# Review of LAr TPC event reconstruction: Progress and Challenges

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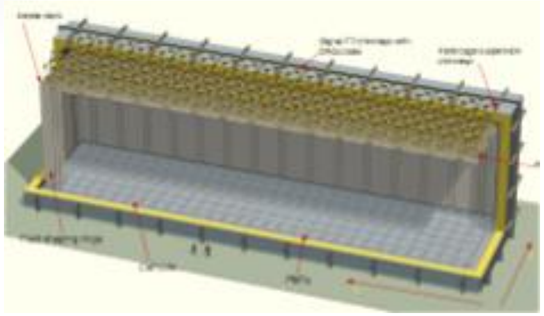
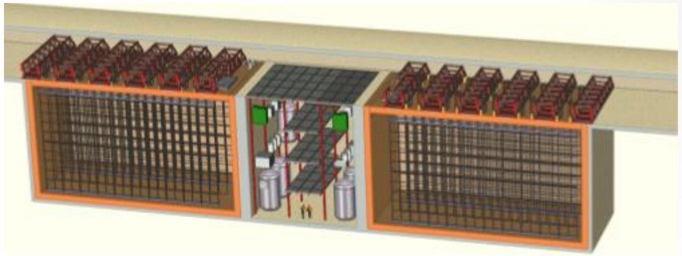
**NNN15**
International Workshop for the Next Generation Nucleon Decay and Neutrino Detector
UD2 Unification Day 2 (UD2)

**October 28-31, 2015**

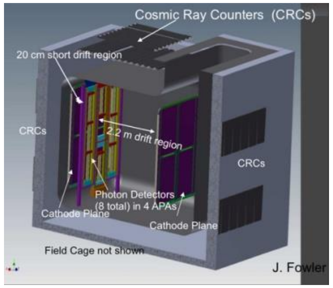
Background: Jackson Pollock

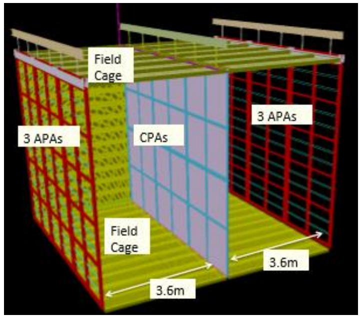
# Experiments with LArTPC

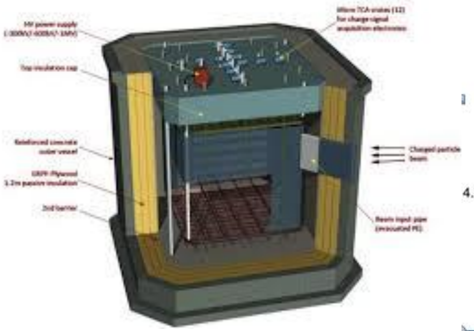


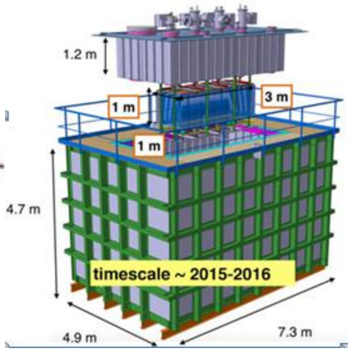


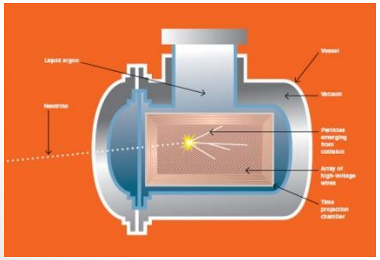
share the same design principles

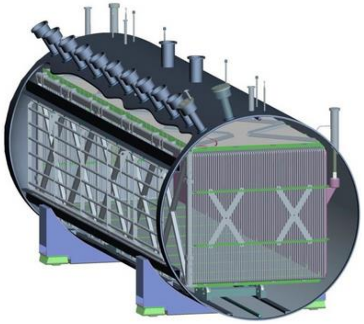


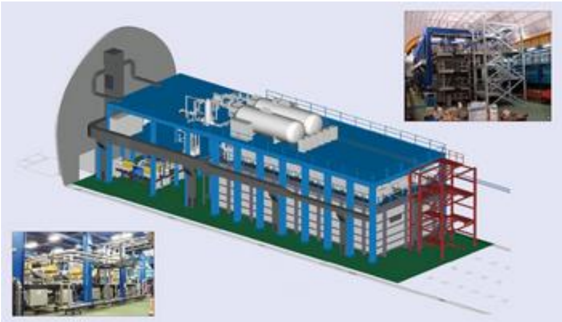



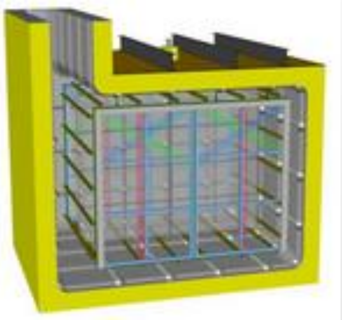





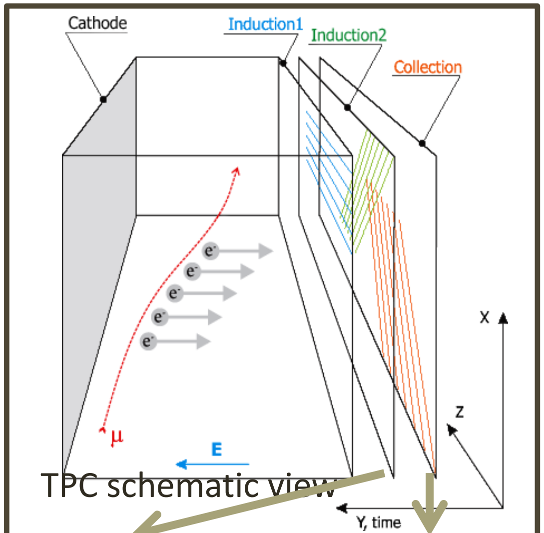




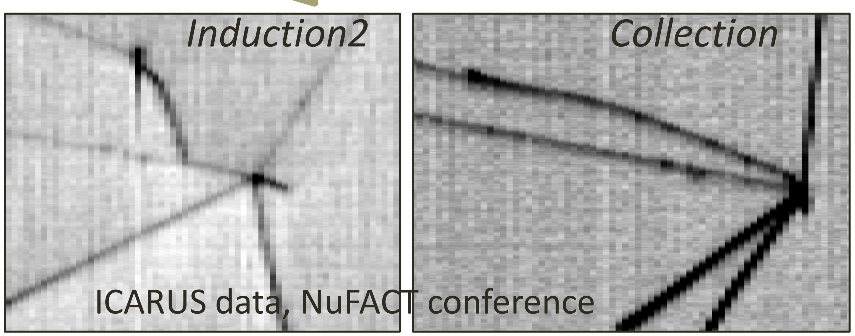


# LArTPC principles – single and double phase

**Single phase**

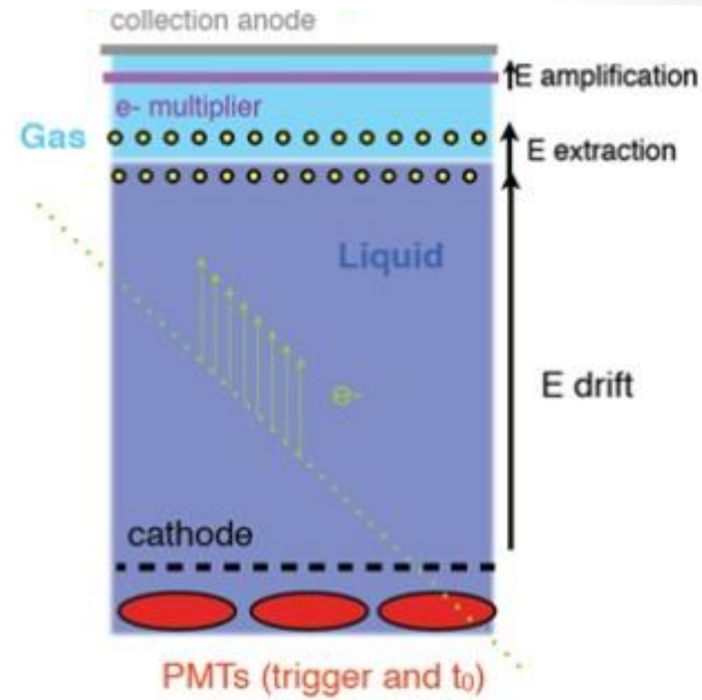



TPC schematic view




ICARUS data, NuFACT conference

**double phase**




- Prompt **scintillation light**, light collection system gives the **time reference ($t_0$)** and/or trigger signal
- **e⁻** from ionized track drifted in LAr by **E field**.
- Readout wires planes at different angles.
- **ADC** waveforms versus time read from wires form **2D projections** of events.

# Software frameworks

## simulation, reconstruction, analysis

**QSCAN**

early stage in ICARUS, then LAGUNA - LBNO designed by the ETH group. Now is used by WA105 project:

- hits, PANDORA (hits, clustering)
- Latte framework (PID, energy)

**ICARUS SOFTWARE**

software, begun with *Qscan*,
Later: improved simulation (FLUKA), interface improved, redesigned reconstructions:
* fitting hits * Clusters (event segmentation) * 3D tracks * PID

**LARSOFT**

FNAL, **aim**: work with any liquid argon TPC.
Simulation: mainly Genie + Geant4.
Full chain of reconstruction, various, independent algorithms , interface to PANDORA, WIRE CELL, used in MicroBooNE, ArgoNeuT, LArIAT, DUNE: 35t prototype, protoDUNE. → ***Gianluca Petrillo talk NNN14***

**PANDORA**

Developed mainly at Cambrige University **more in following slides**

**WIRE CELL PACKAGE**

Recently developed by BNL group.

**more in following slides**

# Aims of reconstruction

Enable physics analysis: CP violation in neutrino flavor mixing, nucleon decay, neutrinos from supernovae, searches for sterile neutrino…

<u>We have to identify incident particle ($\nu_e$, $\nu_\mu$, nucleon decay, muon…) and measure momenta.</u>

**HOW**?

- **Find primary vertex**
- **Identify outgoing particles**
- **Measure their momenta**

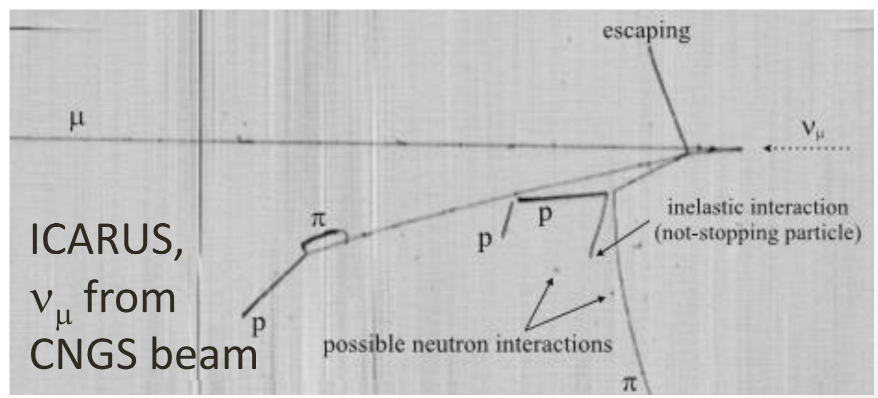
RECONSTRUCTION

# Various event topologies

- Ideally would be to have a general tool: reconstruct neutrino events, nucleon decay, cosmics…
- There are usually EM showers and tracks, they need different treatment.
- LArTPC is all about non-uniformities in every possible aspects:

  direction-dependent resolution, signal attenuations and diffusion, parallel to drift direction problems, space charge effect, …and we have to be prepared for usual hardware failures.


http://icarus.lngs.infn.it/photos/testEvent2001/index.html



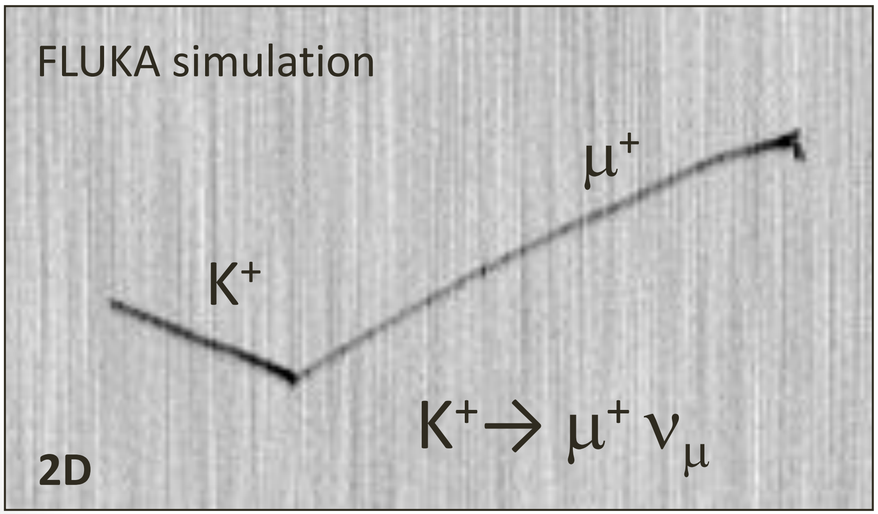

From *European Strategy for Neutrino Oscillation Physics* – II, poster, Cern 2012

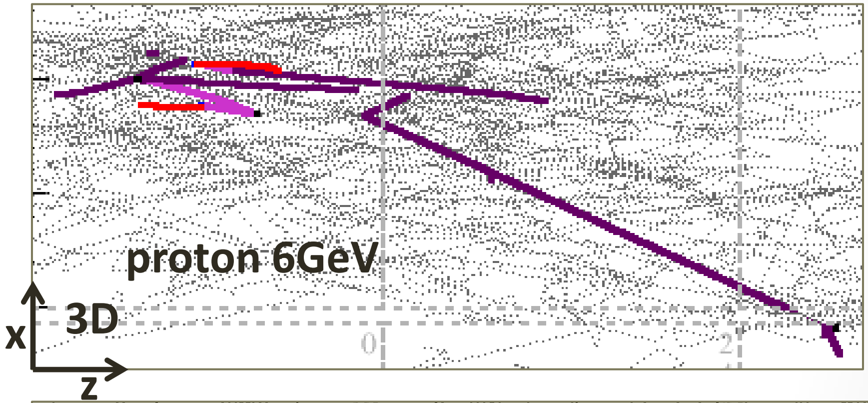
# Hadronic shower and track topologies

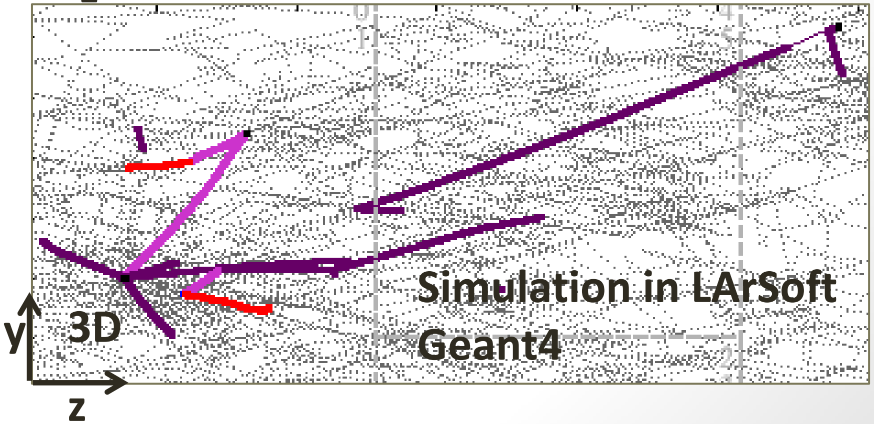
**hadronic shower (or single tracks)**

**stopping**
**(detect by dE/dx)**
**PID, momenta**

**Interacting,**
**PID/momenta of secondaries,**
**potentially only an approximated momentum**

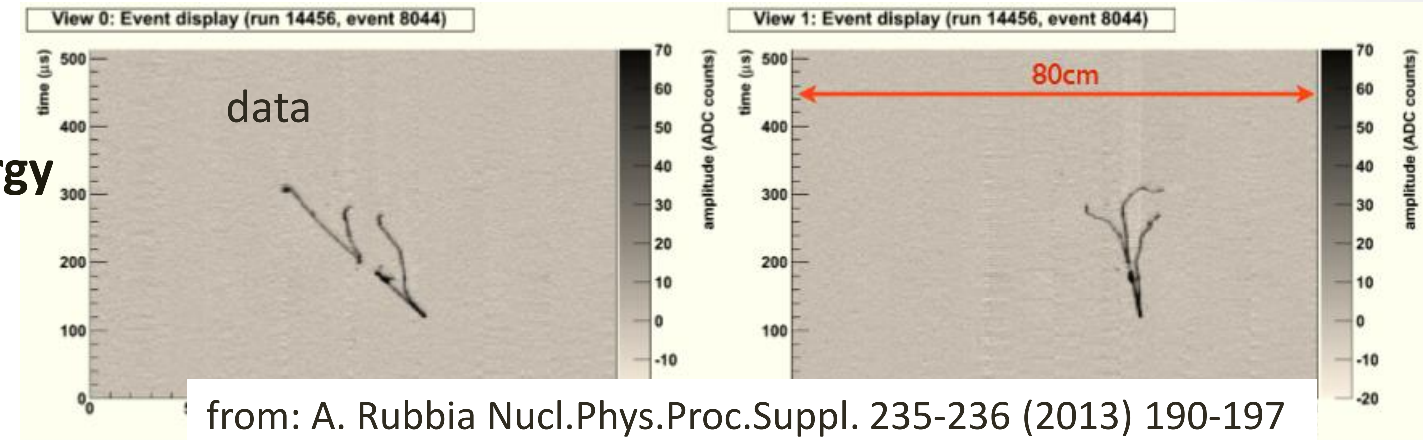


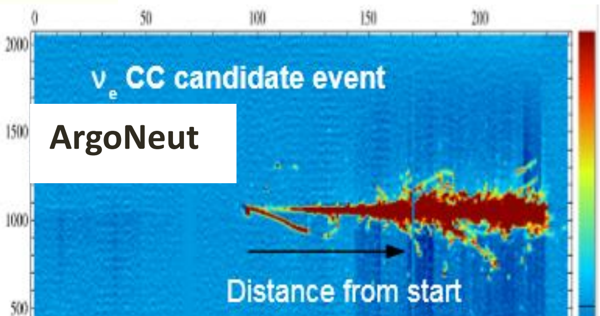
# Electromagnetic showers

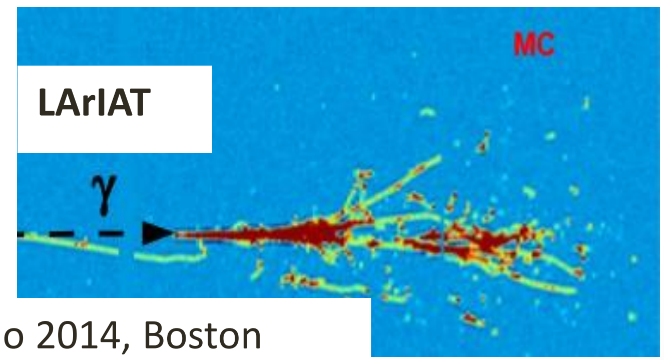
- **low energy cascade**




from: A. Rubbia Nucl.Phys.Proc.Suppl. 235-236 (2013) 190-197

- **fully developped cascade**

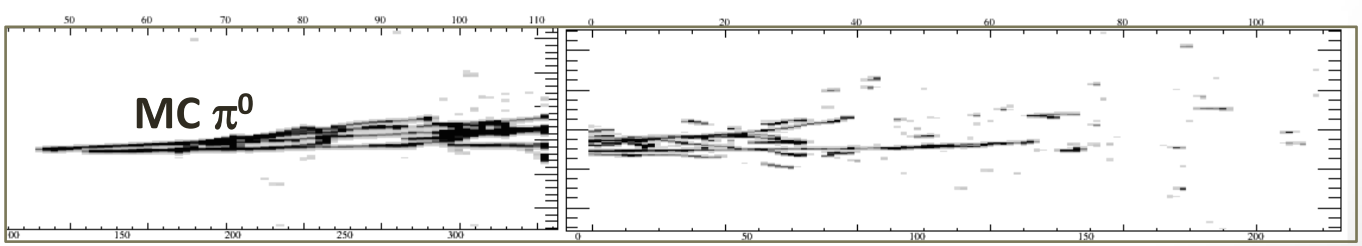



from: A. Szelc, conference Neutrino 2014, Boston

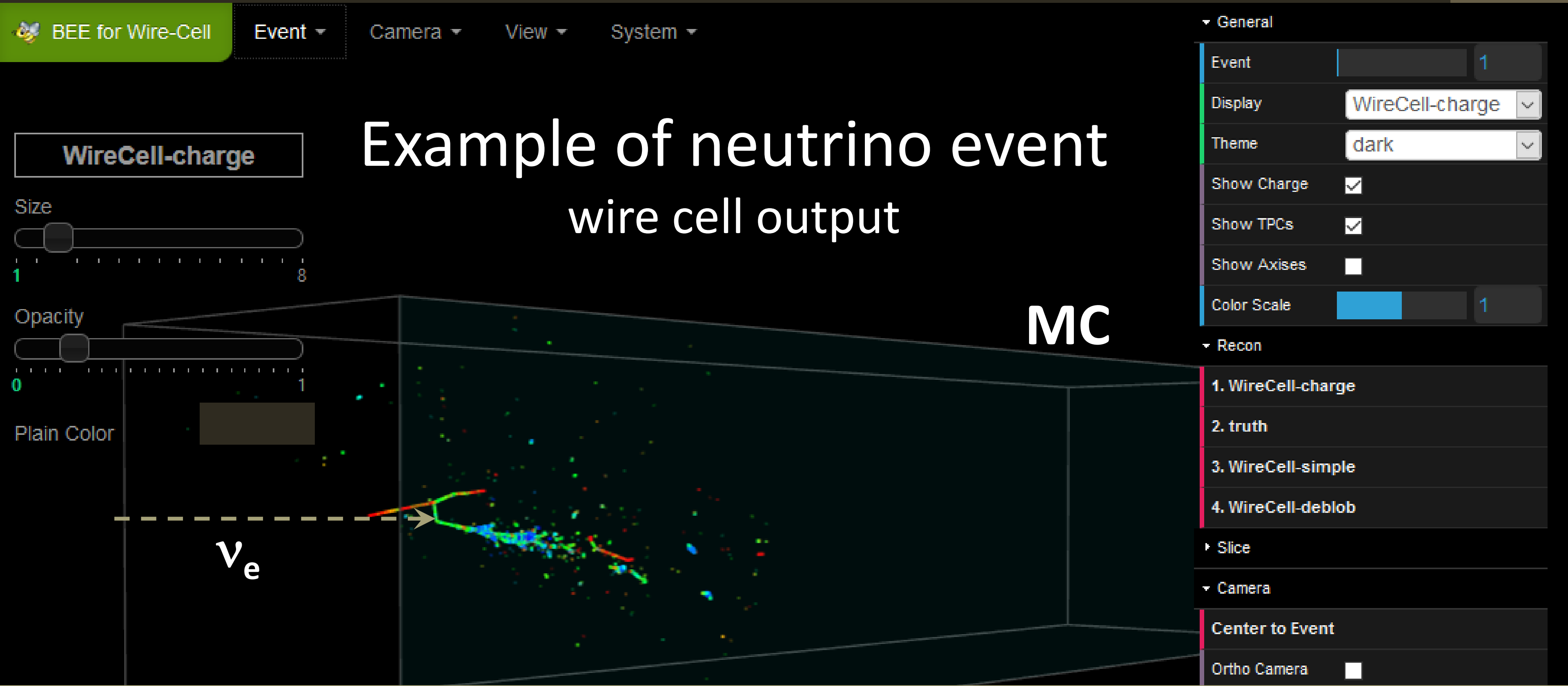
- **multiple showers**

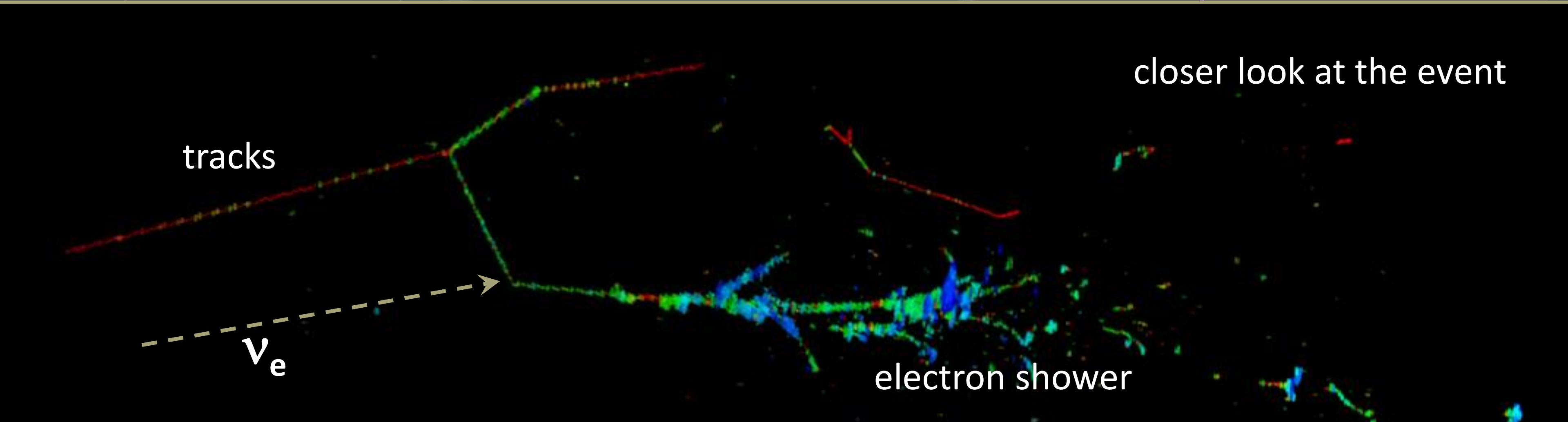
simulated $\pi^0$ with energy ~ 1 GeV in LArSoft



# Example of neutrino event

wire cell output

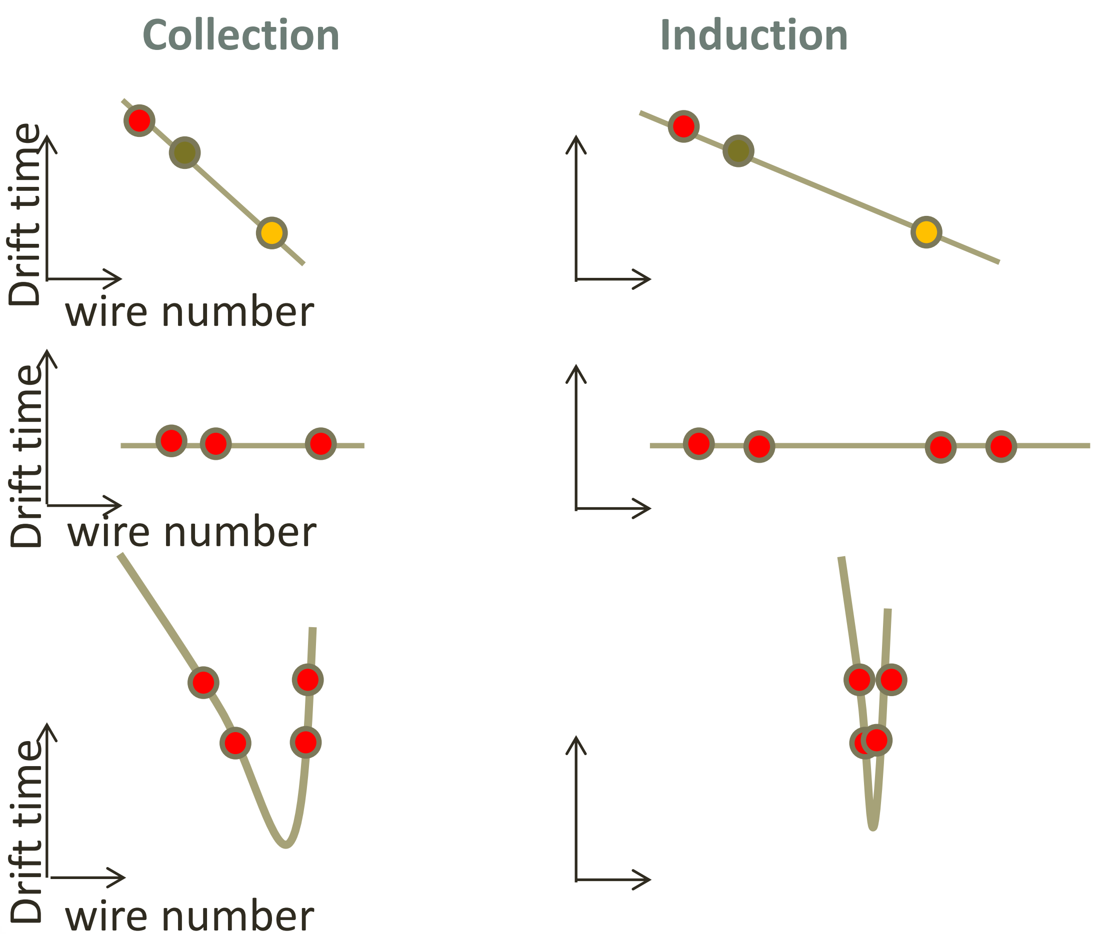


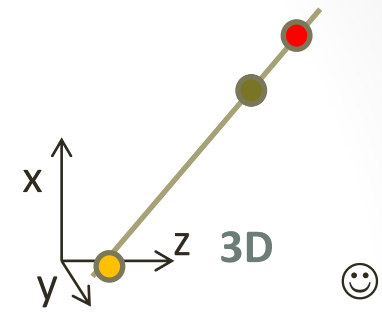




BEE viewer developed in BNL : http://www.phy.bnl.gov/wire-cell/

# Our first attempts

RECIPE for 3D reconstruction: *associate hits in different projections according to the electron drift time*.




maybe we manage
if we find enpoints…

It would help if
we sort hits along
the trajectory…

Early „clustering” methods are another example of too simplified thinking applied to hard problem. Development of more advanced methods was natural.

# 2D / 3D reconstruction – where is the problem?

- wire views:  3D structure in „stereoscopic" 2D projections taken at different angles.
    - event looks very different in each projection   (rotation)
    - very likely there will be something difficult in each projection: overlapping, running in the wire direction, „horizontal", missing, …
- wire signal characteristics may be different in each plane.
- little help for reconstruction from external detectors
  approximate location / ID with PMTs, in general whole event details to be reconstructed from TPC data solely.
- Results can depend on:
    - Wire pitch
    - Wire orientation
    - Wrapped wires
    - Number of readout wire planes
    - Screening plane
    - Detector division into many TPCs
    - Detector orientation w.r.t. beam line
- …plus LArTPC non-uniformities

# Reconstruction in LArTPC – how we do it?

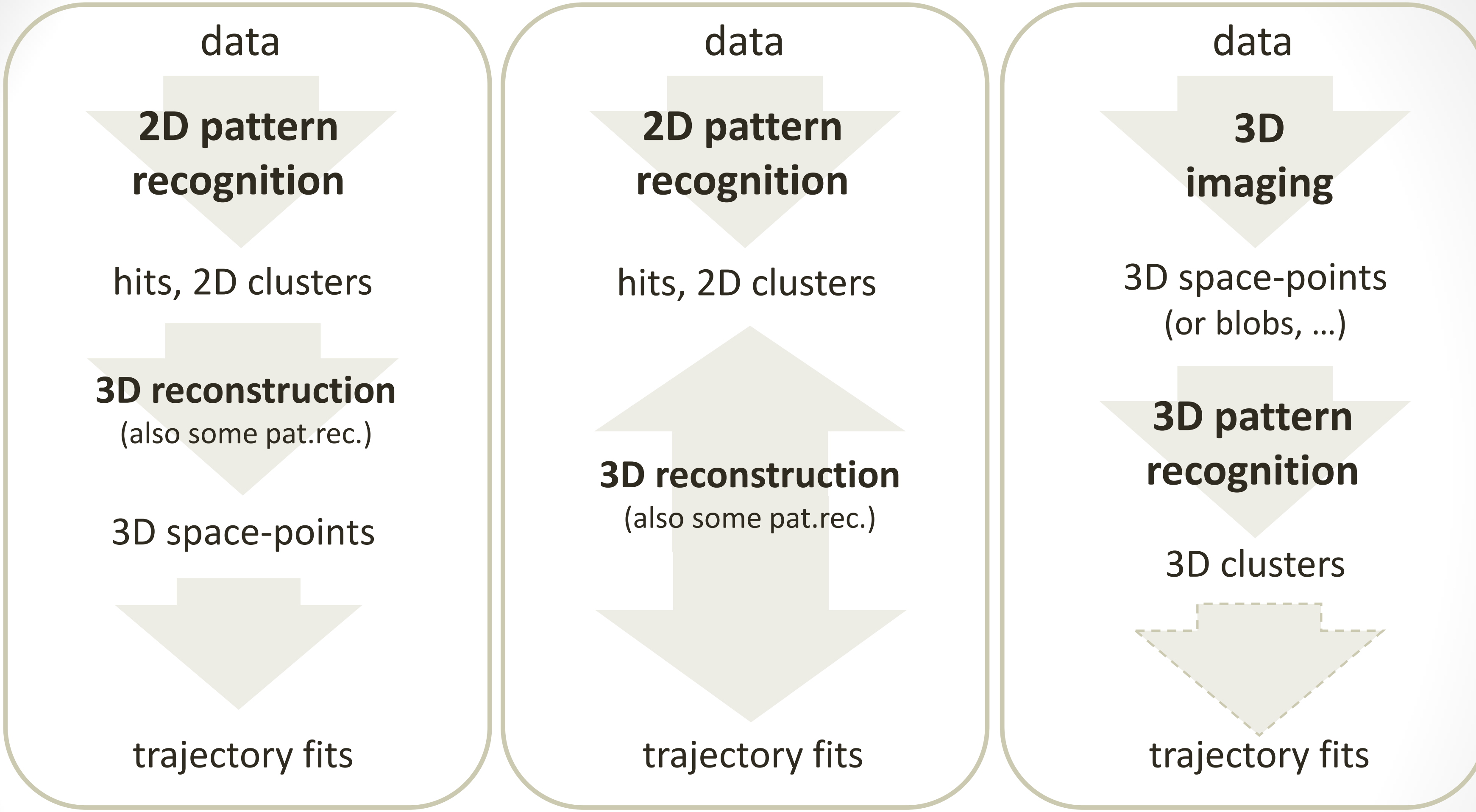
**Event reconstruction in LArTPC** has to look at 2D projections of 3D object; machine learning (pattern recognition) approaches are applied in several stages to interpretate data.

**Pattern recognition is extensively used in LArTPC data processing**

Wikipedia:
*„pattern recognition is a branch of machine learning that focuses on the recognition of patterns and regularities in data(…)"*

- **low level**: basic object spatial recognition, shower-like vs track-like distinction
- **high level**: physics interpretation of objects, e.g. PID, points of interactions

# Different approaches of reconstruction

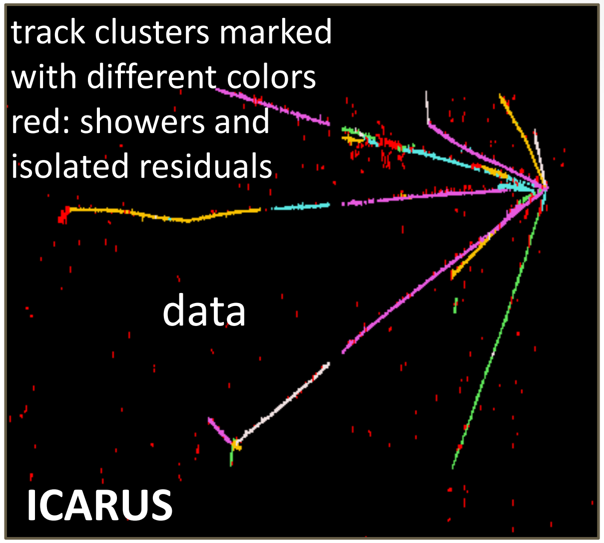



**Analysis**

**Now**: it is based mostly on features identified and selected by physicists. There is still possibility of new approach, e.g. one can think of throwing more on the machines: direct transition from data → 3D pattern recognition

# Examples of low level pattern recognition

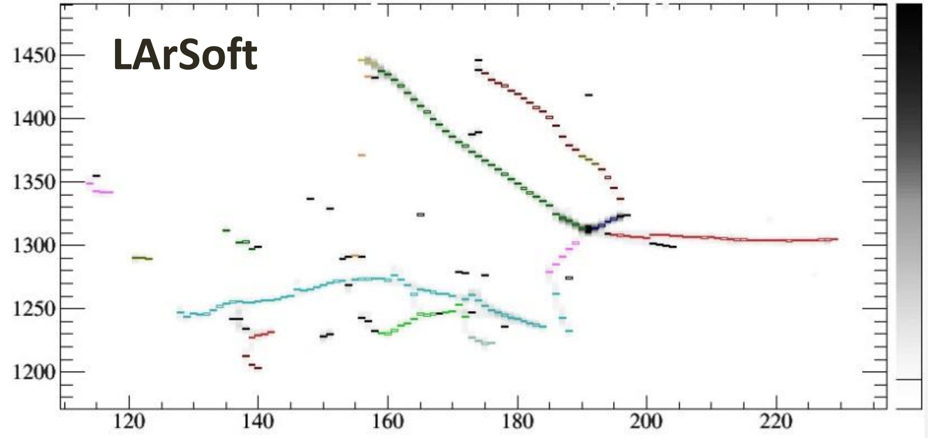
- **2D: the most direct information**
- **Shower-like, track-like clusters**




by DS


**PANDORA** output

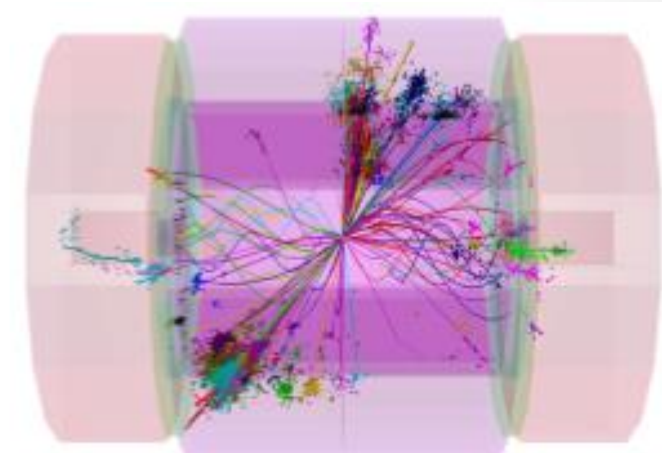
Eur. Phys. J.C. (2015) 75:439 J.S. Marshall, M.A. Thomson




event from LArSoft: Cluster Crawler
by Bruce Baller

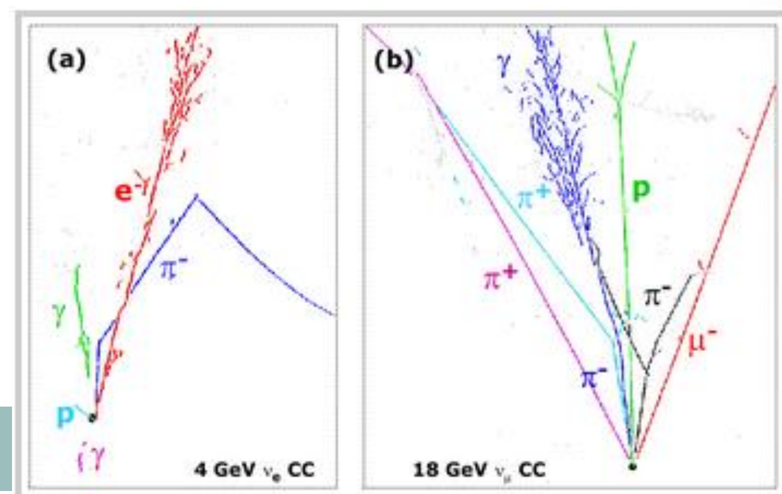
# Pandora

- Pandora is a toolkit of pattern recognition algorithms for fine-grain detectors.
  - Initially written for linear collider. Has become central to ILC/CLIC physics studies.



From *International Conference on Computing in High Energy and Nuclear Physics*, 2012

- The tools are fast, flexible and reusable – readily applicable to automated event reconstruction in Liquid Argon.




http://www.hep.phy.cam.ac.uk/microboone/

Andy Blake, John Marshall, Mark Thomson

# Pandora

**Overall scope:**

-Inputs: 2D hits
-Outputs: 3D particles (*Particle Flow Particles*)

**Pattern recognition based on many algorithms that gradually *grow* events:**

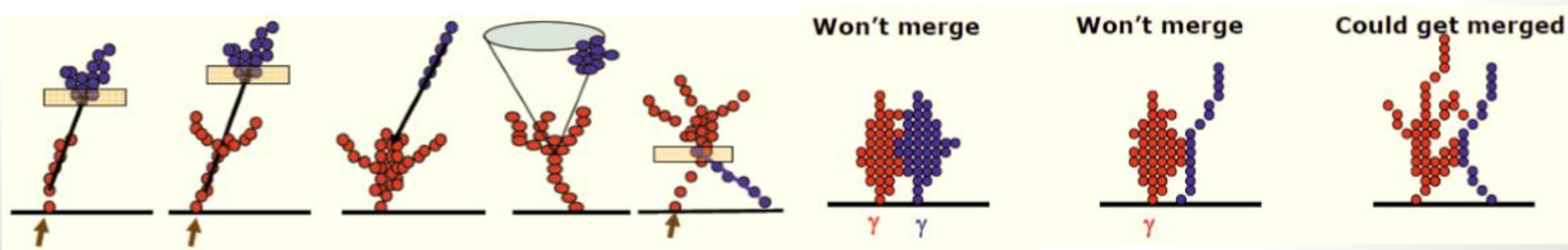
-2D clustering: separate track-growing and shower-growing alg.
-3D matching: uses 3D information to improve 2D clusters
-vertex reconstruction: identifies feature points, then interaction vertex

- **Algorithms often are based on *microscopic* associations of hits and clusters.**

- The general technique of breaking down the problem into small steps.
- Many algorithms allow to chain together many complementary approaches.

Used in MicroBooNE, 35t, WA105

Andy Blake, John Marshall, Mark Thomson

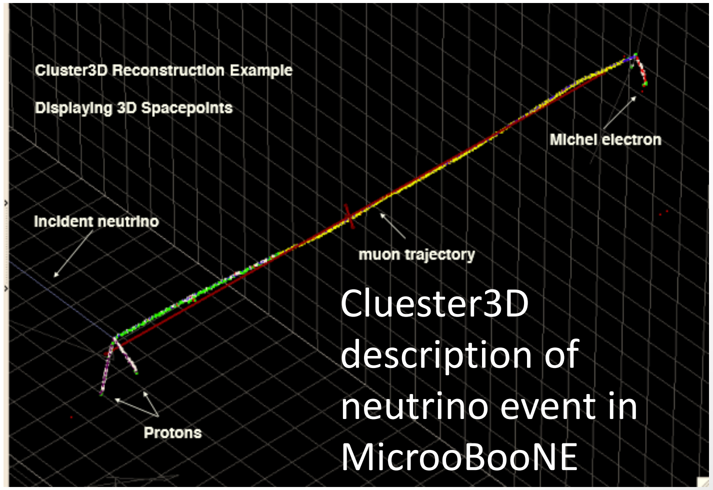


# Cluster3D, precursor of 3D imaging

- **Basic idea**: Form 3D hits from all „allowed" 2D hit matches across planes
  - Problem: don't a priori know which 2D hit in one plane corresponds to the 2D hits in the other planes (not well separated in time, fluctuations)
    - Leads to lots of ambiguous 3D hits
  - Solution: Let a „global" picture of the event resolve the ambiguity
- **General strategy**:
  - Build complete picture of event starting from all allowed 3D points
  - Use pattern recogntion in 3D.

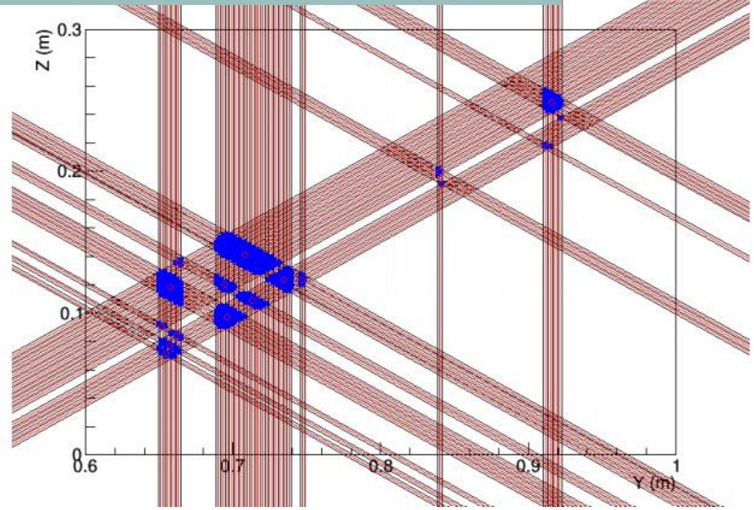
from Tracy Usher

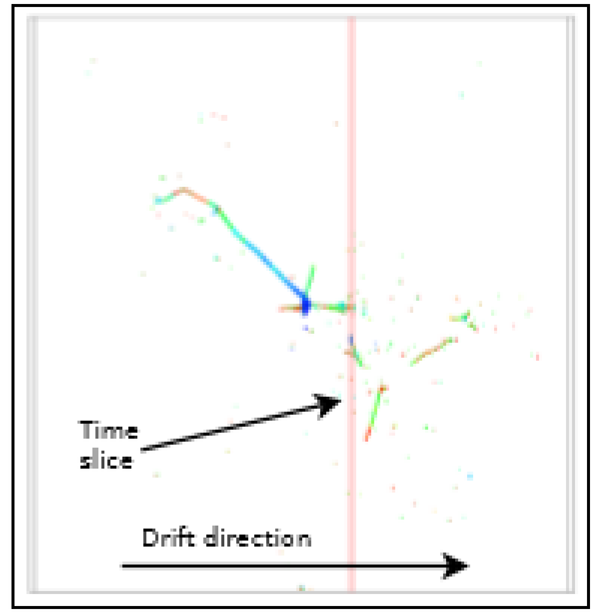
Used in MicroBooNE



# Novel 3D imaging: Wire Cell

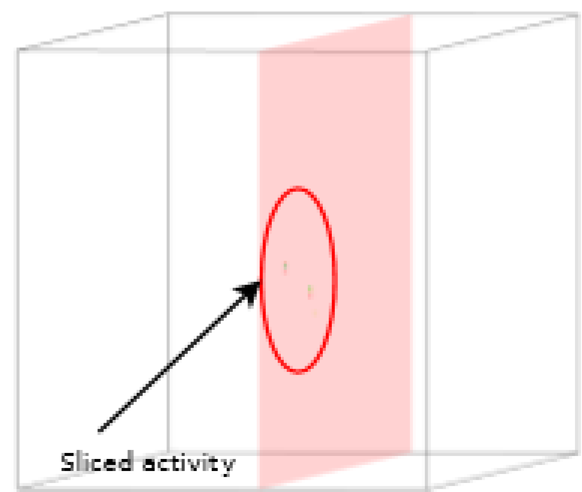
Xin Qian, Brett Viren, Chao Zhang




- Form time slices on wire signals.
- Construct Wire-Cell association.
- Merge adjacent cells into „blobs”.
- Construct $\chi^2$ through matrix equations.
- Obtain best matched 3D space points through $\chi^2$ minimization.

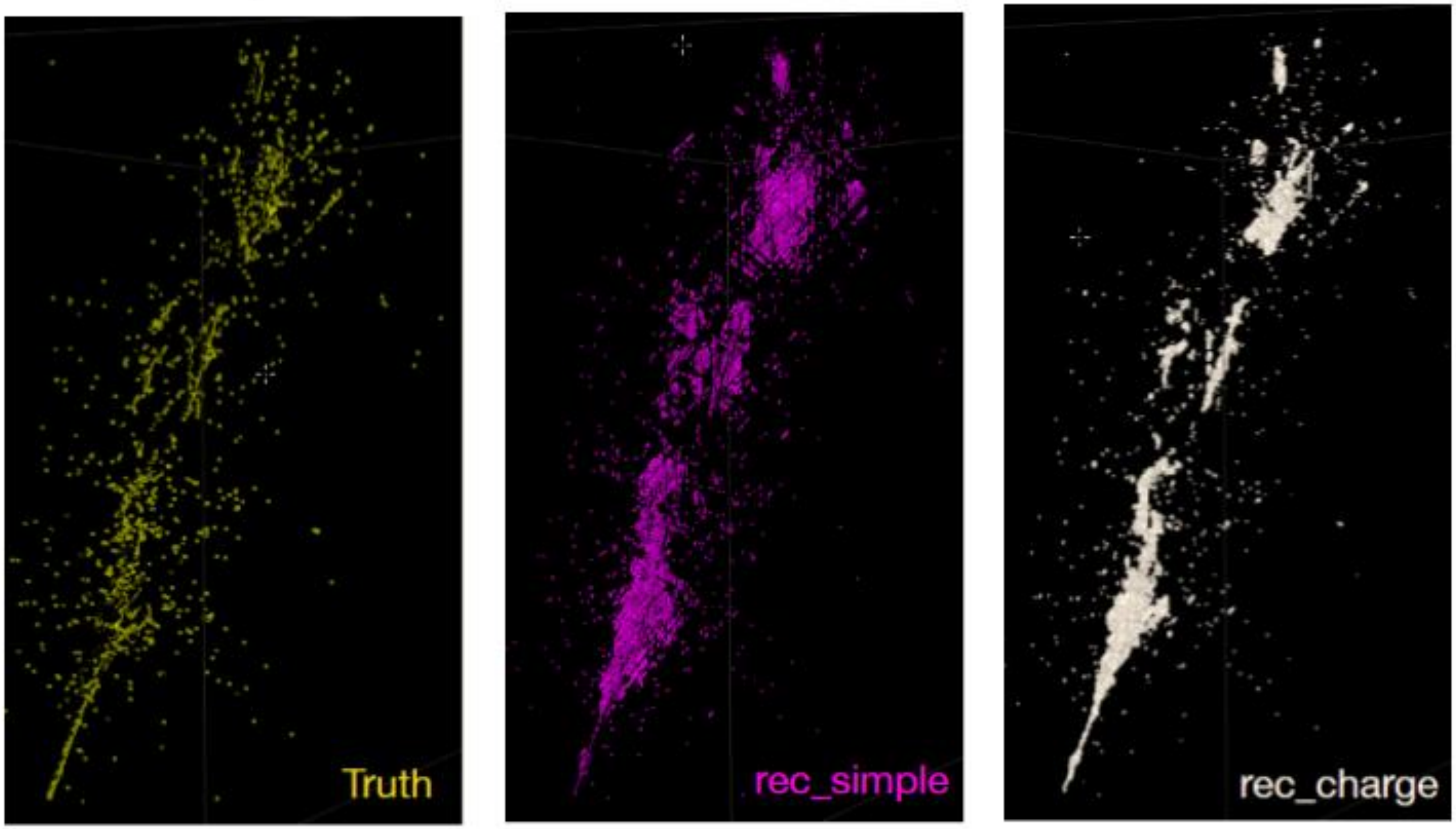
**clusters, trajectory, physics**




**POSTER:** ***Wire-Cell Tomographic Event Reconstruction for large LArTPCs***

# 3D imaging: Wire Cell

Example: a 1.5 GeV electron




Use only geometry information

Use geometry and charge information

Xin Qian, Brett Viren, Chao Zhang

# Reconstruction chain

- DATA
- hits, space points, cells, blobs
- clusters: track like, shower like objects — **PATTERN RECOGNITION**
- trajectory, vertices — **FIT**
  - Use 3D space points from preceding stage: refit reduced information
  - Or look at 2D data selected by clustering: fit directly to measurement
- recognize track directions, primary vertex
- extract full event features

PATTERN RECOGNITION:

- DBSCAN
- Fuzzy Clustering
- Charge distribution matching
- Clustercrawler/ CCTrackMaker
- Hough transform
- Cellular automaton
  Eur. Phys. J. C73 2591

FIT:

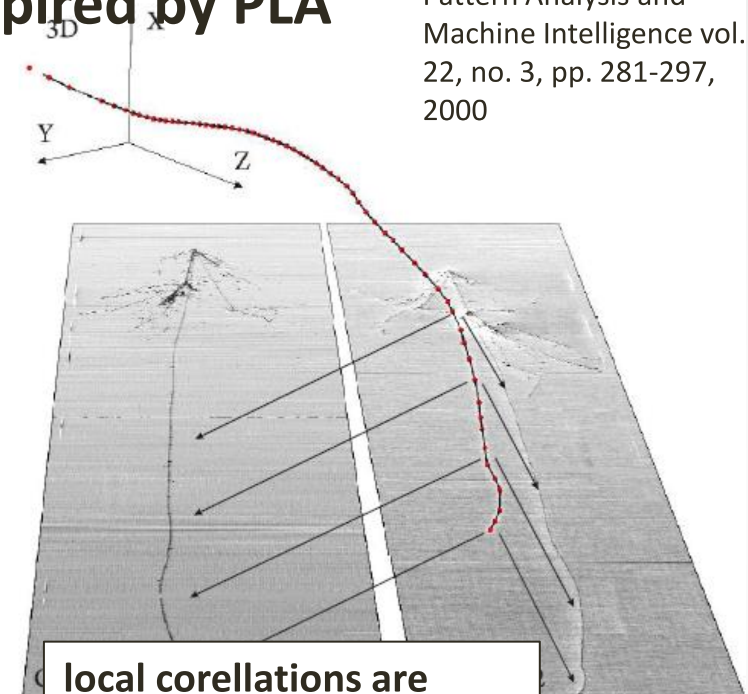
- Kalman Filter
- Bezier Tracking
- Local Principle Curves
  Eur. Phys. J. C74 2832
- Polygonal Line

# 2D ↔ 3D Projection Matching Algorithm

**Specially desinged for LArTPC and inspired by PLA**

IEEE Transactions on Pattern Analysis and Machine Intelligence vol. 22, no. 3, pp. 281-297, 2000

- Create and optimize object in 3D to match its multiple 2D projections:
    - what should be the 3D shape that results with what we see in 2D's.
    - a generic way of direct and complete use of LArTPC data.
    - no intermediate step with 3D hits/points to be refitted again into tracks in 3D space.
    - can take into account also 3D info: vertices, feature points, …, if available from other algorithms.
- Missing parts are acceptable
- Single-view parts are still useful.
- PMA native features used to complement pattern recognition stage.
- Basic idea can be widely extended.



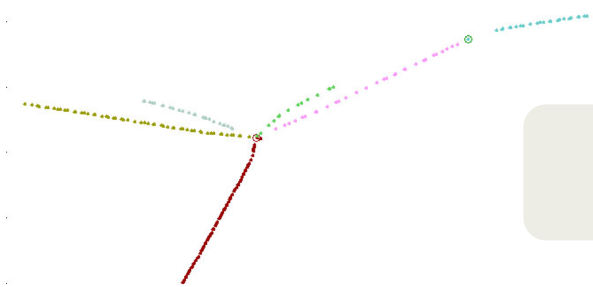

**local corellations are success to the reconstruction of difficult or complex topologies**

AHEP 2013, http://dx.doi.org/10.1155/2013/260820
Single tracks in ICARUS and with new developments of track-vertex structure in LArSoft

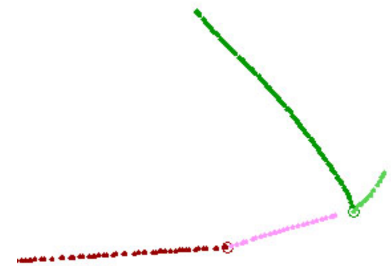
# Full PMA

**grow single tracks**: cluster matching and track validation

**PATTERN RECOGNITION**



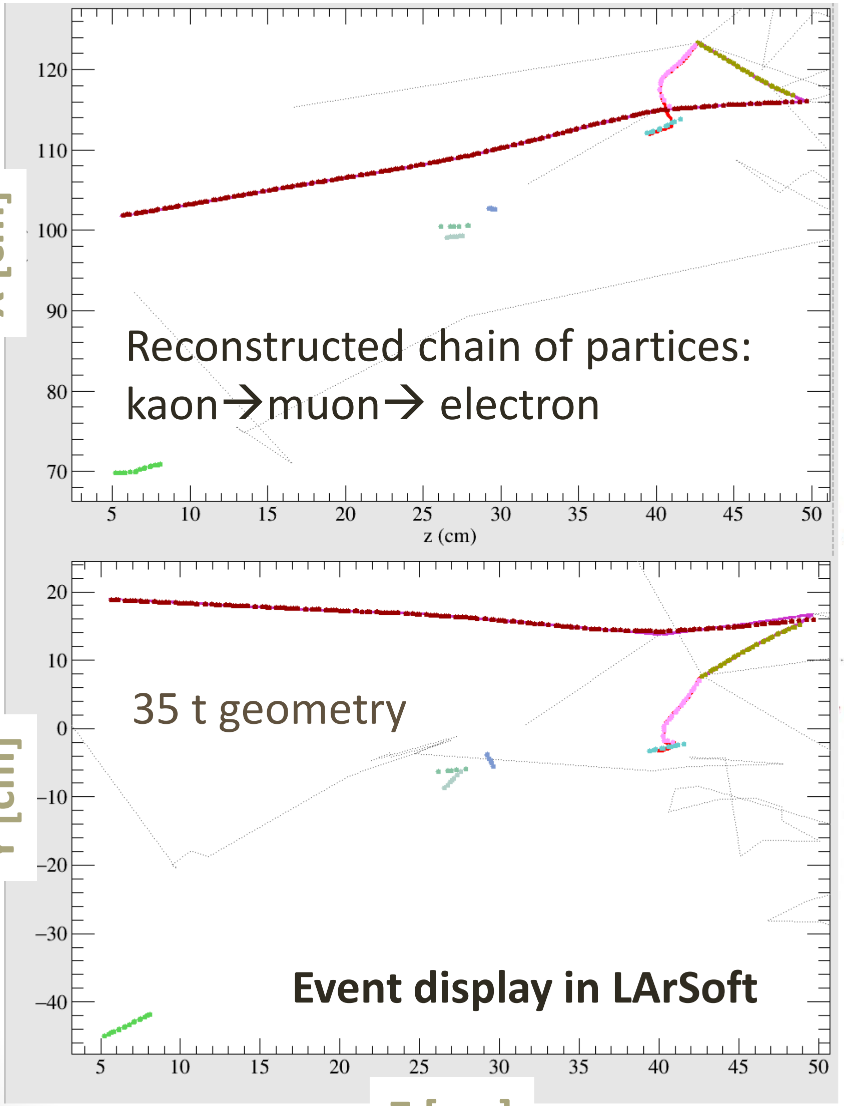
**Projection Matching**



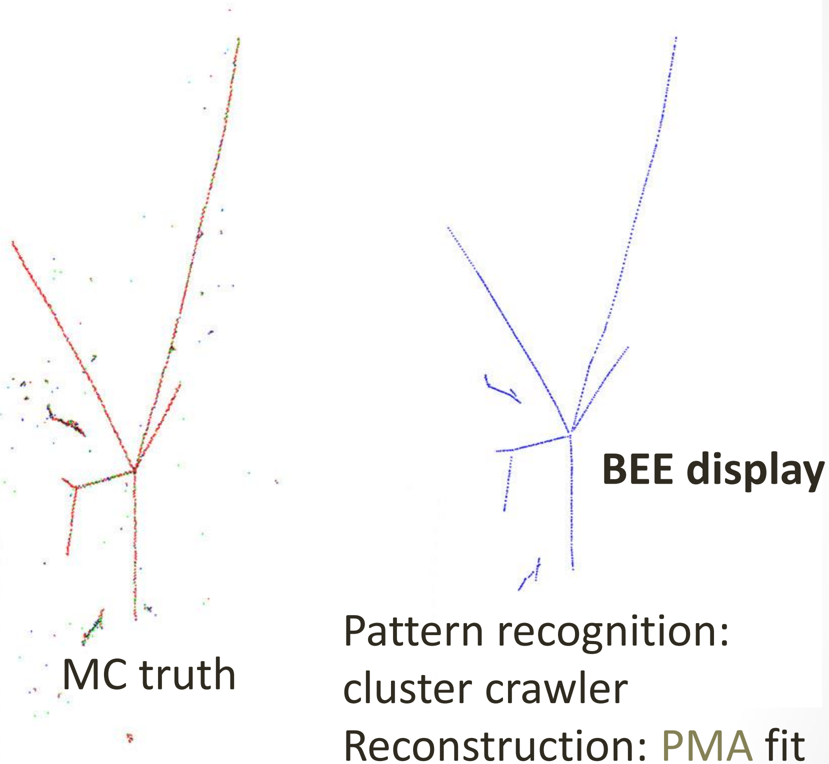
**vertex finding and track-vertex structure optimization**

**HIGH LEVEL STRUCTURE**

# Events reconstructed with PMA




$\pi^-$ **2GeV**




Pattern recognition:
cluster crawler
Reconstruction: PMA fit

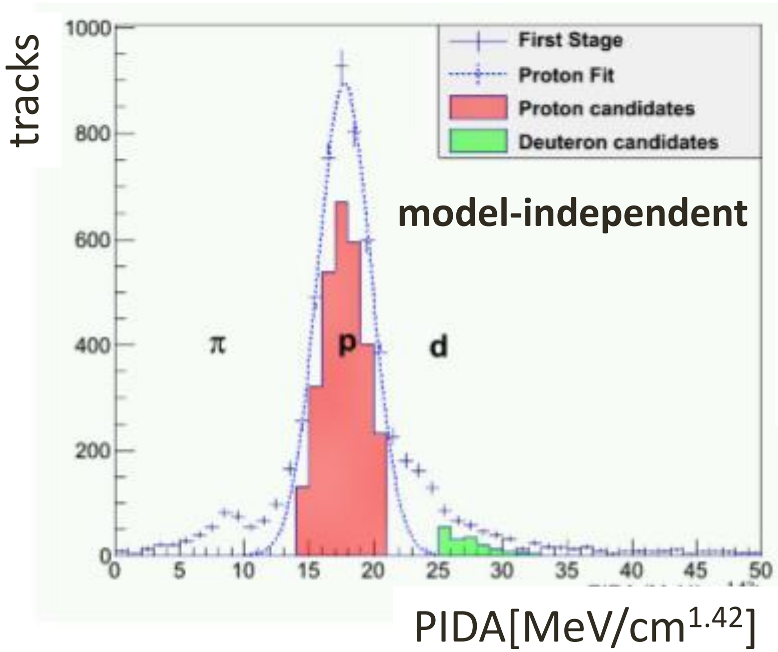
**Input: clusters from any algorithm**

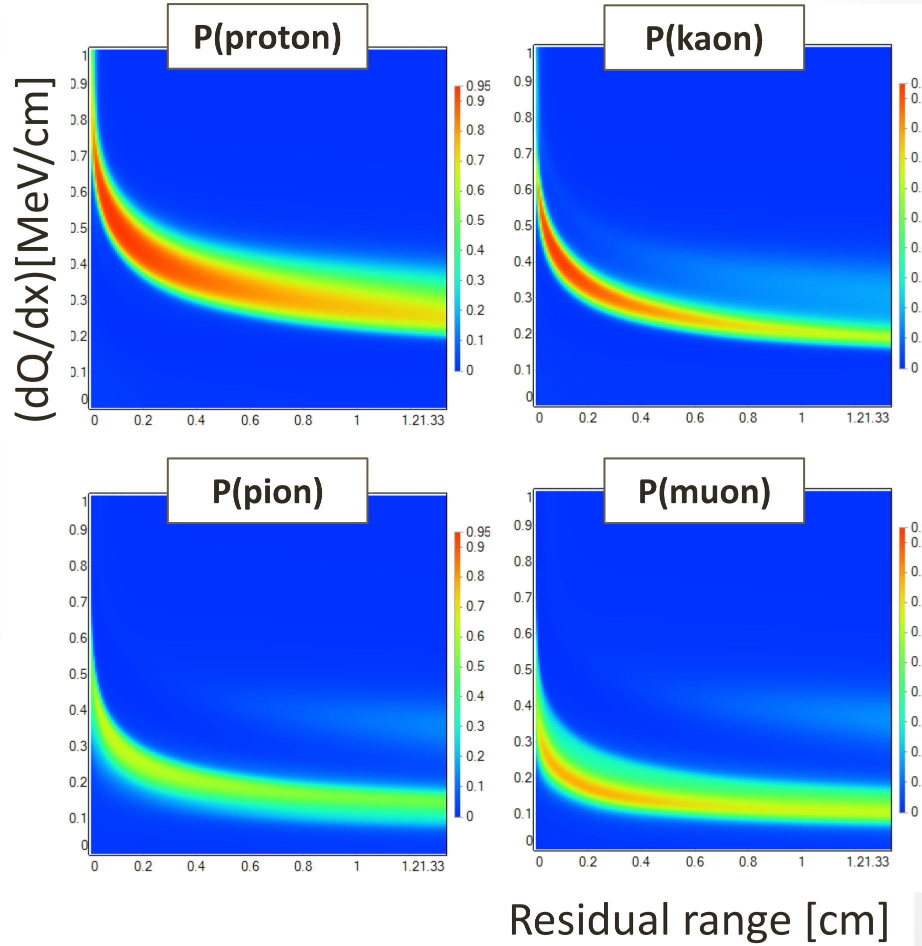
Tested/applied in: 2-plane: ArgoNeuT, LArIAT (data), 3-plane: 35t, ProtoDUNE (sim)

# Examples of high level pattern recognition

**Particle identification in ArgoNeut and ICARUS**

Neural Net patterns: p, K, $\pi$, $\mu$, unknown




From ArgoNeut, JINST 8 (2013) P08005

$(dE/dx)_{hyp} = A\,R^{b}$

$T_{range} = A/(b+1)\,R^{b+1}$

patterns -> P(stopping), P(particle ID)

NetMaker by Robert Sulej

# Do we have full reconstruction?

- ArgoNeuT produced results with automated reconstruction, since then many new advanced and general methods were developed.
- MicroBooNE is capable of reconstructing data, several algorithms are being compared.
- LArIAT is carrying data analysis with fully automated tracking and vertexing.

BUT…

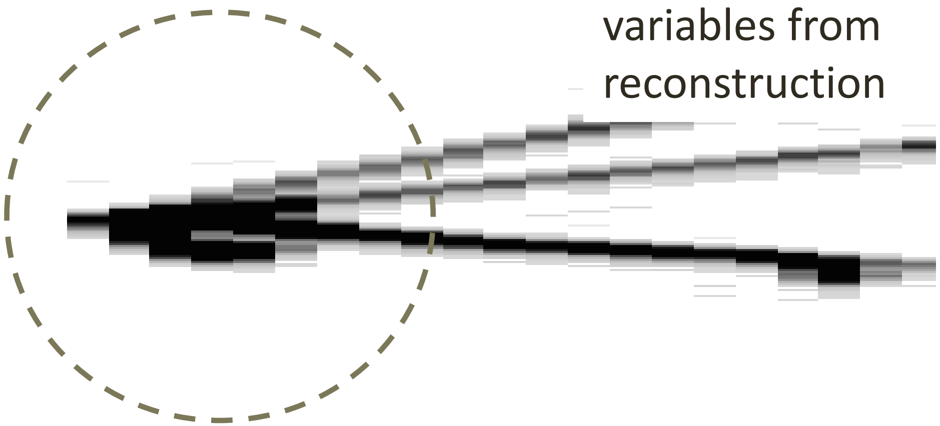
- Full reconstruction is a long chain of algorithms, each has its inefficiences.
- Hardware is not as easy as MC.
- We have full reconstruction, it is rough at some points, and to be well assessed against requirements.

# Challenges

- Shower reconstruction: merging  of shower fragments and identifying overlaps.
- Wire-plane-parallel tracks: missing information (constant drift time), especially difficult in dense regions.
- Tracks parallel to E field: signal processing on a single wire.
- Reconstruction of details in the vertex region: tracks in a narrow cone.
- Analysis: calibrate meausrement of momenta of escaping and interacting particles.
- Real life: hardware effects influence data.
- Pixelized TPC readout: could solve many issues, but it is challenge itself.
- Efficiency evaluation, comparison between mc and reconstruction, many intermediate stages of reconstruction before reaching the final analysis values.
- Organization: many frameworks, many ideas and a lot of people.

# From rough to detailed reconstruction

$\nu_e$ CC event



Higher- level variables from reconstruction

PRIMARY VERTEX

Larsoft simulation

**We can reconstruct a lot**:

- Global features: energy deposition, profiles, ...
- Spatial/calorimetric track details.
- Particle identification.
- Topology of points of interactions in the event.
- …
- Algorithms on this level of detail are being perfected

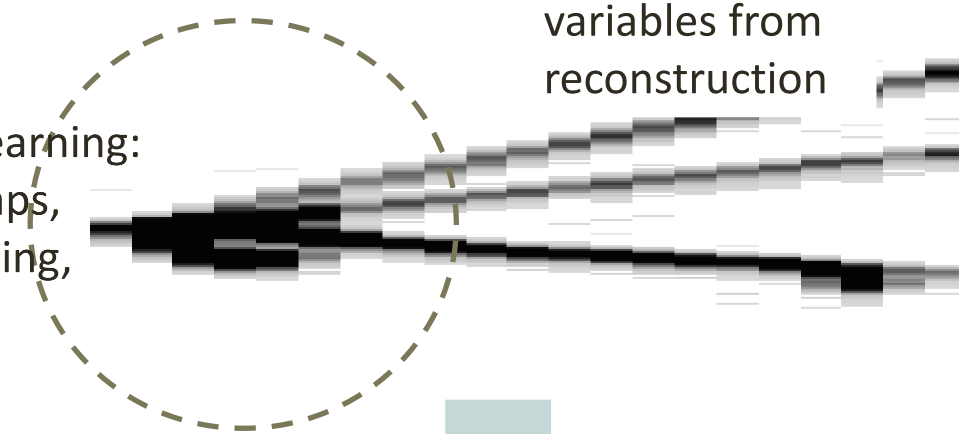
**But still full information is not yet explored.**

**Especially features of primary vertex are still challenging**.

# Future of event classification?

higher-level
variables from
reconstruction

machine learning:
feature maps,
deep learning,
…



**CLASSIFIER**

technique capable of extracting discriminating features and/or building class models automatically, without human input to the process.

e.g. $P(\nu_e \text{ CC})$

# Thank you!

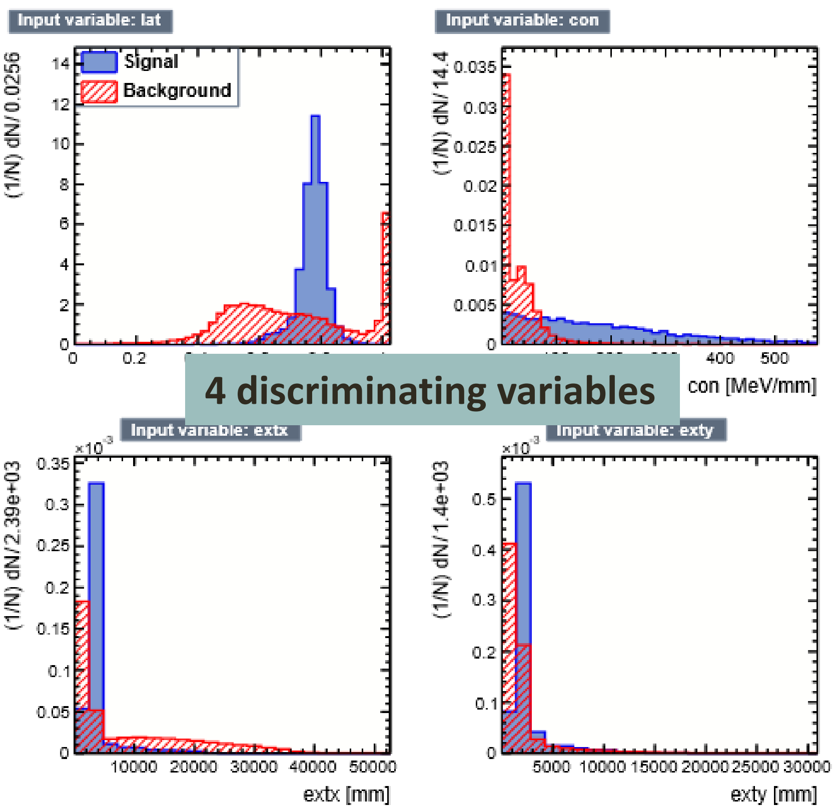
# backup

# Examples of high level pattern recognition

## Electron-Hadron shower discrimination

Eur.Phys.J. C73 2369

Singal events are defined as electromagnetic shower events compared to the complete shower background, which includes protons, charged pions, neutral pions, charged and neutral kaons and muons.

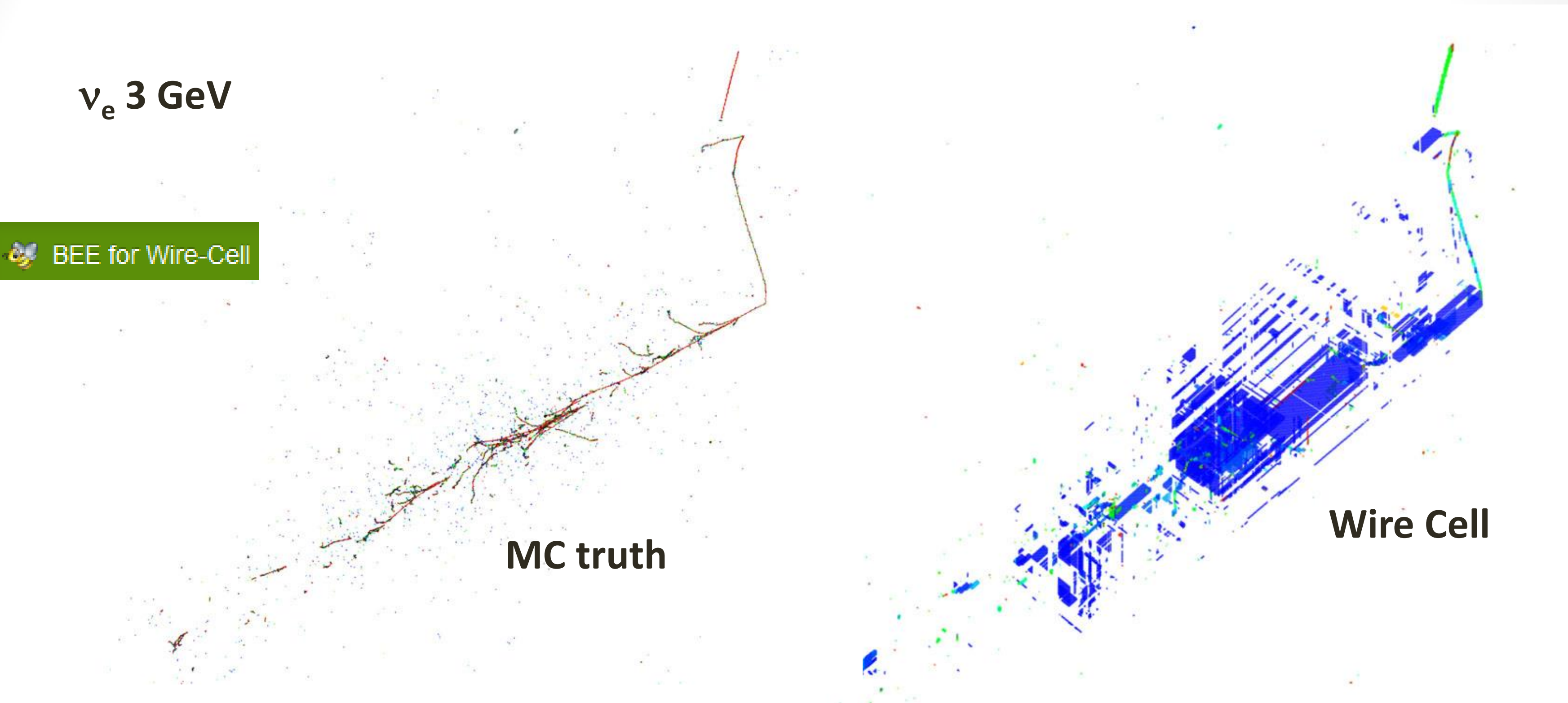



**4 discriminating variables**

Classifiers from TMVA toolkit Physics/0703039:

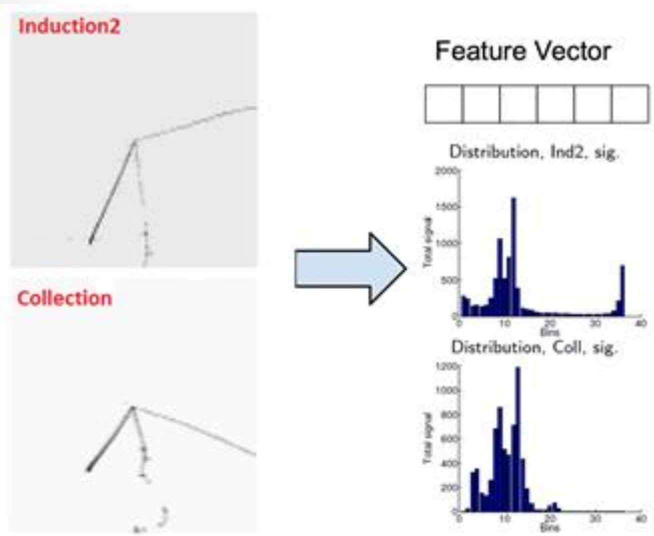
- KNN
- BDT
- Neural Network

# 3D imaging

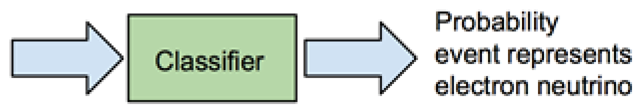



- Residual ambiguity, inherent in LArTPC technology
- 3D Image → Pattern recognition and high level reconstruction is progressing

# Future of event classification?

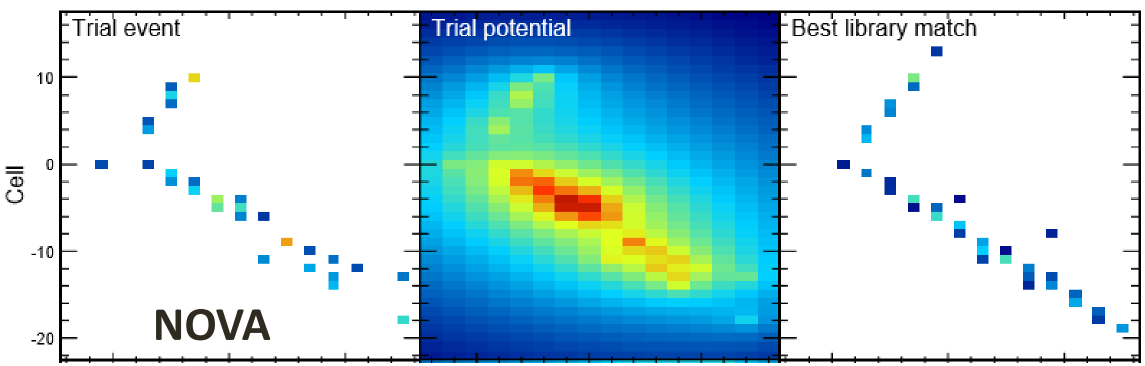



**Classification of *raw data features* created on basis of experience and observations.**




Piotr Płoński

http://arxiv.org/abs/1505.00424




**Classification of *high level features* in events selected with:**

**Library Event Matching**

From: *Nucl. Instr. and Meth. in Physics Vol. 778 (2015)*

C. Backhouse, R. B. Patterson

**Or another technique capable of extracting discriminating features and/or building class models automatically, without human guidance.**