Simulation and Reconstruction of ND-GAr with GArSoft

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DUNE Phase II Near Detector Workshop

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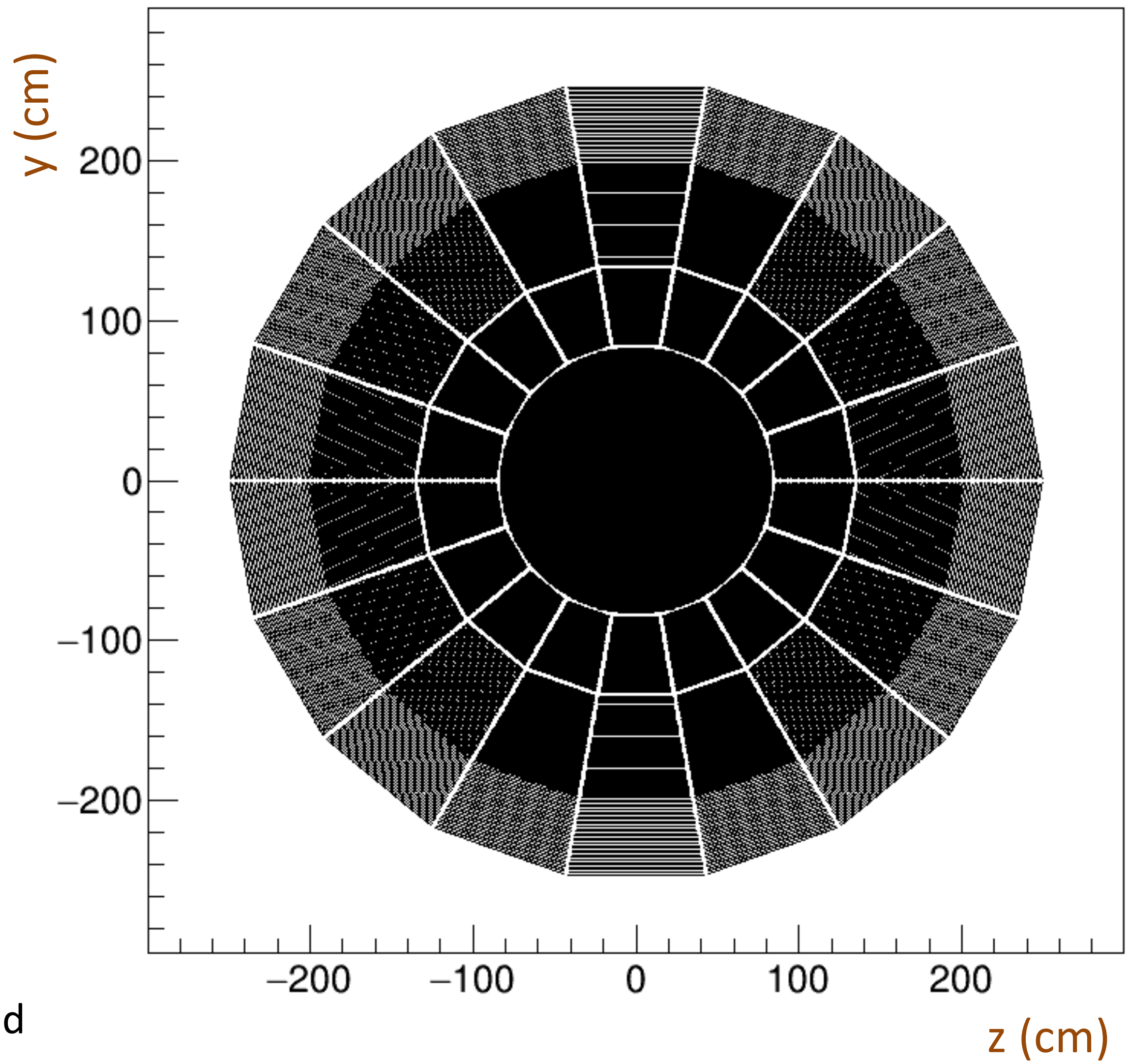
What's Available in GArSoft

- Event Generators:
  - GENIE (v3)
  - Text File Gen
  - CRY (not tested)
- ALICE-like tracker + ECAL + muon ID geometries
- GEANT4
  - Copied from LArG4 in 2017 but with features of the refactoring
  - GArSoft can read and process edep-sim files
- Detector response – TPC and ECAL
- Track reco (patrec, Kalman filter). Vertex finding and fitting. Vee finding. Cathode stitching
- ECAL clustering
- All done with *art* and nutools

TPC channel positions

- 18 Sectors of IROC and OROC channels now using ALICE nominal geometry – but easy to change. Channels assigned in code, not GDML.
- Rectangular array of pixels in a disk in the center
- Pixel size: 6mm x 6mm c.f. 4 mm x 7.5mm for inner pad rows.
- Total channels per side is now 339068.
- Total on both sides: 678136
- About 18% of channels are in the CROC
- CROC channel design can be adjusted easily. This one's probably optimistic.



ALICE Readout Chambers

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

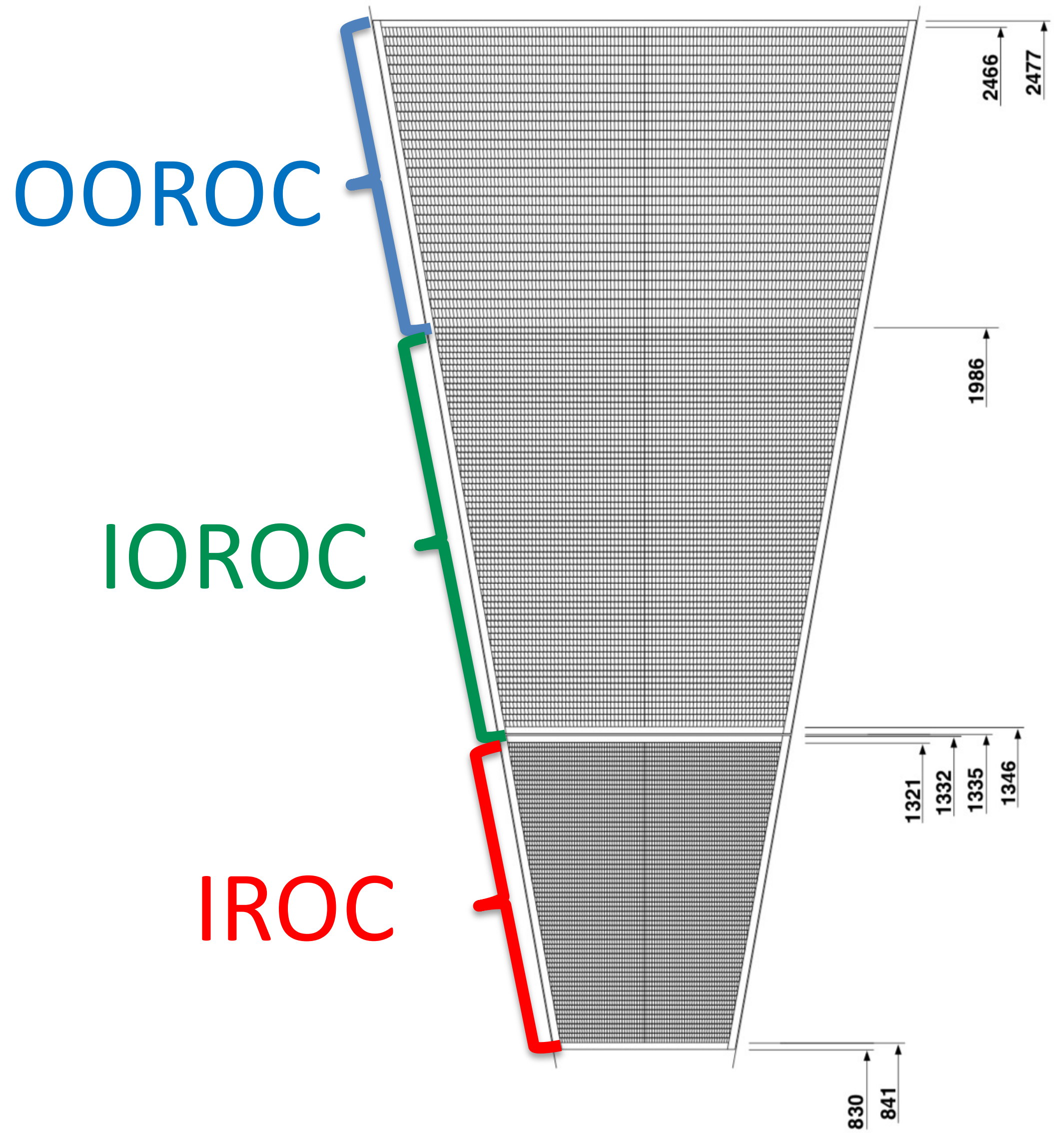


Figure 4.12: Pad layout of the ALICE TPC readout chambers. Distances from the beam axis are in mm.

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

Straw-person CROC pads: 6 x 6 mm^2

Readout Geometry

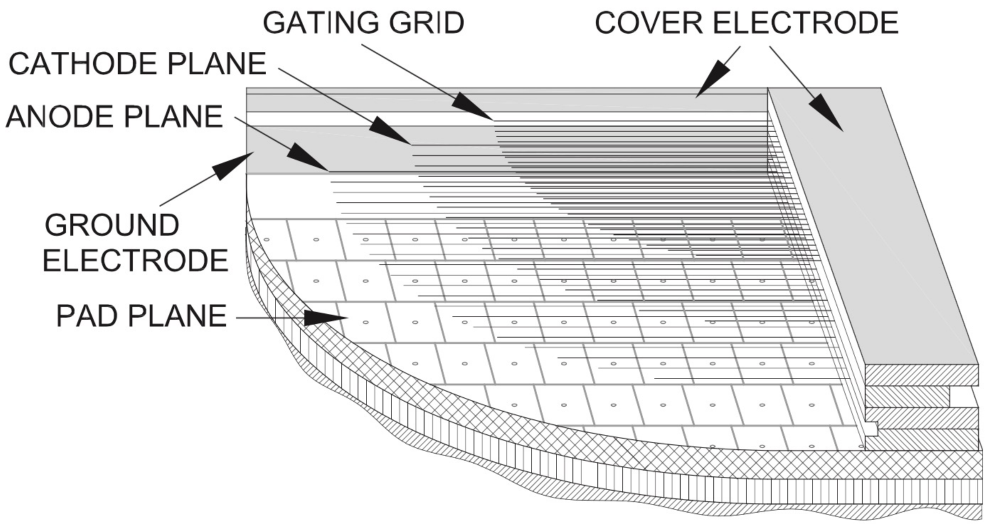


Fig. 9. Cross-section through a readout chamber showing the pad plane, the wire planes and the cover electrode.

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

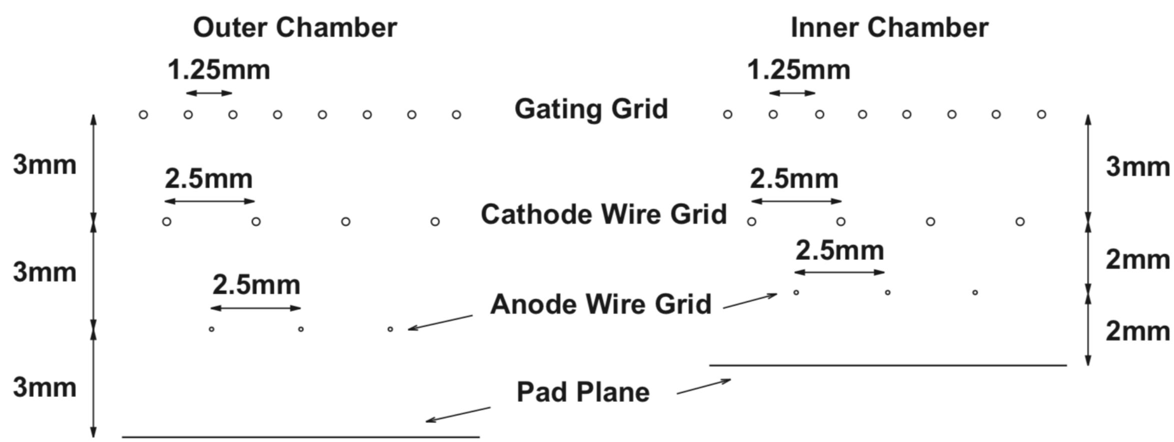


Fig. 10. Wire geometries of the outer (left) and inner (right) readout chambers.

Pad Response Function

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

4 x 7.5 mm pad

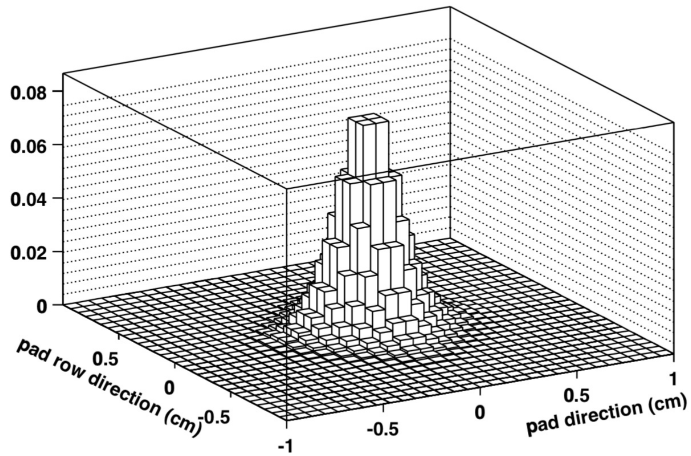


Figure 7.6: Induced-charge distribution according to Ref. [11]. Normalization is arbitrary.

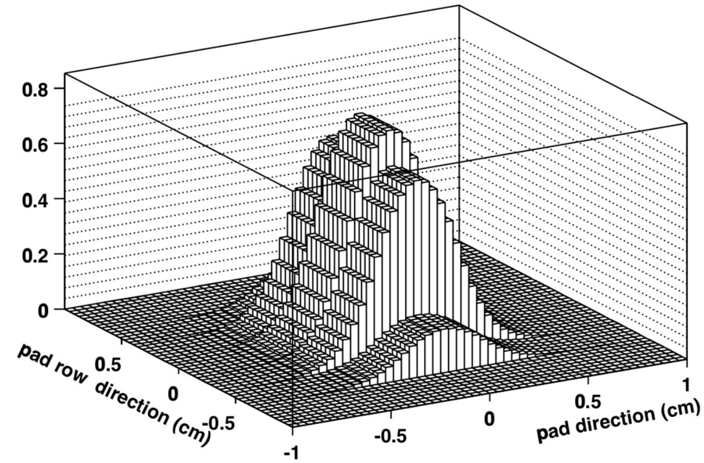


Figure 7.7: Pad response function for rectangular 4×7.5 mm^2 pads. Normalization is to unity.

Q(*x,y*) function

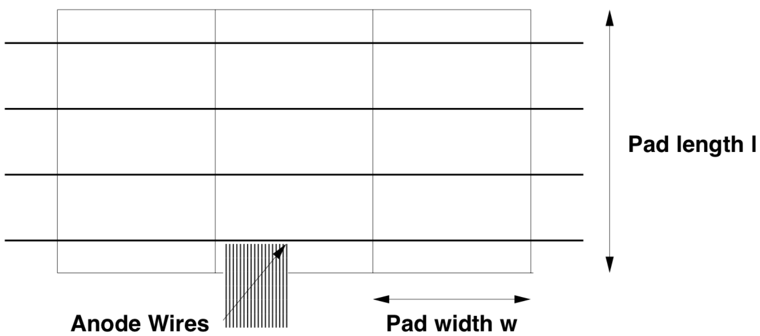
Width ~1.2 mm, with a small tail

Anode-plane wires are spaced 2.5 mm apart.

$$\mathrm{PRF}(x,y) = \int_S Q(x',y')\mathrm{d}S,$$

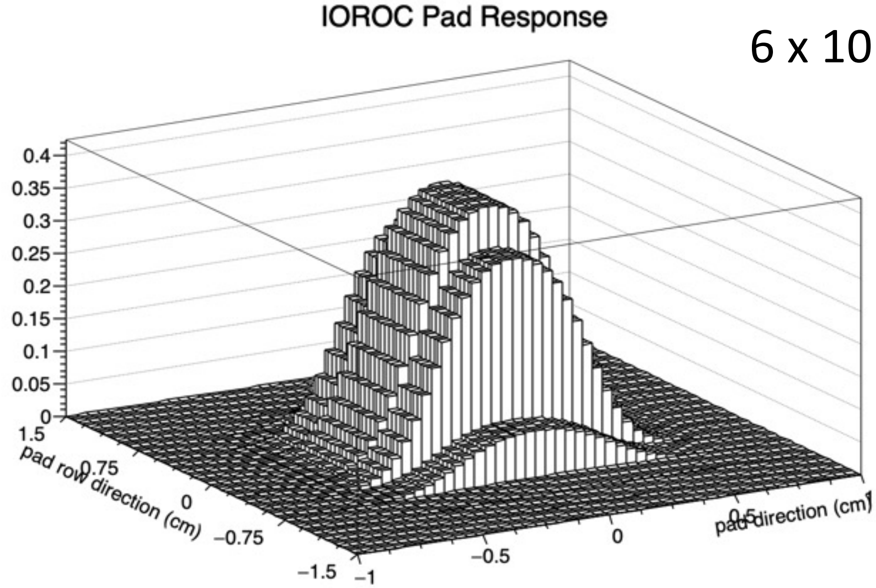
Calculations of IOROC and OOROC PRFs

ALICE TDR IOROC: 6 x 10 mm^2

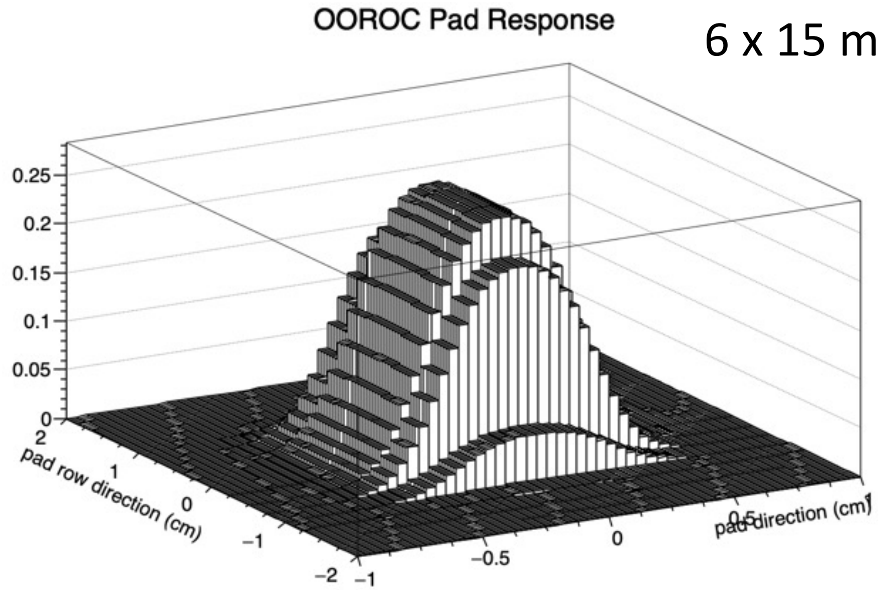


Gives spacing and locations of anode wires. IROC: wire in the middle of pad.
IOROC and OOROC, wires offset by 1/2 wire spacing from pad edge

6 x 10 mm^2 pad

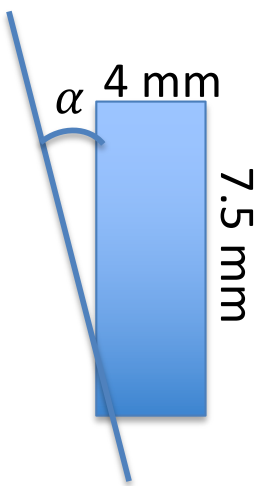


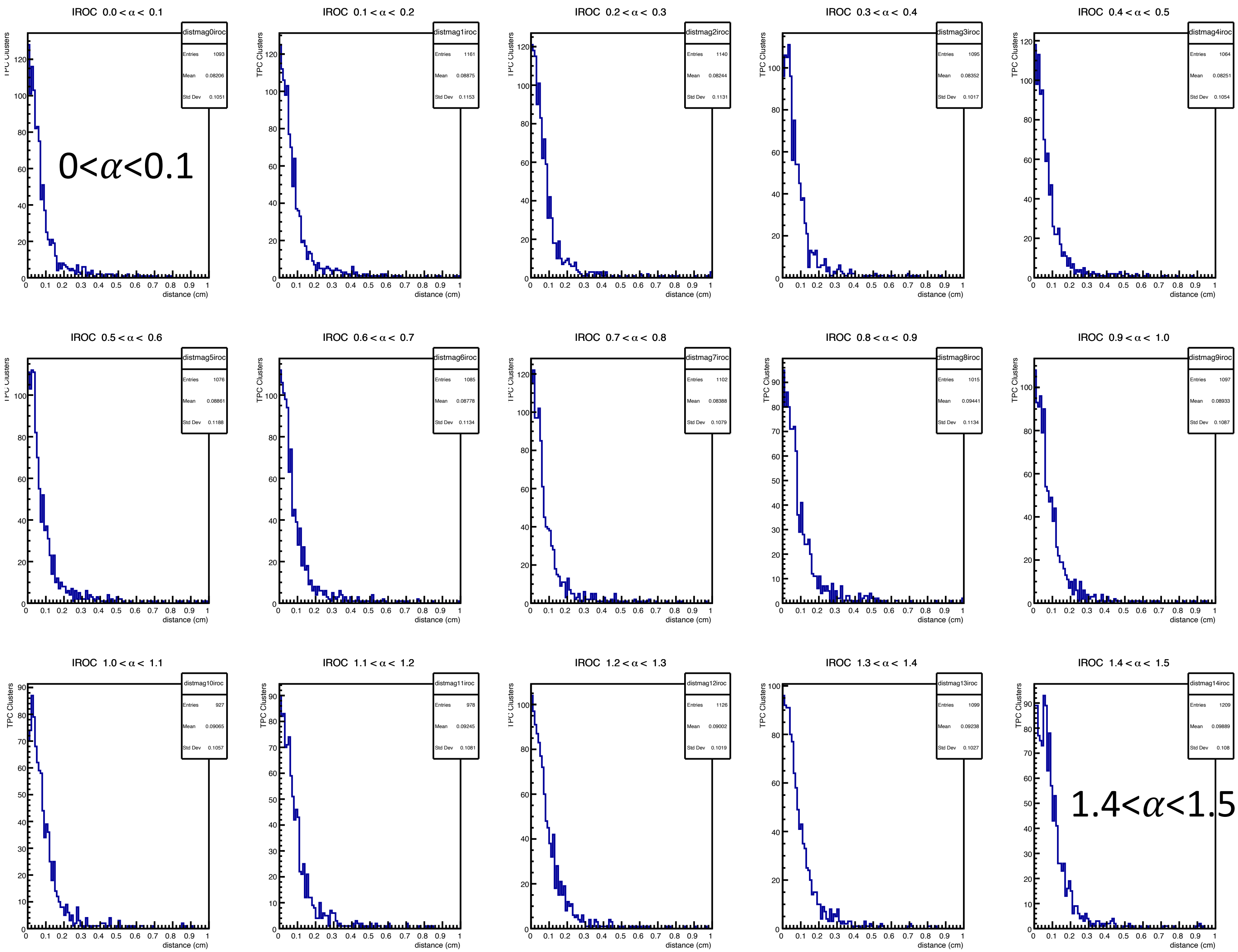
6 x 15 mm^2 pad



TPC Cluster Residuals vs. Angle: IROC

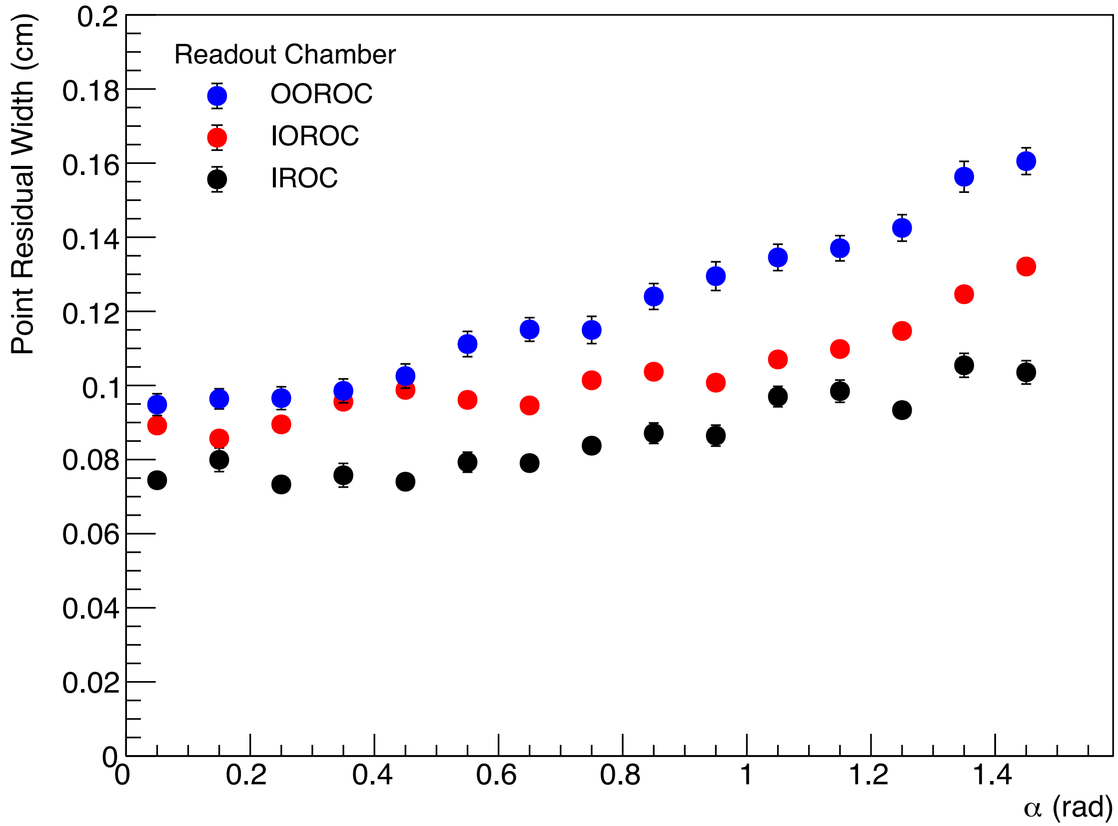
Pad center location bug affecting collab mtg talk fixed now.





Wide hit clustering: 4 cm (transverse) x 2 cm (longitudinal) search window

Point Resolution Summary

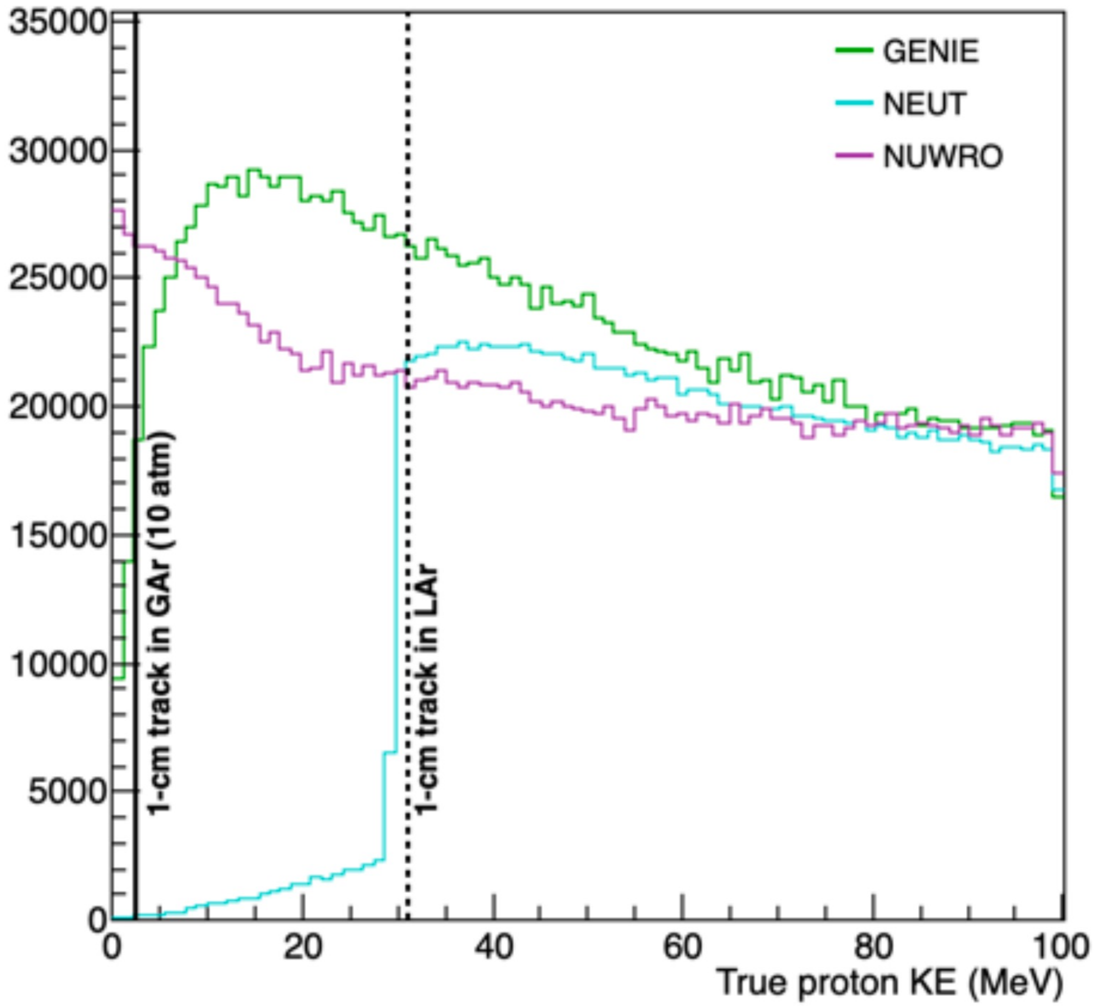


Residuals perp to track, *not* just rϕ

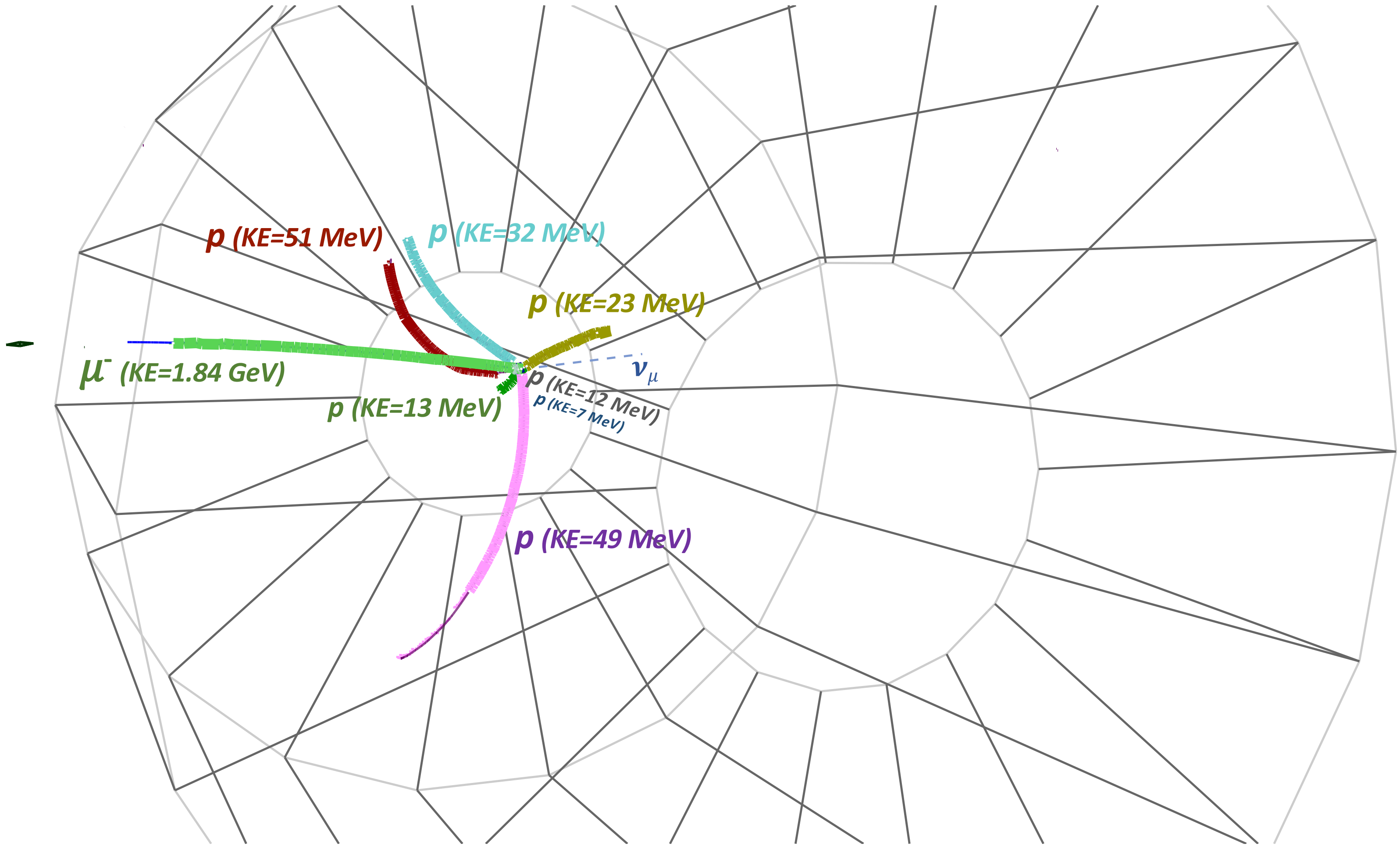
Widths of fits of Gaussians to the abs val. residuals on previous pages

Resolution of OOROC for tracks 90˚ from the pad axis is still good – 1.6 mm.
Optimization of TPC Clustering algorithm expected to improve all resolutions.
Fiducial volume cuts (already in the 1 ton definition) ensure enough hits are on tracks to make a good momentum measurement.

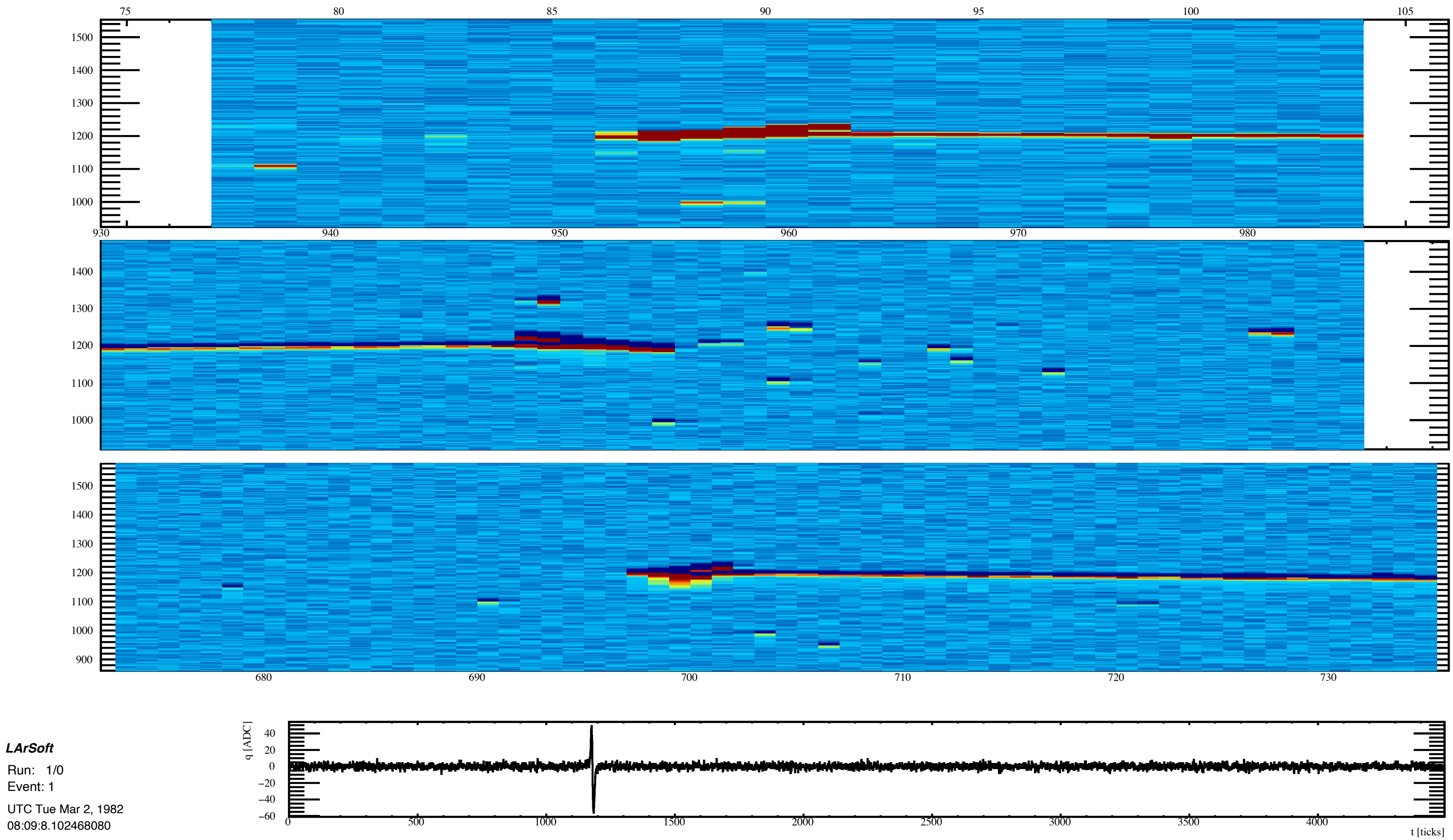
Low-Energy Protons in Neutrino Scatters



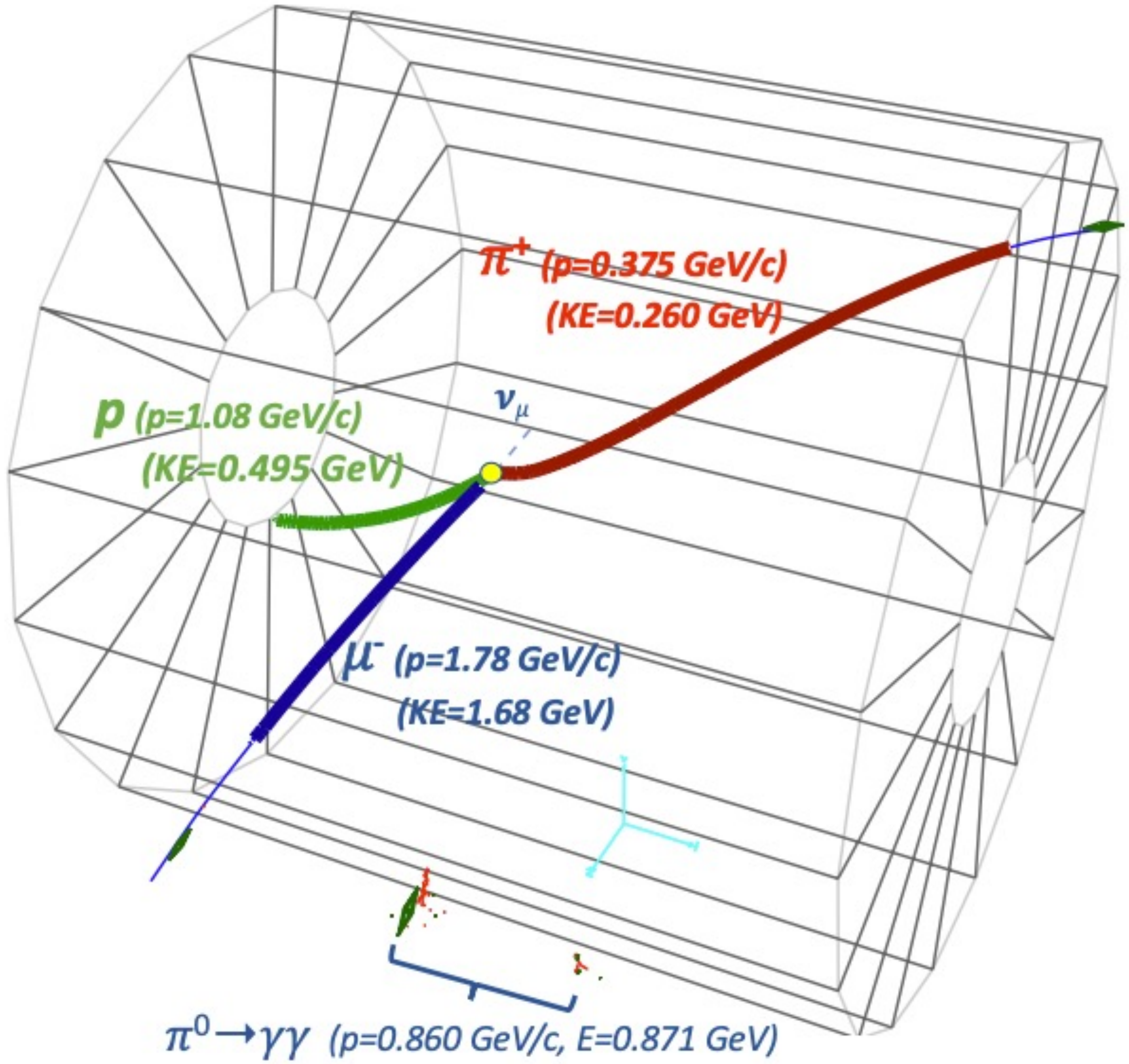
An Event with Seven Protons and Muon



The Same Event in LAr



An Event with a Pizero



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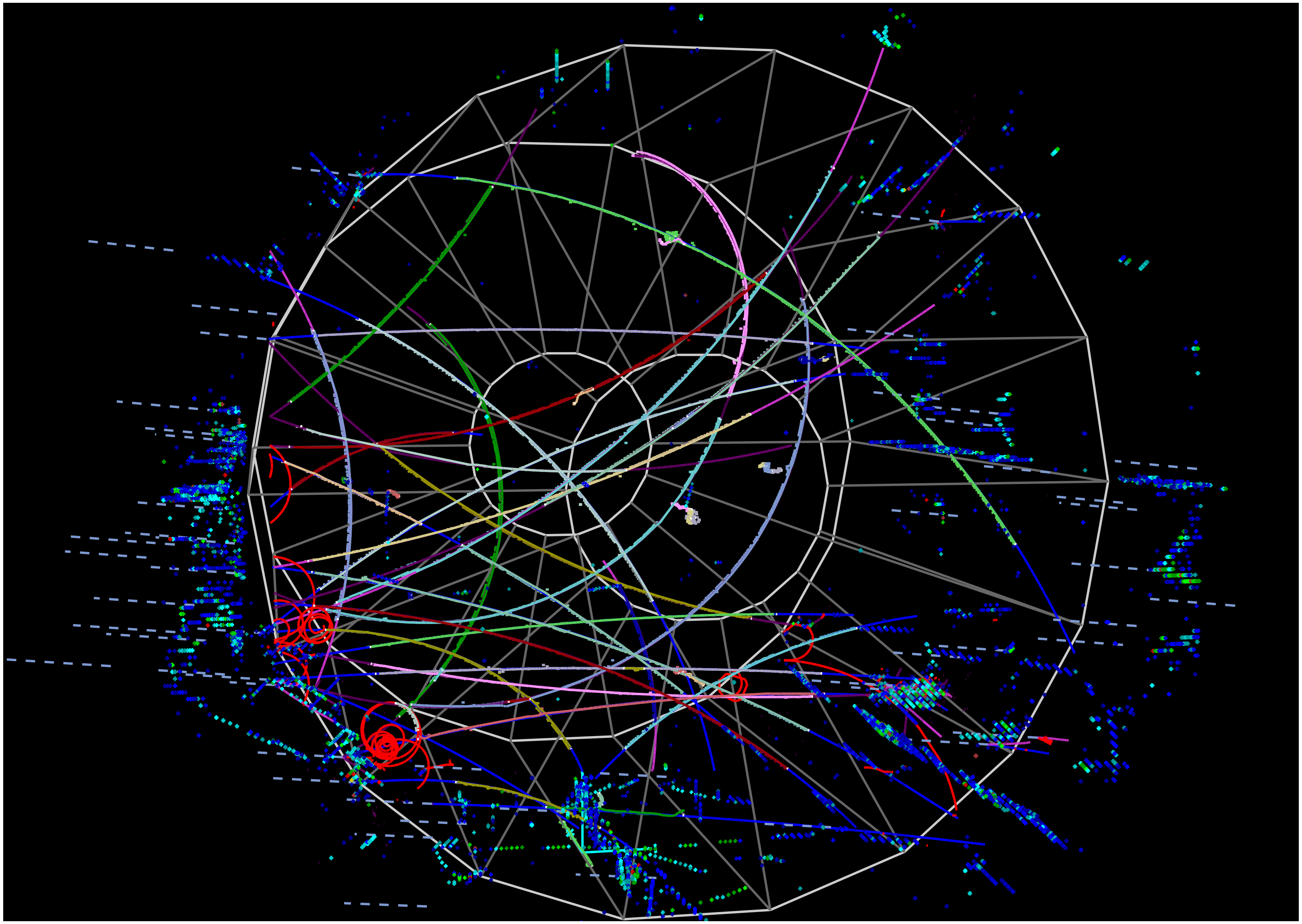
Events Will Look Like This

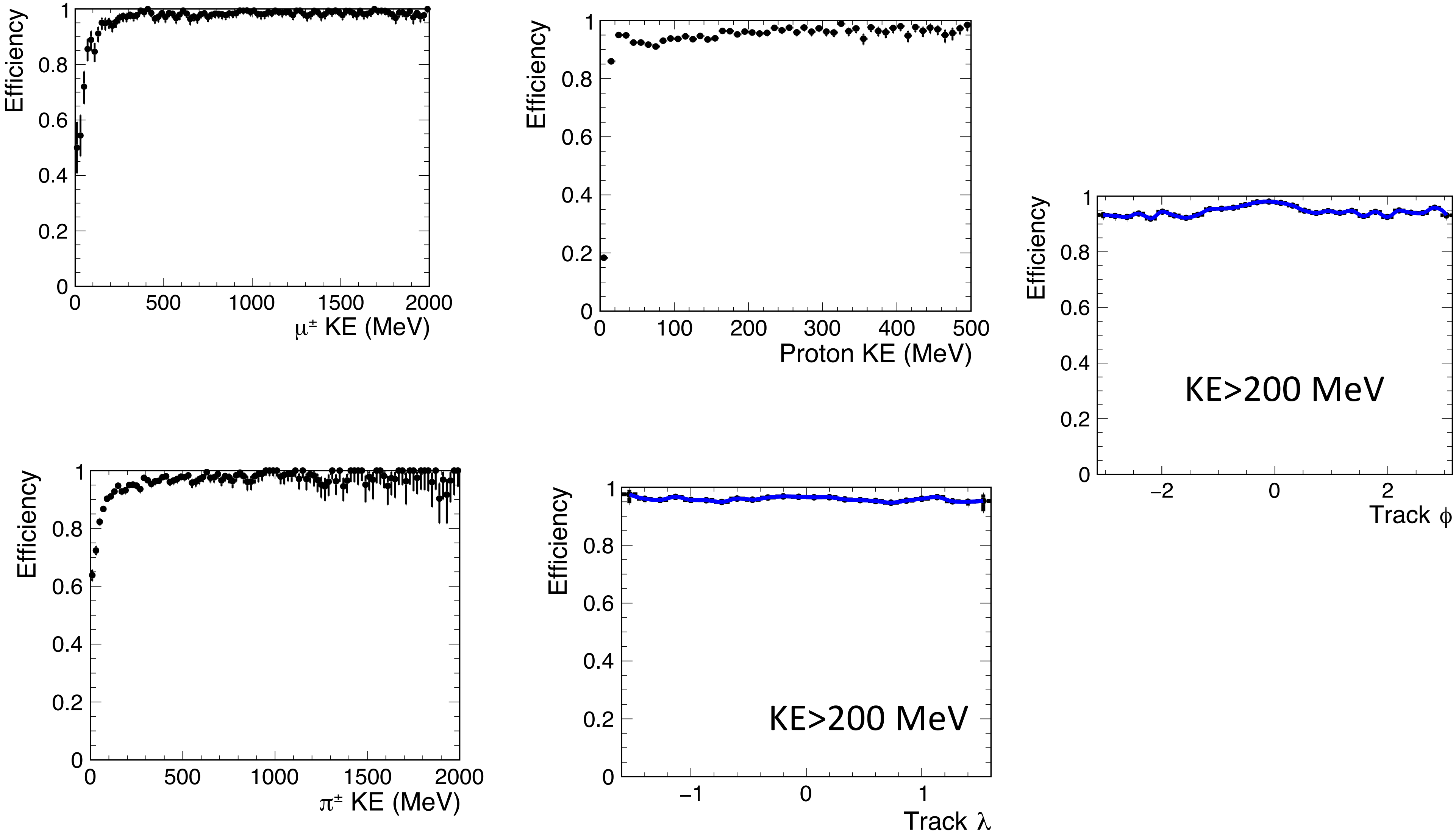


60 pileup interactions, with thick upstream ECAL

Tracking is not a problem with this occupancy

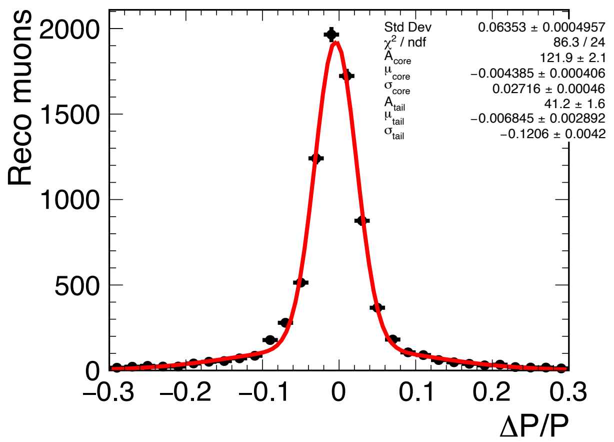
Tracking Efficiency

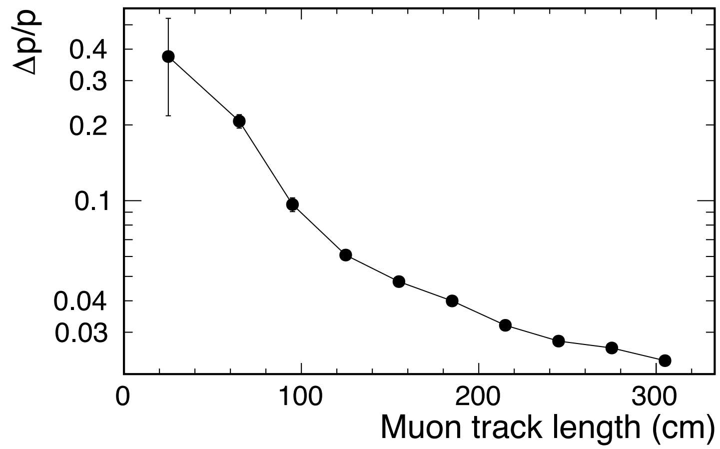
Not perfect, but pretty good.



Muon Momentum Resolution

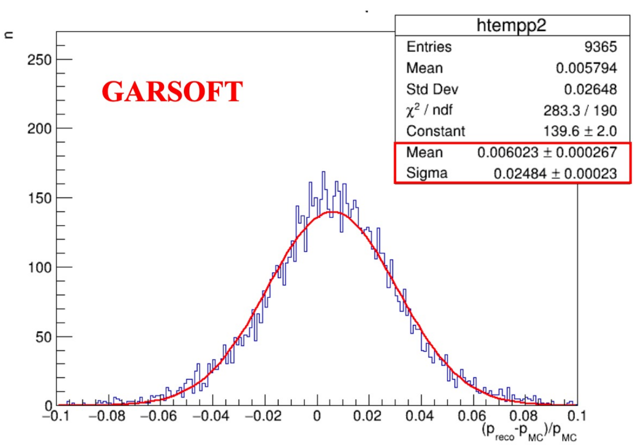
Muons in numuCC events, CDR performance

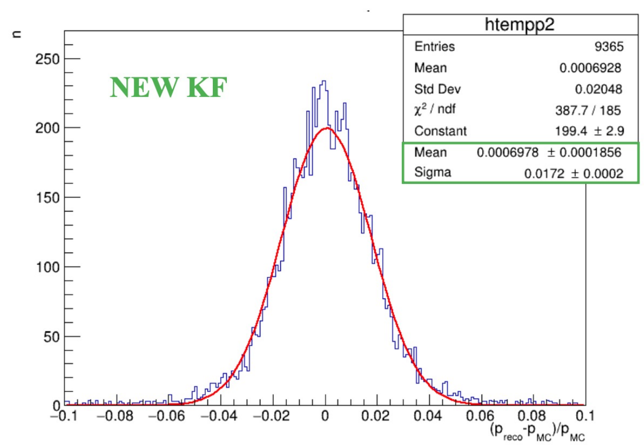




Throughgoing muons

MOMENTUM RESOLUTION AND BIAS: GARSOFT VS NEW KF

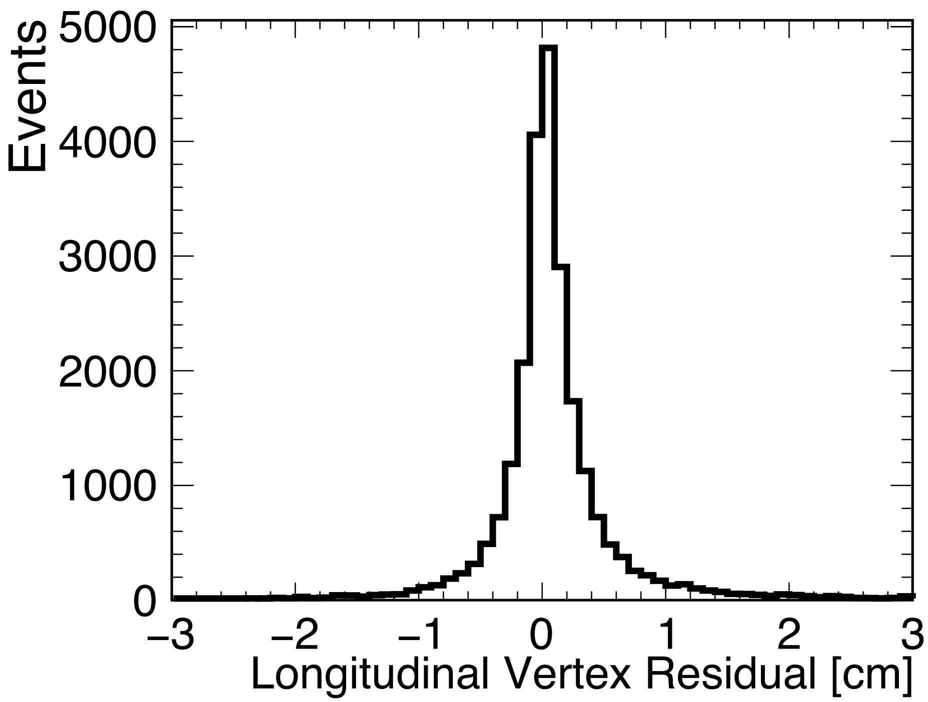


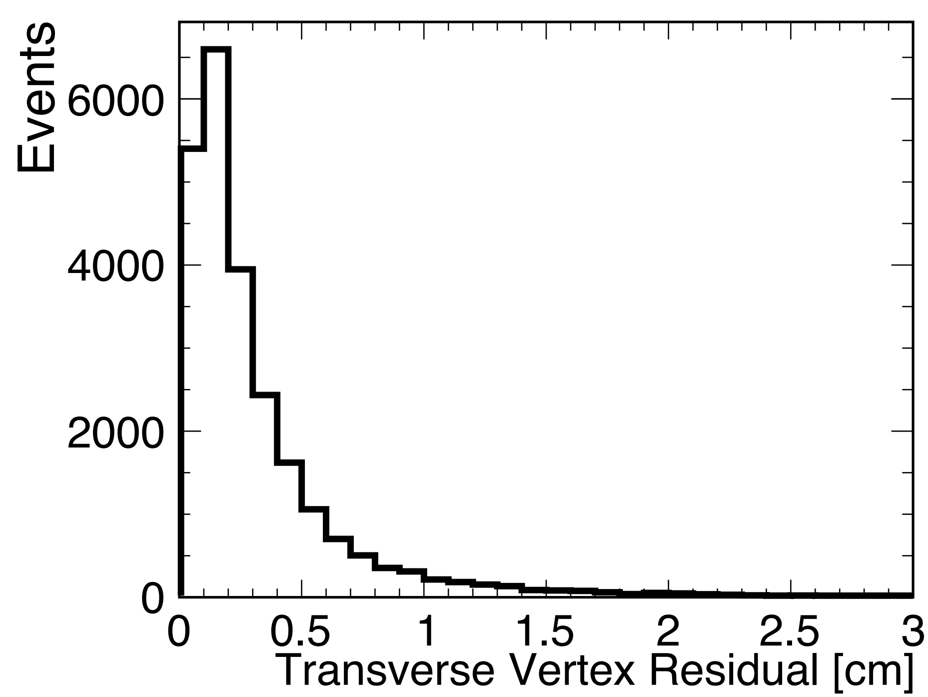


Federico Battisti

- Total momentum bias and resolution for the sample can be defined as the μ and σ from a Gauss fit of the momentum fractional residuals distributions $(p_{reco}-p_{MC})/p_{MC}$

Vertex Position Resolution





Simulation to-dos

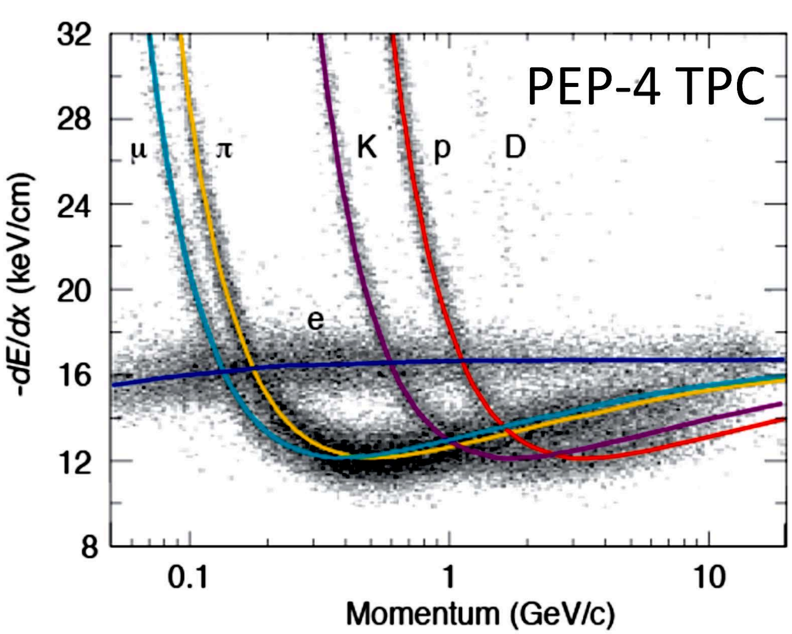
- Time structure of arriving signals
  - Currently very naive – raw waveform just has unconvoluted charge arrival times. Diffusion and spatial extent of tracks make for smooth waveforms however
  - Lack of confidence in choice of re-use of ALICE ROCs has dampened enthusiasm on this front
- Scintillation light – S1 and S2 need to be simulated, and a model of the photon detection system needs to be added
- Would like CORSIKA interface. But maybe this comes with the integration group via edep-sim
- Update calorimeter geometry current one is uniformly thick as a function of phi
- More realistic CROC pad geometry

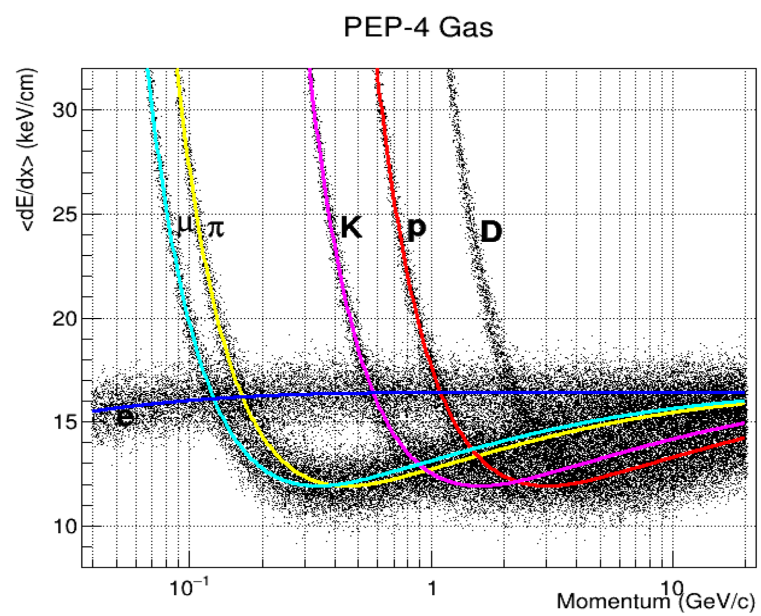
Project: Study and Improve TPC Cluster Resolution

- Current algorithms are quick and dirty
  - TPC Hits are formed from the zero-suppressed raw digits just by looking at over-threshold time periods
  - Some logic added to keep hits from becoming very long when a track is pointed at a pad (or a looper corkscrews towards a pad)
  - TPC Clusters really just start with any hit and keep adding until they collect charge from too far away. Charge centroid calculated.
  - ALICE code provides examples of how to do this better (but it is tied to their geometry. We need something that works for us in 3D with the hole-filler too)
- O. Gagota and V. Aushev have been working on this

Near-Term Project – Study dE/dx

- For now – parameterized for CAF files using PEP-4 data as a guide for resolution. ALICE resolution is similar between 5 and 8%.
- Need to produce this from GEANT4-simulated and fully reconstructed MC. Needs realistic waveform simulation
- Good work from Francisco Martinez Lopez – should check effect of pattern recognition – completeness of tracks.

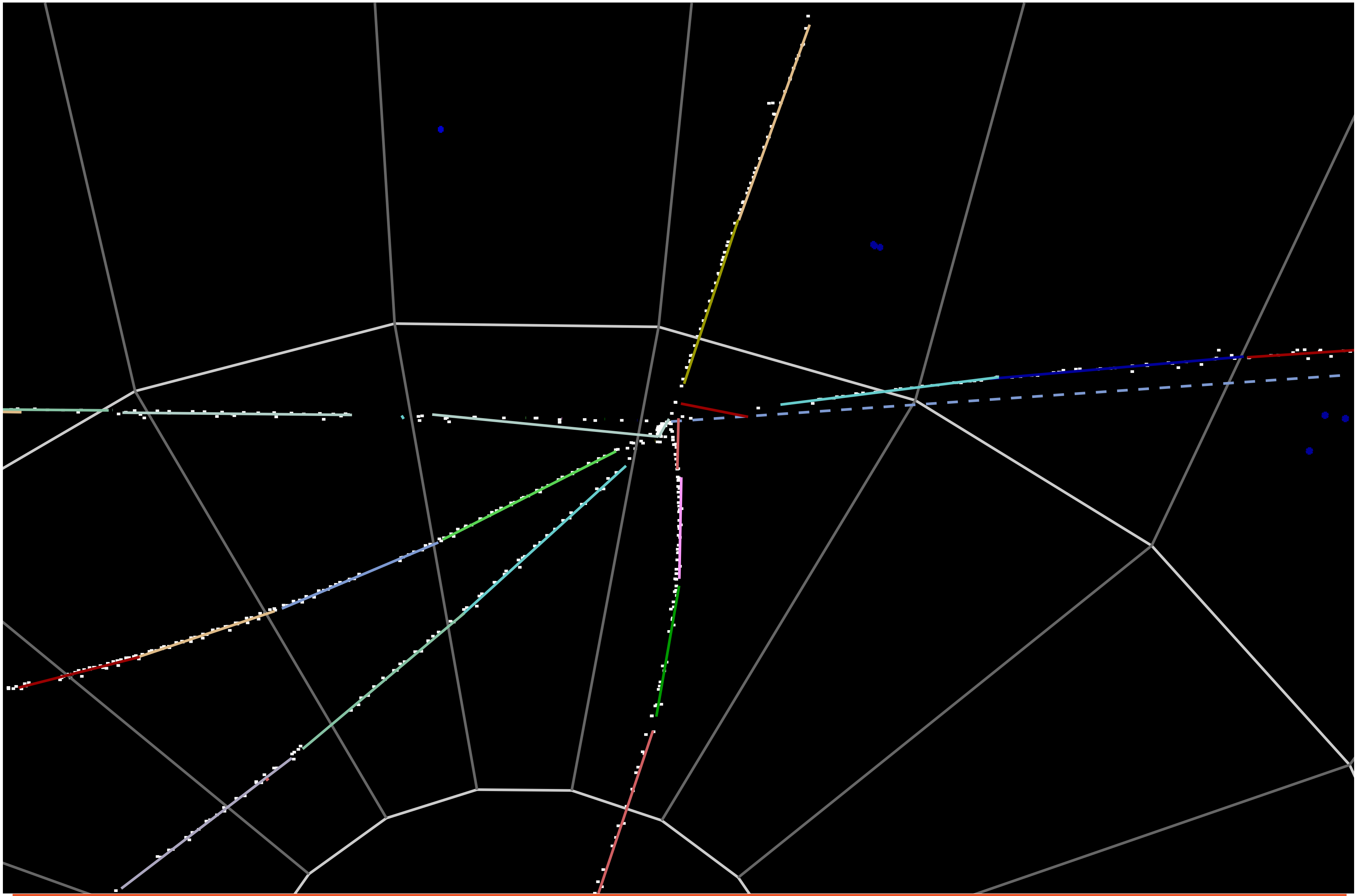




Project: Vertex and Track-Finding Improvements

- Vertex finder tends to find many vertices in a crowded environment
- Tracks are split near the primary vertex
  - Tracklets steal hits from each other
  - Tuneable parameters are set to break tracks easily into pieces
    - Do not want to miss a real vertex
    - But a scatter can look like a vertex
- Split tracks make for many combinations of possible vertices at the primary.
- Project: Select the best vertex and constrain tracks to it. Refit tracks after constraint.
- Started looking at a GNN to identify and measure the location of the primary vertex. Need a full training sample with pileup

Example Patrec Problems near PV



A Project: Track Pattern Recognition Improvements

- Tracks are found by grouping vector hits together
- Vector hits are like ALICE's "seeds".
- ALICE uses the track Kalman filter to search for hits to add after an unambiguous seed has been found
- ALICE's problem is "easier" in that the primary vertex position is known (it's in the beampipe). Tracks are fit "outside-in". We do not have either luxury.
- Don't want to continue tracks through the primary vertex.
- Adding hits consistent with an extrapolation of the track path will do this – need to look at activity nearby to indicate a vertex.

Near-Term Project: Identify and Reconstruct Low-Energy Loopers

- Target physics: Conversions and Compton scatters
- Currently apply a momentum cut on tracks which is effective at reducing Comptons and Conversions
- Need to be able to pair up the e^+ and e^- tracks as conversion candidates
- One electron may have much lower energy than the other
- Collider tracking algorithms are notoriously inefficient for low-energy looping tracks.

Calorimeter Simulation and Reconstruction

Pointing Resolution Optimization study for the CDR

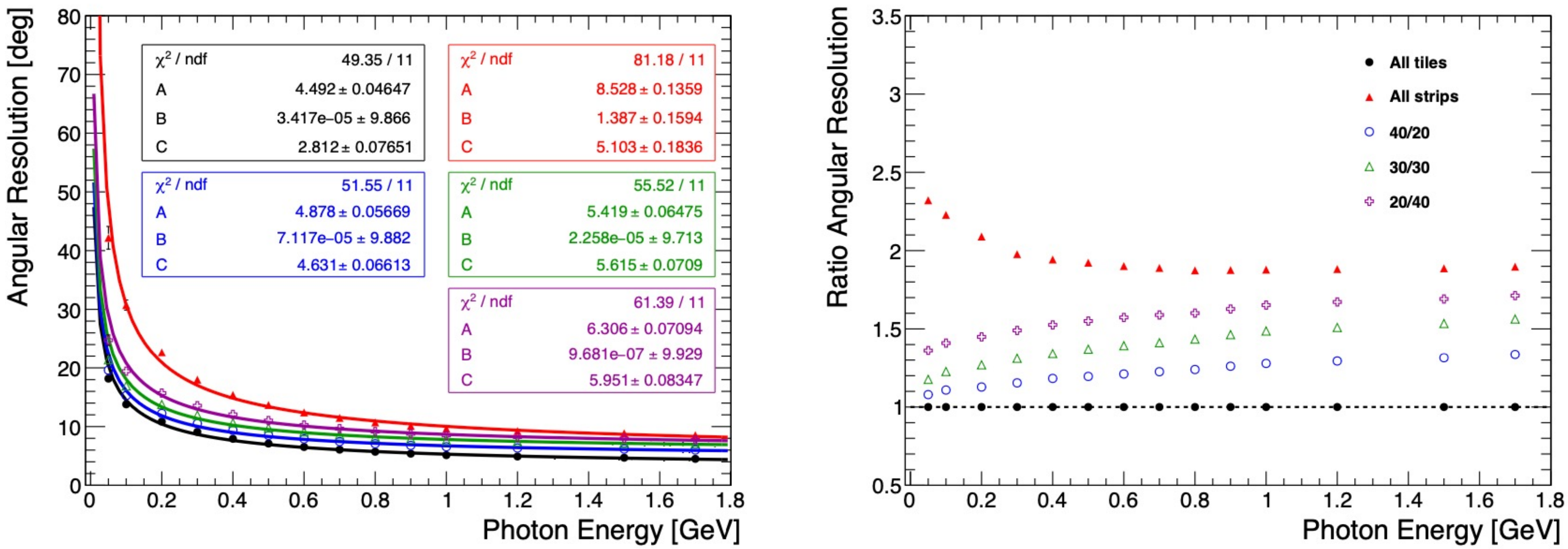
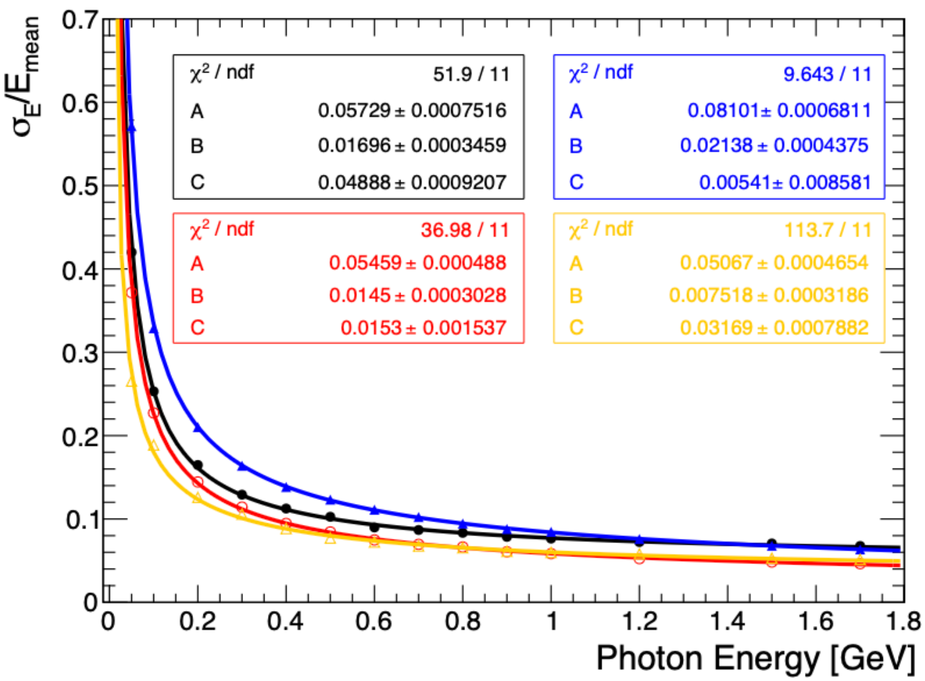


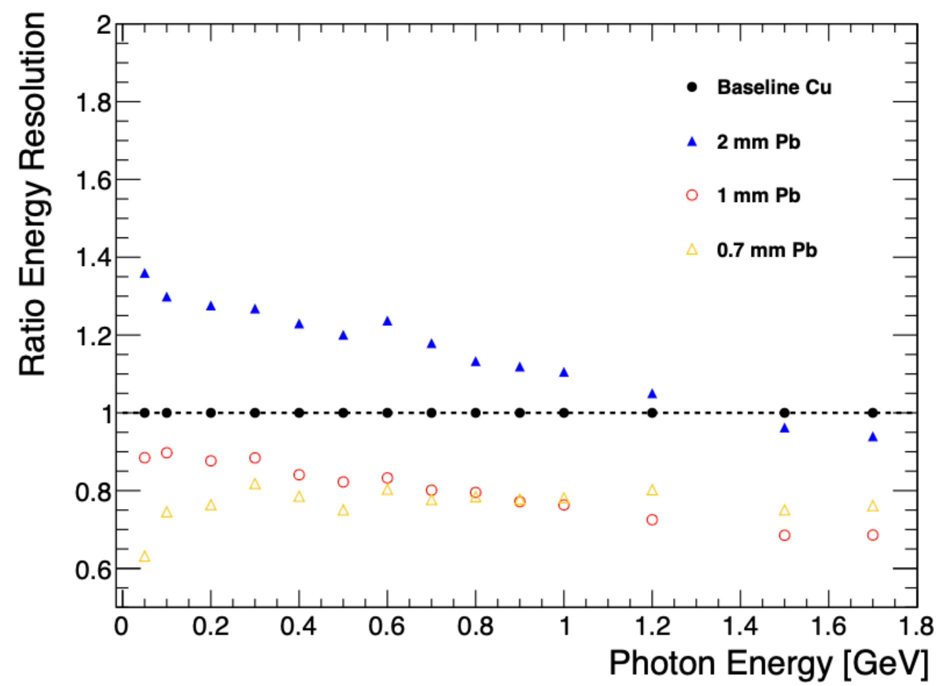
Figure 3.35: Angular resolution and ratio for different ECAL detector granularity configurations

arXiv:2103.13910

arXiv:2103.13910

Calorimeter EM Energy Resolution





$$6\%/\sqrt{E(\text{GeV})} \oplus 1.6\%/E(\text{GeV}) \oplus 4\%$$

Ongoing work to improve clustering, cluster matching by Leo Bellantoni and Vivek Jain

Table 3.4: Expected ND-GAr performance according to the studies reported in this chapter and also extrapolated from ALICE and PEP-4 (marked with an *). Here $\perp$ and $\parallel$ refer to the directions perpendicular and parallel to the drift direction. The momentum and angular resolutions were estimated using reconstructed ν_μ CC events generated with the LBNF flux. That study is described in Section 3.4.5.1. The proton energy threshold study is described in Section 3.4.5.2. The ECAL performance is described in Section 3.4.6.

Parameter	Value	Comments
Single hit resolution $\sigma_\perp$	250 μm	*$\perp$ to TPC drift direction
Single hit resolution $\sigma_\parallel$	1500 μm	*$\parallel$ to TPC drift direction
Two-track separation	1 cm	*
$\sigma(dE/dx)$	5%	*
μ reconstruction: σ_p/p	(2.9%, 14%)	(core, tails), ν_μ CC events, LBNF flux
μ σ_p/p vs. track length	(10%, 4%, 3%)	(core),(1,2,3 m), ν_μ CC events, LBNF flux
Angular resolution	0.8°	ν_μ CC events, LBNF flux
Energy scale uncertainty	$\lesssim$ 1%	*(by spectrometry)
Proton detection threshold	5 MeV	kinetic energy
ECAL energy resolution	$6\%/\sqrt{E(\text{GeV})} \oplus 1.6\%/E(\text{GeV}) \oplus 4\%$	
ECAL pointing resolution	10° at 500 MeV	

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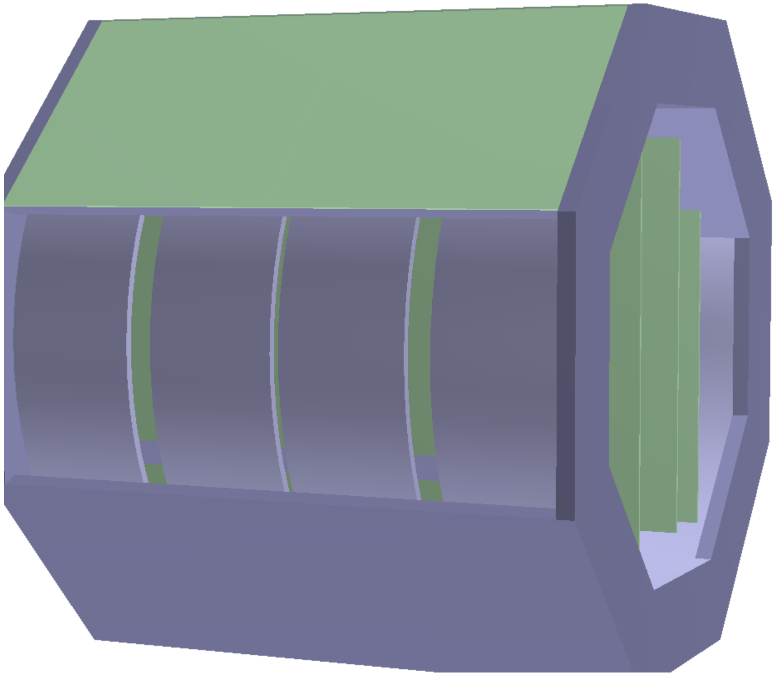
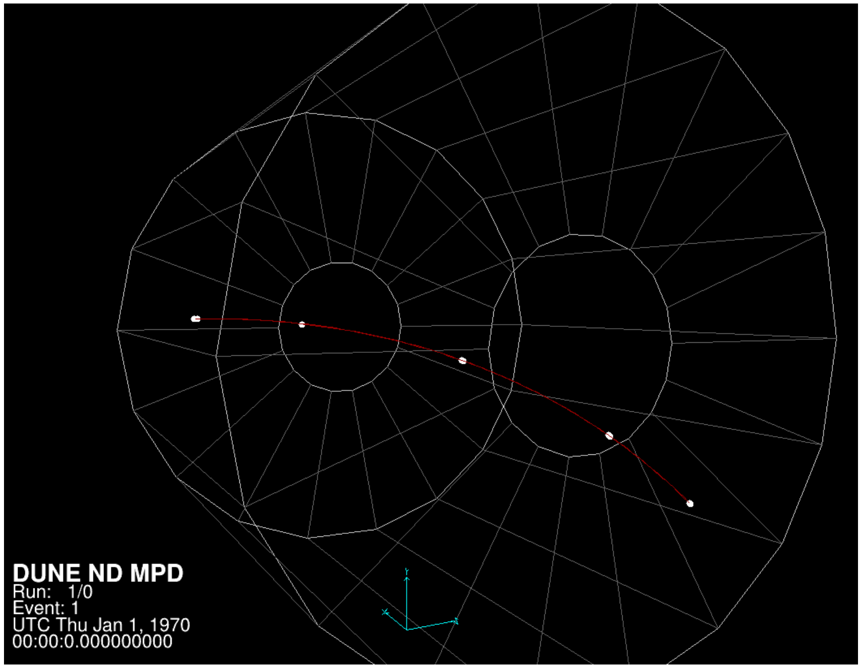
ND-GAr-Lite

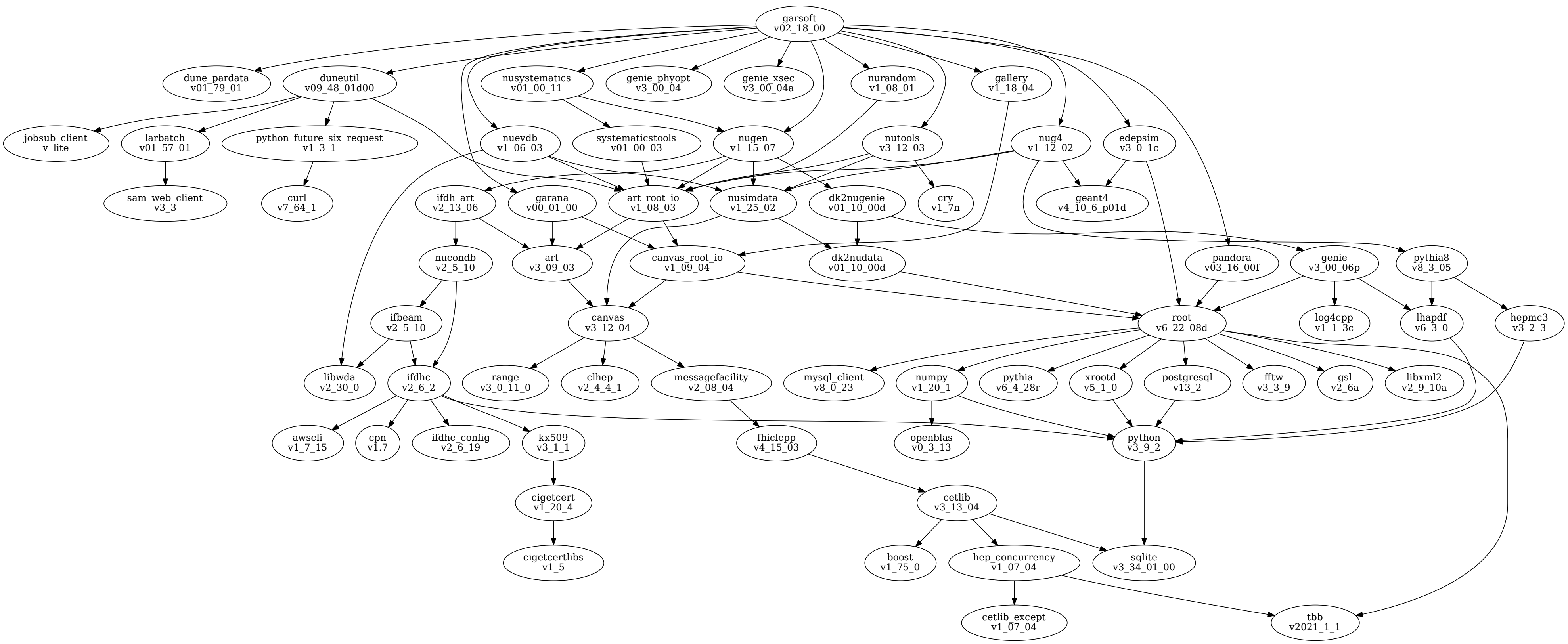
Sim + Reco algorithms are in garsoft but not maintained anymore





Recent work by Federico Battisti with a Kalman filter looks very good. Not yet included in GArSoft.

GArSoft's UPS Dependency Tree



https://github.com/DUNE/garsoft

Mostly art and nutools + dependencies. GENIE, ROOT, GEANT4, SAM, IFDH, Python

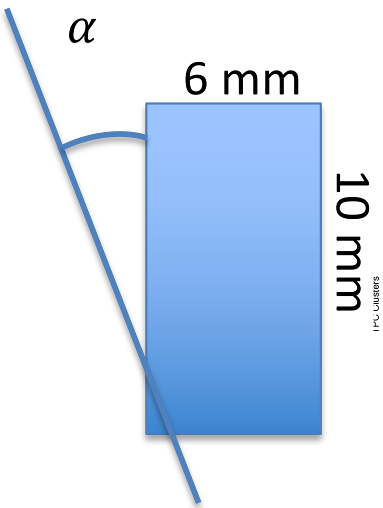
gcc and clang builds available in CVMFS. prof (optimized) and debug (non-optimized).

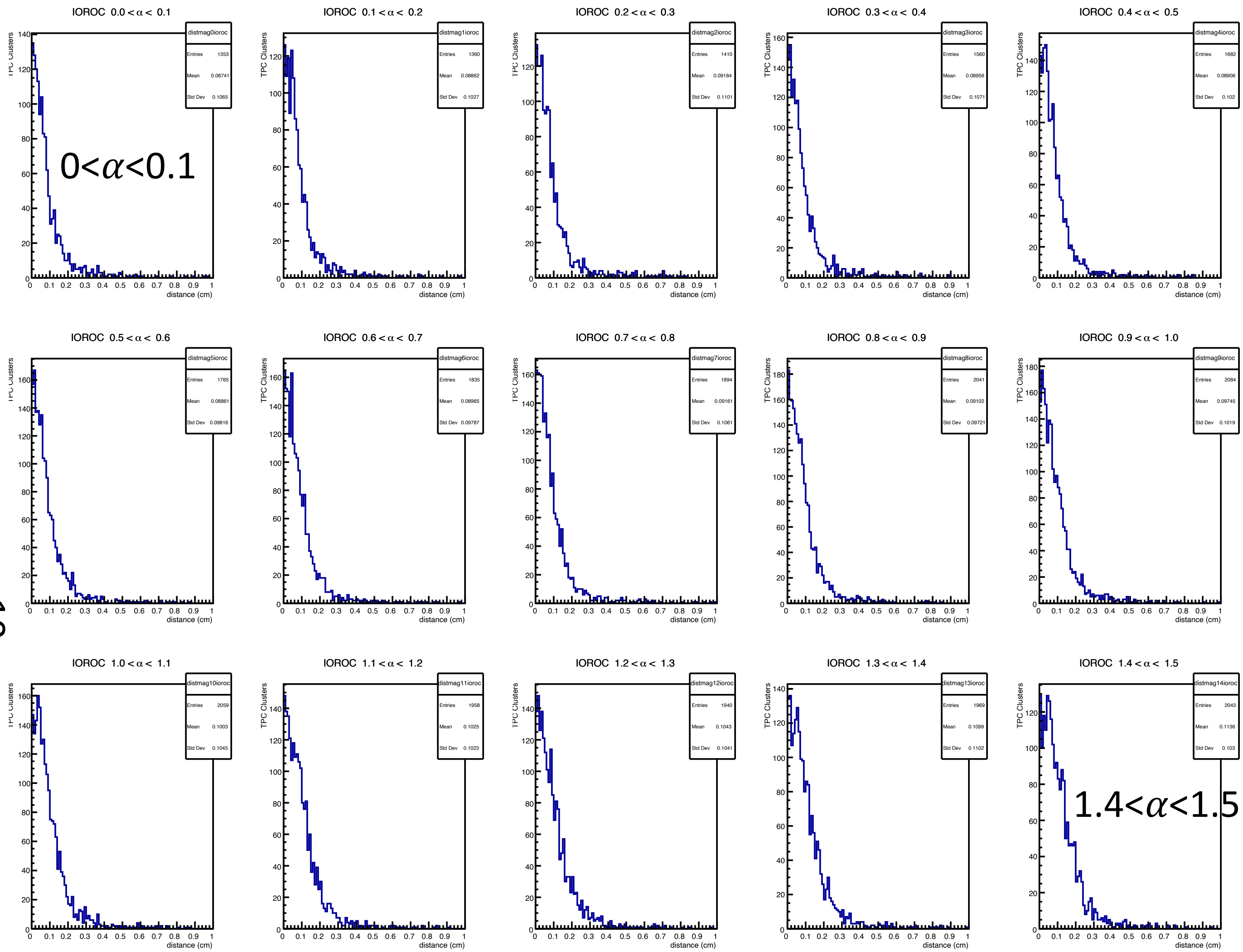
Software To-Dos

- Upgrade framework version
- Scintillation light simulation (S1 and S2) and reco support.
- Add CORSIKA, BXDECAY0 support
- Move to Spack
- Add CI tests
- Disable pushes to github repo and insist on pull requests
- Add a channel map and data unpacker for TOAD -- Anežka has made good progress on this.
- Analysis ntuple upgrades
- Analysis!

Extras

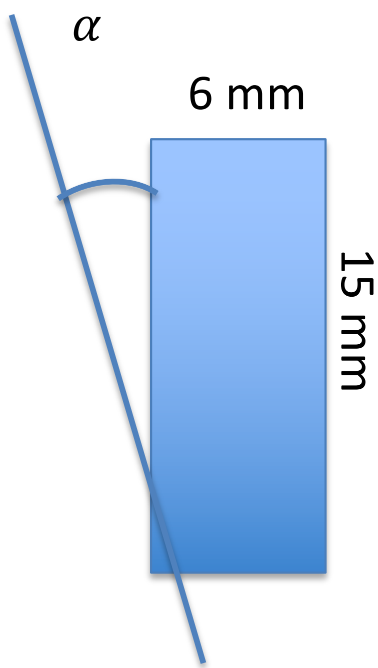
TPC Cluster Residuals vs. Angle: IOROC

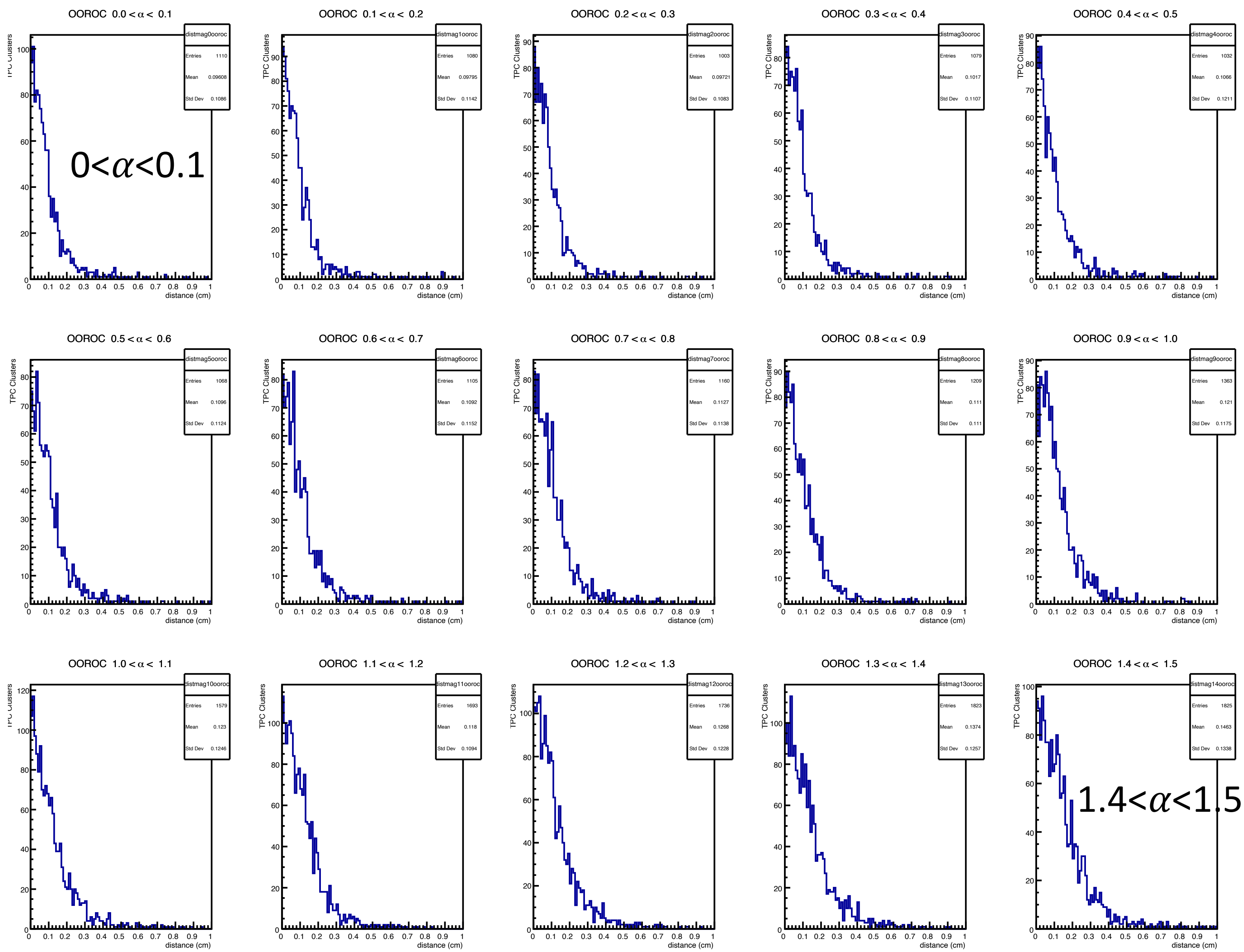




Wide hit clustering: 4 cm (transverse) x 2 cm (longitudinal) search window

TPC Cluster Residuals vs angle: OOROC





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My Reproduction of the IROC PRF

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

4 x 7.5 mm^2 pad

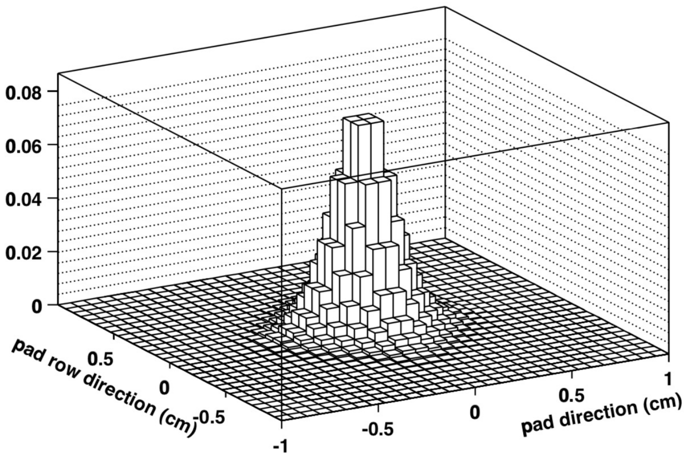


Figure 7.6: Induced-charge distribution according to Ref. [11]. Normalization is arbitrary.

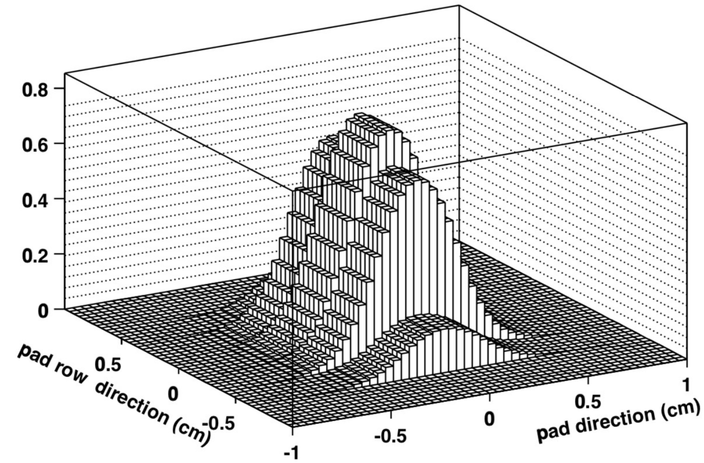
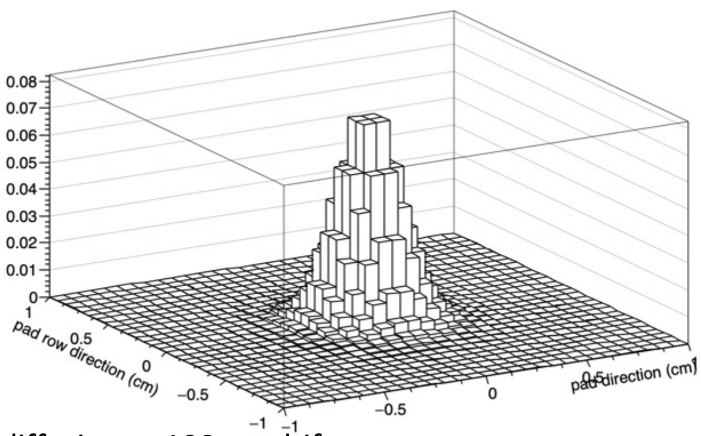
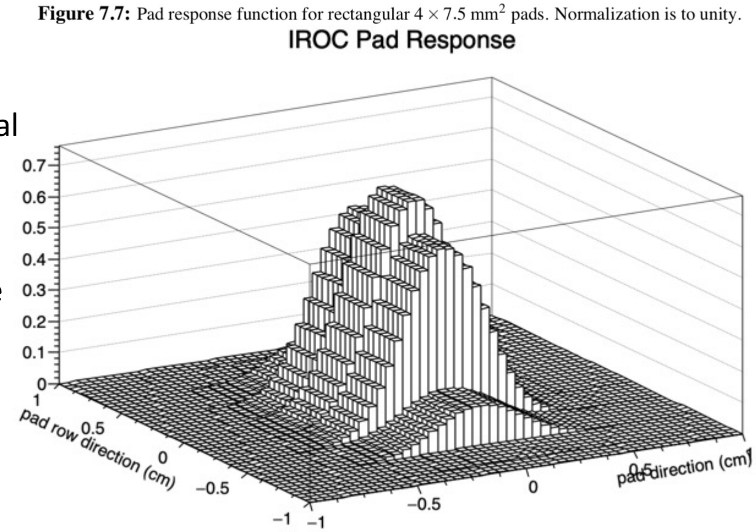


Figure 7.7: Pad response function for rectangular 4 × 7.5 mm^2 pads. Normalization is to unity.

7:1 mix of Gaussians with 1.22 mm and 2 mm widths c.f. 1.6 mm transverse diffusion at 100 cm drift



numerical integral over pad starting at anode wires



Short Stubs at the Primary Vertex

- Thomas Campbell started a project to use machine learning techniques to find short stubs (mainly protons, but we expect some pions down there too) at the primary vertex
- RANSAC-based pattern recognition and stub counting
- The low threshold is one of the selling points of a HPGTPC
- Thomas moved on to an industry job, and we need a replacement
- Mahmoud Ibrahim has gotten a start on ML reco starting with Thomas Campbell's work. Talk @May 2, 2023 ND-GAr meeting

Geometry Files: MPD-only World Volume

- MPD_ECalOctagon_60l_UniformMagnet.gdml

Baseline MPD with HPgTPC and Pressure Vessel (PV), an ECAL in Octagonal shape (8 sides) with 60 layers in Barrel and Endcap of 2 mm Cu, 5 mm Scint and a uniform cylinder magnet of Aluminium of around 100 turns

- MPD_ECalDodecagon_80l_UniformMagnet.gdml

MPD with HPgTPC and PV, an ECAL in Dodecagonal shape (12 sides) with 80 layers in Barrel and 60 layers in the Endcap of 2 mm Cu, 5 mm Scint and a uniform cylinder magnet of Aluminium of around 100 turns

E. Brianne

Geometry Files: MPD with LAr in ND Hall

- MPD_LAr_Hall_2CoilsMagnet_NoYoke.gdml

LArTPC and Baseline MPD with HPgTPC and PV, an ECAL in Octagonal shape (8 sides) with 60 layers in Barrel and Endcap of 2 mm Cu, 5 mm Scint and a 2 Helmholtz coil configuration w/o PRY

- MPD_LAr_Hall_4CoilsMagnet.gdml

LArTPC and Baseline MPD with HPgTPC and PV, an ECAL in Octagonal shape (8 sides) with 60 layers in Barrel and Endcap of 2 mm Cu, 5 mm Scint and a 4 Helmholtz coil configuration (removed central coil)

- MPD_LAr_Hall_5CoilsMagnet.gdml

LArTPC and Baseline MPD with HPgTPC and PV, an ECAL in Octagonal shape (8 sides) with 60 layers in Barrel and Endcap of 2 mm Cu, 5 mm Scint and a 5 Helmholtz coil configuration

E. Brianne

Geometry Files: MPD with LAr in ND Hall

continued from previous slide

- MPD_LAr_Hall_SPYMagnet.gdml

LArTPC and Baseline MPD with HPgTPC and PV, an ECAL in Octagonal shape (8 sides) with 60 layers in Barrel and Endcap of 2 mm Cu, 5 mm Scint and the SPY Magnet configuration and a PRY according to the ND WS at DESY (https://indico.fnal.gov/event/21340/session/5/contribution/40/material/slides/0.pdf)

- MPD_LAr_Hall_UniformMagnet.gdml

LArTPC and Baseline MPD with HPgTPC and PV, an ECAL in Octagonal shape (8 sides) with 60 layers in Barrel and Endcap of 2 mm Cu, 5 mm Scint and a uniform cylindrical magnet of Aluminium of around 100t

E. Brianne

Geometry Files: Full ND Complex

- ND_Baseline_Hall.gdml

Full ND Complex baseline in the hall

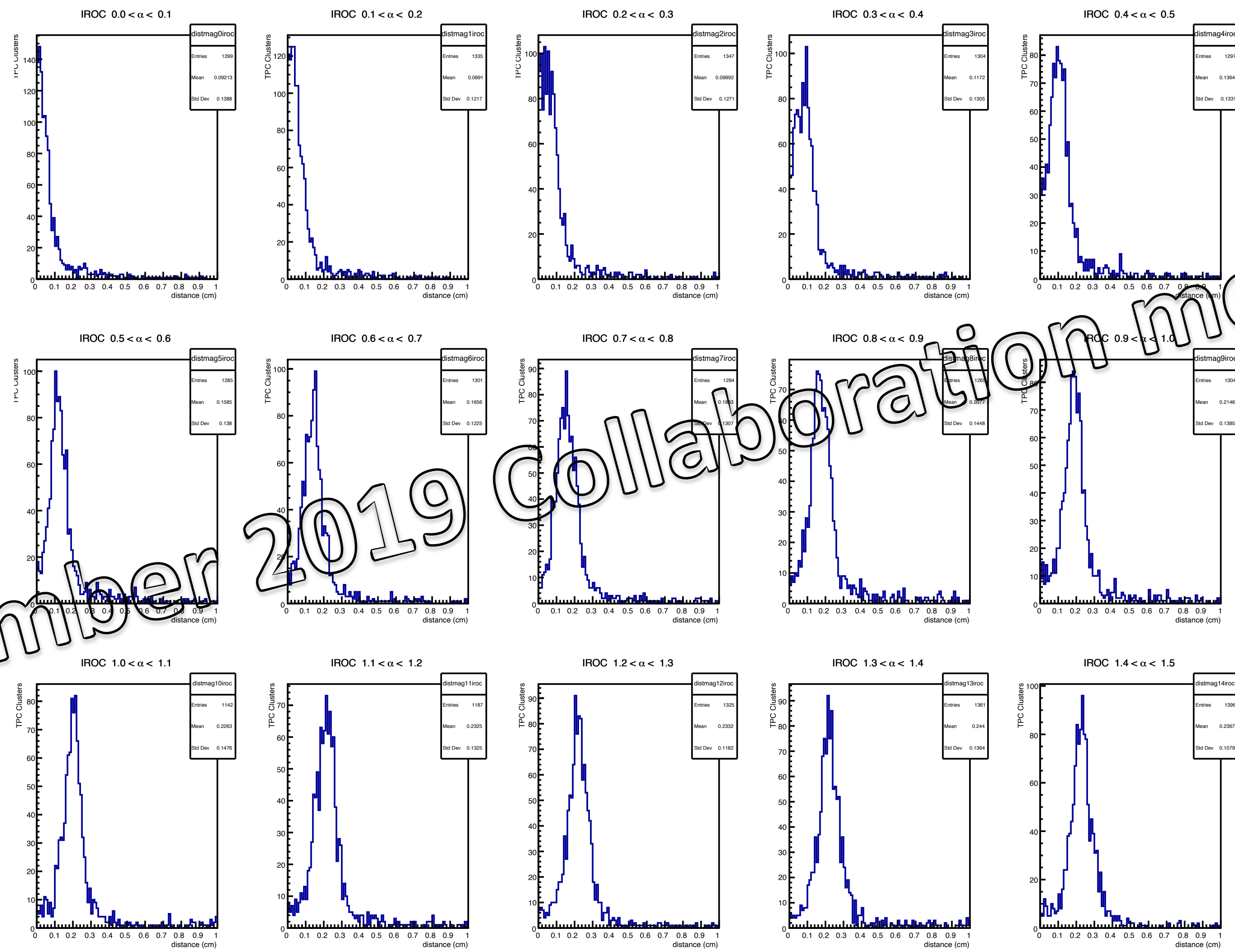
- ND_onlyMPD_Hall.gdml

Only MPD baseline in the hall

E. Brianne

TPC Cluster Residuals vs. Angle: IROC

Work In Progress



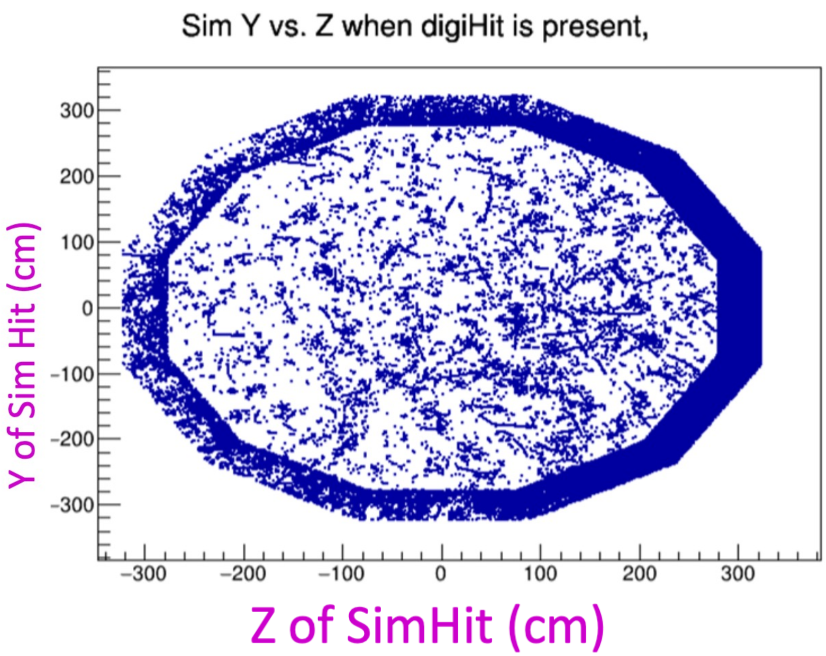
Wide hit clustering: 4 cm (transverse) x 2 cm (longitudinal) search window

Off by ~half a pad – to fix

Some Tracking Reco To-Dos

- Characterize and improve TPC Cluster resolution – V. Aushev and O. Gagota
- Improve vertex finding and resolution – Tom is starting to investigate a GNN for doing this in 3D
- Improve short-track reconstruction near the primary vertex
  - TPC clusters from separate tracks are nearby, causing pattern-recognition mistakes

Calorimeter Simulation and Reconstruction



Leo Bellantoni and Vivek Jain

12-sided geometry of uniform thickness from Eldwan Brianne

Many recent fixes and upgrades from Leo:

- skip Eldwan's strip-splitter algorithm which made ghost clusters
- Fix speed of light in scintillator
- Harmonize code and gdml files – some gdml files had evolved faster than the code -- also an issue for LArSoft – make sure gdmls match corresponding code
- Add muons to BackTracker

Leo's ECAL To-Do:

1. Tune the clustering parameter using electrons in events with overlays.
2. Spend some time looking at track reco failures.
   1. Maybe we should just throw some packaged algorithm at our tracking?
   2. If the track reco failure level gets low enough, try *dE*/*dx* again.
3. Retune the ECAL – reco track matching
4. Take another go at identification of ν_e events
5. As we get results from TOAD re the pulse shape, incorporate them into the TPC simulation.

Vivek Jain has also been looking at clustering parameters using electrons (but without overlays), uncovering and fixing bugs. He's working with Leo.