3D reconstruction
with Projection Matching Algorithm

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Outline

- Reconstruction chain: 3D steps depend on preceding stages
- General 3D approach: motivation and features of the developed new concept
- Present developments of Projection Matching Algorithm
  - LArSof implementation
  - multi-track structures
  - cascades – just a few words on the progress
- Summary

Note: basic idea for 3D was developed in the ICARUS software, together with the 2D segmentation algorithm and initial work on automatization and multi-track structure optimization.

Tracking module implemented for LArSoft and many concepts as shown today were designed from scratch during our recent work in 35t / DUNE group.

LArSoft implementation of 3D is being developed to use input from any LArSoft algorithms (2D clusters, vertices) as much as we can.

Reconstruction chain

wire hits

- ***huge*** *topic, out of today's slides*

2D clusters

- Cluster Crawler extensively tested and used in the presented work
- however, other algorithms can be applied as well
- track- / shower-like distinction desirable at 2D level

3D reco

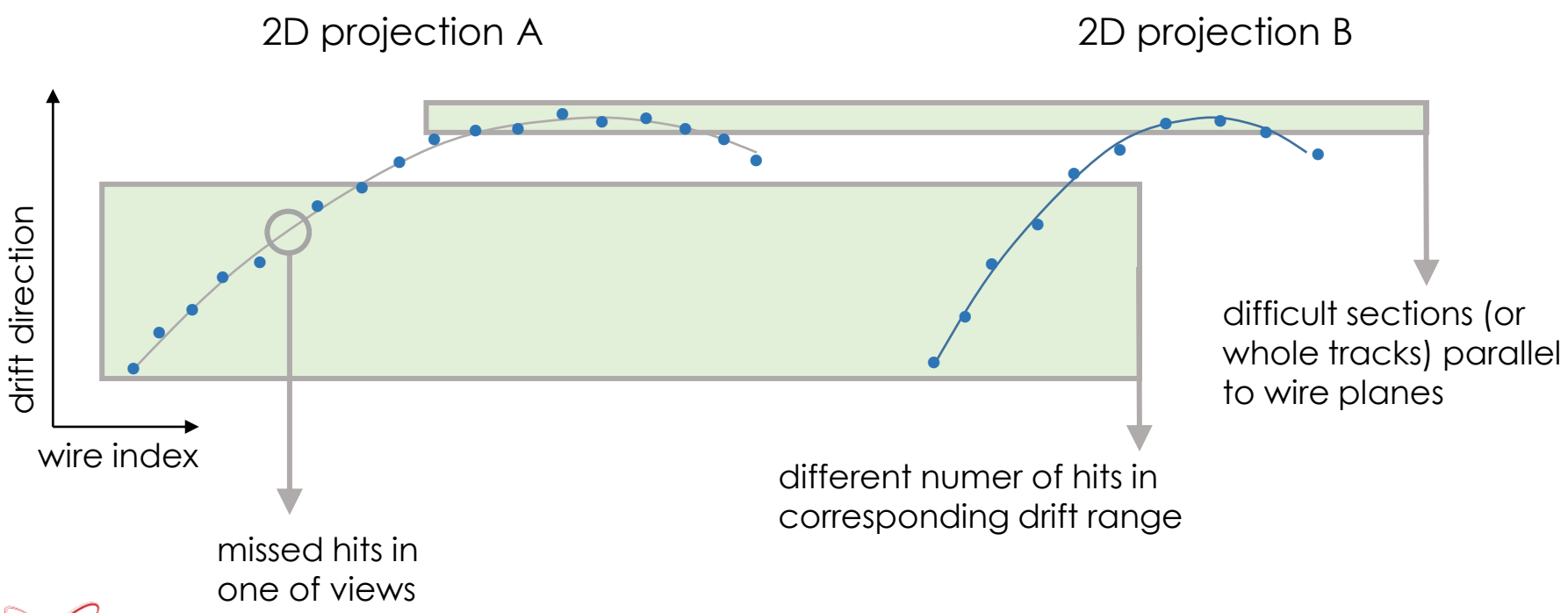
- cluster-cluster association → isolated tracks
- stitching between TPCs, optionally within TPCs, track tuning
- track- / shower-like distinction (likely compl. to 2D algorithms)
- multi track structures interconnected with vertices

Up to some (small) extent each stage can correct mistakes of the preceding one.

→ dE/dx, PID, physics …

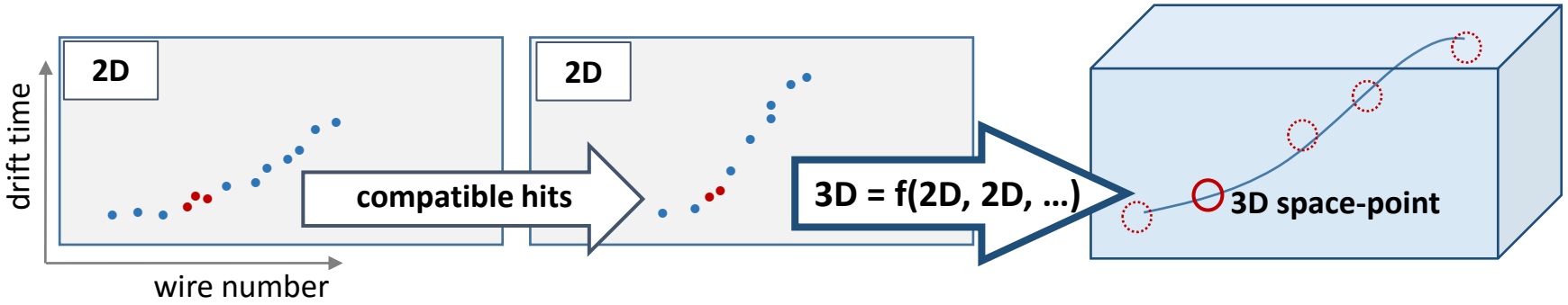
Motivation for developing new 3D approach

- 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



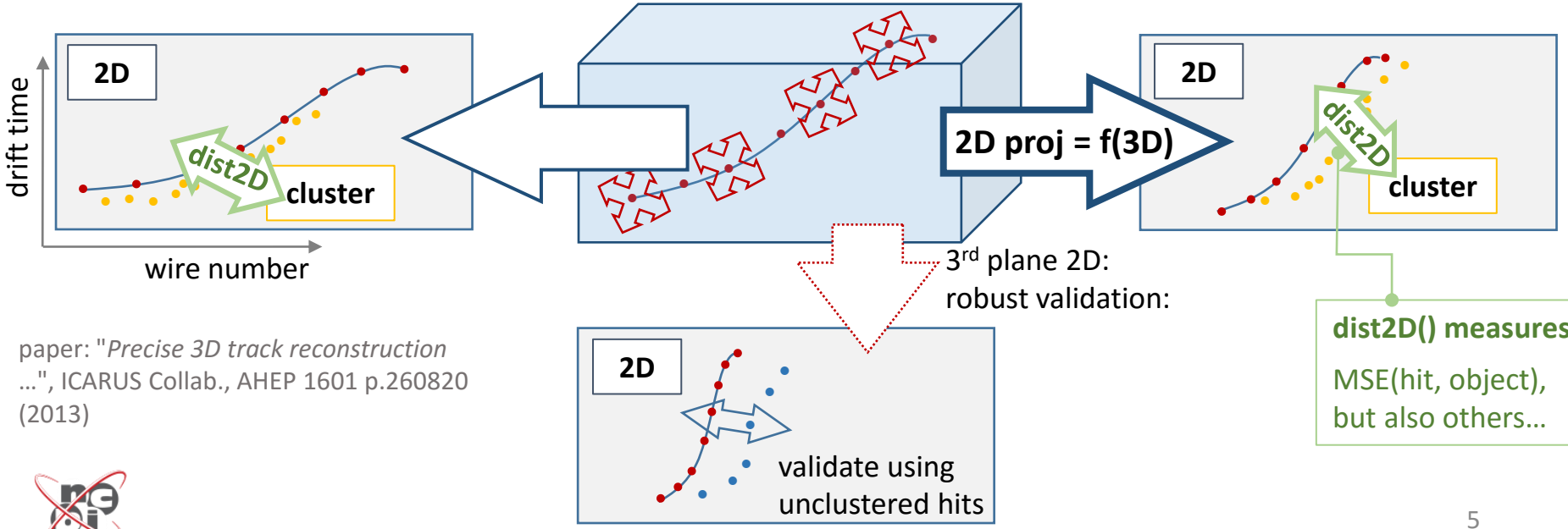
New 3D approach: general concept

usual: *n* 2D hits → 3D space point → 3D tracks, etc.



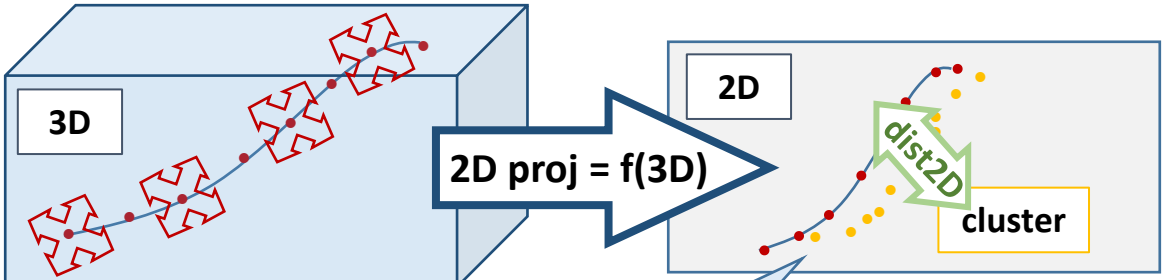
other way around: ***Projection Matching Algorithm***

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)

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

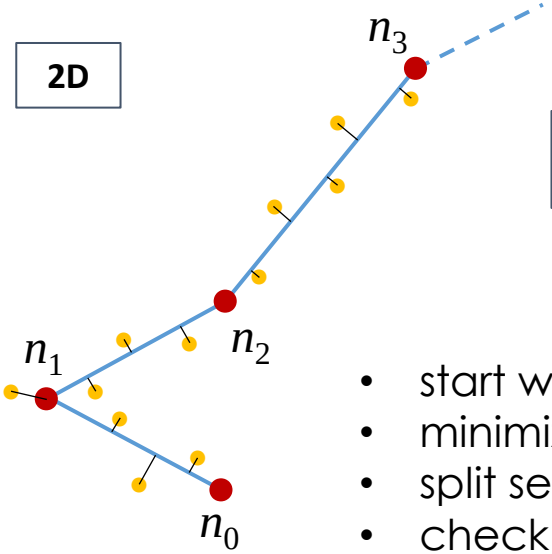
$$G(F) = \Sigma_k g(\mathbf{n}_k)$$

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

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, …

Features of the 3D approach

- **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 optimzation, 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

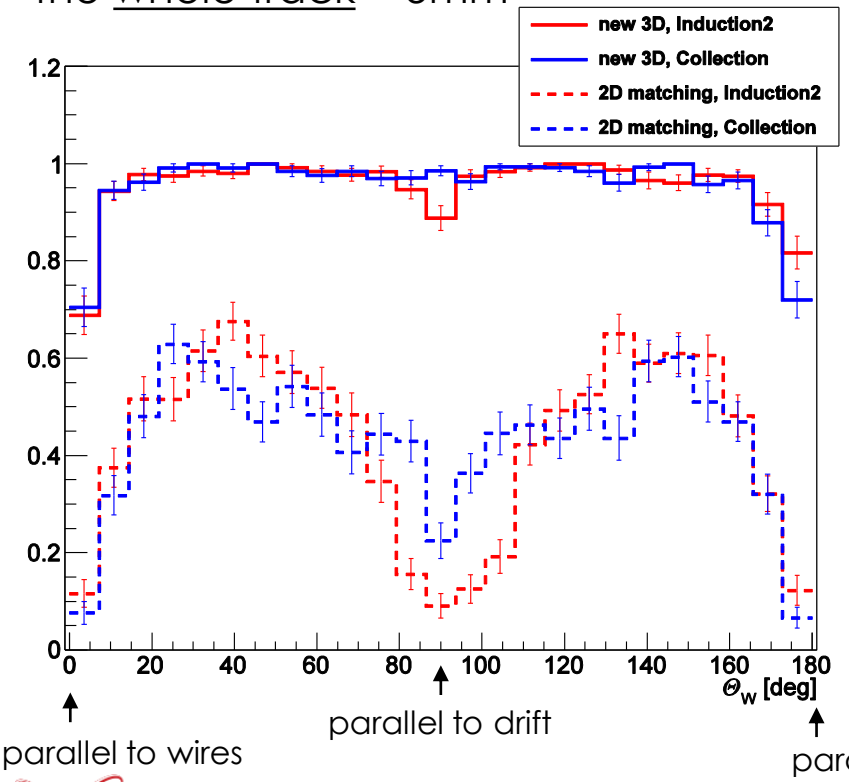
New 3D approach vs previous works

First efficiency was measured on 30 cm stopping muon tracks, ratio:

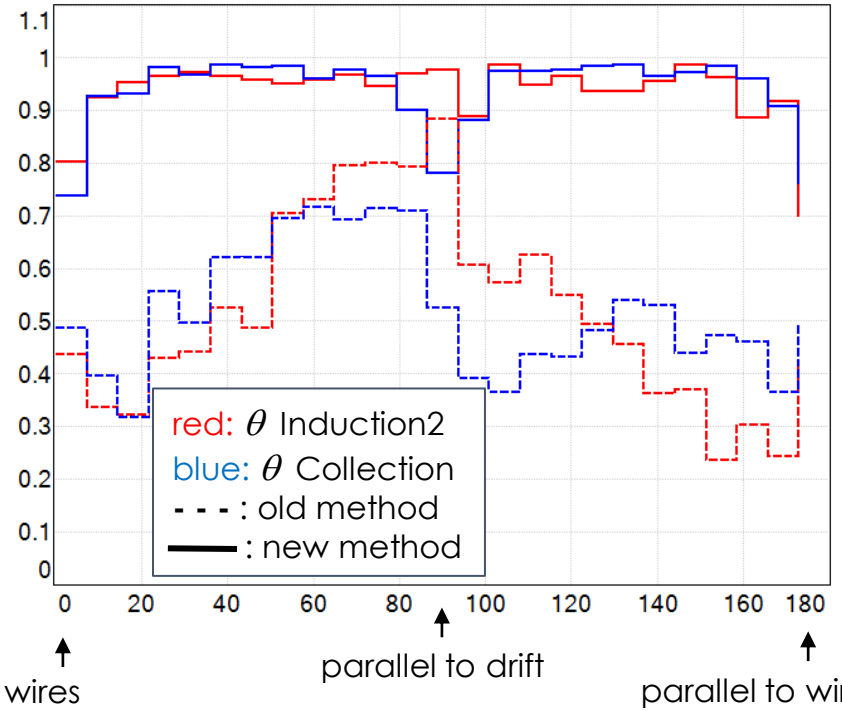
$$\frac{\text{good tracks}}{\text{all tracks}}$$

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 whole track < 5mm



good = initial direction (reco,MC) < 5°

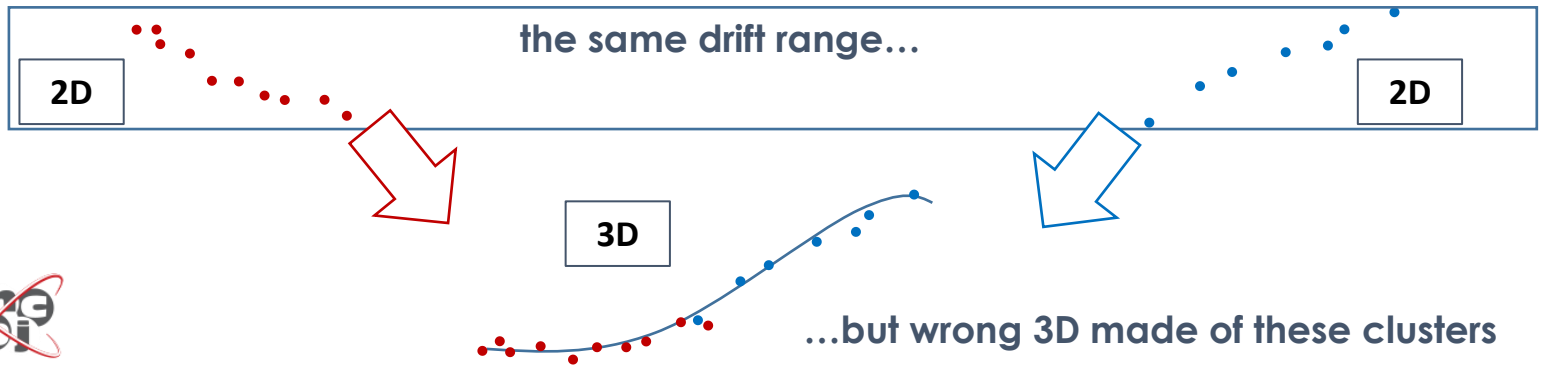


PMA practical implementation in LArSoft

- **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 …

Tingjun and Tracy noticed low speed for MicroBooNE multi-muon events - optimizations done / on the way

- **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)

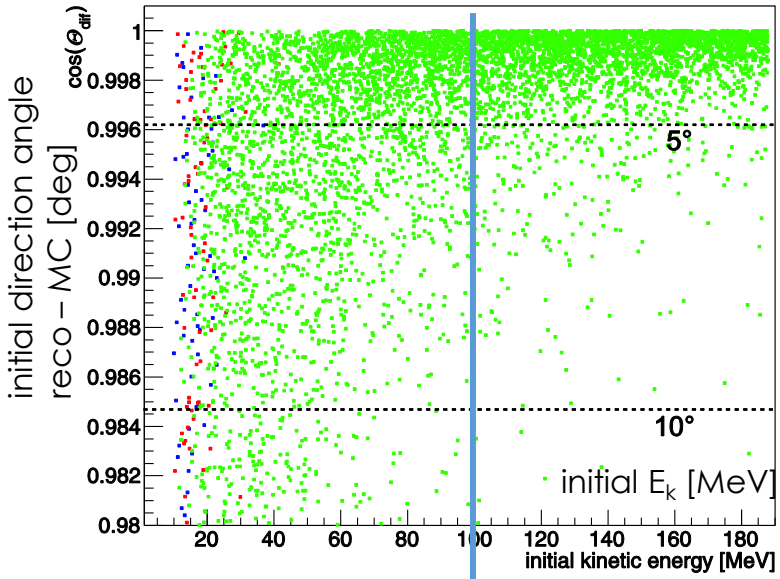


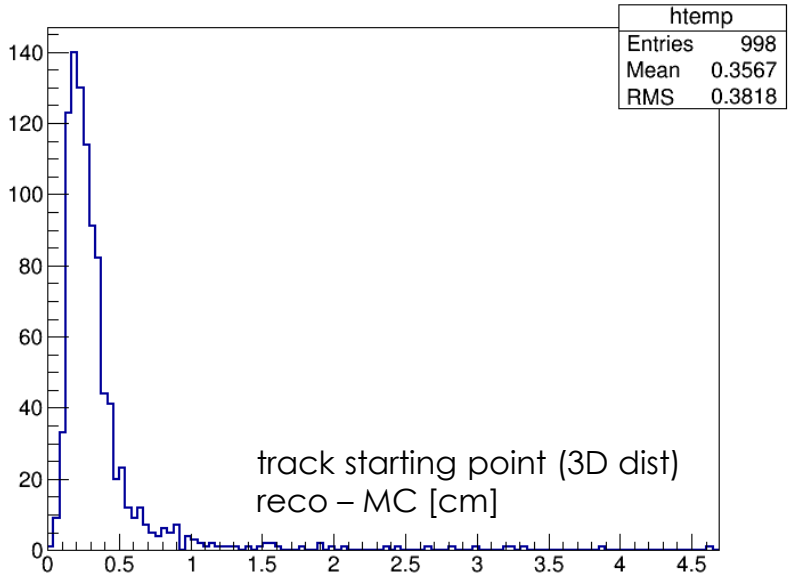
Single track reconstruction

Systematic efficiency tests on 35t MC are in progress (and some done by MicroBooNE).

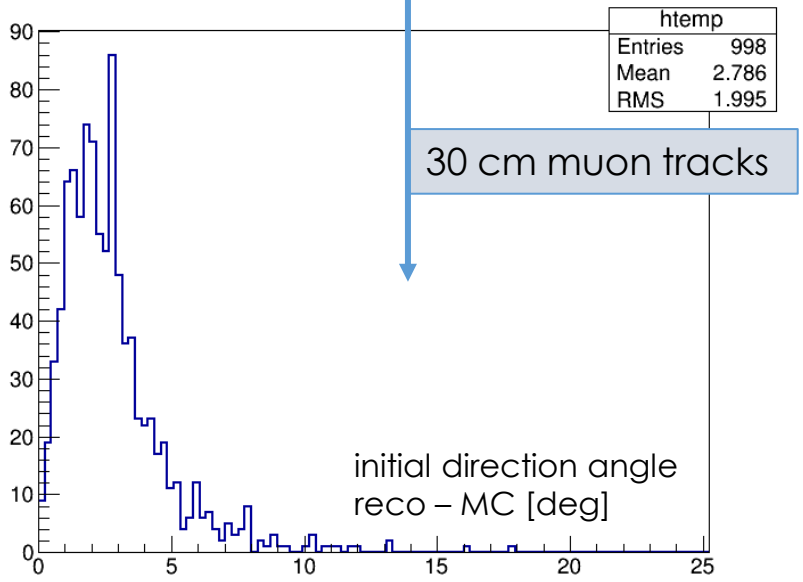
- need comparison to other tracking algorithms in *LArSoft*
- current tests on individual tracks show very similar performance to the *ICARUS* implementation
- here: 30cm (E_k=100MeV) muon tracks

ICARUS implementation, **3mm** wire pitch





LArSoft implementation, **~5mm** wire pitch



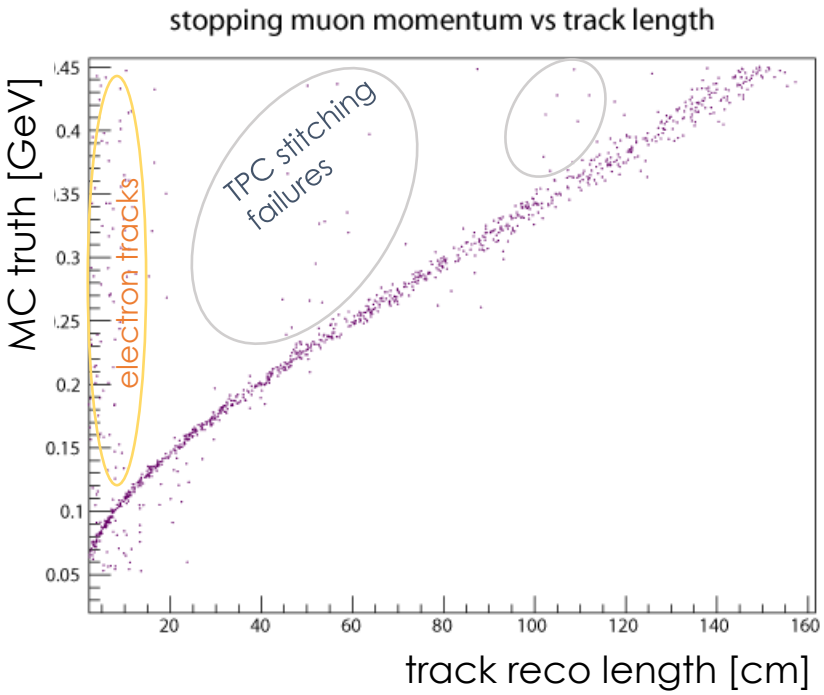
30 cm muon tracks

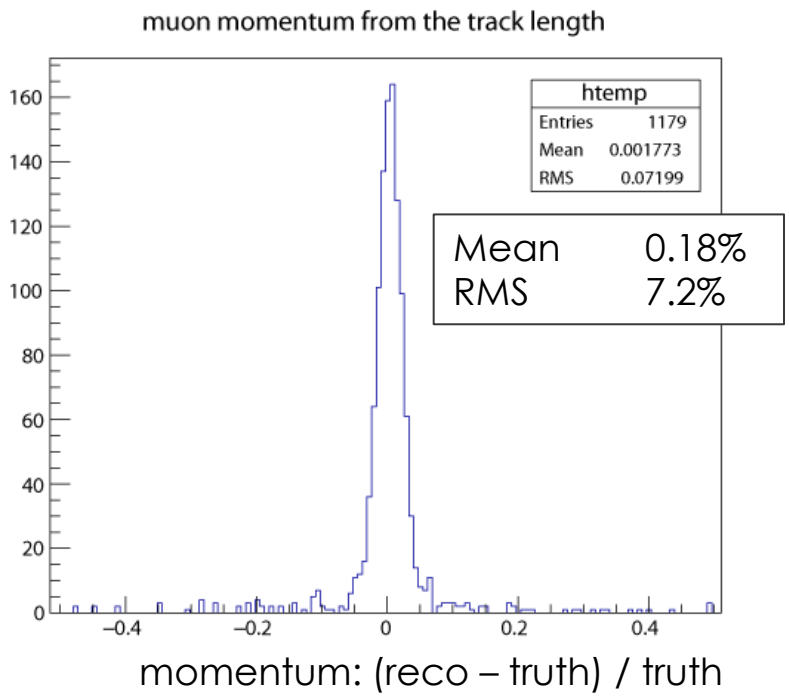
LArSoft implementation, **~5mm** wire pitch

Single track reconstruction

Another quick performance test, stopping muon momentum reconstruction based on the track length:

- 50 – 450 MeV/c tracks simulated, varying angle w.r.t. the wires, crossing up to 3 TPC
- some tuning needed, e.g.: selection of decay point by dQ/dx (to avoid electron track if colinear with the muon), stitching between TPC's (some corrections done)

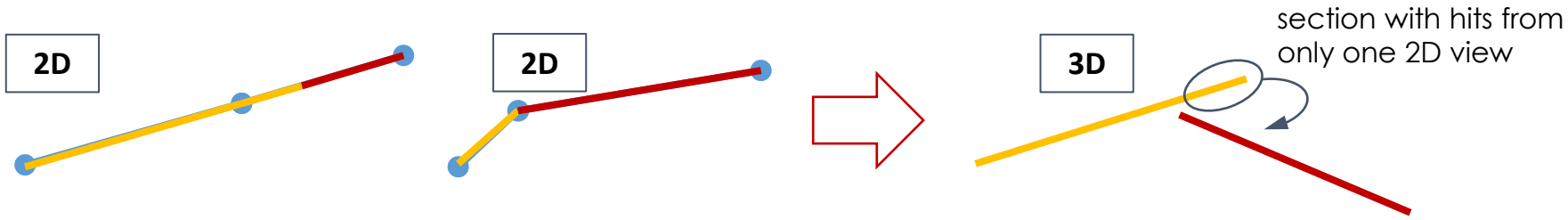




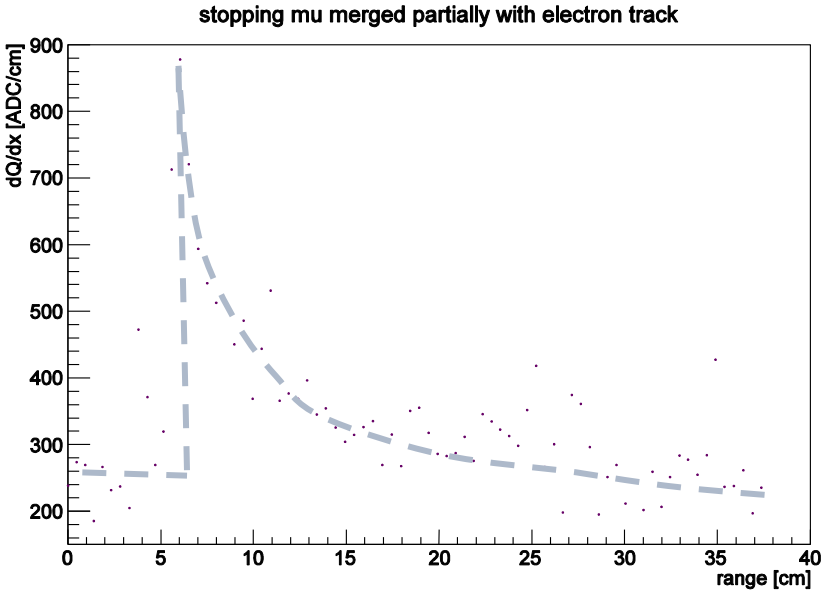
ADC to energy calibration not yet tried and *much more precise calorimetric method* not yet applied, however dQ/dx is up and running.

Single track reconstruction – track tuning

- correct hit-track assignment caused by linear projection of kinks in one of 2Ds



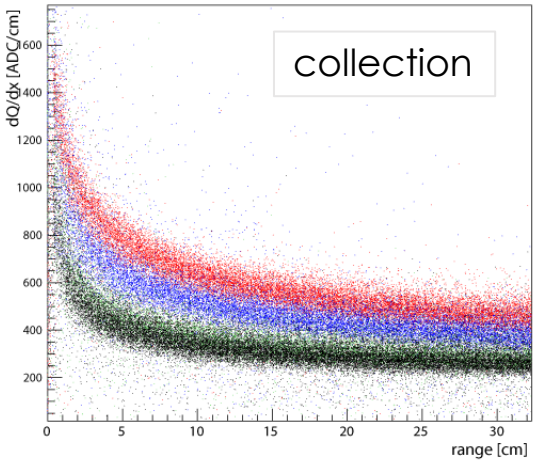
if tracks colinear in both 2D views then correction of similar mistakes needs to look at e.g. dQ/dx (one of things to implement…)

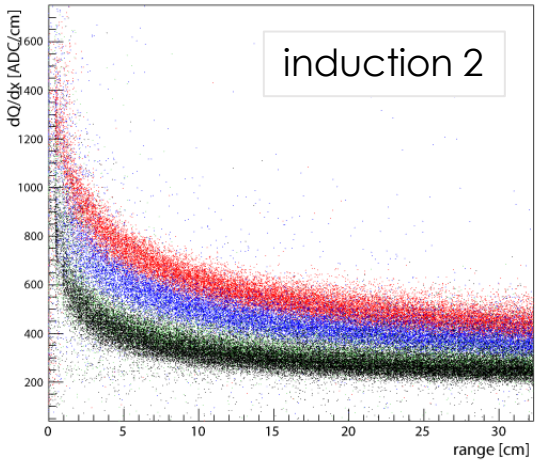


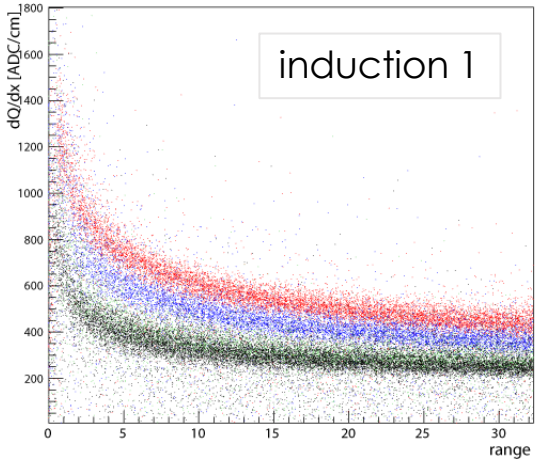
stopping μ partially merged with the electron track

- …but **do not go too far with corrections** before vertex reconstruction

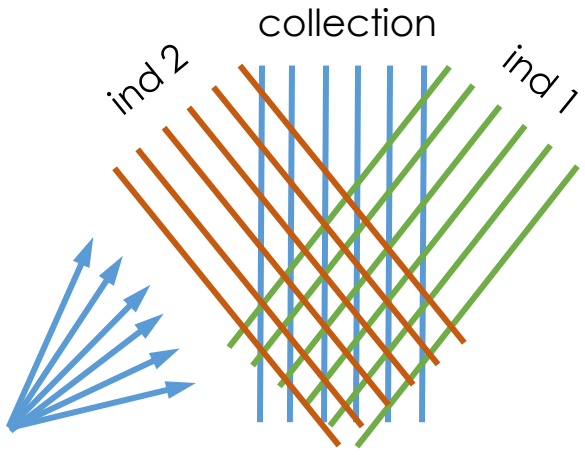
Single track: stopping particle patterns



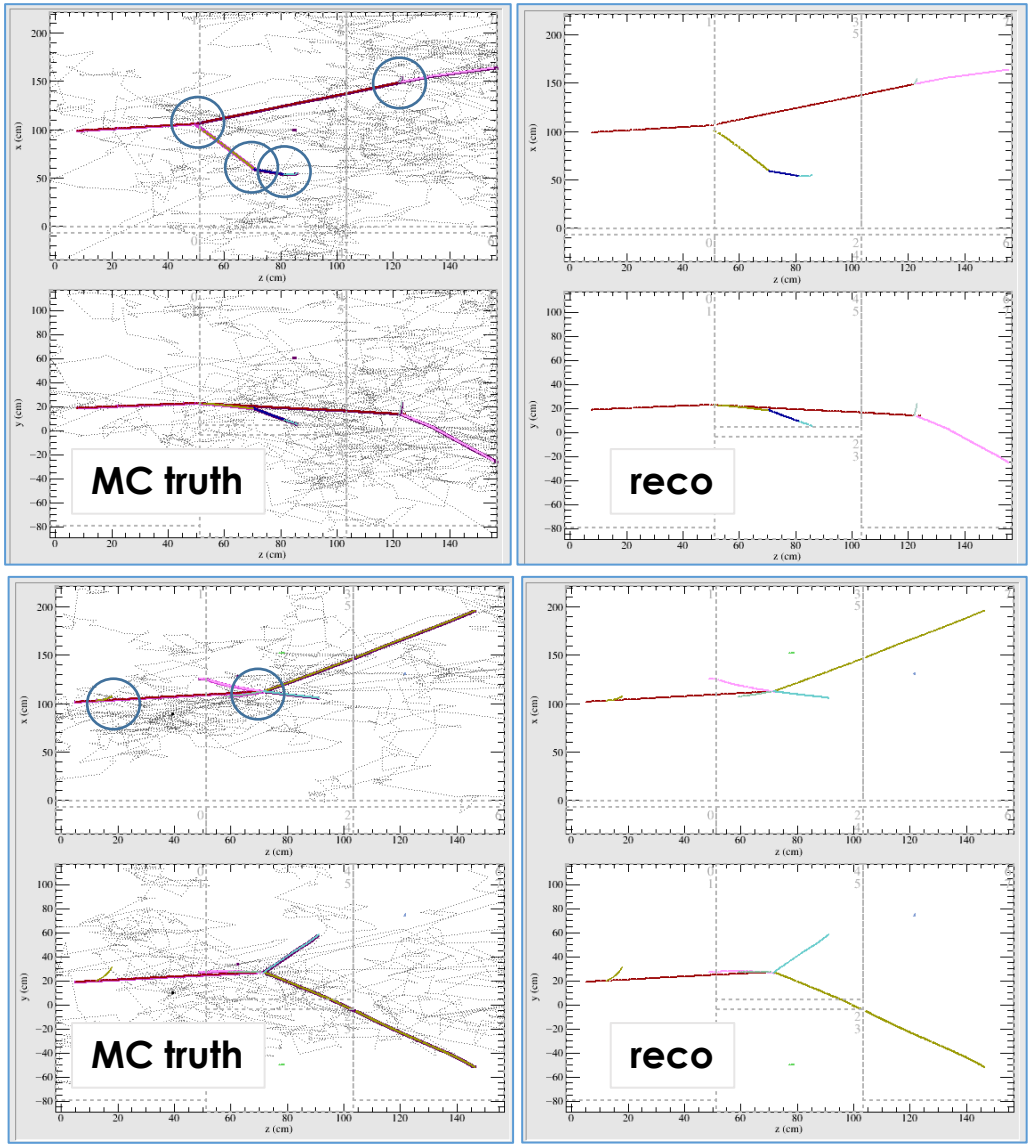


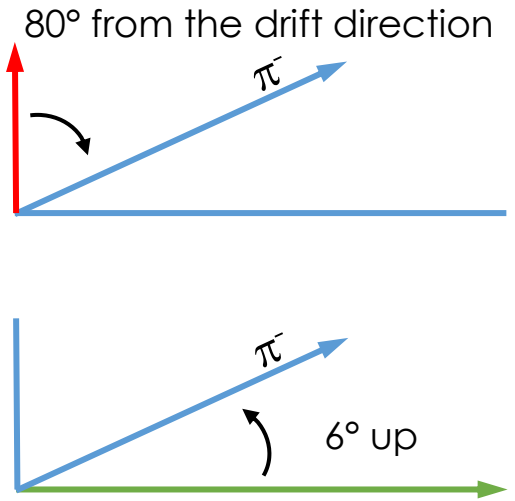


- dQ/dx up and running in `recob::Track`
- here: ~5mm wire pith → narrow bands, but fewer data points along the track w.r.t. 3mm
- best (longest) projection can be selected
- here: beam in cone most favorable for induction2 and most parallel to induction1 wires
- again – vertexing should improve decay product separation and reconstruction precision



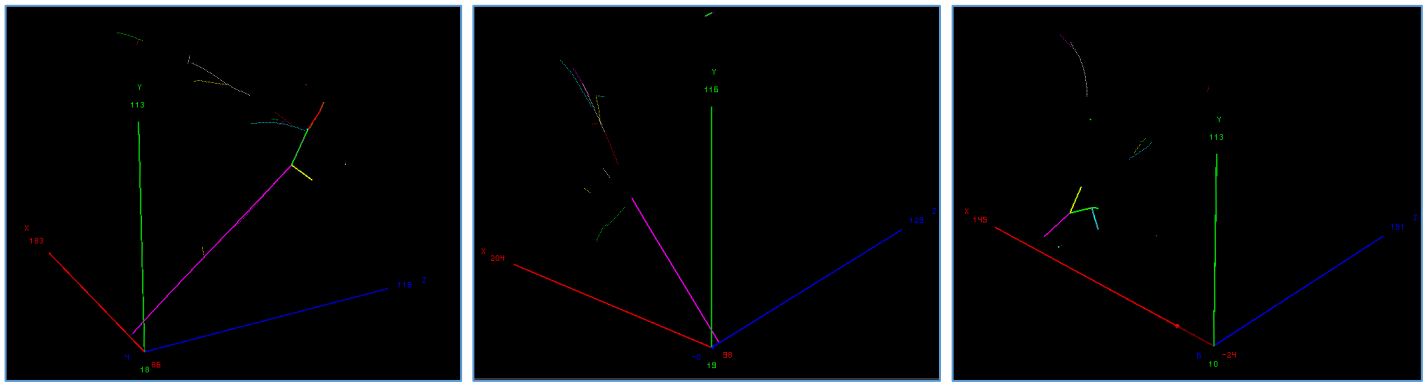
Multi-track structures: π^- @ 2GeV: hadronic showers



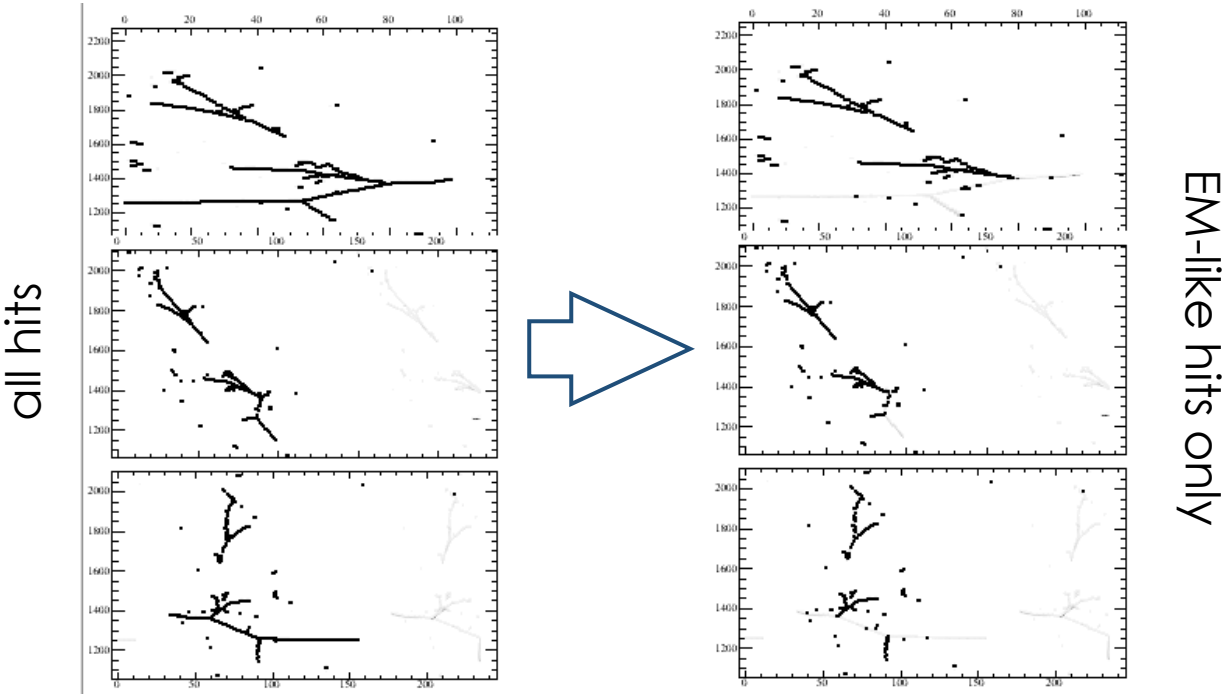


- in plan for protoDUNE at CERN test beam
- range of secondaries cover also „parallel to wire planes" orientation.
- multiplicity low enough for efficient track reconstruction
- π^0s multiplicity: 1-2 per event on average
- clear need for vertex reconstruction

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

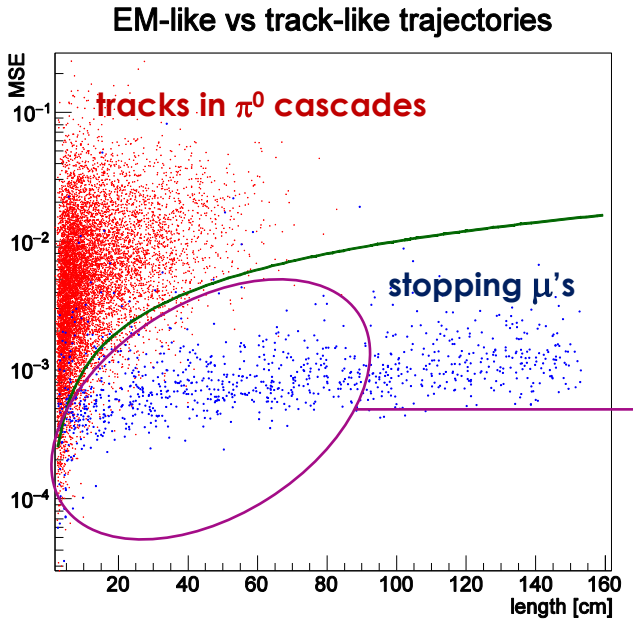


solid: MC truth hadrons overlapped with reconstructed tracks
dotted: EM fragments reconstructed as tracks

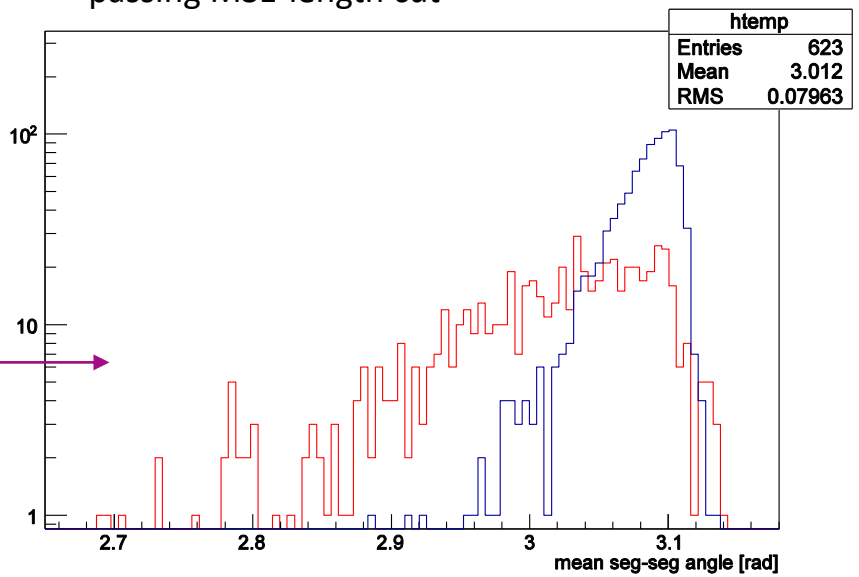


EM parts selection

- 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**



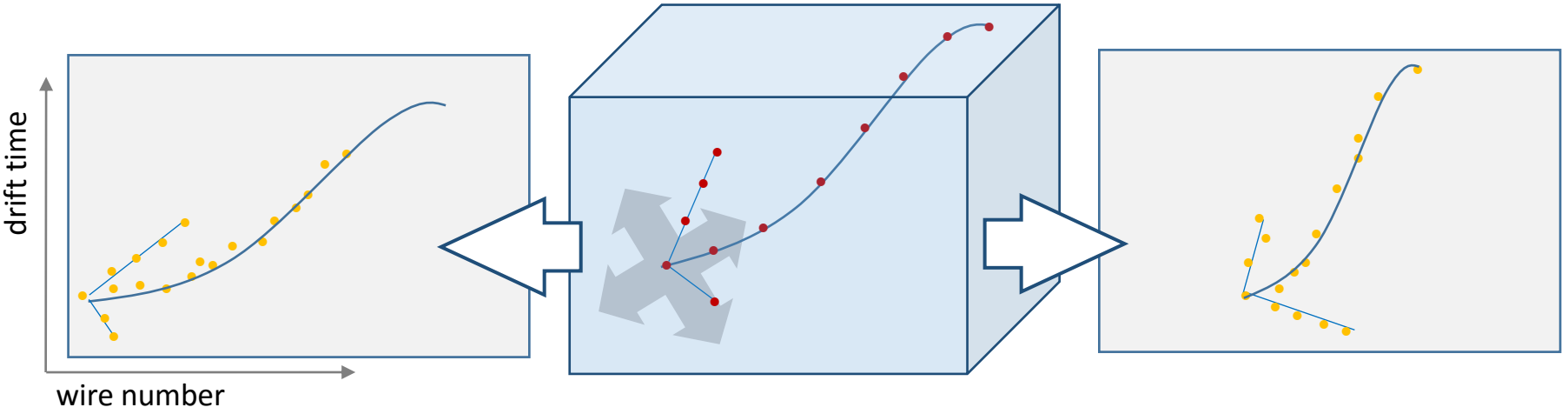
mean angle between segments for tracks passing MSE-length cut



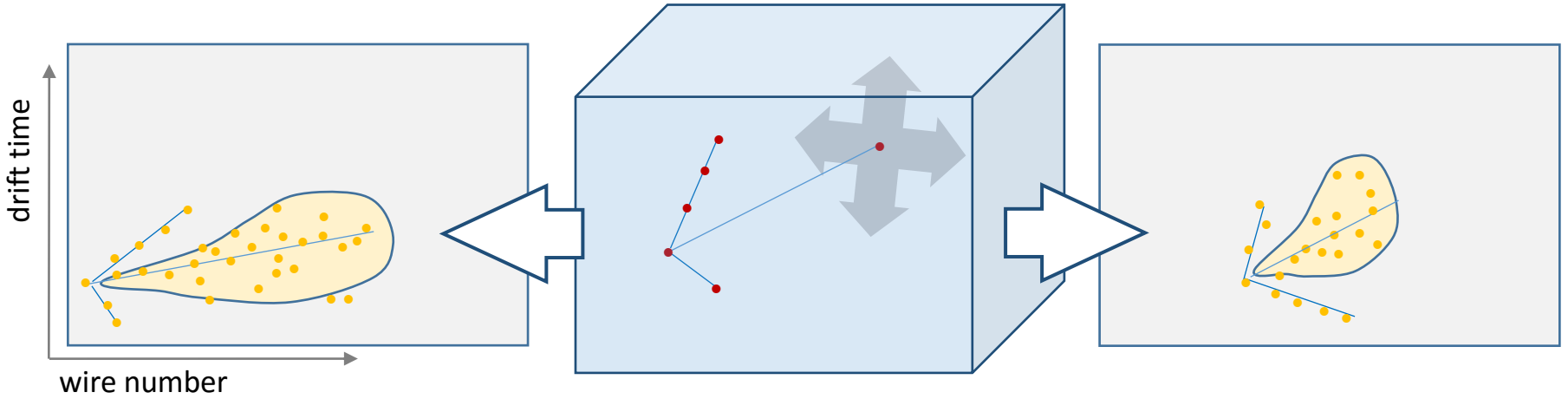
- first trials, still testing, **not ready solution for large showers**…
- global MSE / curvature measures are not completely enough, would like to try rough checks of dQ/dx
- may need to apply measures locally along the long track (as in large EM shower or track partially overlapped with EM cascade)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

Present developments

- 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

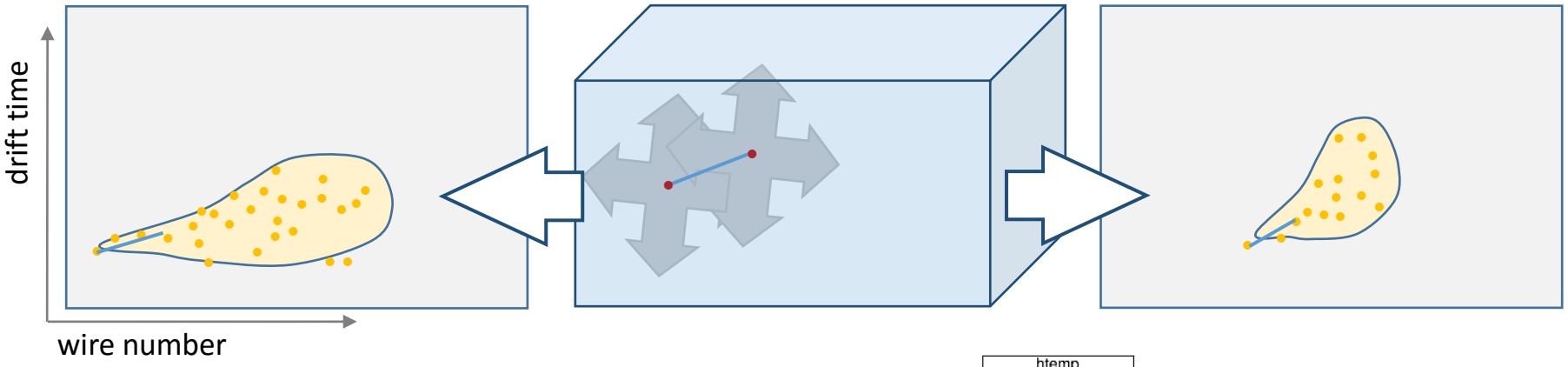


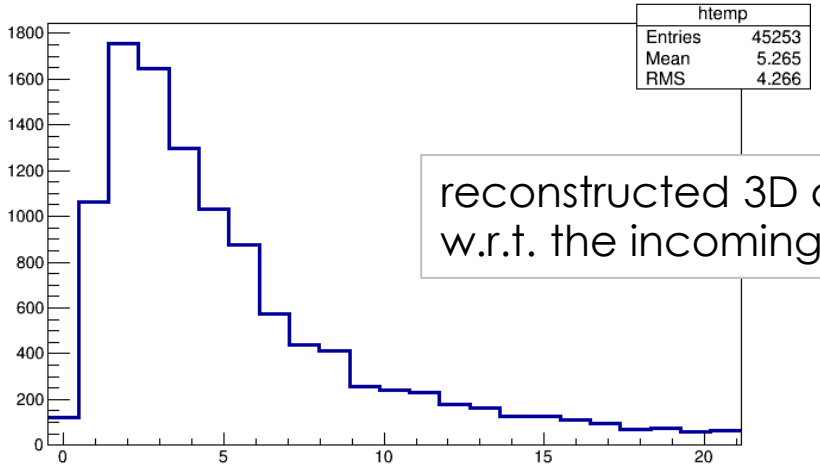
Present developments

EM cascade **starting segment** made without vertex, also for low energy cascades

- find conversion point in 2D view
- match 2D views (highly efficient, follow 35t meetings)
- reconstruct 3D direction (resolution on the plot below)

(**P**oint **o**f **C**onversion **A**lgorithm or **C**ascade **I**nitial **P**oint **A**lgorithm - TBD)





reconstructed 3D direction
w.r.t. the incoming photon direction

Summary

- PMA LArSoft module developed enough to be practically applied
  - efficient use of input clusters

    results depend on clustering efficiency, however we try to provide generic processing that may work with various clustering algorithms
  - stitching for multi-TPC ready
  - tested on ArgoNeut data, tried on MicroBooNE simulation: many bug fixes made, speed improvements on the way
  - behaviour in large EM cascades improved

    in the next days minor addition: track trimming to the TPC volume

- Multi-track structures and vertex oprimization is the priority in the current developments, time scale is 1-2 weeks

- Components needed for EM cascade reconstruction developed together with 35t group, however consider initial EM/track separation on 2D level.

- Number of possible improvements was spotted – to be implemented.

- We appreciate very much tests on various geometries / data conditions, such feedback is invaluable!

Thank You