MPD Software Overview.

DUNE ND Workshop

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

The MPD Software.

Based on art

- MPD Software called GArSoft is based on art
  - Very similar to LArSoft used for liquid Argon detectors
  - Developed separately as needs are very different from it
- GArSoft
  - Generation (GENIE)
  - Simulation (Geant4 simulation)
  - Digitization (TPC pad response, ECAL readout)
  - Reconstruction (Tracking, pattern recognition, ECAL position and energy reconstruction)
  - Event display (2D and 3D)

The current To do list.

An exhaustive list

- Available list of all the task done or to be done by order of priority
  - https://docs.google.com/spreadsheets/d/1DhdW7R8iKR6Aar7AmC-4Lswt-z_RvrImx1bjAPQYa-A/edit?ts=5c58b34b#gid=1386834576
- Few examples
  - TPC Pad response added by Tom (**done**)
  - ECAL SSA, angle correction (**to do**)
  - MCTruth/Reco associations (**to do**)
  - Machine learning techniques (**stalled**)
  - Tweaks to pattern recognition (**ongoing**)
  - Calibration
  - … and much more

ALICE TPC Readout Chambers.

Pad dimensions

- From the ALICE TDR
  - CERN/LHCC 2000-001
  - CERN-OPEN 2000-183
  - http://cds.cern.ch/record/451098

- Outer Outer Readout Chamber
  - pad dimensions: 6 x 15 mm^2
- Inner Outer Readout Chamber
  - pad dimensions: 6 x 10 mm^2
- Inner Readout Chamber
  - pad dimensions: 4 x 7.5 mm^2

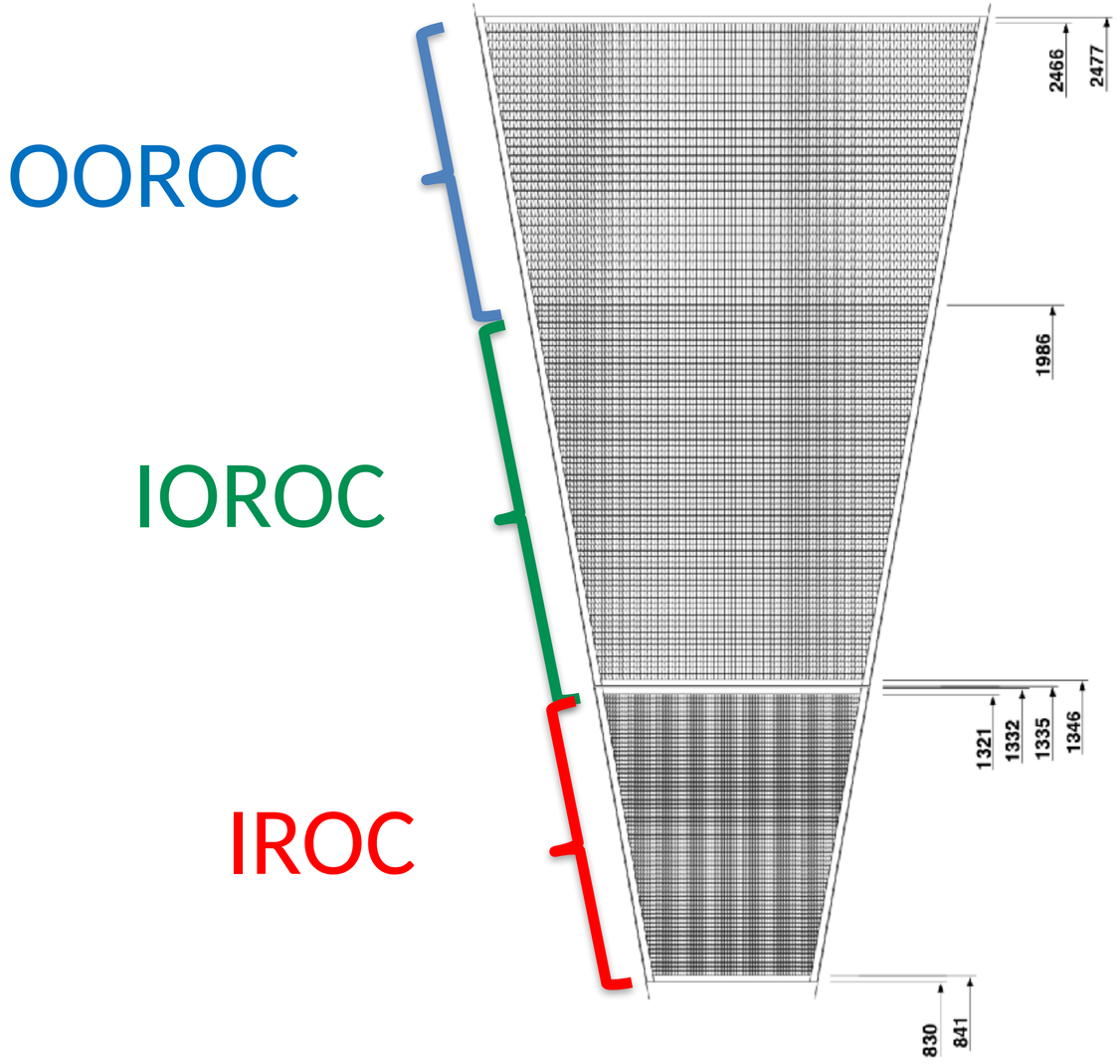


Figure 4.12: Pad layout of the ALICE TPC readout chambers. Distances from the beam axis are in mm.

RO Geometry.

Channel mapping

- 18 Sectors of IROC and OROC channels now using ALICE nominal geometry
- Rectangular array of pixels in a disk in the center
- Pixel size:
  - 6mm x 6mm
  - 4 mm x 7.5mm for inner pad rows.
- Total channels per side is now ~0.34M.
- Total on both sides: ~0.67M
- About 18% of channels are in the disk.

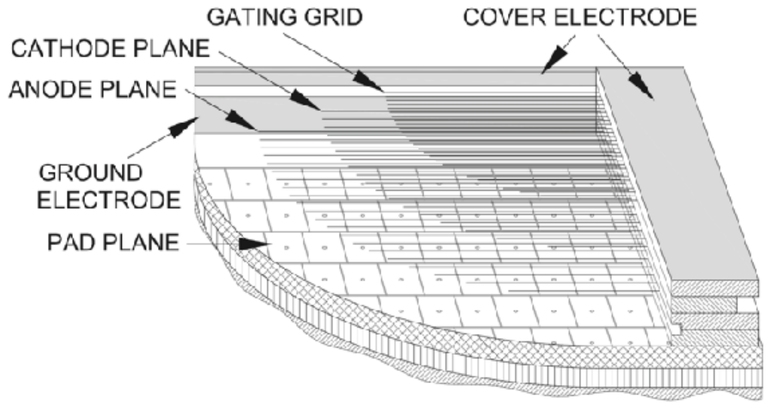
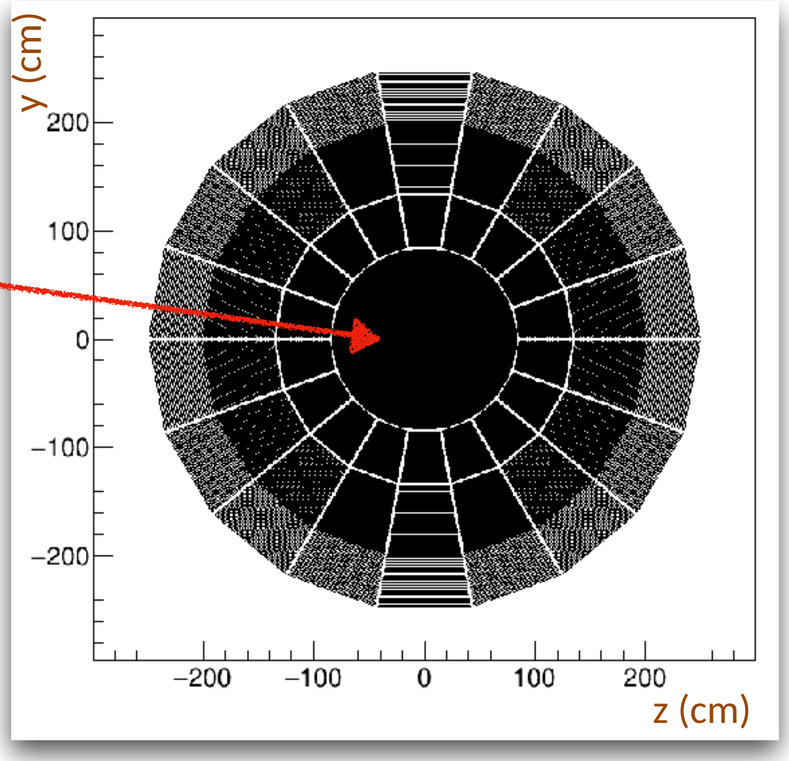


Fig. 9. Cross-section through a readout chamber showing the pad plane, the wire planes and the cover electrode.

J. Alme *et al.*, NIM A 622 (2010), 316-367

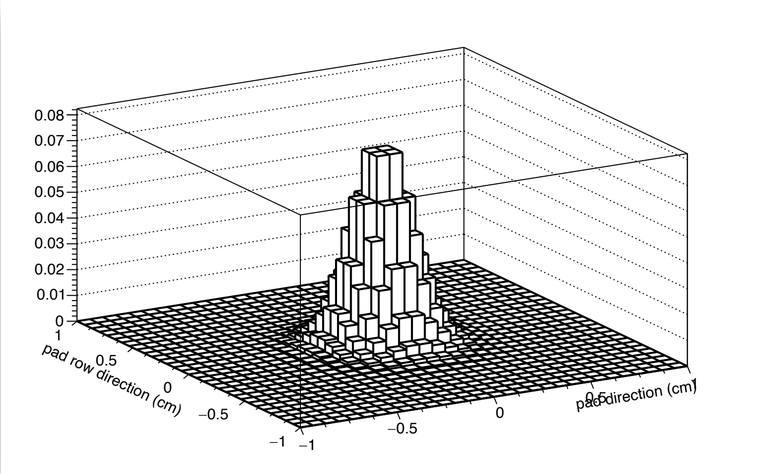


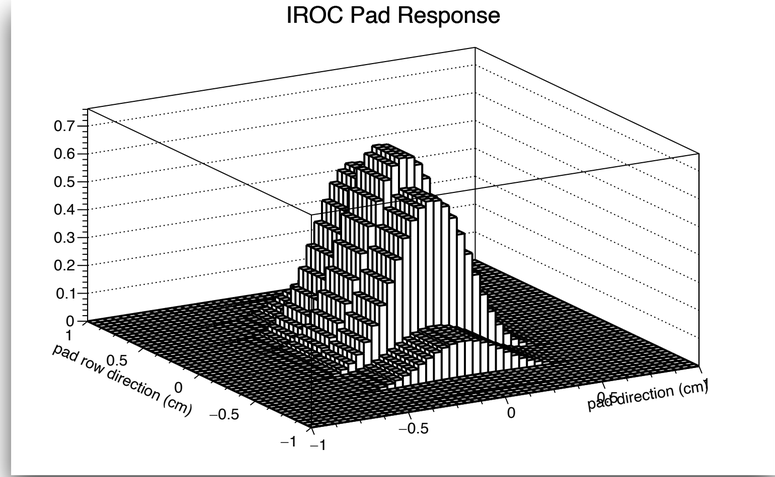
Pad response function (PRF).

Simulating charge spread and pad response

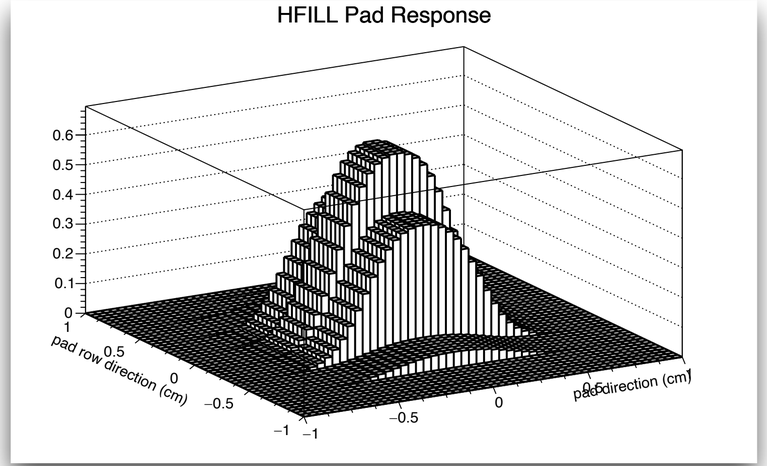
From the ALICE TDR: Charge Induction Response and IROC pad response

Replica of ALICE TDR plots

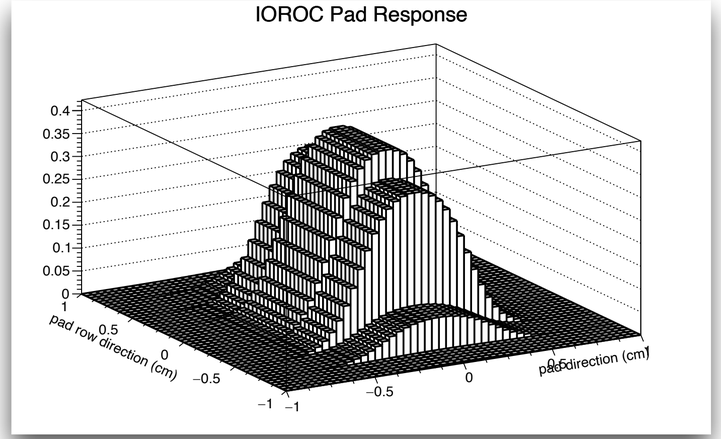


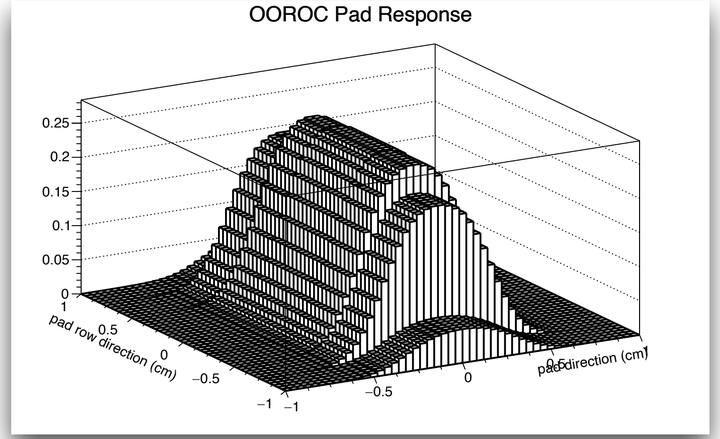


6x6 mm^2 hole-filler PRF



Extrapolation to IOROC and OOROC





GArSoft.

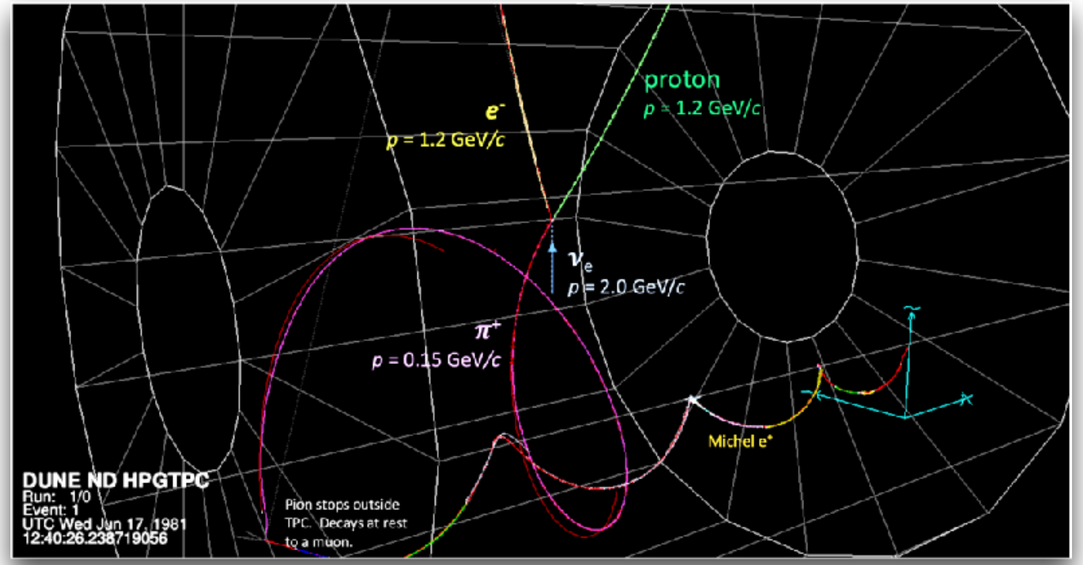
Tracking simulation

- What's there
  - GENIE, CRY, radiologicals, text-file generators
  - GEANT4 interactions in gas and calorimeter – fairly detailed geometry
  - LArSoft-style drift, attachment, diffusion simulation
  - Pad-response functions
  - Digitisation and zero-suppression of raw waveforms
  - Saved to output: ZS waveforms, MC particles, neutrino info, true energy deposits.
- What's lacking
  - Realistic pulse shapes
  - Noise
  - LArPix-style electronics simulation
  - Magnetic Field Map

GArSoft.

Tracking reconstruction

- What's there:
  - Raw Digits ➠ Hits.
    - A "hit" belongs to a particular pad, similar to a LArSoft "recob::Hit".
  - Hits ➠ TPCClusters
    - The centroid of the charge deposited on several neighbouring channels has much better resolution than just using the pad centres. Plots follow.
  - TPCClusters ➠ Vector Hits.
    - “tracklets" up to 20 cm long
  - Vector Hits ➠ PatRec Tracks
  - PatRec Tracks ➠ Fitted Tracks.
    - 3D Kalman fitter using TPCClusters associated with PatRec tracks. Each track is fitted both ways.
  - Vertex finder and fitter.
  - Extrapolation to ECAL
  - Event Display. (two of them!)

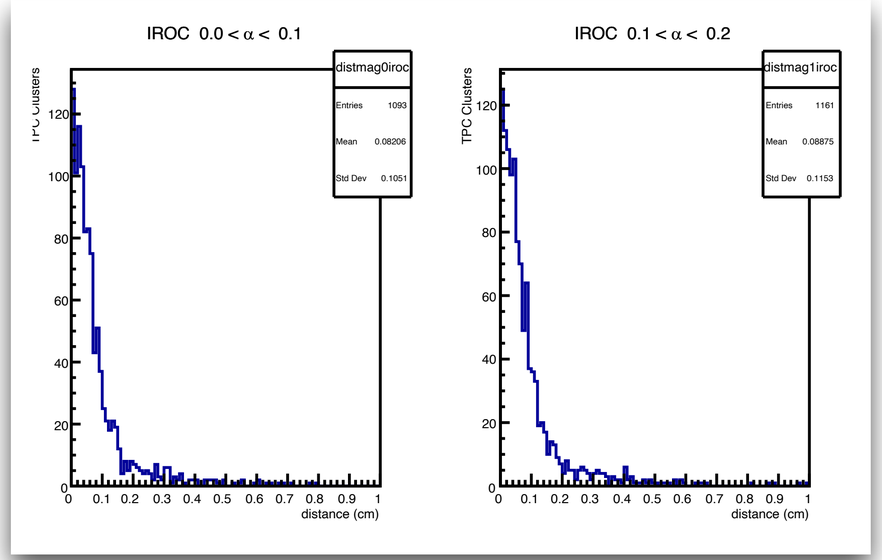


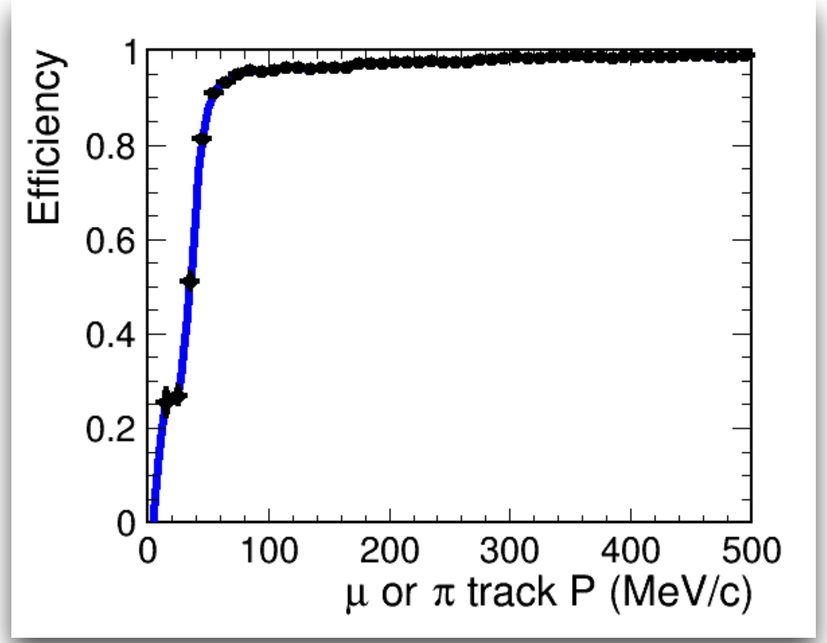
GArSoft.

Tracking performance

- TPC Cluster reconstruction
  - Similar performance as ALICE
  - Expect somewhat better perf at high pressure due to more electrons arriving
- Tracking performance
  - Estimated using Leo's sample of ν_μ events with the optimised LBNF FHC spectrum
  - $\pi^\pm$ and $\mu^\pm$
    - Electrons are similar, but including them produces a kink at 20 MeV (bigger than the one that's there).
    - Low-energy electrons curl around – only partial efficiency for them
    - Low-energy pions and muons stop – have a track length cut of 20 TPC Clusters
    - Protons with P < 150 MeV have very little KE and thus stop quickly

IROC Hit Residuals (abs. value)

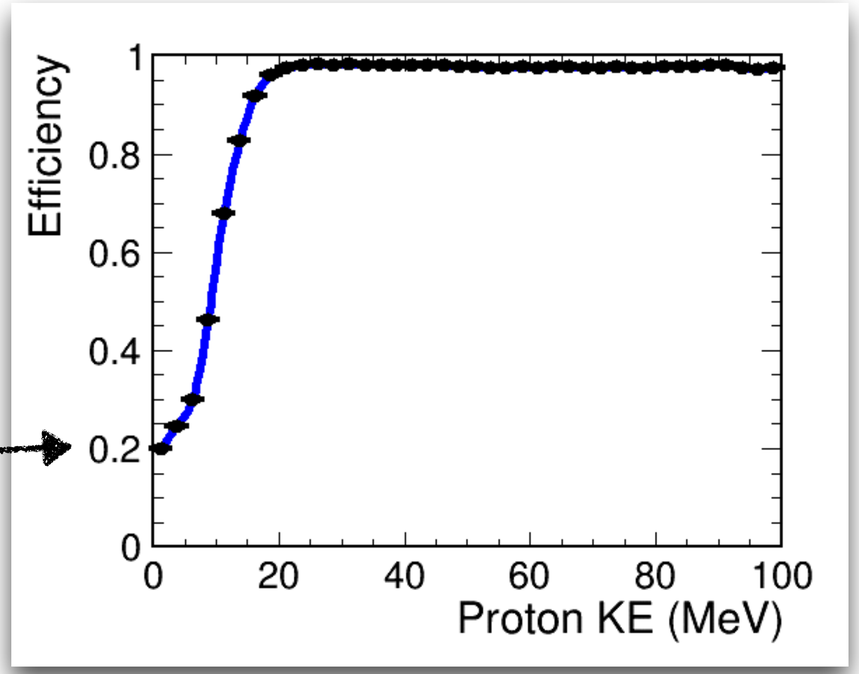


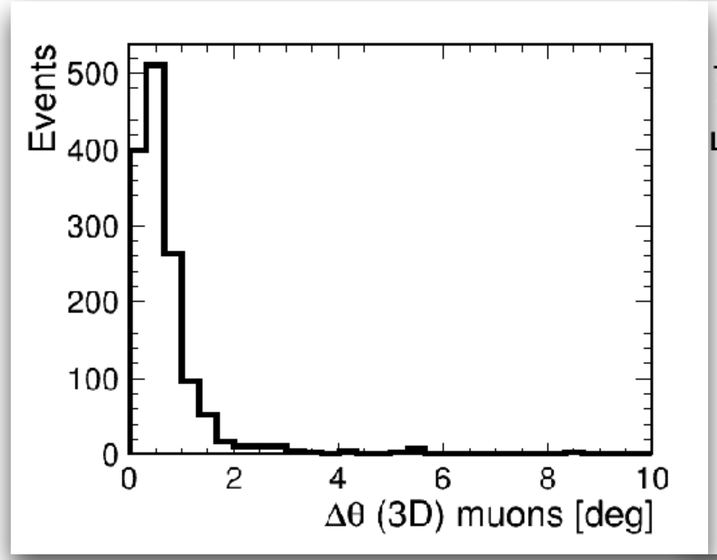


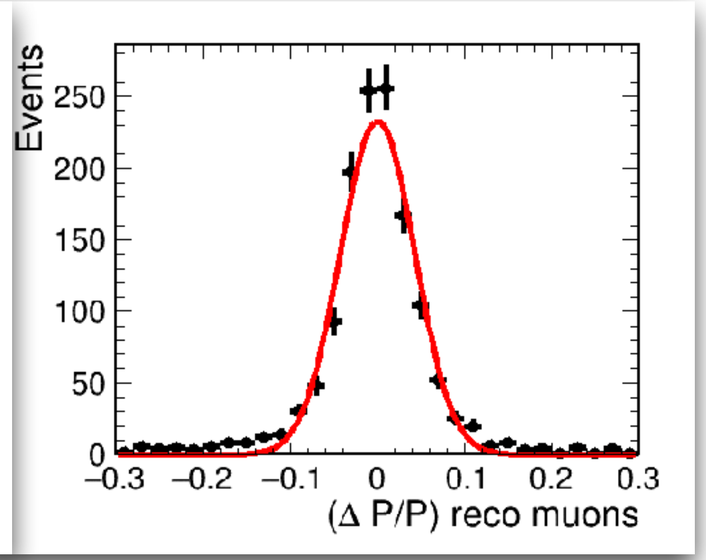
GArSoft.

Tracking performance

- Tracking performance
  - Protons
    - Very short track efficiency overestimated near a dense primary vertex due to combinatorics – fake matches.
    - Efficiency should go to zero at KE=0.
    - Work in Progress – Optimisations will improve this
      - Lower kinetic energy region -> using ML techniques (see Jen's talk)
  - Muon Angles and Momenta
    - ~1 Degree angular resolution
    - ~4.2% momentum resolution







GArSoft.

Tracking performance

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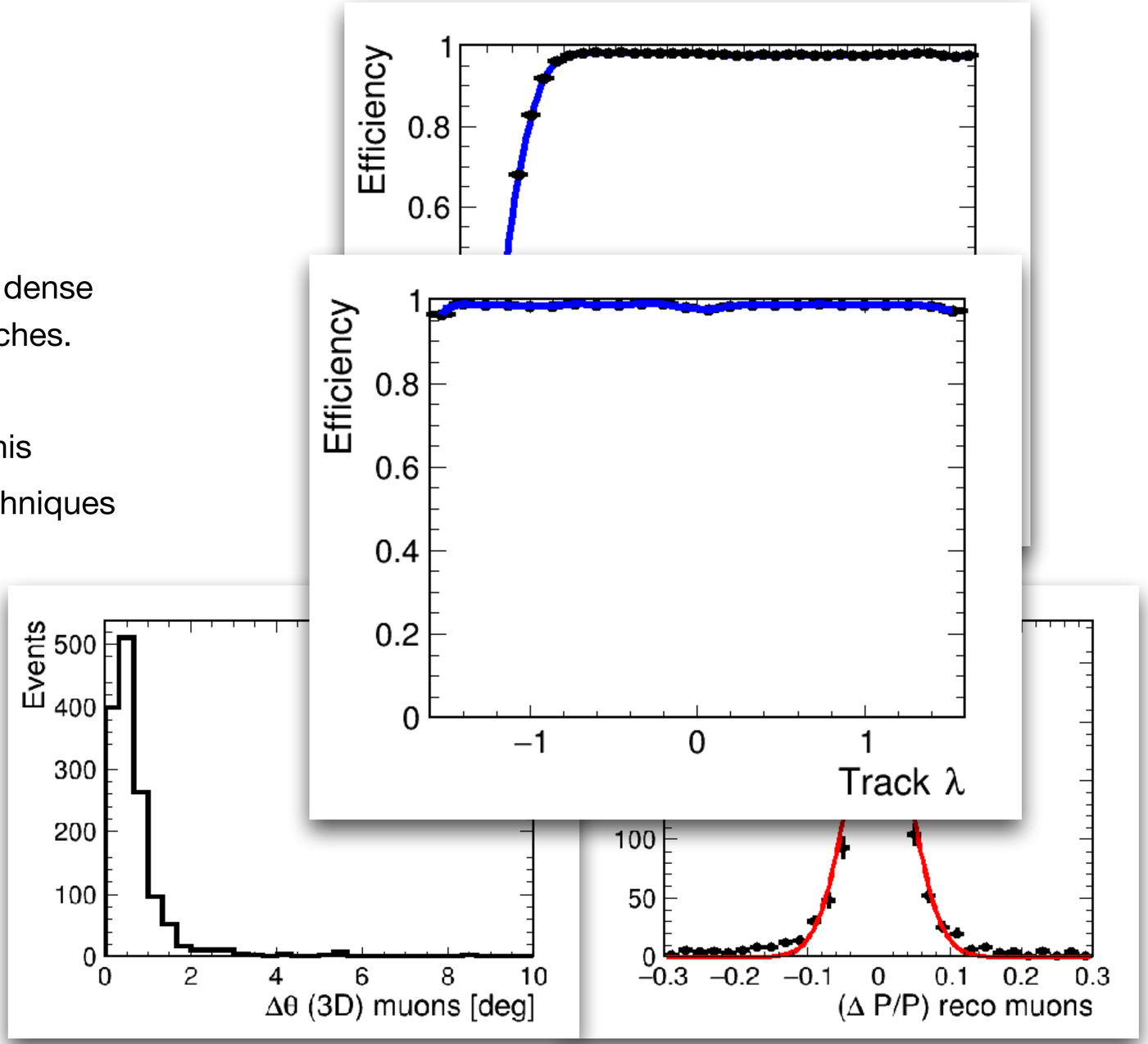
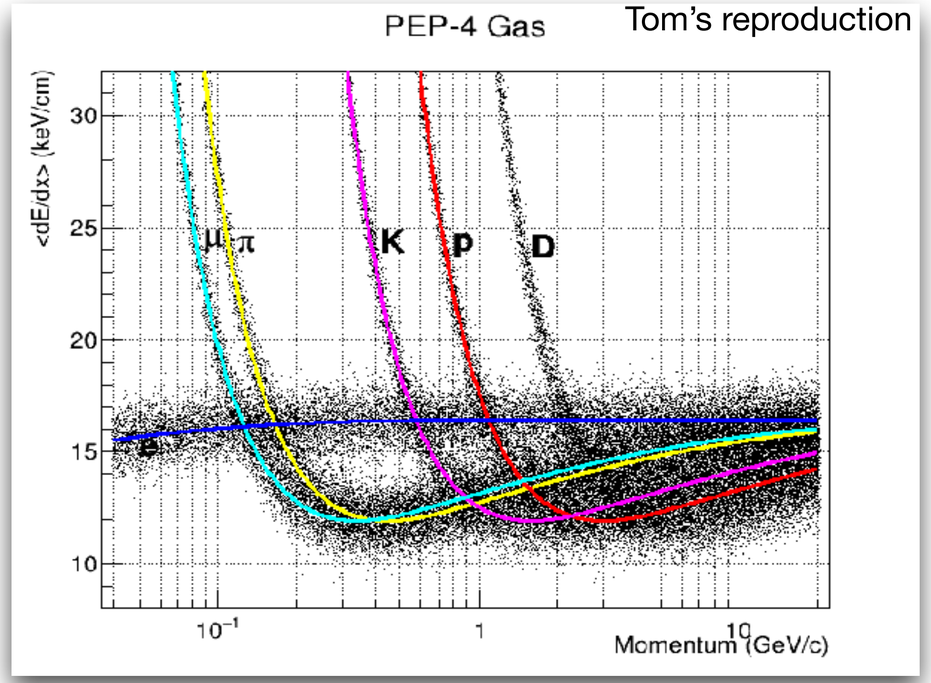
  - Muon Angles and Momenta
    - ~1 Degree angular resolution
    - ~4.2% momentum resolution
  - 4π Coverage

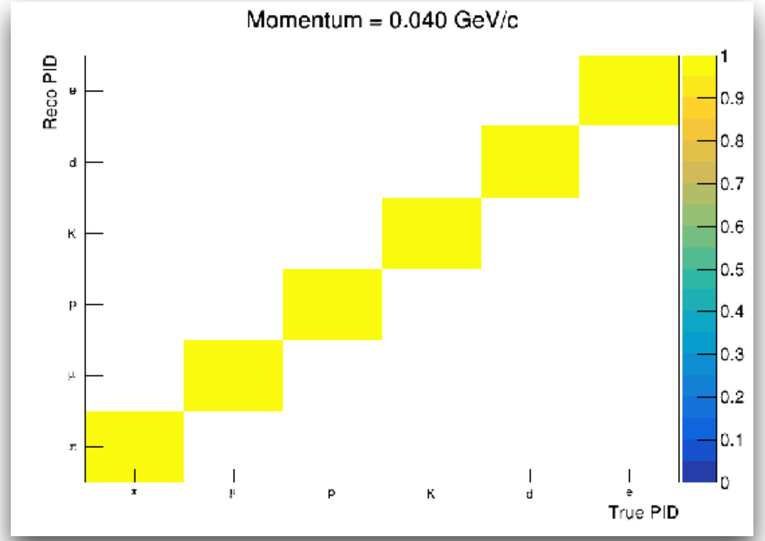


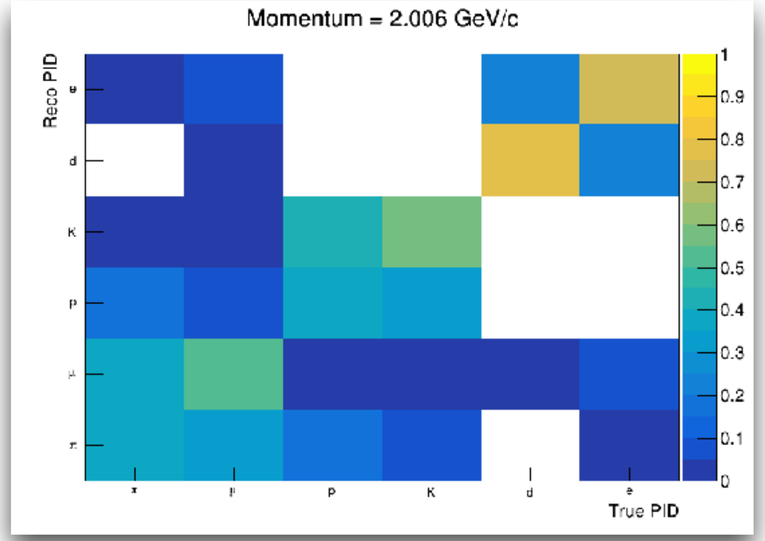
GArSoft.

dE/dx performance

- Particle identification performance
  - https://home.fnal.gov/~trj/mpd/dedx_sep2019/ ← Animations!
  - PID integrated into GArSoft
    - Can be used for analysis
  - Used for PID in parametrised reconstruction (see Jen's and Tanaz's talks)
- Still need to integrate with non-dE/dx PID variables (ex. ECAL)







Picks the closest predicted MPV to the observed, and matrix filled with 10K random throws.

GArSoft.

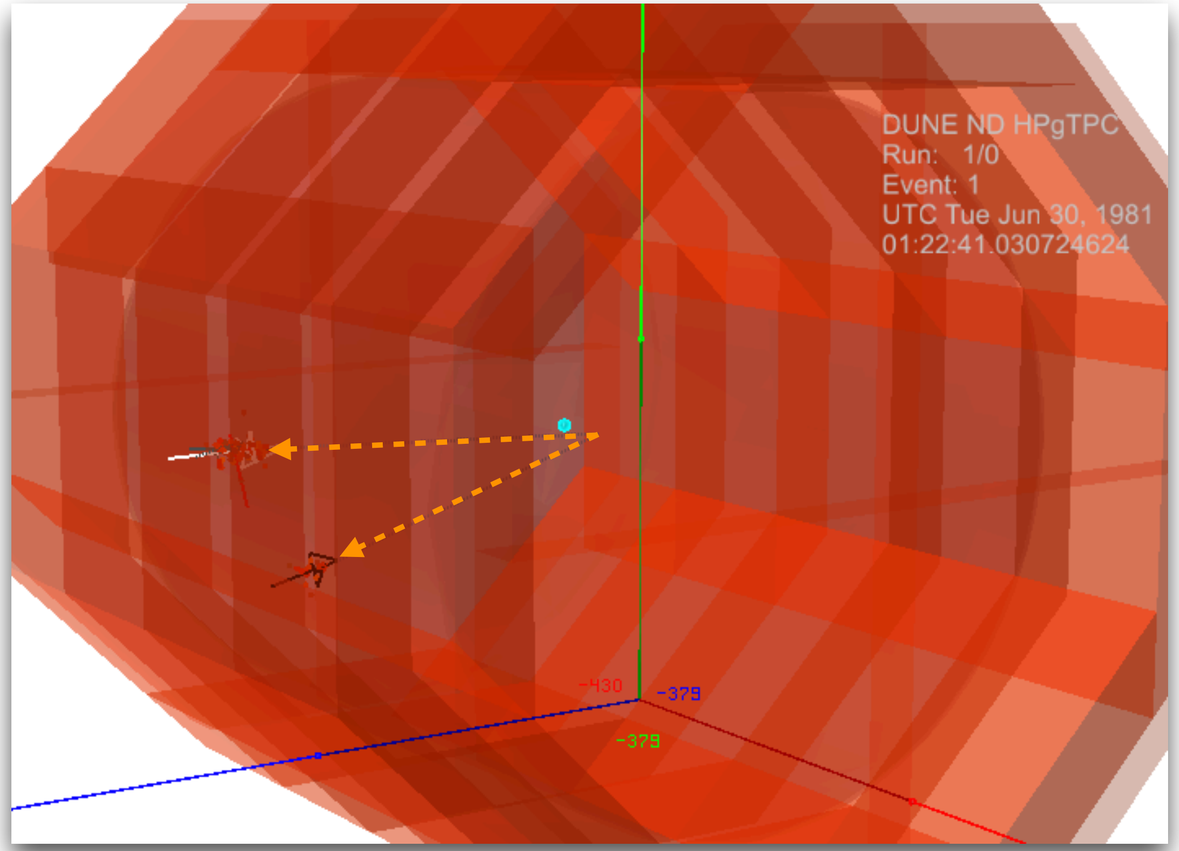
Tracking To dos

- Improve simulated charge waveform (time structure, gain) and noise
- LArPix / GArPix simulation
- Re-tune hit clustering algorithm
- Study *dE/dx* measurement using hits
  - charge sharing for close tracks near vertex
- Reboot machine-learning techniques for identifying short tracks near the primary vertex
- Add magnetic field map effects in to pattern recognition, fitting, and extrapolation
- Analysis! Select ν_μCC and ν_eCC events, separating out pileup. Use ECAL for timing.
- Lots of optimisation: Low-momentum track finding, second-pass fit allowing hits to be reassigned, better vertexing, conversion ID

GArSoft.

ECAL

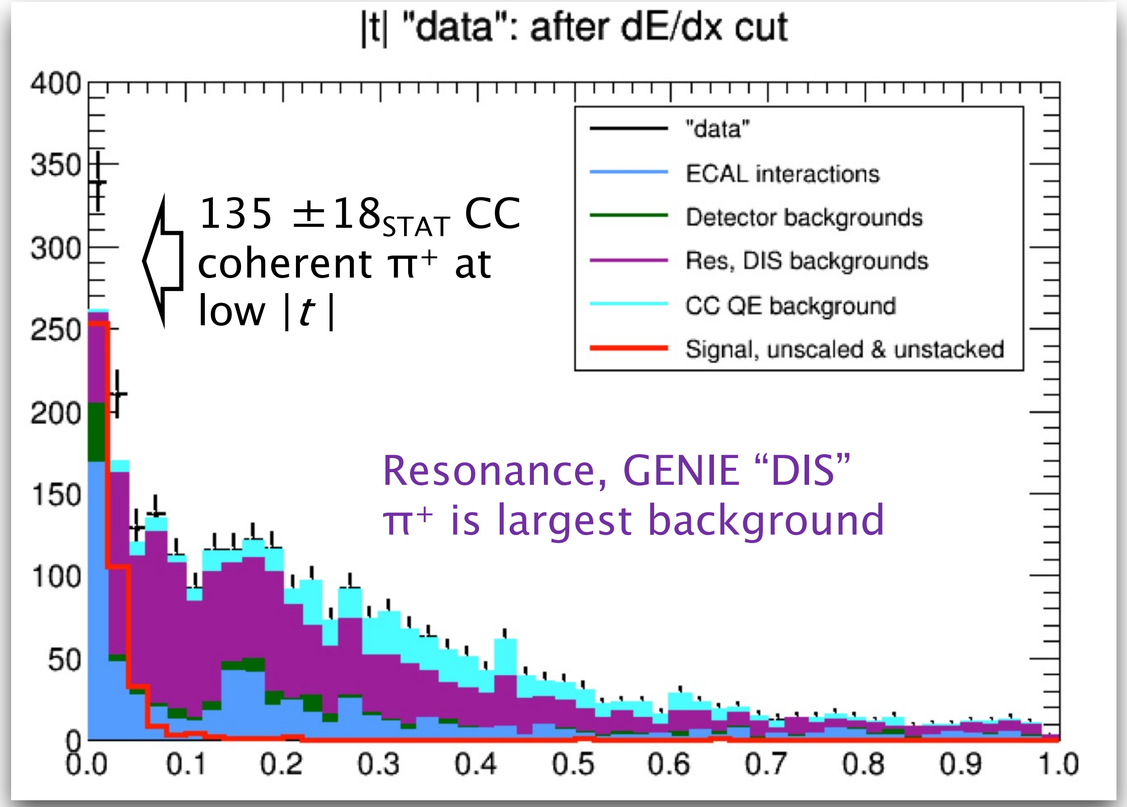
- ECAL is fully integrated to GArSoft
  - Digitisation: SiPM Saturation, energy threshold, strip digitisation
  - Reconstruction: Hit energy and position reconstruction
- Clustering
  - Using naive NN search
  - Need for more tuning
  - MCTruth Clustering needs to be done
- Particle ID
  - Standalone pi0s and neutron reconstruction ongoing
  - Should be integrated later on
- To Do:
  - SSA, angle correction in scintillator
  - Clustering, better TPC-ECAL pattern reco…



GArSoft.

Ongoing analysis

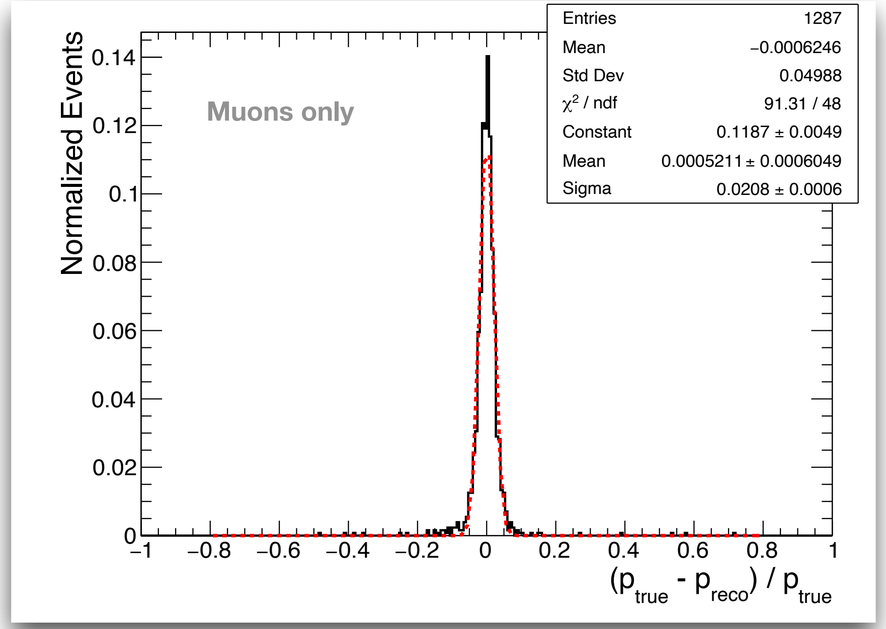
- Leo is working on coherent pion analysis
  - full simulation & reconstruction
  - Includes ECAL background overlay
- “Data” is a set of ~22 x 10^6 GENIE 2.12.10
- Corresponds to about 11 shifts of data at 1.2 MW and 100% uptime
- Nov 2017 optimized flux, 4 flavors of ν, FHC
- ECAL geometry (80 layers of 2mm Cu, 5mm polystyrene)
- Backgrounds defined in backup slide

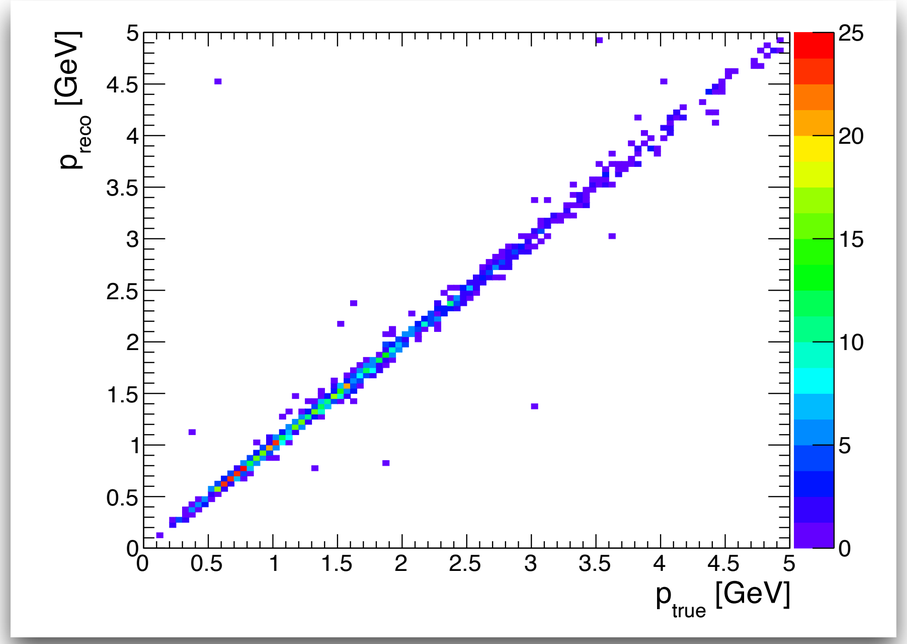


GArSoft.

Parametrised reconstruction

- ND Software Integration group
  - ➠ full spill simulation with all near detector components and surrounding rock
- A new tool has been developed by me and Tanaz on parametrised reconstruction of the MPD to be used for CDR analyses
  - Should include most “reco” variables
    - Truth information, reco p, reco energy (gamma, neutrons…), pid …





Conclusion and Outlook.

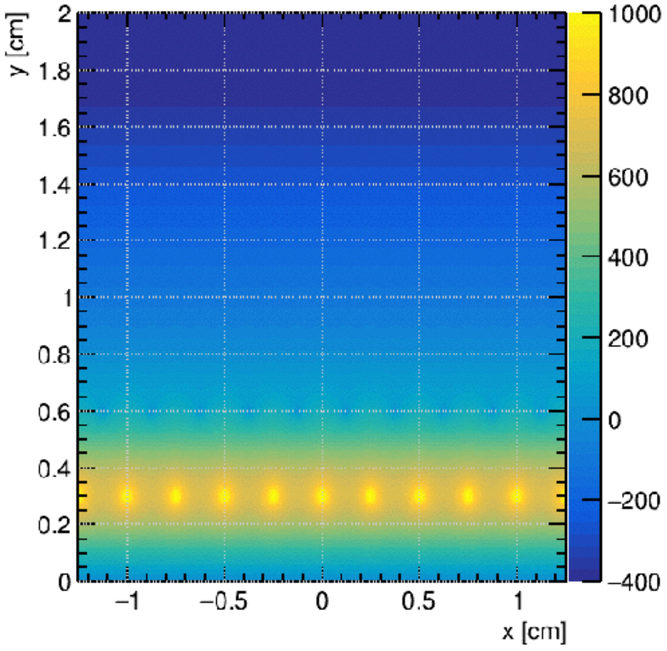
A lot done but still a lot to do…

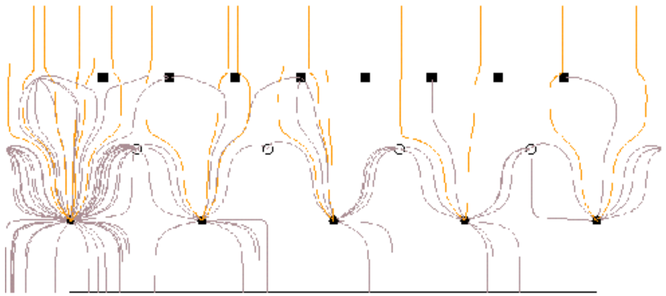
- GArSoft is getting more mature with time
- Tweaks to be done but can be used already for full simulation analysis!
- Looking forward
  - Machine learning techniques (NN, CNN…)
  - Integration of PandoraPFA?
  - Integration of the other ND detectors into the framework! Needs to keep sth compatible between all.
- If you are interested to contribute, contact the HPgTPC+ECAL group.

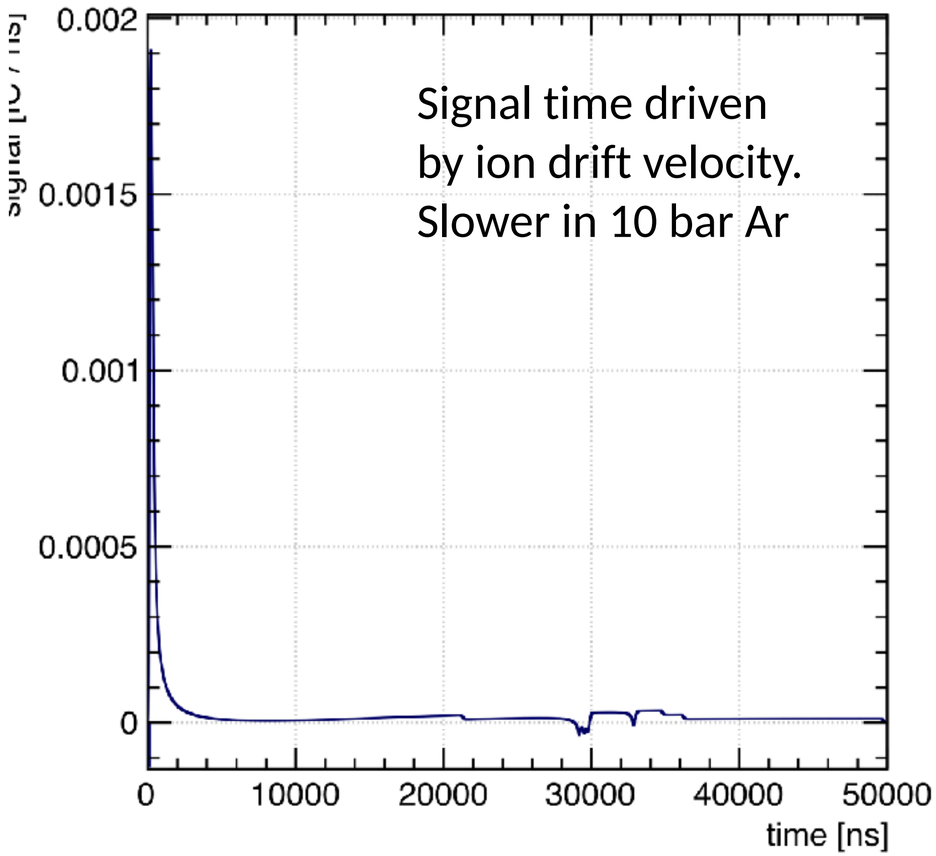
Backup Slides.

The Other Dimension: Time

- From Kim Baraka's ALICE example GArField program







Separate pads not in example program. K. Baraka used neBem for that. CERN-STUDENTS-Note-2013-029. Erica Smith (Indiana) has started work on this.

Extras

ALICE TDR

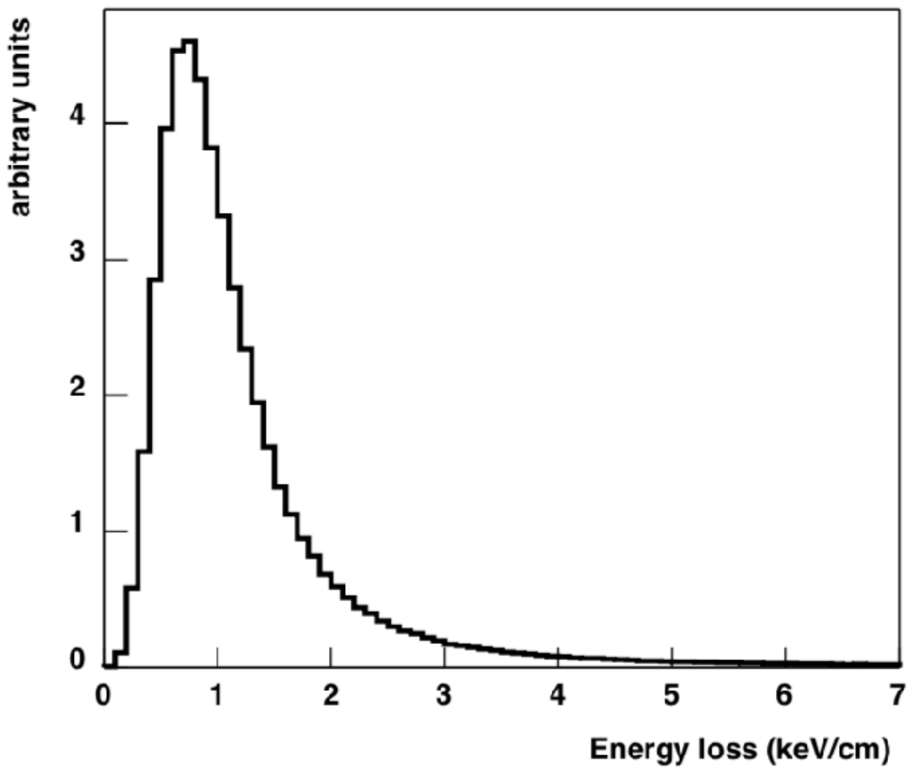
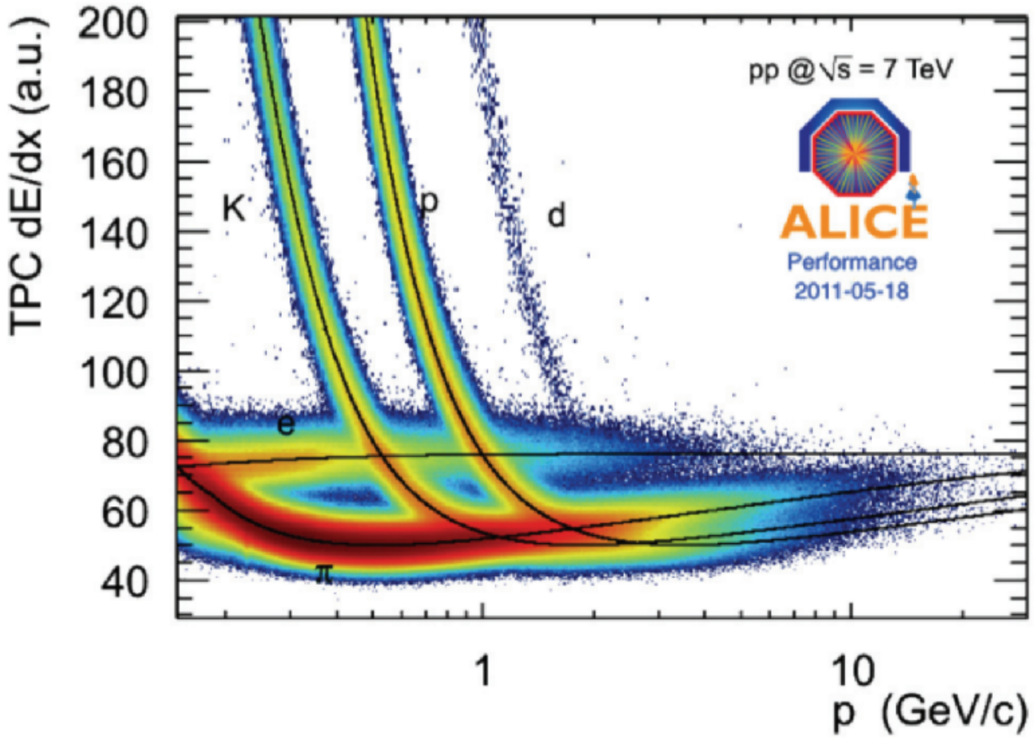
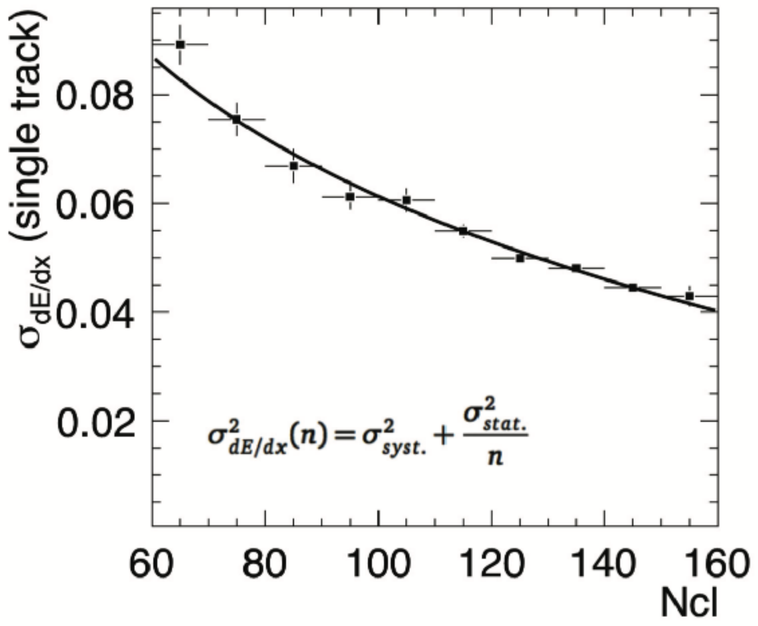


Figure 7.4: Energy loss of electrons per 1 cm for MIP in 90 % Ne, 10 % CO_2.

ALICE *dE/dx*



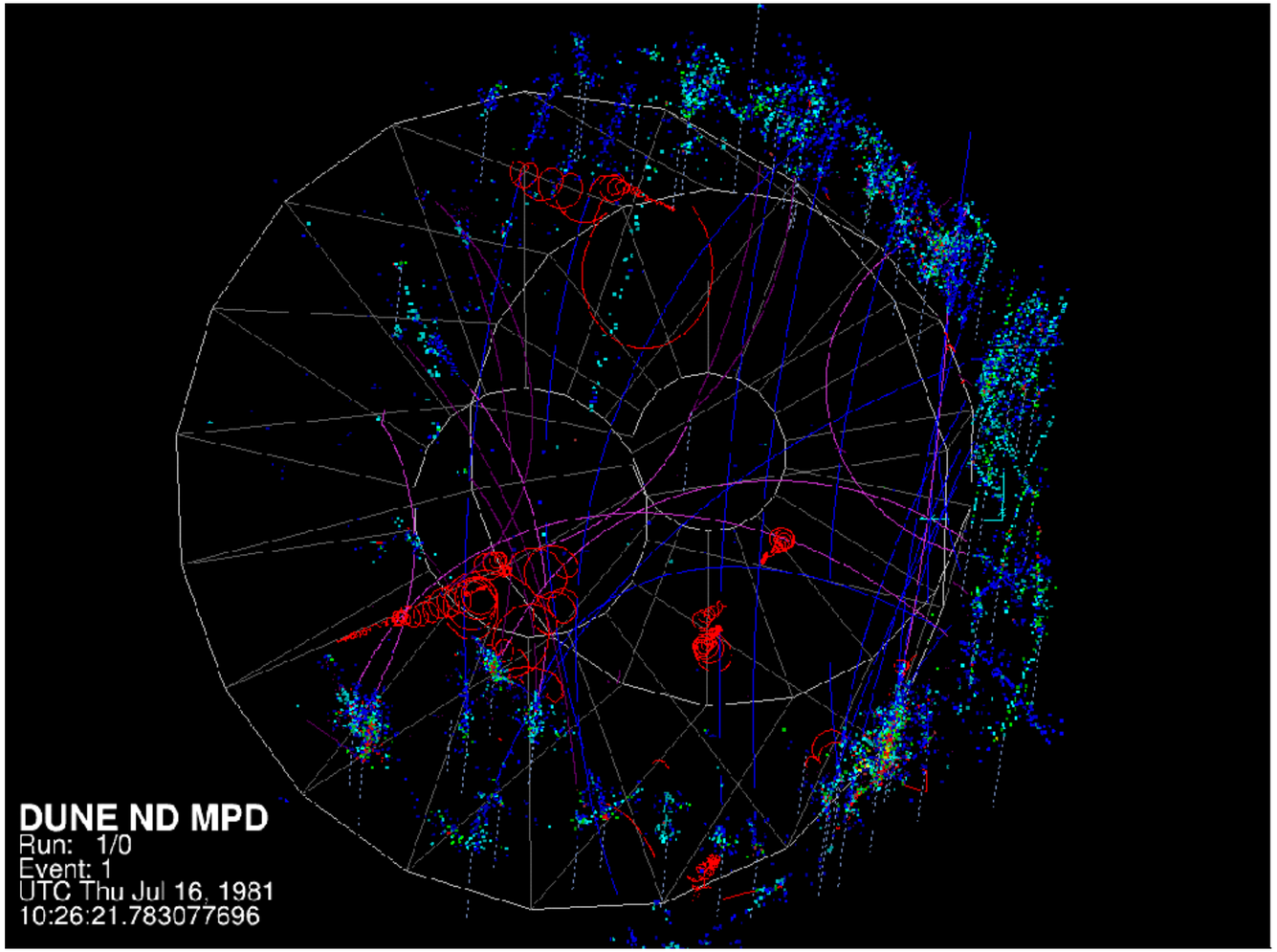


C. Lippmann, "Performance of the ALICE Time Projection Chamber", *Phys Procedia* **37** (2012) 434-441.

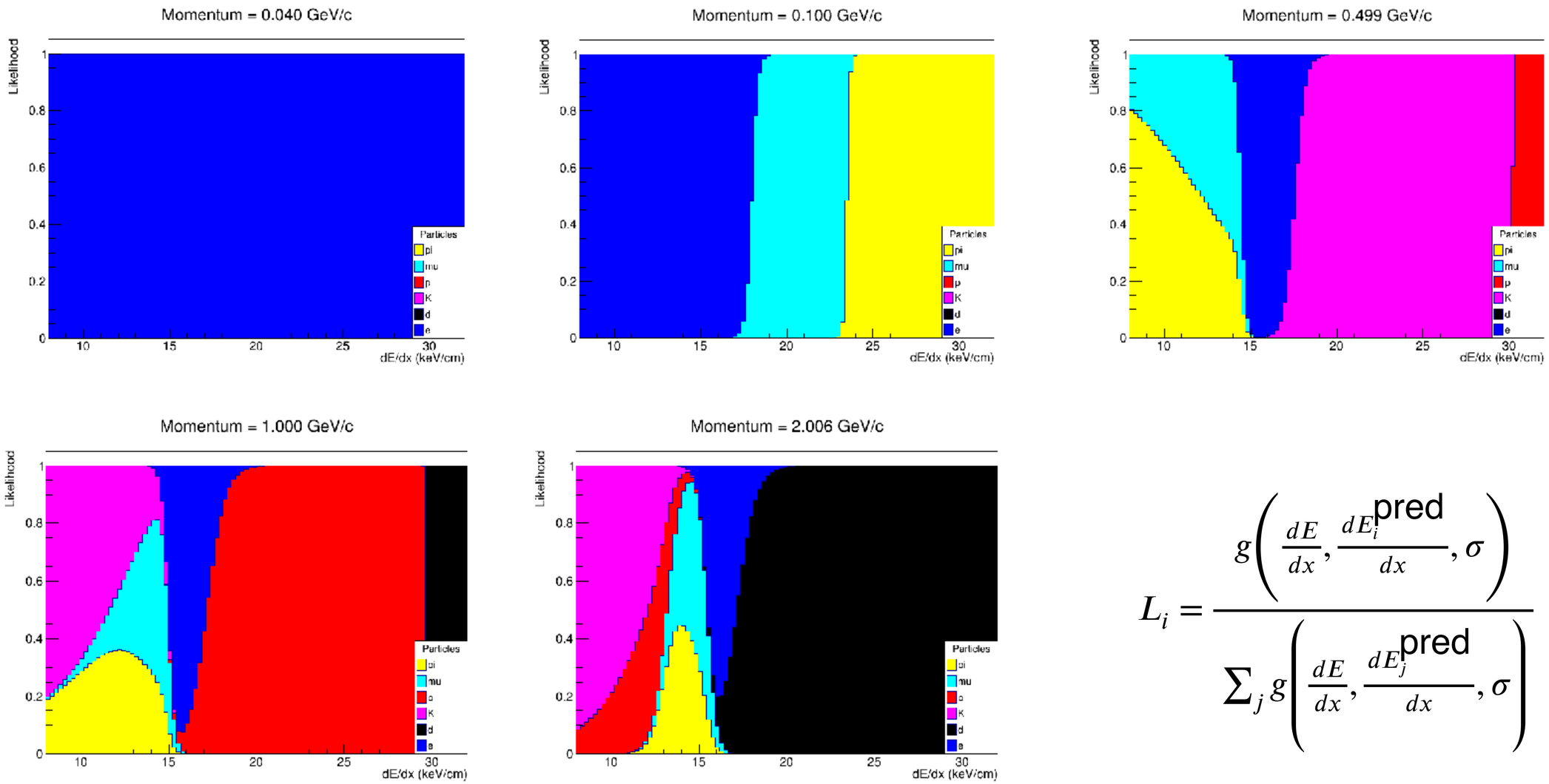
Event Display: Calo Hits

This display:

- true tracks + reco calo hits
- Calo hits are color coded by energy
- True tracks:
  - red: electrons
  - blue: muons
  - magenta: pions
  - purple: protons
  - dashed blue: incident neutrinos



Parameterized *dE/dx* Response



$$L_i = \frac{g\left(\frac{dE}{dx}, \frac{dE_i^{\text{pred}}}{dx}, \sigma\right)}{\sum_j g\left(\frac{dE}{dx}, \frac{dE_j^{\text{pred}}}{dx}, \sigma\right)}$$

A Newer PEP-4 *dE/dx* Plot

Aihara, H., Alston-Garnjost, M., Avery, R.E., Barbaro-Galtieri, A., Barker, A.R., Barnett, B.A., Bauer, D.A., Bengtsson, H.U., Bobbink, G.J., and Buchanan, C.D. *Charged hadron production in e/sup /+//e/sup /-// annihilation at. sqrt. s = 29 GeV*. United States: N. p., 1988. Web. doi:10.2172/5059741.

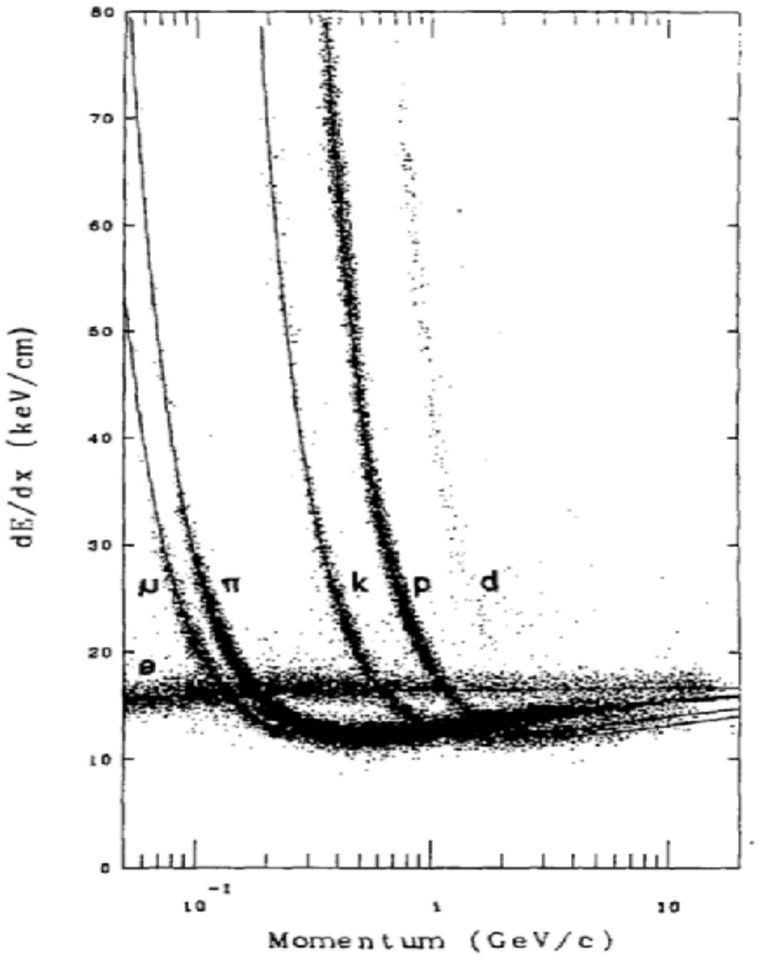


Figure 18: Measured dE/dx as a function of momentum. The bands of electrons, muons, pions, kaons, and protons are clearly visible. The appropriate curves from the fitted truncated mean dE/dx vs. $\beta\gamma$ plot (obtained by scaling the abscissa by the particle mass) are also shown.

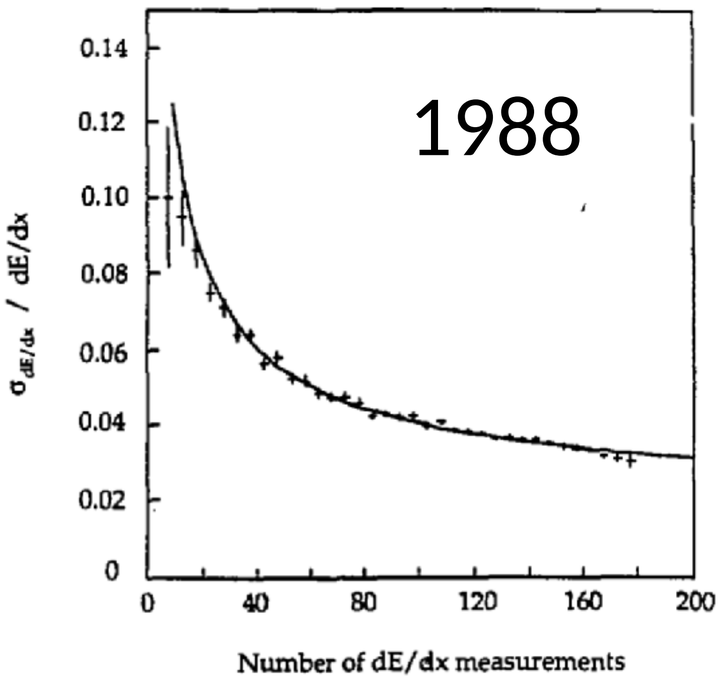
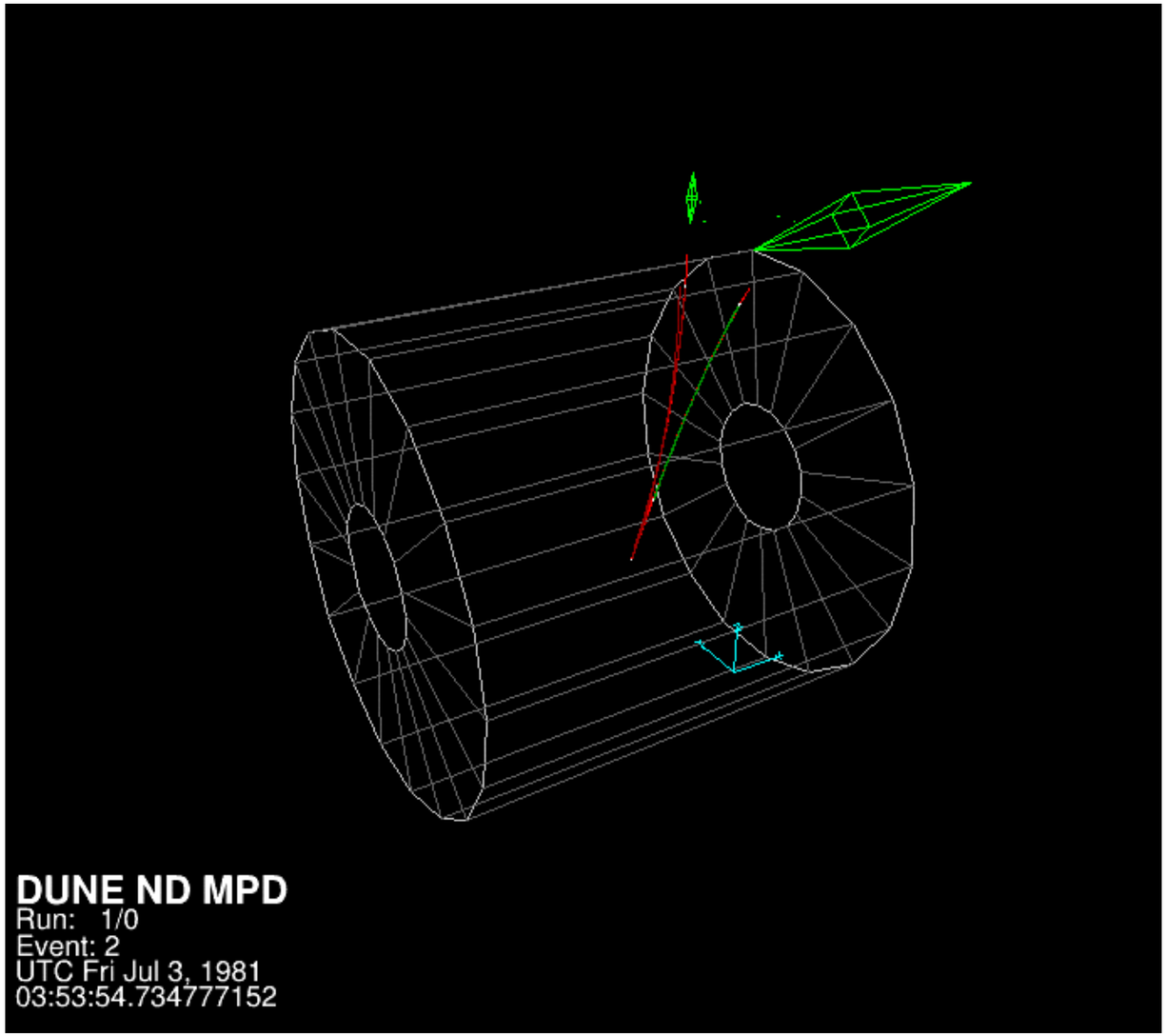


Figure 19: Plot showing the dependence of the dE/dx resolution on the number of wires.

Better reconstruction – converting 4 GeV γ

Also improves the K^0_{short} analysis



Field Map from Vladimir Kashikhin

Notes:

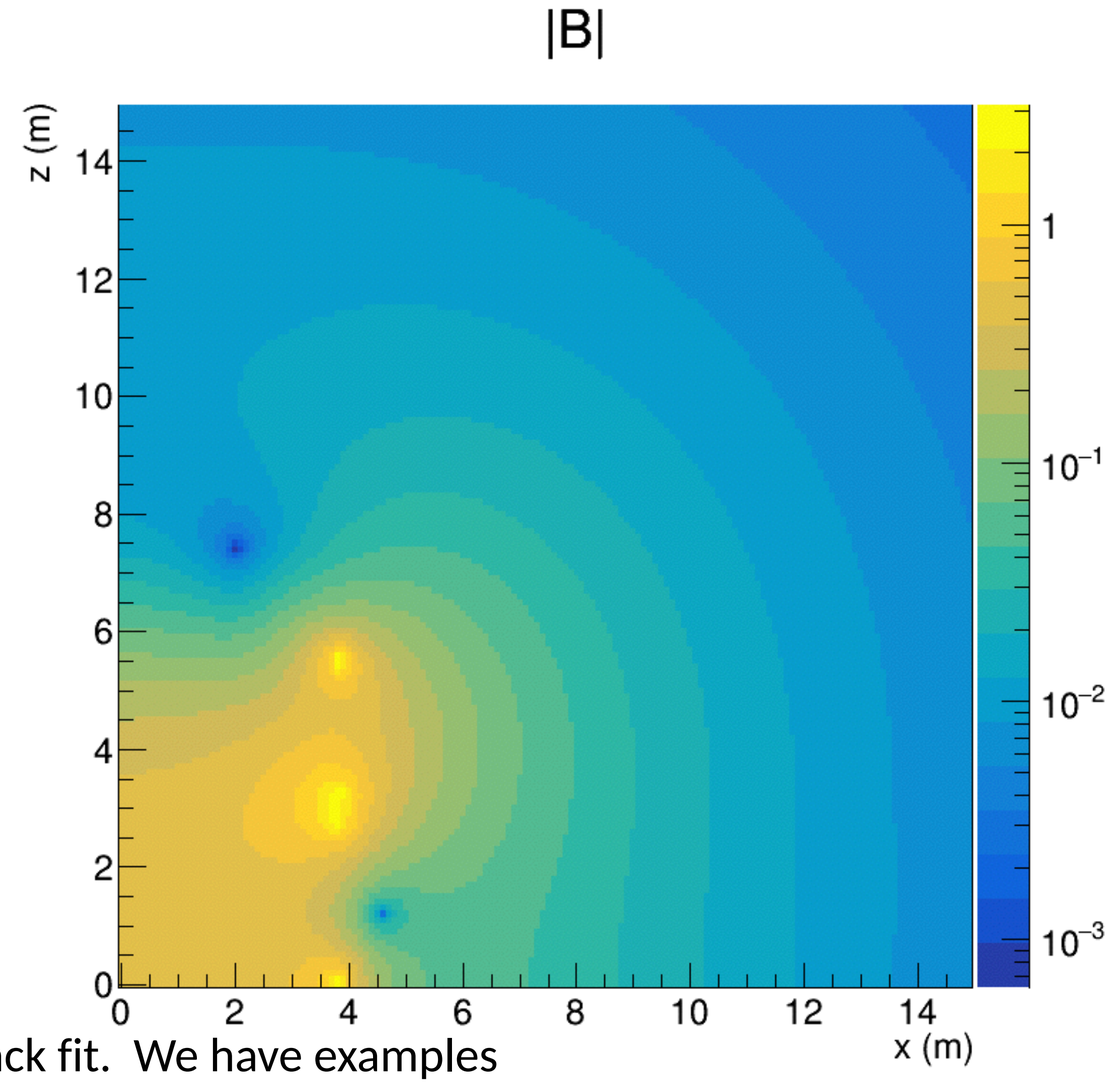
B on a Log scale!

Axial symmetry
assumed.

No Kloe, ArgonCube

Vladimir's *x* and *z* are our
-*z* and *x*.

From Vladimir:
The coil inner radius is 3.8m (ID 7.6m).
TPC has OD 5.725 m.



To do: Get GEANT4 to use a real field map, and also the track fit. We have examples of the former in G4LBNF.

Background definitions

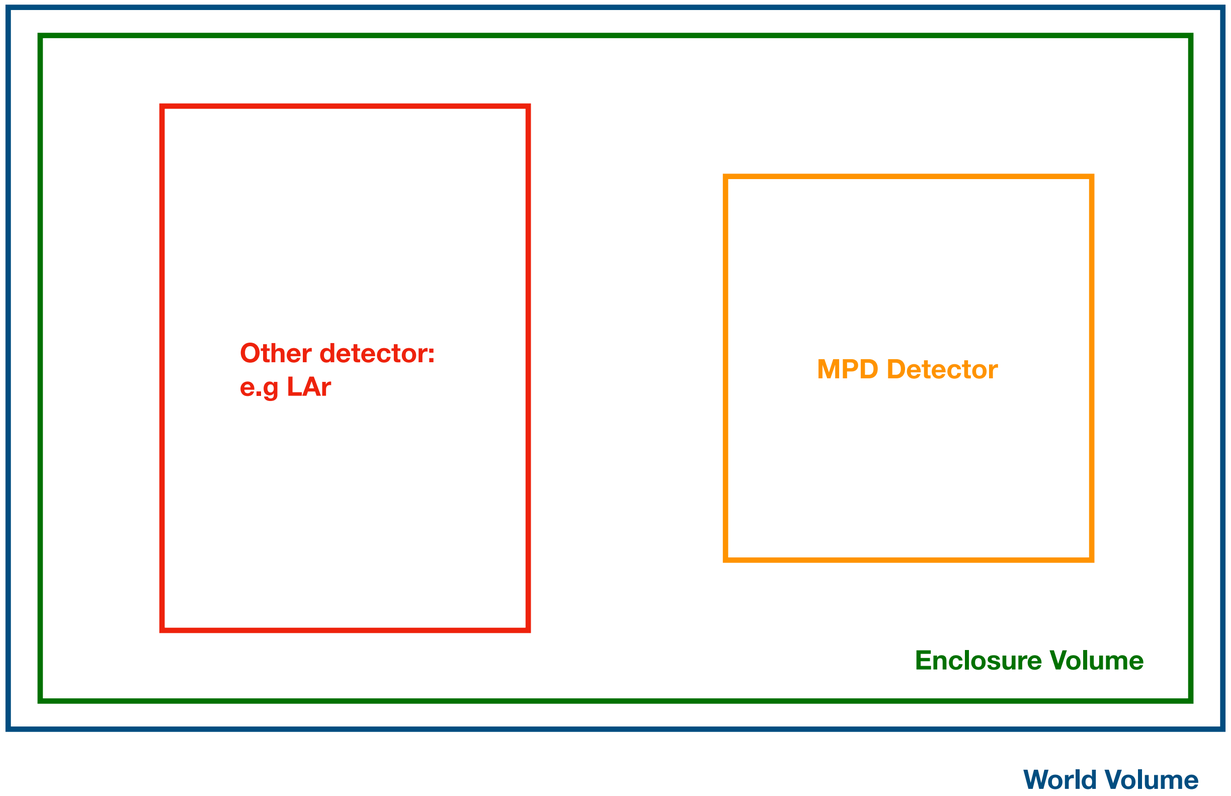
- **ECAL:** The primary vertex is in the ECAL, but the reconstructed vertex is in the fiducial.
- **detBkg:** The PV is not inside the ECAL, and the reconstructed vertex is in the fiducial. The reconstructed fiducial is more than 15 cm from the MC true vertex.
- **phyBkg:** The vertex is in the fiducial and matches the MC true vertex. The GENIE interaction type corresponds to a resonant or DIS process.
- **isCCQE:** The vertex is in the fiducial and matches the MC true vertex. The GENIE interaction type corresponds to a CCQE process.

2

Current MPD Geometry.

The core component

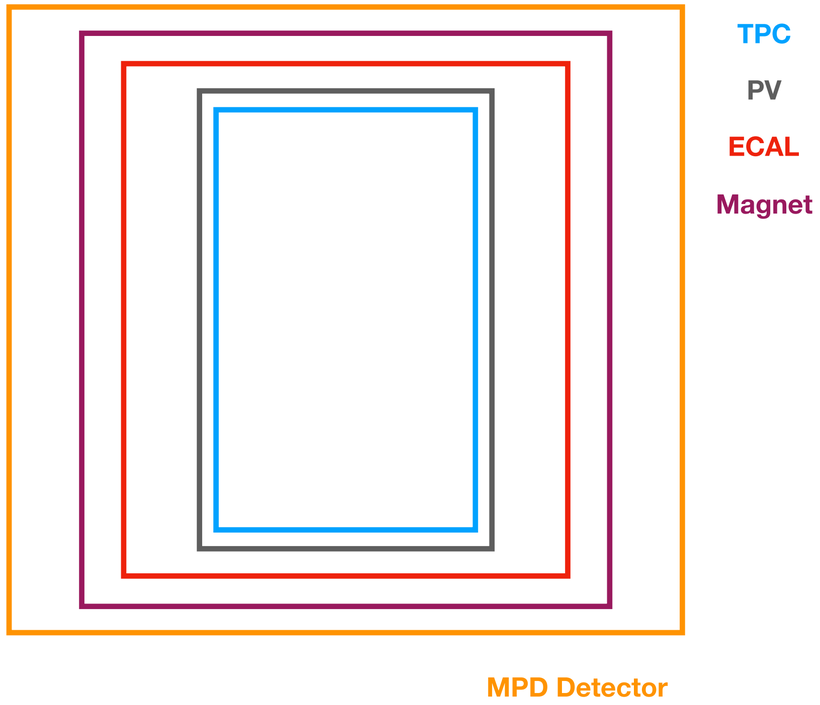
- Geometry generated with gegede and dunendggd
  - Subdetector/NDHPgTPC.py
- Global geometry structure
  - Construct all sub-components: TPC, PV, ECAL Barrel, ECAL Endcap, Magnet
  - Place them in the detector enclosure volume ➠ can place several ND components: ArgonCube, MPD and 3DST
  - Place the enclosure in the world volume ➠ Cavern made of rock (needed for background)
- For development
  - Perform first bullet then just place the detector into a world volume filled with Air.
- Important
  - Each volume has its own coordinates!
  - Enclosure defines position of the sub-detectors and world defines position of enclosure

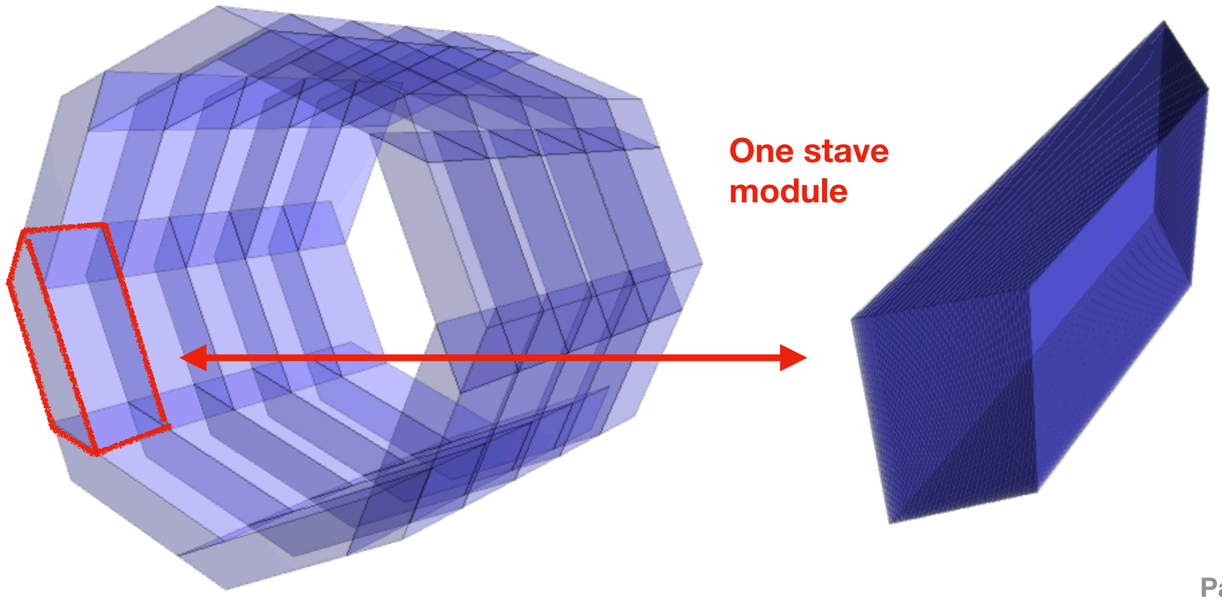


Current MPD Geometry.

Details for the MPD

- Each sub-component are built individually
- For the ECAL Barrel
  - A global envelope is built first (octagonal barrel - Polyhedra Regular)
  - For each octant, the stave is built - this is done to assign different names to staves (later used for segmentation purposes)
  - Each stave can be cut in smaller small modules along the x-axis
  - Each type of layer (pre-built) is then placed accordingl in the stave volume
  - The stave is then placed correctly into the envelope

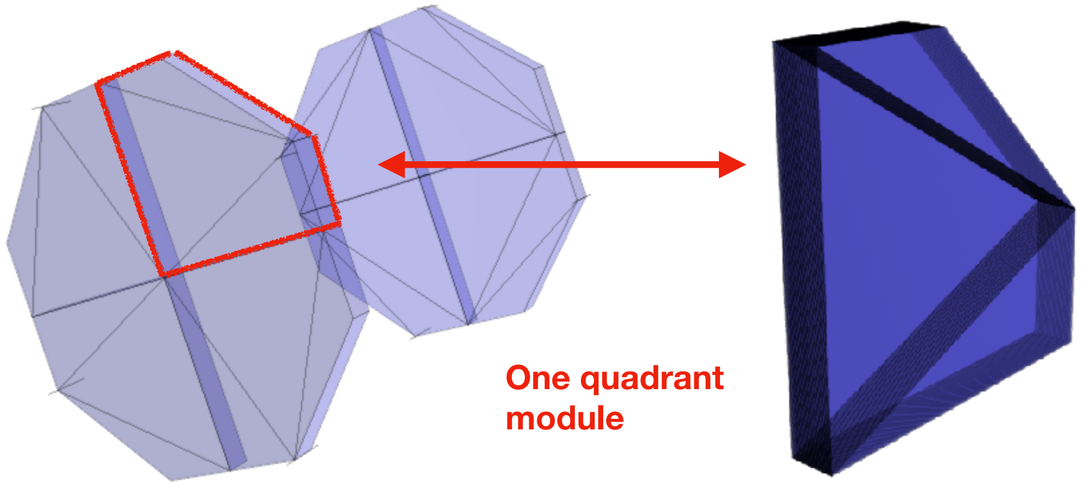


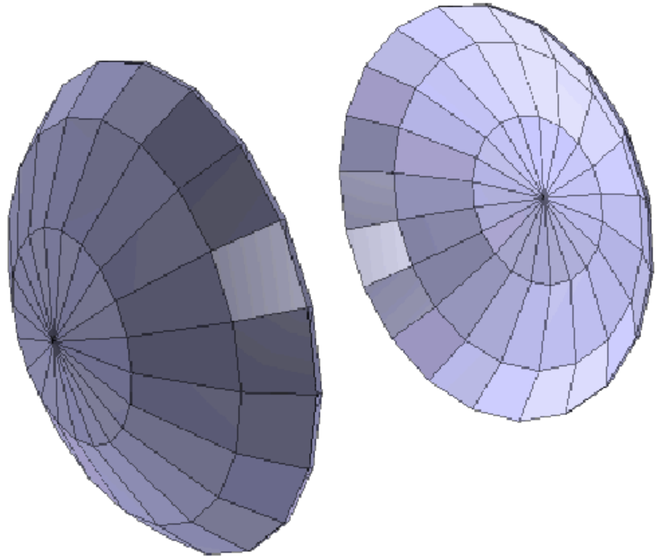


Current MPD Geometry.

Details for the MPD

- For the ECAL endcap
  - Similar ➠ Envelope is subtraction of two Polyhedra Regular
  - Each quadrant is the intersection of a Square and a Polyhedra Regular
  - Each quadrant can be divided in sub-modules ➠ to be done
- For the pressure vessel
  - Similar thing ➠ endcap is intersection of cylinder and sphere
  - Something to improve her) ➠ too much space between PV endcap and ECAL endcap

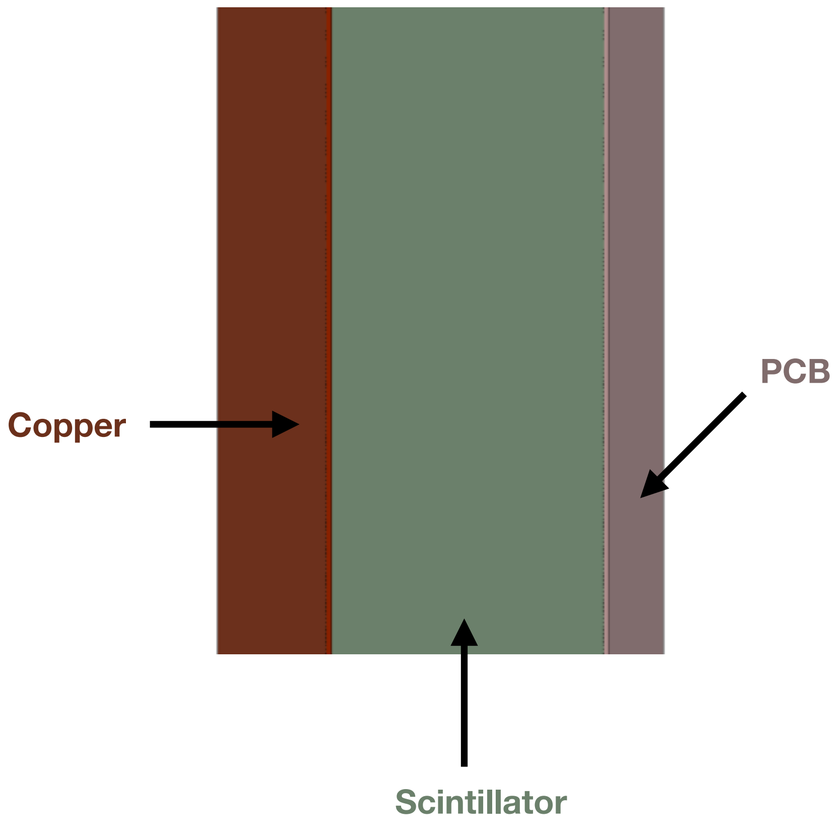




Current MPD Geometry.

Details for the MPD

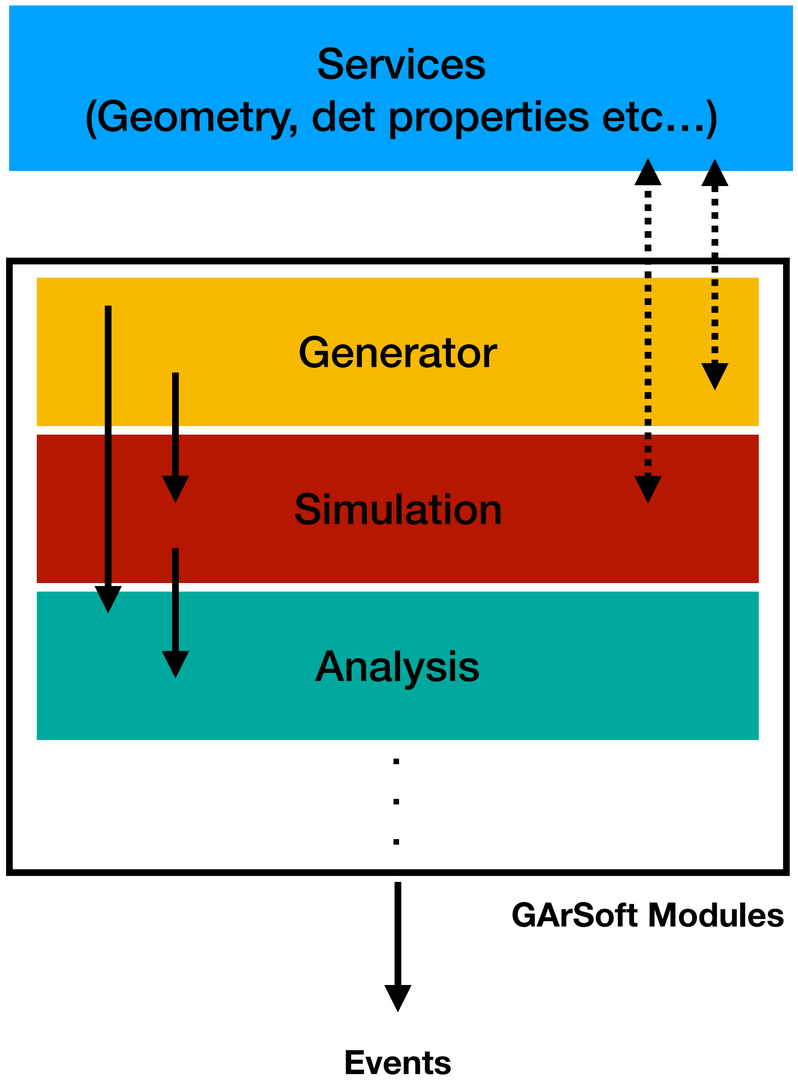
- Layer details
  - Simple model of a layer inserted into the stave
    - Similar to previously - envelope defines the layer volume, insert slices inside of material
  - No description of services/dead zones! ➠ once the design is fixed
  - No description of each individual tile or strip
    - Too much memory and file size would explode ➠ simple scintillator plane.
    - Segmentation in the digitisation phase
  - Several models of layers can be done and then inserted according to the config file (e.g High/Low granular layers have different structure)
- Current
  - 2 mm Cu / 5 mm Sc / 1 mm PCB (FR4)



MPD Simulation.

Handling of Geometry and running the G4 simulation

- MPD Software based on LArSoft ➠ GArSoft
- Configured using fcl files
- Different services to handle different parts
  - Geometry
  - Detector properties
  - …etc…
- Simulation based on LArSoft model
  - Load services ➠ load gdml, channel mapping, segmentation…
  - Call Generator module ➠ generate single particle, GENIE etc…
  - Call GArG4 module ➠ run the simulation



MPD Simulation.

Handling of Geometry and running the G4 simulation

- GArG4
  - Begin job:
    - User limits: step size, regions, range cut
    - Material properties: i.e optical properties
    - Geometry: load gdml in G4
    - Physics list: pre-built or can be custom via fcl
    - User actions: filter particle to keep, energy deposits actions (user defined)
  - Produce:
    - Take generator particles pass them through G4 (G4Helper)
    - Get back particle list, energy deposits and put them into the event

```
// Get the logical volume store and assign material properties
garg4::MaterialPropertyLoader* MPL = new garg4::MaterialPropertyLoader();
MPL->GetPropertiesFromServices();
MPL->UpdateGeometry(store);

this->SetLimitsAndCuts();

// Intialize G4 physics and primary generator action
fG4Help->InitPhysics();
```

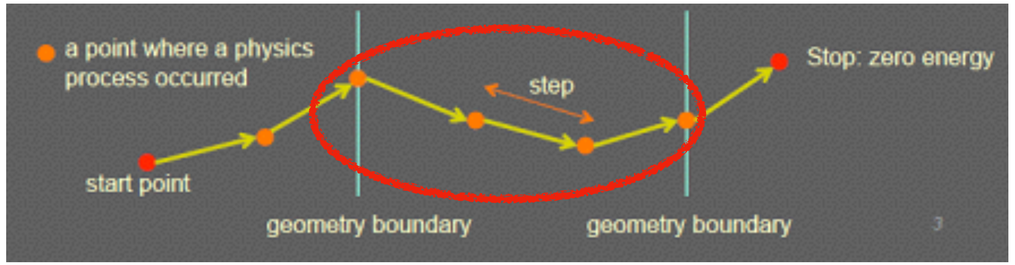
```
// add UserAction for handling steps in gaseous argon
fEDepAction = new garg4::EnergyDepositAction(&(*fEngine),
                                             fEDepActionPSet);
uaManager->AddAndAdoptAction(fEDepAction);
```

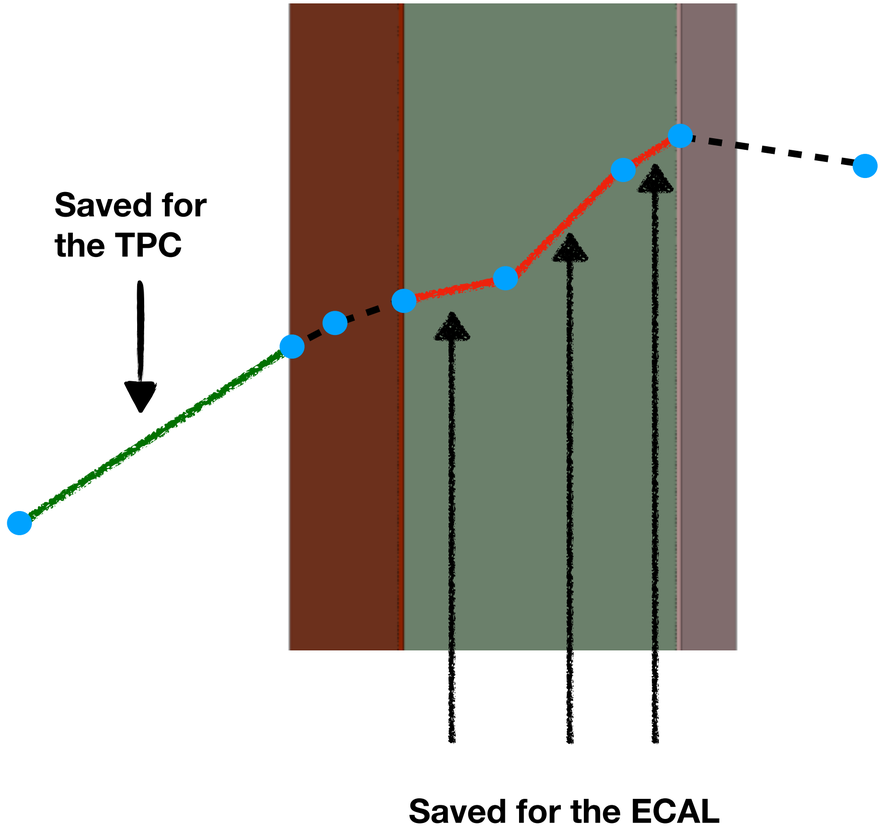
```
// Now for the sdp::EnergyDepositions
for(auto const& tpc : fEDepAction->EnergyDeposits()){
  LOG_DEBUG("GArG4")
<< "adding TPC deposits for track id: "
<< tpc.TrackID();

  TPCCol->emplace_back(tpc);
}

// And finally the sdp::CaloDepositions
for(auto const& hit : fAuxDetAction->CaloDeposits())
{
LOG_DEBUG("GArG4")
  << "adding calo deposits for track id: "
  << hit.TrackID();

ECALCol->emplace_back(hit);
}
```

MPD Simulation.

Particle Tracking in the MPD

- Tracking is handled by G4
- User specific tracking ➠ User Actions!
  - Used to create simulated hits
- Each MPD detector has its own user action function
  - TPC ➠ EnergyDepositAction
  - ECAL ➠ AuxDetAction
- User Actions can be configured with fcl parameters
- In each class, the Stepping Action is defined
  - Check the position (middle of the step), energy of the step
  - Check material in which the step is ➠ sensitive?
  - If sensitive save the step (energy, position, time, length, id…) into a vector
- Perform this for each particle until below a certain E_{kin}!
- Very modular! But can be long depending on the number of particles to track!

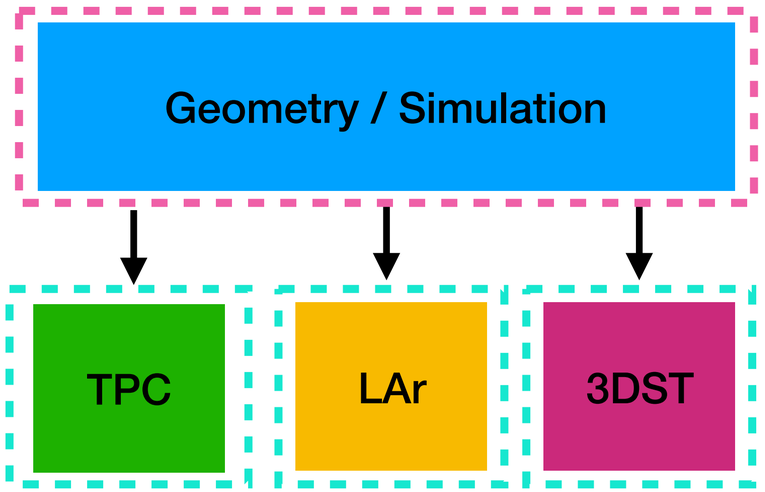


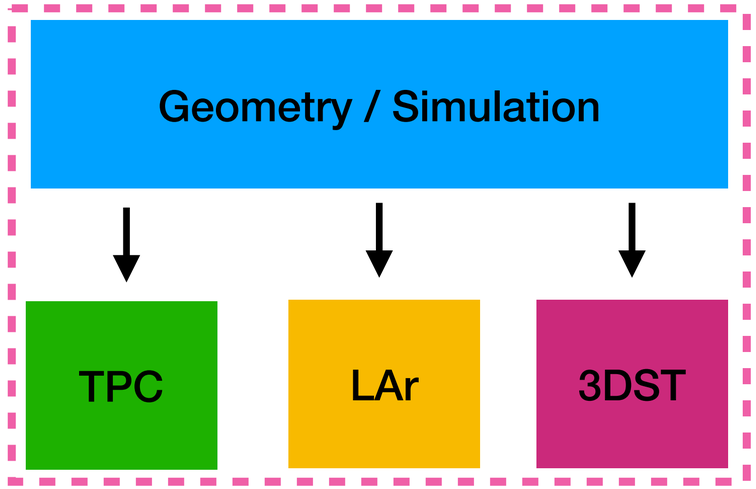


Integration into a common framework.

Ideas

- Need for a common framework in the ND simulation ➠ Not possible to separate the simulations…
- Allows for detector interplay, optimisation…
- What are the needs in term of simulation?
- Possibilities:
  - Create a package specific for the ND simulation containing the common geometry, generators and simulation running code
    - Advantage: Independent of the framework after the simulation
  - Move all sub-detectors to the same framework
    - A lot of work for each sub-detector group depending on the framework chosen…





First look into neutral pion reconstruction.

Setup and method

- Shooting pi0s between 0 and the TPC radius at intervals of 15 cm (x position fixed)
- Simple Method (no MC info used):
  - Take the two most energetic clusters (some case have more than two clusters)
  - Take the direction from the cluster main axis and calculate the PCA between the two cluster axis
  - Calculate the angle between the two cluster axis and reconstruct the pi0 mass
  - Calculate the distance between the true vertex and the geometrical determined one
  - Chi2 minimization can be done after using the energy and geometrical information combined
- Very preliminary study