Machine Learning approach to neutrino experiment track reconstruction

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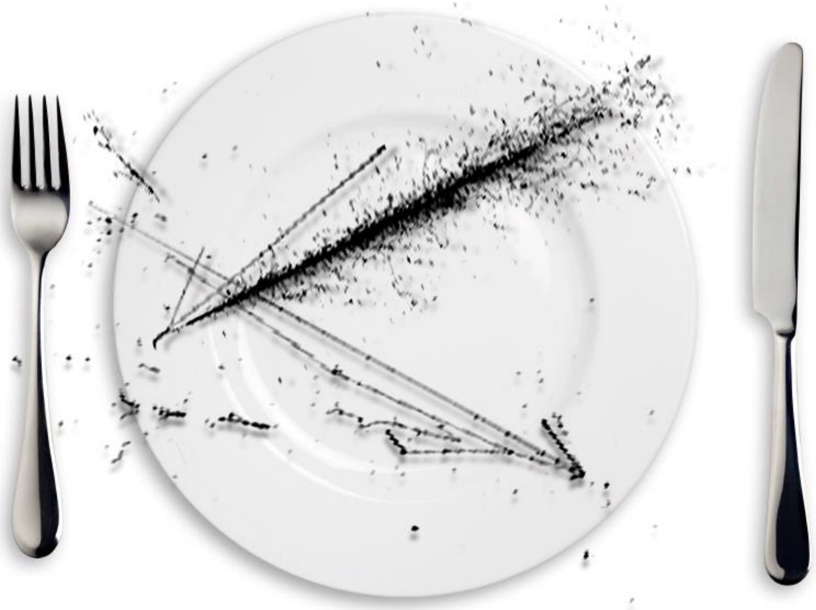
Connecting The Dots / Intelligent Trackers 2017

9 March 2017



Fermilab DUNE

Aim of the talk

- Very briefly about physics itself
- A bit more on neutrino detectors and what needs to be reconstructed: **very different from collider experiments**
- Overview ML applications:
  - main application here: **neutrino events**
  - main technology here: **LArTPC**
  - even this is a huge field… I will often limit to the case of the ν_e charge current interaction and its main background, but other examples are here as well
  - **the key is *imaging* nature of presented detectors**
  - there is non-neutrino physics as well.

Outline

- Physics goals
- Neutrino „imaging" detection technologies
  - Scintillators (NOvA)
  - Liquid Argon Time Projection Chamber (DUNE, MicroBooNE, LArIAT, …)
  - **Events as they are seen by detectors, not only neutrinos**
- **Event reconstruction**
  - standard, algorithmic approaches
  - **ML: reconstruction, event classification, future challenges**
- Summary

Physics goals

- NOvA, MicroBooNE (+ SBN programme) and DUNE are targetting many similar, neutrino-based physics goals.
- Exploration of *neutrino oscillations*:
  - send the beam of one ν flavor over some distance
  - look for that or another ν flavors appearing in the detector

  → flavor identification is the key issue

  → the other one is the ν energy: oscillations as f(E) is important

NOvA far detector in Ash River

image source: www-nova.fnal.gov

MicroBooNE detector at Fermilab

image source: vms.fnal.gov

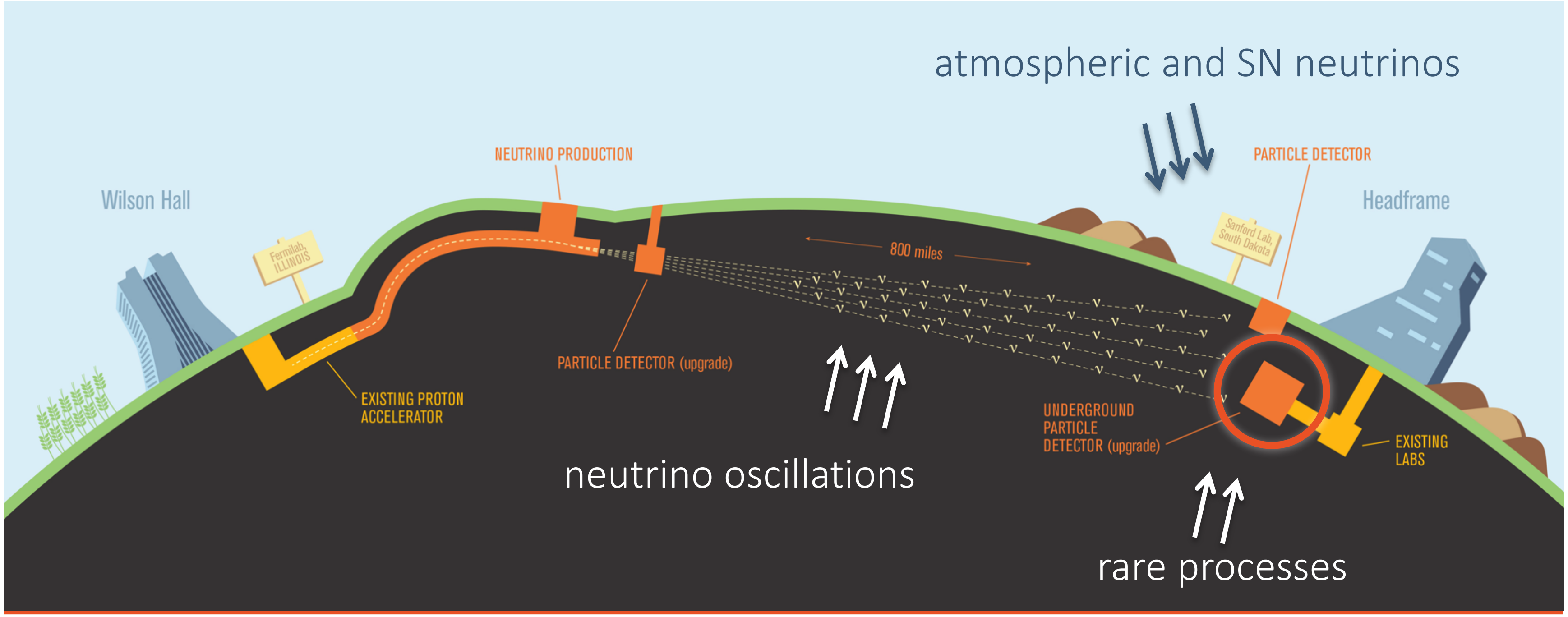
DUNE prototype at CERN

image source: Neutrino Platform

Physics goals (not only neutrinos)

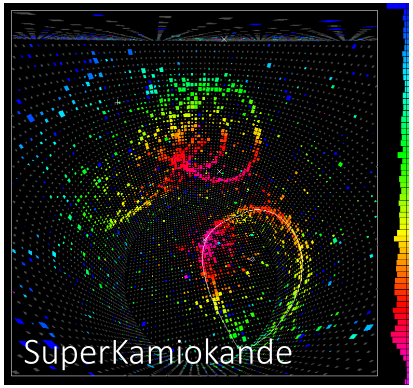
DUNE (Deep Underground Neutrino Experiment)

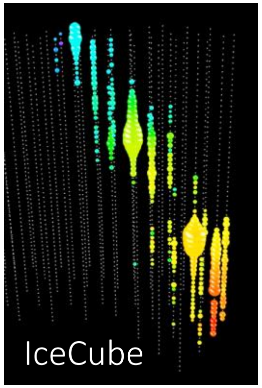
- Leptonic CP violation
- Neutrino mass hierarchy
- Supernova detection
- Nucleon decay
- Octant of ϑ_{23}
- Neutrino interaction physics
- Atmospheric and solar neutrinos
- WIMPs, monopoles...



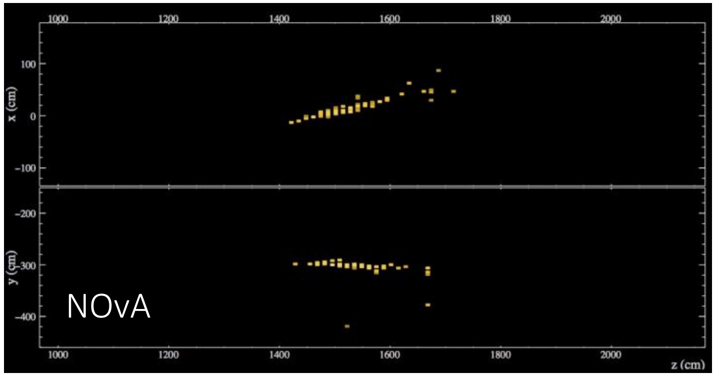
Imaging neutrinos

- Cherenkov (only for completness)
  - → not detailed particle tracks
  - → threshold on cherenkov light production
  - → but active mass really huge, 50kt, 420Mt



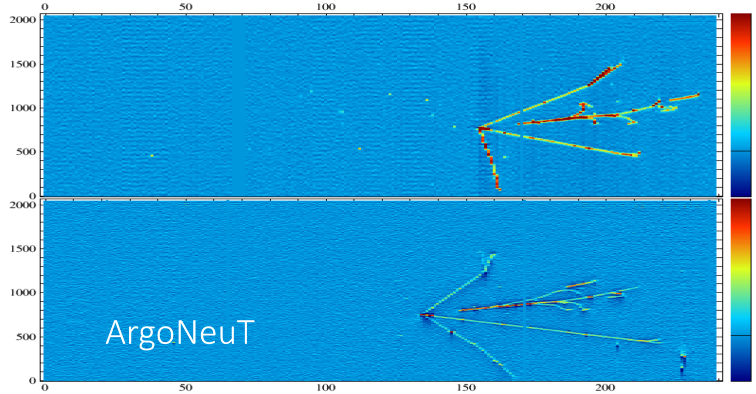


- NOvA Scintillators
  - → O(10 cm) vertex resolution, 2x 2D projections
  - → absolute t0 value for each energy deposition
  - → 14kt active mass
  - → ν_e selection: 76% purity / 73% efficiency
    [arxiv:1604.01444]



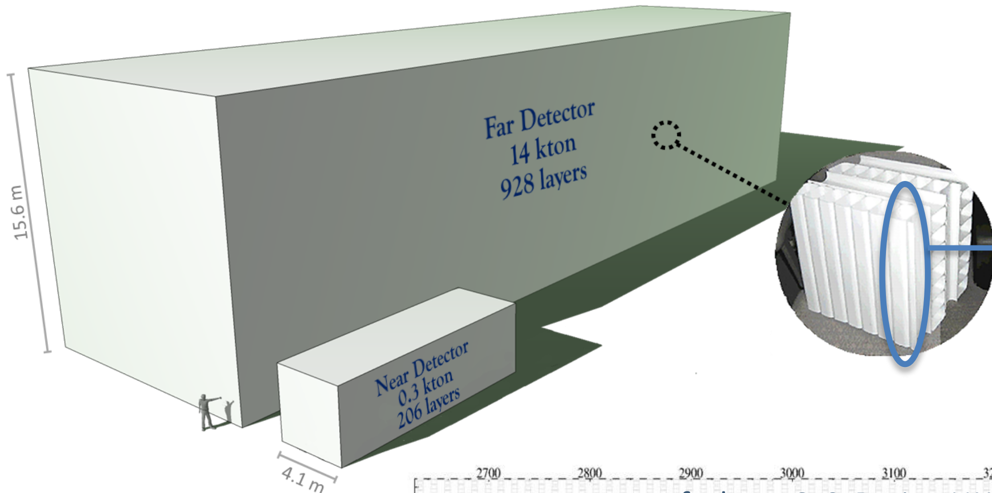
- LAr Time Projection Chambers
  - → O(mm) resolution, 2x or 3x 2D projections
  - → ~20-50MeV/c proton reconstructable

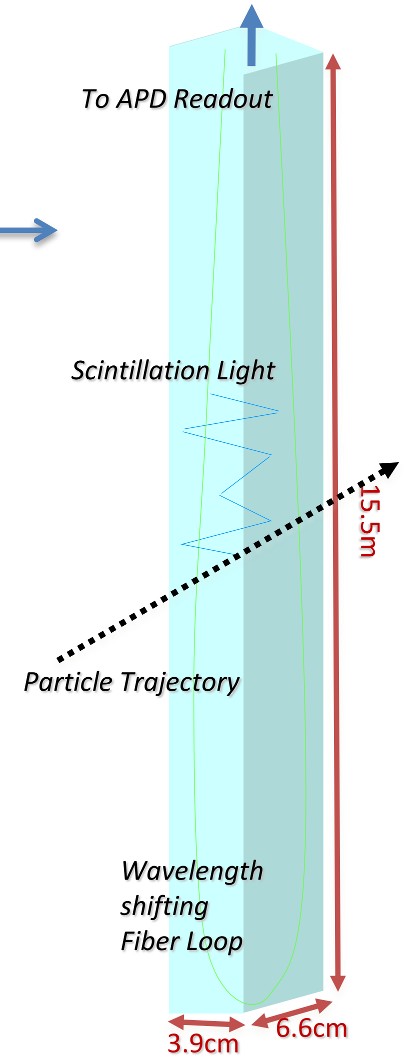
  e.g. DUNE target:
  - → 40kt active mass (4x 10kt modules)
  - → ν_e selection O(95% purity / 90% efficiency)



Imaging neutrinos: NOvA

source: www-nova.fnal.gov, J. A. Sepulveda-Quiroz, APS 11/04/2015 Meeting

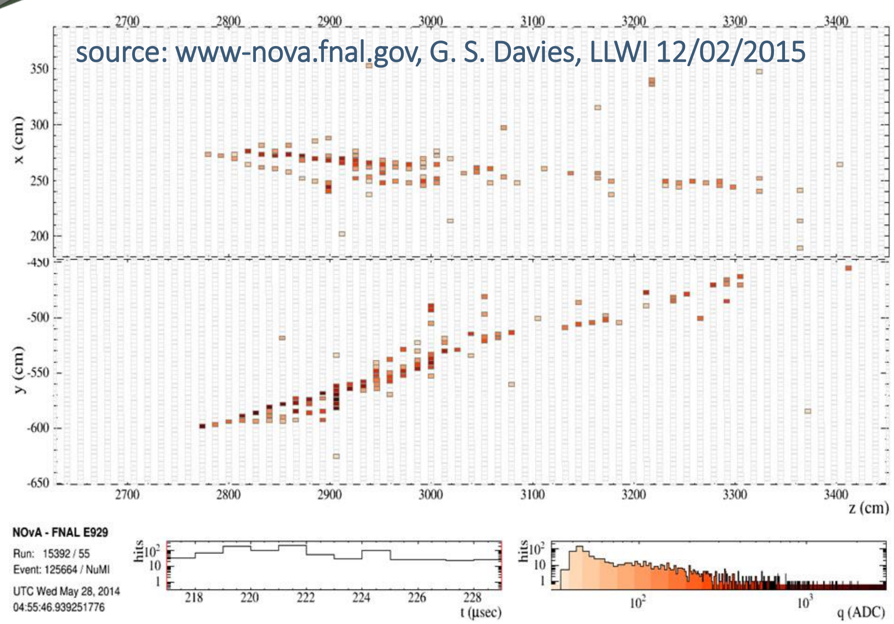




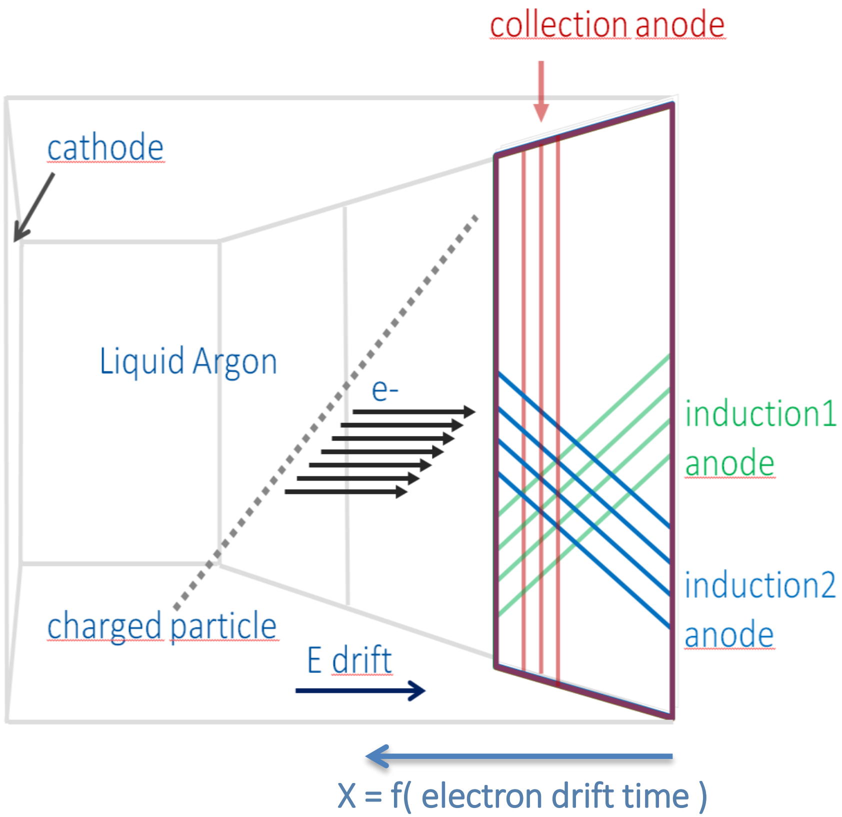
source: www-nova.fnal.gov, G. S. Davies, LLWI 12/02/2015

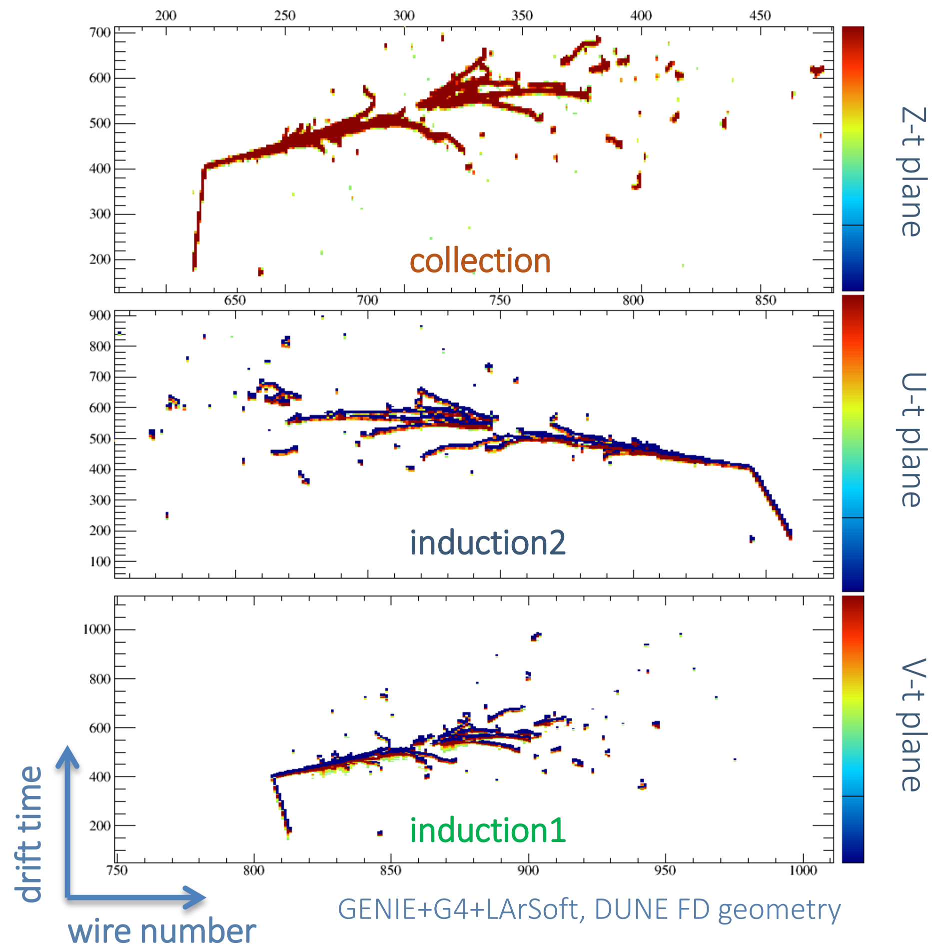
XZ-view

YZ-view



Imaging neutrinos: LArTPC





GENIE+G4+LArSoft, DUNE FD geometry

- multiple **2D views** show event as projected along readout wires/strips directions
- absolute t0 value by scintillation light (association to events in pileup can be hard)

Imaging neutrinos: DUNE

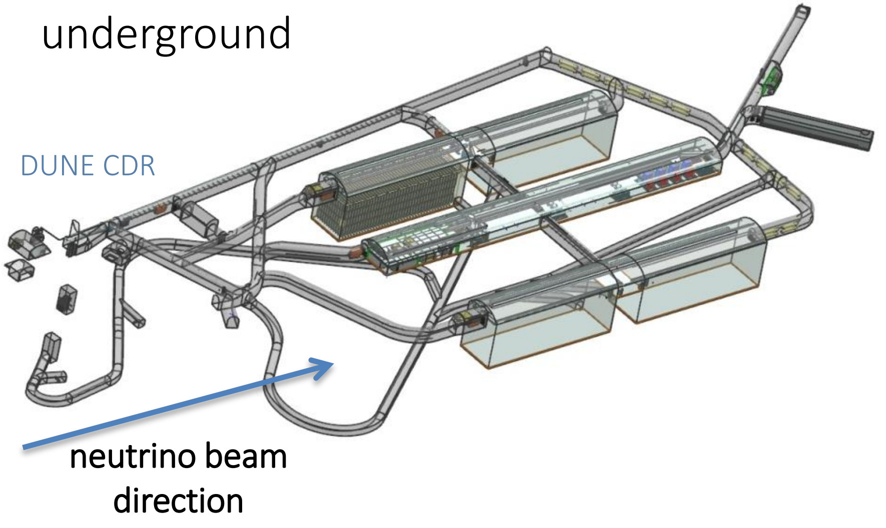
Prototypes at CERN: 2x 700t LArTPC

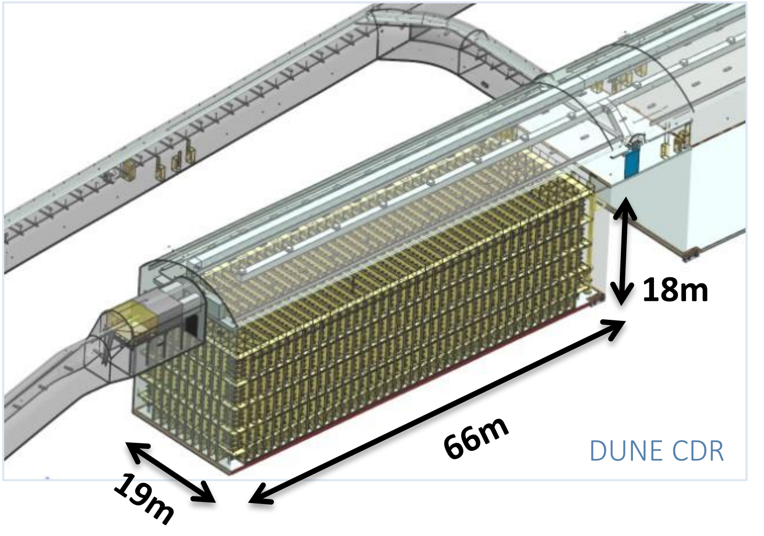
- two technologies: single- and double-phase
- actual components of far detector modules
- test beam of charged particles
- on surface: lots of cosmic rays

courtesy Neutrino Platform, CERN

Far Detector at SURF (US): 4x 10kt LArTPC

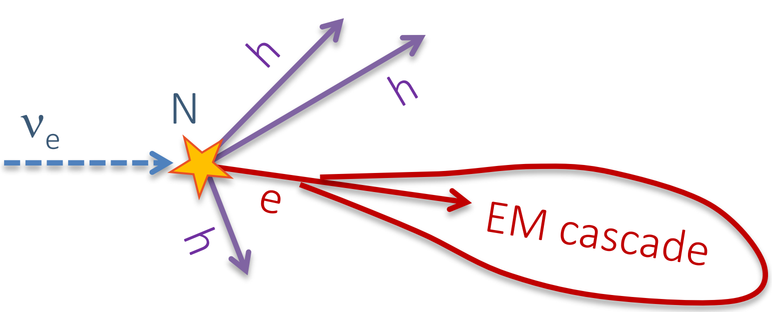
- each 10kt module is 20x prototype
- single- and double-phase
- underground



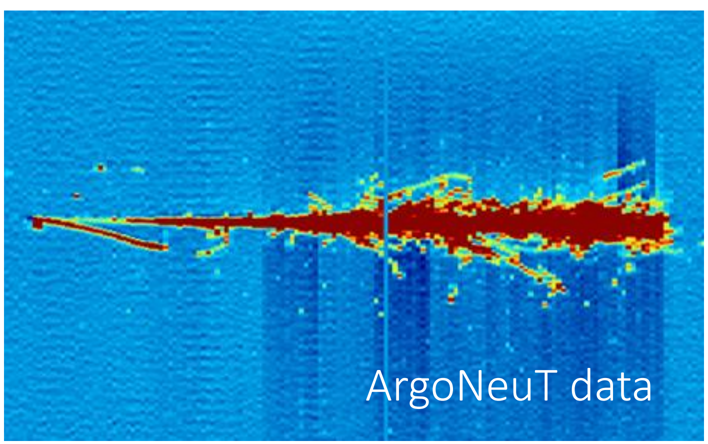


ν_e events vs background events

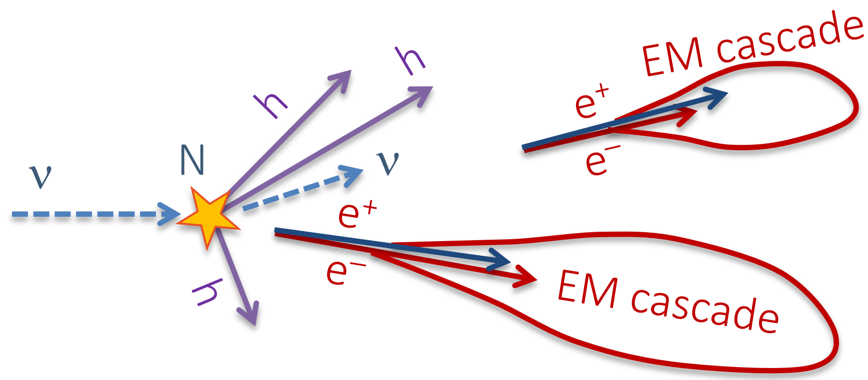
ν_e Charge Current



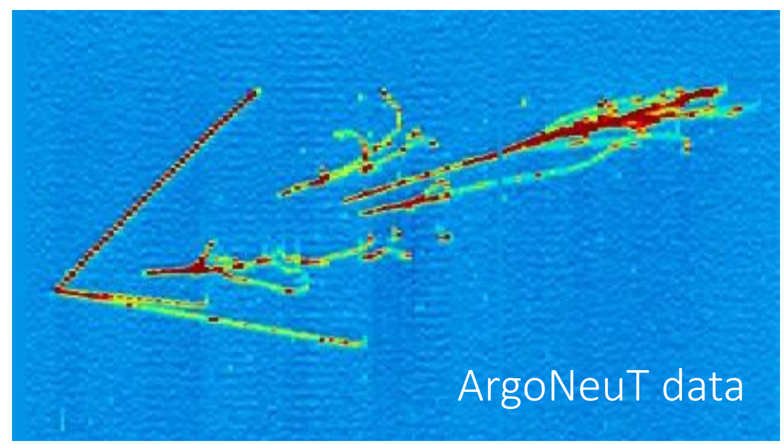
- single e (1 m.i.p.) track, then EM cascade
- e track directly from the interaction vertex



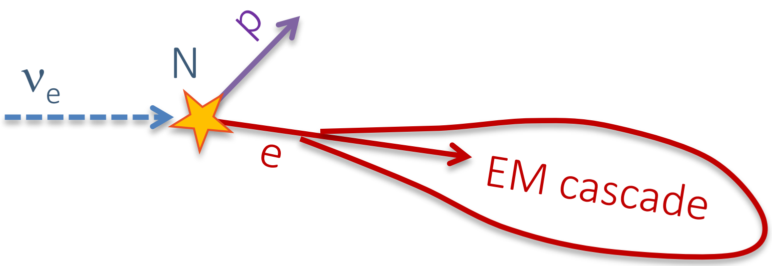
ν Neutral Current

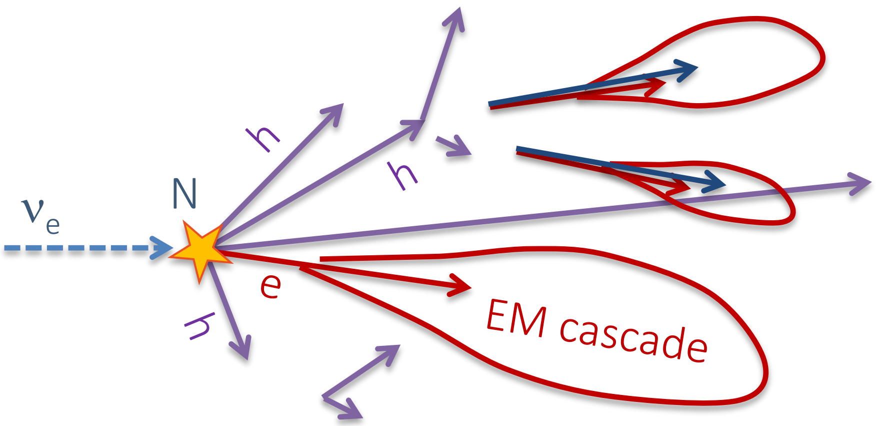


- e^+e^- pair (2 m.i.p.), then EM cascade
- e^+e^- pairs displaced from the vertex
- different also profile/shape of EM cascade



ν energy





- **quasi-elastic** events: simple topology
- electron cascade and stopping proton
- **energy from full kinematics reconstruction**

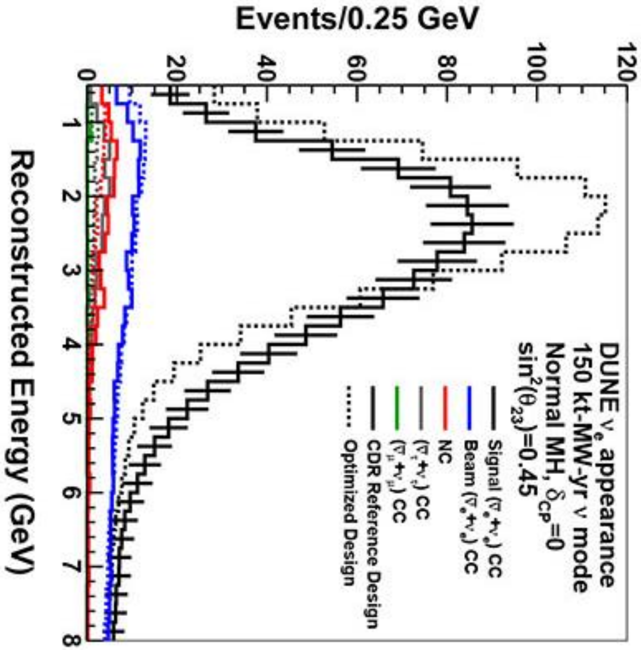
- **high-E**: crowded and complex events
- PID + kinematics impossible for each track
- **energy from calorimetric reconstruction**

not only vertex region details matter, **large-scale features** needed as well

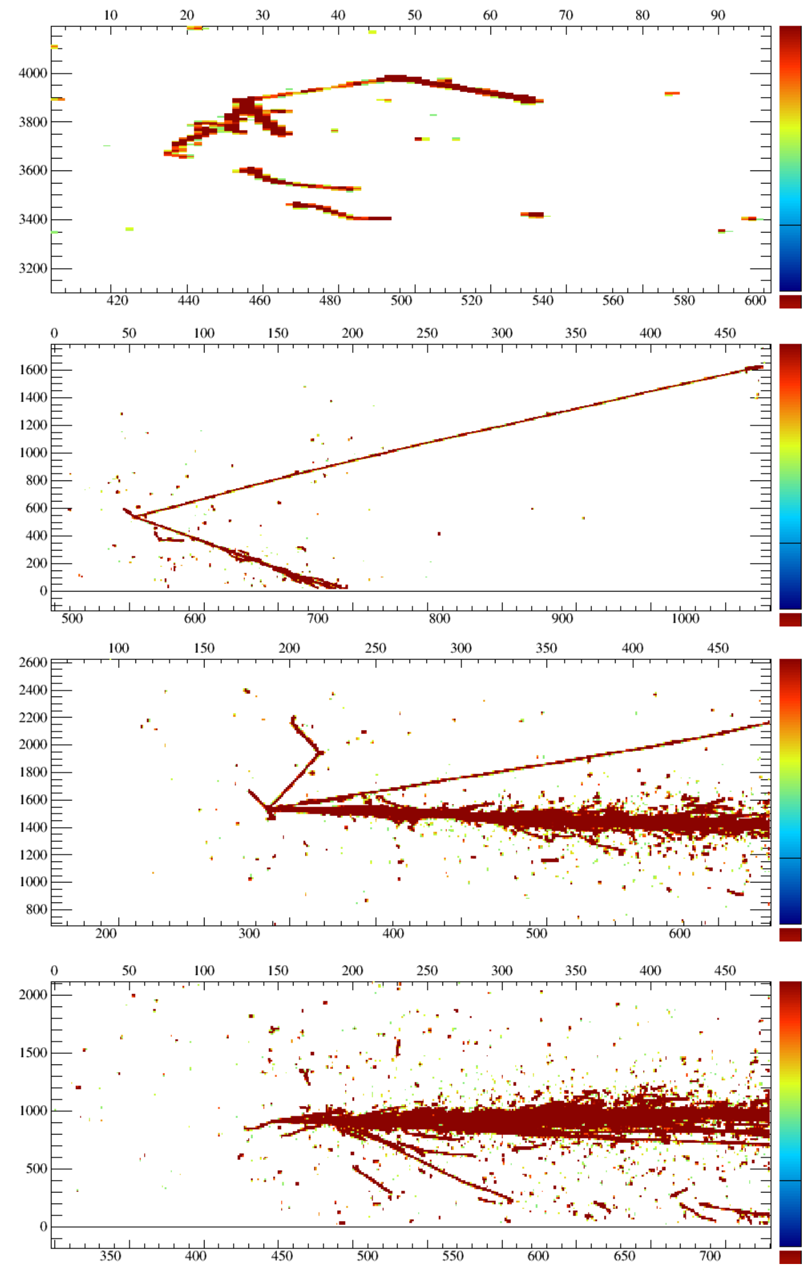
- PID, initial direction and trajectories for particles momenta reconstruction

- EM and hadronic components separation for calorimetry

DUNE energy range



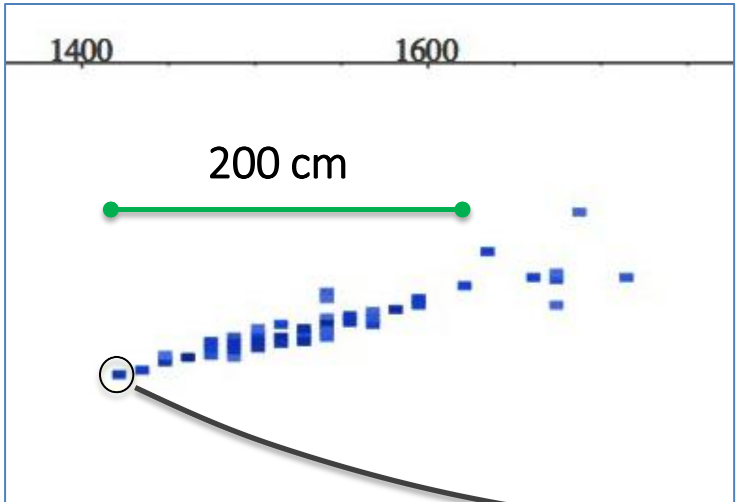
DUNE CDR



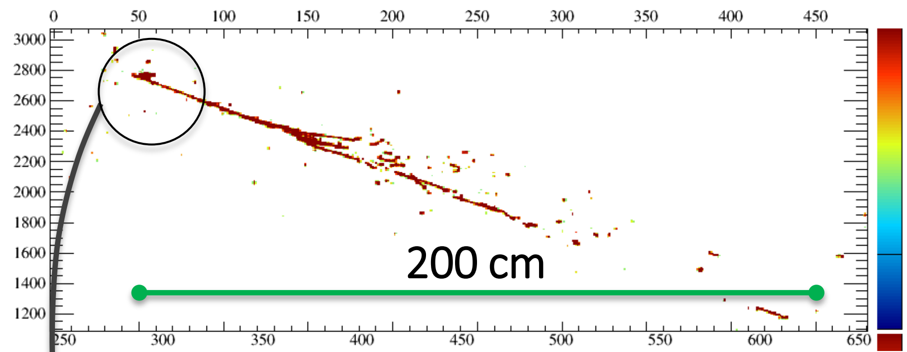
GENIE+G4+LArSoft, DUNE FD geometry

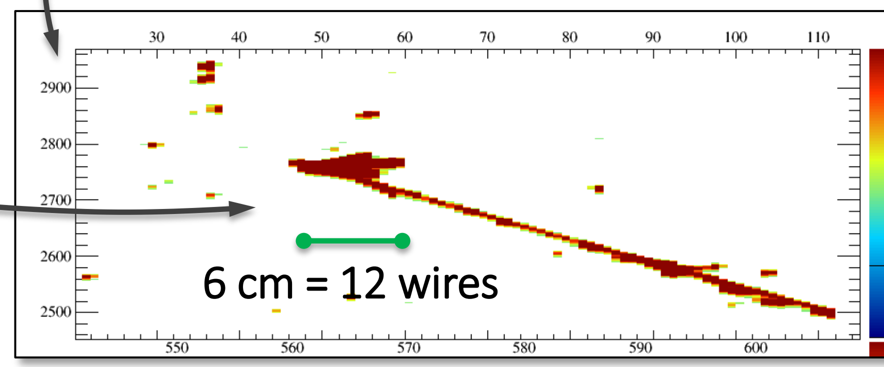
- Low energy
  → chaotic, sparse event fragments
- High energy
  → crowded vertex, overlapping fragments

ν_e events vs background events



NOvA ν_e candidate,
image source: www-nova.fnal.gov





ν_e sim. in DUNE FD, GENIE+G4+LArSoft

- LArTPC can look at the most discriminative features of the vertex region
- we need this to achieve maximum physics sensitivity
- but such enormous amount of information is not easy to digest
- LArTPC is famous for being hard for reconstruction

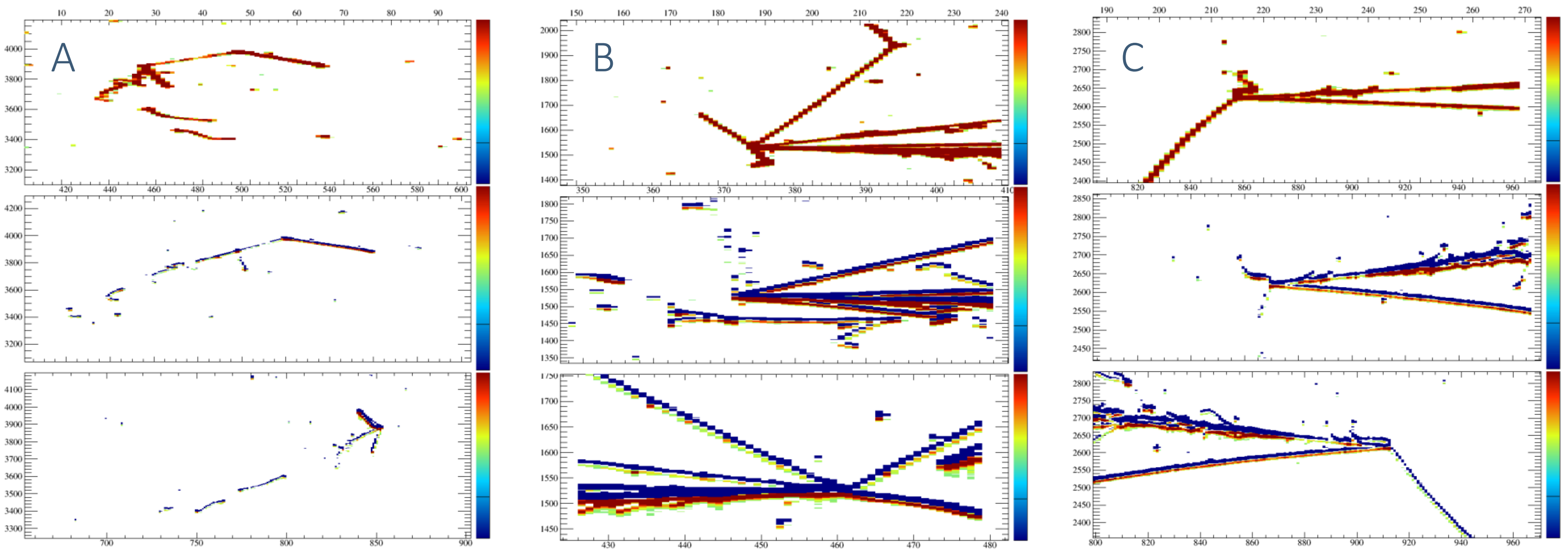
Many corner cases

→ makes the difference when looking for ~95% purity / ~90% efficiency selection

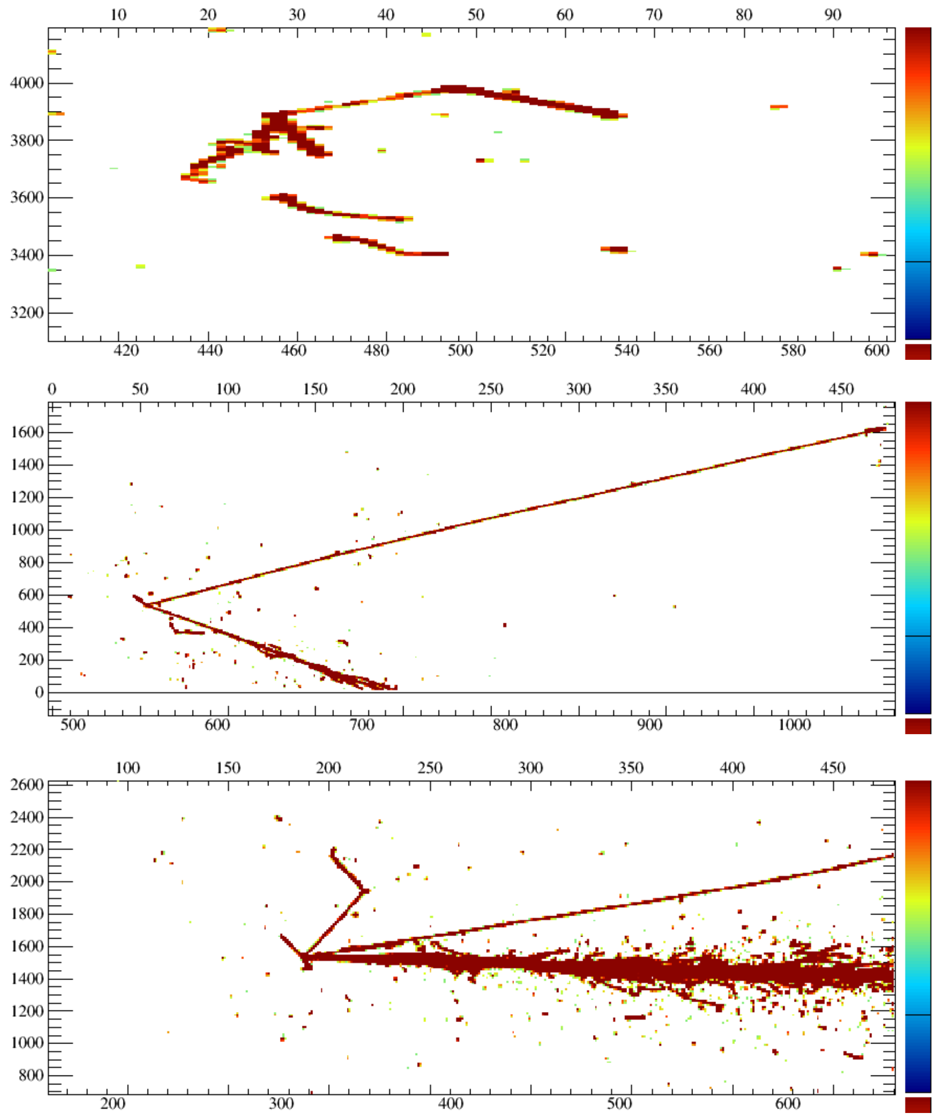
→ ...and per cent level systematics

- low energy electron (A)
- electron + π^0 induced cascades
- electron overlapped with other tracks (B)
- 2 electrons (C)
- ...and other configurations

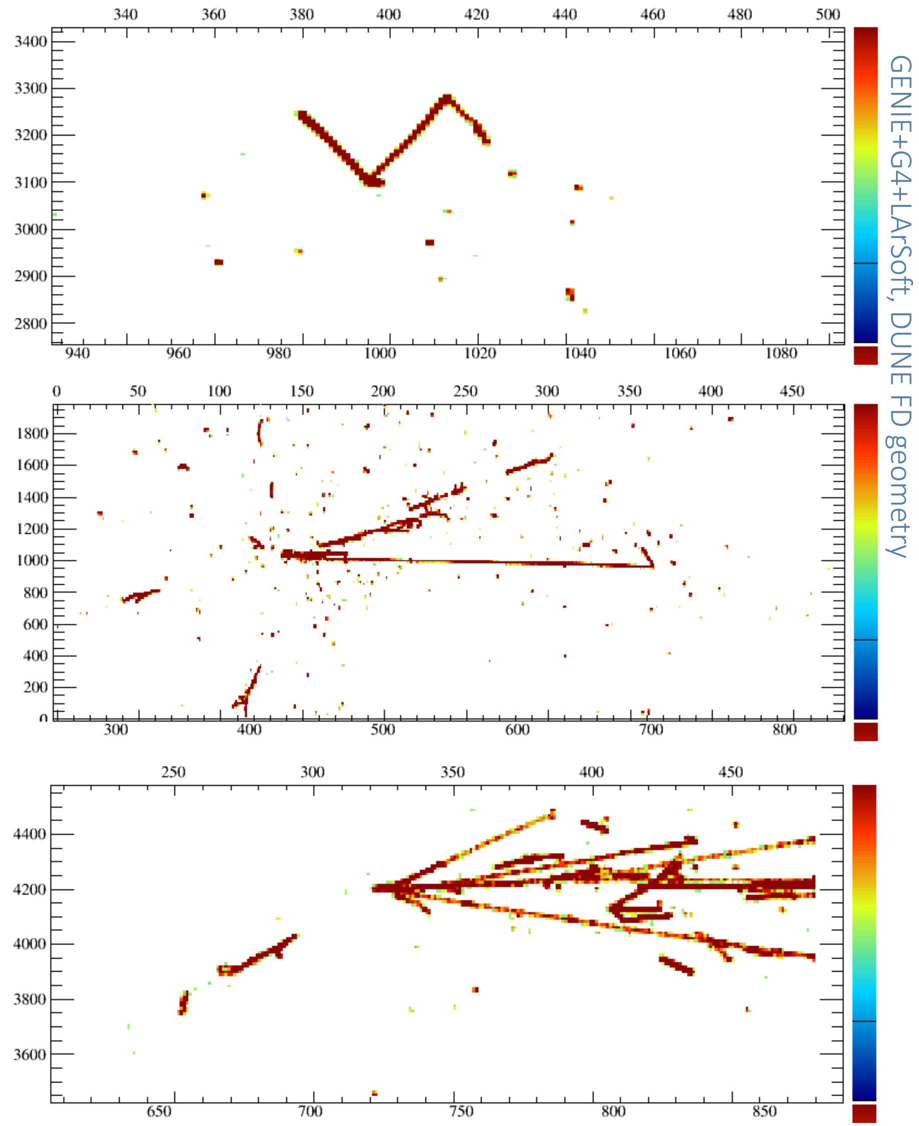
GENIE+G4+LArSoft, DUNE FD geometry



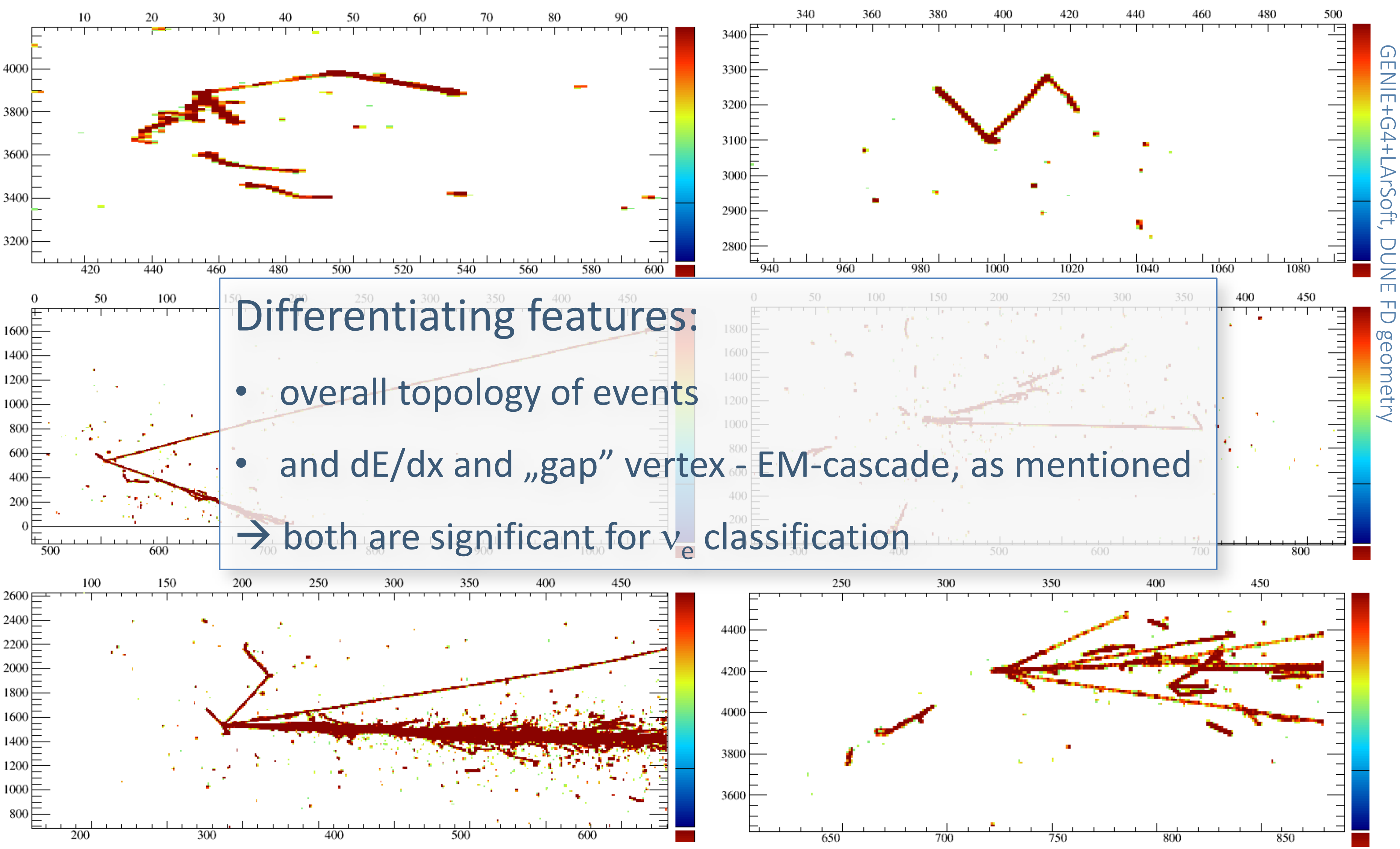
ν_e CC signal



ν NC background



ν_e CC signal ν NC background

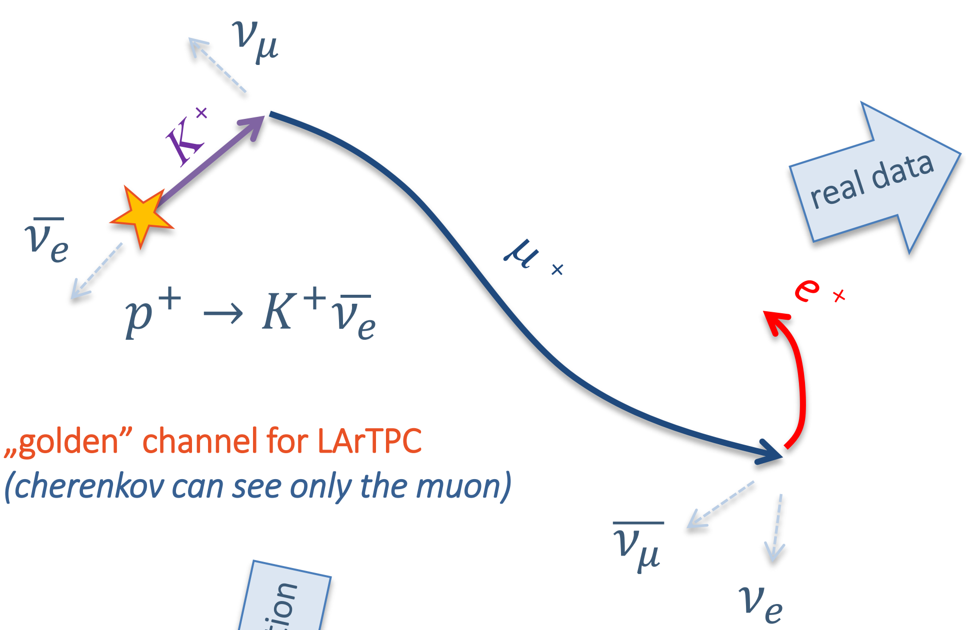


Differentiating features:

- overall topology of events
- and dE/dx and „gap” vertex - EM-cascade, as mentioned

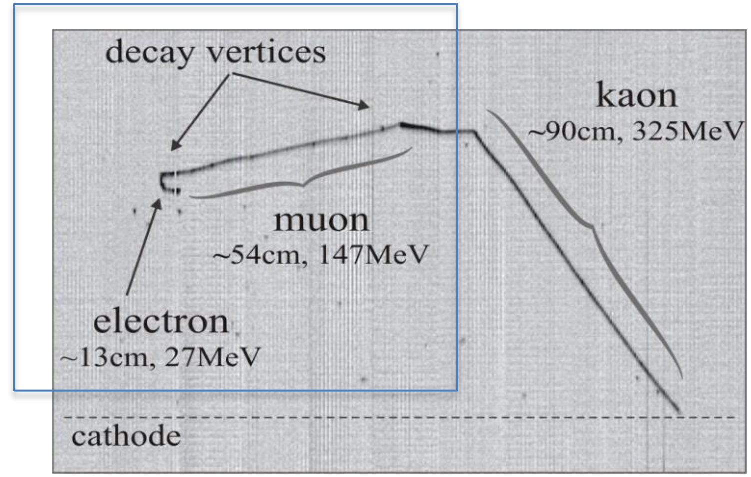
→ both are significant for ν_e classification

Proton decay



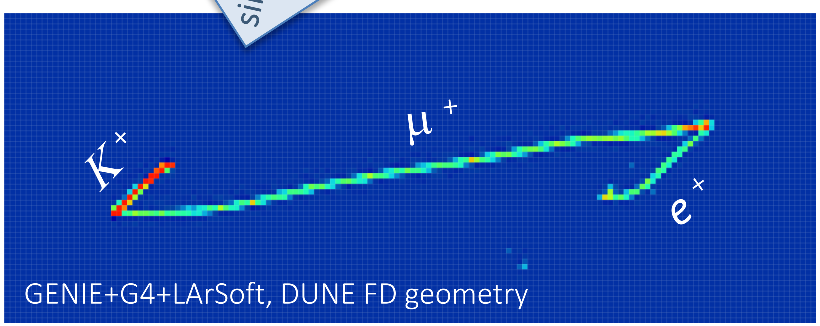
„golden" channel for LArTPC

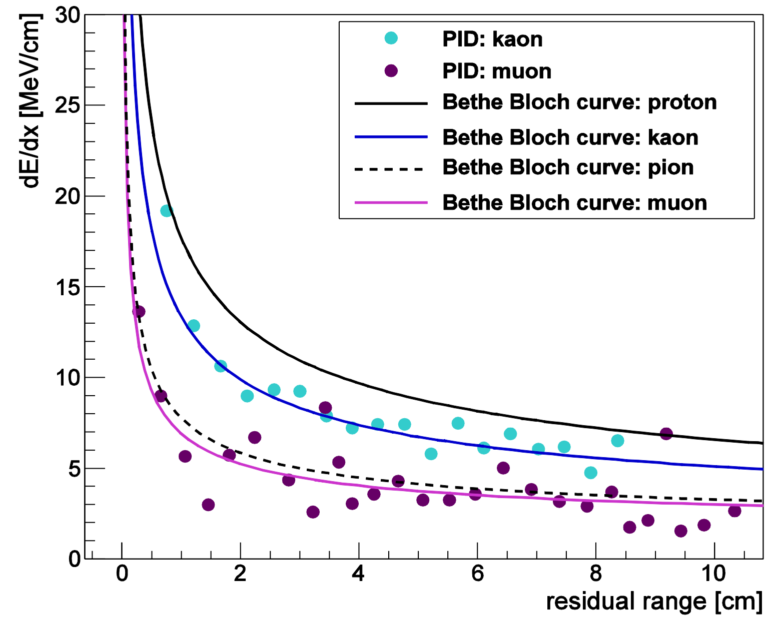
(cherenkov can see only the muon)



Kaon candidate decay in CNGS beam data

source: AHEP, article ID 260820





- characteristic topology features: dE/dx, decays
- even simple geometrical rotation can make it hard

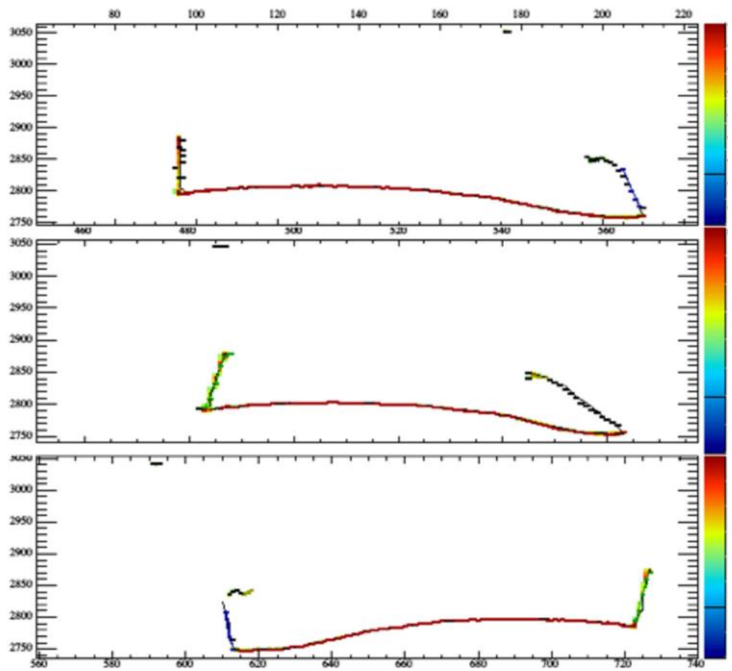
Proton decay

„Golden” channel for LArTPC:

$$p^+ \rightarrow K^+ \overline{\nu_e}$$

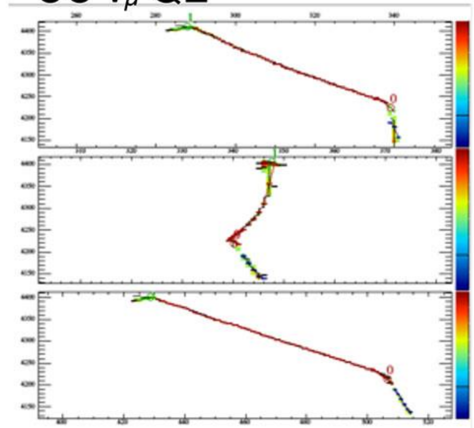
$$K^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$$

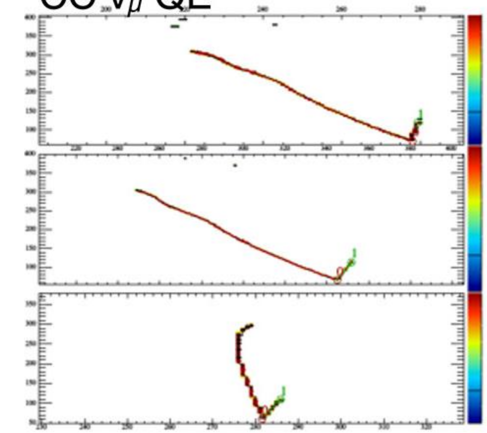


Atmospheric neutrino interactions:

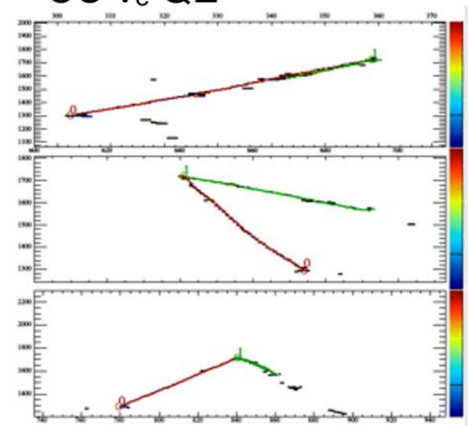
CC ν_μ QE



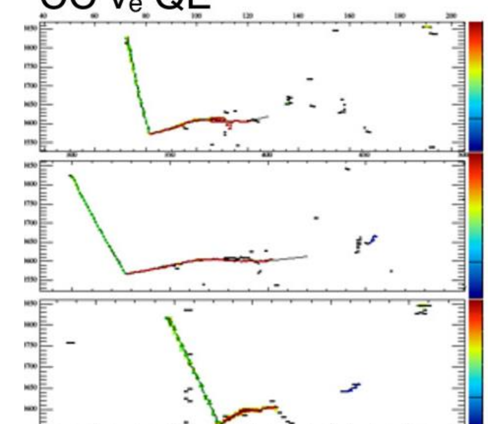
CC ν_μ QE



CC ν_e QE



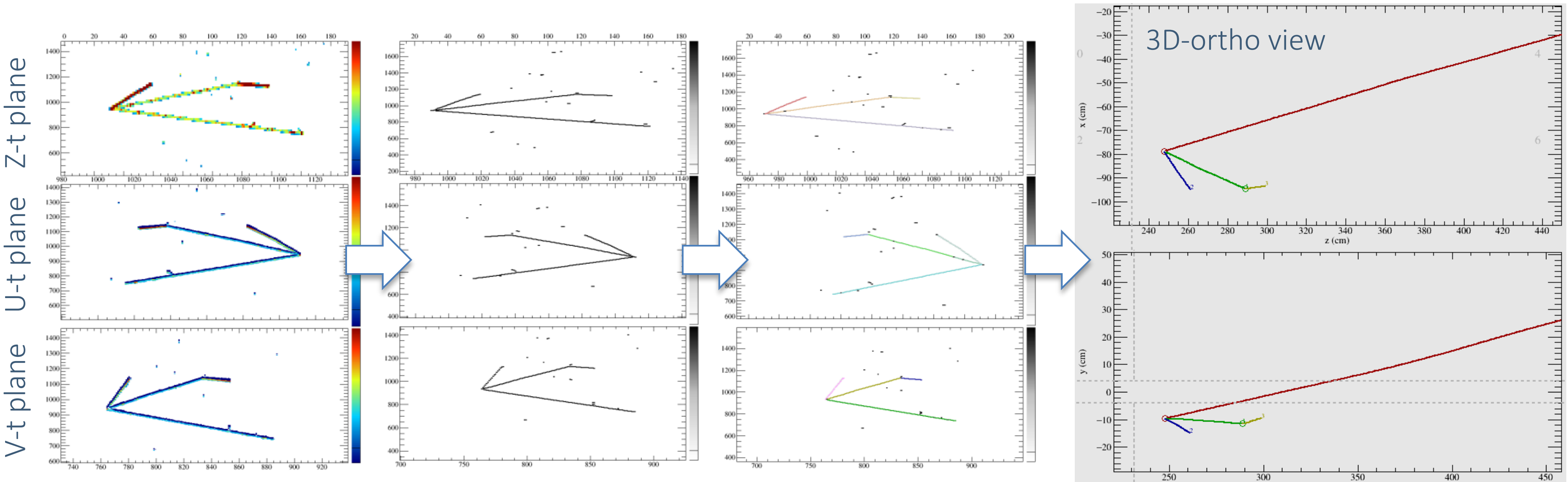
CC ν_e QE



sim: GENIE+G4+LArSoft, reco: TrajCluster + PMA, DUNE FD geometry   courtesy A. Higuera

Event reconstruction: *standard* algorithmic approach

2D ADC → 2D hits → 2D objects → 3D structures → PID & energy



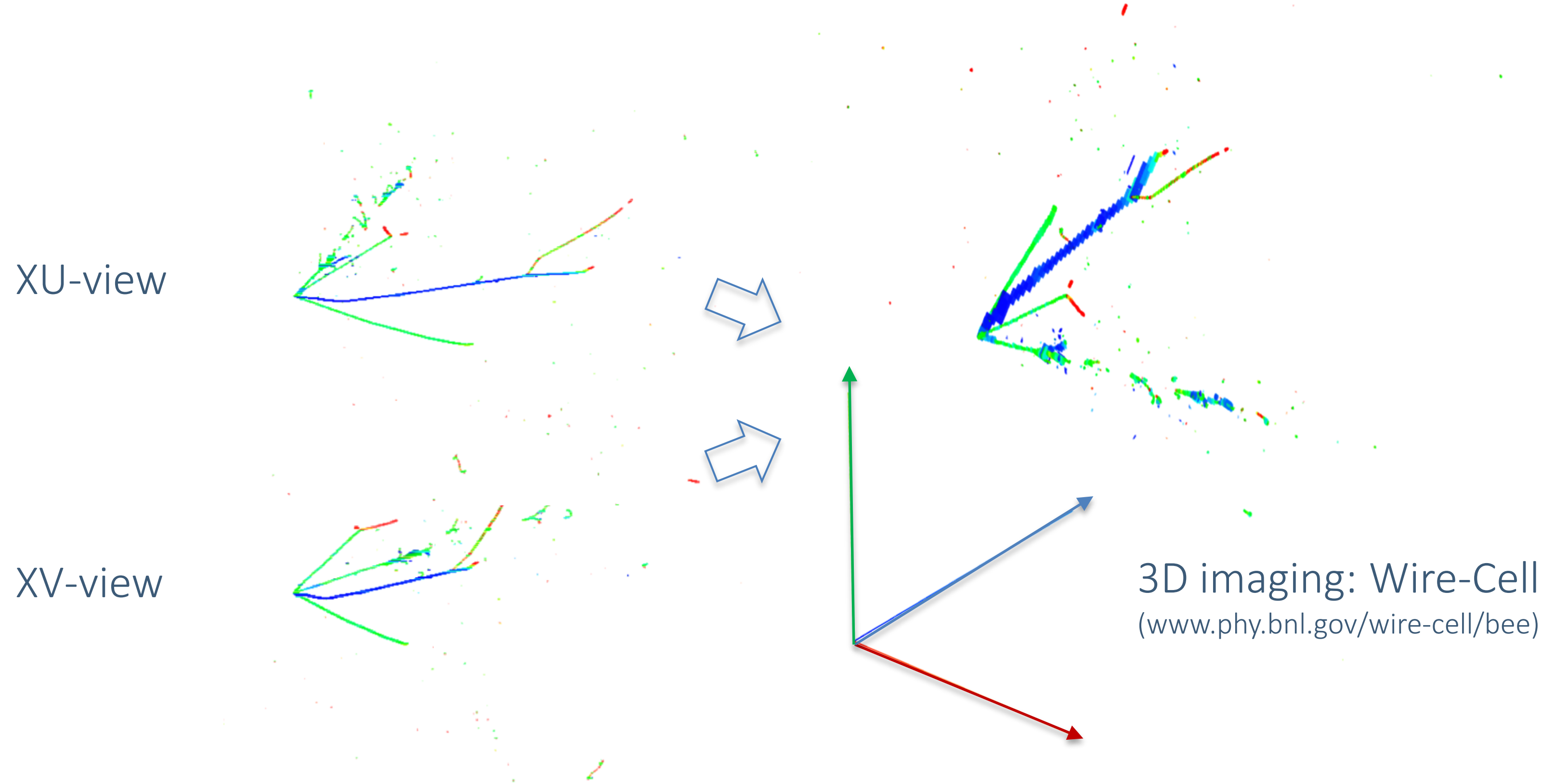
sim: GENIE+G4+LArSoft, reco: gaushit + linecluster + PMA, DUNE FD geometry

Here: trivial topology for illustration, all tracks/vertices correct, but LArTPC can be hard!

- dense medium – multiple scattering, secondary interactions
- **unlike colliders:** no fixed interaction location, no hits ordering, no event direction in non-beam physics
- „special" orientations in LArTPC: isochronous, along drift, along readout wire
- difficult pattern recognition of low energy and/or multiple EM cascades
- **long chain of pattern reco / 3D reco algorithms prone to inefficiency accumulation**

Event reconstruction: *standard* algorithmic approach

2D ADC → 3D imaging → 3D objects → 3D structures → PID/energy



Pattern recognition in this case starts from 3D points – less ambiguous than 2D projections

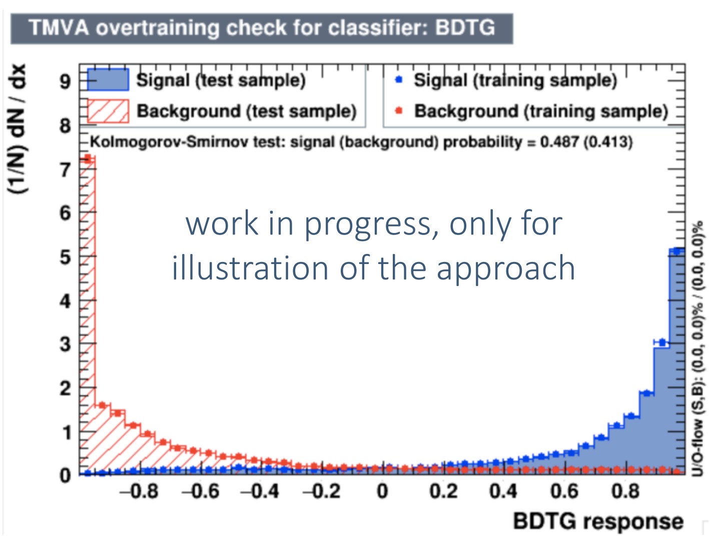
- however, difficulties of angular dependencies of LArTPC still apply
- **also in this case: chain of pattern recognition, tracking and vertexing algorithms to be applied**

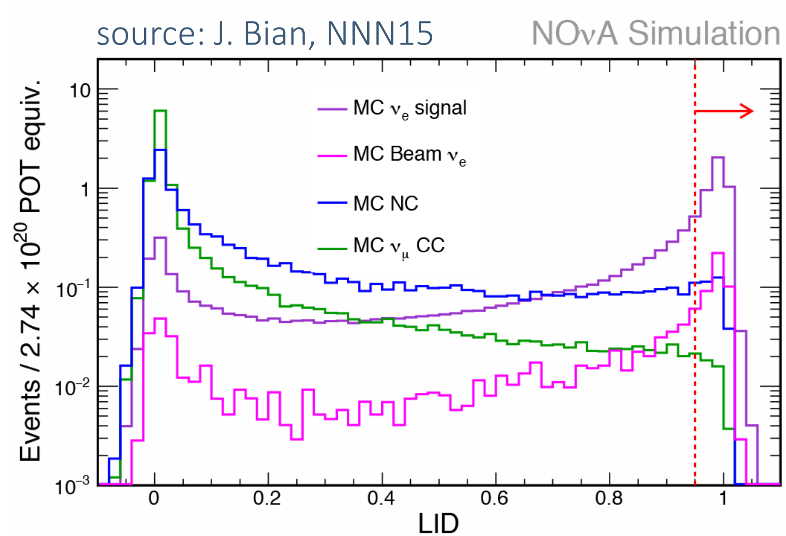
MVA on *reconstructed* events

Examples: BDT for ν_e selection in DUNE FD, LID in NOvA

Input: *high level* features of reconstructed objects: vertices, tracks, showers, calorimetry.

- DUNE's BDT (Boosted Decision Trees):
  - 30 input variables in total in DUNE selections
  - captures features of an overall event topology and calorimetry
  - still can miss significantly discriminative features of the interaction vertex
- NOvA's LID (Likelihood IDentification):
  - ANN applied to the reconstructed topology features



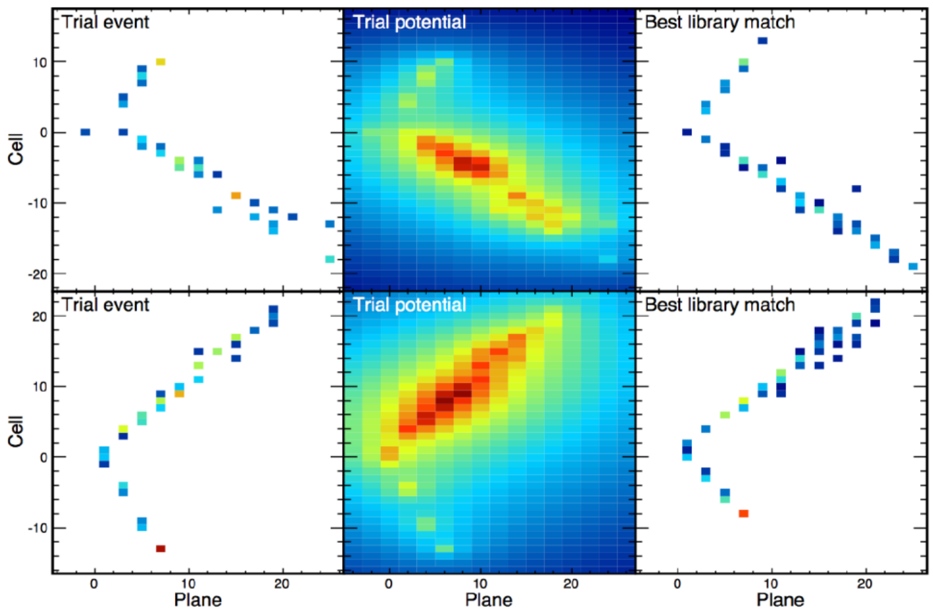


Step towards raw data

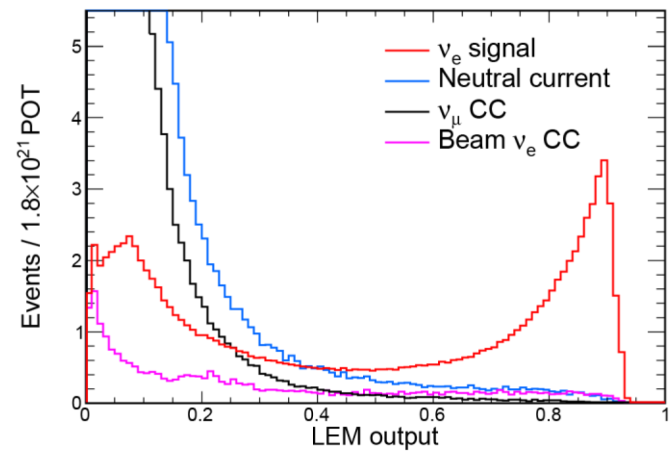
Library Event Matching (LEM) for ν_e selection in NOvA

Input: map of energy deposits, no higer level reconstruction variables.

- Trial potential constructed from an event energy deposits
- 77M simulated events in the library to compare to
- 1k best matches from the library → *5 low level* features + tested event calorimetry → input to decision tree for the final classification



source: NIM A778 (2015) 31-39



source: NIM A778 (2015) 31-39

ML using *raw* 2D projections

- ROI: localization of a particle or interesting interaction
  → on-surface detectors need such *a helper* functionality
- classification of an interaction visible within the image
  → all-at-once, no intermediate reconstructions between *raw* and *goal*
- classification of an individual particle in the image
  → more informed decision about event ID, need some pre-reconstruction
- pixel-level event feature labeling
  → guide simple high-level reconstruction or use for target feature detection

- and next challenges: full objects segmentation in 2D / 3D, …

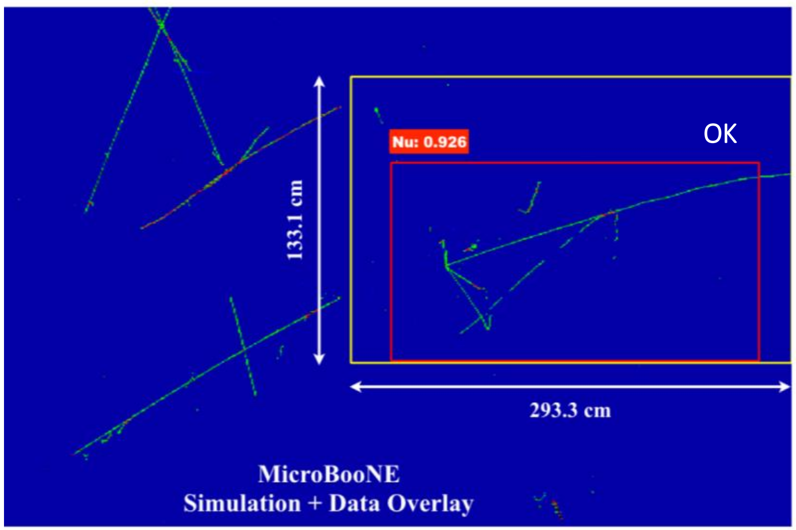
Localization of particles or interactions

Extensive studies of CNN and RNN applications to LArTPC by MicroBooNE

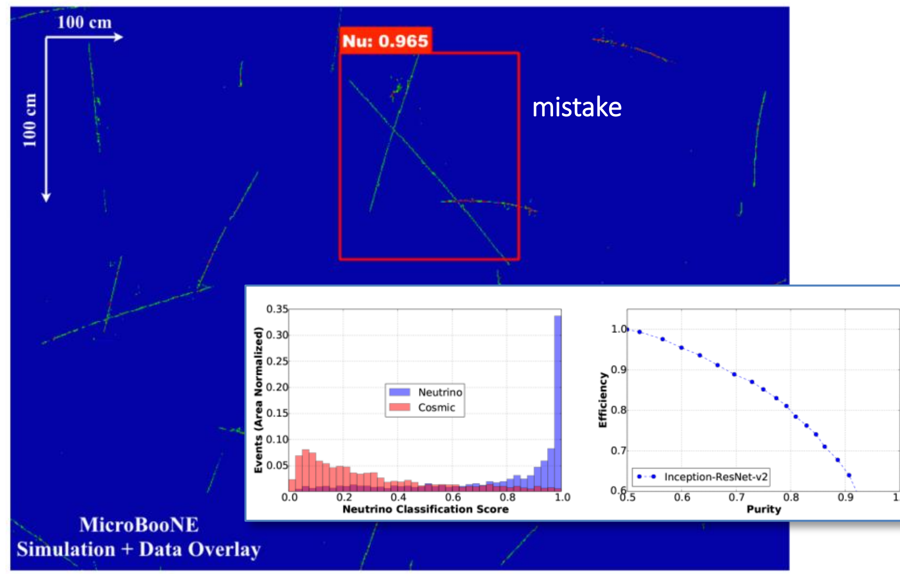
JINST 11 (2016) no.09, P09001

on-surface LArTPC detectors suffer from cosmic muons pileup: drift time ~ms / event

- identify events with the ν interaction among cosmic muon tracks
- select region of the ν interaction



source: JINST 11 (2016) no.09, P09001



source: JINST 11 (2016) no.09, P09001

N.B: 2D shows *some* topology features, while dE/dx is only available in 3D domain,

valid on this and following slides

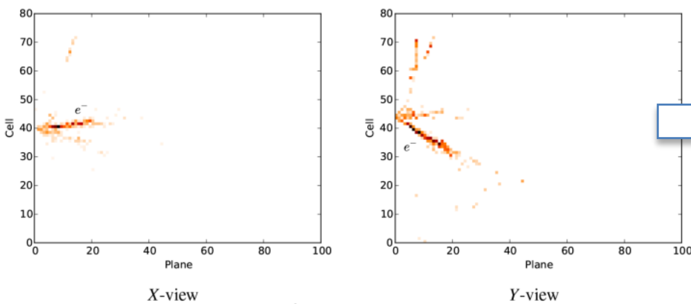
Interaction classification

Examples: CVN in NOvA, and the same tool used now in DUNE for ν_e selection

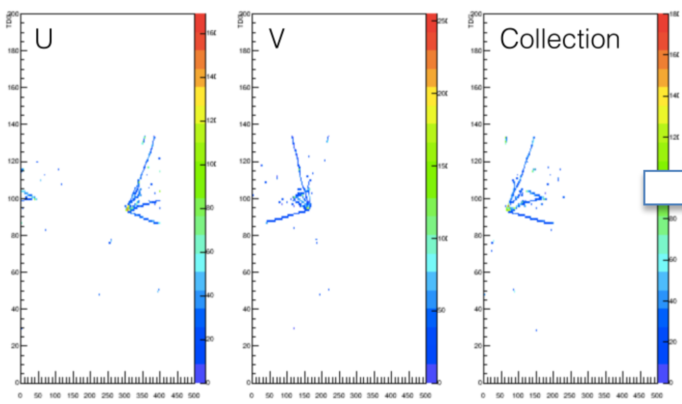
Input: image-like raw charge in 2D projections (NOvA), ADC at 2D hit positions (DUNE)

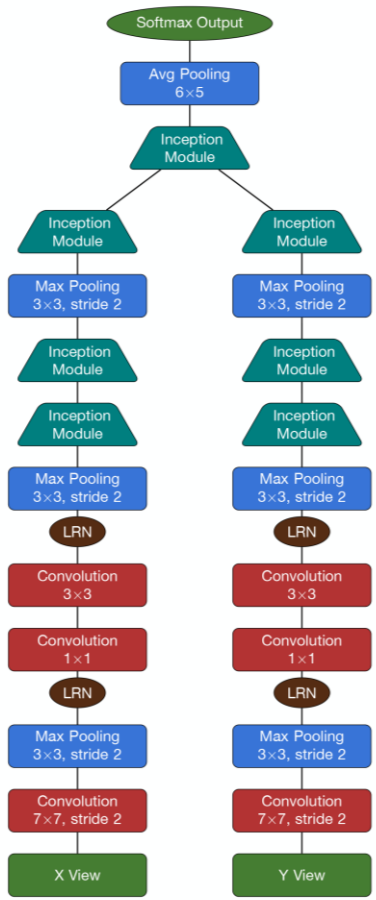
NOvA:

2016 JINST 11 P09001

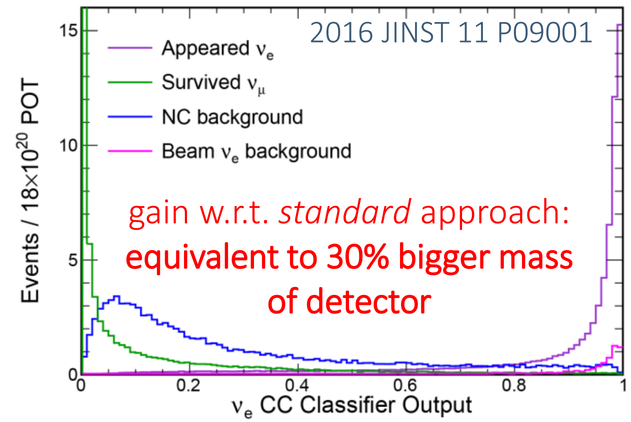


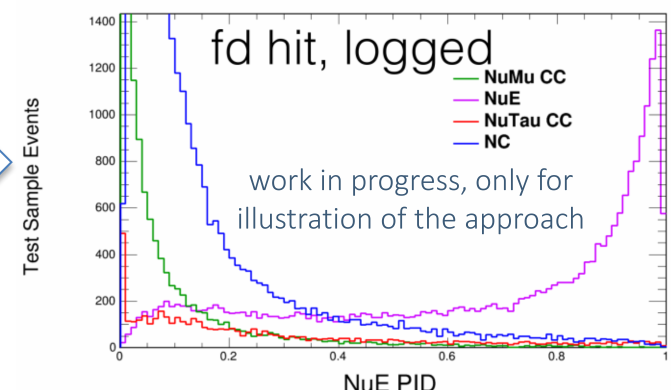
DUNE:





reconfigured GoogLeNet, Caffe toolkit
2016 JINST 11 P09001



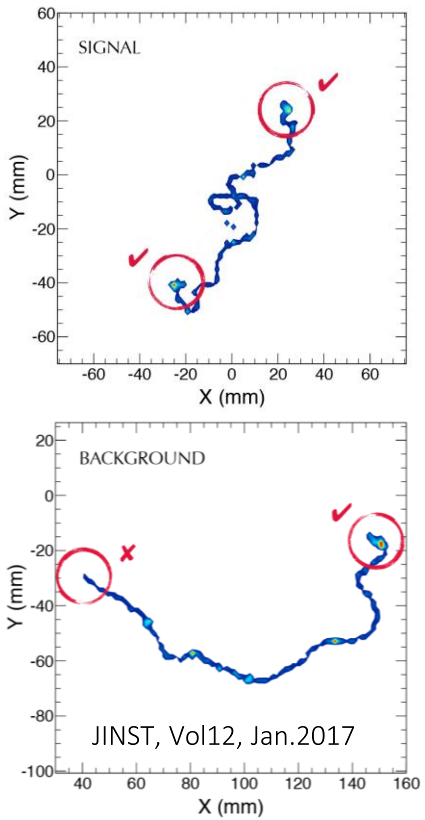


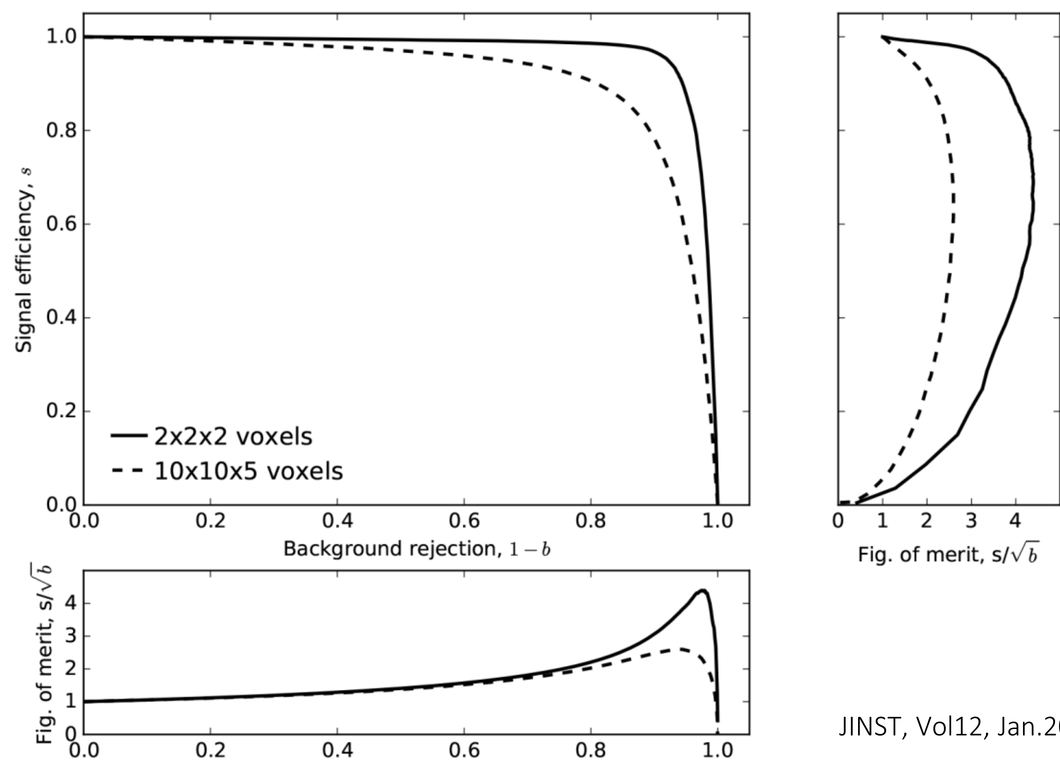
Interaction classification

Example: NEXT, neutrino-less double beta decay selection [JINST, Vol12, Jan.2017]

Input: 2D projections (NEXT is also TPC, but high pressure Xe gas instead of LAr)

- NEXT aims for **3D readout** (*xy* array of SiPM and time for *z*), here projected to 2D images
- GoogLeNet used, 1.2-1.6 improvement in bkg. rejection over standard approach





JINST, Vol12, Jan.2017

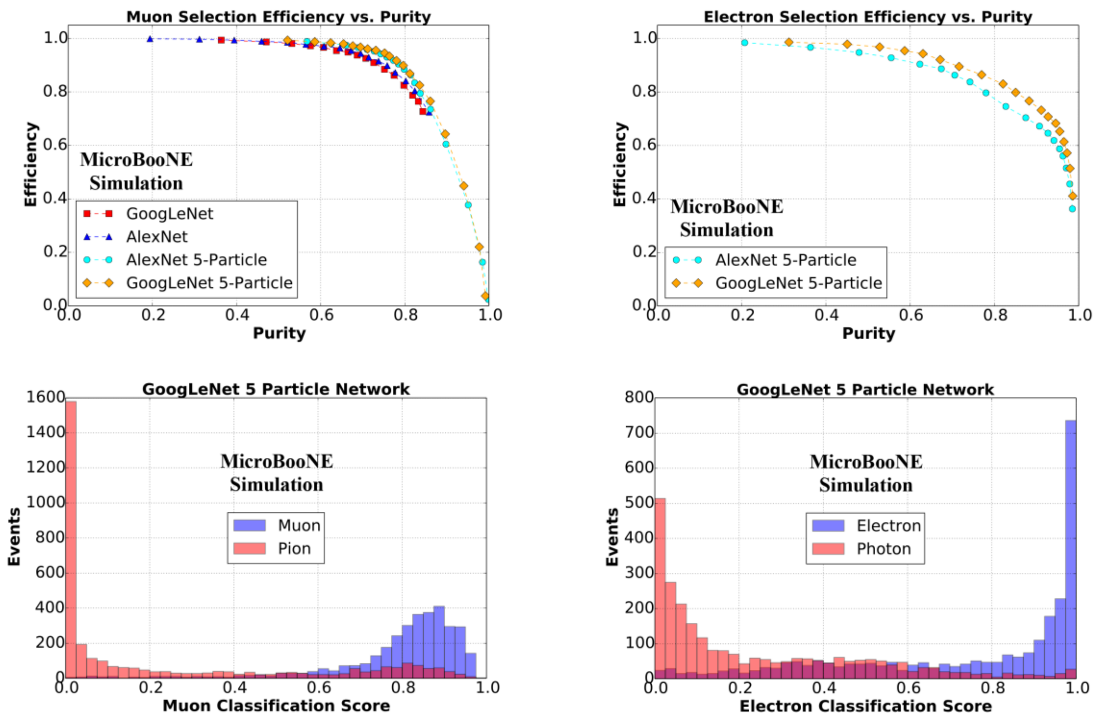
Classification of single particles

Extensive studies of CNN and RNN applications to LArTPC by MicroBooNE

JINST 11 (2016) no.09, P09001

can be step forward better understanding the whole event classification decision

- single μ^- vs single π^- - similar track features, pions interact, muons stop
- single e^- vs photon conversion - EM cascades starting with 1m.i.p. (e) or 2m.i.p. (γ)

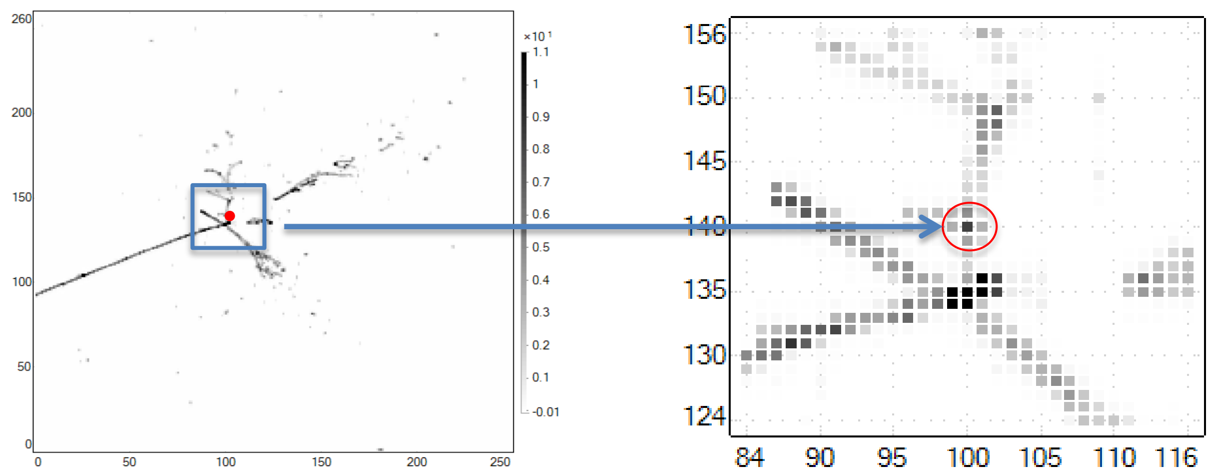


source: JINST 11 (2016) no.09, P09001

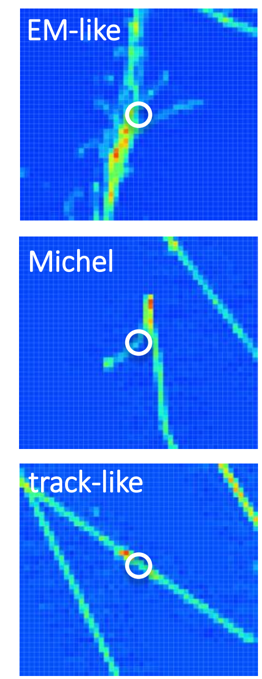
Event feature labeling (DUNE/ProtoDUNE)

Try to solve inefficiencies where they appear: in the low level pattern recognition.

- labeling on the level of **individual pixels**



Example input patches:



LArSoft, ProtoDUNE

- context provided to CNN large enough to classify the point
- ...and small enough to be relatively independent from the event type
- can combine high/low resolution patches, or use of multiple views if points associated

Event feature labeling (DUNE/ProtoDUNE)

- simple logic applied to per-pixel-output in multiple views
  - obtain segmentation
  - select interaction points
- easily combined with existing algorithmic approaches
  - e.g. clustering adds reliable information on long-range objects
- less coupled to the correctness of the full event simulation
  - little effect if MC is wrong about e.g. partilce multiplicity
- models more simple, data volumes lower than for entire event processing
- but still looking at 2D only (today…)

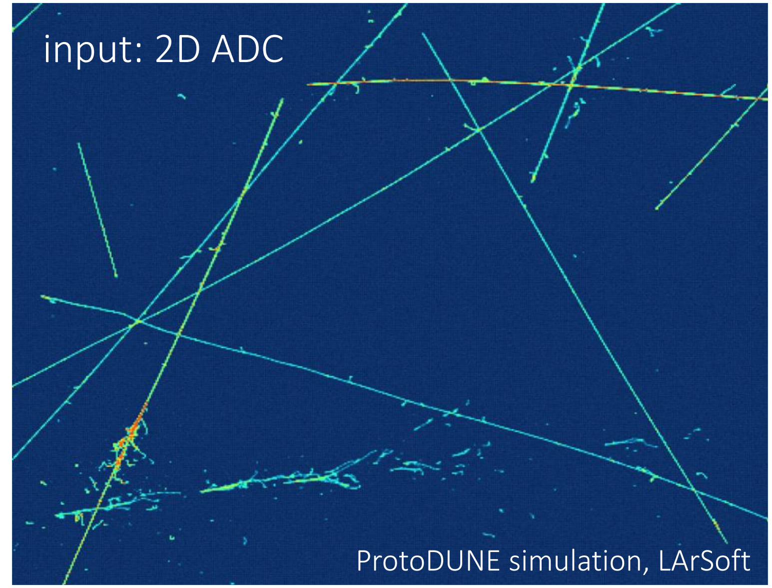
Event feature labeling

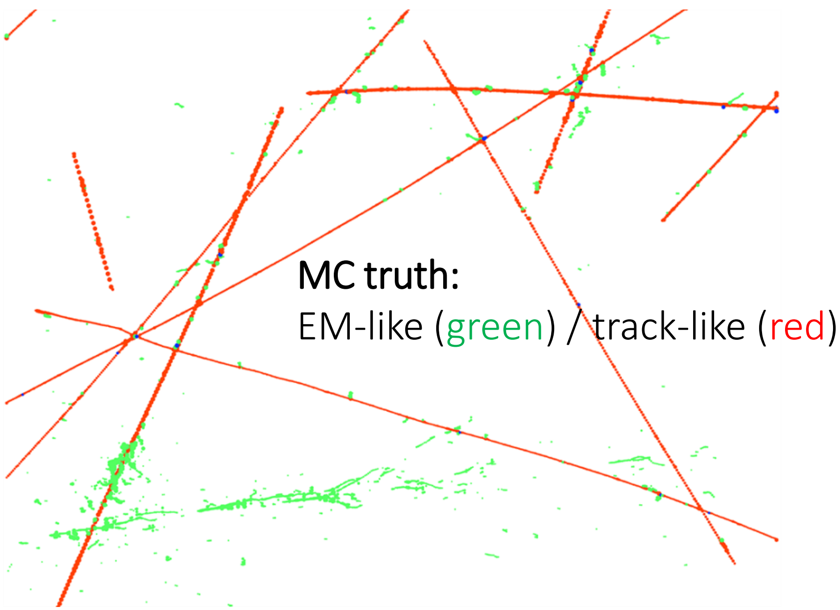
EM-like vs track-like activity separation

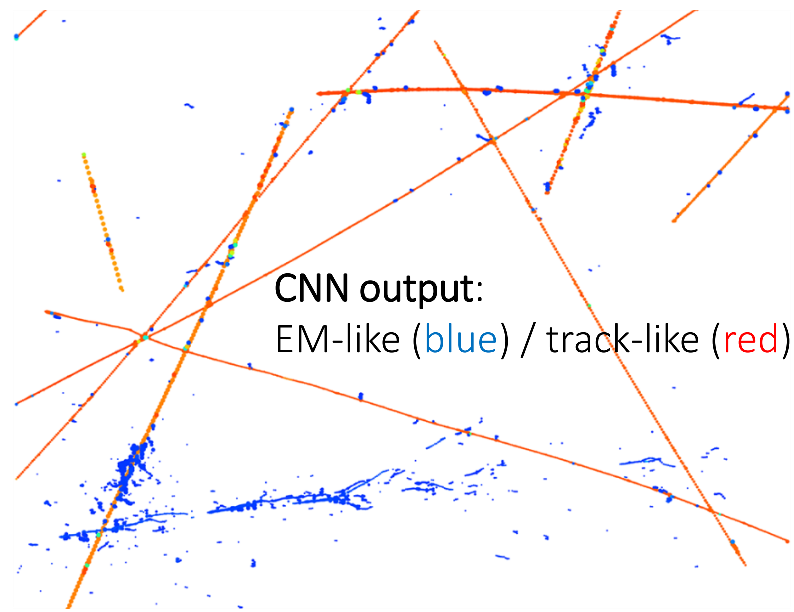
- prerequisite for most LArTPC reconstruction tasks
- one of problems proven hard to deal with algorithmic approaches:

  easy for an eye looking at raw image, but not for an algortithm looking at hits.

- already *in use*





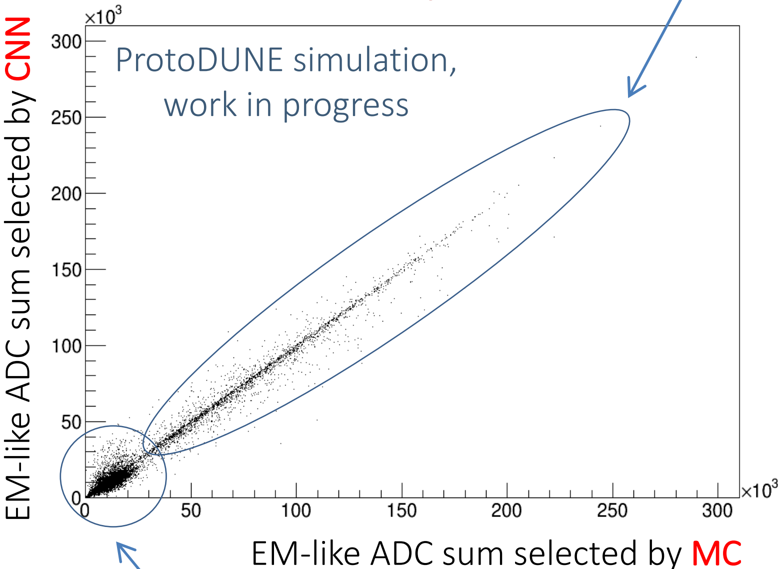


Event feature labeling

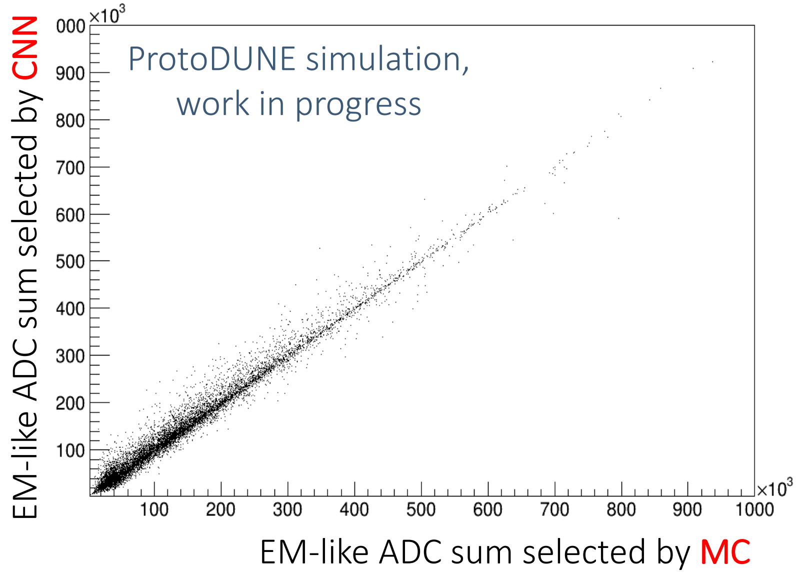
Test beam events in ProtoDUNE, selection of EM component in the hadronic showers from π^+:

events composed of hadron tracks and π^0 showers

1GeV/c pions

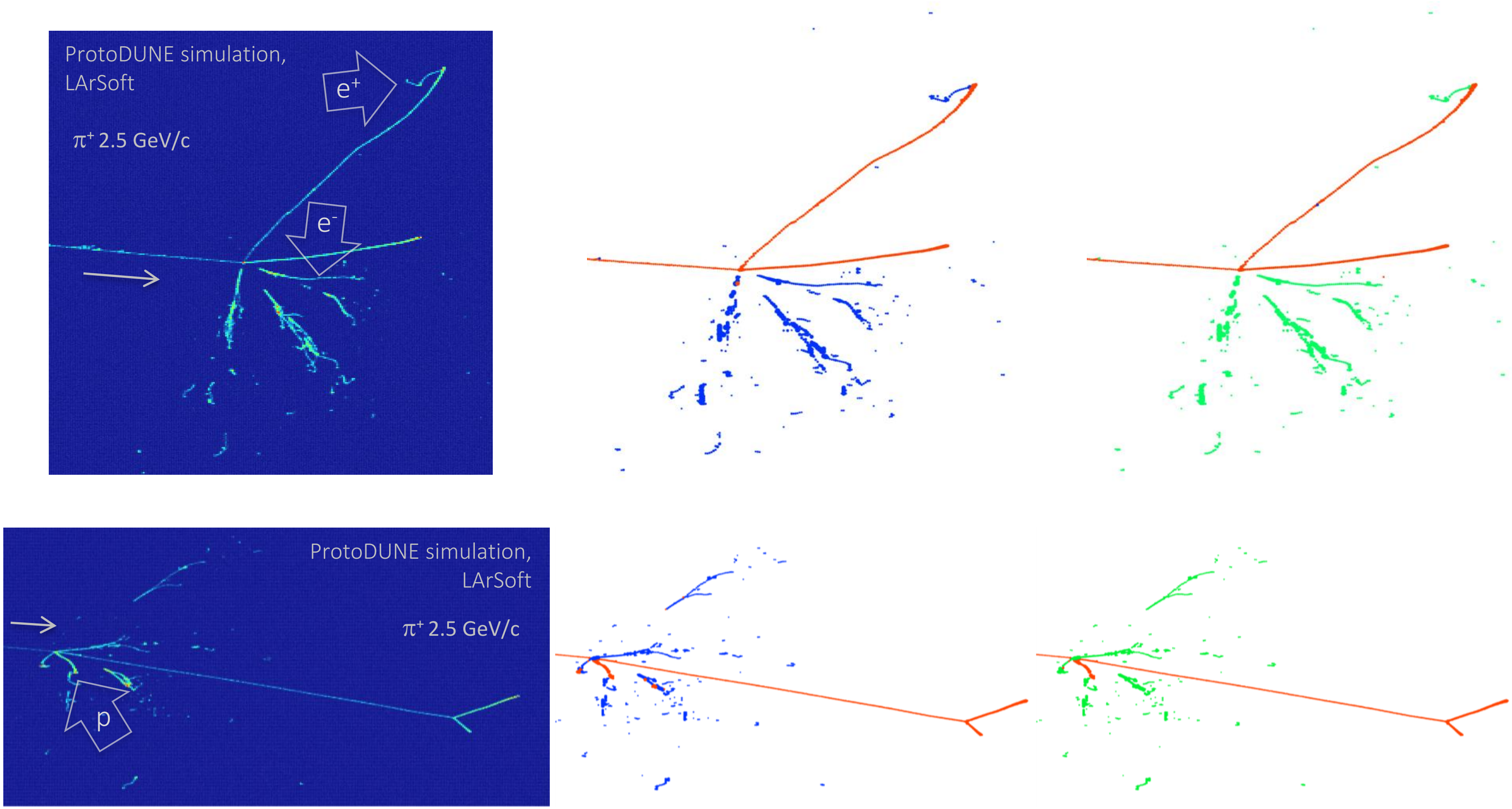


4GeV/c pions



events composed of hadron tracks (small fraction of EM-like deposits are delta electrons)

Event feature labeling



input: 2D ADC

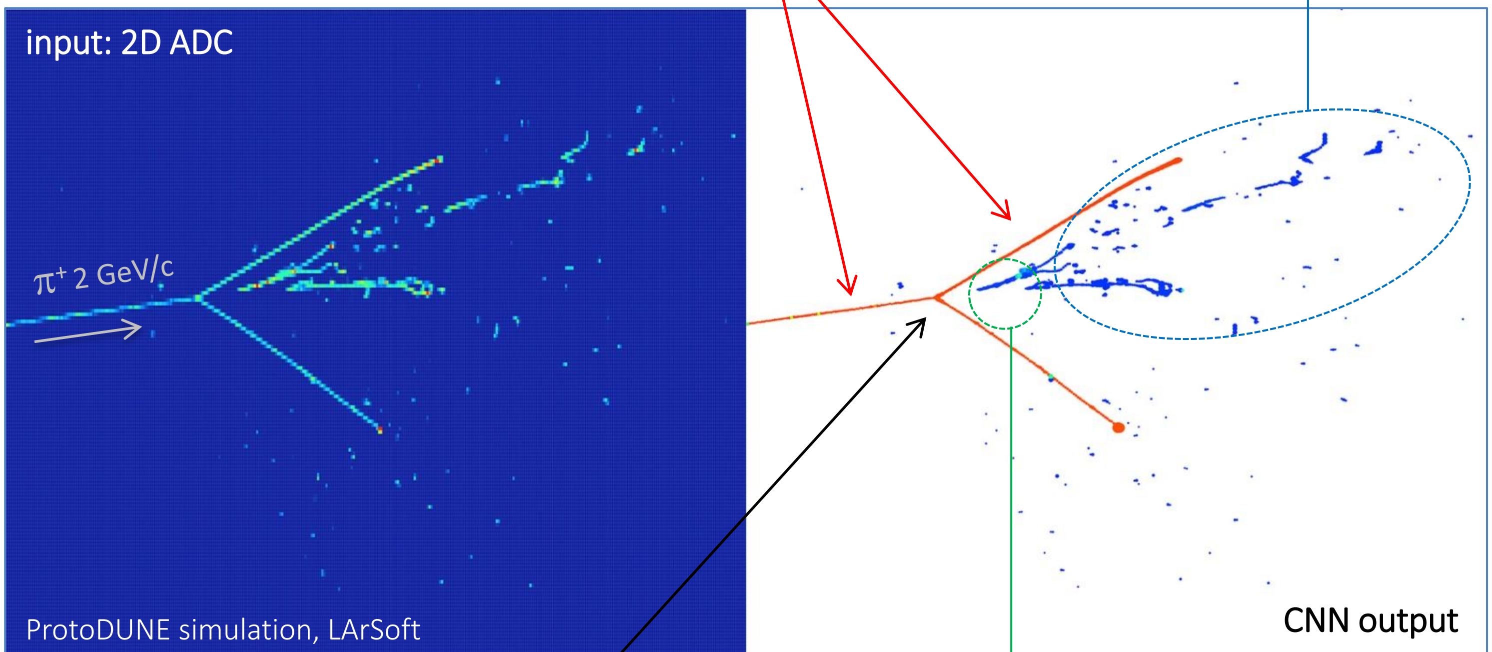
CNN output:
EM-like (blue) / track-like (red)

MC truth:
EM-like (green) / track-like (red)

Event feature labeling

2. hadron tracks reconstruction:
→ once EM separated, efficient standard algorithms

1. EM selection: quite done
→ labeled with CNN



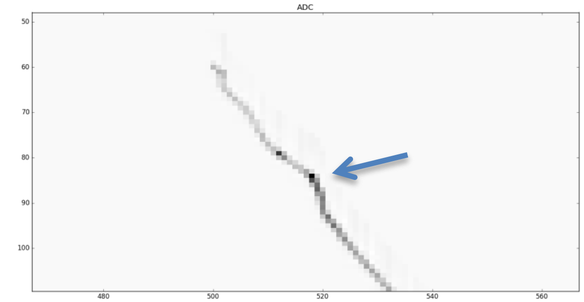
3. interaction vertex:
→ reconstructed with standard tracking
→ or „todo": labeled with CNN

4. „todo": EM cascade start finding
→ most significant for e/γ separation and ν_e selection
- EM shower displacement from the vertex
- 1m.i.p. vs 2m.i.p. dE/dx in the initial part

Event feature labeling

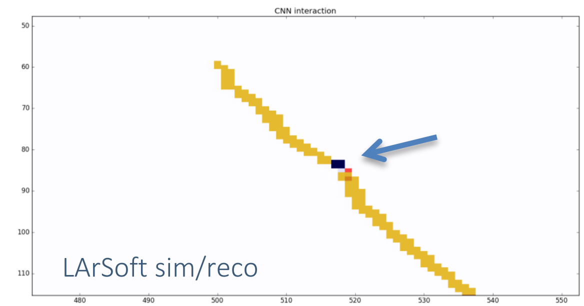
Decay point location and classification

- can deal with non-trivial topologies
- decay point location is a key for PID and calibration

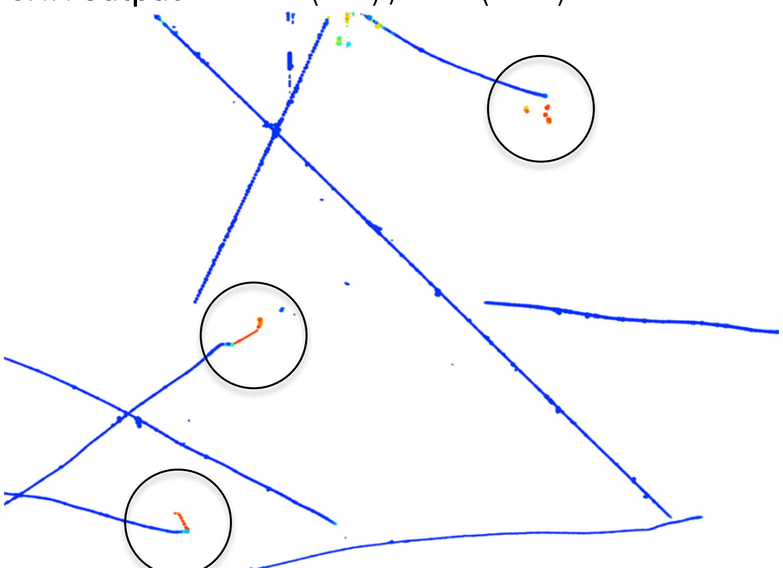


Michel electron activity selection

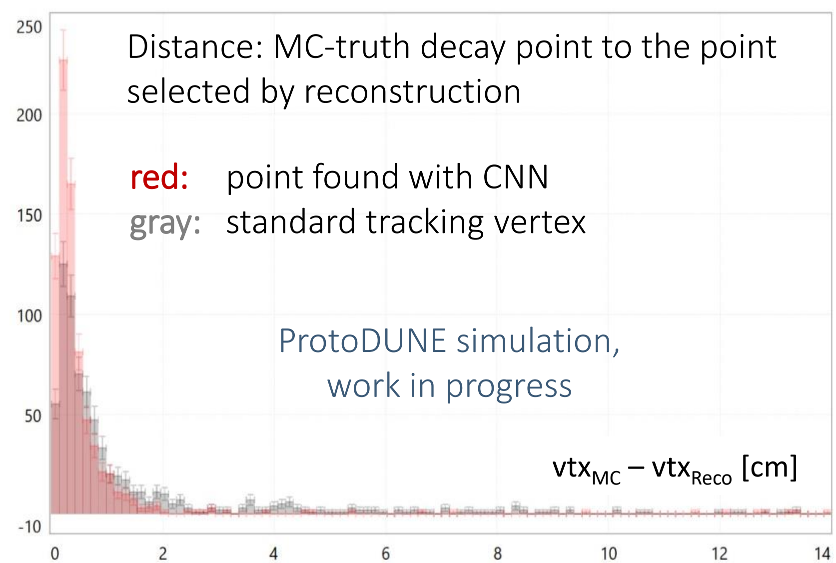
- important for detector calibration
- and for neutrino/anti-neutrino tagging



CNN output: Michel (red) / else (blue)

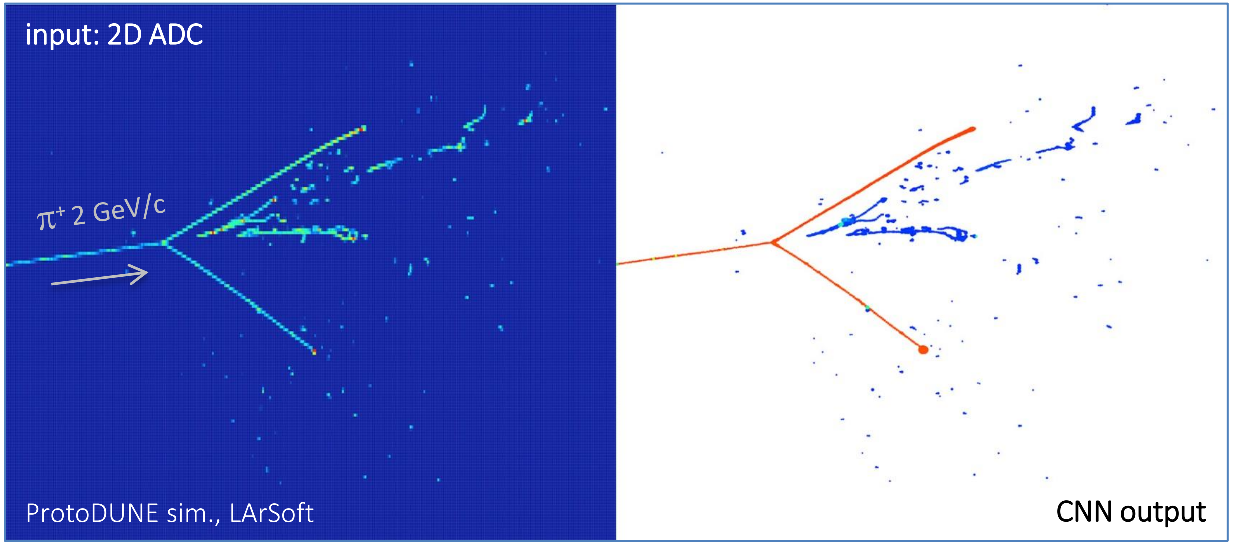


CORSIKA+G4+LArSoft, ProtoDUNE event

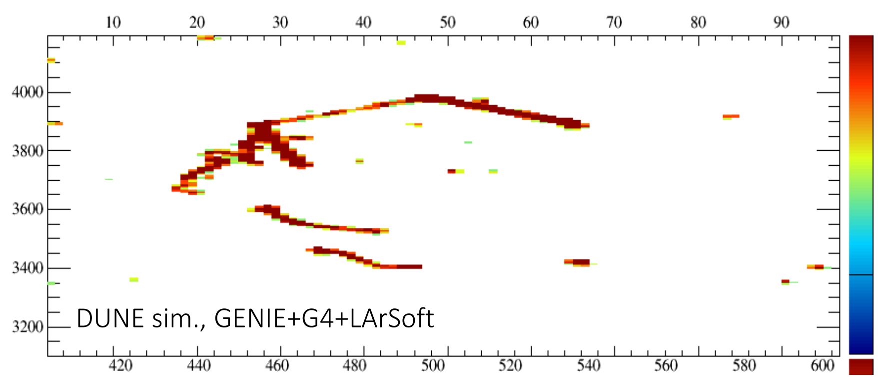


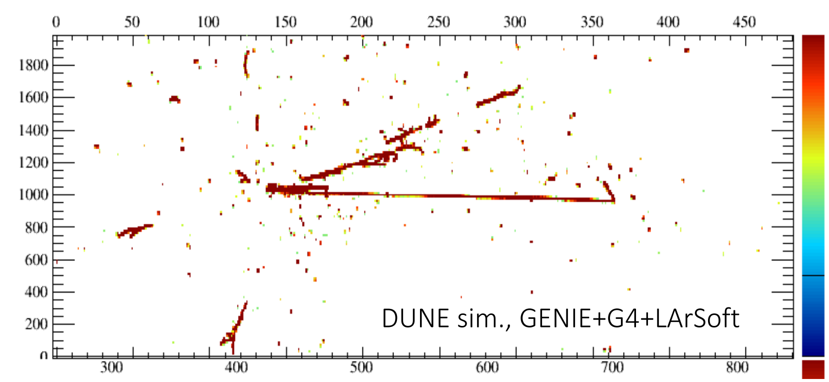
Next challenges: objects segmentation

2 photons converted here (I know this from MC), but try to collect these fragments in **2 EM cascades**:



And the same problem here: **collect EM cascade fragments, but also decide how many are they!**



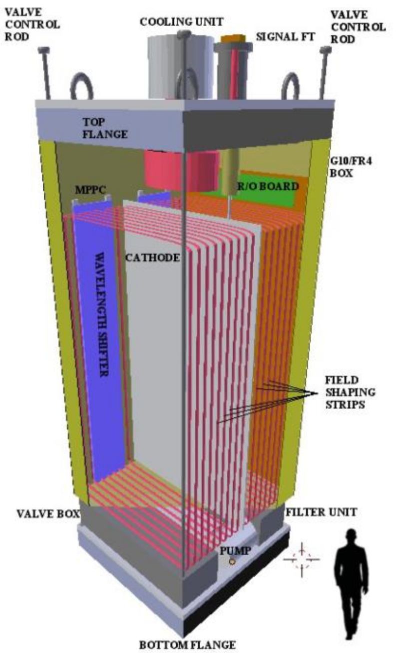


Next challenges: need to use 3D

3D pixels instead of 2D projections can solve many ambiguities

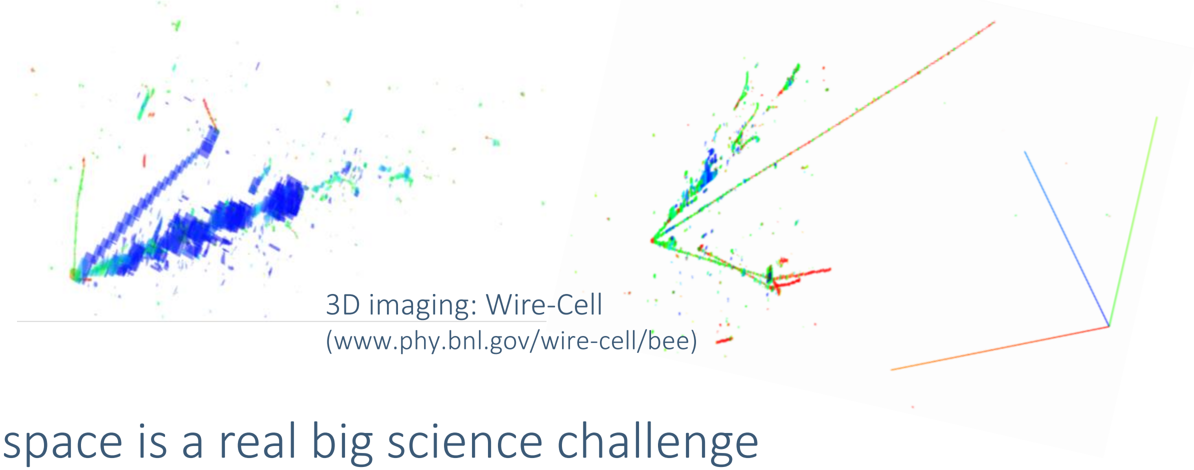
- ArgonCube prototype, 3D readout of the LArTPC volume:

ArgonCube module



Present/constructed detector readouts are however 2D…

- 3D imaging (e.g. mentioned Wire-Cell): use as a **3D re-processed raw** or as a way of association of points in raw 2D



3D imaging: Wire-Cell
(www.phy.bnl.gov/wire-cell/bee)

In any case 3D space is a real big science challenge

Summary

- LArTPC are really perfectly suited for image-based ML
- LArTPC based (neutrino) experiments are many, all are trying ML
  - ~year ago ideas were there, now: first production implementations
- Still, explorations just touched the surface
  - lots to be learned on real data: robustness, systematics
  - applications now using mostly 2D-topology, but there is 3D waiting:
    - needs association of 2D features, trajectory tracking, …
    - exploitation of full information provided *only* with 3D
  - objects segmentation, and many obvious applications are still awaiting
- LArTPC reconstruction was hard for decades, this may end

Thank you!

ML using *raw* 2D projections

Typical DUNE ν event image: 3x ~2000x1000 „pixels"

→ ν energy spectrum higher than in NOvA: variety of event topologies

→ statistics needed for good generalization: $O(10^{6-7})$ events

→ ν events simulation O(10TB); training data sets O(100GB); using GPU's O(10GB)

- managable volumes, however needs care with the selection of network architecture, usually downsampling is applied in drift coordinate
- acceptable training time O(10h) per model
- inference mode not very CPU/memory demanding

→ 3D readout (ArgonCube) or 3D imaging (Wire-Cell) volumes still challenging for today's CPU/GPU memory…