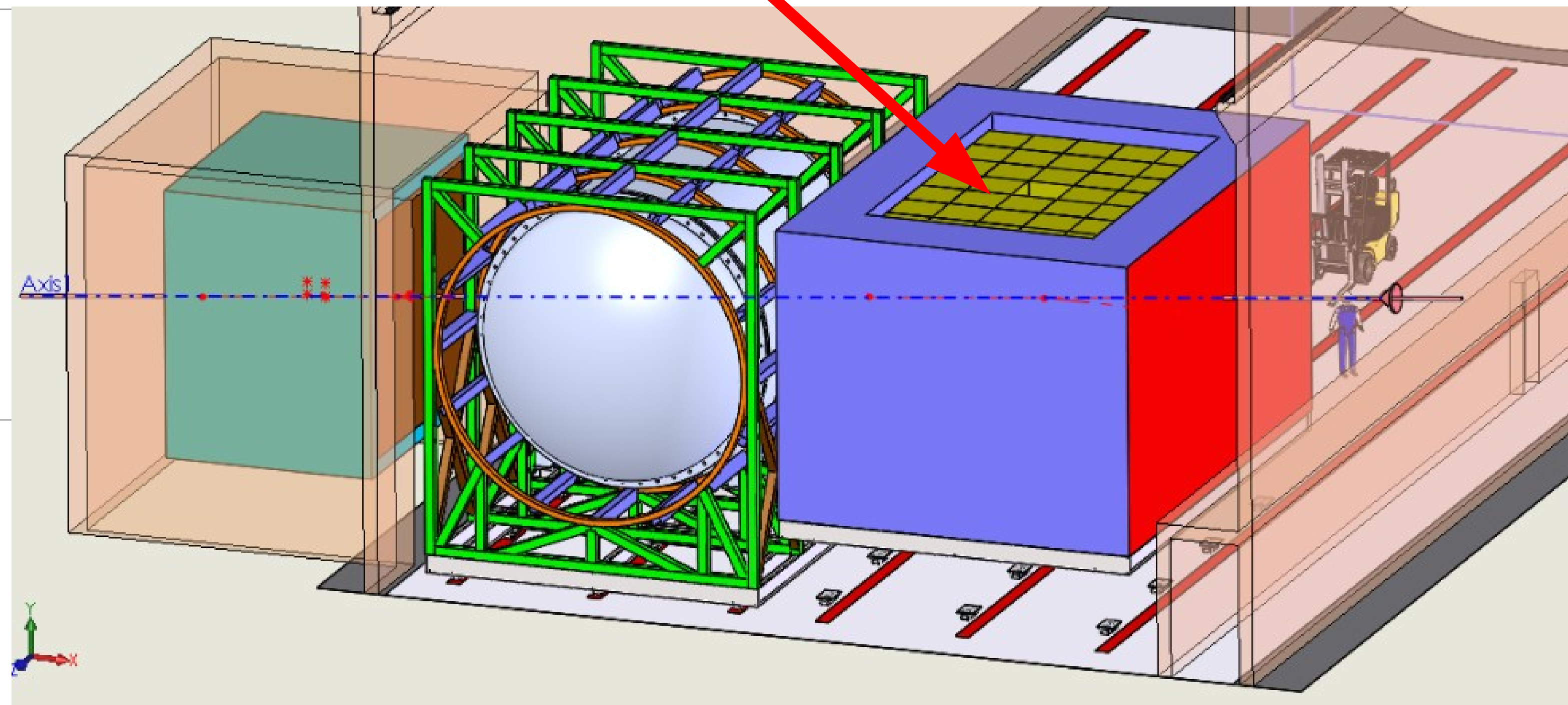


ArgonCube Design Status



What Motivates LAr at the Near Site?

Sample the unoscillated beam using the same target material as the FD.

Essential in order to constrain uncertainties on neutrino cross sections.

Major uncertainties (event topology, secondary interactions) primarily common to near-far.

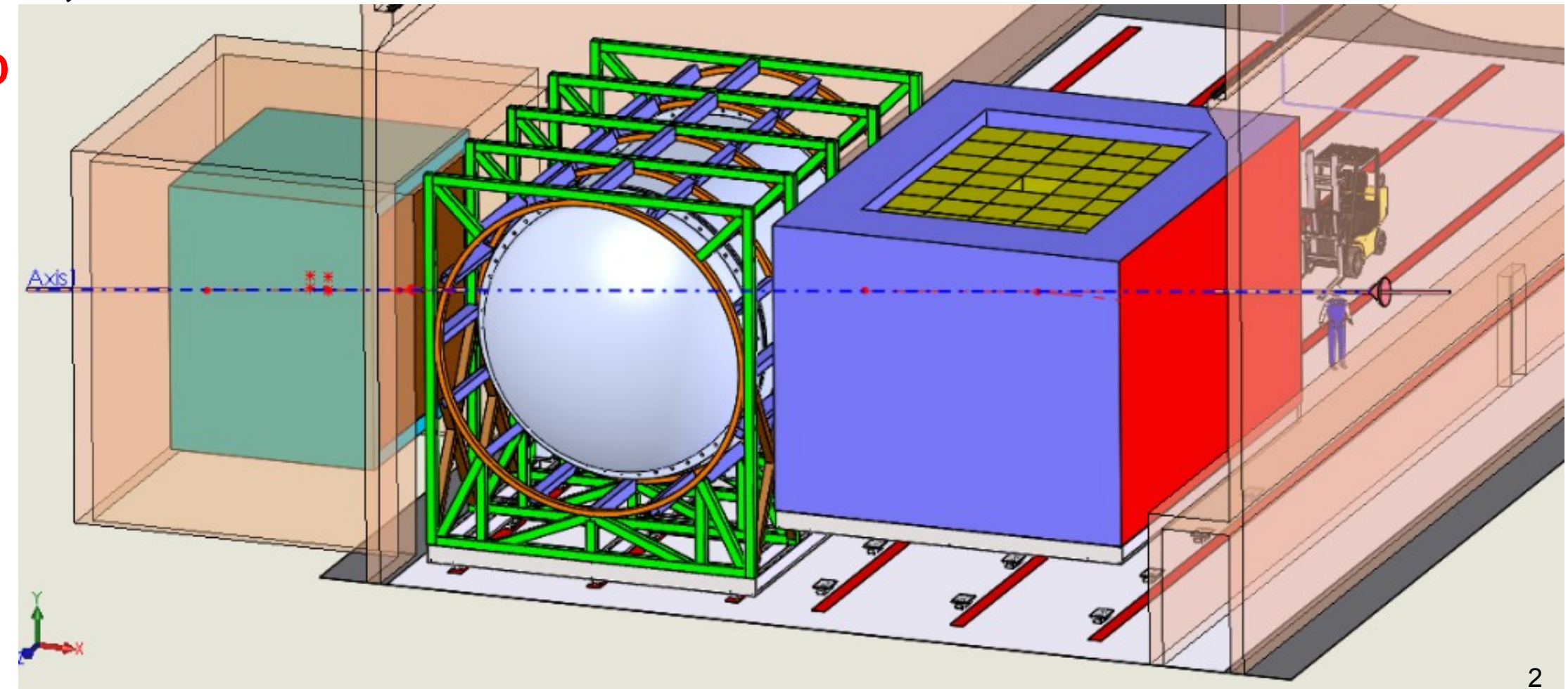
High multiplicity at near site necessitates differences in design, differences are likely second-order.

The energy and angular resolution and mass is sufficient to extract a high-statistics sample of neutrino-electron elastic scattering events, which have a known cross section.

Can be used to constrain the flux to better than 2%

Constrain electron neutrino contamination.

Use e/ γ separation to reduce NC background.



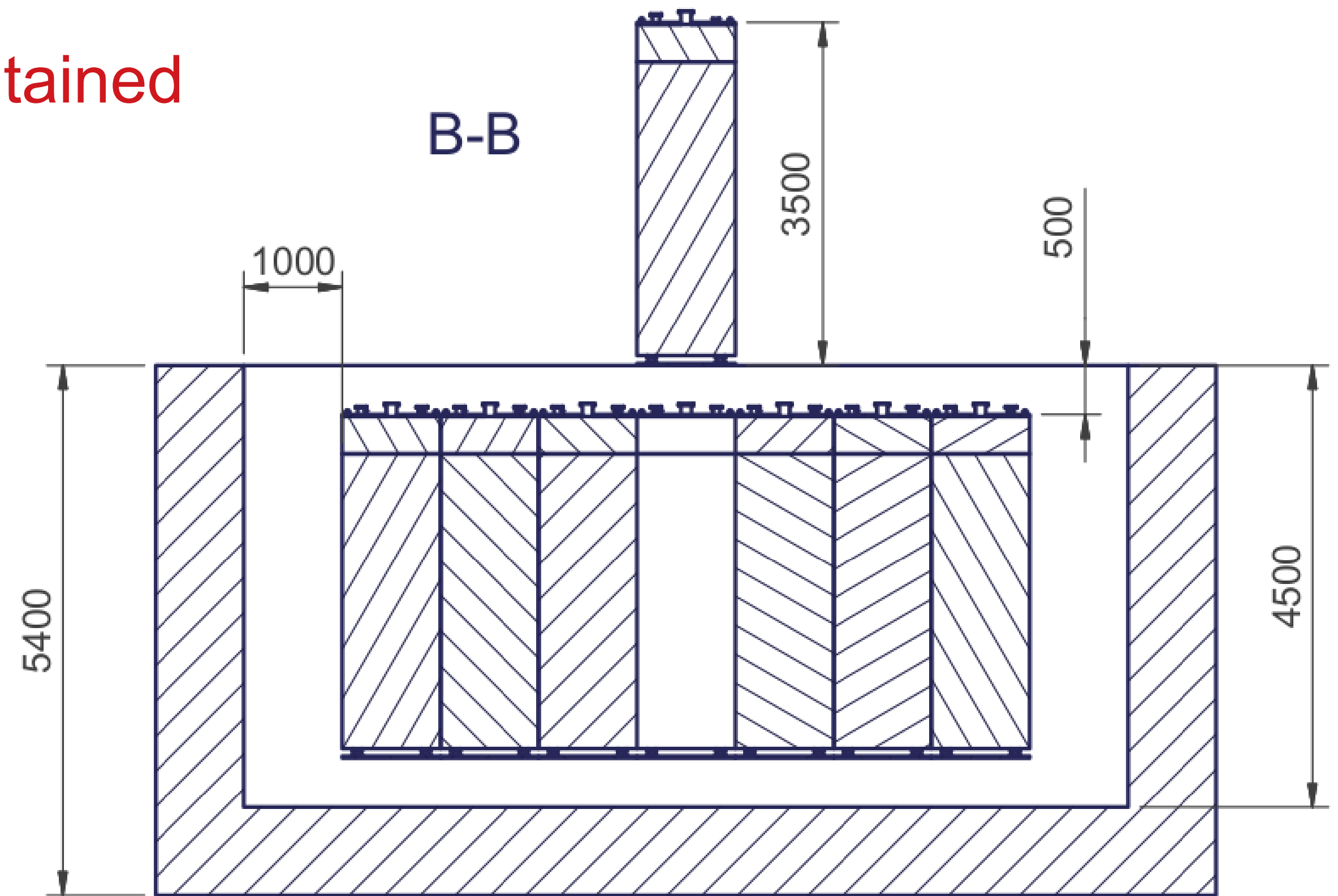
How to make a LArTPC in the ND - ArgonCube

ArgonCube was motivated by mitigating risks associated with high voltage. The core concepts also serve to reduce pileup.

Separate the detector volume into self-contained modules sharing a common cryostat

Short drift distances
Contained scintillation light

Unambiguous pixelated charge R/O



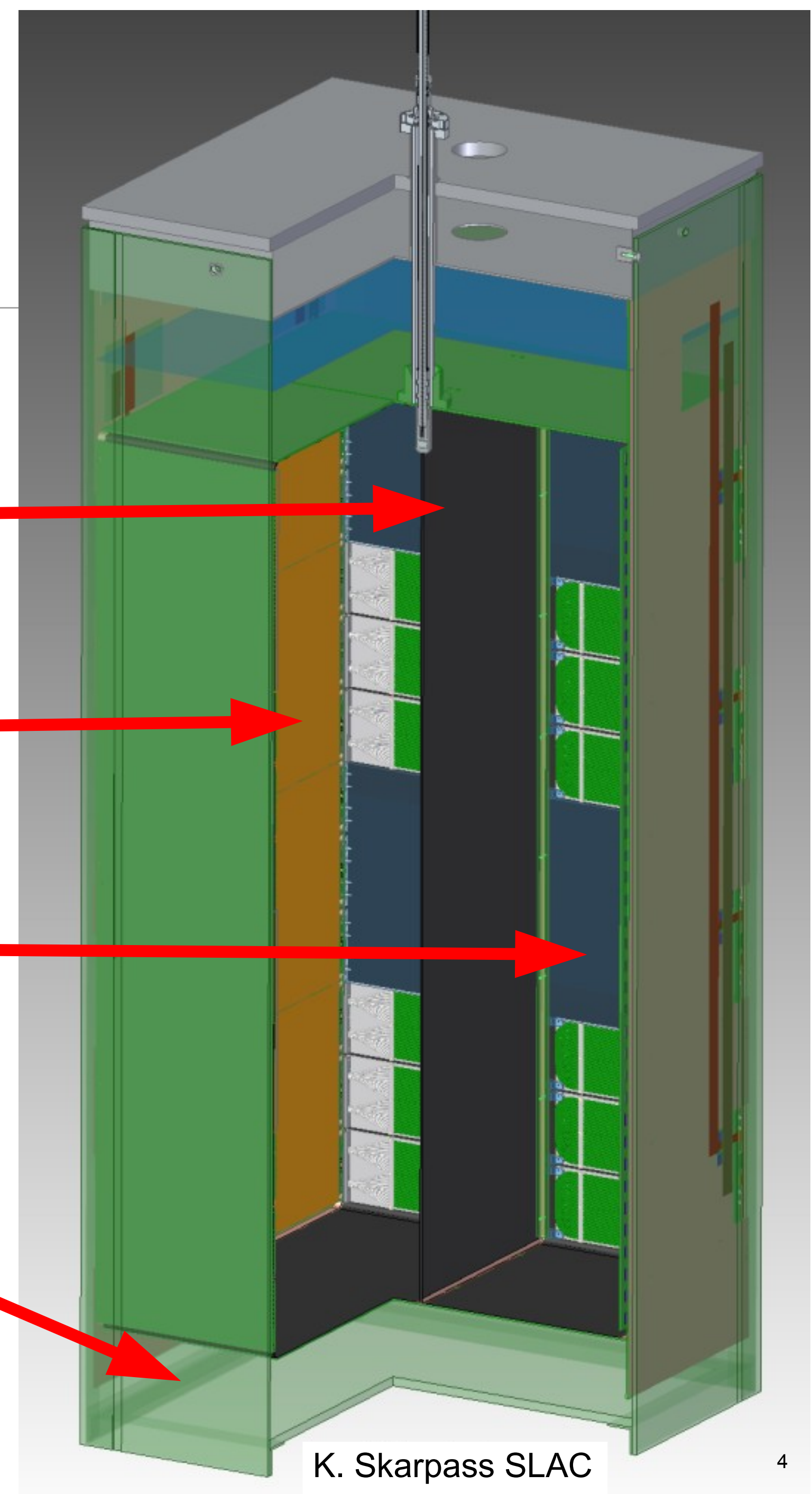
An ArgonCube Module

Central Cathode: splits the module into 2 TPCs

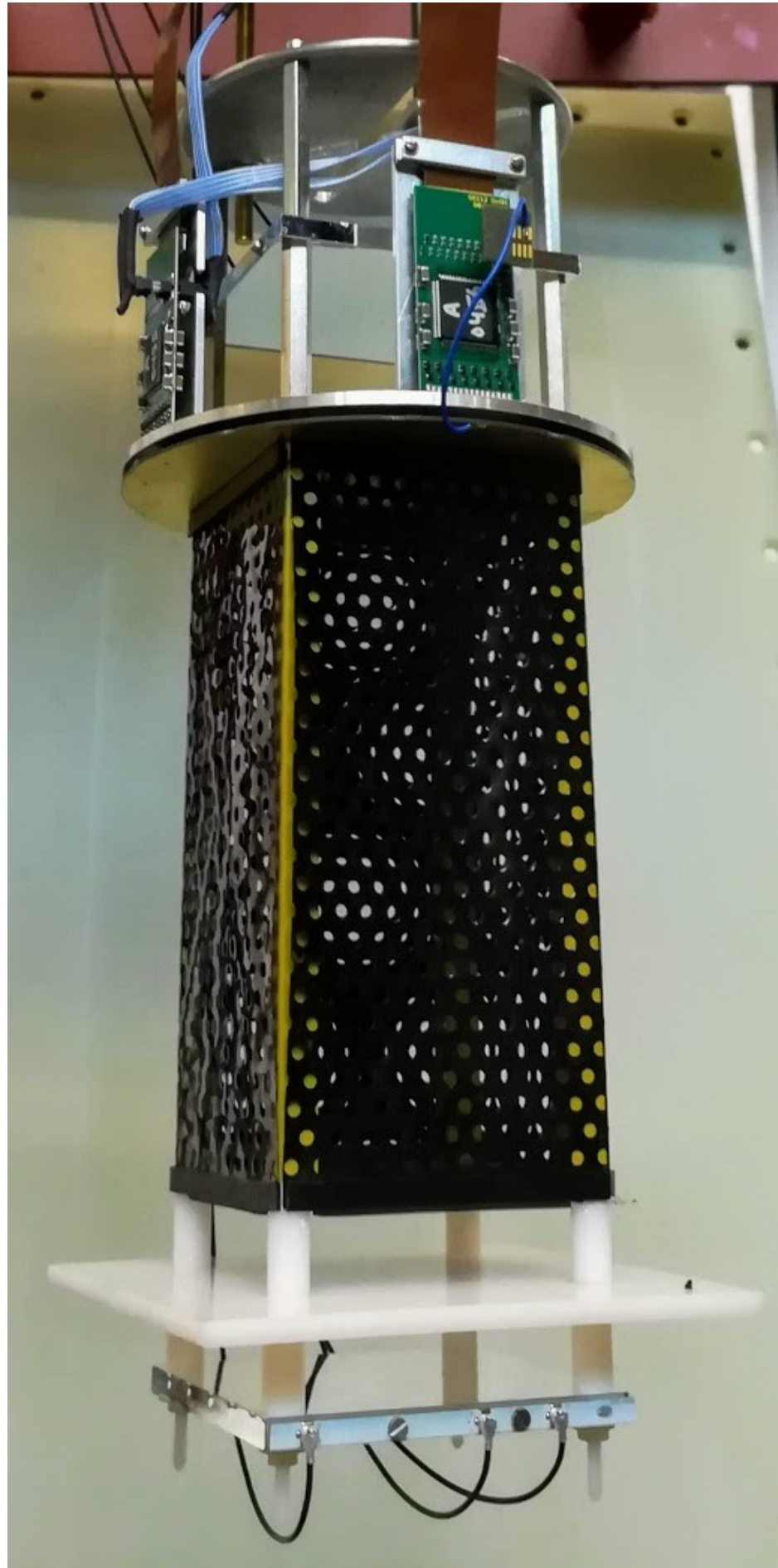
Pixelated anode plane

Dielectric light readout within TPCs

G10 structure: good dielectric shielding, and comparable radiation & hadronic interaction lengths to LAr



Resistive Shell TPC



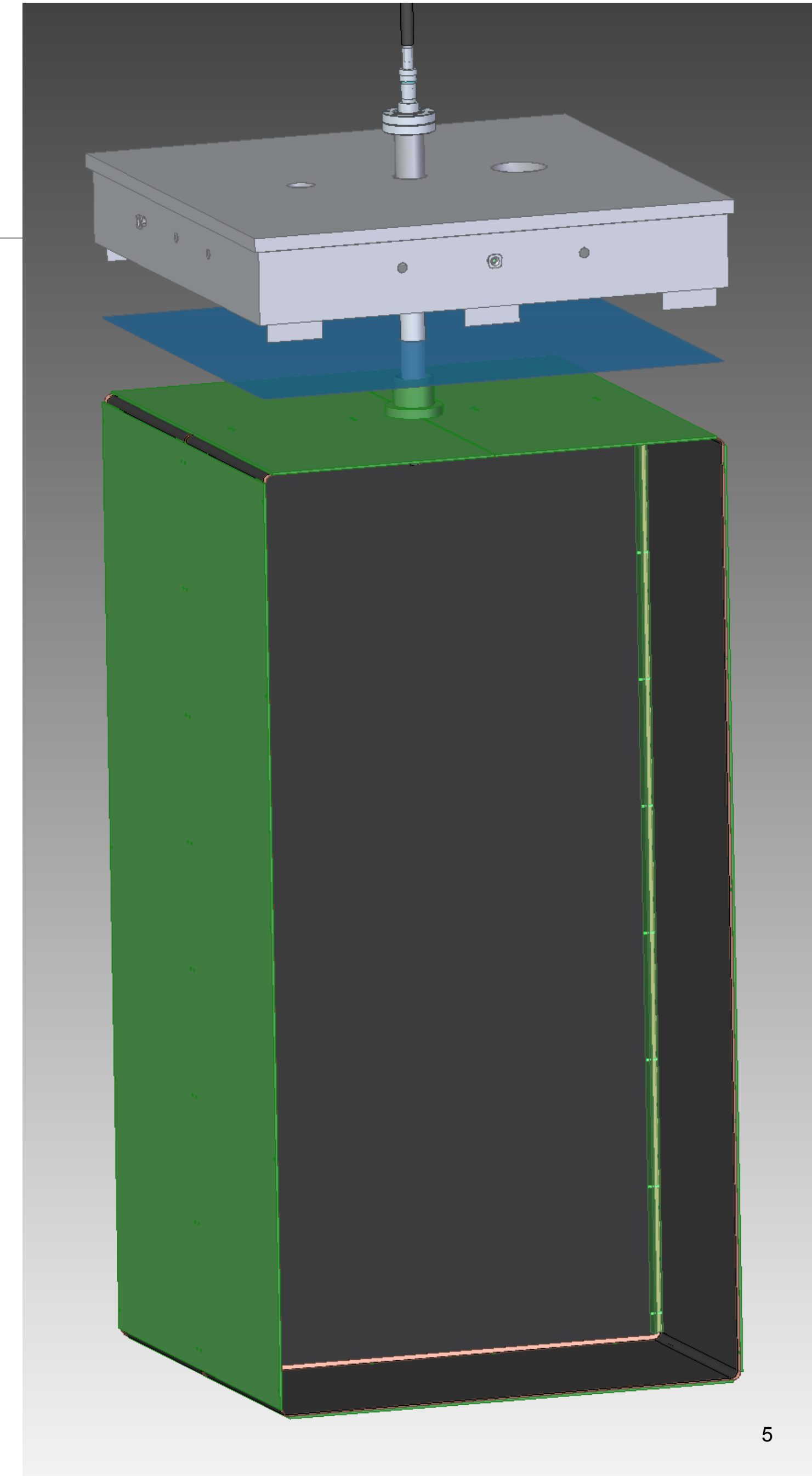
Minimise dead material and maximise the active volume.

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.

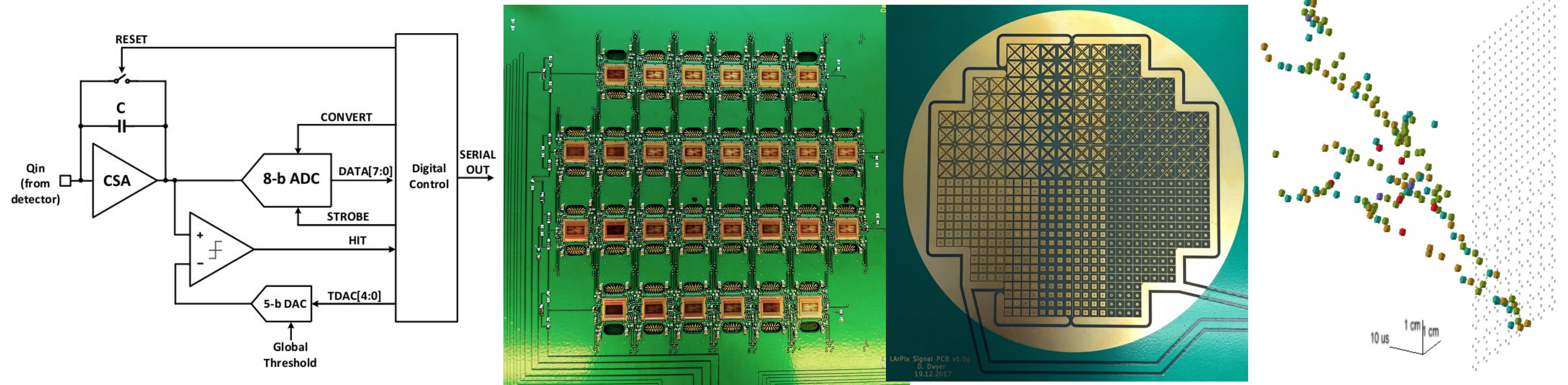
15 cm drift resistive shell TPC
Bern 2018



Unambiguous Charge Readout

True 3D event reconstruction is achieved using a pixelated charge readout, with cold amplification and digitisation of every pixel. (N.B. pixel pitch is set to match the wire spacing of the FD.)

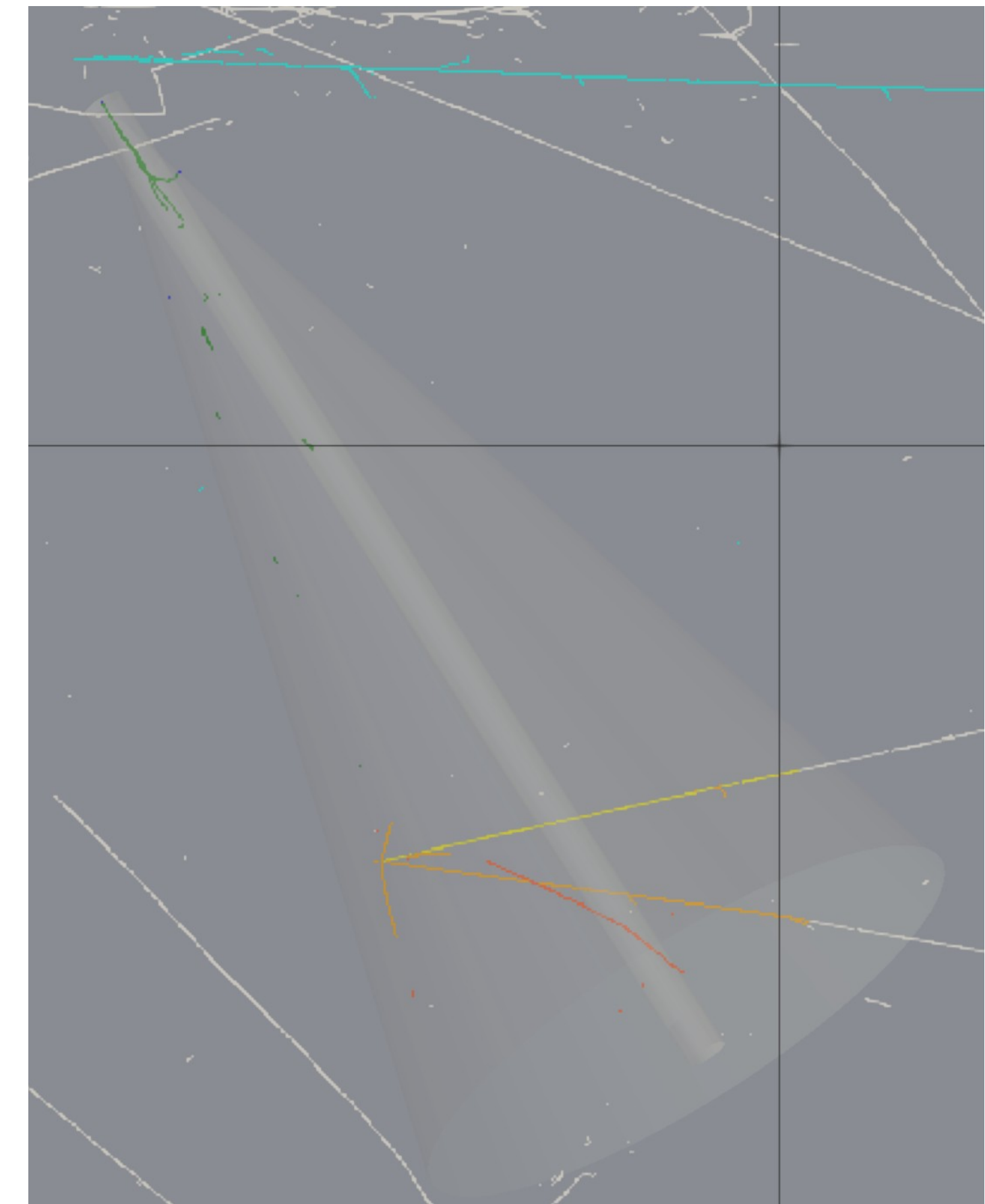
This was enabled by the low-power LArPix ASIC, developed at LBNL. JINST 13 (2018) no.10, P10007.



Left to right: LArPix block diagram. LArPix ASIC mounted at the rear of a prototype pixel anode. Unfiltered 3D information from cosmic muon. JINST 13 (2018) no.10, P10007 .

Pixelated Charge Readout

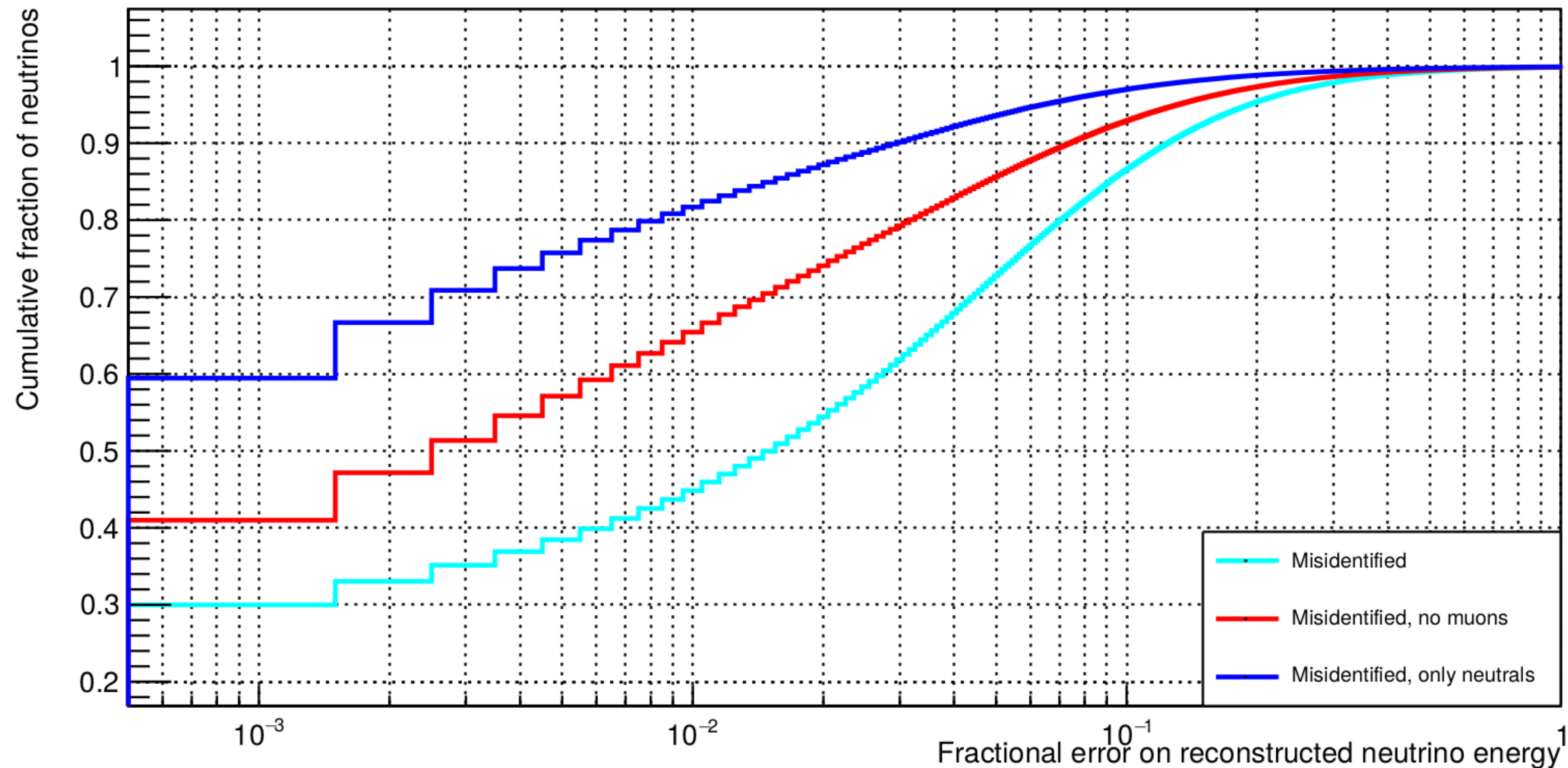
Using 3D information, it was shown that pileup in π^0 reconstruction is $< 1\%$ for $> 70\%$ of events.



Event display showing simulated LBNF beam spill in ArgonCube (5 x 4 x 3 m³) FHC 2 MW beam, 80 GeV protons, including rock events.
D. Goeldi, 2018 JINST TH 002.

Pixelated Charge Readout

Using 3D information, it was shown that pileup in π^0 reconstruction is $< 1\%$ for $> 70\%$ of events.



Cumulative fraction of neutrinos versus misidentified energy fraction for 3D π^0 shower reconstruction. FHC 2 MW beam, 80 GeV protons. D. Goeldi, 2018 JINST TH 002.

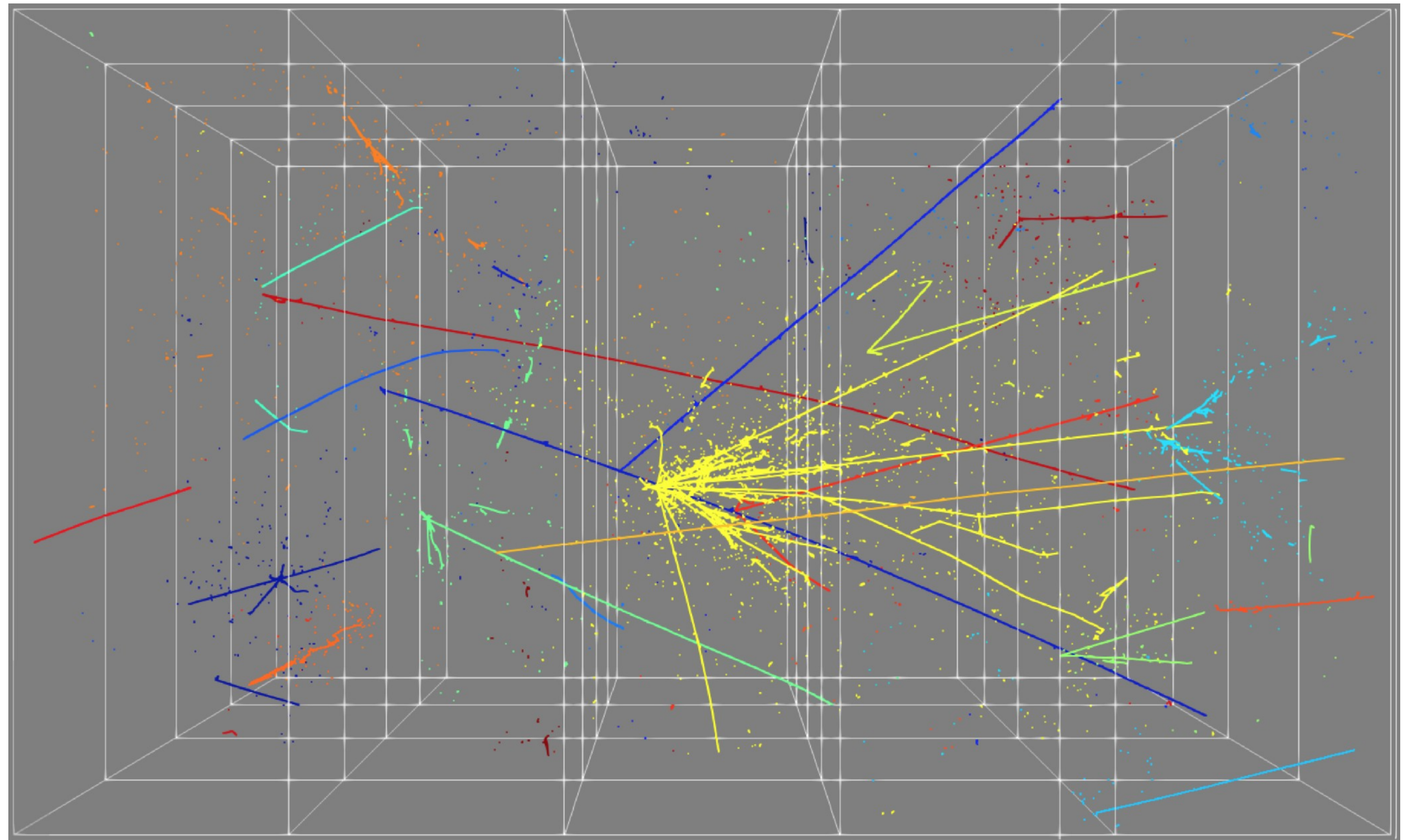
Detached Energy Deposits

Unambiguous charge R/O will simplify reconstruction, but it is still timing limited:

Drift window = 250 μ s.
Spill = 10 μ s.

It is not trivial associating isolated/detached deposits to correct vertex – fast neutrons.

Contained scintillation can help, light R/O with \sim ns resolution needed.



1 MW 3 horn optimised spill, FHC, including rock. 4x5 geometry.
Colouring by nu.

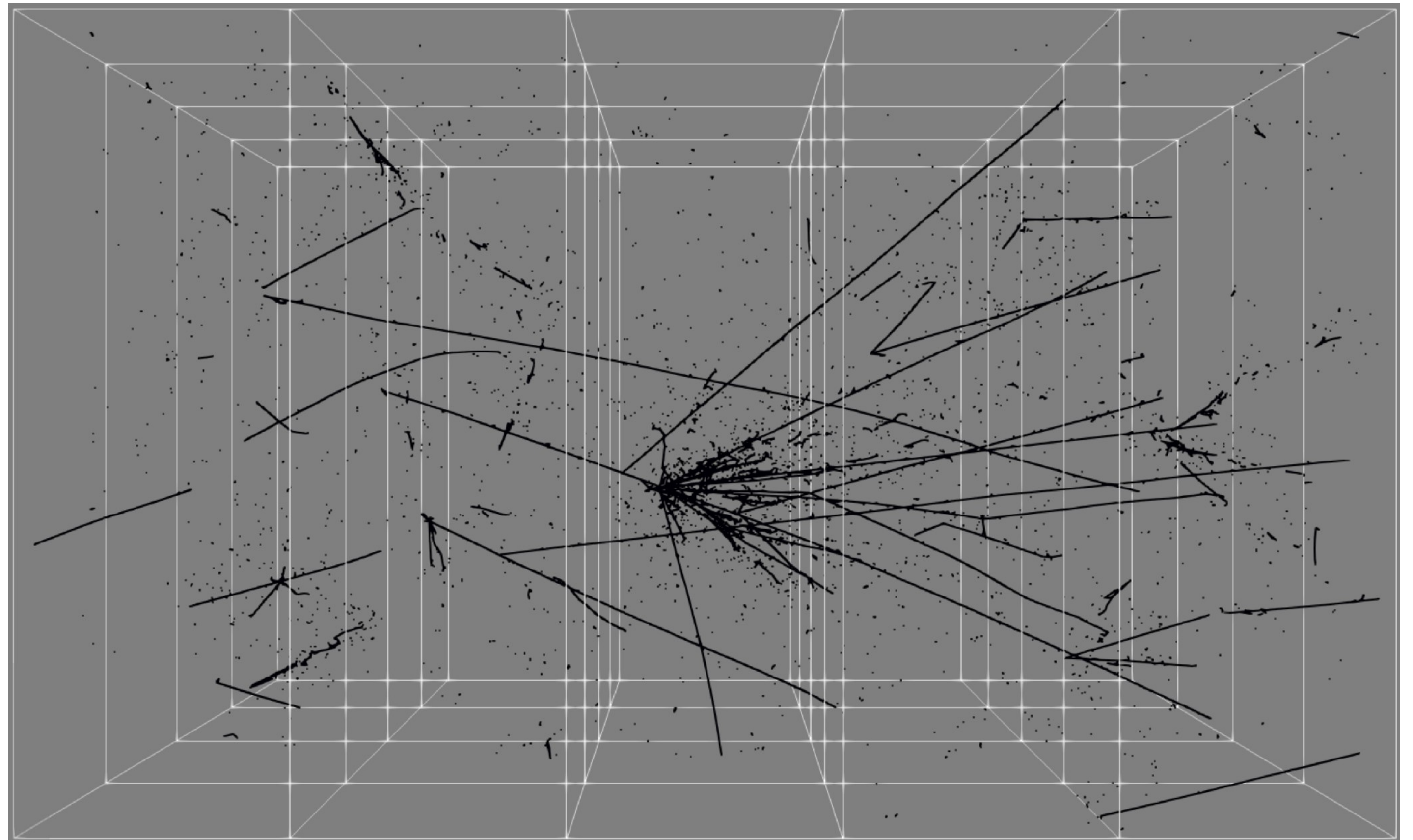
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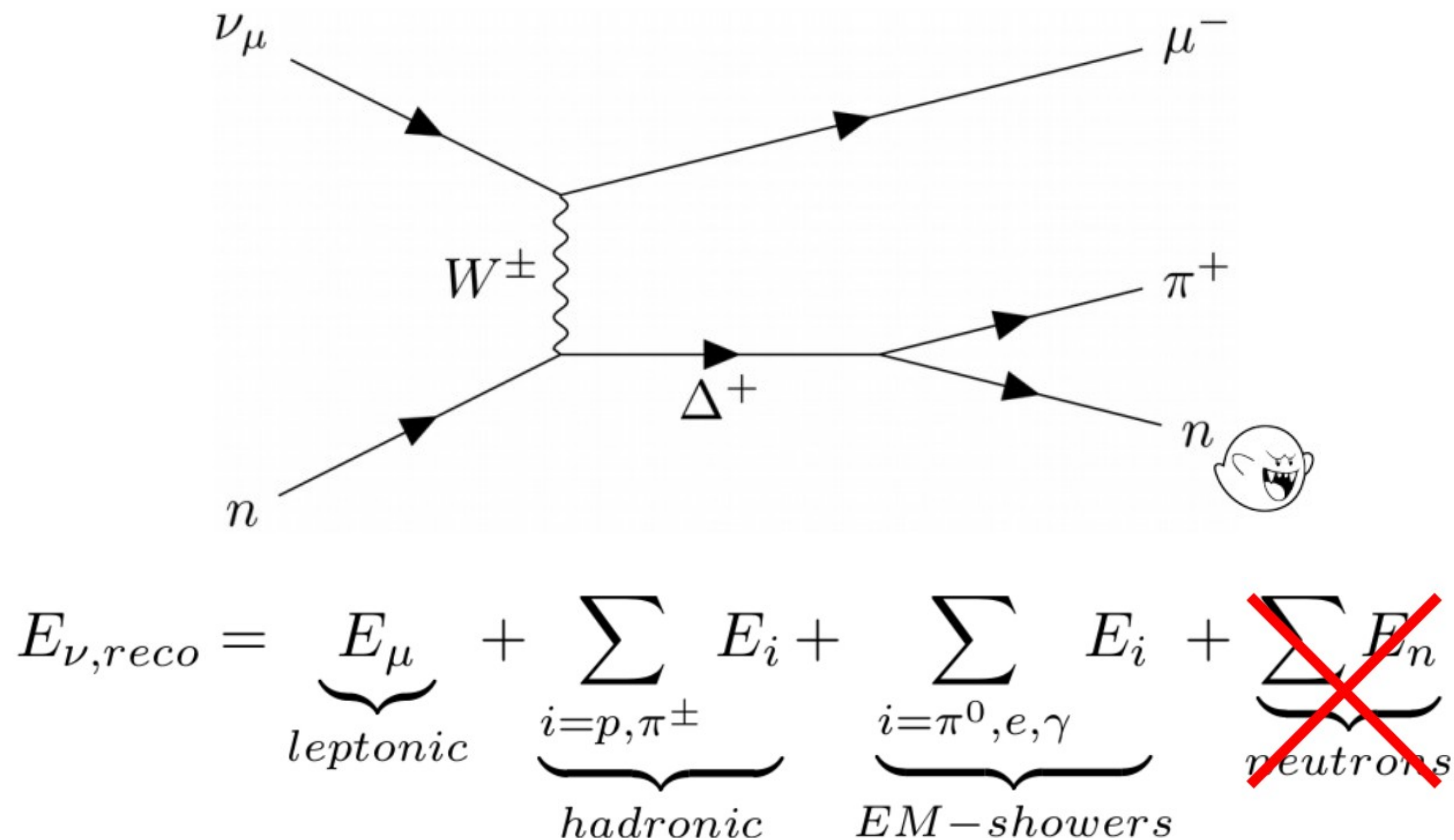
Contained scintillation can help, light R/O with $\sim\text{ns}$ resolution needed.



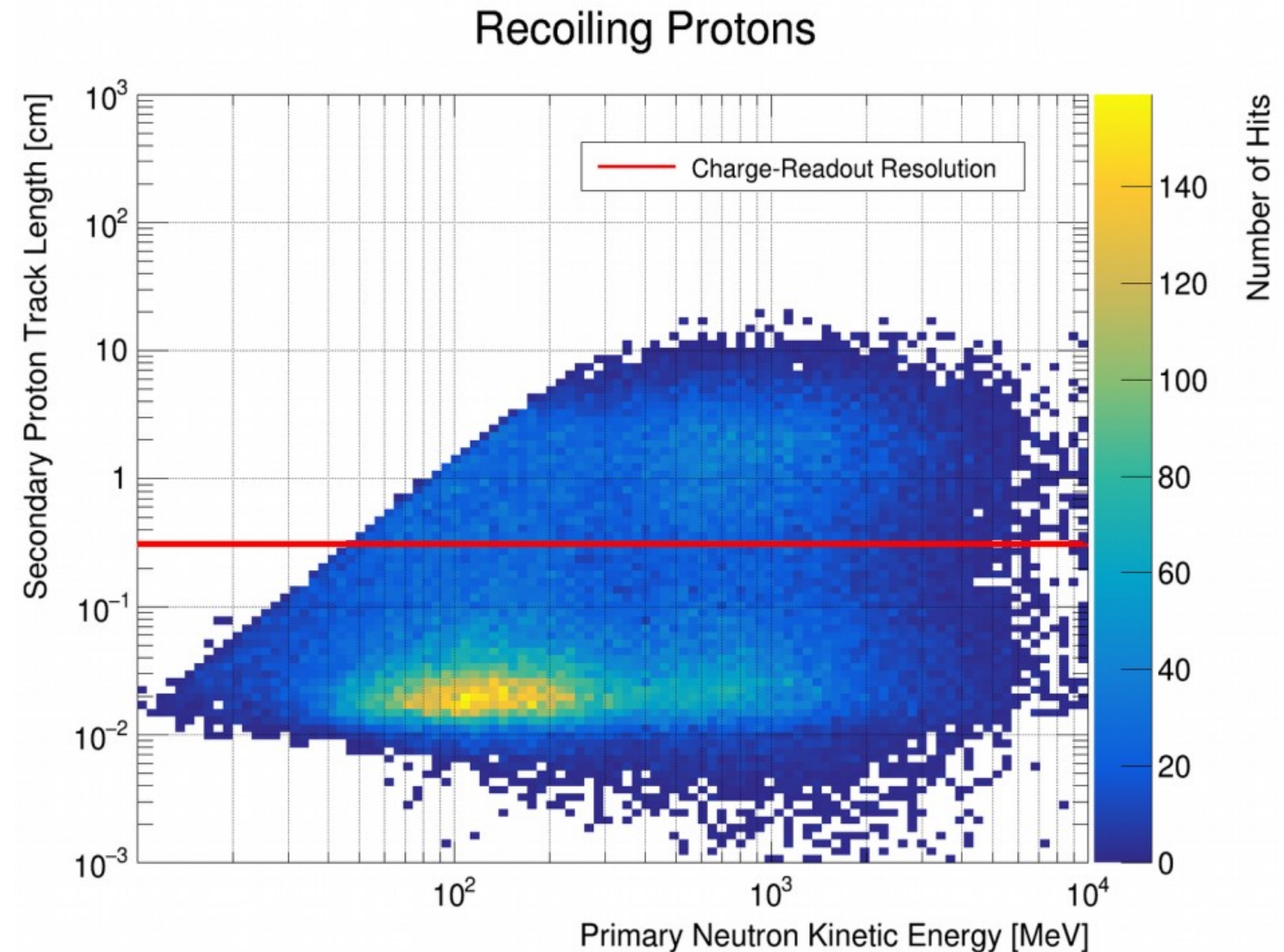
1 MW 3 horn optimised spill, FHC, including rock. 4x5 geometry.
Colouring by charge R/O.

Detached Energy Deposits

A large uncertainty in energy reconstruction

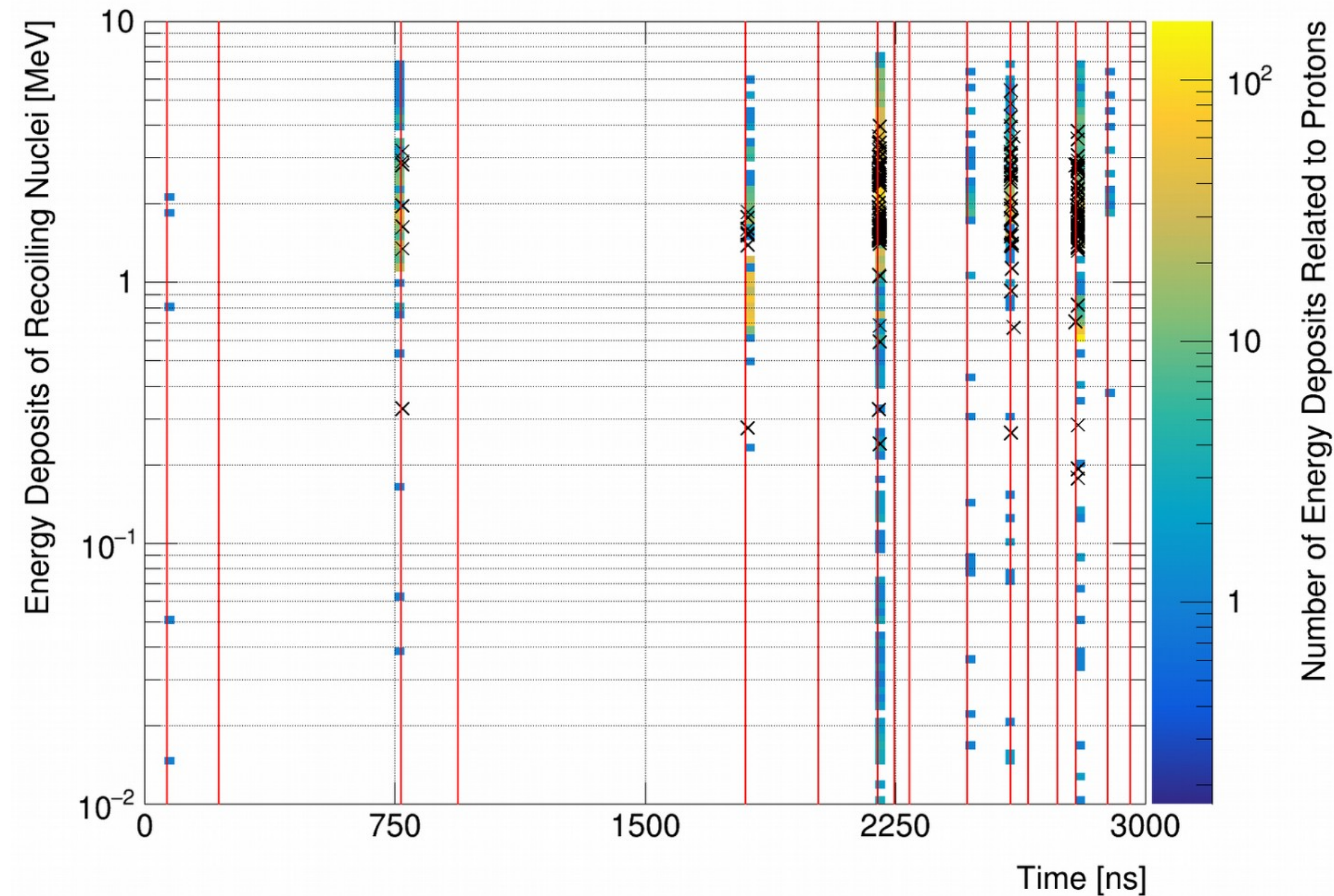


Hadronic showers can also fluctuate to neutrons

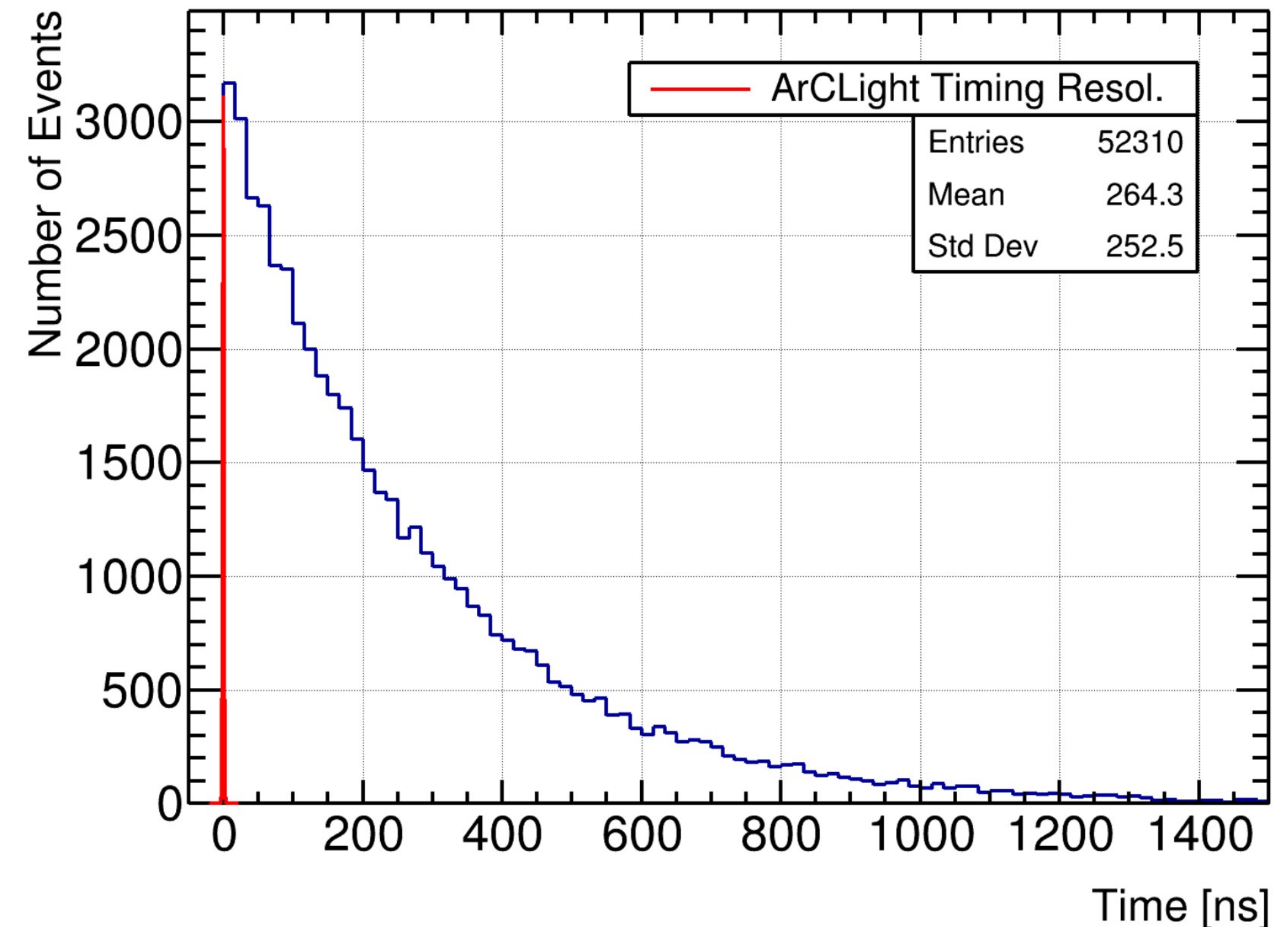


Tracks from recoiling protons at neutron energies > 50 MeV ($\sim 30\%$ of all recoiling protons)

Neutrino Vertex Temporal Separation



A 3rd of a LBNF spill (1 MW 3 horn optimised, FHC)
Nu vertex (red), recoiling p (coloured), nuclear recoil (X)



Nu separation within a LBNF beam spill. Only events entering the
60 m³ active volume of $\sim 100'000$ neutrino events. Mean 264 ns.

Use prompt light from protons and vertex to associate tagged fast neutrons with correct ν -interactions.

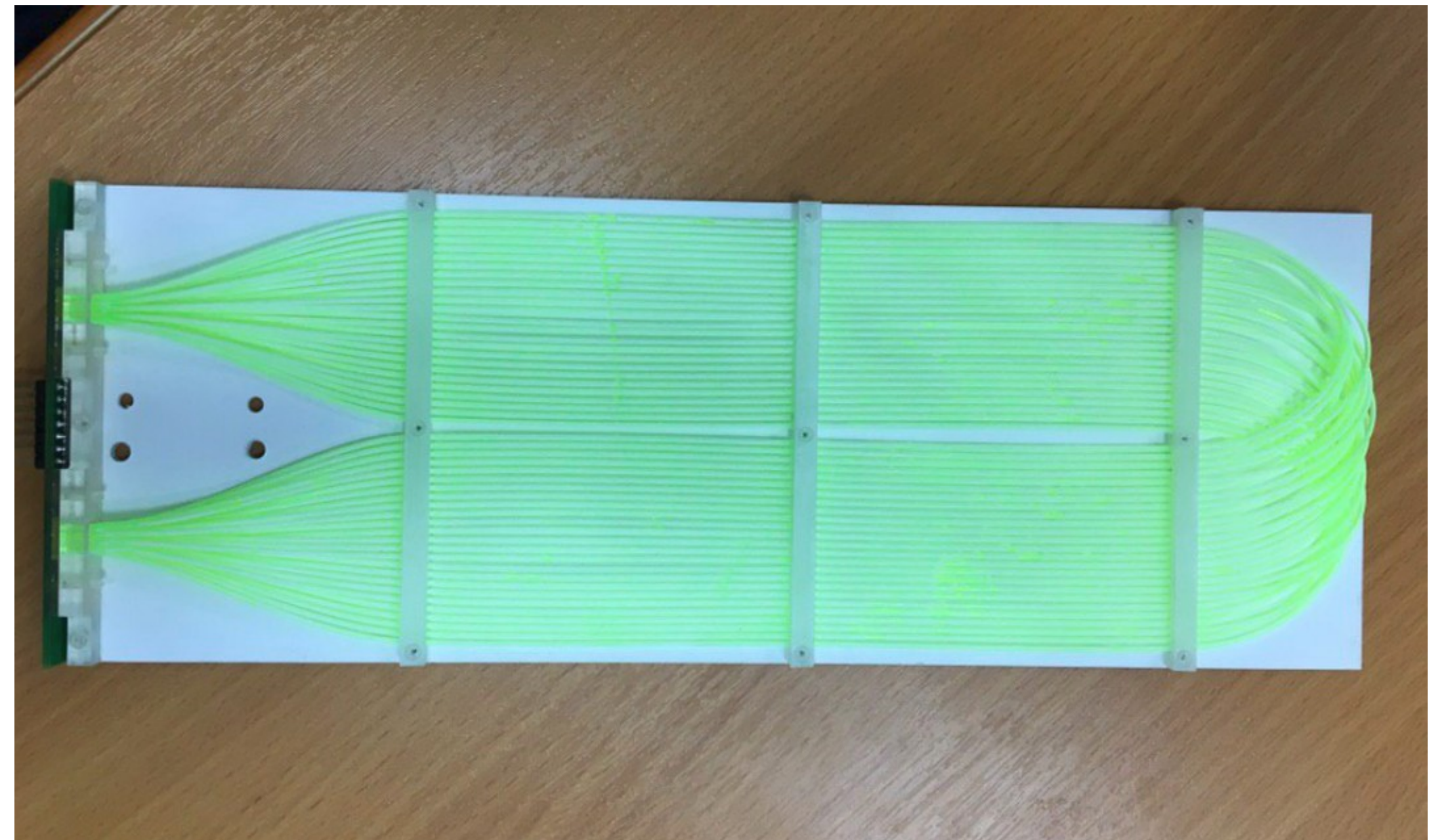
Light Readout

Two complementary dielectric light R/O systems have been developed: Bern's ArCLight and JINR's Light Collection Module(LCM). Both use the same SiPMs, and TPB to convert from 128 nm to 425. ArCLight uses sheets WLS plastic and dichroic mirrors. LCM uses WLS fibres.

ArCLight has better position resolution, LCM has higher efficiency.



Prototype ArCLight tile (Instruments 2 (2018) no.1, 3).

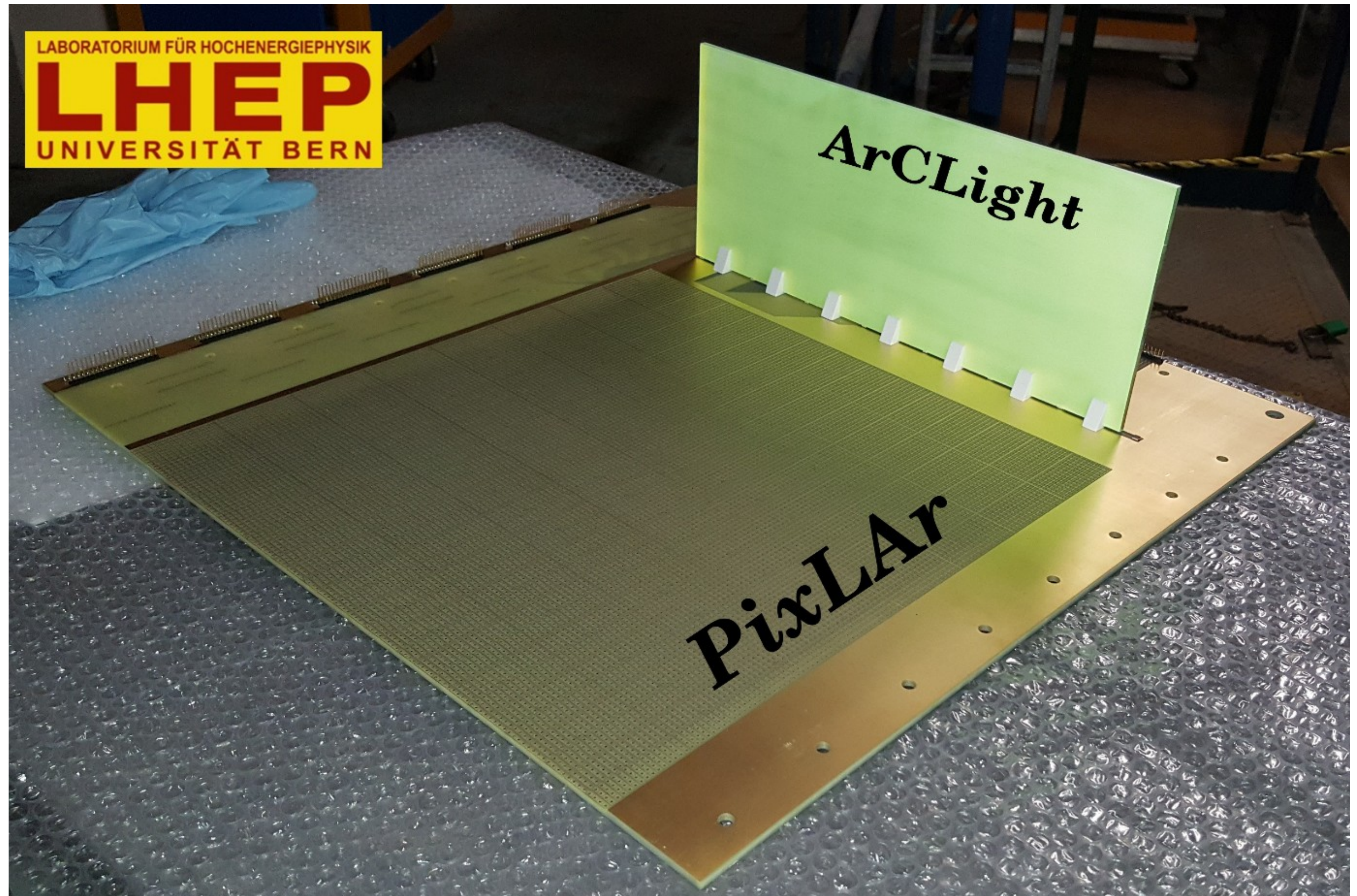
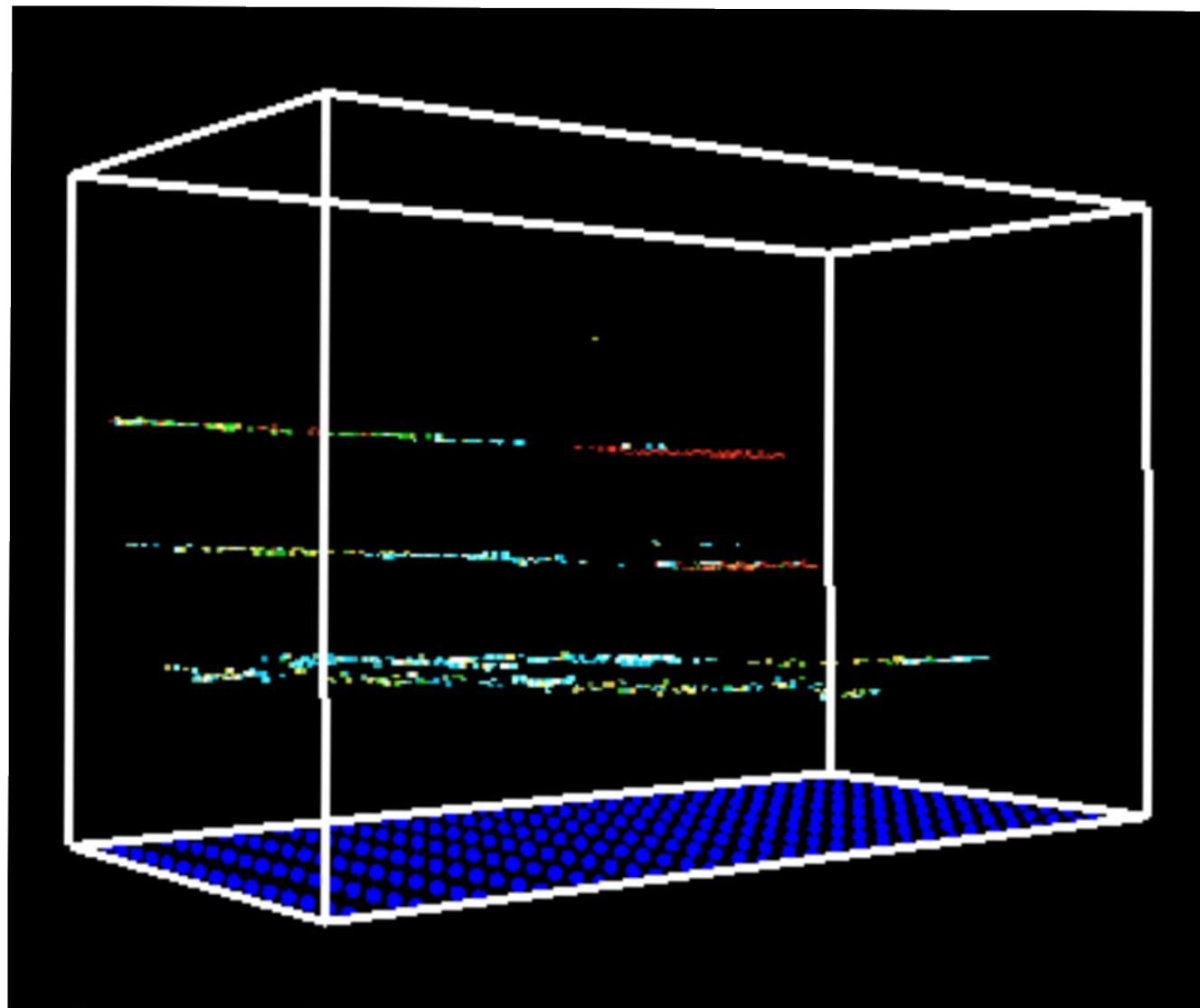


JINR's Prototype LCM

ArCLight in a Test Beam

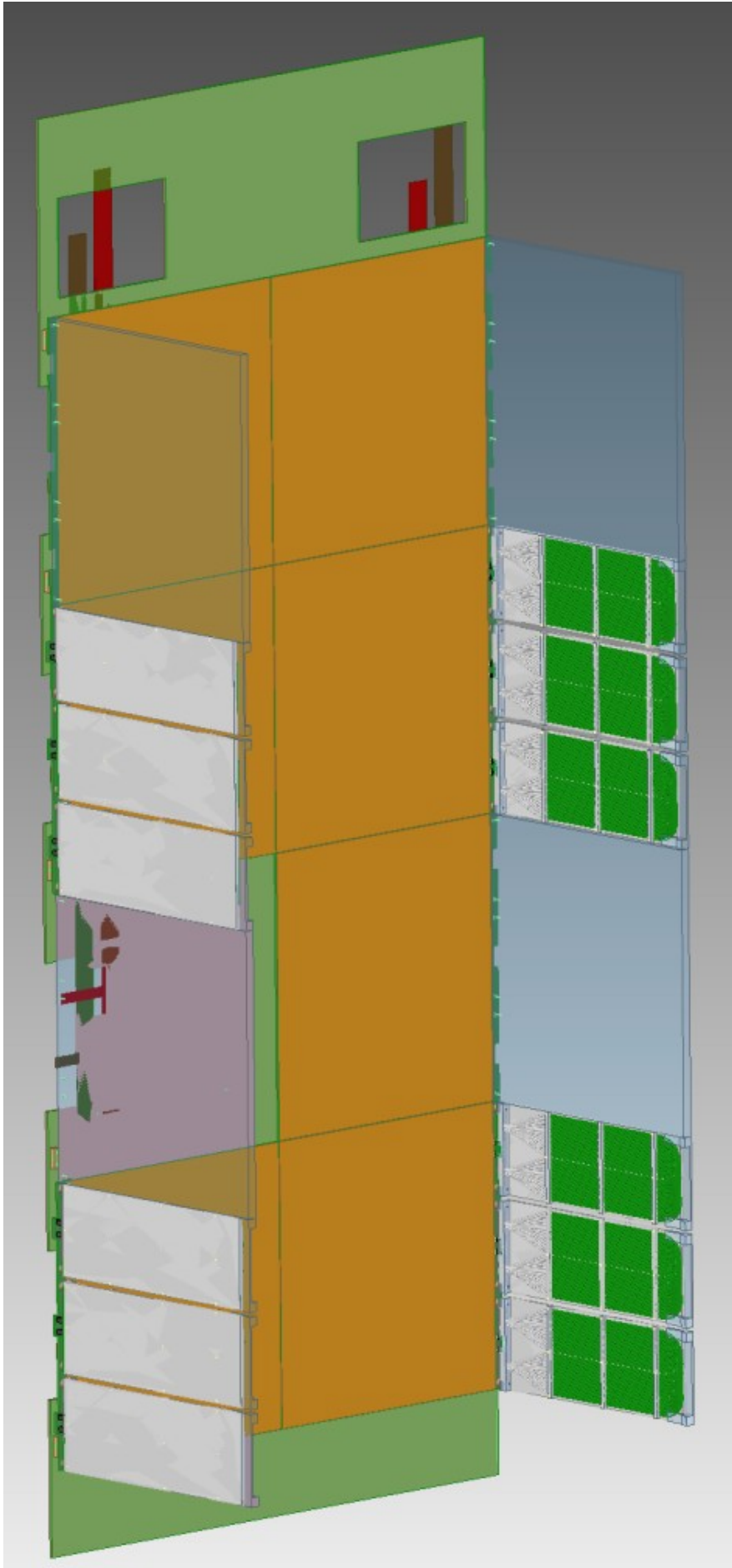
An ArCLight prototype was mounted to the PixLAr anode during test beam studies at Fermilab.

No distortion in E-Field was observed in crossing tracks

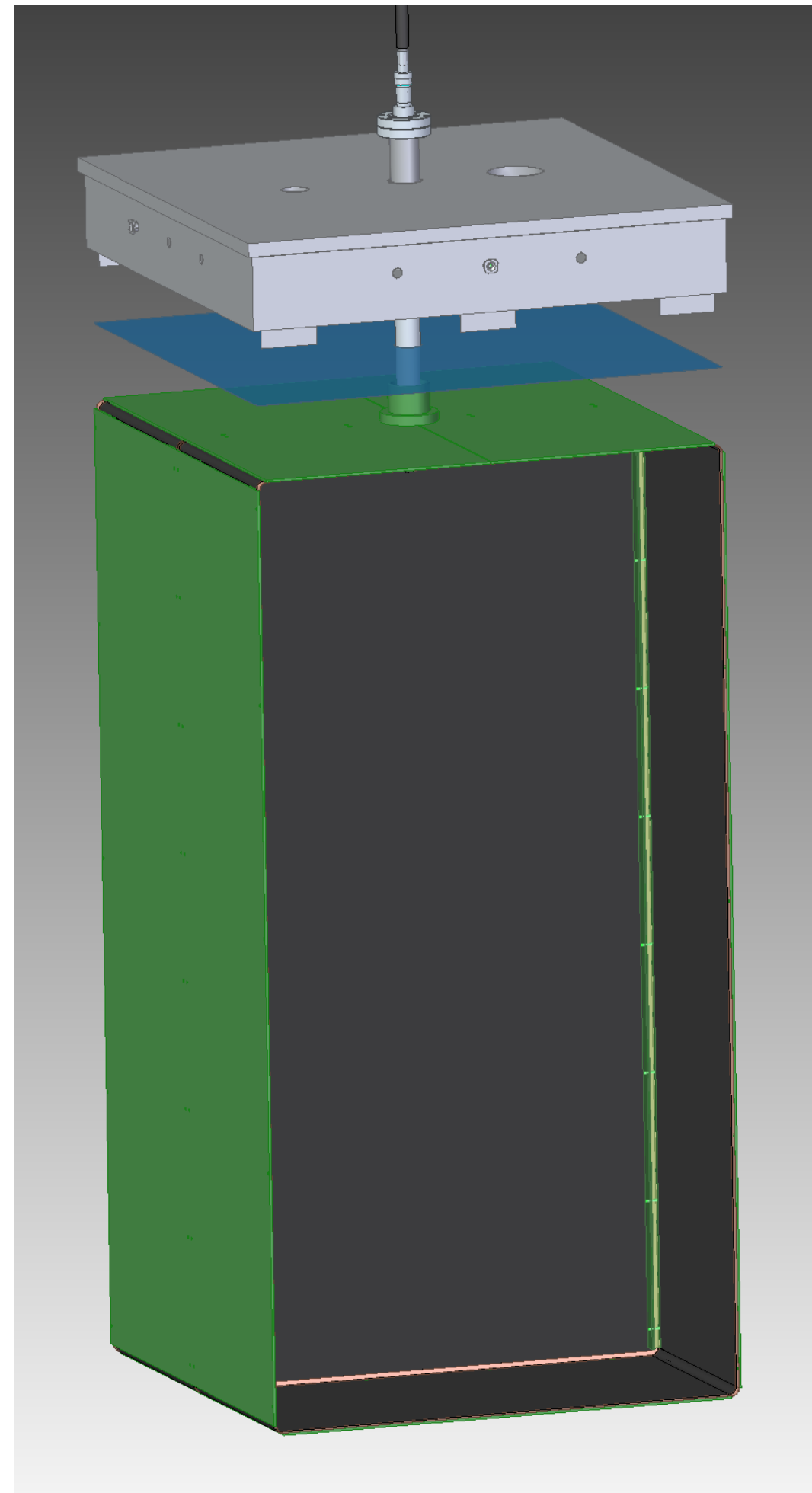


ArCLight mounted on one half of the PixLAr pixel plane

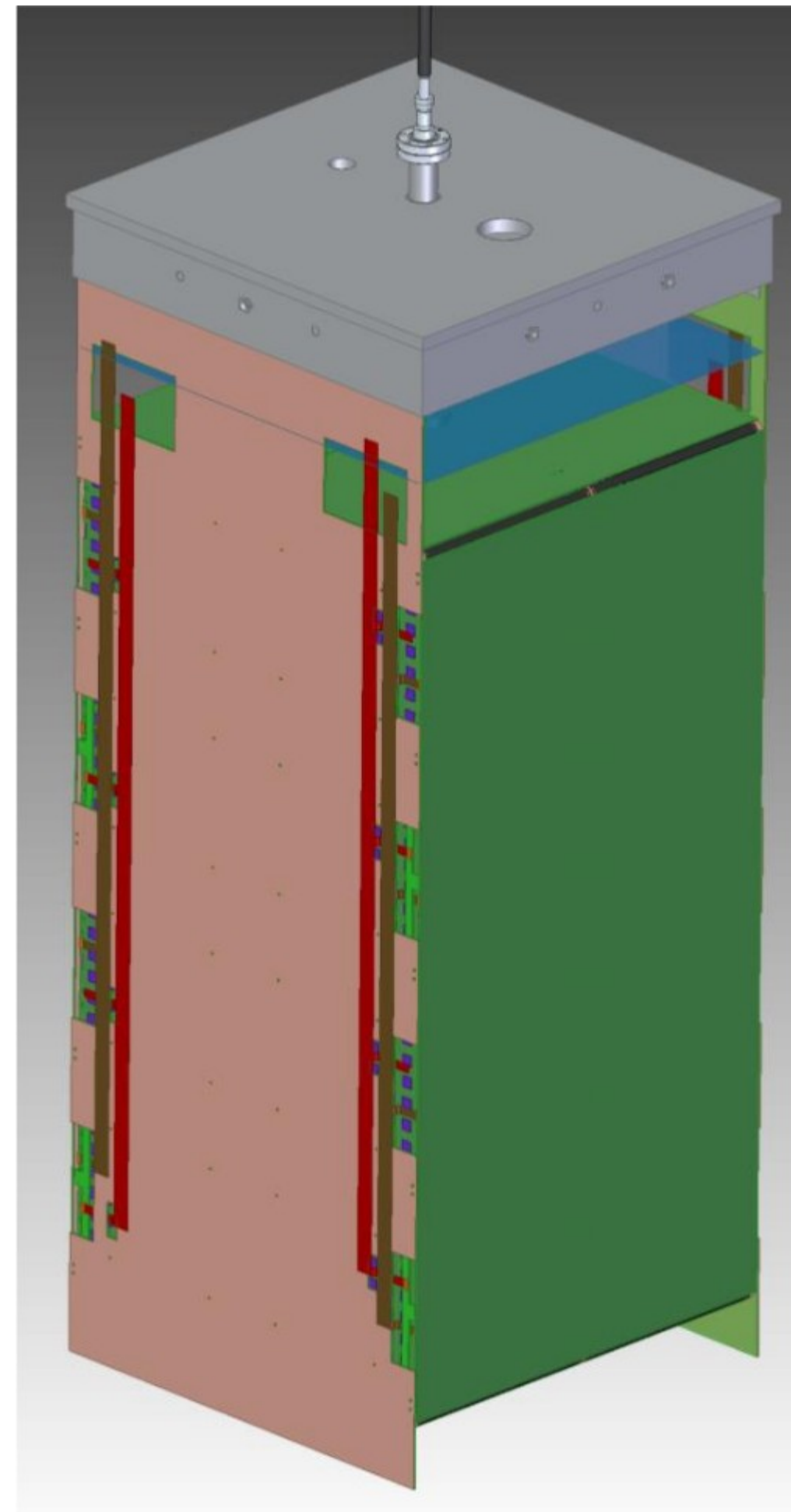
Module Structure



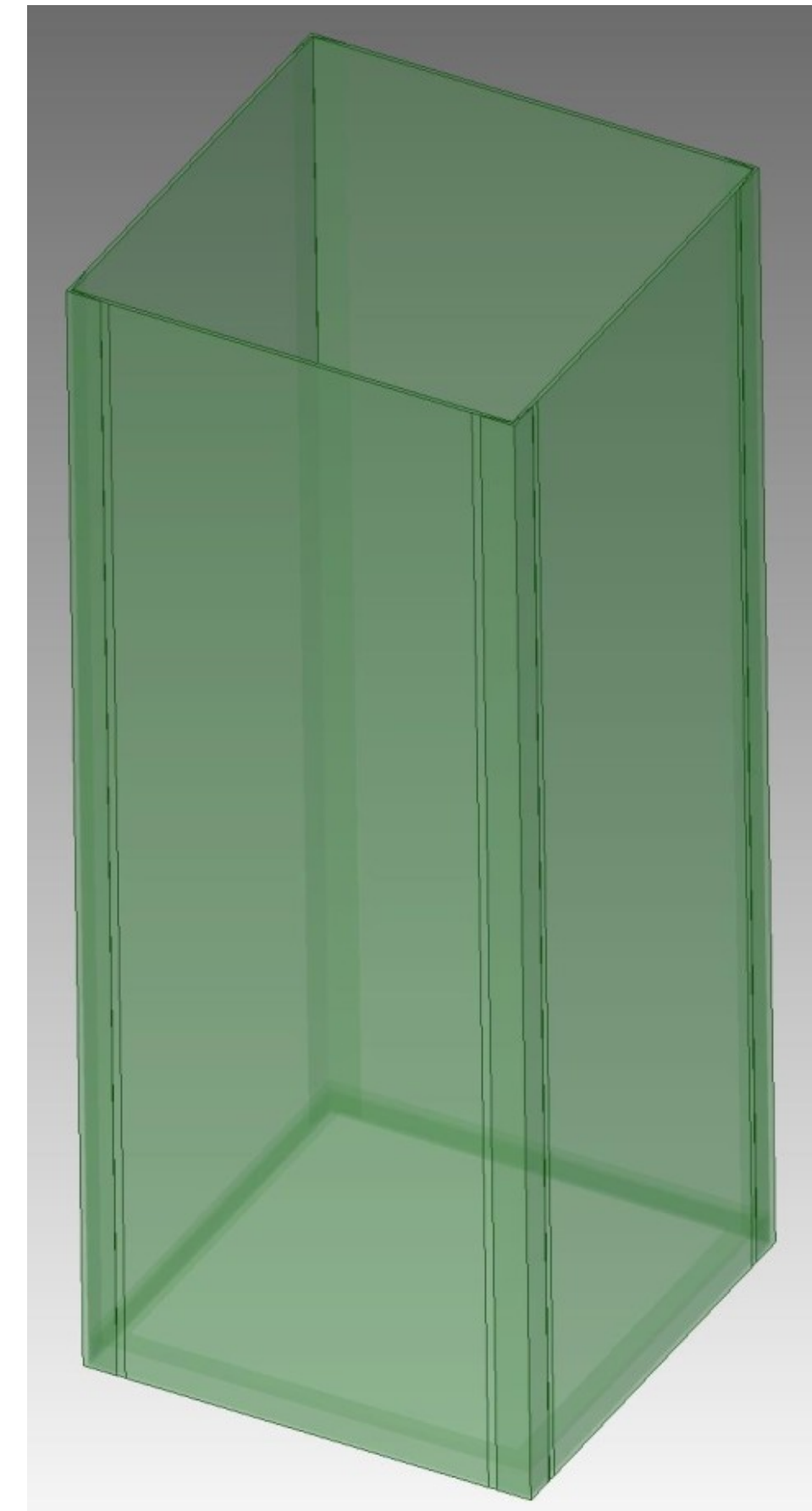
Light & Charge R/O,
half detector



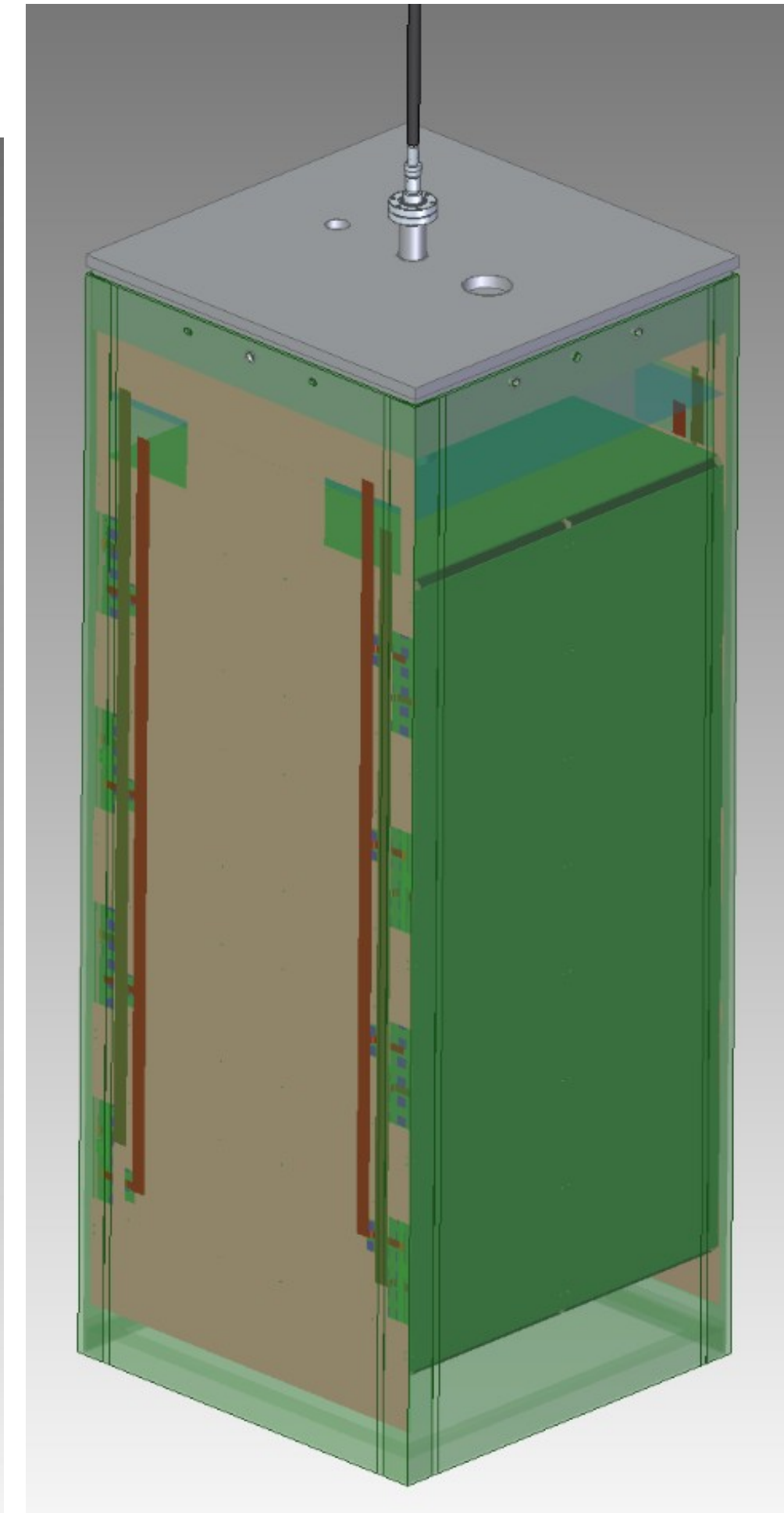
Resistive shell TPC



Naked detector



Module bucket



Module

ArgonCube Requirements

Provide a high fidelity picture of how neutrino interactions will appear in the far detector, addressing both neutrino interaction and detector systematics (secondary interactions, recombination, etc.) **in a high multiplicity environment**.

Essential requirements:

Unambiguous charge R/O

Modularisation (short drift length, optical segmentation).

Dimensions:

Must contain ionizing particles produced by neutrino interactions, bar neutrons and high-energy muons. Overall cross-section coverage vs. final state kinematics is a driving factor; modest efficiencies are tolerable given the large statistics.

****Not feasible to build a LArTPC large enough to contain muons at the near site****

Assume coupling to a down-stream spectrometer with a large geometric acceptance

Module dimensions

Module dimensions (foot print) are set to simplify reconstruction for light and charge readout.

Prompt scintillation ($\tau = 6.2$ ns) used for precise trigger and to associate detached energy deposits to correct vertex.

Optical path ideally less than Rayleigh scattering length (66 cm), and E-field should be maximal to suppress slow scintillation component.

Diffusion must be much less than pixel pitch (3 mm). Readout window (drift time) should be short to minimise pileup.

13 cm²/s diffusion at 1 kV/cm, 50 cm drift length give readout window of 250 us and transverse diffusion of 0.8 mm.

Module (TPC): 3 m tall, 1 m x 1 m foot print, central cathode 50 cm drift, max 50 kV bias. 2.1 t active LAr per TPC, 0.21 neutrino events per module per spill.

Overall Detector Dimensions

Detector dimensions set by need to measure hadronic showers directly to avoid reliance on models to correct for unobserved energy, across a wide range of neutrino interaction kinematics.

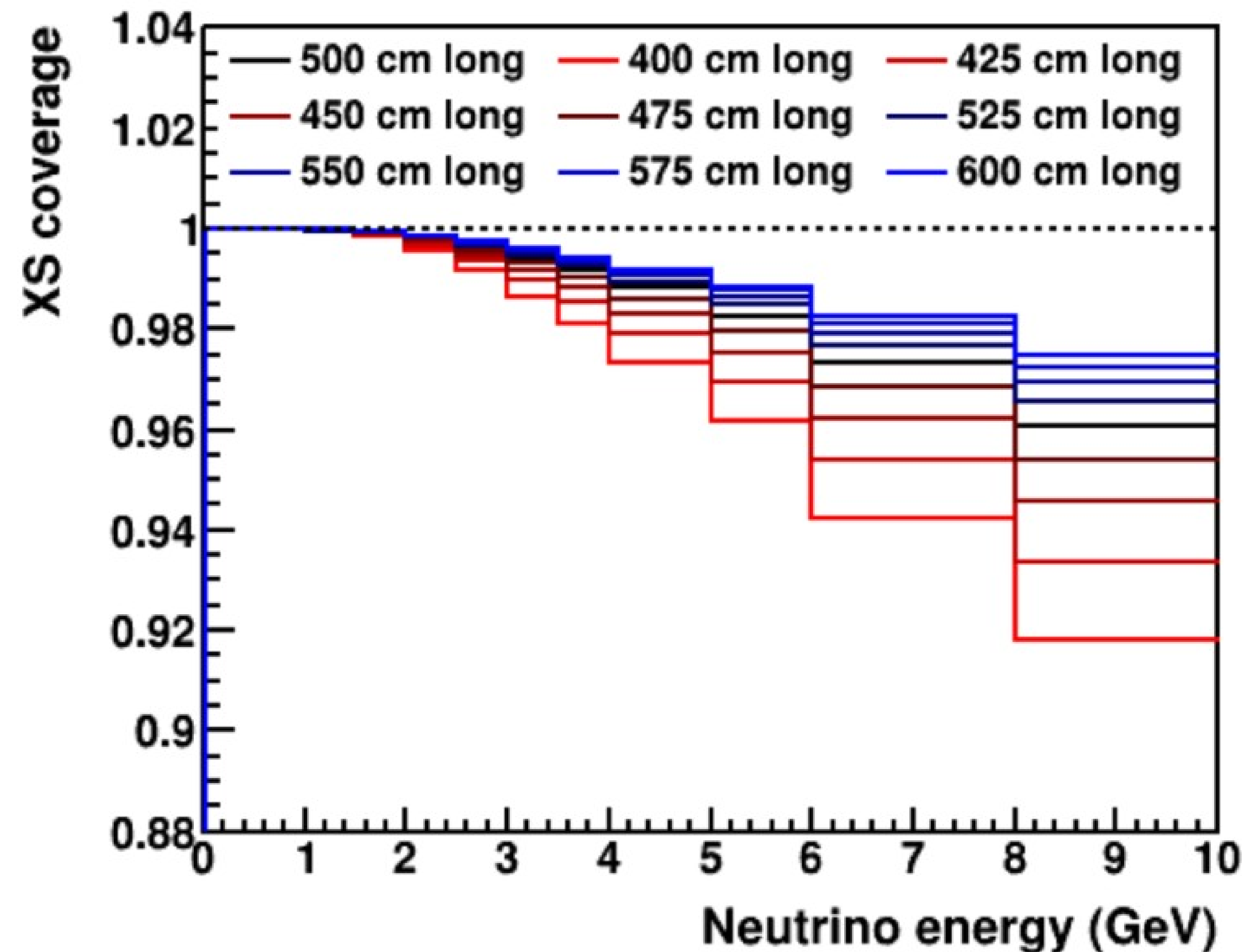
The optimal size is **4* m wide, 3 m tall, and 5 m** in beam.

*7 m to mitigate a side muon spectrometer.

Transverse dimensions differ due to height constraints. Rotational symmetry utilised to maintain coverage.

To mitigate external photons, a fiducial volume is defined to exclude 50 cm around the sides of the detector and 150 cm from the downstream end. In this FV, the acceptance does not change rapidly as a function of hadronic energy, or position of the interaction vertex.

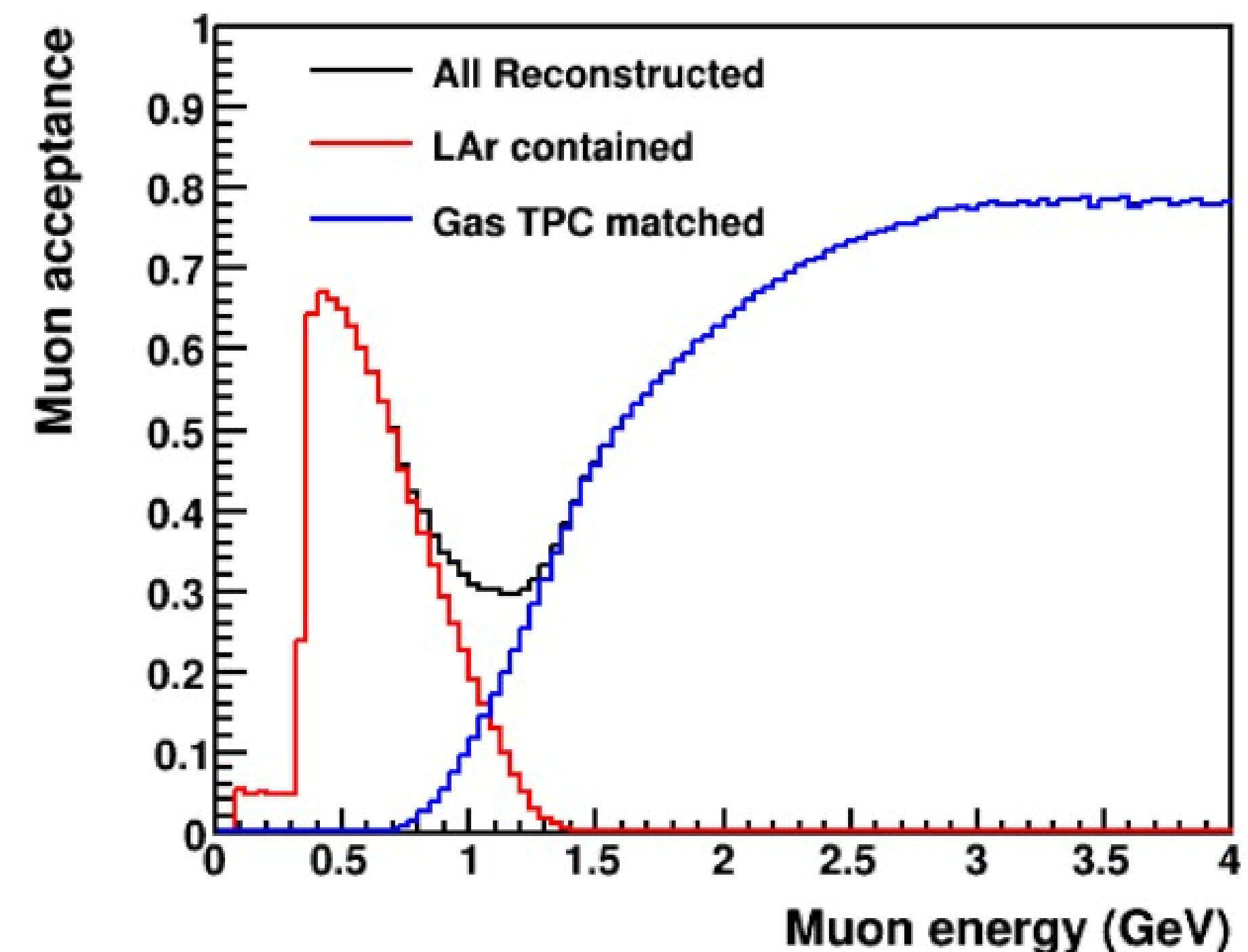
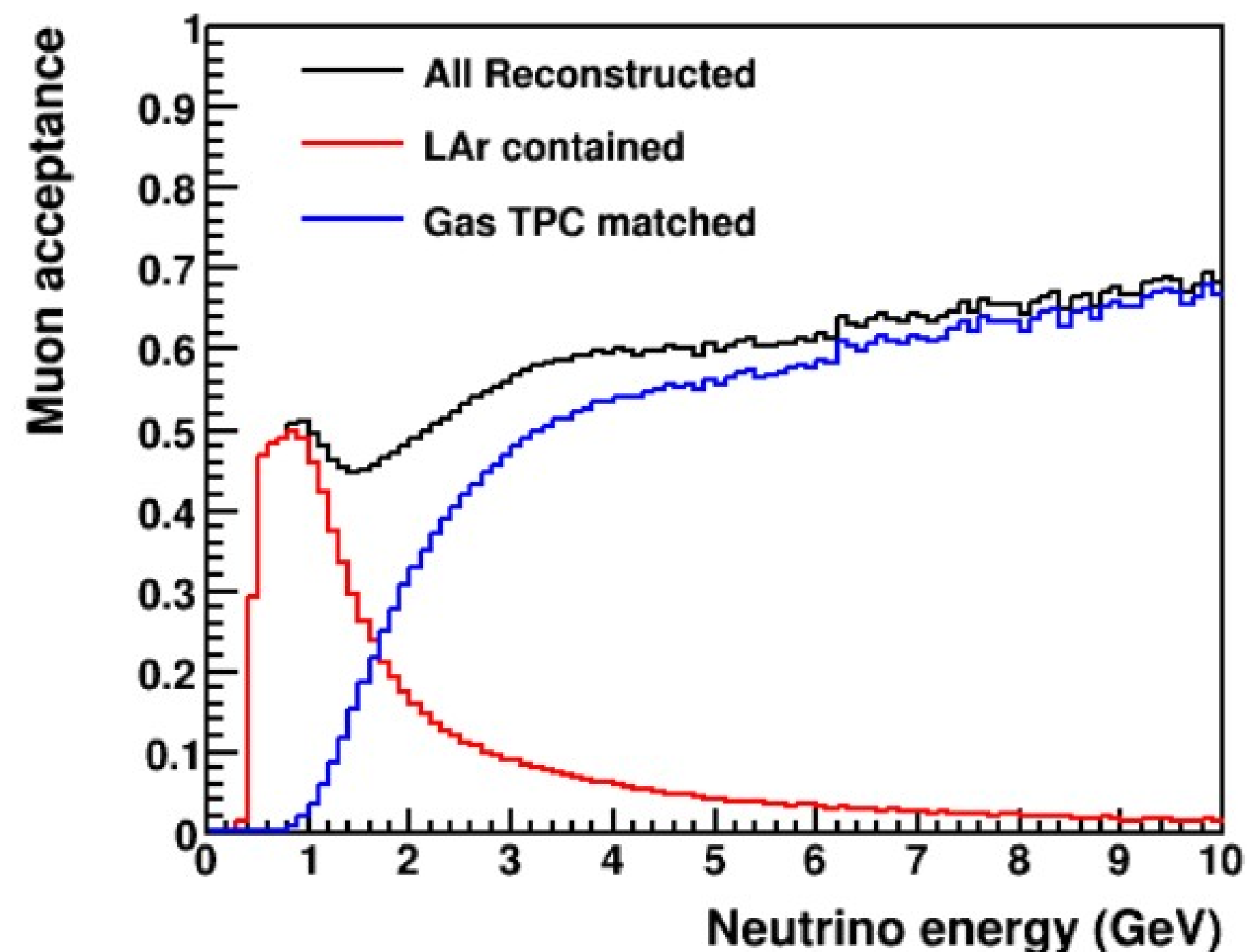
Optimizing Detector Dimensions



Influence of detector length on cross-section coverage as a function of neutrino energy. The optimal length is 5 m. Going beyond 5 m does little to improve cross section coverage, but reducing to 4 m begins to limit coverage at higher energies. **1 minus the cross section coverage gives the fraction of events that can never be well reconstructed.**

Geometric Acceptance to a Spectrometer

Muons can be measured when they stop in ArgonCube, or when they pass into the spectrometer. Muons that stop between the two regions cannot be reconstructed accurately. **ArgonCube must be long enough so that there is no hole in the geometric acceptance as a function of muon momentum.**



Is ArgonCube plausible and achievable?

LArTPCs of this scale and larger have been demonstrated. The primary goal of ArgonCube was mitigating the risks normally associated with LArTPCs.

All novel aspects of ArgonCube have been demonstrated:

Charge R/O – [arXiv:1801.08884](#), JINST 13 (2018) no.10, P10007

Light R/O – [Instruments 2 \(2018\) no.1, 3](#)

Field shell – [Instruments 3 \(2019\) no.2, 28](#)

All the design elements will be incorporated into $\sim 2/3$ scale LAr ND prototype (ProtoDUNE-ND) that will operate on-axis in NuMI in 2020.

Bern has secured funding for production of 4 modules.

FNAL is providing support for facilities to deployment in NuMI.

JINR is providing the light R/O.

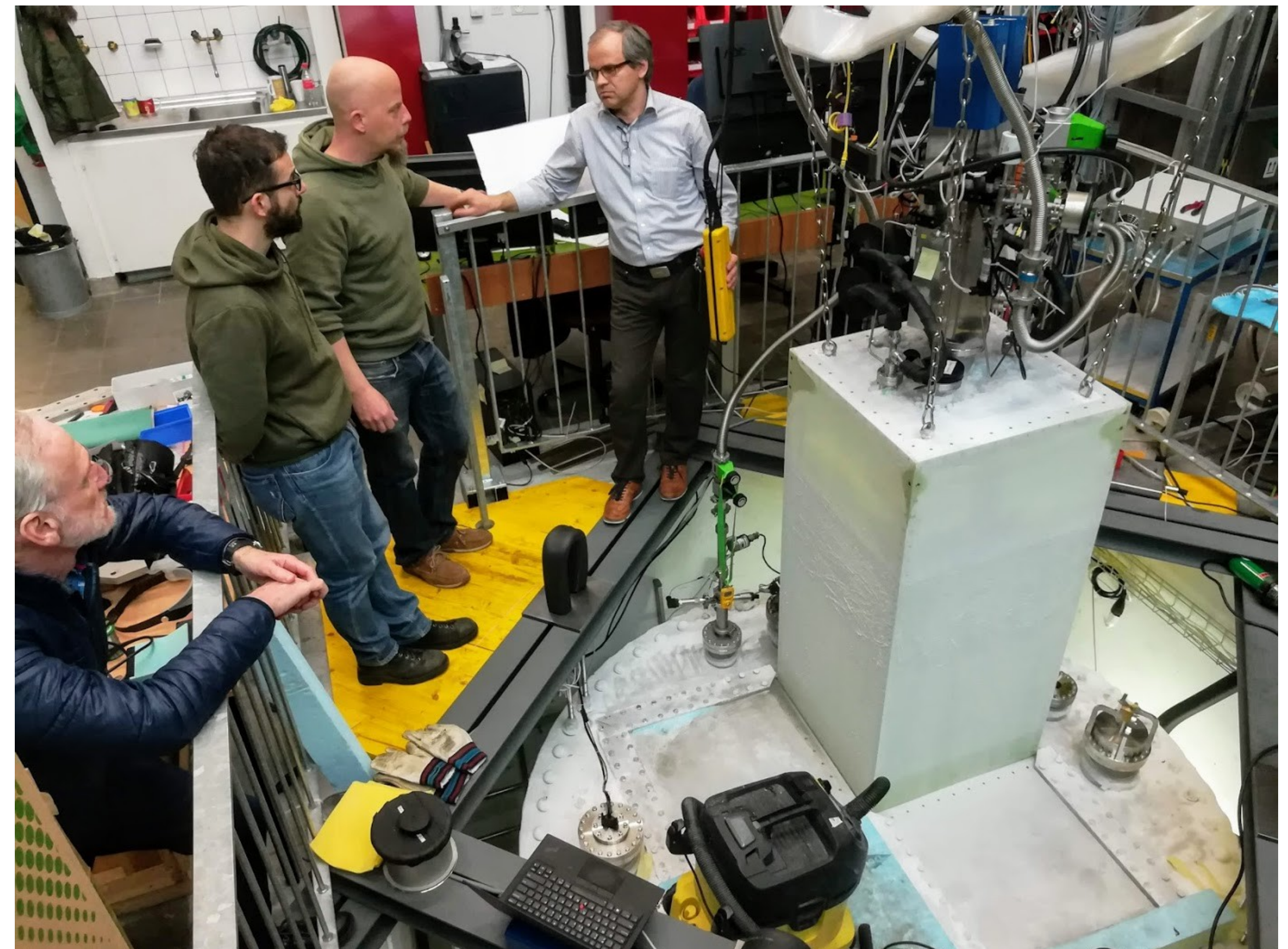
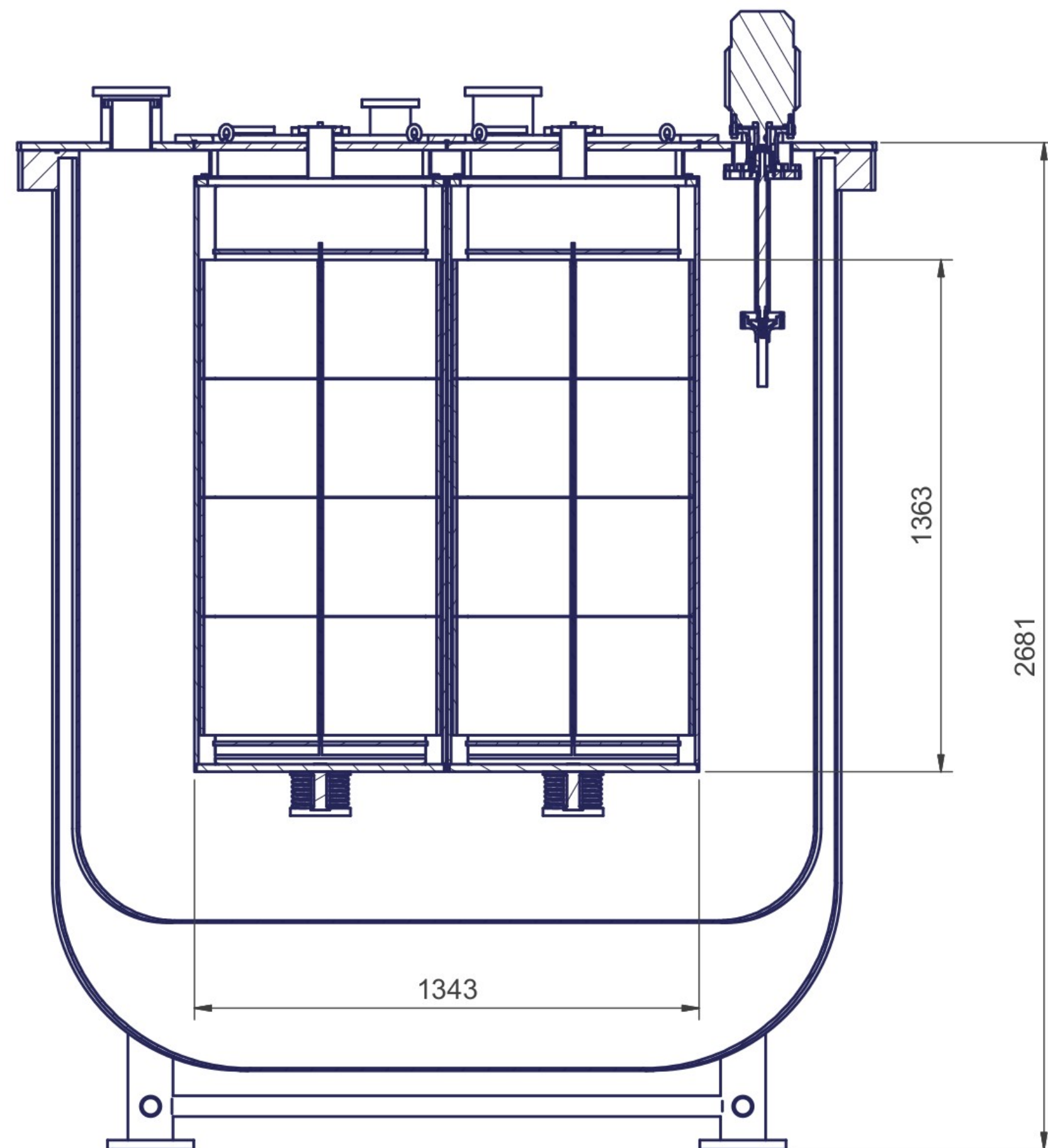
LBNL has secured funding for the charge R/O (supplemented by Bern).

Rochester is providing a high level DAQ, beam trigger, and muon tagger.

SLAC is providing the mechanical module design & production of TPC components.

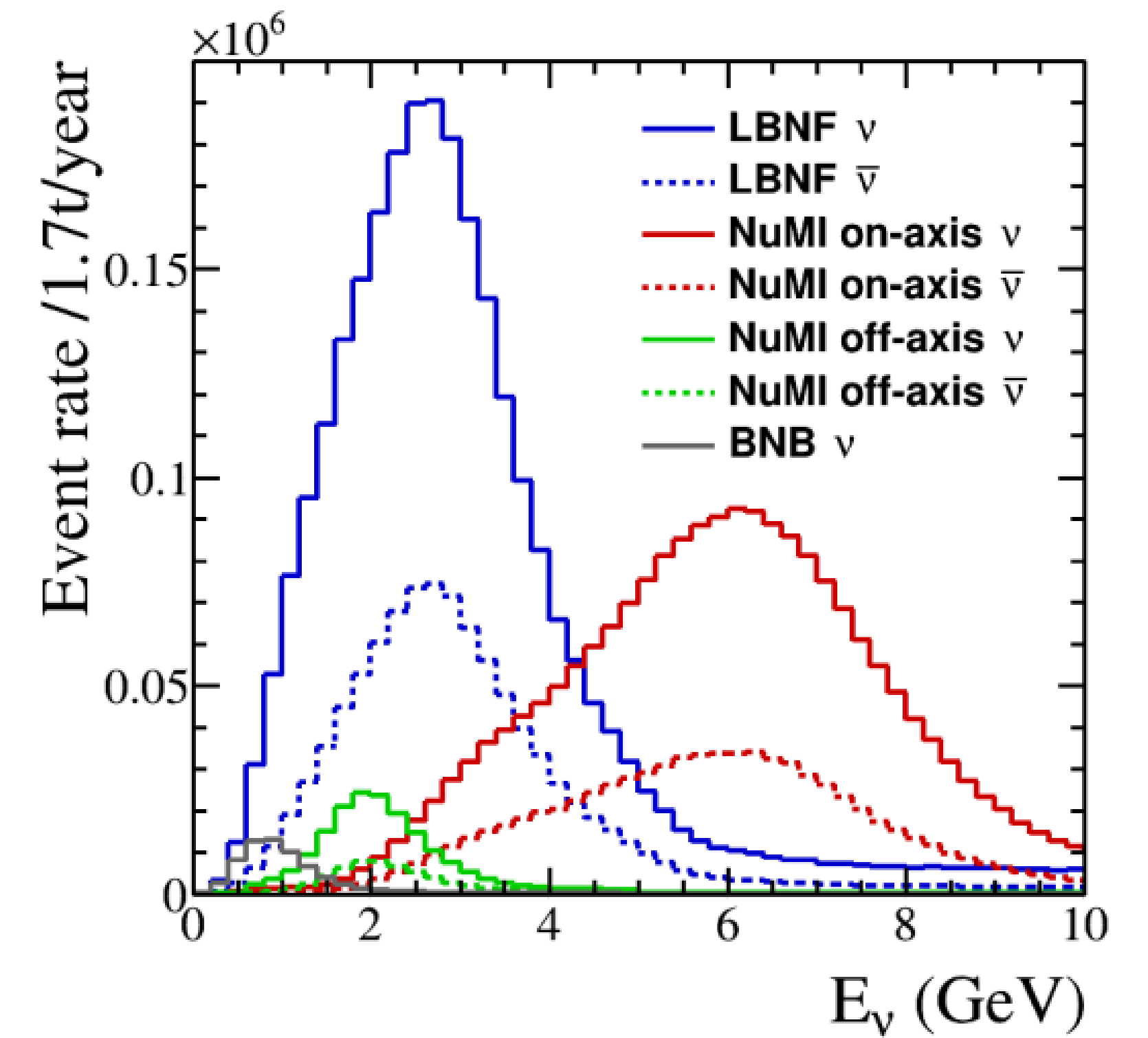
The 2x2 Demonstrator

Vacuum insulated LN₂-cooled cryostat, housing 4 modules, 2.4t Active LAr



2x2 in ProtoDUNE-ND

In spring of 2020, the 2x2 will be moved into the MINOS-ND hall forming ProtoDUNE-ND



ProtoDUNE-ND Detector Physics Goals

Combining light and charge readout.

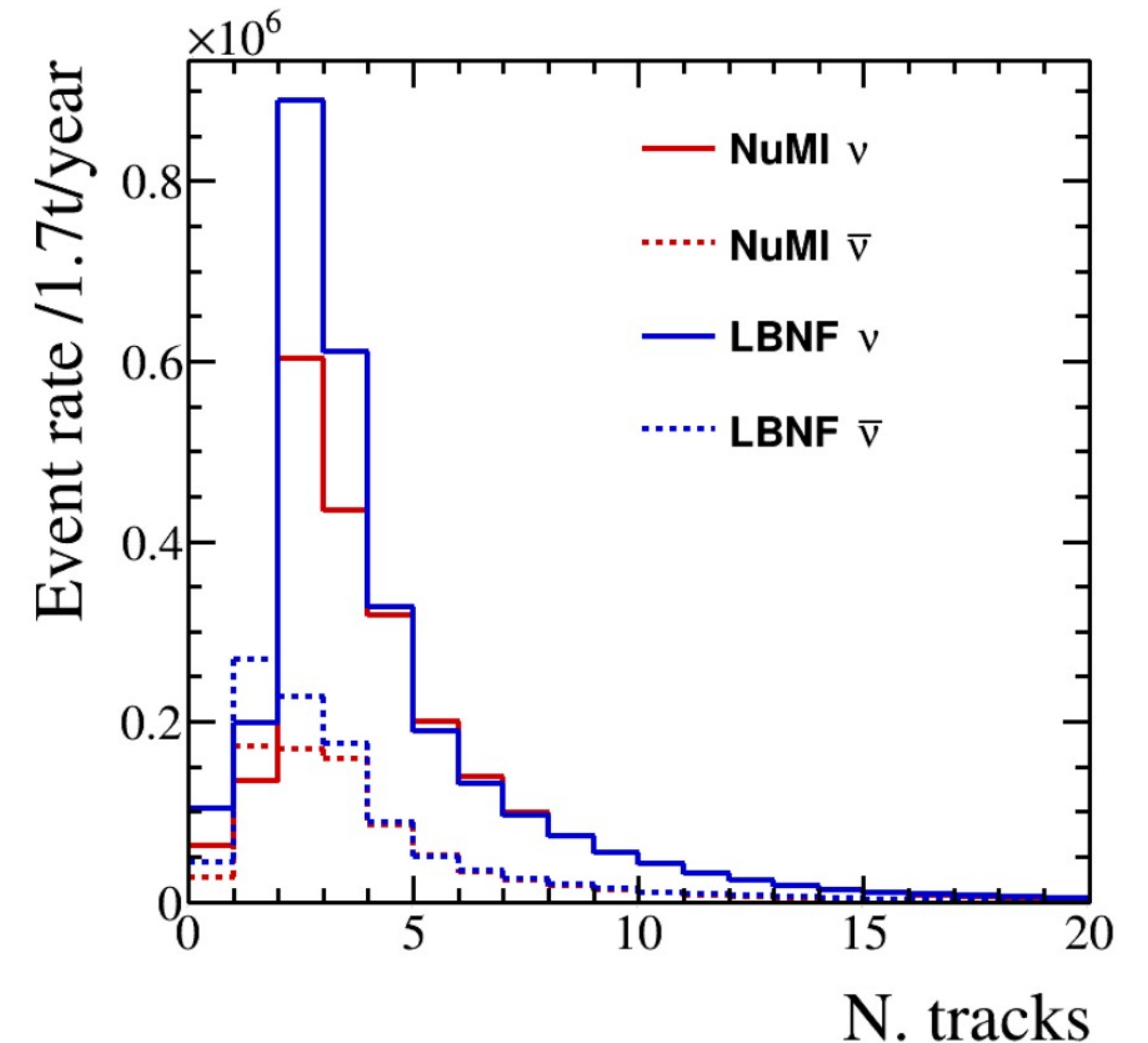
Reconstructing showers and tracks with charge sharing across modules.

Reconstructing events between fast (scintillator), and slow (LAr) detector components.

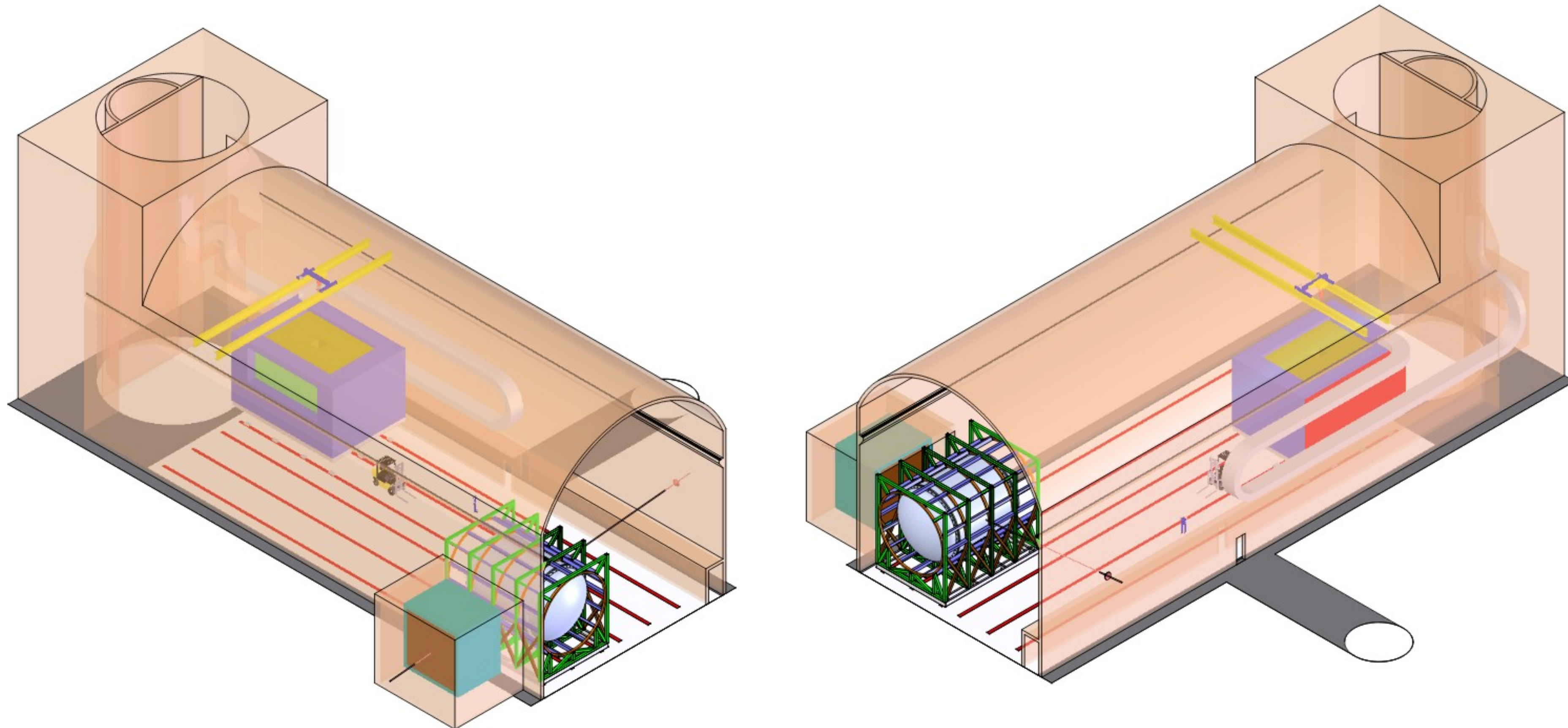
Validate MCS for momentum determination.

Reconstruct contained showers for π^0 mass peak, standard candle for electron energy scale.

Verify e/ γ separation with a pixelated charge readout.

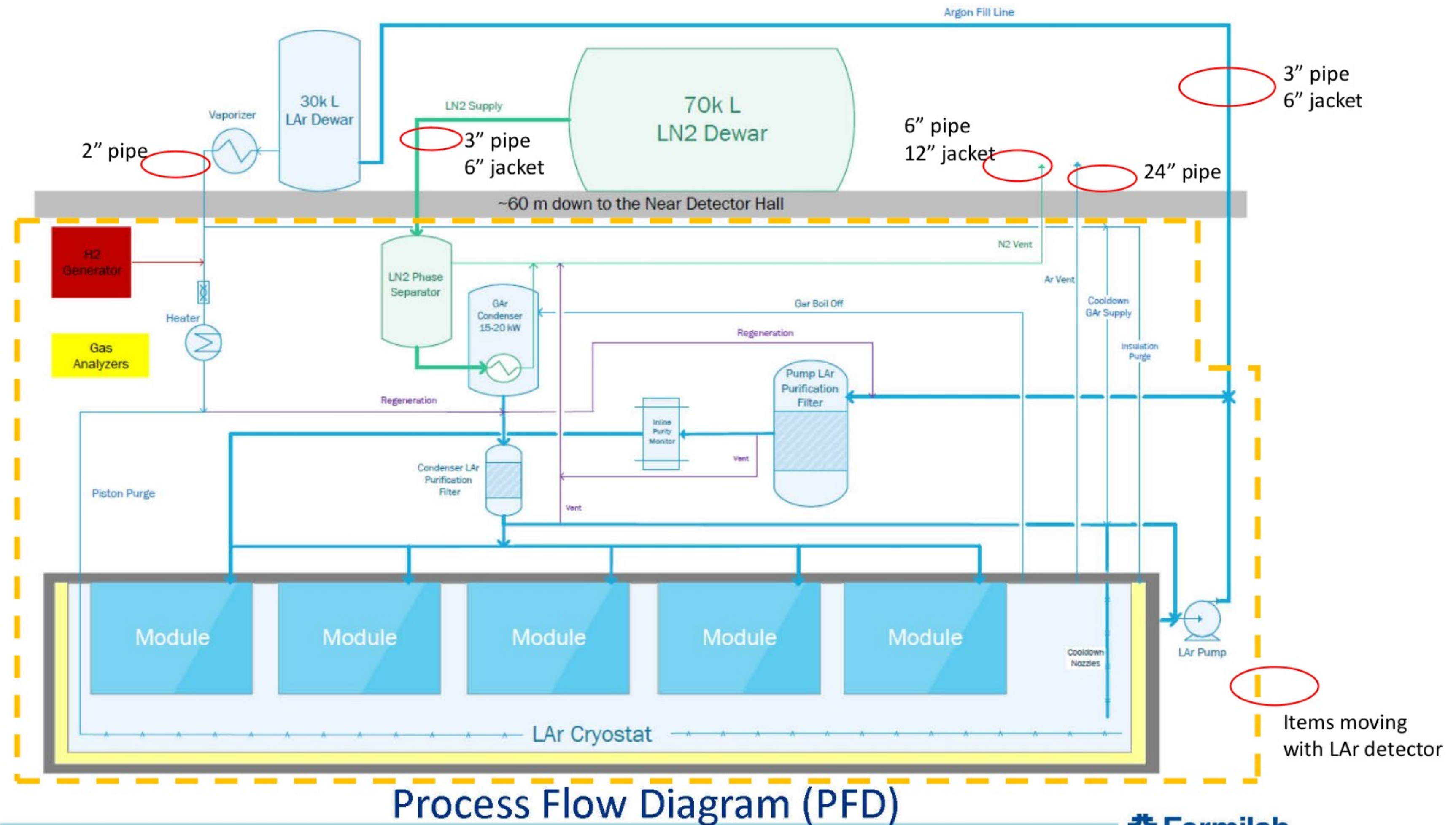


Considerations for Moving ArgonCube in the ND



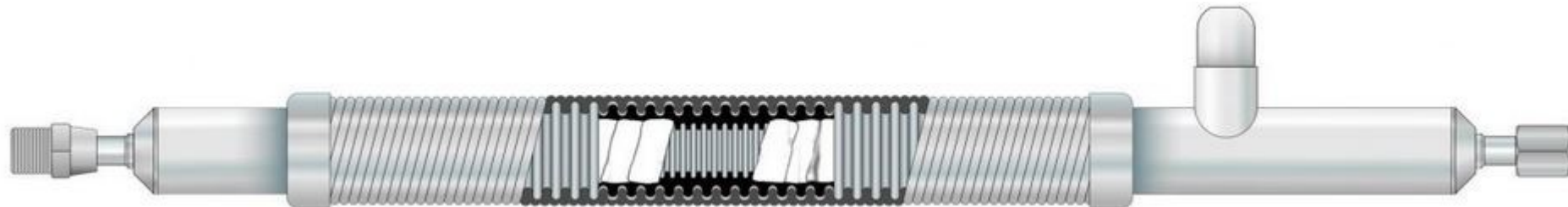
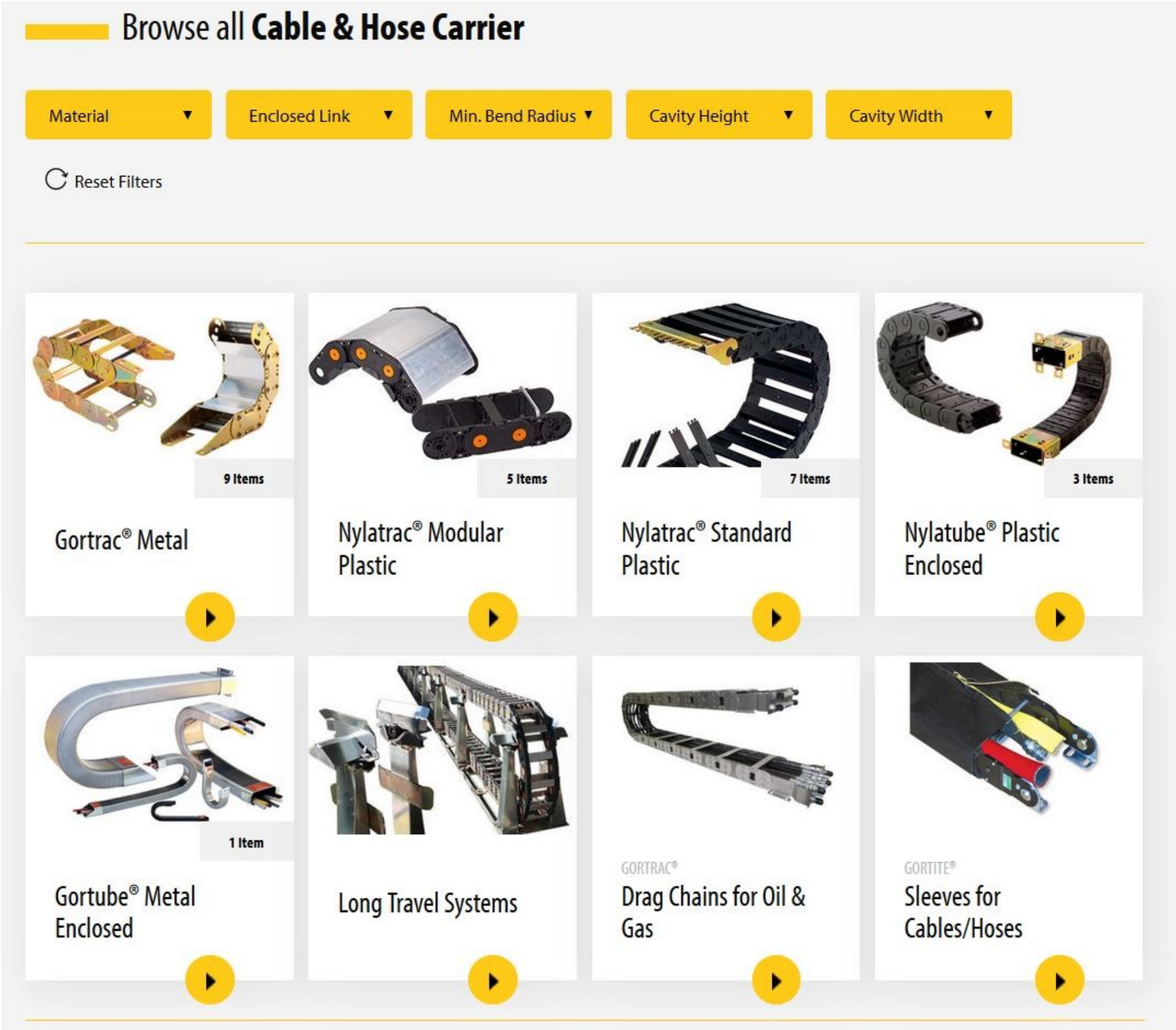
Considerations for Moving ArgonCube in the ND

In the current cryogenic design, everything within the yellow would have to move with ArgonCube



Considerations for Moving ArgonCube in the ND

Such schemes are possible; many commercially available components exist to enable this.



Closing Comments

ArgonCube has been designed to operate in the ND environment. Therefore, it will outperform the FD.

However, the operating E-Field of ArgonCube can be reduced to match that of the FD. In order to assess detector response systematic near to far.

Experience with ProtoDUNE, and other LArTPCs, has informed how to degrade the unambiguous 3D information to match the wire readout of the FD.

Backup - Reducing Overall Detector Dimensions

The effect on the fiducial volume is important to consider when deducing detector dimensions. A 2 m buffer volume is required around the fiducial volume to achieve good containment, therefore a 5 m long detector has a 3 m fiducial volume. Reducing the length to 4 m would reduce the fiducial volume to 2 m, i.e. a 20% reduction in length reduces the fiducial volume by 33%. **This has particularly concerning implications for measurements of nu-e scattering, where the statistics would be cut by 33%.**

The current detector width is 7 m across the beam to mitigate the need for a side muon spectrometer. **The width could be reduced to 4 m, but this will entail the inclusion of a side muon spectrometer plus all additional dead material and costs.**