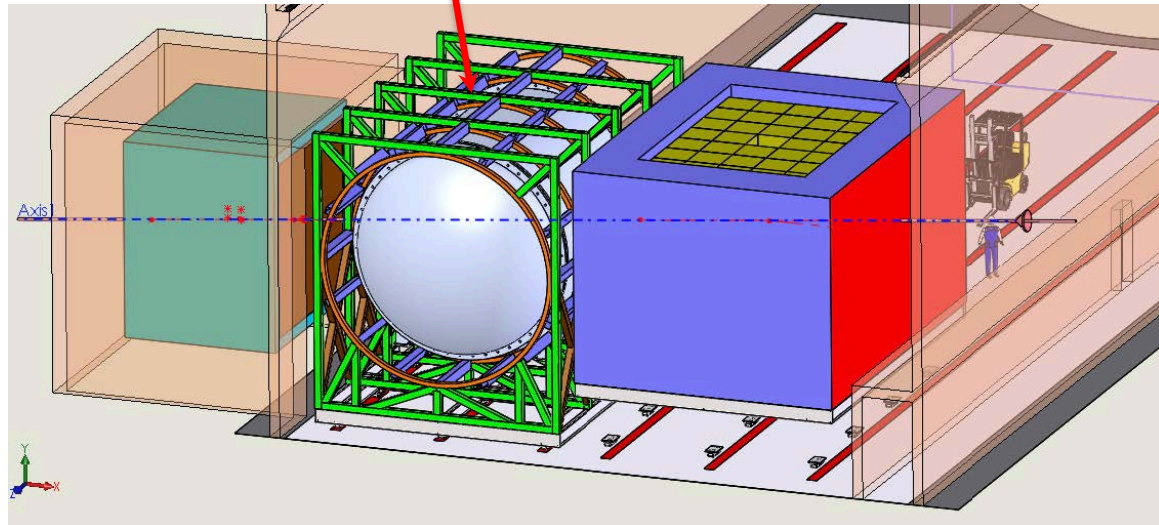


# Multi-purpose detector (MPD) *Design Status*

Alan Bross  
LBNC Meeting, Fermilab  
June 4<sup>th</sup> , 2019





# Goals for this talk

- Provide the review committee with an “existence proof” for a plausible and achievable MPD design that will meet the requirements set in the physics TDR. *This will not be an optimized design, but will, we believe be enough to permit sign-off on the physics TDR.*
  - What are the detector requirements?
    - *One highly desired, but not requirement per se*
  - What are the MPD’s capabilities w/r to the oscillation analysis?
  - Is the MPD plausible and achievable?
  - Is the detector complexity, size well motivated?
  - What are the technical risks?



# Performance requirements for MPD

- Measure particles that leave the LAr ND component and enter the MPD
- Constrain neutrino-nucleus interaction systematic uncertainties
- Precisely measure all-components of the neutrino flux
  - $\nu_\mu$ ,  $\bar{\nu}_\mu$ ,  $\nu_e$ ,  $\bar{\nu}_e$
- Reconstruct neutrino energy via spectrometry and calorimetry
- Constrain LArTPC detector response and selection efficiency
- Measure energetic neutrons from  $\nu$ -Ar interactions via time-of-flight with the ECAL (*Desired*)



# Capabilities that deliver on the requirements

- Provide statistically significant, independent  $\nu$  event sample on Ar
- High-resolution particle momentum and charge determination via magnetic curvature.
  - $\nu_e$  and  $\nu_\mu$  tagging with little background contamination
  - $\nu_e$  and  $\nu_e$ -bar tagging (only system that can do this reliably)
  - Energy scale to 1% (Curvature, Ks,  $\Lambda$ s)
  - Provides measurement of the momentum of higher-energy charged particles without requiring containment.
    - Acceptance mimics the FD (i.e. is essentially flat)
- High-resolution imaging of particles emerging from the  $\nu$ -Ar vertex (including nucleons).
- Separation of tracks and showers for less-ambiguous reconstruction (low-density detector).



# Multi-purpose detector details

- High-Pressure (10 bar) Ar gas TPC (HPgTPC)
  - Copy of ALICE TPC (5m in diameter X 5m long active)
    - Coincidentally the right size
      - Good  $\mu$  (from LAr) acceptance
      - 1t fiducial target mass (90-10 Ar-CH<sub>4</sub>, 97% interactions on Ar)
  - Very low recon  $E_{\text{thres}}$  for charged tracks ( $\sim 5$  MeV)
  - Exquisite PID
  - In  $\sim 0.5$ T field (magnetic spectrometer)
- Surrounded by high-performance ECAL and muon tagger
  - Calorimetric analysis for neutrals
  - Optimization study just getting started
  - Neutron detection (tagging) using ECAL
    - With potential to measure  $E_n$  via TOF



# Event rates in HPgTPC

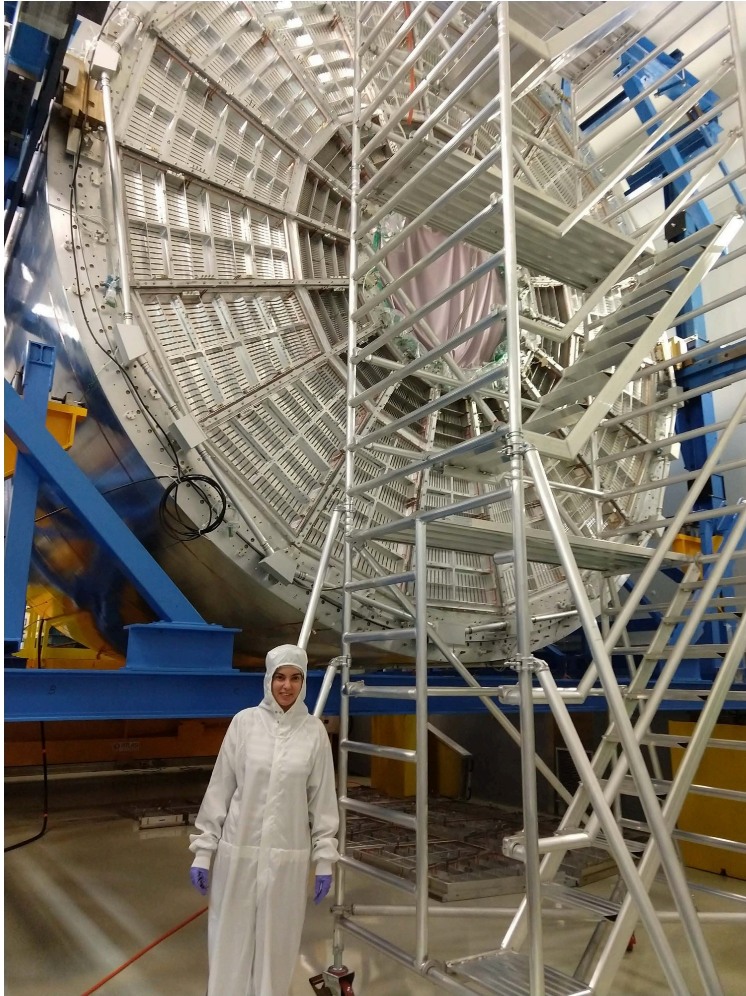
FHC

Event Class	#evts per year
$\nu_{\mu}$ CC	$1.5 \times 10^6$
$\nu_{\mu}$ CC-bar	$5 \times 10^4$
$\nu_e$ CC	$2 \times 10^4$
$\nu_e$ CC-bar	$5 \times 10^3$

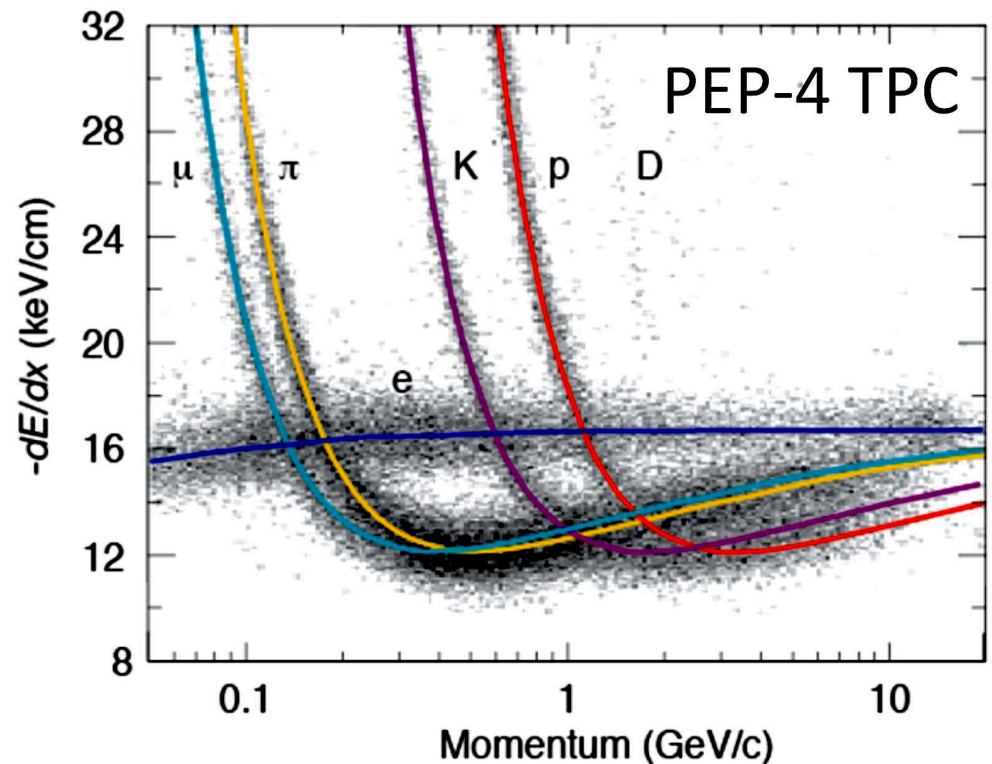


# MPD – High-pressure gas TPC

US, India, Spain, UK



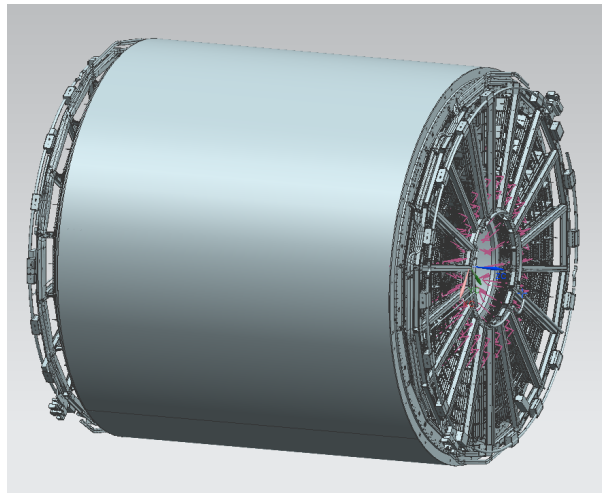
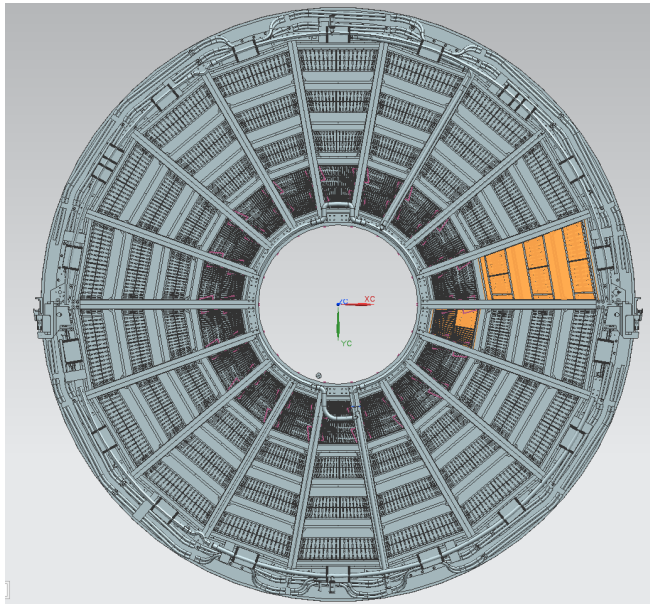
Well established technology  
Vetted detector design



We expect  $\sim 2\%$   $dE/dx$  resolution based on PEP4  
ALICE obtains 5-6%



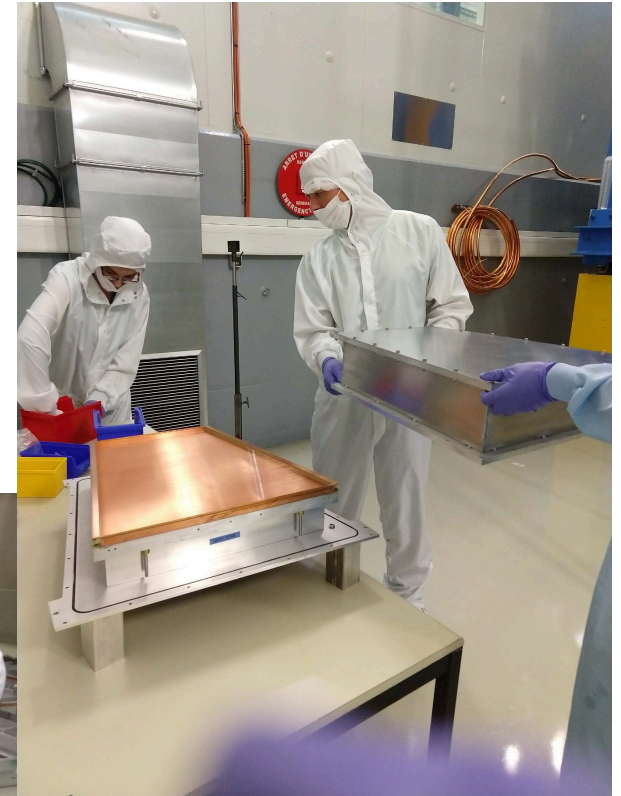
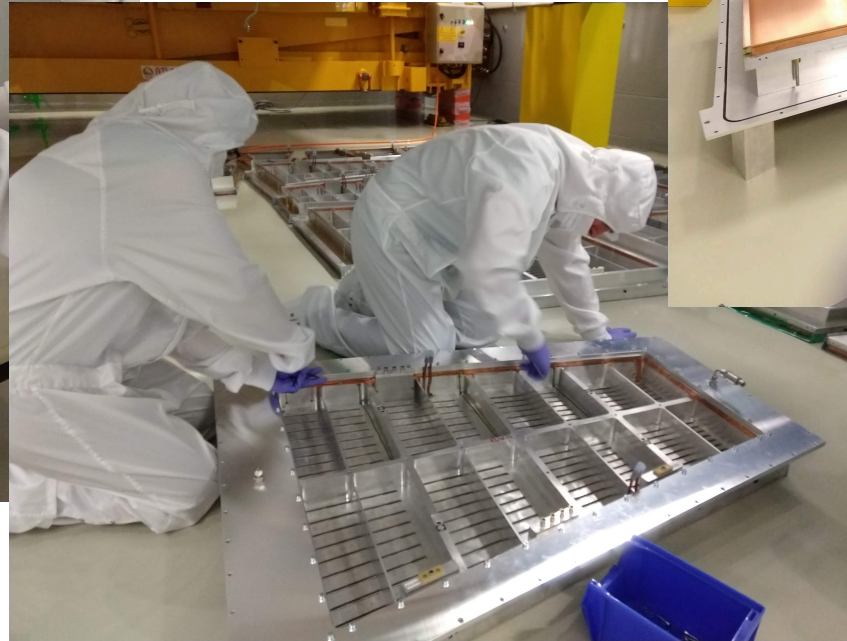
# Readout chambers



- We are acquiring 36 outer readout chambers and 36 inner readout chambers from ALICE.
- I wanted to show these figures because they represent a full as-built 3D, CAD model of the detector. This alone is a significant contribution
- And also note that we will have to build two chambers to fill in the central hole
  - No inner field cage



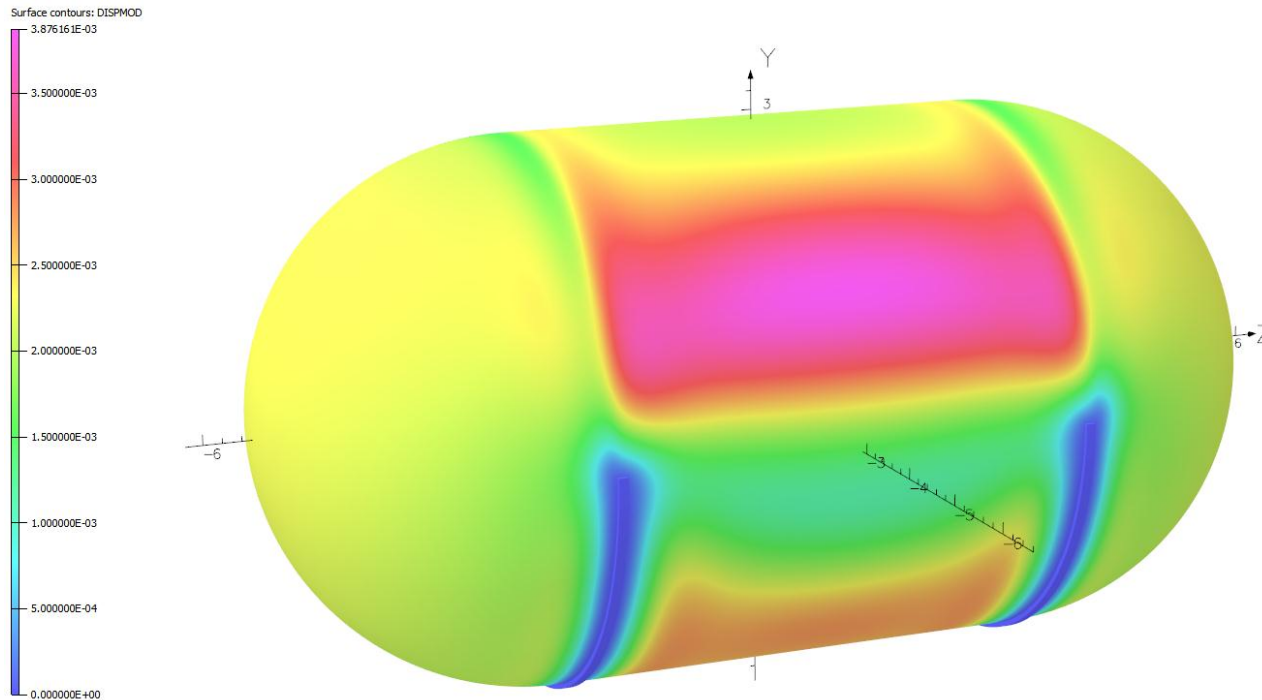
# ALICE chamber acquisition





# Pressure Vessel

- Bhabha Atomic Research Centre (BARC), Mumbai, is working on optimizing the design of the HPgTPC pressure vessel
- Good progress to date
  - Using Al alloy reached thickness of  $\sim 0.4X_0$

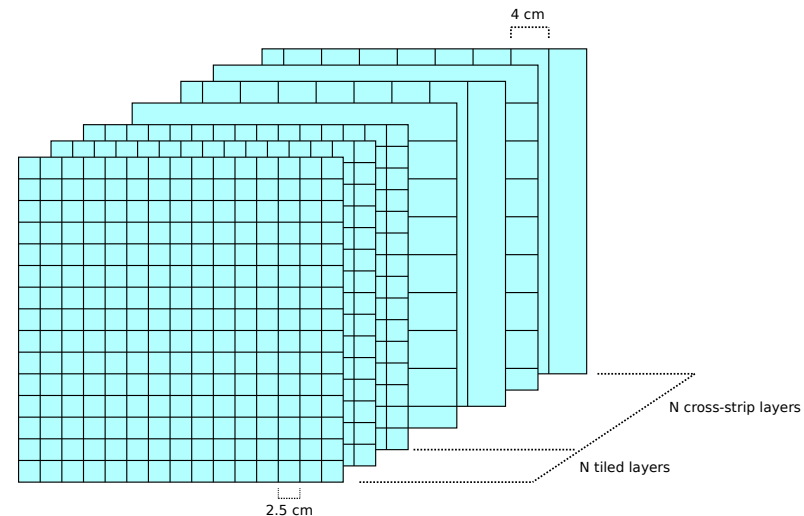
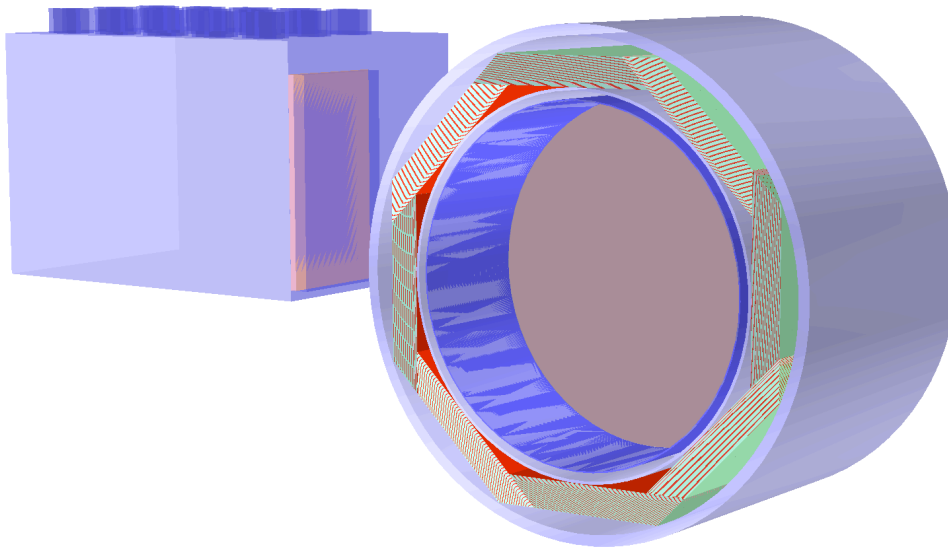




# ECAL

Germany, US

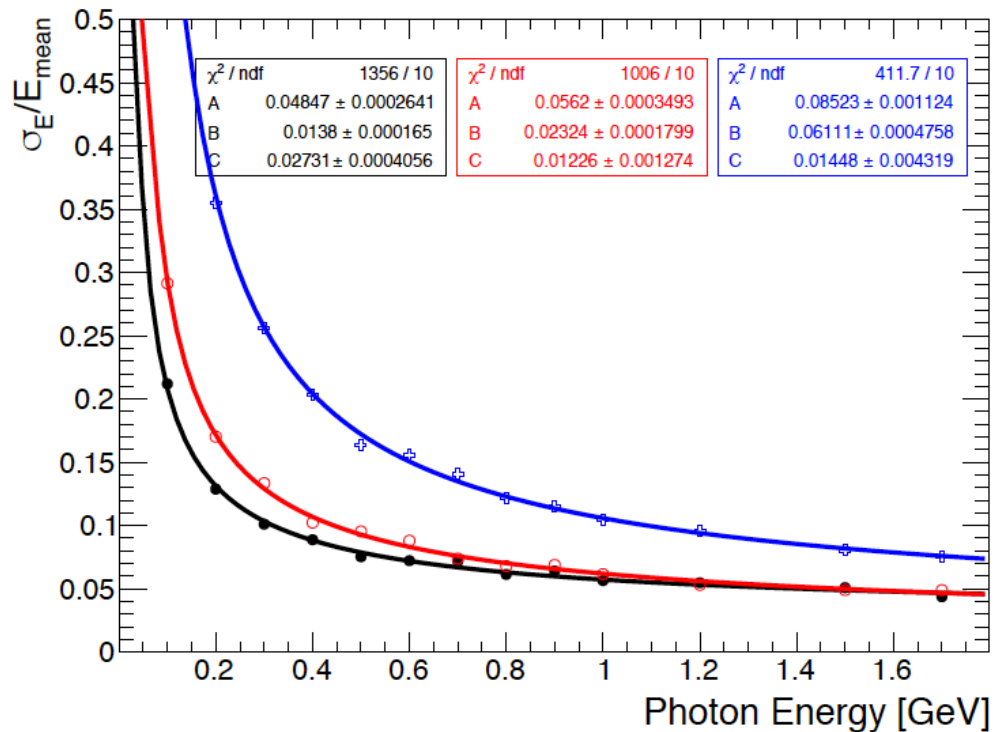
- Surrounds HPgTPC to detect photons and neutrons
- Plastic scintillator tiles & strips
- SiPM readout now affordable due to recent significant cost reductions





# ECAL optimization

- Optimization  $\Rightarrow$  calorimeter energy resolution, angular resolution, neutron detection specification
- Cost drivers: Granularity, absorber material/thickness, number of layers (depth)
- Look at the influence of:
  - Granularity
  - Absorber thickness
  - Scintillator thickness
  - Pressure vessel



From the point-of-view of  $\sigma_E$ , the pressure vessel design already meets spec.

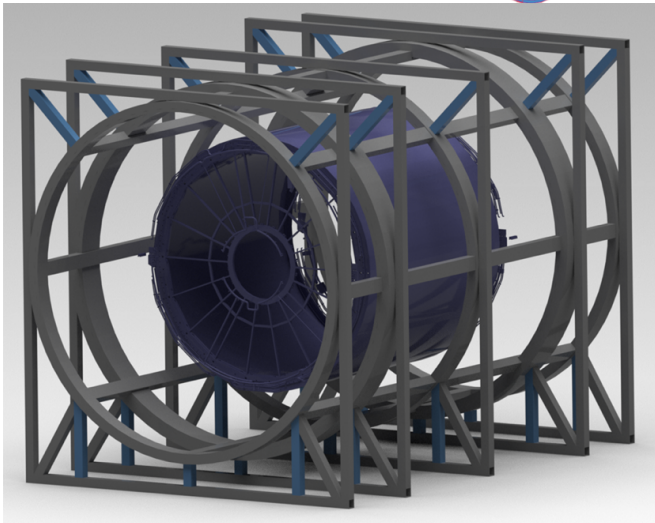
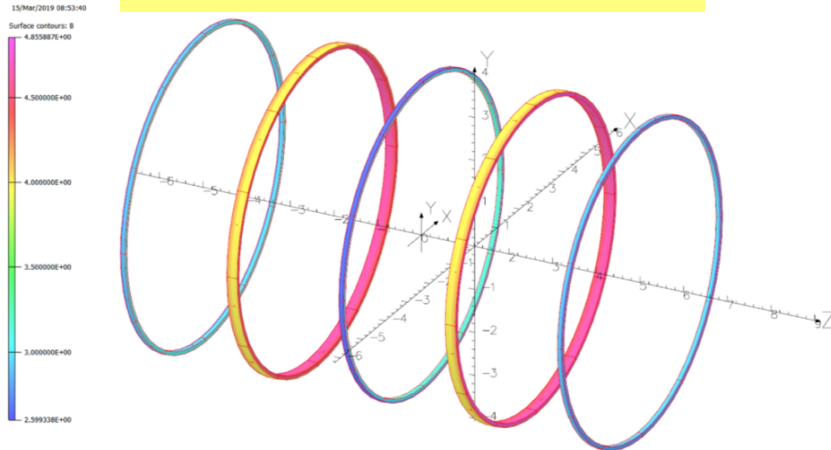
Blue ( $2X_0$ ), Red ( $1X_0$ ), Black ( $0.5X_0$ )



# Magnet: Superconducting 3-coil Helmholtz with superconducting bucking coils

US, India, Italy

Magnetic model showing coils only.



Current mechanical design concept

- Overarching requirements
  - Large acceptance for particles leaving LAr
  - Present minimal mass
- Central field = 0.5T
- Side coils at 2.5 m, shielding coils placed at 5 m from the magnet center in Z.
  - All coils have the same inner radius 3.5 m and outer radius 3.59 m.
  - Center and shielding coils are identical.
- Our BARC colleagues have looked at NC design optimization
  - Still very high power– 4MW



# MPD: Reconstruction: GArSoft

## Implemented

- Event Generation
- Detector Geometry
- Particle Interactions & Energy Deposits
- Drift and Diffusion
- Digitization
- Hit finding and clustering
- Pattern recognition
- Track fitting
- ECAL Digitization
- ECAL Reconstruction
- Ionization-Based Particle ID
  - Initial version exists – needs work

## To do (to some degree optimization)

- TPC Field Response and Electronics Response
- Optimize pattern recognition in difficult cases
- Optimize track fit
- Very short tracks in crowded environments will require innovative algorithms
  - Deep learning methods being studied now
- Vertexing
  - Preliminary vertex-finding algorithm written and tested
- ECAL
  - Cluster-Track matching
  - Full energy reconstruction (only visible energy for now)
  - .....

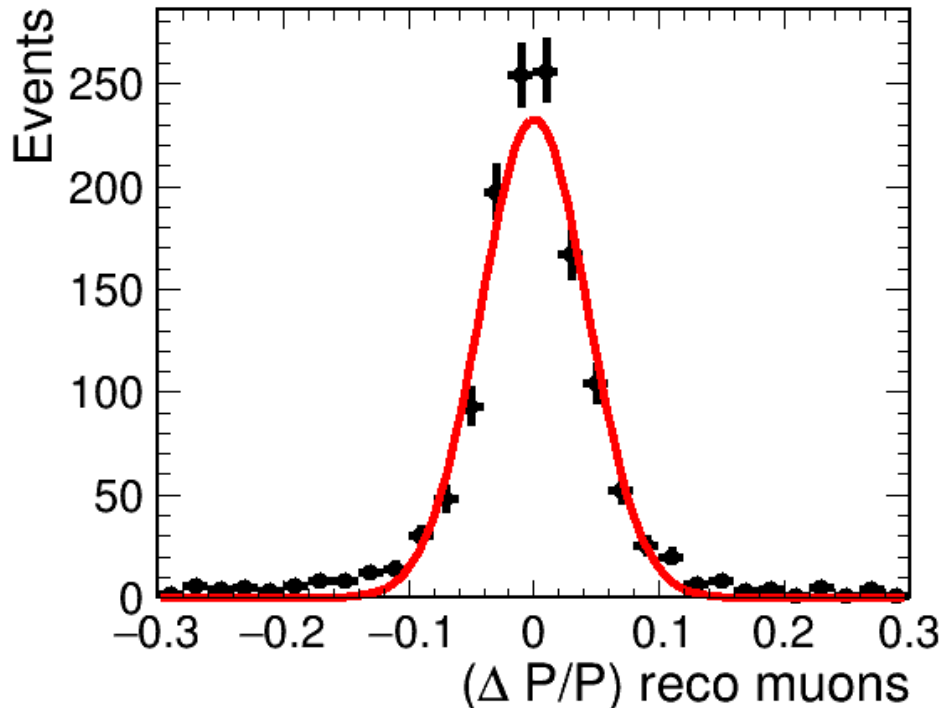
DUNE-Doc 13933



# GArSoft Tracking Resolution: muons

Test sample: 1477  $\nu_\mu$  CC events, with neutrino energy = 2 GeV

$B = 0.4T$



First pass “snap shot”  
at full  
analysis

Muon momentum resolution: 4.2% in this sample

[Note: With 0.5T field  $\rightarrow$  3.4%]

Currently using a point set resolution of  $\sim 1\text{mm}$

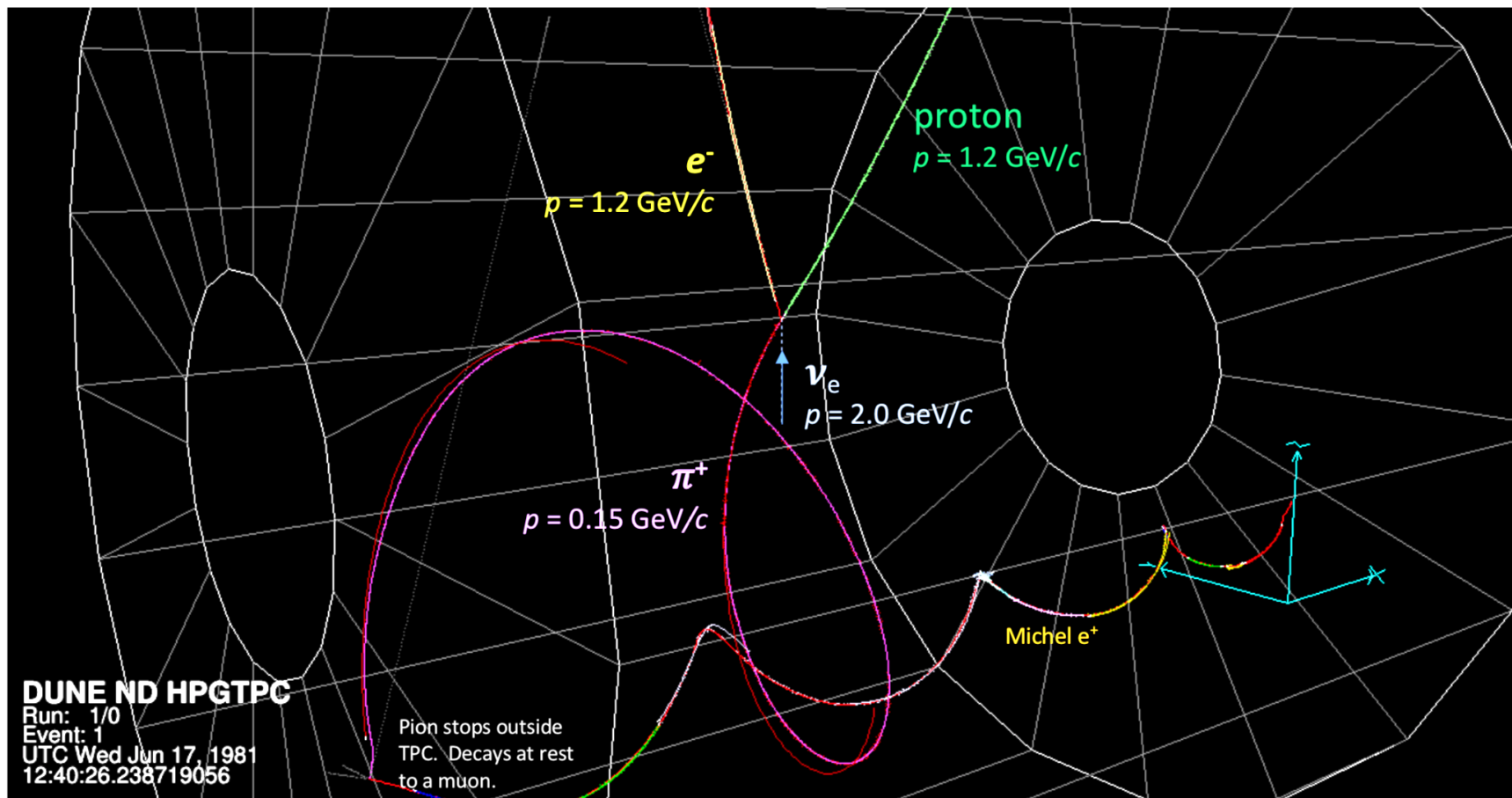
At 10 Atm, we should do much better: 200-300  $\mu\text{m}$  (PEP4)

Should approach 2%



# A Simulated and Reconstructed $\nu_e$ Charged Current Event in the HPGTPC

$$\nu_e + \text{Ar} \rightarrow e^- + \pi^+ + p + n$$



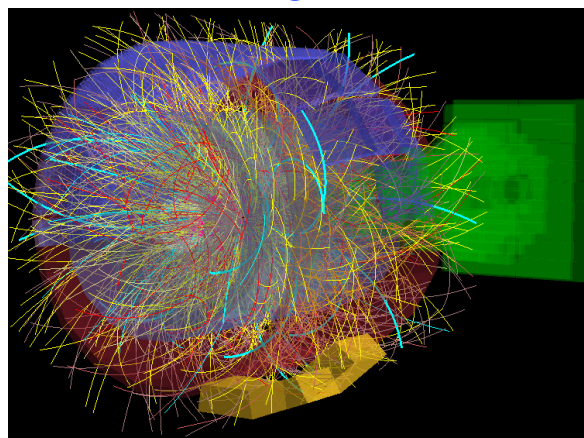
Neutron with  $p = 0.23 \text{ GeV}/c$  at the P.V. not shown



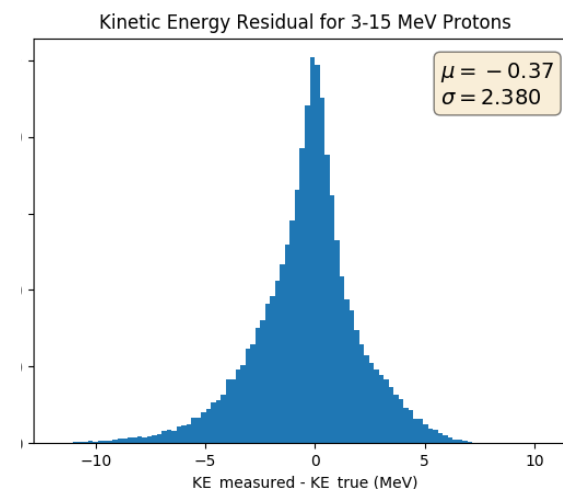
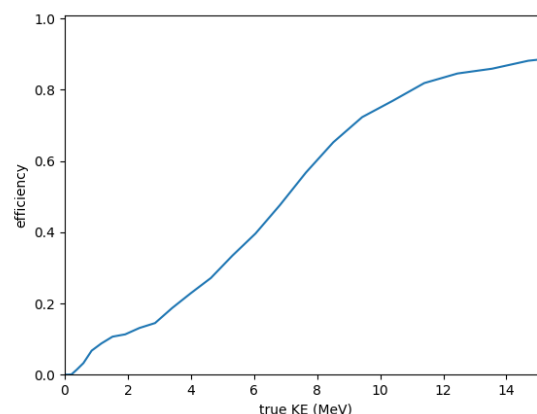
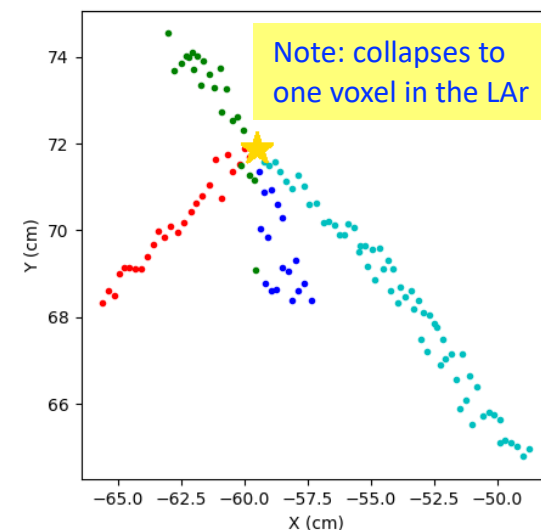
# Finding Short Tracks Near the Primary Vertex

- Although the average occupancy per spill in the HPgTPC is very small ( $\mathcal{O} 10^{-4}$ ), the local (near vertex) occupancy can be large ( $\mathcal{O} 10^{-1}$ )
- RANSAC line finding + Neural Network for p/ $\pi$  separation and energy estimation
- $\varepsilon$ :  
20% @ 5 MeV  $\rightarrow$  80% @ 10 MeV

ALICE



This is 15  $\rightarrow$  40% pad occupancy  
 $\mathcal{O} 10^{-1}$  voxel occupancy

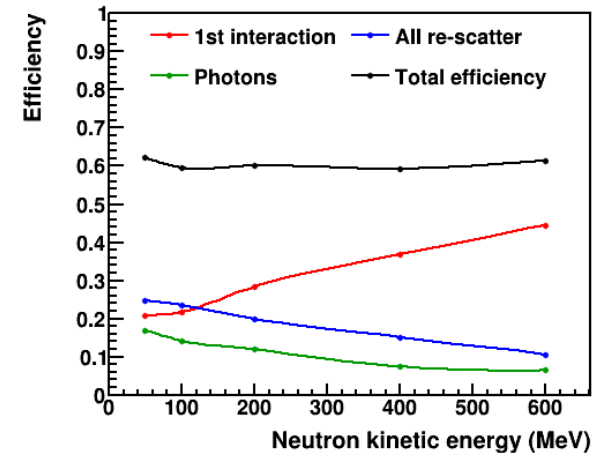




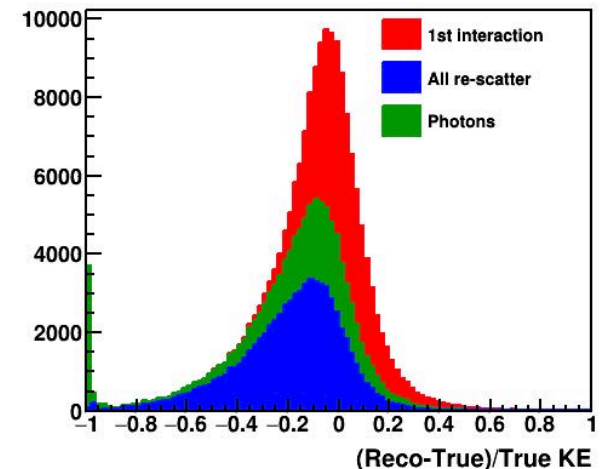
# Event reconstruction: neutrons

60 modules

- Top plot: Efficiency for neutron event classes
- Bottom plot shows the relationship between reconstructed and true neutron energy for the three categories laid out above.
  - Although overall e high, re-scatters and photons degrade  $E_{\text{reco}}$
  - Background neutrons need to be added
- Event-by-event n recon will be difficult
  - Average over event class ( $\nu_{\mu}$  CC QE-like) with tight cuts



KE = 100 MeV, 60 modules, 100 - 400cm lever arm





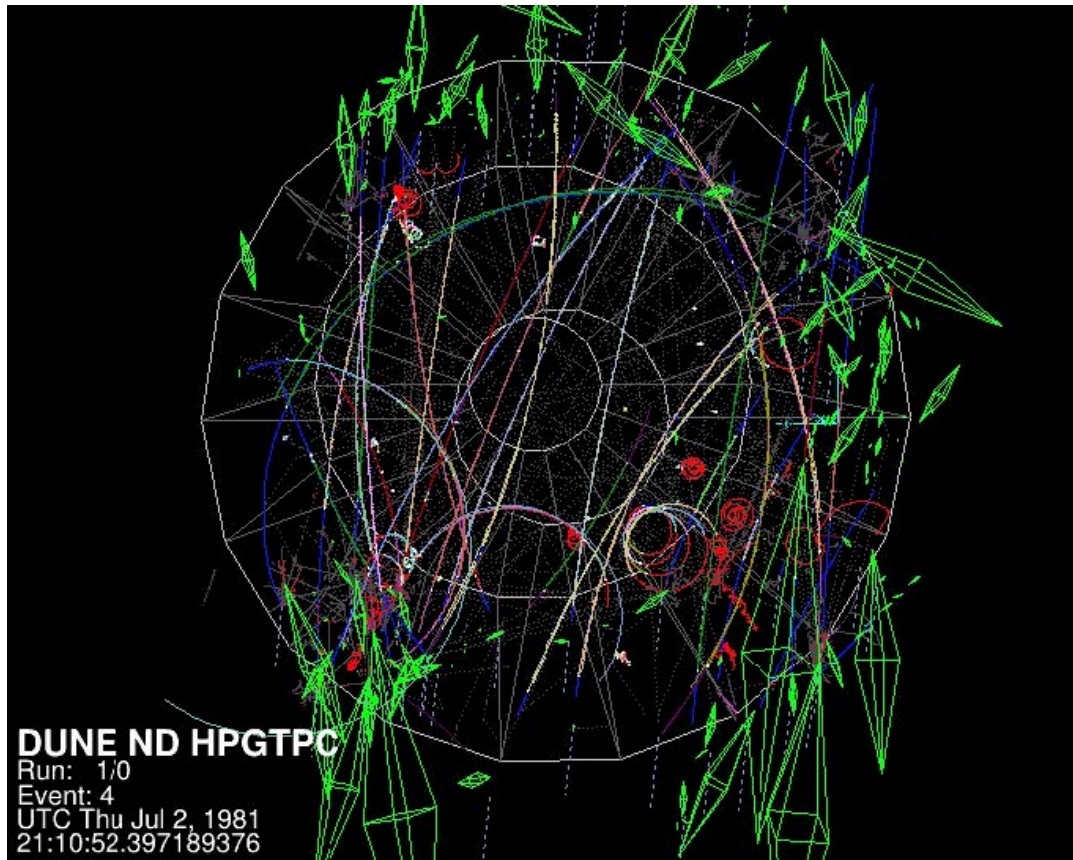
# Backgrounds

- Although the HPgTPC's fiducial mass is large for a gas device, its mass is  $\ll$  smaller than the ECAL (X300) and the magnet (X100)
- Interactions outside of the HPgTPC can cause issues, since the HPgTPC is a slow device without a fluorescence tag
- Two classes
  - Reconstruction of real events in the gas are “distorted” by activity not associated with the event
    - Can both add unrelated activity or cause activity from the event to be missed/lost
  - Background activity in the gas is reconstructed as a false event
    - $\nu_\mu$  from entering  $\mu$
    - $\nu_e$  from entering  $\gamma$



# Background activity per spill

Hits integrated over full spill

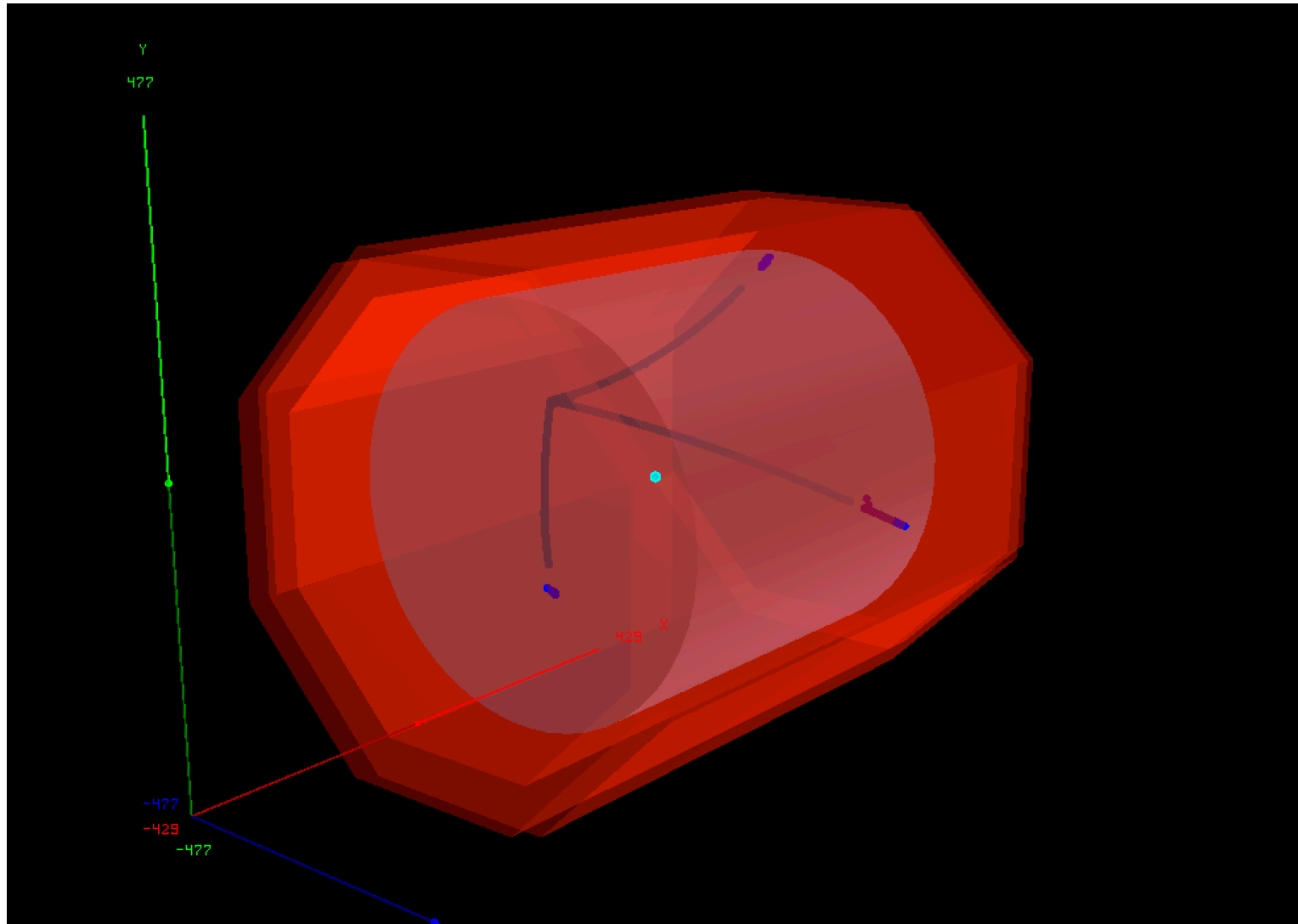


Background	# per spill
Muons	20
Photons (>150 MeV)	3

- We can cut on
  - Timing
  - Direction
  - $dE/dx$
  - Opening angle
  - Momentum analysis

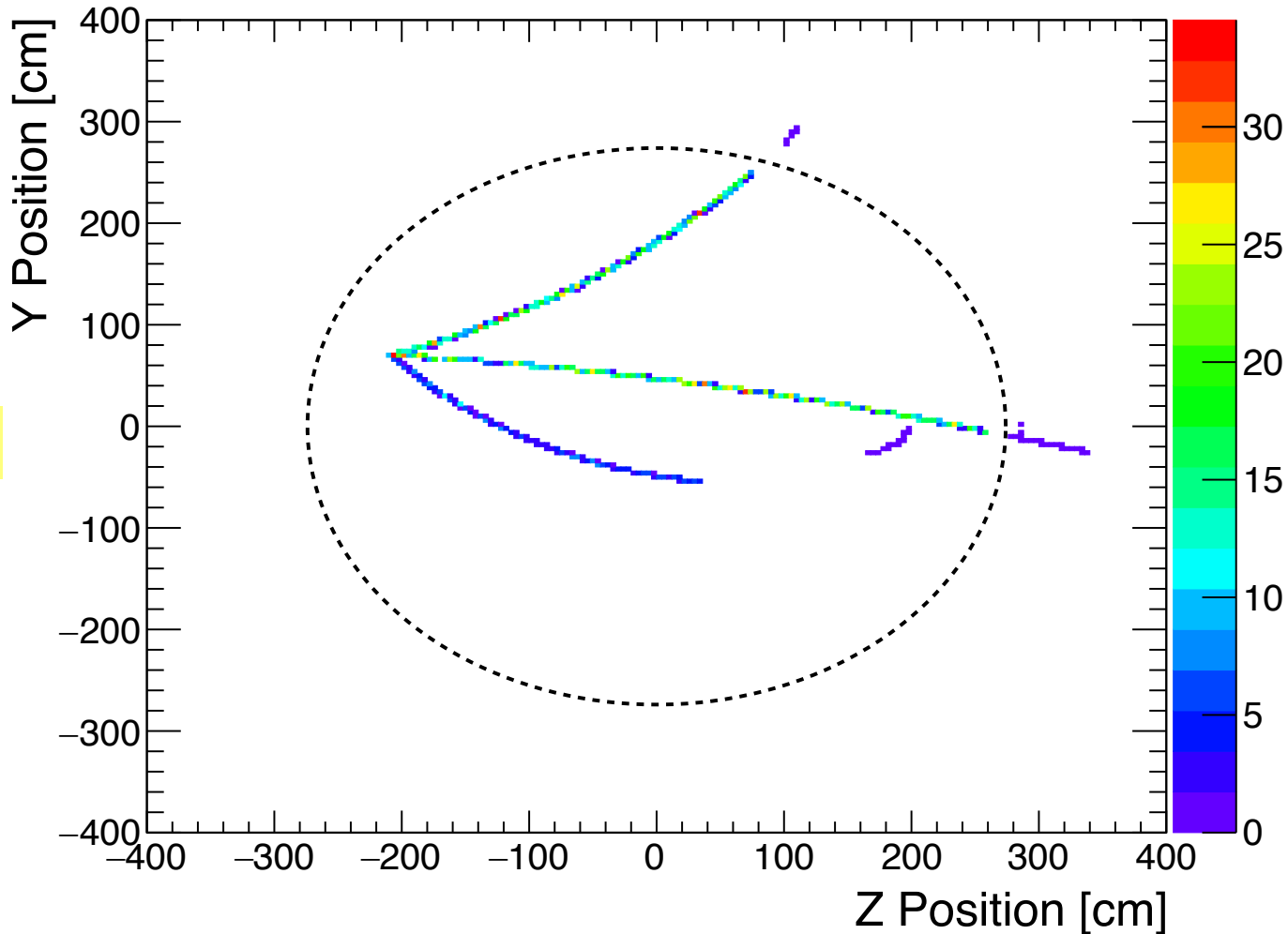


# $\nu_\mu$ CC background study – test event





# Z-Y Projection: Sample event - $\nu_\mu$ CC

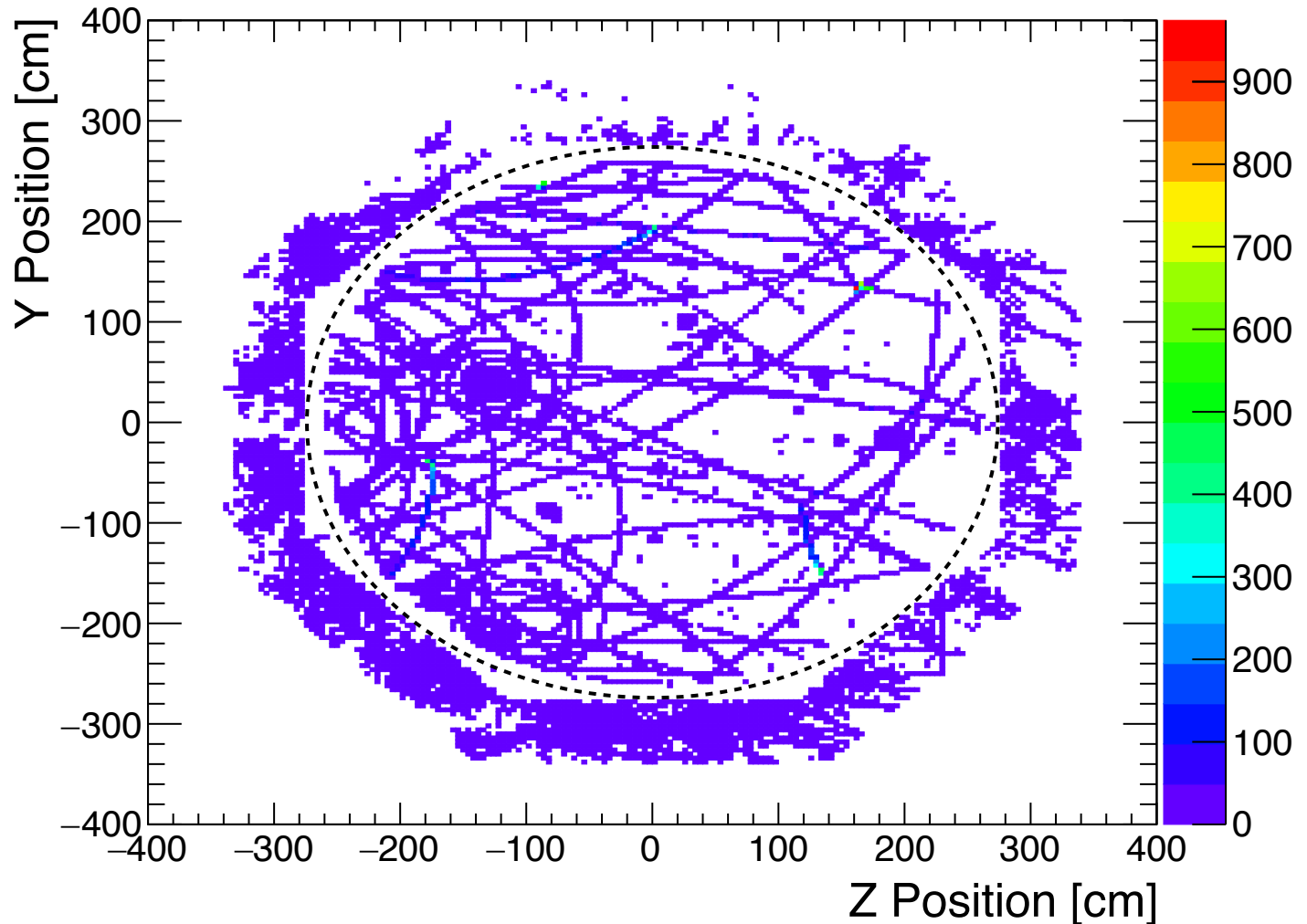


Test event



# Z-Y projection full spill & event

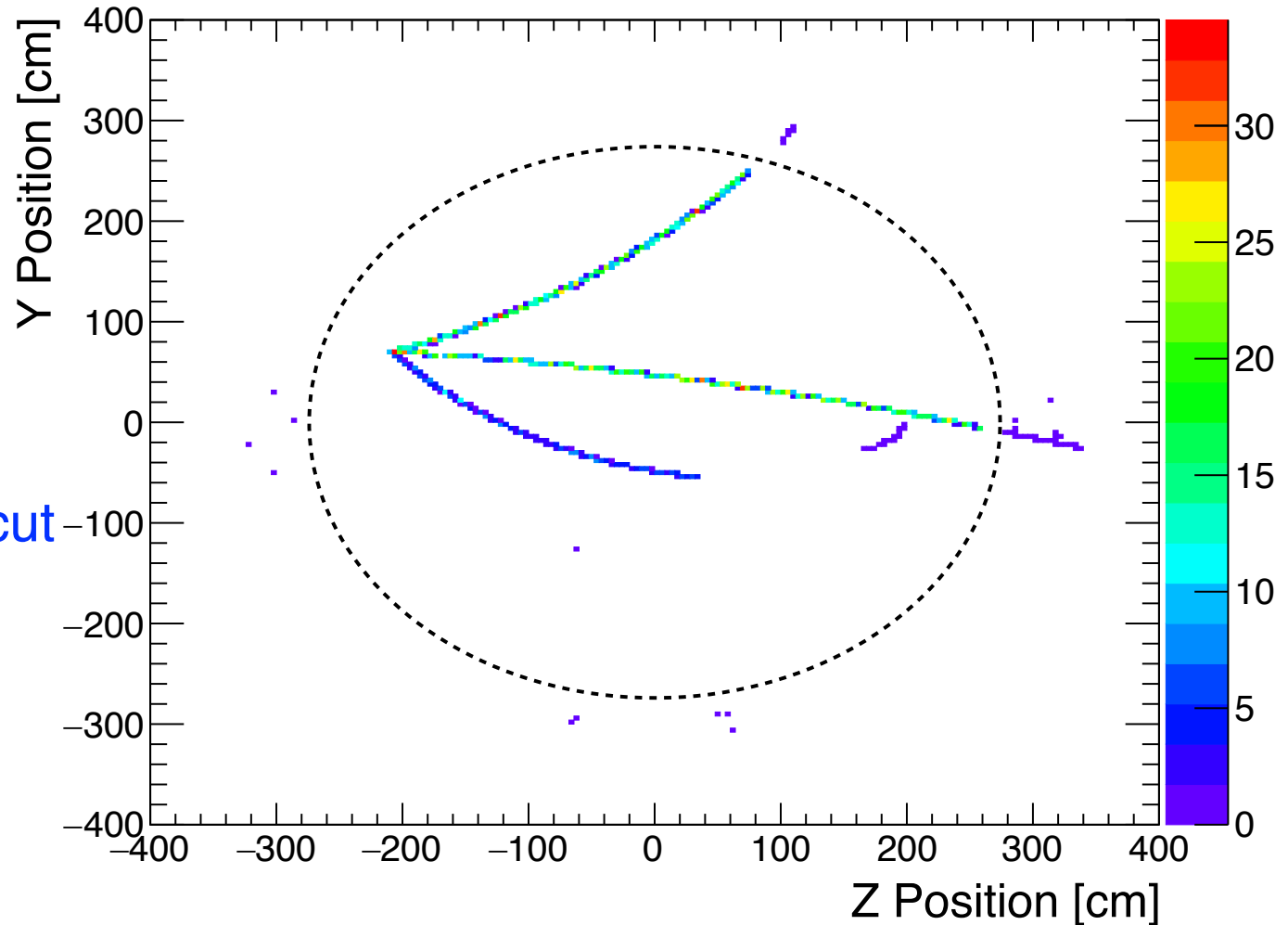
- Corresponds to full spill exposure
- Overlay of test event plus 60 events in the ECAL





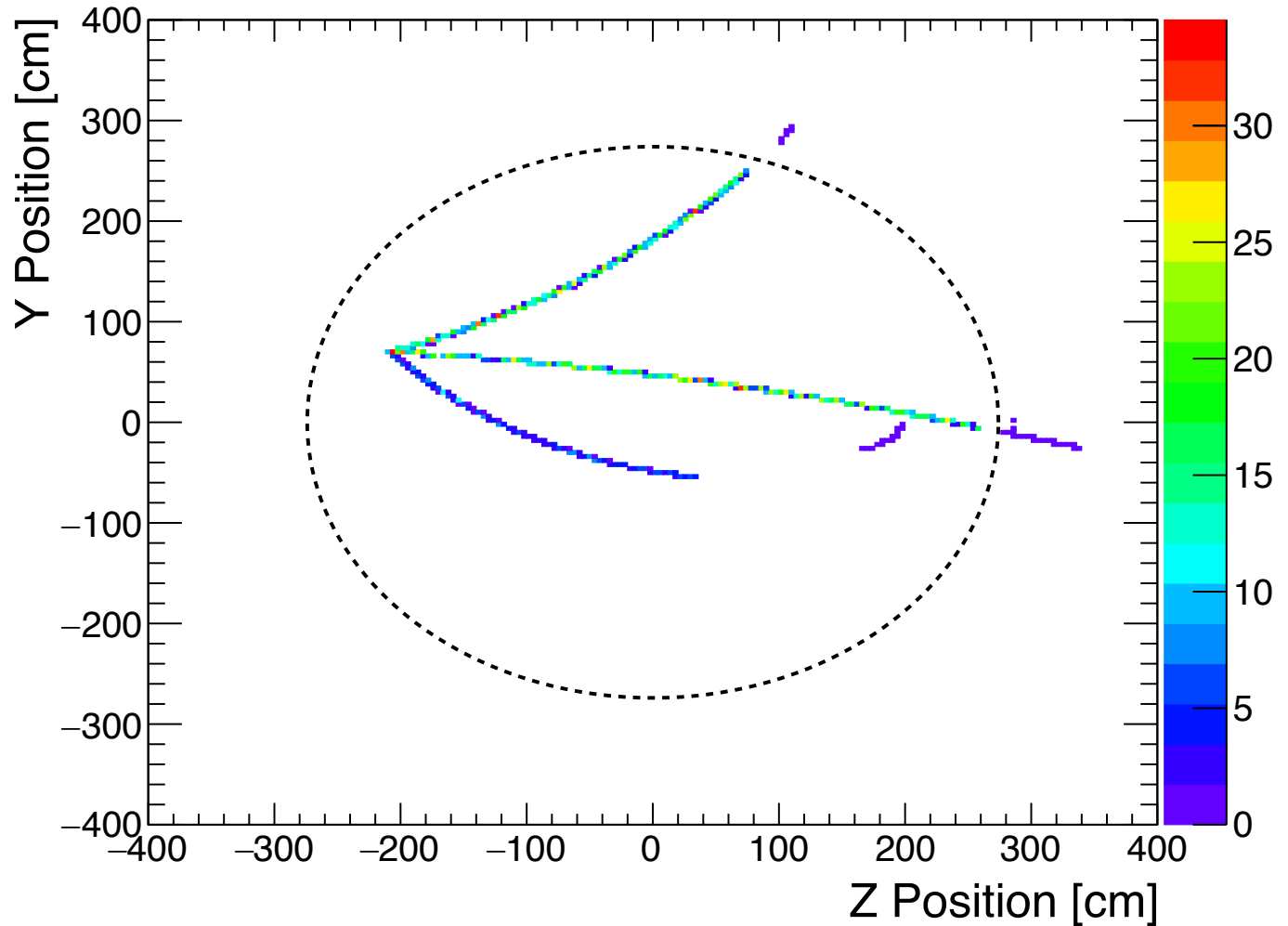
# Z-Y projection full spill w/ timing cut

- 0.6 evts/ $\mu$ sec
- 50 ns timing cut





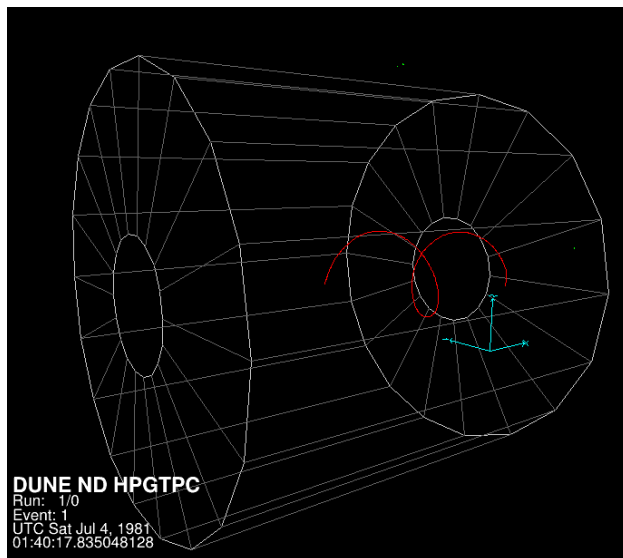
# Z-Y Projection: Sample event - $\nu_\mu$ CC



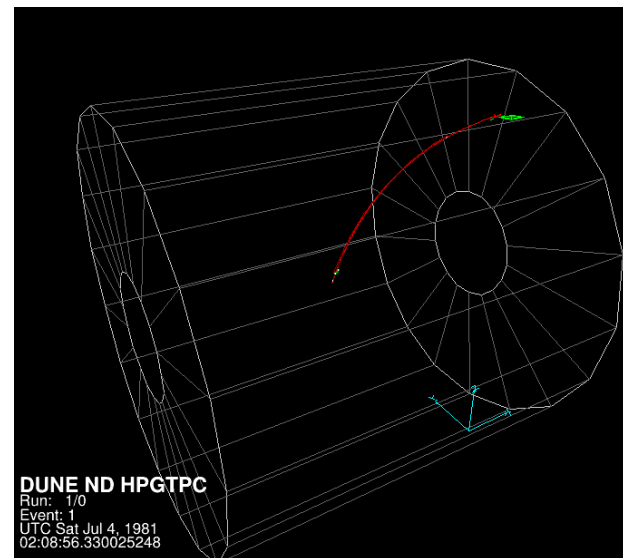


# Backgrounds to $\nu_e$ CC

- Background impact on  $\nu_e$ CC is more difficult to evaluate without full end-to-end Monte Carlo
  - $\nu_e$ 's are only  $\sim 1\%$  of the beam
  - Below  $\sim 350$  MeV/c many electrons will not hit ECAL (no  $t_0$ )
- Compton scatters can closely mimic the signal



150 MeV/c

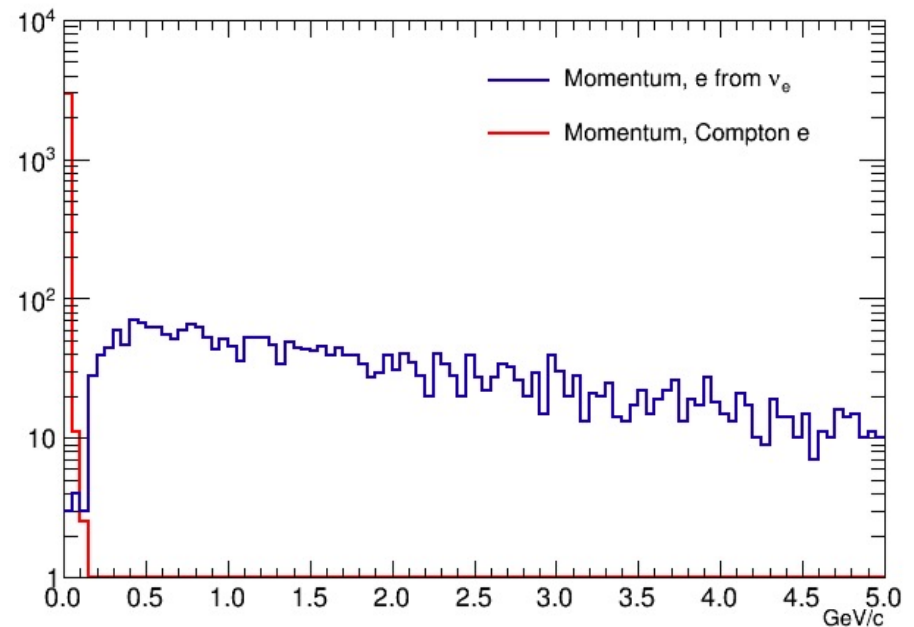


375 MeV/c



# EM Backgrounds to $\nu_e$ CC

- $\mathcal{O}$  [ a few/spill ]  $\gamma$ ,  $e^\pm$  with  $P > 150\text{MeV}$  towards TPC from  $\nu$  interactions in ECAL inner surface
- $\mathcal{O}$  [ 3% ] of  $\gamma$  produce Compton electrons which could fake  $e^-$  from CCQE  $\nu_e$ . There are  $\mathcal{O}$  [  $3 \times 10^{-4}$  ] of these signal events per spill - but
- $P > 450\text{MeV}$  suppresses Comptons by  $10^4$ 
  - with signal efficiency 93%  $\Rightarrow$
  - background / signal  $\sim 10^{-2}$
- Can also cut on
  - Angle w.r.t. beam
  - Charge for RHC running
  - Details of vertex
  - Point back to timed ECAL hits
    - For  $P_e \gtrsim 200 \text{ MeV}/c$





# Design decisions, technological risk

No technological show-stoppers

- Magnet

- Must provide large  $\mu$  acceptance with minimal material
  - $\mu$  catcher for LAr
- Magnet design does not push the state-of-the-art
  - Similar in scope to CLAS12 Toroid system
- Enables Near Detector program

- ECAL

- Ongoing optimization driven by performance & cost
- Based on established & heavily prototyped design

- HPgTPC

- Size driven by  $\nu$  event sample size, but also matches well to  $\mu$  acceptance criterion
  - Significant cost savings: ALICE chambers & engineering
- Based on established & tested detector design



# Conclusions

- The Multi-purpose detector provides a large acceptance muon spectrometer for muons exiting the LAr detector with minimal dead material between the liquid and the HPgTPC
- The resultant fiducial mass of the HPgTPC provides a statistically significant independent sample of neutrino interactions on Ar gas
  - Capable of tagging & analyzing all components of the  $\nu$  beam
    - $\nu_\mu$ ,  $\nu_e$ ,  $\nu_\mu$ -bar,  $\nu_e$ -bar
  - Performance benchmarks equal to or superior to Far detectors
    - Momentum resolution, energy scale, “containment”
- No component is pushing the state-of-the-art
- **It is plausible and achievable**



# Questions?



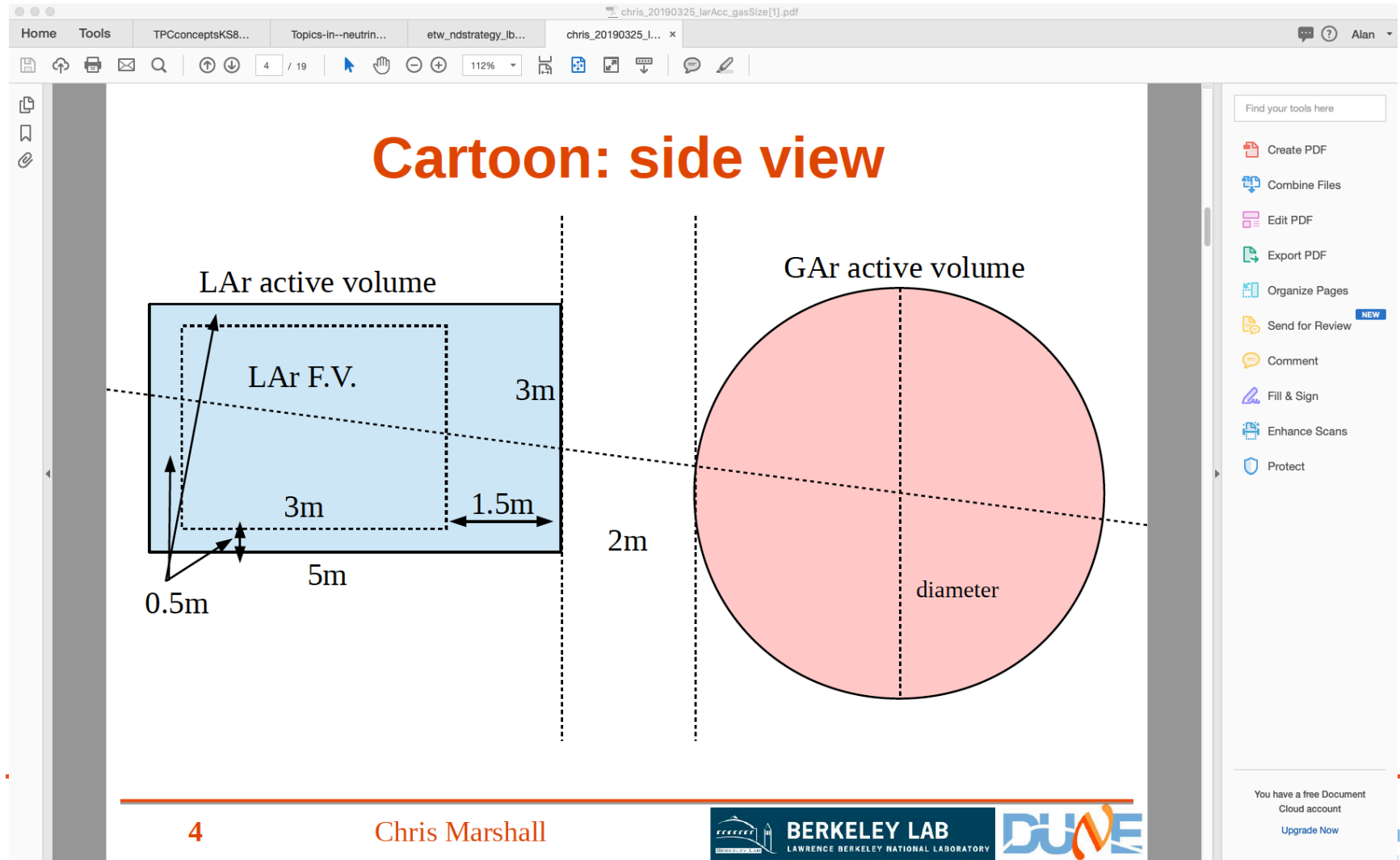
# BACK UPS

Suggestions regarding what I should include, NOT include, etc.  
Will have slides on most important questions. +?



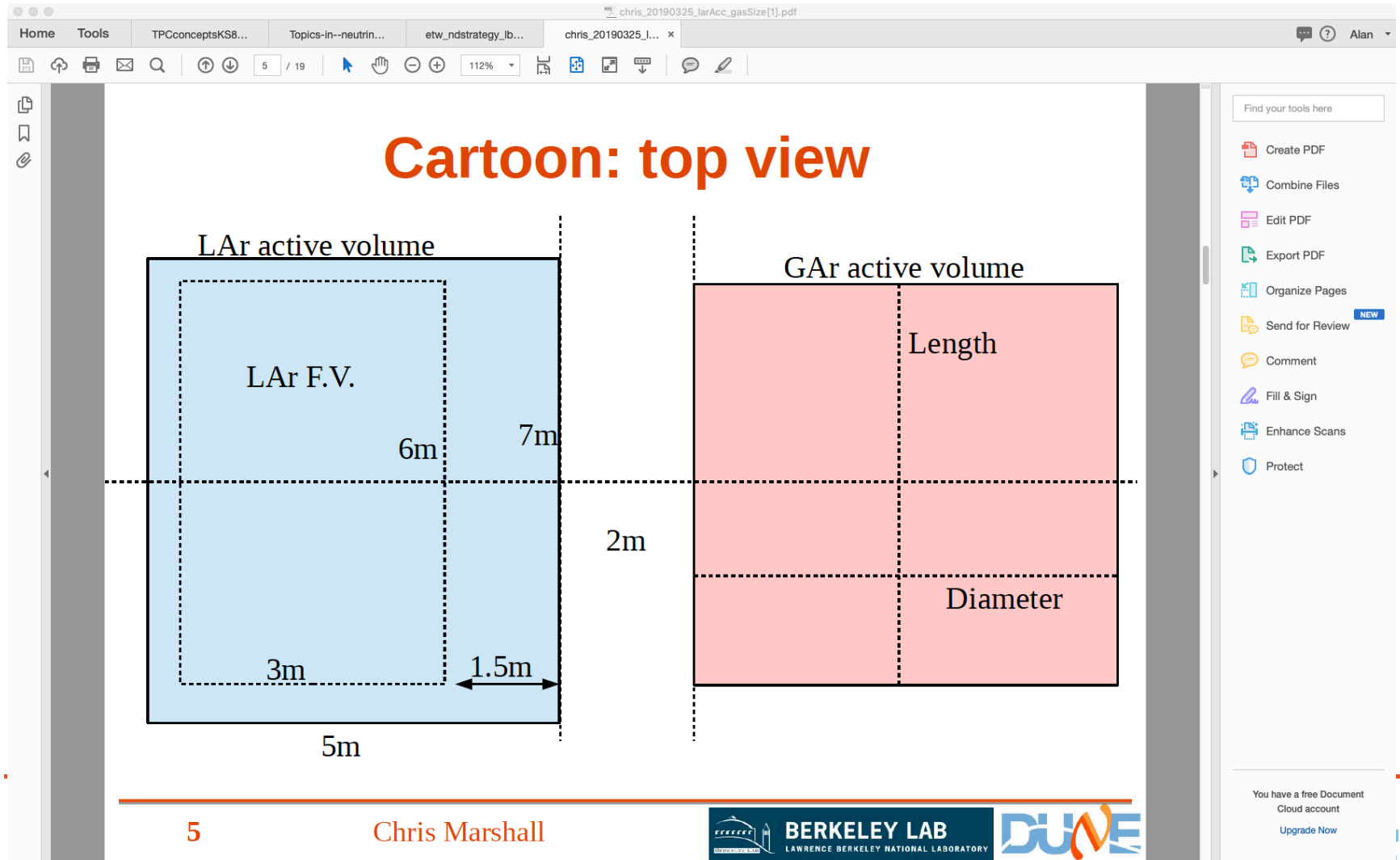


# HPgTPC size



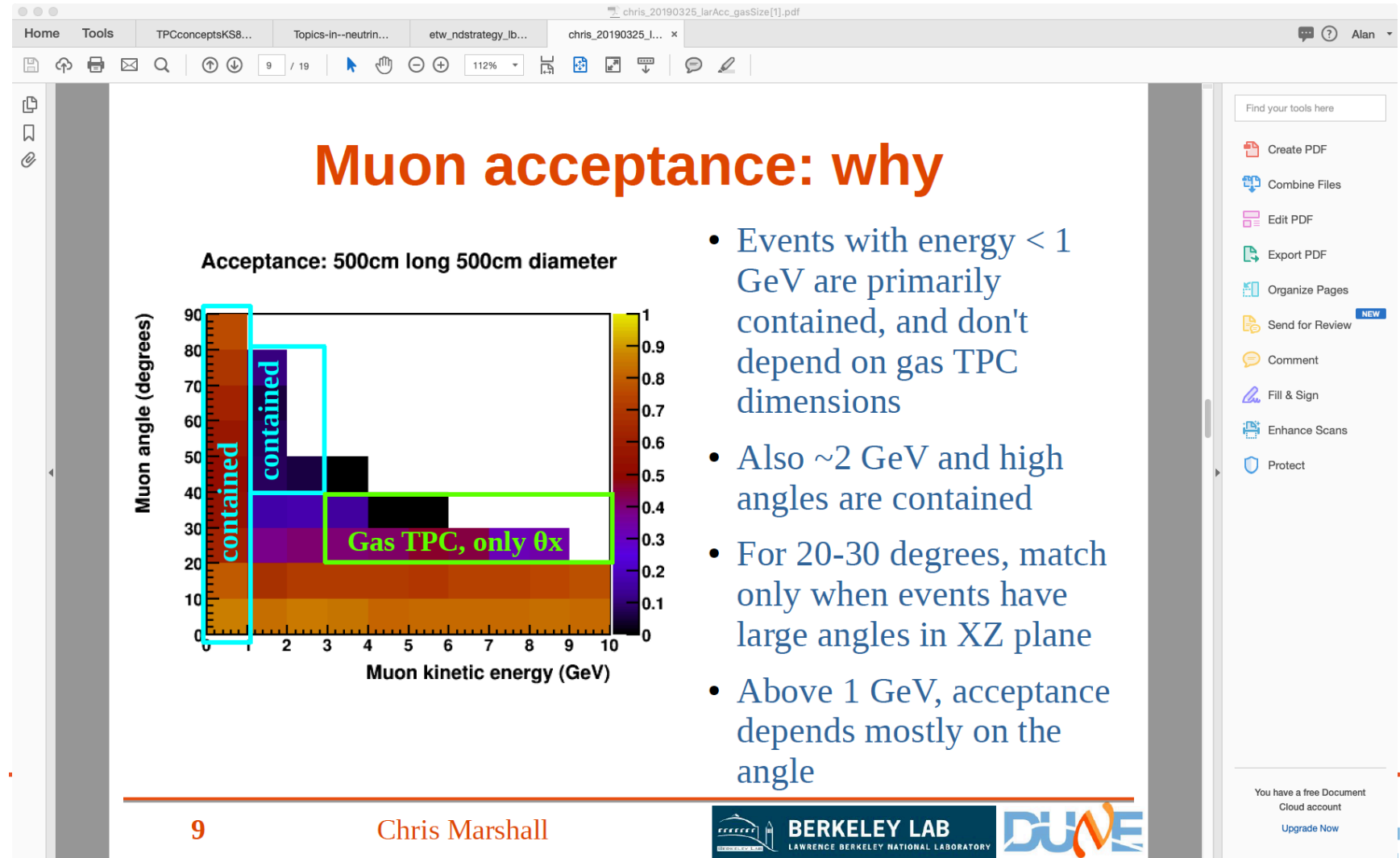


# Model



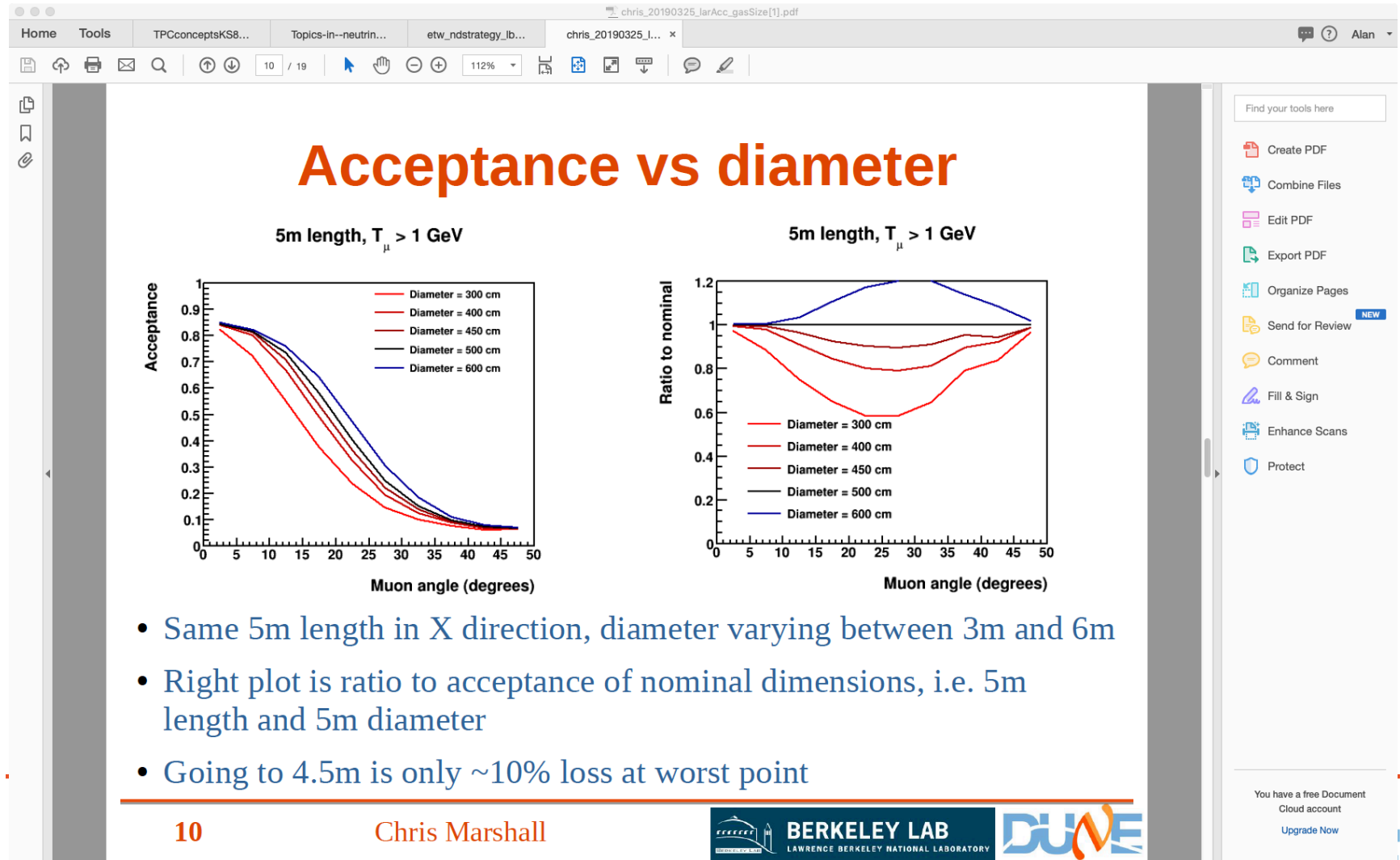


# Acceptance



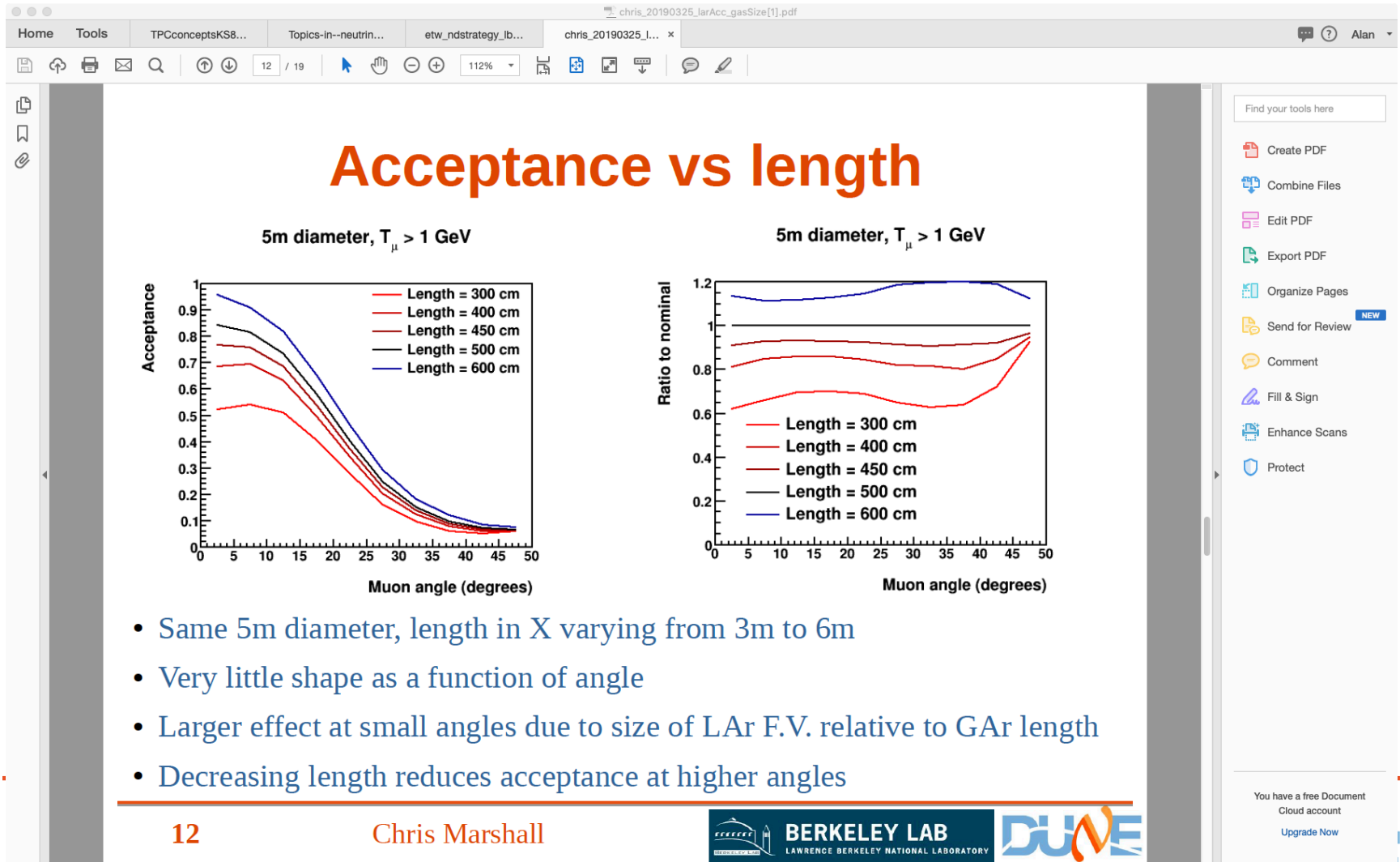


# Acceptance vs. diameter





# Acceptance vs. length





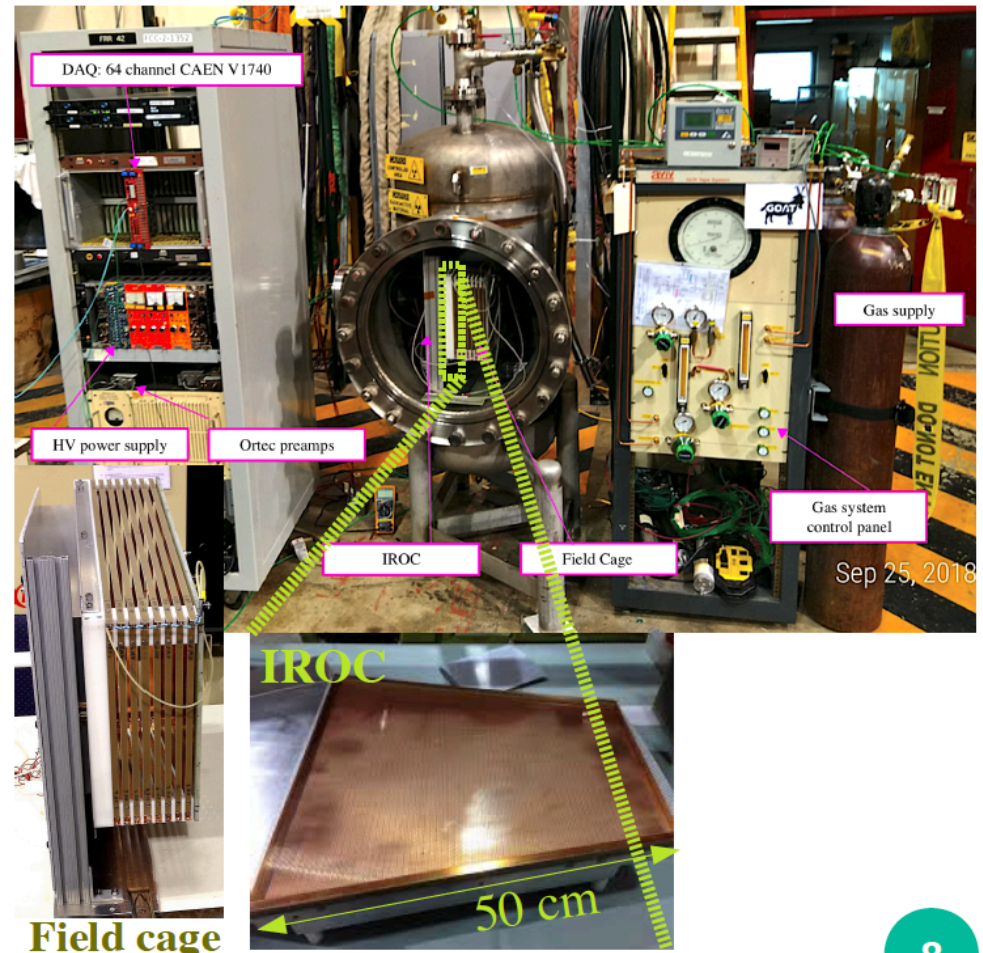
## Conclusions

- Acceptance losses due to small reduction in GAr TPC size are not significant, and do not create regions of phase space where there is zero efficiency
- Reducing diameter by  $>1\text{m}$ , or length by  $>1.5\text{m}$ , would have significant consequences
- Acceptance is more sensitive to gas TPC length than to diameter due to the larger size of the LAr in that dimension
- Compensating for a reduction in diameter with an increase in length actually improves the acceptance, and saves space in the more constrained Z dimension



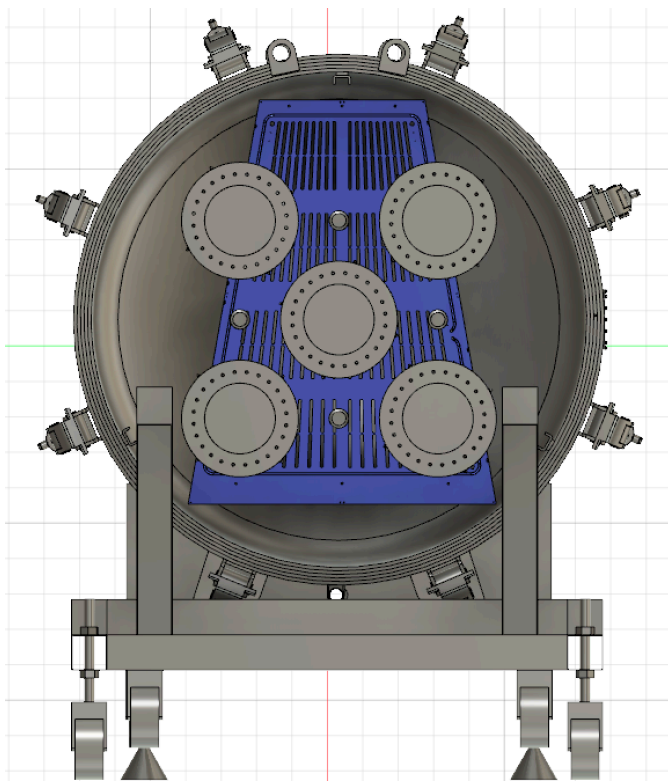
# HPgTPC Test Stand @ FNAL

- **Gaseous-Argon Operation of the ALICE TPC, GOAT**
  - Test ALICE readout chambers at 10 atm and in various gas mixture (currently 90-10 Ar-CO<sub>2</sub>)
  - Develop full front-end electronics chain
- Various components in **GOAT**:
  - Signal readout with ALICE **IROC**
  - **Field cage**
  - Front-end with preamps and CAEN digitizers
- Upgrades to components underway; stay tuned!





# OROC Test Stand @ RHUL



Groups at Royal Holloway & Imperial College London are getting involved with tests of ALICE readout chambers

- 5 bar pressure vessel will accommodate one OROC
- Plan tests of gas mixtures & gas gain
- Future possibility to use vessel for IROC/OROC acceptance tests

