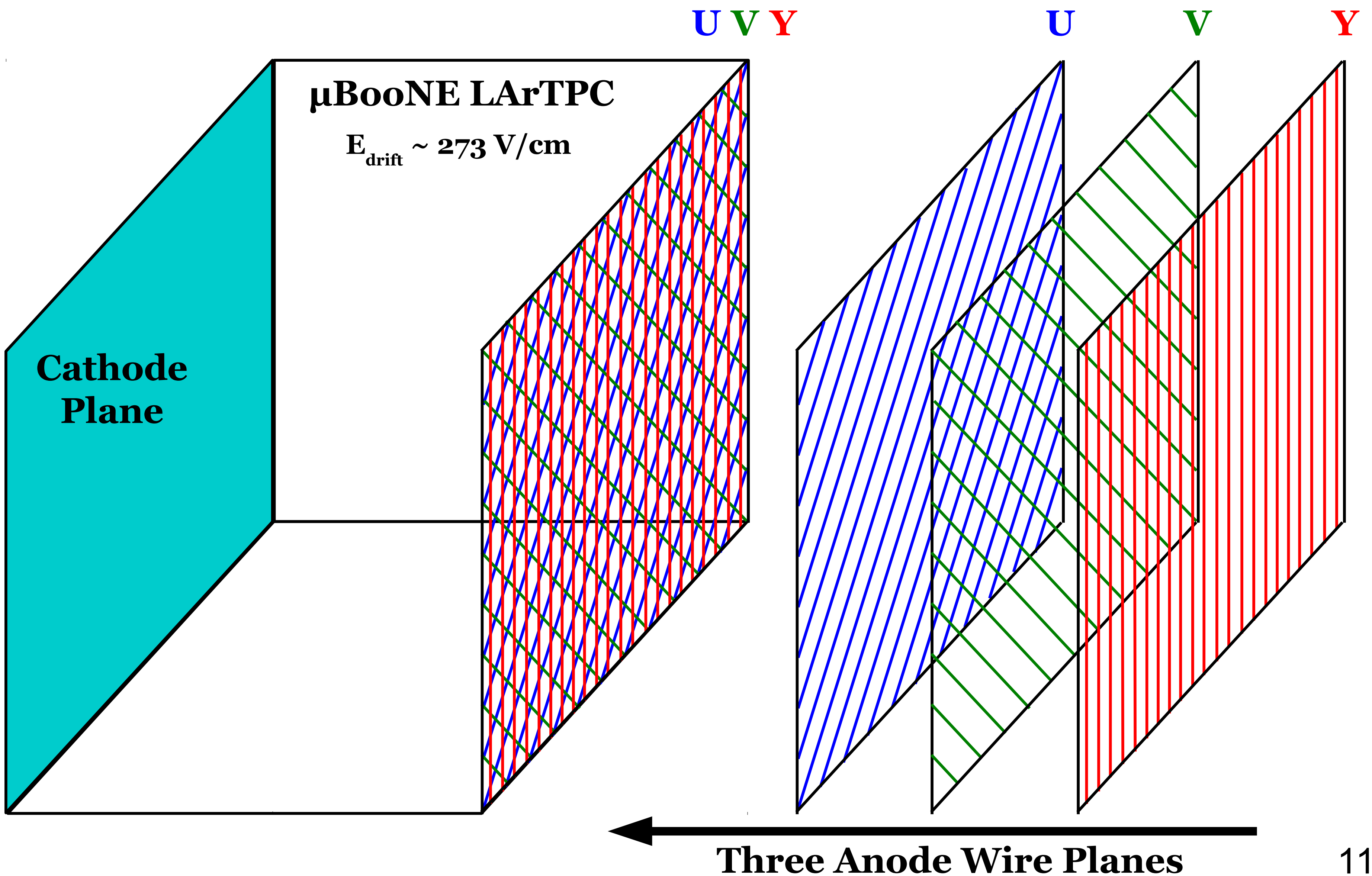
LArTPC Fundamentals

LArTPC Event Display

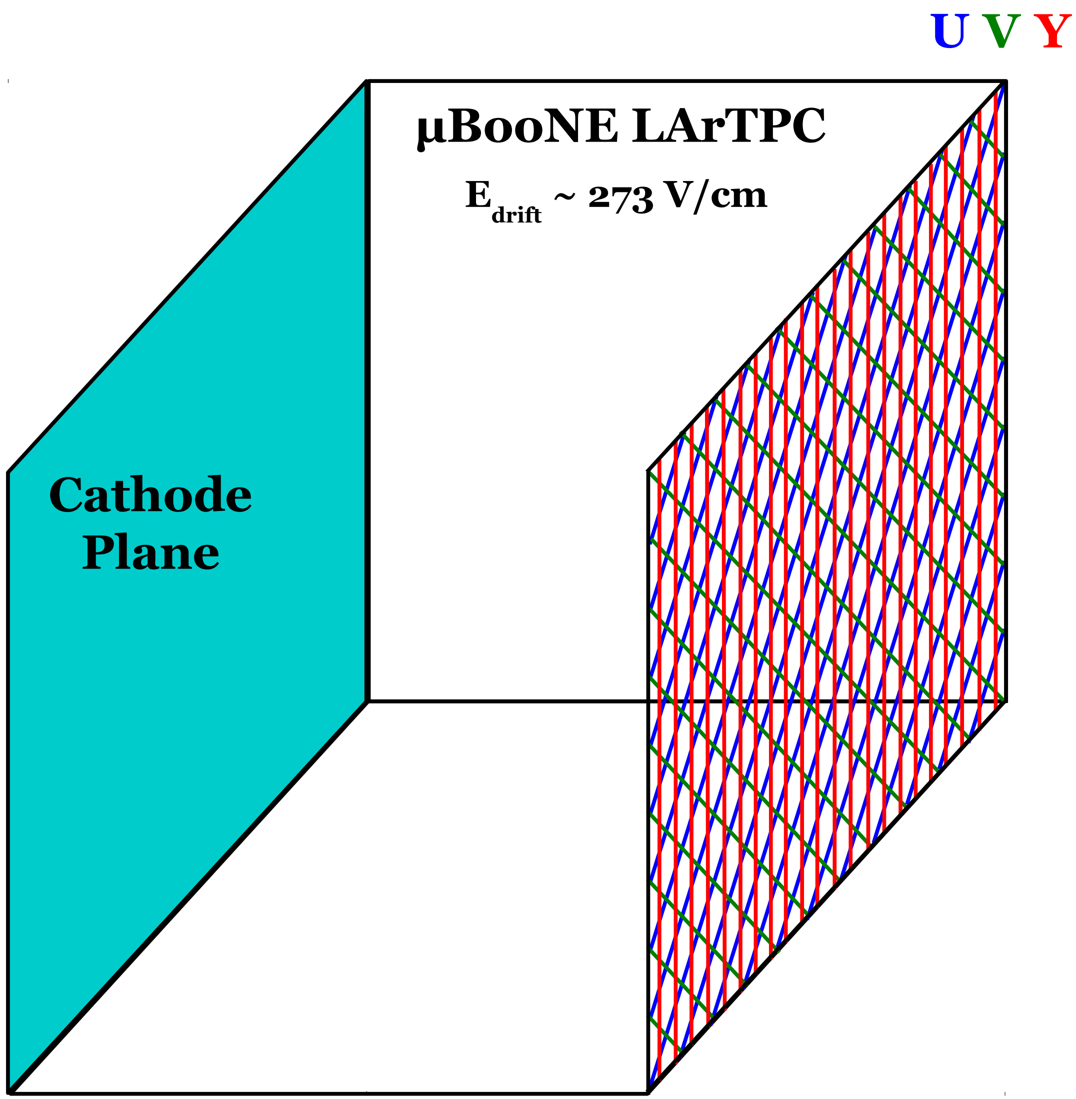
- Raw data representations are images with very fine-grained spatial resolution (~1 mm)!



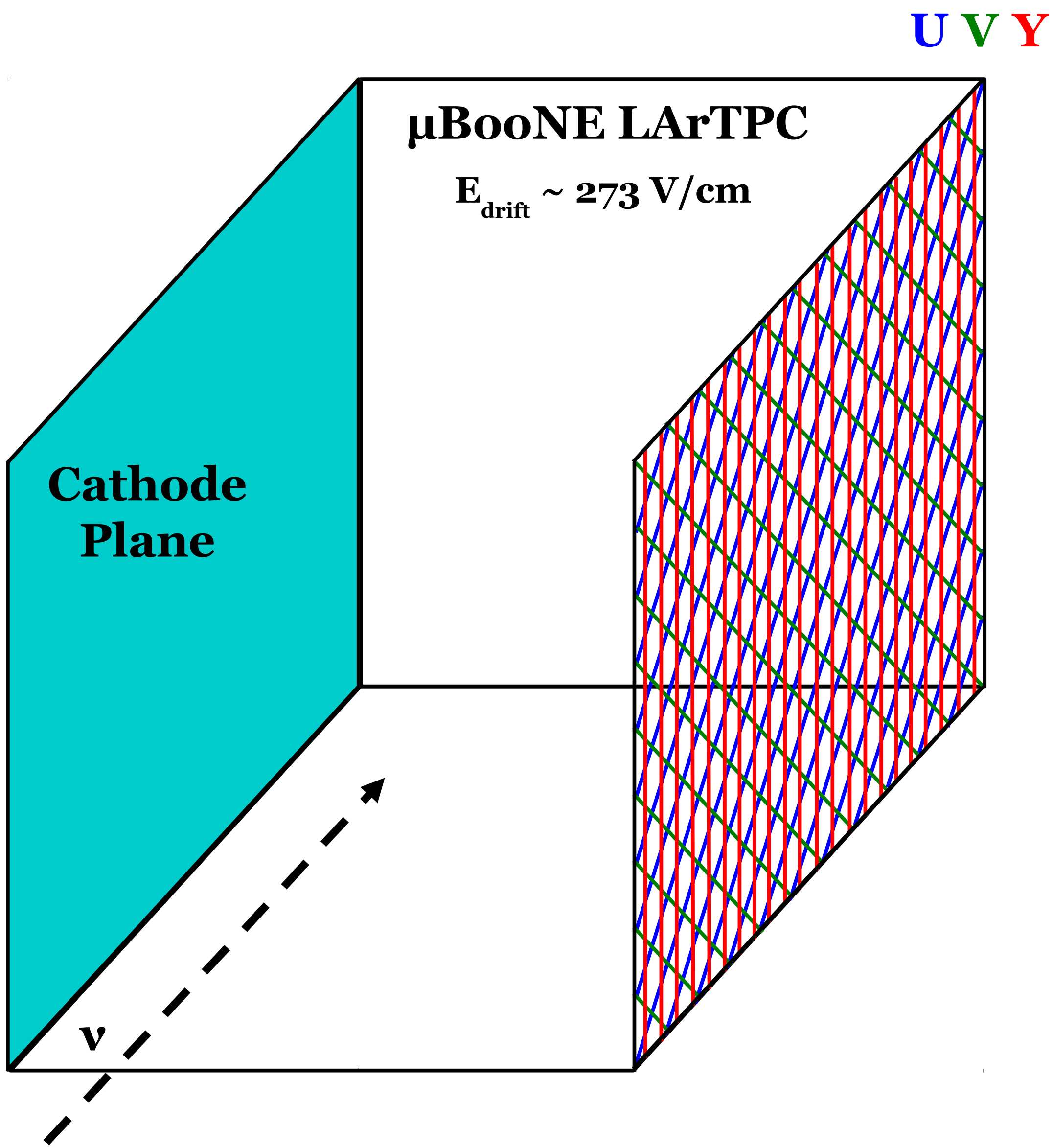
Signal Formation



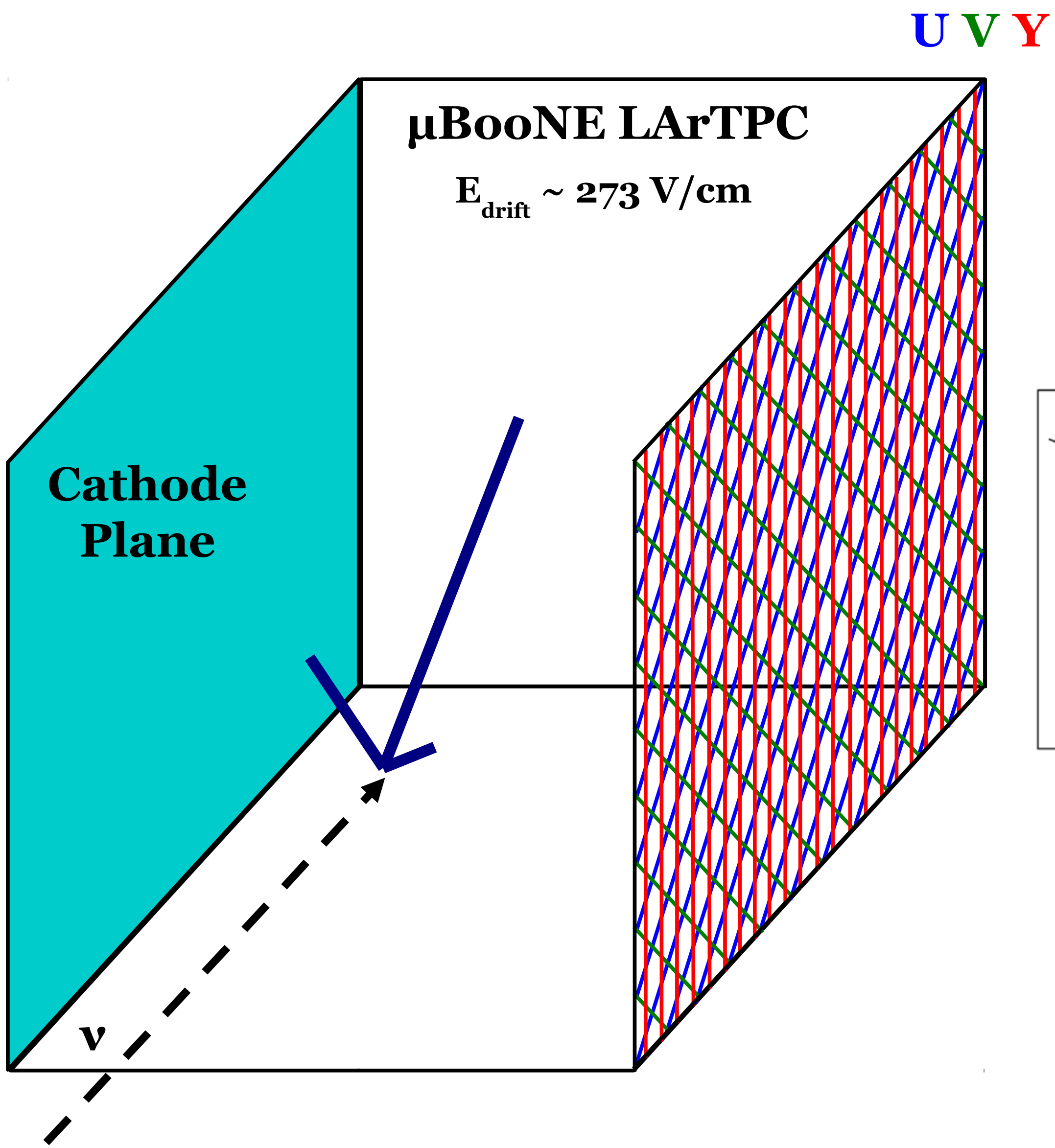
Signal Formation

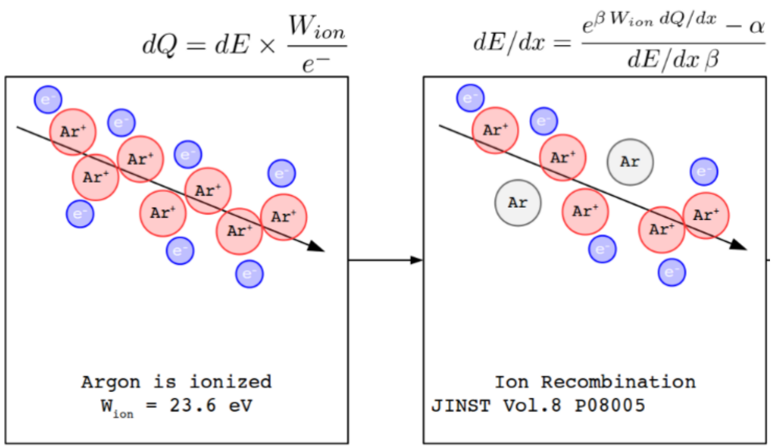


Signal Formation



Signal Formation





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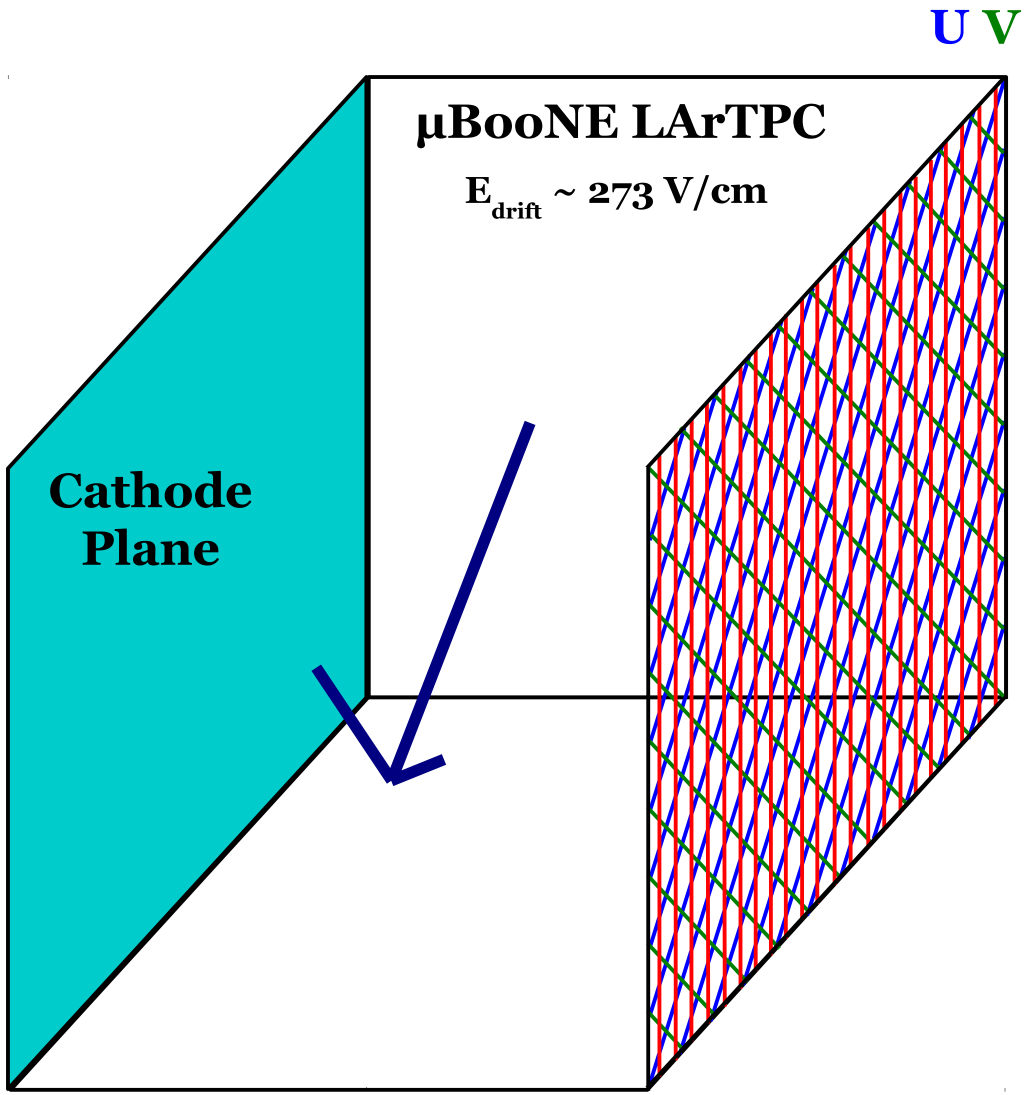

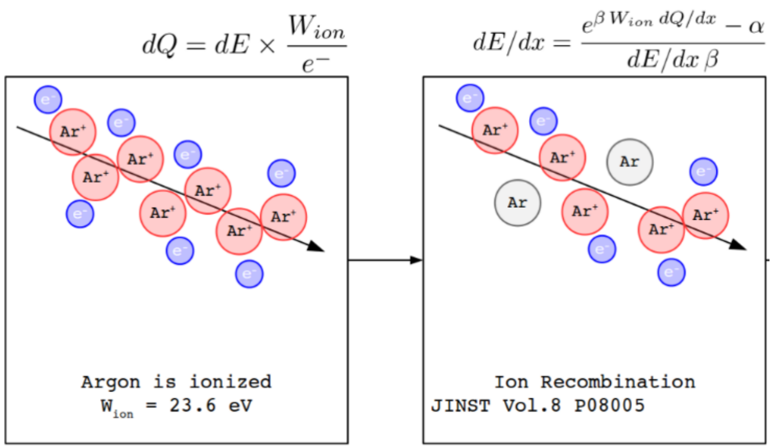

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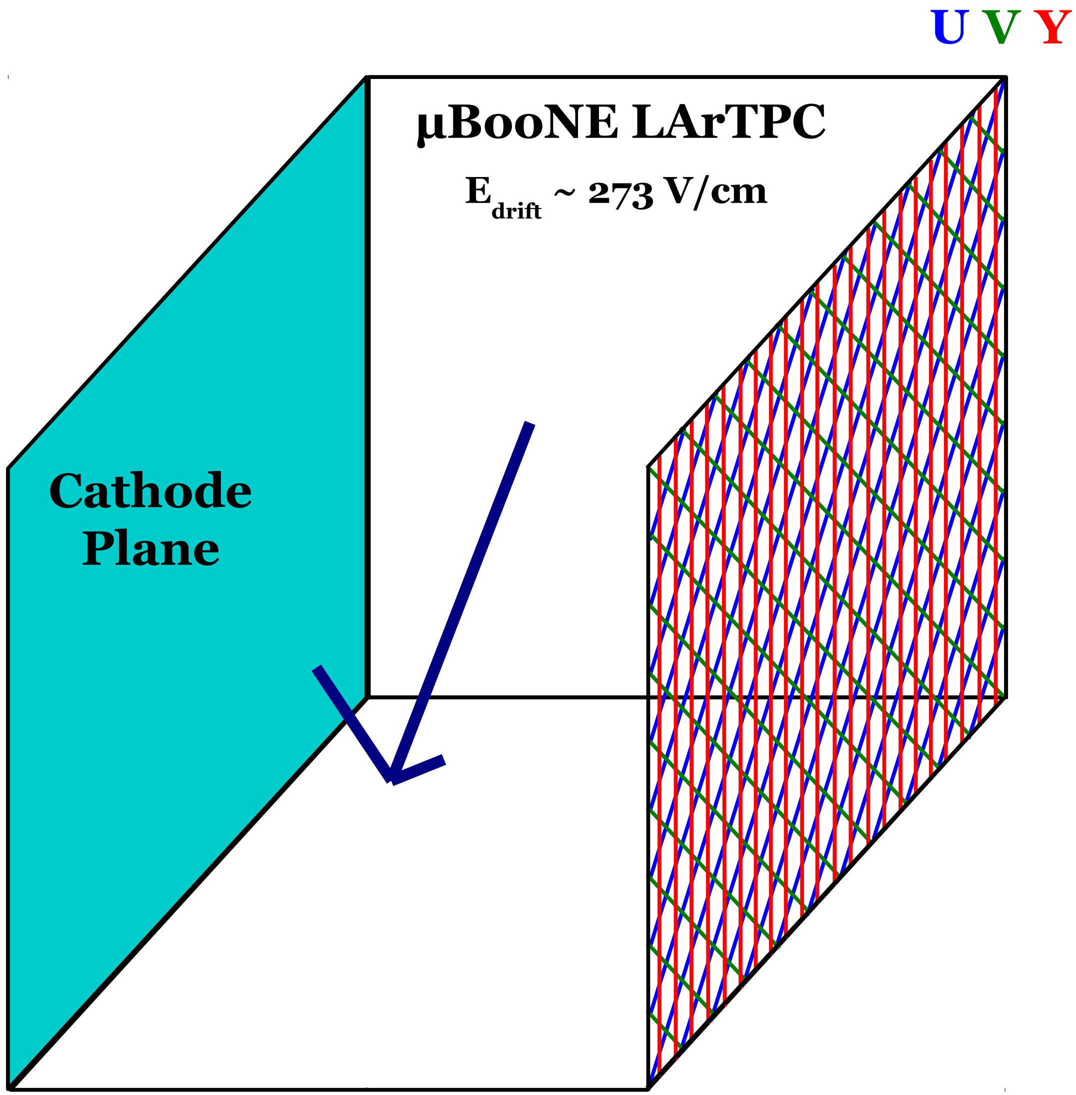
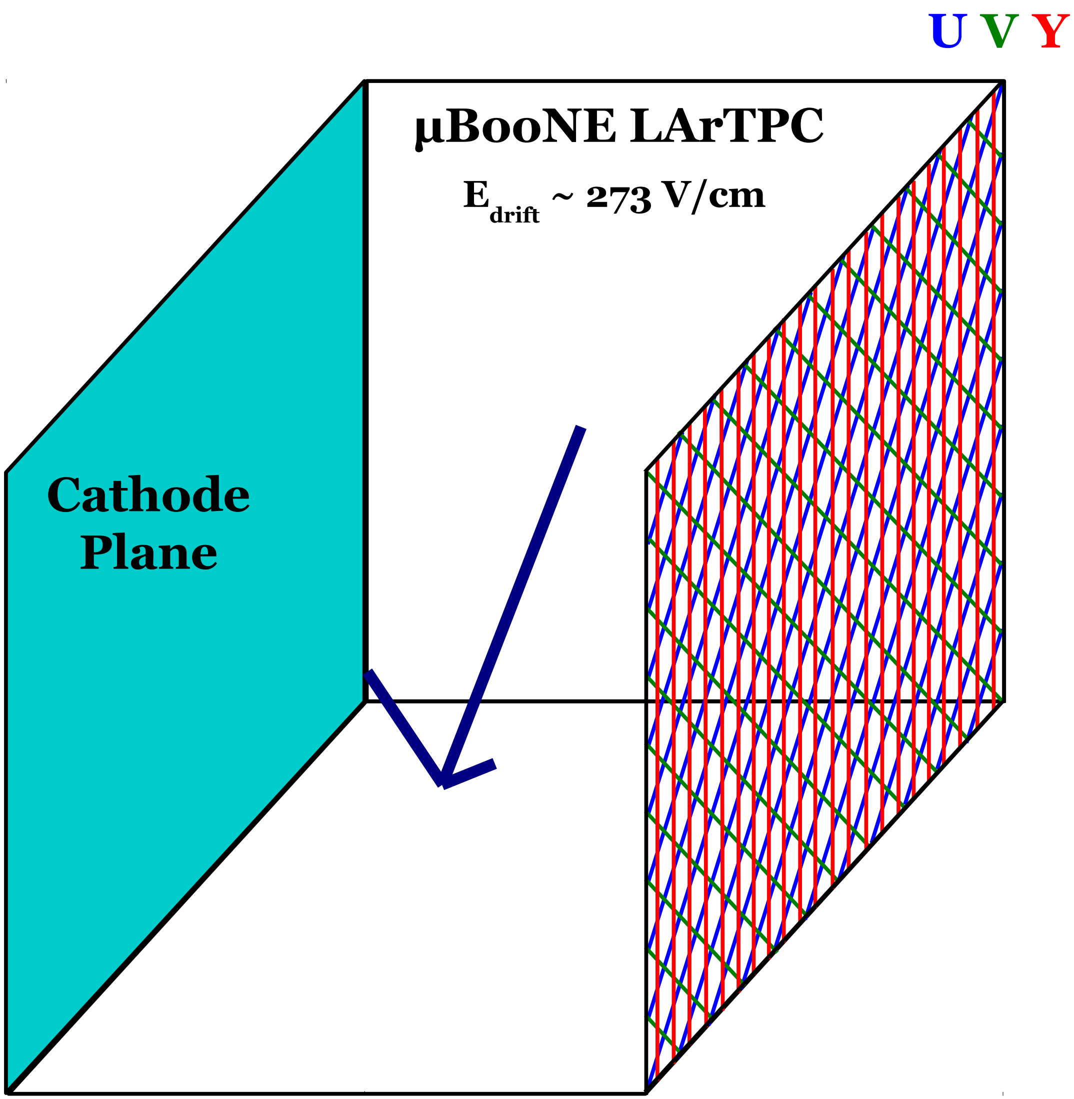
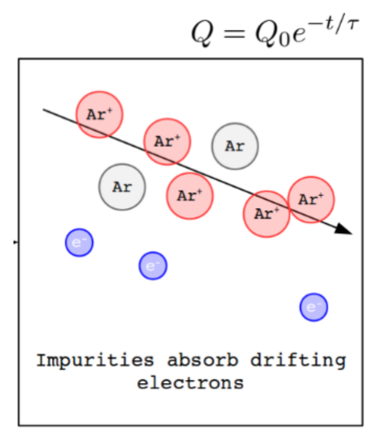


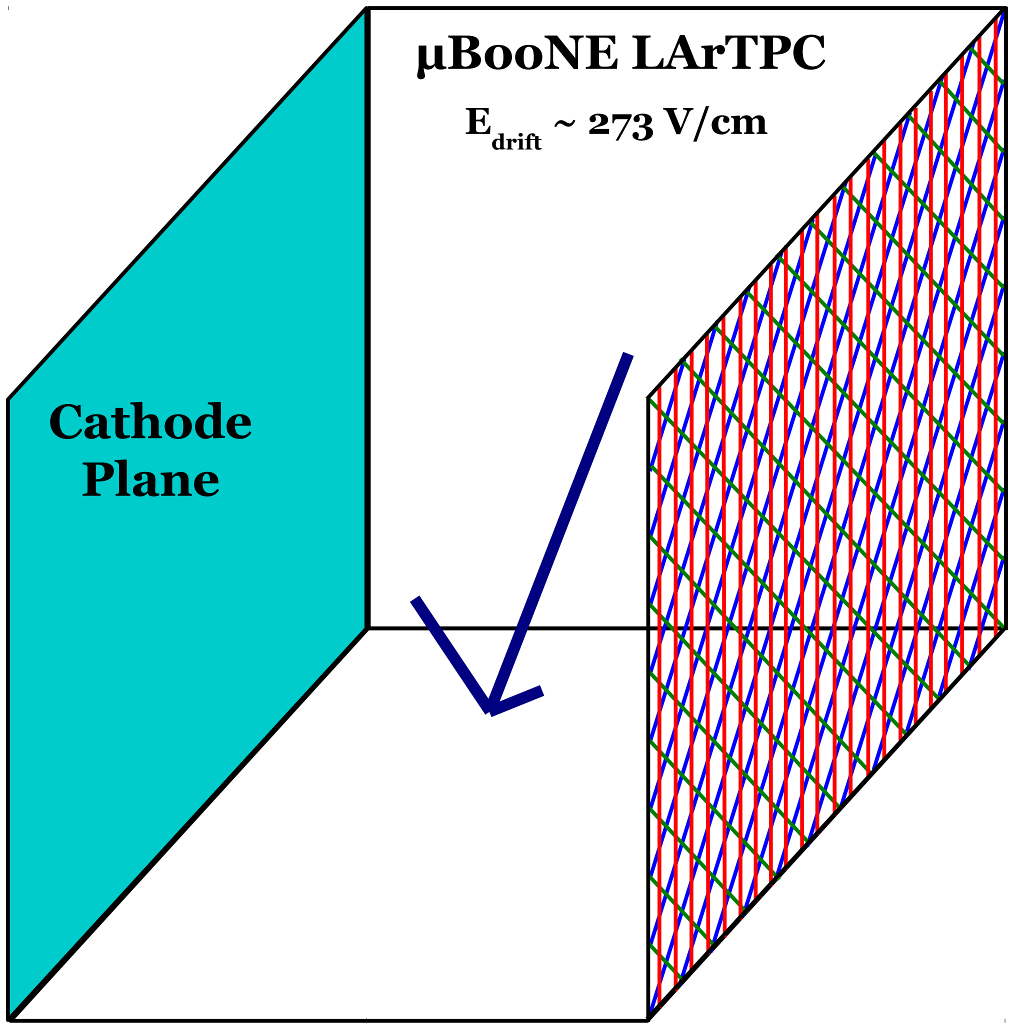
Signal Formation



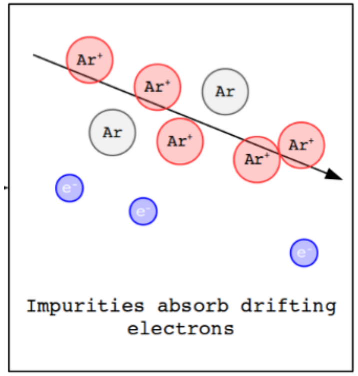


Signal Formation

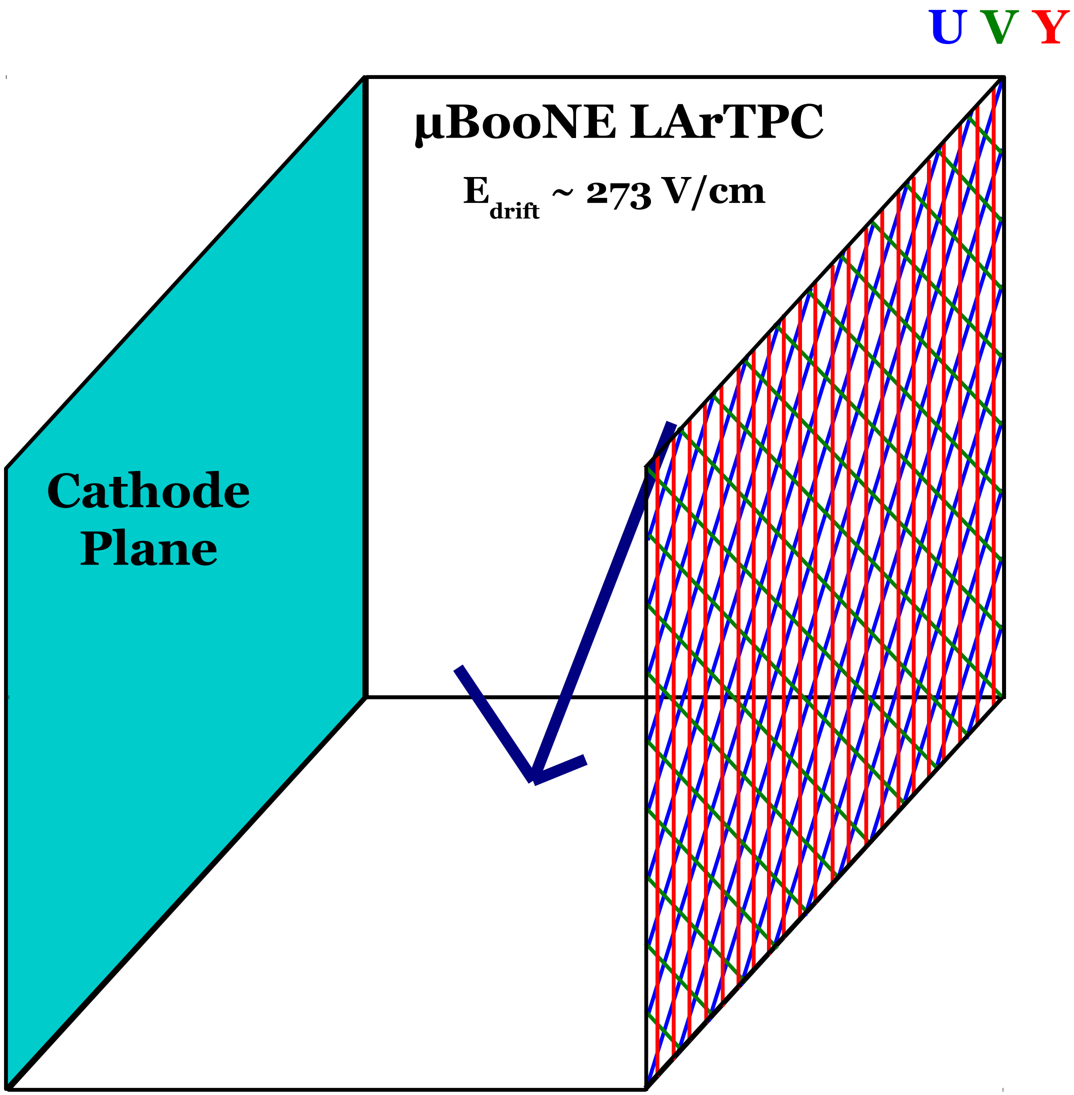
U V Y



$Q = Q_0 e^{-t/\tau}$



Signal Formation



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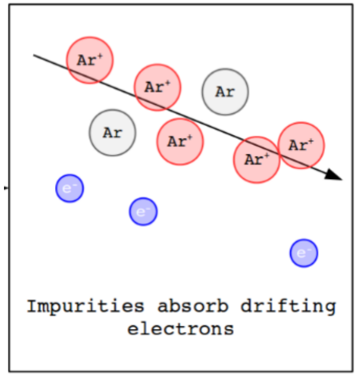
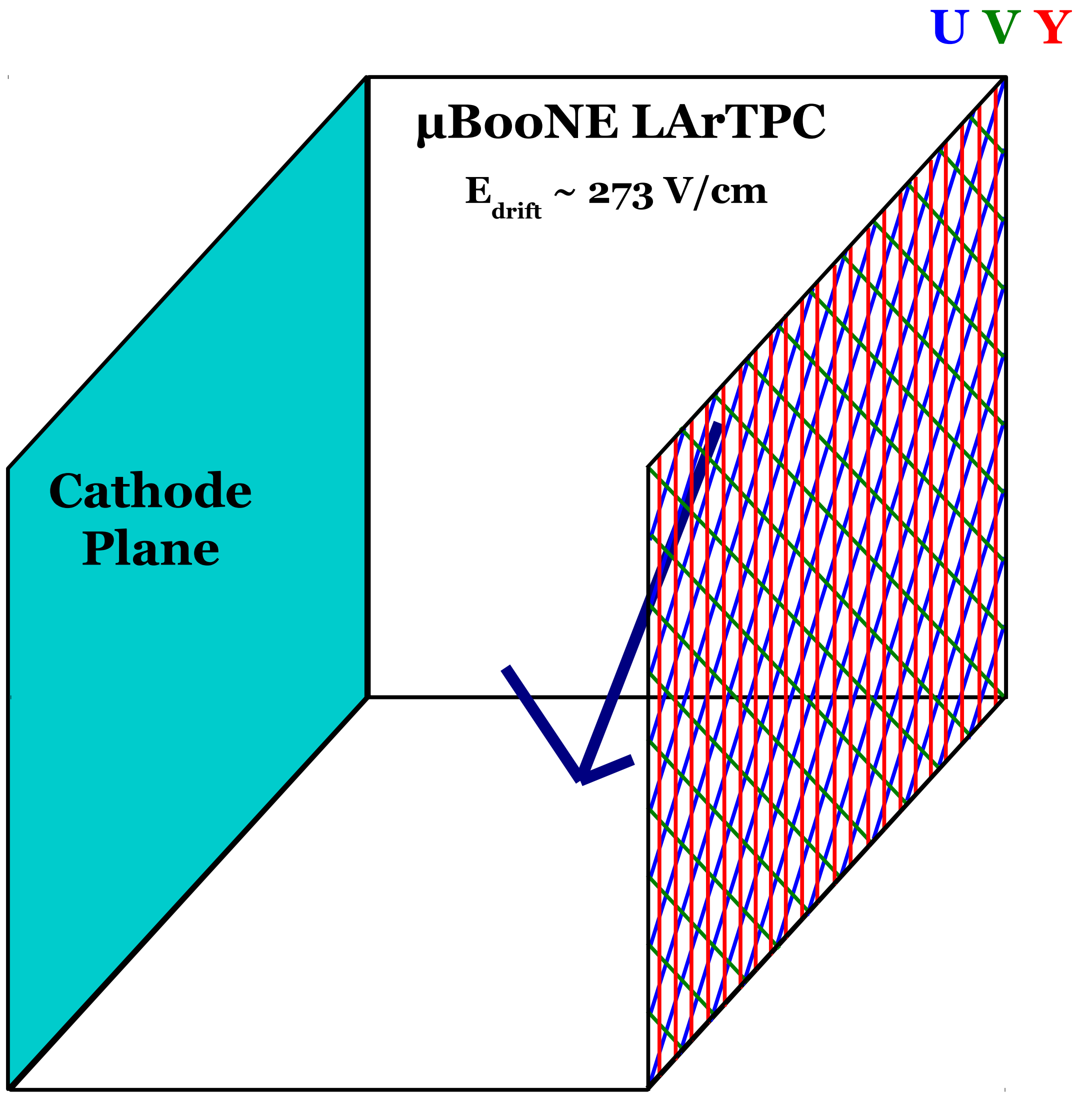
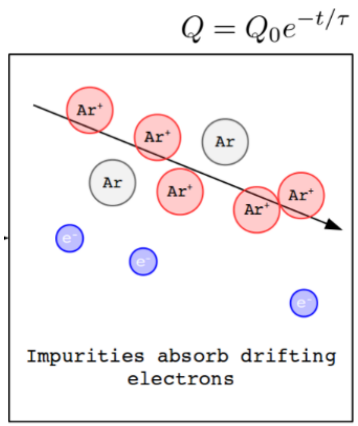
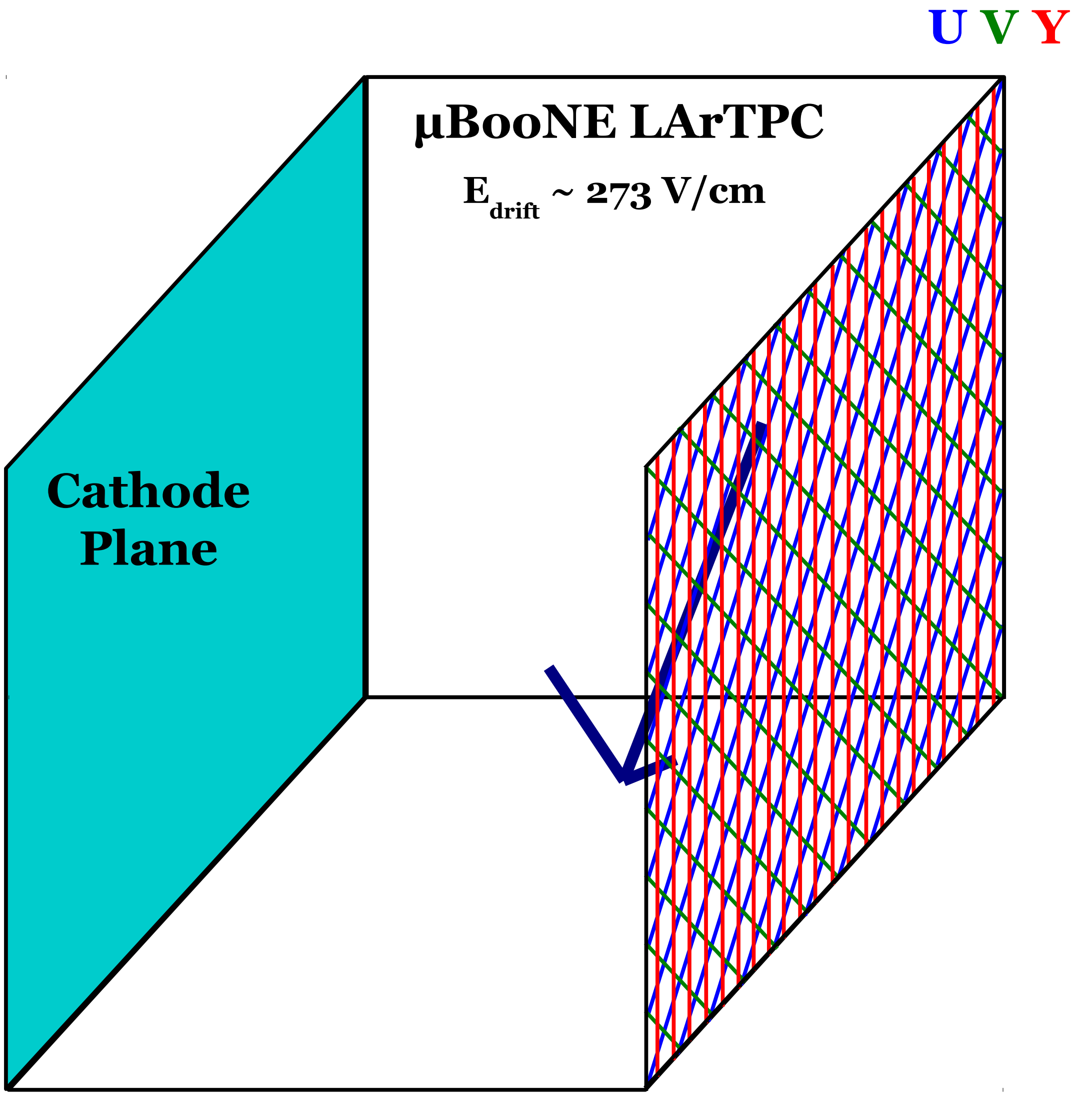


Signal Formation





Signal Formation



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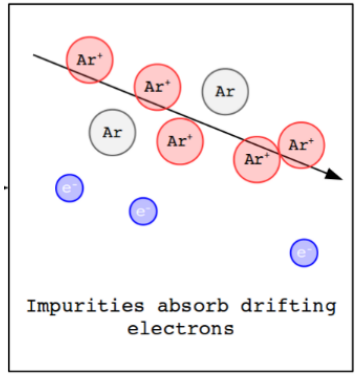
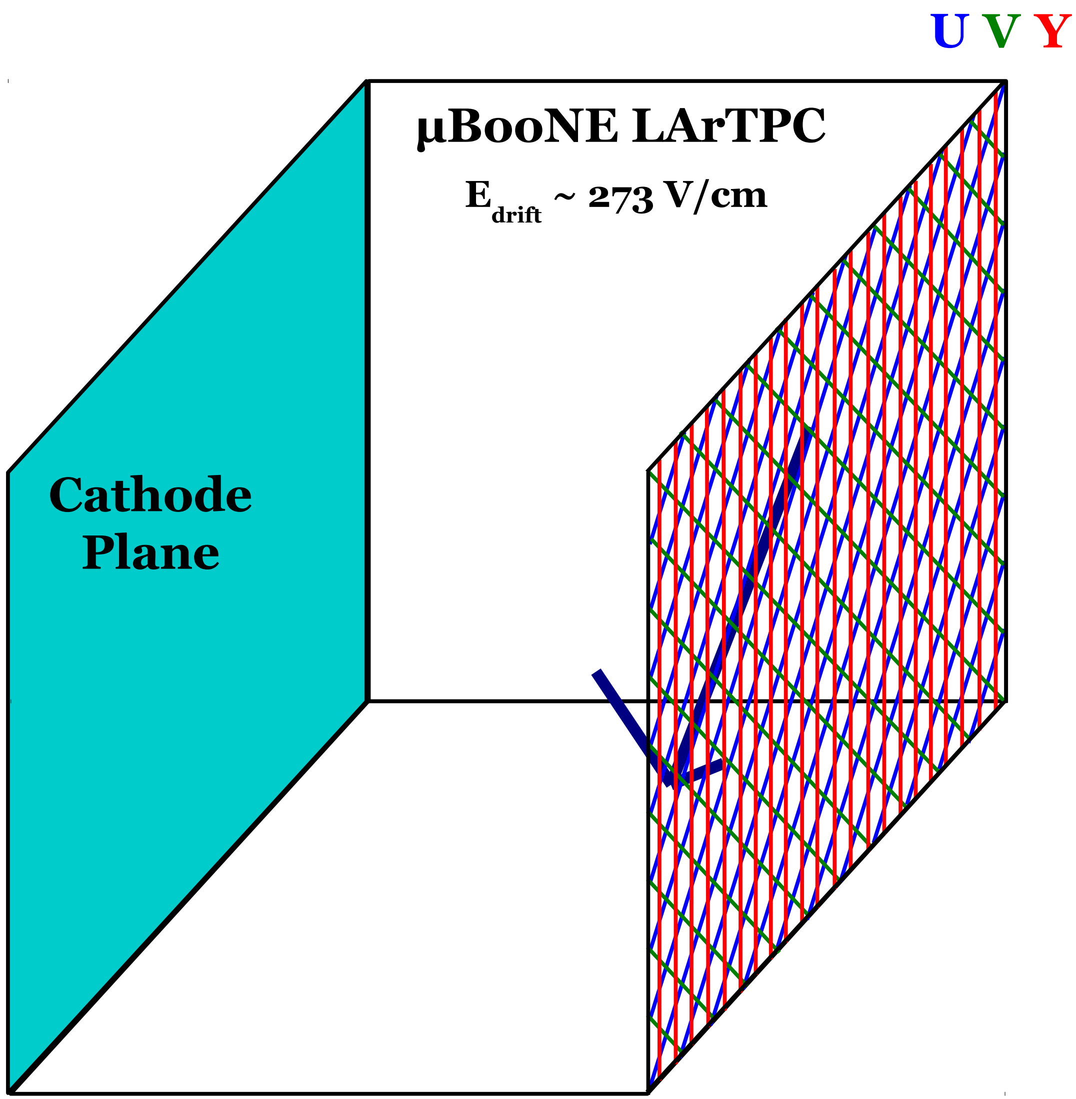


Signal Formation



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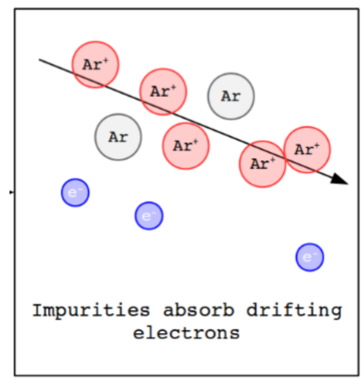
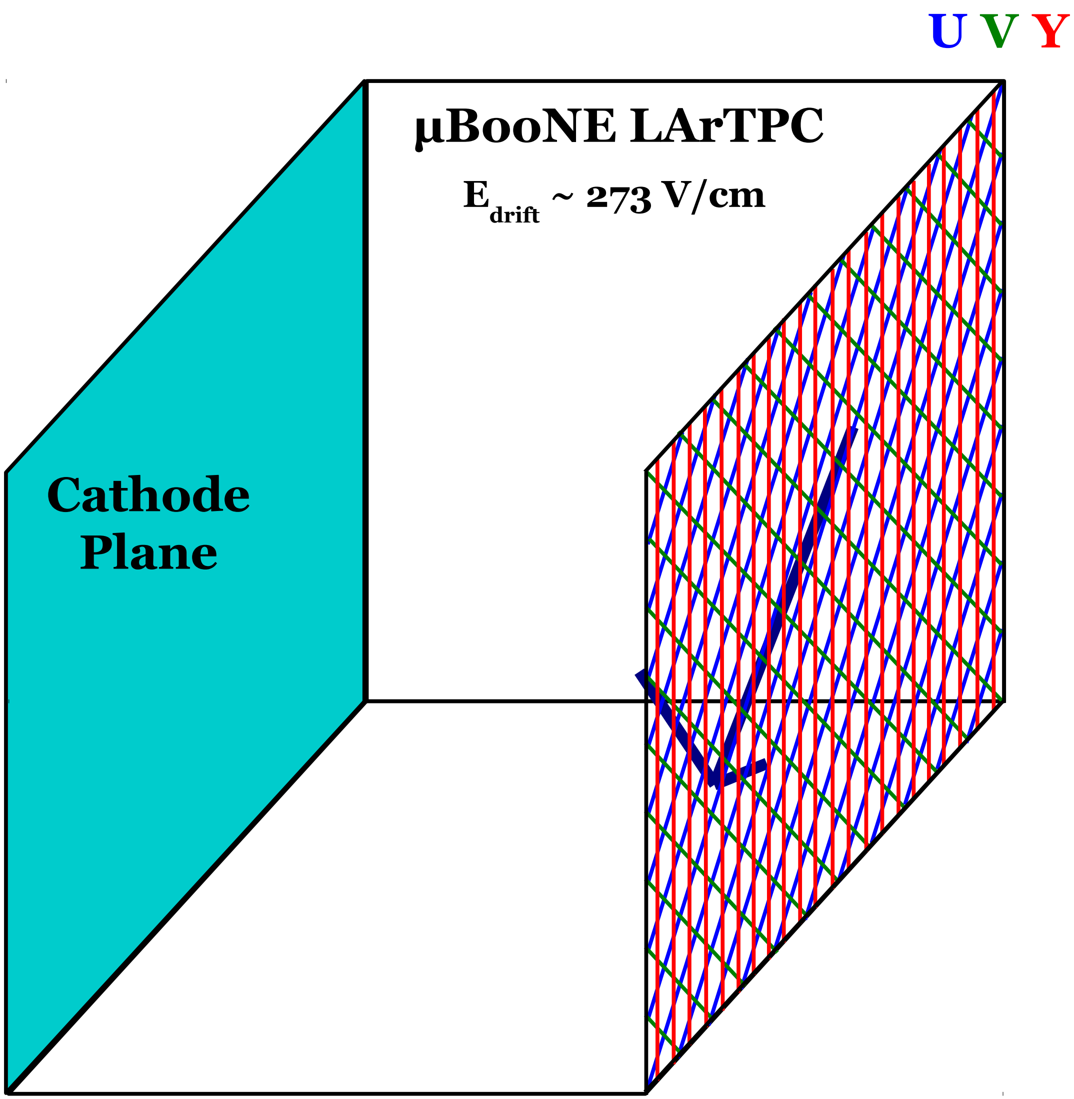


Signal Formation



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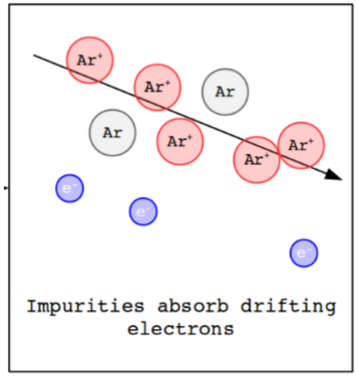
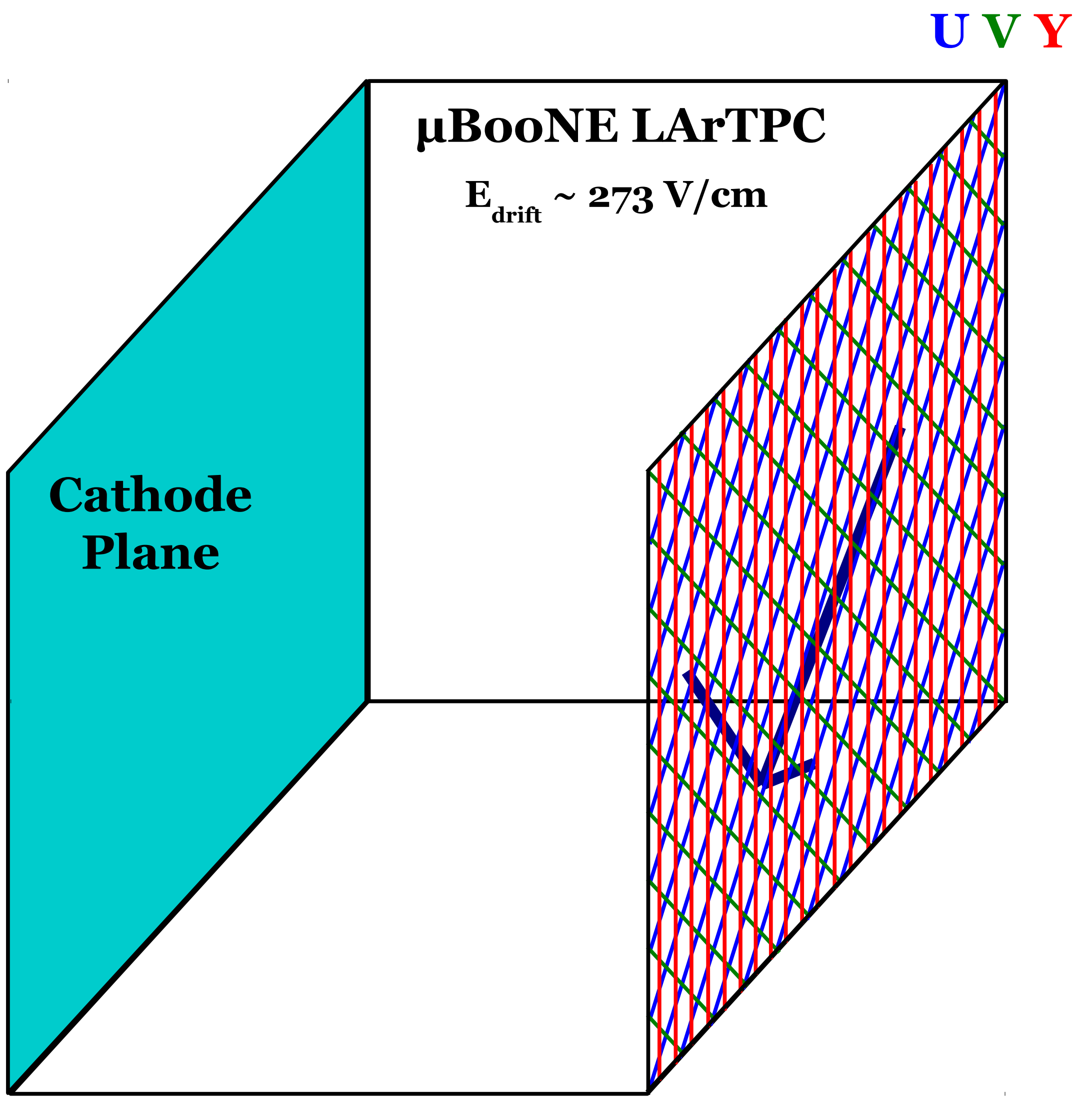
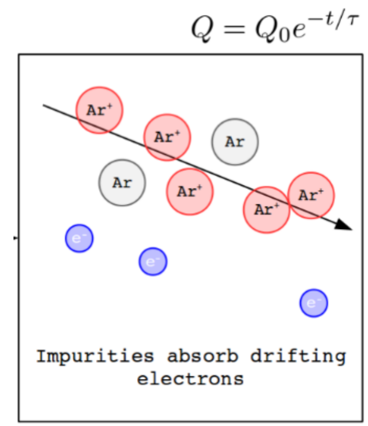
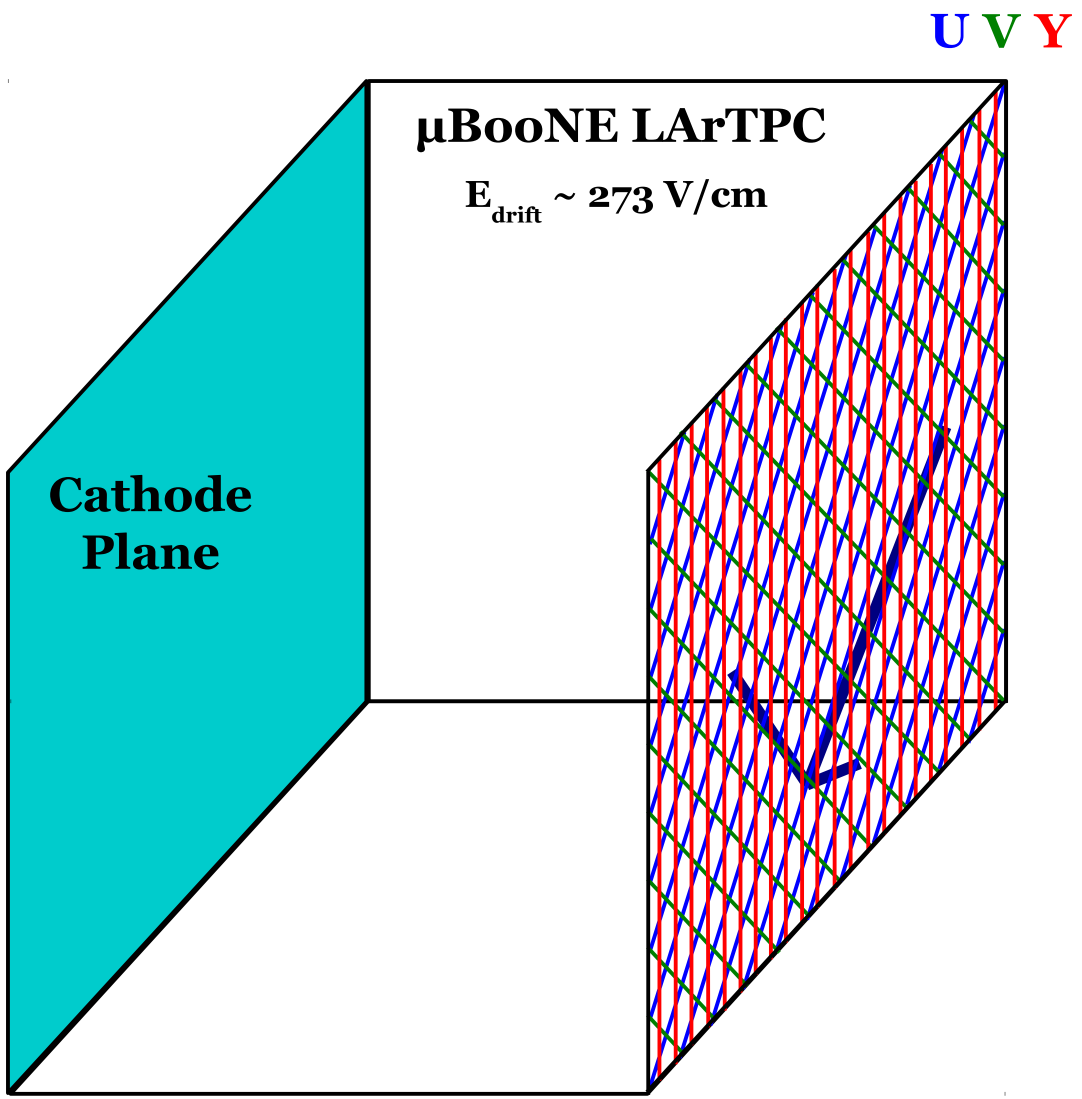


Signal Formation





Signal Formation



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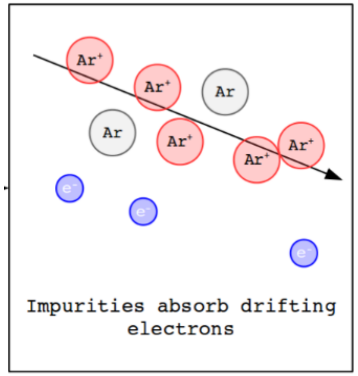
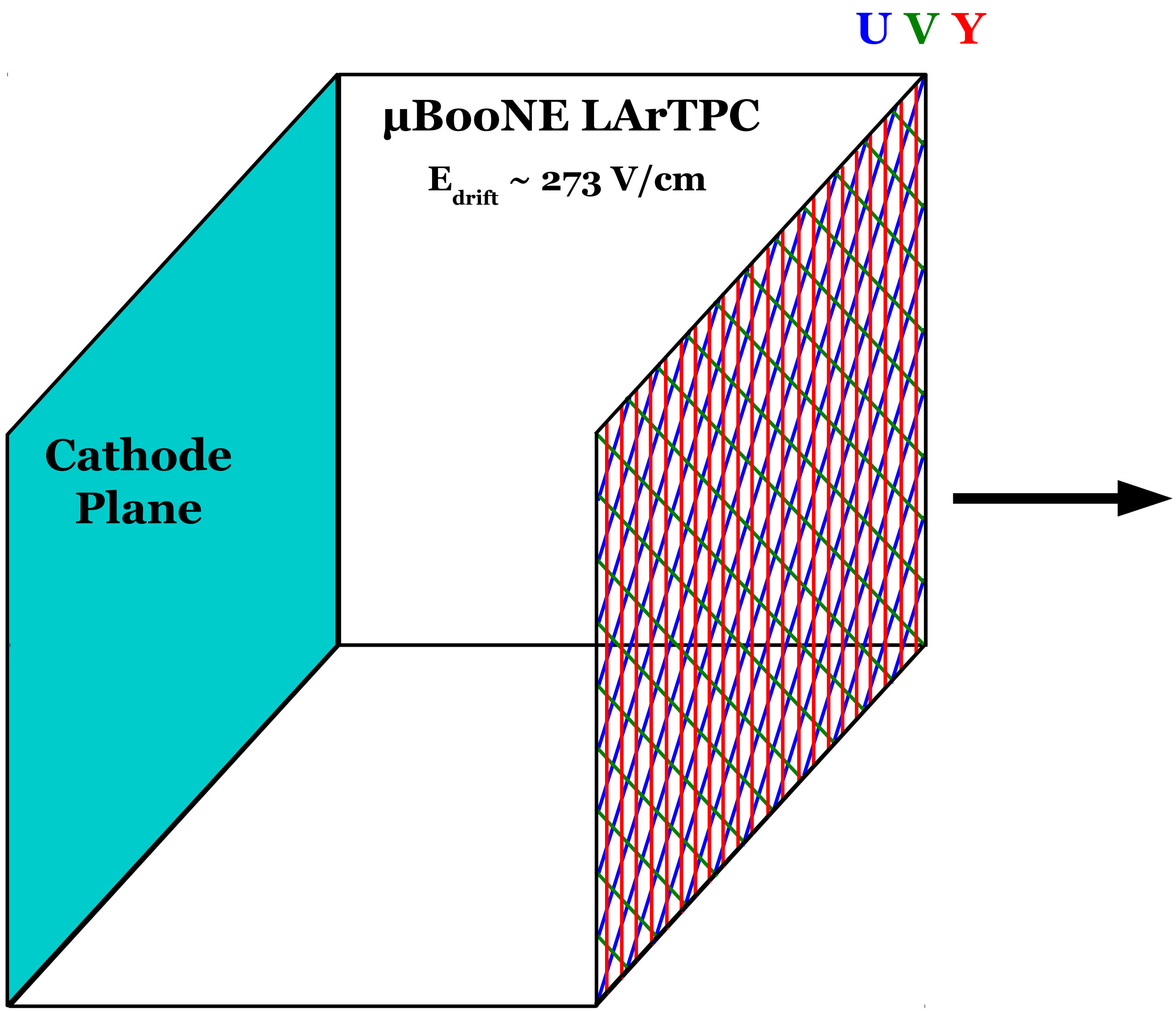
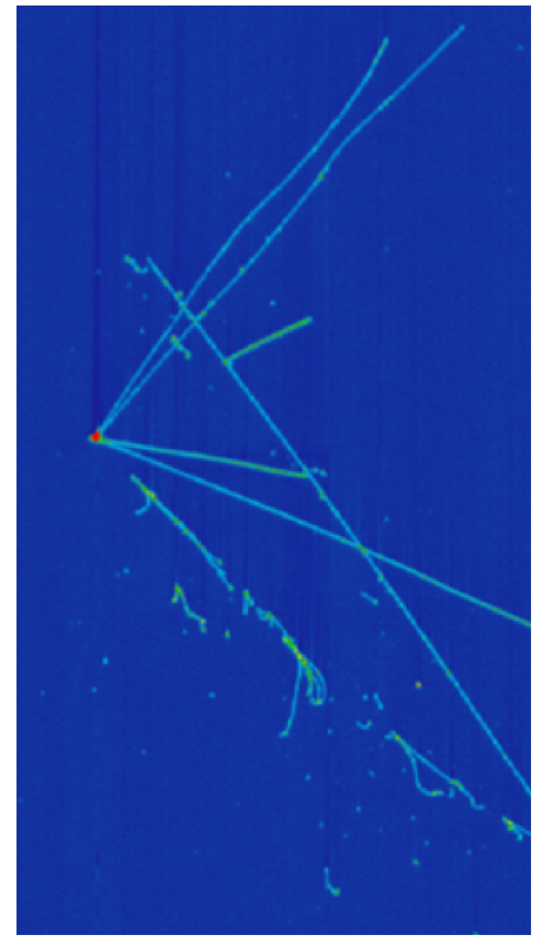


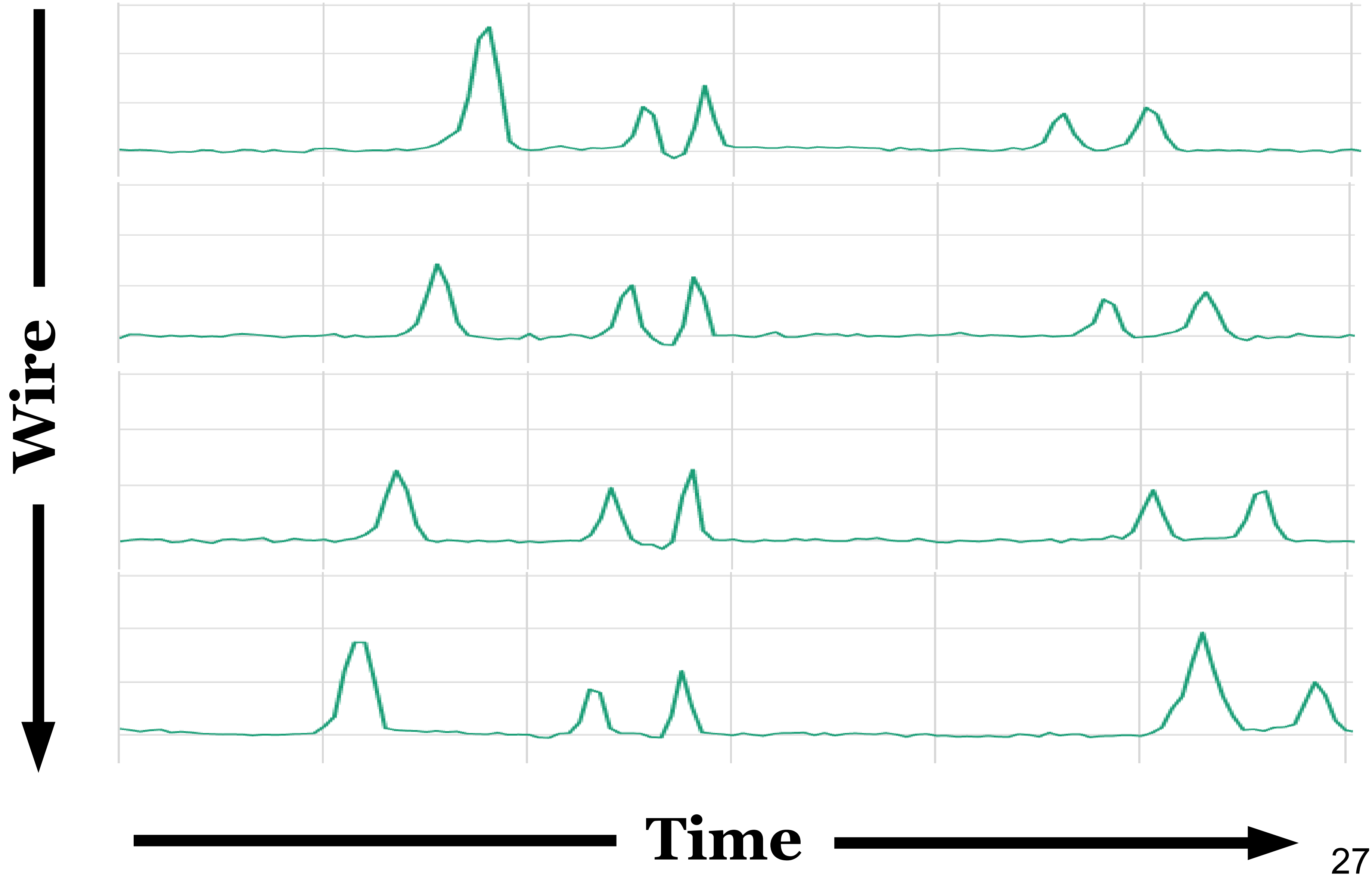
Signal Formation





Three Images (One Per Wire Plane)

Raw Waveform Output



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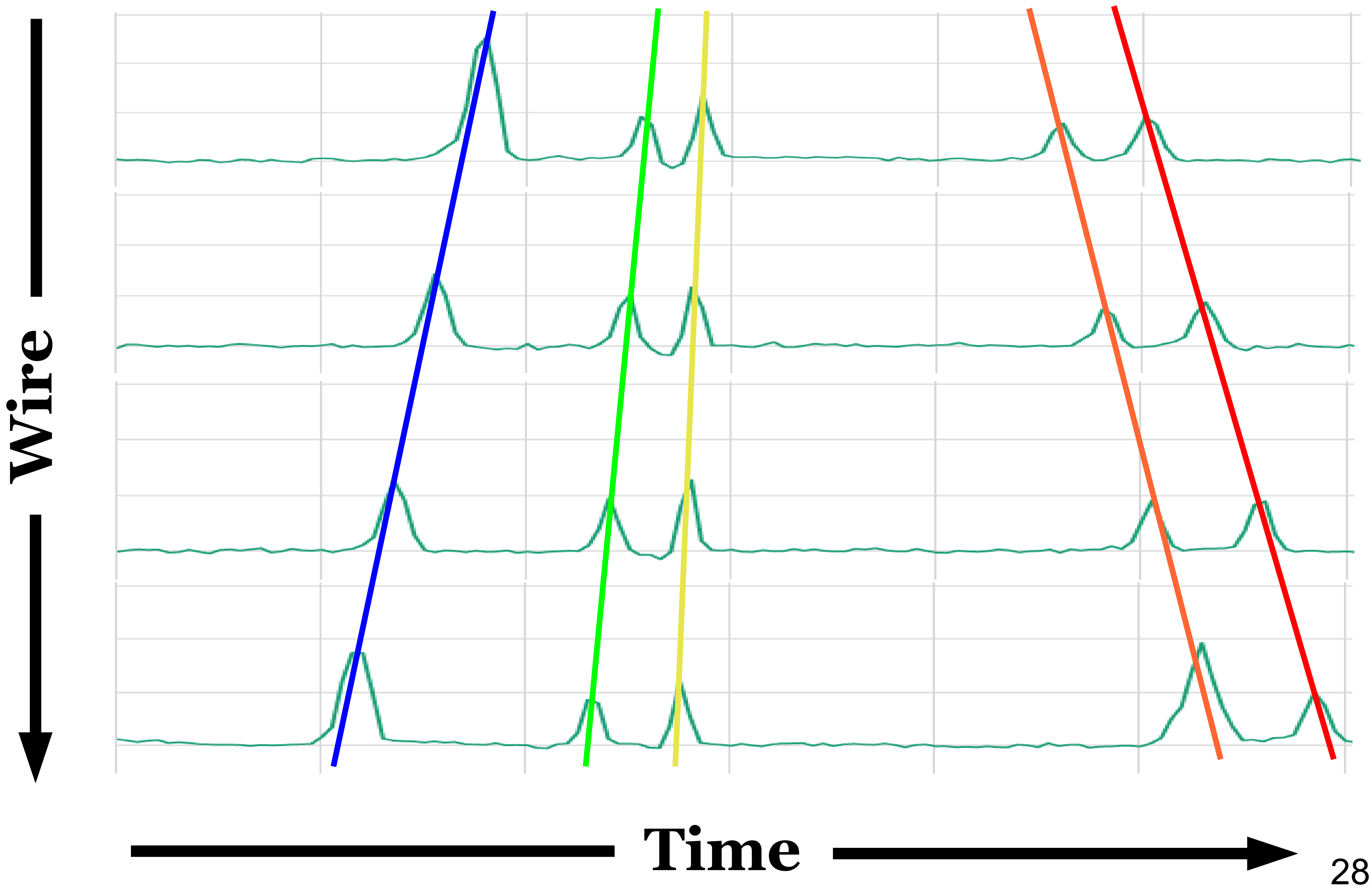
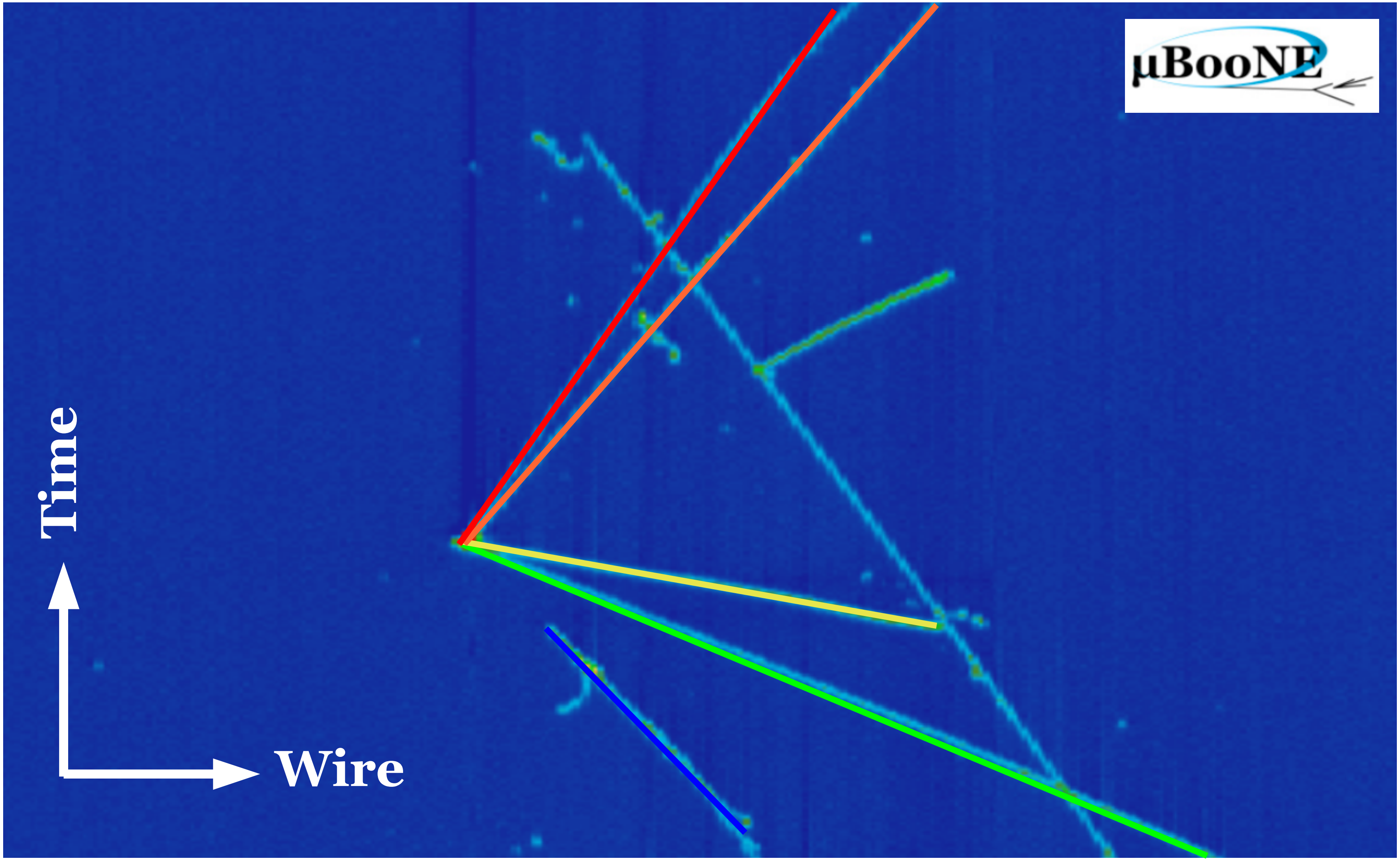
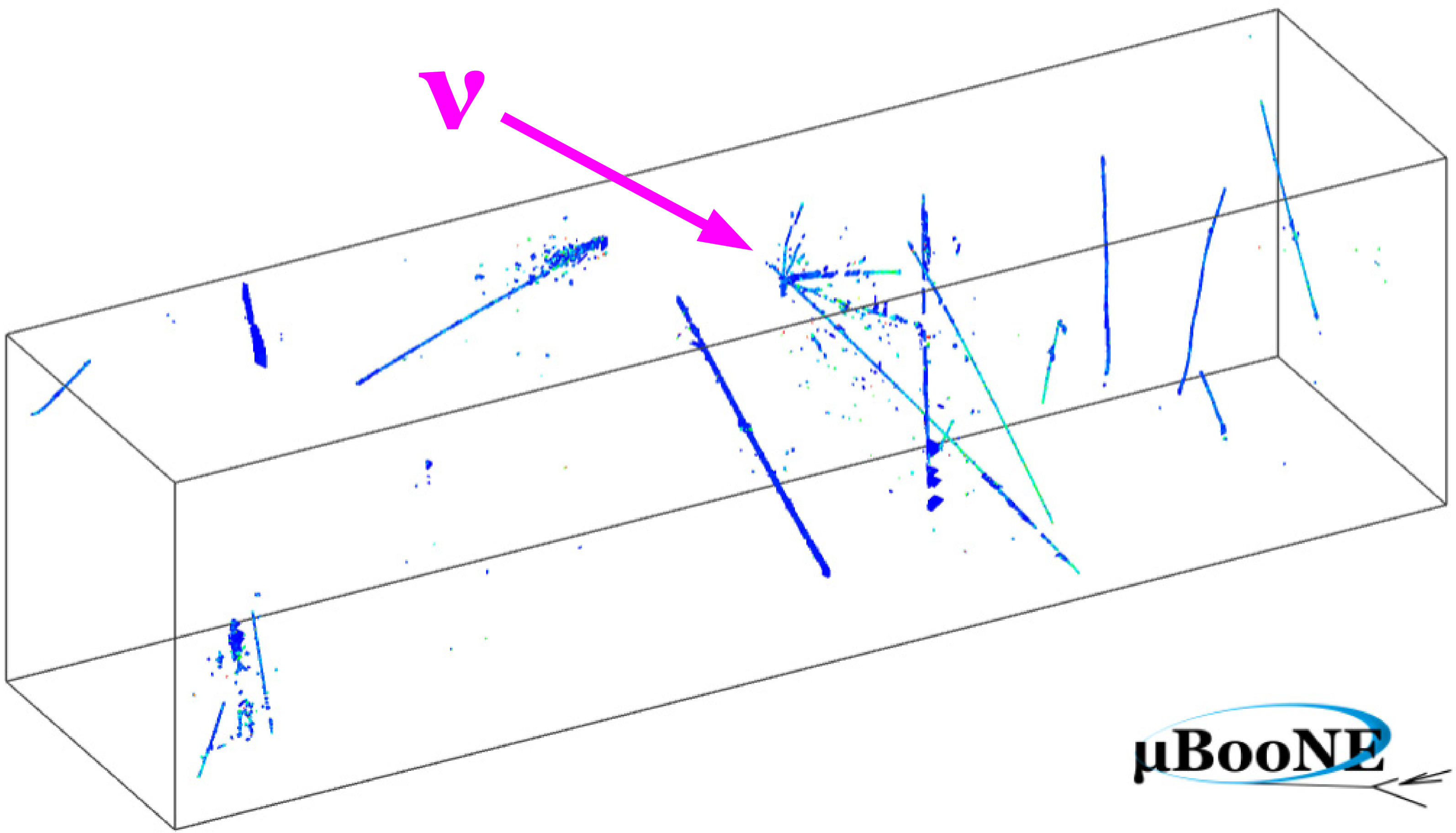


LArTPC Imaging



3D Event Reconstruction

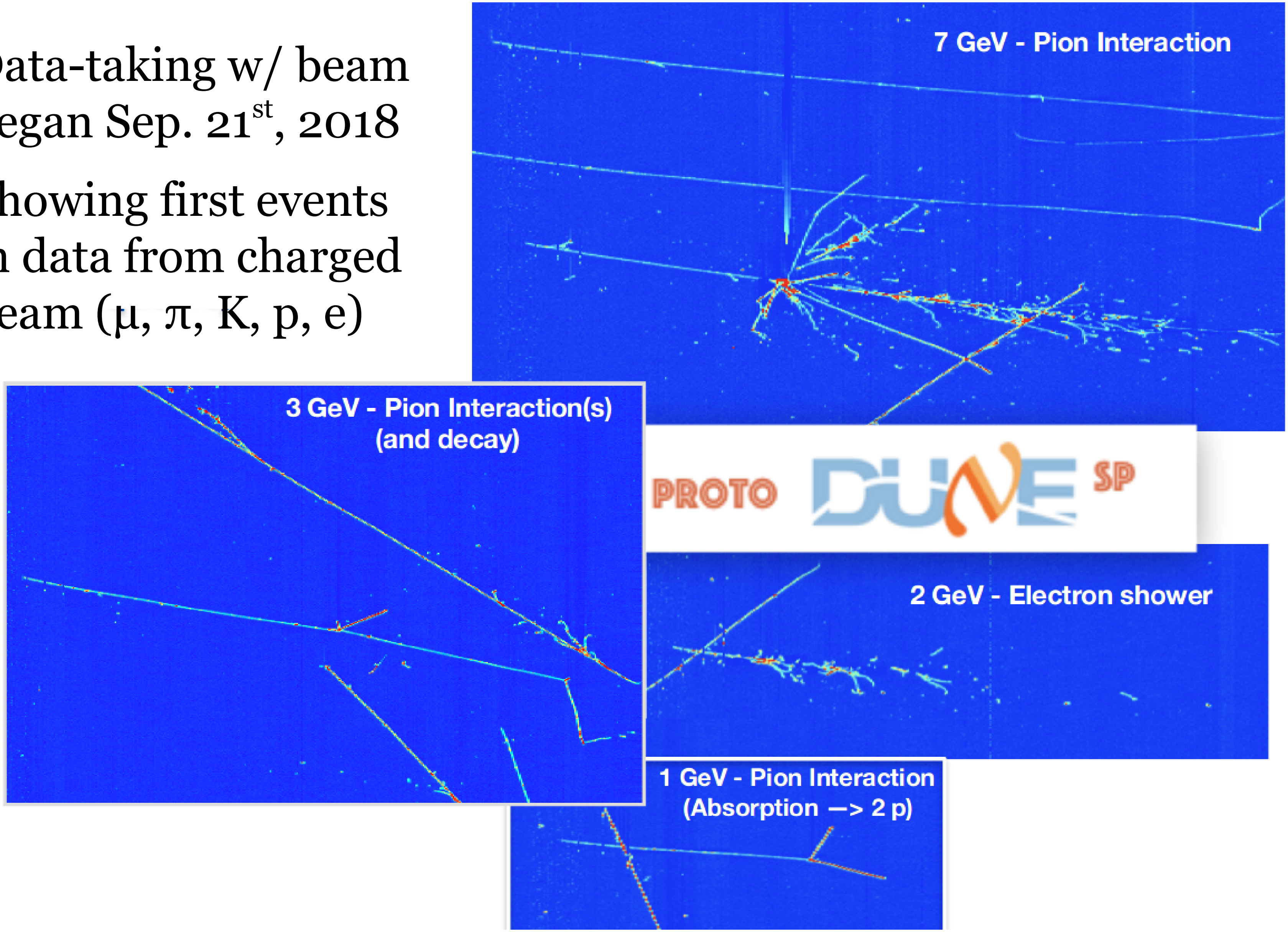
- ♦ Combine two/three 2D wire plane views → reconstruct event in **3D**
  - Below: **neutrino interaction** event from MicroBooNE **data**



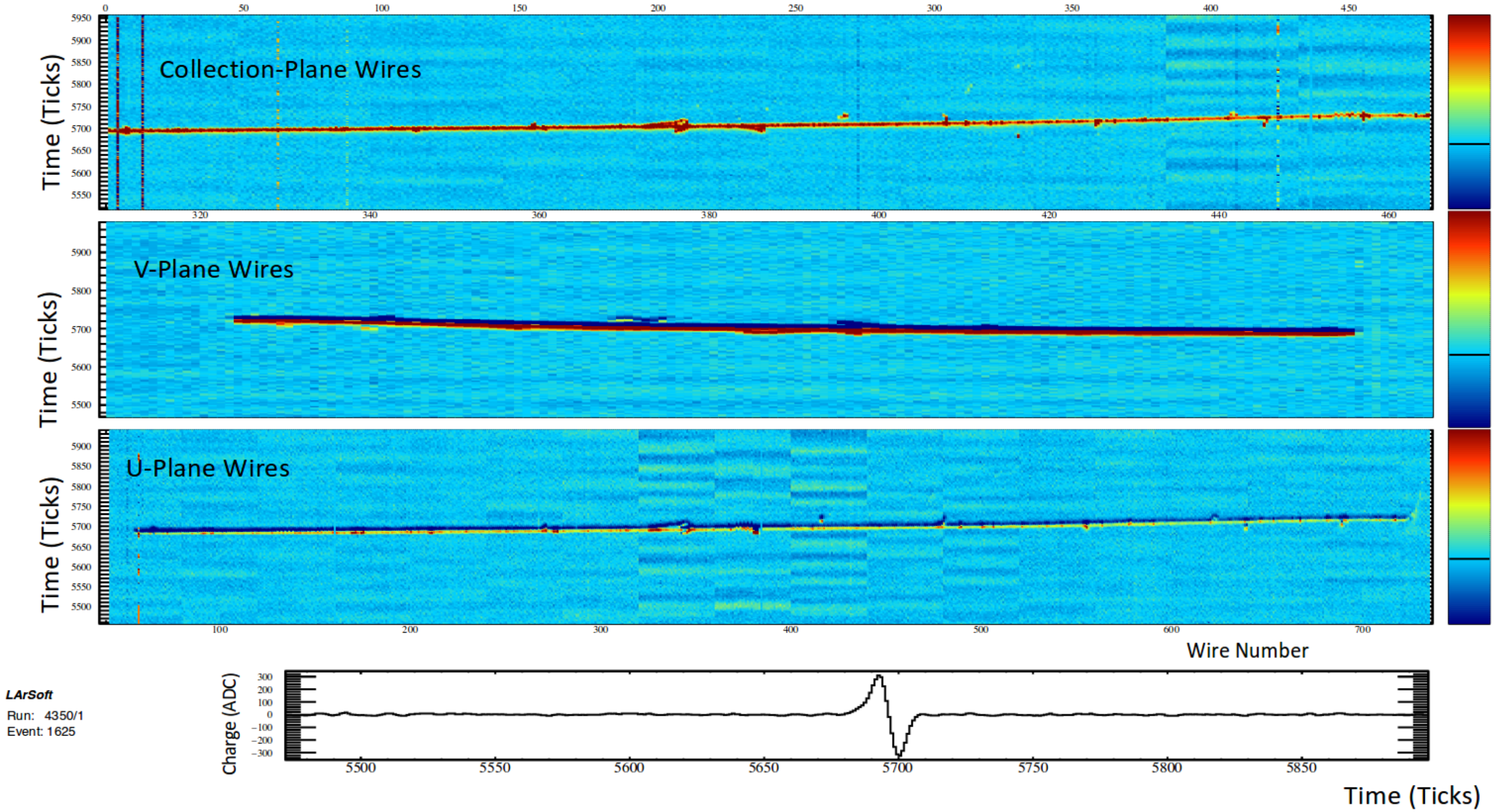
First Results from ProtoDUNE-SP

First Beam Events

- Data-taking w/ beam began Sep. 21st, 2018
- Showing first events in data from charged beam (μ, π, K, p, e)



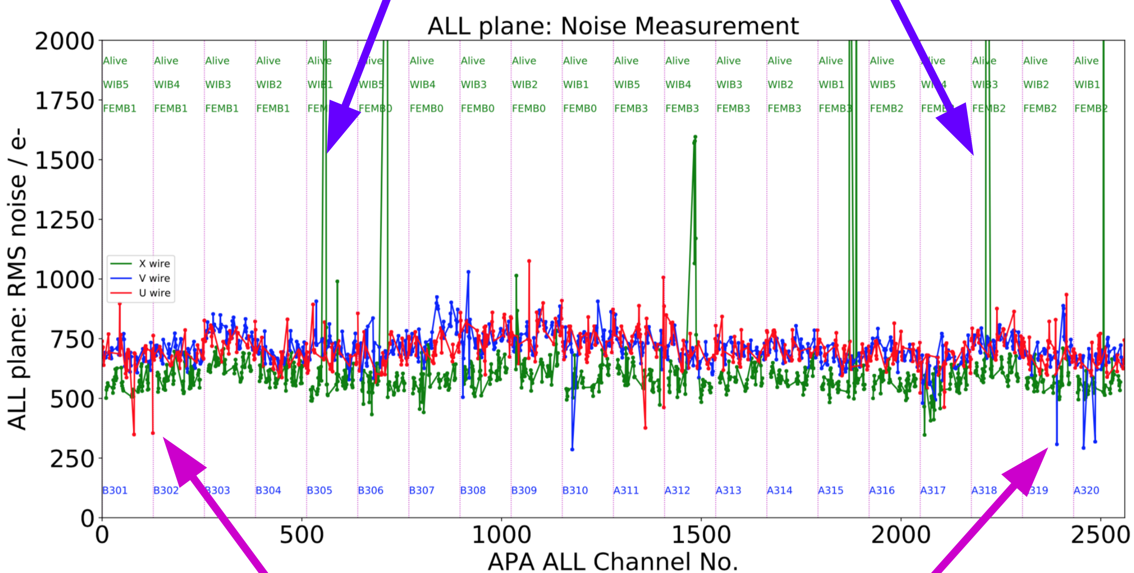
First Tracks – Low Noise!



- **First tracks in data** – without any software noise filtering, event display looks very clean!
- Some very mild coherent noise, but manageable

Noise Performance

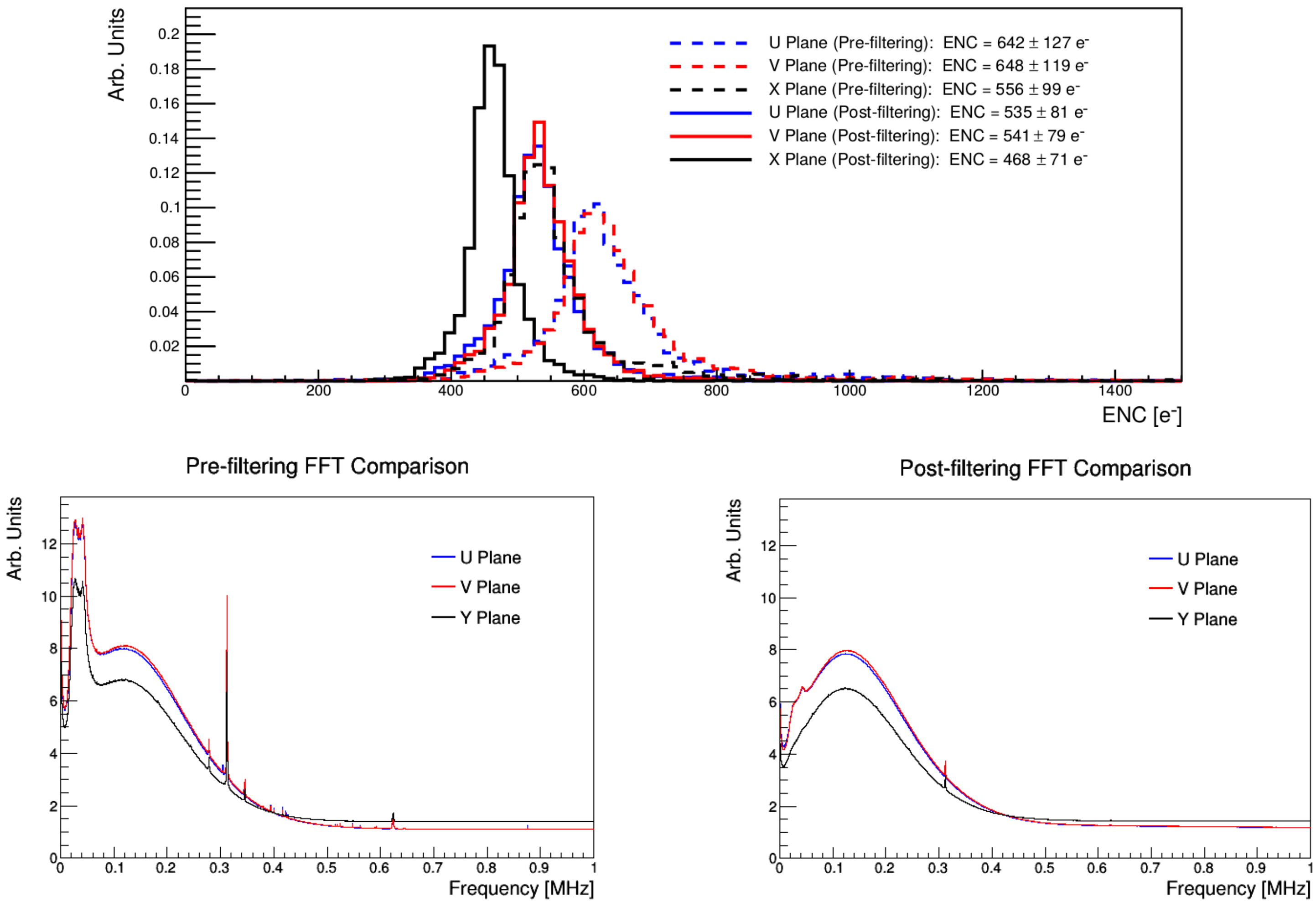
Known Issues with Cold ADC (Fixing for DUNE Far Detector)



Unresponsive Channels (0.3% of All Channels)

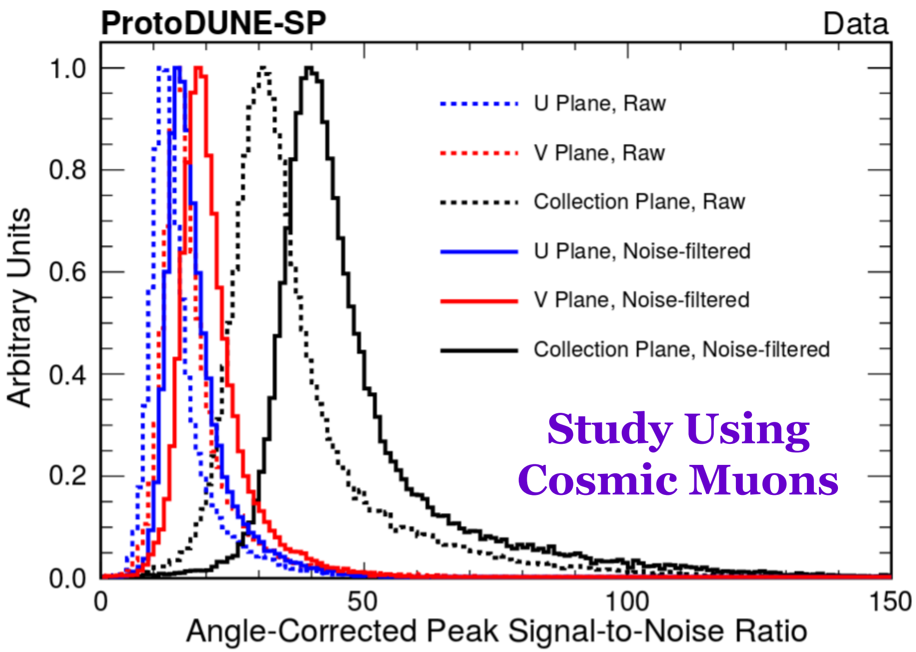
- Noise: 550 (480) e^- for collection plane, 650 (550) e^- for induction planes without (with) coherent noise filtering

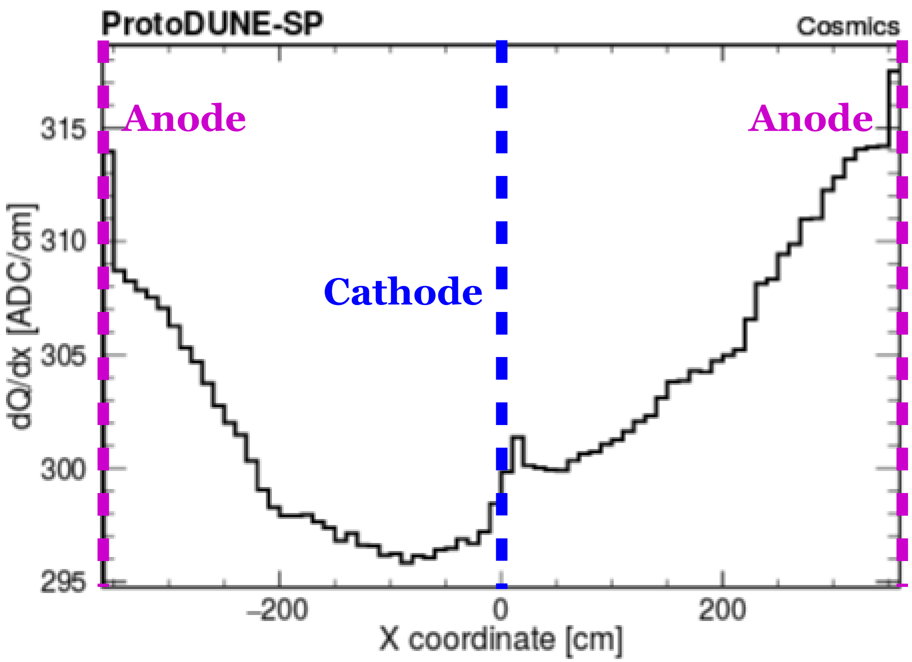
Noise Performance (cont.)



- Noise: 550 (480) e$^-$ for collection plane, 650 (550) e$^-$ for induction planes without (with) coherent noise filtering

Signal-to-Noise Ratio, Lifetime

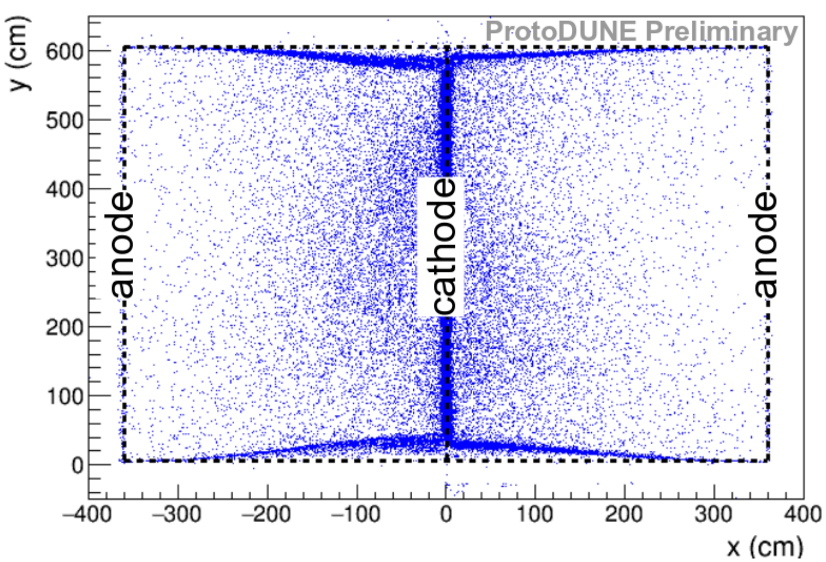


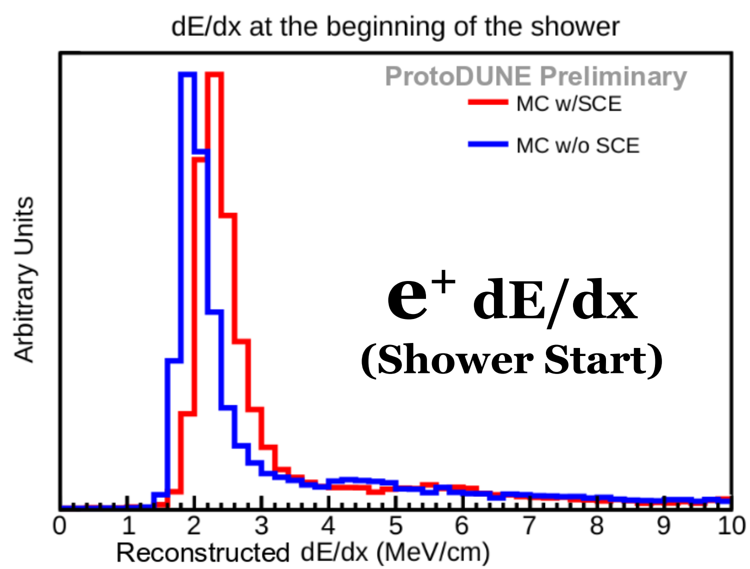


- Signal-to-noise ratio very high (**before** **or** **after** noise filtering)!
  - U Plane: **16** → **18**
  - V Plane: **19** → **21**
  - Y Plane: **38** → **49**
- After corrections for space charge effects (see later), electron lifetime observed to be very high: **> 20 ms**

Space Charge Effects

- Looking at cosmic data, notice offsets in track start/end points from top/bottom of TPC
  - Very suggestive of space charge effects (SCE) **as expected** as the ProtoDUNE-SP is near the surface; also seen at MicroBooNE
  - **Space charge**: build-up of slow-moving Ar^+ ions due to e.g. cosmic muons impinging active volume of TPC (via ionization)
  - Leads to E field distortions, distortions in reconstructed ionization position
    - Both can bias particle dE/dx and energy! Important to calibrate!



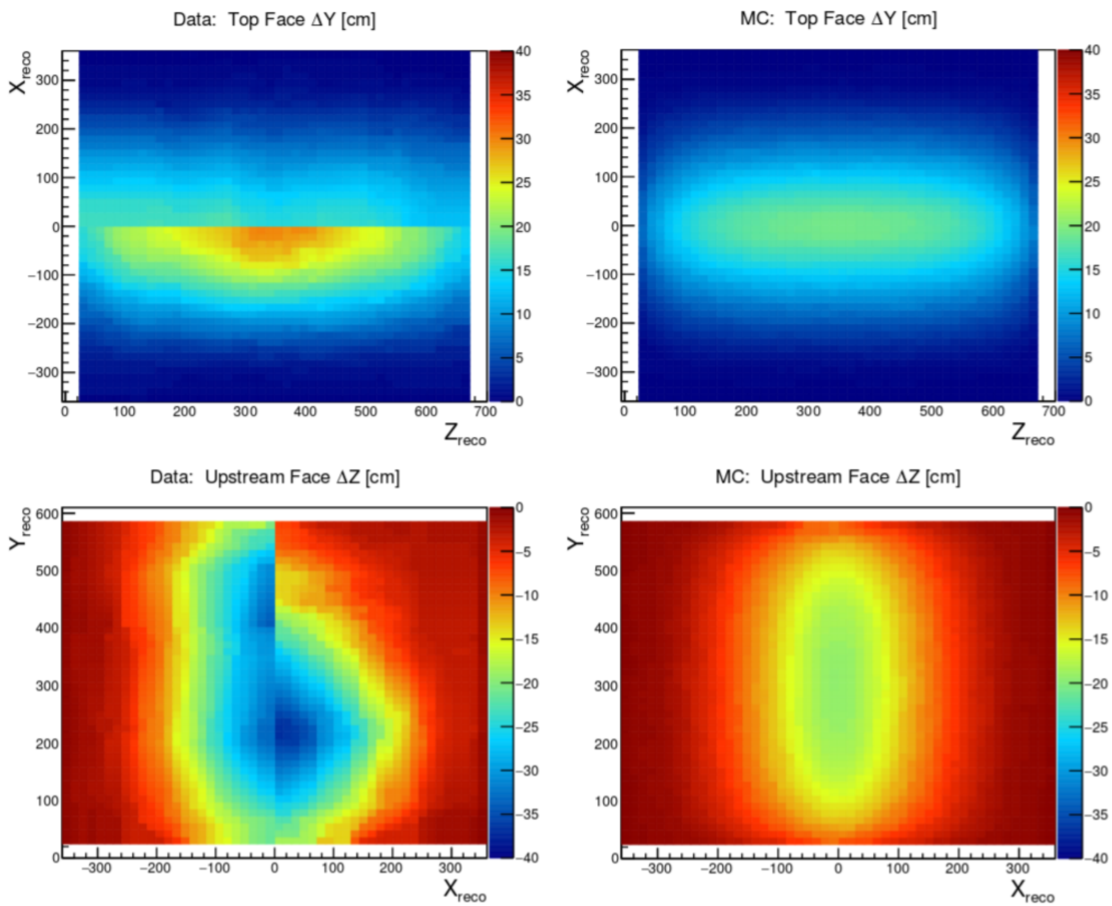


e^+ dE/dx
(Shower Start)

Space Charge @ TPC Faces

Data: **TPC Top**

Simulation: **TPC Top**

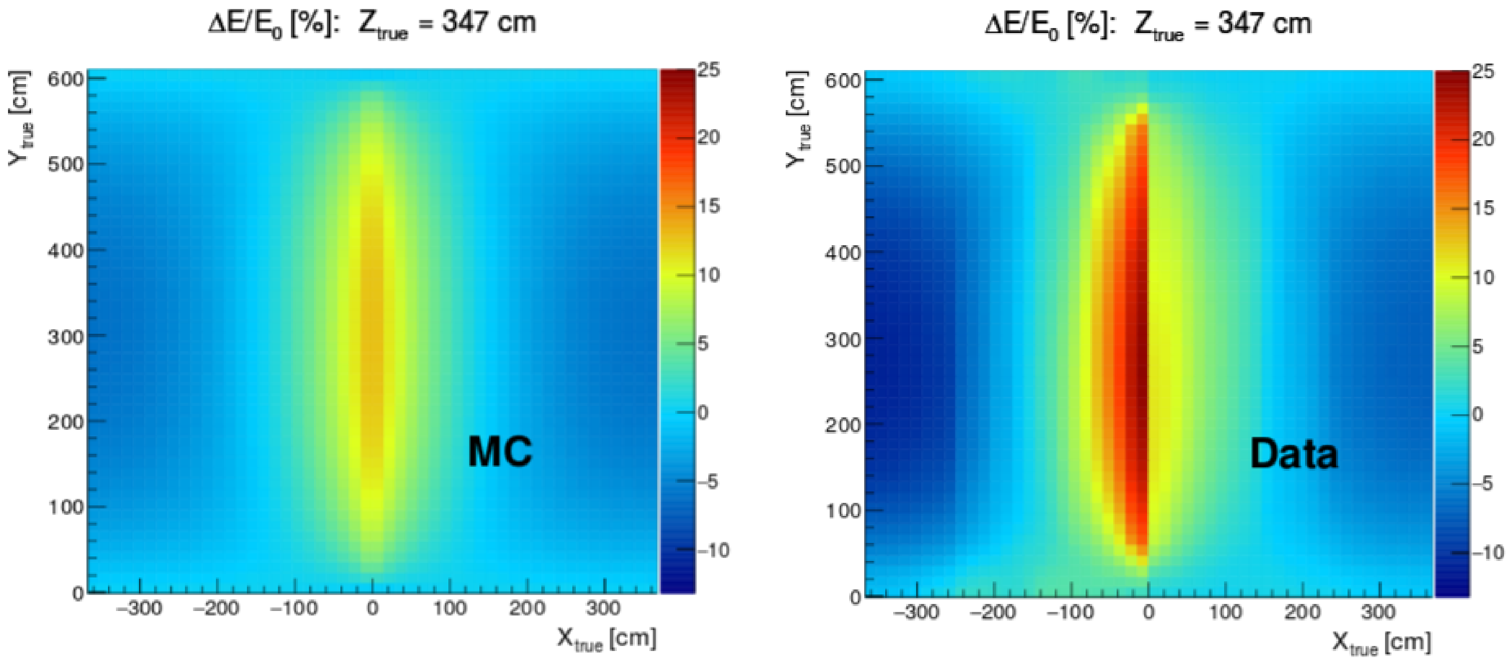


Data: **TPC Front**

Simulation: **TPC Front**

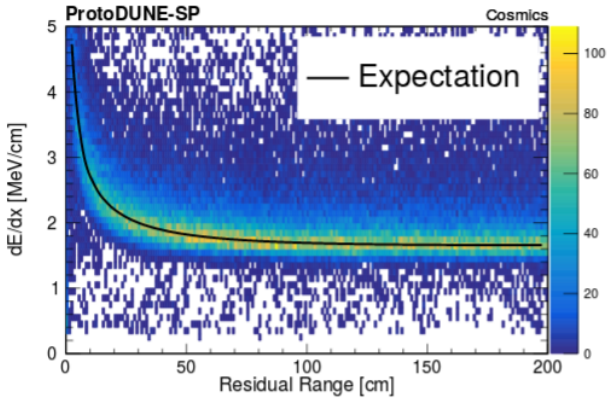
- Look at spatial offsets from top, front edges of TPC
- SCE **50-75% larger** than prediction from simulation (up to 35 cm!)
  - Still investigating – tune argon flow model, and/or ion drift speed?

Electric Field Distortions

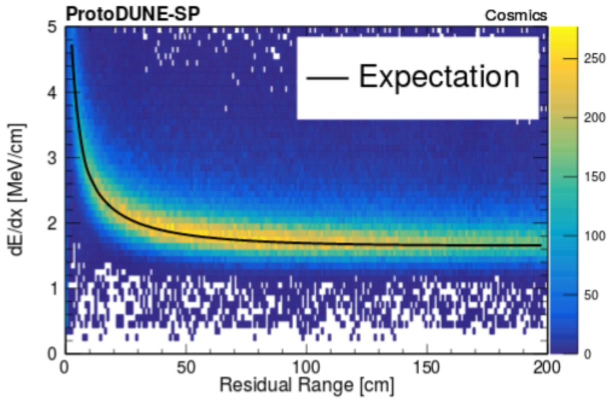


- Straightforward to calculate E field distortions everywhere in detector with measured spatial offsets → **also put in simulation**
- <u>Result</u>: nearly 25% higher E field near cathode than nominal E field
  - Reminder: nominal E field is 500 V/cm
  - That means E field near cathode **greater than 600 V/cm!**
- Following results include calibration of SCE (spatial, E field)

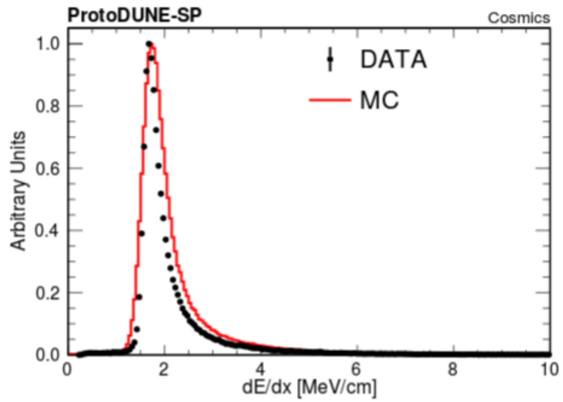
Cosmic Muons



(a) Data



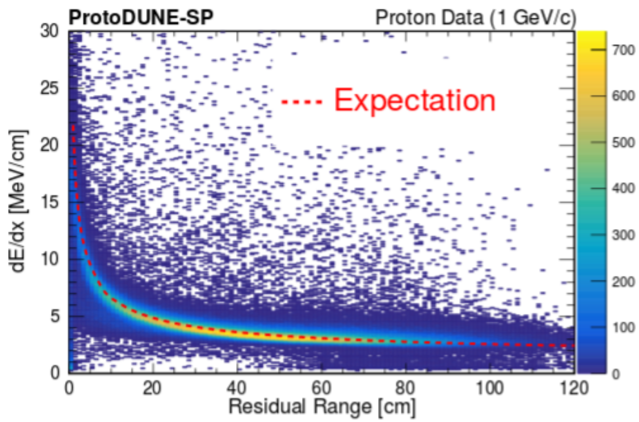
(b) MC



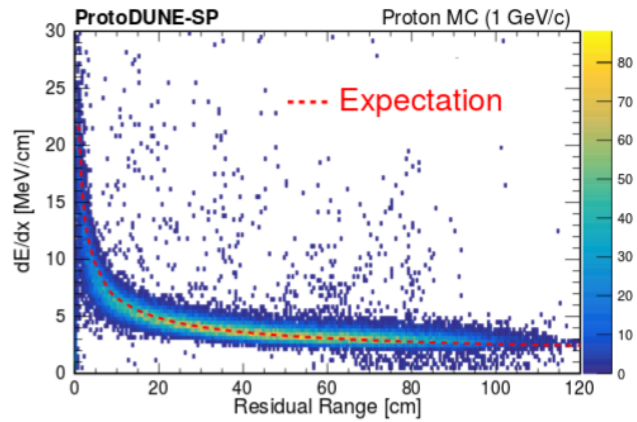
(c) dQ/dx comparison

- Use muon dE/dx at high residual range for absolute energy scale
- After calibration, good agreement between data and simulation for cosmic muon dE/dx – smearing in MC slightly larger

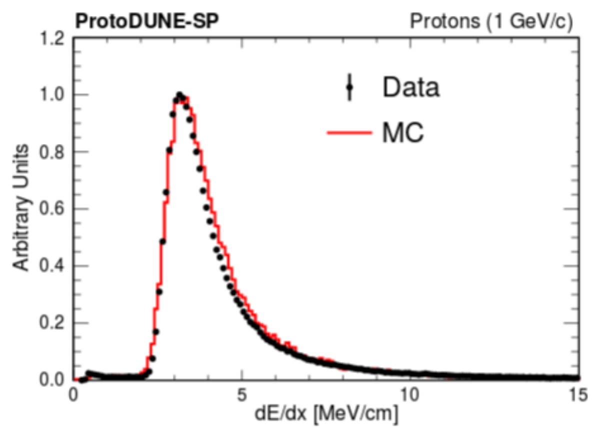
Protons



(a)



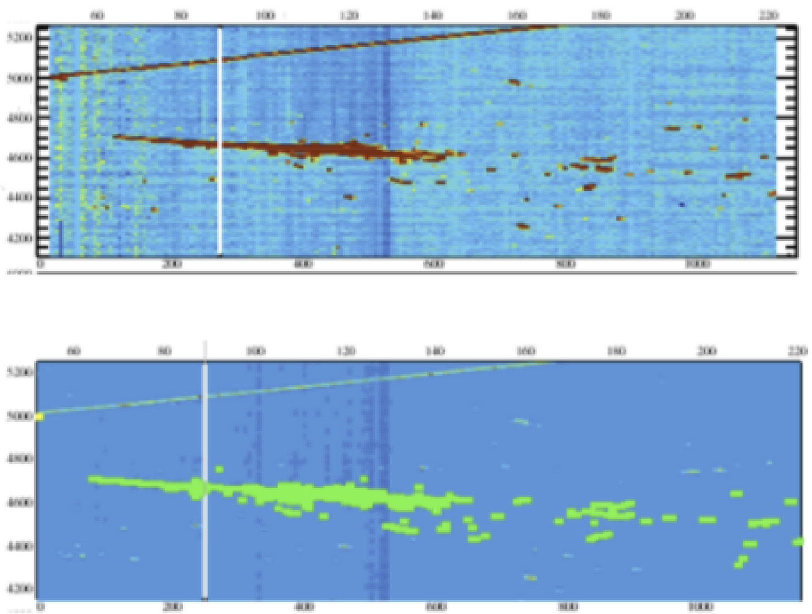
(b)

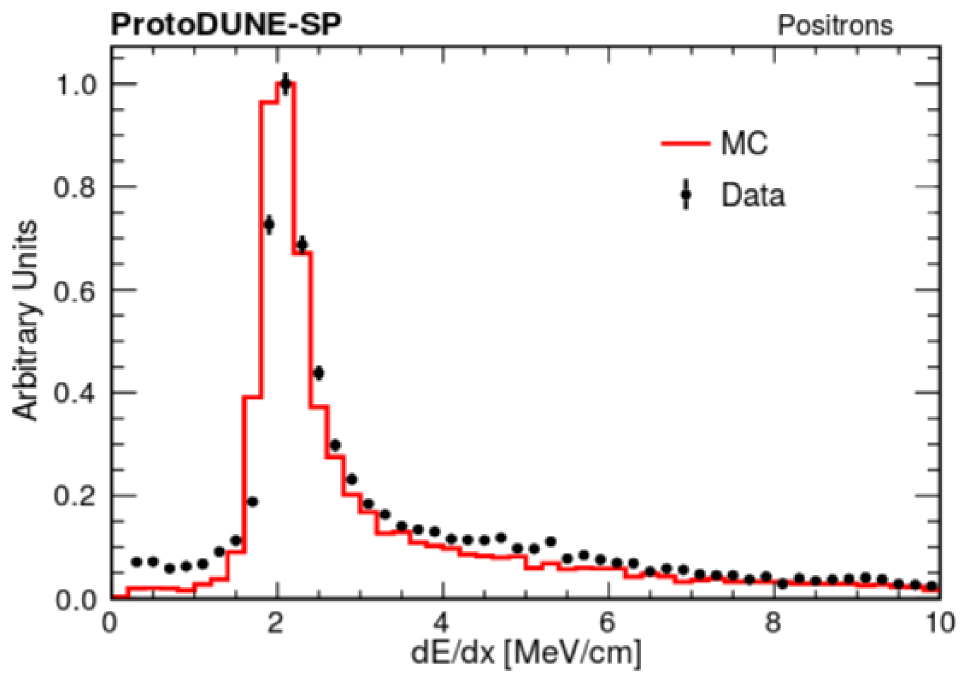


(c)

- Proton dE/dx distribution sees very good agreement between data and simulation – sign that calibrations are working well

Positrons





- First studies of beam positron selection carried out, including study of dE/dx near beginning of shower
  - Good agreement between data and MC
- Shower reconstruction (beam positrons, photons from neutral pions) is major focus of ProtoDUNE-SP analysis moving forward

Final Remarks

- ProtoDUNEs are necessary step along way to construction and successful data-taking with DUNE far detector
  - ProtoDUNE-SP: took data with beam in late 2018
  - ProtoDUNE-DP: will begin first run in late 2019
- First ProtoDUNE-SP results presented here – promising!
- ProtoDUNE-SP continues to take cosmic data
  - Plan is to continuing to take data for a while in order to study detector performance, reconstruction, calibration
- Discussion of second ProtoDUNE-SP run in beam in 2022
  - Study detector performance after upgrade of TPC electronics
  - Test dedicated calibration systems for DUNE far detector

Thanks!

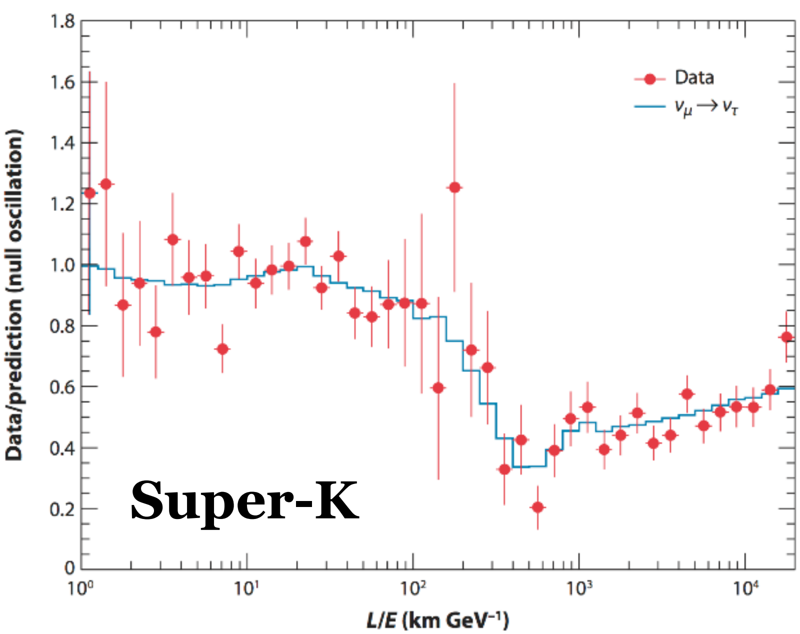
Backup

Neutrino Oscillations

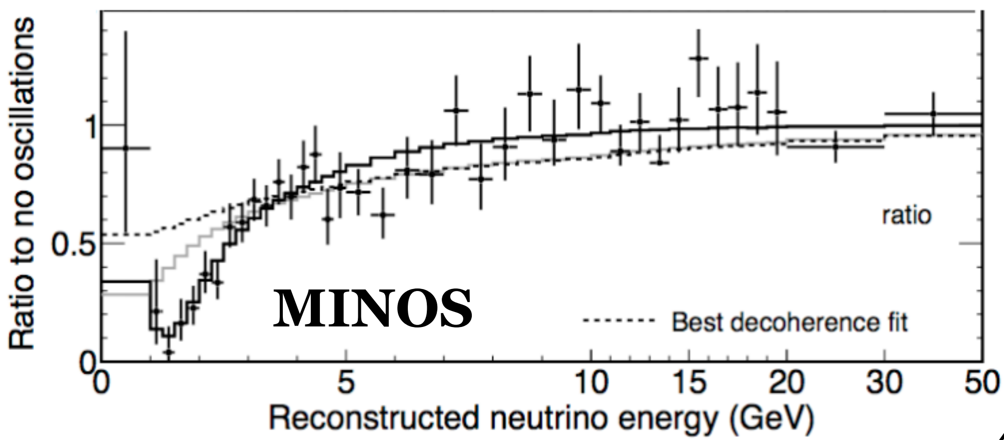
- Neutrinos oscillate → neutrino flavors mix → **neutrinos have mass!** **Not predicted by Standard Model!**

Two-Flavor Approximation:

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\text{eV}^2]\,[\text{km}]}{[\text{GeV}]}\right)$$

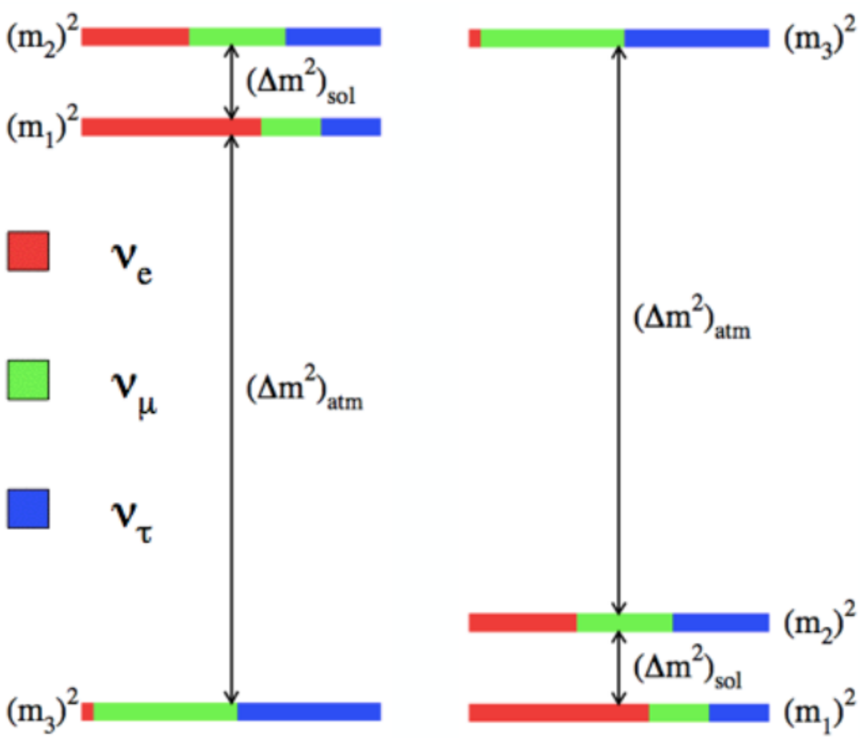


See oscillations in data, with multiple experiments using different detector technology and neutrino sources!



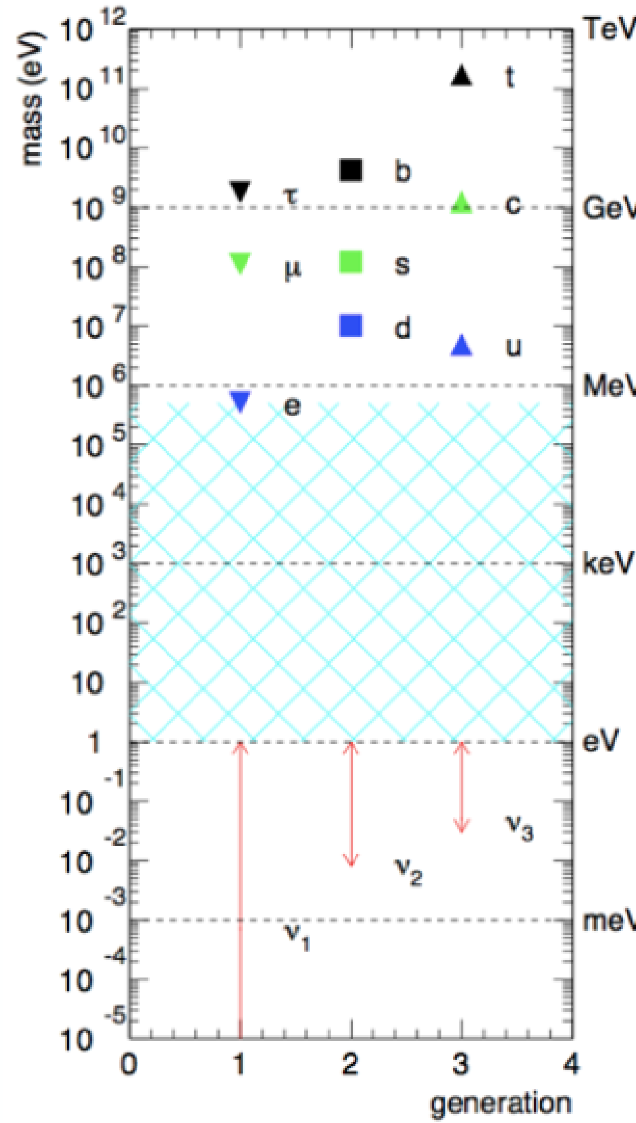
Ordering Neutrino Mass

- <u>Open question</u>: is neutrino mass ordering "normal" or "inverted"?



"Inverted" Mass Ordering

"Normal" Mass Ordering



Matter-Antimatter Asymmetry

- Open question: do neutrinos **violate CP** (charge-parity)?
  - Or: do neutrinos and antineutrinos have different oscillation probabilities? (smoking-gun feature of non-zero δ_{CP})
  - Could explain **matter-antimatter asymmetry in universe**
  - If so, precise measurement of δ_{CP} tells us *details of mechanism*
  - **If not**, there must be **new physics** to explain asymmetry!

$$P(\nu_\alpha \to \nu_\beta) \stackrel{?}{=} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$\stackrel{?}{\sin\delta = 0}$$

DUNE Physics Milestones

Physics milestone	Exposure (kt · MW · year)	Exposure (years)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	29	1
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	77	3
MH at 5σ (worst point)	209	6
10° $\delta_{\rm CP}$ resolution ($\delta_{\rm CP} = 0$)	252	6.5
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	253	6.5
CPV at 5σ 50% of $\delta_{\rm CP}$	483	9
CPV at 3σ 75% of $\delta_{\rm CP}$	775	12.5
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	857	13.5

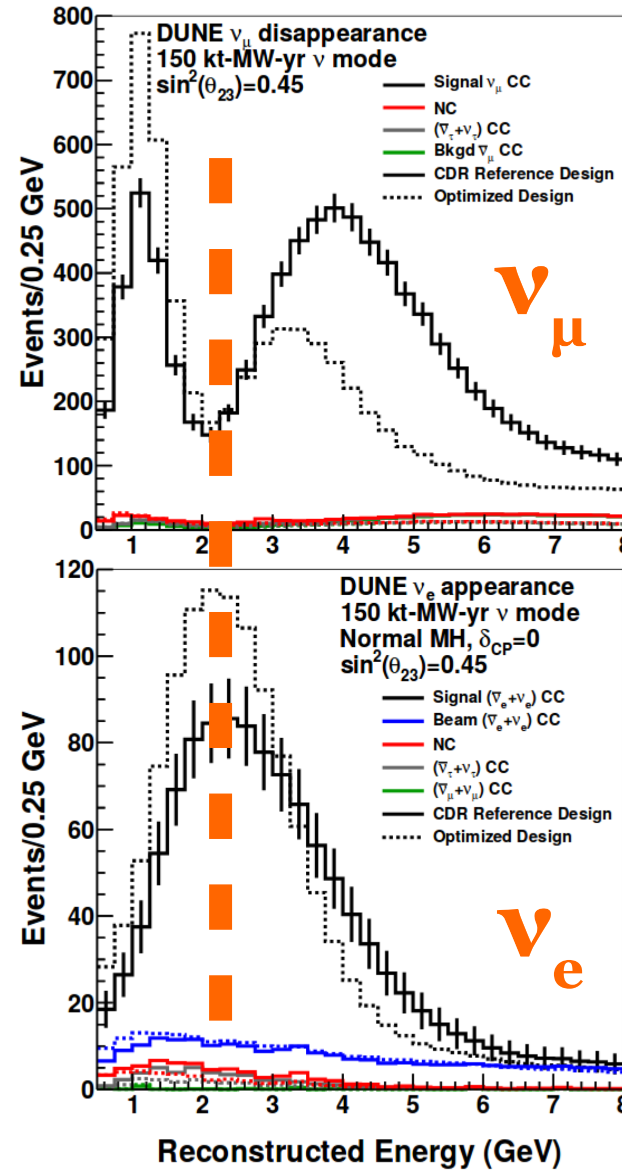
Why Liquid Argon?

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3	1
Radiation Length [cm]	755.2	24	14	4.9	2.8	36.1
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	
Approx. Cost [$/kg]	52	330	5	330	1200	

- Argon is cheap: **~1%** of atmosphere
- Dense target (more ν-N interactions per unit time)
- High scintillation light yield, argon transparent to own light
- Relatively small radiation length for shower containment

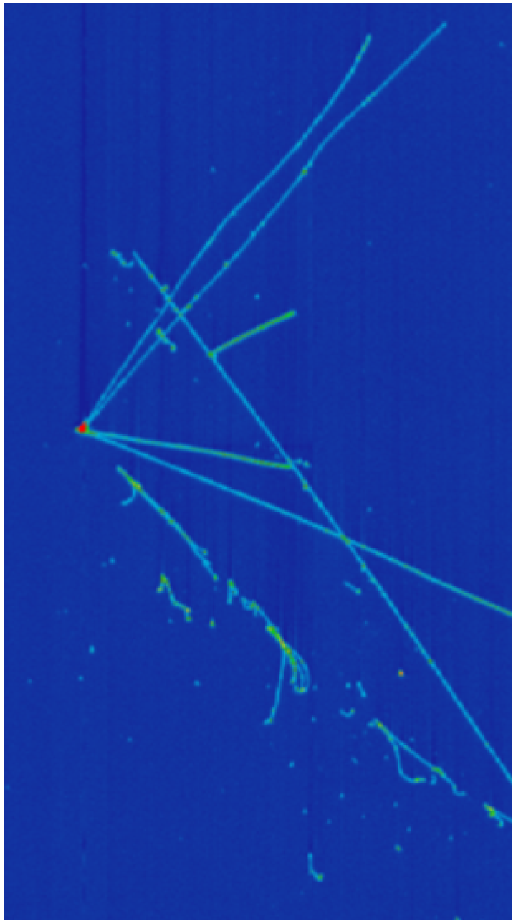
DUNE Oscillation Physics

- LArTPC provides high signal efficiency, low backgrounds for oscillation physics
  - Key to answering open questions from previous two slides
- Extract ν oscillation parameters by means of a 4-sample (ν_μ / $\bar{\nu}_\mu$ / ν_e / $\bar{\nu}_e$) fit
  - Constrain flux, cross section systematics using LAr near detector (ND)
- DUNE currently studying impact of detector systematics on measurements
  - <u>Preliminary goal</u>: constrain detector systematics to 1-2% level (difficult!)



Introducing… the LArTPC

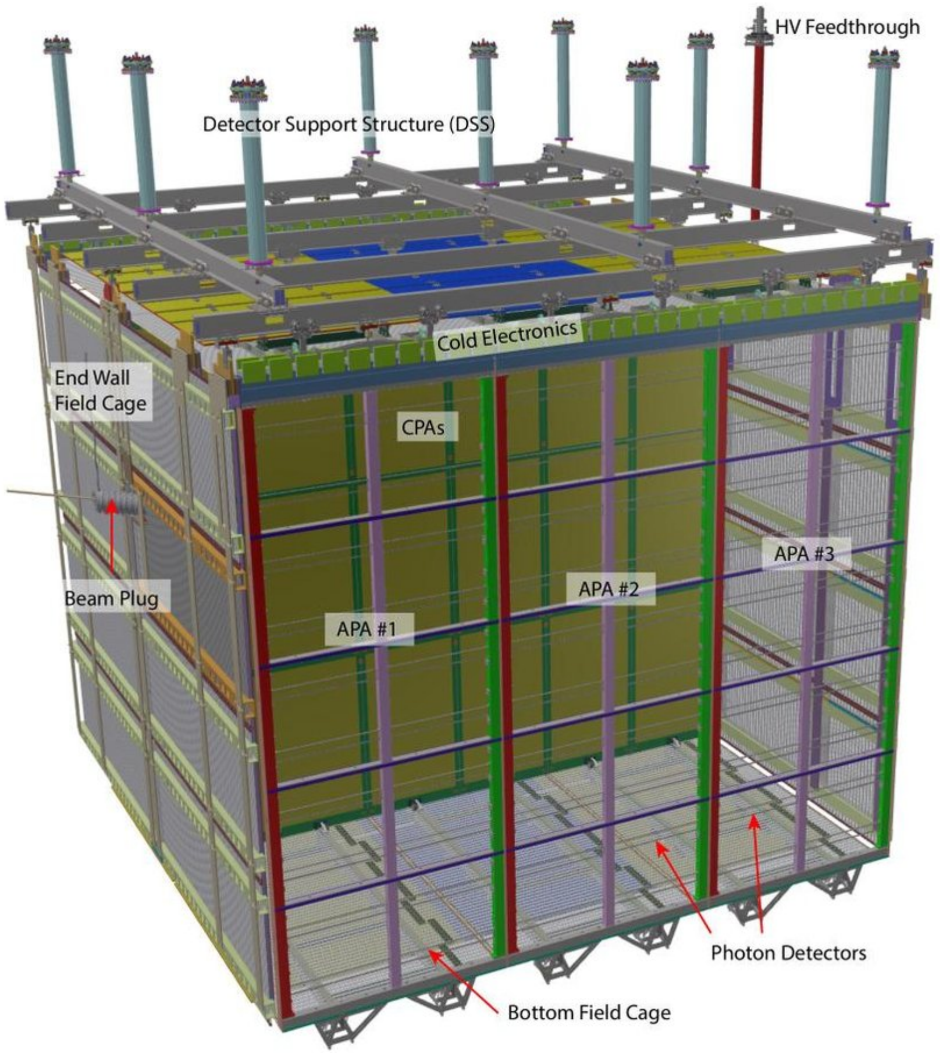
- DUNE physics program requires detector technology with:
  - ***Low Thresholds*** – important for detecting low-energy particles (e.g. in supernova/solar neutrino detection)
  - ***Excellent Calorimetry*** – important for precise estimation of neutrino energy, particle ID with dE/dx
  - ***High Spatial Resolution*** – allows for background rejection and particle ID
  - ***Scalability*** – large detectors yielding high event rates for precision physics measurements



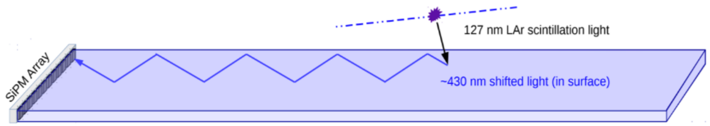
- These are all traits of the LArTPC!
  - **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber

ProtoDUNE-SP Geometry

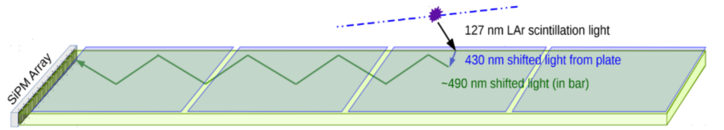
- 1/20 of full 10-kt FD module
  - 0.77 kt total LAr mass
  - Components are 1:1 scale
- Six APAs (three per side)
  - 2,560 channels per APA
- Central cathode plane (CPAs) divides active volume into two separate drift volumes
  - 3.6 m max drift length
  - E field of 500 V/cm
- Field cage for keeping E field uniform (up to space charge)
- Cryogenic TPC electronics



Photon Detection System

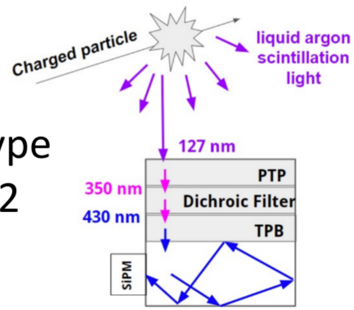


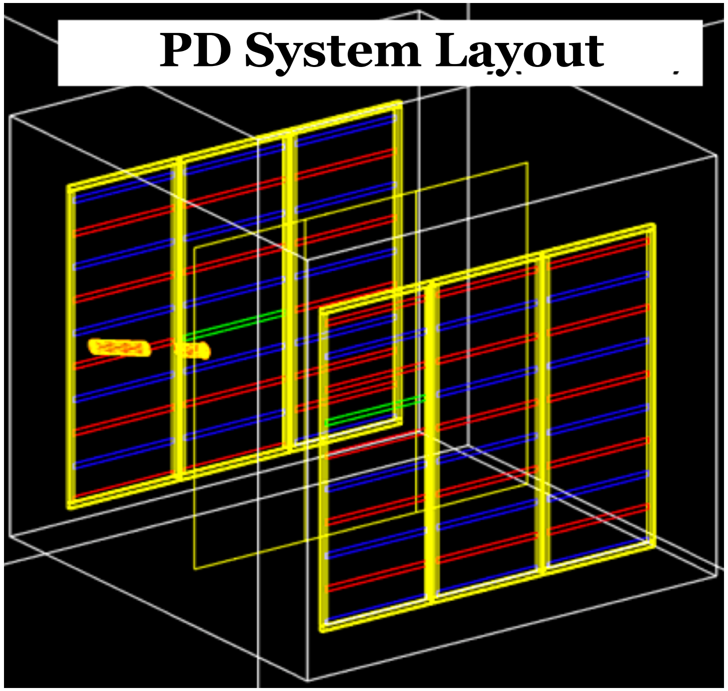
"Dip-Coated" (DC) Type Collector ✕ 29



"Double-Shifted" (DS) Type Collector ✕ 29

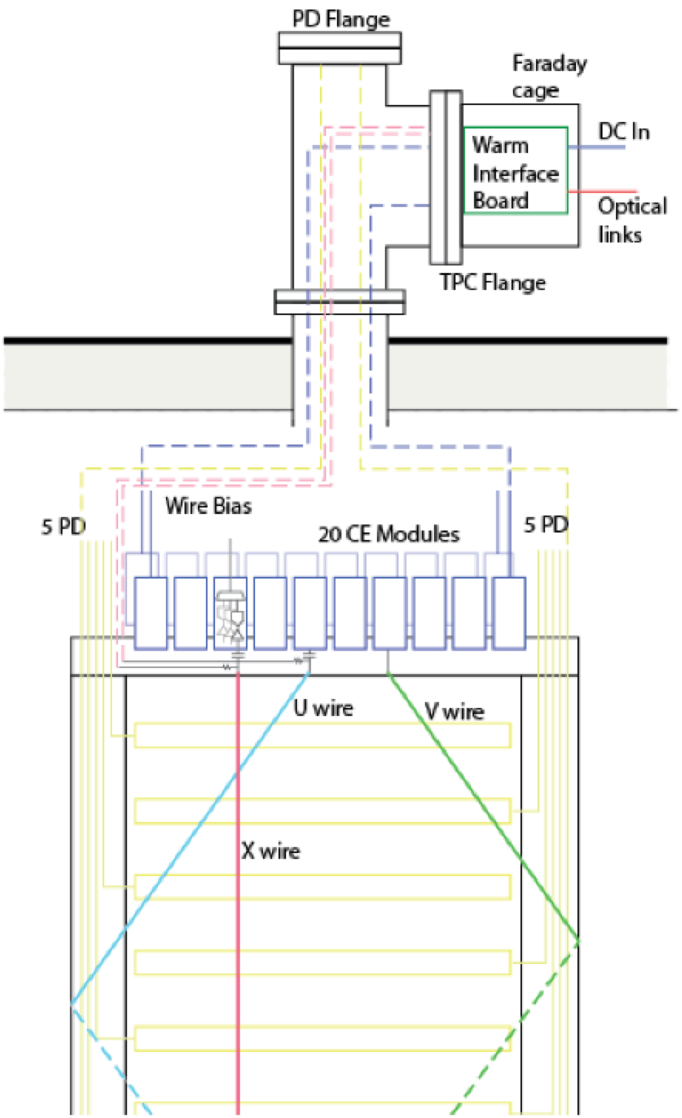
"ARAPUCA" Type Collector ✕ 2





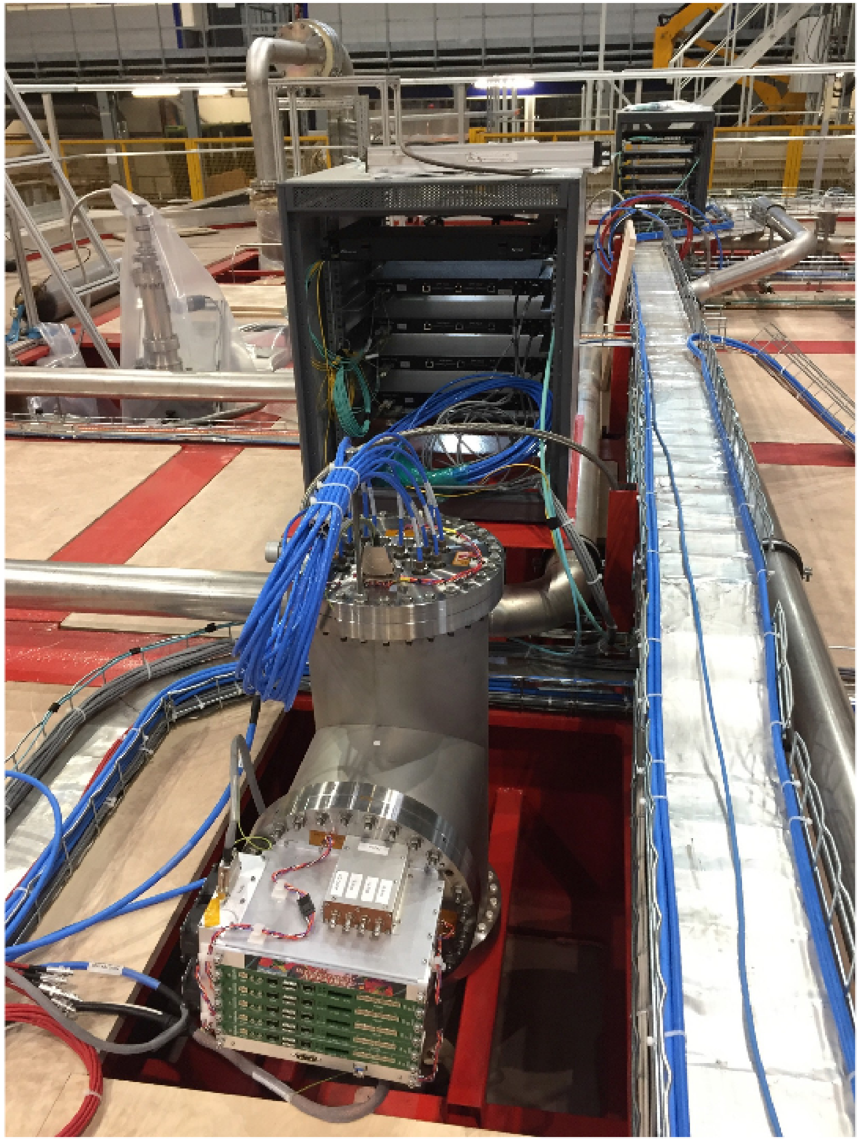
- Three types of photon detection units (60 in total, 10 per APA)
  - Detect prompt (τ = 6 ns) and late (τ = 1500 ns) scintillation light
- Key for proton decay and supernova/solar neutrino physics (trigger)
- Provides timing information (t_o) for non-beam particles
  - Allows one to perform/apply drift-dependent calibrations

Cryogenic TPC Electronics



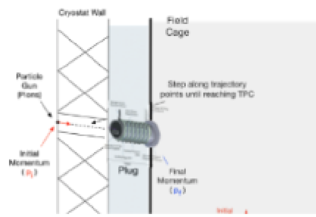
- ♦ Cold electronics (in LAr) directly attached to APA → low noise levels
- ♦ 1 APA → 20 Front-End Mother Boards (FEMBs)
  - 128 channels/FEMB
- ♦ FEMB holds 8 Front-End (FE) ASICs (16 channels/ASIC) and 8 ADC ASICs (16 channels/ASIC)
- ♦ FE ASIC performs two tasks:
  - Pre-amplification of signals
  - Signal shaping (0.5-3 μs)
- ♦ Each FEMB multiplexed to 4 outputs (via FPGAs)

Inside/Outside Cryostat

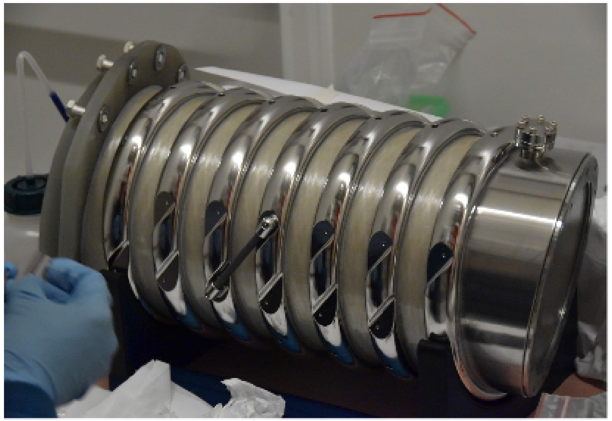


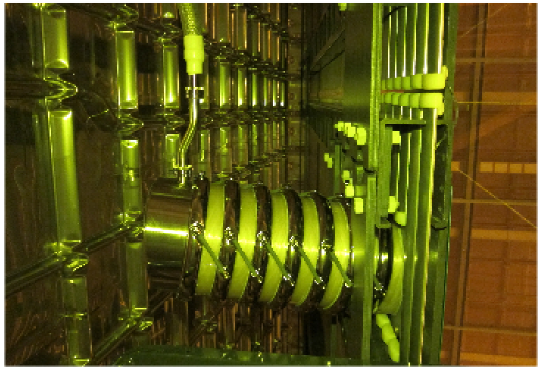
Beam Plug

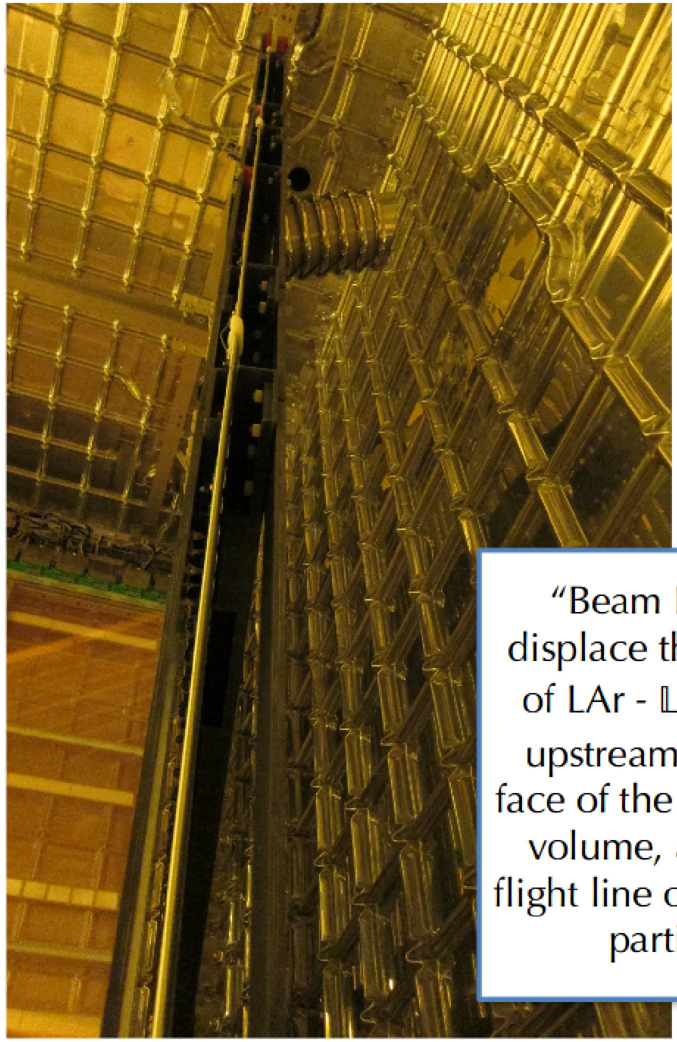
w/ BP



	w/ BP	w/out BP
Material Budget	$0.1X_0$, 0.01 λ	$3.5X_0$, 0.9 λ





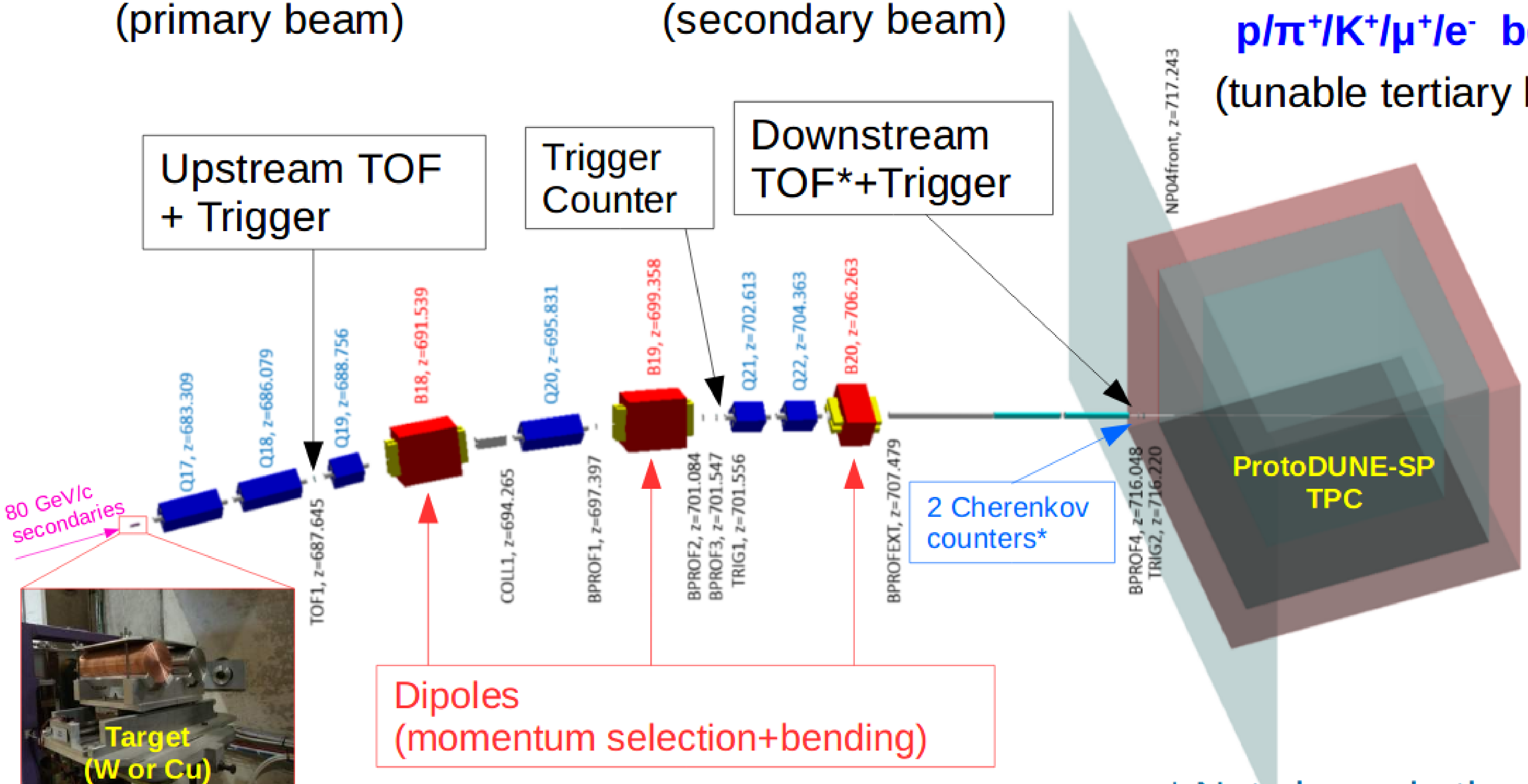


"Beam Plug" to displace the amount of LAr - $\mathbb{L}$~*50 cm* - upstream the front face of the TPC active volume, along the flight line of the beam particles

Beamline Instrumentation

- CERN H4 beamline-extension & Beamline Instrumentation
  - Known particle type (hadrons and electrons) & incident energies

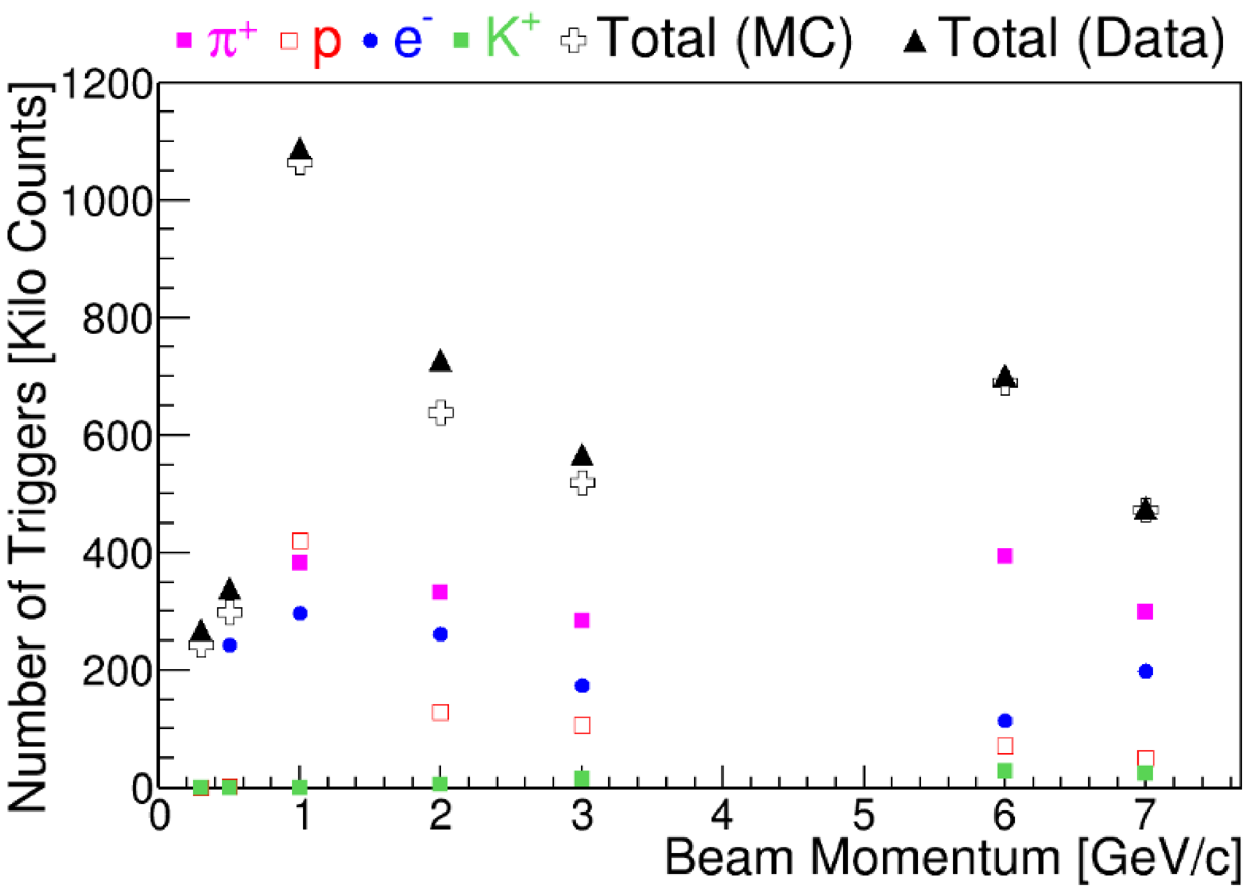
400 GeV/c protons → target → 80 GeV/c beam → target → **0.5 – 7 GeV/c**
(primary beam) (secondary beam) **p/π^+/K^+/μ^+/e^- beam**
(tunable tertiary beam)



* Not shown in the plot

Beam Data Collection

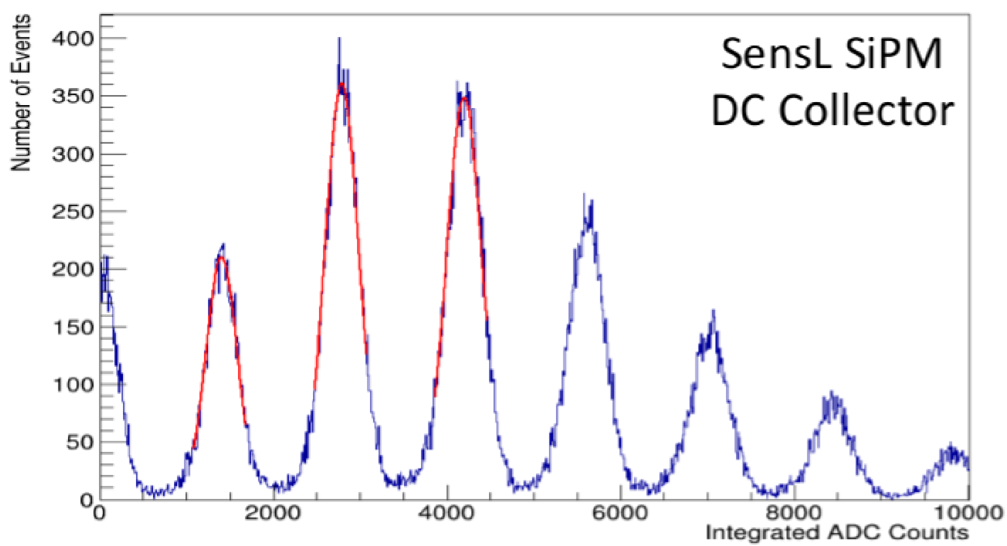
- Beam data taking: from 09/21/2019 to 11/12/2019
- Beam momentum: 0.5-7 GeV/c (**p/π⁺/K⁺/μ⁺/e⁻**)
- Over 4 million beam events (all momenta) collected
- Successful data collection as designed

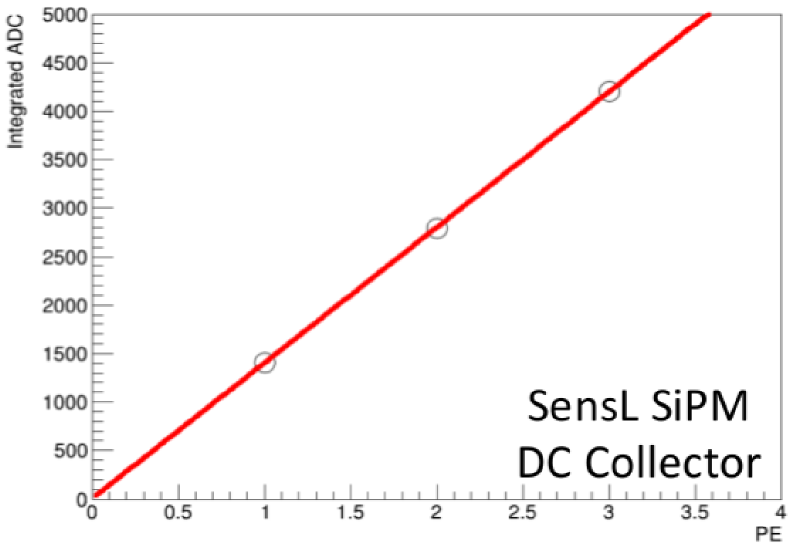


All Beam Momenta

Total (Data): 4173 K
Tota (MC): 3924 K
π^+: 1694 K
p: 779 K
e^-: 1384 K
K^+: 73 K

Photon Detector Results

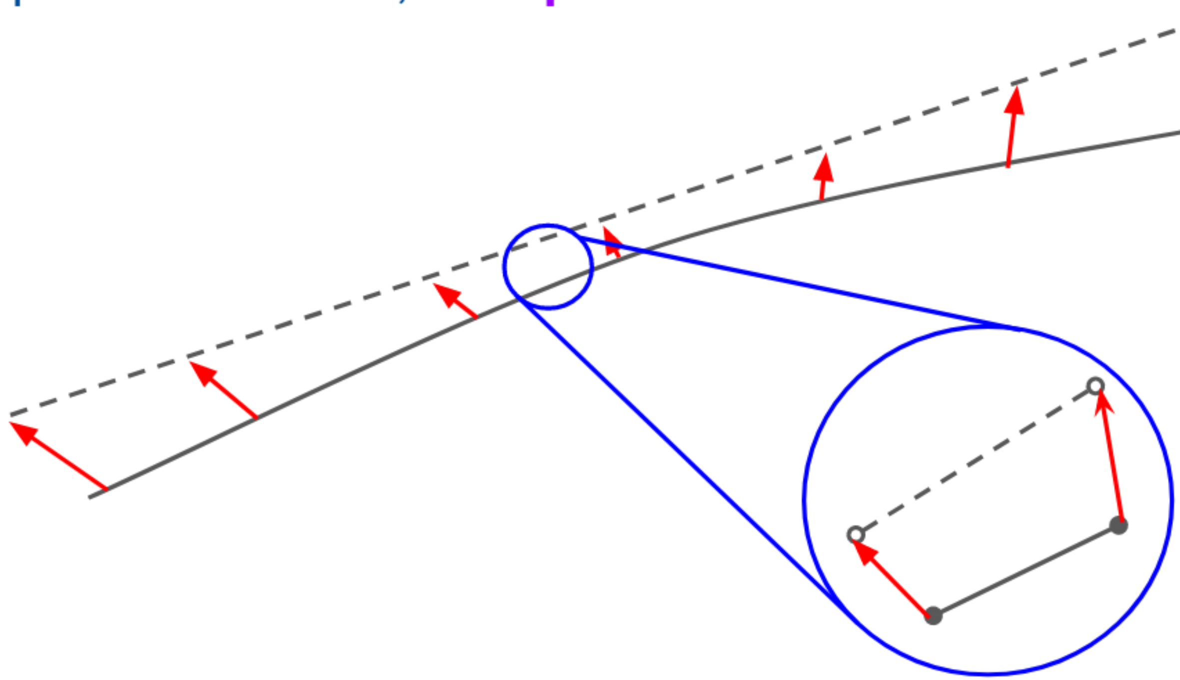




- Have begun characterizing gain and relative timing of PD units
  - Plots above: characterizing gain of dip-coated light bars
- Studies underway on performing energy reconstruction using light signals
  - 60% of energy converted to light at 500 V/cm → use to help energy measurement obtained nominally using ionization signals

SCE Calibration

- Calorimetry information (*dQ/dx* or *dE/dx*) is affected by both spatial and electric field distortions (latter: through electron-ion recombination)
- From spatial distortions, both **position** and **dx vector** must be corrected



Will include SCE corrections in next round of data processing!

SCE Calibration (cont.)

- Calorimetry information (*dQ/dx* or *dE/dx*) is affected by both spatial and electric field distortions (latter: through electron-ion recombination)
- From spatial distortions, both **position** and **dx vector** must be corrected
- Corrected **electric field** used to calculate *dE/dx*

$$\frac{dE}{dx} = f\left(\frac{dQ}{dx}, |\vec{E}|\right)$$

Previous spatial correction

Electric field correction

Will include SCE corrections in next round of data processing!