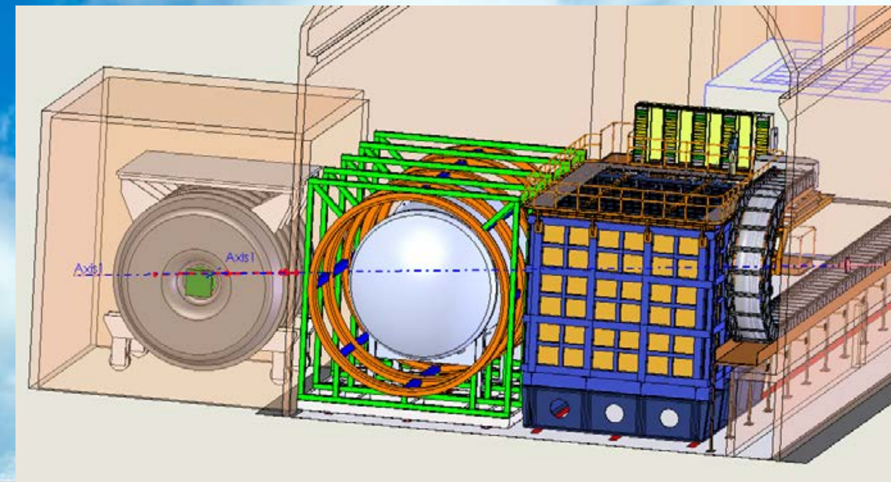
DUNE Near Detector

Design Status

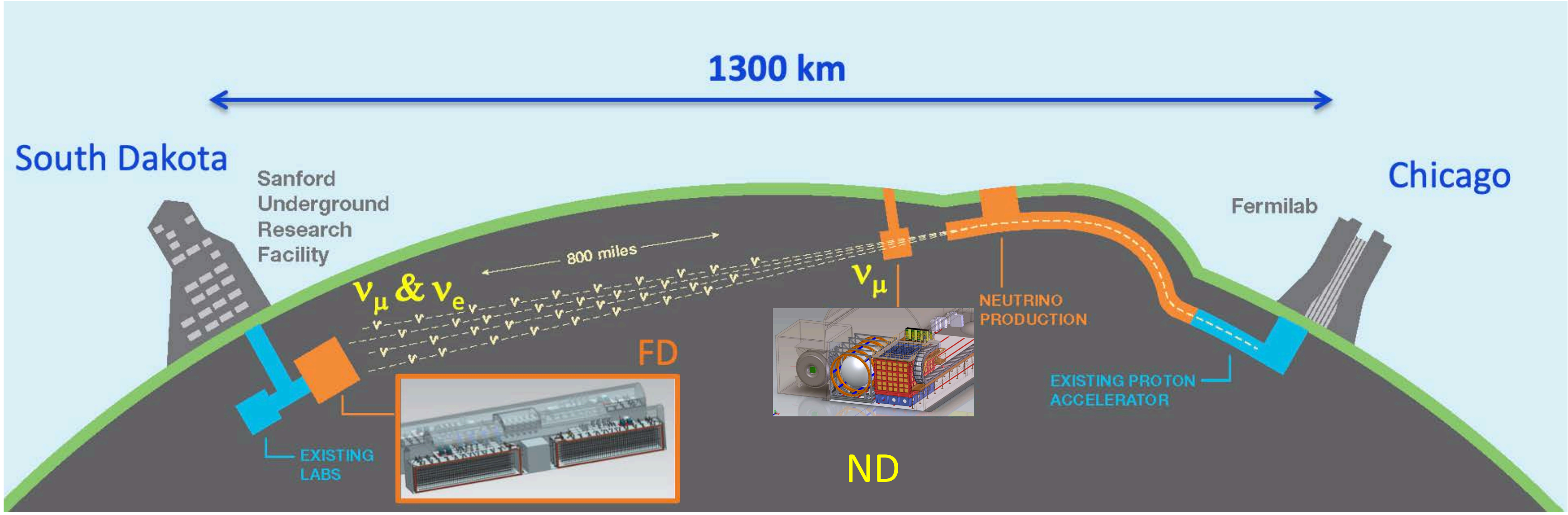


Alan Bross

NuFact 2019

August 29th, 2019

DUNE & Near Detector requirements

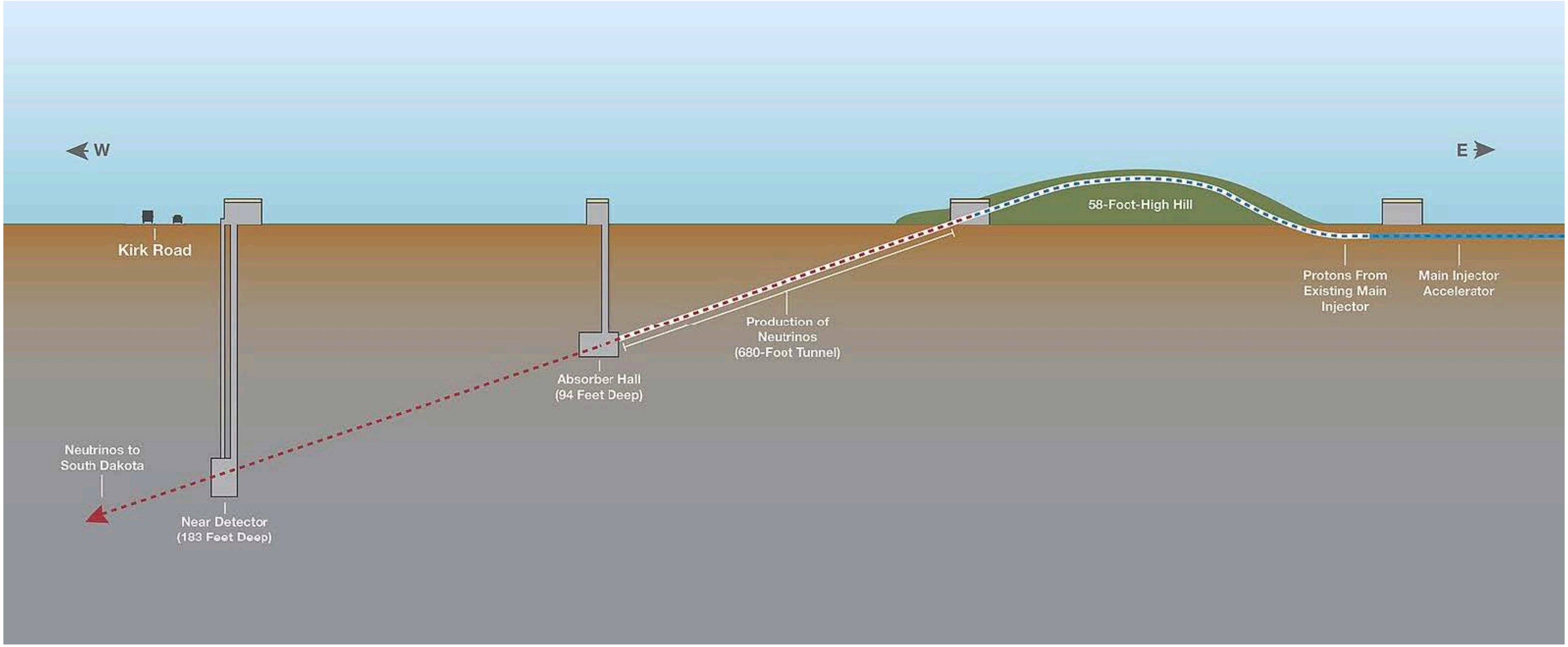


- LBNF sends an intense, broadband ν_μ (or anti- ν_μ) beam ~1300 km from Fermilab to the DUNE far detectors in South Dakota
- The Near Detectors must provide enough information so that we can develop a model that predicts the # evts observed

$$N_{FD}(\nu_\alpha \to \nu_\beta, E_{rec}) = \int dE_\nu \Phi_{\nu_\alpha}(E_\nu)\sigma_{\nu_\beta}(E_\nu)R_{\nu_\beta}(E_\nu, E_{rec})P(\nu_\alpha \to \nu_\beta, E_\nu)$$

  - Where: Φ is the flux, σ the xsec and R the detector response

DUNE near site



Near detector hall located 574m from the target and ~200' below the surface

The DUNE Near Detector complex

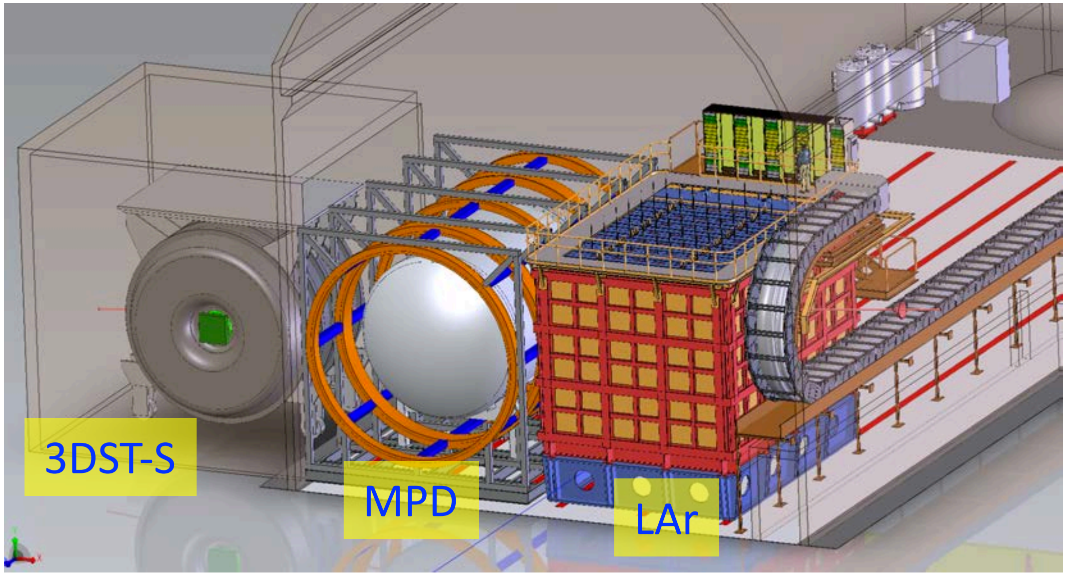
- Over the past 2 ½ years the DUNE collaboration has developed requirements and a concept design for the near detector complex
- Currently, the Near Detector Design Group is tasked with developing a reference design that meets all physics requirements
  - Deliver CDR by end of CY 2019
- I will present an overview of the requirements and then detail the current reference design

Overarching Requirements

O0: Predict the neutrino spectrum at the FD: The Near Detector (ND) must measure neutrino events as a function of flavor and neutrino energy. This allows for neutrino cross-section measurements to be made and constrains the beam model and the extrapolation of neutrino energy event spectra from the ND to the FD.

O0.1	**Measure interactions on argon**	Measure neutrino interactions on argon, determine the neutrino flavor, and measure the full kinematic range of the interactions that will be seen at the FD.
O0.2	**Measure the neutrino energy**	Reconstruct the neutrino energy in CC events and control for any biases in energy scale or resolution.
O0.3	**Constrain the xsec model**	Measure neutrino cross-sections in order to constrain the cross section model used in the oscillation analysis.
O0.4	**Measure neutrino flux**	Measure neutrino fluxes as a function of flavor and neutrino energy.
O0.5	**Obtain data with different neutrino fluxes**	Measure neutrino interactions in different beam fluxes in order to disentangle flux and cross sections and verify the beam model. **(PRISM)**
O0.6	**Monitor the neutrino beam**	Monitor the neutrino beam energy spectrum with sufficient statistics to be sensitive to intentional or accidental changes in the beam on short timescales.

Reference Design



- 3 components
  - LAr TPC with pixelated readout (50t)
  - Multi-Purpose Detector (MPD)
    - HPgTPC(1t) + ECAL + magnet
  - 3DST-S: Three-Dimensional Scintillator Tracker-Spectrometer (8t)
    - 3DST + Trackers + ECAL + magnet
- In addition, allow the LAr and MPD to move off-axis in order to implement the PRISM concept

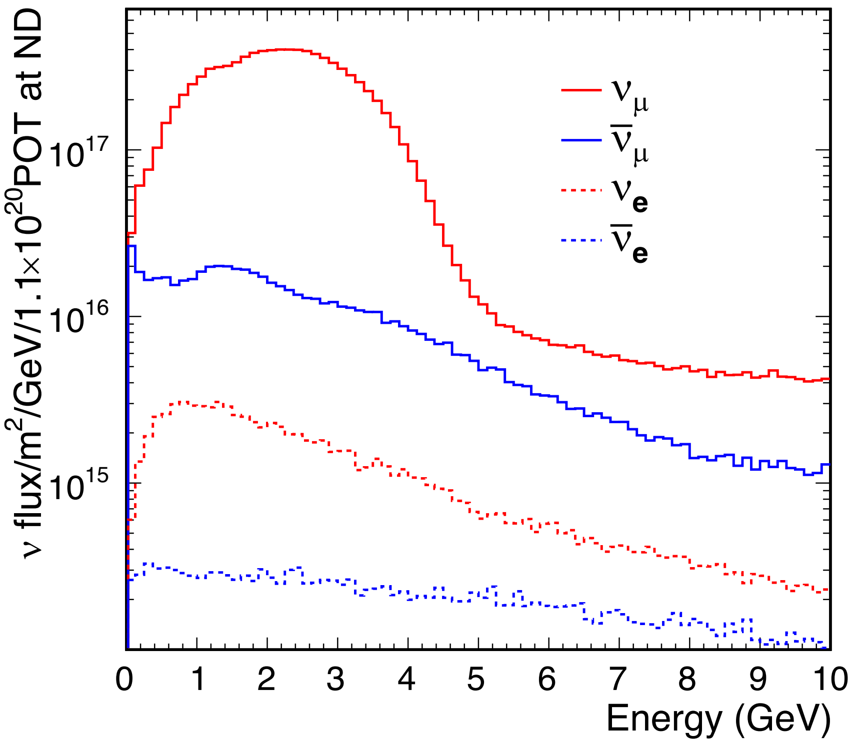
Detector functionality

Multi-pronged approach with complementary integration leading to tremendous robustness:

- ν interactions on Ar
  - LAr provides ν-Ar interaction as seen by FD
  - MPD provides ν-Ar interactions with sign selection, very low thresholds, and minimal secondary interactions
- Integration
  - MPD is necessary to complete reconstruction of events in LAr detector
    - μ spectrometer
  - ECAL necessary to complete reconstruction of interactions in the HPgTPC (like collider detector)
- Extended capability and robustness
  - 3DST-S provides detailed fixed, on-axis beam monitoring
  - 3DST-S provides look at ν-CH interactions with novel neutron detection capabilities

Flux, event rates @ ND570

Optimized CPV tune
FHC On-axis



Events/year in Fiducial volume

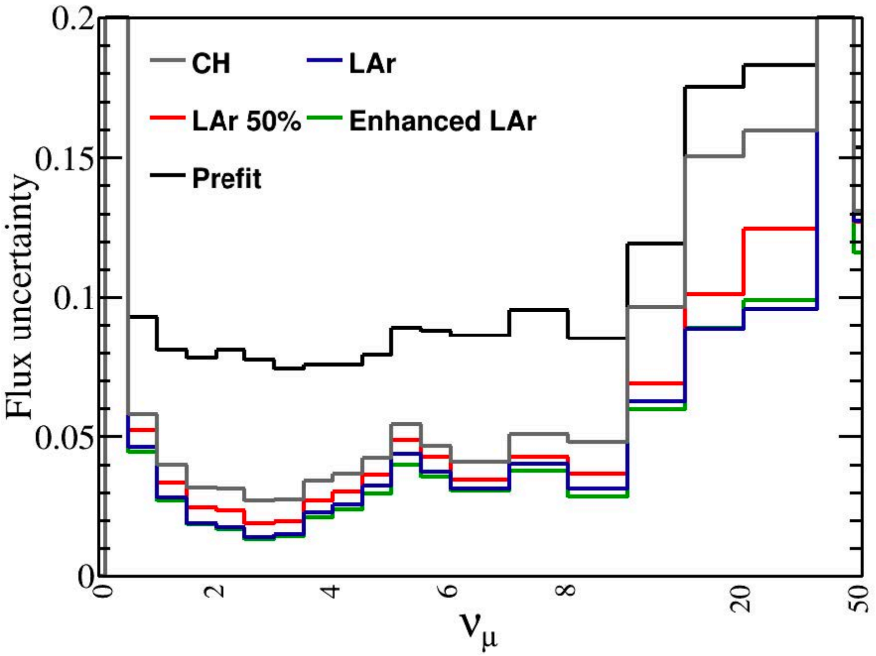
Detector	Target (Fid. mass t)	# ν_μ CC ($X10^6$)
LAr	Ar (50)	80
HPgTPC	Ar (1)	1.5
3DST-S	CH (8)	12

ν – electron elastic scattering

- Our "standard candle" for overall flux normalization is

$$\nu + e^- \rightarrow \nu + e^-$$

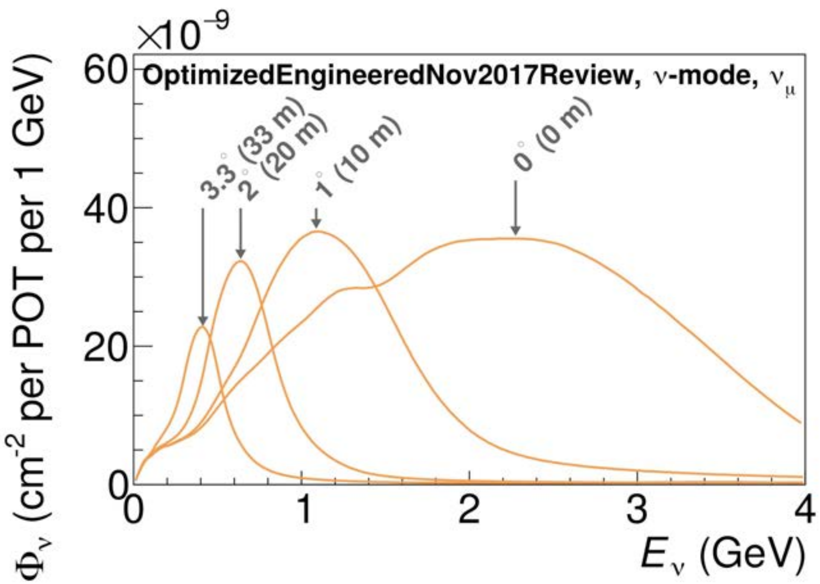
- The LAr detector is the principal device with 50t fiducial mass ➛ ~6500 evts/yr
  - Better than 1% statistical precision
  - Capacity to probe spectrum
  - 50t fiducial mass is based on hadronic containment requirement
    - Can extend (re-optimize) for forward electrons (~70t) tbd



Taking data off axis

- The DUNE near detector complex will allow for off-axis running in order to accommodate the PRISM concept
  - Precision Reaction Independent Spectrum Measurement
- Flux varies as a function of detector transverse position

- Pseudo-monochromatic beams (PMBs) can be formed by taking linear combinations of beam data at different off-axis positions
- These PMBs can help in understanding of relationship between E_ν and E_{reco} and thus help deconvolve the flux and cross section uncertainties
- Can predict oscillated neutrino event spectra at FD with reduced model dependence

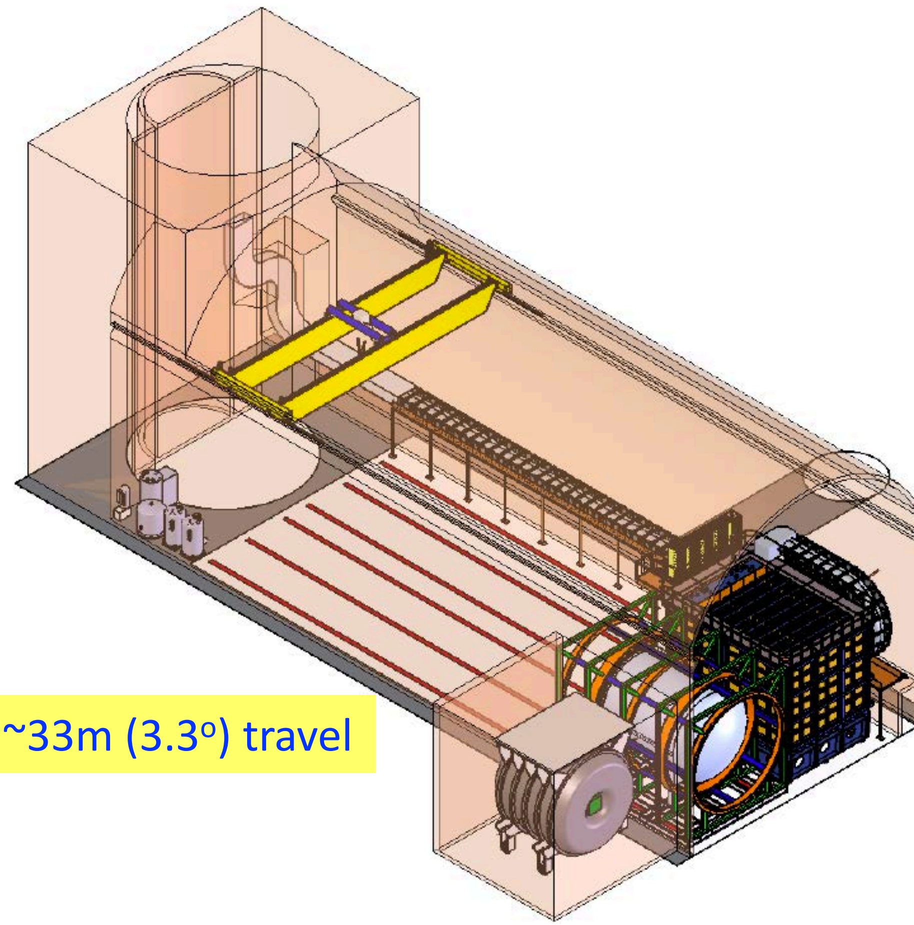


Extensive program for beyond νSM physics @ ND

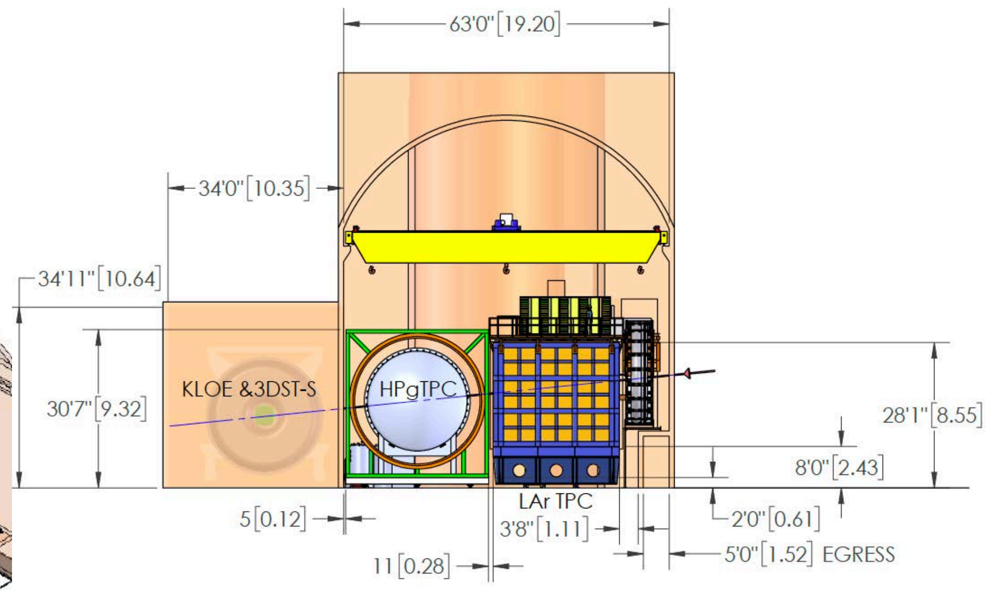
- The near detector facility will provide a very powerful tool to study:
  - Boosted dark matter
  - Sterile neutrinos
  - Neutrino tridents
  - millicharged particles
  - Unknown, unknowns………

See: POND^2
Physics Opportunities in the Near DUNE Detector Hall
https://indico.fnal.gov/event/18430/overview

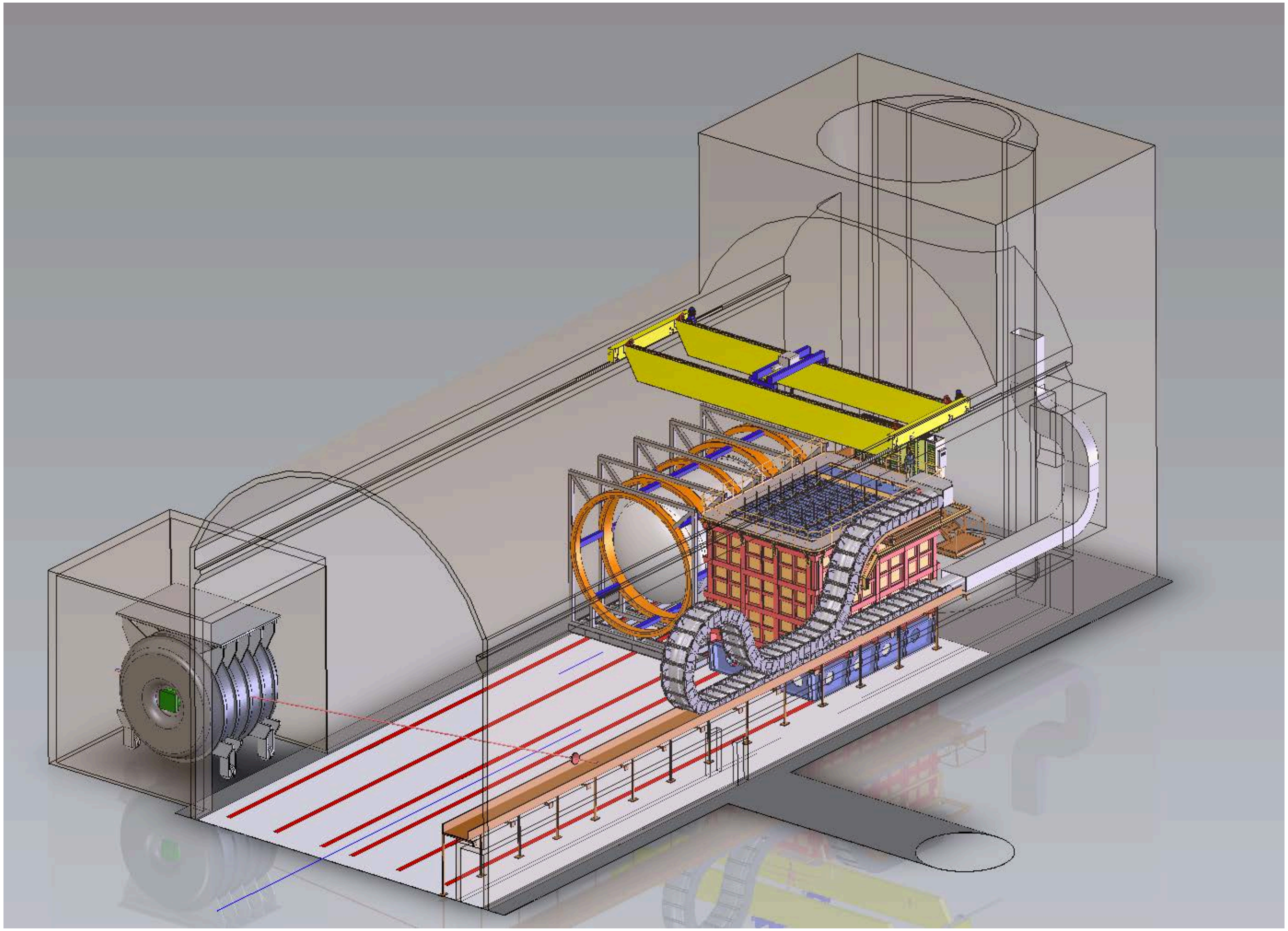
Near detector hall



~33m (3.3°) travel

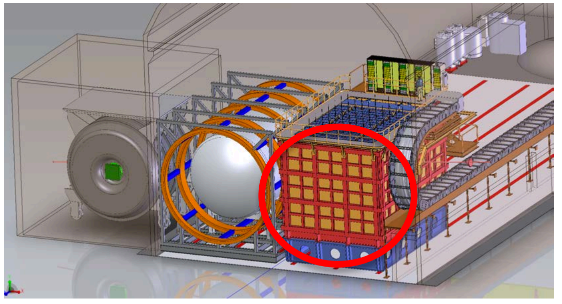


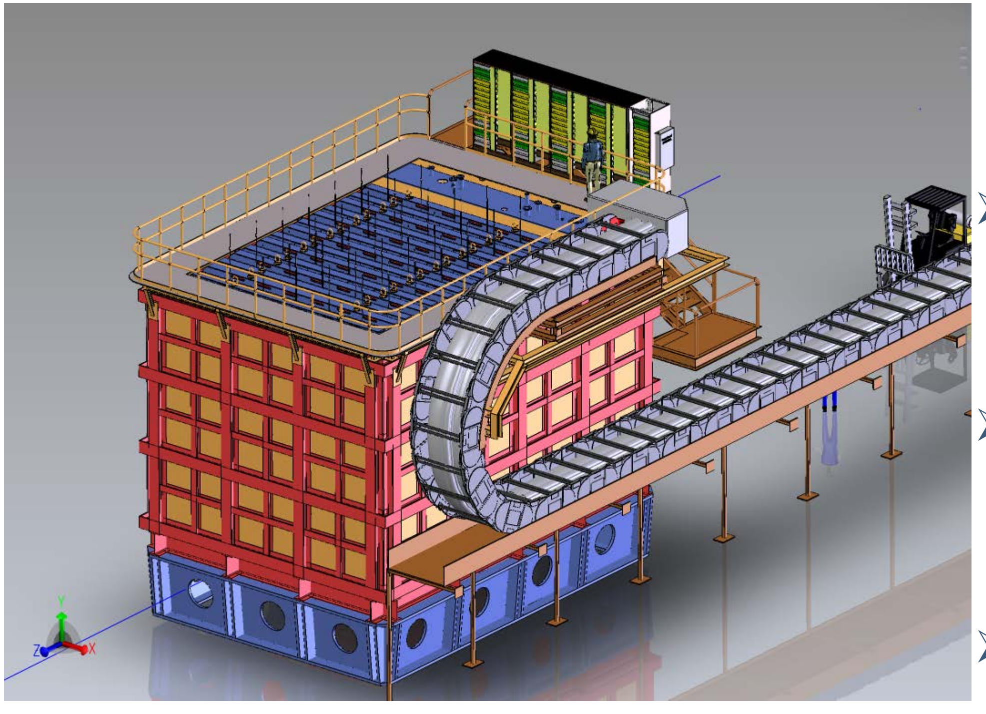
Detectors at extreme off-axis position



Detector systems

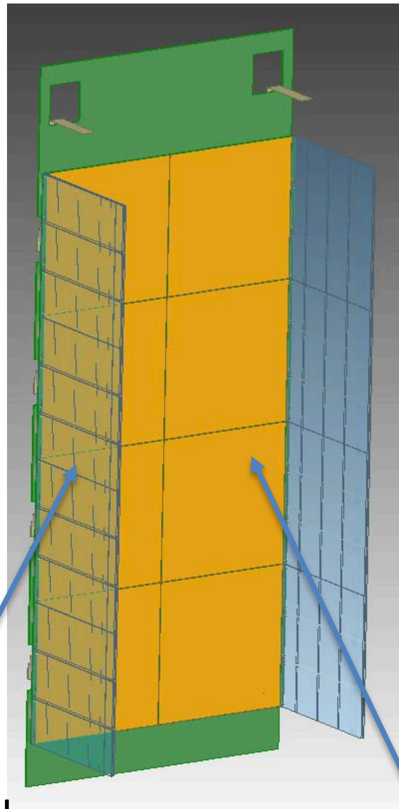
LAr overview

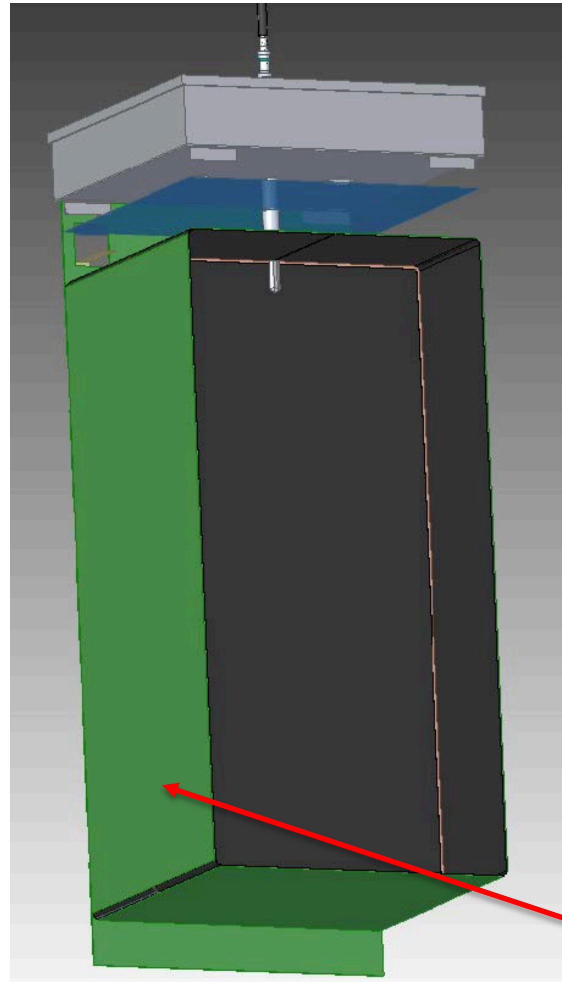




- ArgonCube concept
- Pixelated readout to accommodate high rate (>5 evts/spill)
  - 12 million pads
  - ~2 billion voxels
- Active volume:
  - 5 m deep in beam direction and 3 m tall for hadronic shower containment.
  - 7 m transverse to mitigate side muon spectrometer.
- Active mass ~ 150t
  - 50t fiducial (3m X 2m X 6m)
    - Hadronic containment
- Divided into 35 modules:
  - 1 m x 1 m x 3.5 m
  - 50 cm drift, 50 kV max
- Can move off axis

LAr: Module design

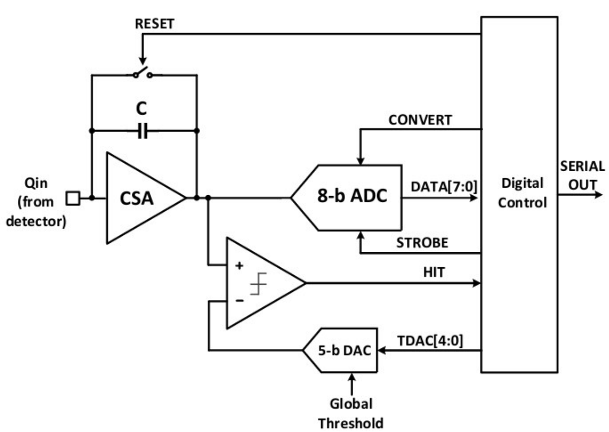


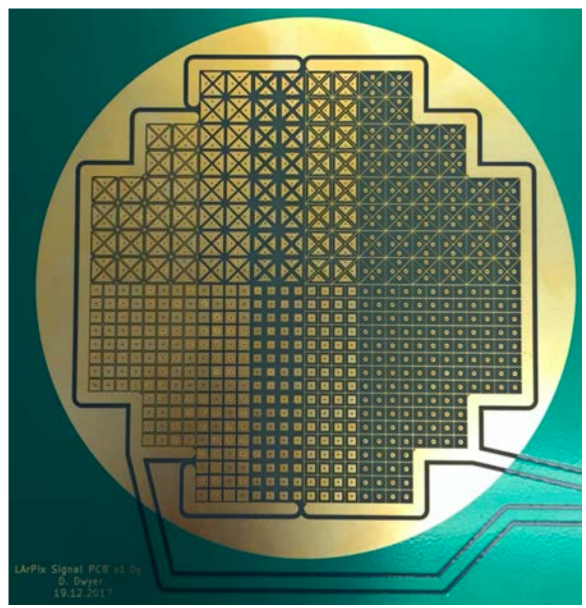


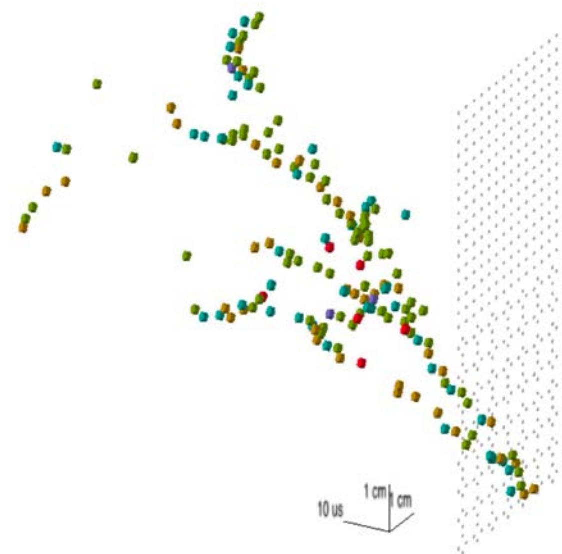
Light coverage % of charge readout area = 100%
(compared to SP Far detector of ~ 14%

Pixelated charge readout

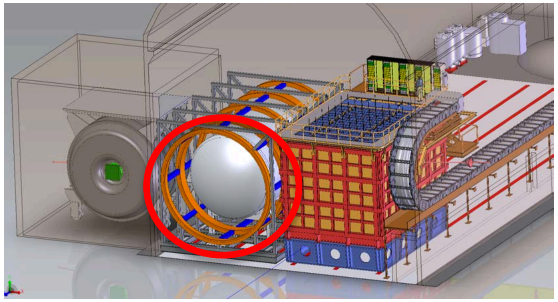
- True 3D event reconstruction is achieved using a pixelated charge readout, with cold amplification and digitization of every pixel. (N.B. pixel pitch is set to match the wire spacing of the FD.)
- This was enabled by the low-power LArPix ASIC, developed at LBNL. JINST 13 (2018) no.10, P10007.

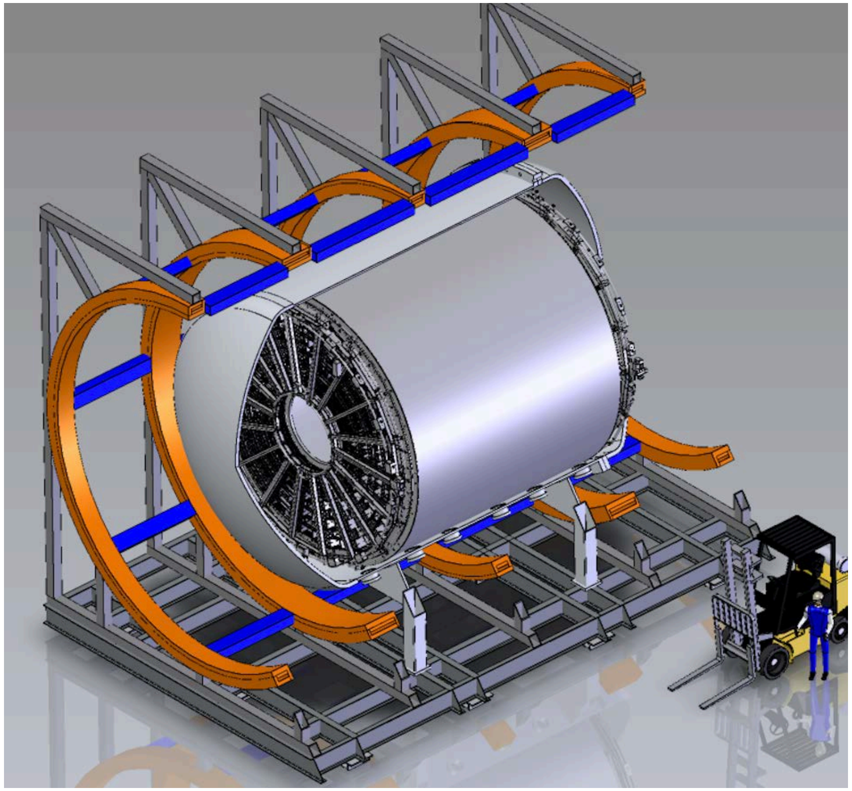






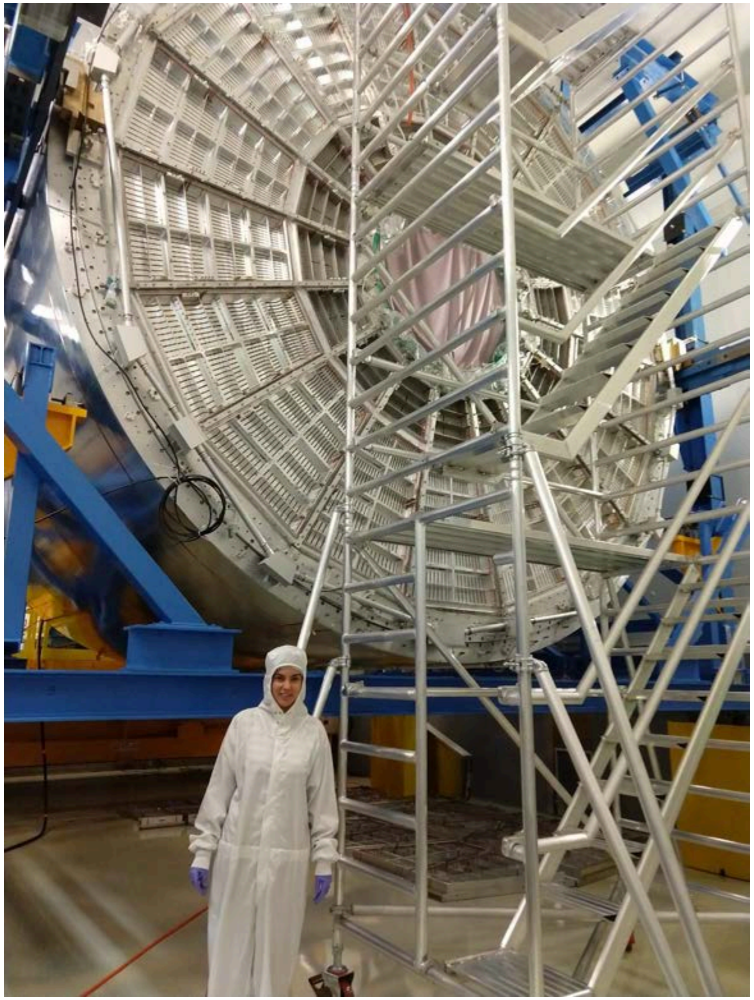
Multi-purpose detector overview





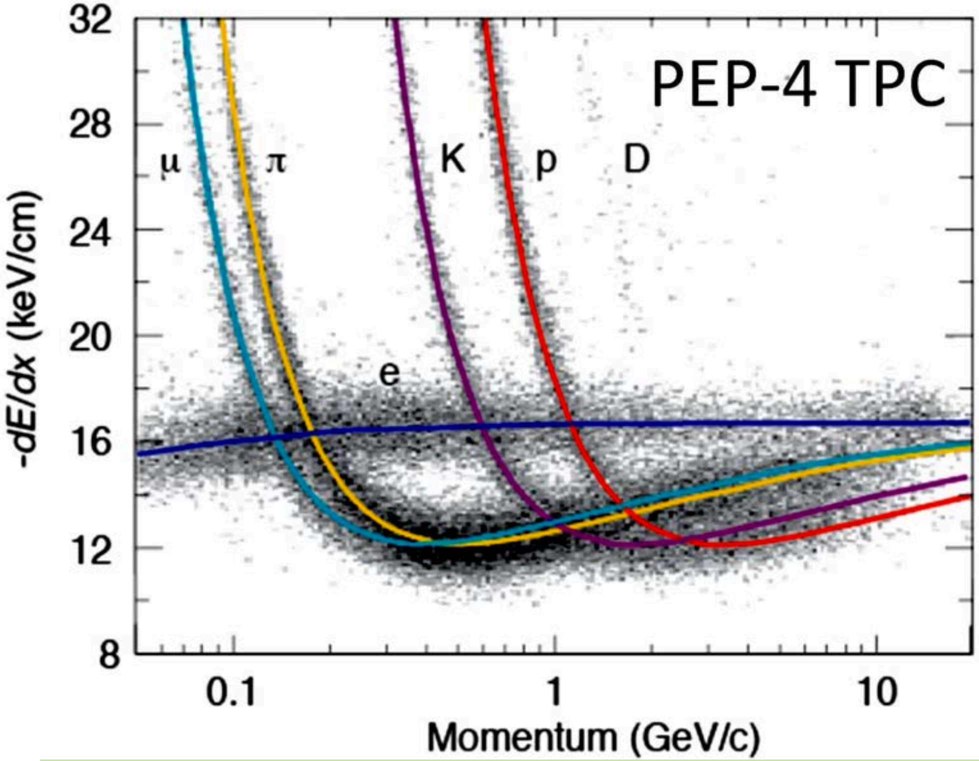
- High pressure (10bar) gas TPC + ECAL + SC magnet + μ tag
- Provide muon spectrometry for muons leaving LAr
  - LAr event containment
- Provide an independent, statistically significant event sample on Ar gas
  - Sign selection
  - Full 4π coverage
  - Very-low tracking threshold
  - Essentially no secondary interactions
    - Low density
- Can move off axis

High-pressure gas TPC (HPgTPC)



Build copy of ALICE TPC reusing their wire chambers

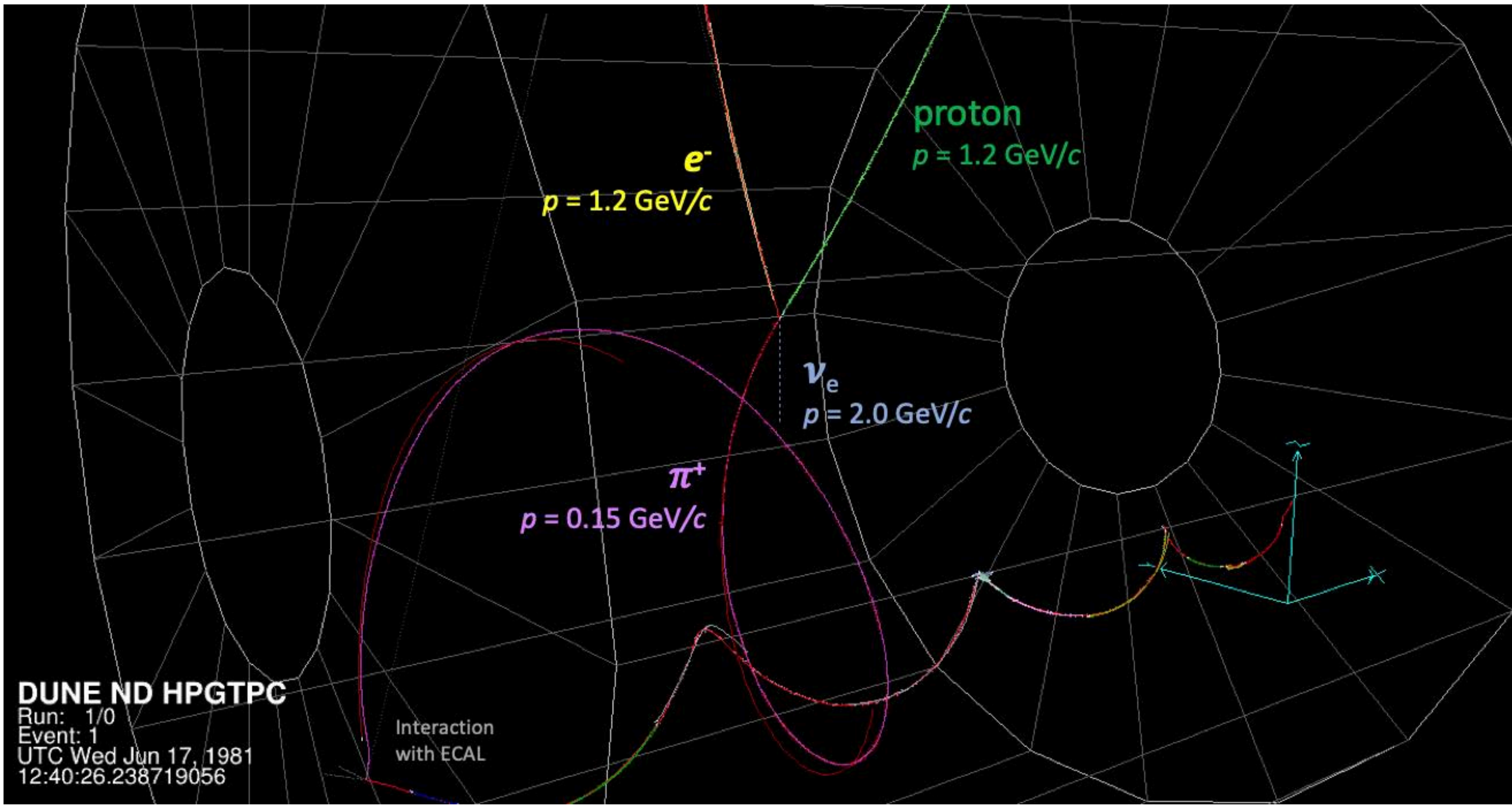
Well established technology
Vetted detector design



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

A Simulated and Reconstructed ν_e Charged Current Event in the HPgTPC

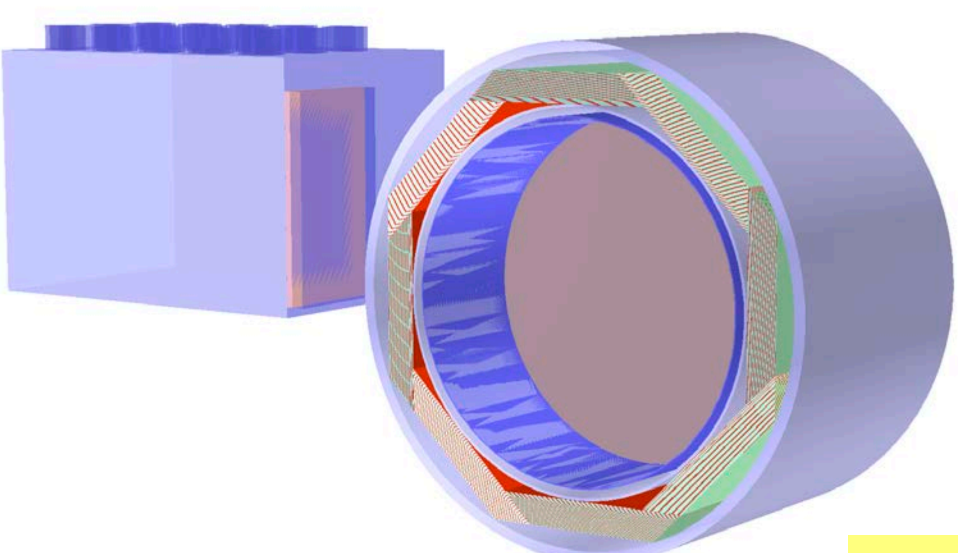
$\nu_e + Ar \rightarrow e^- + \pi^+ + p + n$

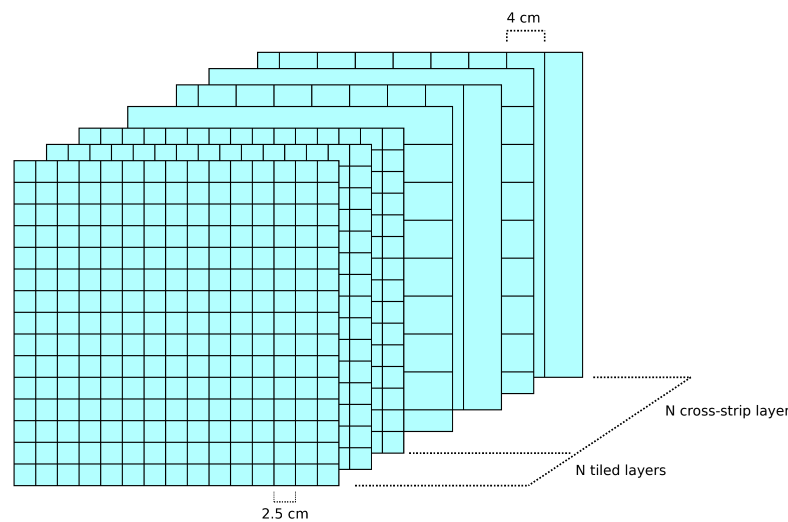


Neutron with p = 0.23 GeV/c at the P.V. not shown

ECAL

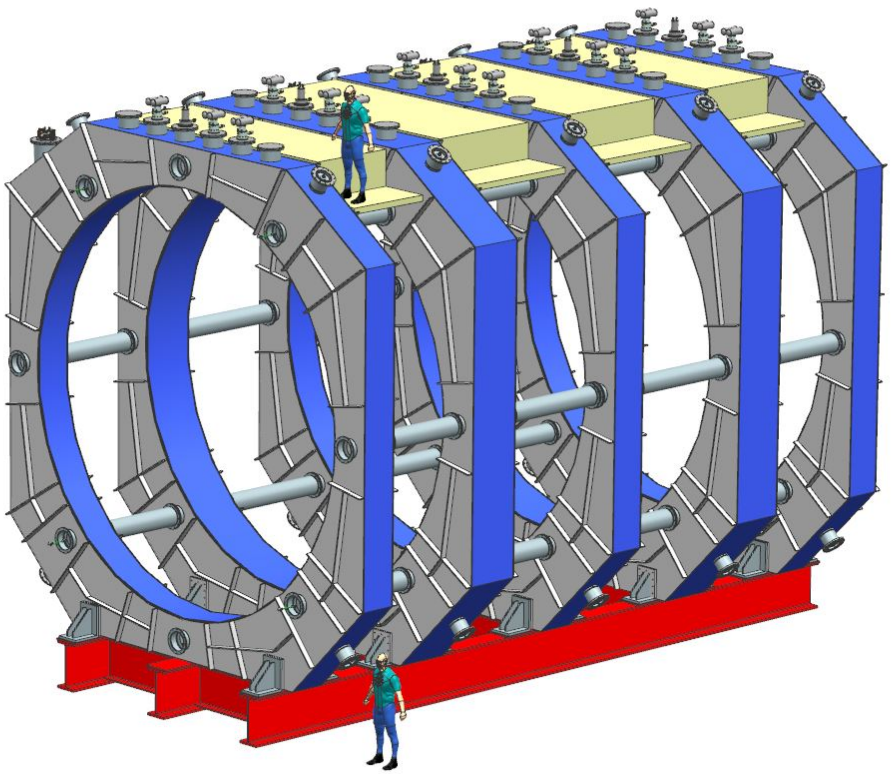
- Surrounds HPgTPC to detect photons and neutrons
- Plastic scintillator tiles & strips – CALICE architecture
- SiPM readout now affordable due to recent significant cost reductions





Initiated detailed optimization study

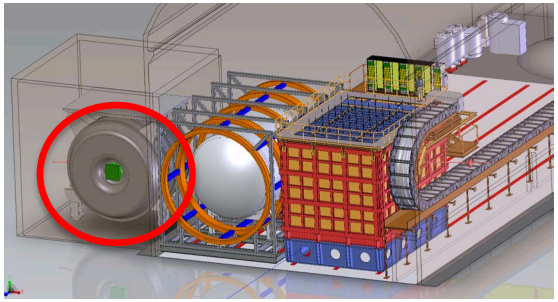
Magnet: Superconducting 3-coil Helmholtz with 2 superconducting bucking coils

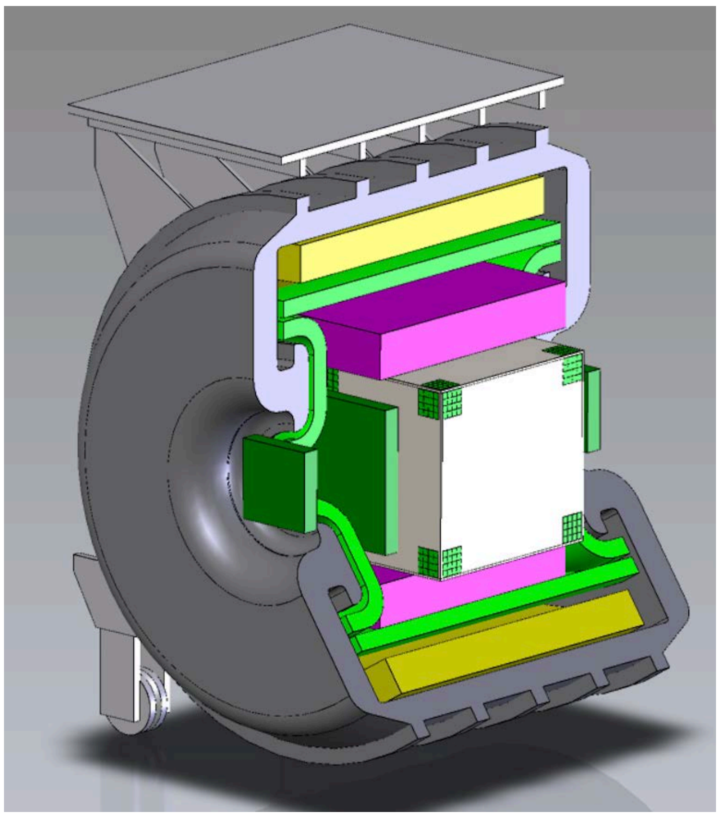


Magnet design concept

- 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 (3.5m)
  - Center and shielding coils are identical.
- Basic magnetic, cryostat and structural designs complete

3DST-S overview



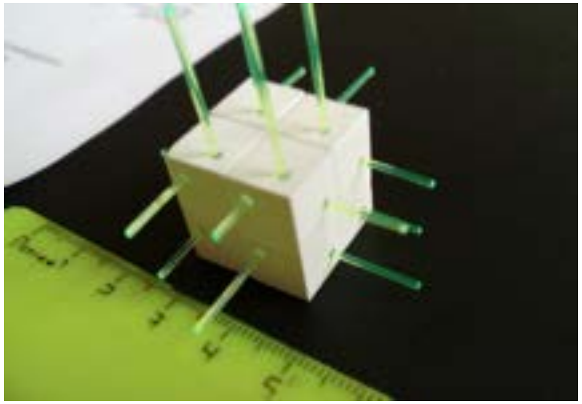


- Provides precision on-axis monitoring of neutrino beam through rate, profile, and spectrum measurements
- Consists of
  - 3-dimensional scintillator tracker active target (8t)
  - Gas tracking chambers (1 atm TPCs)
  - KLOE EM calorimeter
    - Scintillator fiber + Pb
  - KLOE magnet system
    - 0.6T central field (SC magnet)
    - Return Fe
- Fixed on-axis position

3DST details

- Active scintillating target composed of 1x1x1cm^3 scintillator cubes
  - 2.4 x 2.4 x 2 m^3 total volume
  - fine-grained, isotropic tracking (proton tracking to ~300 MeV/c)
  - neutron tagging and spectrometry by time-of-flight
- Surrounded by gas (1bar) TPC for tracking and ECAL in magnetic field

High-performance beam monitor
+
Independent physics program (ν_μ + CH)



3DST capabilities

- **Precision on-axis flux monitor**
  - Sufficient rate, spectrometry capabilities, and transverse span
- Neutron detection
  - New capability in neutrino detectors
  - Nascent capabilities in MINERνA show potential
- ν-CH sample
  - Cross check ν-A modelling across A
  - Connect to "historic" data sets
  - Provides cross check on flux measurements with very different detector technology and capabilities

Comparison between Ingrid-like system and spectrometer.
Preliminary

sqrt(chi2)	4 modules One-side rate	Muon spectrometer
Beam targ. dens.	1.9	7.8
Beam offset x	0.7	6.7
Beam theta	0.2	19.9
Horn 1 X 0.5 mm	1.9	8.8
Horn 1 Y 0.5 mm	0.7	12.8
Horn 2 X 0.5 mm	0.2	9.9
Horn 2 Y 0.5 mm	0.4	6.3

Conclusions

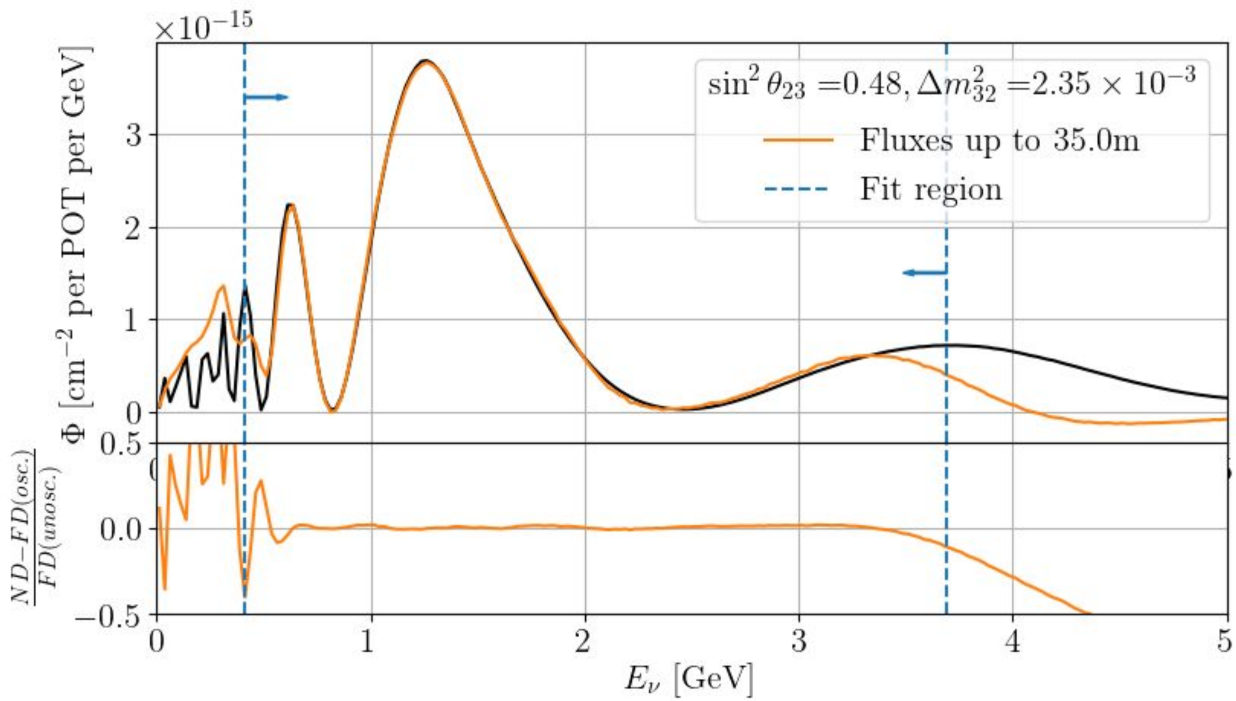
- DUNE has developed a near detector reference design that has wide-ranging capability (calorimetric, spectrometer, PID, multiple target nuclei, off-axis measurements)
  - LAr, MPD (HPgTPC+ECAL+Magnet+μ tagger) & 3DST-S
    - Basic technical/engineering foundations in place for most
- With these detectors and the LBNF beam, we will accumulate enormous statistics in all channels, including neutrino-electron elastic scattering
- Aggressive 3-pronged approach to CPV
- Opportunities to study physics beyond the νSM and neutrino interaction physics are extensive

Thank You

BACKUPS

PRISM

- Predict oscillated neutrino event spectra at FD with reduced model dependence
  - Form “oscillated” flux at near detector with linear combinations of off-axis data
  - Extrapolate to Far detector
  - Interaction model independent

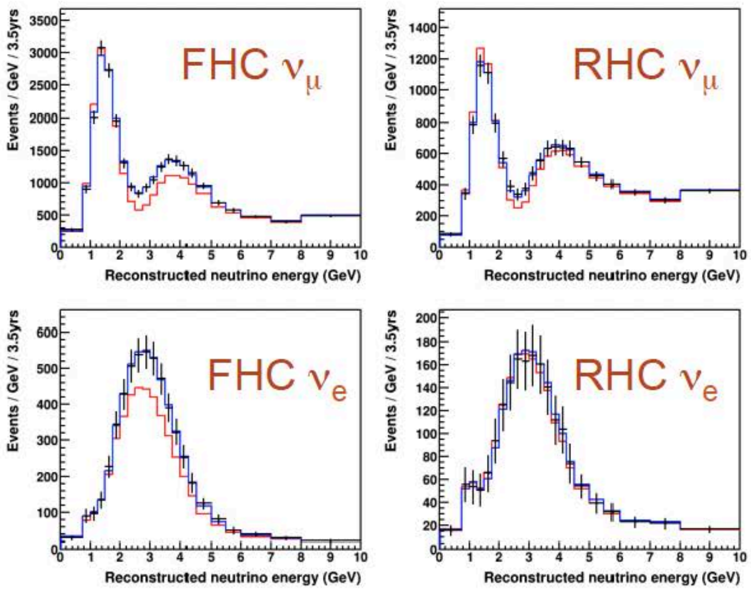


LBL Analysis, bias studies & DUNE-PRISM

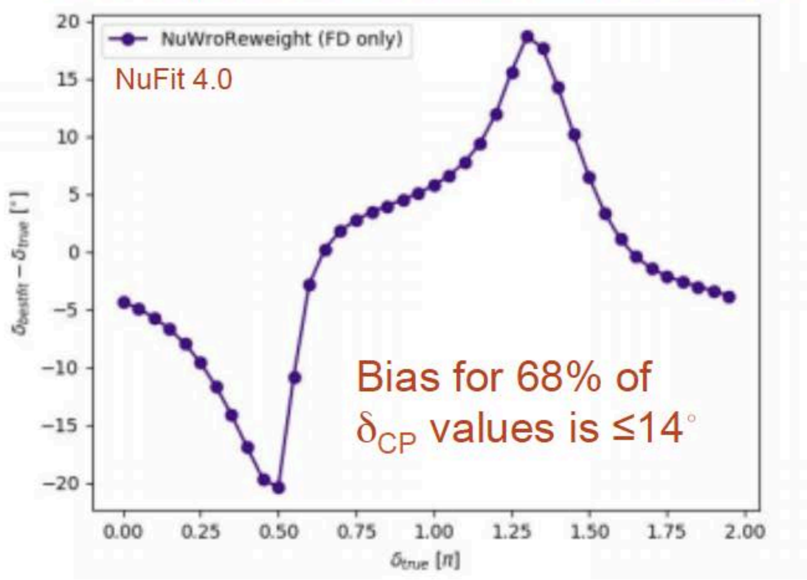
GENIE→NuWro

- FD-only fit appears fine, but result is biased!

Fit χ^2/d.o.f. < 1



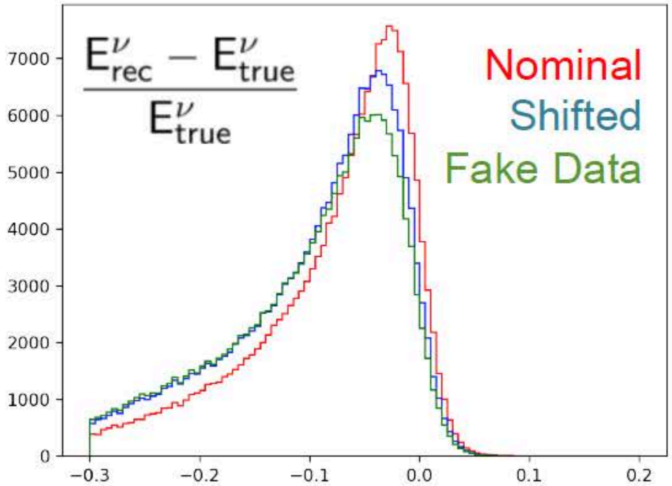
Bias depends on oscillation parameters



- ND-FD fit has χ^2/d.o.f. > 30! With a ND we would not miss this bias. For an FD-only result, we would have to take this bias as a systematic uncertainty.

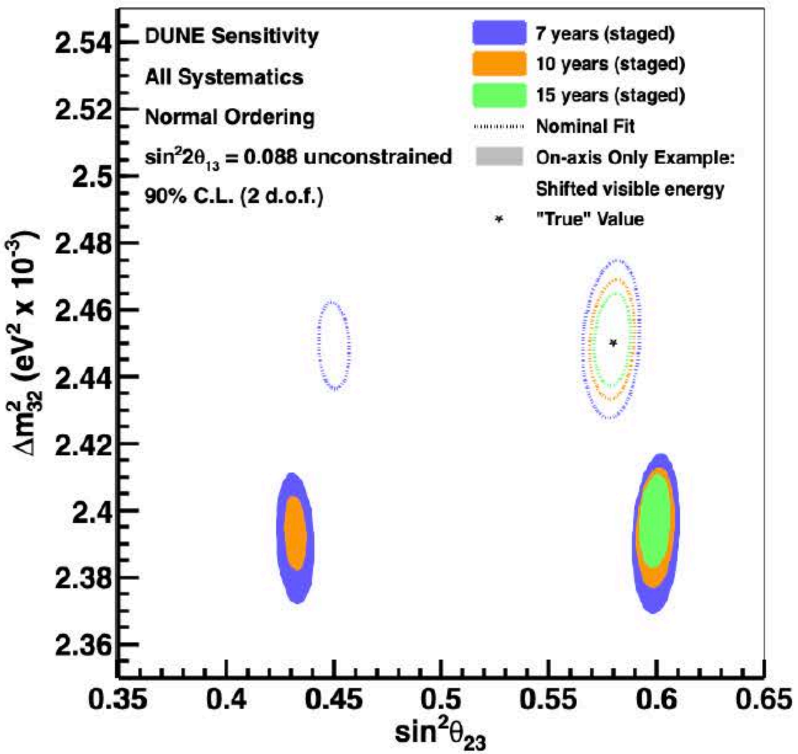
Bias studies II

Reconstructed E_ν



Significant impact on relationship between E_{true} and E_{rec} leads to large bias in Δm^2_{32} measurement that would be undetectable without off-axis measurements.

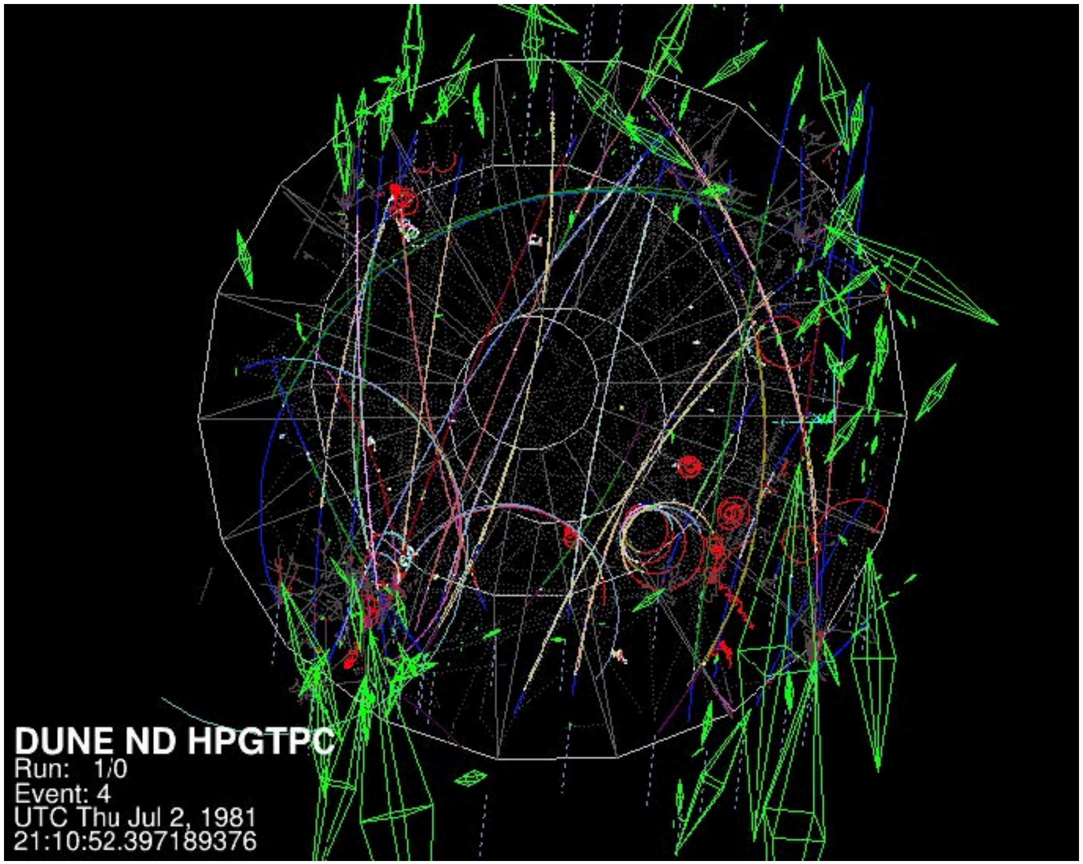
Δm^2_{32} vs $\sin^2\theta_{23}$



Very strong case made for NDs and the need for them to take data off axis

Background activity per spill

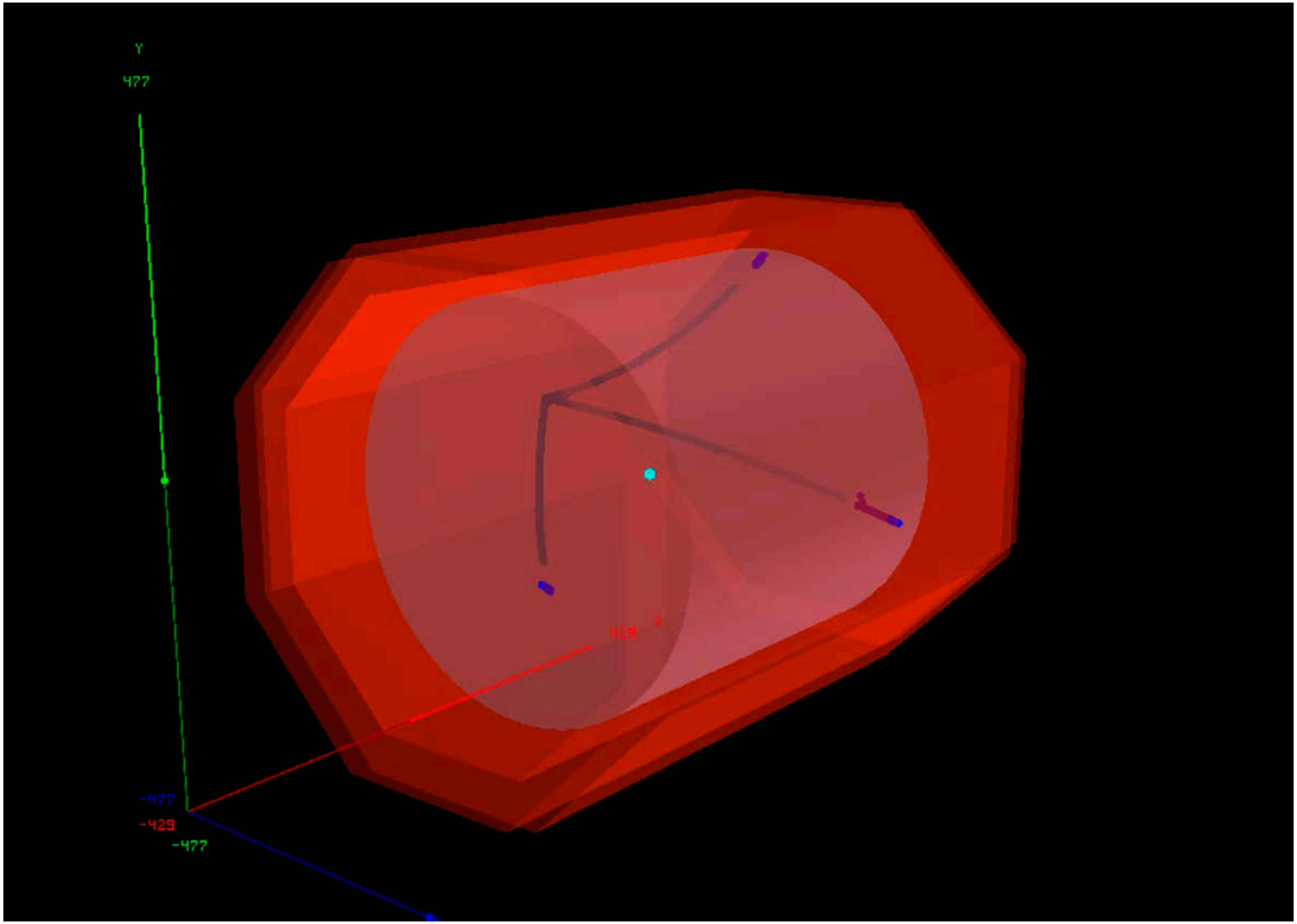
Hits integrated over full spill



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

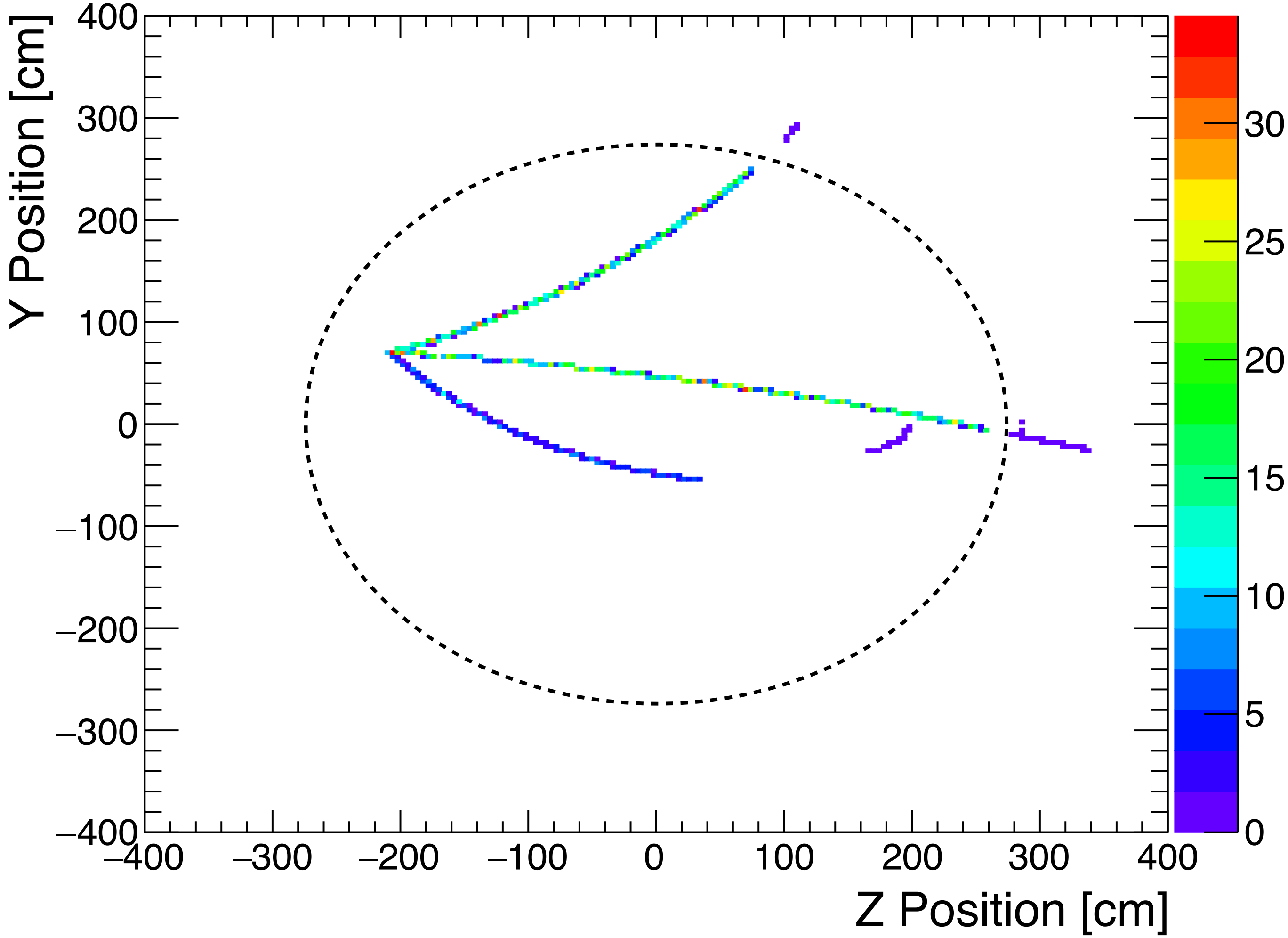
- We can cut on
  - Timing
  - Direction
  - dE/dx
  - Opening angle
  - Momentum analysis

ν_μCC background study – test event



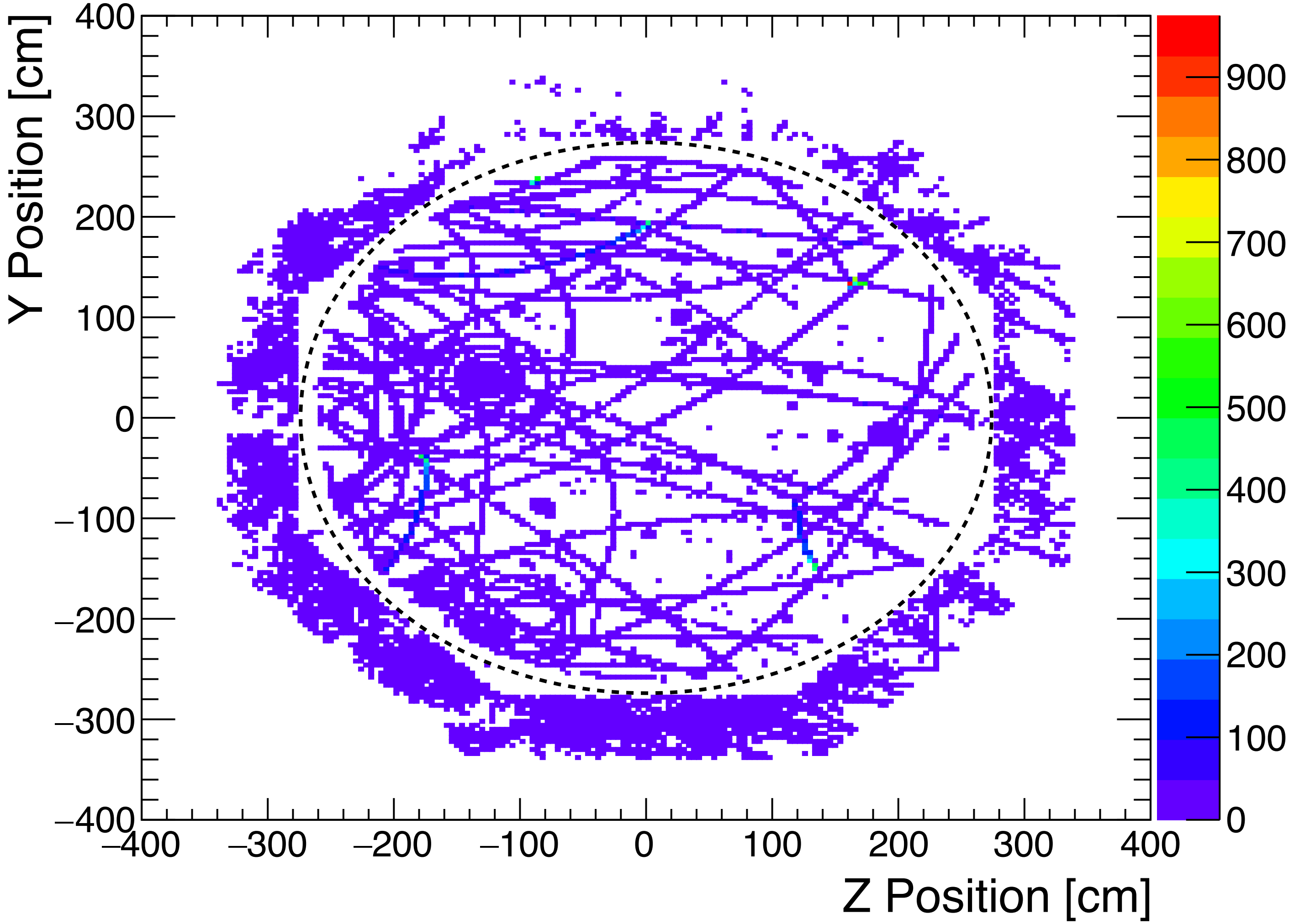
Z-Y Projection: Sample event - $\nu_\mu CC$

Test event



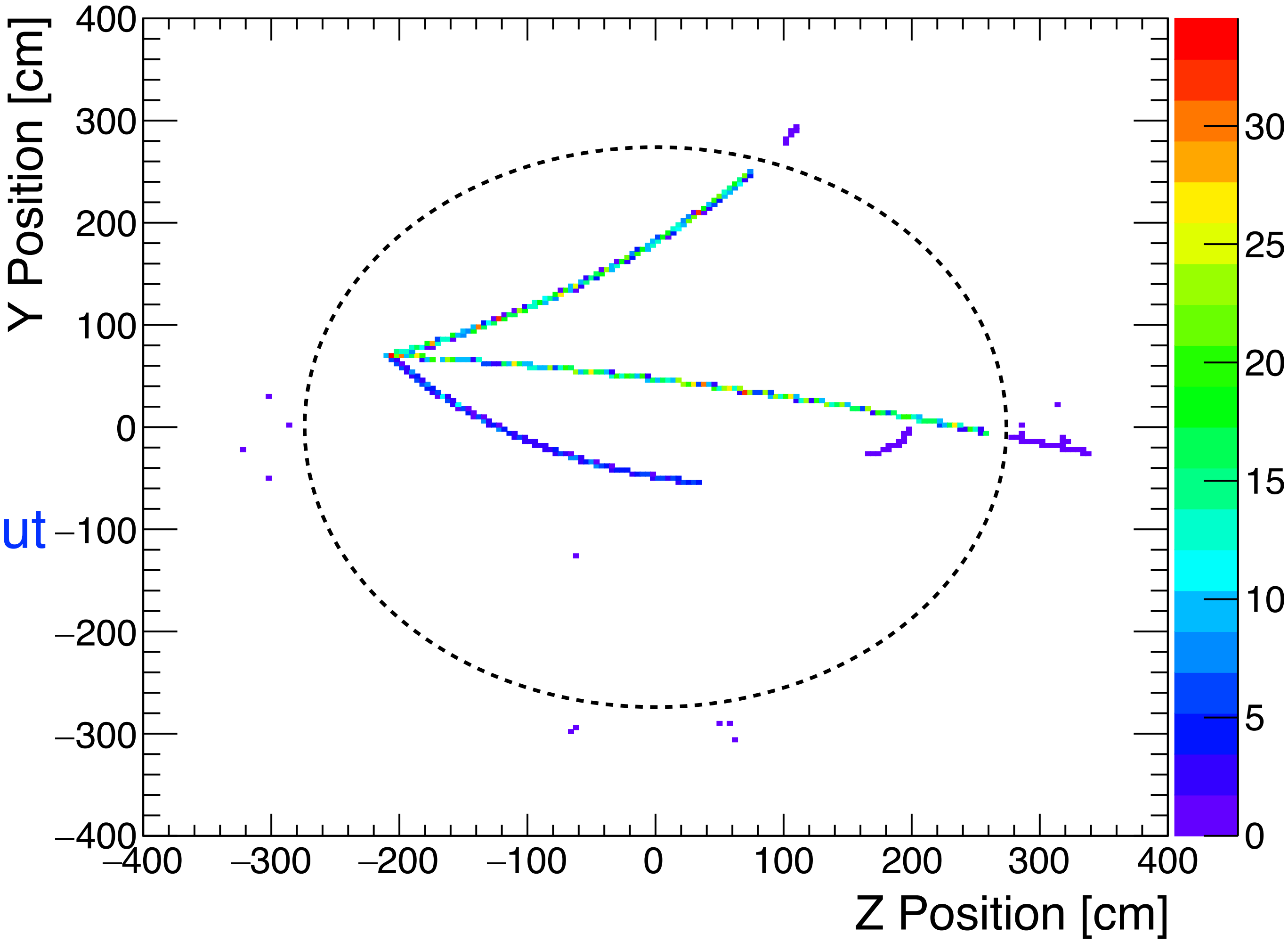
Z-Y projection full spill & event

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

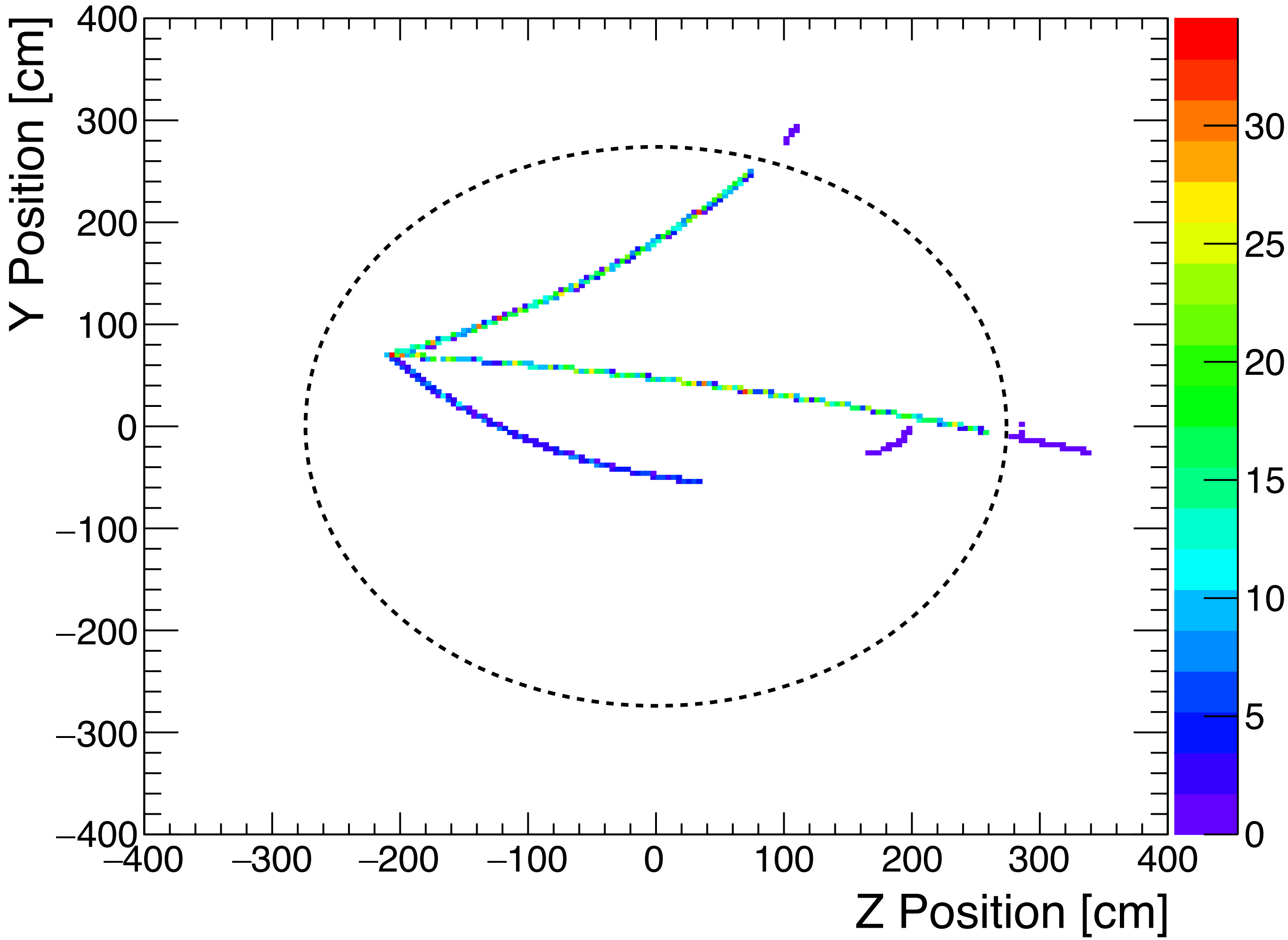


Z-Y projection full spill w/ timing cut

- 0.6 evts/μsec
- 50 ns timing cut



Z-Y Projection: Sample event - ν_μCC



Resistive shell TPC

- Minimize dead material and maximize the active volume.
- Reduce component count and points of failure.
- Limit power dissipation in the case of HV breakdown.
- Carbon-impregnated Kapton foil is laminated to G10 planes, forming the field shell and cathode of the TPC.