DUNE
Near Detector Overview

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for the DUNE ND Design Group

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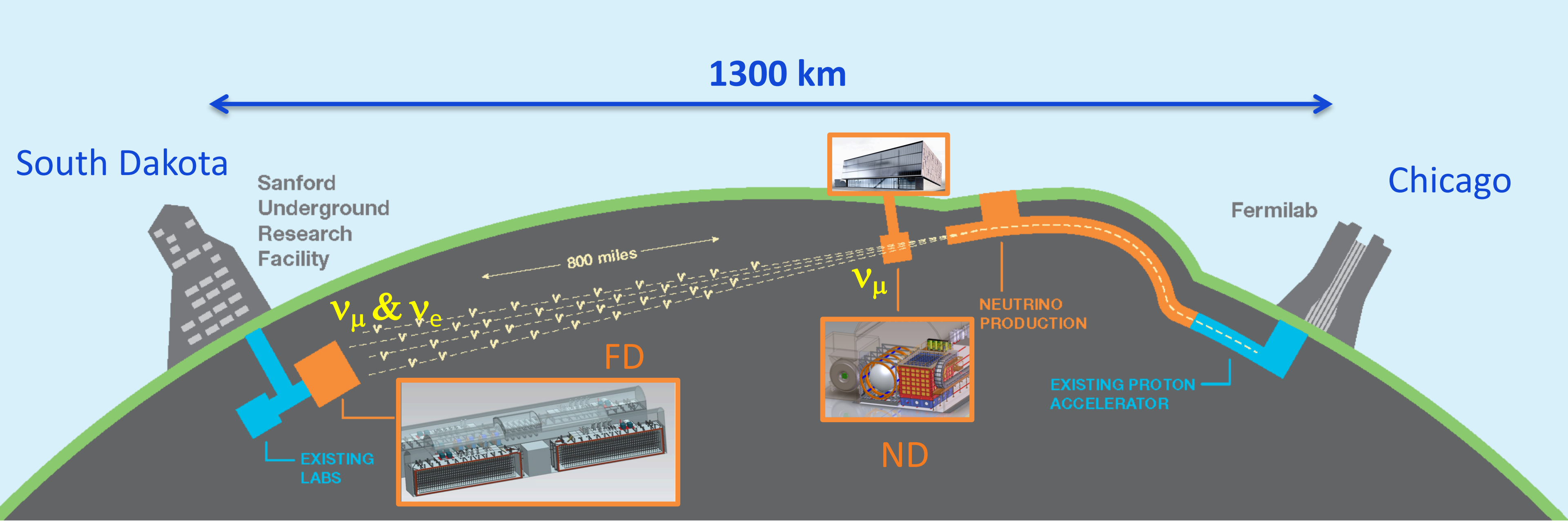
UNIVERSITY OF OXFORD

UKRI Science and Technology Facilities Council

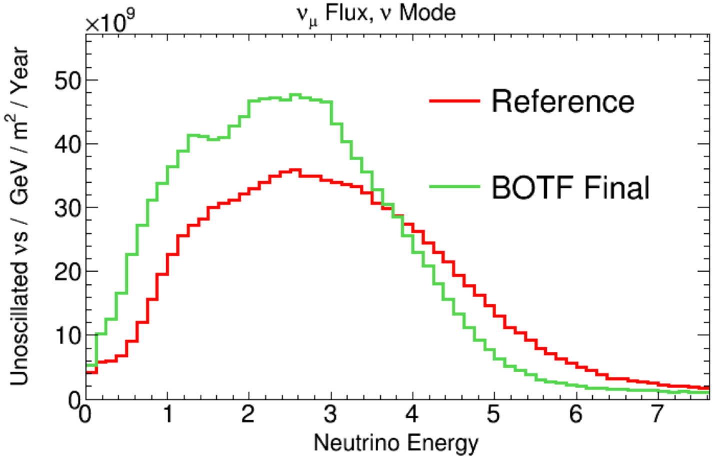
DUNE

General Setup

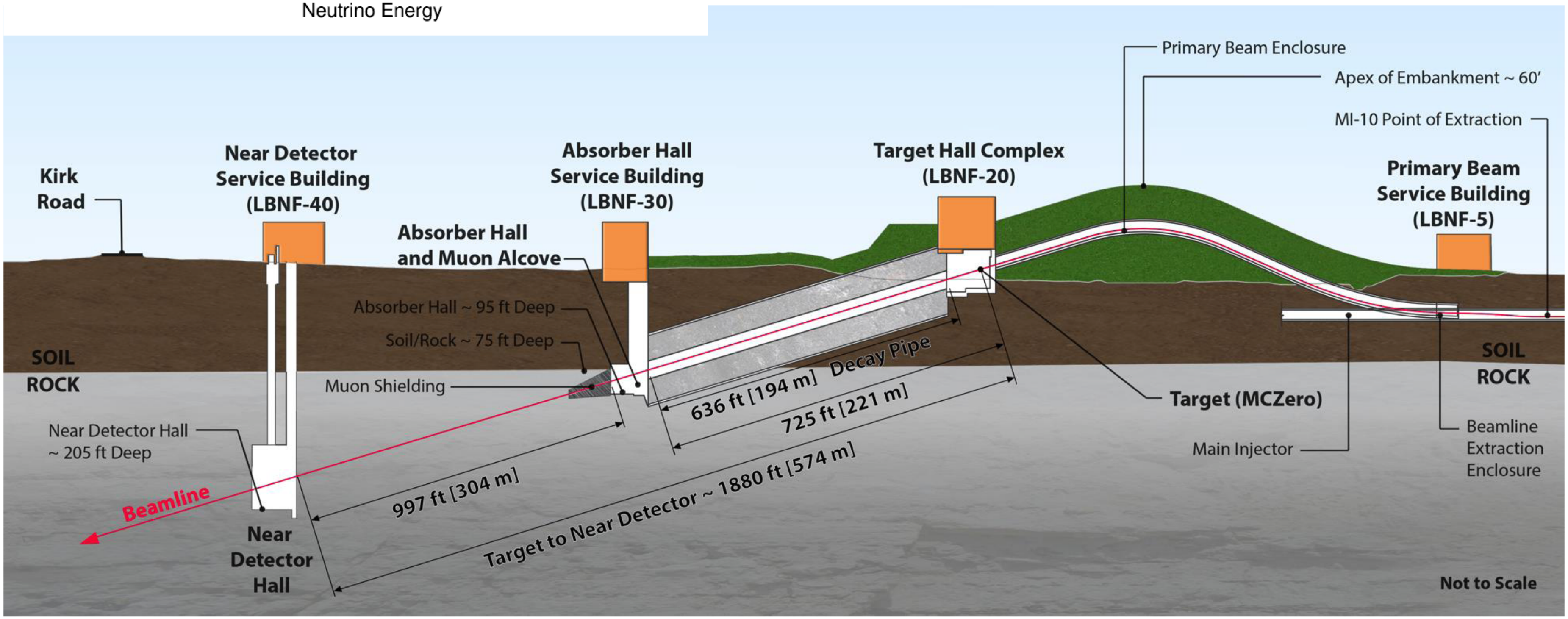
- LBNF/DUNE will consist of
  - An intense 1.2 MW upgradeable ν-beam fired from Fermilab
  - A massive 68 kt (40kt instrumented) deep underground LAr detector in South Dakota and a large Near Detector at Fermilab
  - A large international collaboration



Beam



- Proton beam energy 60-120 GeV
- Power 1.2 MW ➔ 2.4 MW
- Neutrinos and anti-neutrinos



The DUNE Near Detector Complex

- Over the past 3 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
  - CDR in advanced draft
- I will present an overview of the requirements and then detail the current reference design

How to Measure Oscillations

- Oscillation probabilities

$$P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,no-osc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}\ (E_\nu)}$$

Well known (1-2%)

- Number of events/energy spectrum

$$\frac{dN_\nu^{det}}{dE_\nu} = \phi_{\nu_\mu}^{det}(E_\nu) * \sigma_{\nu_\mu}^{Ar}\ (E_\nu)$$

- In reality

$$\frac{dN_\nu^{det}}{dE_{rec}} = \int \phi_\nu^{det}(E_\nu) * \sigma_\nu^{target}\ (E_\nu) * T_{\nu_\mu}^{det}(E_\nu, E_{rec})\ dE_\nu$$

- Folding of detector effects
  - Prevents (easy) cancellations of many systematic effects
  - Needs unfolding

Are there cancellations?

- Oscillation signal

$$\frac{dN^{far}_{\nu_e}}{dE_\nu} \Bigg/ \frac{dN^{near}_{\nu_\mu}}{dE_\nu} = P_{\nu_\mu \to \nu_e}(E_\nu) * \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * F_{far/near}(E_\nu)$$

Small theo. uncertainty or measurement

1-2% uncertainty

- Near muon/electron ratio

$$\frac{dN^{near}_{\nu_e}}{dE_\nu} \Bigg/ \frac{dN^{near}_{\nu_\mu}}{dE_\nu} = \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * \frac{\phi^{near}_{\nu_e}(E_\nu)}{\phi^{near}_{\nu_\mu}(E_\nu)}$$

Not so small uncertainty

- Need to know
  - Flux & cross section ratios
  - Far/near extrapolation

But in Reality

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * T_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * T_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

- No cancellations
  - Unless you unfold
- Need to understand especially
  - Detector effects in near and far detector
  - Relation of visible to neutrino energy
  - Cross section ratios
  - Near to far flux extrapolation
- Flux normalisation cancels
  - Shape is more important

Overarching ND 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.

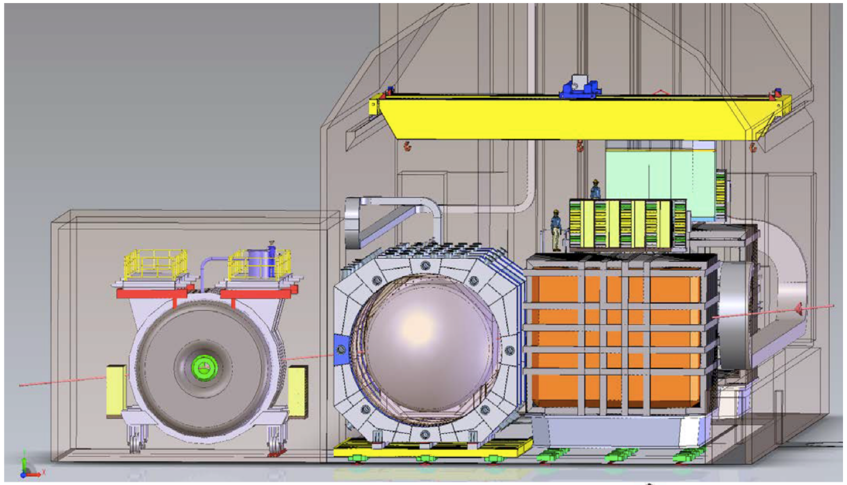
Beyond νSM Physics

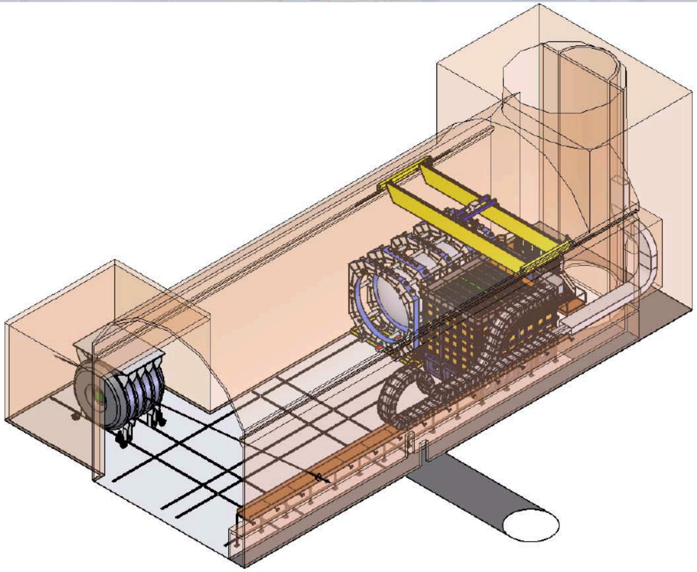
- The near detector facility will provide a very powerful system to study:
  - Boosted dark matter
  - Sterile neutrinos
  - Neutrino tridents
  - Heavy Neutral Leptons
  - millicharged particles
  - Unknown, unknowns………

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

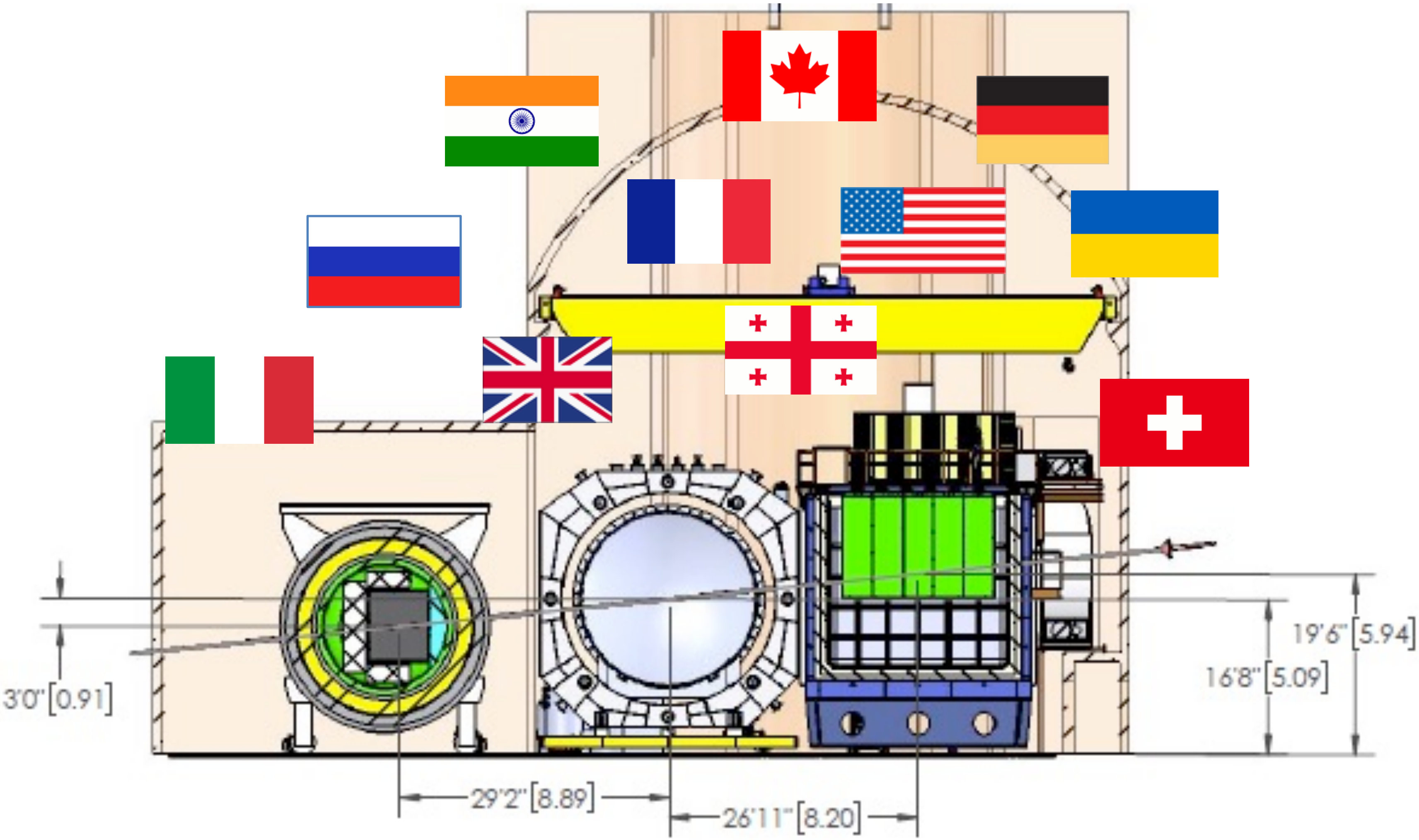
Near Detector Complex

- Four main components, working together:
    1. Liquid argon detector (ArgonCube)
    2. Downstream tracker with gaseous argon target (MPD)
    3. LAr and GAr systems can move to off-axis fluxes (PRISM concept)
    4. **S**ystem for on-**A**xis **N**eutrino **D**etection (SAND)
- High statistics constrains
    - Cross section & neutrino flux





International Involvement



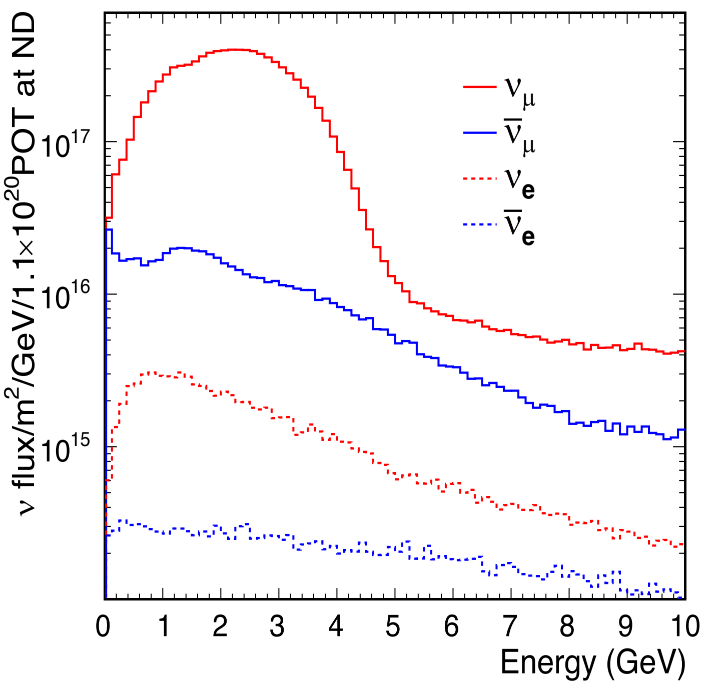
Detector Functionality

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)
  - Muon system to help with muon/pion separation
- Beyond interactions on Ar: Extended capability with SAND
  - provides detailed fixed, on-axis beam monitoring
  - provides look at ν-CH interactions with novel neutron detection capabilities

Flux & Event Rates @ ND570

Optimized CPV tune
FHC On-axis
1.25 MW



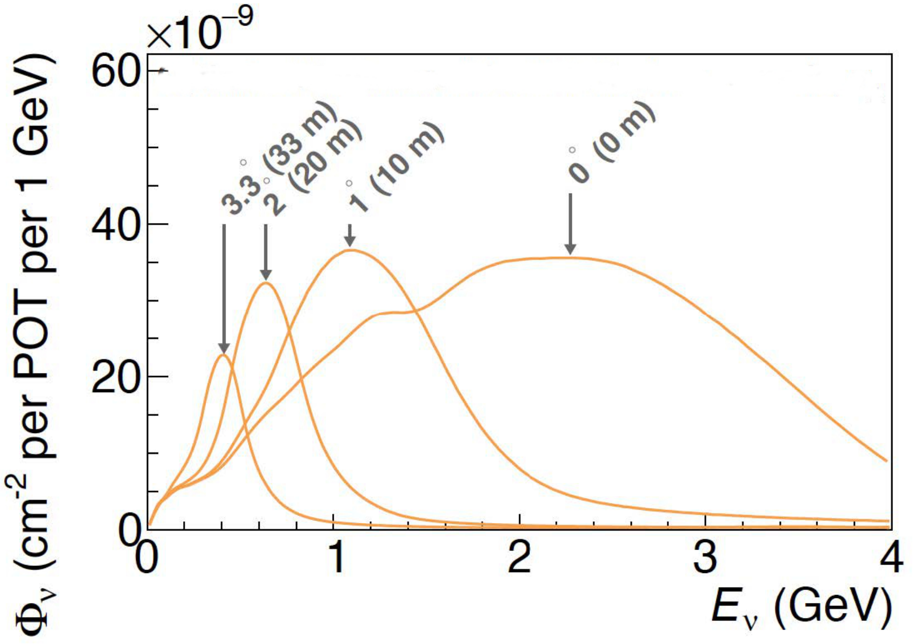
Events/year in Fiducial volume

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

Taking Data Off-axis

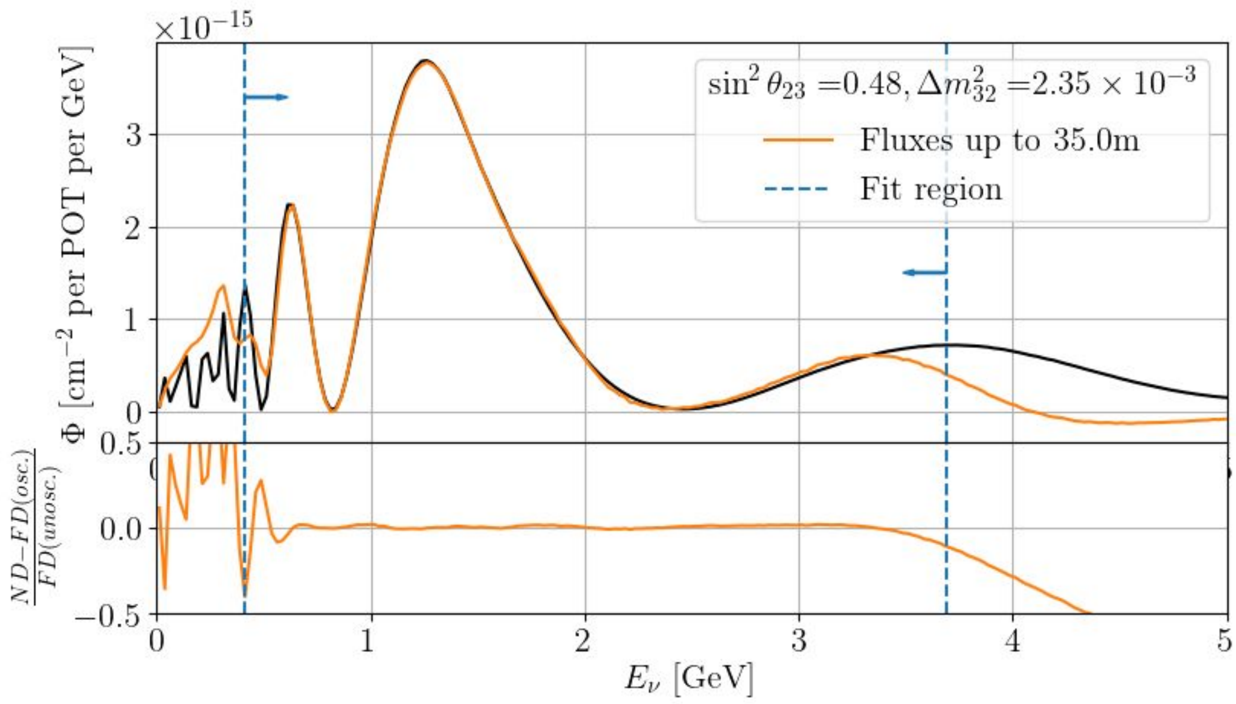
- The DUNE near detector complex will allow for off-axis running in order to accommodate the PRISM concept
  - Precision Reaction Independent Spectrum Measurement
- Flux varies as a function of detector transverse position

  - Pseudo-monochromatic beams can be formed by taking linear combinations of beam data at different off-axis positions
  - These 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



PRISM

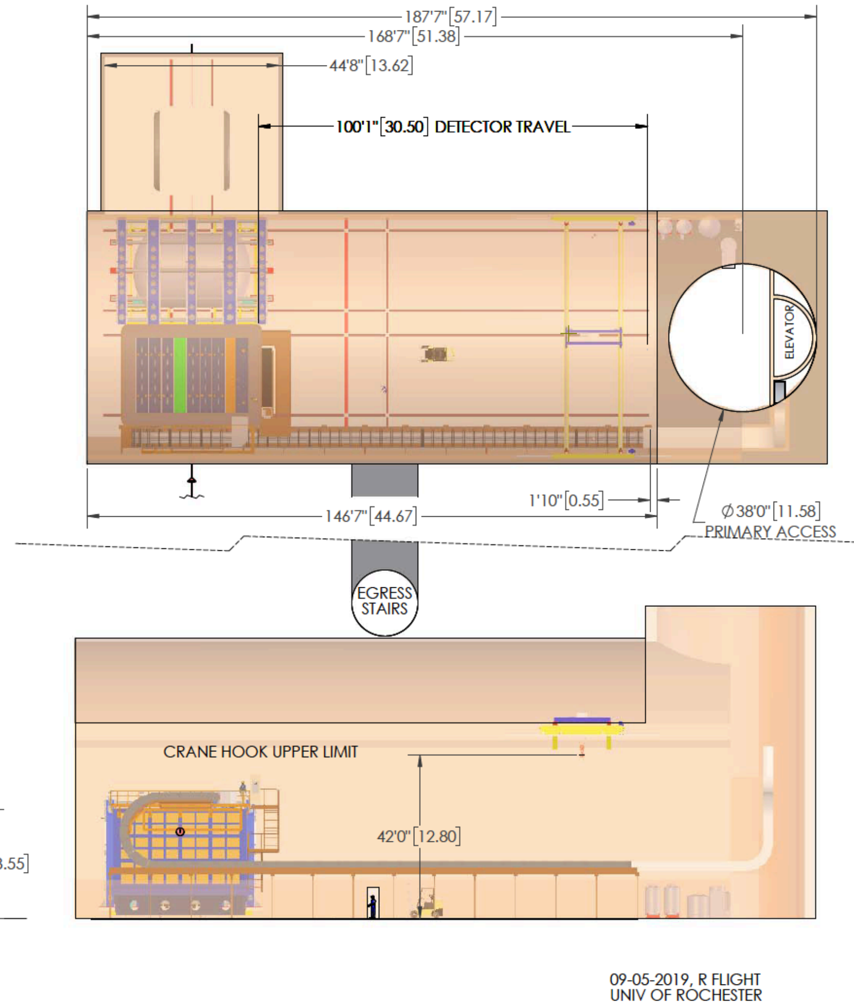
- Predict oscillated neutrino event spectra at FD with reduced model dependence
  - Form "oscillated" flux at near detector with linear combinations of off-axis data
  - Extrapolate to Far detector
  - Interaction model independent



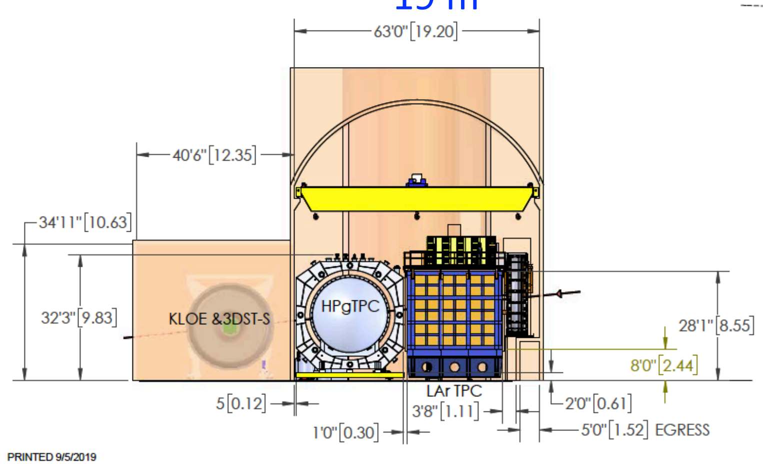
Near Detector Hall

- Design is progressing
- No show stoppers identified by engineering company
- Value engineering (cost savings) under discussion

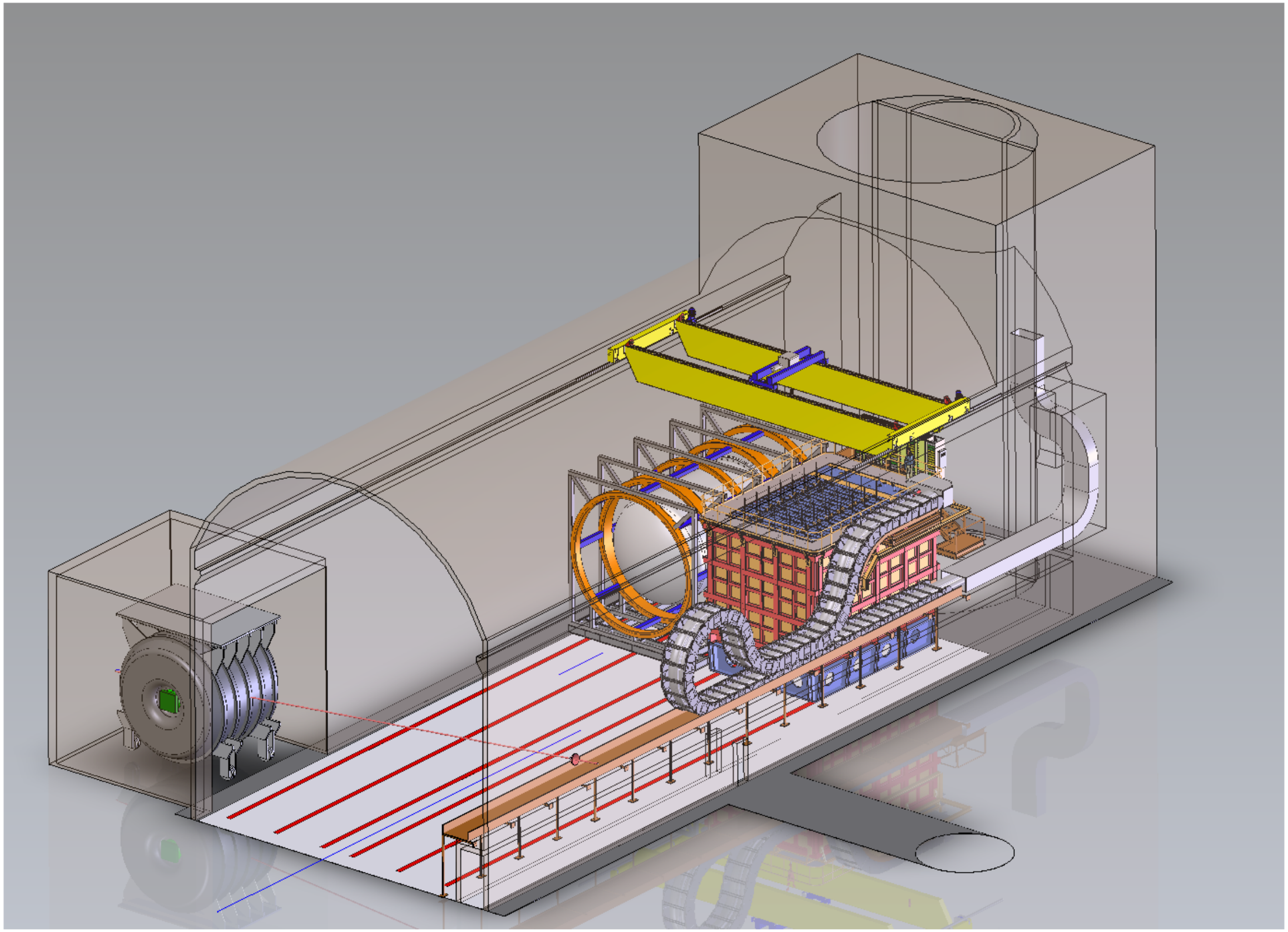
~31 m (3.3°) travel



~19 m

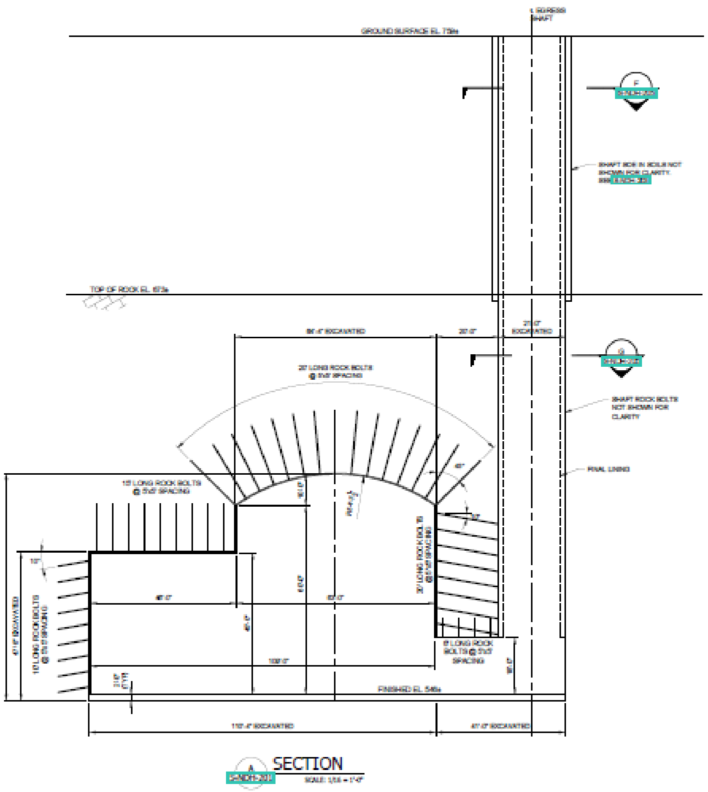


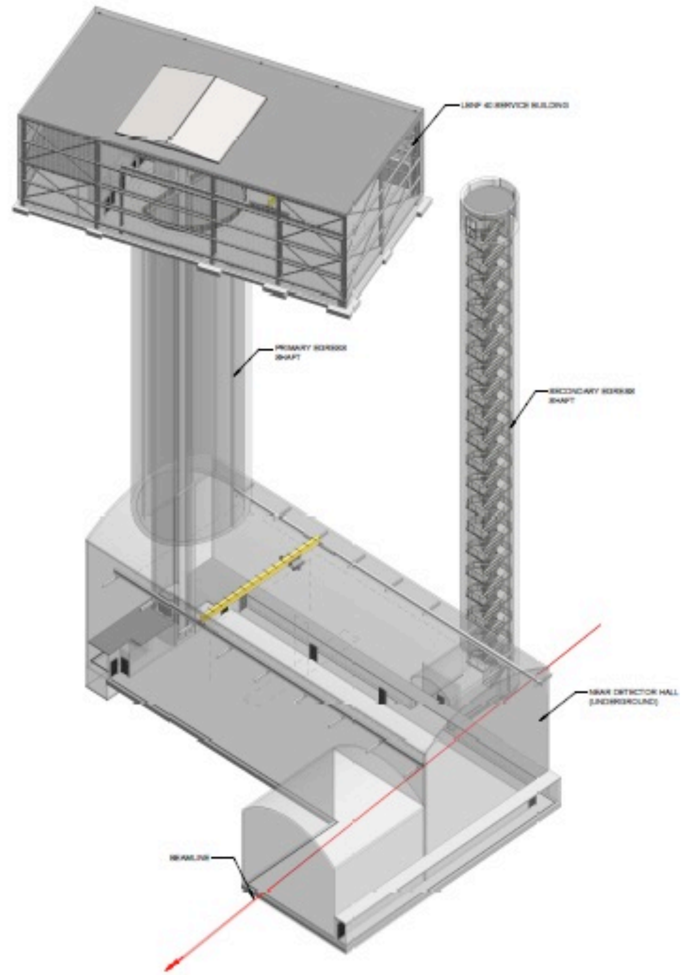
Detectors at Extreme Off-axis Position



Advanced Facility Design

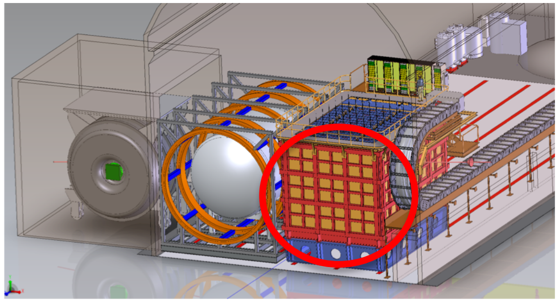
- Around 50% design completed
- No show stoppers

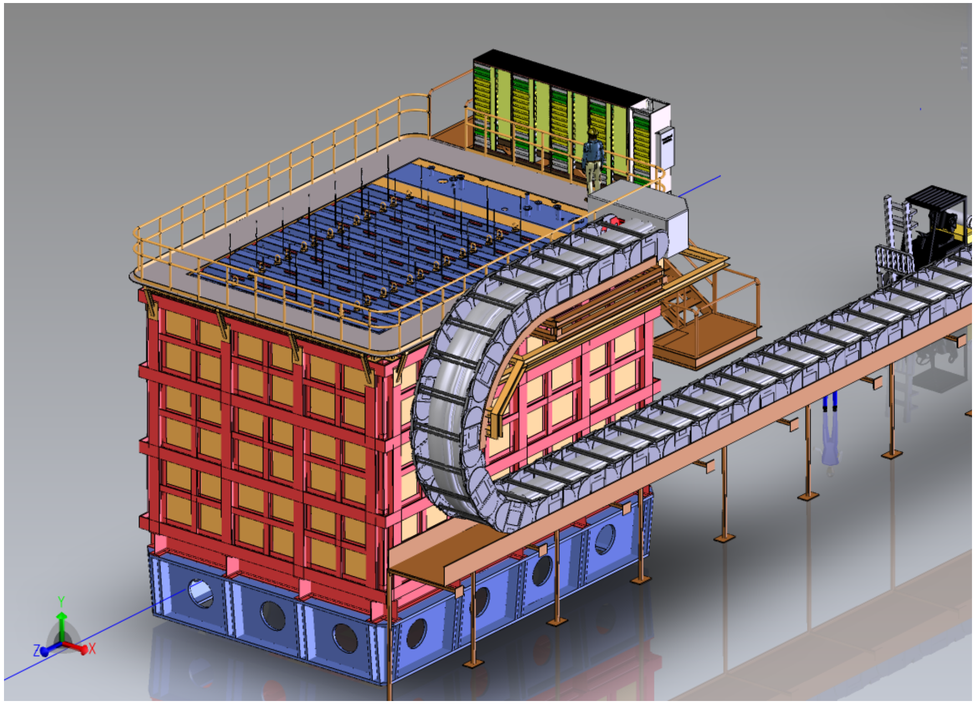




Detector Systems

LAr Overview

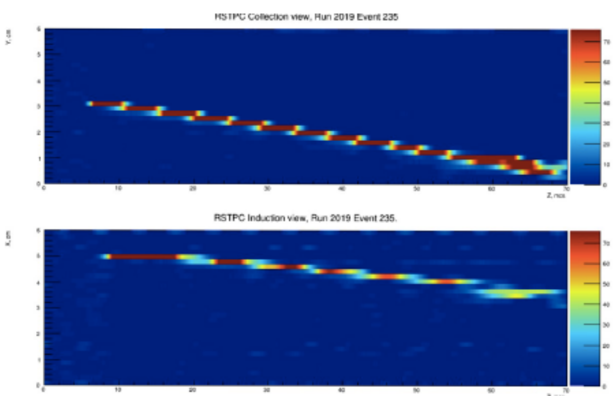


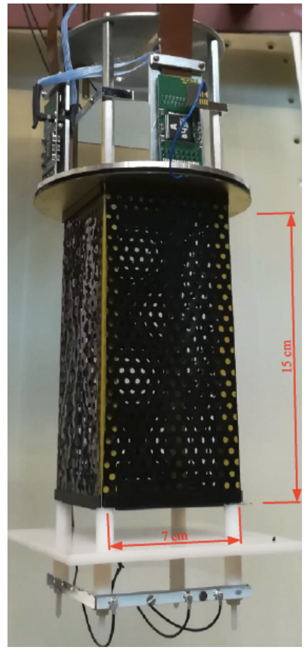


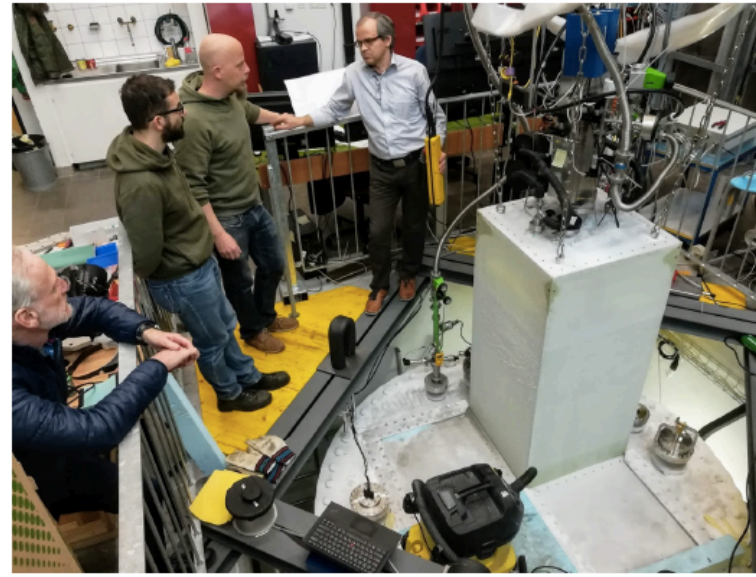
- ArgonCube concept
- Pixelated readout to accommodate high rate (>5 evts/spill)
  - 12 million pads
  - ~2 billion voxels
- Active volume:
  - 5 m deep in beam direction and 3 m tall for hadronic shower containment.
  - 7 m transverse to mitigate side muon spectrometer.
- Active mass ~ 150t
  - 50t 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

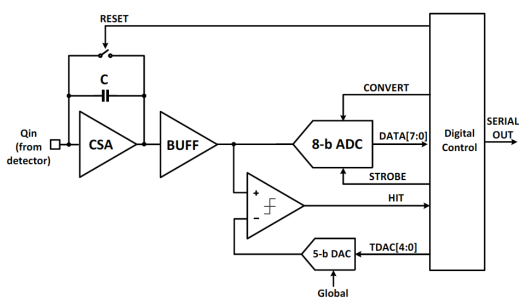
Prototyping Activities

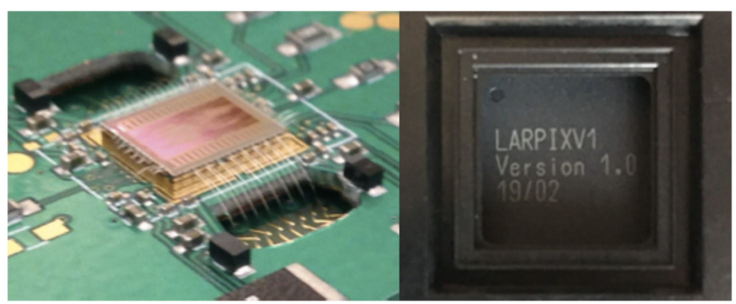
- Almost full size module in 2x2 cryostat
- Pixel ASIC
- Resistive shell TPC

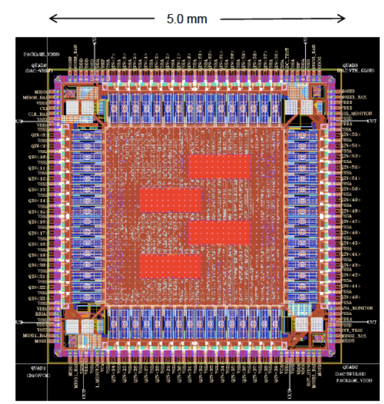






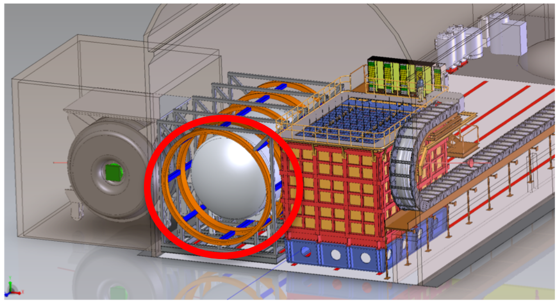


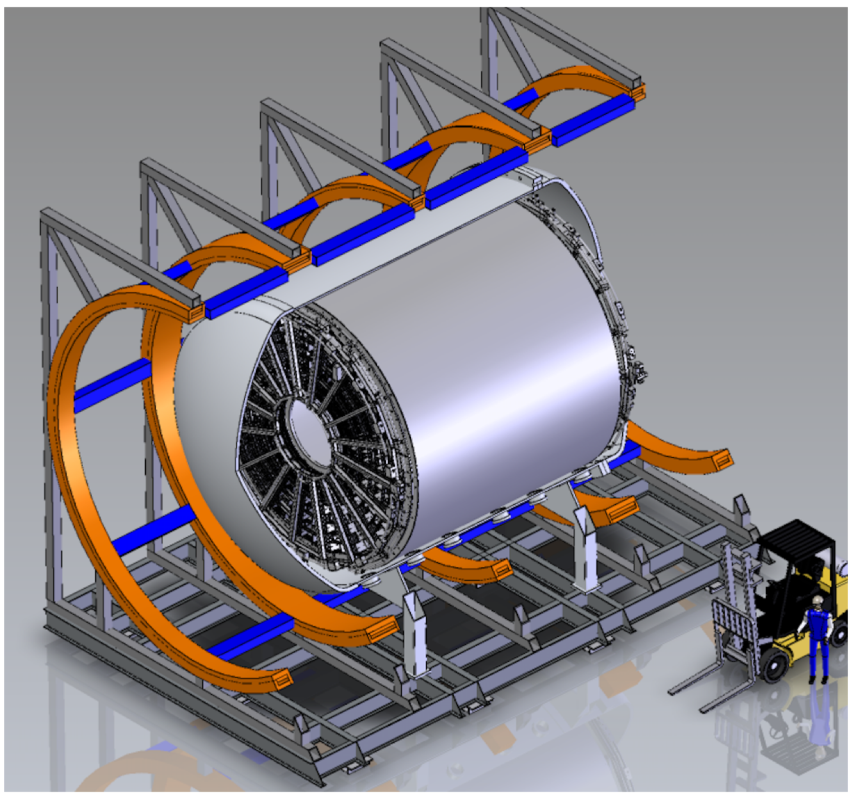




LArPix-v2
64 channels, 25 mm^2

Multi-Purpose Detector Overview

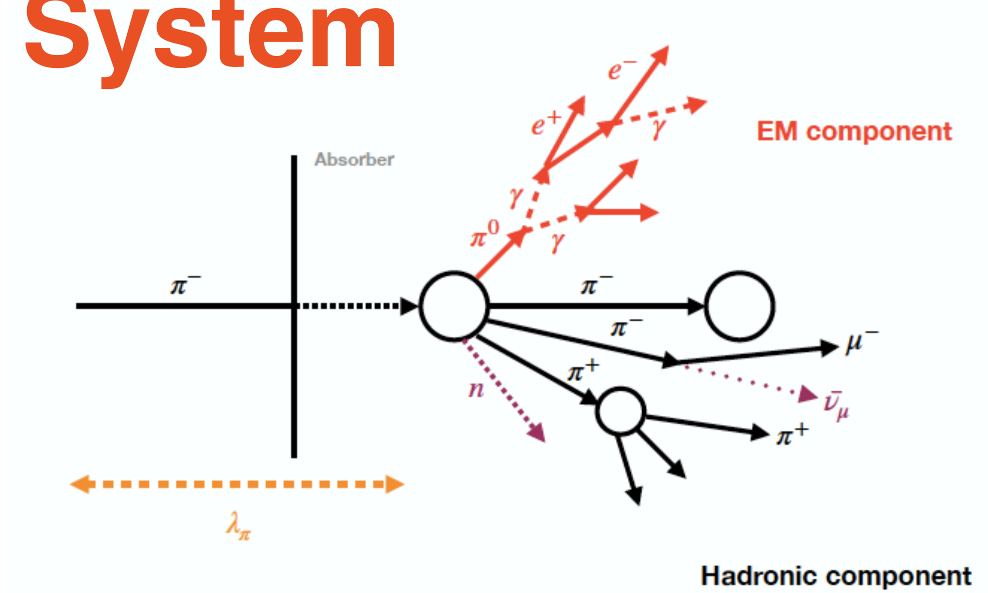


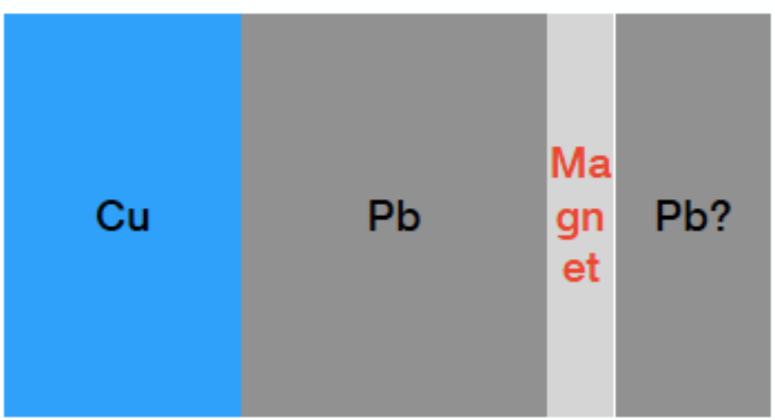


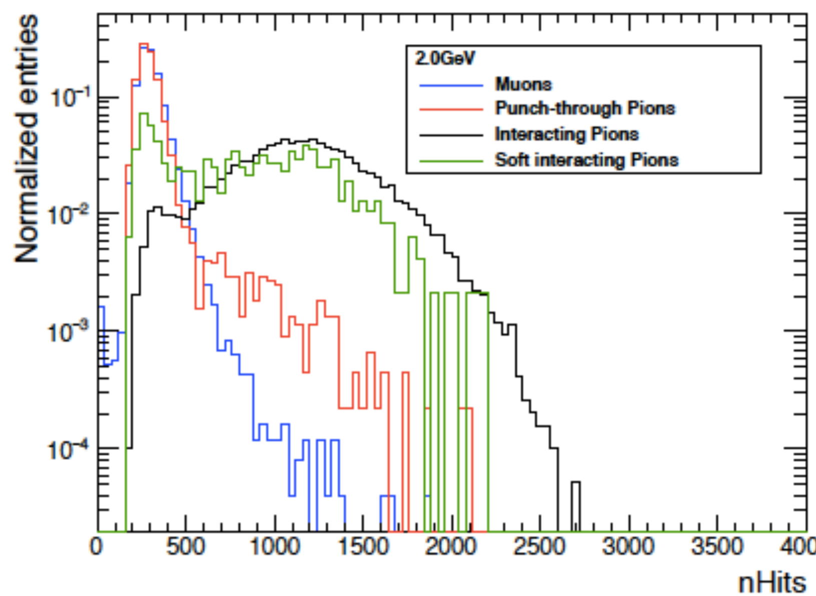
- High pressure (10bar) gas TPC + ECAL + SC magnet + μ tag
- Provides muon spectrometry for muons leaving LAr
  - LAr event containment
- Provides an independent, statistically significant event sample on Ar gas
  - Can move off axis
- Some Indian involvement already
  - Collaboration on magnet design
  - Muon tag system
  - Pressure vessel
- More information in next talks

Need for Muon System

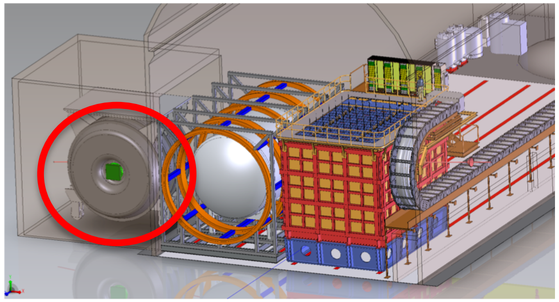
- ECal thickness ~ 1 λ
- 1/3 of pions don't interact in ECal
- Solution
  - additional absorber
  - Muon system

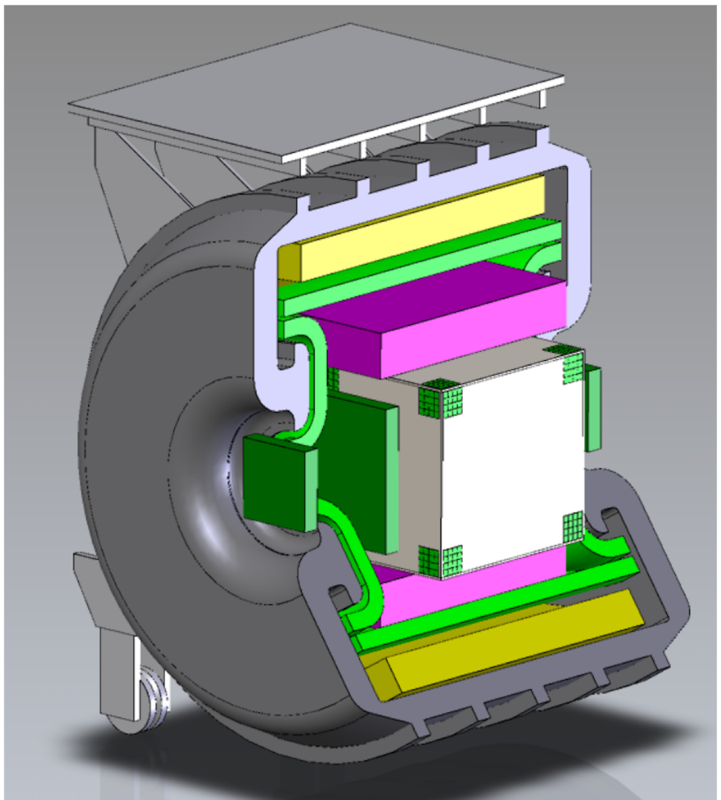






SAND Overview



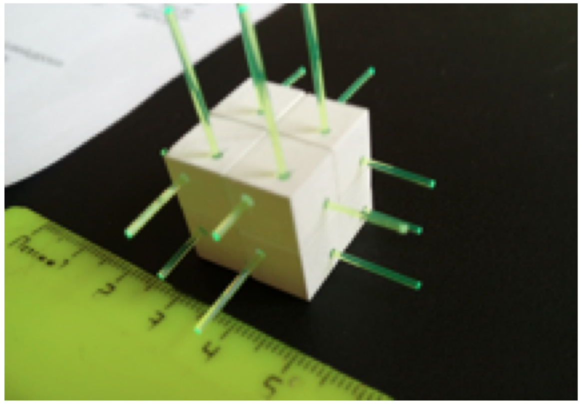


- Provides precision on-axis monitoring of neutrino beam through rate, profile, and spectrum measurements
- Consists of
  - Active target (8t) consisting of 3-dimensional plastic scintillator tracker
  - tracking
    - Atmospheric pressure TPCs or straws
  - KLOE EM calorimeter
    - Scintillator fiber + Pb
  - KLOE magnet system
    - 0.6T central field (SC magnet)
    - Return Fe
- Fixed on-axis position

SAND 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 tracking detectors and ECAL in magnetic field

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



SAND Capabilities

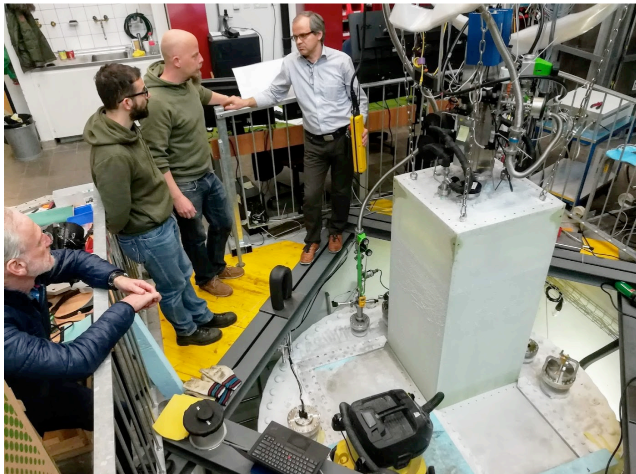
- **Precision on-axis flux monitor**
  - Sufficient rate, spectrometry capabilities, and transverse span
- Neutron detection
  - New capability in neutrino detectors
  - Nascent capabilities in MINERνA show potential
- ν-CH sample
  - Cross check ν-A modelling across A
  - Connect to “historic” data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

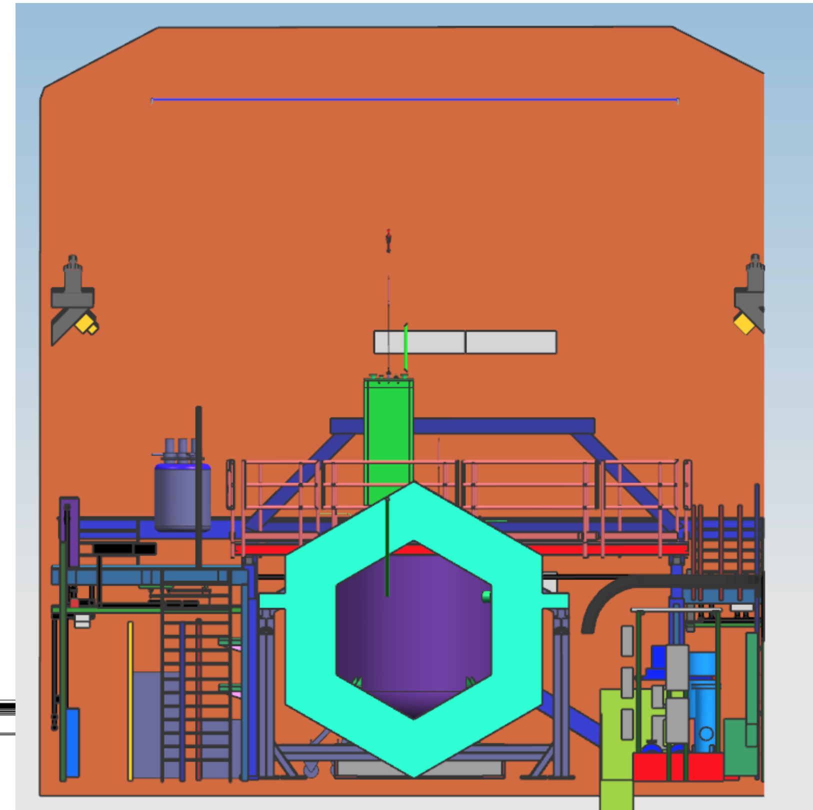
Comparison between Ingrid-like system and spectrometer.
Preliminary

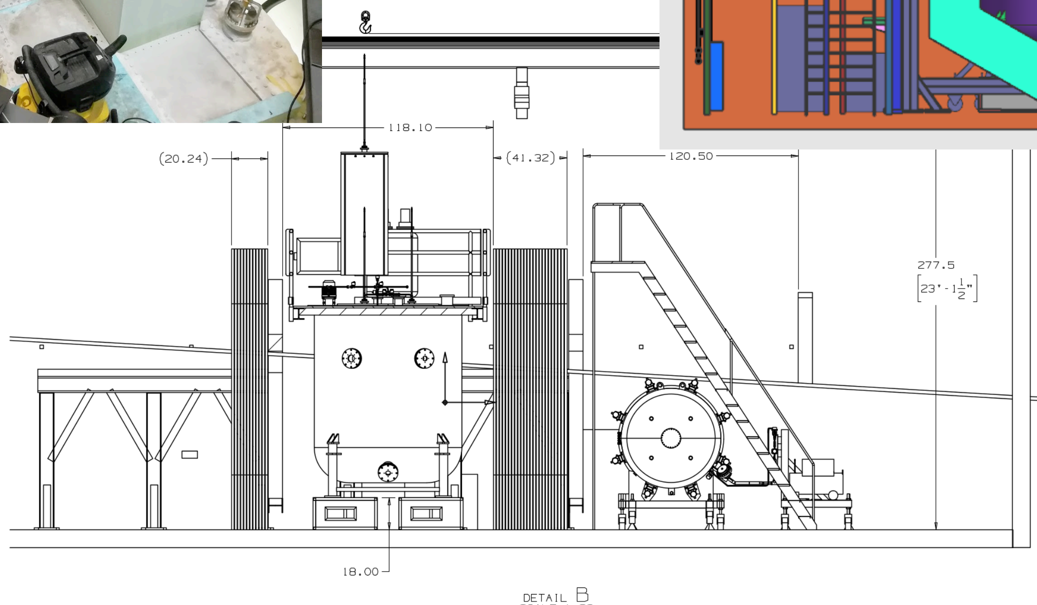
sqrt(chi2)	4 modules One-side rate	Muon spectrometer
Beam targ. dens.	1.9	7.8
Beam offset x	0.7	6.7
Beam theta	0.2	19.9
Horn 1 X 0.5 mm	1.9	8.8
Horn 1 Y 0.5 mm	0.7	12.8
Horn 2 X 0.5 mm	0.2	9.9
Horn 2 Y 0.5 mm	0.4	6.3

ProtoDUNE-ND

- ND prototypes in neutrino beam







Timeline

- May 2018: Conceptual design of ND
- May 2018: FD IDR
- July 2018: Completion of ProtoDUNE-SP construction
- July 2019: Commissioning of ProtoDUNE-DP
- March 2020: ND CDR
- Mid 2020: baseline LBNF & DUNE-US (CD2/3a)
- Dec 2020: ND IDR, reviews
- 2021/22: ProtoDUNE running post LS2
- Aug 2024: Installation Module 1
- Aug 2025: Installation Module 2

Opportunities

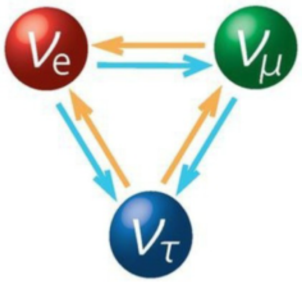
- We are close to a CDR ➔ Conceptual
  - Everything needs more thought, design, work,…
- Examples (incomplete)
  - Muon system
    - Muon/pion separation & Cosmic trigger
  - DAQ
    - LAr, MPD, …
  - Trigger and timing
    - Beam, calibration, cosmic
  - Detectors
    - Pay attention to the talks!
- Forming ND Consortia now
  - Will be charged to deliver NDs

Conclusions

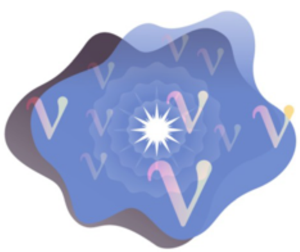
- DUNE has developed a near detector reference design that has wide-ranging capability (calorimetric, spectrometer, PID, multiple target nuclei, off-axis measurements)
  - LAr, MPD (HPgTPC + ECAL + Magnet + μ tagger) and SAND
    - Basic technical/engineering foundations in place for most
- With these 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 the νSM, BSM physics and neutrino interaction physics are extensive

Thank You

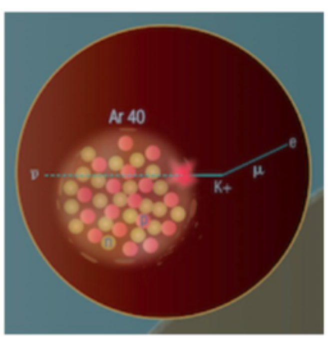
Physics Program



- Neutrino Oscillations
  - Search for leptonic CP violation
  - Determine neutrino mass ordering
  - Precision PMNS measurements

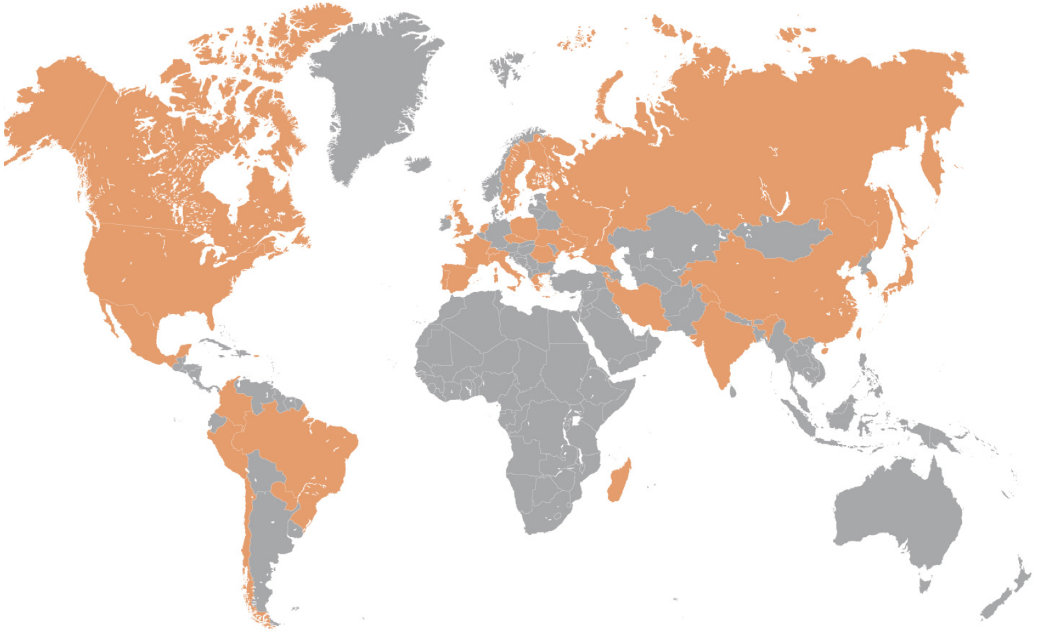


- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos



- Baryon number violation
  - Predicted by many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, $p \rightarrow K^{+}\bar{\nu}$)
  - $\Delta(B-L) \neq 0$ channels accessible (*e.g.*, $n \rightarrow \bar{n}$)

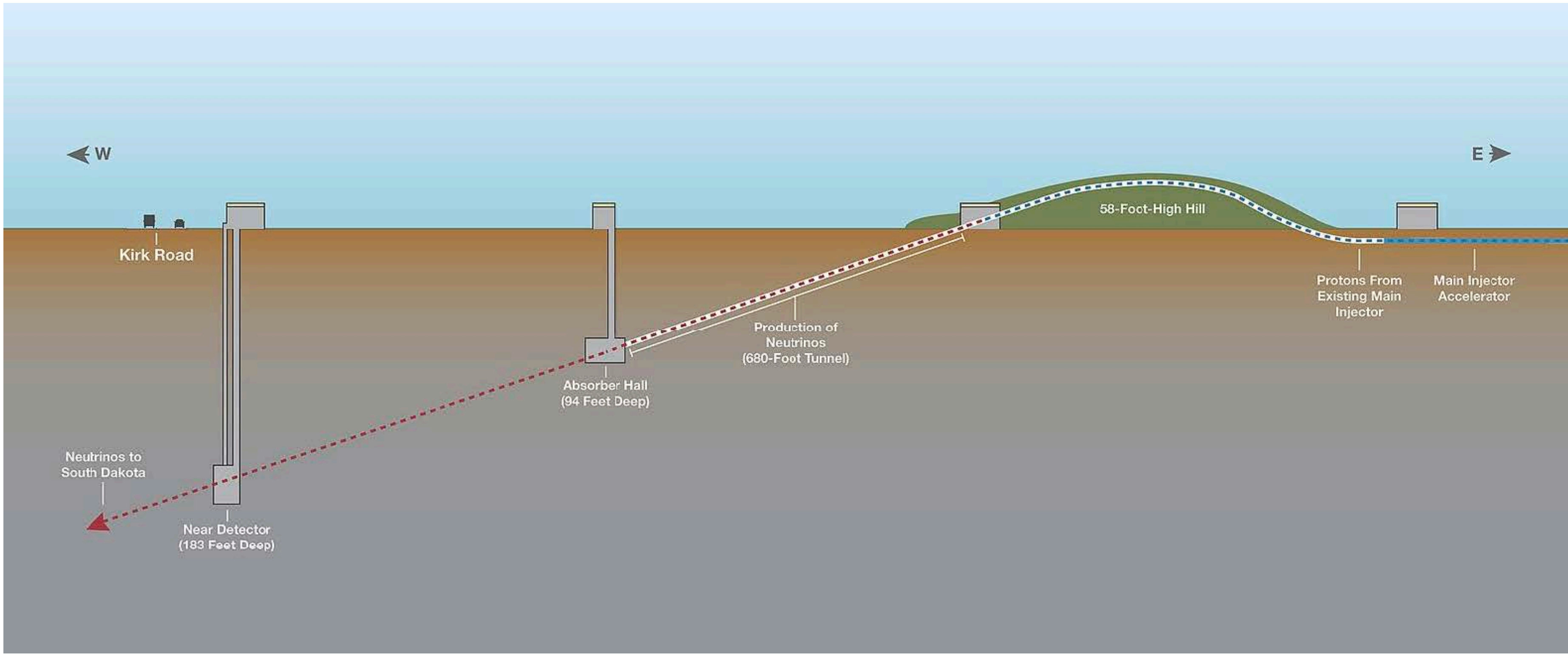
DEEP UNDERGROUND NEUTRINO EXPERIMENT



An international science collaboration

1106 collaborators from **184 institutions** in **31 countries**

DUNE Near Site



Near detector hall located 574 m from the target and 60 m below the surface