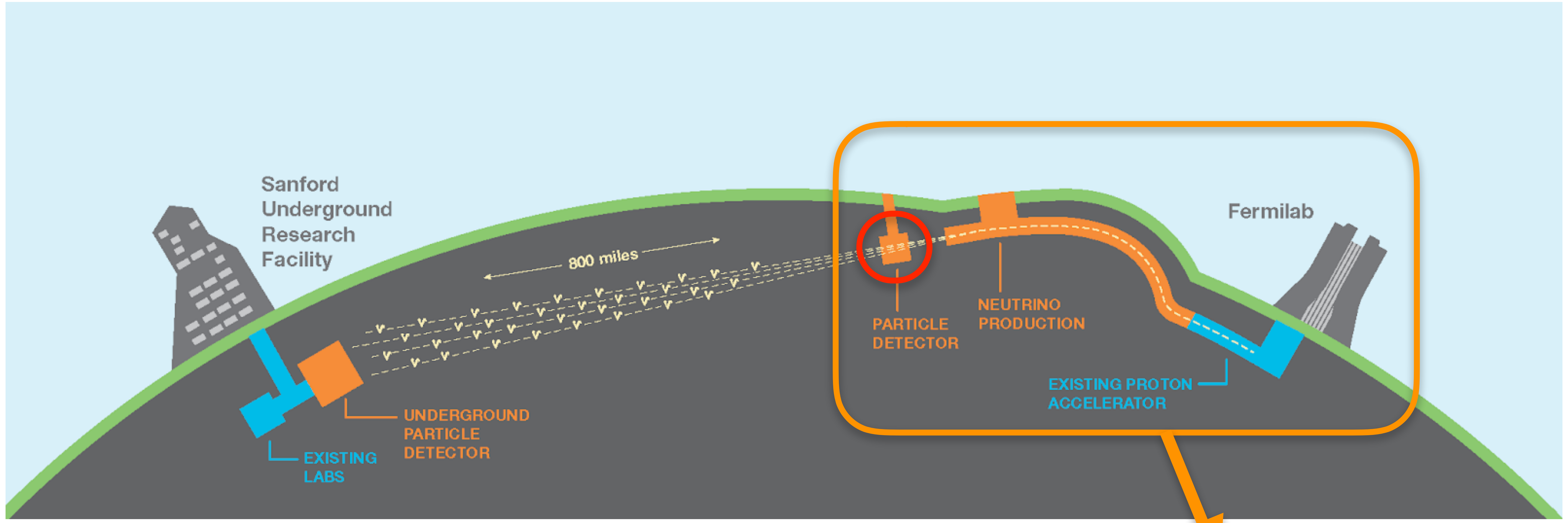
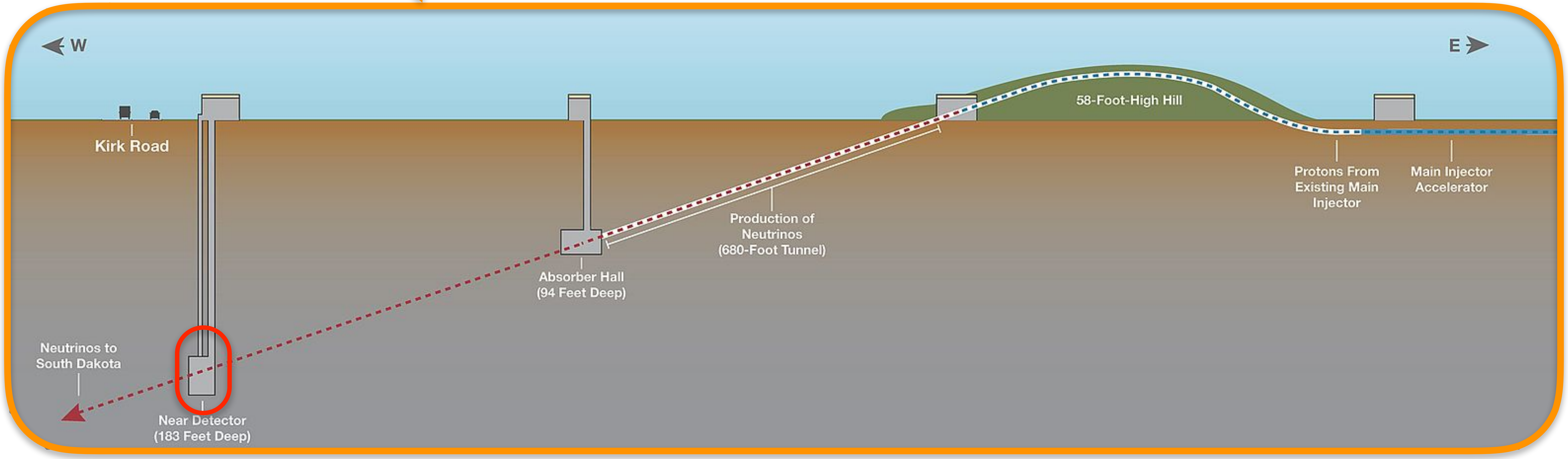
DUNE/LBNF AND THE NEAR DETECTOR

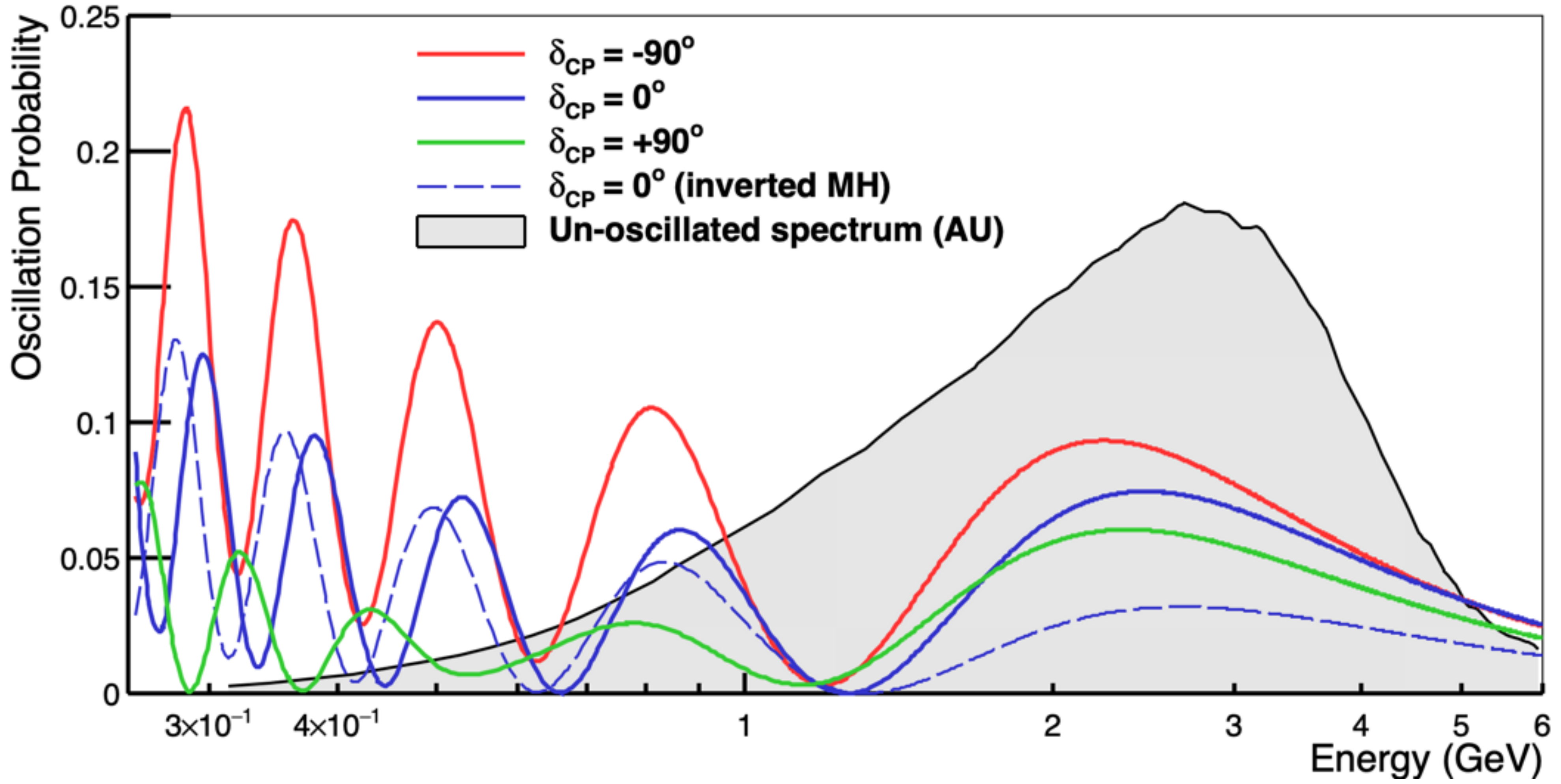


- LBNF sends an intense, broadband $\nu_\mu/\bar{\nu}_\mu$ beam 1280 km from FNAL to the DUNE far detector at SURF in South Dakota
- Near Detector makes measurements 575 m from the production target before (standard) oscillation effects occur

- ~0.2 events/ton/spill at 1.2 MW beam power



PHYSICS AT THE NEAR DETECTOR



Primary purpose: support long-baseline oscillation measurements:

- Predict rate/energy spectrum of $\nu_{\beta=\mu,e}$ interactions from initial ν_μ beam after traveling 1285 km to the far detector as a function of neutrino mixing parameters:

$$N^{\rm far}_{\nu_\beta}(E_{rec}) = \int dE_\nu \; P_{\nu_\mu\to\nu_\beta}(E_\nu) \times \phi^{\rm near}_{\nu_\mu} \times F_{\rm far/near}(E_\nu) \times \sigma^{\rm Ar}_{\nu_\beta}(E_\nu) \times D^{\rm far}_{\nu_\beta}(E_\nu, E_{rec})$$

$P(\nu_\mu \to \nu_\beta)$: the probability for ν_μ to oscillate to ν_β

$\phi_{\nu_\mu}{}^{near.}$: flux of ν_μ at near detector

$F_{far/near.}$: ratio of ν_μ flux between far/near detectors

$\sigma_{\nu_\beta}{}^{Ar.}$: cross section for ν_β

$D_{\nu_\beta}{}^{far}(E_\nu, E_{rec})$: Efficiency/migration of ν_β with energy E_ν to be reconstructed as E_{rec}

Each element of the convolution (except oscillation probability) has significant uncertainty that must be constrained by the near detector

At the near detector, we observe:

$$N^{\rm near}_{\nu_\beta}(E_{rec}) = \int dE_\nu \; \phi^{\rm near}_{\nu_\mu} \times \sigma^{\rm Ar}_{\nu_\beta}(E_\nu) \times D^{\rm near}_{\nu_\beta}(E_\nu, E_{rec})$$

- constrain elements of the convolution to reduce systematic uncertainties ($\phi_{\nu_\mu}{}^{near}$, $\sigma_{\nu_\beta}{}^{Ar}$, $D_{\nu_\beta}{}^{far}(E_\nu, E_{rec})$)
- High statistics monitoring to constrain neutrino beam variations that impact $F_{far/near}$

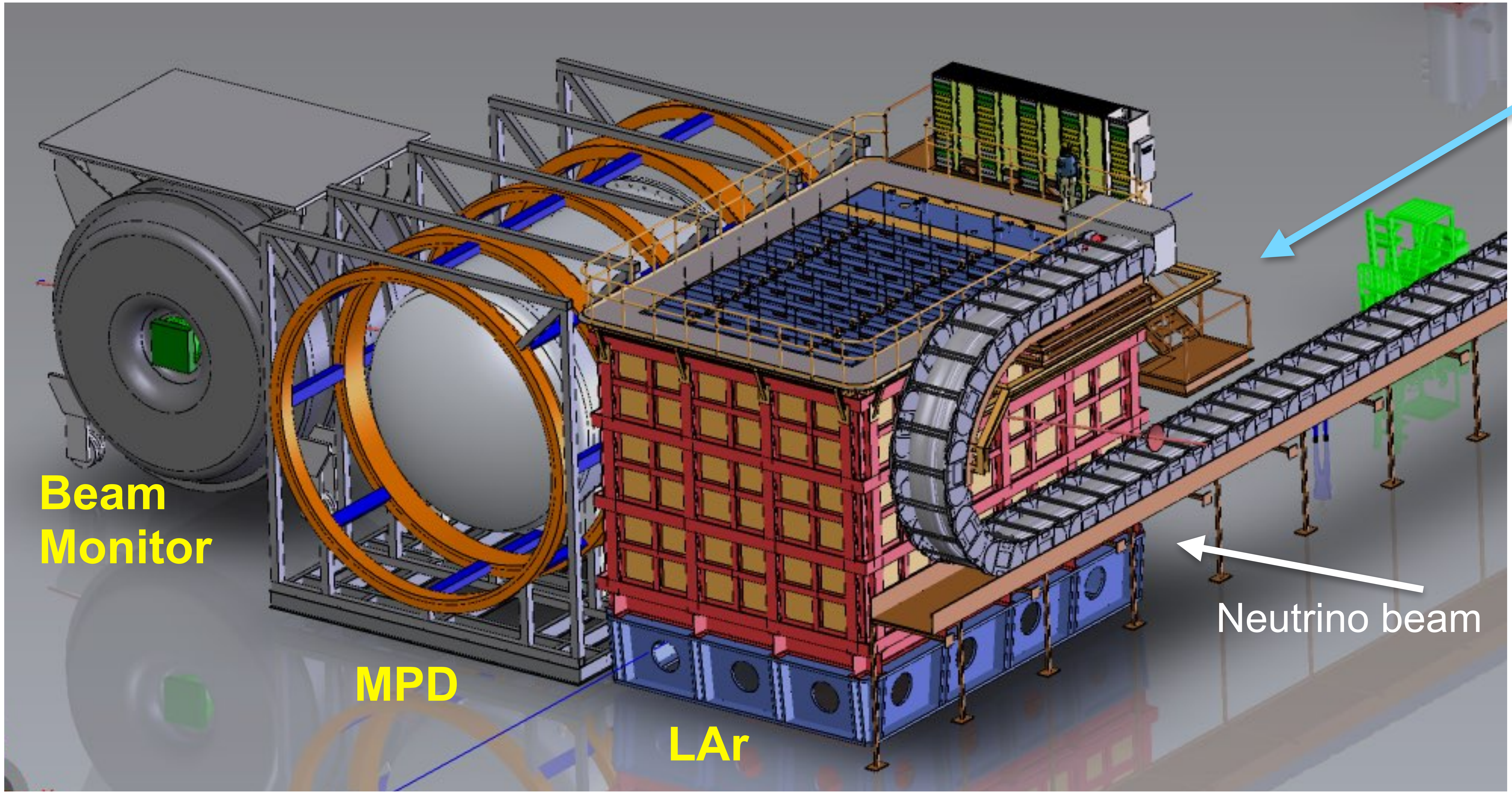
High statistics, powerful detectors allow many other physics studies

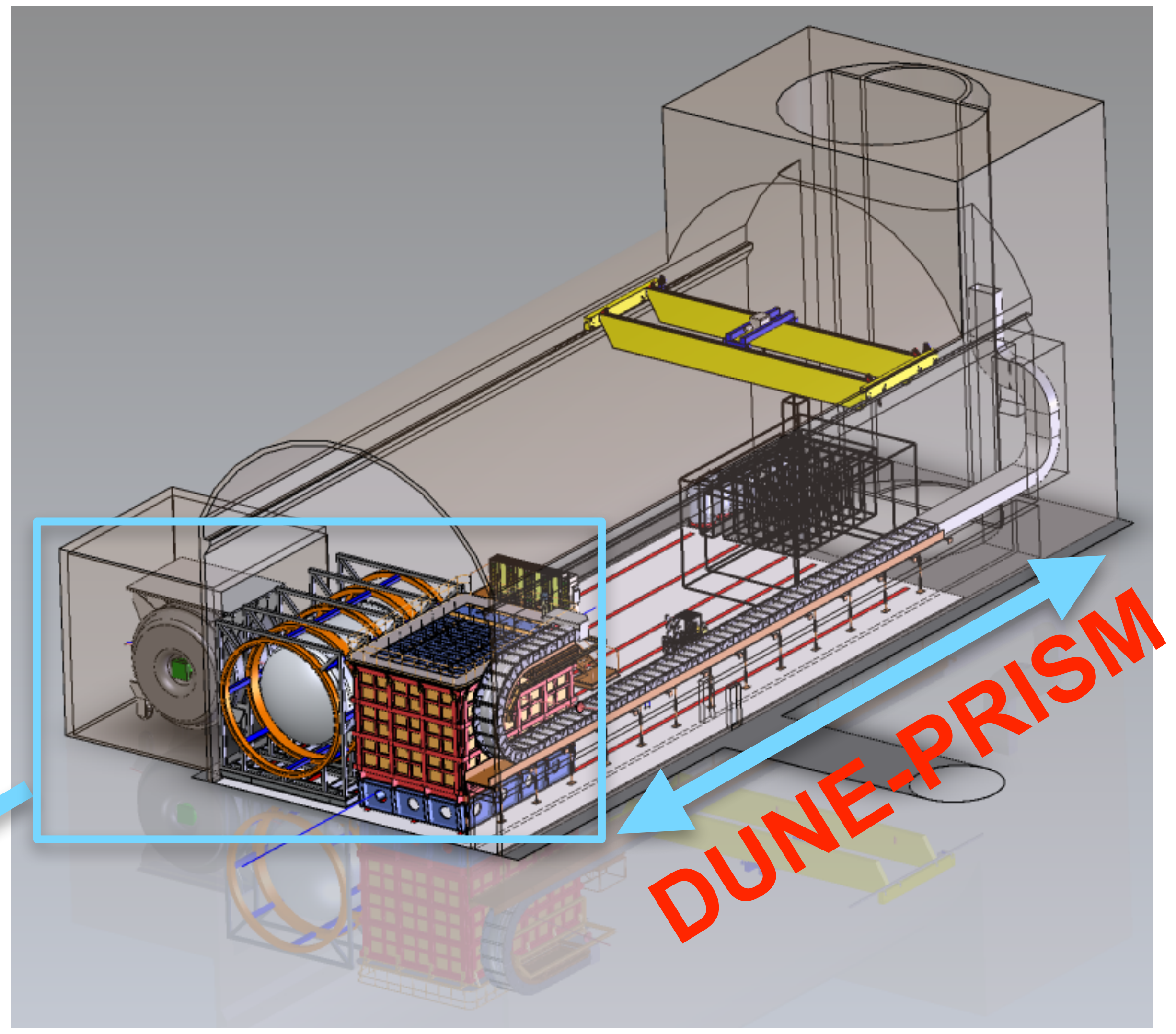
- Exotic physics (dark sector searches, non-standard neutrino properties . .)
- Neutrino-nucleus interaction studies
- . . . .

OVERARCHING REQUIREMENTS

O0 Predict the neutrino spectrum at the FD (Far Detector): 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 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 and transfer them 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 including potential mismodeling that causes incorrect FD predictions.
O0.4	**Measure neutrino flux**	Measure neutrino fluxes as a function of flavor and neutrino energy to enable neutrino cross-section measurements to be made and constraint the beam model
O0.5	**Obtain data with different neutrino fluxes**	Measure neutrino interactions in different beam fluxes (especially with different mean energies) to disentangle flux and cross-sections, verify the beam model, and guard against systematic uncertainties.
O0.6	**Monitor the neutrino beam**	Monitor the neutrino beam energy spectrum with sufficient statistics to be sensitive to changes in the beam on short timescales.

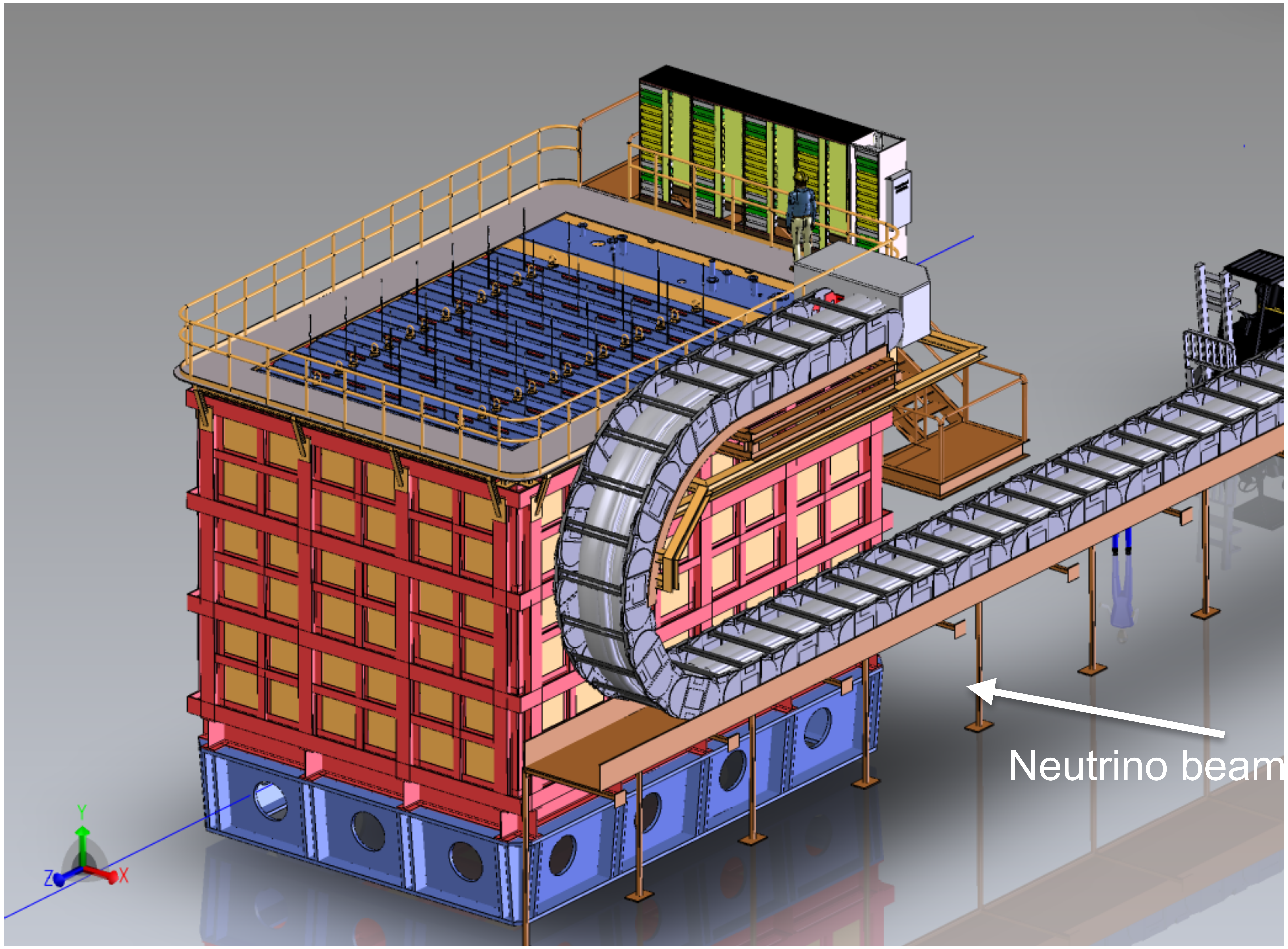
OVERALL SYSTEM:

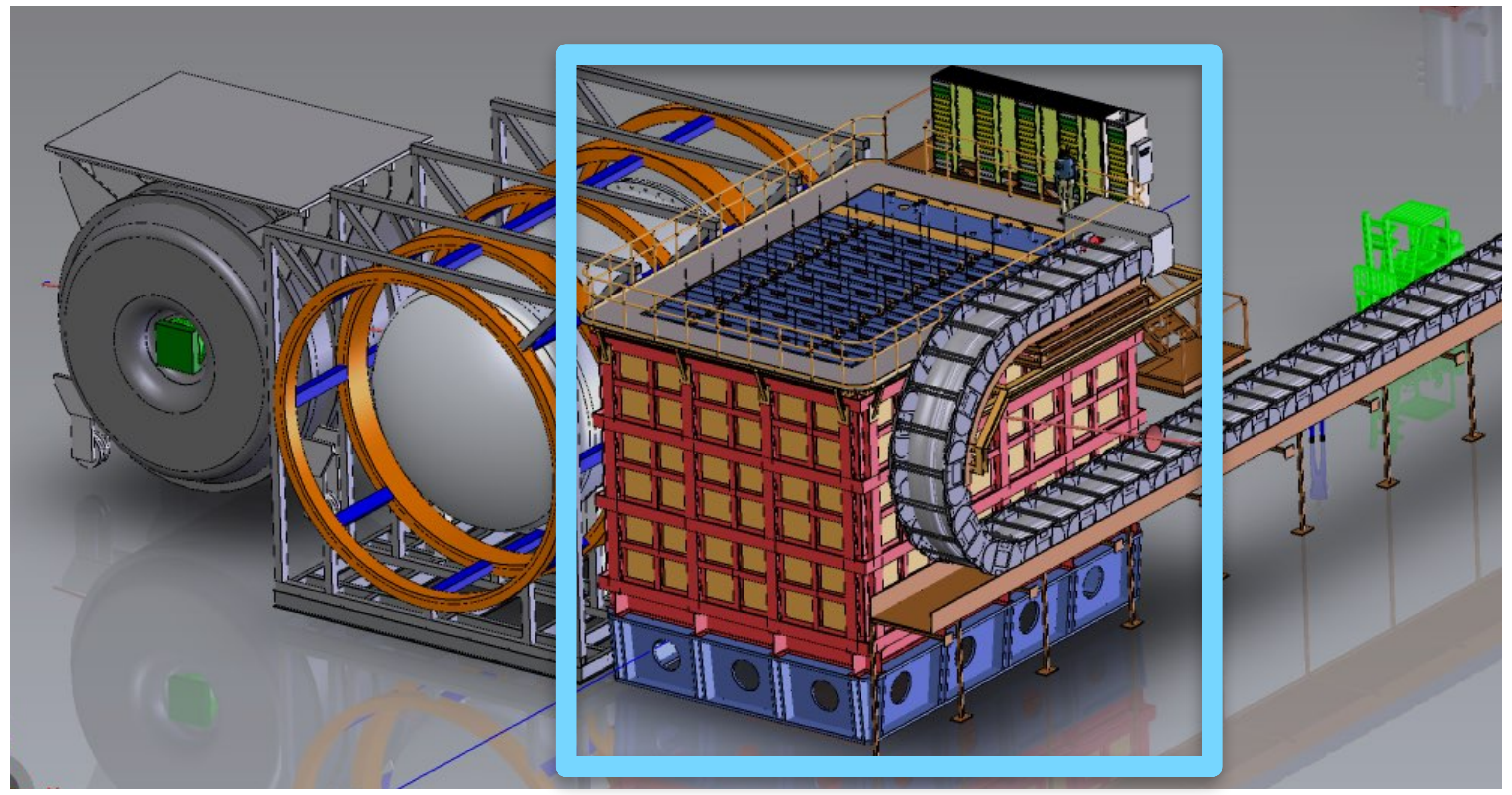




- **LAr:** Array of Liquid Argon TPC modules
- **MPD:** High Pressure Gas Argon TPC, Calorimeter, and muon system magnetized by superconducting coils
- **Beam Monitor:** High density plastic scintillator detector with tracking chambers and calorimetry in KLOE magnet
- **DUNE-PRISM:** Movement of LAr+MPD transverse to the beam to observe interactions at different off-axis positions/spectra

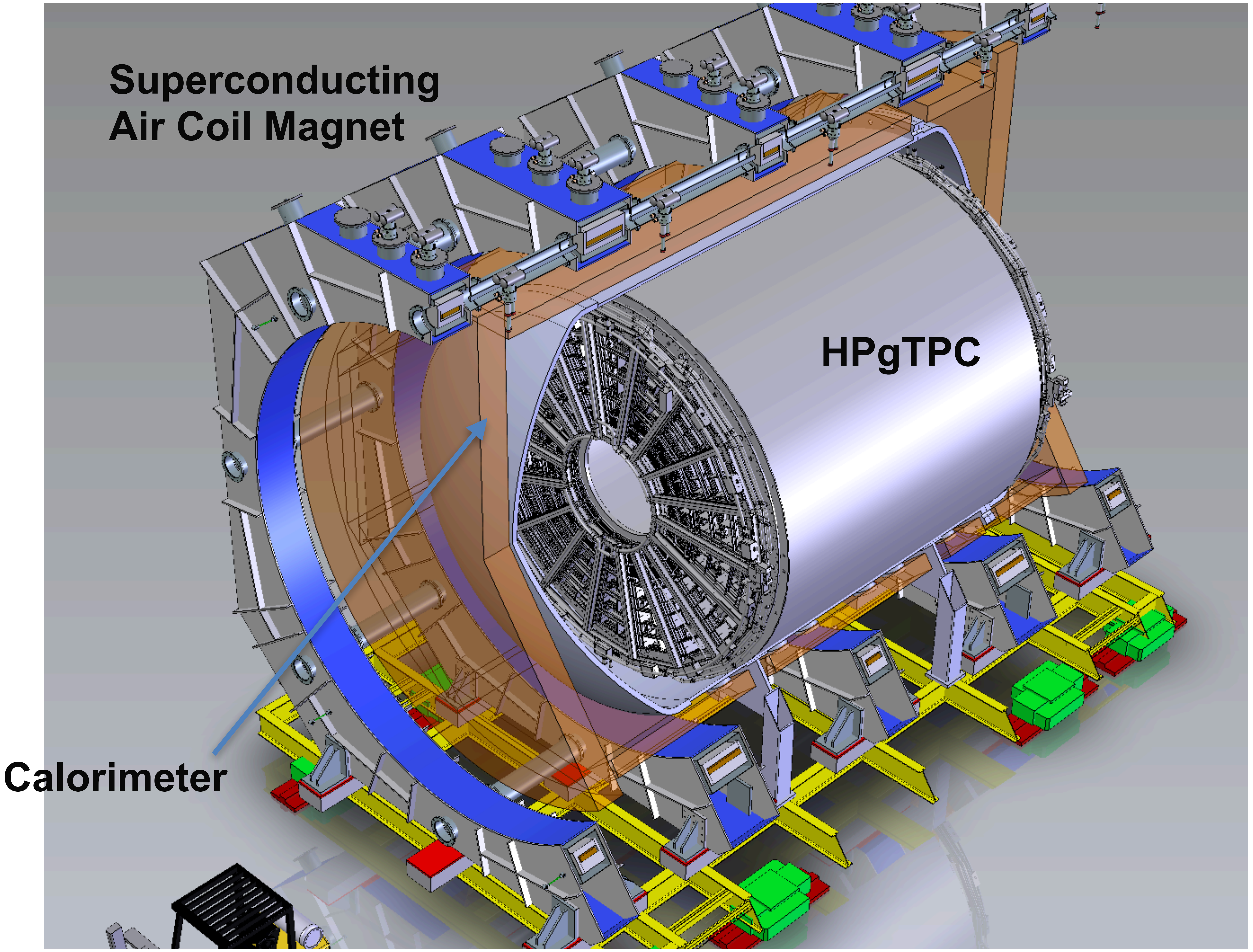
LAr

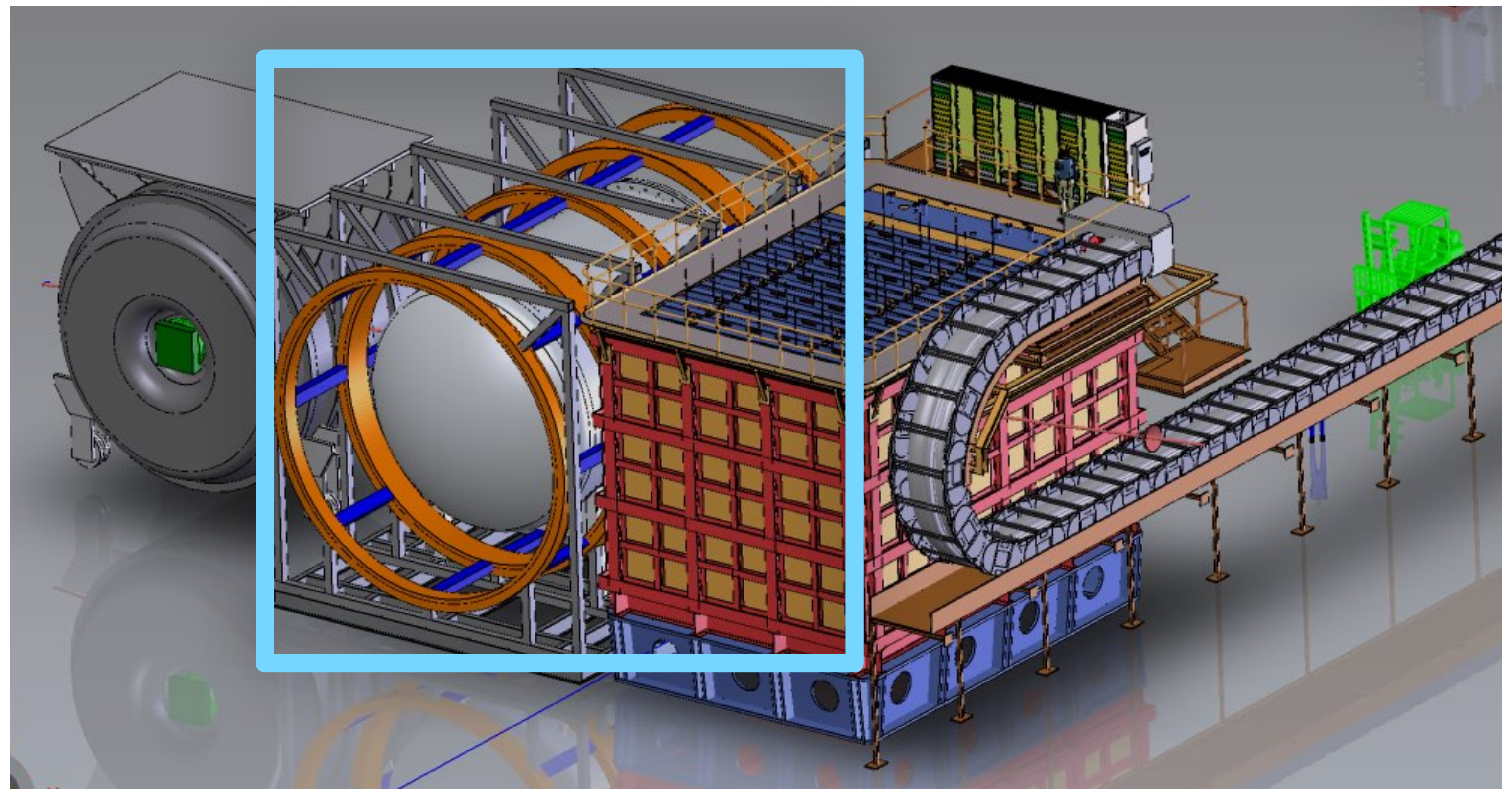




- **Optimization for high rate environment**
  - Same detection principles as FD to allow systematic studies and error reduction based on ArgonCube concept
- **7x5 array of 1x1x3 m³ LArTPC modules with:**
  - **~50 tons of LAr**
  - **Two-sided drift (~50 cm) within module:**
    - cathode plane parallel to beam axis
    - faster readout of ionization signals
  - **Pixel readout planes**
    - image ionization activity directly in 3 dimensions
  - **Optical isolation**
    - LAr scintillation light is localized within module
  - Requires a downstream spectrometer to measure sign/ momentum of muons exiting the detector system
    - → **MPD**
  - Moves transverse to beam lime
    - → **DUNE-PRISM**

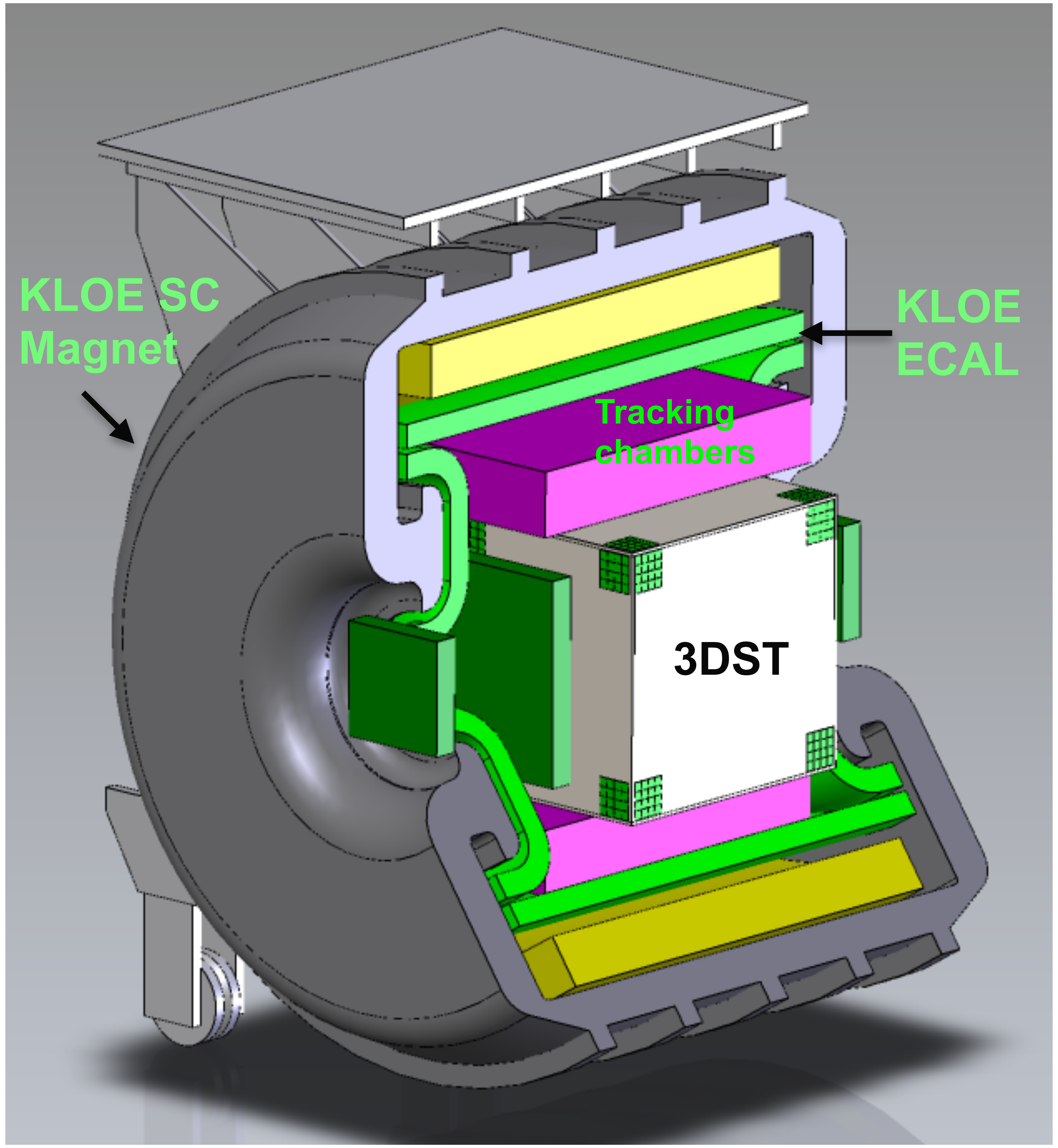
Multi Purpose Detector (MPD)

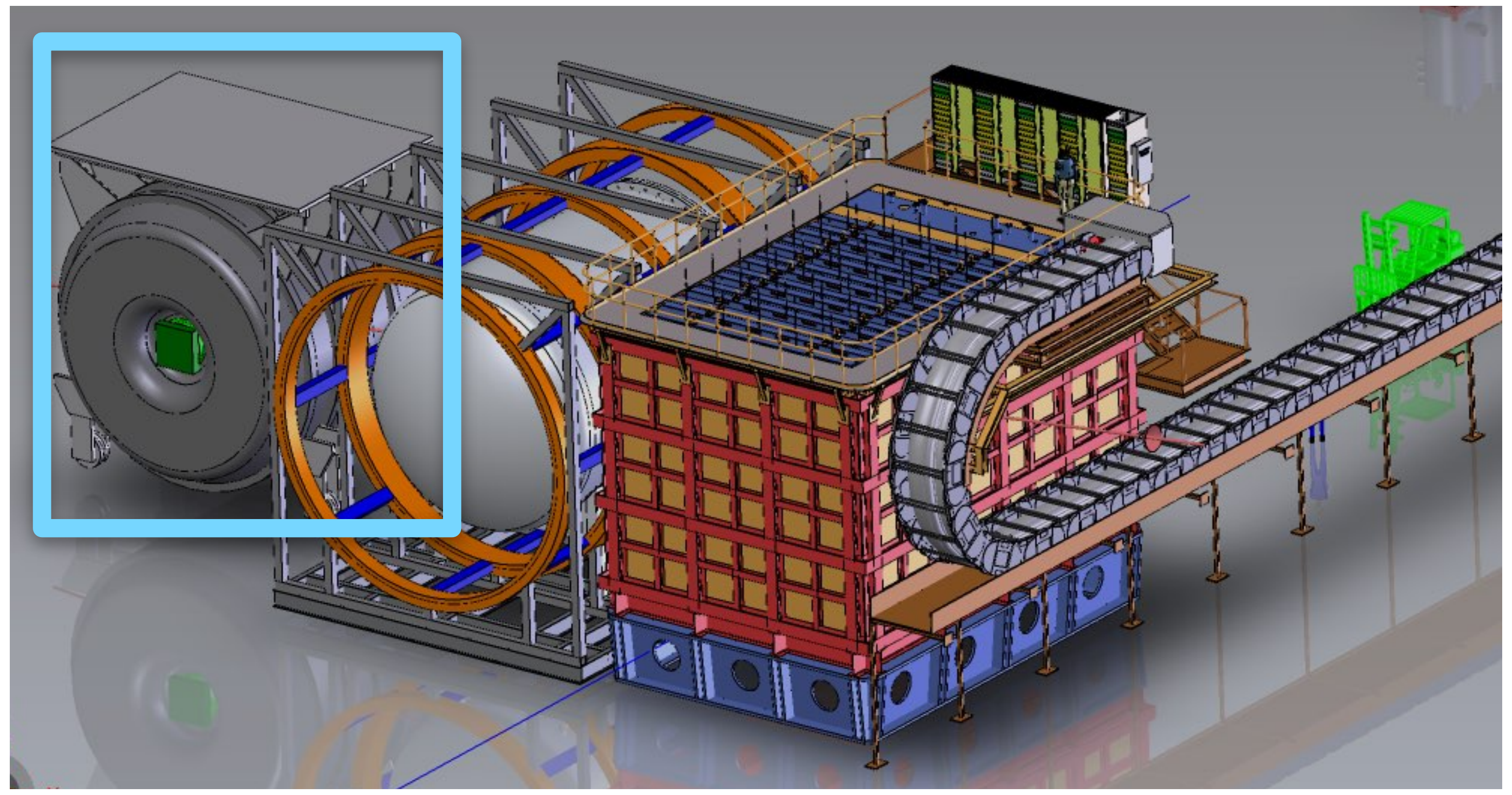




- **Provide downstream muon spectrometry for LAr**
- **Observe ν-Ar interactions with very low tracking thresholds, sign selection, minimal secondary interactions, full geometric acceptance.**
- **Components:**
  - **Superconducting Air Coil Magnet (0.6 T)**
    - Minimize material between LAr and MPD to allow precise muon momentum/sign measurements
  - **High Pressure Gas Ar TPC (HPgTPC)**
    - ~1 ton of argon in 10 Atm., reuse ALICE readout chambers
  - **Electromagnetic Calorimeter (not shown)**
    - Identify neutral particles exiting HPgTPC
    - Tile/bar scintillator array with radiator layers (e.g. brass) surrounding HPgTPC read out with SiPM (CALICE concept)
  - **Muon Detectors (not shown)**
    - Resistive Plate Chamber (RPCs)?
- **Moves transverse to beam lime**
  - **→ DUNE-PRISM**

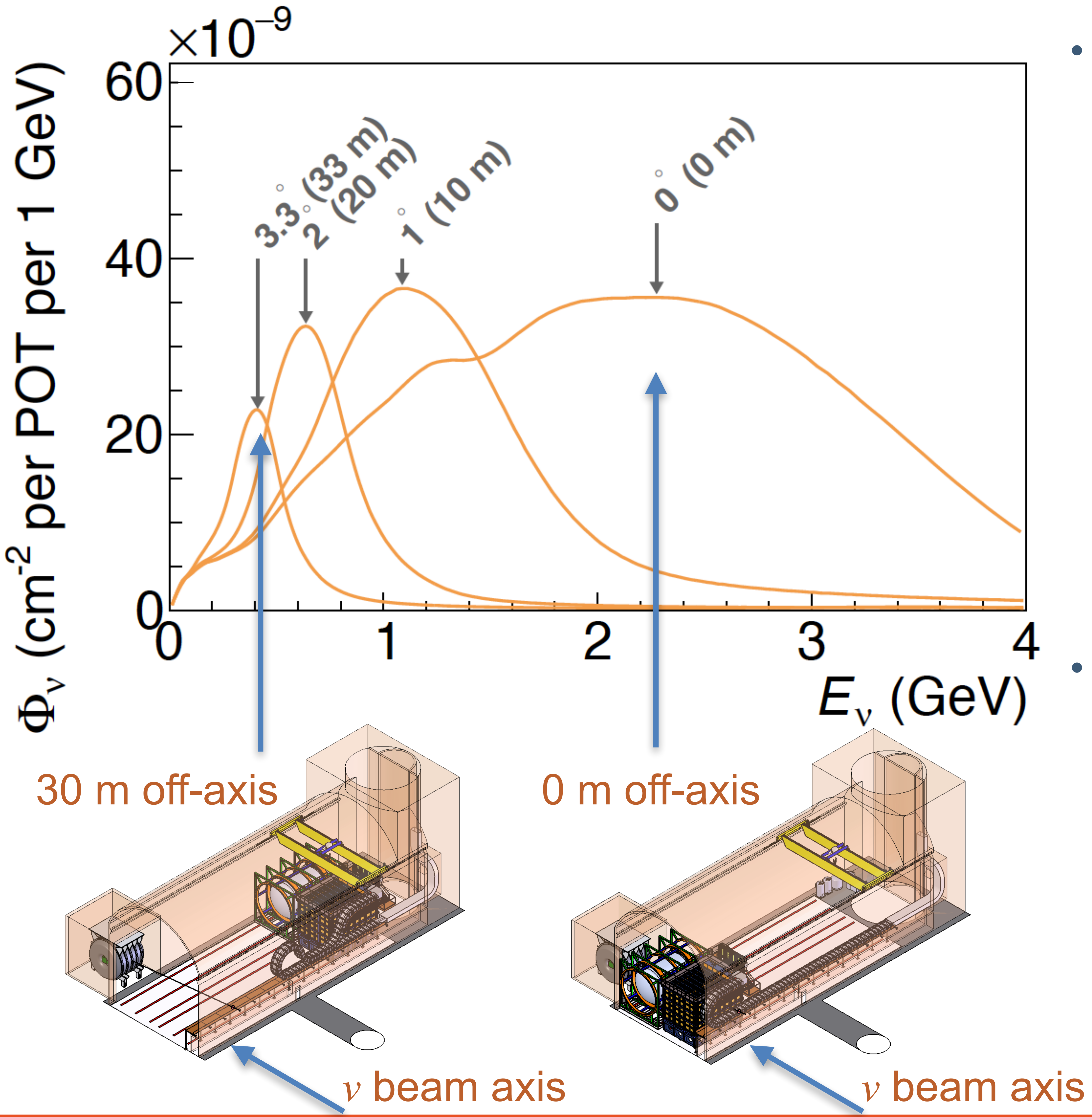
Beam Monitor





- **On-axis monitoring of neutrino beam with rate, profile, spectrum measurements**
- **Observe neutrino interactions on CH target with fast O (1 ns) timing**
- **Components:**
  - **KLOE Superconducting Magnet (0.6 T)**
  - **3DST scintillator target**
    - Array of 1x1x1 cm^3 scintillator cubes (8 ton), provide native 3D reconstruction
    - Neutron detection and reconstruction through time-of-flight
  - **Low-density Tracking Chambers**
    - Provide sign/momentum measurements of tracks exiting 3DST
    - Gaseous Time Projection chambers? Straw Tubes?
  - **KLOE lead/fiber electromagnetic calorimeter**
    - Matrix of lead/fiber surrounding tracking region
    - Provides tracking of electromagnetic showers and precise timing.
  - **Fixed in on-axis location**

DUNE-PRISM



- Neutrino beam spectrum varies as one moves "off-axis" transversely from the beam center:
  - Energy spectrum moves towards lower energies and narrows.
  - Neutrino energy, is a fundamental variable in neutrino oscillation effects:
    - Is *a priori* unknown for a given event and must be reconstructed (E_{rec})
    - E_{rec} is highly model dependent and as a distribution, embedded within a convolution over the entire (true) neutrino energy spectrum (E_ν):

$$N^{\rm near}_{\nu_\beta}(E_{rec}) = \int dE_\nu \; \phi^{\rm near}_{\nu_\mu} \times \sigma^{\rm Ar}_{\nu_\beta}(E_\nu) \times D^{\rm near}_{\nu_\beta}(E_\nu, E_{rec})$$

- DUNE-PRISM:
  - Movement of LAr+MPD to collect data up to 33 m off-axis with varying energy spectra
  - Independent handle on E_ν
    - Comparison of data at different off-axis angles can constrain E_ν dependence of observables such as E_{rec}
  - Breaks degeneracies in the convolution observed in a single measurement
    - Resolves potentially dangerous systematic uncertainties that may lead to biased extracted oscillation parameters.