LAr TPC data reconstruction

Dorota Stefan
CERN/NCBJ Warsaw Poland

BNL Seminar 11.5.2015

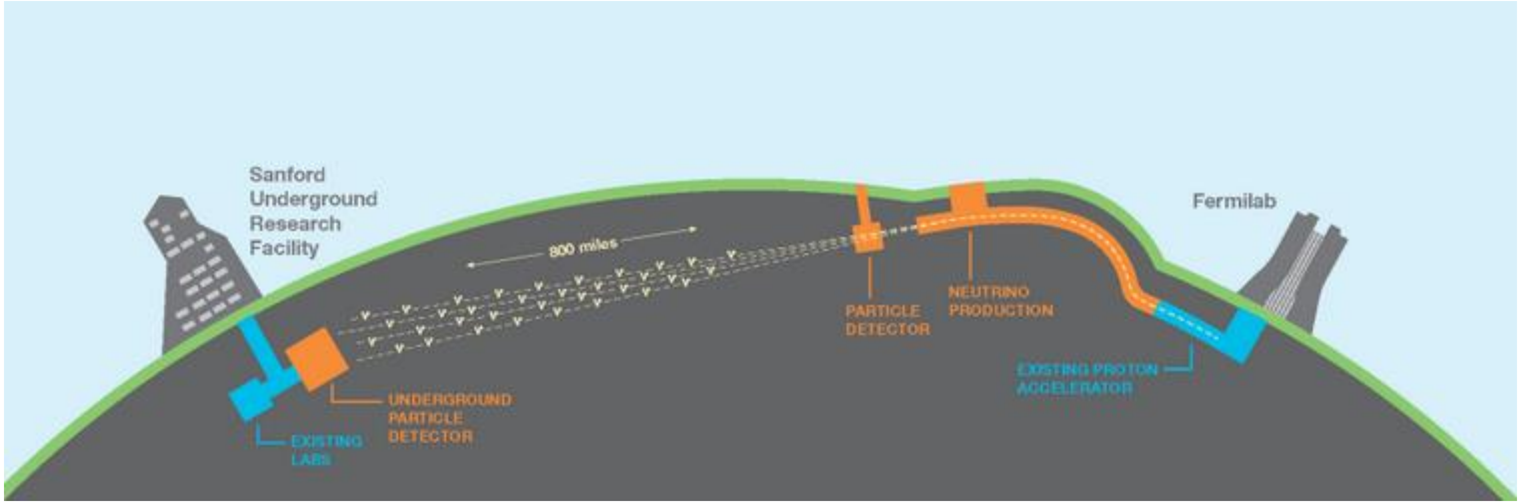
Outline

- Introduction: Liquid Argon TPC’s and reconstruction challenges in these detectors.
- Chain of LAr TPC data processing, closer look at new approaches designed for ICARUS experiment which are now continued for application in next LAr TPC projects.
- Examples of applications in ICARUS, 35t and protoDUNE.
- Summary.

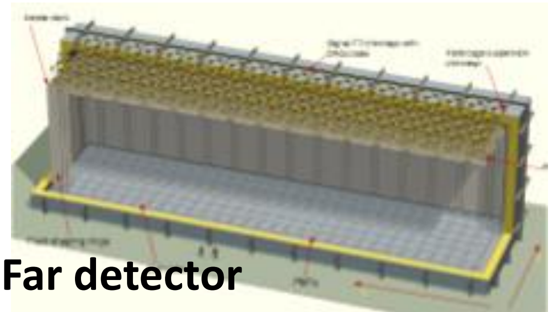
Physics in DUNE

DUNE
Deep Undeground
Neutrino Experiment

- CP symmetry violation in neutrino interactions.
- Neutrino mass ordering.
- Neutrino oscillation parameters.
- Nucleon decay.
- Neutrino bursts from supernova.



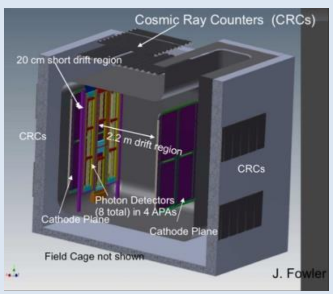
Experiments with LArTPC



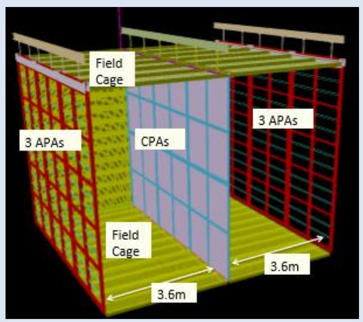
Far detector (dualphase)

Far detector (singlephase)

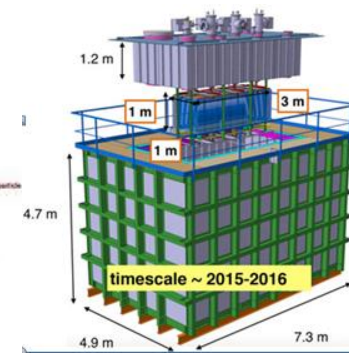
share the same design principles



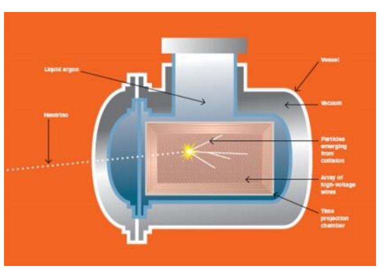
35t prototype



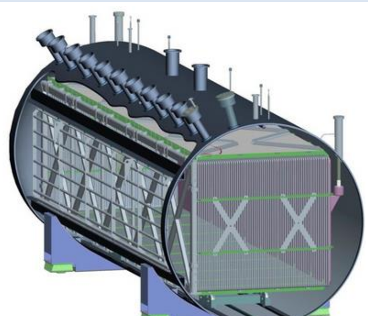
protoDUNE



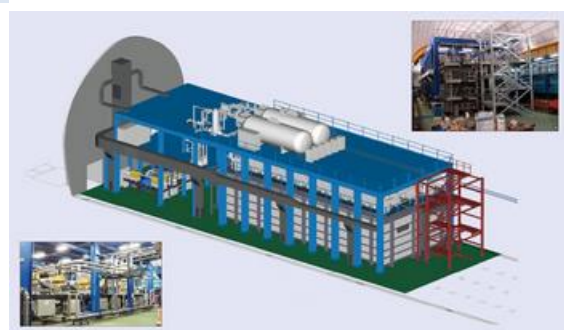
dual-phase WA105 prototypes



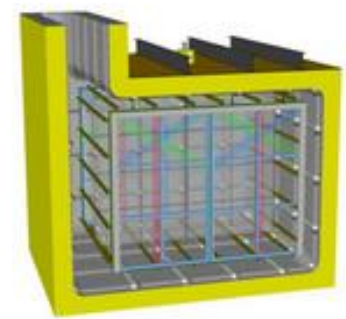
ArgoNeuT/LArIAT



MicroBooNE

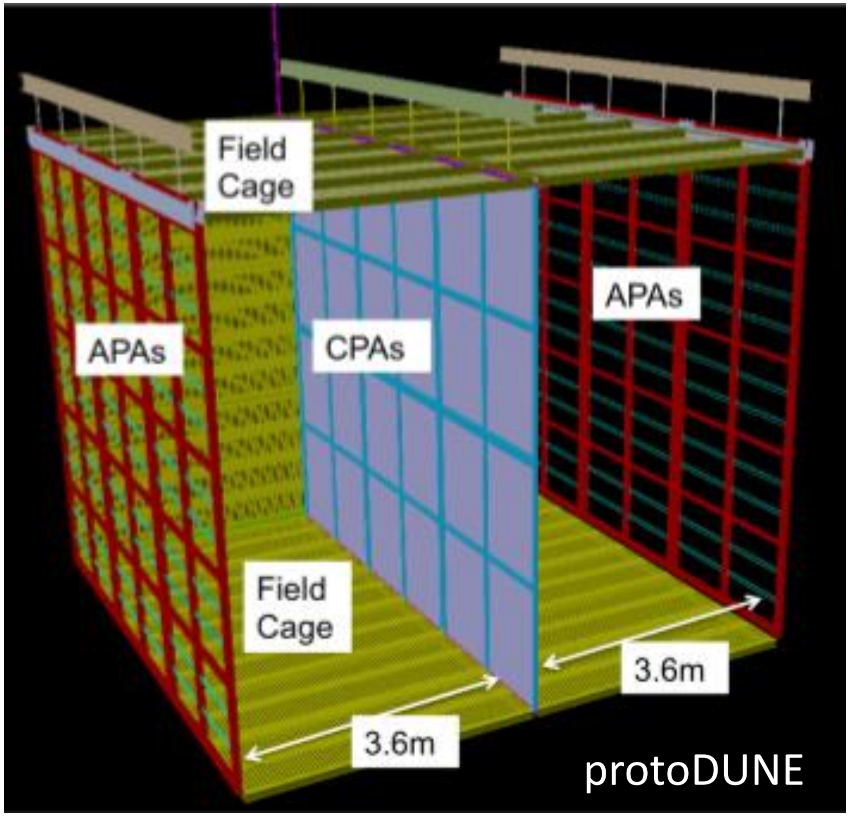


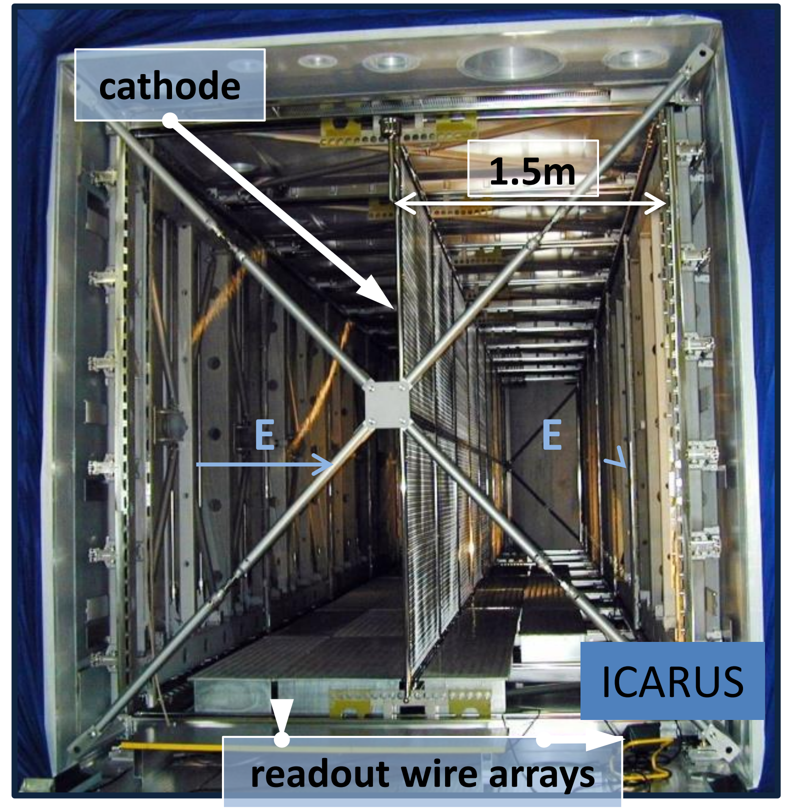
ICARUS



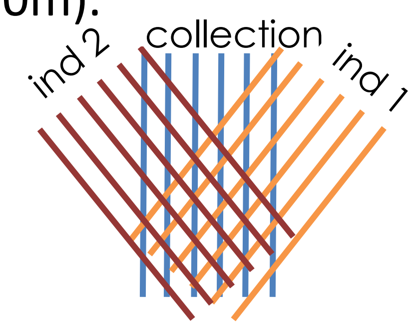
SBND

LArTPC detectors - different designs



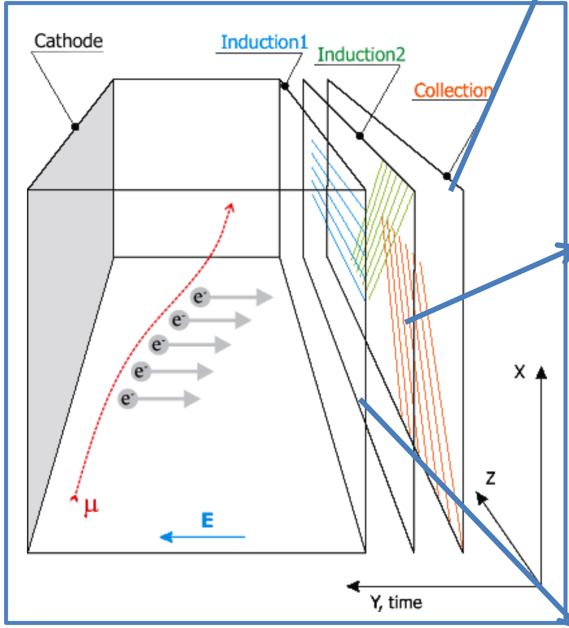


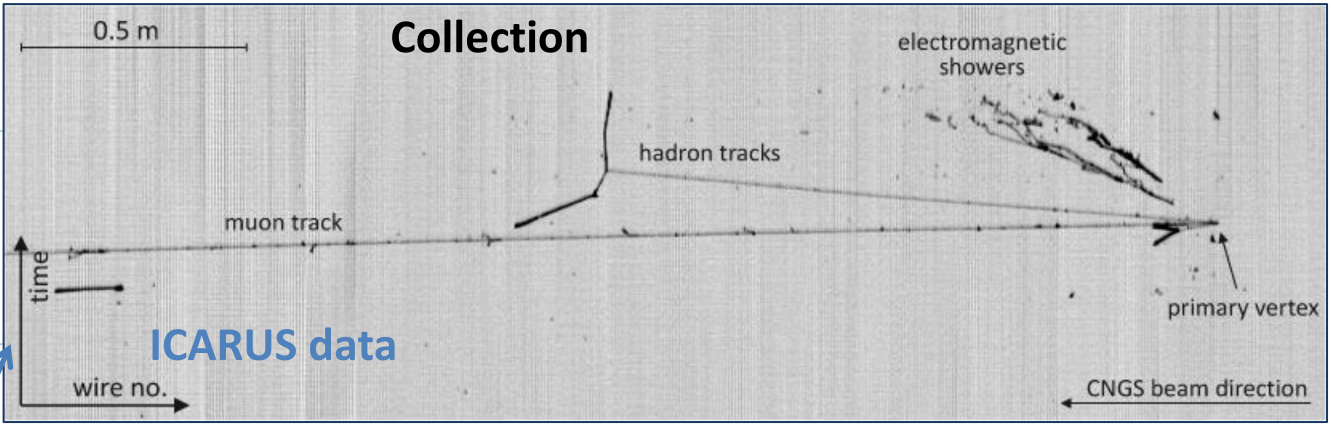
- Modularized anodes (2m x 6m) vs single anode (4m x 20m).
- 5 mm wire pitch vs 3 mm wire pitch.
- Wire orientation.
- Number of readout wire planes (3 or only 2).
- And many more differences…

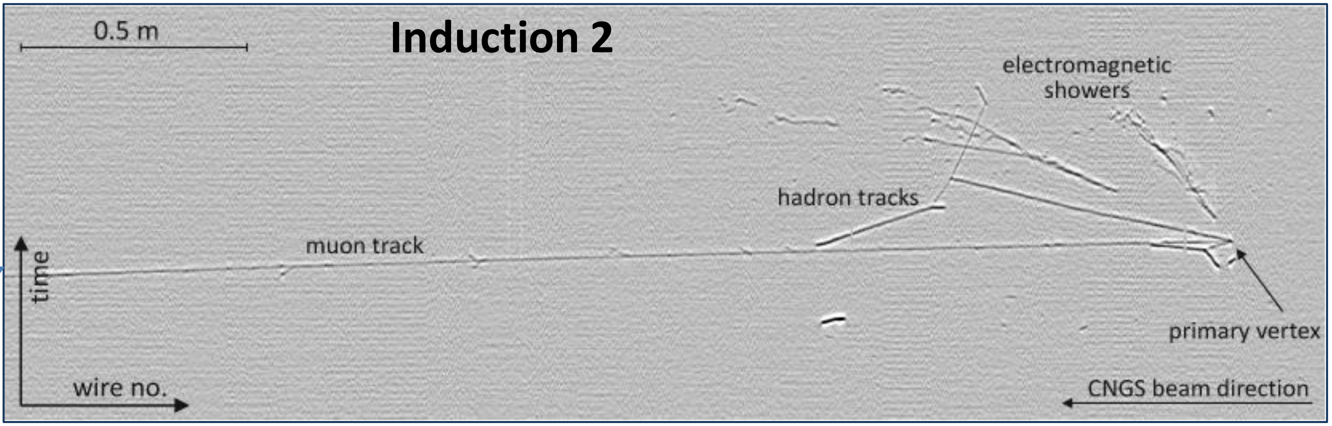


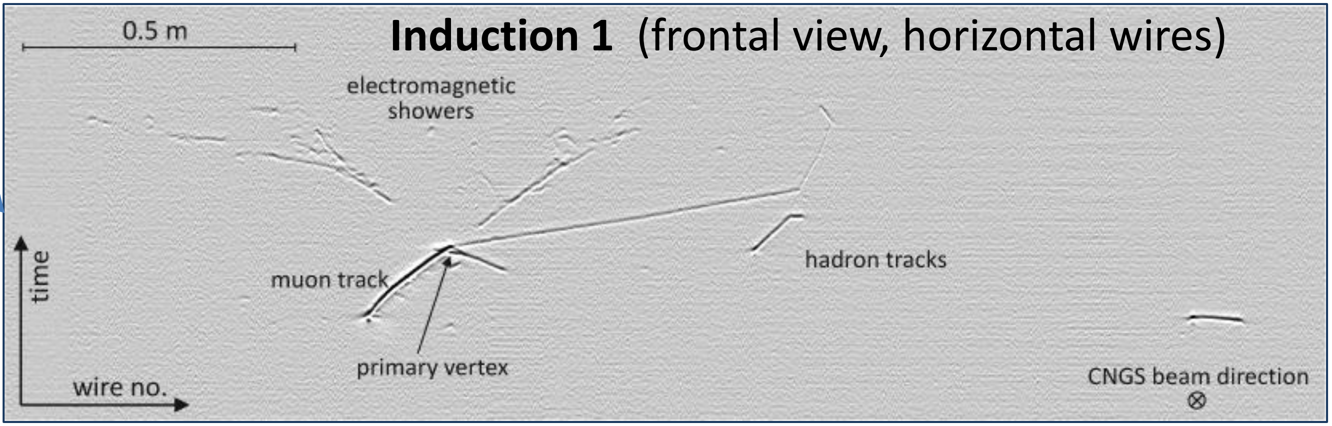
LArTPC principles

An example of ν_μ charge current interaction, one of TPC's shown









Aims of reconstruction

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

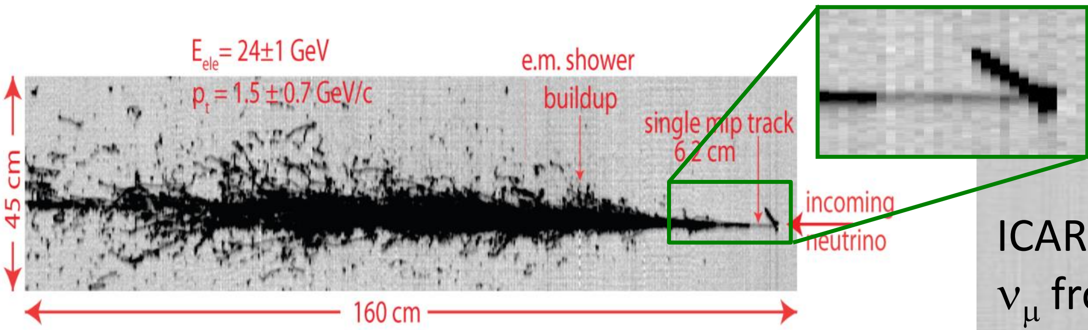
- <u>We have to identify incident particle (ν_e, ν_μ, nucleon decay, muon…) and measure momenta.</u>

- How?
  - Find primary vertex
  - Identify outgoing particles
  - Measure their momenta

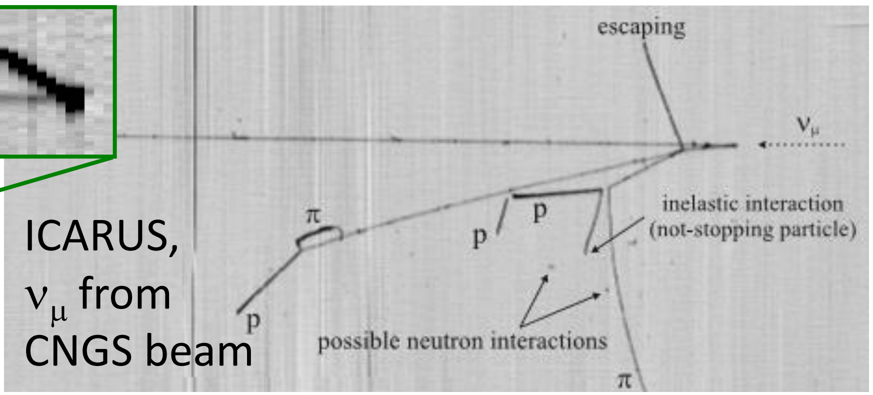
RECONSTRUCTION

What should we expect in data?

- There are usually EM showers and tracks, they need different treatment.
  - detailed trajectories of tracks needed for correct reonstruction/analysis
  - details of the initial direction and <u>complete</u> energy of EM shower
- There are various difficult topologies to be reconstructed and LArTPC is all about non-uniformities in every possible aspects.
- Ideally would be to have a general tool: reconstructs neutrino events, nucleon decay, cosmics…



Alessandro Menegolli NNN15



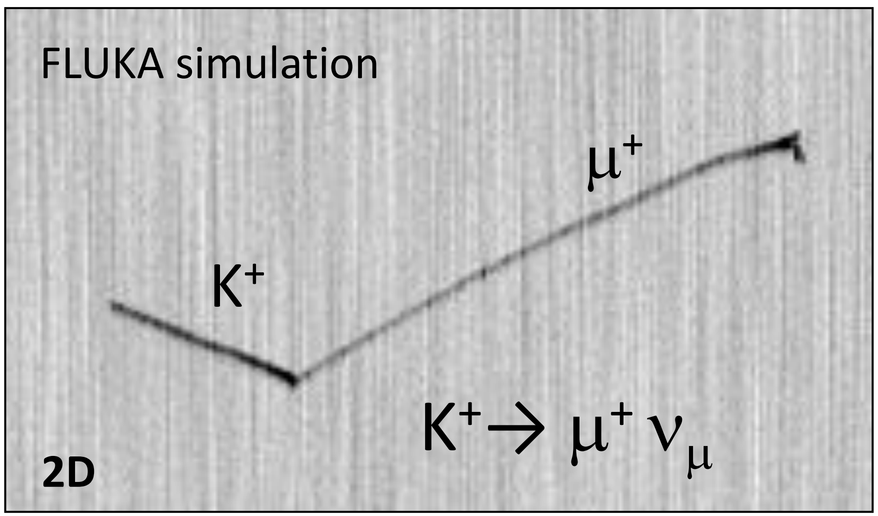
From *European Strategy for Neutrino Oscillation Physics* – II, poster, Cern 2012

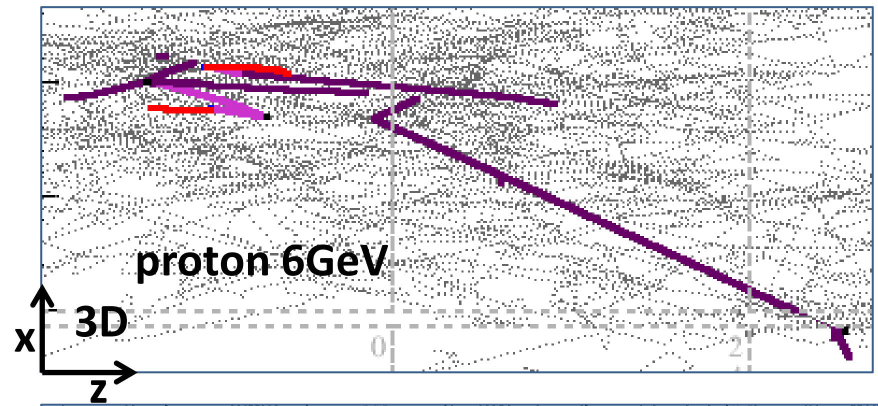
Hadronic shower and track topologes

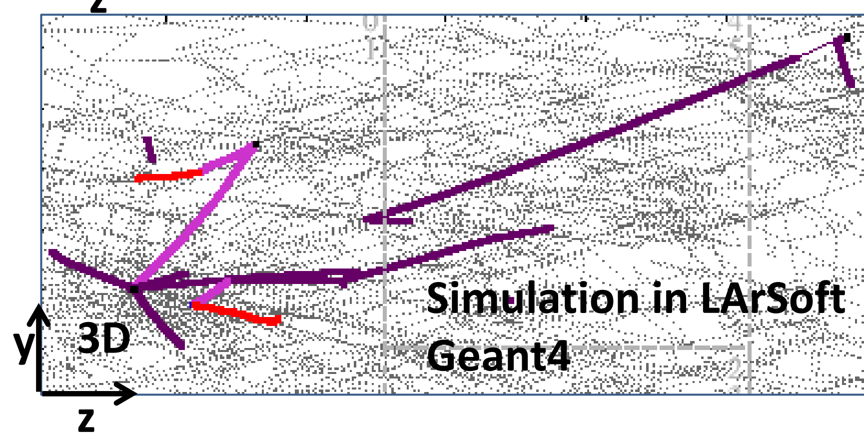
hadronic shower (or single tracks)

stopping (detect by dE/dx) PID, momenta

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

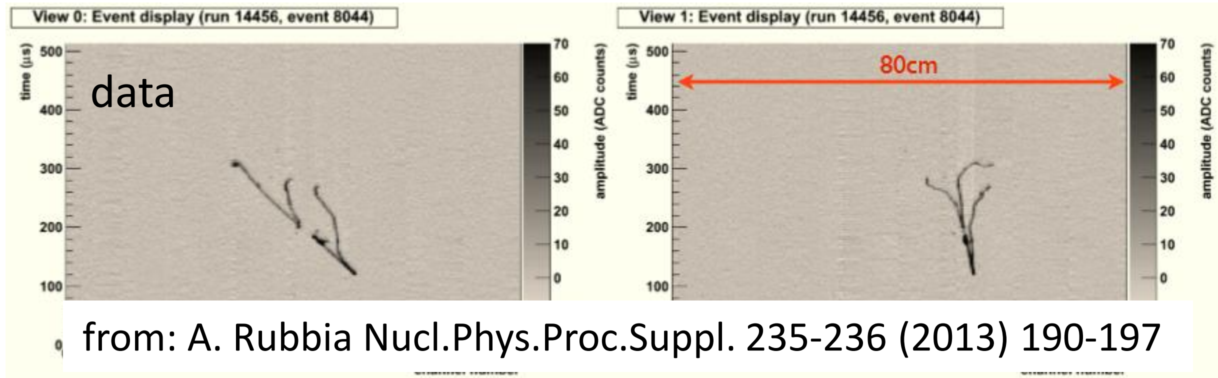






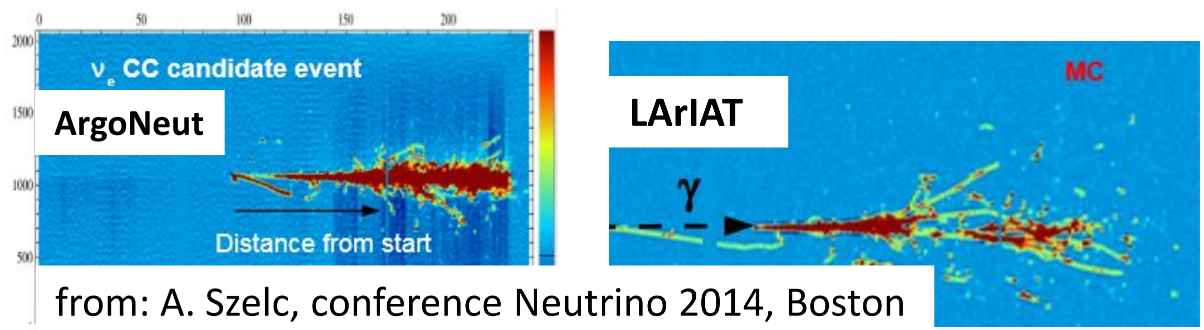
Electromagnetic showers

- **low energy cascade**



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

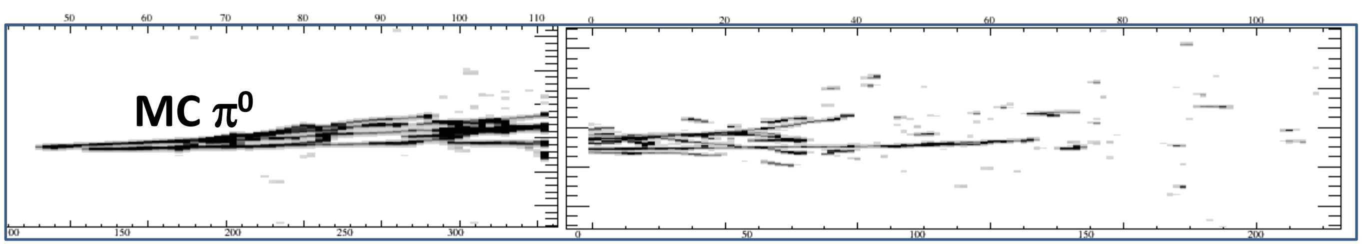
- **fully developped cascade**



from: A. Szelc, conference Neutrino 2014, Boston

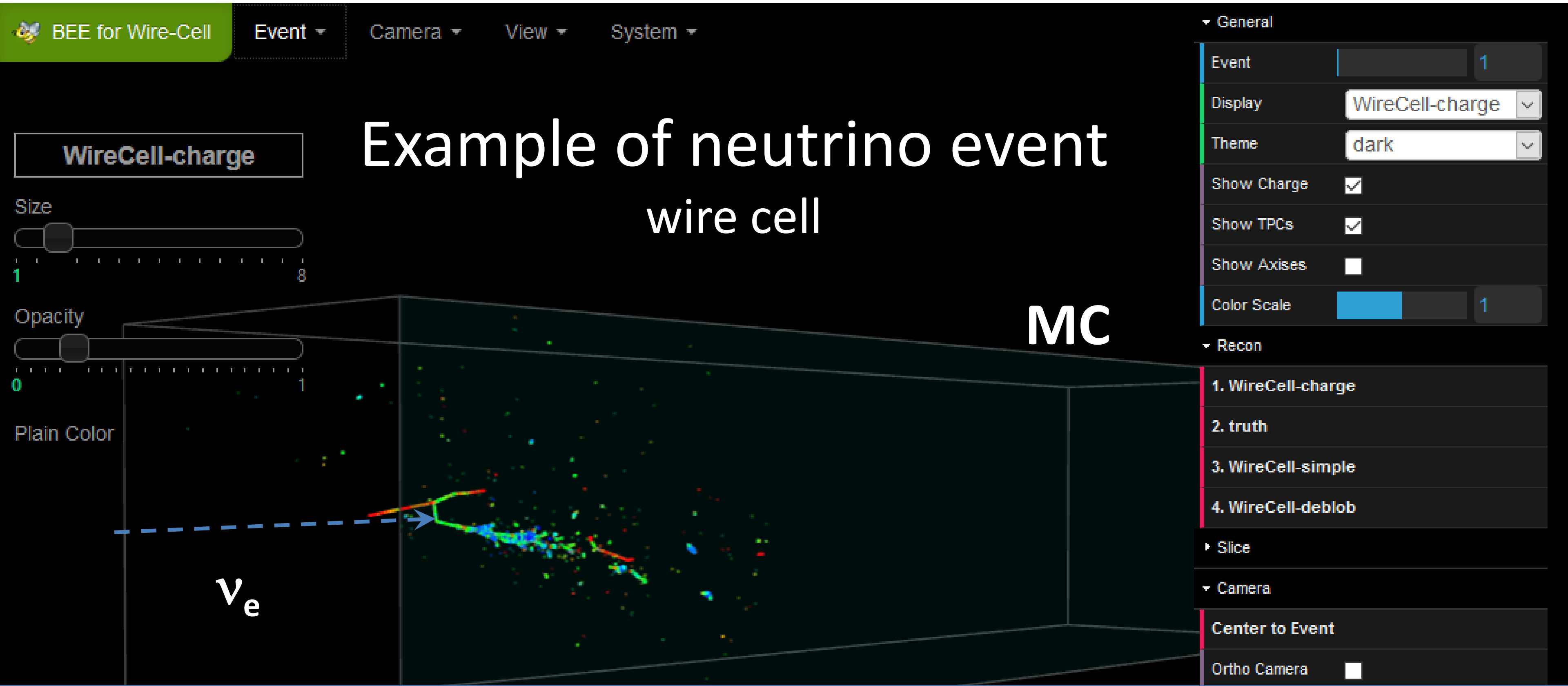
- **multiple showers**

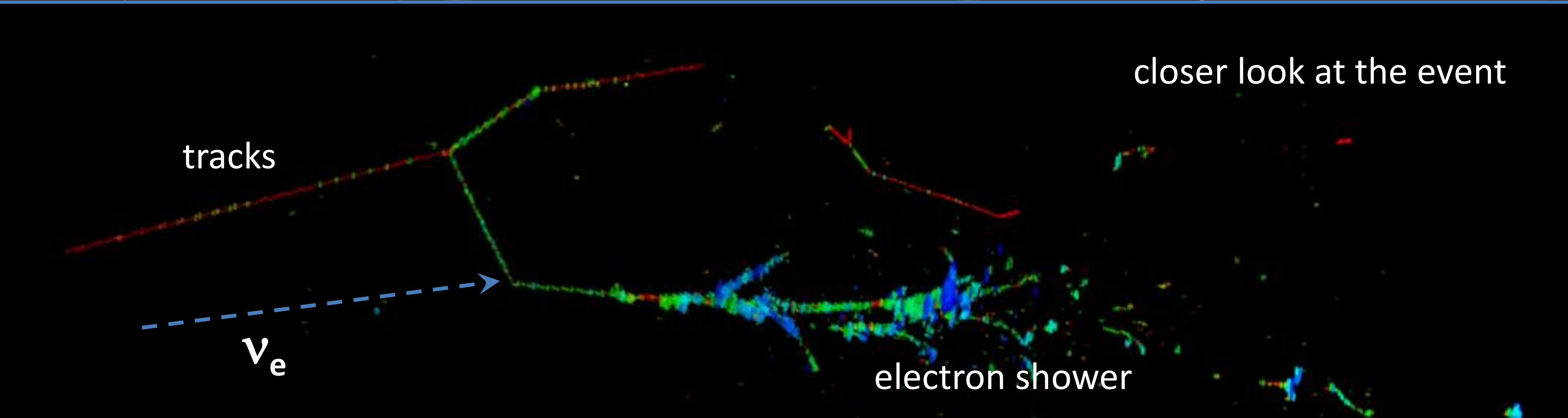
simulated π^0 with energy ~ 1 GeV in LArSoft



Example of neutrino event

wire cell





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

Non-uniformities in LArTPC

- Direction-dependent resolution:
  wire spacing differs from signal sampling rate.
- Signals of tracks parallel to the electric field.
- Signal attenuation:
  - LAr impurities,
  - recombination effect – can have angular dependance.
- Diffusion.
- Space charge effects.
- We have to be prepared for usual hardware failures.

Spatial reconstruction – why is it so difficult?

- 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, …
- Little help for reconstruction from external detectors
  approximate location / ID with PMTs, in general whole event details to be reconstructed from TPC data solely.
- wire signal characteristics may be different in each plane.

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 chain

DATA

2D or 3D hits, space points, cells, blobs

clusters: track like, shower like objects

PATTERN RECOGNITION

- DBSCAN
- Fuzzy Clustering
- Charge distribution matching
- Clustercrawler/CCTrackMaker
- Hough transform
- Cellular automaton

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

- Kalman Filter
- Bezier Tracking
- Principle Curves
- Polygonal Line

identification of particles and interactions

HIGH LEVEL PATTERN RECOGNITION

hits, space points,
cells, blobs

● **clusters: track like,
shower like objects**

trajectory, vertices

- Use 3D space points from preceding stage: refit reduced information
- Or look at 2D data selected by clustering: fit directly to measurement

identification of particles
and interactions

2D clusters reconstruction in ICARUS – event segmentation

1. Hits $\Rightarrow$ strictly linear segments

Basic requirement for the segment:

- hit positions on line;
- hits touching each other

Result:

- **clusters that do not mix hits from different objects**
- usually large number of small clusters;

(long straight tracks are also accepted, if found at this stage)

algorithm starts from external parts of the event towards its primary vertex

2. Segments merging

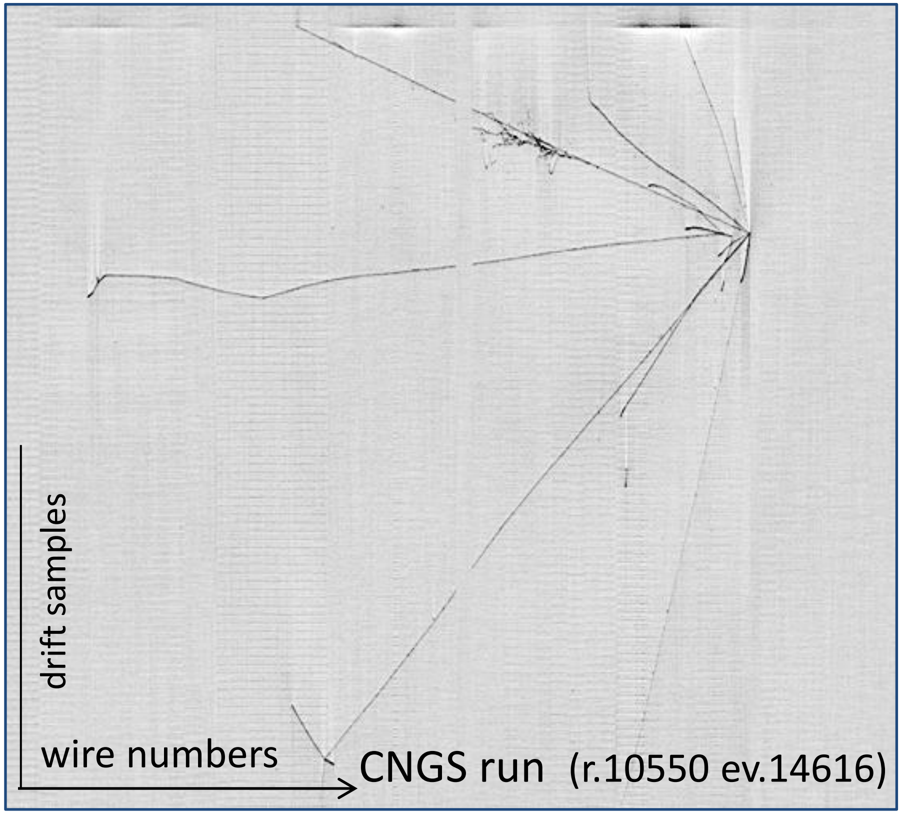
Grow track segments by merging based on:

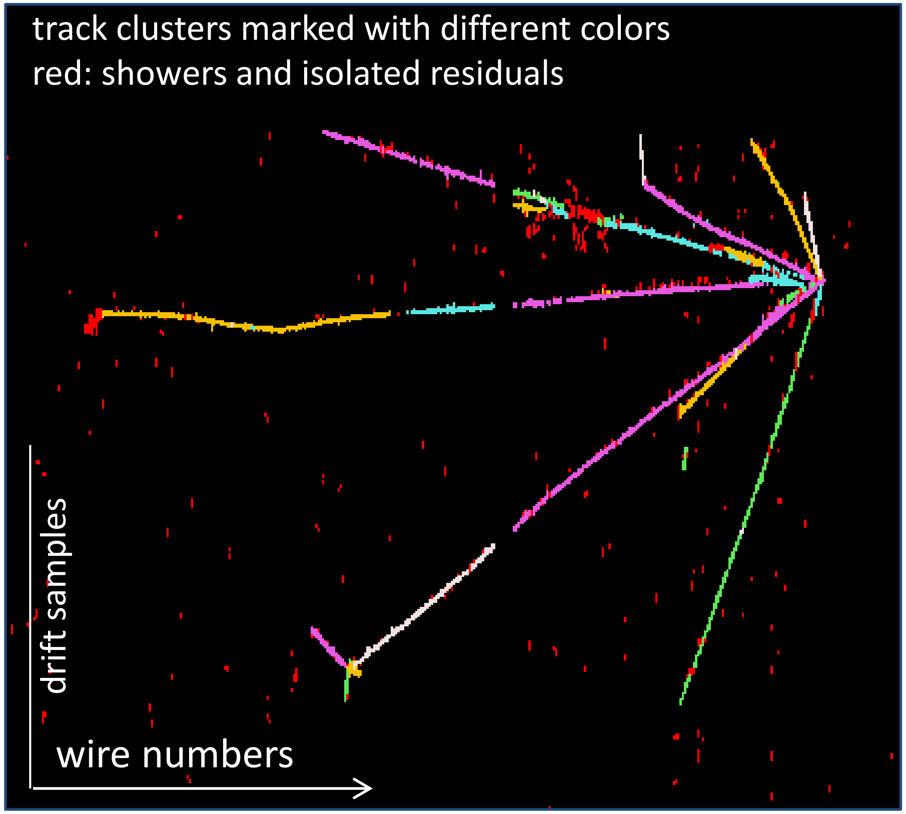
- distance between segment endpoints
- angle between segments

3. Shower or track classification

Based on sizes and configuration of segments from step #2.

Example of event segmentation output





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

hits, space points,
cells, blobs

clusters: track like,
shower like objects

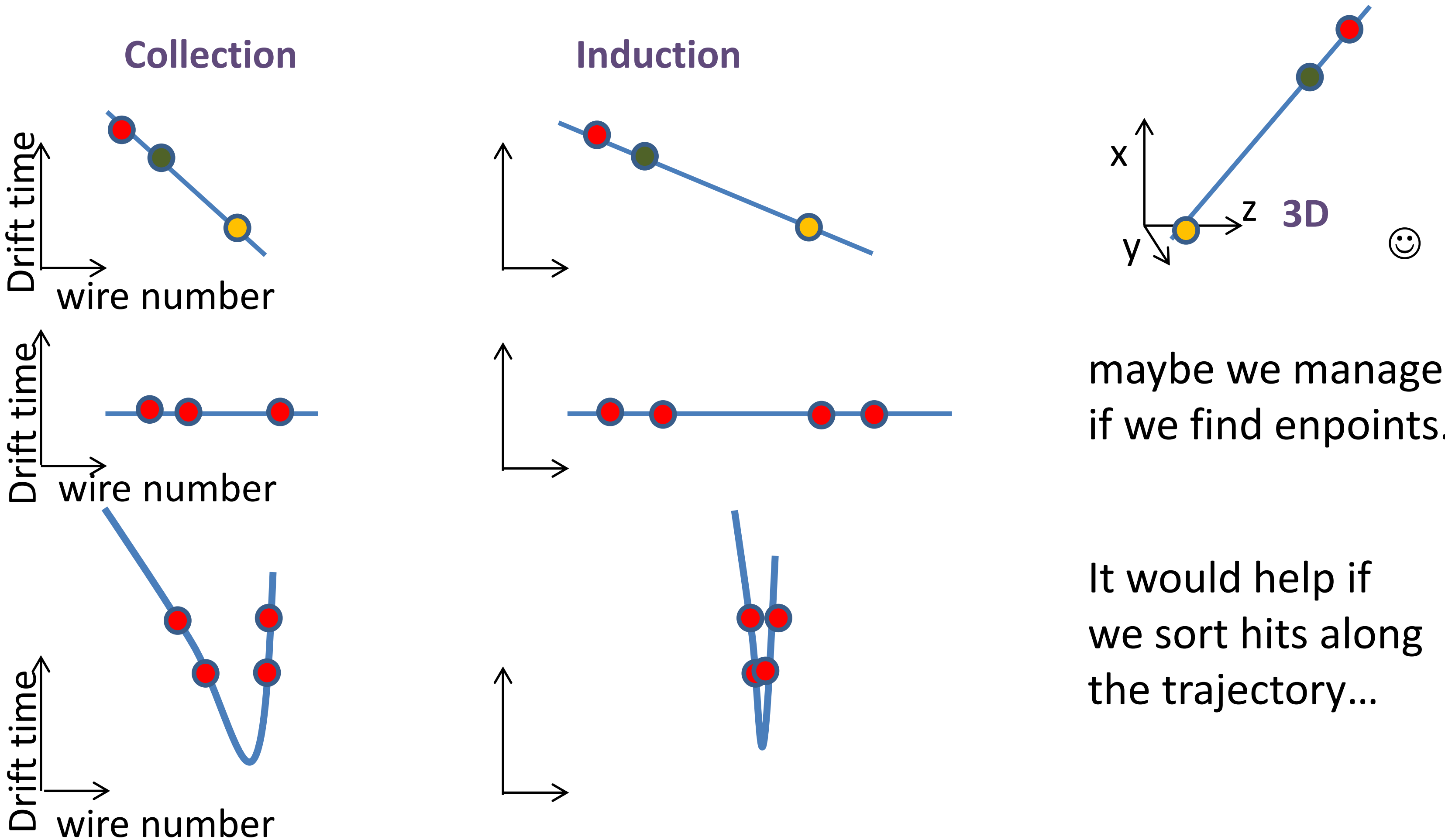
trajectory, vertices

- **Use 3D space points from preceding stage: refit reduced information**
- **Or look at 2D data selected by clustering: fit directly to measurement**

identification of particles
and interactions

3D reconstruction – first attempts

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

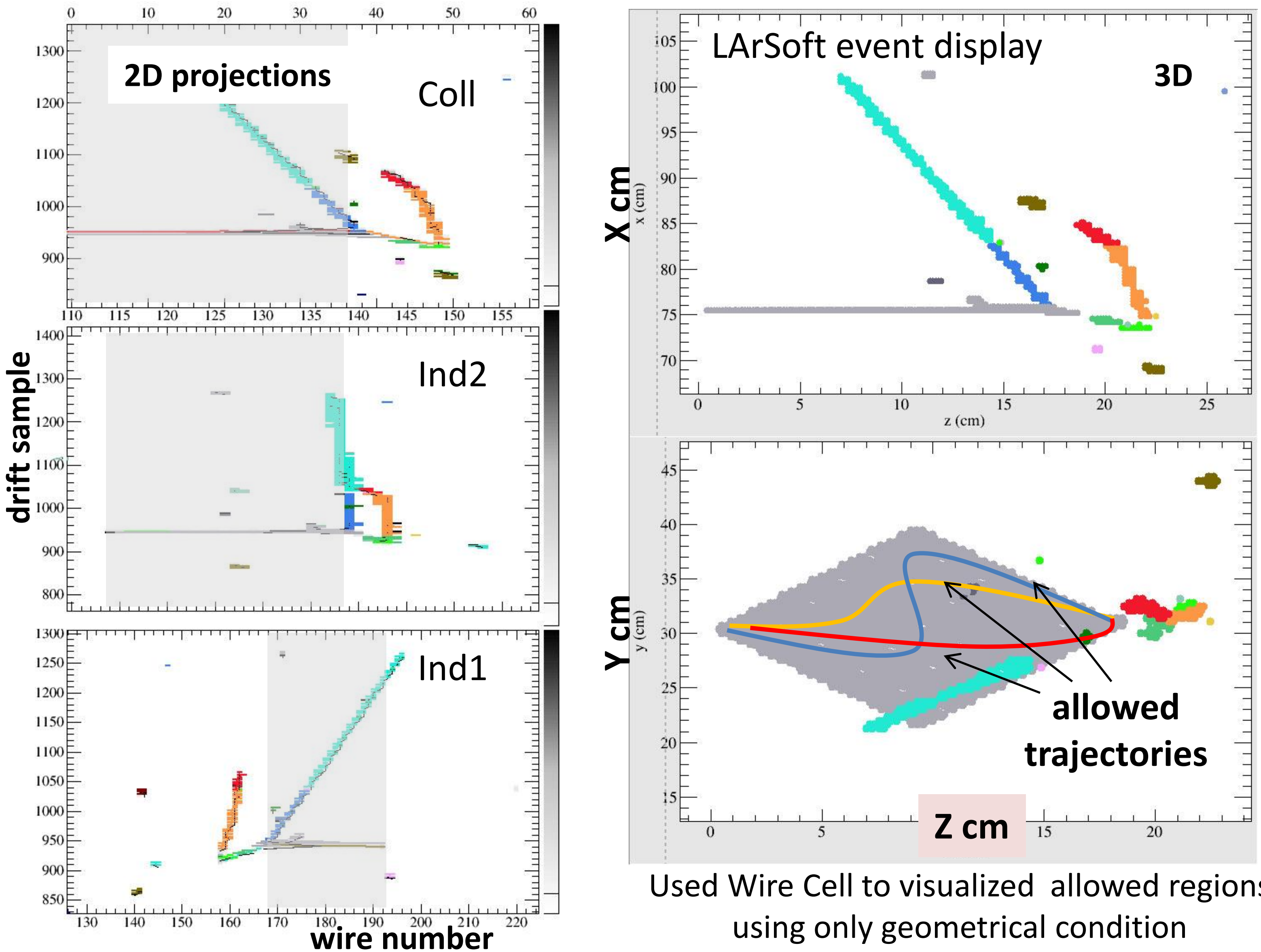


maybe we manage if we find enpoints…

It would help if we sort hits along the trajectory…

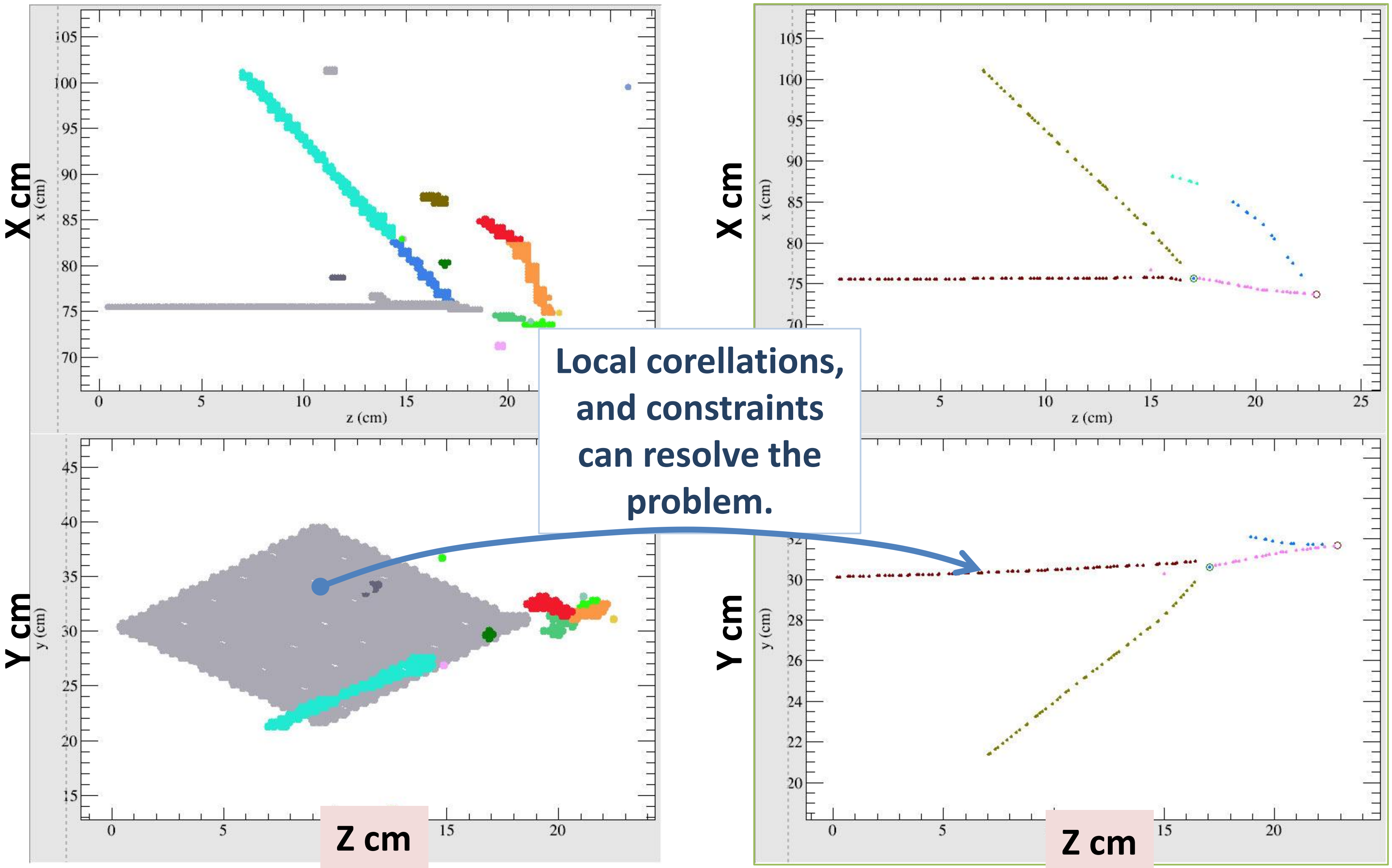
Development of more advanced methods was natural.

Special case: wire plane parallel blindness



Used Wire Cell to visualized allowed regions using only geometrical condition

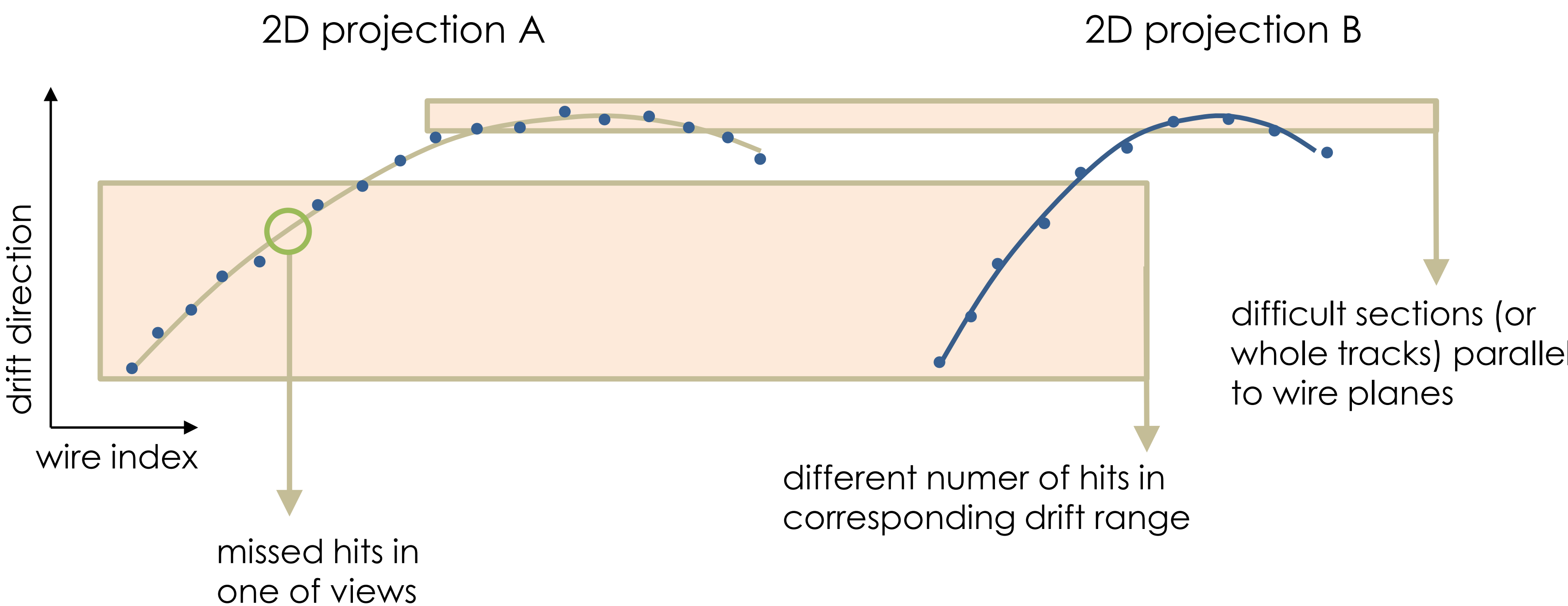
Special case: wire plane parallel blindness



Wire Cell: geometrically *allowed regions*

PMA trajectory fits

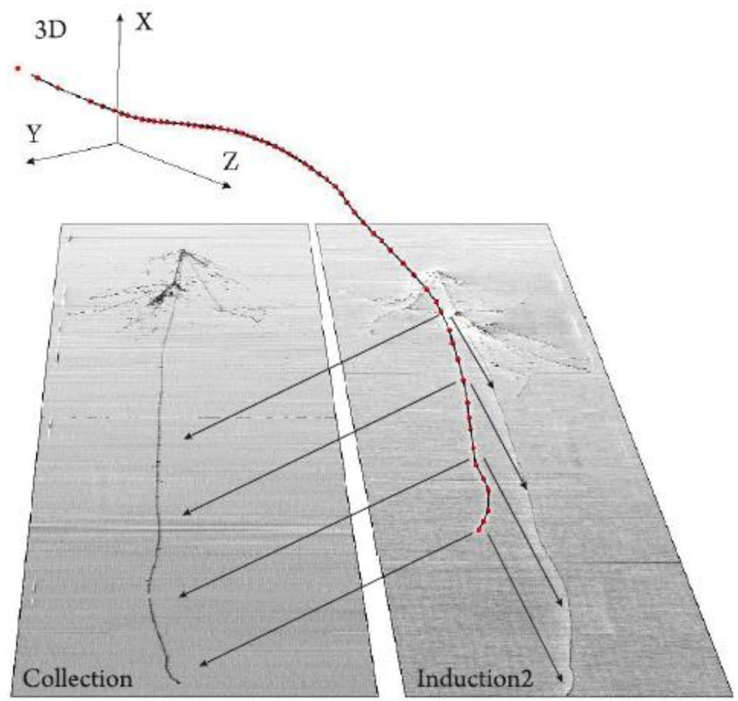
More on realistic conditions in reconstruction



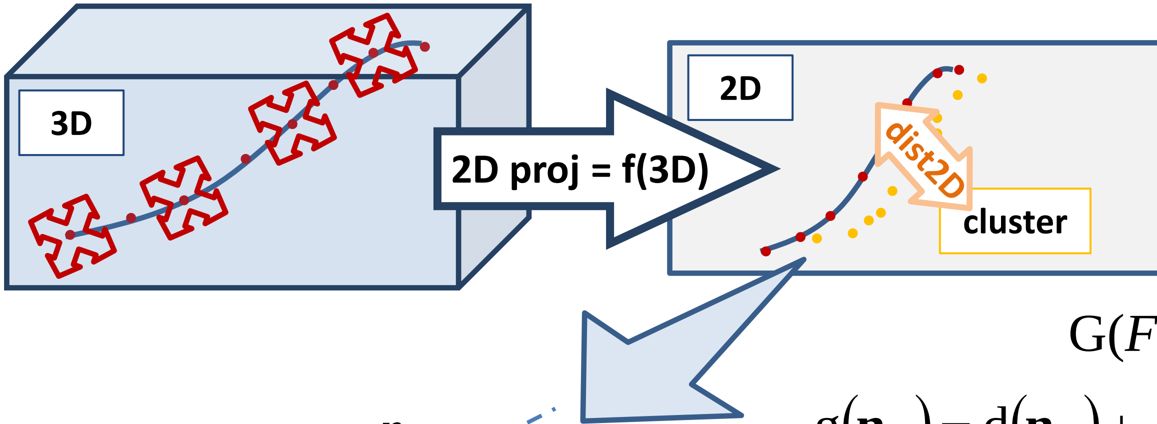
- hit positions are not perfect, 2D views are independent, corresponding track sections are made of different numbers of hits, … …
- → **problematic search for (*approximately*) compatible hits between 2D projections**, especially for tracks parallel to drift field and parallel to wire planes.
- work with independent 2D tracking, hit sorting along the trajectory, … → satisfactory results in performance tests were not achieved.

Trajectory reconstruction - Projection Matching Algorithm

- Reconstruction chain: 3D steps depend on preceding stages.
- Recent developments of Projection Matching Algorithm:
  - Single track.
  - multi-track structures.
  - Initial part of the cascade.



New 3D approach: basics of a single track building



Polygonal Line Algorithm for *Principal Curve Analysis*, with „local" objective function for node position optimization, adopted to work in 3D⇔*n*2D

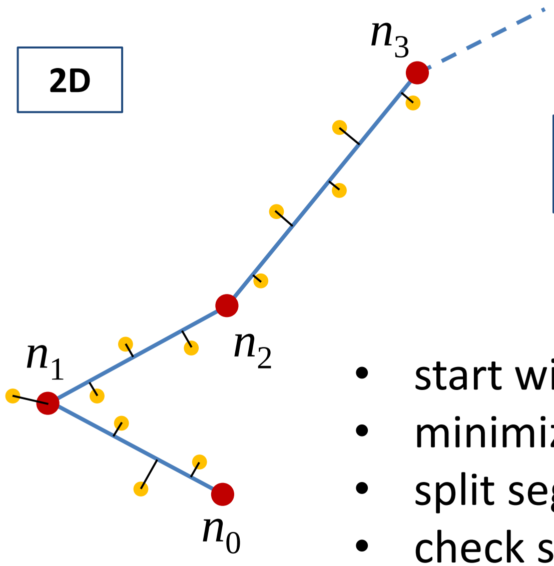
$$G(F) = \Sigma_k g(\mathbf{n}_k)$$

$$g(\mathbf{n}_k) = d(\mathbf{n}_k) + \beta_a c_a(\mathbf{n}_k) + \beta_v c_v(\mathbf{n}_k)$$

2D distance to hits assigned to node *k* and connected segments

penalty on angles between segments for nodes *k*, *k*-1, *k*+1

3D distance to ref. points assigned to node *k* and connected segments



- start with a single 3D segment (2 nodes)
- minimize G(F) with hits to segment/node re-assignment
- split segment (add node)
- check special topologies (e.g. narrow angle in 2D view of the track)

penalty on segment angles = minimal length needed to fit hits;

hits sorted according to their projection to the track, in 2D view;

hit projection to 2D view of the track segment defines its 3D position;

straight-forward calculation of d*X seen* by a hit, …

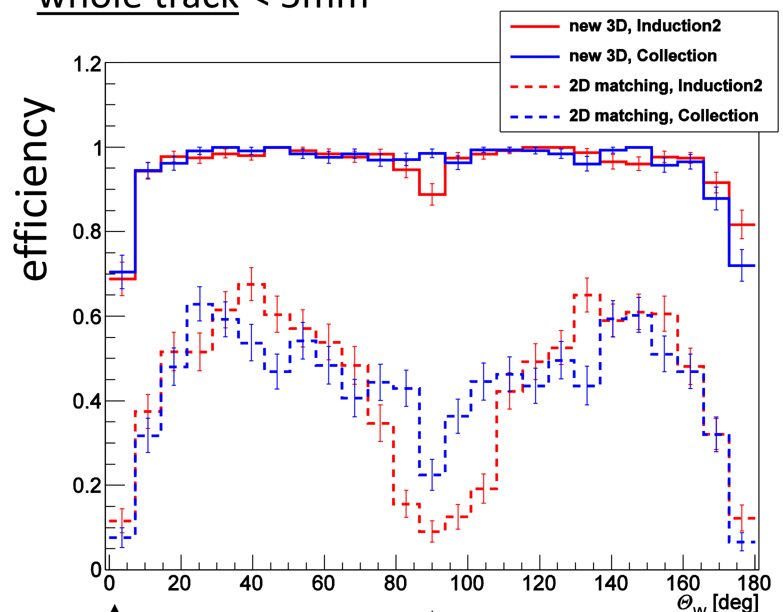
PMA vs old approach

Efficiency was measured on 30 cm stopping muon tracks, ratio:

$$\text{Efficiency} = \frac{\text{good tracks}}{\text{all tracks}}$$

as a function of an angle of the *initial direction w.r.t. the wires*, with a **strict definition of a „good" track** to enchance the difference (note: many other eff. measures can be invented)

good = max dist. to 3D MC cell along the <u>whole track</u> < 5mm



parallel wire plane

parallel to drift

parallel wire plane

Features of PMA

- **hit – hit association is not needed**, each 2D hit has its own 3D position on the trajectory, it is *independent* from hits in other projections
  - reconstruction can use 2 or 3 views; even sections with only 1 view are still useful (in case of e.g. dificult track orientation, hit/cluster inefficiency, hardware problems, …).

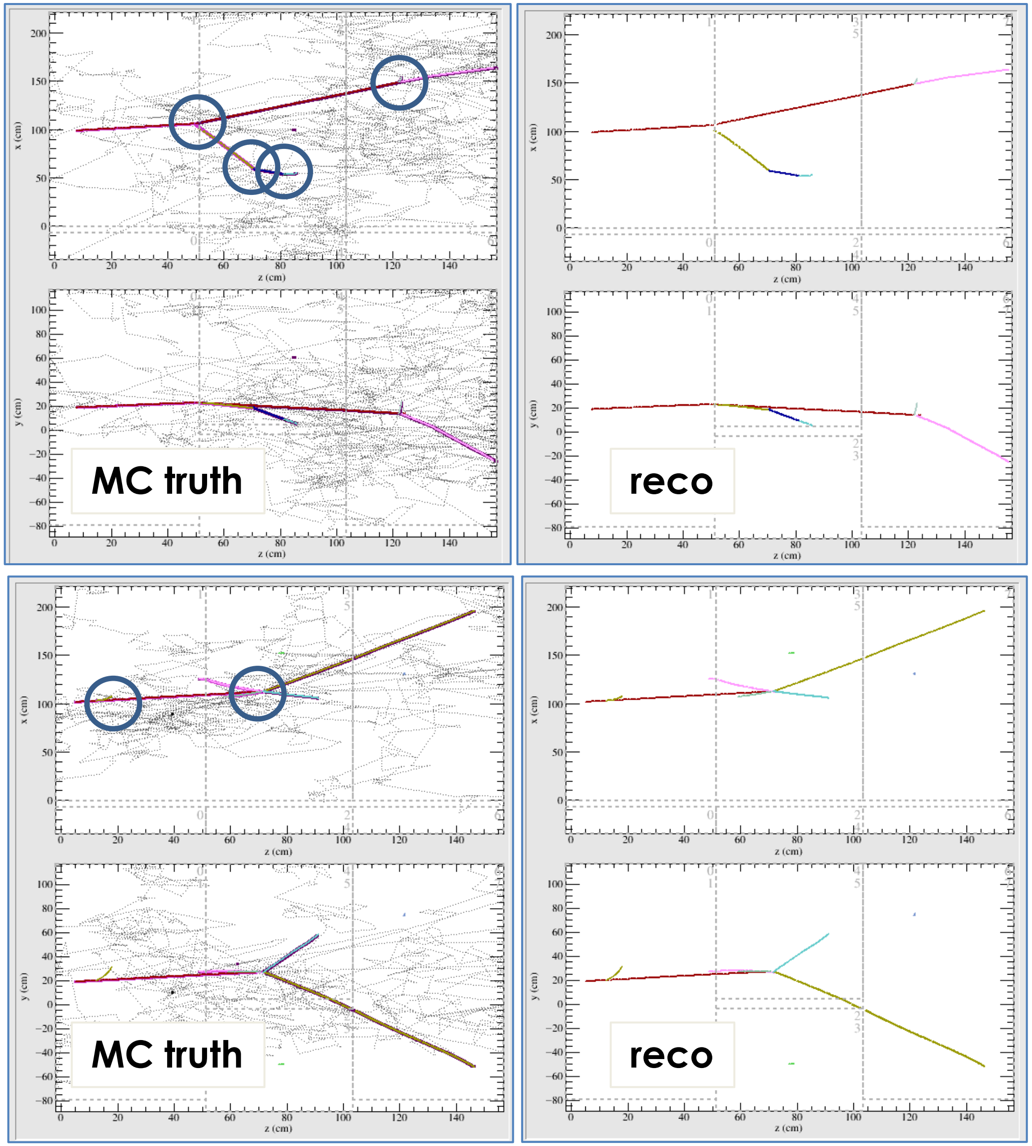
- **full 3D objects are driven directly by 2D information;** no intermediate step with 3D hits/points to be refitted again into tracks in 3D space.

- the optimization can take into account also 3D points: vertices, feature points, …, if available from other algorithms.

- **space charge can be easily accomodated** in the 3D→2D projection function used during the optimization, as well as any other non-uniformities resulting in spatial distortions, if such mapping is available (however computational cost can increase).

- **basic idea can be widely extended** to many aspects of reconstruction – next slides.

Multi-track structure example (π^- @ 2GeV)

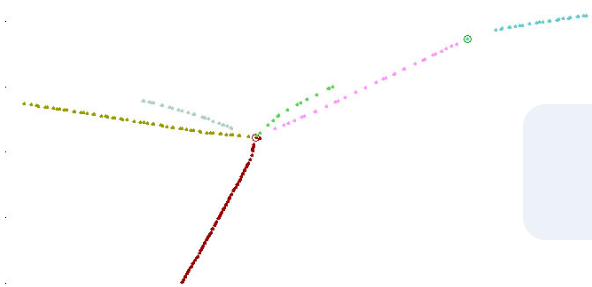


- multiplicity low enough for efficient track reconstruction.
- π^0s multiplicity: 1-2 per event on average.
- **need vertexes to understand relation between isolated tracks.**

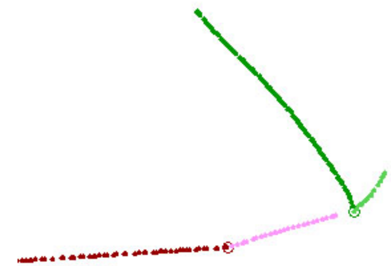
Full PMA

grow single tracks: cluster matching and track validation

PATTERN RECOGNITION



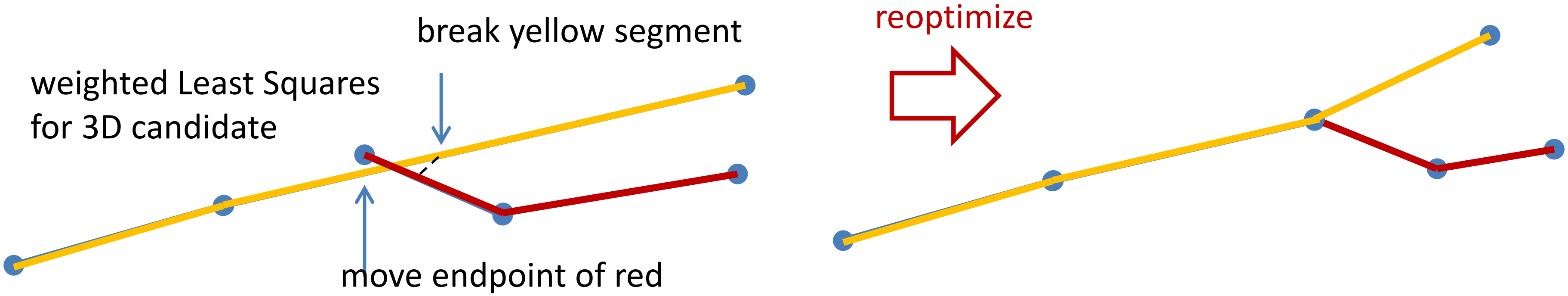
Projection Matching

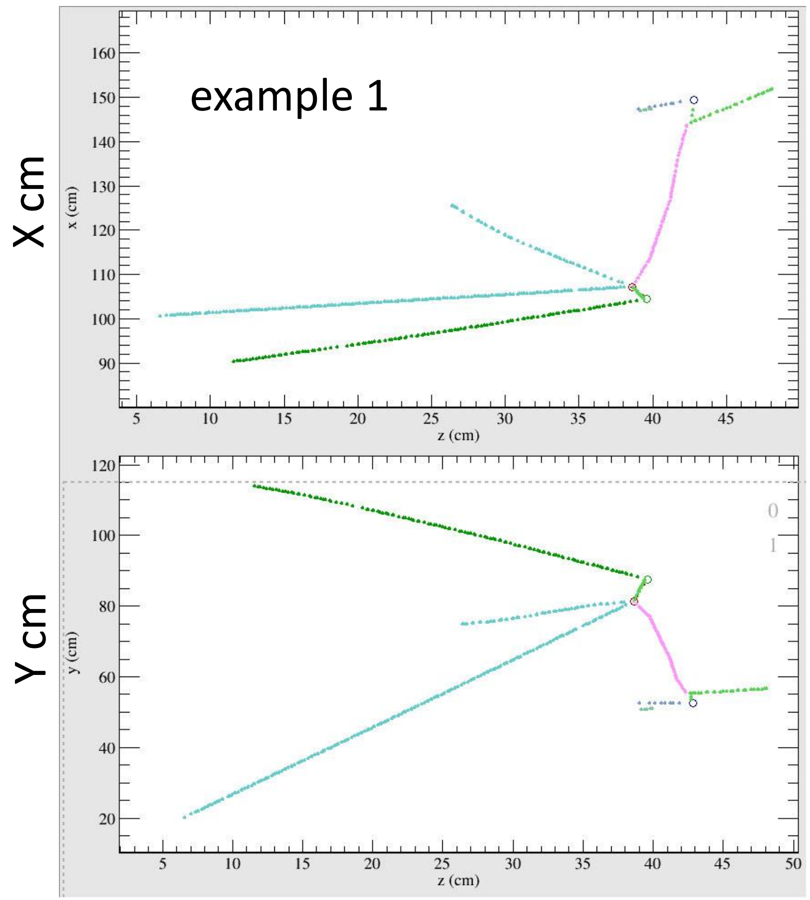


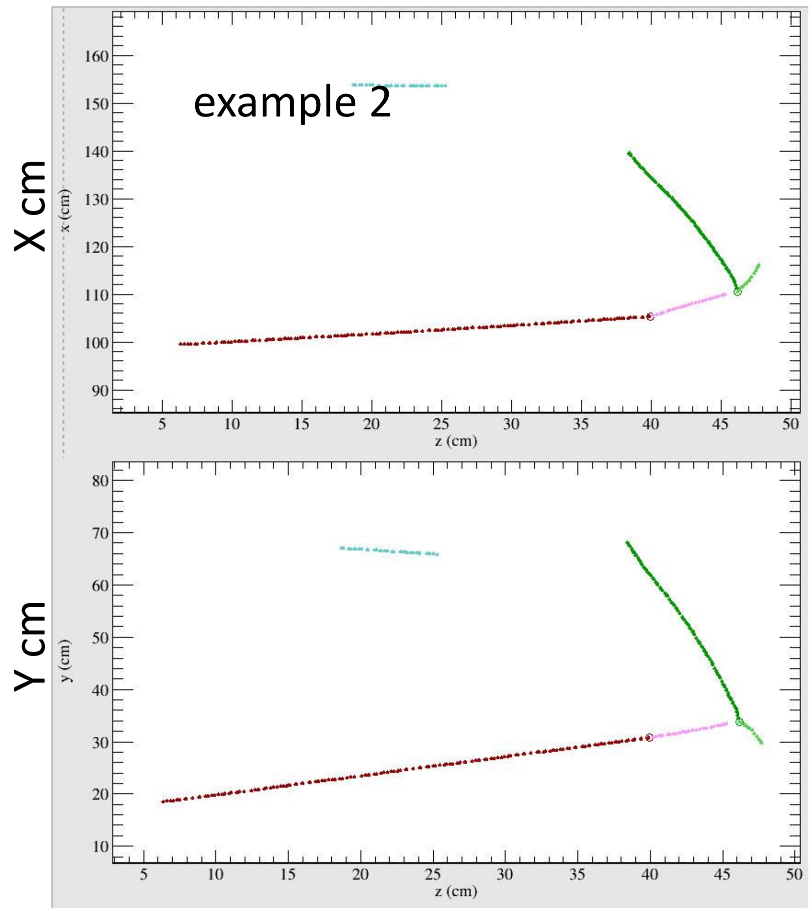
vertex finding and track-vertex structure optimization

HIGH LEVEL STRUCTURE

Full PMA: meaningful structure of an event

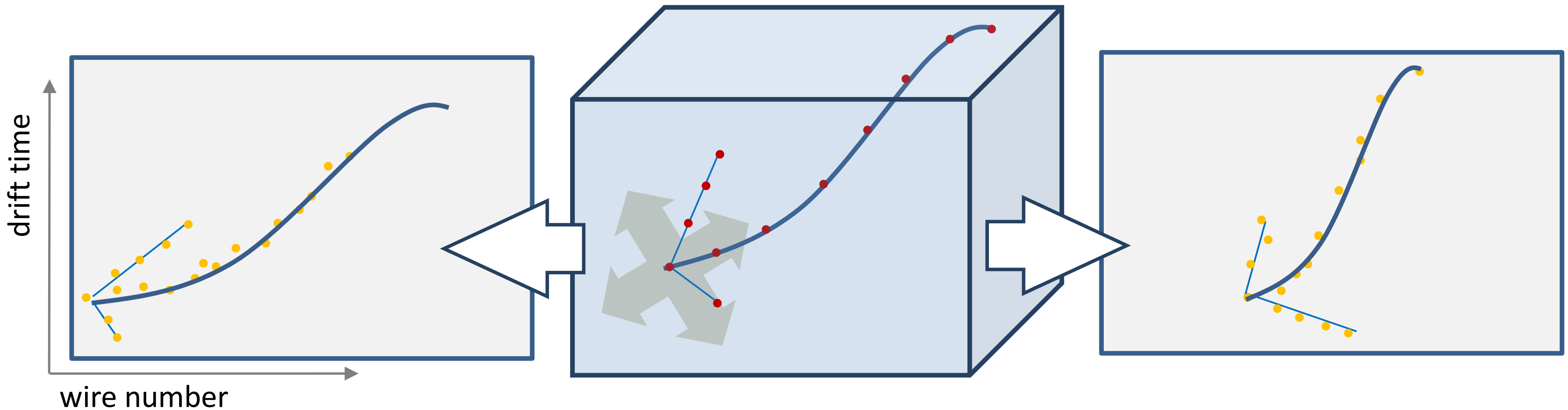




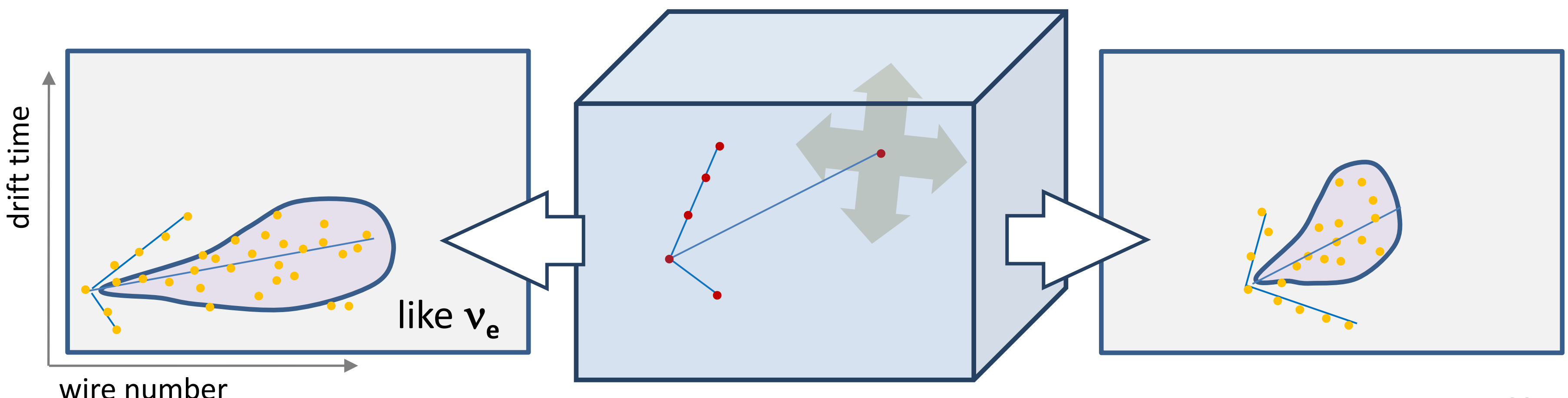


Full PMA: tracks, vertices, also cascades

- mutli track structures → **vertex position + track directions** using full information available in the vertex region.

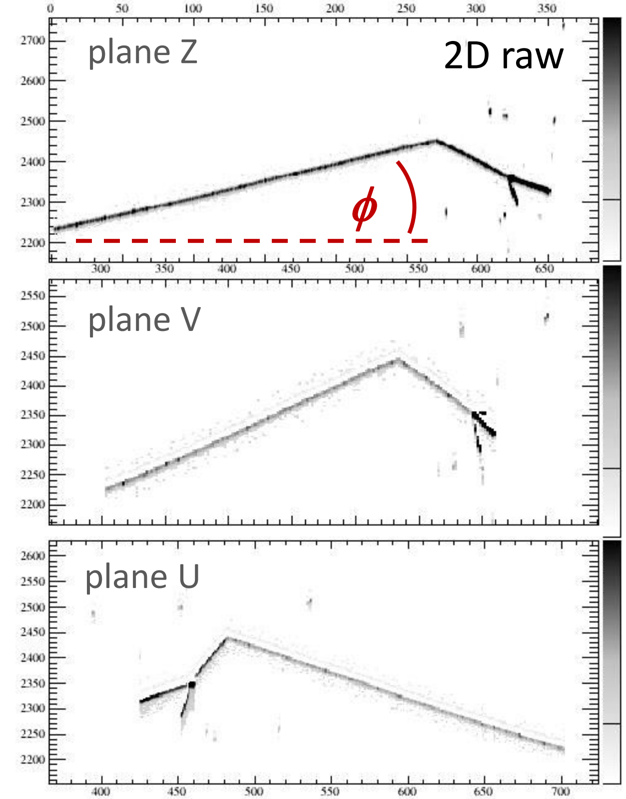


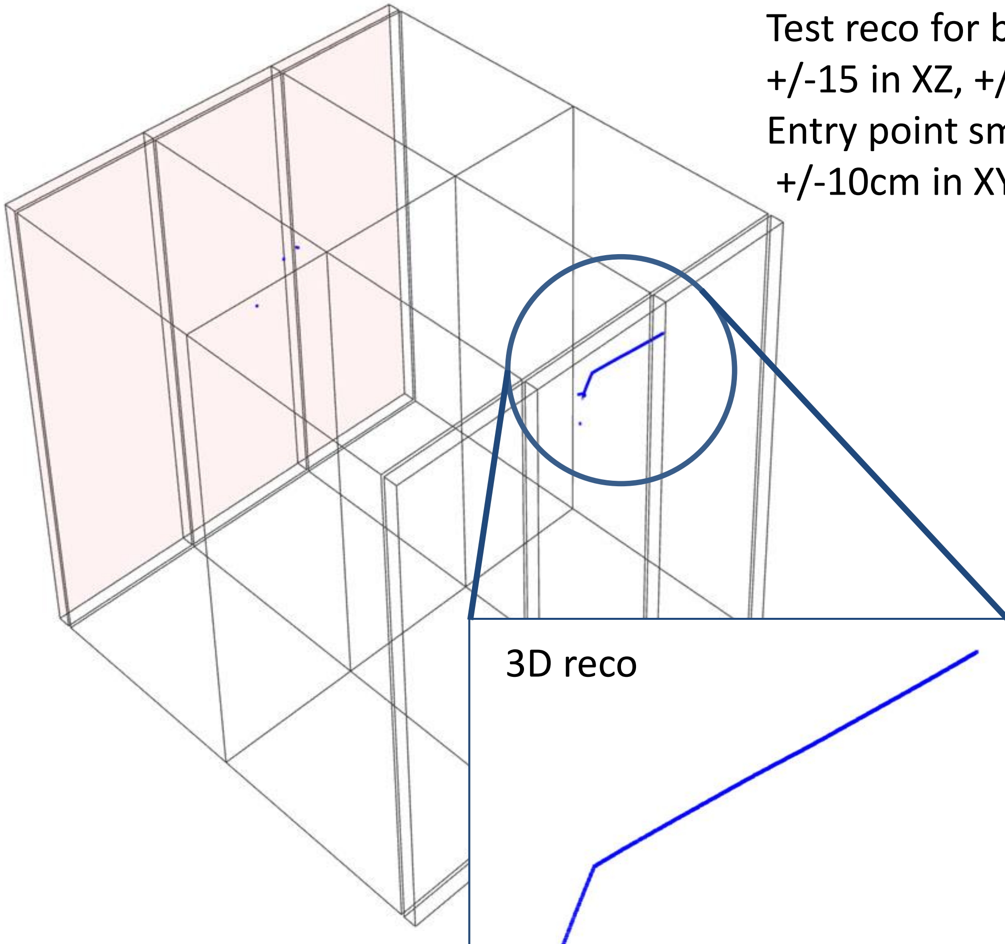
- EM cascade **axis** or its **starting segment** made from a few hits only.



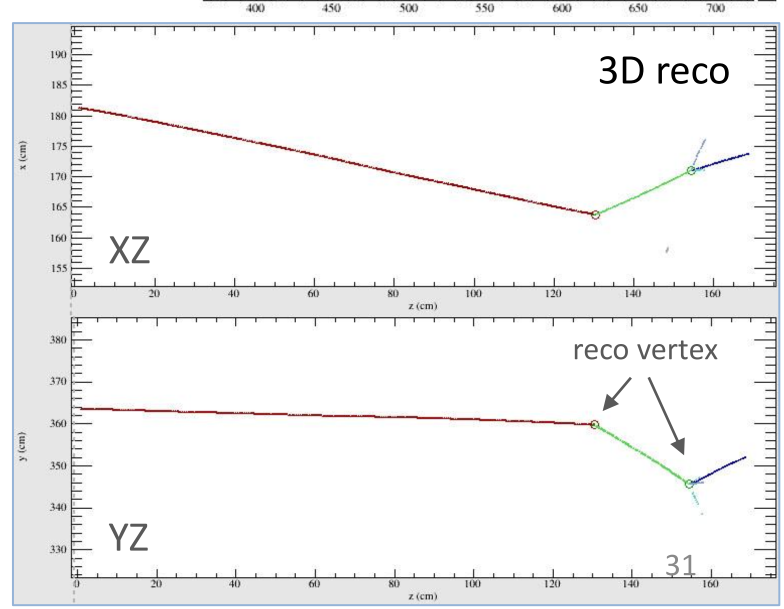
Test beam in protoDUNE

Test reco for beam angles:
+/-15 in XZ, +/-10 in YZ
Entry point smearing
+/-10cm in XY, +/-0.5 in Z





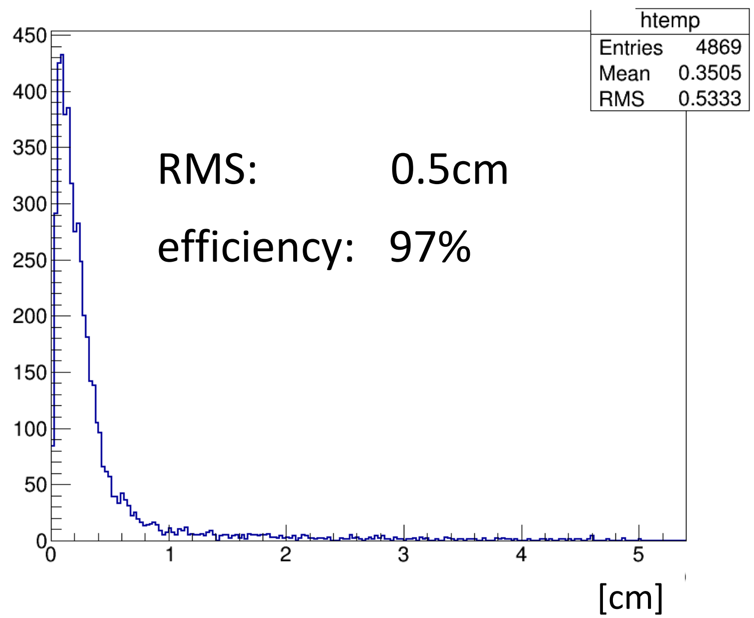
protoDUNE geometry



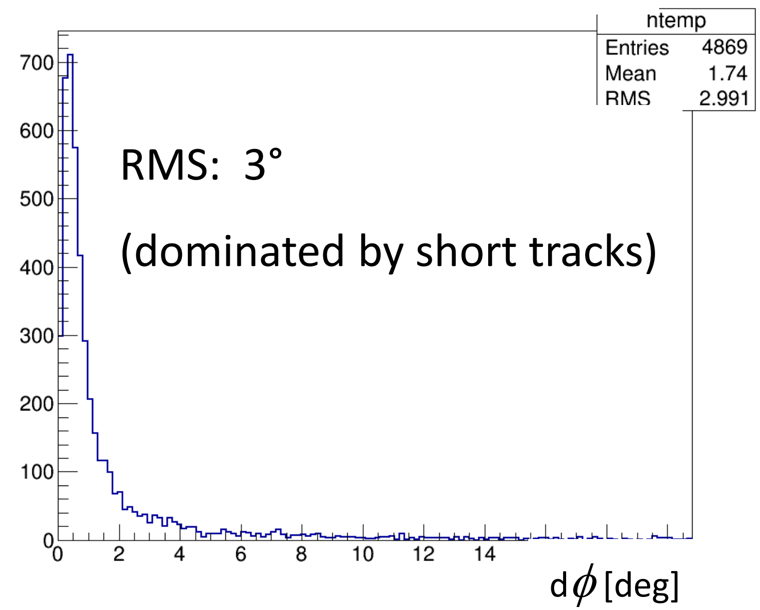
Clean track spatial reconstruction

- π^+ beam at 2GeV simulated,
- plots: reconstruction quality of the incident particle,
- easy case: clean track,
- but includes short trajectories and many wire-plane parallel tracks.

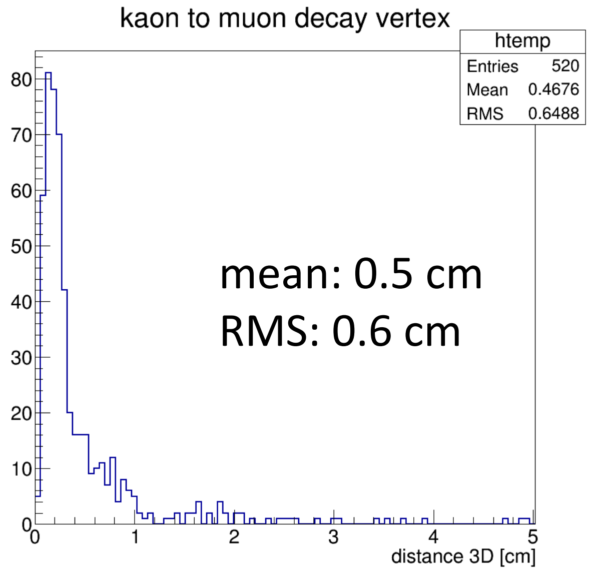
3D distance: entry point

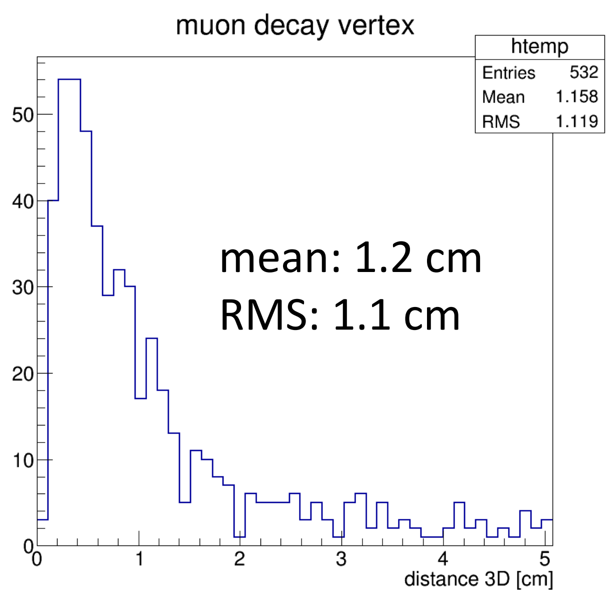


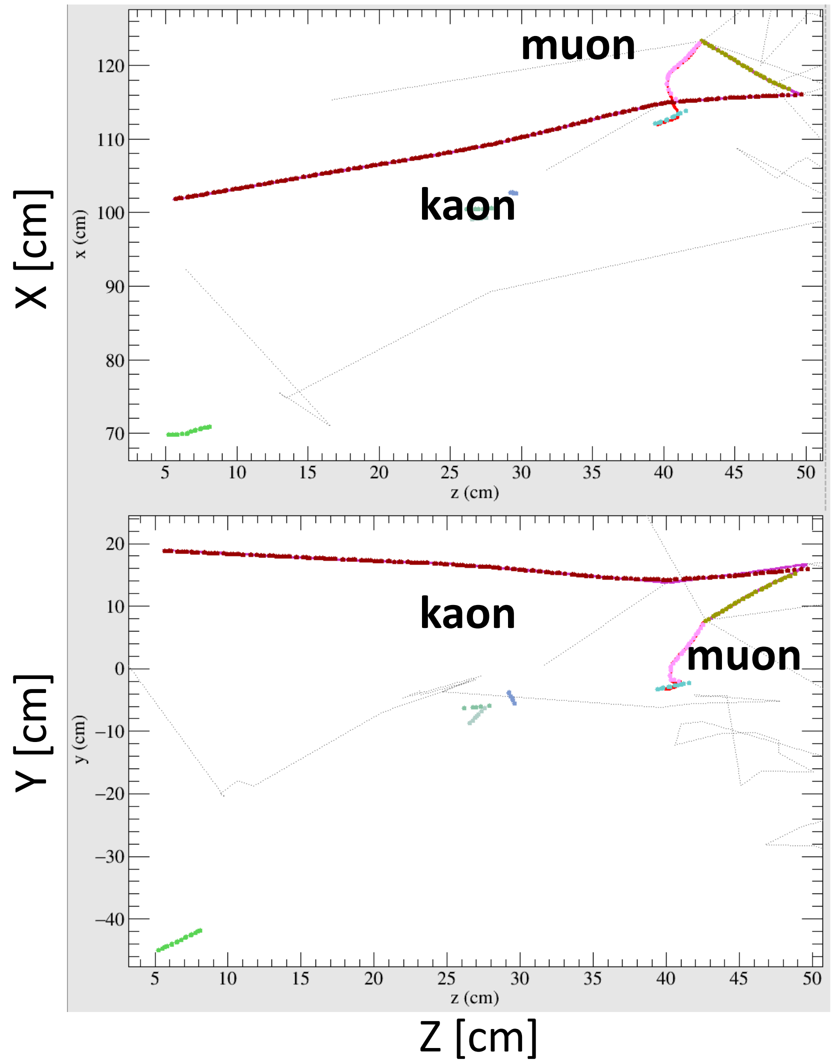
initial direction



Particle decay chain: K →μ →e

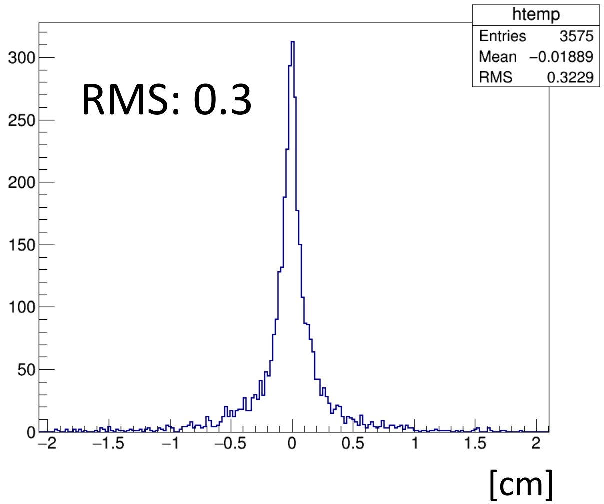




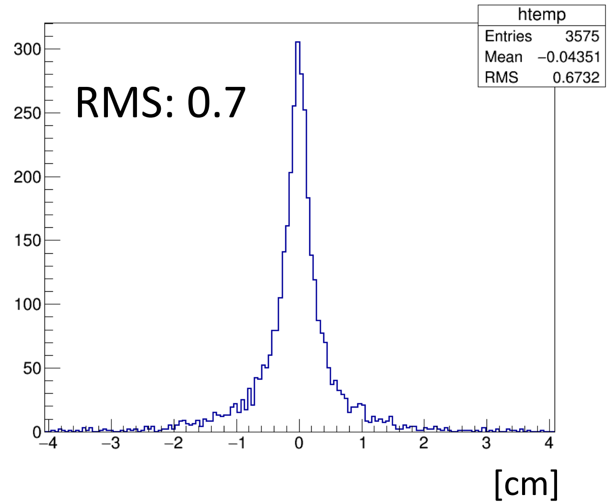


Secondary vertices of inelastic scatterings

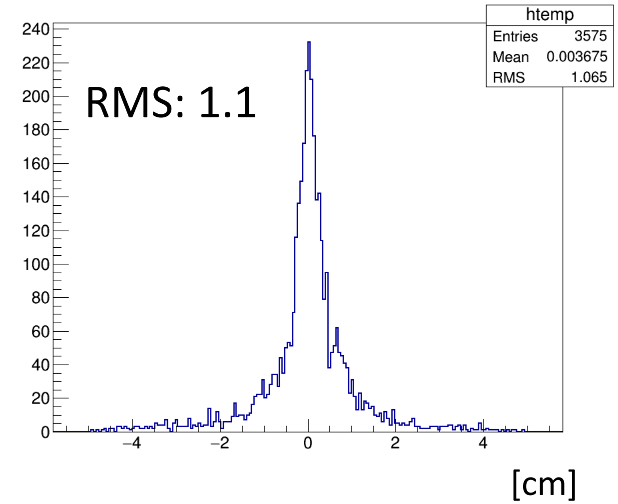
dX



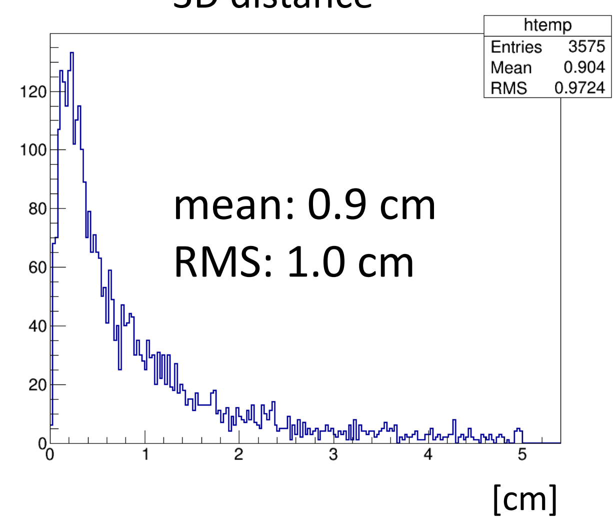
dY



dZ

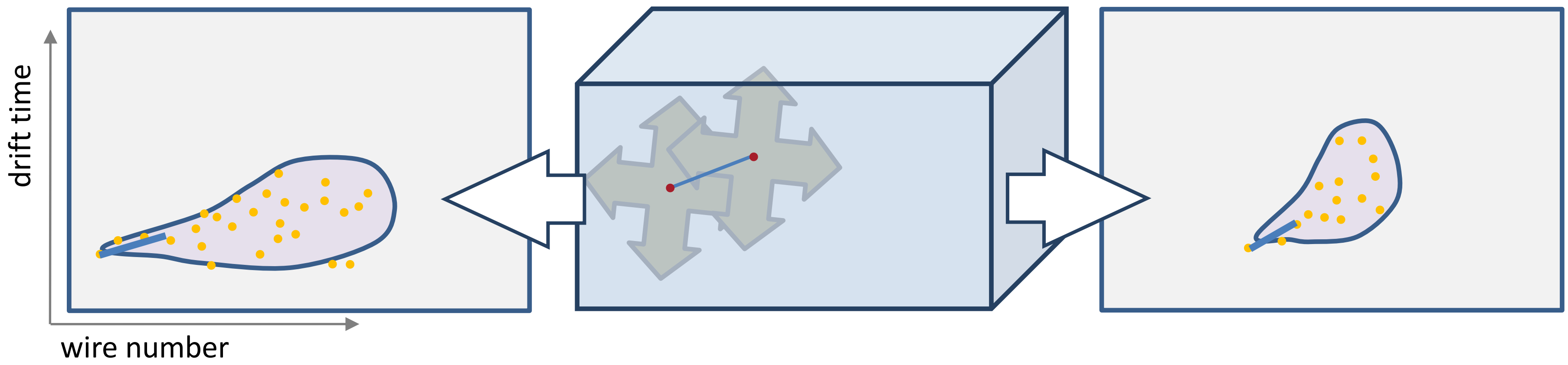


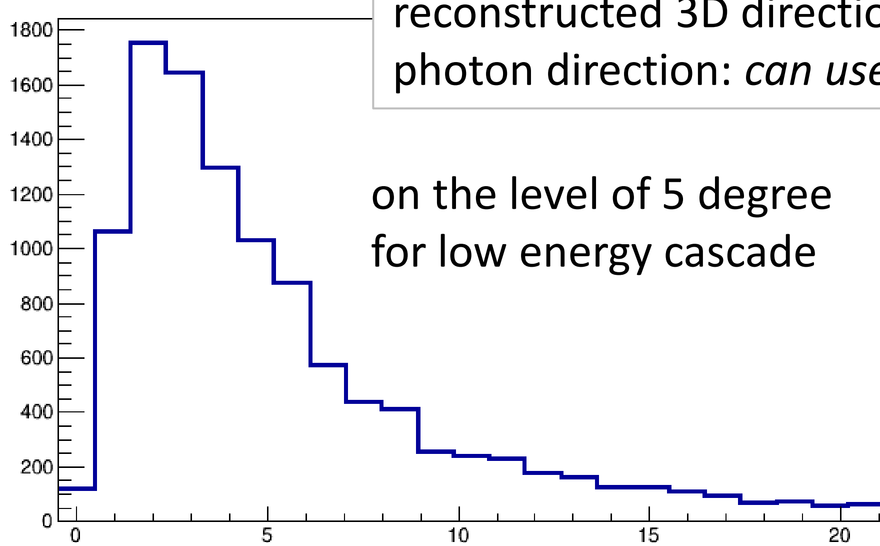
3D distance



- Protons with initial momentum 2 GeV/c.
- Inelastic interaction vertex positions tested (realistic visibility citerion: min. 2 daughters > 50MeV kinetic energy).

Initial segment of EM shower

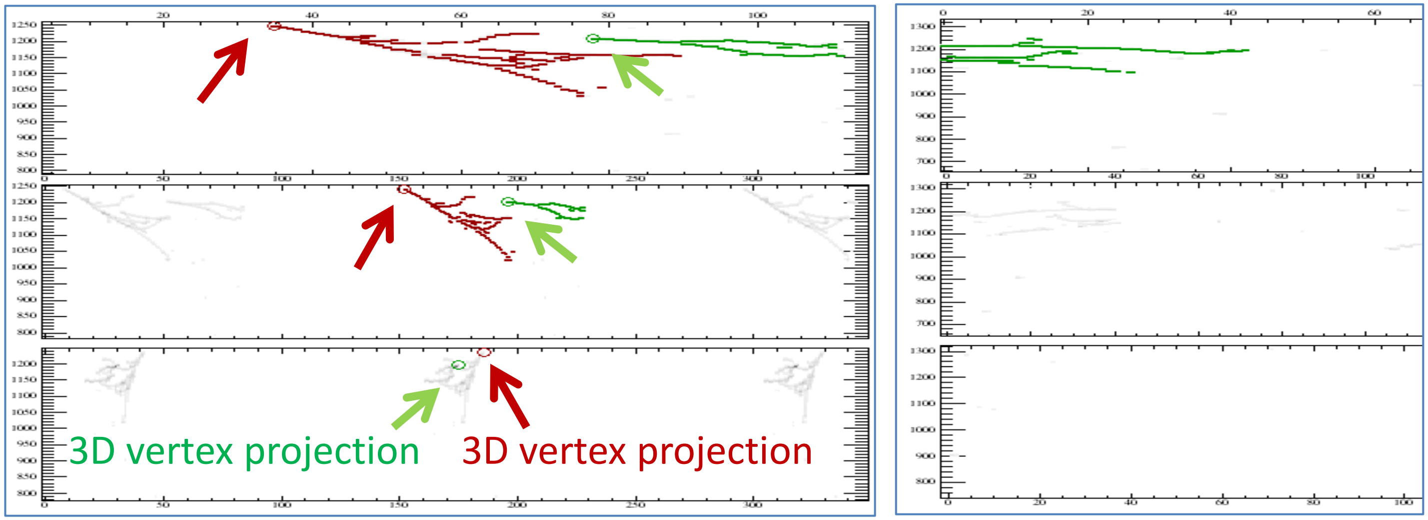


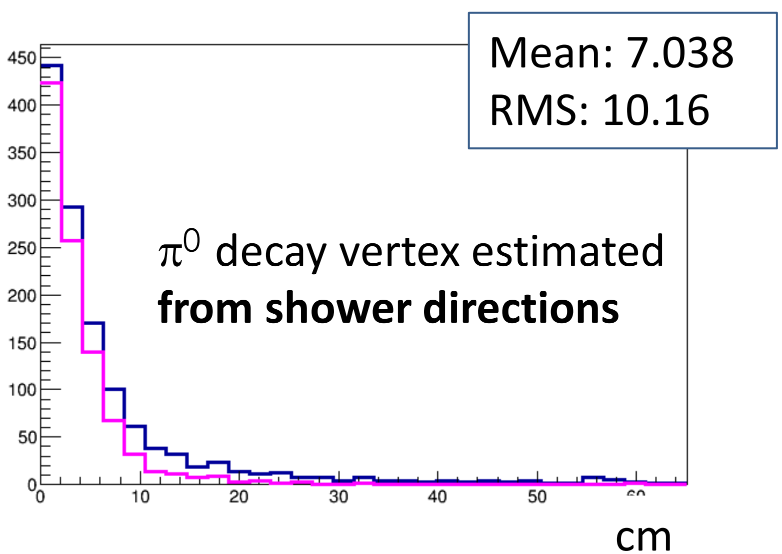


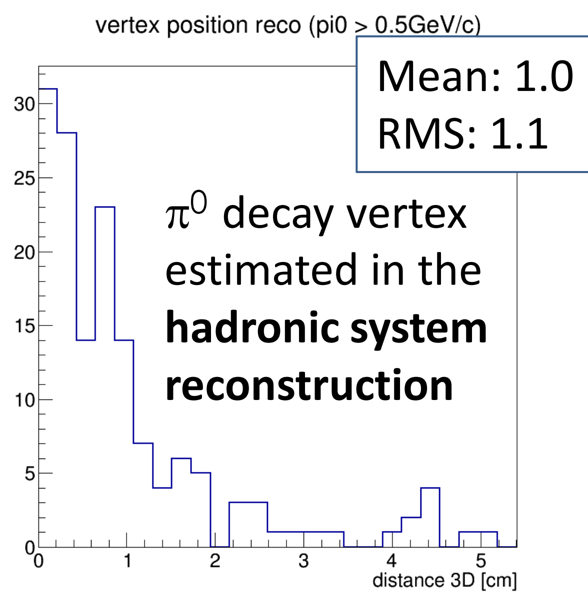
reconstructed 3D direction w.r.t. the incoming photon direction: *can use a few hits*

on the level of 5 degree for low energy cascade

π^0 vertex reconstruction







Both methods to be used to find showers compatible with hadronic interaction vertex.

hits, space points,
cells, blobs

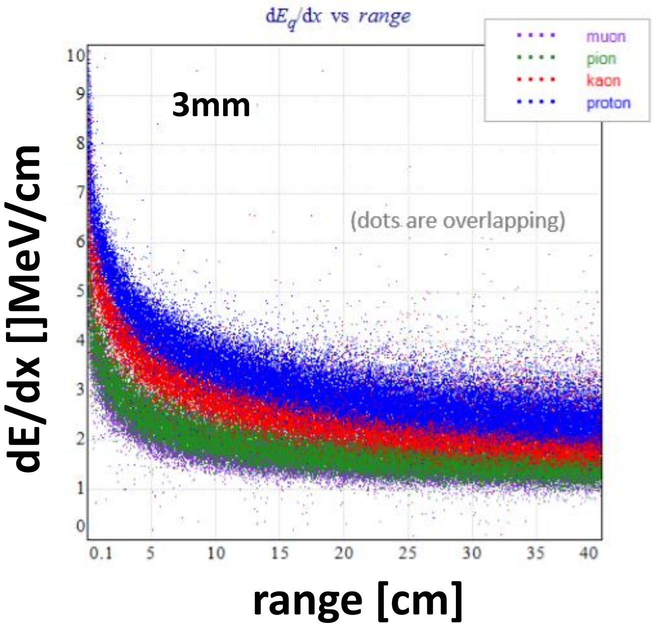
clusters: track like,
shower like objects

trajectory, vertices

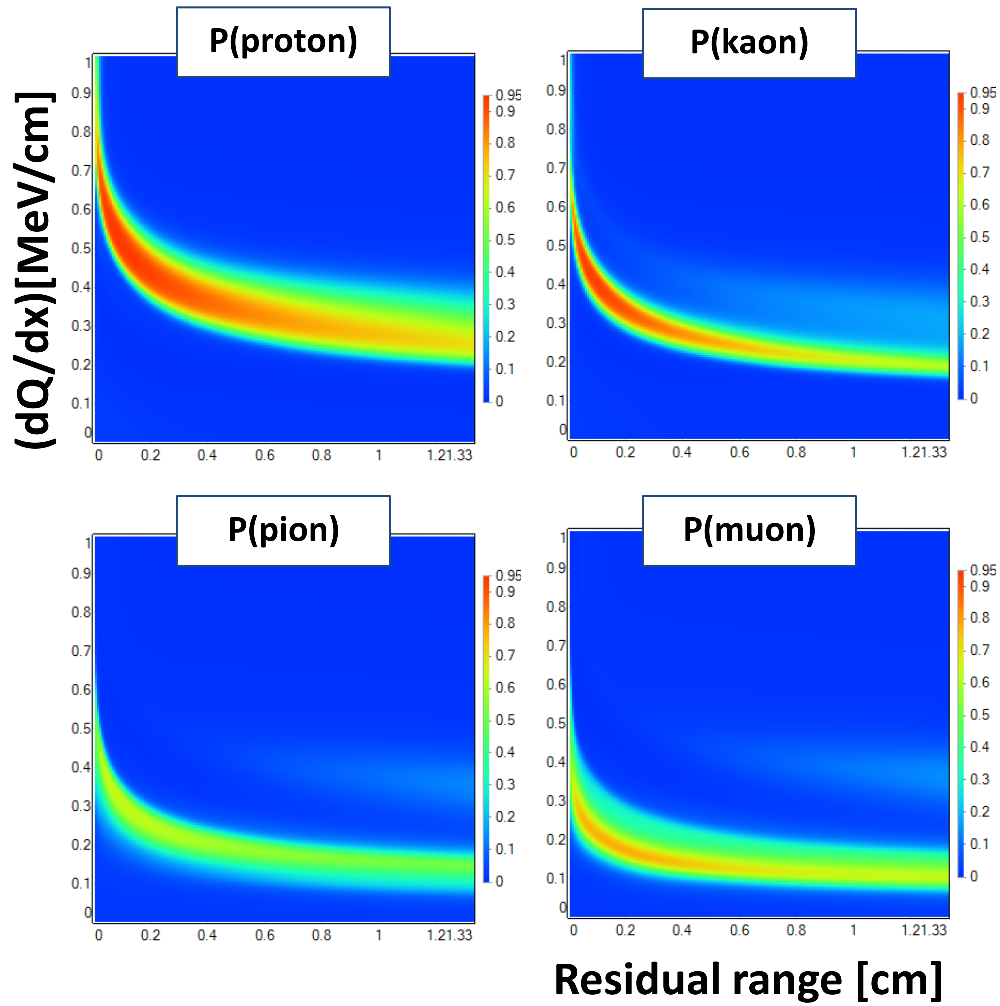
- Use 3D space points from preceding stage: refit reduced information
- Or look at 2D data selected by clustering: fit directly to measurement

- **identification of particles and interactions**

Stopping particle identification by dE/dx



Neural Net patterns: p, K, π, μ, unknown

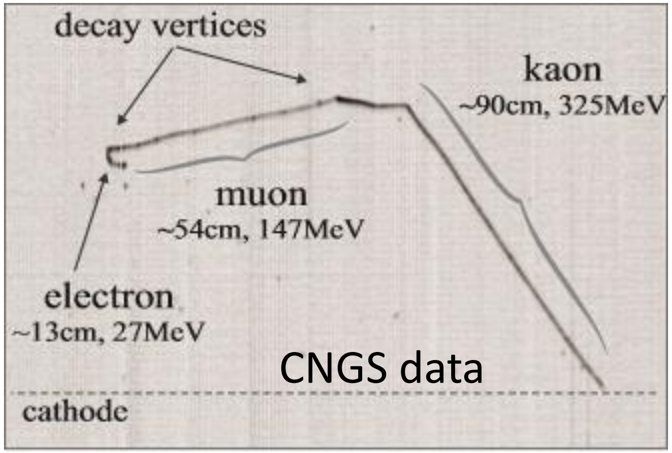


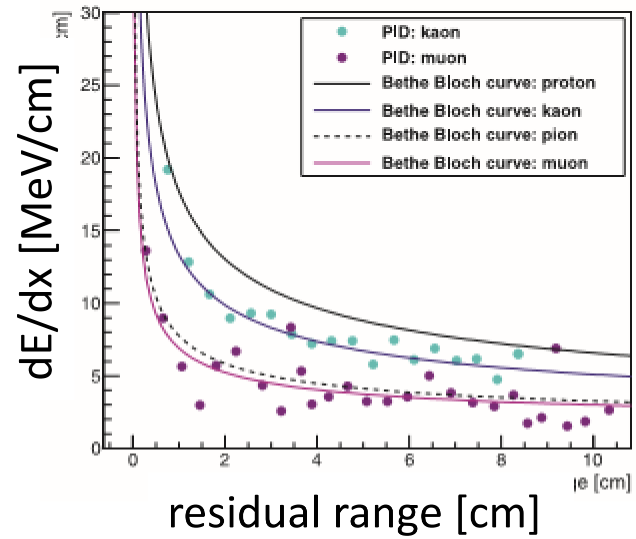
- dE/dx distribution at given range: not gaussian, not even symmetric, reconstruction artifacts, … → χ^2 not enough.

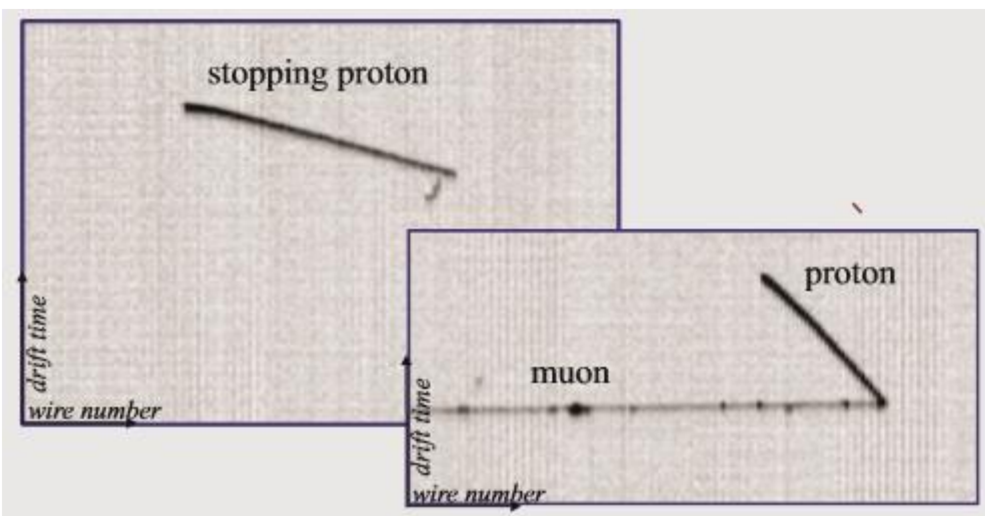
- neural network classification, with number of free params optimized.

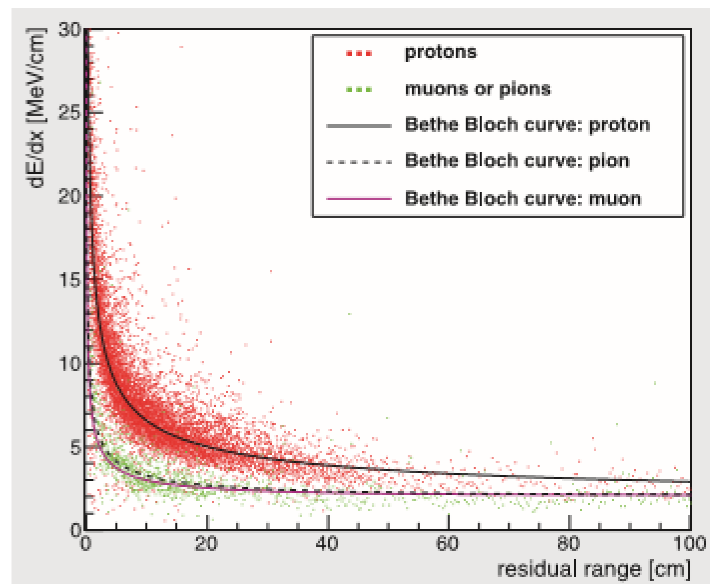
patterns -> P(stopping), P(particle ID)

Stopping and decaying particles in ICARUS

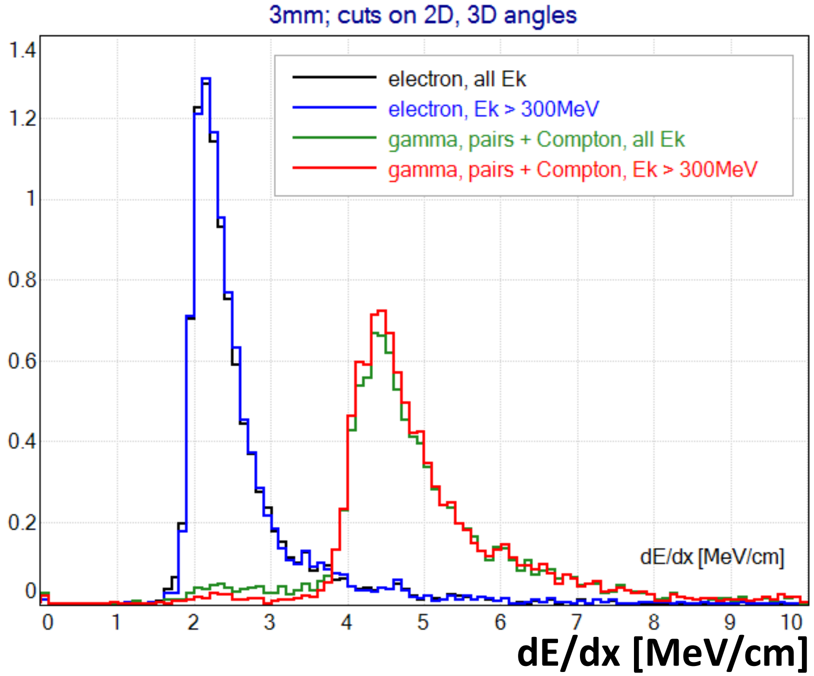


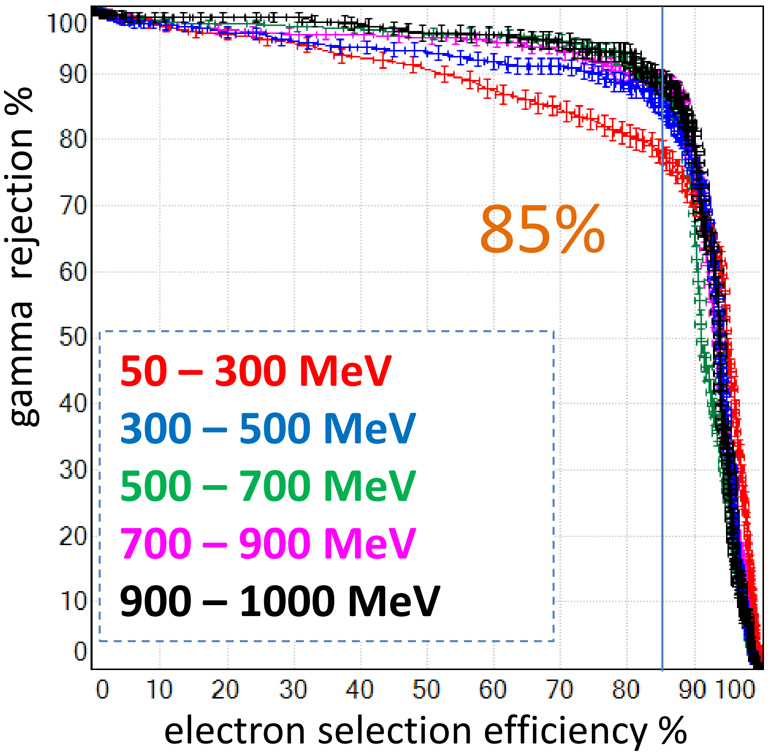






Type of neutrino interaction: dE/dx ingredient





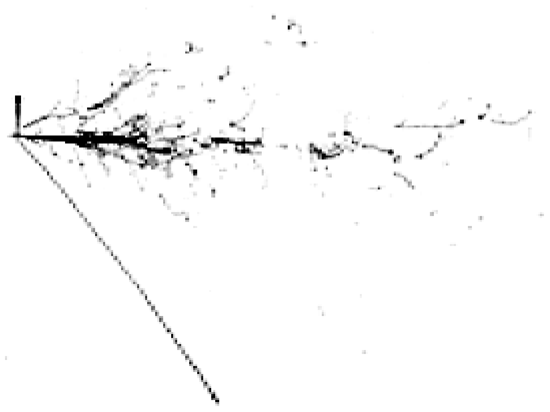
survey

http://goo.gl/forms/d2cqv6G64f

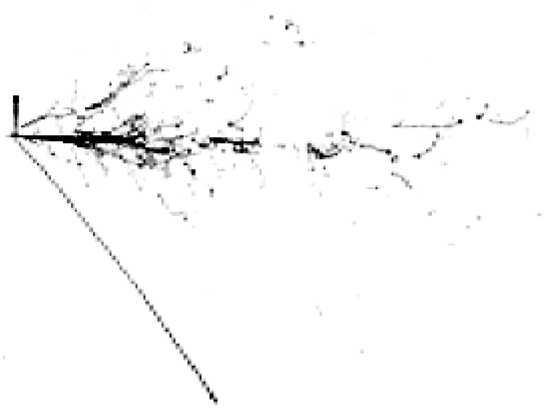
by Piotr Płoński

?

signal



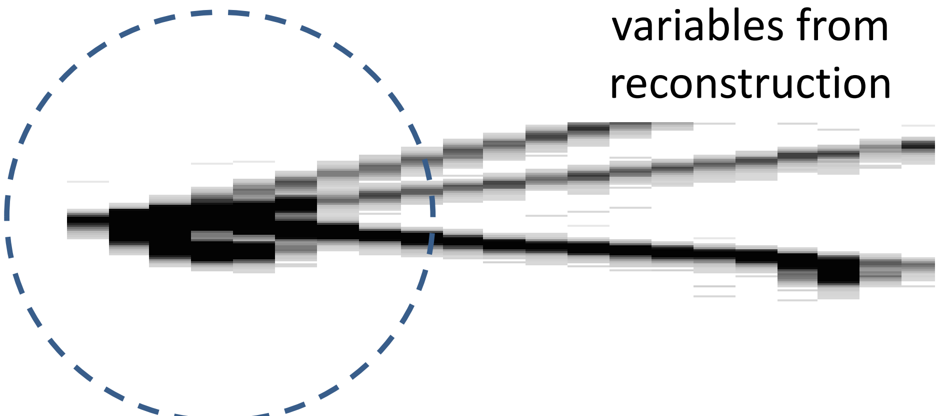
background



Contact: pplonski86@gmail.com

Type of neutrino interaction: topology and vertex region exploration

Higher- level variables from reconstruction



„Standard" reconstruction does a lot:

- Global features: energy deposition, cascade profiles, ...
- Features of cascade initial part – to some extent.
- Spatial/calorimetric track details.
- Particle identification.
- Topology of points of interactions in the event.
- Algorithms on this level of details are being perfected.

Still: full information is not yet used.

Especially features of primary vertex are challenging, more advanced methods will come.

Summary of neutrino ineraction analysis

Physics needs: neutrino flavor identification, neutrino energy.

Flavor: we know quite well how to do it

Topological recognition of

- Electron / gamma cascade.
- Long muon candidate: no inelastic scatterings at enough distance.

Topological/calorimetric reconstruction of

- dE/dx in electron / gamma cascade start.
- dE/dx for shorter muons identification: stopping muon (very hard, rather unlikely), identified Michel electron at the endpoint.

Energy:

- Precise at low energies if simple topology and stopping particles.
- <u>Challenge</u>: quickly limited by uncertainties related to interacting particles: PID much harder, neutral particles, escaping etc.:
  - use test beams data, not only MC modeling – projects are starting.
  - obtain calibration factors as a function of reconstructed quantities: observed energy, multiplicity of tracks, vertices, EM/hadron separation, many, many other quantities can be tested.

Summary

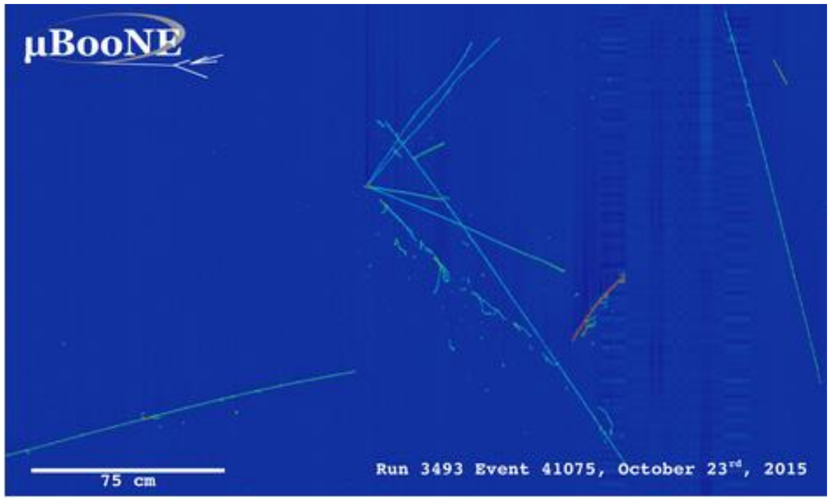
- Reconstruction in LArTPC: complexity of detector properties and detection technique.

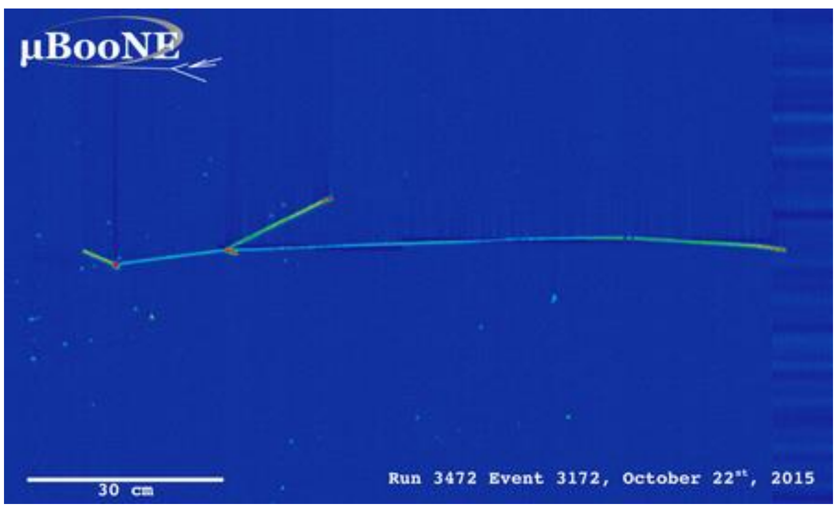
- Presented reconstruction chain is one of main presently developed approaches. Similar stages can be identified in all of them, despite significantly different underlaying ideas.

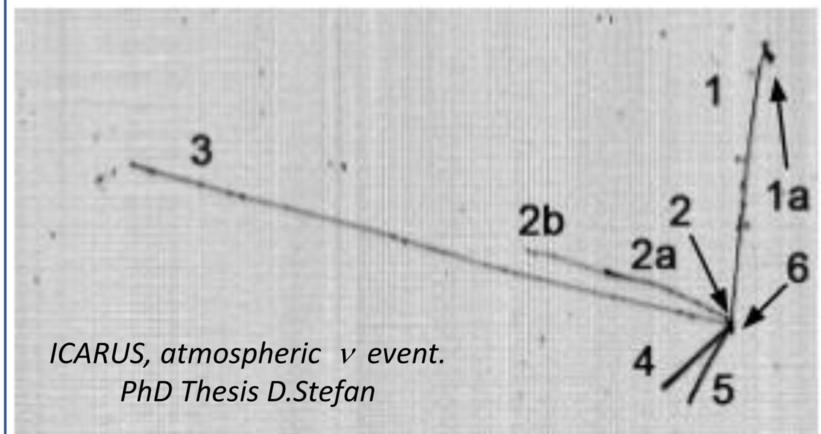
- Several practical applications were presented. Complete reconstruction and analysis of neutrino event is still being developed, but many smaller physics tasks are achievable now.

Backup

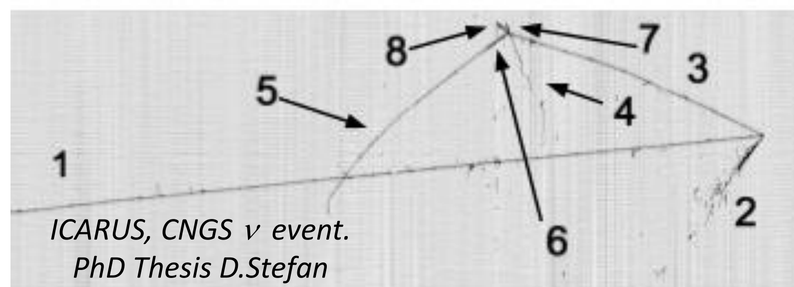
LAr TPC: resolution and details at different scales







ICARUS, atmospheric ν event.
PhD Thesis D.Stefan



ICARUS, CNGS ν event.
PhD Thesis D.Stefan

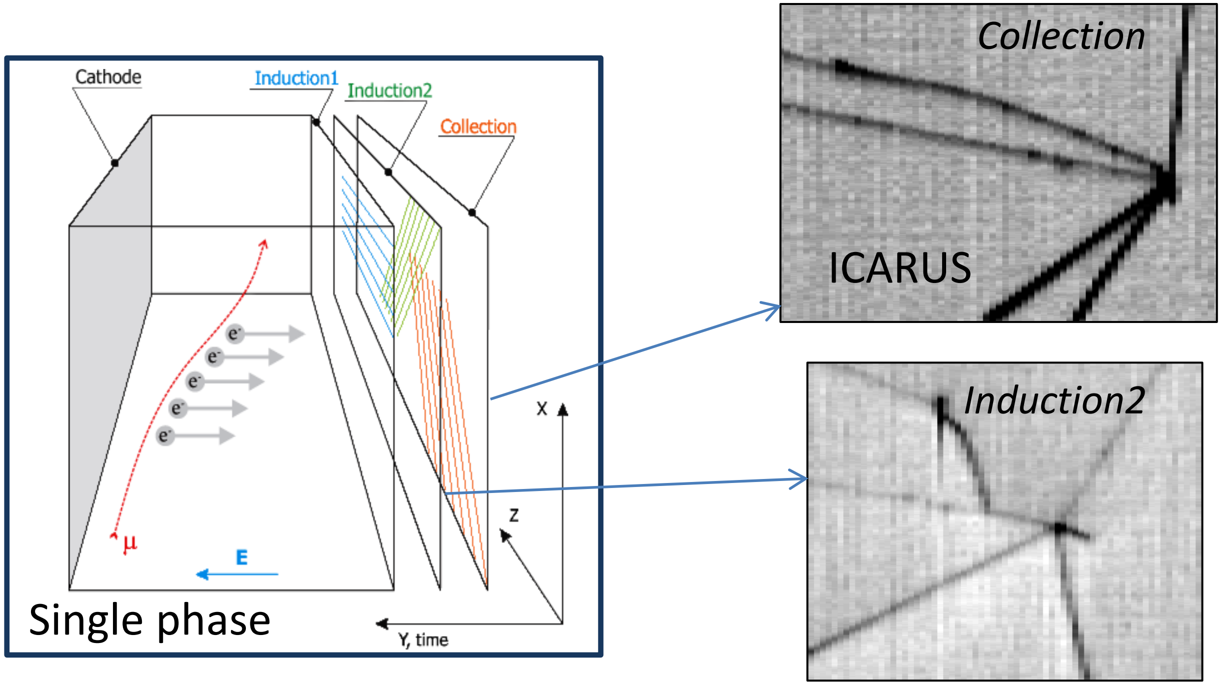
Conclusion

Physics needs
- Neutrino flavor identification
- Energy of neutrino

Flavor:
- Topological recognition of
  - Electron / gamma cascade
  - Long muon candidate: no inelastic scatterings at enough distance
  - …
- Topological/calorimetric reconstruction of
  - dE/dx in electron / gamma cascade start
  - dE/dx for shorter muons identification: stopping muon (very hard, rather unlikely), identified Michel electron at the endpoint

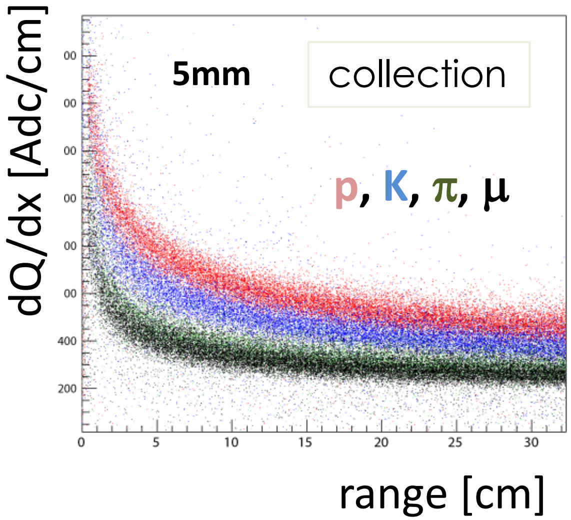
Energy:
- Precise at low energies if simple topology and stopping particles.
- Quickly limited by uncertainties related to interacting particles: PID much harder, neutral particles, escaping …
- Only estimation is possible: note that not much work is done in this direction!
  - Use test beams, not only MC modeling – projects are starting
  - Obtain calibration factors as function of reconstructed features: observed energy, multiplicity of tracks, vertices, EM/hadron separation, many, many

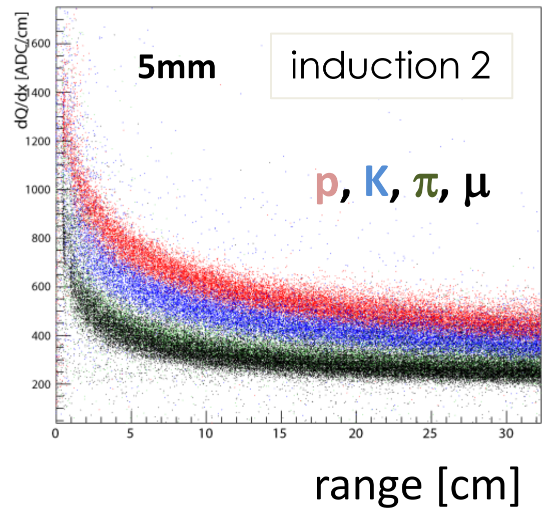
LArTPC principles

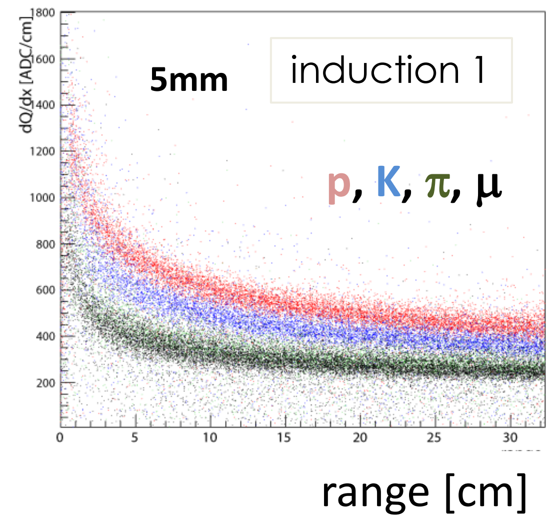


- Prompt **scintillation light**, light collection system gives the **time reference (t_0)** and/or trigger signal
- **e⁻** from ionized track drifted in LAr by **E field**.
- Readout wires planes at different angles.
- **ADC** waveforms versus time read from wires form **2D projections** of events.

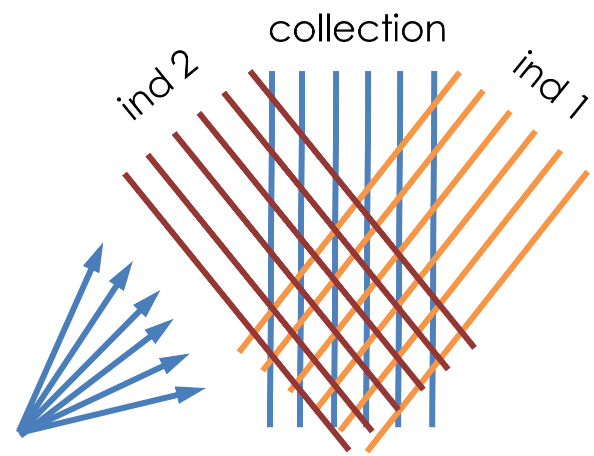
Single track: stopping particle patterns







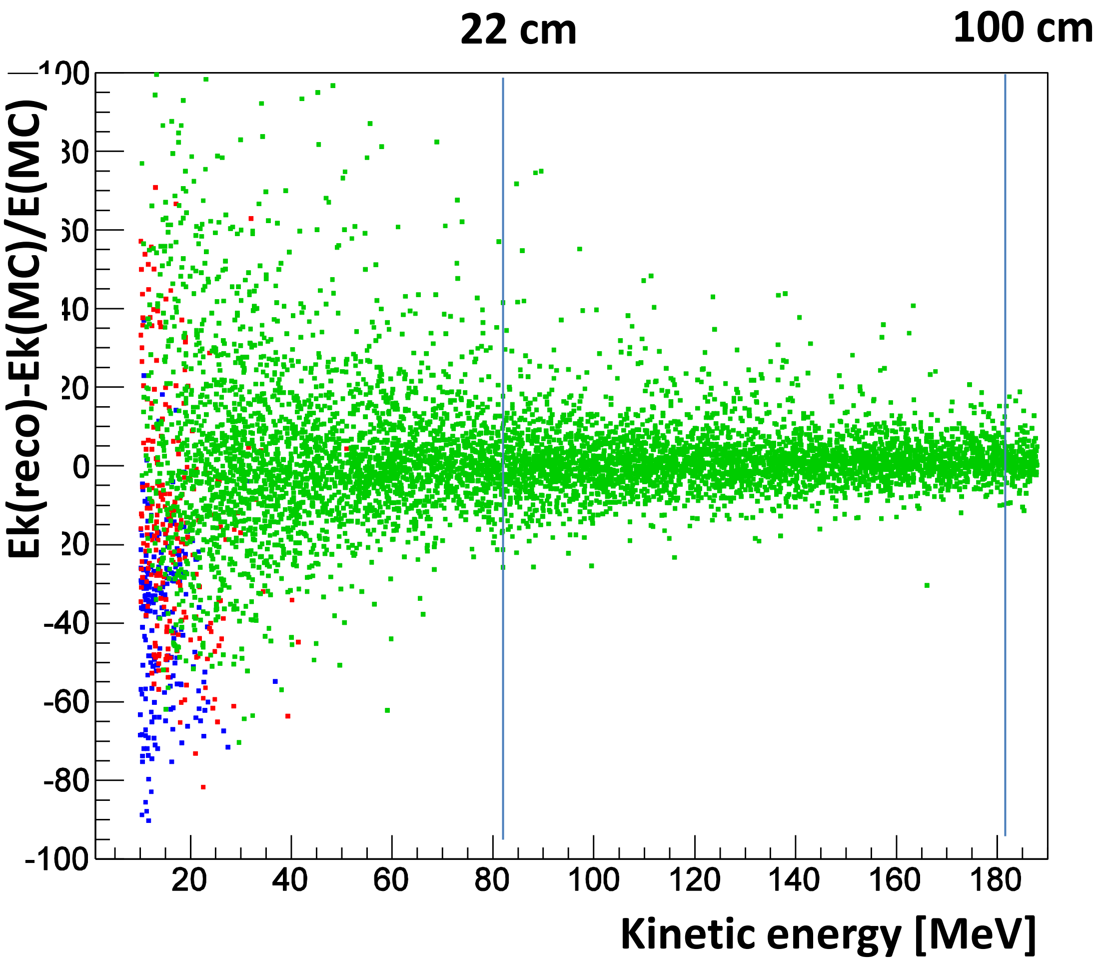
- here: ~5mm wire pith → narrow bands, but fewer data points along the track w.r.t. 3mm.
- best (longest) projection can be selected.
- here: beam in cone most favorable for induction2 and most parallel to induction1 wires.



Some examples of application

- electron/gamma seperation,
- simple topologies like in proton decay,
- π^0 reconstruction,
- angular recombination studies.

Muon calorimetric reconstruction



3D muon reconstruction,
Birks formula was used to correct for the recomb.

momentum reconstruction for muons with momentum **< 1GeV/c**:

- use range
- use calo with exact recombination correction (Birks)

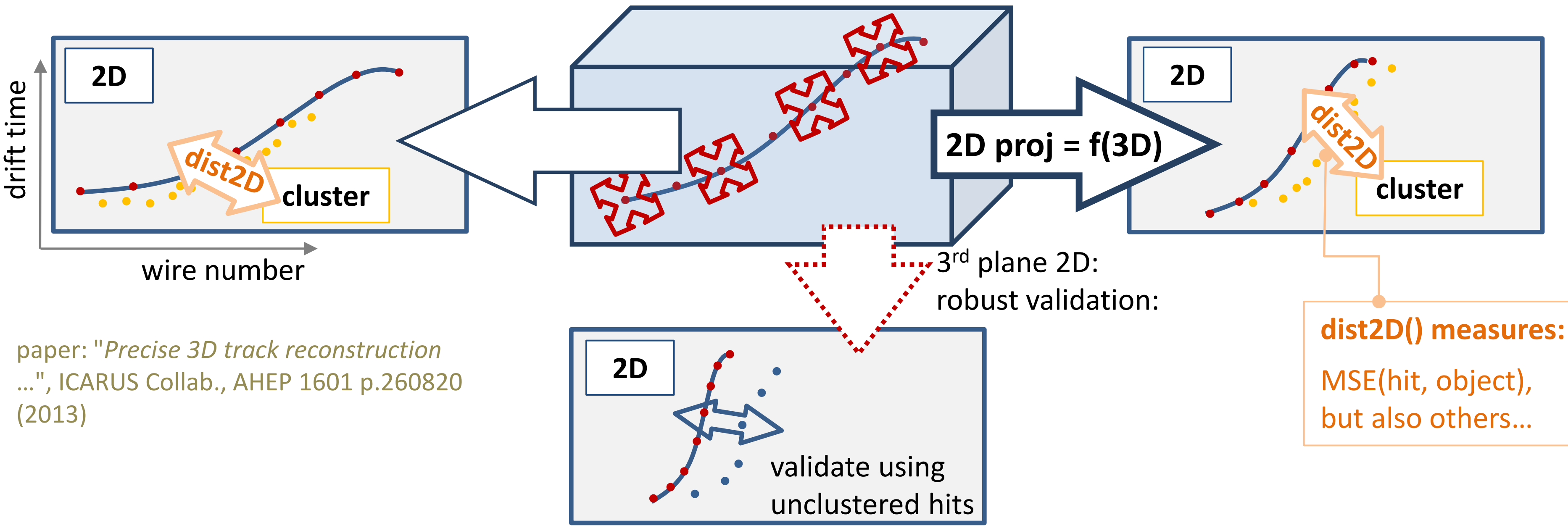
momentum reconstruction for muons with momentum **> 1 GeV/c**:

- in this range the energy deposition from clusters gives best estimate.
- Birks formula overestimates the momentum.

from paper (AHEP, http://dx.doi.org/10.1155/2013/260820)

New 3D approach: general concept

works in 3D (on ***single track*** or ***full track structures***) to match the object’s 2D projections to hits



paper: "*Precise 3D track reconstruction* …", ICARUS Collab., AHEP 1601 p.260820 (2013)

Summary

- Projected Matching Algorithm (PMA): initial work for ICARUS, now reimplemented in LArSoft, track-vertex structure fit developed.

- PMA can be used with any clusters, in LArSoft tested on Cluster Crawler (2D pattern recognition) and on Cluster3D (3D pattern recognition)…
- …therefore it is natural to try PMA fit with Wire-Cell cluster.

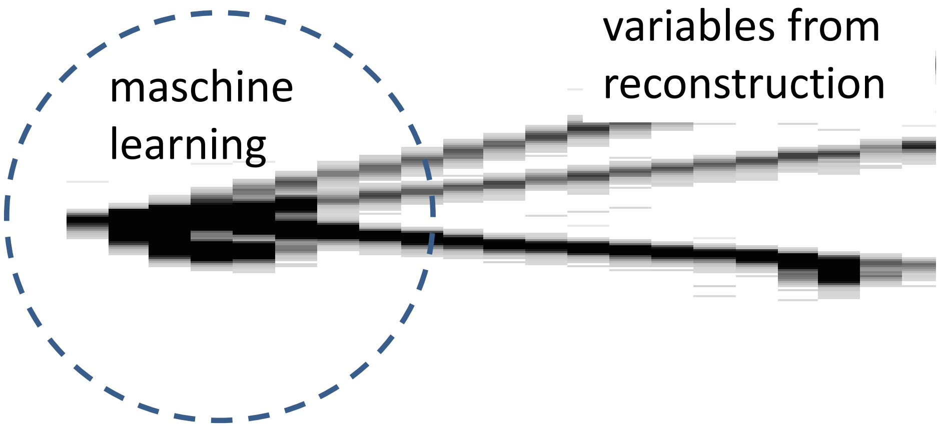
- PMA had been tested on data: ICARUS, LArIAT, ArgoNeuT.

- Many many ideas for the future…

From rough to detailed reconstruction

ν_e CC event

Higher- level variables from reconstruction



PRIMARY VERTEX

Larsoft simulation

We can reconstruct a lot:

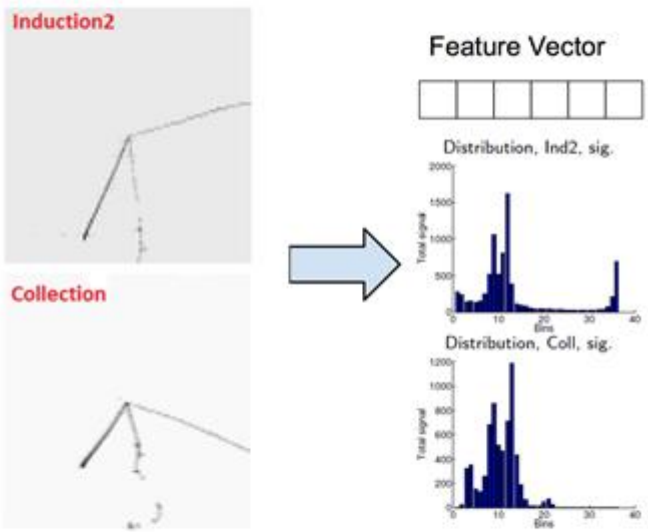
- Global features: energy deposition, profiles, ...
- Spatial/calorimetric track details.
- Particle identification.
- Topology of points of interactions in the event.
- …

- Algorithms on this level of detail are being perfected

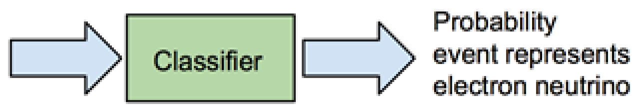
But still full information is not yet explored.

Especially features of primary vertex are still challenging.

Future of event classification?

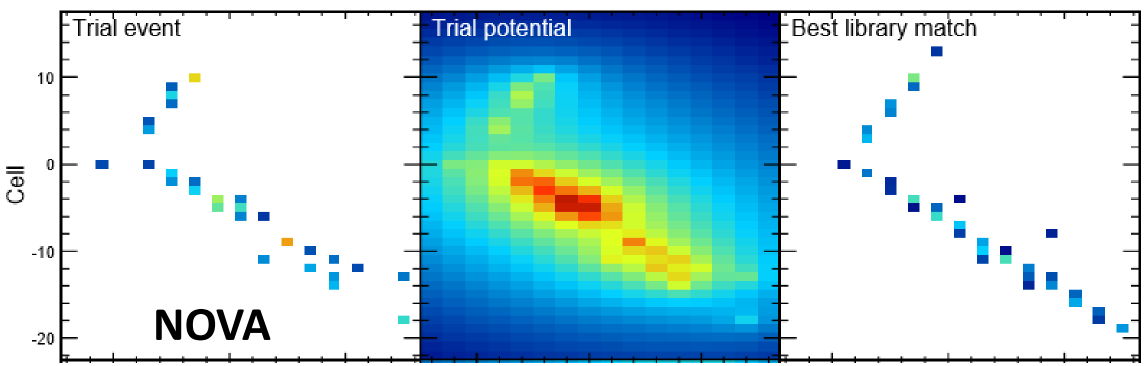


Classification of *raw data features* created on basis of experience and observations.



Piotr Płoński

http://arxiv.org/abs/1505.00424



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

Library Event Matching

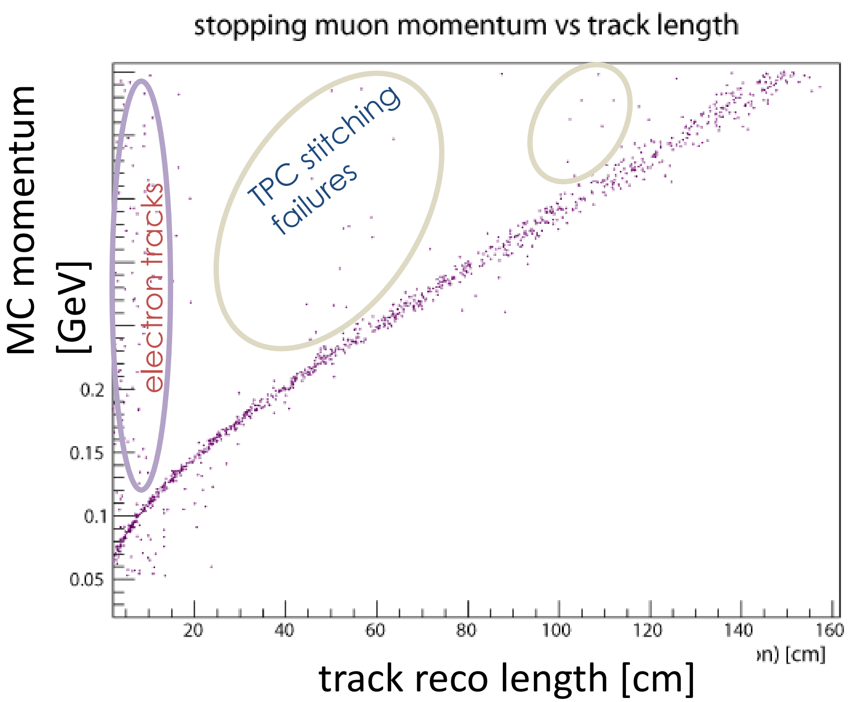
From: *Nucl. Instr. and Meth. in Physics Vol. 778 (2015)*

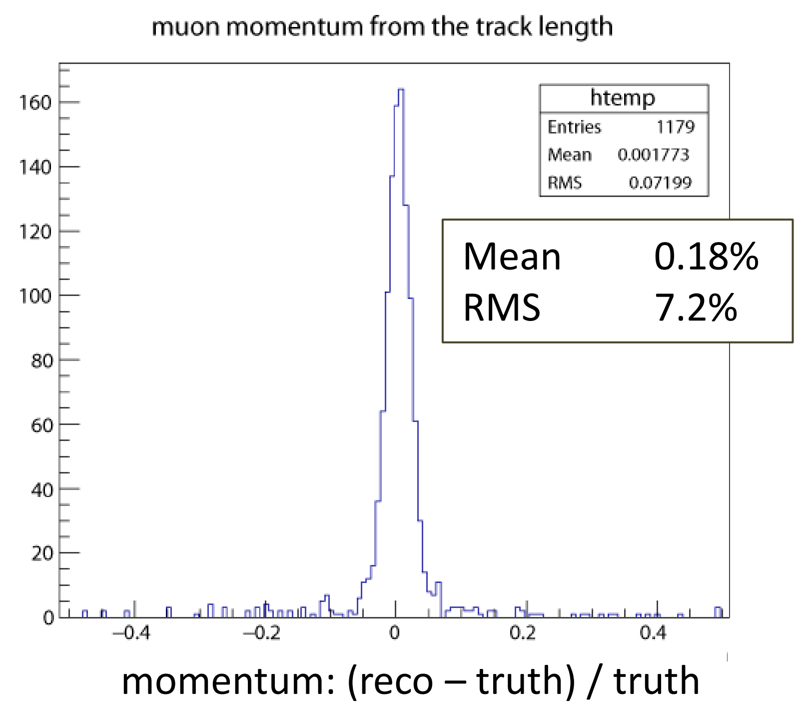
C. Backhouse, R. B. Patterson

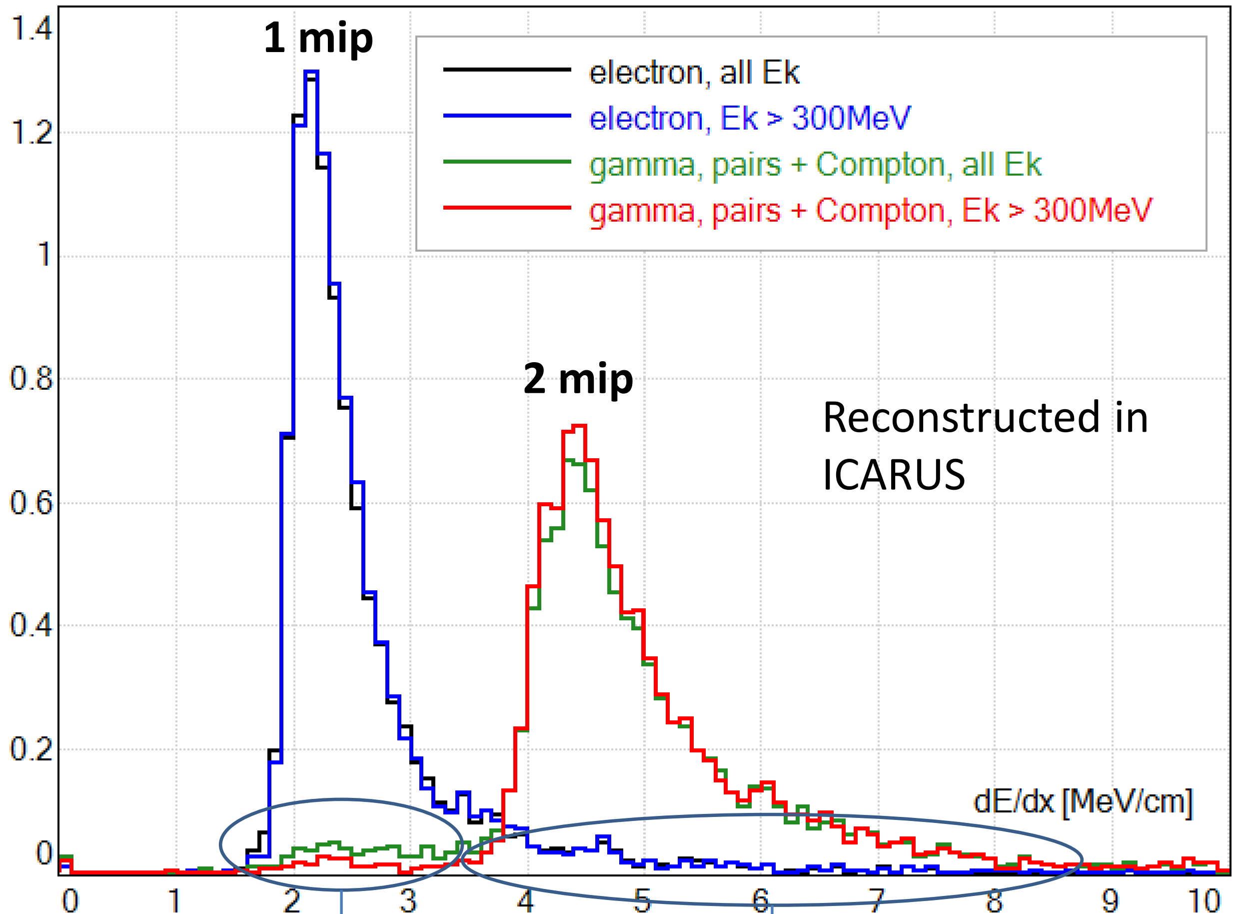
Or another technique capable of extracting discriminating features and/or building class models automatically, without human guidance.

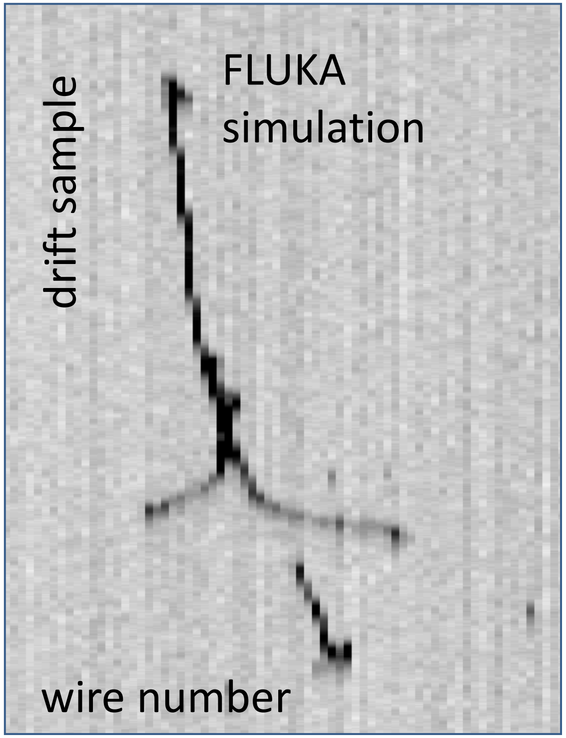
Single track reconstruction

stopping muon momentum reconstruction is based on the track length: 50 – 450 MeV/c tracks simulated, varying angle w.r.t. the wires, crossing up to 3 TPC in 35t geometry.









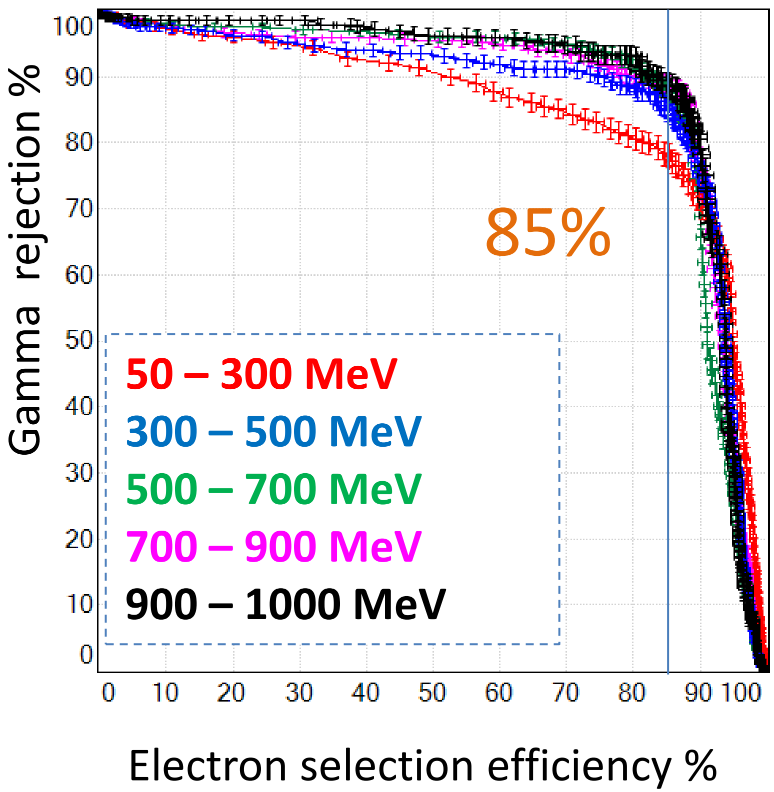
Asymmetric and open pairs:

- can mimic signal
- cut on energy in vertex
- try identify particle in vtx
- **depends on spatial orientation**

electrons from compton
and asymmetric pair production

Difficult to reduce the number of events from the tail.
High dE/dx is due to the secondary tracks within the selected initial part of the shower.

Electron selection efficiency vs gamma rejection
Various momenta of incoming electron/photon



Moreover:

- angular cuts can improve bkg rejection.
- realistic instead of isotropic cascade directions should be also better separable.

- preliminary results for higher momenta cascades seem to be better: can reach 90%/90% or higher.

Summary: ν_eCC and ν_μCC

- **ν_eCC identification**:
  - Shower coming out from primary vertex.
  - dE/dx of initial part of cascade corresponds to 1 m.i.p.
  - Shower should be attached to the primary vertex – have to be studied in the real situation of crowded vertex.

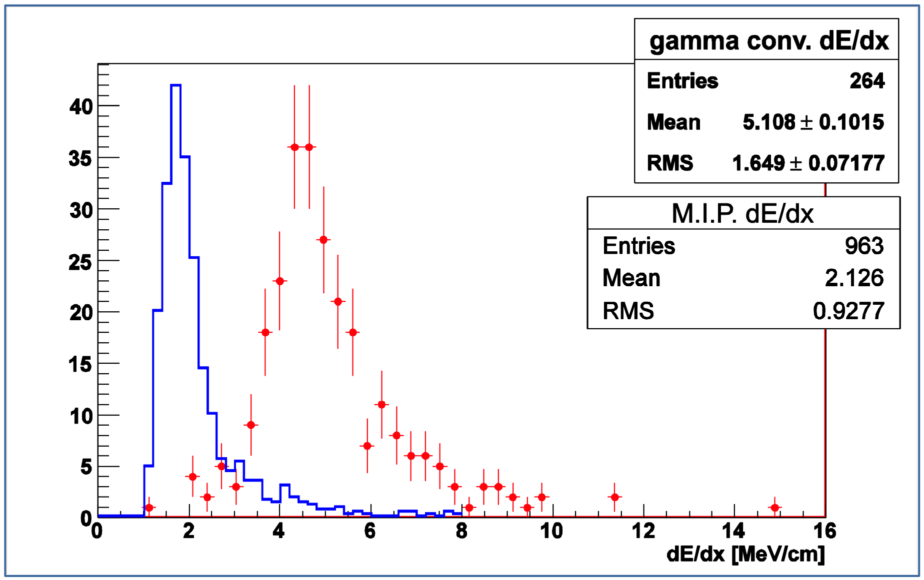
- **ν_μCC identification**:
  - Muon coming out from primary vertex.
  - Possibility of identification of stopping particle, however recognition. between pion and muon is very hard.
  - Identification of muon based on the particle length.

- Reconstruction is progressing very well:
  CERN, England, Poland, Spain, Switerland, USA…..
  - Single particles can be reconstructed automatically.
  - Simple topologies without showers can be also reconstructed automatically.
  - **Usually many vertices in the event: one should develop the method of identifing primary vertex. The most important missing piece in order to start the real analysis! – then we can try to understand how all uncertentities from different measurements affect final measurement sensitivities.**

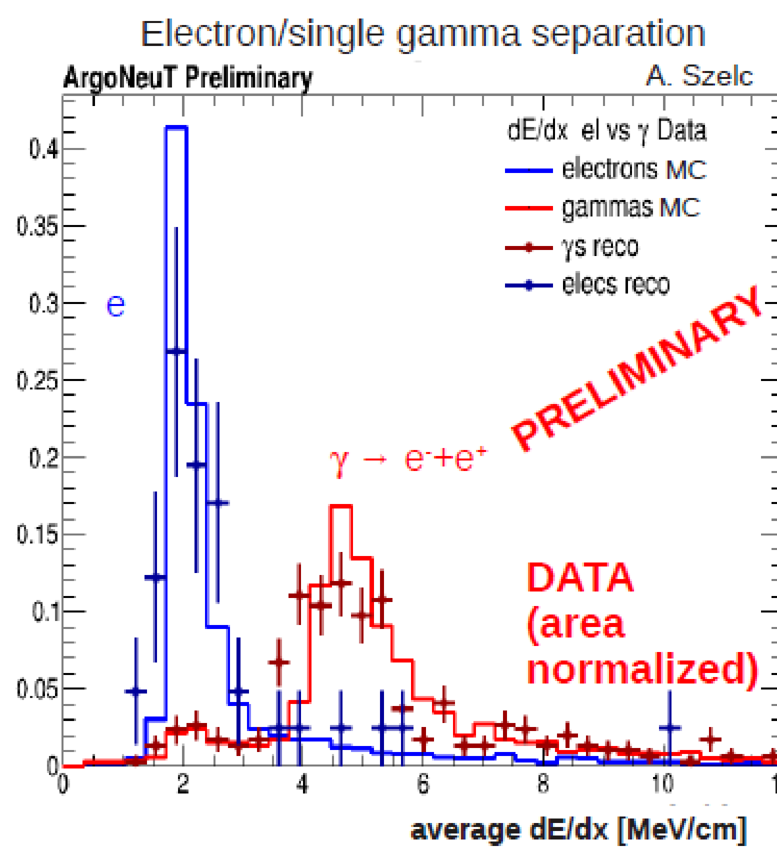
dE/dx measurement in data

~200 – 1000 MeV

1 mip   2 mip



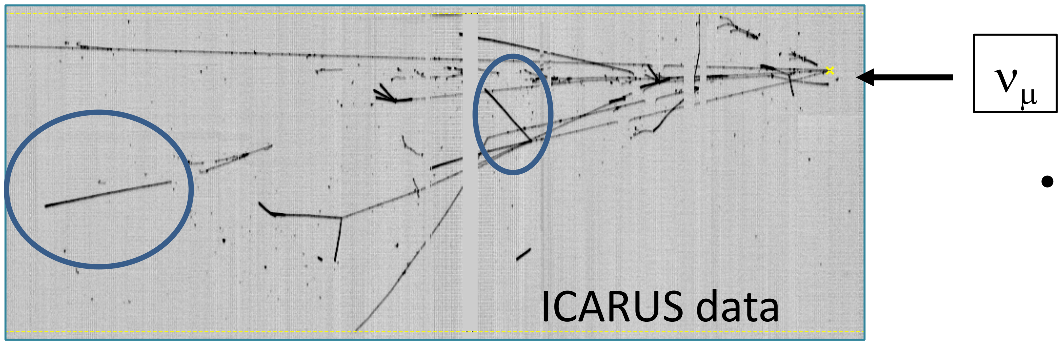
ICARUS data



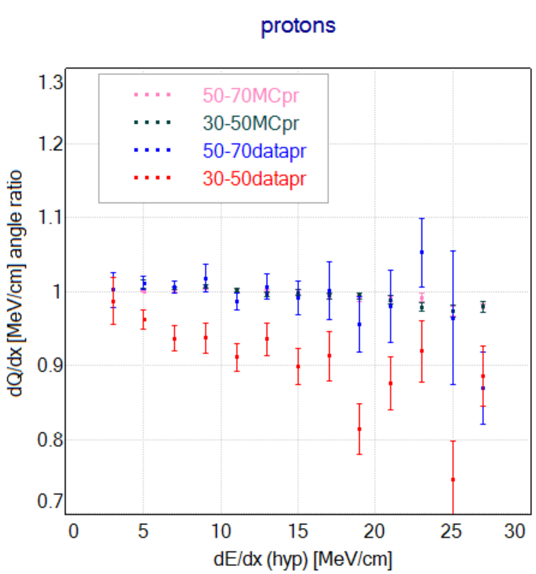
ArgoNeuT data, A. Szelc

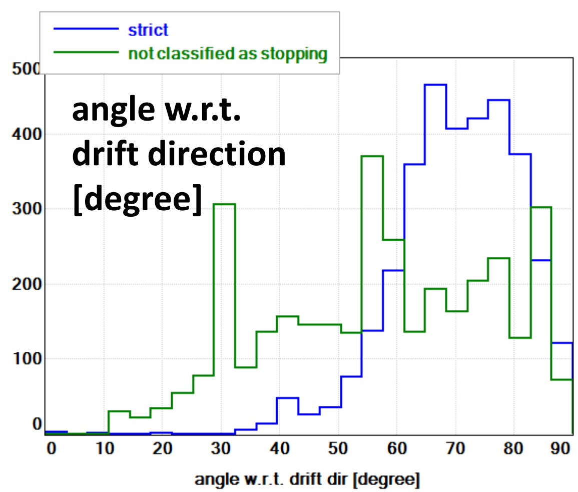
(note: different properties of data sample, another processing algorithms, ...)

Angular recombination studies with ICARUS data

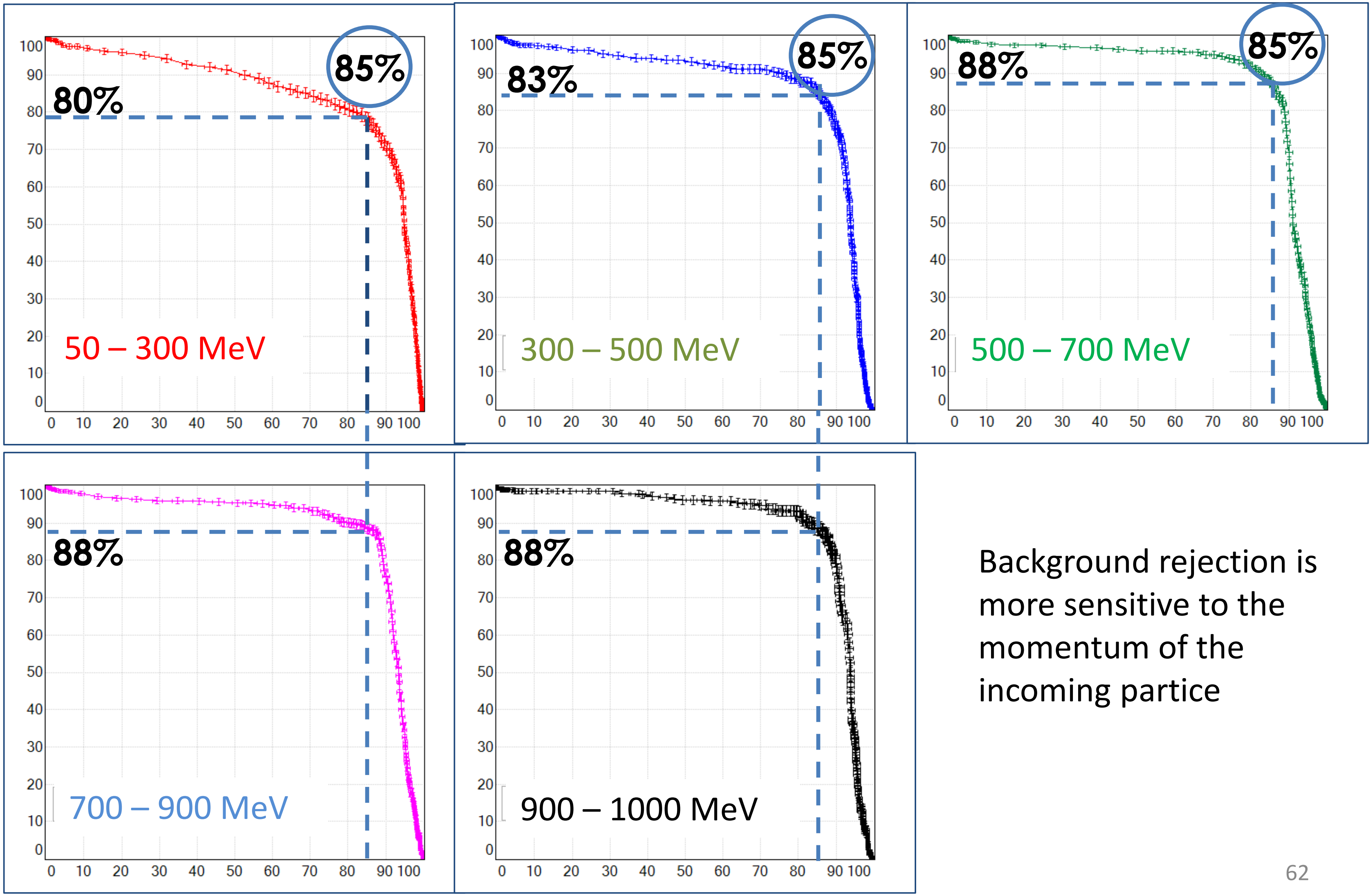


- work inspired by ArgoNeuT publication JINST 8 (2013) P08005.
- measurement of lower dQ/dx for tracks parallel to the drift direction w.r.t. to tracks parallel to the wire plane.
- very low statistics – analysis to be repeated in protoDUNE





Electron selection efficiency vs gamma rejection
Various momenta of incoming electron/photon



Background rejection is more sensitive to the momentum of the incoming partice

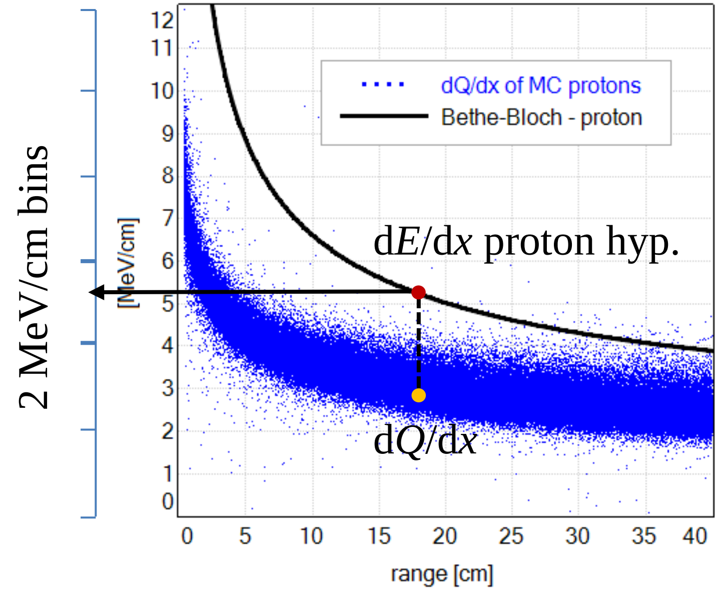
Studies of angular effects in recombination

Calculation

$$Q \approx Q_0 \frac{A}{1+k(dE/dx)/(\varepsilon \sin\phi)}$$

For each data point, on each track:

1. Take **[dQ/dx; *range*; ϕ]** data point.
2. Take **dE/dx** from proton Bethe-Bloch curve corresponding to ***range***.
3. Put ratio **dQ/dx / dE/dx** in the histogram for each 2 MeV/cm bins according to **dE/dx**, for one of ϕ **bins**:
   - **90° – 70° (reference for the two below)**
   - **70° – 50°**
   - **50° – 30°**



Calculate mean value for each **dQ/dx / dE/dx** ratio bin, for each ϕ **bin**: reproduces recombination factor vs. hypothetical dE/dx at given angle w.r.t. drift direction.

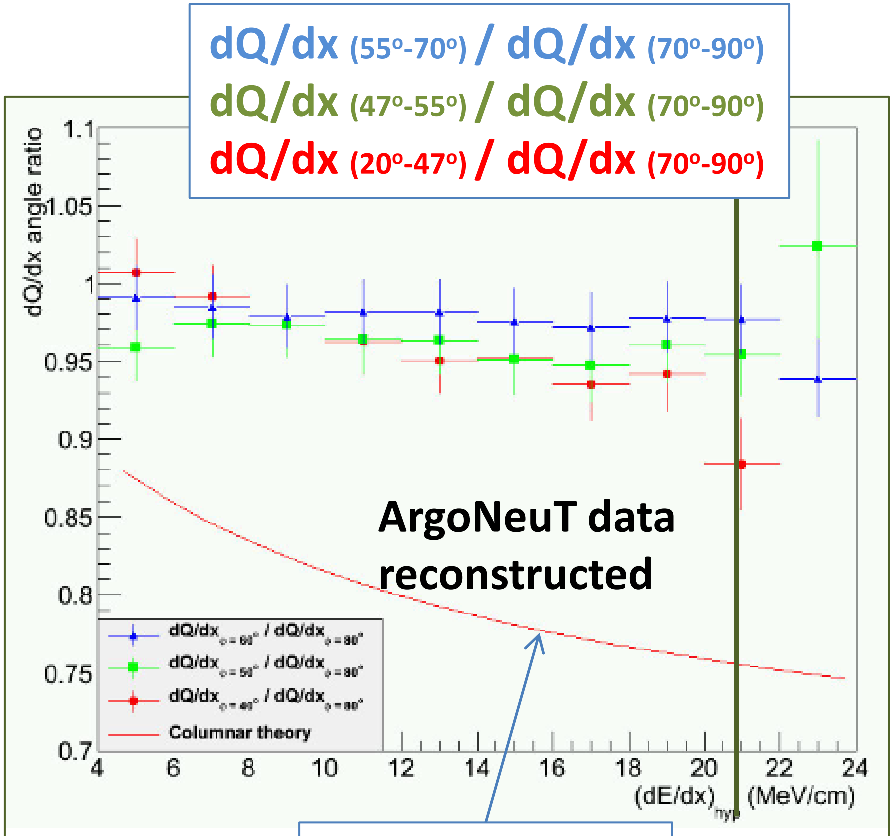
Calculate **final result**: ratio between

- **<dQ/dx / dE/dx> at 70° – 50°** and the reference **<dQ/dx / dE/dx> at 90° – 70°**
- **<dQ/dx / dE/dx> at 50° – 30°** and the reference **<dQ/dx / dE/dx> at 90° – 70°**

Apply procedure to MC (no angular dep. in recombination) to quantify systematics due to reconstruction.

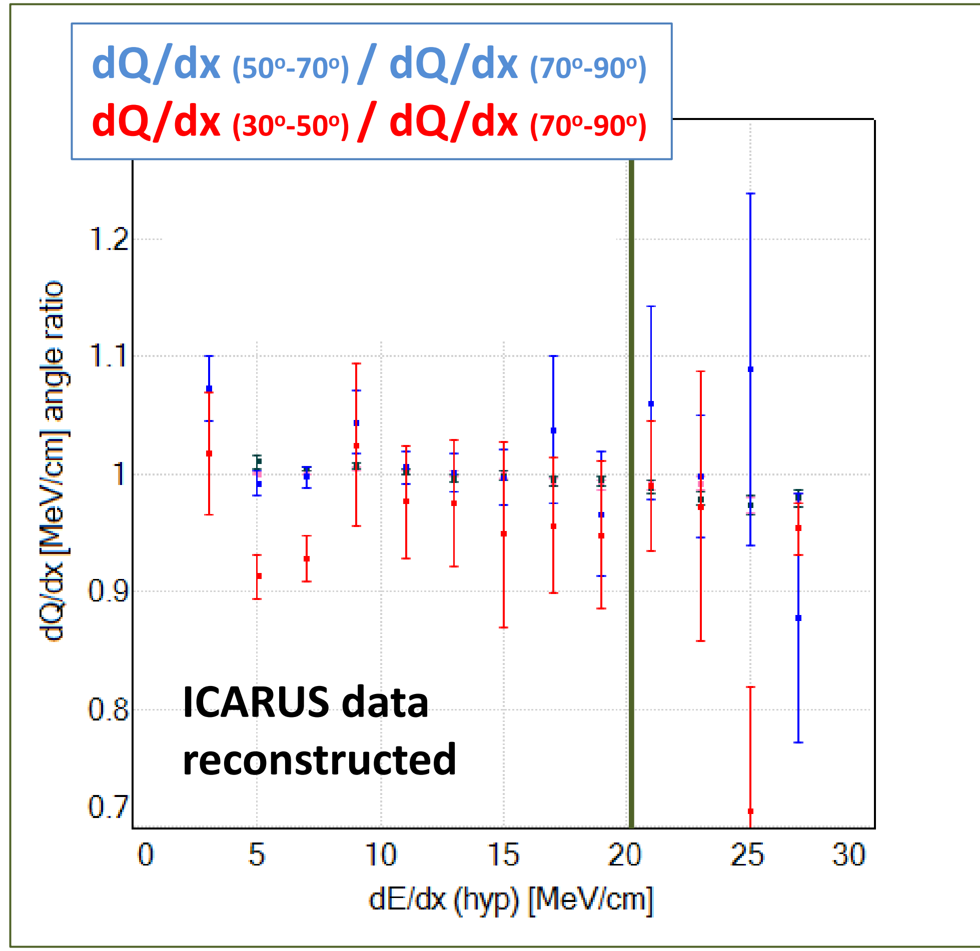
Apply procedure to data: is there any dependence or all the final ratios are flat at 1.0?

ArgoNeuT-ICARUS protons data comparison



Columnar theory

arXiv:1306.1712 – ArgoNeuT paper



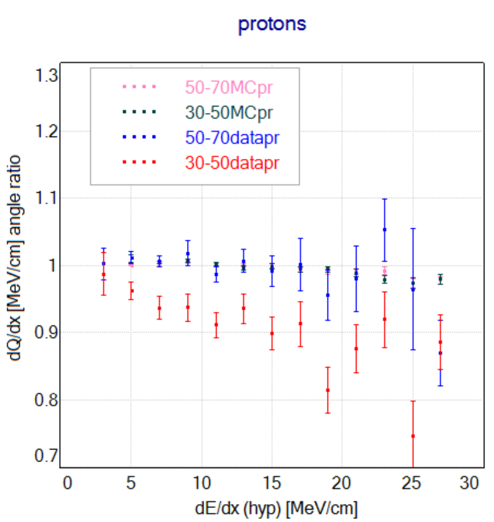
Overall systematic errors of *final ratios* based on MC reconstruction:
(plots on next slides)

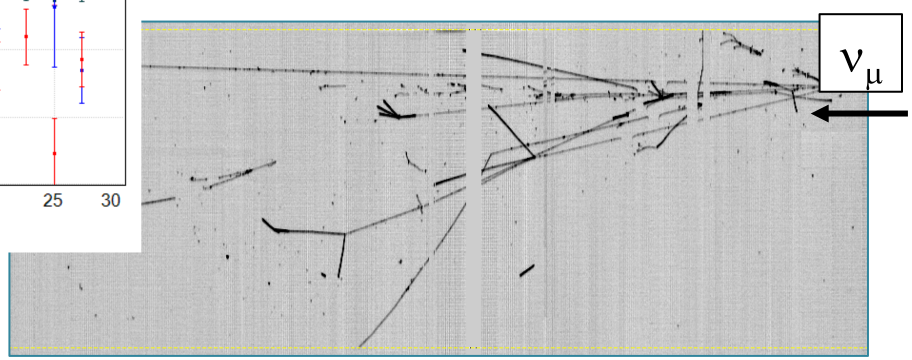
- **protons: 1.0 ± 0.01**
- **pions: 1.0 ± 0.05**

Angular recombination effect - comment

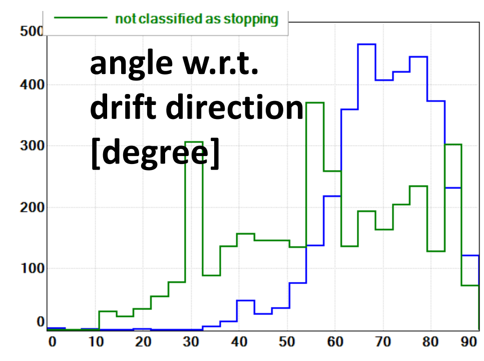
Important: PID is selecting what looks like stopping proton with no angular effects, but:

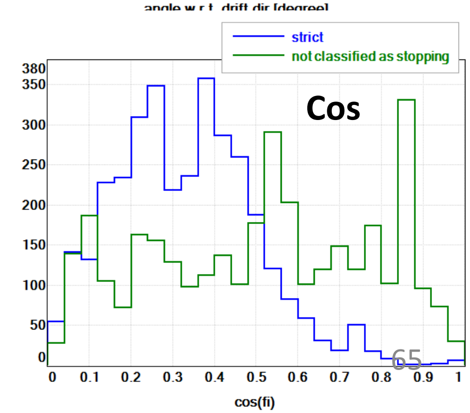
- some protons interacting w/o visible secondaries;
- if stopping protons are attenuated due to ϕ, they have similar dE/dx as the above;
- <u>this is what we may consider important to investigate</u>.





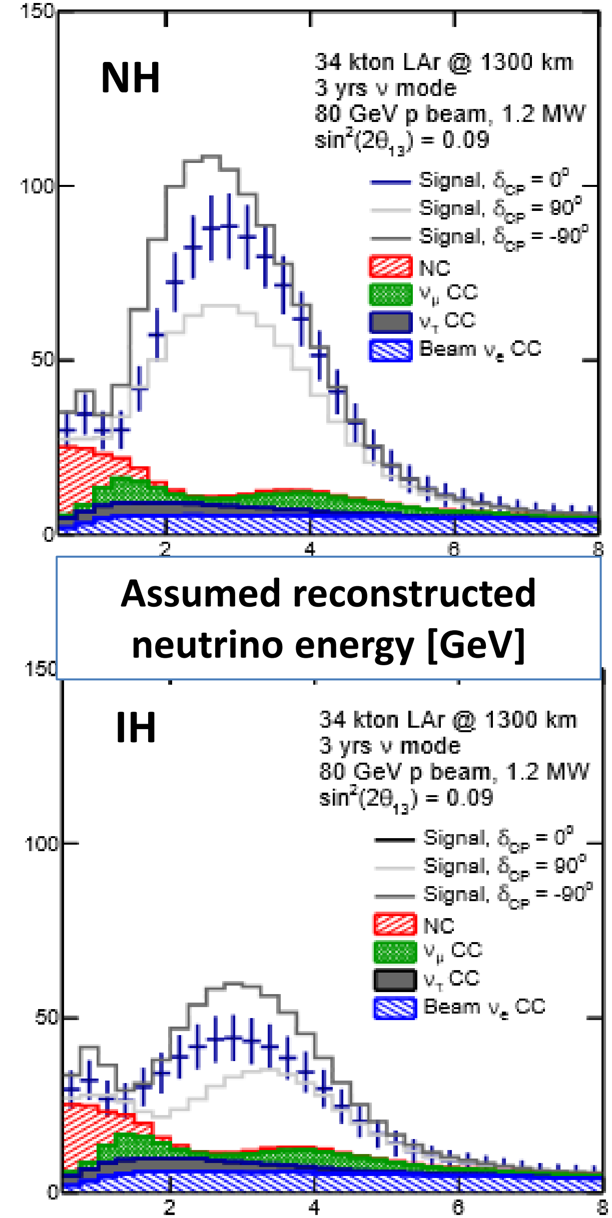
ICARUS data





DUNE experiment

- reconstruction is being automatized;
- reconstuction has impact on CP violation/MH sensitivities and data analysis.
- focus on $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$



Plots from: *The Long-Baseline Neutrino Experiment Exploring Fundamental Symmetries of the Universe* arXiv: 1307.7335 [hep-ex] 22 April 2014

Neutrino event reconstruction and analysis

1. 3D topology reconstruction AND calorimetry needed

ingredients

- Tracks
- Identify particles
- Interaction vertices
- Showers

primary vertex, particles hierarchy

momentum reconstruction (transverse and total)

full event

After we reconstruct the position of the primary vertex and outgoing particles:

2. Electron neutrino event – focus on shower

spatial: shower starting point (check if attached to pri vtx); shower direction.
calorimetry: shower energy.
particle identification via dE/dx of the first part of cacade.
+ other particles which are coming out from primary vertex.

3. Muon neutrino event – focus on muon

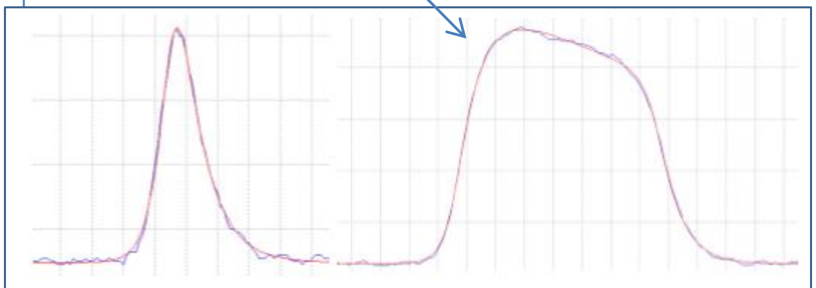
spatial: initial direction and trajectory reconstruction for momentum estim.
calorimetry: muon momentum.
particle identification absence of inelastic interactions; via dE/dx if stopping (efficiency can be low, depends on the detector calibration).
+ other particles which are coming out from primary vertex

Non-uniformities in LArTPC

1. direction-dependent resolution: wire spacing differs from signal readout

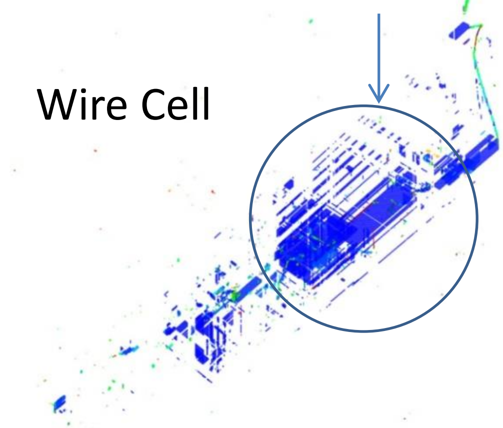
2.

parallel to wire direction



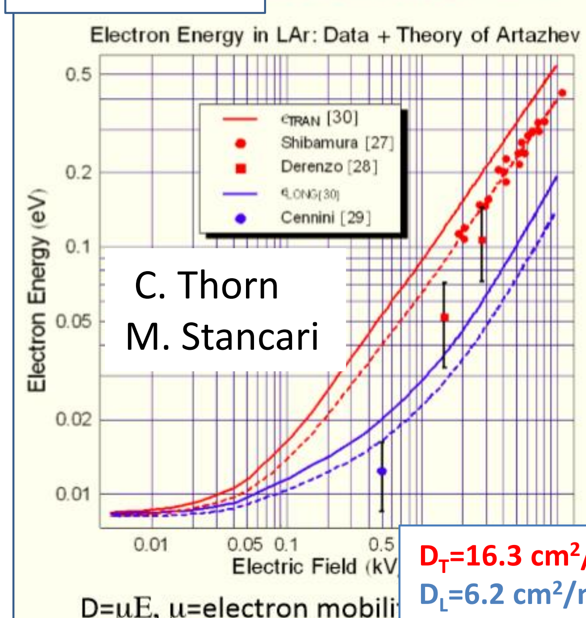
3. wire plane parallel blindess

Wire Cell



8. signal attenuation: purity

4. diffusion

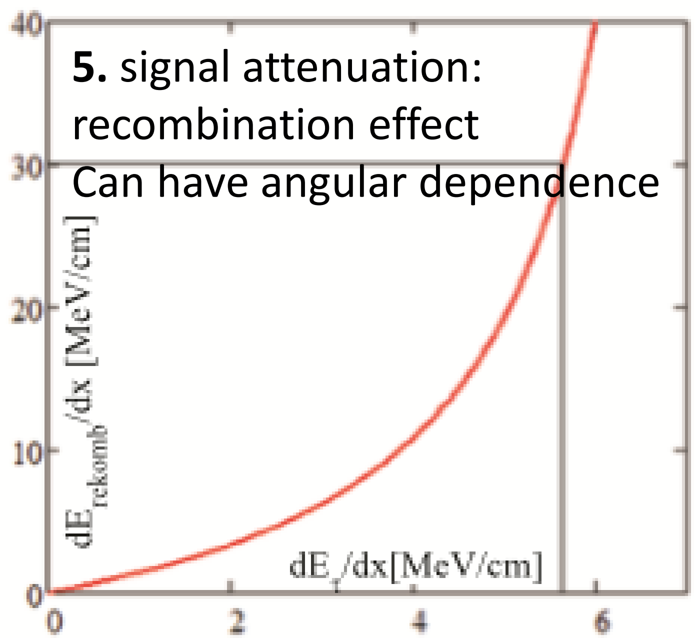


C. Thorn
M. Stancari

D=μE, μ=electron mobili

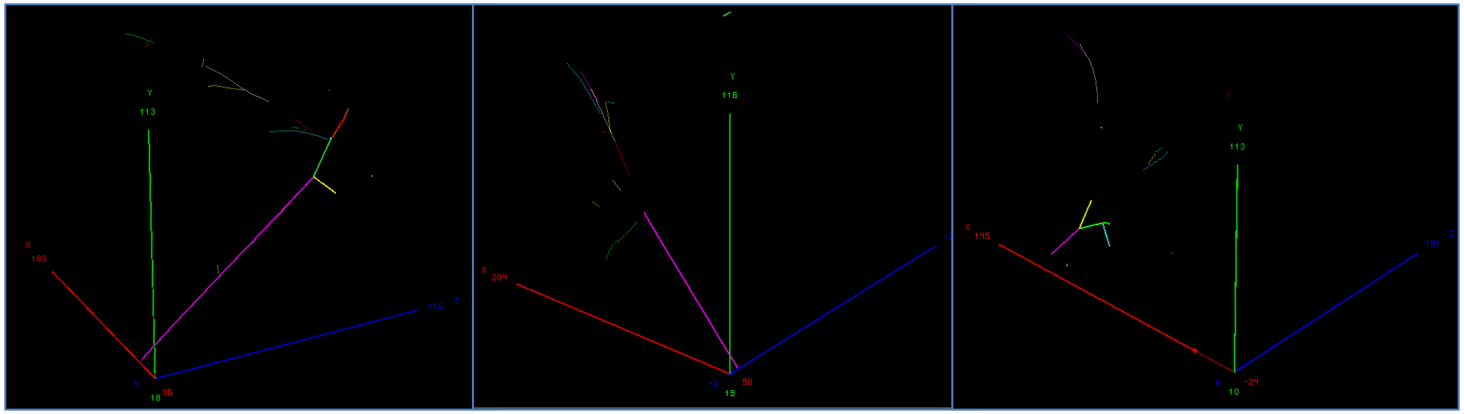
D_T=16.3 cm²/ns
D_L=6.2 cm²/ns

5. signal attenuation: recombination effect
Can have angular dependence



6. … and space charge effect, …and we have to be prepared for usual hardware failures.

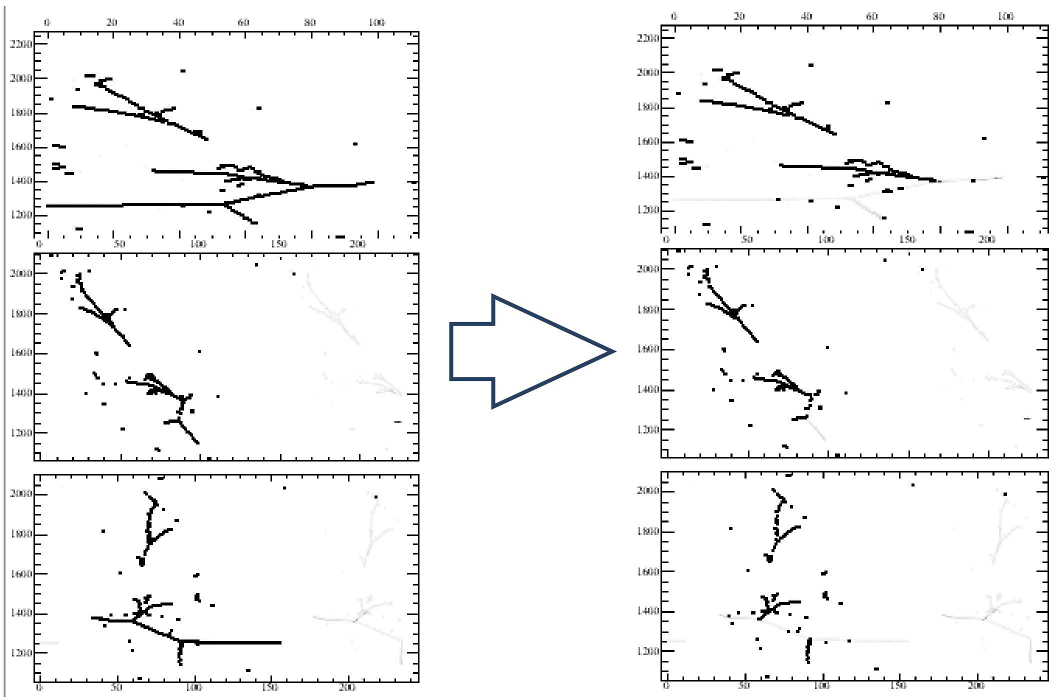
Multi-track structures:π^- @ 2GeV: π^0 production, EM part seperation



solid: MC truth hadrons overlapped with reconstructed tracks

dotted: EM fragments reconstructed as tracks

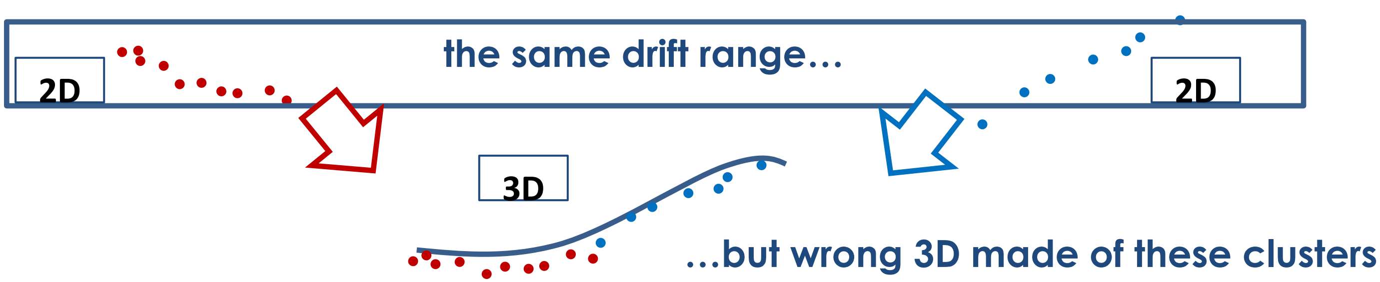
all hits



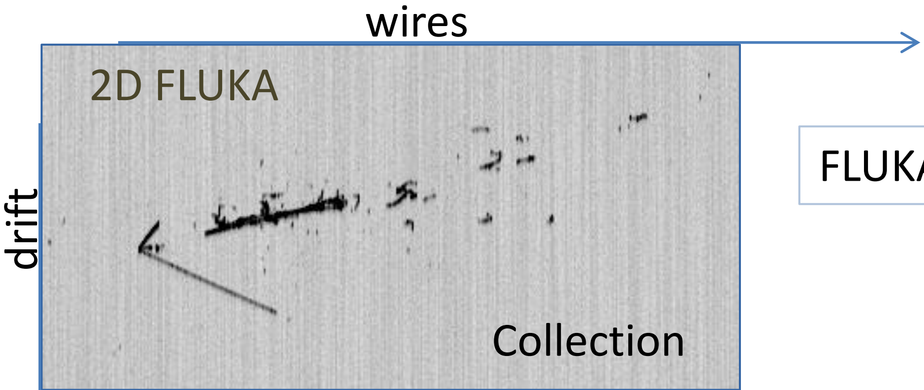
EM-like hits only

PMA practical implementation in LArSoft

- **efficient use of 2D clusters,** can select best 2D views combination
  - start with the largest cluster (#hits)
    - use cluster most overlapped in drift time
    - make 3D track candidate
    - select best candidate (based on: validation in 3rd view; MSE; fraction covered by intertwined hits from 2 views)
    - grow the track by adding clusters (partially) matching the trajectory
      - while checkinng validation measures
    - finally, add matching clusters from the validation plane
  - loop for large / then for small starting clusters size
  - correct / merge / stitch / reoptimize …
- **quickly reject track candidate** if 2D hits are not intertwined enough along 3D track: better behaviour in EM cascades and 2-plane geometry (thanks to Tingjun testing PMA on ArgoNeut data)



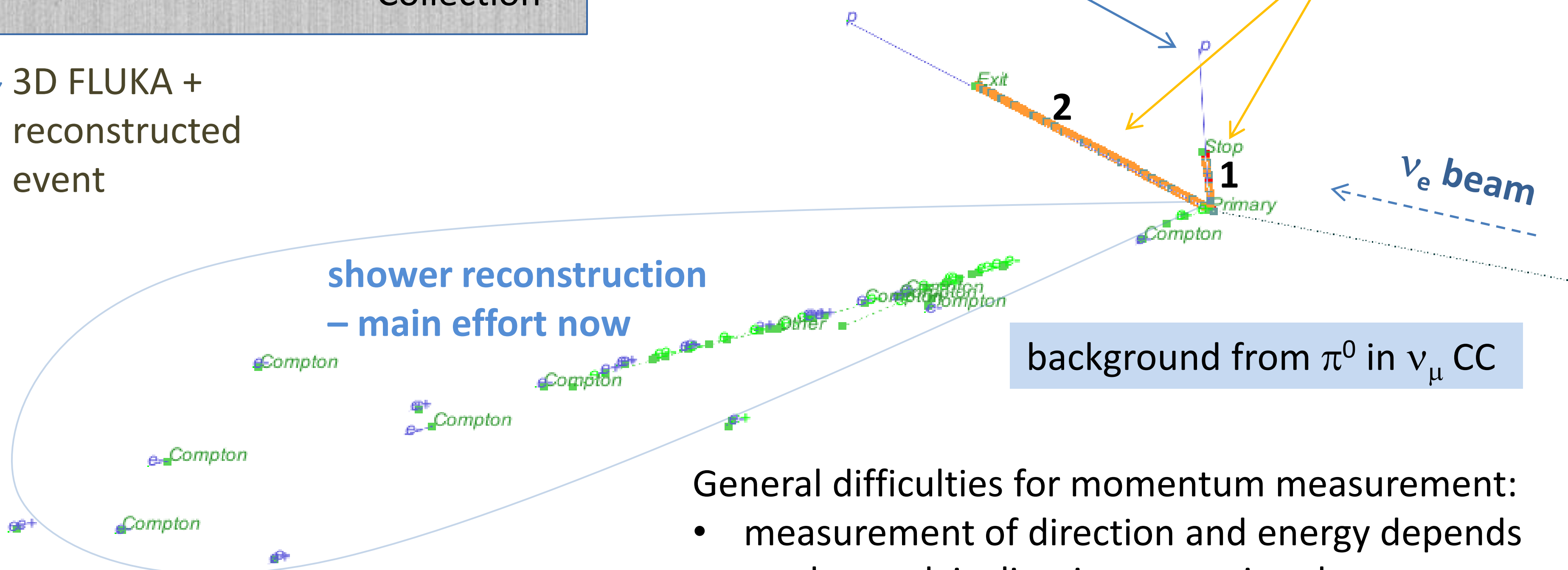
ν_e CC



3D FLUKA + reconstructed event

FLUKA protons directions

Reconstructed tracks correctly reflect the MC directions



ν_e beam

shower reconstruction – main effort now

background from π^0 in ν_μ CC

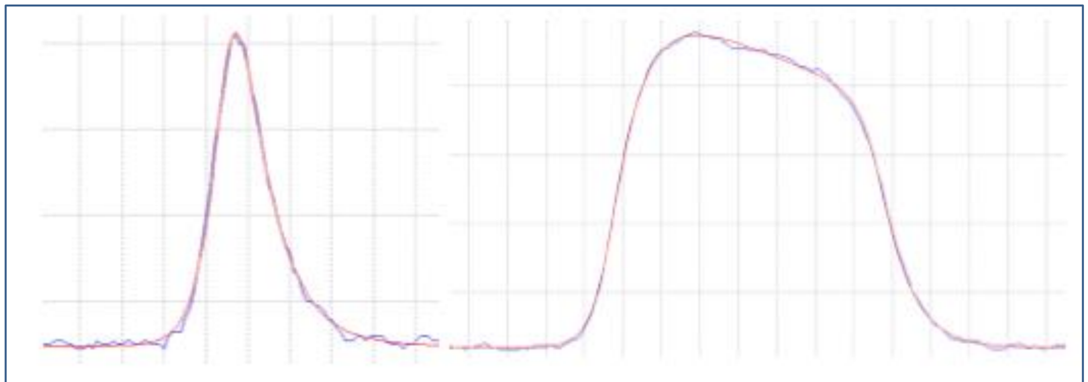
General difficulties for momentum measurement:

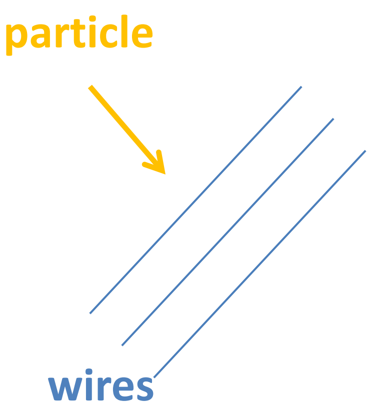
- measurement of direction and energy depends on the track inclination w.r.t wire plane
- tracks overlapping, escaping tracks

1 – stopping particle: particle identification via dE/dx shows proton at 99.96% probability. Reconstrycted kinetic energy: 92 MeV +/- 8 MeV

2 – particle exits the detector: 1mip – not possible to make particle identification via dE/dx

Tracks parallel to the drift direction

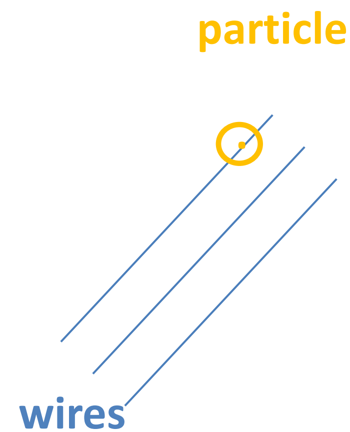




Signal generated by particle going perpendicular to the wire.

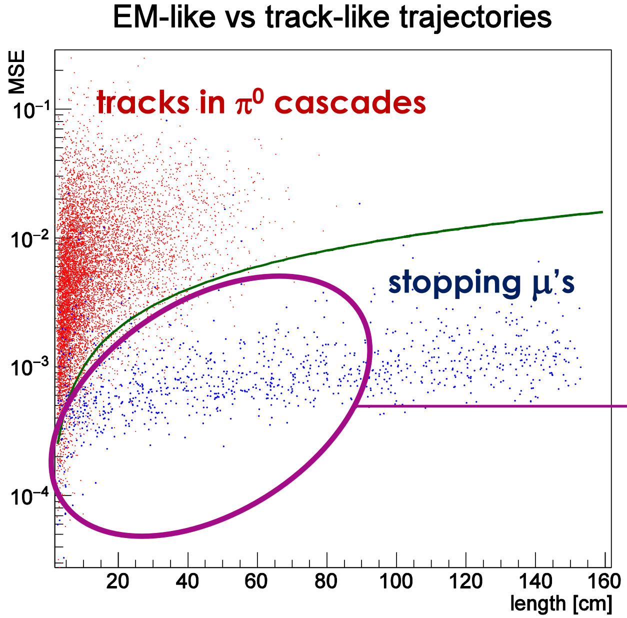
Signal generated by particle going parallel to drift direction.

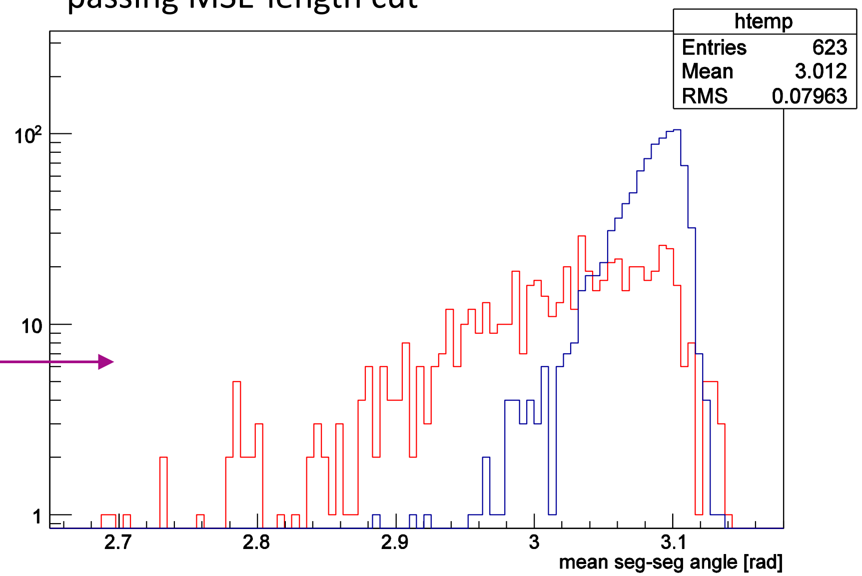
Challenge in signal processing and spatial reconstruction.



EM part selection

- idea is quite a specific to PMA-based tracks, still would prefer to have it on the cluster level
- **electron/EM-cascade-part** versus **hadron/muon track**

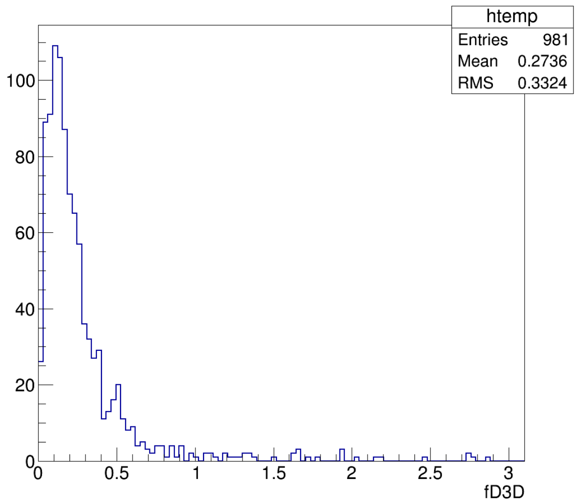




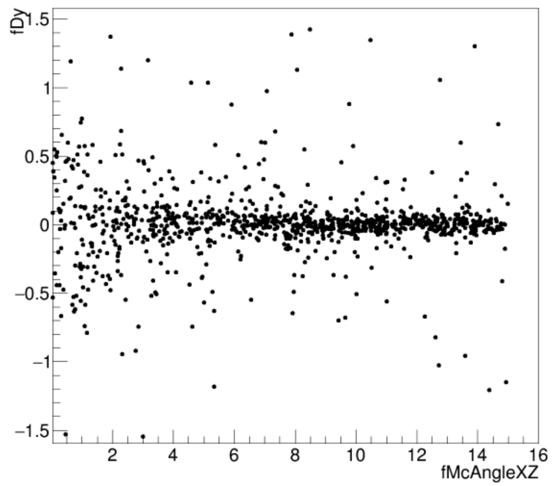
- first trials, still testing, **not good solution for large showers**…
- global MSE / curvature measures are not completely enough, would like to try rough checks of dQ/dx
- may need to apply measures locally along the long track (as in large EM shower or track partially overlapped with EM cascade)
- subtract tracks and produce container of remaining EM-cascade-hits

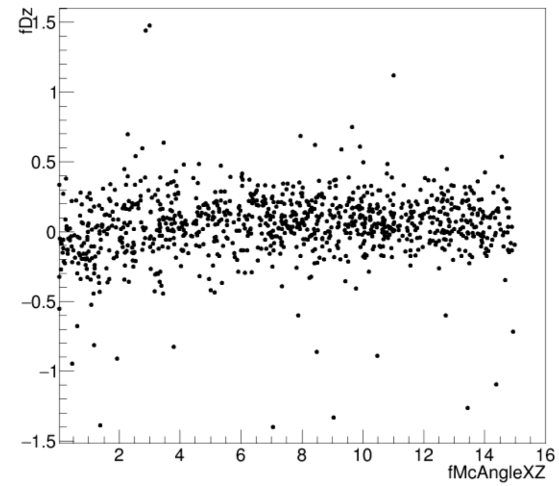
Protons @ 2 GeV/c – some plots

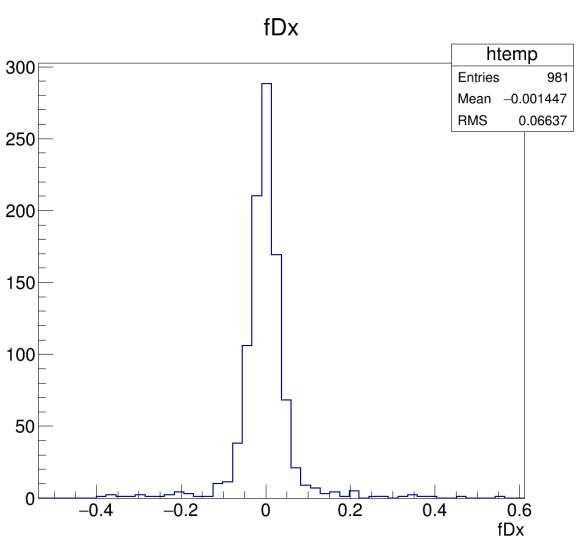
3D distance

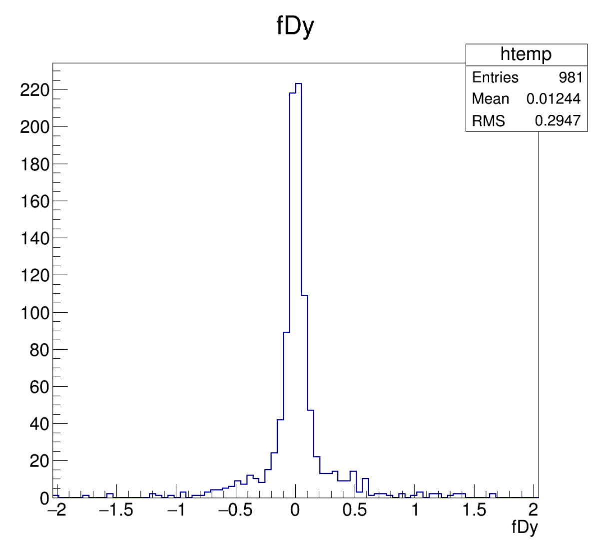


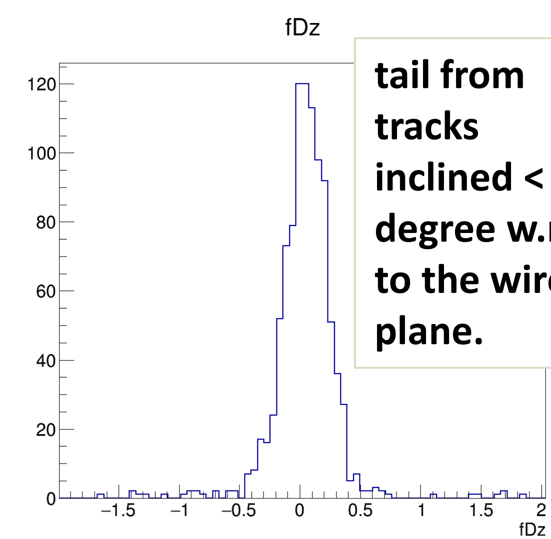
dY ← vs beam angle w.r.t. wire planes → dZ











tail from tracks inclined < 4 degree w.r.t. to the wire plane.