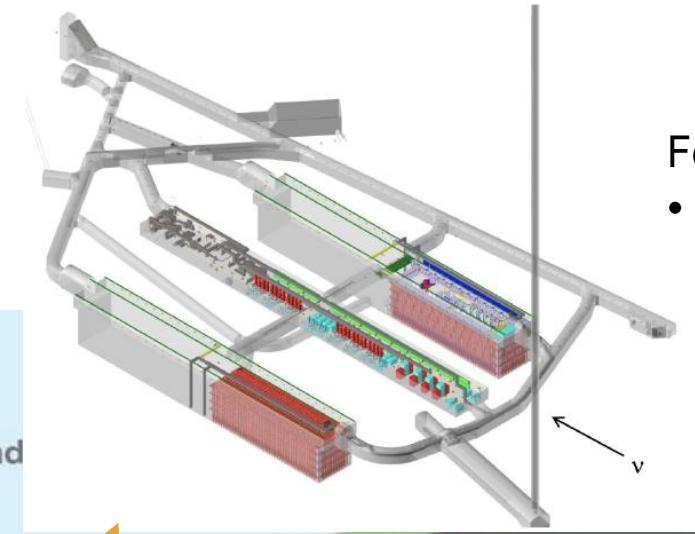
Pandora in LAr TPC reconstruction for DUNE

IP2I

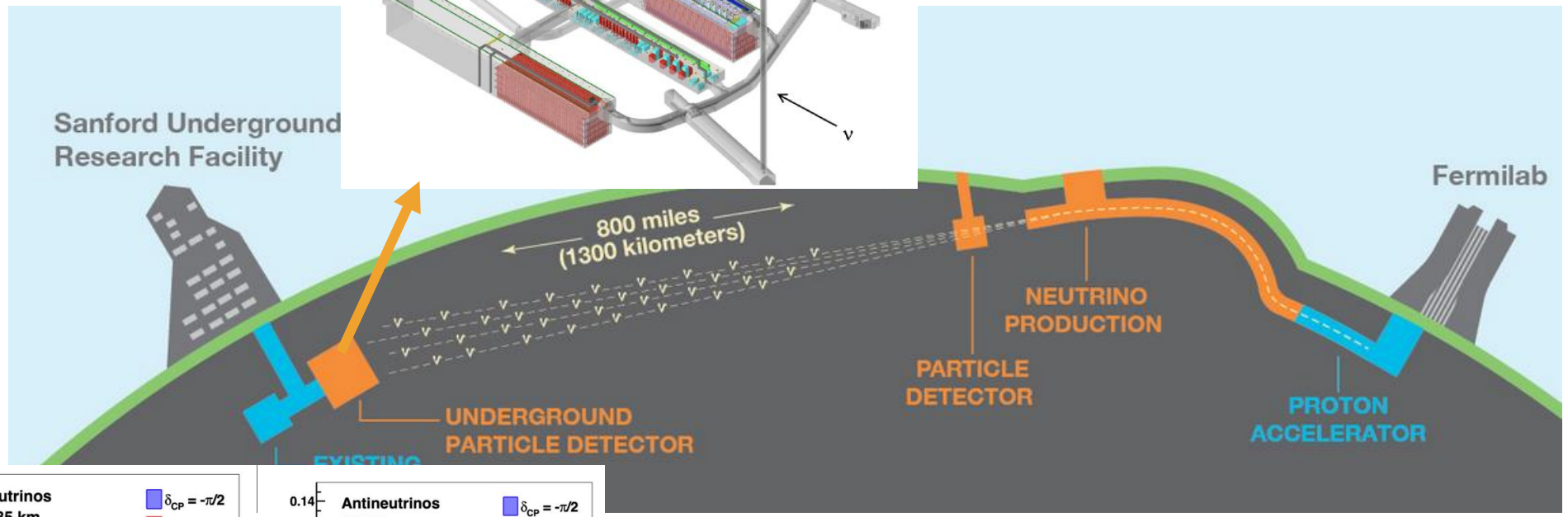
18 Oct 2023

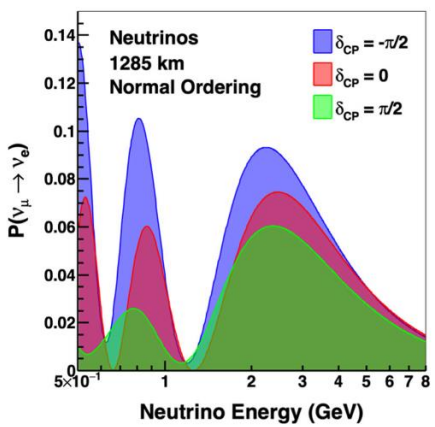
DUNE

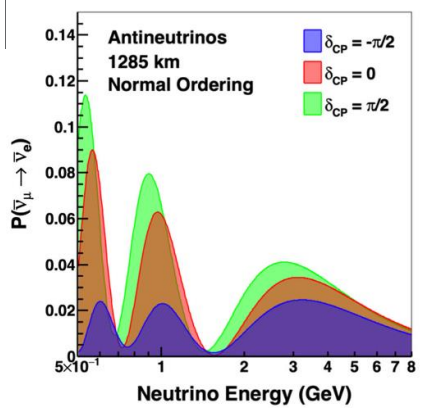


For detector modules ~1.5 km underground:

- LAr TPC modules : 17 kton of LAr each

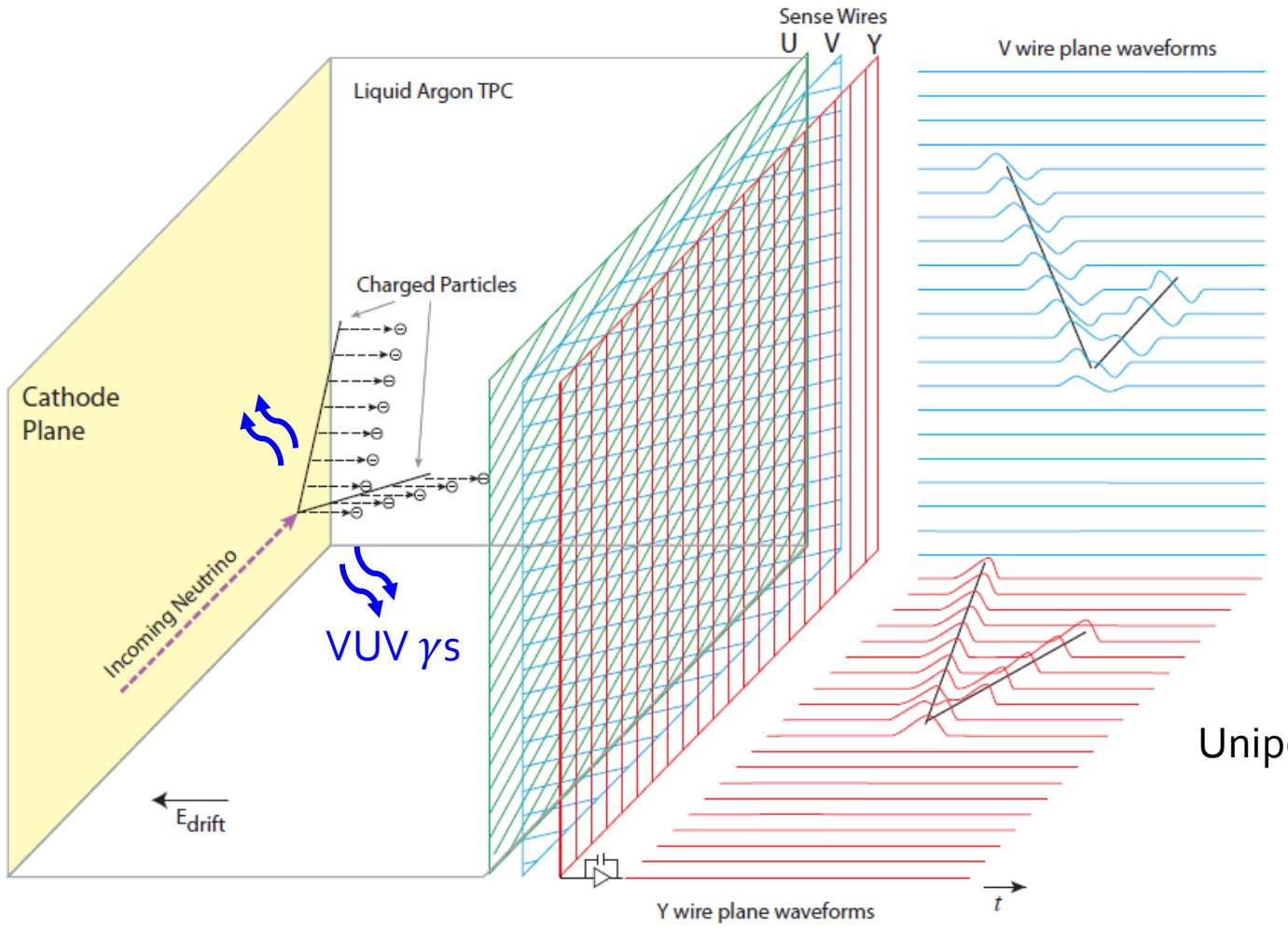






- One of the key goals is precise measurement of $\nu_\mu \to \nu_e$ oscillations (ν_e appearance probability) to determine unknown leptonic CPV phase δ_{CP}
  - CPV is required to produce the baryon asymmetry of universe

(LAr)TPC readout cartoon



Bipolar signals on induction wires

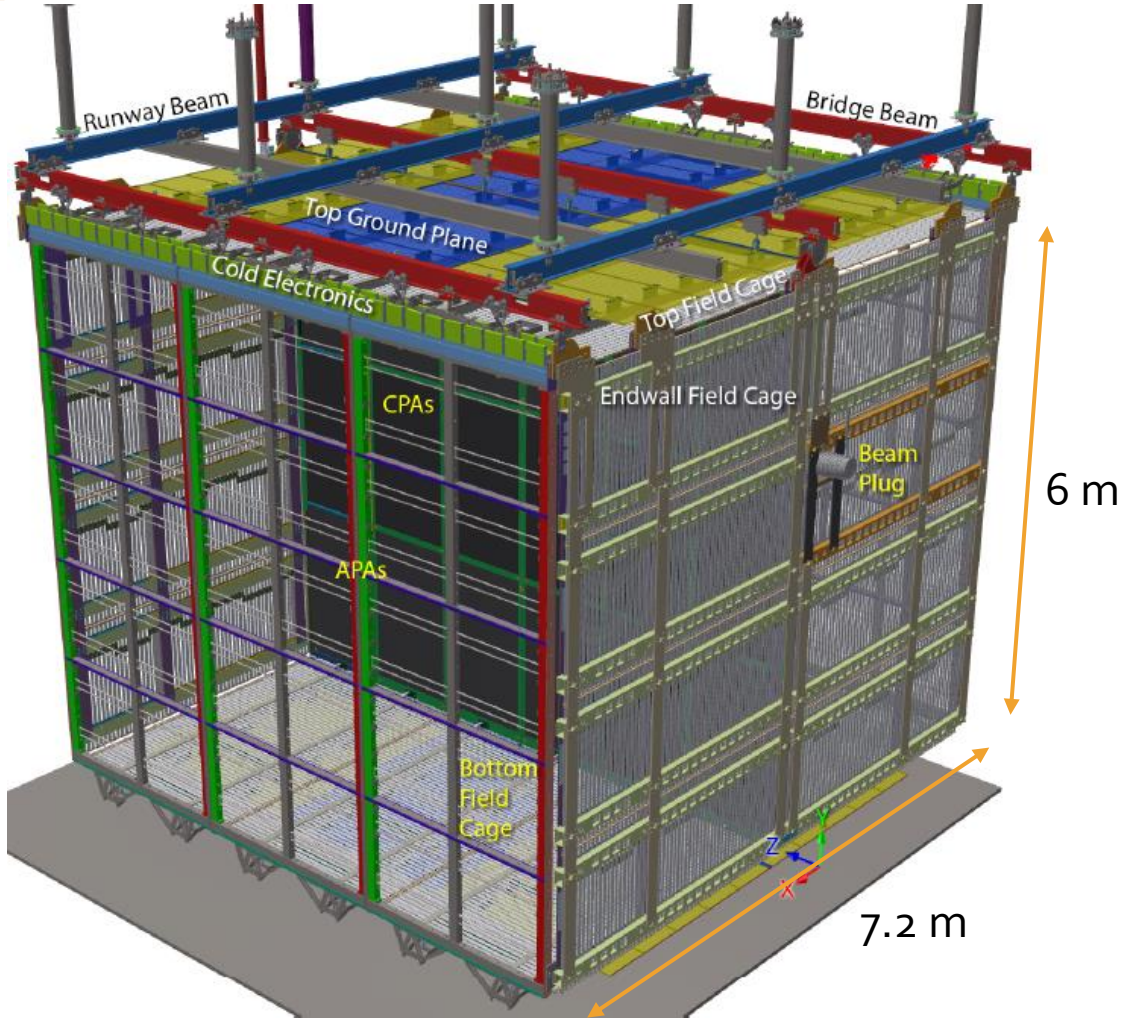
Unipolar signals on collection wires

+ photon system to detect prompt scintillation

Case study: ProtoDUNE SP

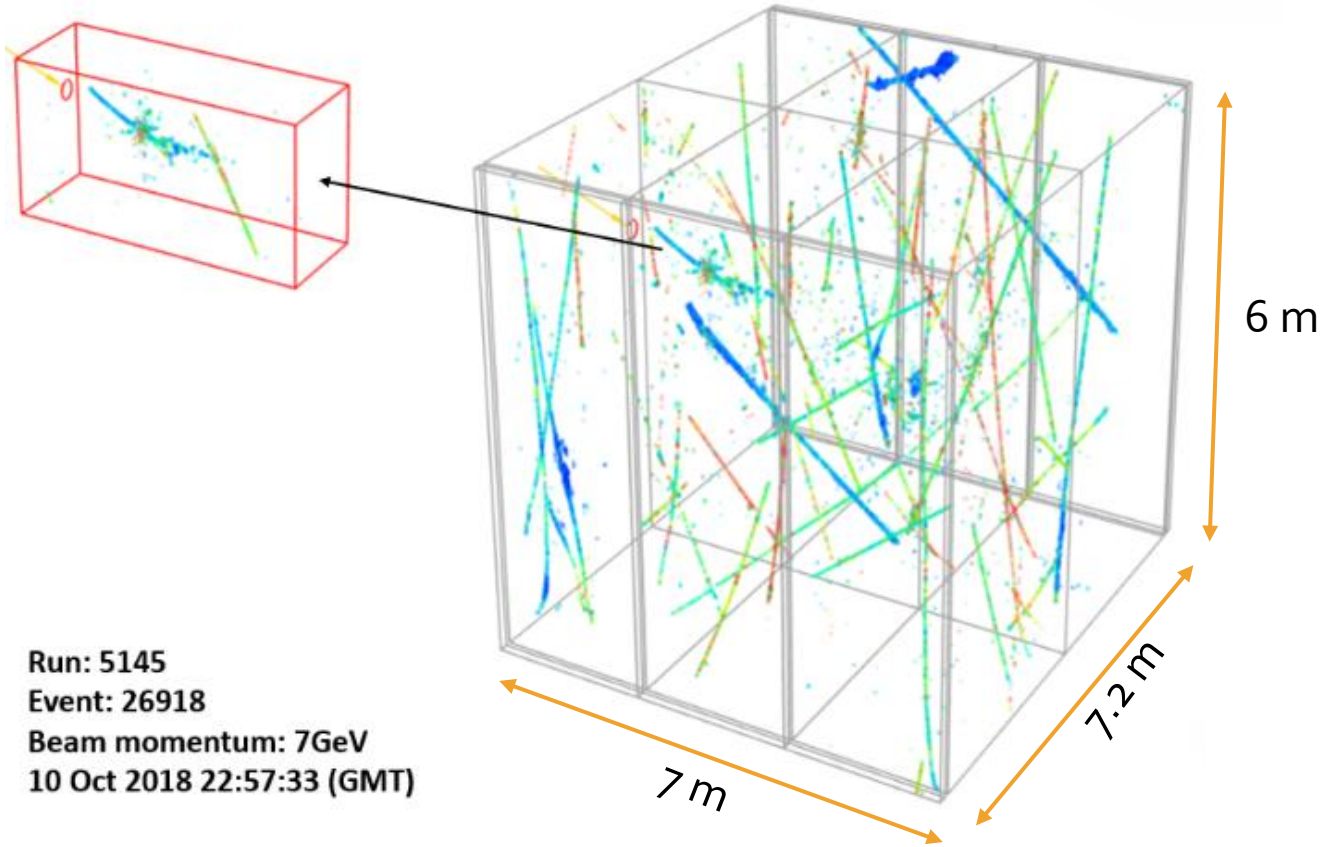
ProtoDUNE-SP

- One of two DUNE FD prototypes (ProtoDUNE-DP only took cosmics)
- 420 ton LAr TPC active volume
- Two drift volumes 3.6 m long each
- Exposed to charged beam (π, K, p, e) 0.3 – 7 GeV/c at CERN



Reconstruction on surface

- LAr TPC is a "slow" detector
  - Takes a couple of ms to drift charge from cathode to anode: vdrift ~ 1.6 m / ms (@500 V/cm)
- On-surface substantial activity due to cosmic rays
- Large sample of "free" cosmics:
  - Good for detector characterization
  - But an additional complication for reconstruction



Environment / Tools

- ART [J.Phys.Conf.Ser. 396 (2012) 022020] is an event-processing framework built and maintained at FNAL
  - Used as a basis by Fermilab experiments (e.g., NOvA, Mu2e, LAr TPC experiments)

- Particular adaptation for LAr TPC (ArgoNeuT, LArIAT, MicroBooNE, SBND, ICARUS, DUNE) experiments is LArSoft framework/toolkit
  - Interface to Pandora Software Development Kit [Eur. Phys. J., C75(9):439, 2015] used for reconstruction and pattern recognition
  - Pandora SDK development started for ILC and then undergoing extensive development in the context of LAr TPC experiments

LAr TPC event processing

Raw ADC channel data

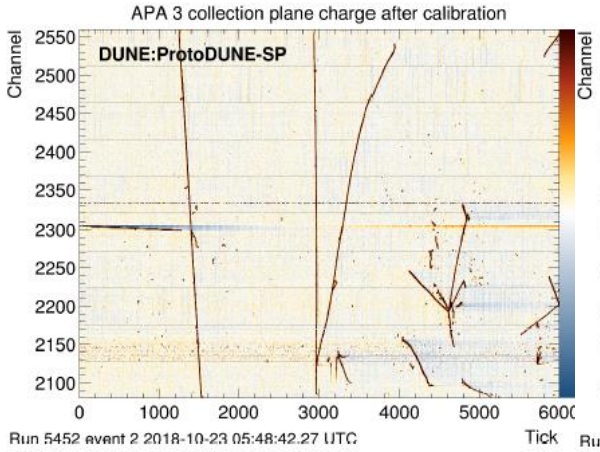
Signal (pre)processing:

- Electronics response calibration
- Coherent noise filtering
- Field response deconvolution
- Regions of interest selection

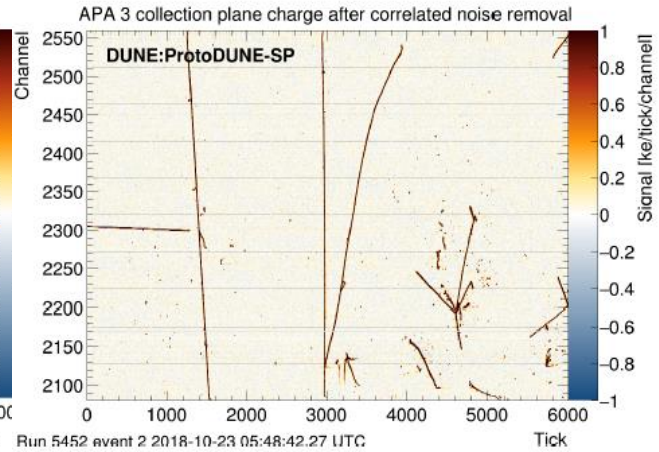
Charge "seen" (induction) or deposited (collection) on each wire / strip

Noise filtering

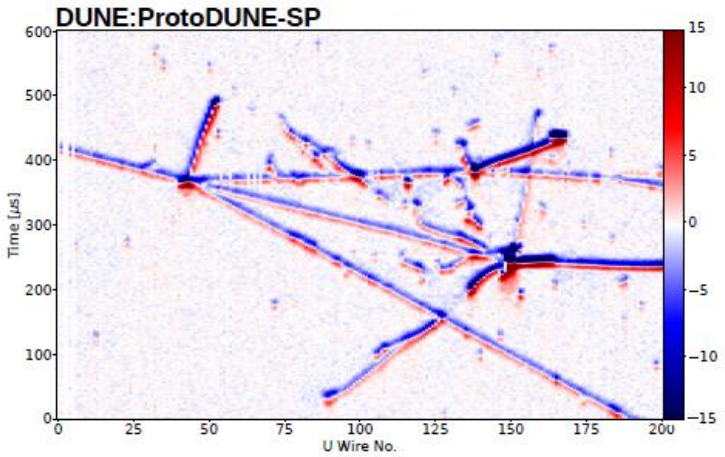
Raw ADC channel data



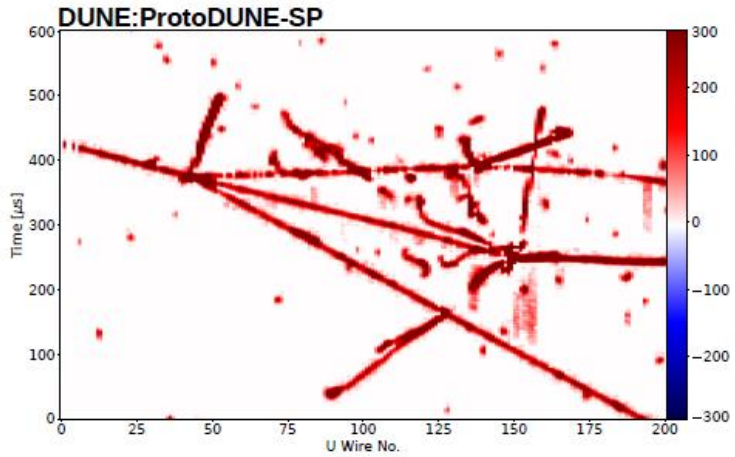
Filtered ADC channel data



Field response deconvolution



(a) After Noise Filtering



(b) After Deconvolution

LAr TPC event processing

Raw ADC channel data

Signal processing:
- Coherent noise filtering
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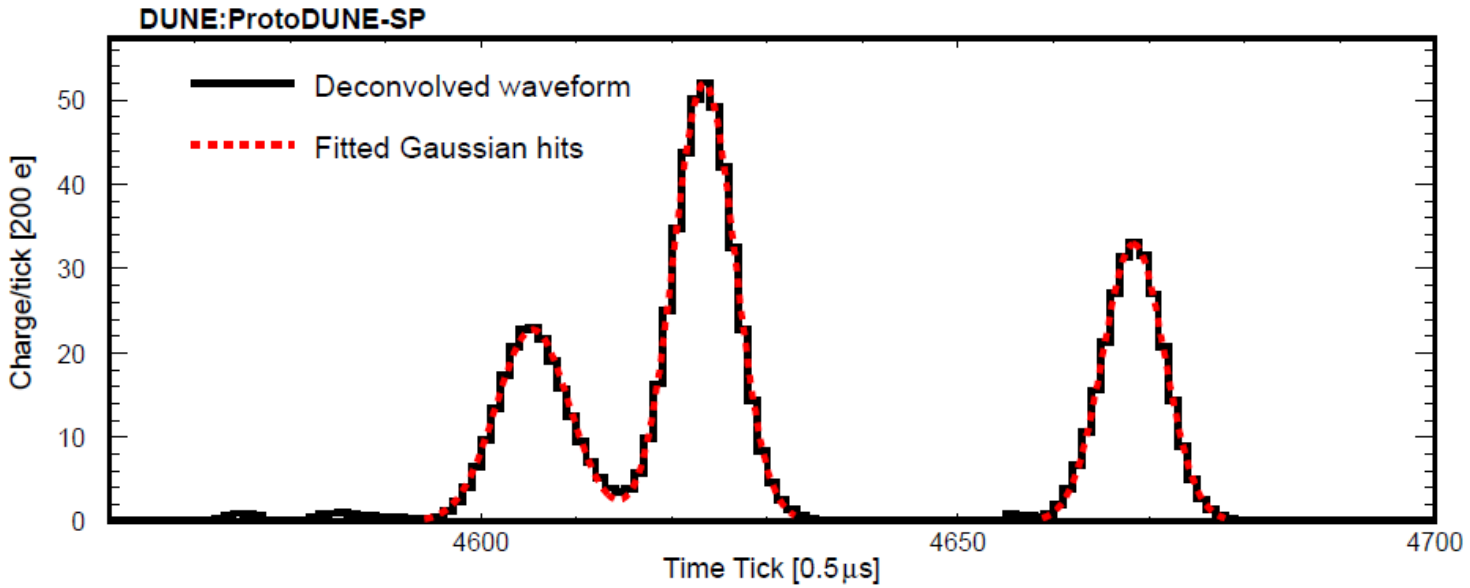
- Field response deconvolution
- Regions of interest selection

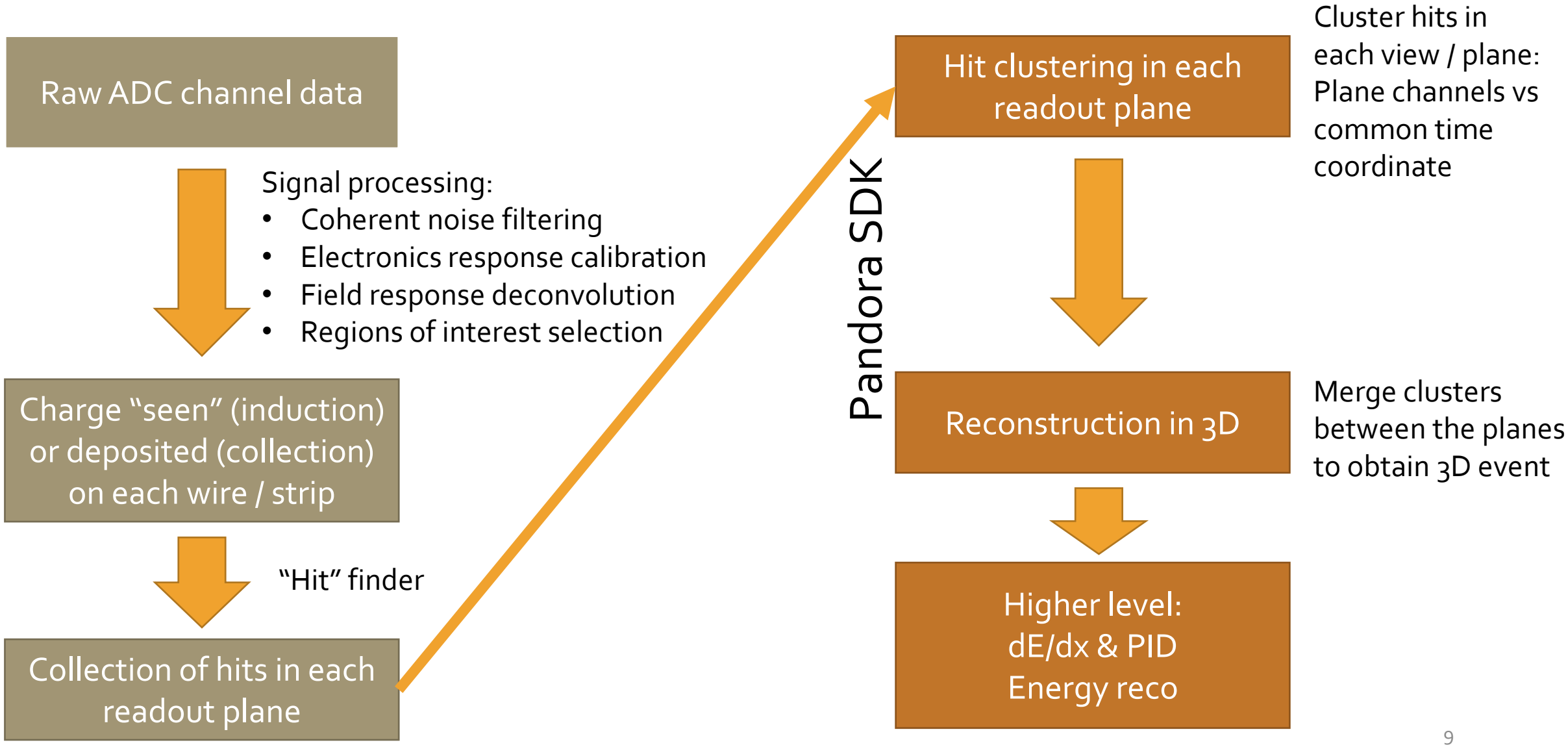
Charge "seen" (induction) or deposited (collection) on each wire / strip

"Hit" finder

Collection of hits in each readout plane



LAr TPC event processing (LArSoft)



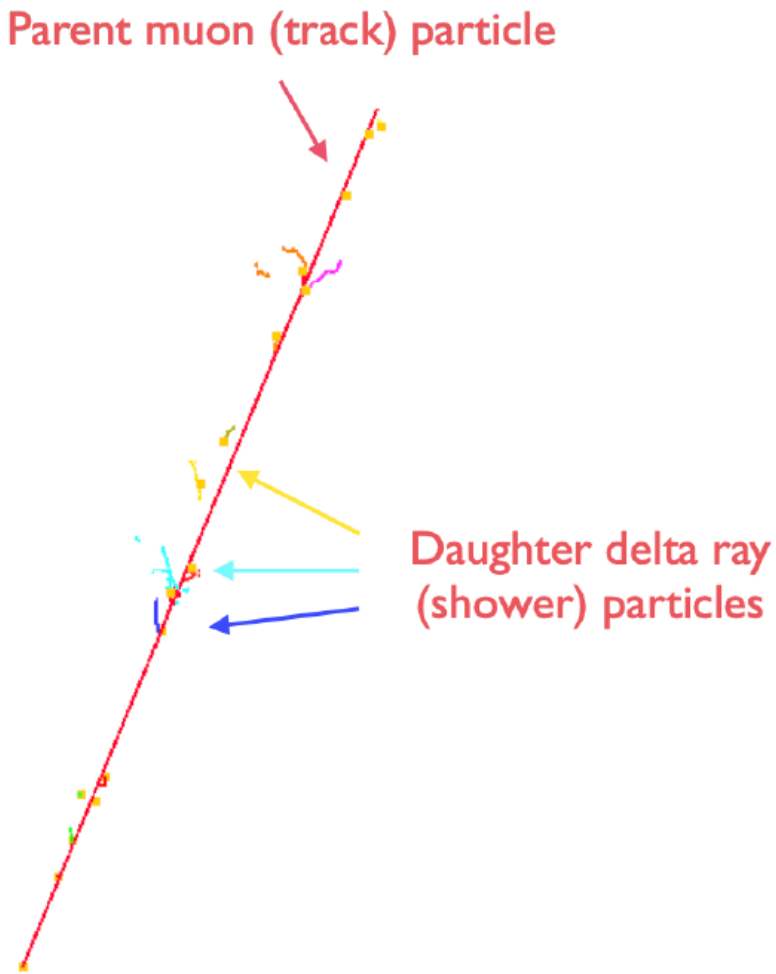
Pandora reconstruction workflow

- Over a hundred of algorithms are used to gradually build up and improve reconstruction of event features

- Two principal chains have been developed for and deployed in MicroBooNE/ProtoDUNE
  - **PandoraCosmics** : an algorithm chain targeting the reconstruction of cosmic ray muon tracks
  - **PandoraNu / PandoraTestBeam** : an algorithm chain that is built around identifying interaction vertex and then reconstructing individual tracks / showers left by emerging particles

PandoraCosmics

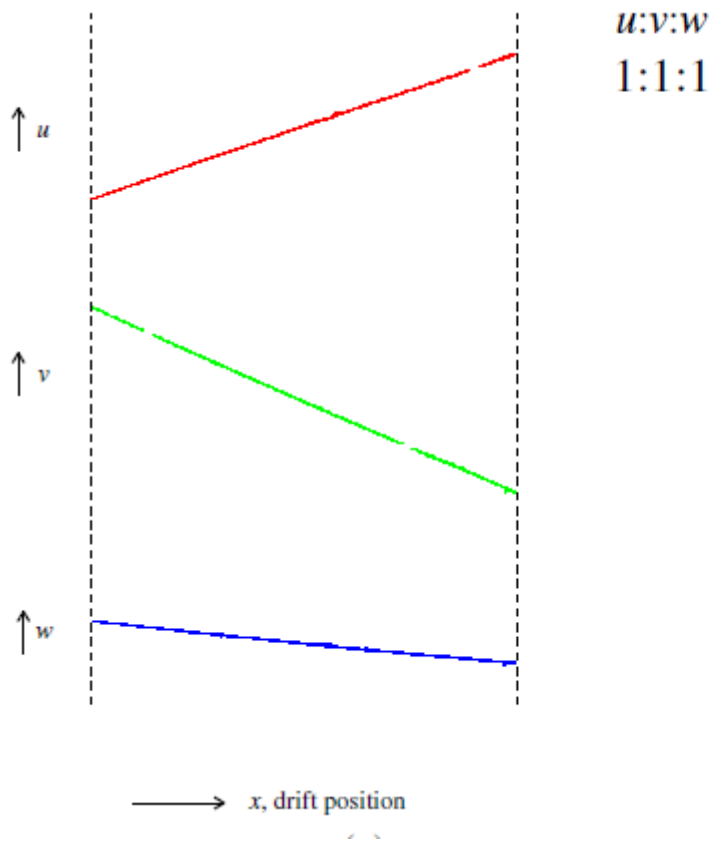
- Track-oriented clustering
- Muons are assumed downward going: the vertices are at highest *y* (up)
- Showers are delta rays / decay electron and added as daughters to primary muon
- Flow:
  - 2D reconstruction
  - 3D track reconstruction
  - Delta-ray reconstruction

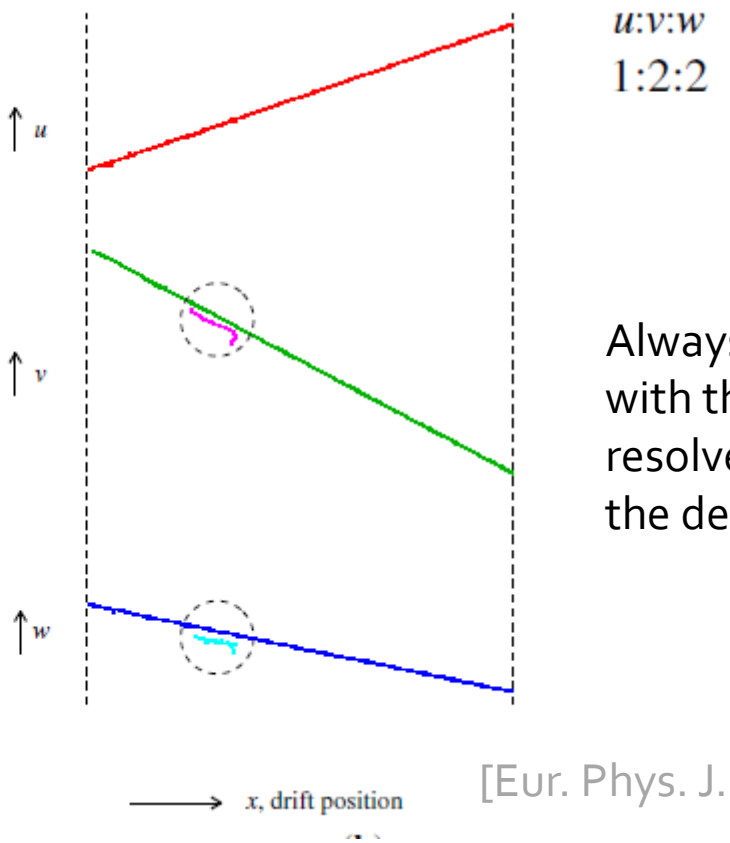


Matching 2D projections

- Rely on common time coordinate and readout plane geometry to merge 2D clusters

Require >90% overlap for all clusters



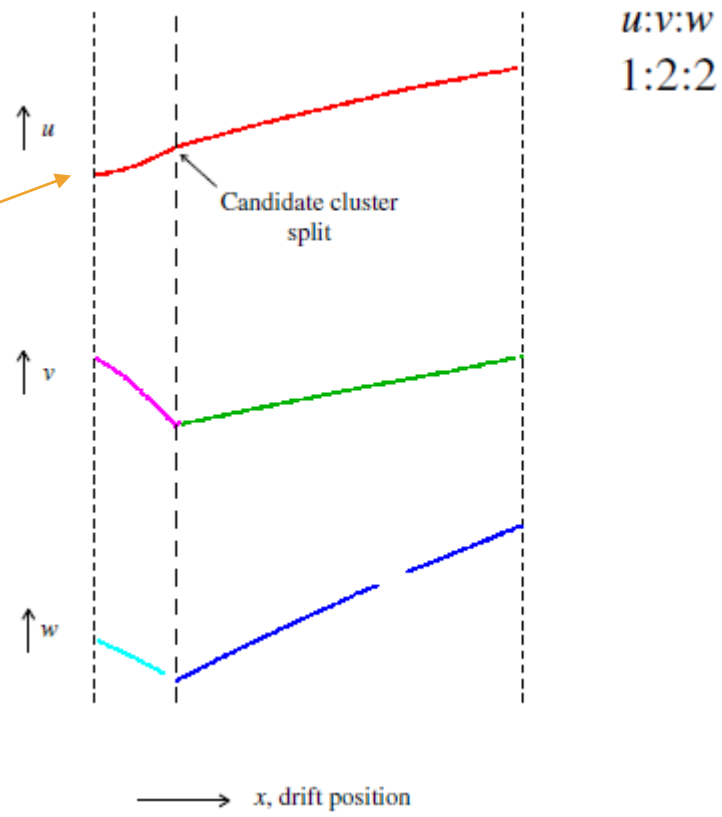


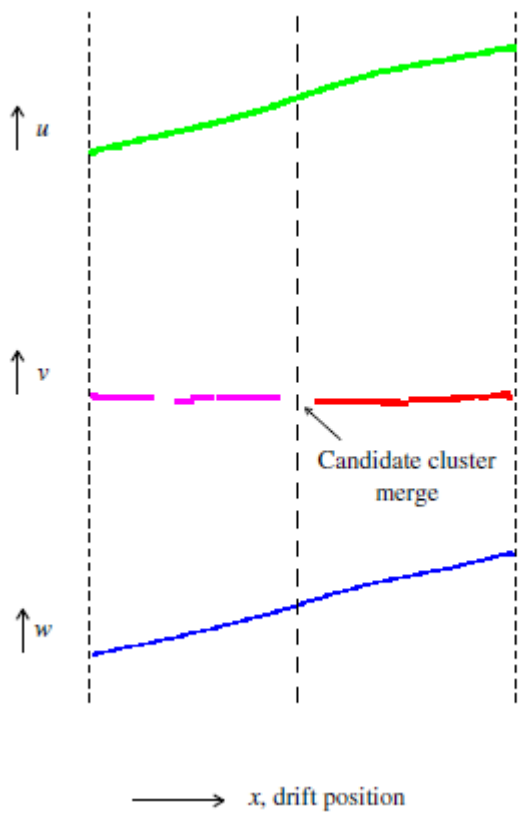
Always select the clusters with the best match to resolve ambiguities with the delta rays

[Eur. Phys. J. C (2018) 78:82]

Matching 2D projections

Split clusters that are appear to "overshoot" in one of the views



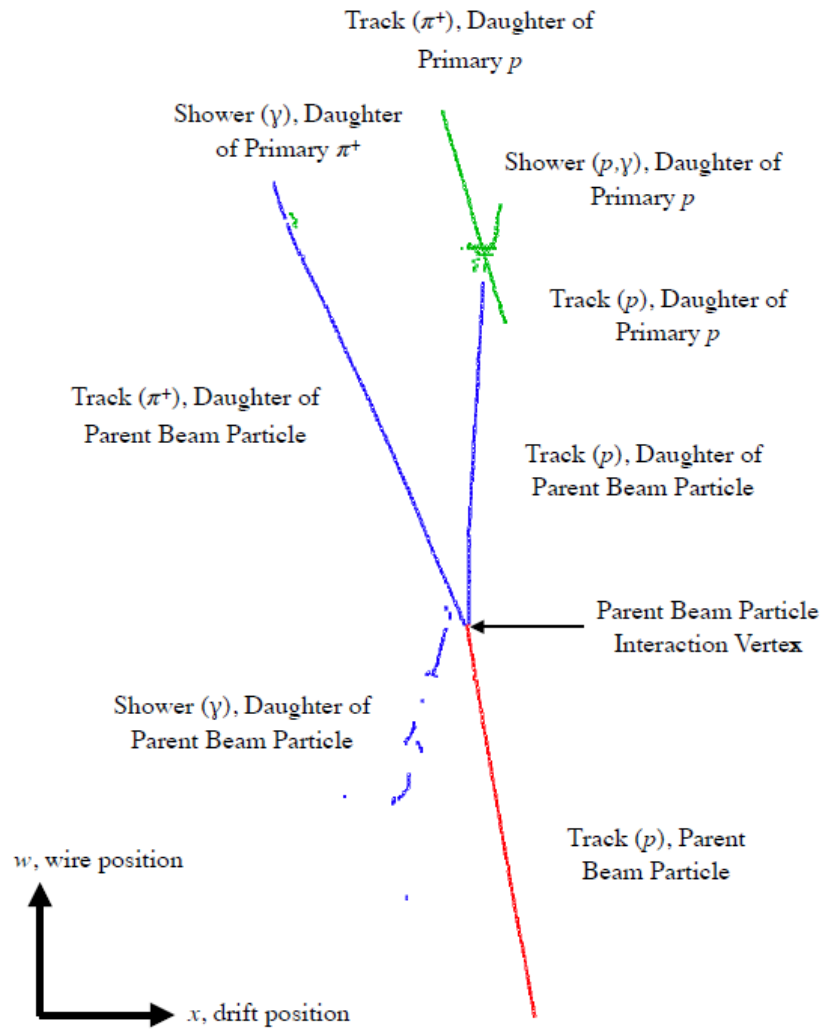


Undershoot tracks: merge broken v clusters if can be matched to other two planes

PandoraNu/PandoraTestBeam

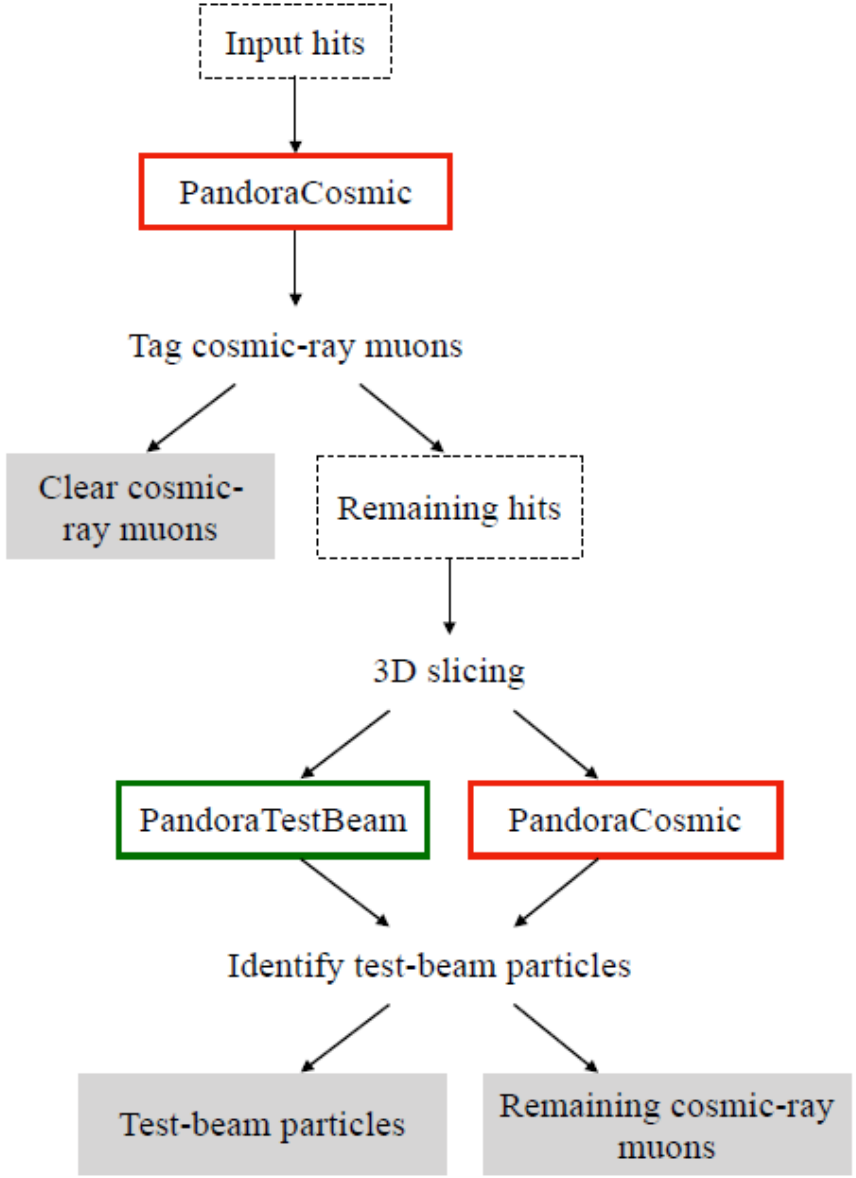
- Flow
  - 2D reconstruction
  - 3D vertex reconstruction
  - Track and shower reconstruction
  - Particle hierarchy reconstruction

- For test beam:
  - Revisit particles emerging from the vertex and find the one most consistent with the incoming test beam particle



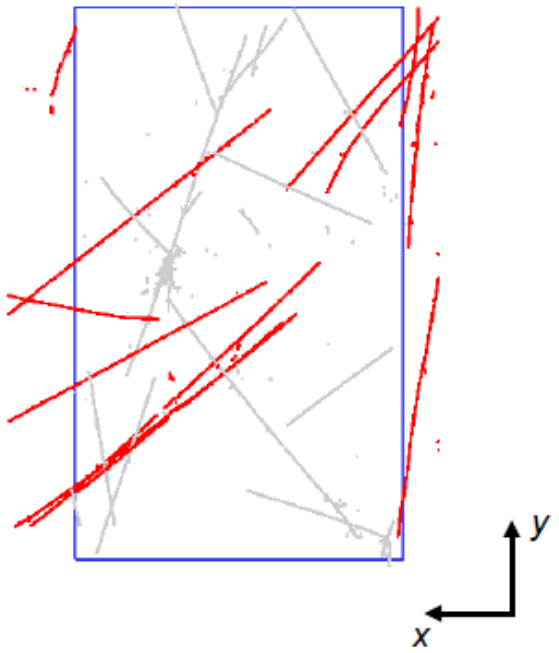
Consolidated reconstruction for test beam events in ProtoDUNE

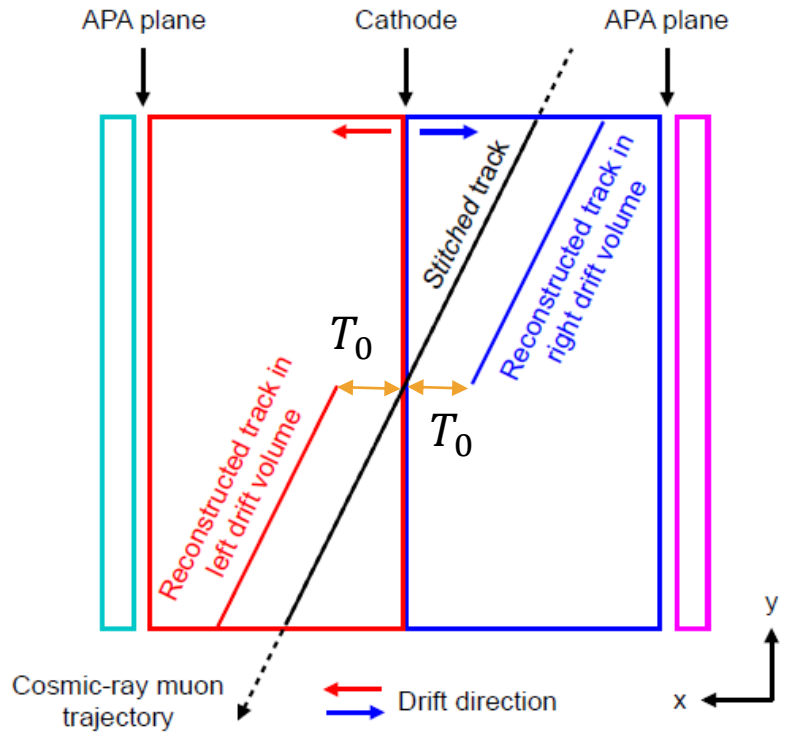
- Both Cosmics and TestBeam chains combined in order to reconstruct on-surface events
- Run cosmic reconstruction on all particles as a first step
- Tag clear cosmic ray rays
- Make 3D slices and run TestBeam and Cosmic chains on each slice



Cosmic ray tagging

Tagged CR



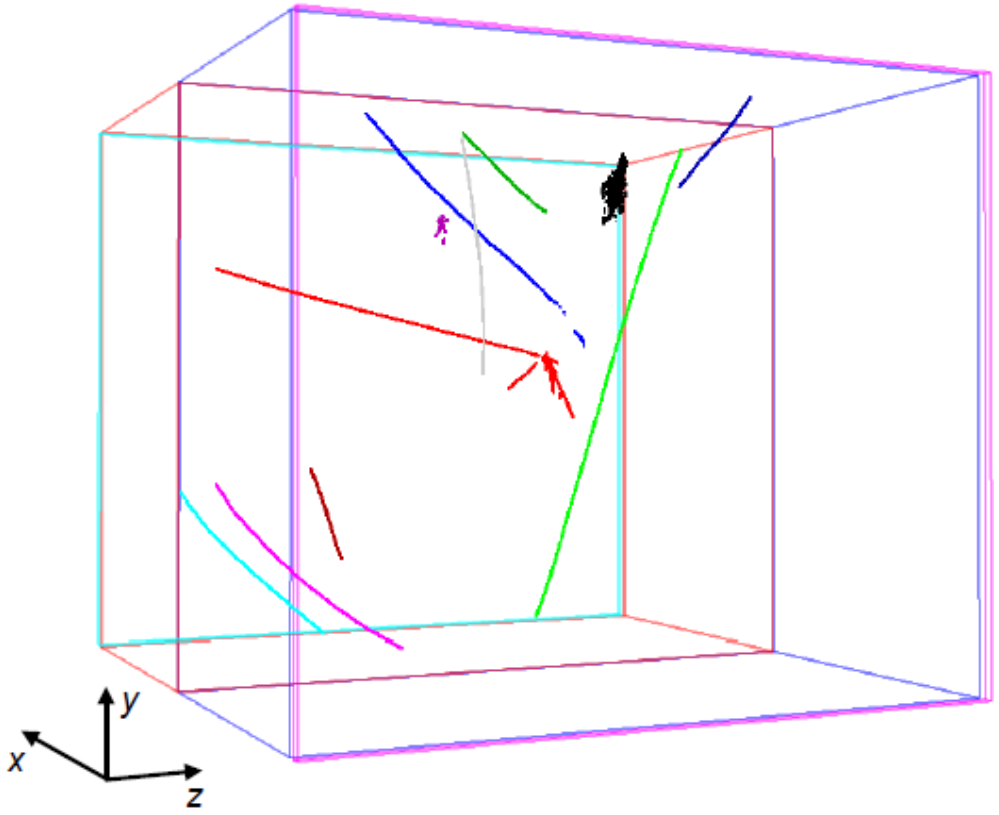


- Clear cases when cosmics out of beam time enter / exit TPC volume
- Cosmics crossing the cathode plane are "stitched" to find their arrival time wrt beam time

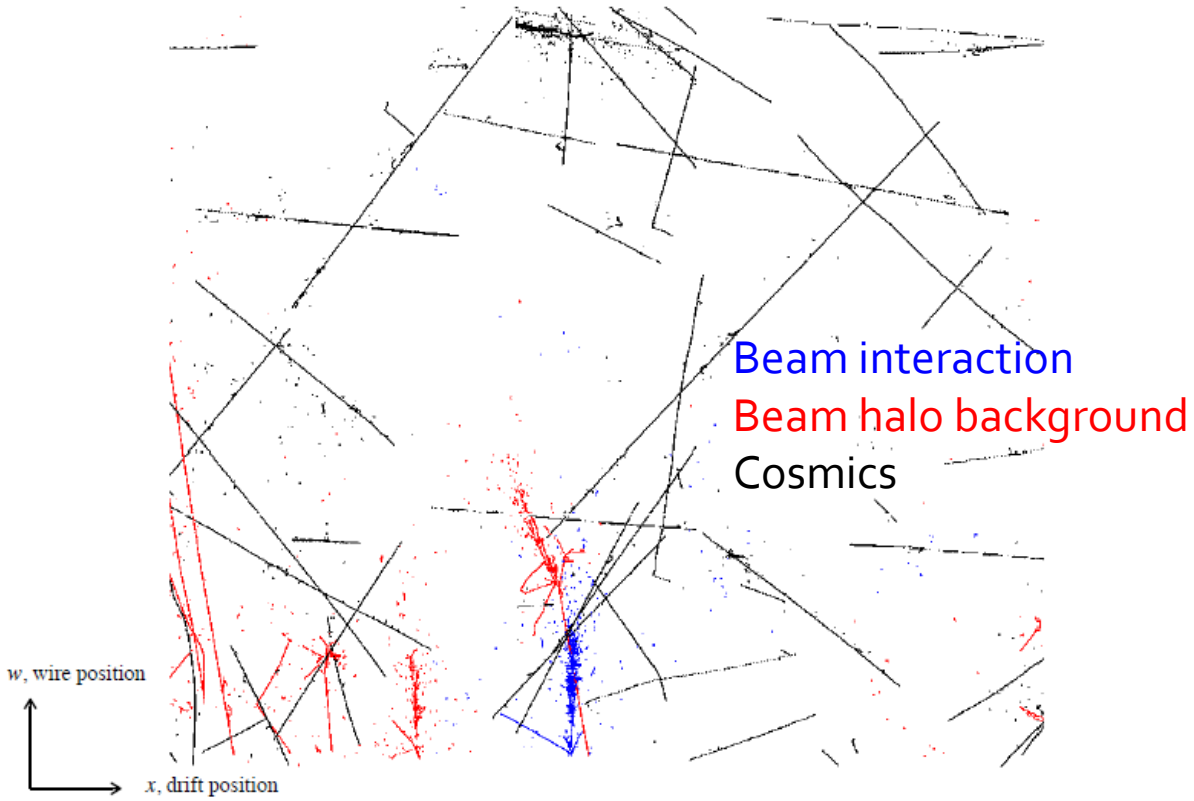
Event slicing

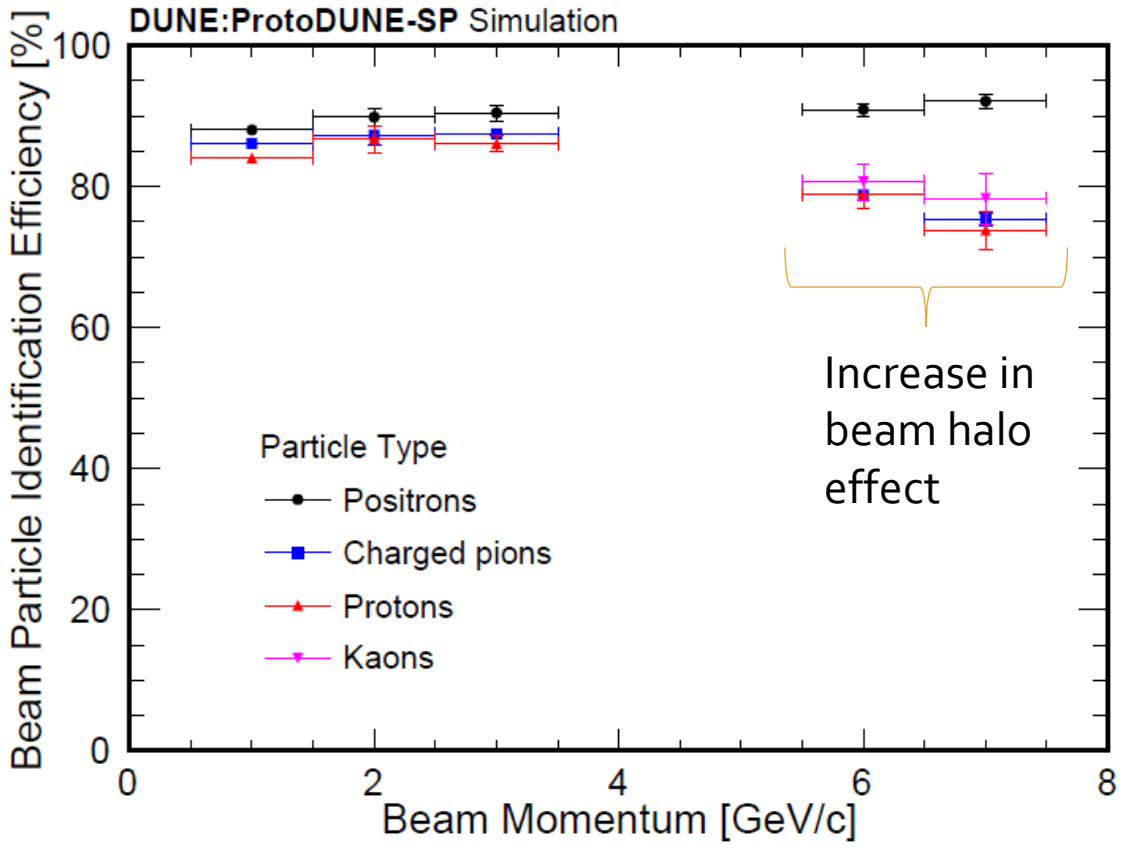
- Separate / slice hits from different interactions
- Run TestBeam / Cosmics reconstruction on each slice and select the "best" beam event
- Boosted Decision Tree (BDT) built around the test beam entrance is known and cosmics typically have track-like topologies compared to complex ones from test-beam particles

Different colors mark different slices
A 3 GeV/c π^+ beam event is in bright red



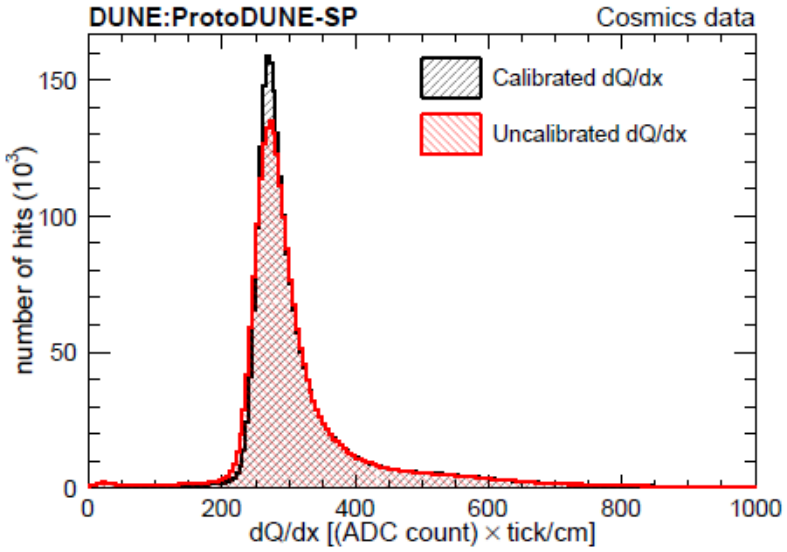
Beam particle identification efficiency



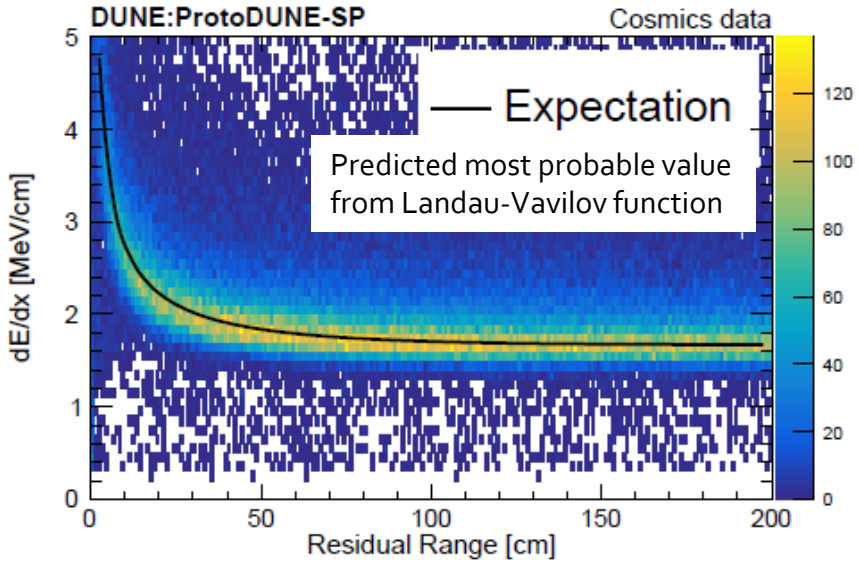


Measured dE/dx for cosmic-ray muons

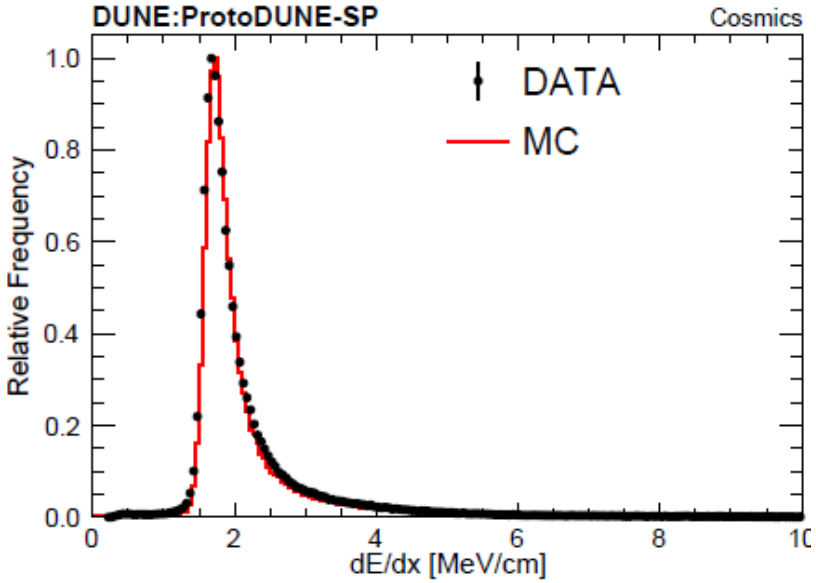
[JINST 15 P12004, 2020]



Stopping muons dE/dx distribution



dE/dx Data / MC comparison



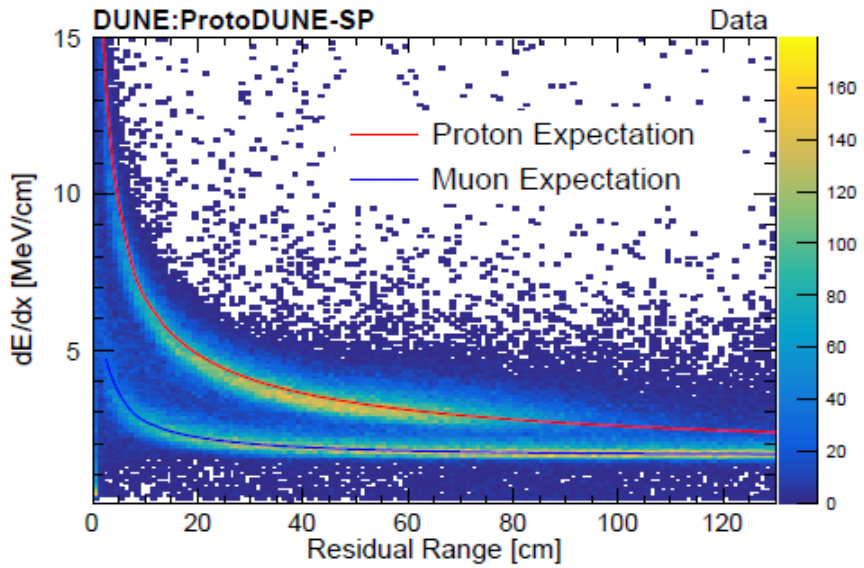
Reconstructed dQ/dx → measured dE/dx

- Measured correction for attachment to electronegative impurities
- Measured uniformity of readout plane response
- Absolute energy scale determined by fitting a sample of stopping muons

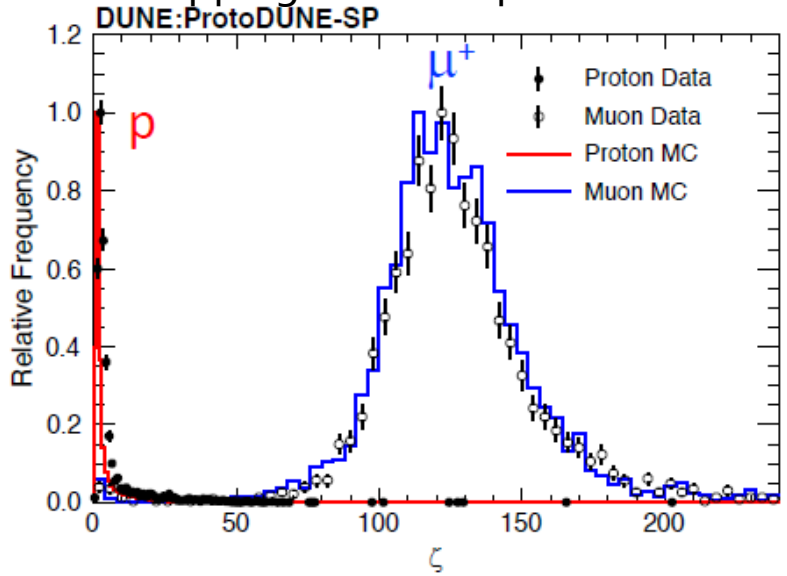
Obtained from cosmics data

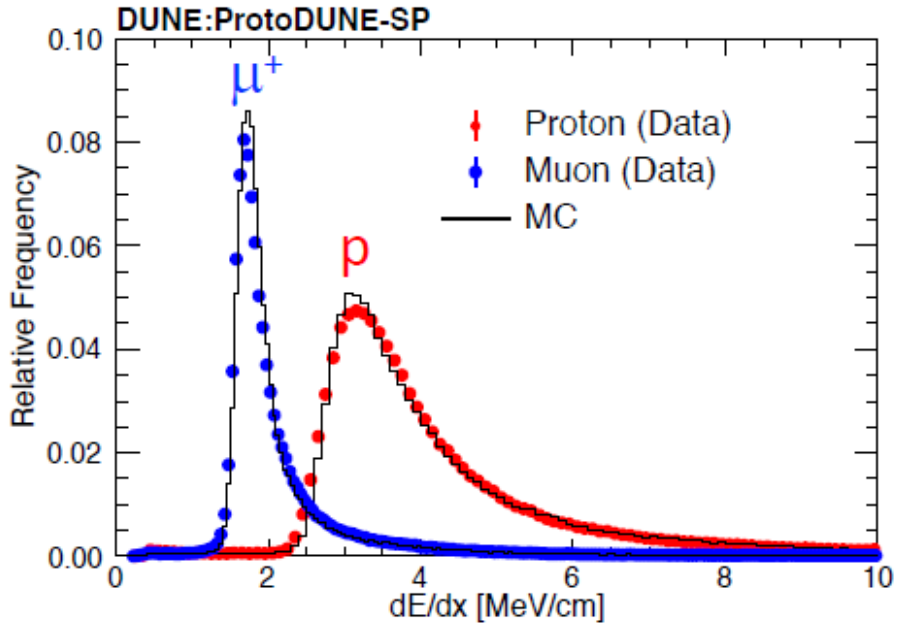
- Charge recombination effects in LAr taking into account local electric field strength

Beam particles



Stopping muons & protons PID



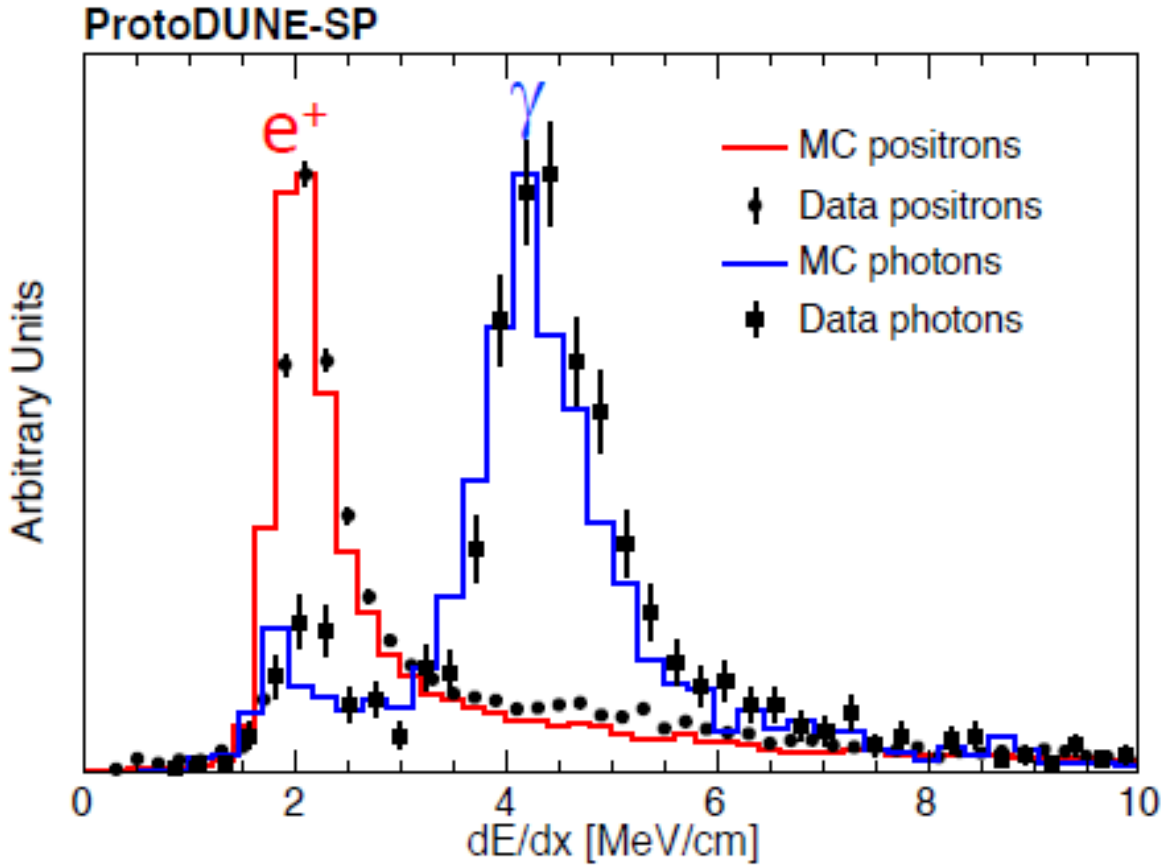


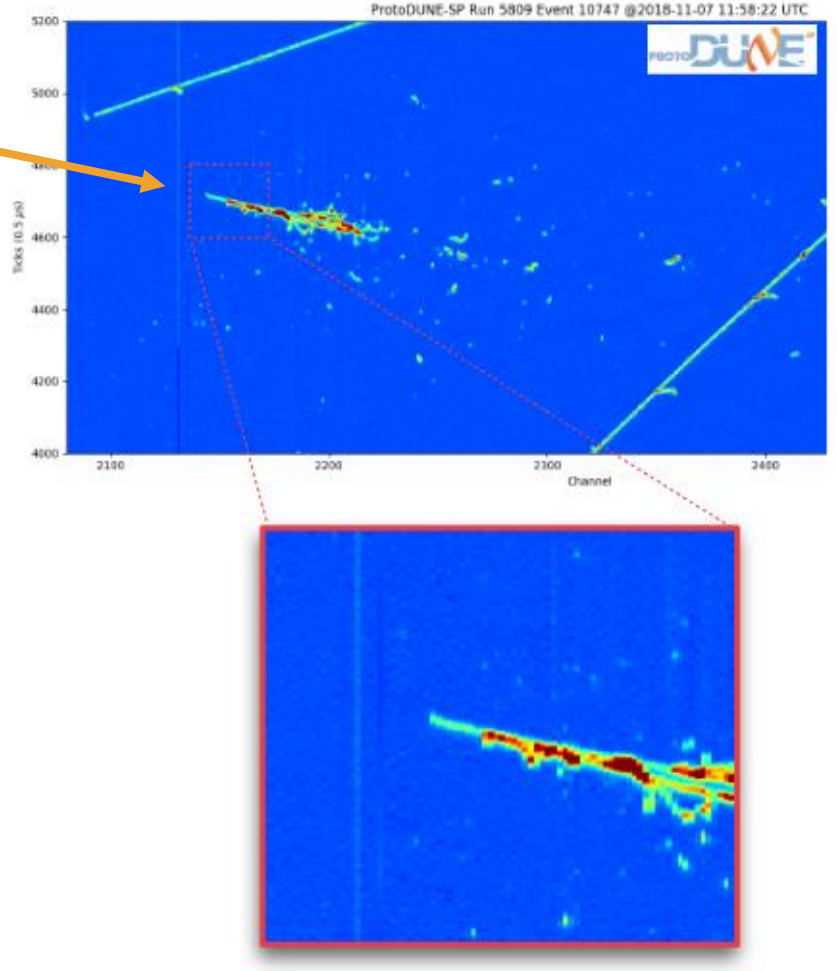
With calibrations derived from cosmic ray analyses are applied to beam particles

Electron / gamma separation

Photon production in neutrino interactions is a nuisance for ν_eCC event id: golden signal for DUNE to measure CPV

e/γ separation based on dE/dx in the pre-shower region





Conclusions

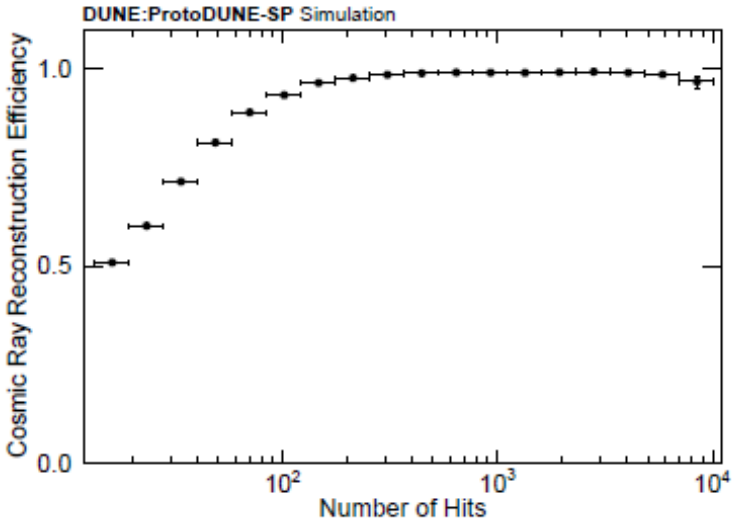
- Remarkable progress in automated reconstruction of events in LAr TPC have been made in the last decade

- For on-surface detectors the reconstruction tools handle complicated events containing beam interactions in large sea of cosmic ray background

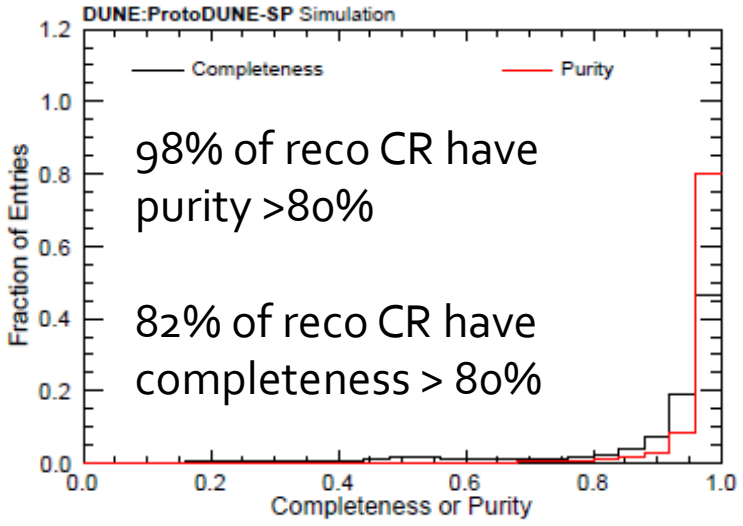
Extra

Pandora cosmic-ray track reconstruction

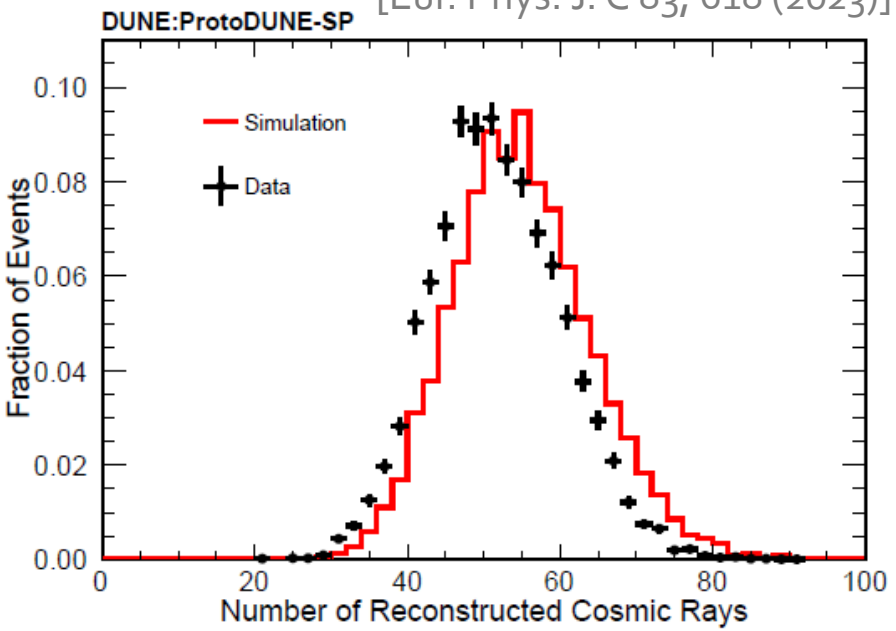
Efficiency as a function of Nhits



Purity & completeness



[Eur. Phys. J. C 83, 618 (2023)]



Efficiency: fraction of MC particles that are matched to at least one reconstructed particle
Purity: fraction of hits in reconstructed particle that are shared with an MC particle
Completeness: fraction of hits in the MC particle that are shared with a reconstructed particle

Data/MC: ~5% fewer CRs reconstructed than in simulation possibly due to slight overestimation of the cosmic ray flux in MC