# THE DUNE NEAR DETECTOR REFERENCE DESIGN

H. A. Tanaka

# INTRODUCTION

- Agenda for the review
- Introduction to LBNF/DUNE
- The Overarching Requirements
- The PRISM Concept
- The DUNE Near Detector Reference design
- Subsystem overviews (LAr, MPD, 3DST-S)
- Towards the CDR and ND Requirements

# AGENDA

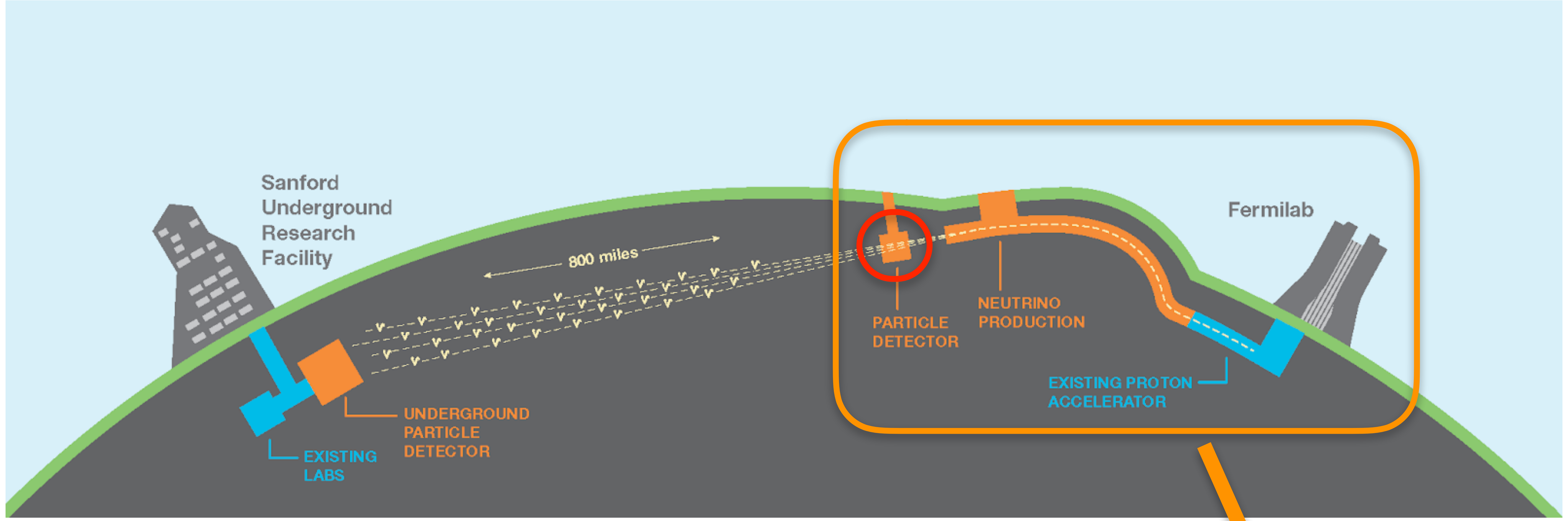
| | | |
|---|---|---|
| **0800 - 0900** | Executive Session | |
| **0900 - 1000** | DUNE ND Requirements and Reference Overview | 40+ 20 (Tanaka) |
| **1000 - 1015** | Break | |
| **1015 - 1100** | Constraining interaction model uncertainty | 30 + 15 (Wilkinson) |
| **1100 - 1145** | Long-baseline physics analysis status overview | 30 + 15 (Worcester) |
| **1145 - 1230** | DUNE-PRISM capability for determine energy response | 30 + 15 (Wilking) |
| **1230** | Committee gets lunch from Director's CR and returns | |
| **1245 - 1330** | Executive Session over lunch | |
| **1330 - 1400** | Direct flux measurements with neutrino-elastic scattering | 20 + 10 (Marshall) |
| | DUNE Near Detector subsystem details | |
| **1400 - 1430** | LAr | 20 + 10 (Sinclair) |
| **1430 - 1445** | Break | |
| **1445 - 1515** | MPD | 20 + 10 (Bross) |
| **1515 - 1545** | 3DST-S | 20 + 10 (Manly) |
| **1545 - 1645** | Executive Session | |
| **1645 - 1715** | Close out | |

# GUIDANCE FROM THE COMMITTEE

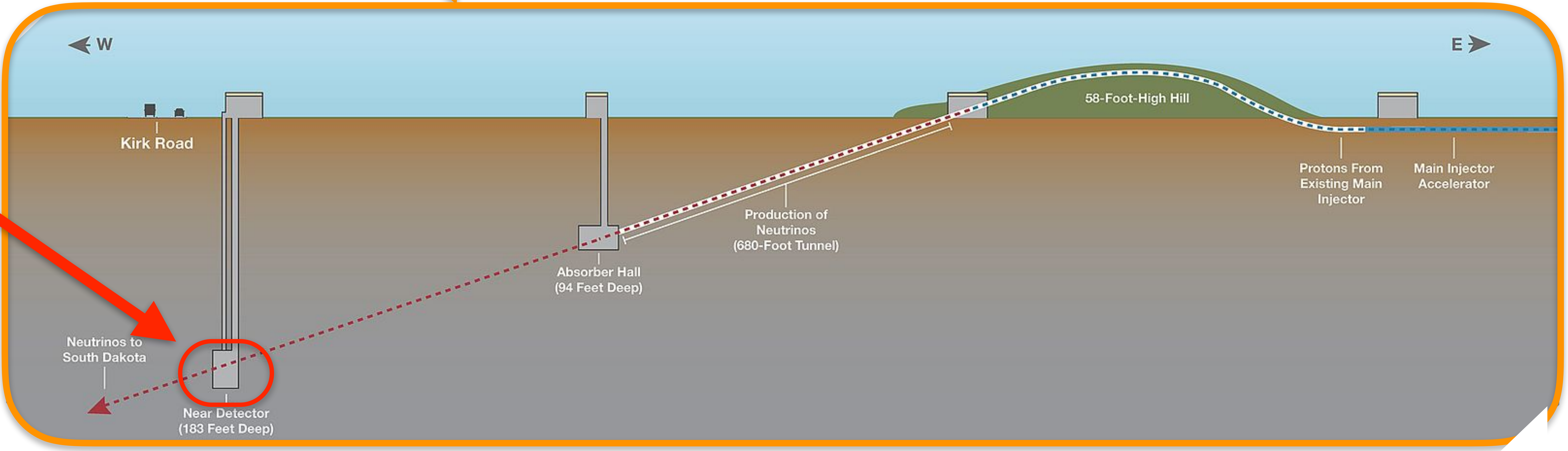
- DUNE should provide the ND review committee with an “existence proof” of a plausible and achievable ND design that will meet the requirements set in the physics TDR
  - This need not be an optimized design, but enough to permit sign-off of on the physics TDR
- The review committee will advise the LBNC on whether the ND concept is feasible and appropriate
- The review committee will provide early constructive feedback to DUNE, as DUNE prepares to complete the ND CDR

- From the DUNE collaboration:
  - We sincerely thank the committee for its in-depth review of the ND “Executive Summary” document and for the insightful and probing questions.
  - Our submitted document is our primary response but we will return to key points through the presentations

# DUNE/LBNF AND THE NEAR DETECTOR

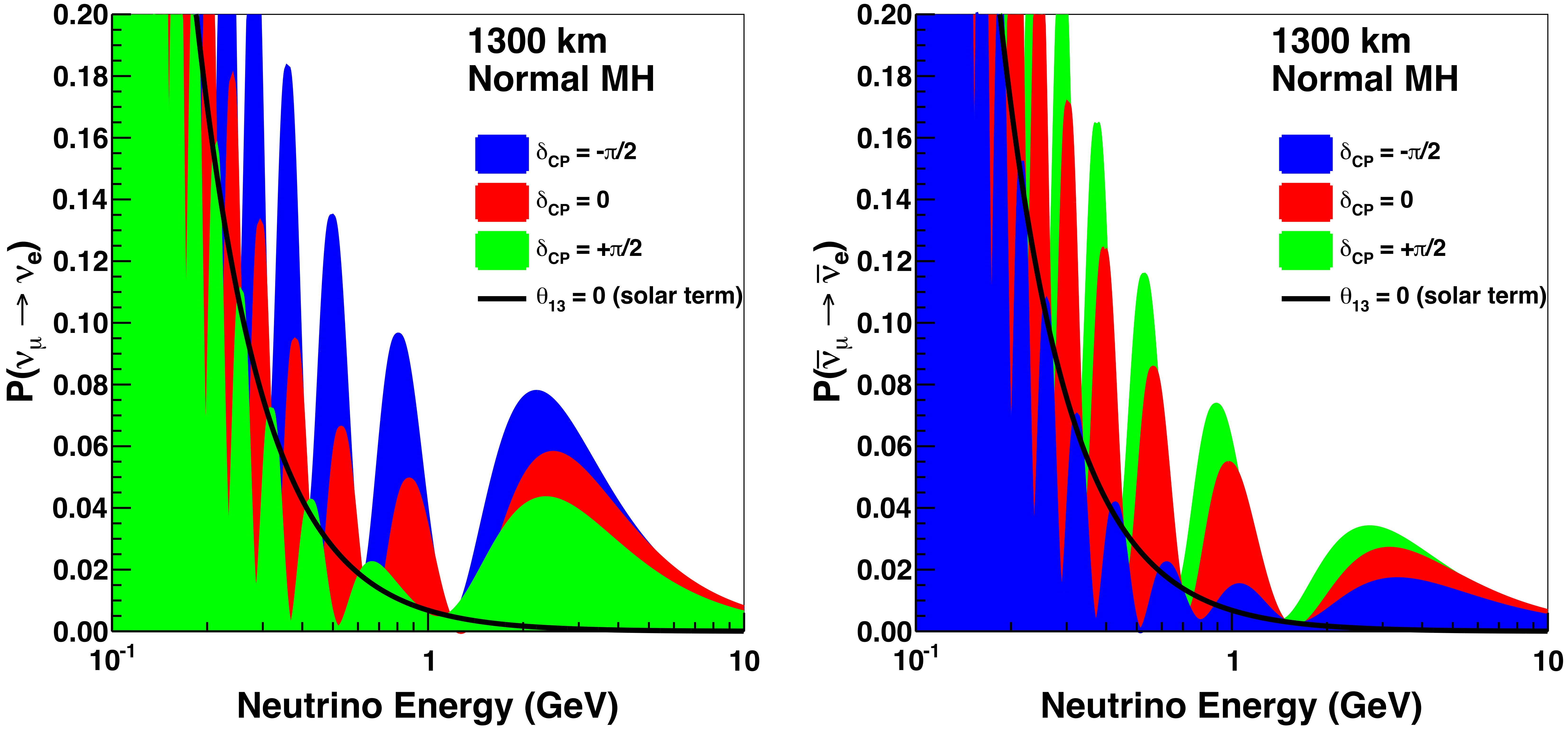



- LBNF sends an intense, broadband $\nu_\mu$ ($\bar{\nu}_\mu$) beam 1280 km from FNAL to the DUNE far detector (FD) at SURF
- Here, we talk about measurements at the near site, 575 m from the production target
- At 1.2 MW, ~0.16 events/ton/spill at the near site



# NEUTRINO OSCILLATIONS AT DUNE

more in
E. Worcester's talk




- Neutrino oscillation parameters are extracted via the rate and energy spectrum of $\nu_\mu$ ($\bar{\nu}_\mu$), $\nu_e$ ($\bar{\nu}_e$) events observed at the far detector
- Fully exploit broad band LBNF neutrino beam to measure oscillation probability vs. $E_\nu$

# ROLE OF NEAR DETECTOR

- The primary role of the near detector (ND) is to serve to serve as the experiment's control for the long baseline analysis.
- It must provide enough information to sufficiently model each component of the following convolution

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

  which involves

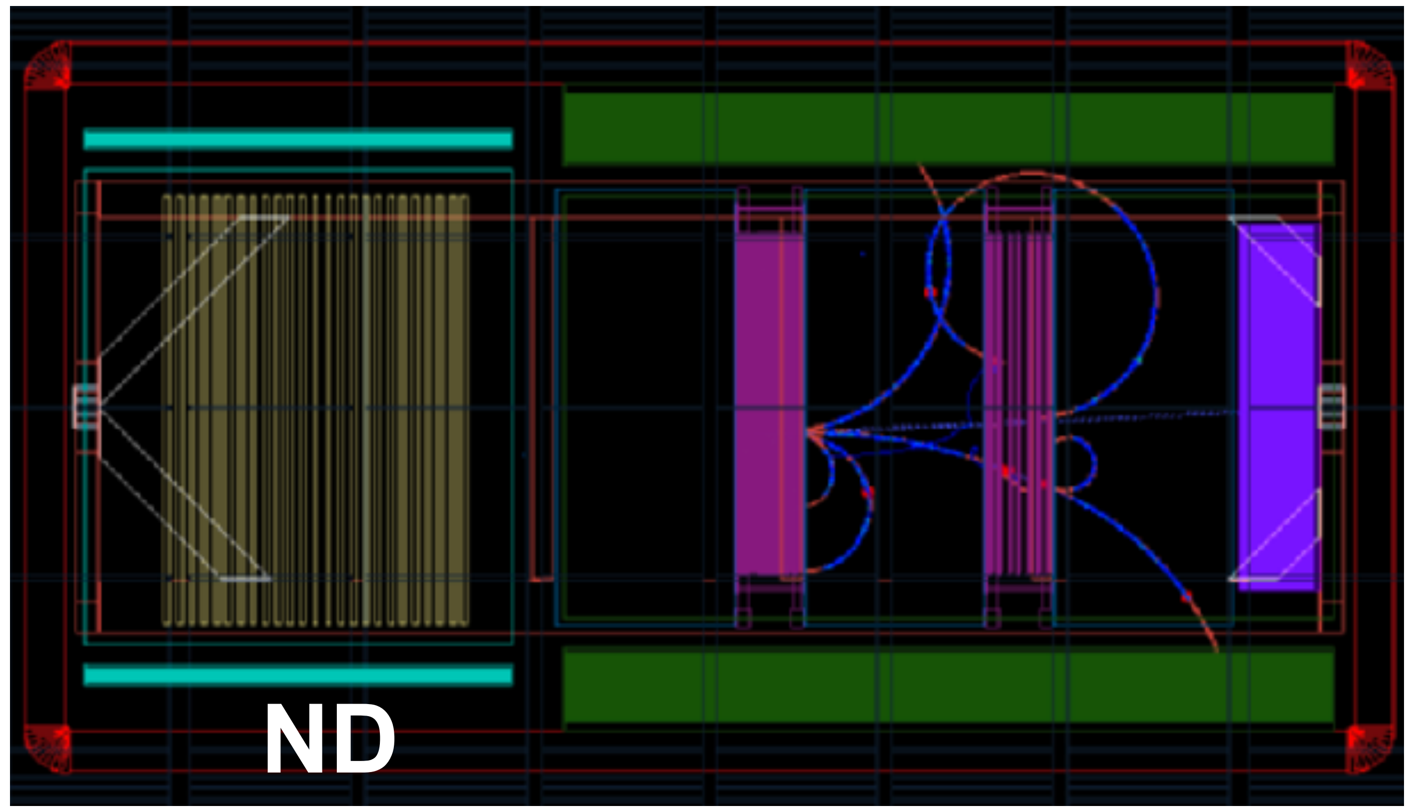
  - **$\Phi$ :** the initial neutrino flux
  - ***$\sigma$* :** the neutrino interaction cross section
  - **R:** the response, encapsulating how a neutrino with energy $E_\nu$ is reconstructed in the detector ($E_{rec}$)
    - incorporates both the modelling of the $\nu$-Ar interaction final state and the detector response
- such that the number and spectrum of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$ at the FD can be predicted as a function of the oscillation parameters with sufficient precision.

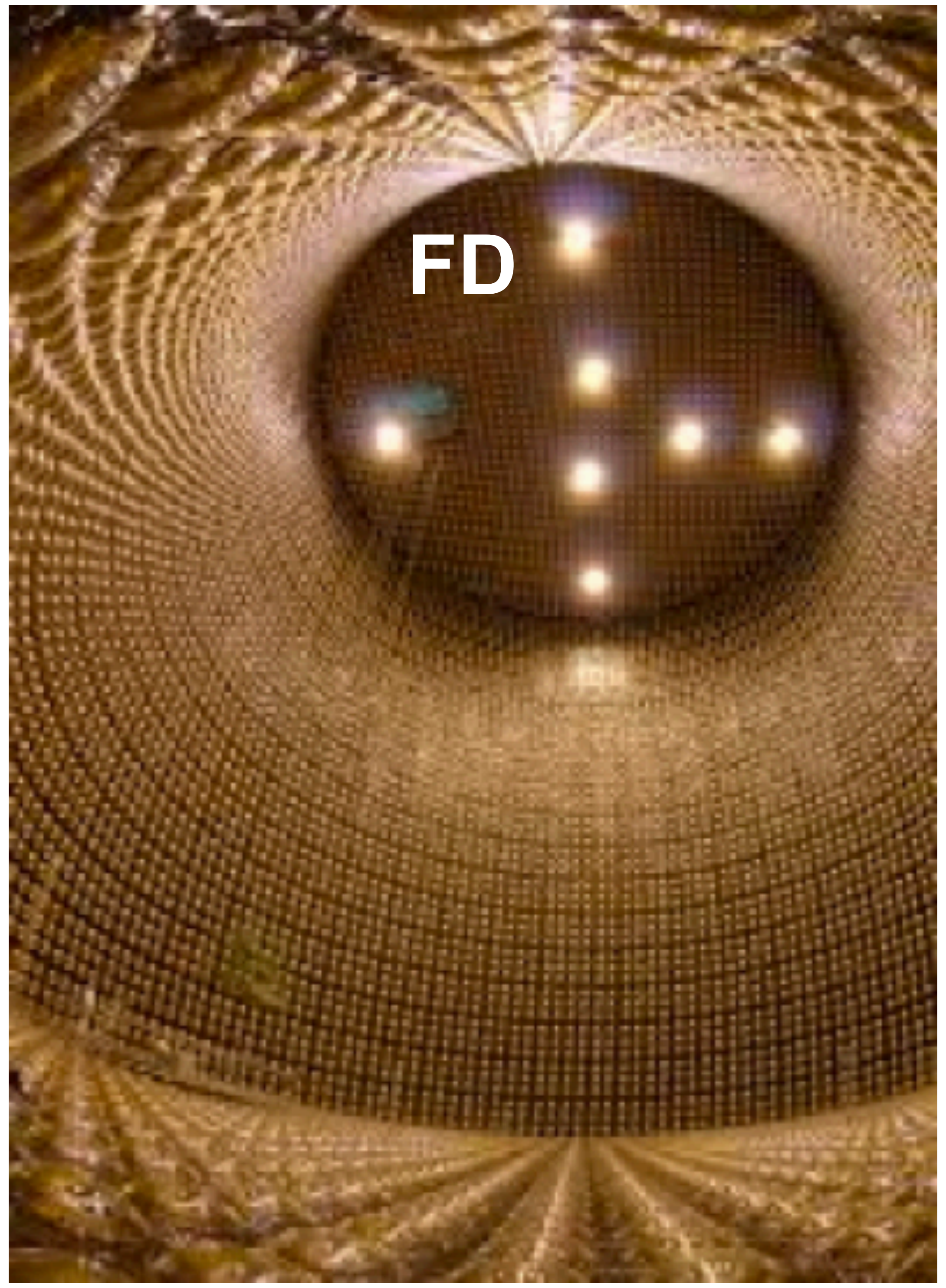
# BEYOND THE MODELS:

- The neutrino oscillation analysis is built on models of:
  - The neutrino flux using Monte Carlo simulation tuned with external data (e.g. hadron production @ NA61)
  - Neutrino interactions using a generator incorporating nuclear physics and tuned to historic data
  - The detectors using full Geant4 simulations tuned with calibrations and other data (e.g. ProtoDUNE)
- This foundation is known not to be solid:
  - We know that the neutrino interaction models are deficient, particularly with regard to the nuclear physics
    - Current data cannot be fully explained by existing models
    - Recent “surprises” in qualitatively new effects (e.g. multinucleon interactions) not previously considered
    - etc.  . . . there are bound to be more surprises
  - Neutrino beams are based on very well known physics, but are complex and operate in harsh environments
    - careful monitoring and precise cross checks on the neutrino flux are critical
- DUNE ND must be designed to address these issues

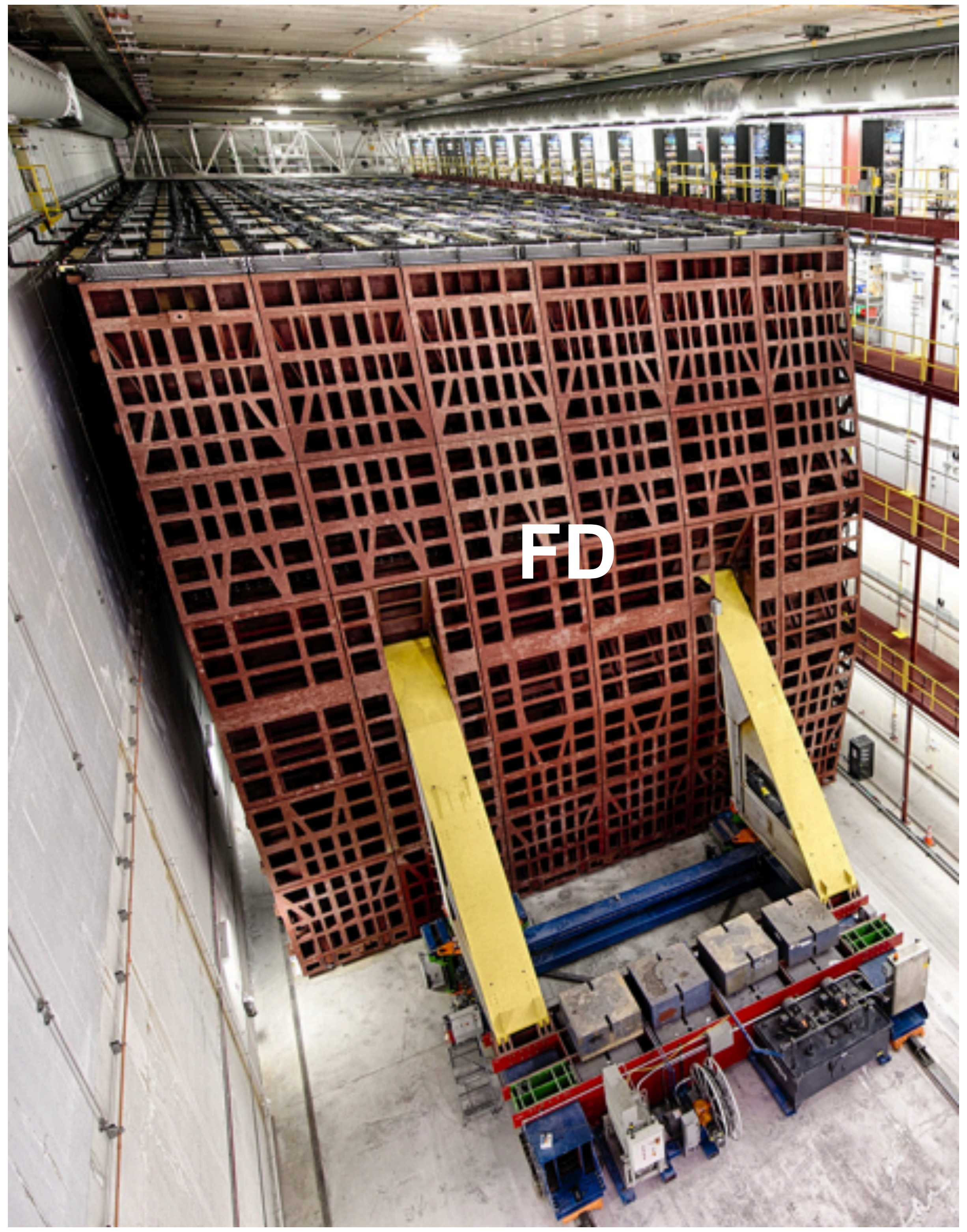
# ONGOING EXPERIENCE

- T2K:
  - Near detectors with capabilities beyond those of the far detectors can further inform flux, neutrino interaction modeling, etc.
  - subsystems have specialized roles




- NOvA
  - Near detector that is functional identical to far detector can directly inform far detector distributions and cancel systematic errors


- DUNE Approach
  - Near detectors with capabilities beyond the far detector are needed to sufficiently constrain uncertainties
  - A detector functionally very similar to the FD is needed to inform how the interactions will actually appear there

# DRAFT OVERARCHING REQUIREMENTS* (I)

| | | |
|---|---|---|
| **O0 Predict the neutrino spectrum at the FD:** The ND must provide a prediction for the energy spectrum of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, and $\bar{\nu}_e$ at the FD. The prediction must be provided as a function of the oscillation parameters and systematic uncertainties must be small enough to achieve the required CP coverage. This is the primary requirement of the DUNE ND. | | |
| O0.1 | **Measure interactions on argon** | Measure neutrino interactions on argon to reduce uncertainties due to nuclear modeling, 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, keeping them small enough to achieve the required CP coverage. These measurements must also be transferable to the FD |
| O0.3 | **Constrain the cross section model** | Measure neutrino cross-sections in order to constrain the cross-section model used in the oscillation analysis. Mismodeling that causes incorrect FD predictions as a function of neutrino flavor and true or reconstructed energy must be constrained well enough to achieve the required CP coverage. |



* Requires DUNE Executive Board sign off

# DRAFT OVERARCHING REQUIRMENTS* (II)

| | | |
|---|---|---|
| O0.4 | **Measure neutrino flux** | Measure neutrino fluxes 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 spectra from the ND to the FD. |
| O0.5 | **Obtain data with different neutrino fluxes** | Measure neutrino interactions in different beam fluxes (especially ones with different mean energies) to disentangle flux and cross-sections, verify the beam model, and guard against systematic uncertainties on the neutrino energy reconstruction. |
| 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. The precise requirement will be informed by the run plan as well as experience from previous experiments. |



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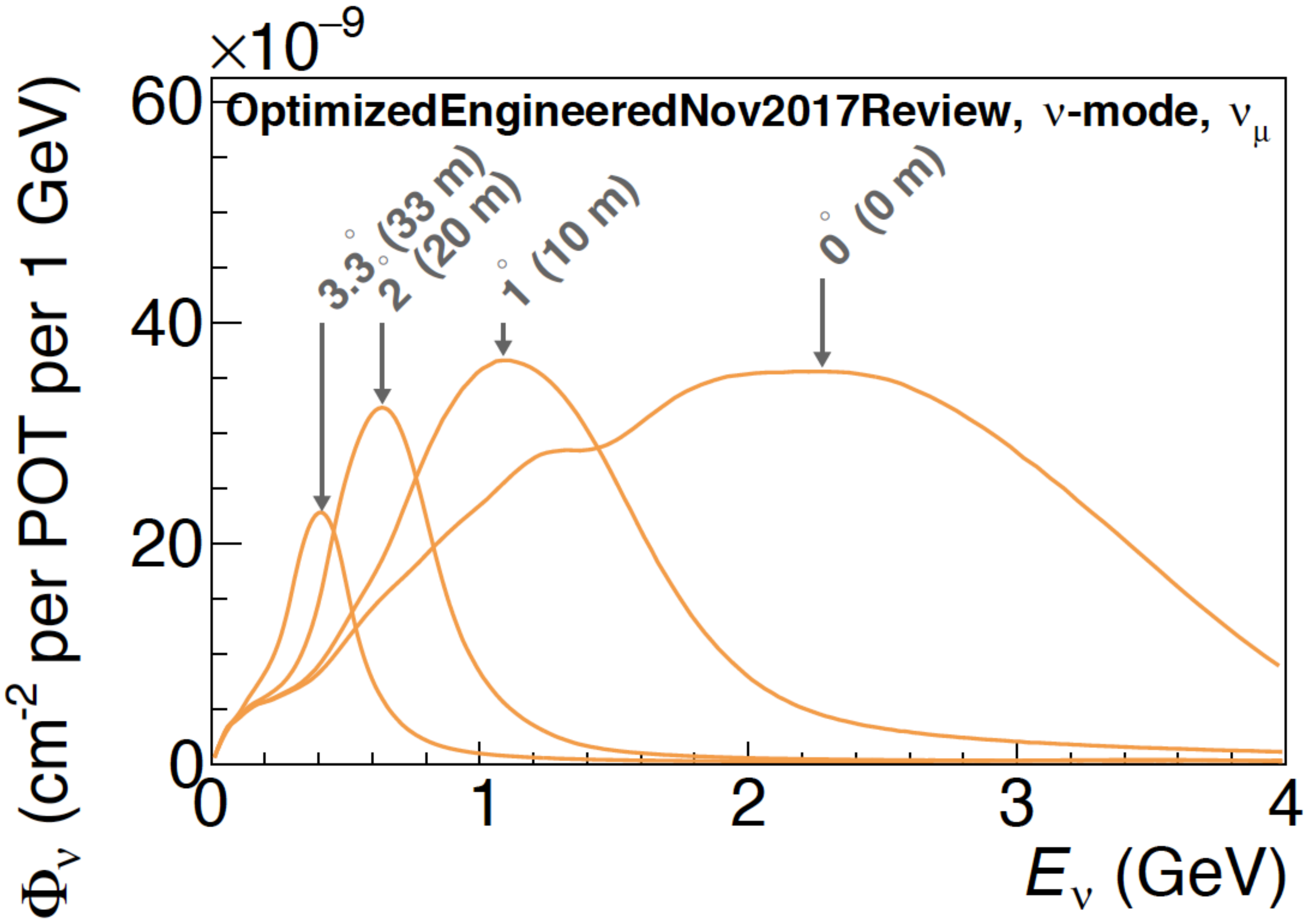
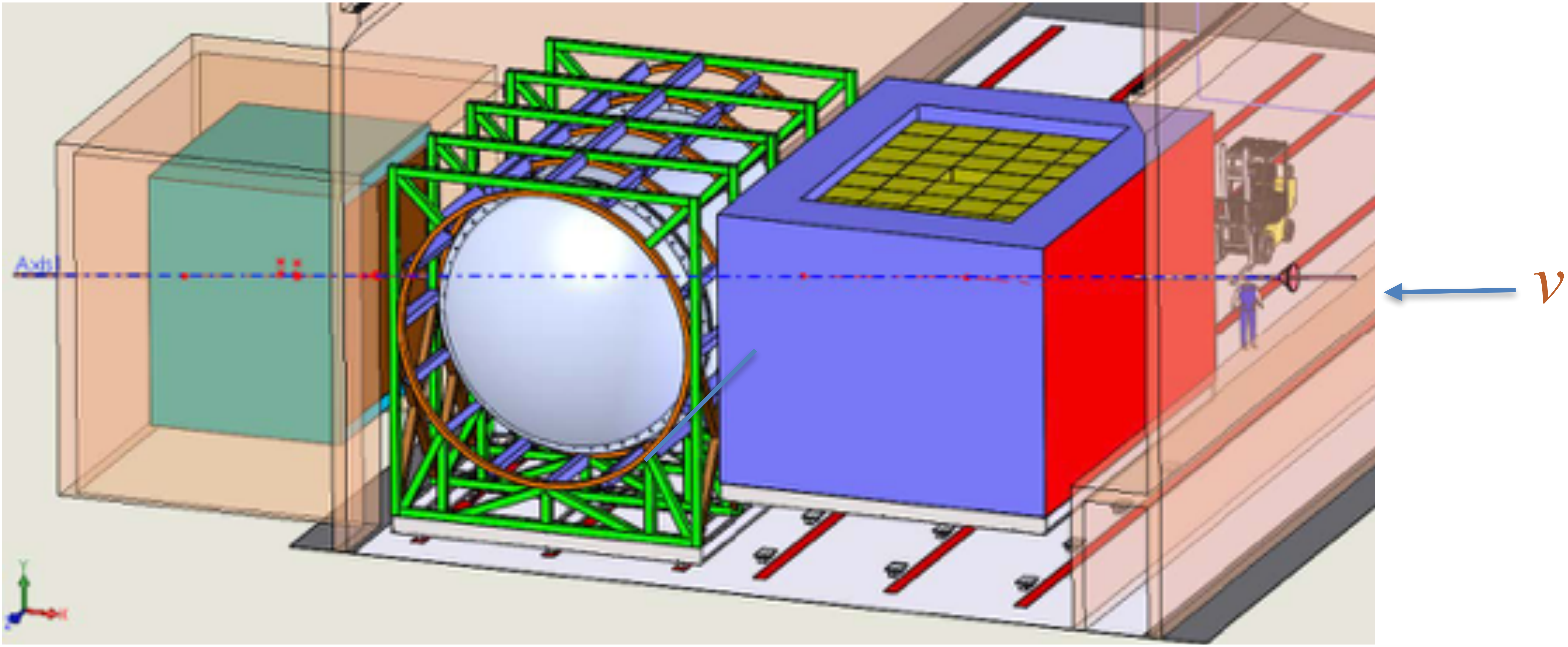
# OFF-AXIS NEUTRINO FLUXES




more in M. Wilking's talk

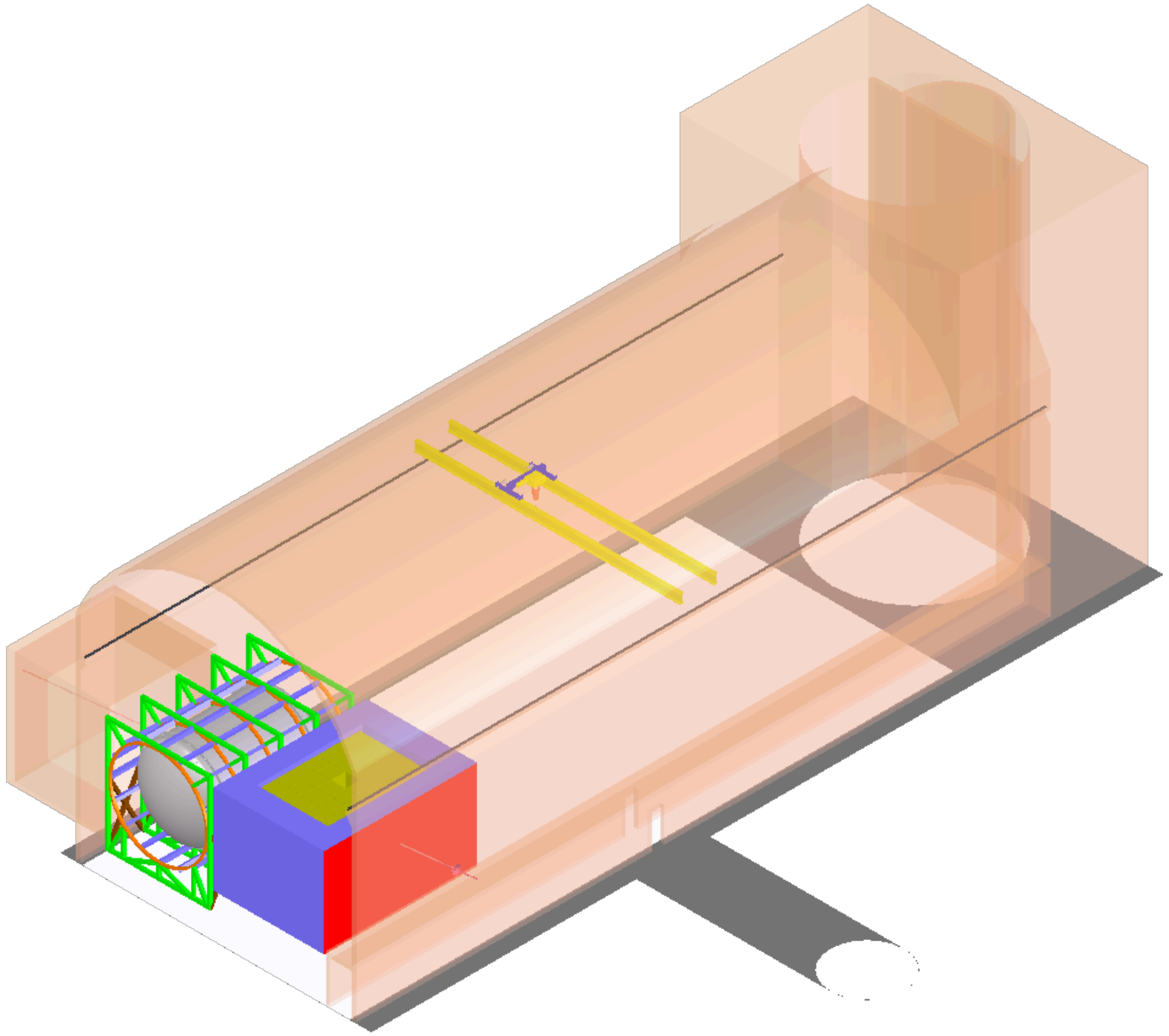
- Neutrino interactions observed in a fixed flux of neutrinos are a convolution of the flux and cross section
- Data taken at varying off-axis positions expose the detector to fluxes with different spectra ("PRISM")
  - handle to deconvolve the flux and cross section
  - break degeneracies in modelling that may result from taking data only on-axis (one off-axis position/ spectra)
  - predict oscillated neutrino event spectra at FD with reduced model dependence
- **This is a qualitatively new element of ND design that we will introduce to DUNE**

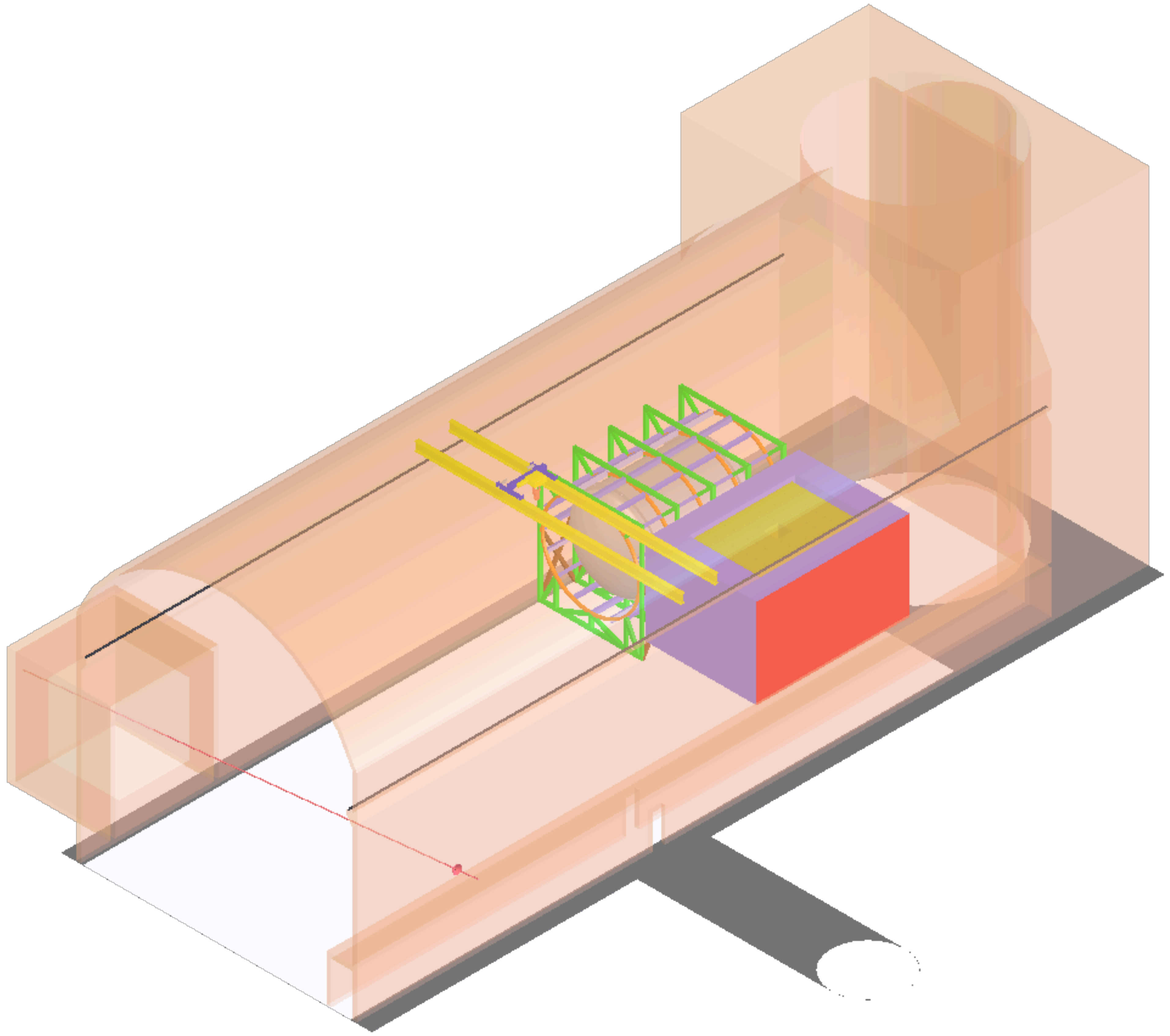
# DETECTOR OVERVIEW




- From left-to-right (upstream-to-downstream)
  - LAr: Liquid Argon Time Projection Chambers
  - MPD: Multi-Purpose Detector
  - 3DST-S: Three Dimensional Scintillating Tracker-Spectrometer

# THE NEAR DETECTOR HALL

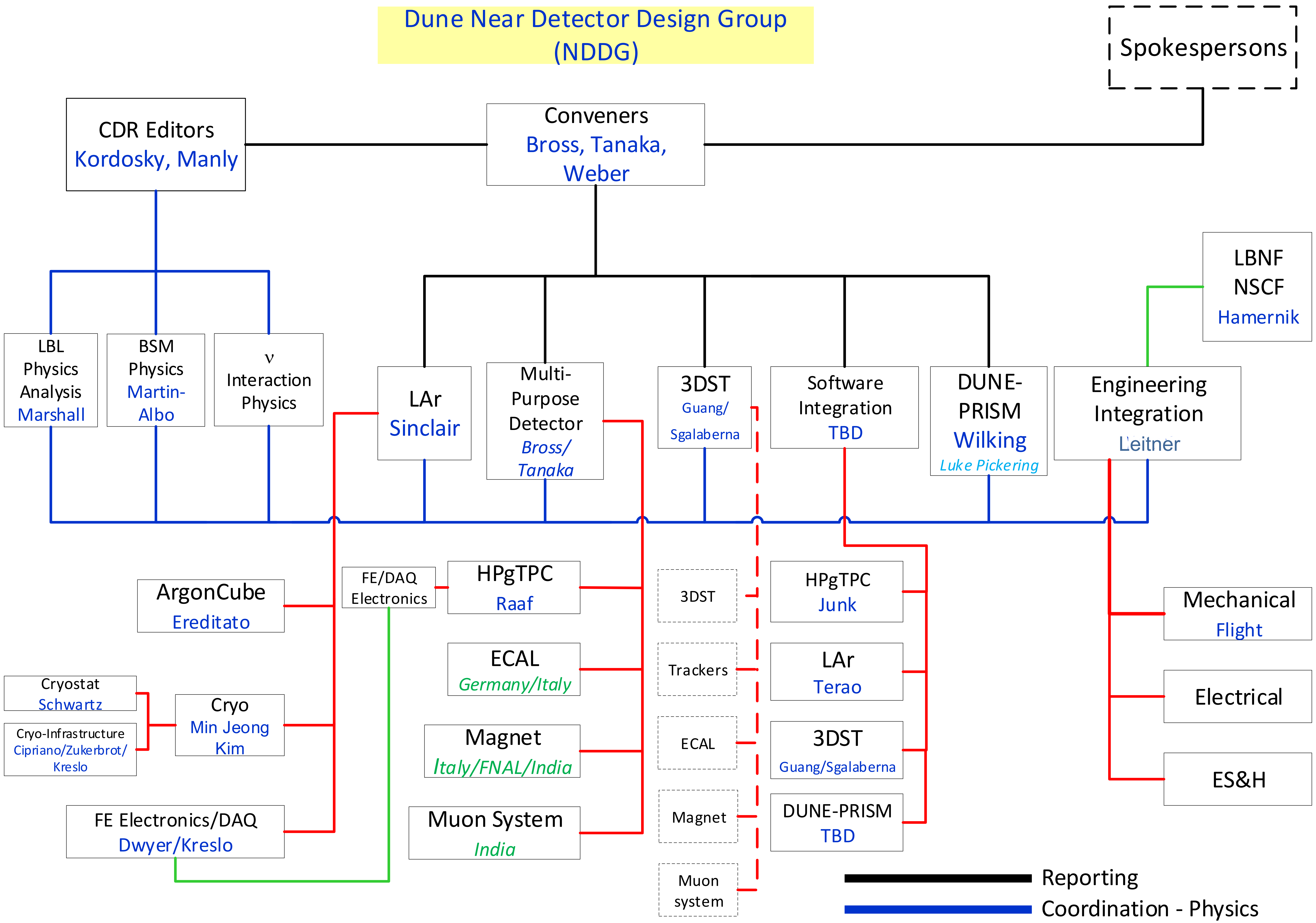




- LAr + MPD move transverse to the beam to effect DUNE-PRISM (*i.e.* exposure to off-axis fluxes)
- 3DST-S remains on-axis as a beam monitor

# ORGANIZATION

- Near Detector Design Group formally launched in 9/2018
- Biweekly general meetings
- Individual subgroup meetings
- Regular engineering/facility interface and integration meetings



# MATRIX OF SUBCOMPONENT ROLES

Complementarity in:

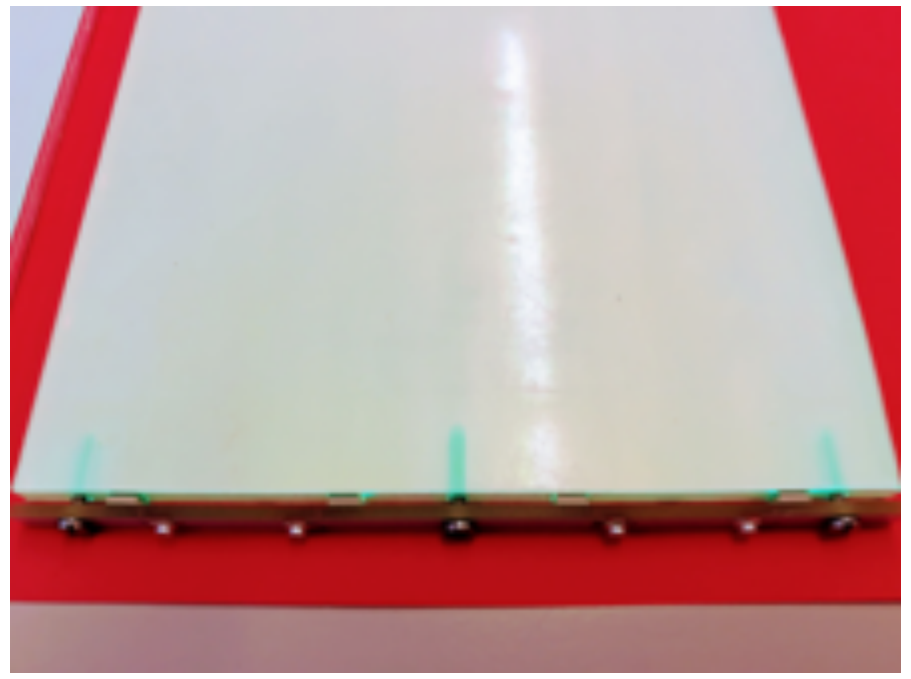
- Event reconstruction:
  - MPD necessary to complete reconstruction of events in LAr detector
  - ECAL necessary to complete reconstruction of HPgTPC interactions (like collider detector)
- Viewing of $\nu$-Ar interactions
  - MPD provides look at "bare" $\nu$-Ar interaction with sign selection, very low thresholds, and minimal secondary interactions
  - LAr provides look at "full" $\nu$-Ar interaction as seen by FD
- Capability and Robustness:
  - 3DST-S provides look at $\nu$-CH interactions with novel neutron detection capabilities
  - 3DST-S provides detailed on-axis beam monitoring

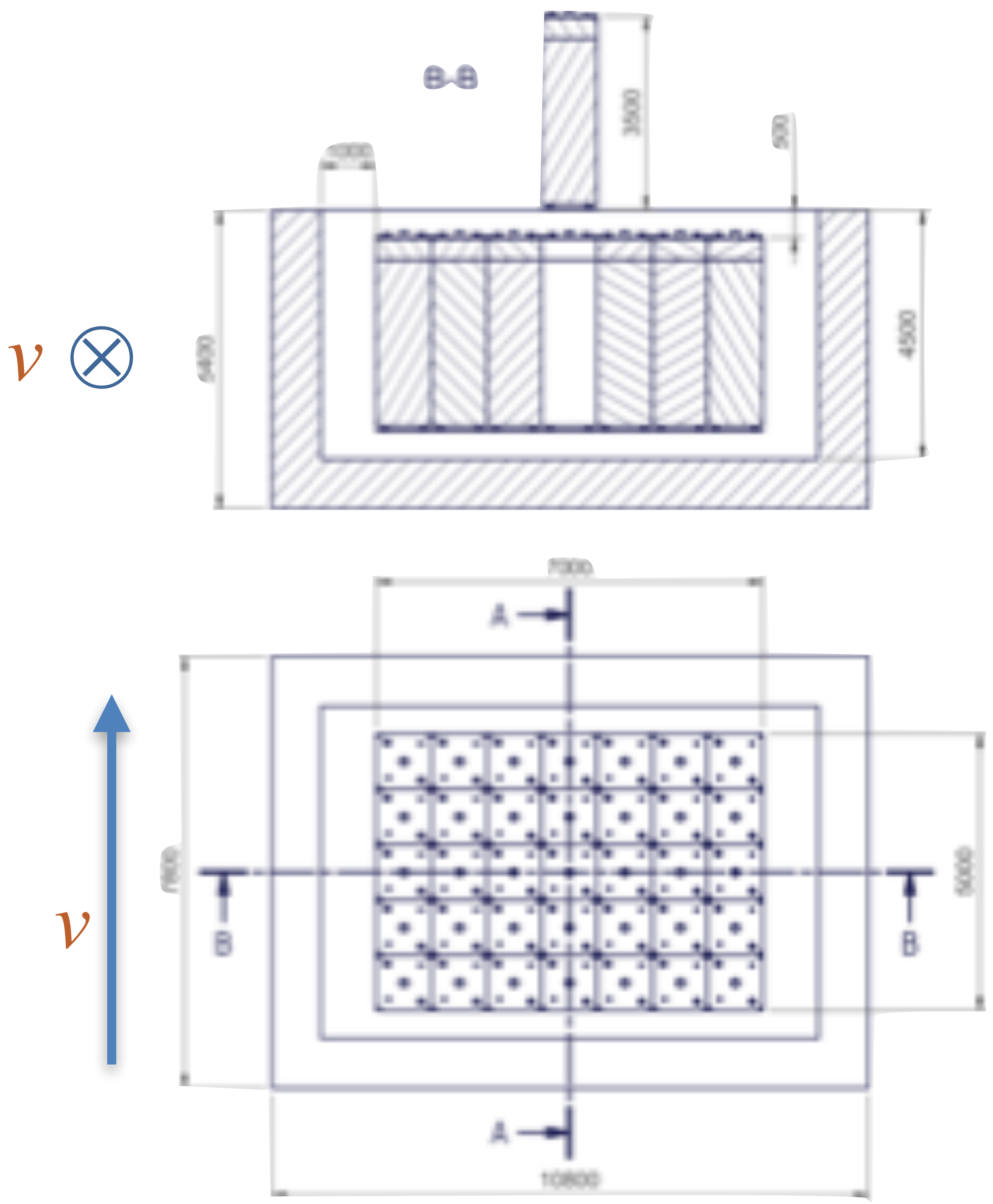
| | Essential Characteristics | Primary Function | Select Physics Aims |
|---|---|---|---|
| **LAr** | Mass<br>Target nucleus (Ar)<br>Technology: FD-like | Experimental control for FD<br>Measure unoscillated $E_\nu$ spectra<br>Flux determination | $\nu_\mu$ ($\bar{\nu}_\mu$) CC<br>$\nu$-e scattering<br>$\nu_e$+$\bar{\nu}_e$ CC<br>$\nu$ interaction model |
| **MPD** | Magnetic field<br>Target nucleus (Ar)<br>Low density<br>Hermeticity | Experimental control for LArTPCs<br>Momentum analyze μ from LAr<br>Measure exclusive final states with low threshold, minimal secondary interactions | $\nu_\mu$ ($\bar{\nu}_\mu$) CC<br>$\nu_e$ ($\bar{\nu}_e$) CC<br>$\nu$ interaction model |
| **3DST-S** | On axis<br>Mass<br>Magnetic field<br>CH target | Neutrino beam monitor<br>Neutron detection | On-axis flux stability<br>$\nu$ interaction model A-dependence<br>$\nu$-e scattering |
| **DUNE-PRISM** | LAr+MPD move off-axis | Change neutrino flux spectrum | Deconvolute flux x σ<br>Energy response<br>Provide FD-like energy spectrum at ND<br>Uncover mismodeling |

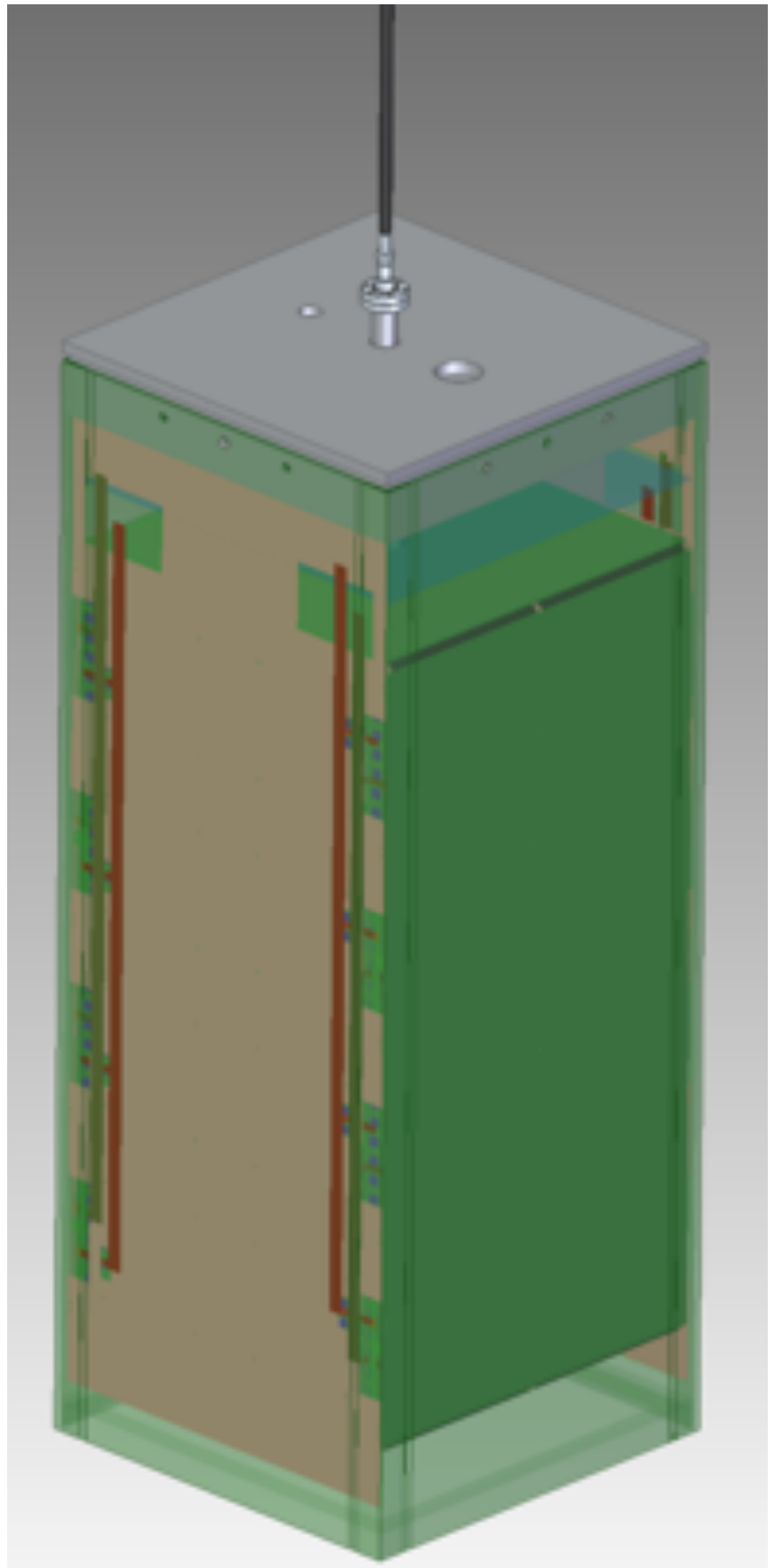
more in
J. Sinclair's talk

# LAR DETECTOR

- Liquid Argon Time Projection Chamber (LArTPC) based on modularized design:
  - Same basic detection principles as DUNE Far Detector
- Detector built from 1 x 1 x 3 m³ self-contained modules
  - two sided-drift with pixel readout proves direct 3D representation of ionization activity
  - optical isolation provides *a priori* localization of scintillation signal
- Full detector is an array of 7 (width) x 5 (depth) modules with a total of ~150 tons of active LAr volume





# LAR: BASIC CONSIDERATIONS

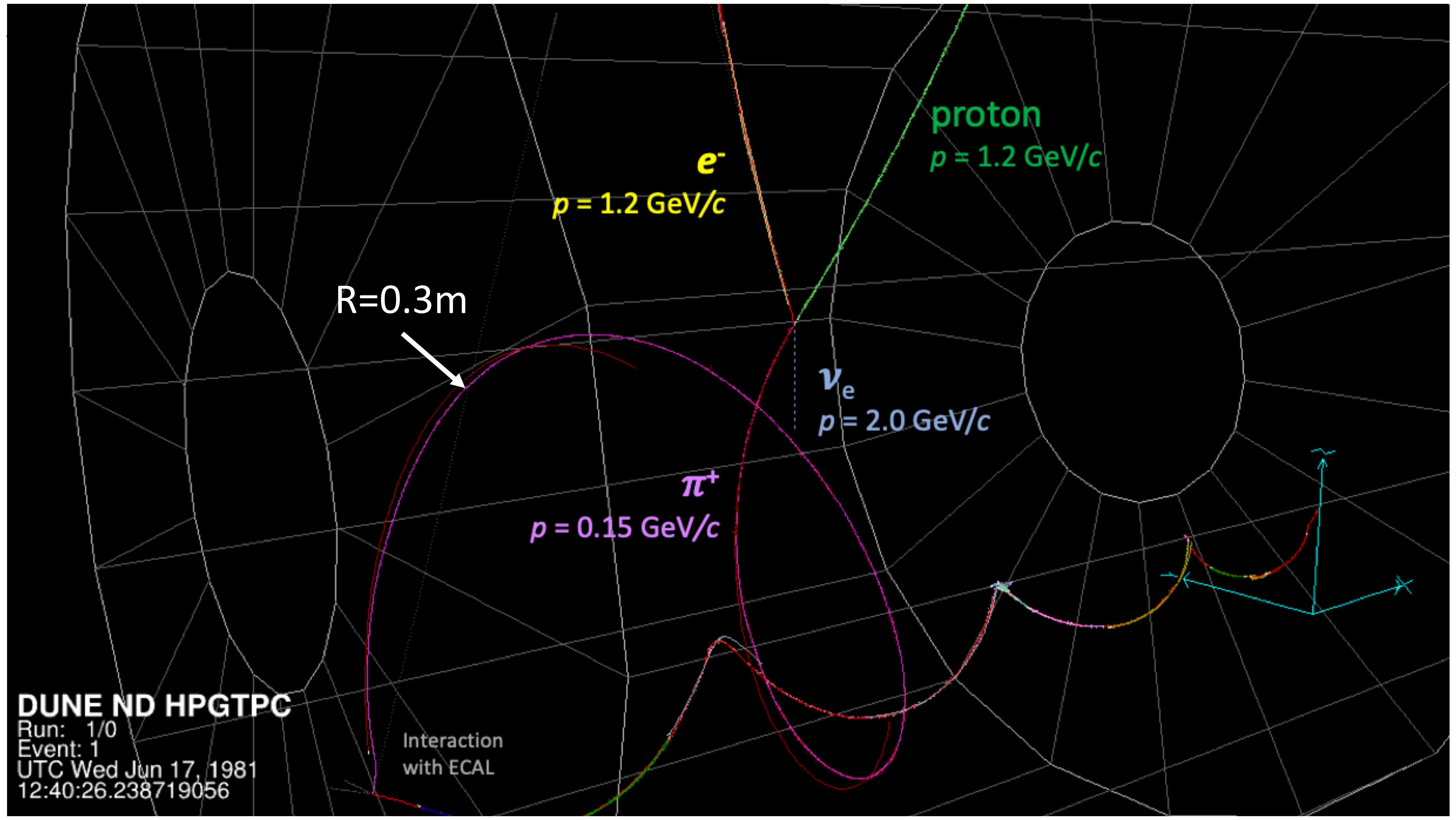
- High rates in the Near Detector Hall
  - Pixelization:
    - Overcome occupancy and ambiguity issues in wire readout detectors
  - Modularization
    - Faster drift and localization of scintillation signal to aid in associating to individual interactions
- Number/size of overall detector
  - Muon momentum reconstruction and hadron containment

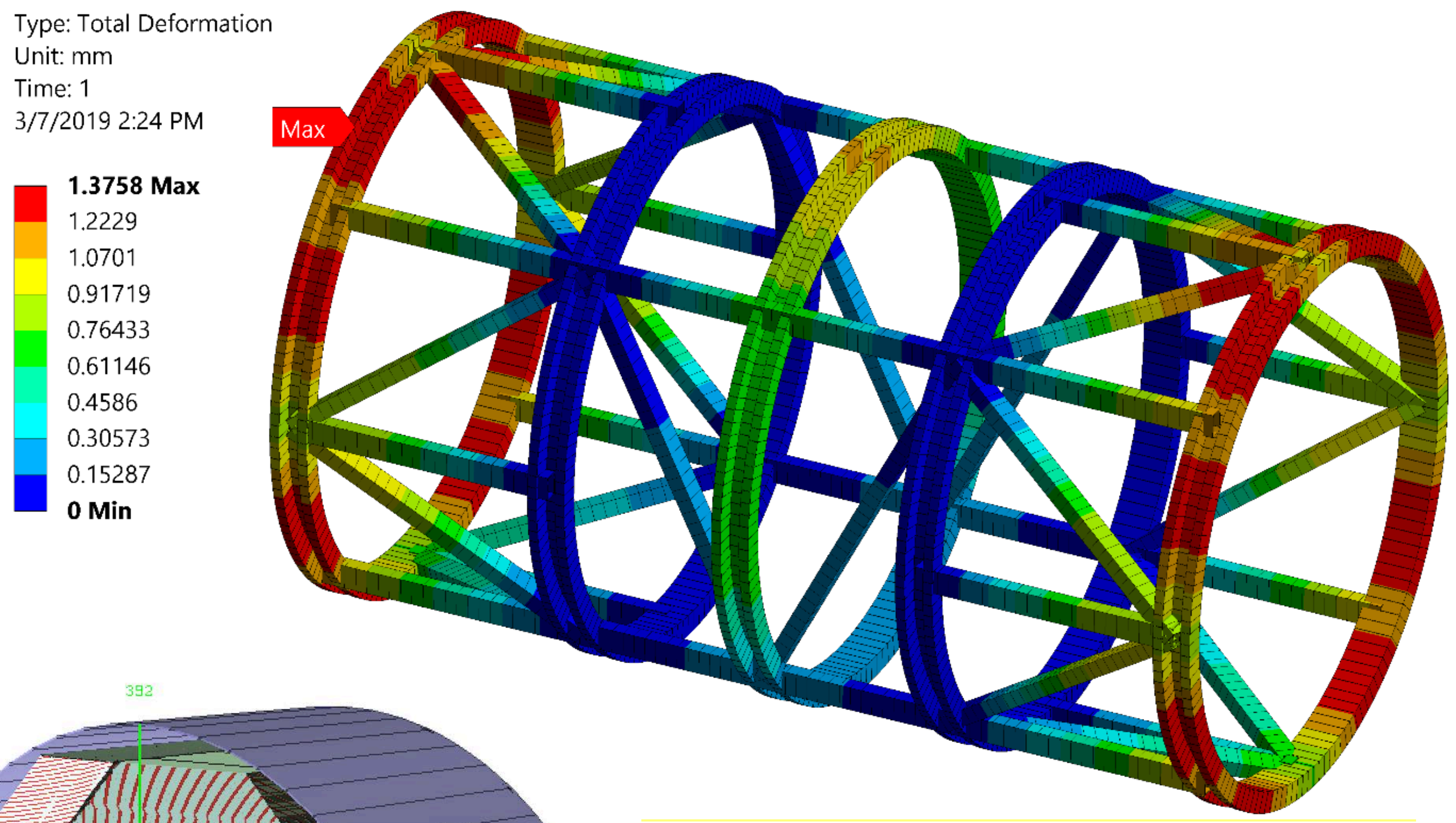
- Primary and most direct view into how events look at FD
- Sufficient mass and capability for flux measurements via $\nu$-e elastic scattering, low-$\nu$

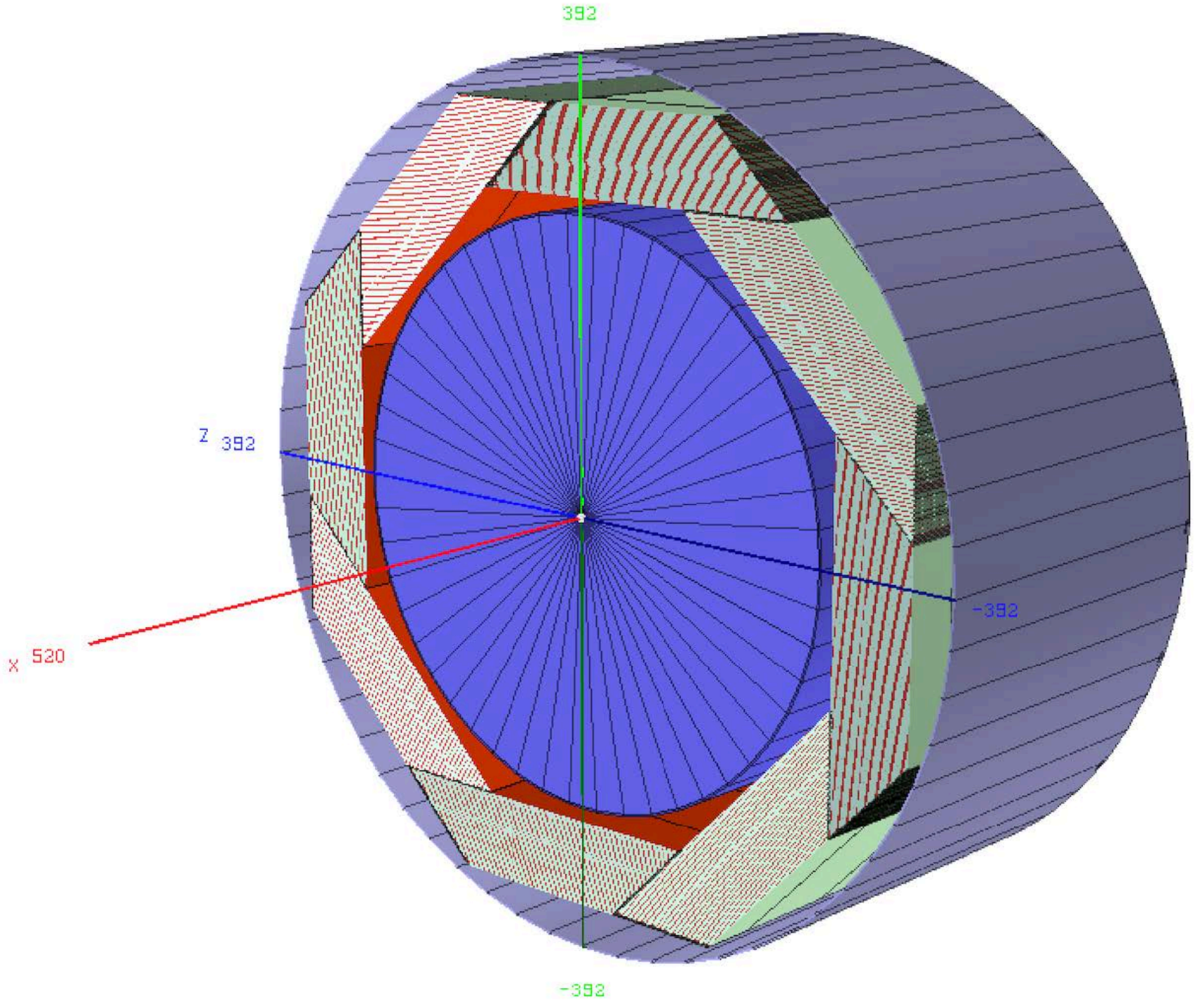
# MULTI-PURPOSE DETECTOR (MPD)

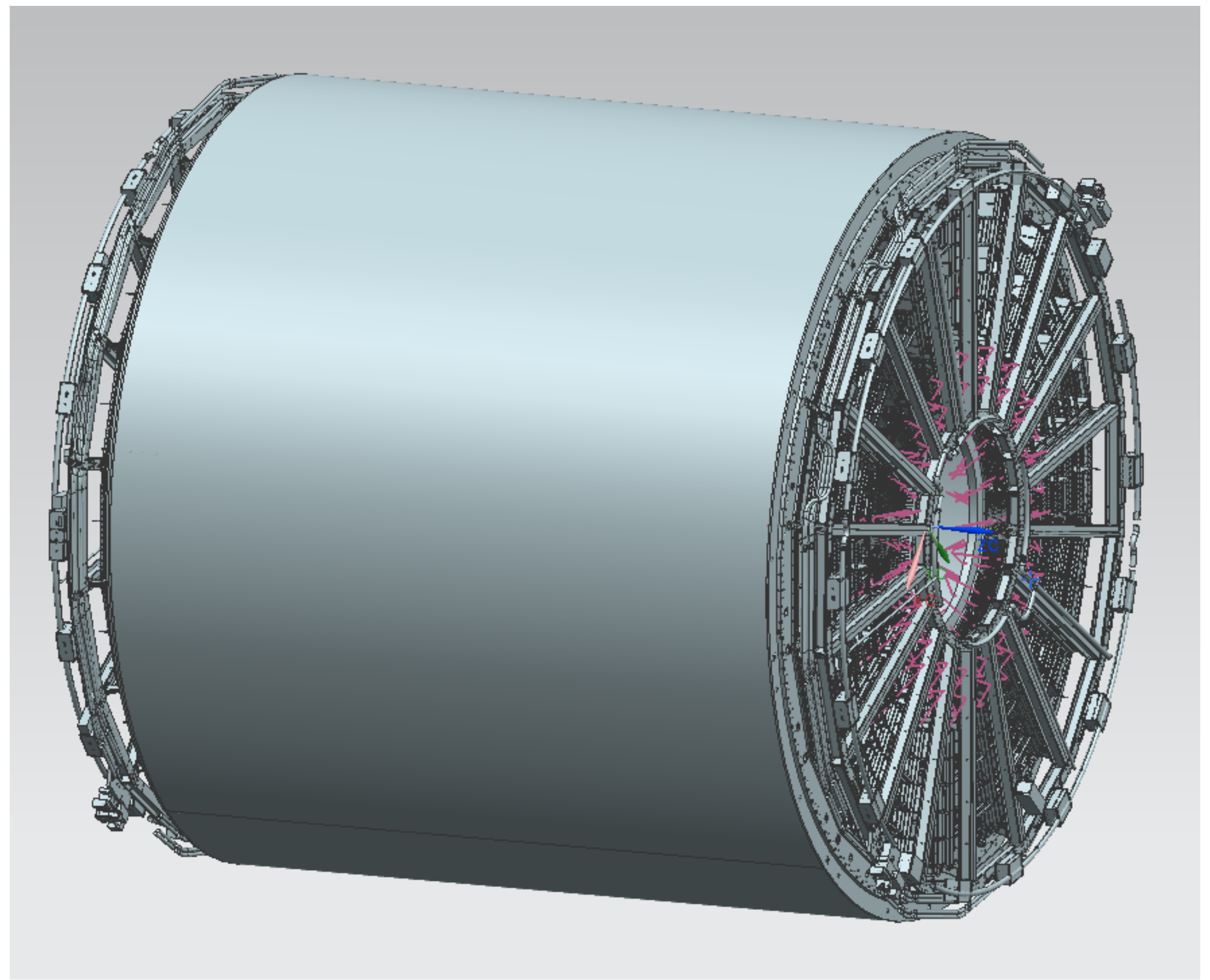
more in
A. Bross's talk

- Magnetized: 0.5 T field
  - 3 coil system with 2 bucking coils to minimize material
- High Pressure (10 Atm) gaseous argon TPC
  - reuse the ALICE design (fully engineered) and readout chambers
  - design and construct new central tracking chamber
- High performance calorimetry surrounding TPC





# MPD: BASIC CONSIDERATIONS

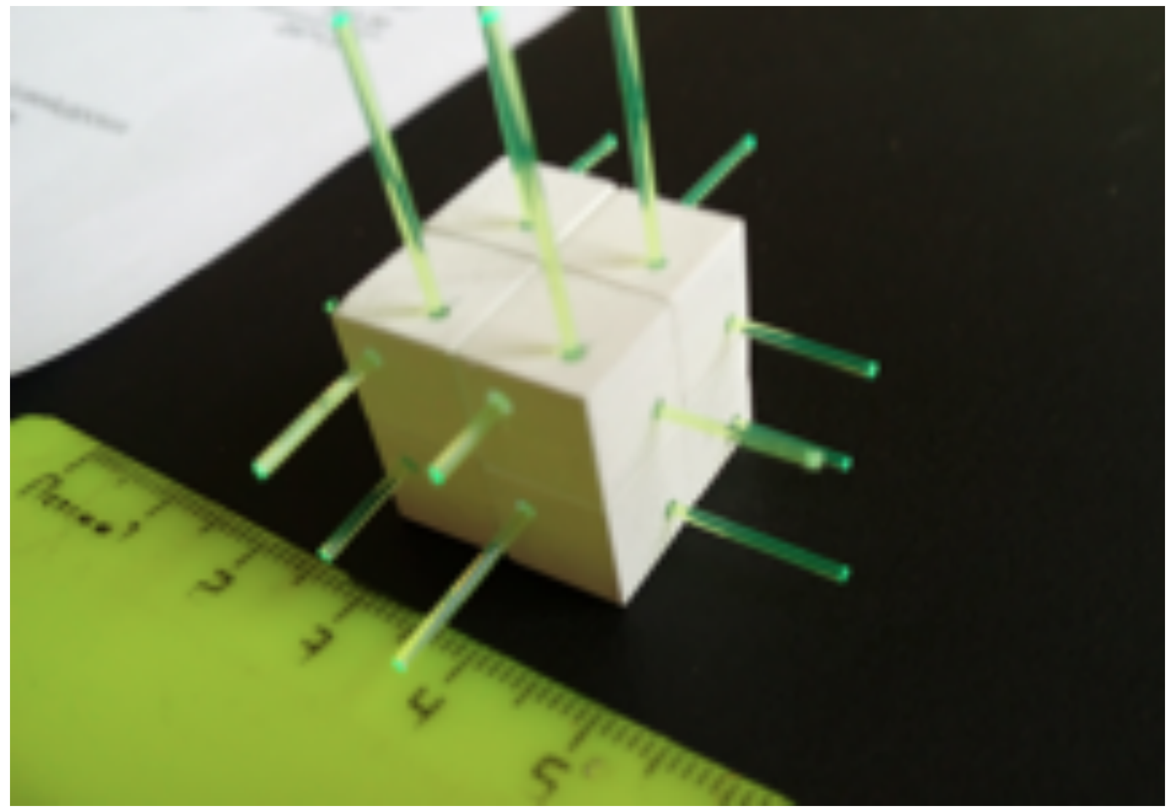
- Downstream muon spectrometer for LAr detector with HPgTPC
  - Acceptance (covers high energy muons coming from LAr)
  - Minimize material between LAr/HPgTPC (Air coil magnet, ribbed pressure vessel, optimize upstream ECAL)
- Observe $\nu$-Ar events with:
  - Sign-selection, magnetic spectrometry
  - Very low tracking thresholds
  - Minimal secondary interactions
- Flavor specific measurements by tagging lepton/sign

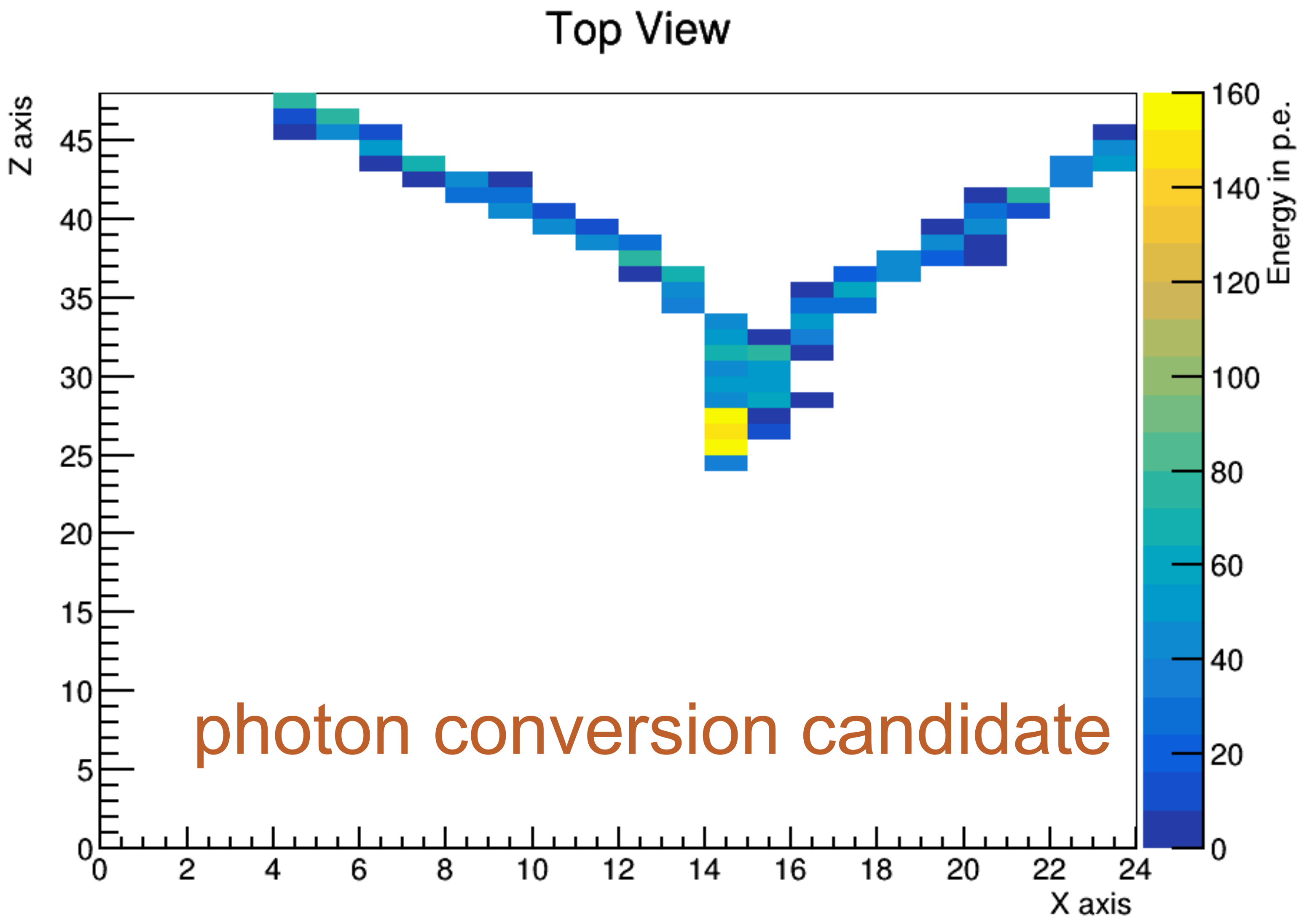
- Fully observe “bare” $\nu$-Ar interactions:
- disentangle: $\nu$-Ar from secondary interactions from detector response
- powerful tool in transferring ND measurements to FD

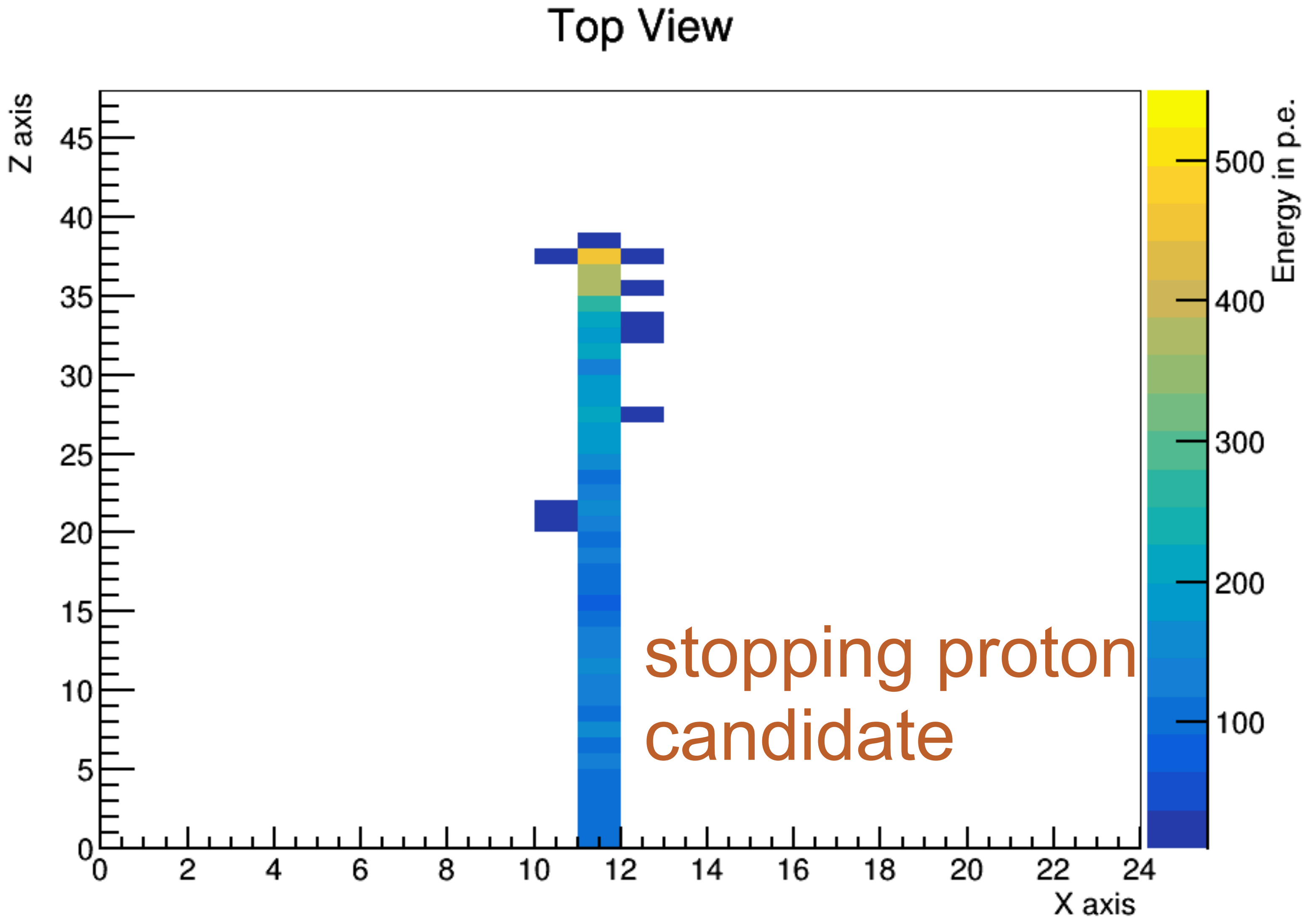
# 3DST-S

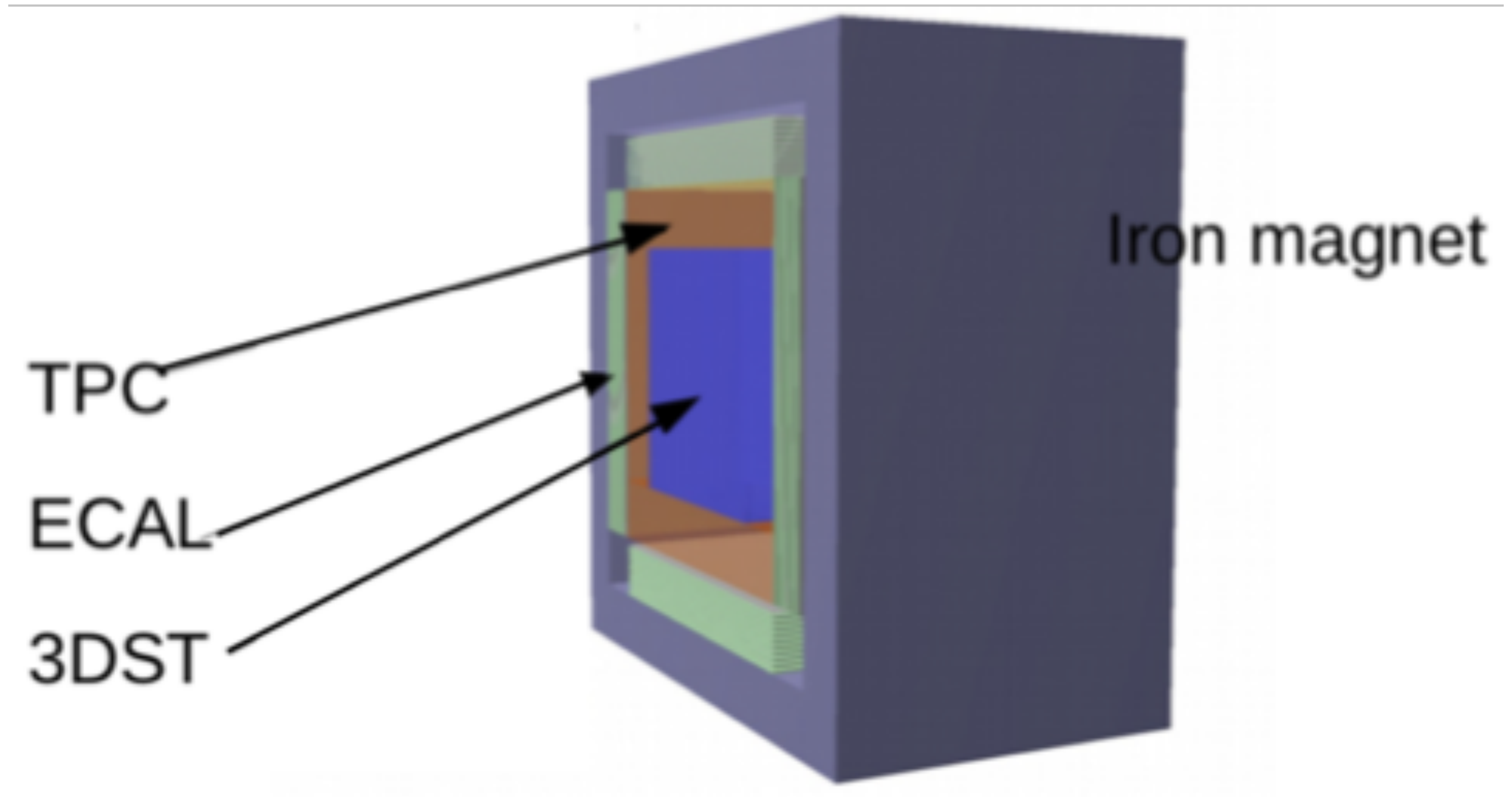
more in
S. Manly's talk

- 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 TPC for tracking and ECAL in magnetic field





# 3DST-S: BASIC CONSIDERATIONS

- On-axis flux monitor
  - sufficient rate, spectrometry capabilities, and transverse span
- Neutron detection
  - New capability in neutrino detectors
  - Nascent capabilities in MINERvA show potential
- $\nu$-CH sample
  - Cross check $\nu$-A modelling across A
  - Connect to “historic” data sets
  - Provides cross check on flux measurements with very different detector technology and capabilities

# BACK TO OVERARCHING REQUIREMENTS

**O0 Predict the neutrino spectrum at the FD:**
The ND must provide a prediction for the energy spectrum of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, and $\bar{\nu}_e$ at the FD. The prediction must be provided as a function of the oscillation parameters and systematic uncertainties must be small enough to achieve the required CP coverage. This is the primary requirement of the DUNE ND.

| | | |
|---|---|---|
| **O0.1** | **Measure interactions on argon** | LAr: very high statistics of $\nu$-Ar interactions using the same detection principles as the FD assisted by the MPD for μ spectrometry.<br>MPD: a very detailed look at the same interactions with additional capabilities (very low thresholds, magnetic spectrometry, etc.). |
| **O0.2** | **Measure the neutrino energy** | Both LAr and MPD have ability to measure neutrino energy in $\nu$-Ar interactions, with complementary methods described in O0.1<br>3DST-S has similar capabilities for $\nu$-CH interactions with additional neutron detection capabilities |
| **O0.3** | **Constrain the cross section model** | LAr + MPD samples as described above<br>Cross checks from 3DST-S on CH with neutron detection<br>O0.6 with LAr + MPD provide powerful variation in underlying energy spectrum to deconvolute the model from the flux. |

# BACK TO OVERARCHING REQUIREMENTS

| | | |
|---|---|---|
| **O0.4** | **Measure neutrino flux** | Primarily LAr detector for $\nu_\mu$ / $\overline{\nu}_\mu$ / ($\nu_e$+$\overline{\nu}_e$)<br>MPD will provide separation into $\nu/\overline{\nu}$<br>3DST-S will provide cross checks with different reconstruction and detection capabilities |
| **O0.5** | **Obtain data with different neutrino fluxes** | DUNE-PRISM will be effected by moving LAr+MPD |
| **O0.6** | **Monitor the neutrino beam** | 3DST-S will provide dedicated measurements on-axis where potential variations are likely to be most visible<br>LAr+MPD can be moved to provide supplemental measurements if needed |

# TOWARDS A CDR REQUIREMENT TABLE

- We proposes hierarchy of requirements working down from the overarching requirements:
- **Overarching (O):**
  - Basic statements of the role/purpose of the near detector in the experiment
  - No reference to individual subsystems of particular implementations
- **Capabilities (C):**
  - Measurements that the ND must make to deliver overarching requirements (e.g. $\nu$-e flux measurement)
  - Refers to subsystem that provide the capability but not the particular implementation
- **Performance (P):**
  - Detector performance (efficiencies, resolution, etc.) needed to deliver the capabilities
  - Refers to specific subsystems and particular implementations as needed
- **Technical (T):**
  - Parameters/other properties (e.g. pixel pitch, magnetic field) specific to detectors to deliver the required performance

# CASE STUDY: BEAM MONITORING

| Label | Name | Description | Driven by | Drives |
|---|---|---|---|---|
| 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. The precise requirement will be informed by the run plan as well as experience from previous experiments. | O0 | |
| C1 | **Monitor the neutrino event rate** | The neutrino event rate must be measured to R% in D days | O0.6 | P1 |
| C2 | **Monitor the neutrino beam direction** | The neutrino beam center in the coordinates transverse to the beam direction must be measured to C cm in D days | O0.6 | P1, P2 |
| C3 | **Monitor the neutrino beam spectrum** | The neutrino event rate must be measured differentially to be sensitive to S% variations in the flux in B neutrino energy bins. | O0.6 | P1, P3 |
| P1 | **Neutrino event rate** | The neutrino beam monitor must detect N neutrino interactions/day | C1, C2, C3 | T1 |
| P2 | **Vertex resolution** | The neutrino beam monitor must resolve neutrino vertices to V cm | C2 | T2 |
| P3 | **Spectrometry** | The neutrino beam monitor must measure muon energy to M% *and hadron energy to H%* | C3 | T3 |

# CONCLUSIONS:

- The DUNE Near Detector Reference design involves three interconnected and complementary subsystems
  - LAr TPC observes $\nu$-Ar interactions based on the same basic detection principles as the Far Detector with enhancements to cope with the high rate environment
  - MPD provides muon spectrometry for the LAr detector and a precise view of the $\nu$-Ar with very low threshold, sign selection, and minimal secondary effects.
  - 3DST-S provides dedicated on-axis monitoring, $\nu$-CH interactions with powerful neutron detection capabilities that can cross check the neutrino model and provide cross checks on the neutrino flux measurement
- The DUNE Near Detector will employ the novel PRISM concept to expose the LAr+MPD system to varying neutrino spectra by moving the detectors off-axis
  - De-convolves the flux and cross section and provides powerful cross checks on the model
- While further study and optimization is needed, we believe this concept is the right one and is plausible in implementation and in meeting the needs of the DUNE physics goals