Reconstruction in LAr TPCs

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Overview

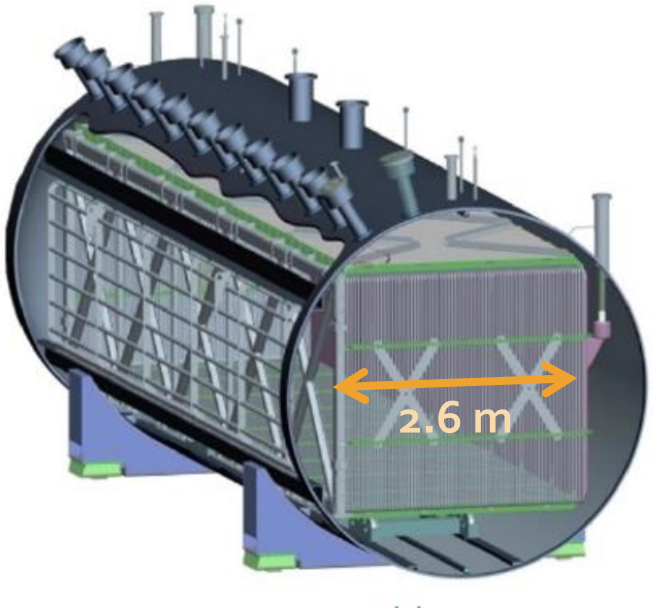
- Reconstruction approaches
  - Focus on the cases of ProtoDUNE-SP (DUNE LAr TPC prototype) and MicroBooNE

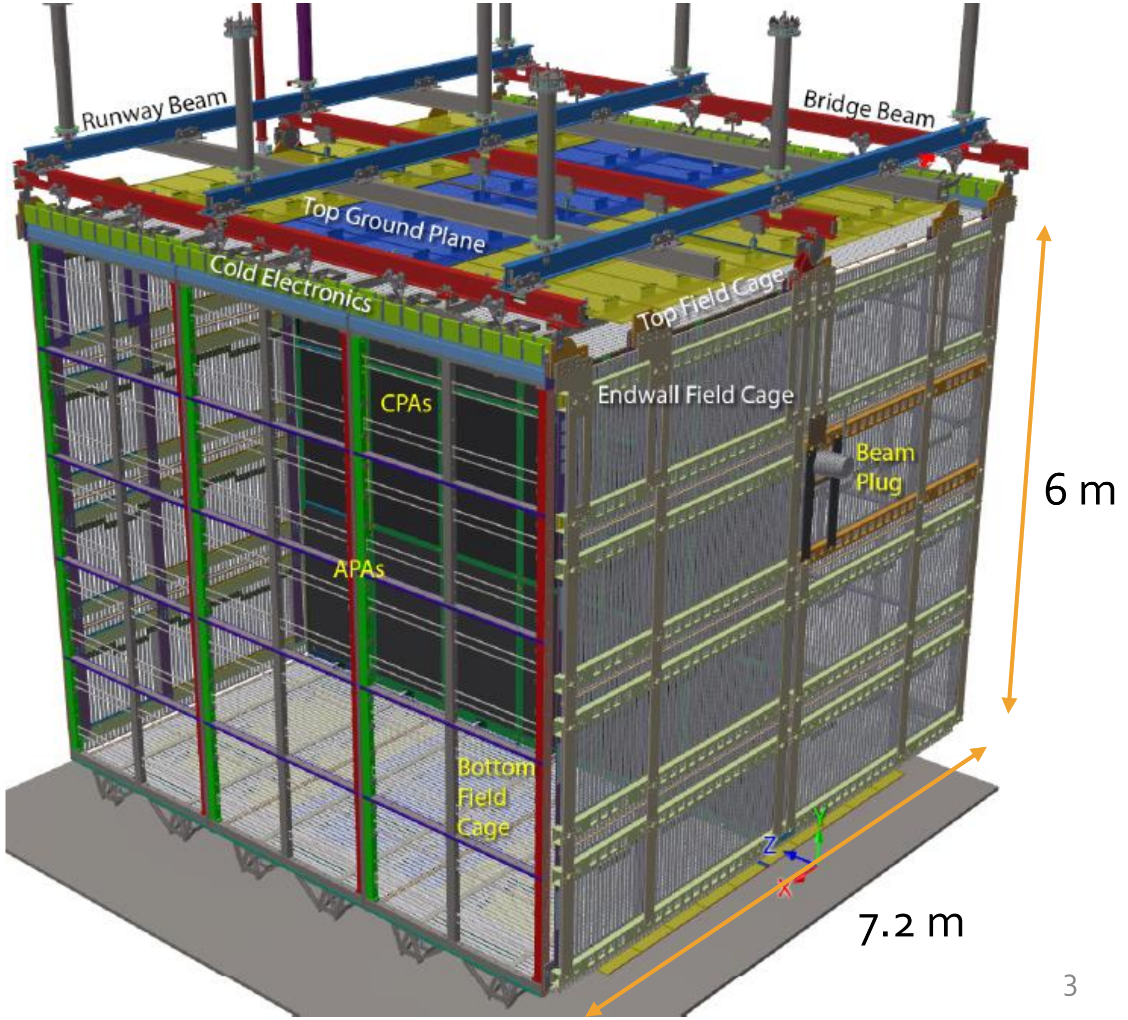
- Incorporation of Machine Learning techniques

Two case studies

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

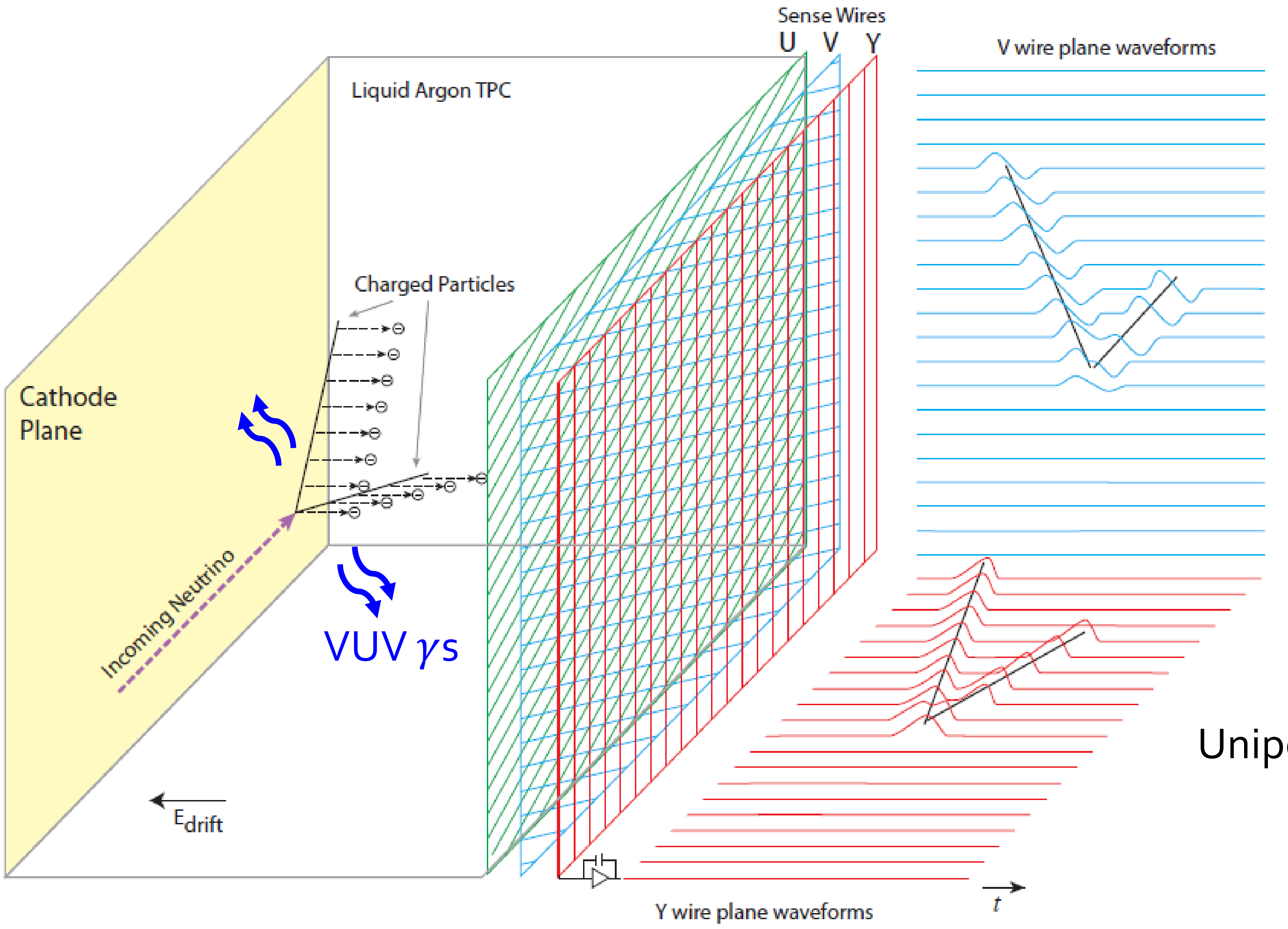
MicroBooNE:
- 90 ton LAr TPC active volume
- Single drift volume of length 2.6 m
- Exposed to booster neutrino beam at FNAL





Both with 3-view wire-plane readout

TPC readout cartoon



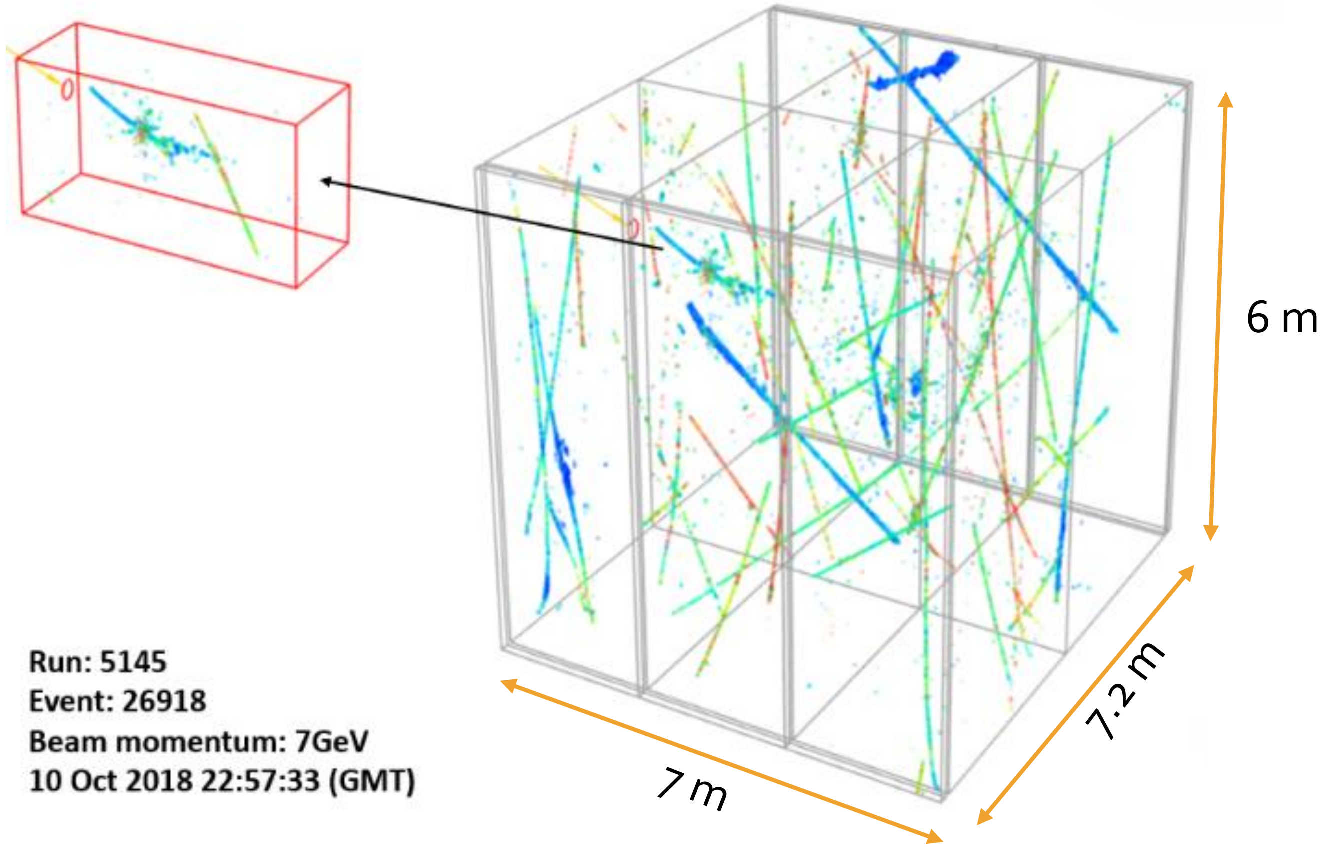
Bipolar signals on induction wires

Unipolar signals on collection wires

+ photon system to detect prompt scintillation

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



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
- For MicroBooNE, a WireCell toolkit have been also developed at BNL
  - Provides a full (MicroBooNE) event reconstruction [JINST 17 P01037, 2022]
  - Some integration within LArSoft for signal simulation and signal processing

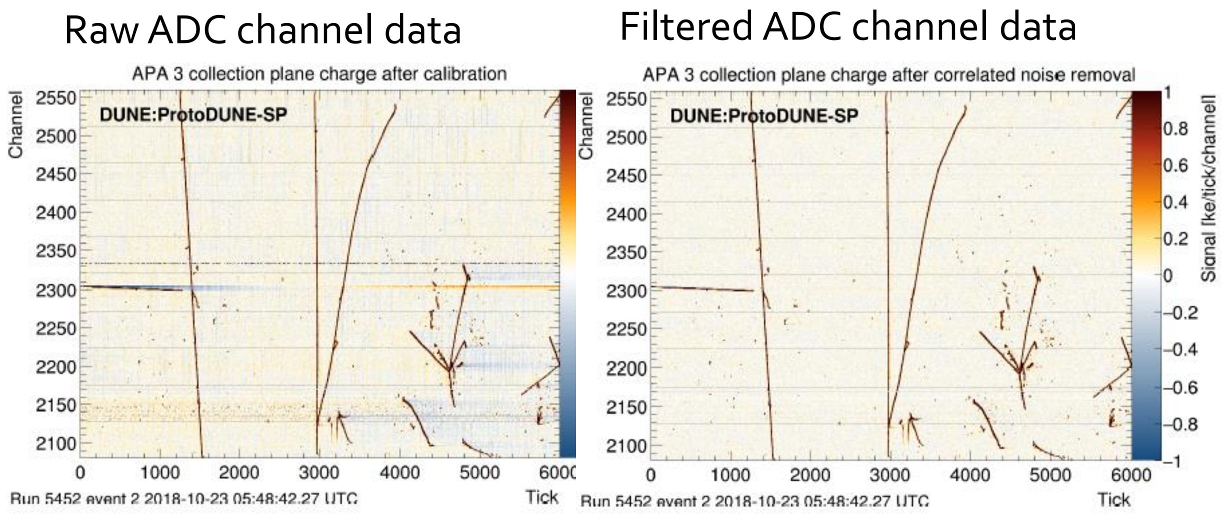
LAr TPC event processing

Raw ADC channel data

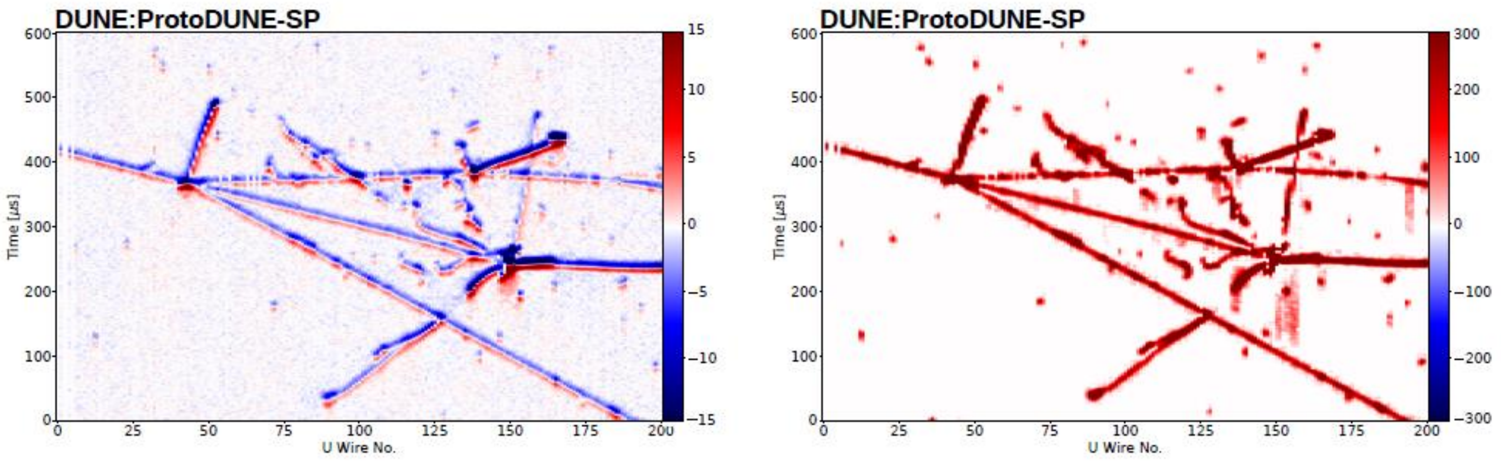
Signal (pre)processing:
- Electronics response calibration
- Coherent noise filtering
- Field response deconvolution
- Regions of interest selection

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

Noise filtering



Field response deconvolution using WireCell



(a) After Noise Filtering

(b) After Deconvolution

LAr TPC event processing

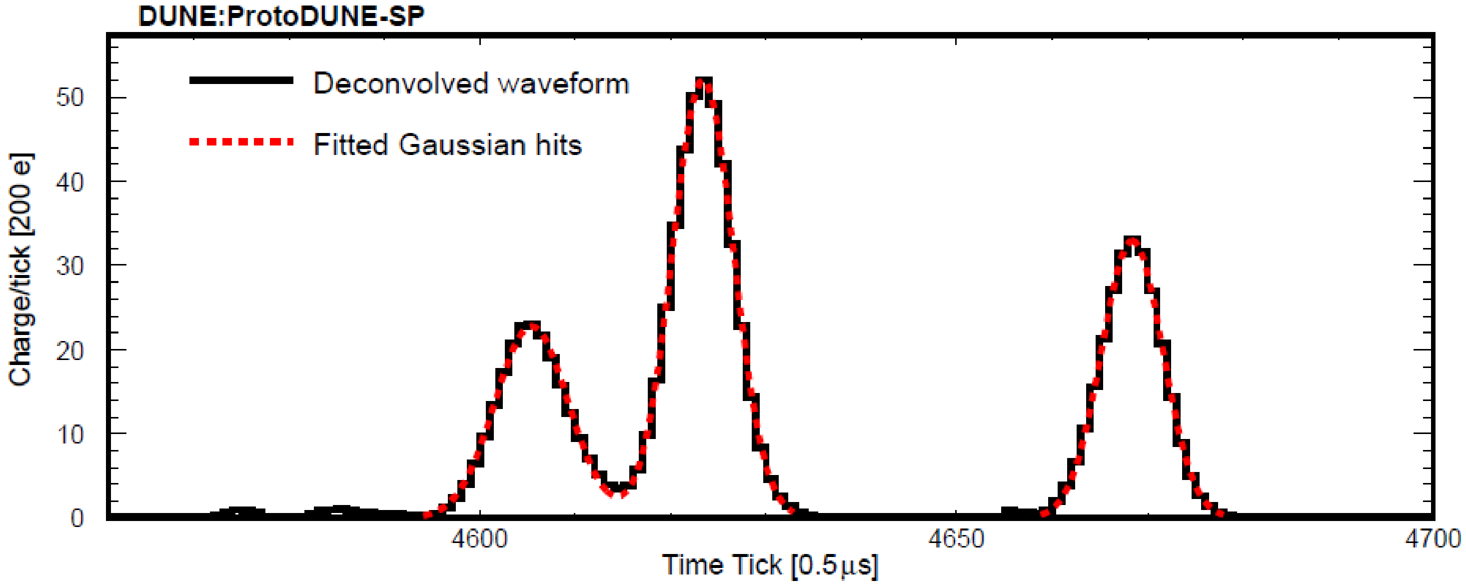
Raw ADC channel data

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

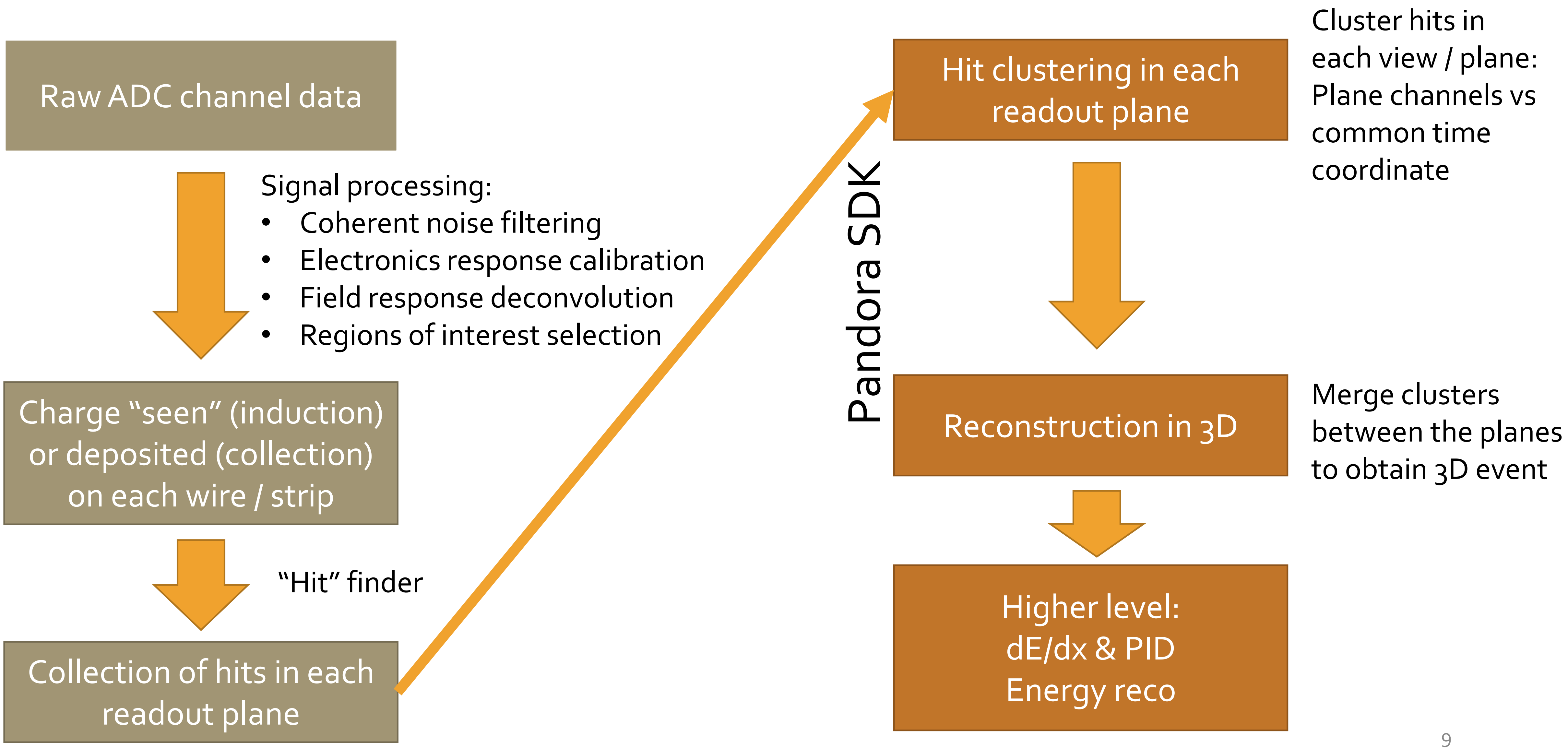
Charge "seen" (induction) or deposited (collection) on each wire / strip

"Hit" finder

Collection of hits in each readout plane



LAr TPC event processing (LArSoft)

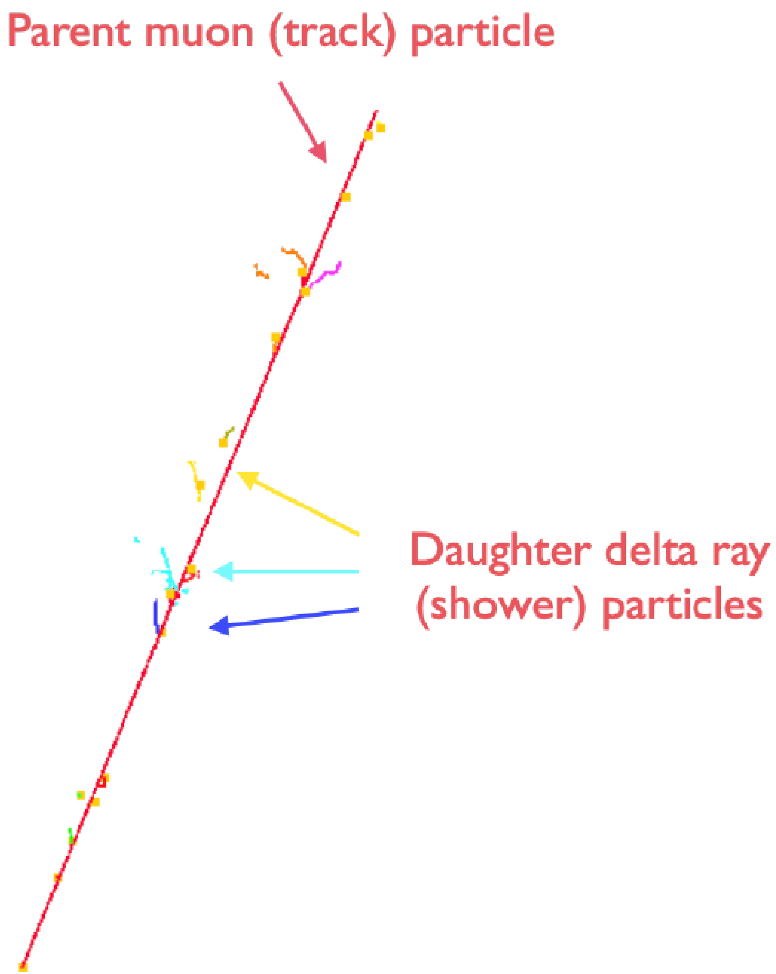


Pandora reconstruction workflow

- 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

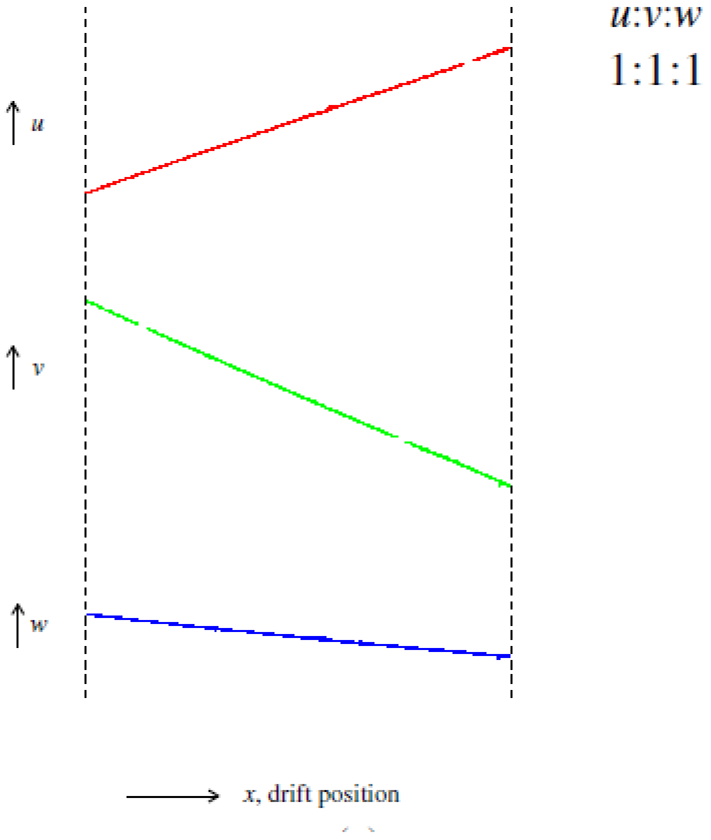
- Muons are assumed downward going: the vertices are at highest y
- Track-oriented clustering
- Showers are delta rays / decay electron and added as daughters to primary muon
- Flow:
  - 2D reconstruction
  - 3D track reconstruction
  - Delta-ray reconstruction
  - 3D space-point reconstruction

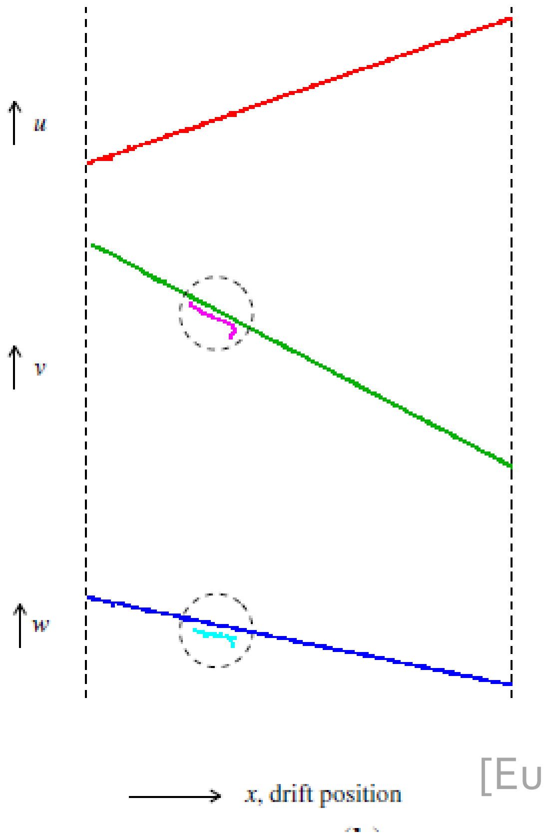


Matching 2D projections

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

Require >90% overlap for all clusters



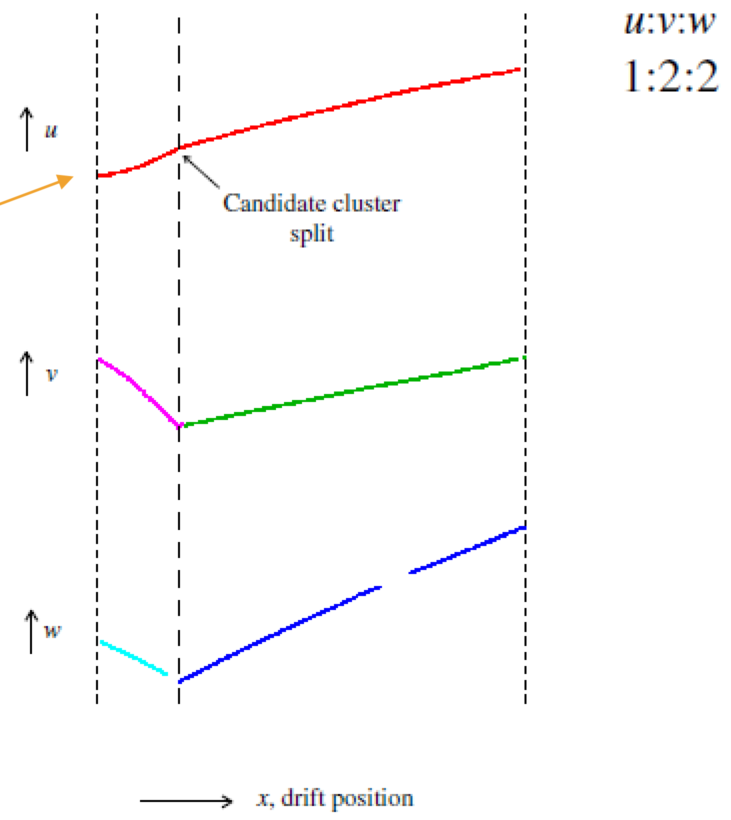


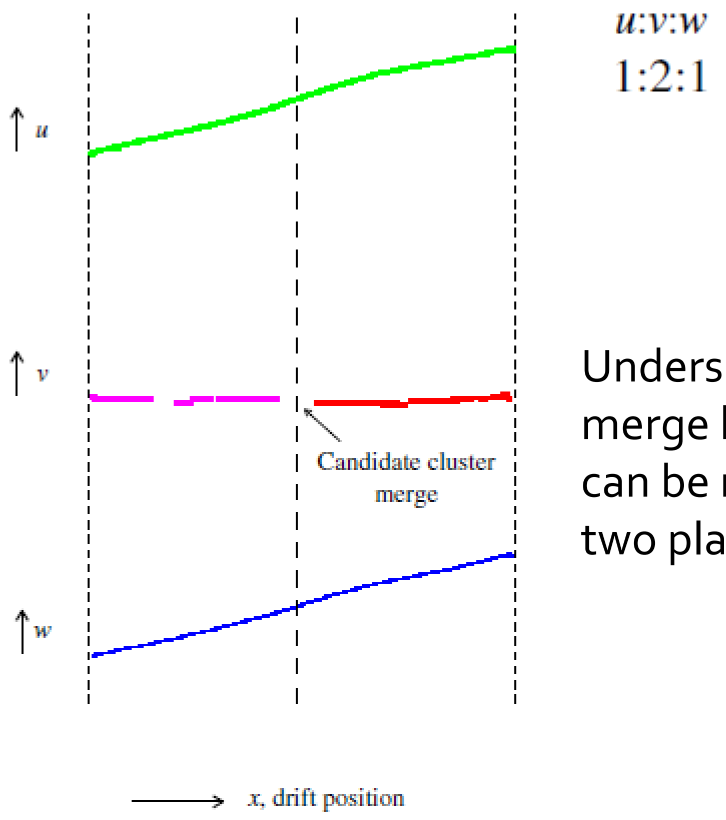
Always select the clusters with the best match to resolve ambiguities with the delta rays

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

Matching 2D projections

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



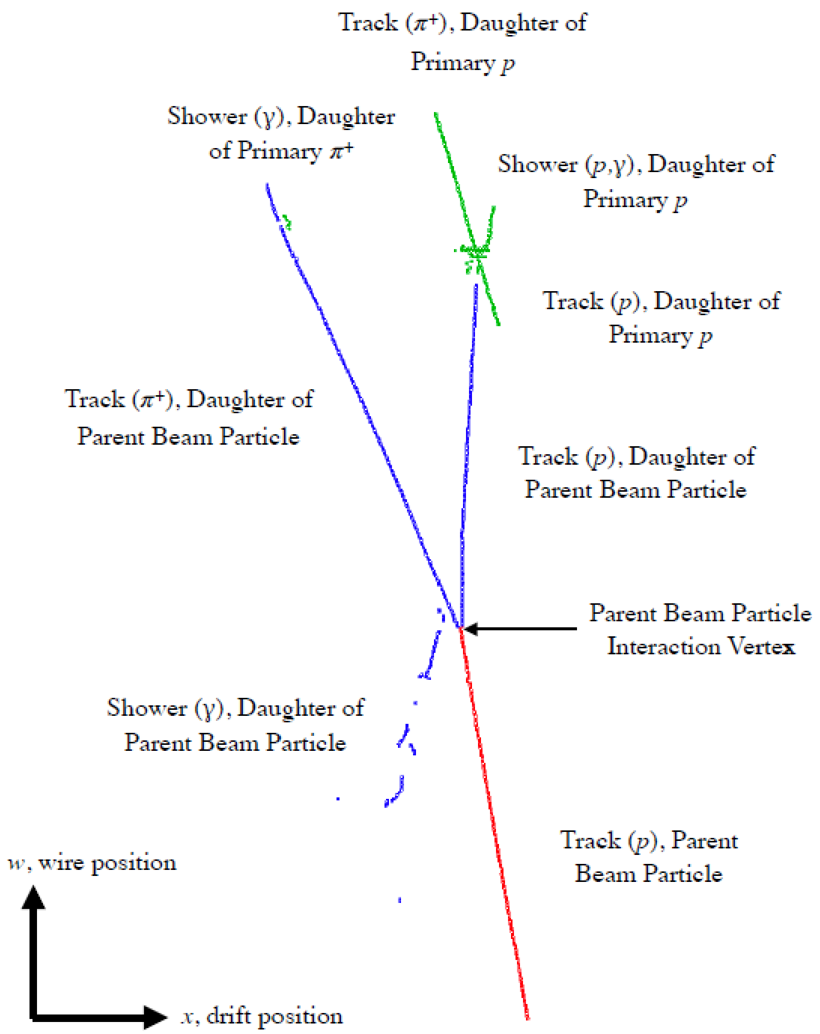


Undershoot tracks: merge broken v clusters if can be matched to other two planes

PandoraNu/PandoraTestBeam

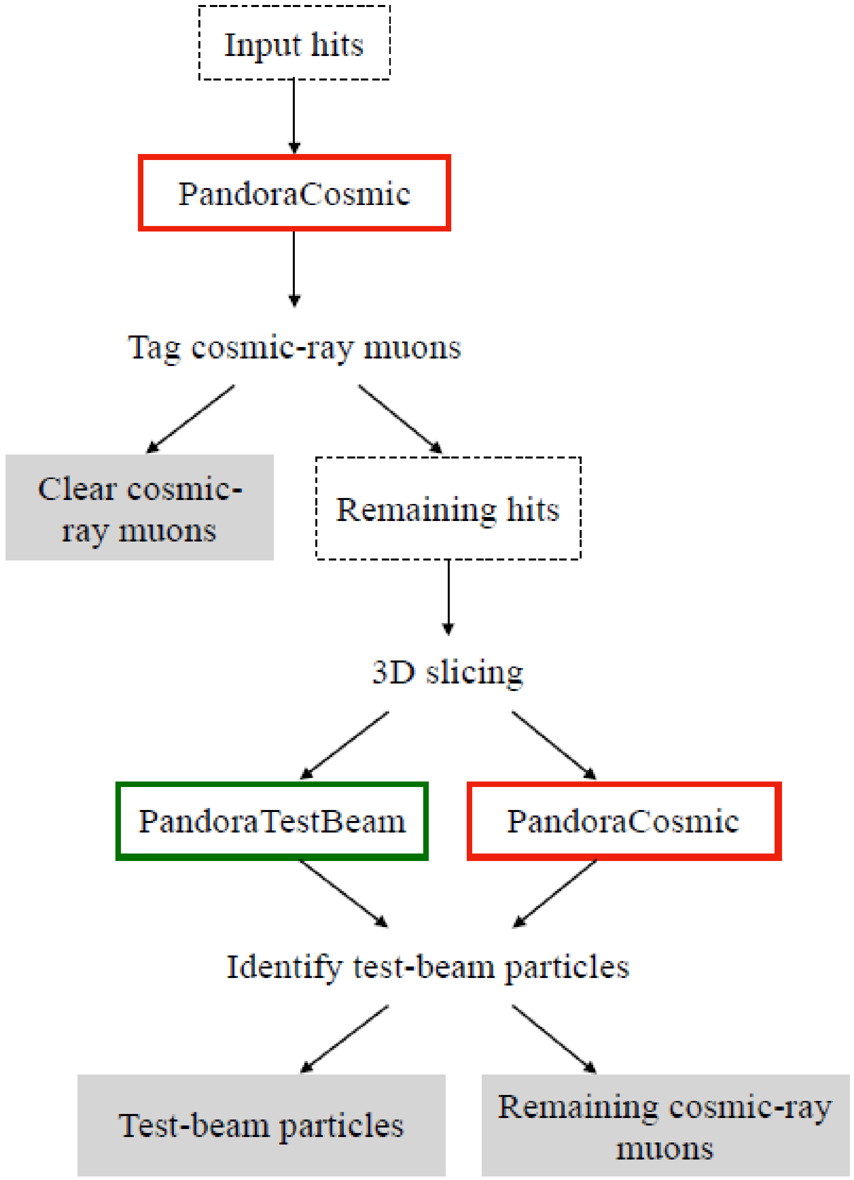
- Flow
  - 2D reconstruction
  - 3D vertex reconstruction
  - Track and shower reconstruction
  - Particle hierarchy reconstruction

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

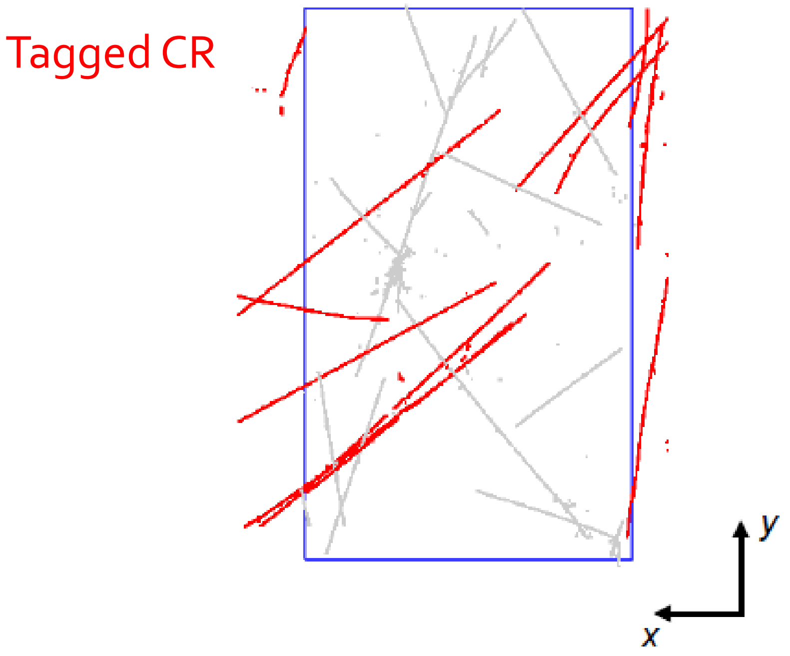


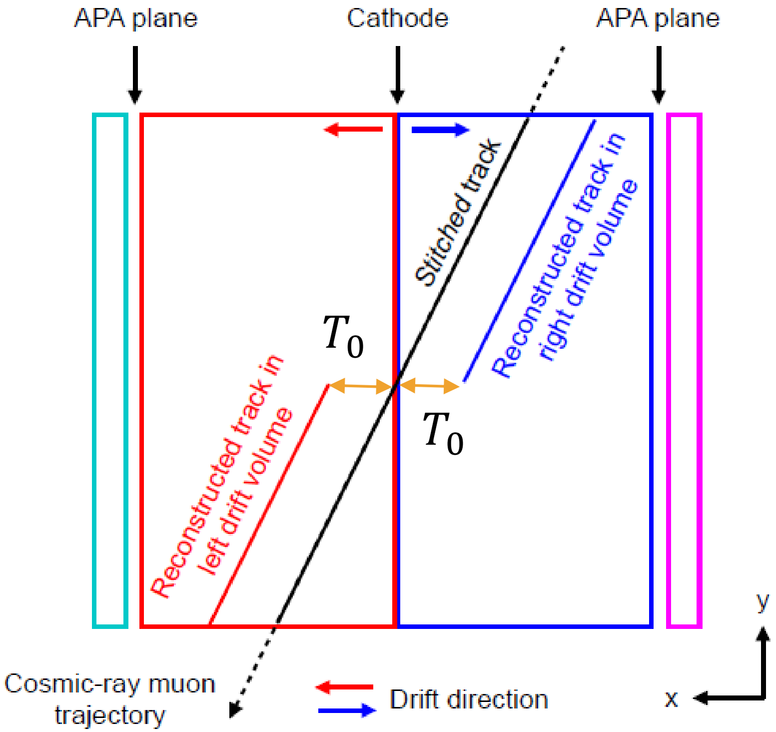
Consolidated reconstruction for test beam events in ProtoDUNE-SP

- 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



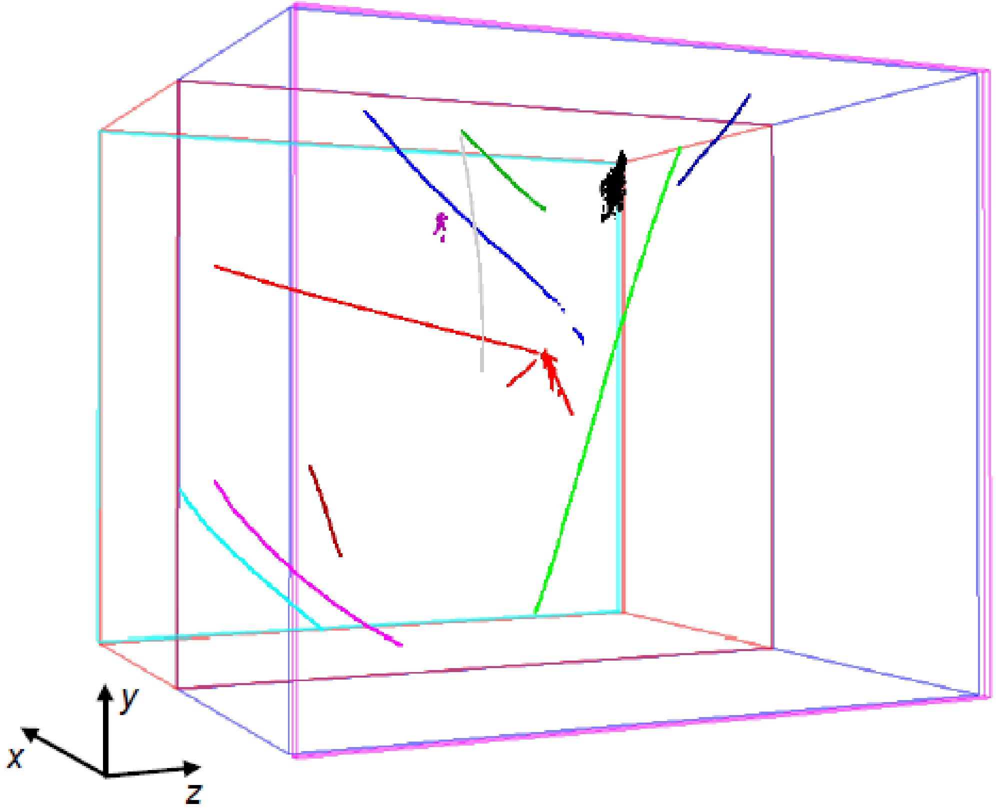


- Clear cases when cosmics out of beam time enter / exit TPC volume
- Cosmics crossing the cathode plane are “stitched” to find their arrival time wrt beam time

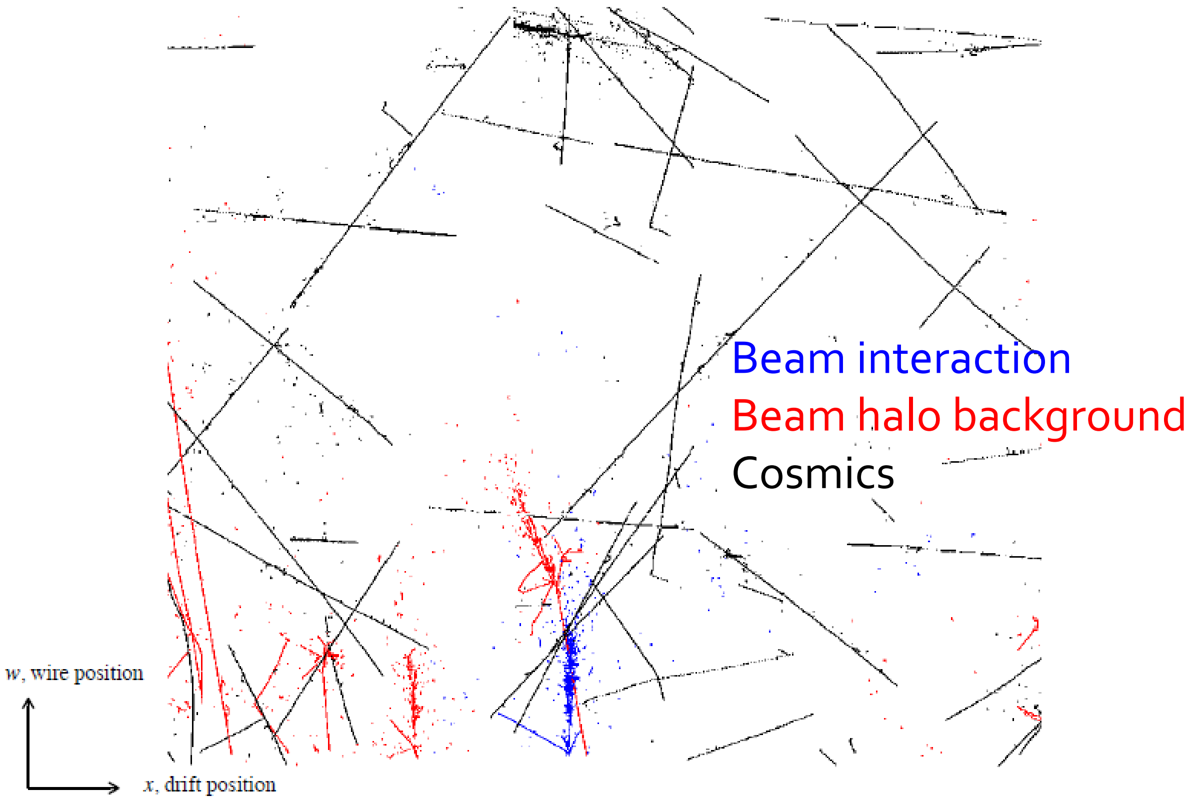
Event slicing

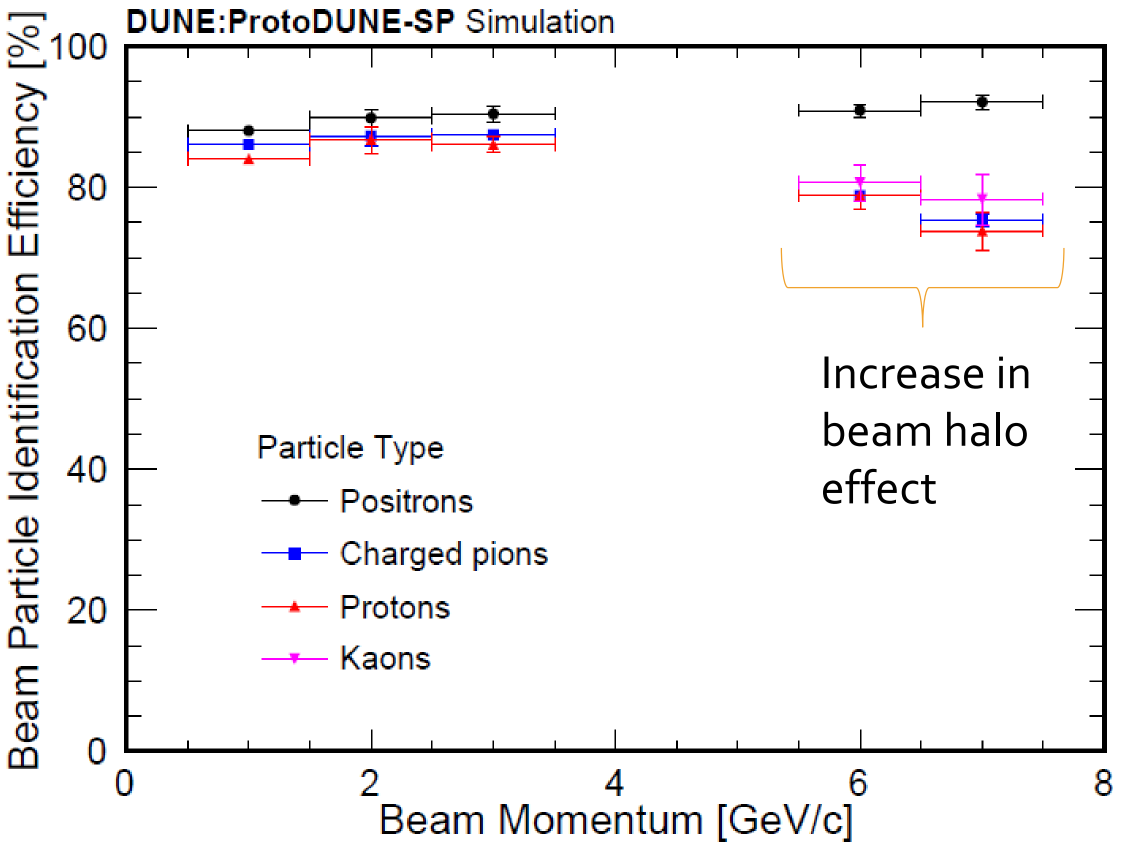
- Separate / slice hits from different interactions
- Run TestBeam / Cosmics reconstruction on each slice and select the "best" beam event
- Boosted Decision Tree (BDT) built around the test beam entrance is known and cosmics typically have track-like topologies compared to complex ones from test-beam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

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



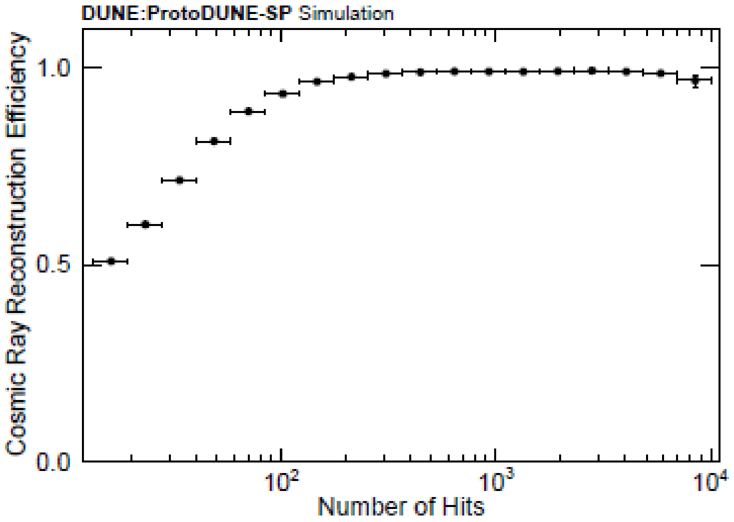
Beam particle identification efficiency



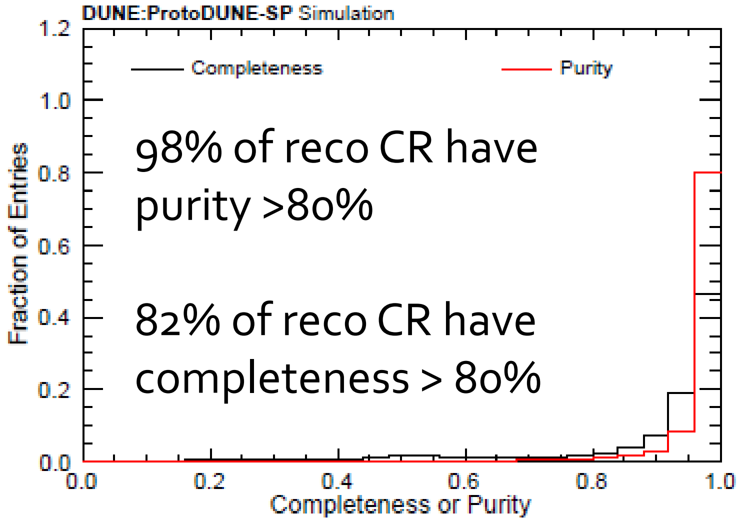


Pandora cosmic-ray track reconstruction

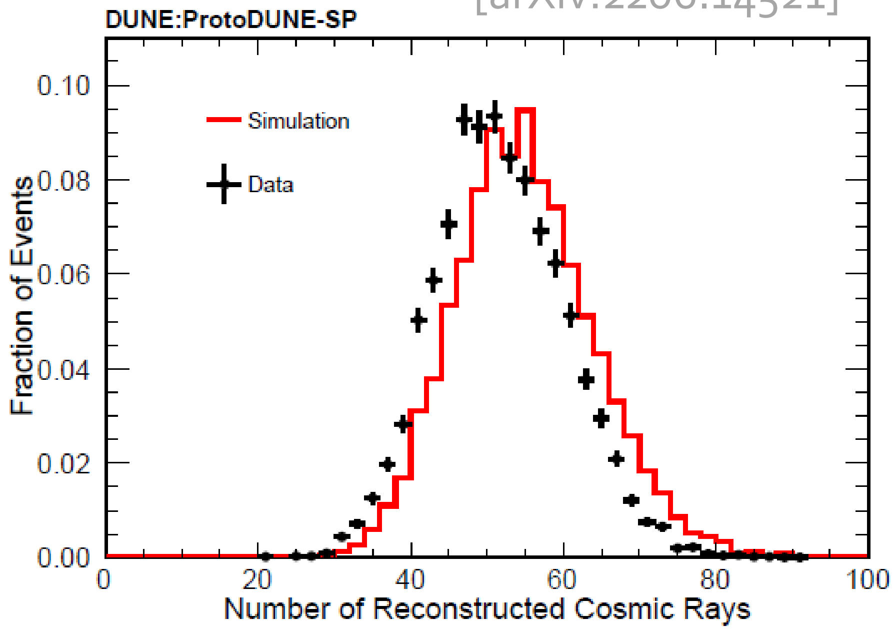
Efficiency as a function of Nhits



Purity & completeness



[arXiv:2206.14521]

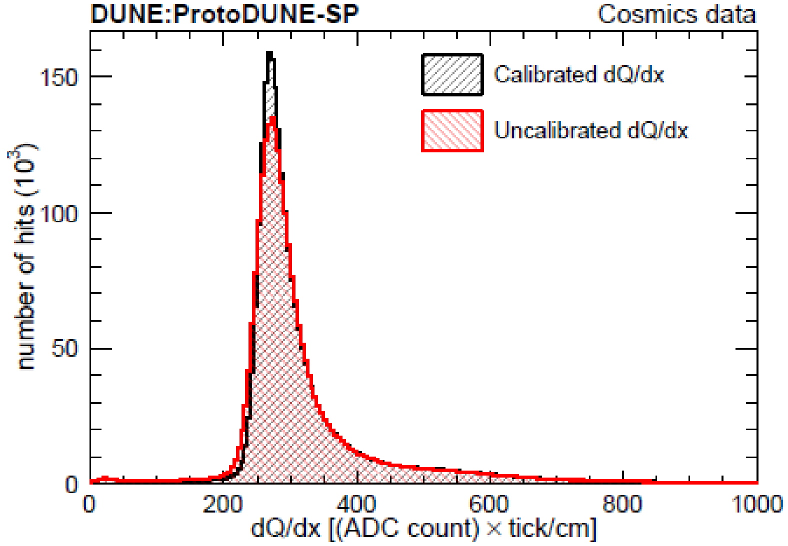


Efficiency: fraction of MC particles that are matched to at least one reconstructed particle
Purity: fraction of hits in reconstructed particle that are shared with an MC particle
Completeness: fraction of hits in the MC particle that are shared with a reconstructed particle

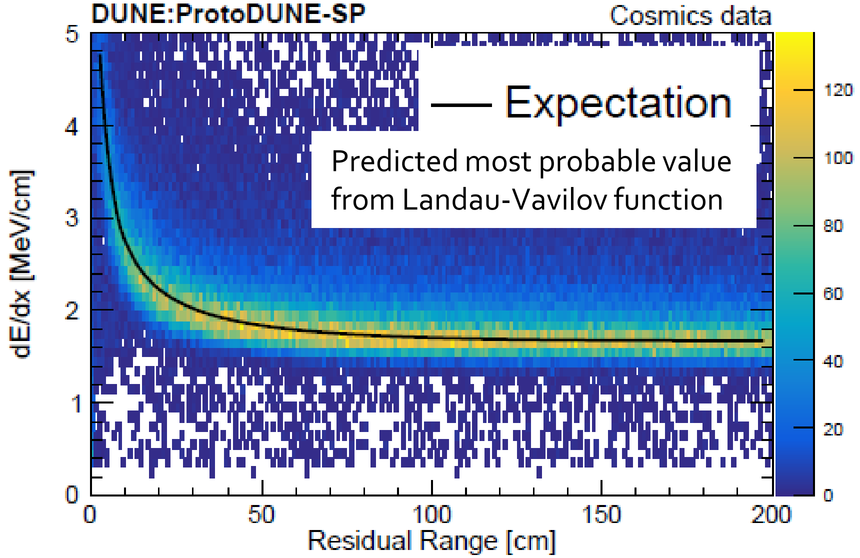
Data/MC: ~5% fewer CRs reconstructed than in simulation possibly due to slight overestimation of the cosmic ray flux in MC

Measured dE/dx for cosmic-ray muons

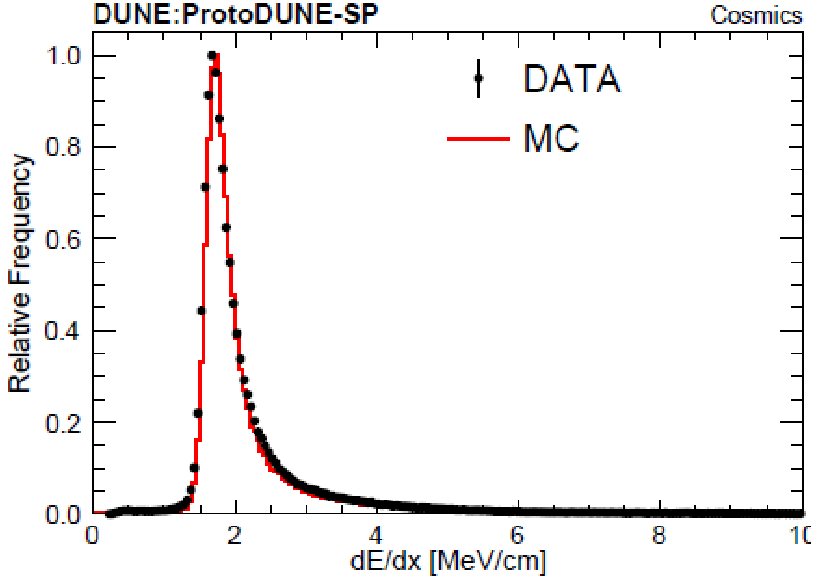
[JINST 15 P12004, 2020]



Stopping muons dE/dx distribution



dE/dx Data / MC comparison

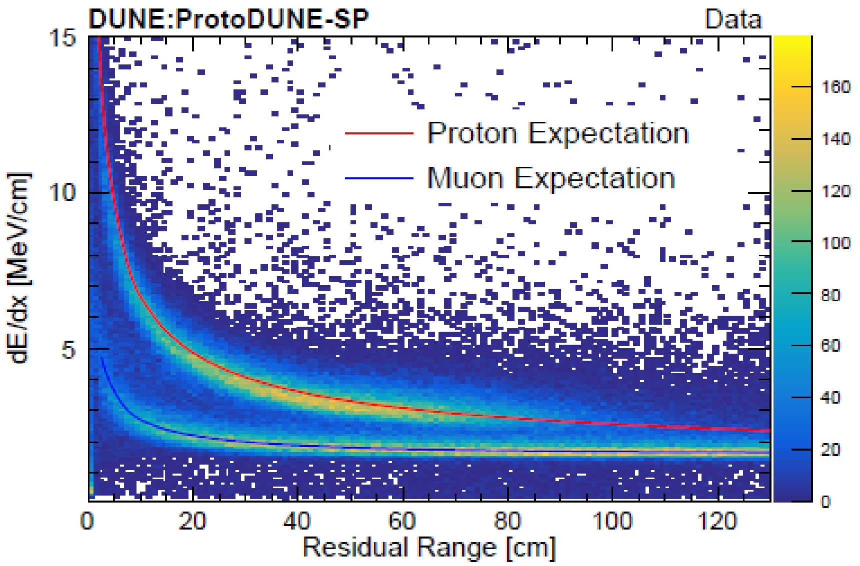


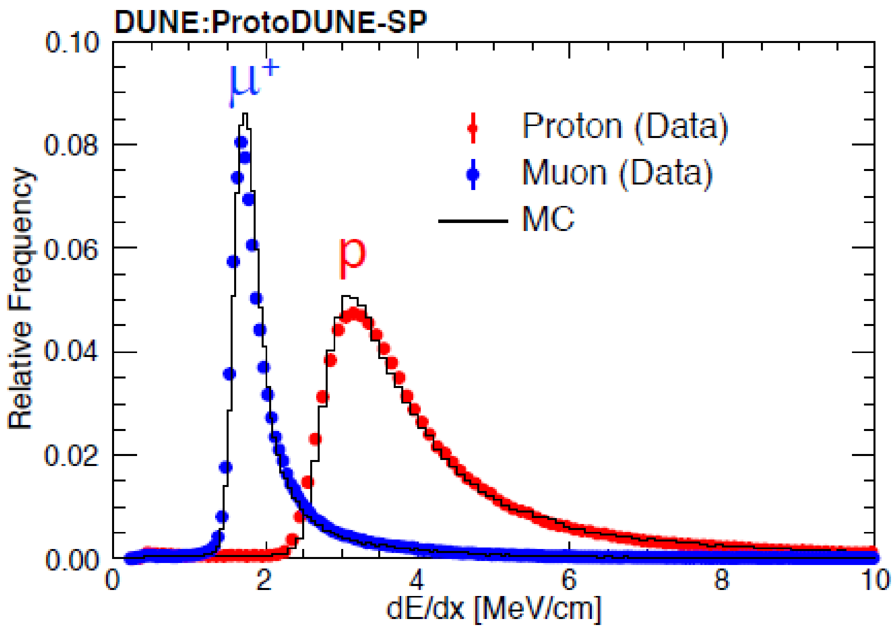
Reconstructed dQ/dx → measured dE/dx

- Measured correction for attachment to electronegative impurities
- Measured uniformity of readout plane response
- Absolute energy scale determined by fitting a sample of stopping muons
- Charge recombination effects in LAr taking into account local electric field strength

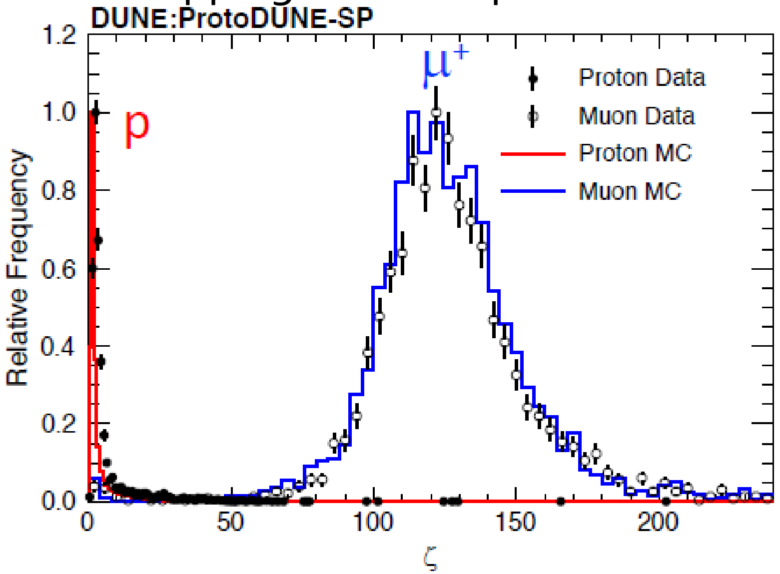
Obtained from cosmics data

Beam particles





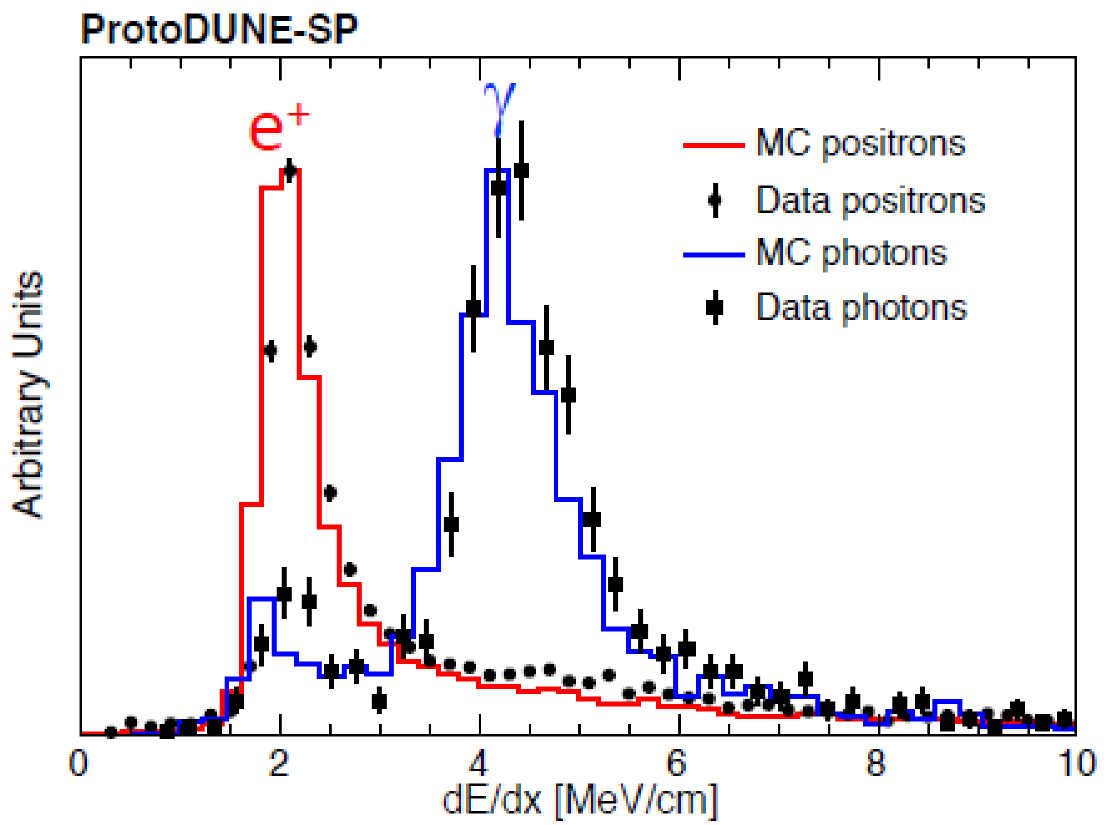
Stopping muons & protons PID

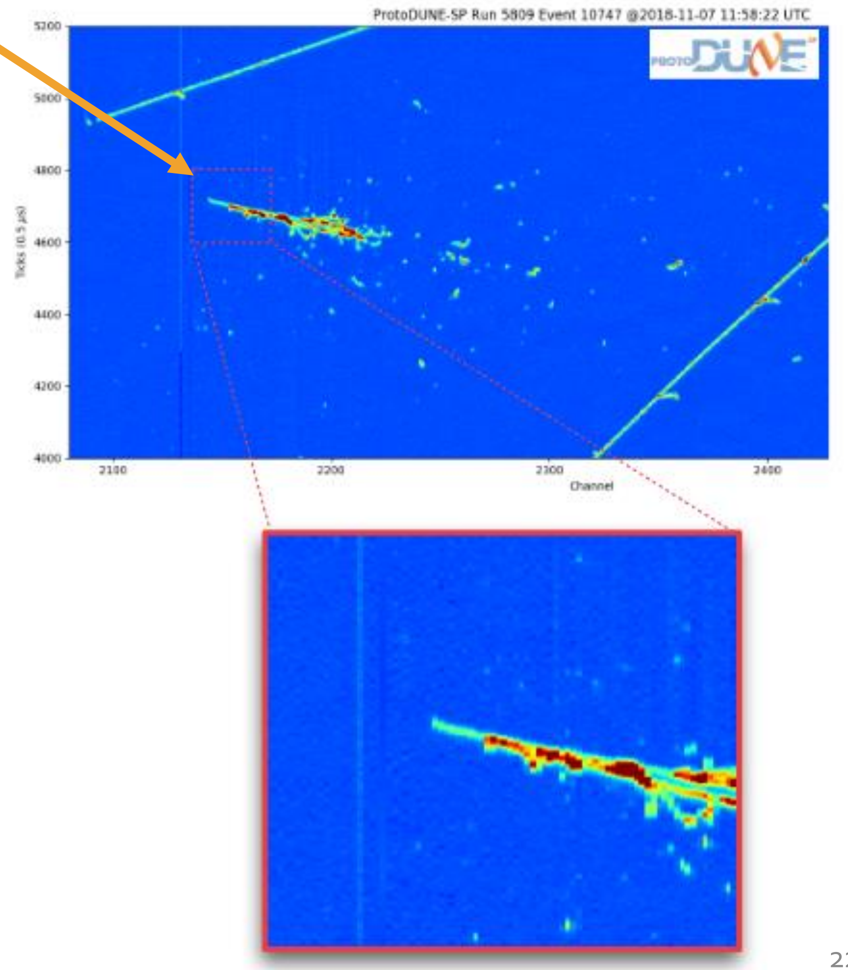


- Calibrations derived from cosmic ray analyses are applied to beam particles
- Many hadron cross-section analysis …

Electron / gamma separation

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

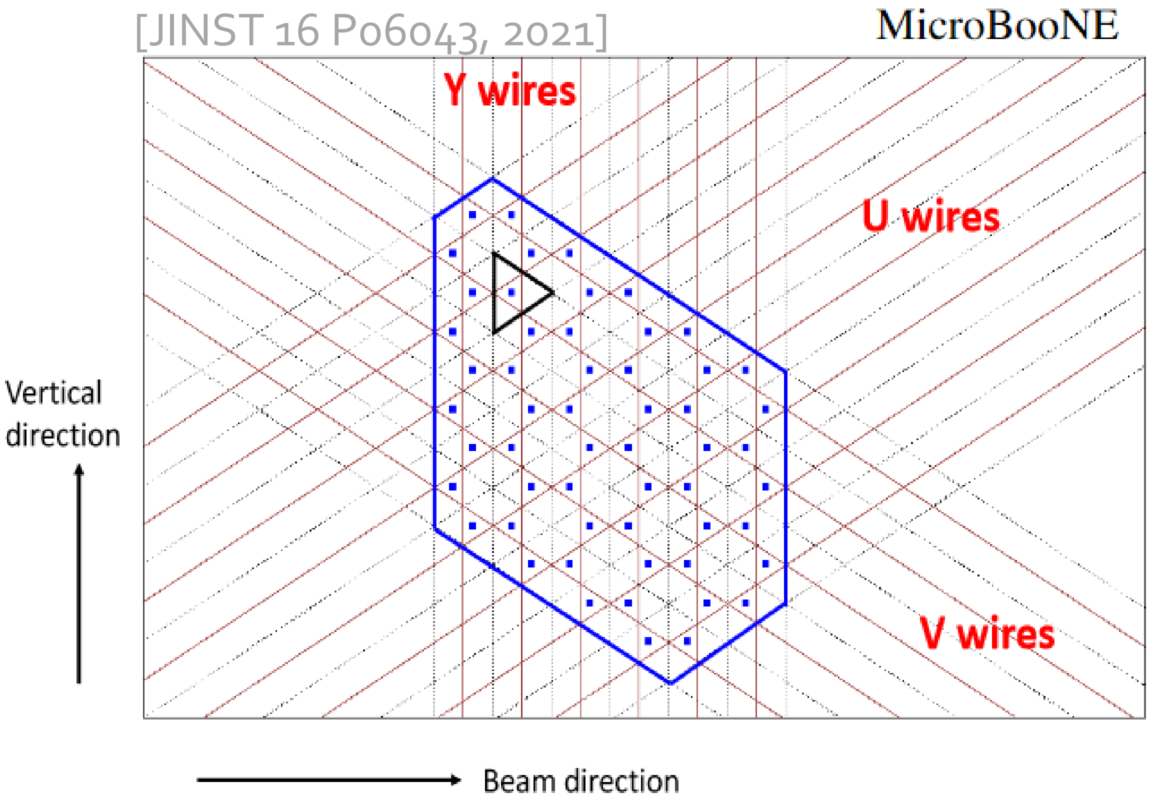




Wire-Cell reconstruction

- A LArSoft interface to wire-cell is used for signal processing
- In MicroBooNE the toolkit has been extended to offer full 3D reconstruction and pattern recognition
  - Search for LEE : Phys. Rev. D 105, 112005, 2022
- As a starting point one attempts to build 3D space points from reconstructed hits
  - The readout plane is portioned into cells given by the anode wire geometry
  - The drift coordinate is sliced and hits within each time slice are used to populate all possible cells
  - For a given space-point same charge should be measured x3 by the wire planes

[JINST 16 P06043, 2021]



Find 2D cell + measured drift time ➔ 3D point

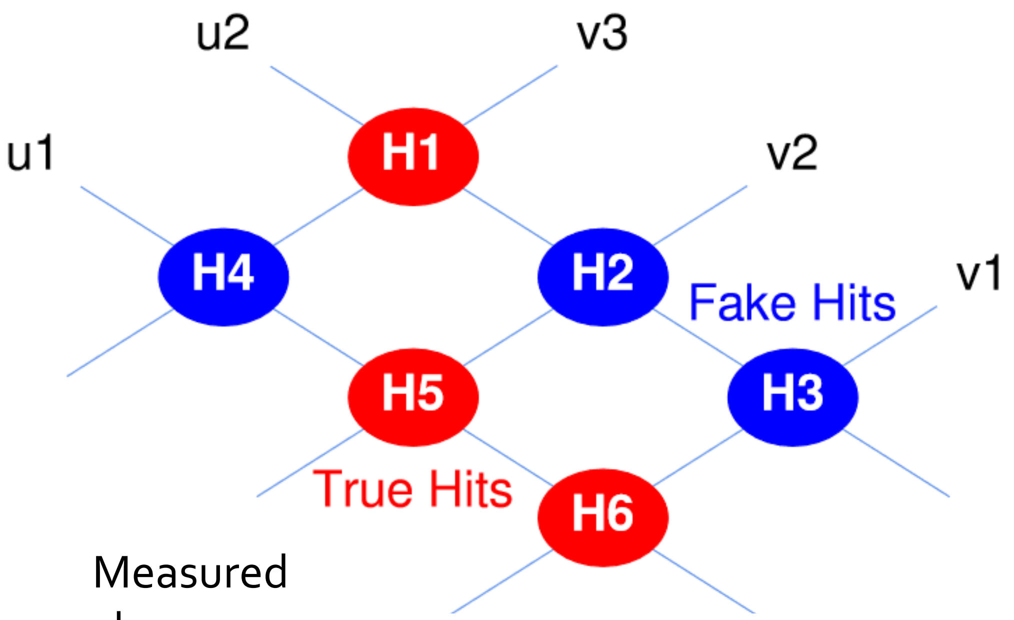
Wire-Cell charge imaging

[JINST 13 P05032, 2018]

- Solve a system of linear equation to simultaneously find the right 2D cell(s) and the best estimate of the "true" charge from measured quantities on each wire:

$$y = Ax$$

- Not a trivial inverse problem: undetermined linear system
- However, true signal is sparse ➔ compressed sensing technique [Comm. Pure Appl. Math., 59: 1207-1223]

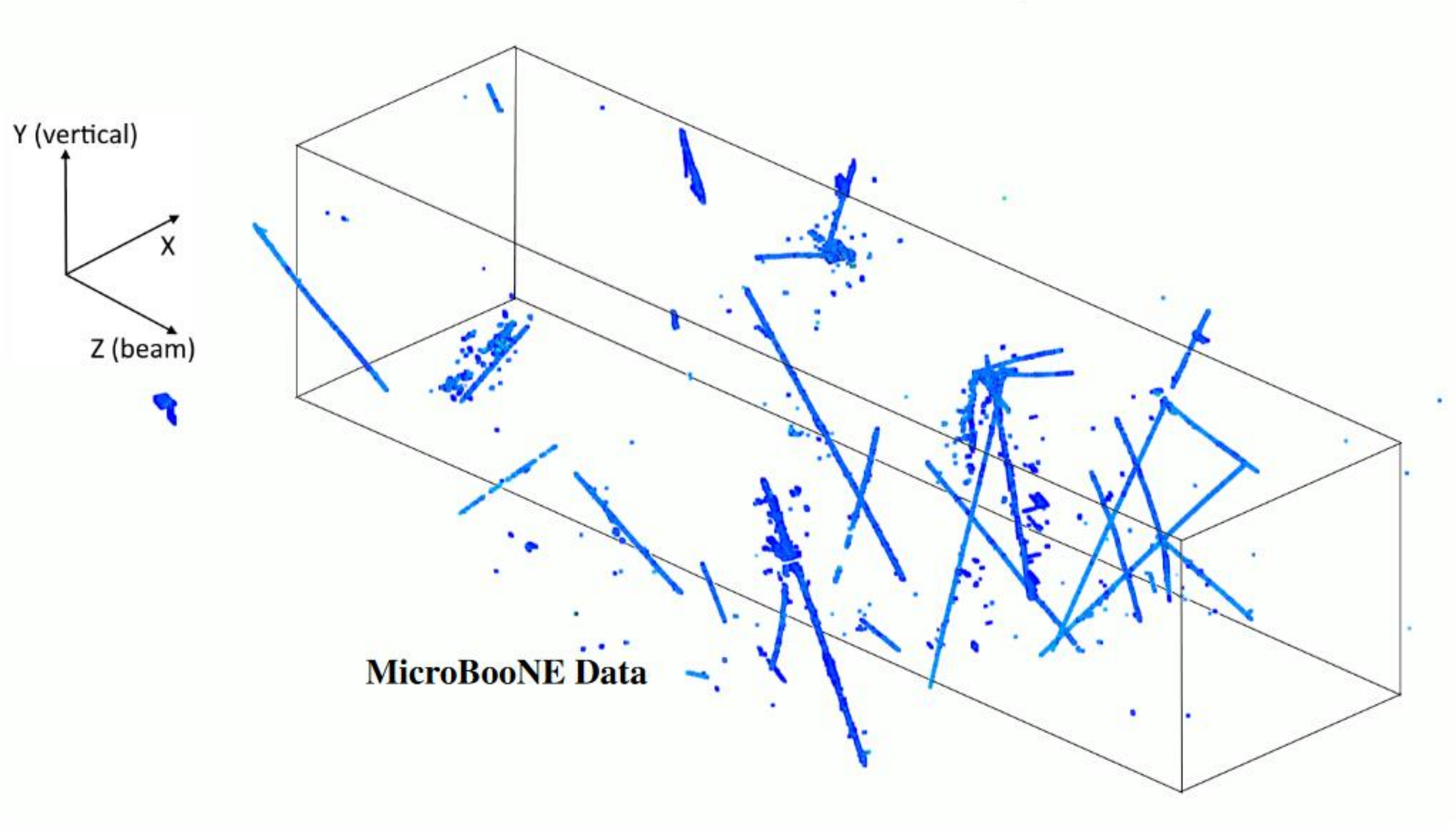


Measured charge

$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix}$$

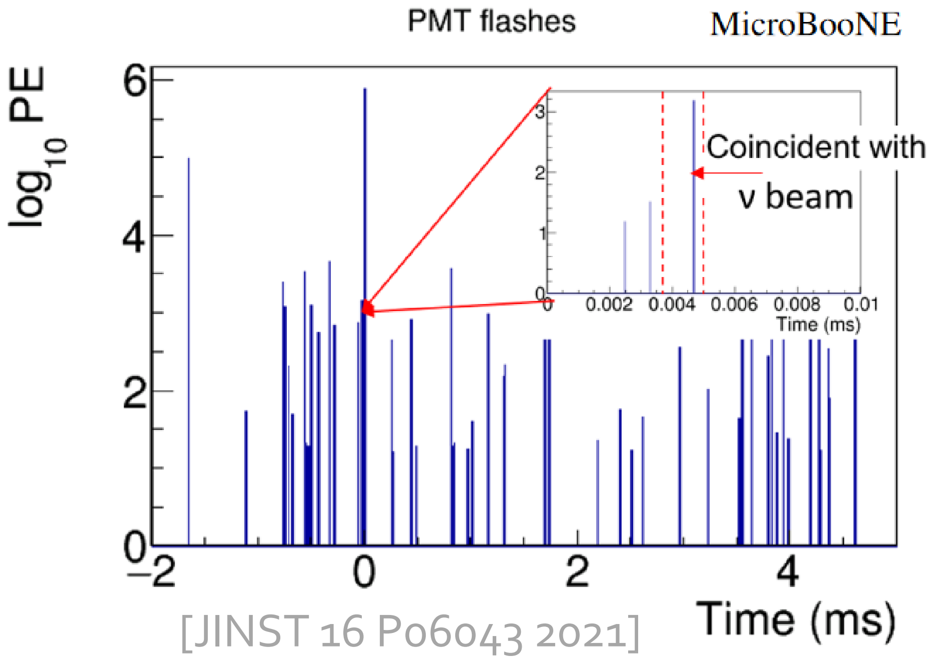
True charge to be solved

Example Wire-Cell 3D imaging



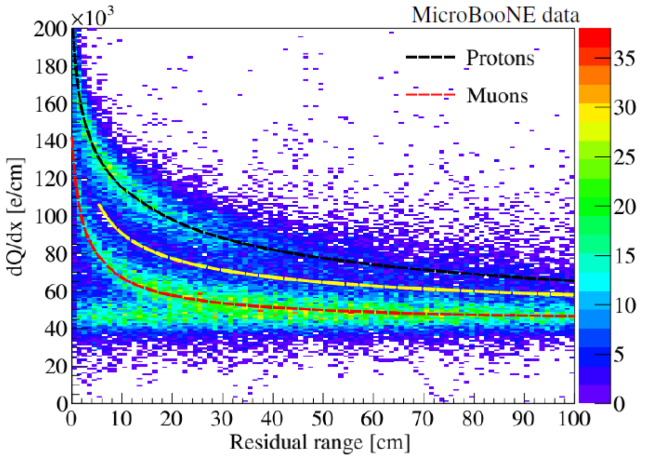
Selection of neutrino event clusters in Wire-Cell

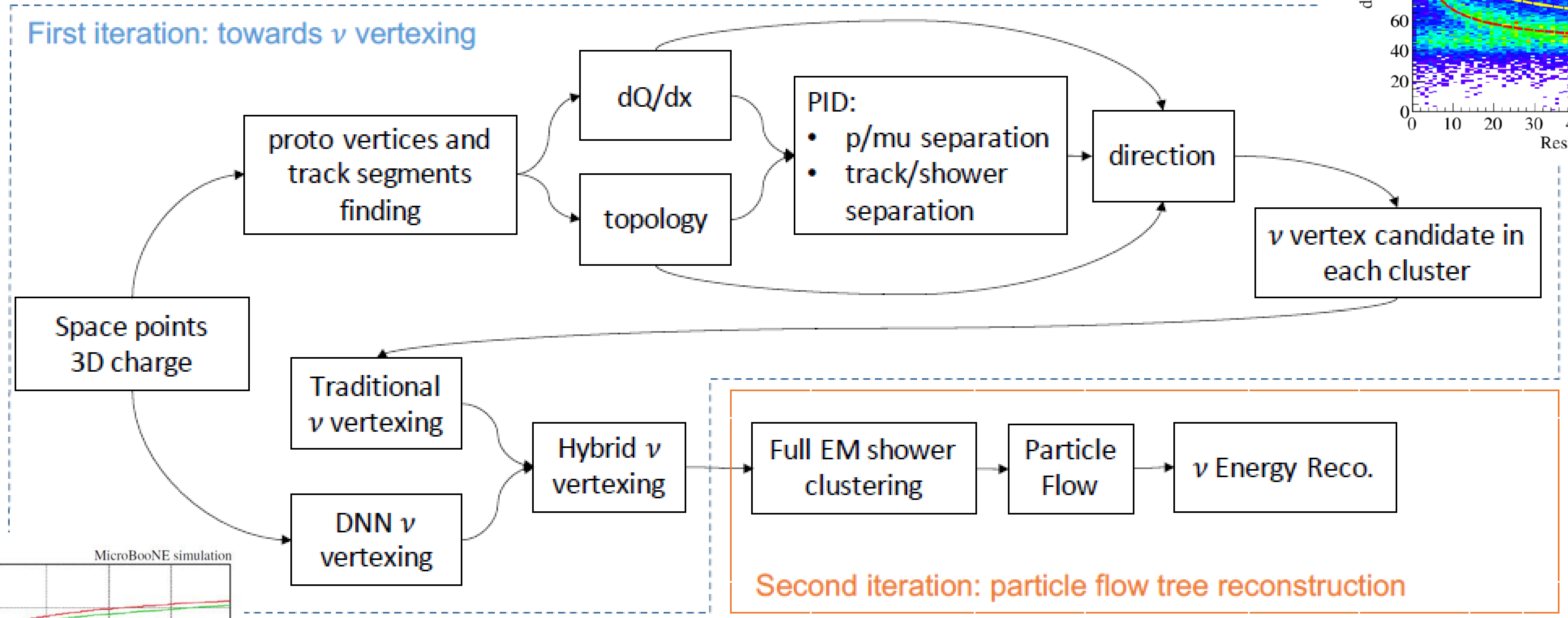
- Space points are grouped in 3D TPC clusters
  - Not a simple grouping by proximity
  - Need to account for gap both due to non-functional channels and physically separated clusters from the same interaction (e.g., π^0 decays)
- Match TPC clusters to reconstructed light flashes & select the ones coincident with beam timing
  - 85% ν_μ CC events have completeness > 80%
  - 90% ν_e CC or NC have completeness > 70%

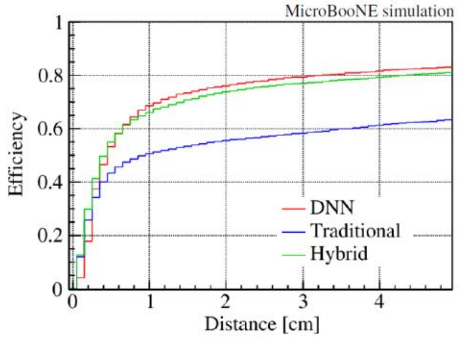


[JINST 16 P06043 2021]

Neutrino event reconstruction







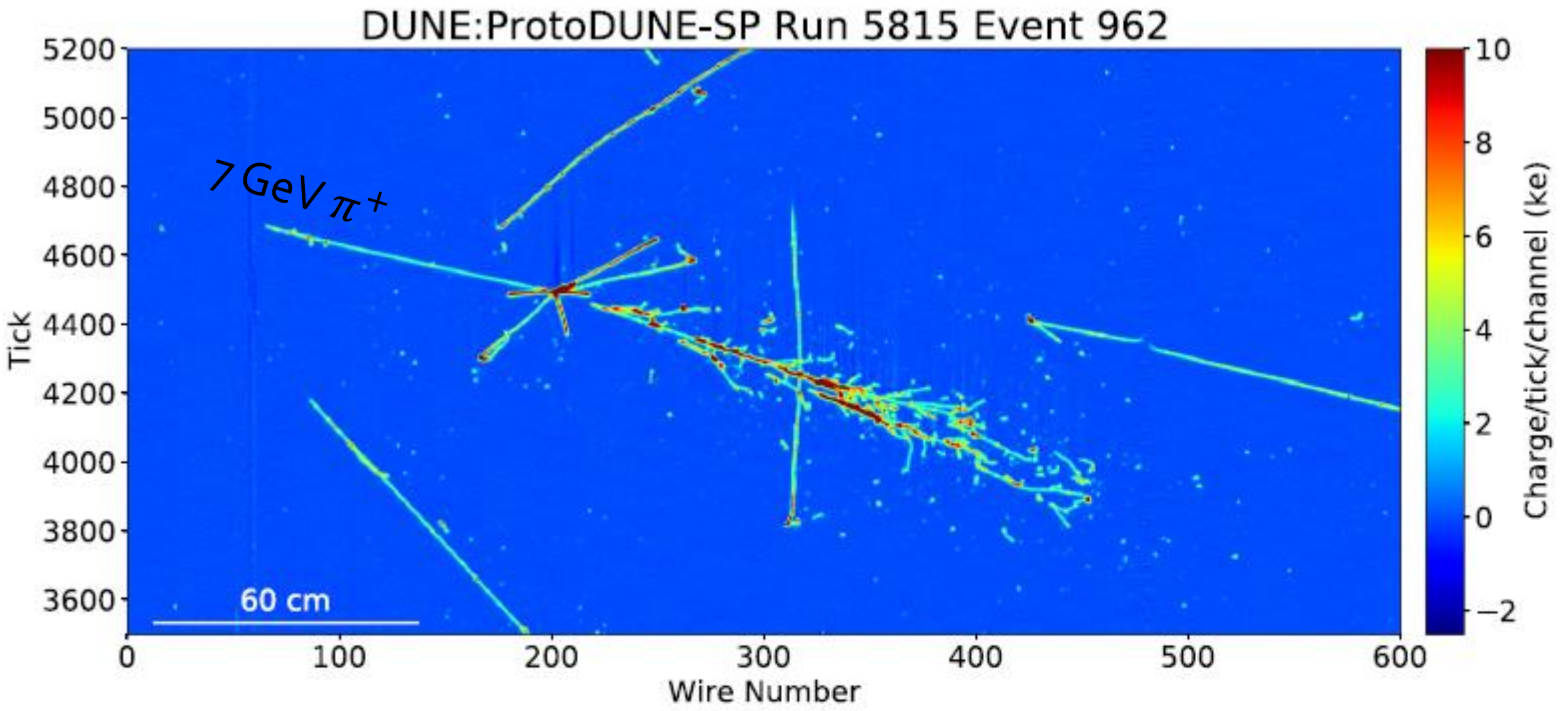
Machine Learning

LAr TPC event is a set of images in time and space

Natural to classify their features with neural networks

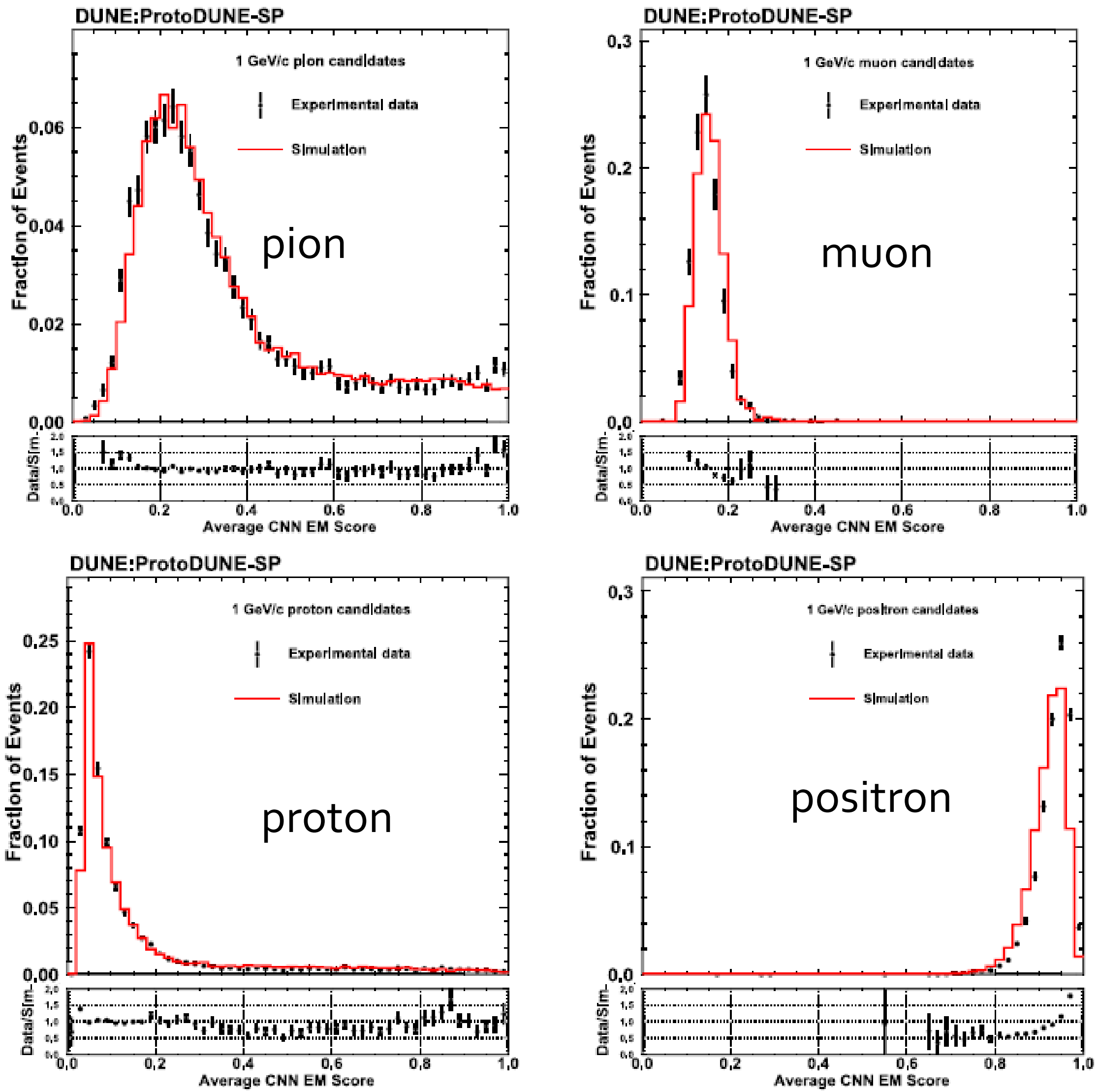
- Overall event classification based on topology : ν_eCC, ν_μCC, NCπ
  - Neutrino interaction classification in DUNE [Phys. Rev. D 102, 092003]
- As part for reconstruction enhancement:
  - Interaction vertex finding (Pandora, Wire-Cell)
  - Classification of hits as belonging to shower or track-like hit collections

Example event

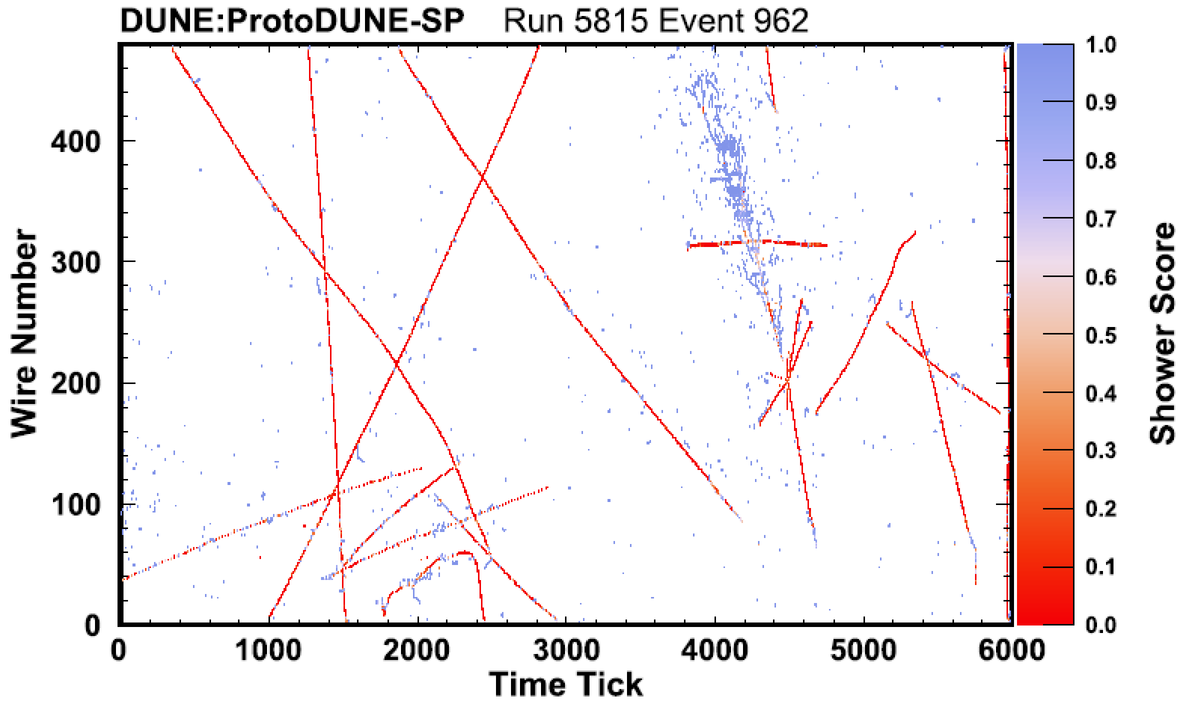


Goal is to classify each hit as either track-like or shower-like with a convolution neural network [Eur. Phys. J. C (2022) 82:903]

Classification of beam events in ProtoDUNE



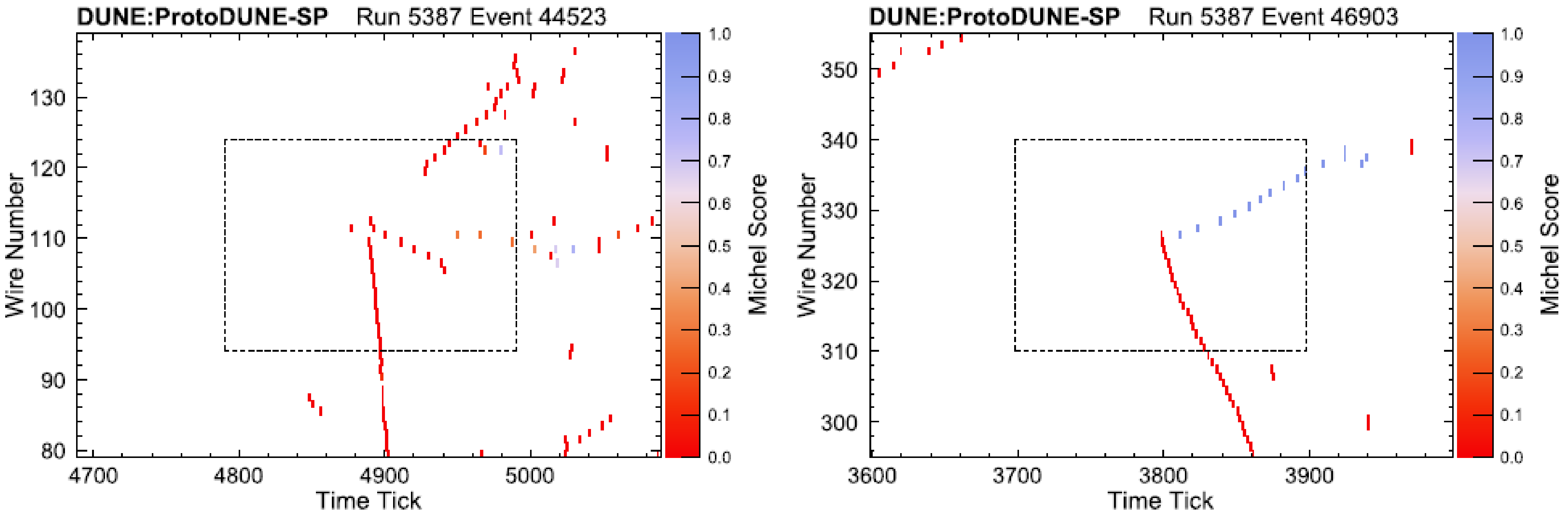
Track-like Shower-like



Fraction of reconstructed particles classified into appropriate class

Hit source	Class	Data fraction (%)	Simulation fraction (%)
Pion	Track	91.7 ± 0.4	92.5 ± 0.2
Muon	Track	$100^{+0.0}_{-0.1}$	$100^{+0.0}_{-0.1}$
Proton	Track	96.9 ± 0.2	97.1 ± 0.1
Positron	Shower	98.8 ± 0.1	97.9 ± 0.1

Michel electron classification



(a) A pion candidate (b) A muon candidate

Hit source	Class	Data fraction (%)	Simulation fraction (%)
Pion daughters	Non-Michel-like	90.4 ± 0.4	92.2 ± 0.2
Muon daughters	Michel-like	73.2 ± 1.3	72.6 ± 1.3

Conclusions

- Remarkable progress in automated reconstruction of events in LAr TPC have been made over the years
- For on-surface detectors the reconstruction tools handle complicated events containing beam interactions in large sea of cosmic ray background

- Incorporation of machine learning techniques is a rapidly developing field
- Currently mostly classification based on the topological information contained in “images”
- Efforts to go beyond classification get the full breakdown of the event with vertex position, PIDs, and energy / momenta of the final state particles …

Extras

Recombination parametrization: Birks form

- Birks form (ICARUS, NIMA 523 (2004) 275):

$$R = \frac{A}{1 + k/\varepsilon \times dE/dx}$$

ε – electric field x LAr density, dE/dx expected energy loss and A, k are constants

- The fitted values (muons) of A and k parameters (NIMA 523) :

$k = 0.0486$ (kV/cm)(g/MeV cm^2)

A = 0.800

Recombination parametrization: modified Box model

- ArgoNeuT [*JINST* **8** P08005 (2013)]:

$$R = \frac{\ln(A + \xi)}{\xi}$$

$$\xi = B/\varepsilon \times dE/dx$$

The fit parameters A & B; ε – electric field x density

- The fitted parameters (stopping protons) in the paper:

$$B = 0.212 \text{ (kV/cm)(g/MeV cm}^2\text{)}$$

$$A = 0.930$$

A = 1 in canonical Box model in [Phys. Rev. A 36 (1987) 614] (hence "modified")

From dQ/dx to dE/dx

$$\frac{dQ}{dx} = \frac{1}{W_{ion}} R\left(\frac{dE}{dx}, \varepsilon\right)\frac{dE}{dx}$$

- To obtain dE/dx from dQ/dx need to invert recombination model

$W_{ion} = 23.6 \times 10^{-6}$ MeV/electron (the work function of argon)

Birks: $$dE/dx = \frac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\mathscr{E}}.$$

ε – electric field x LAr density

Box: $$dE/dx = (exp(\beta W_{ion} \cdot (dQ/dx)) - \alpha)/\beta.$$

$$\alpha = A$$
$$\beta = B/\varepsilon$$