Multi-purpose detector (MPD)
Design Status

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LBNC Meeting, Fermilab

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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
  - ν_μ, ν_μ-bar, ν_e, ν_e-bar
- Reconstruct neutrino energy via spectrometry and calorimetry
- Constrain LArTPC detector response and selection efficiency
- Measure energetic neutrons from ν–Ar interactions via time-of-flight with the ECAL *(Desired)*

Capabilities that deliver on the requirements

- Provide statistically significant, independent ν event sample on Ar
- High-resolution particle momentum and charge determination via magnetic curvature.
  - ν_e and ν_μ tagging with little background contamination
  - ν_e and ν_e-bar tagging (only system that can do this reliably)
  - Energy scale to 1% (Curvature, Ks, Λs)
  - 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 ν-Ar vertex (including nucleons).
- Separation of tracks and showers for less-ambiguous reconstruction (low-density detector).

Multi-purpose Detector (MPD)

Multi-purpose detector details

MPD

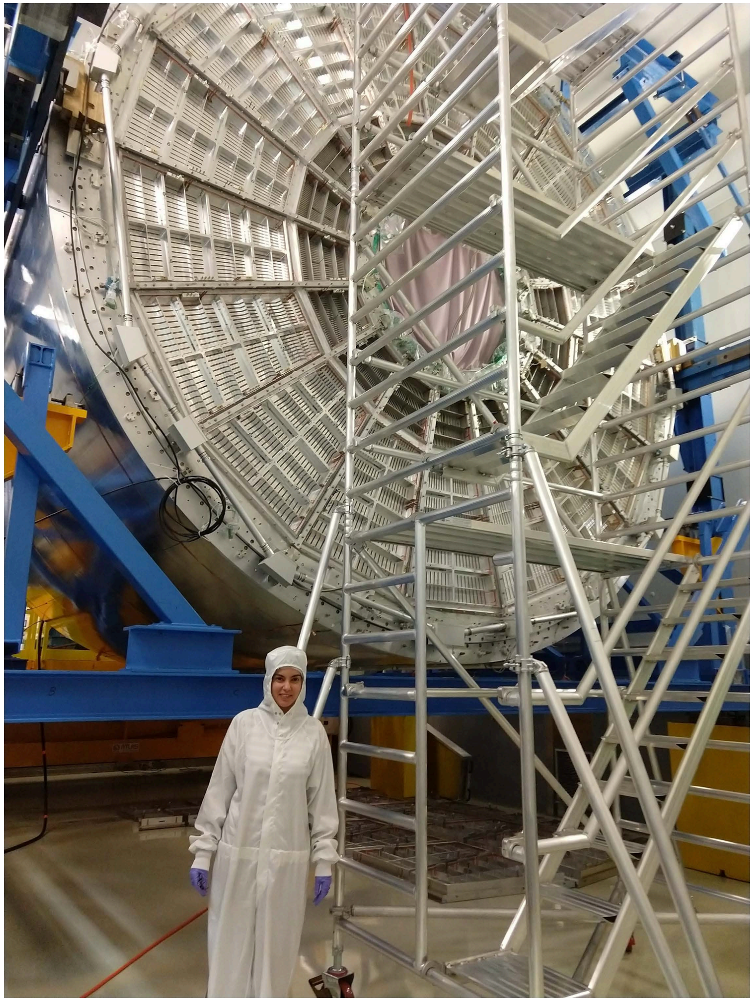
- High-Pressure (10ATM) Ar gas TPC (HPgTPC)
  - Copy of ALICE TPC (5m in diameter X 5m long active)
  - 1t fiducial target mass (90-10 Ar-CH_4, 97% interactions on Ar)
  - Very low recon E_{thres} for charged tracks (~ 5 MeV)
  - Exquisite PID
  - In ~0.5T field (magnetic spectrometer)
- Surrounded by 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

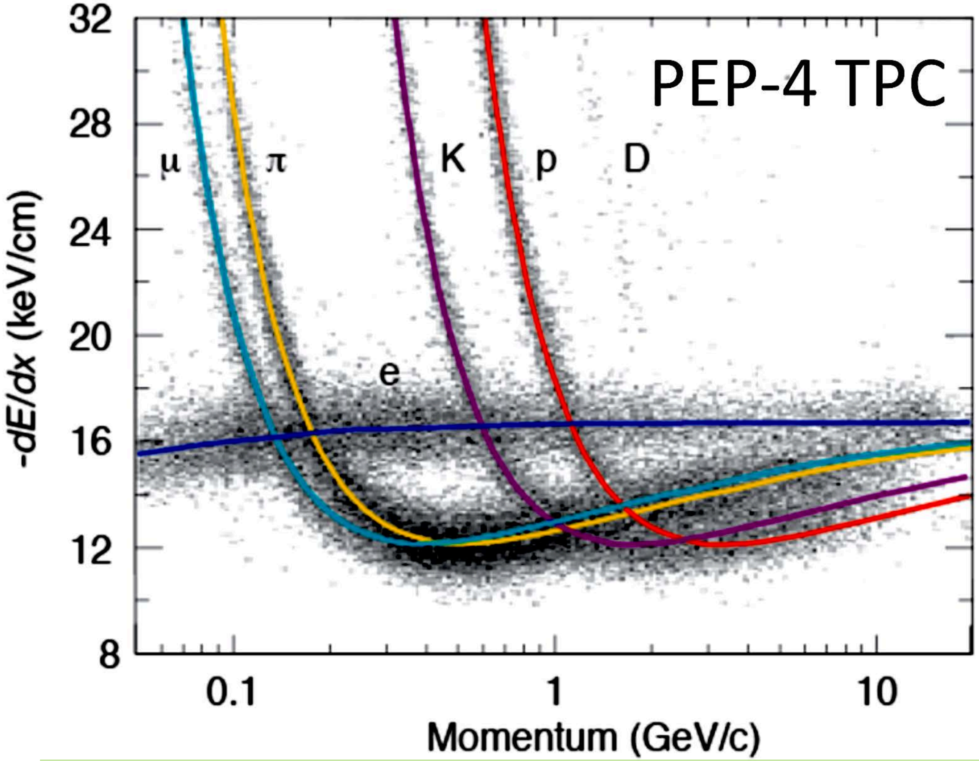
Event class	Number of events per ton-year
ν_μ CC Total	1.64×10^6
ν_μ NC Total	5.17×10^5
ν_μ CC Coherent	8.35×10^3
ν_μ NC Coherent	4.8×10^3
ν_μ - electron elastic	135
ν_μ CC π^0 inclusive	4.47×10^5
ν_μ NC π^0 inclusive	1.96×10^5
ν_μ Low v (250 MeV)	2.16×10^5
ν_μ Low v (100 MeV)	7.93×10^4
$\bar{\nu}_\mu$ CC Coherent ($\bar{\nu}$ mode)	6.90×10^3
ν_e CC Total	1.89×10^4
ν_e NC Total	5.98×10^3
ν_e CC Coherent	93
ν_e NC Coherent	52

MPD – High-pressure gas TPC

US, India, Spain, UK

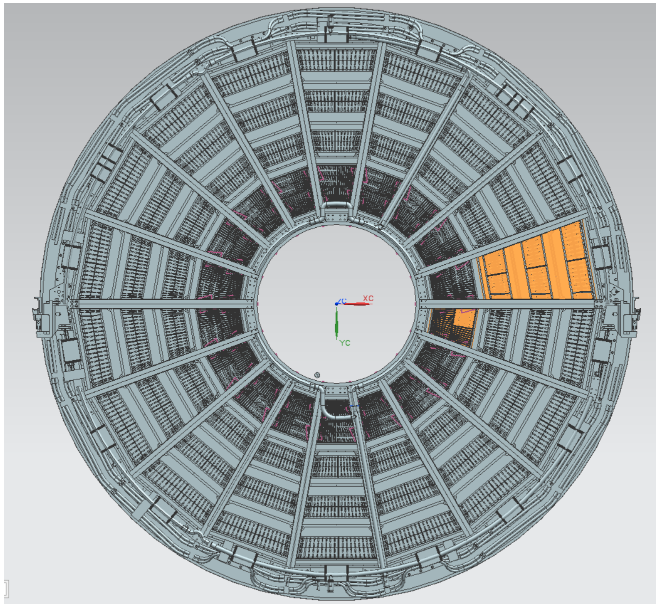


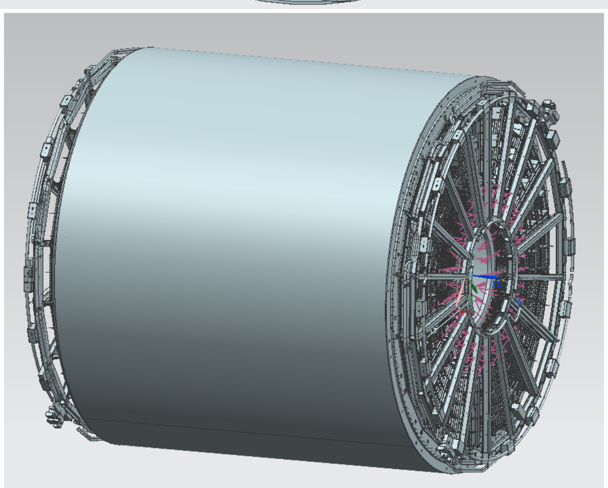
Well established technology
Vetted detector design



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

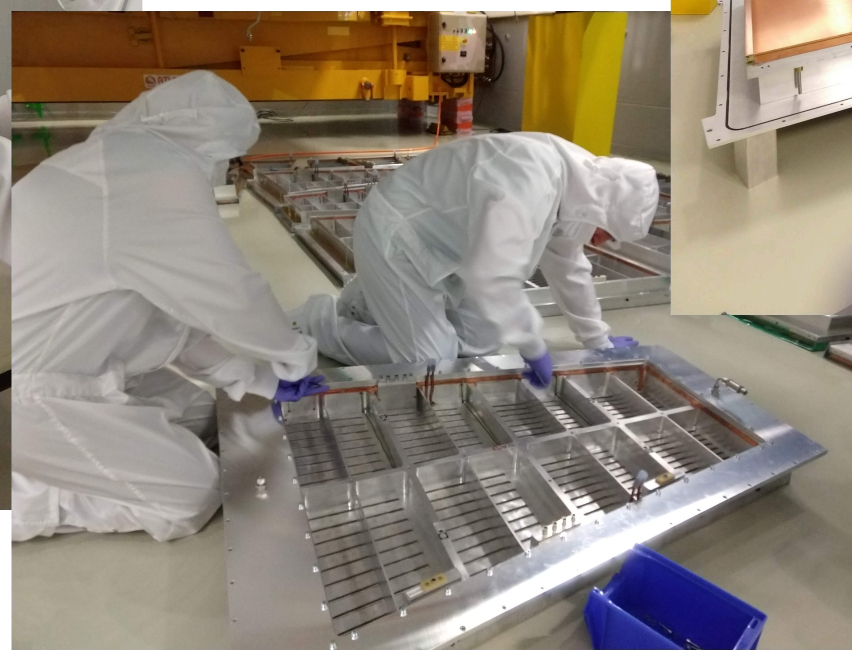
Readout chambers





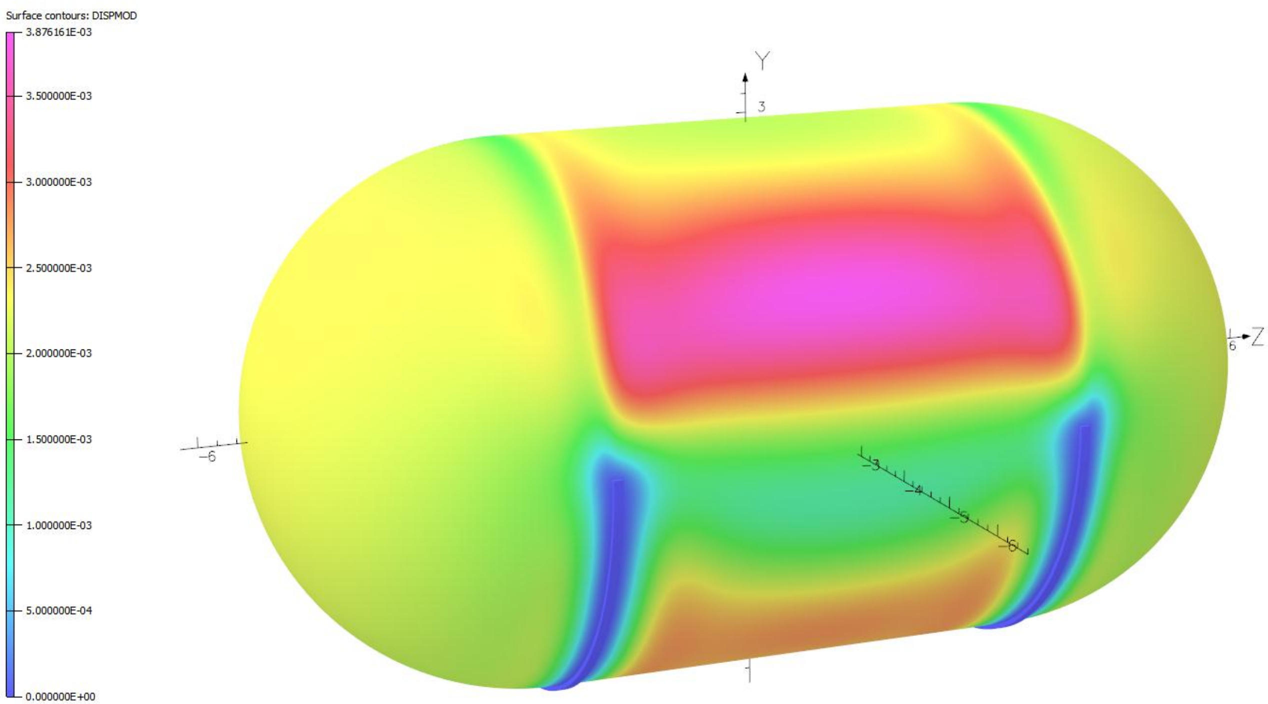
- We are acquiring 36 outer readout chambers and 36 inner readout chambers from ALICE.
- I wanted to show these figures because they represent a full as-built 3D, CAD model of the detector. This alone is a significant contribution
- And also note that we will have to build two chambers to fill in the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

ALICE chamber acquisition



Pressure Vessel

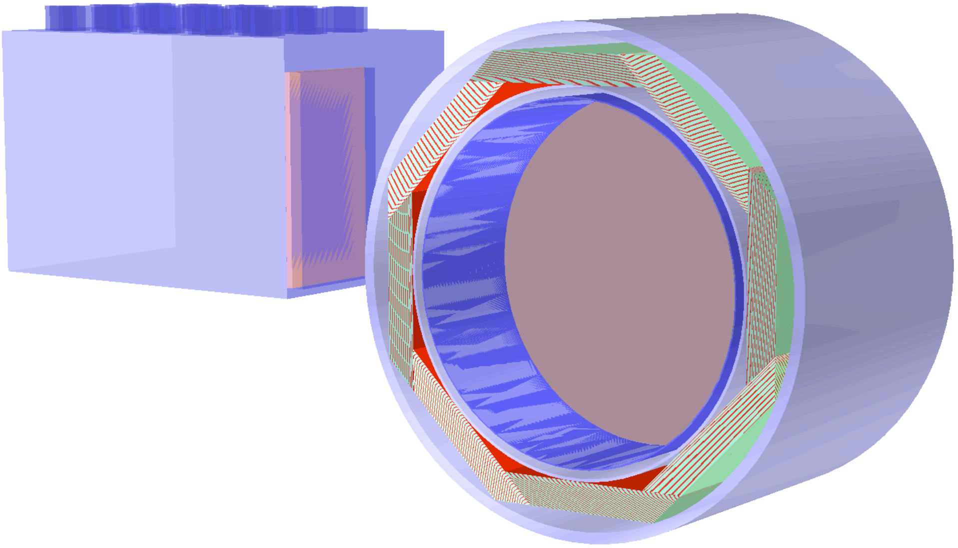
- Bhabha Atomic Research Centre (BARC), Mumbai, is working on optimizing the design of the HPgTPC pressure vessel
- Good progress to date
  - Using Al alloy reached thickness of ~ $0.4X_0$

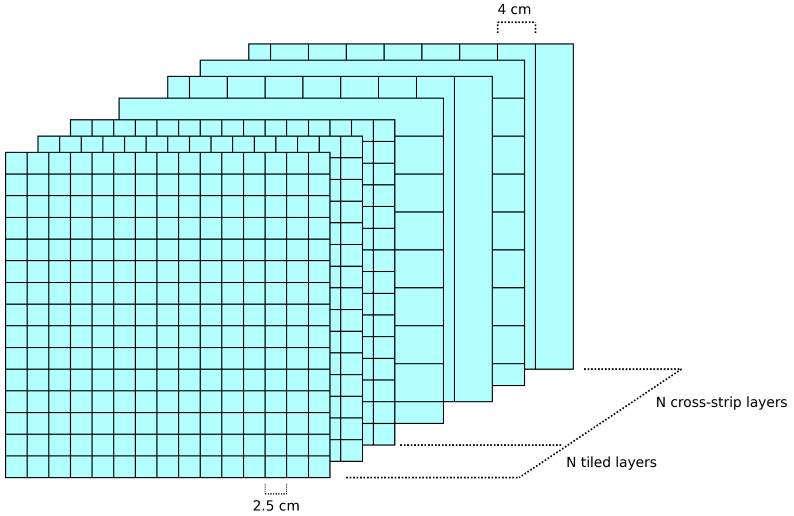


ECAL

Germany, US

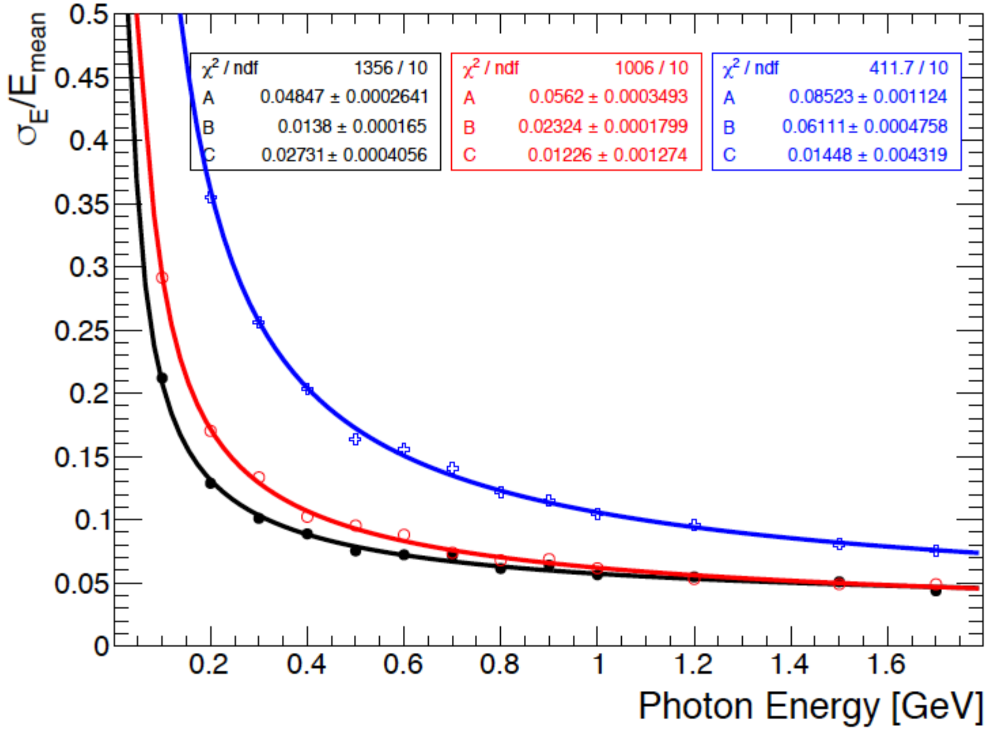
- Surrounds HPgTPC to detect photons and neutrons
- Plastic scintillator tiles & strips
- SiPM readout now affordable due to recent significant cost reductions





ECAL optimization

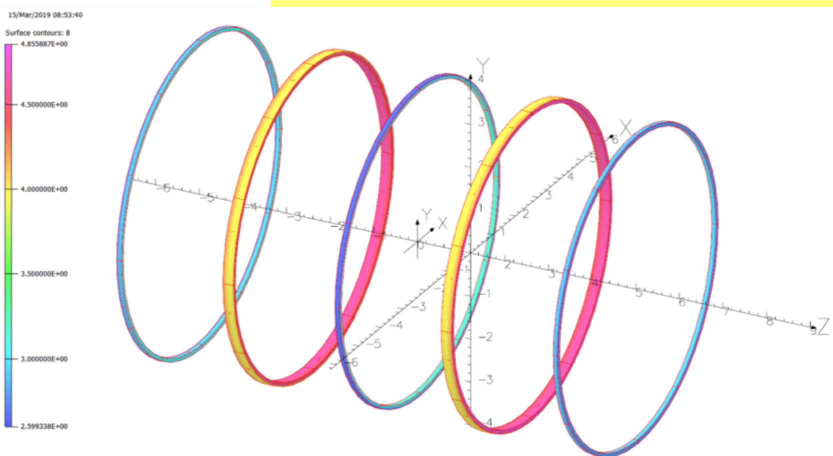
- Optimization ➠ calorimeter energy resolution, angular resolution, neutron detection specification
- Cost drivers: Granularity, absorber material/thickness, number of layers (depth)
- Look at the influence of:
  - Granularity
  - Absorber thickness
  - Scintillator thickness
  - Pressure vessel

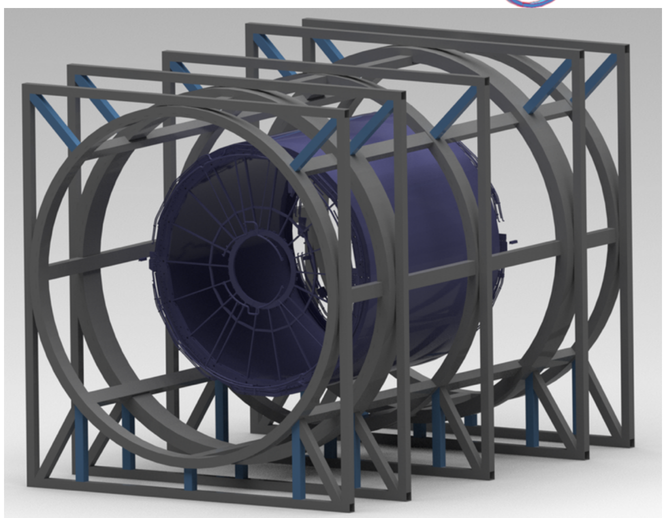


Blue ($2X_0$), Red ($1X_0$), Black ($0.5X_0$)

Magnet: 3-coil Helmholtz with bucking coils

Magnetic model showing coils only.





Current mechanical design concept

US, India, Italy

- 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)
  - …..

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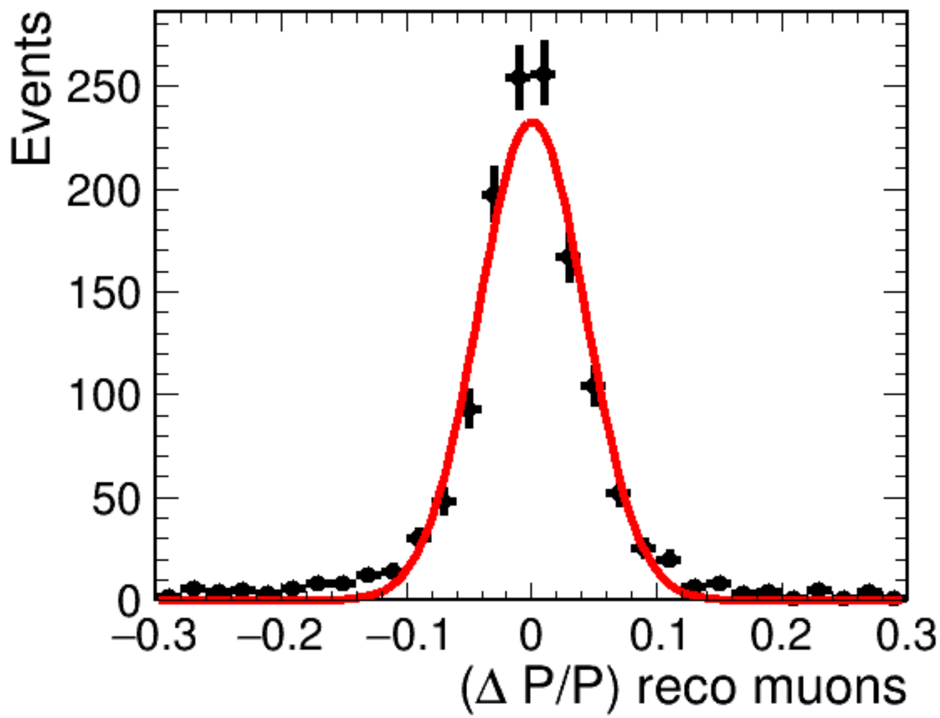
GArSoft Tracking Resolution: muons

Test sample: 1477 ν_μCC events, with neutrino energy = 2 GeV



First pass "snap shot" at full analysis

Muon momentum resolution: 4.2% in this sample.

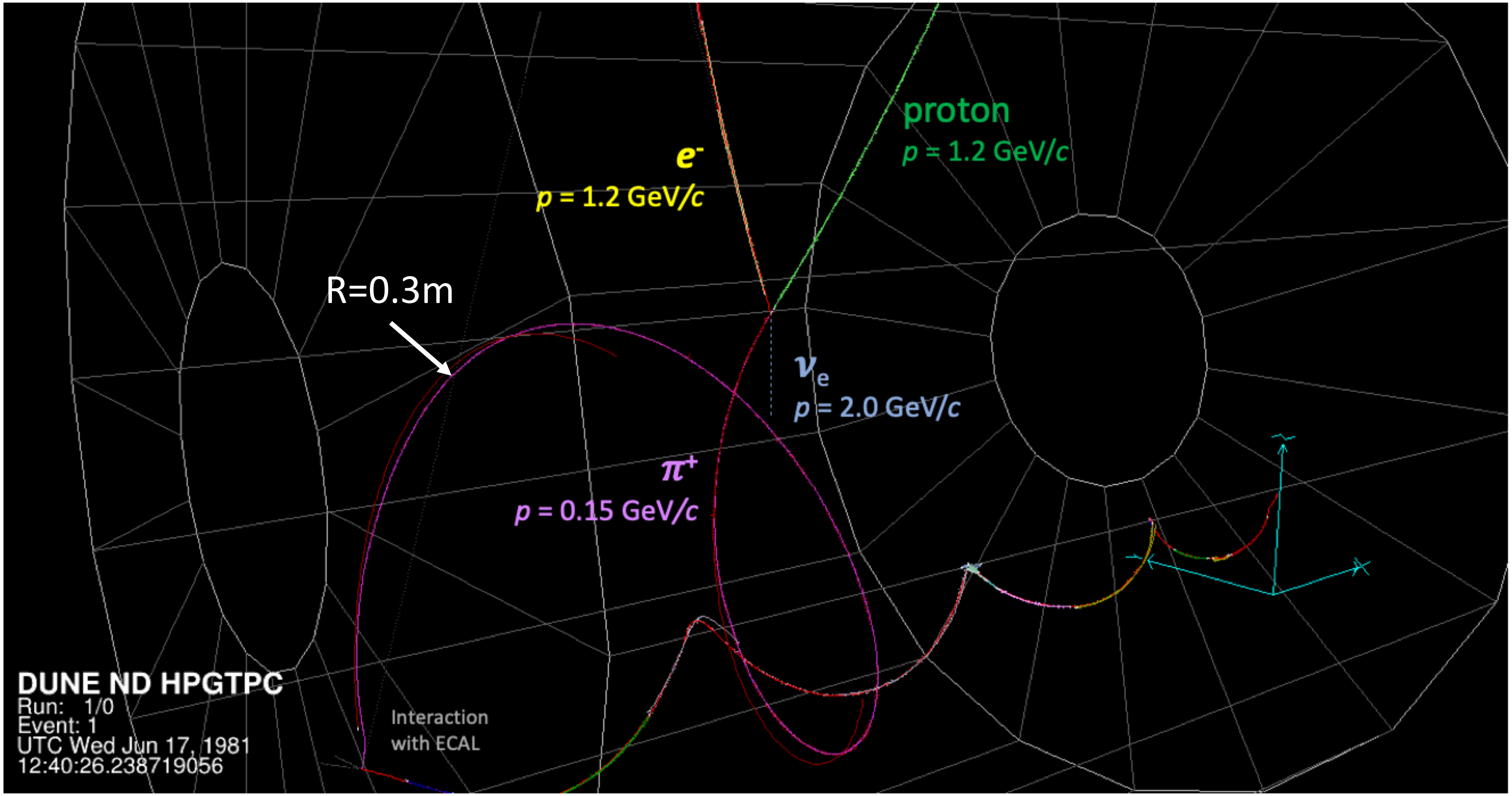
Currently using a point set resolution of ~1mm

At 10 Atm, we should do much better: 200-300 μm (PEP4)

Should approach 2%

A Simulated and Reconstructed ν_e Charged Current Event in the HPGTPC

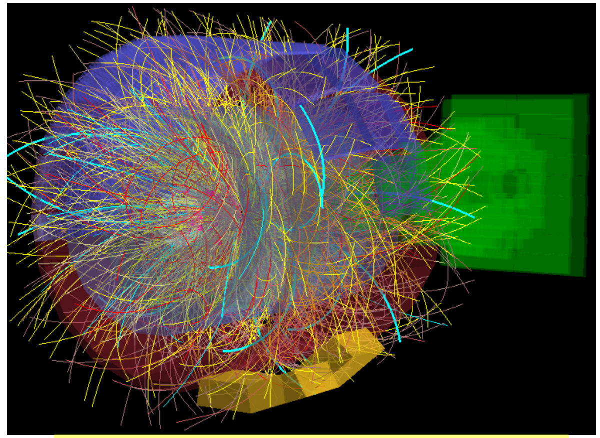
$\nu_e + Ar \rightarrow e- + \pi+ + p + n$



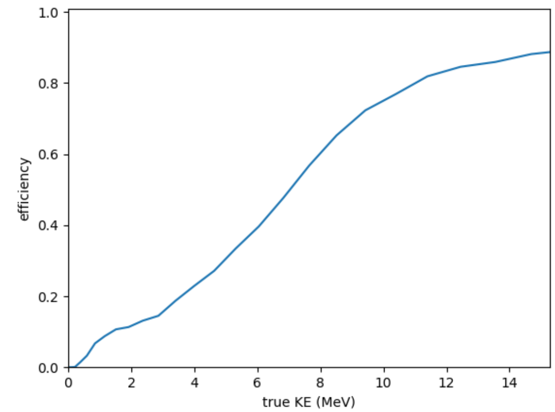
Neutron with p = 0.23 GeV/c at the P.V. not shown

Finding Short Tracks Near the Primary Vertex

- Although the average occupancy per spill in the HPgTPC is very small ($\vartheta\ 10^{-4}$), the local (near vertex) occupancy can be large ($\vartheta\ 10^{-1}$)

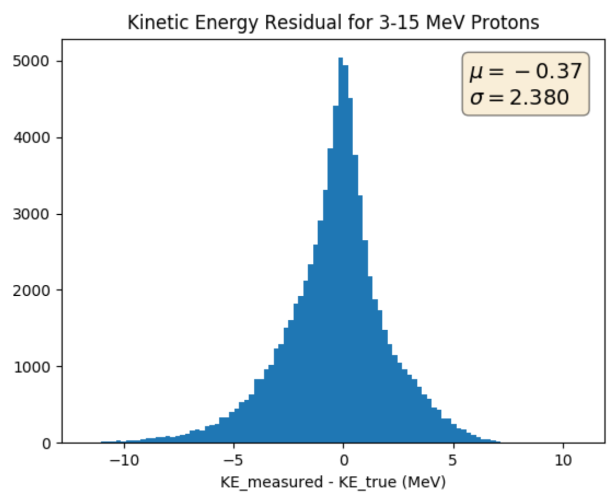


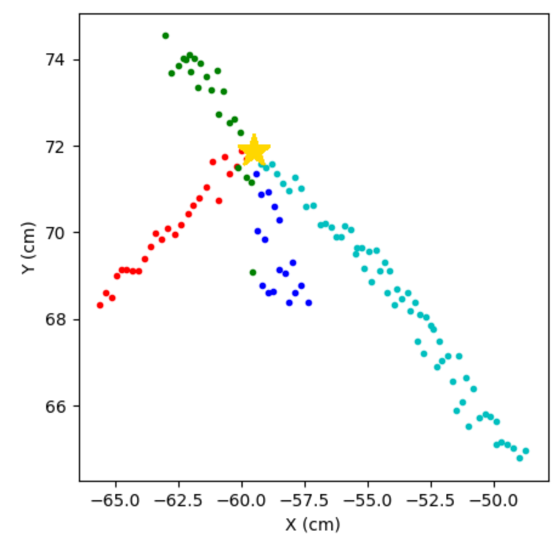
This is 15➛40% pad occupancy
$\vartheta\ 10^{-1}$ voxel occupancy



- RANSAC line finding + Neural Network for p/π separation and energy estimation

- ε: 20%@5MeV➛80%@10MeV



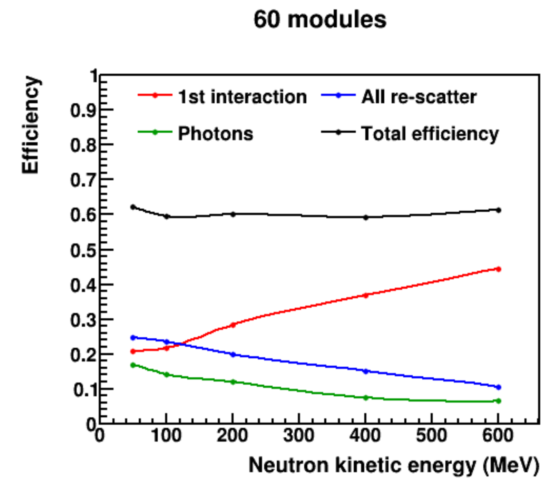


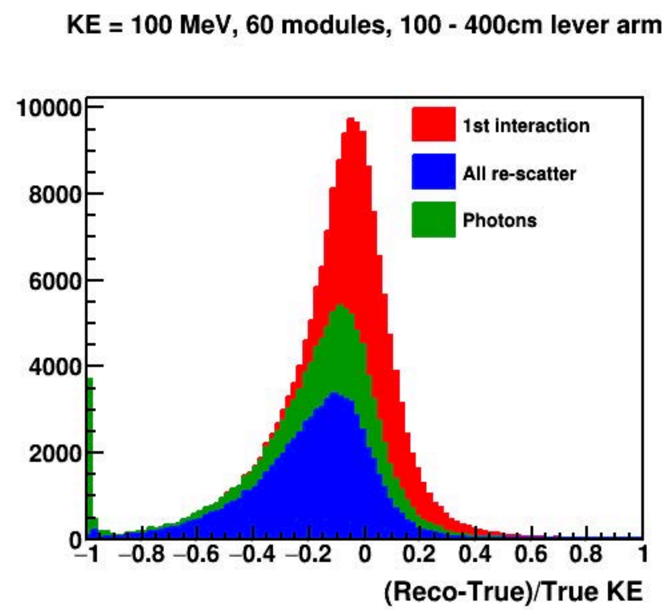
Event recon: neutrons

- 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.

Note to self: more to do on this slide



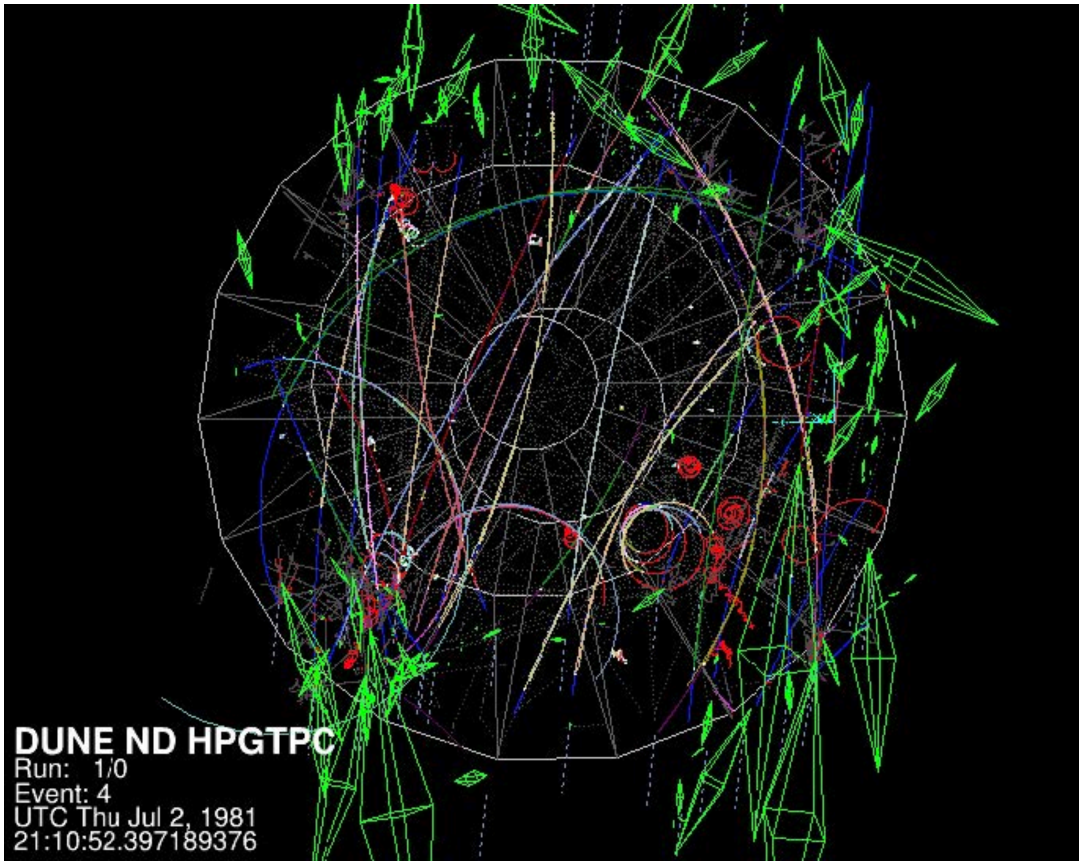


Backgrounds

- Although the HPgTPC's fiducial mass is large for a gas device, its mass is << smaller than the ECAL (X300) and the magnet (X100)
- Interactions outside of the HPgTPC can cause issues
- 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
    - ν_μ from entering μ
    - ν_e from entering γ

Background activity per spill

Hits integrated over full spill

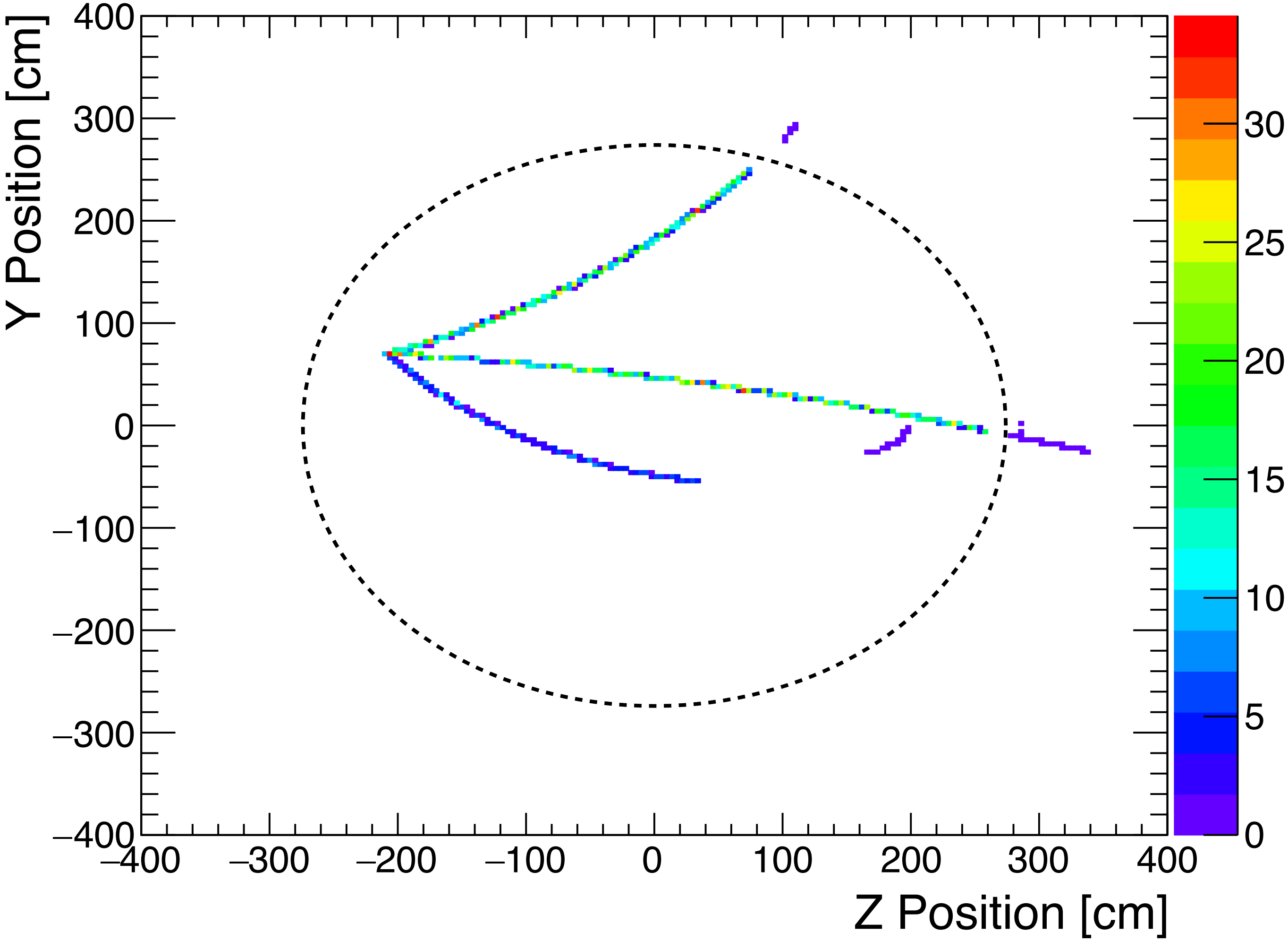


Background	# per spill
Muons	20
Photons (>150 MeV)	3

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

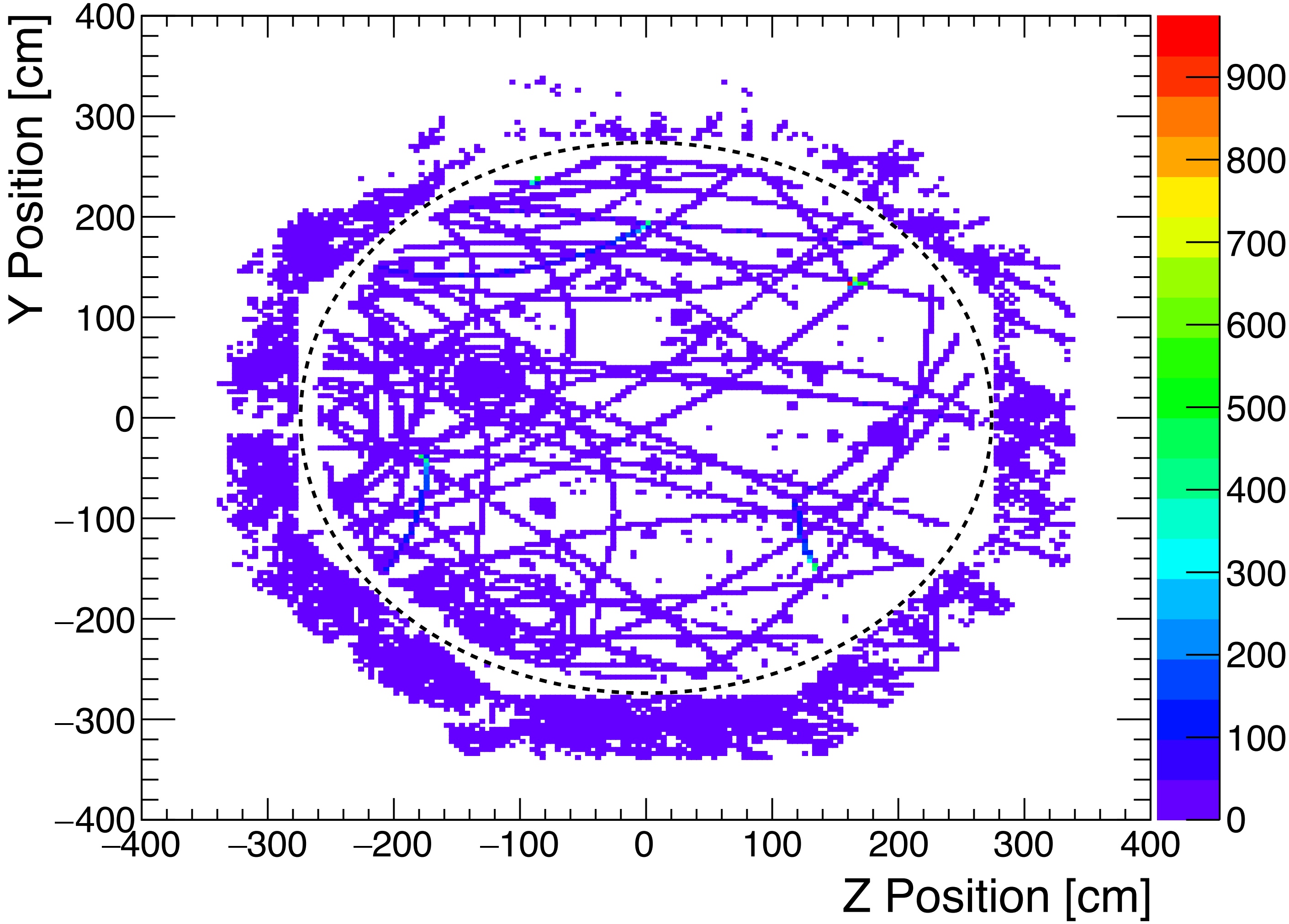
Z-Y Projection: Sample event - ν_μCC

Test event



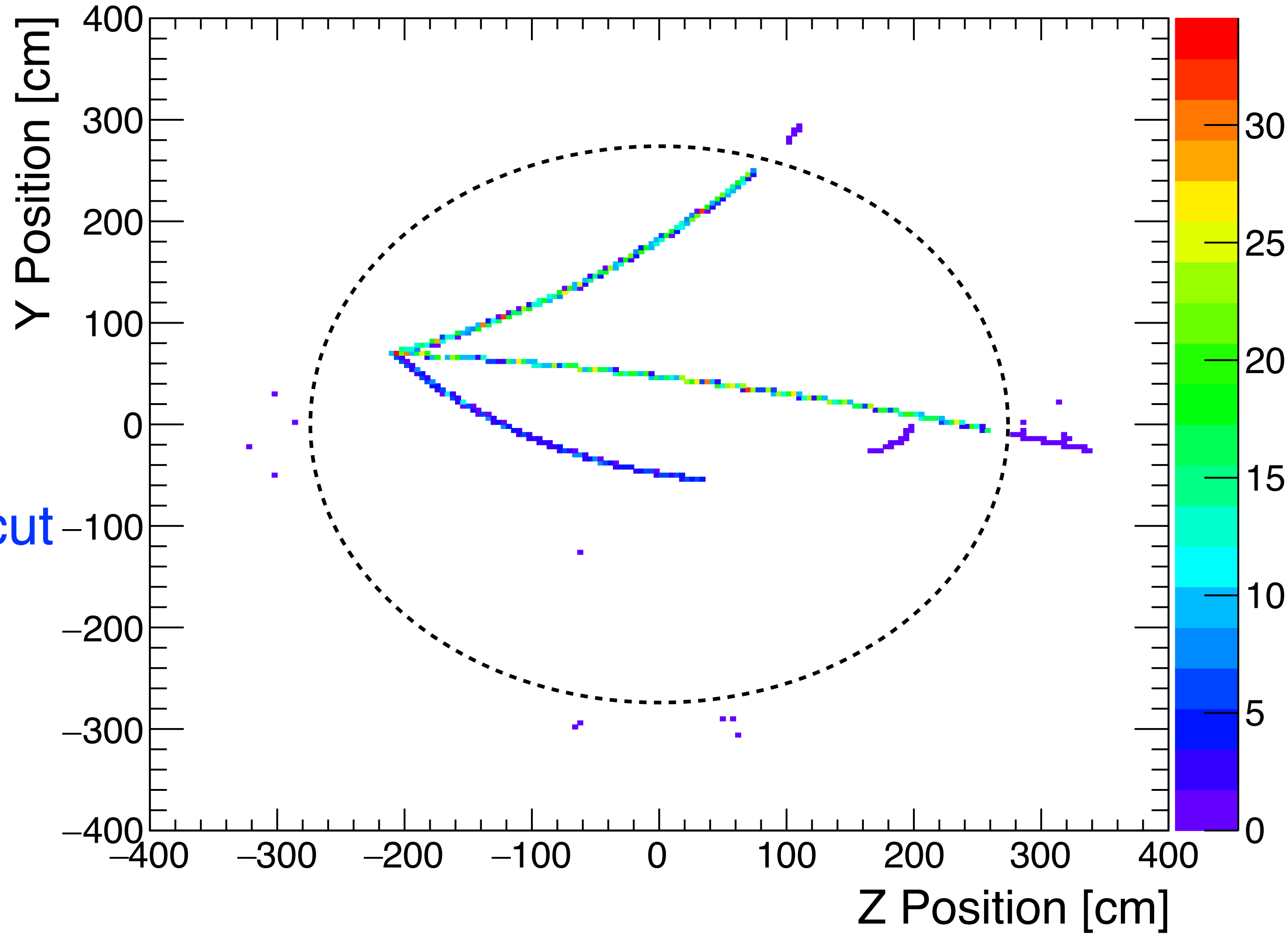
Z-Y projection full spill & event

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

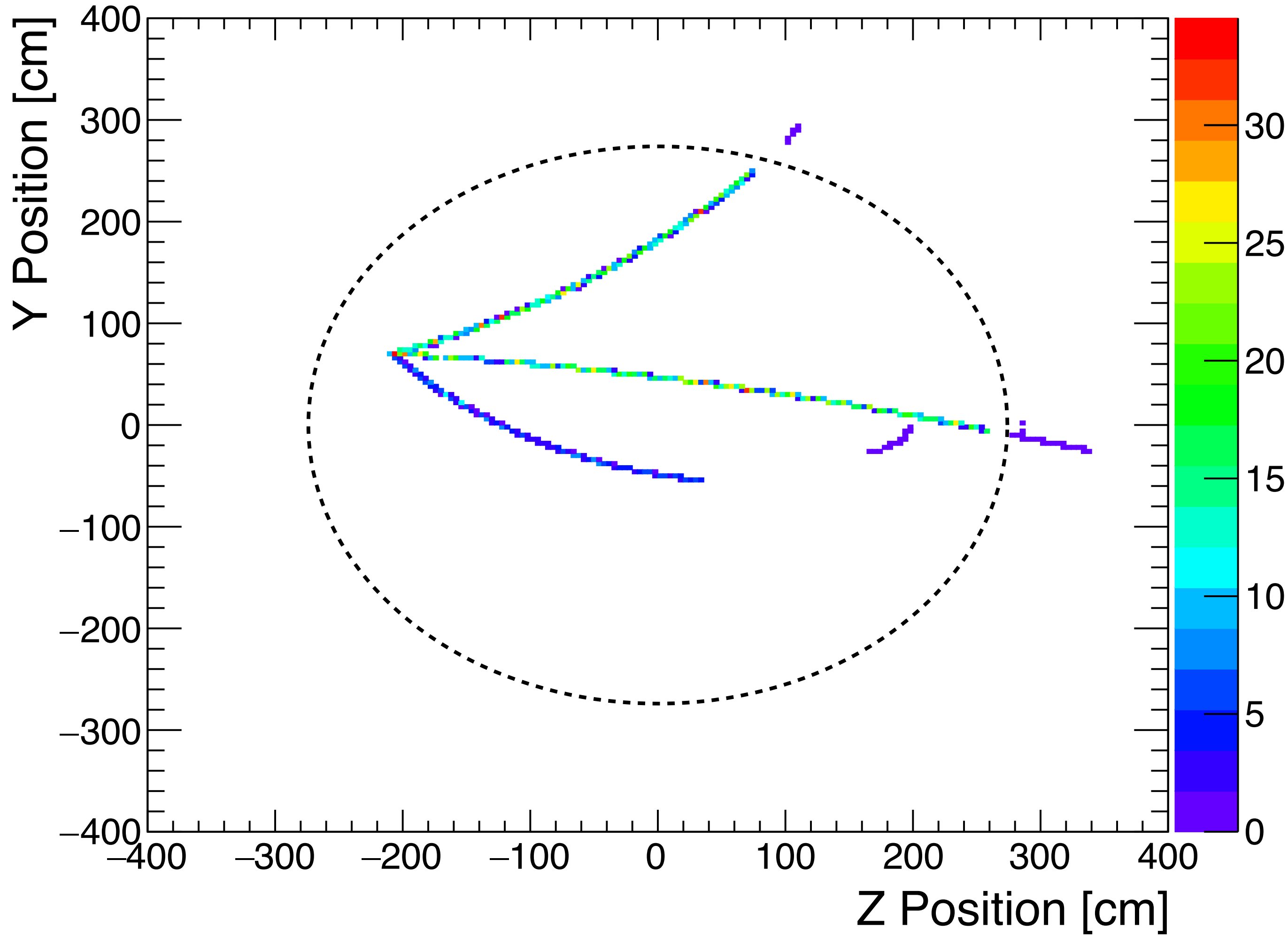


Z-Y projection full spill w/ timing cut

- 0.6 evts/μsec
- 50 ns timing cut



Z-Y Projection: Sample event - ν_μCC



Design decisions, technological risk

- Magnet
  - Must provide large μ acceptance with minimal material
    - μ catcher for LAr
  - Magnet design does not push the state-of-the-art
    - Similar in scope to CLAS12 Toroid system
- ECAL
  - Ongoing optimization driven by performance & cost
  - Based on established & heavily prototyped design
- HPgTPC
  - Size driven by ν event sample size, but also matches well to μ acceptance criterion
    - Significant cost savings: ALICE chambers & engineering
  - Based on established & tested detector design

	Risk
High	(red)
Med	(yellow)
Low	(green)

Conclusions

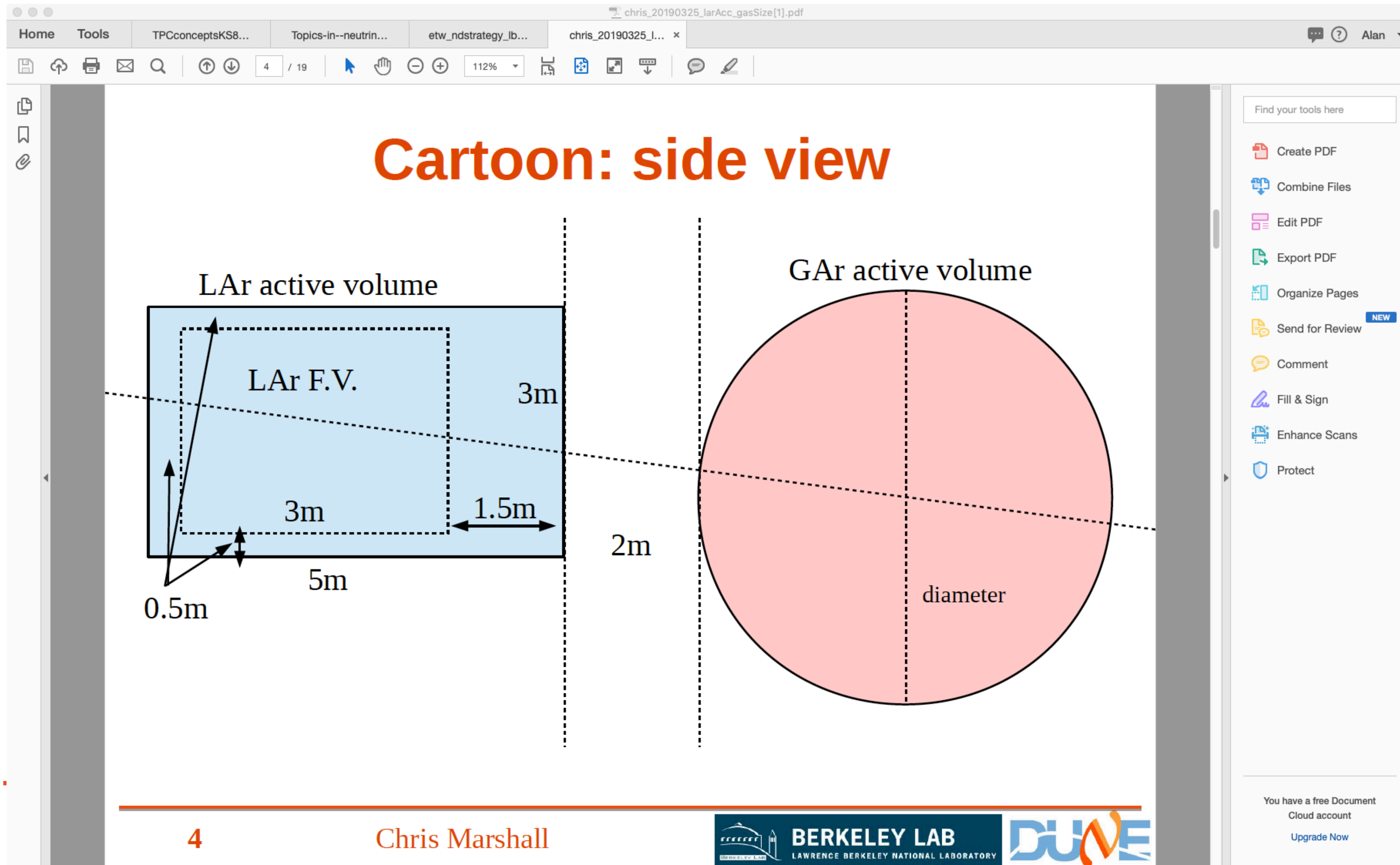
- The Multi-purpose detector provides a large acceptance muon spectrometer for muons exiting the LAr detector with minimal dead material between the liquid and the HPgTPC
- The resultant fiducial mass of the HPgTPC provides a statistically significant independent sample of neutrino interactions on Ar gas
  - Capable of tagging & analyzing all components of the ν beam
    - ν_μ, ν_e, ν_μ-bar, ν_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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Home
Tools
TPCconceptsKS8...
Topics-in--neutrin...
etw_ndstrategy_lb...
chris_20190325_l...
Alan
4 / 19
112%
Cartoon: side view
LAr active volume
LAr F.V.
3m
3m
1.5m
5m
0.5m
2m
GAr active volume
diameter
4
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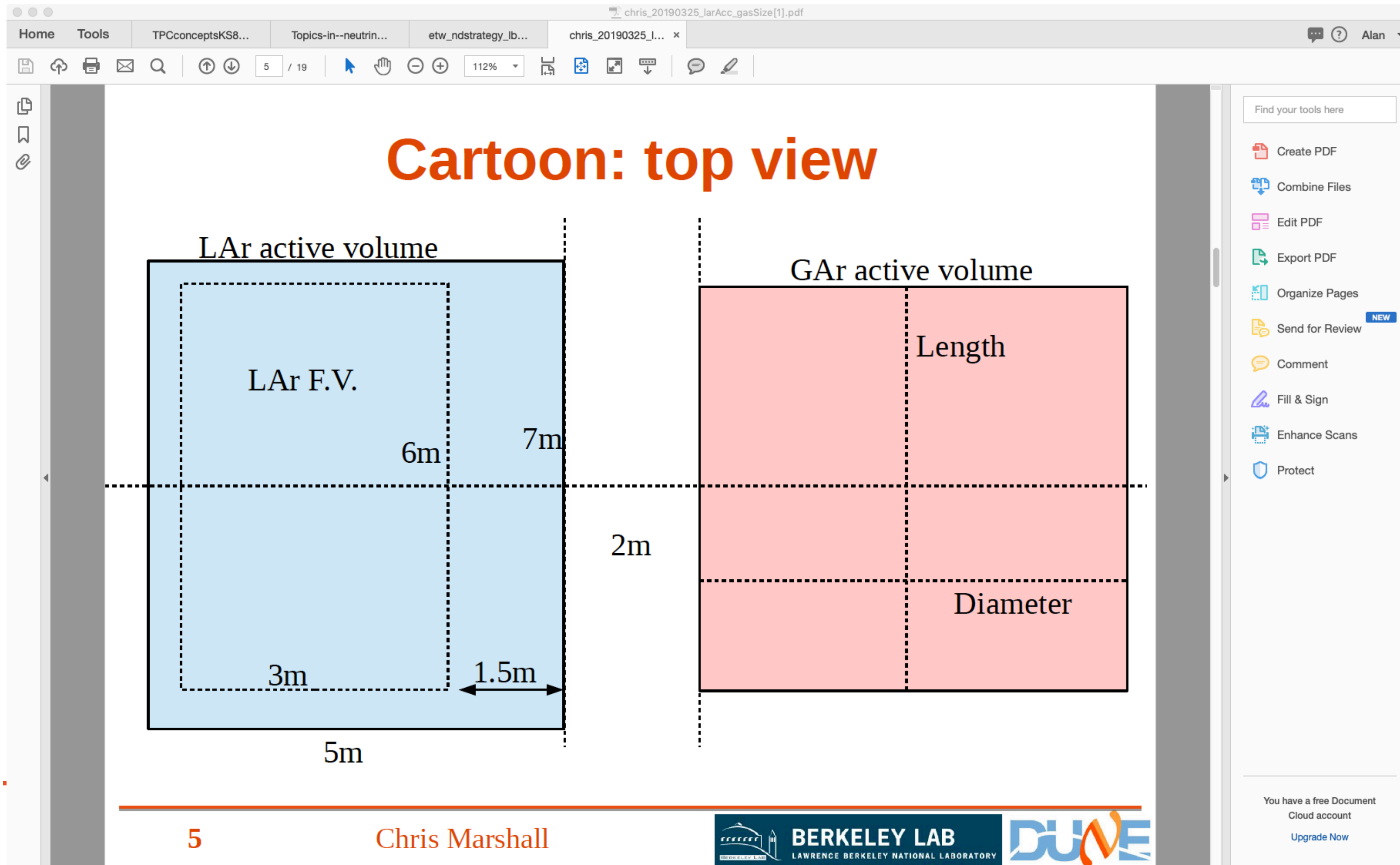
Model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Tools
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Topics-in--neutrin...
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Alan
5
/ 19
112%
Cartoon: top view
LAr active volume
LAr F.V.
6m
7m
3m
1.5m
5m
2m
GAr active volume
Length
Diameter
5
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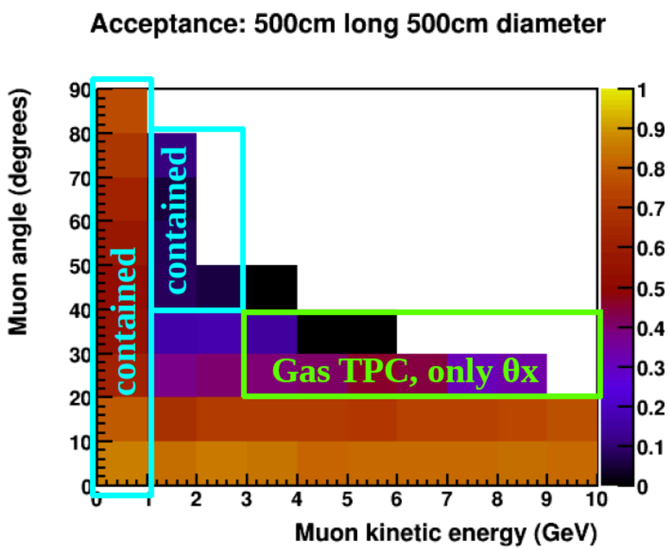
Acceptance

Muon acceptance: why

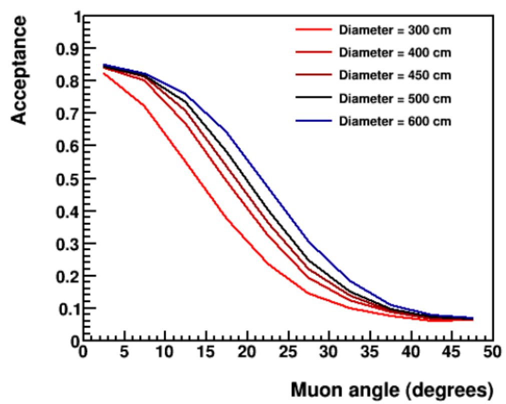


- Events with energy < 1 GeV are primarily contained, and don't depend on gas TPC dimensions
- Also ~2 GeV and high angles are contained
- For 20-30 degrees, match only when events have large angles in XZ plane
- Above 1 GeV, acceptance depends mostly on the angle

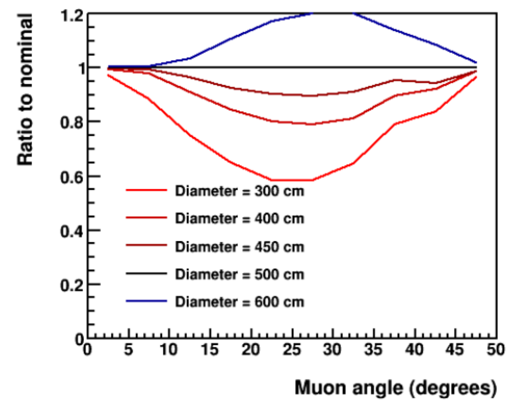
Acceptance vs. diameter

Acceptance vs diameter

5m length, T_μ > 1 GeV



5m length, T_μ > 1 GeV



- Same 5m length in X direction, diameter varying between 3m and 6m
- Right plot is ratio to acceptance of nominal dimensions, i.e. 5m length and 5m diameter
- Going to 4.5m is only ~10% loss at worst point

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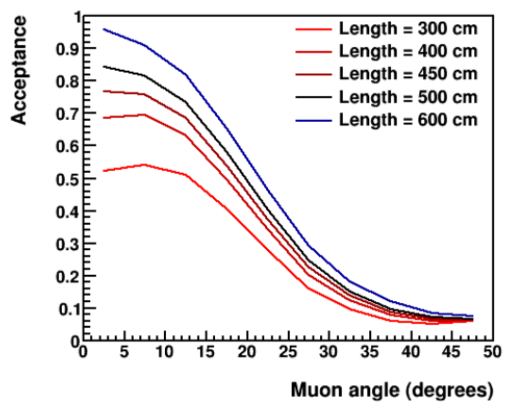
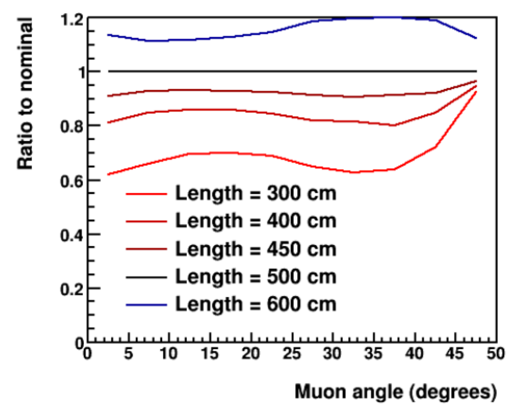
Acceptance vs. length

Acceptance vs length

5m diameter, $T_{\mu} > 1$ GeV



5m diameter, $T_{\mu} > 1$ GeV



- Same 5m diameter, length in X varying from 3m to 6m
- Very little shape as a function of angle
- Larger effect at small angles due to size of LAr F.V. relative to GAr length
- Decreasing length reduces acceptance at higher angles

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 >1m, or length by >1.5m, 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

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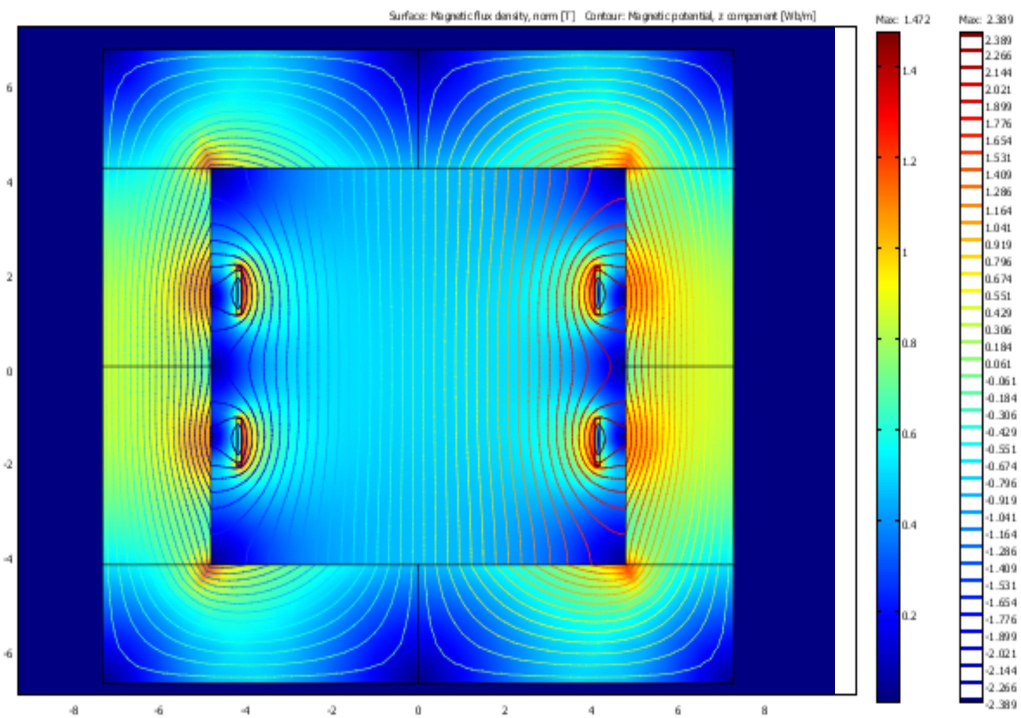
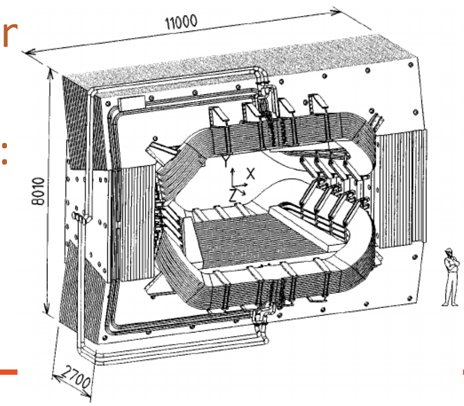
Solution 1 - Iron dominated magnet with SC coils – v1



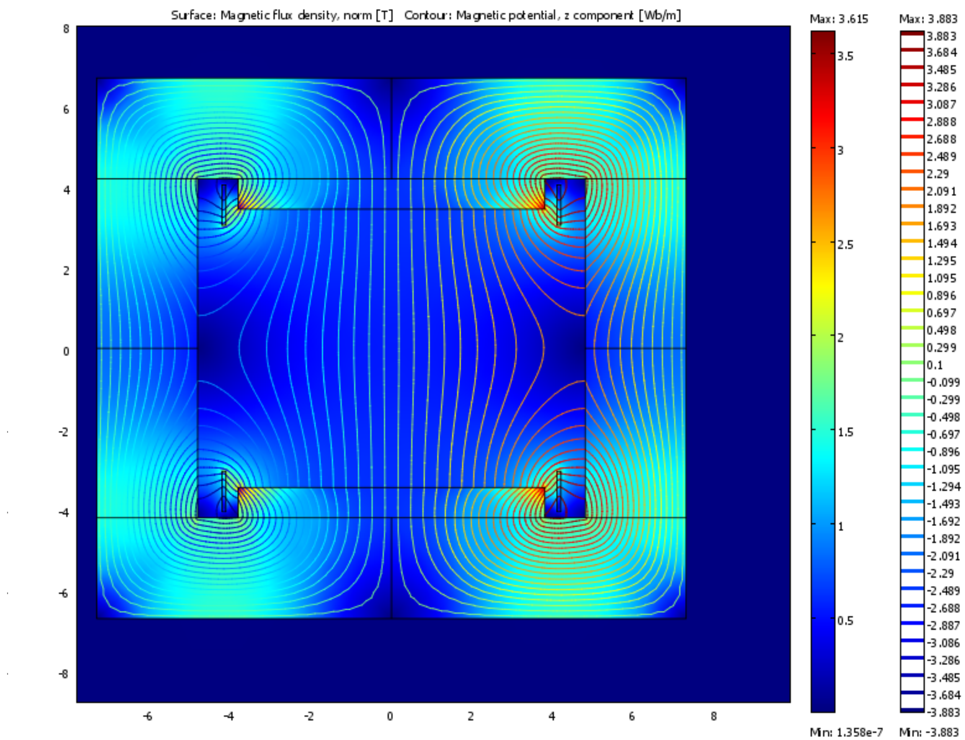
- 2 saddle coils with 119 turns
- 10 km of conductor required
- Current 13.5 kA for a central field of 0.5 T
- Peak field on conductor 1.5 T
- Stored Energy 80 MJ
- Iror



Note:

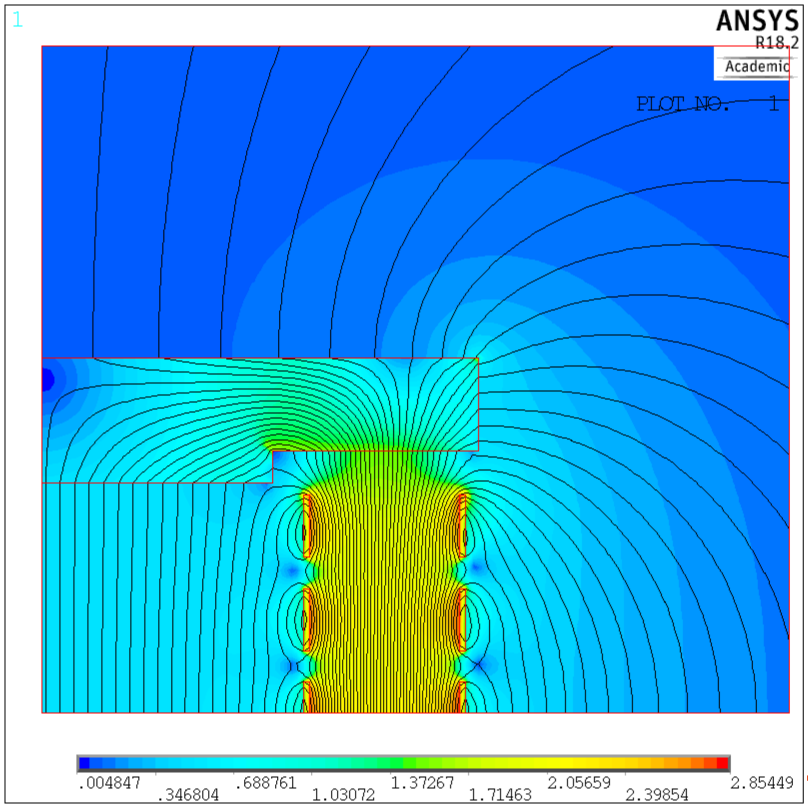
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Solution 1 - Iron dominated magnet with SC coils – v2

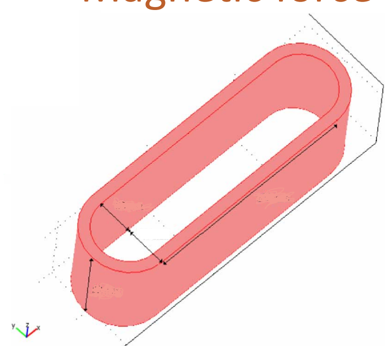


- **2 large racetrack coils** with 119 turns each
- 8.5 km of conductor required
- Current 13.5 kA for a central field of 0.5 T
- Peak Field 2 T
- Stored Energy 120 MJ
- Iron Yoke weigth (10000 t)

Solution 2 – Coil dominated magnet with partial iron yoke – version 1

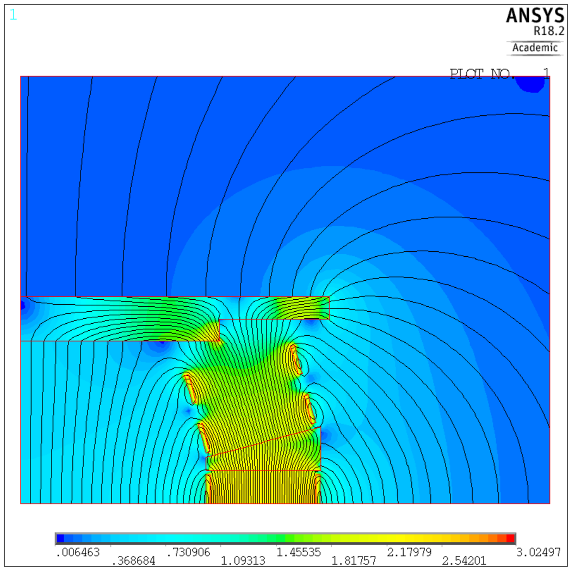


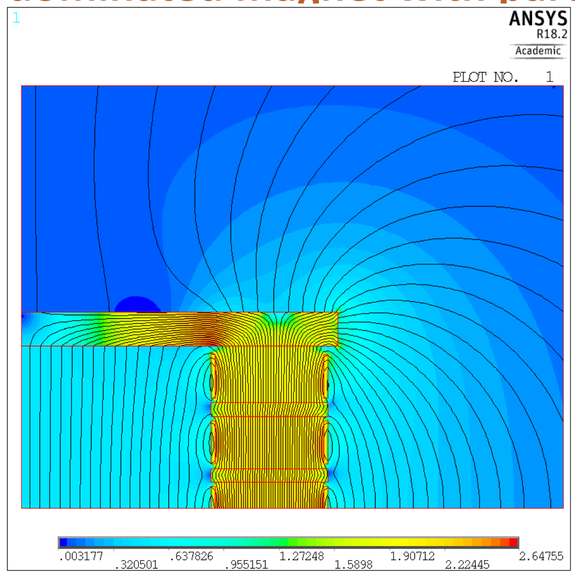
- **10 racetrack** coils with 119 each one
- 32 km of conductor required
- Current 26.7kA for a central field of 0.5 T
- Peak Field 2.85 T
- Stored Energy 828 MJ
- Top and bottom iron yoke (3878 t).
- Magnetic force on yoke 2 MN

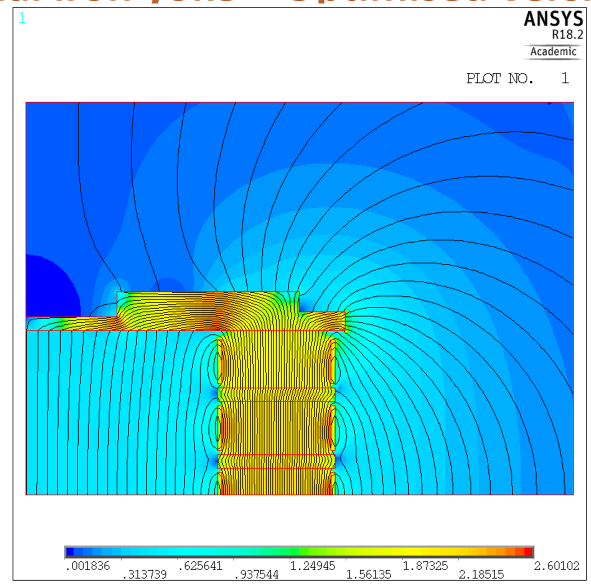


DEEP UNDERGROUND NEUTRINO EXPERIMENT

Solution 2 – Coil dominated magnet with partial iron yoke – Optimised versions







Current	31.5 kA
Peak field	2.78 T
Racetrack coils	12 (792 turns tot.)
Stored energy	611 MJ
Yoke weight	2331 tons

40% less iron; 30% less conductor

Complex mechanics, Less available space

Current	28 kA
Peak field	2.54 T
Racetrack coils	10 (960 turns tot.)
Stored energy	695 MJ
Yoke weight	2135 tons

45 % less iron; 20% less conductor

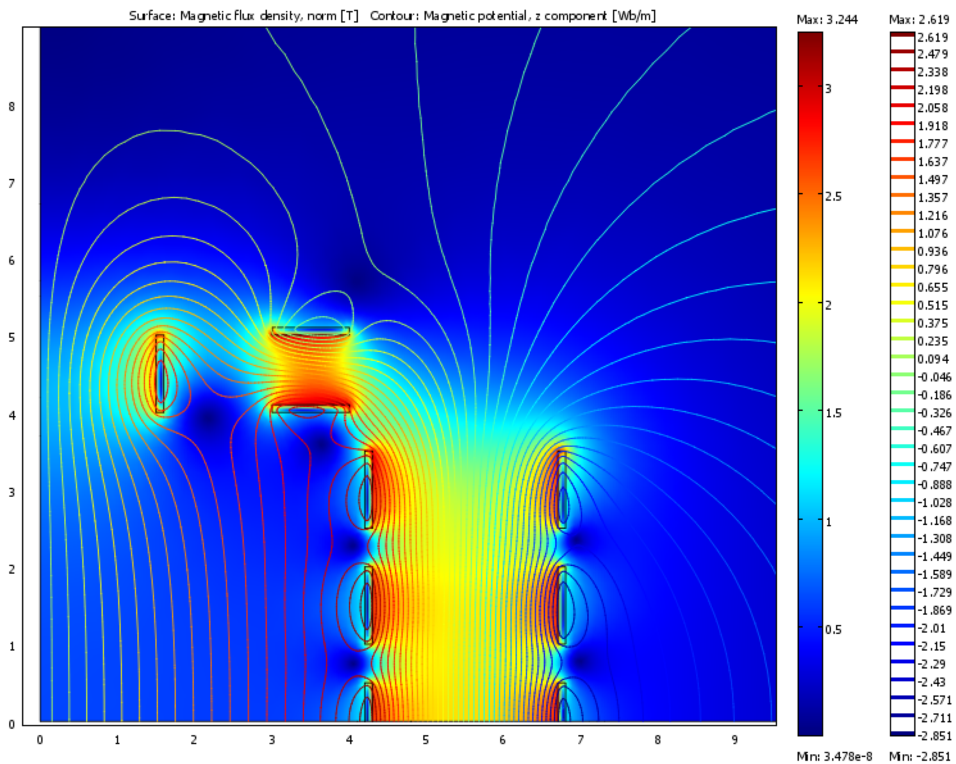
Current	27.8 kA
Peak field	2.51 T
Racetrack coils	10 (960 turns tot.)
Stored energy	680 MJ
Yoke weight	1868 tons

52% less iron; 20% less conductor

(most optimized solution)

DUNE

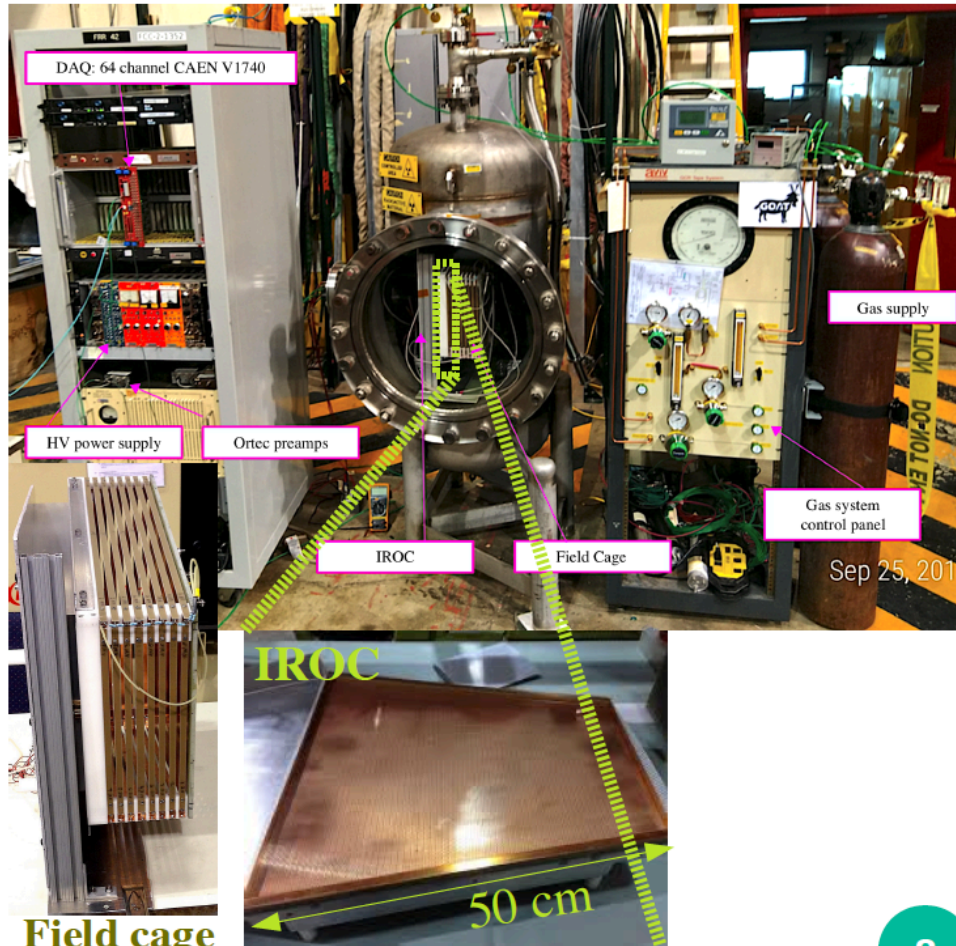
Solution 3 – No iron solution



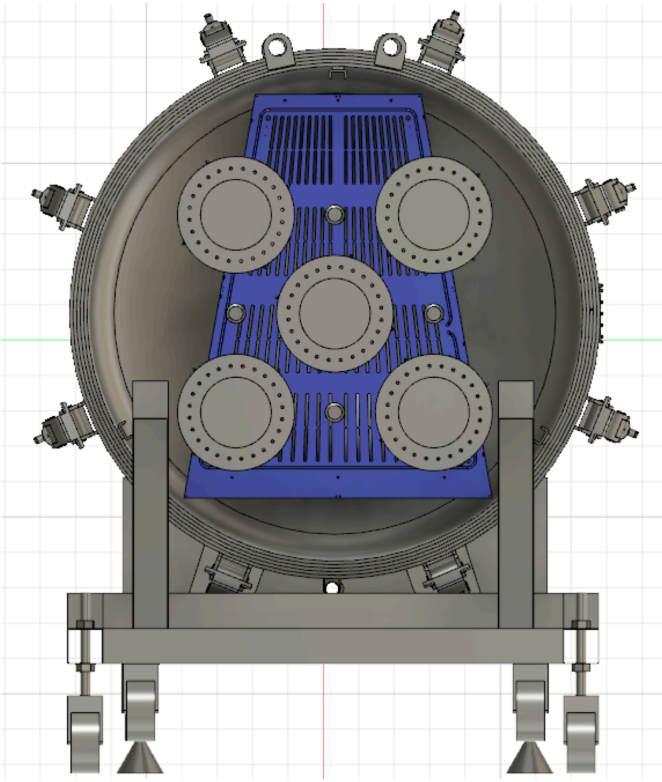
- **16 racetrack** coils (with 119 turn each)
- 47 km of conductor required
- Current 26.7kA for a central field of 0.5 T
- Peak Field 3.2 T
- Stored Energy 1080 MJ

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_2)
  - 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