DUNE
Near Detector Overview

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for the DUNE ND Design Group

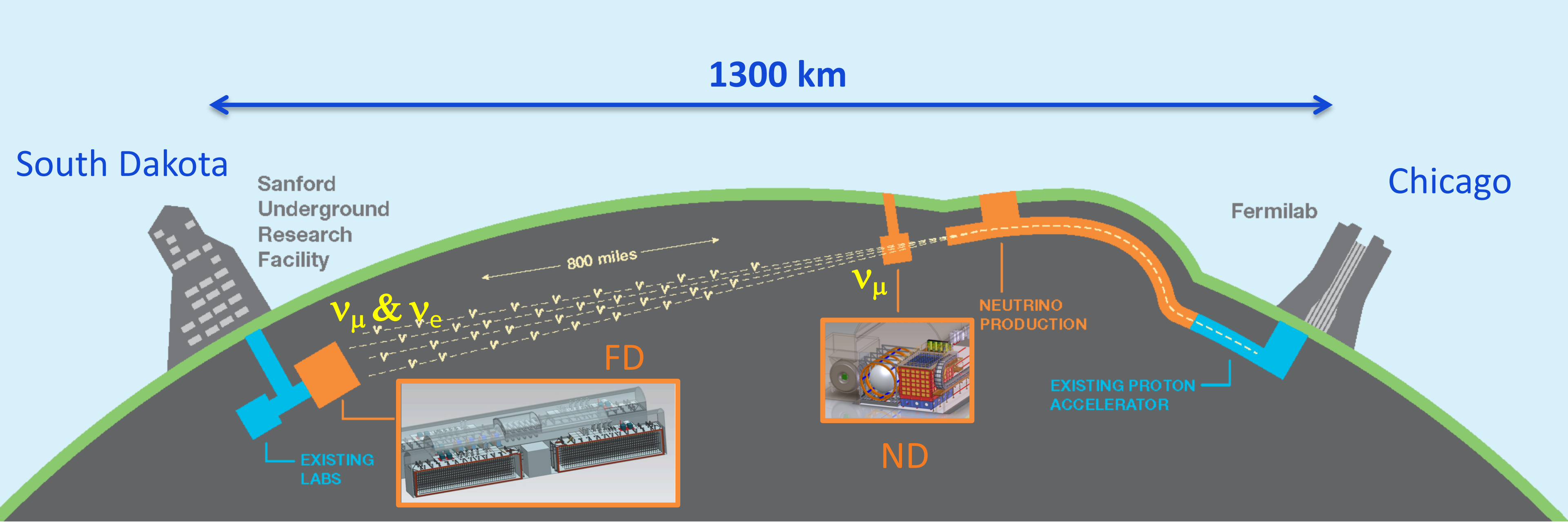
DESY, 21-Oct-2019

UNIVERSITY OF OXFORD

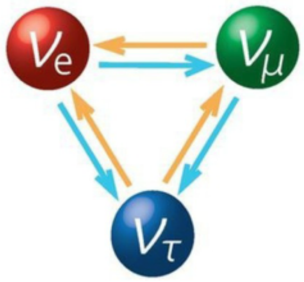
UKRI Science and Technology Facilities Council

General Setup

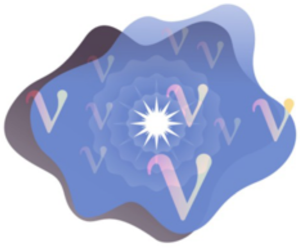
- LBNF/DUNE will consist of
  - An intense 1.2 MW upgradeable ν-beam fired from Fermilab
  - A massive 68 kt (40kt instrumented) deep underground LAr detector in South Dakota and a large Near Detector at Fermilab
  - A large international collaboration



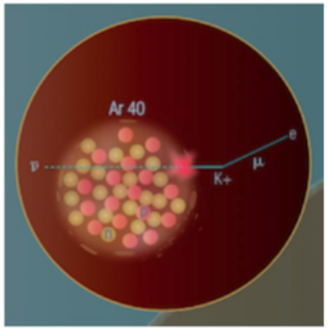
Physics Program



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

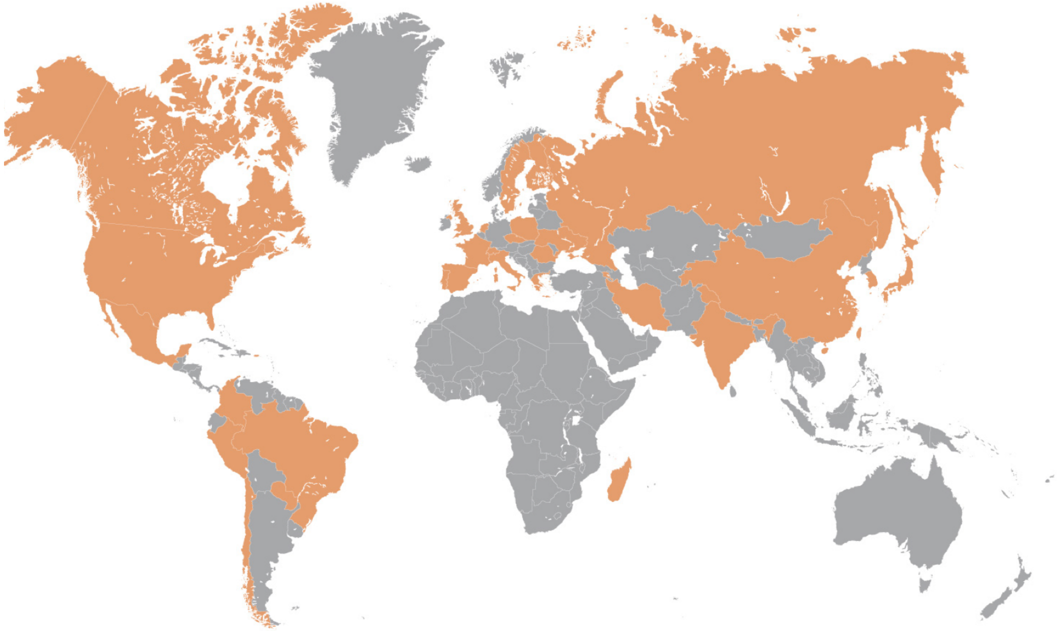


- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos



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

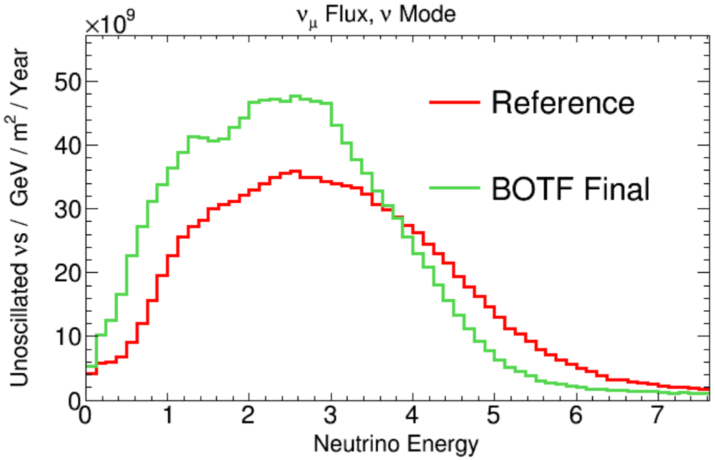
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



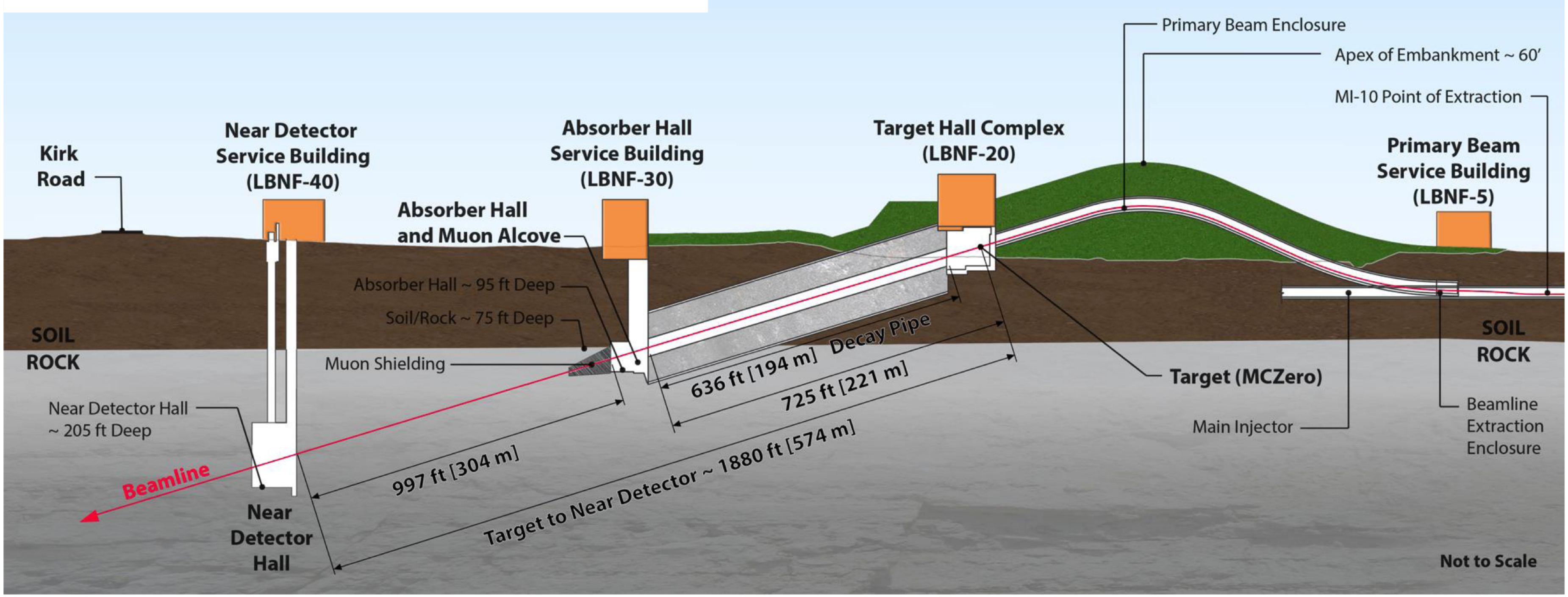
An international science collaboration

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

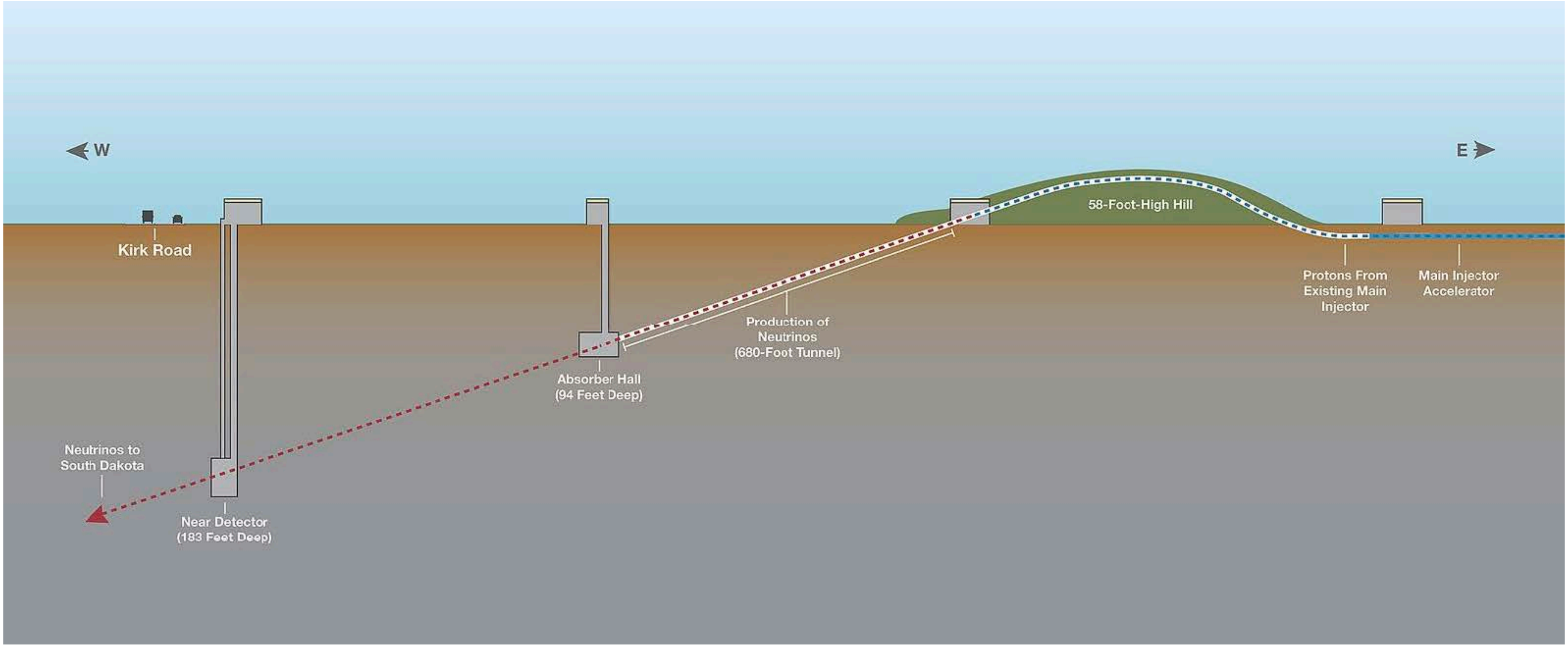
Beam



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



DUNE Near Site



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

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

Small theo. uncertainty
or measurement

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

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

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

- 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.

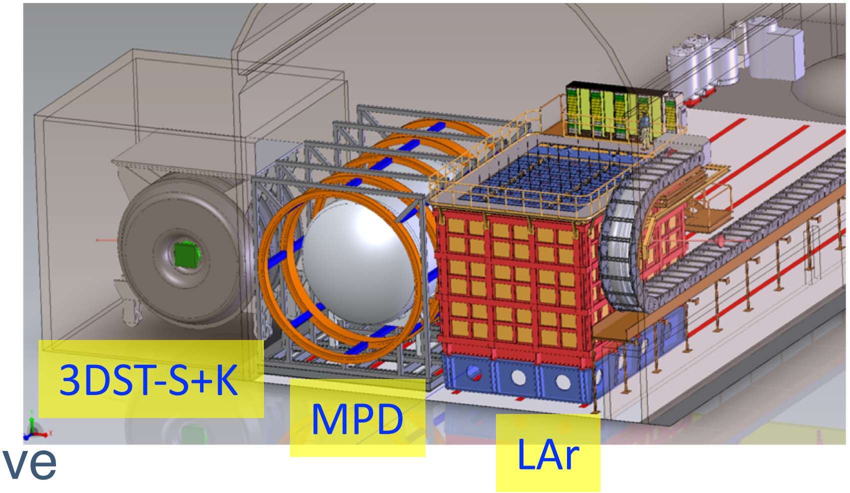
Beyond νSM Physics

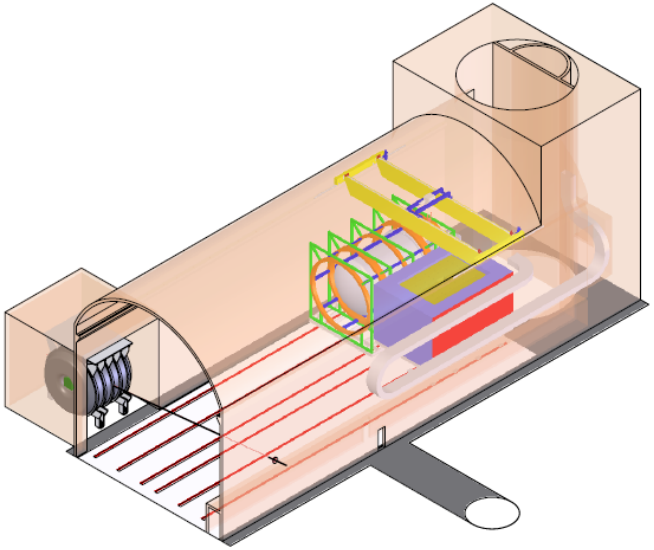
- The near detector facility will provide a very powerful system to study:
  - Boosted dark matter
  - Sterile neutrinos
  - Neutrino tridents
  - Heavy Neutral Leptons
  - millicharged particles
  - Unknown, unknowns………
- More details in Silvia’s talk later

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. On-axis neutrino beam monitor with neutron detection capability (3DST-S+KLOE)
- High statistics constrains
  - Cross section & neutrino flux





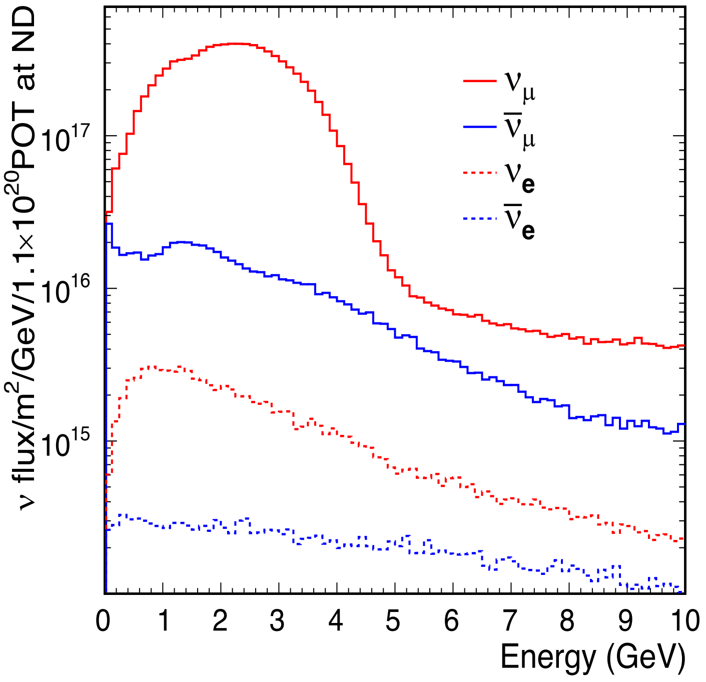
Detector Functionality

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 seperation
- Beyond interactions on Ar: Extended capability in 3DST-S+KLOE
  - 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



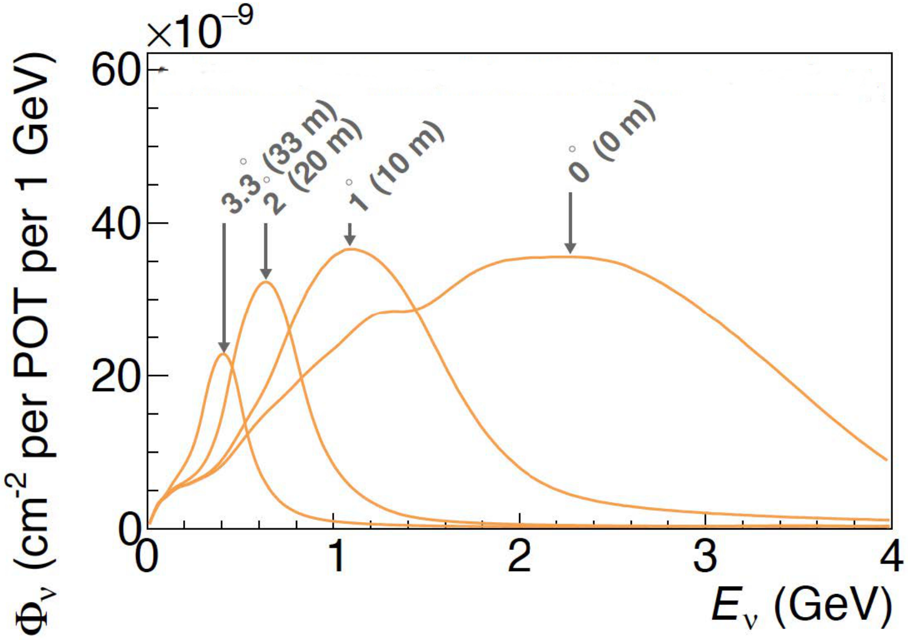
Events/year in Fiducial volume

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

Taking Data Off-axis

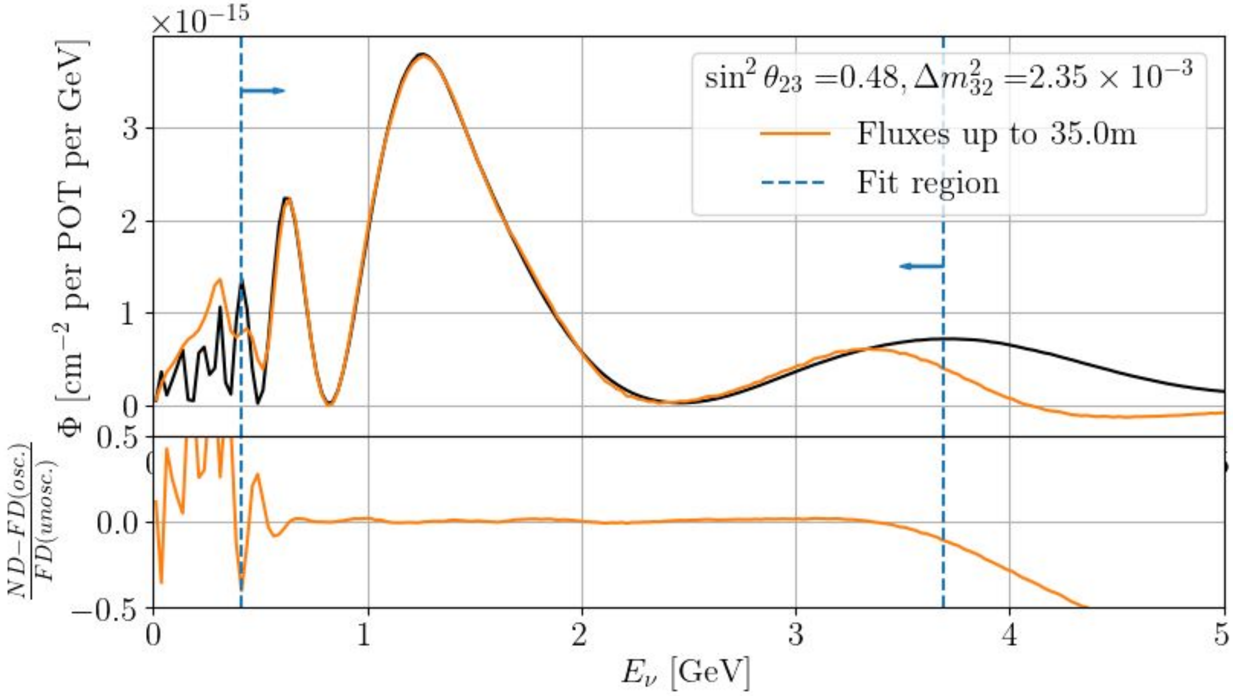
- The DUNE near detector complex will allow for off-axis running in order to accommodate the PRISM concept
  - Precision Reaction Independent Spectrum Measurement
- Flux varies as a function of detector transverse position

  - 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

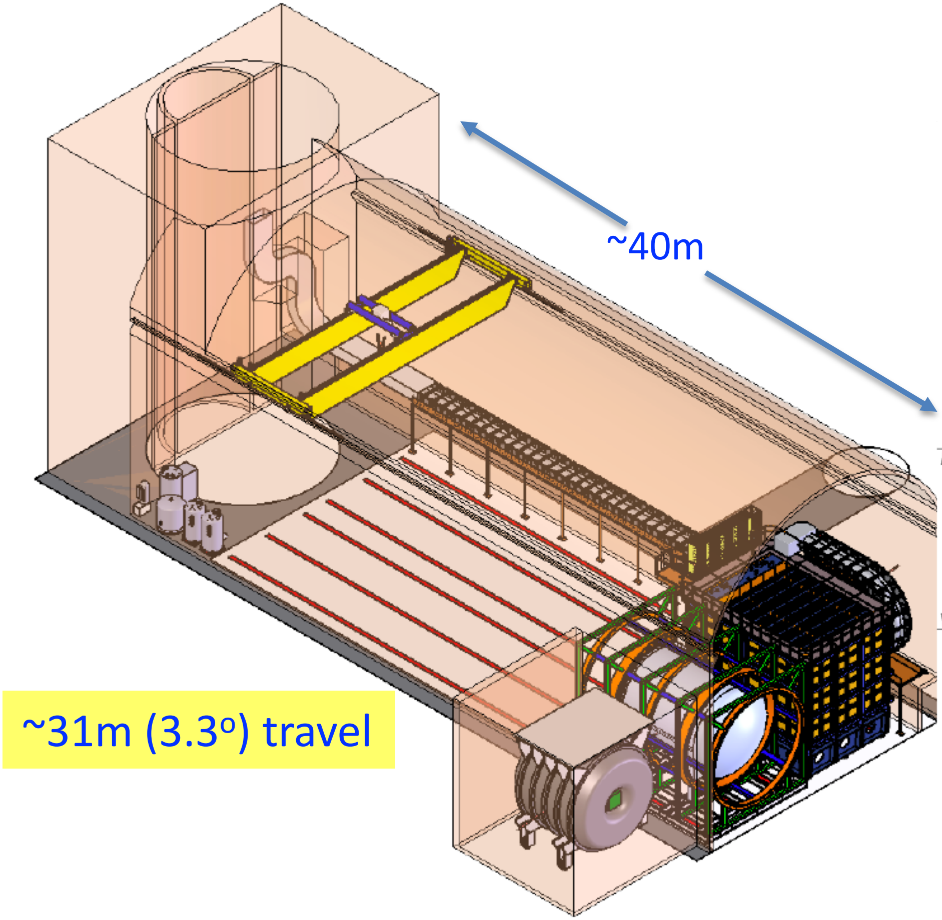


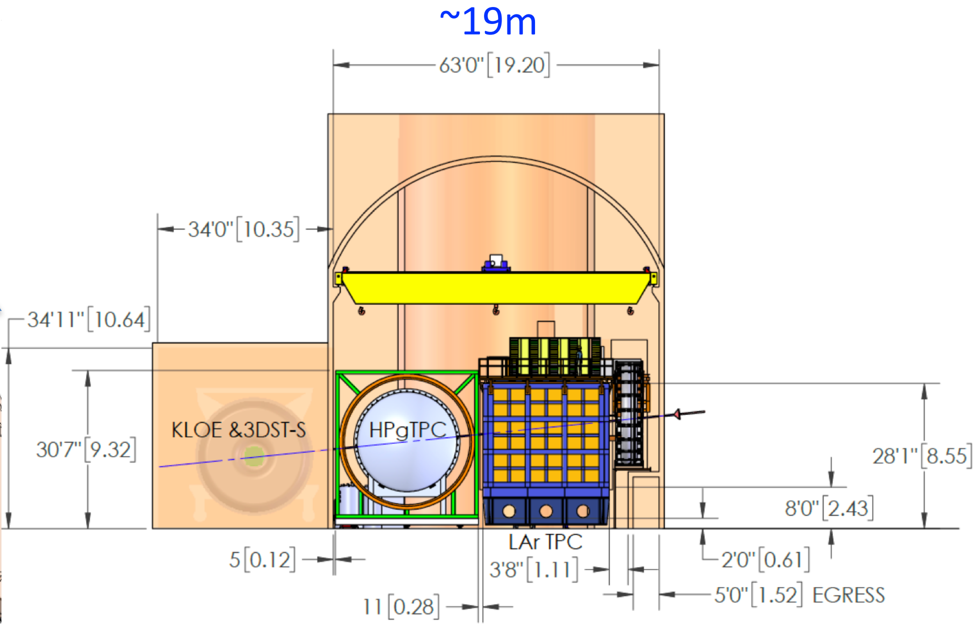
PRISM

- 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

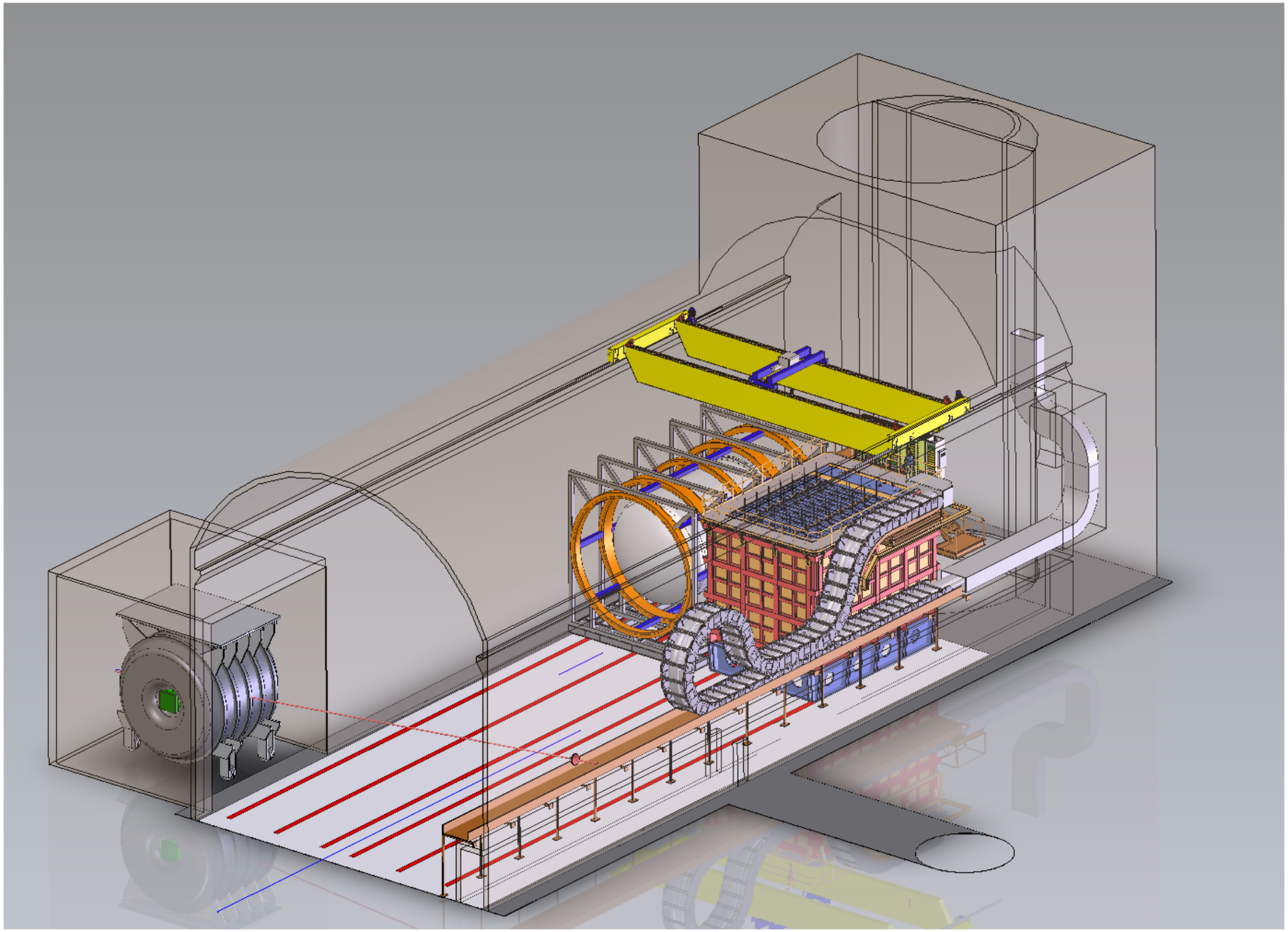


Near Detector Hall



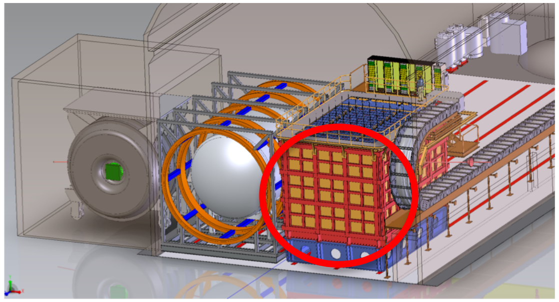


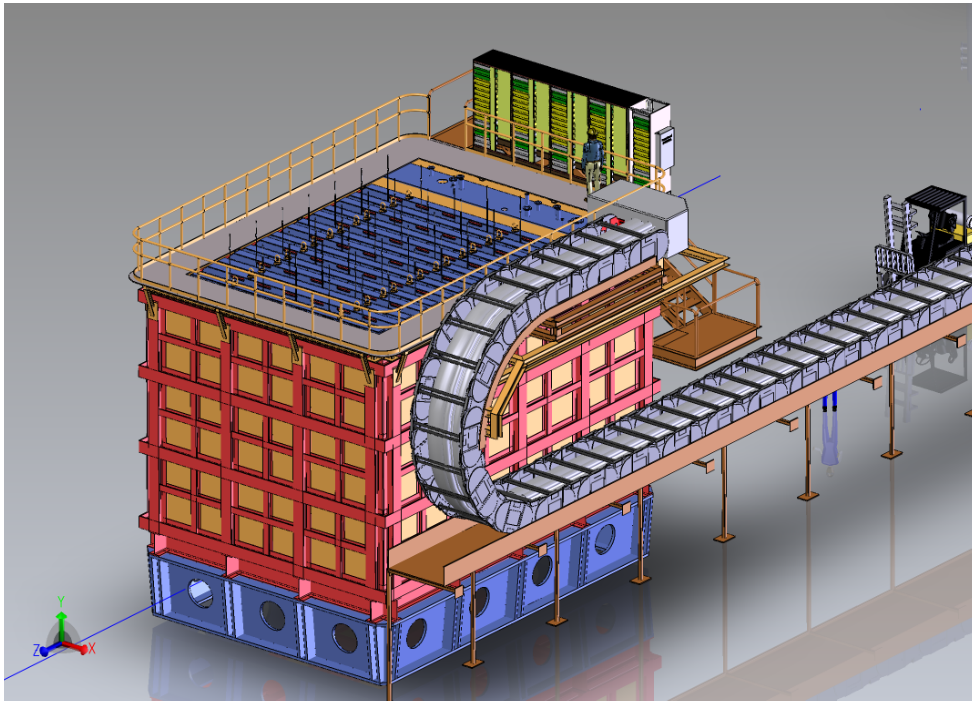
Detectors at Extreme Off-axis Position



Detector Systems

LAr Overview

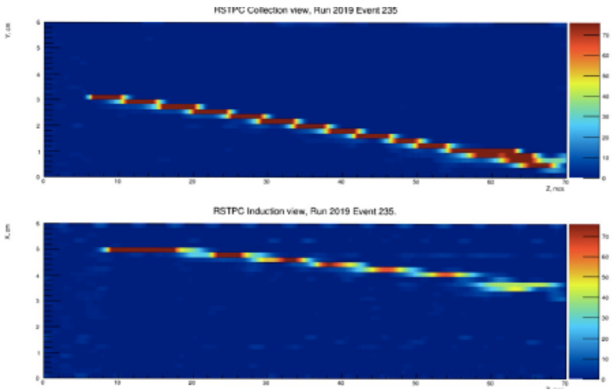


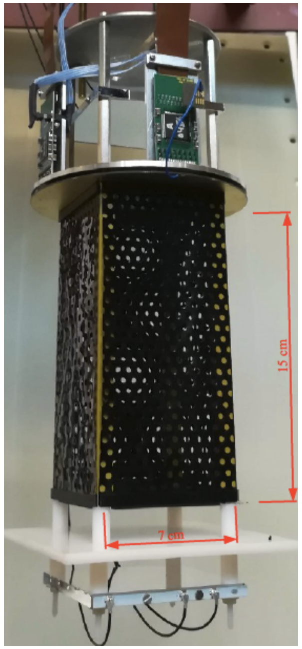


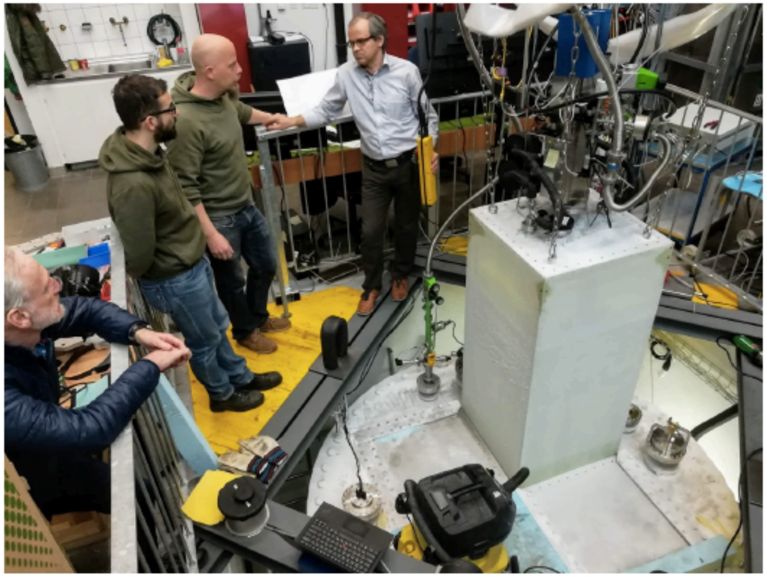
- ArgonCube concept
- Pixelated readout to accommodate high rate (>5 evts/spill)
  - 12 million pads
  - ~2 billion voxels
- Active volume:
  - 5 m deep in beam direction and 3 m tall for hadronic shower containment.
  - 7 m transverse to mitigate side muon spectrometer.
- Active mass ~ 150t
  - 50t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

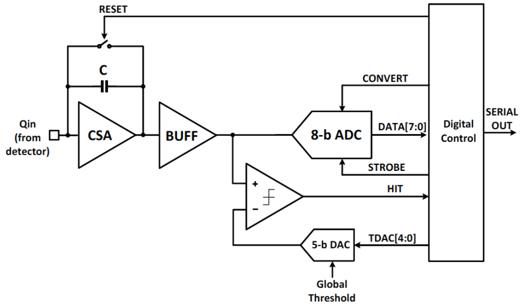
Prototyping Activities

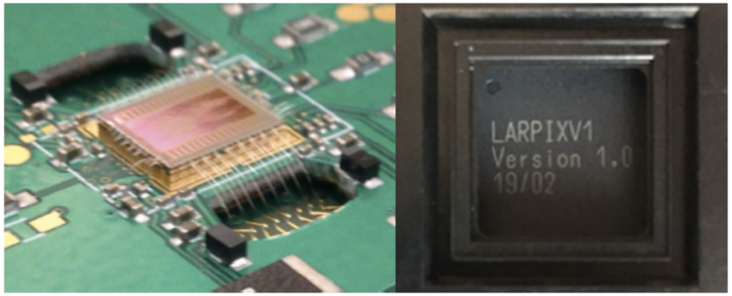
- Almost full size module in 2x2 cryostat
- Pixel ASIC
- Resistive shell TPC

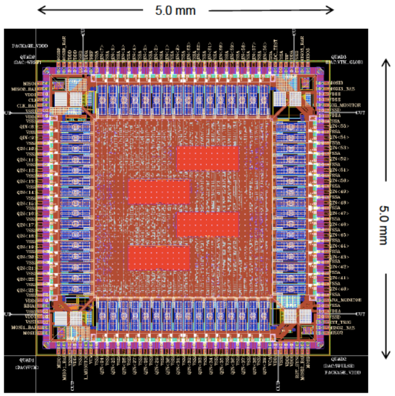








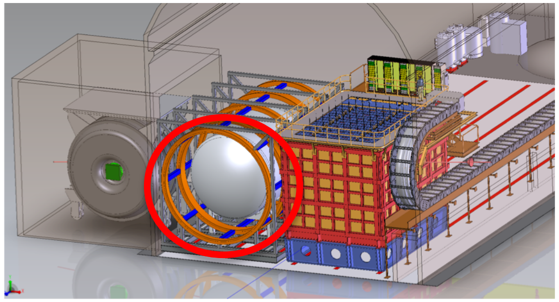


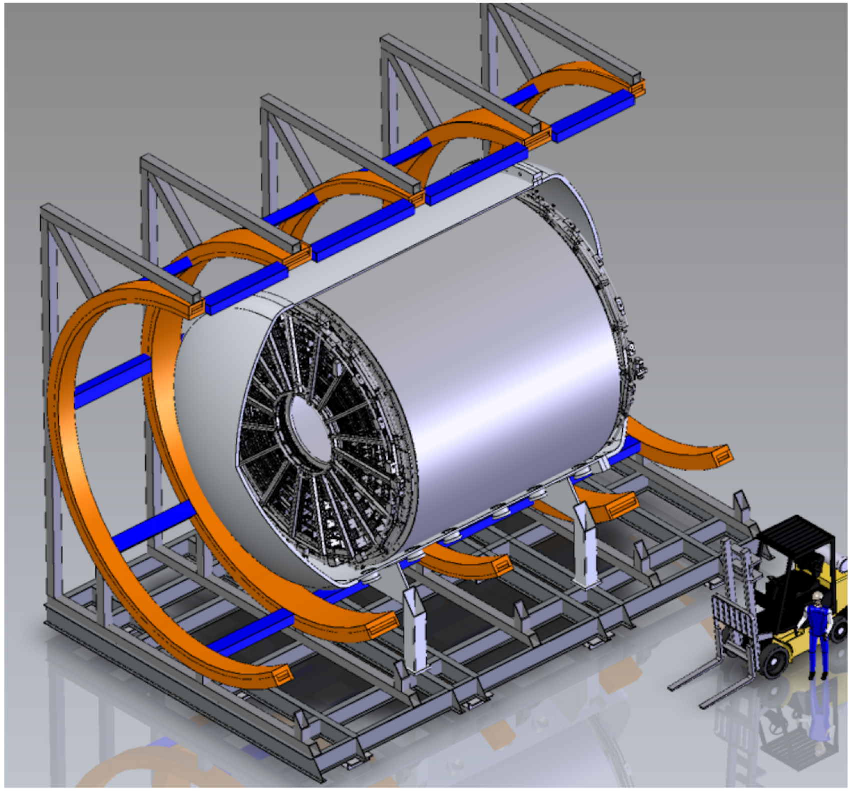


LArPix-v2

64 channels, 25 mm^2

Multi-Purpose Detector Overview

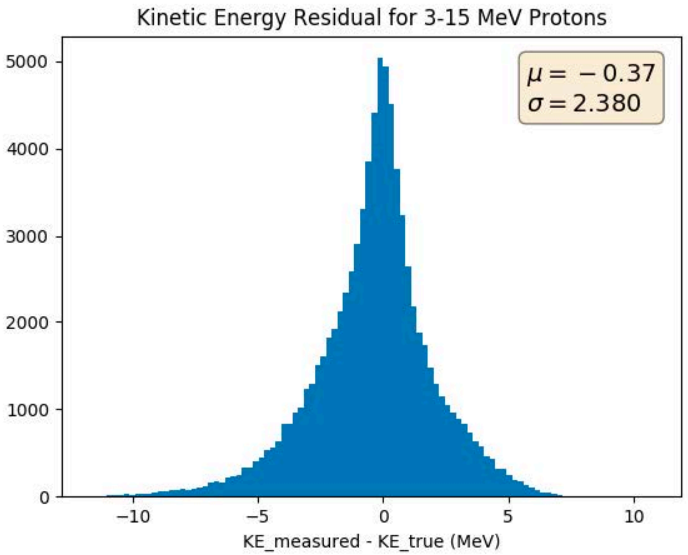




- High pressure (10bar) gas TPC + ECAL + SC magnet + μ tag
- Provides muon spectrometry for muons leaving LAr
  - LAr event containment
- Provides an independent, statistically significant event sample on Ar gas
  - Sign selection
  - Full 4π coverage
  - Very-low tracking threshold
  - Essentially no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

MPD Capabilities

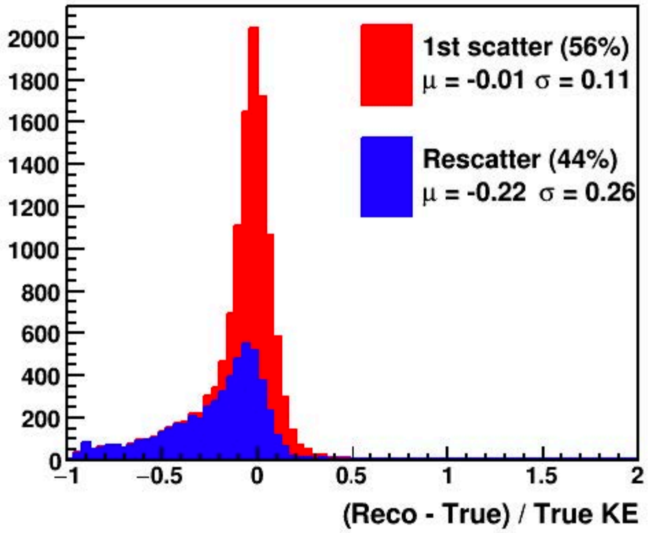
Low-energy protons



- GArSoft reconstructs event, outputs TPC hits
- TPC hits are assigned to proton candidate sets using RANSAC based algorithm
- Each proton candidate set is passed to a neural net trained on single proton events to predict KE

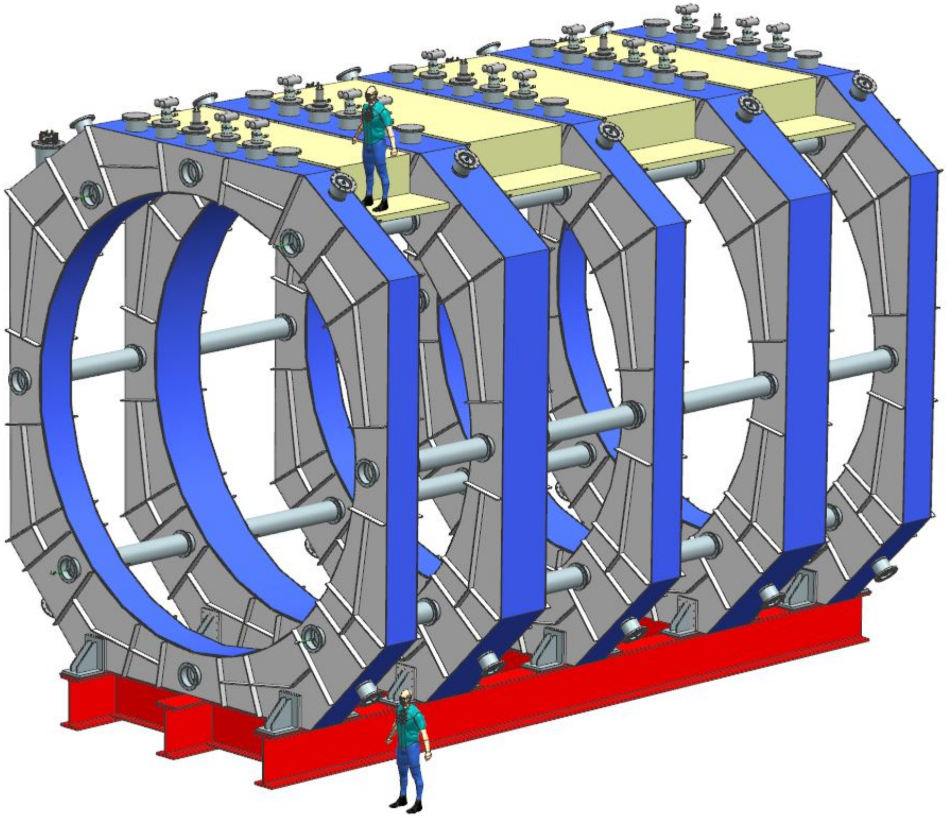
Neutrons

$50 < T_n < 100$ MeV



- The ECAL has neutron detection capability
- With time stamp from charged particle
  - Very good energy resolution when reconstructed neutron scatter is the first one
  - But due to the high passive fraction, ~50% of the events are re-scatters

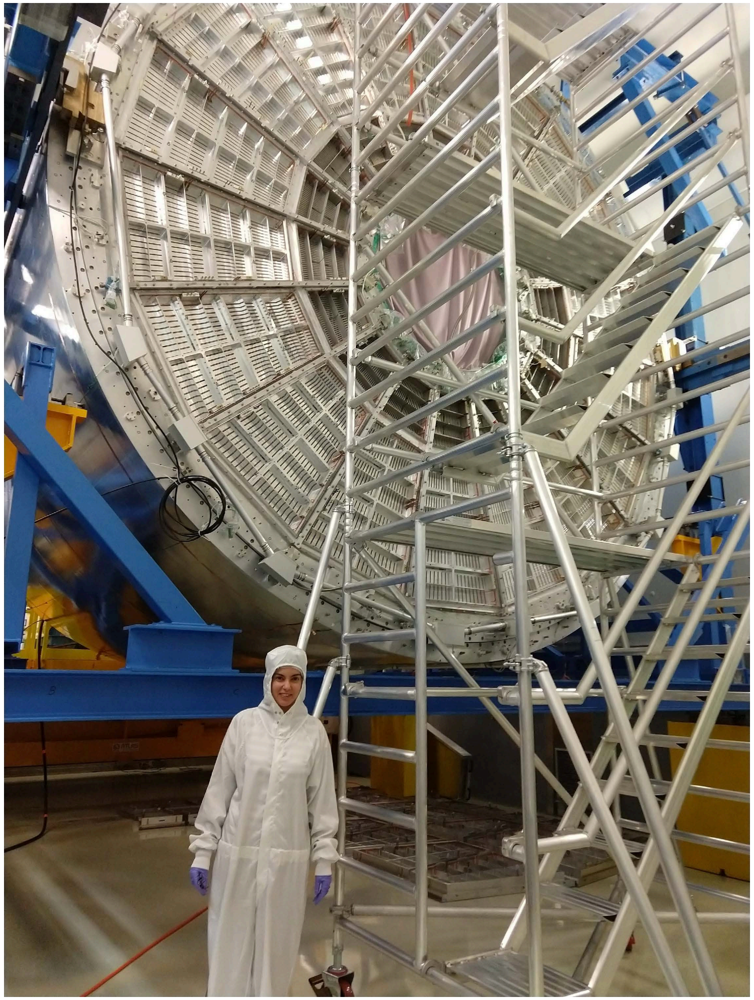
Magnet: Superconducting 3-coil Helmholtz System with 2 Superconducting Bucking Coils



Magnet design concept

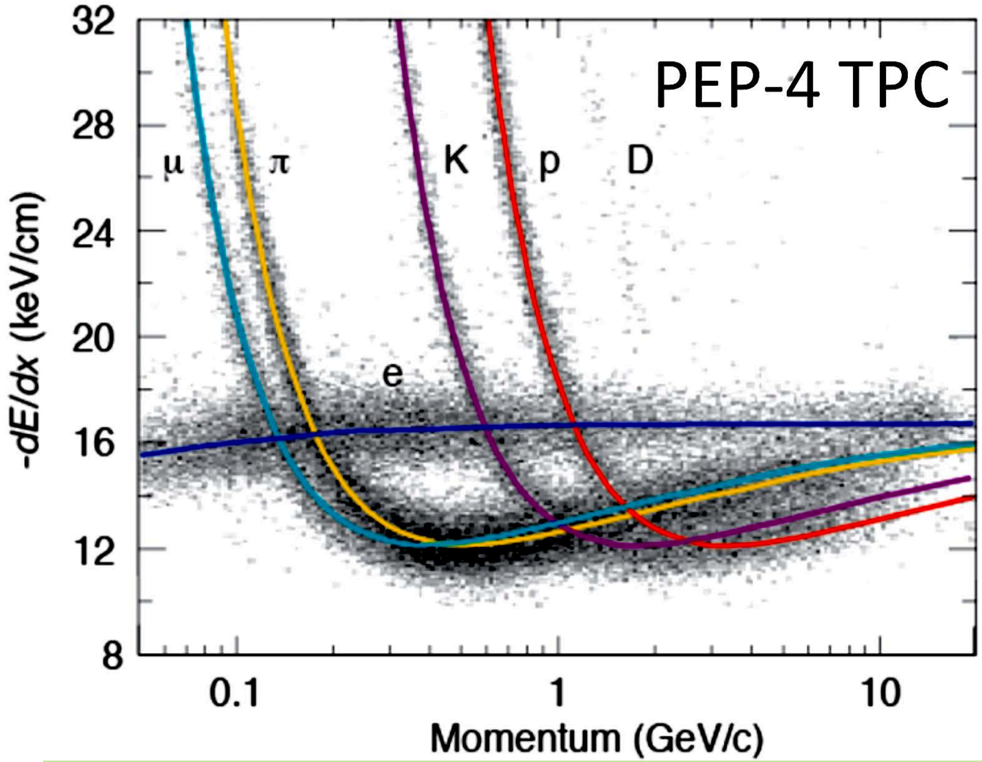
- Overarching requirements
  - Large acceptance for particles leaving LAr
  - Present minimal mass
- Central field = 0.5T
- Side coils at 2.5 m, shielding coils placed at 5 m from the magnet center in Z.
  - All coils have the same inner radius (3.5m)
  - Center and shielding coils are identical.
- Basic magnetic, cryostat and structural designs complete

High-Pressure gas TPC (HPgTPC)



Build copy of ALICE TPC reusing their wire chambers

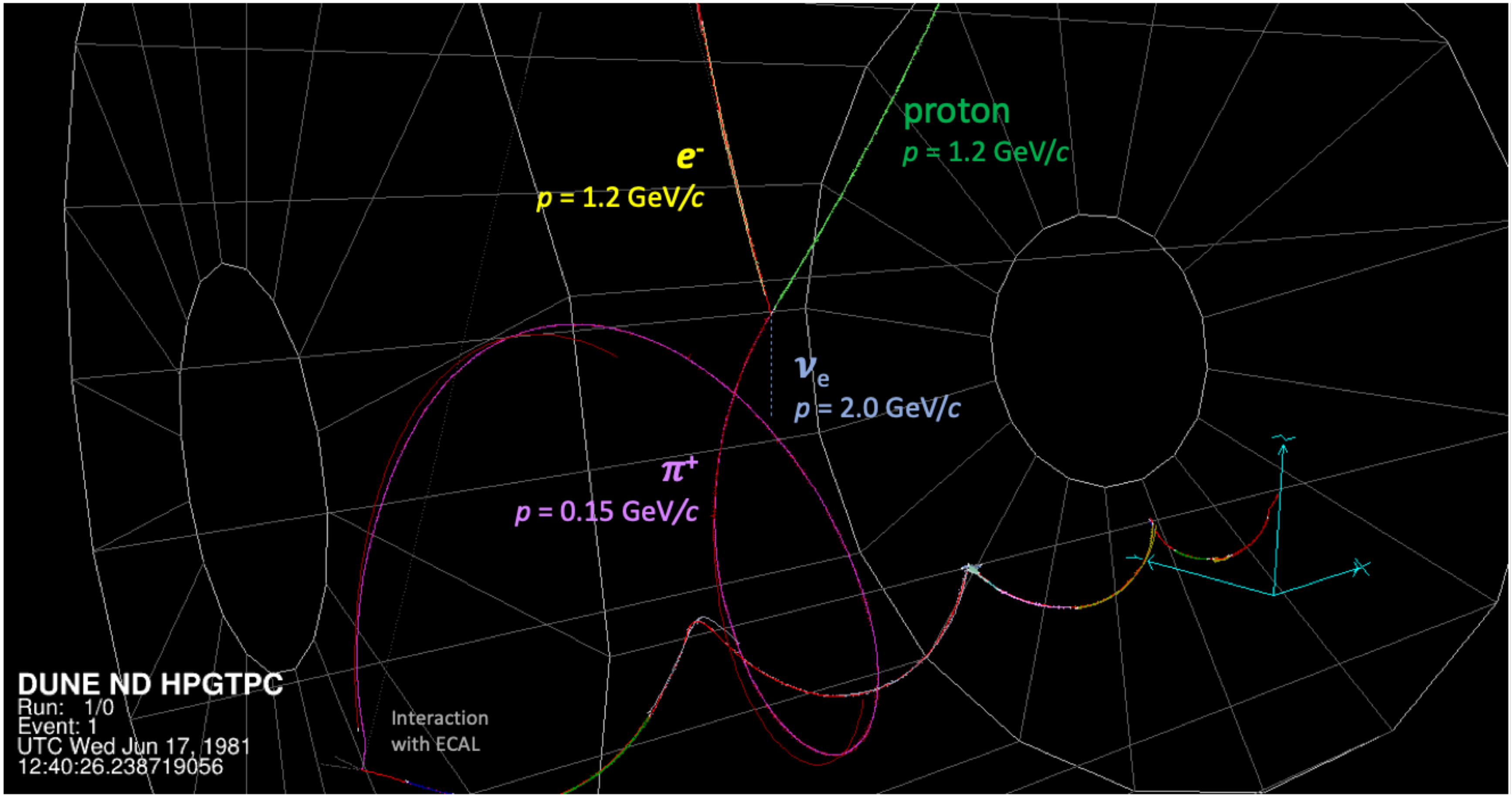
Well established technology
Vetted detector design



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

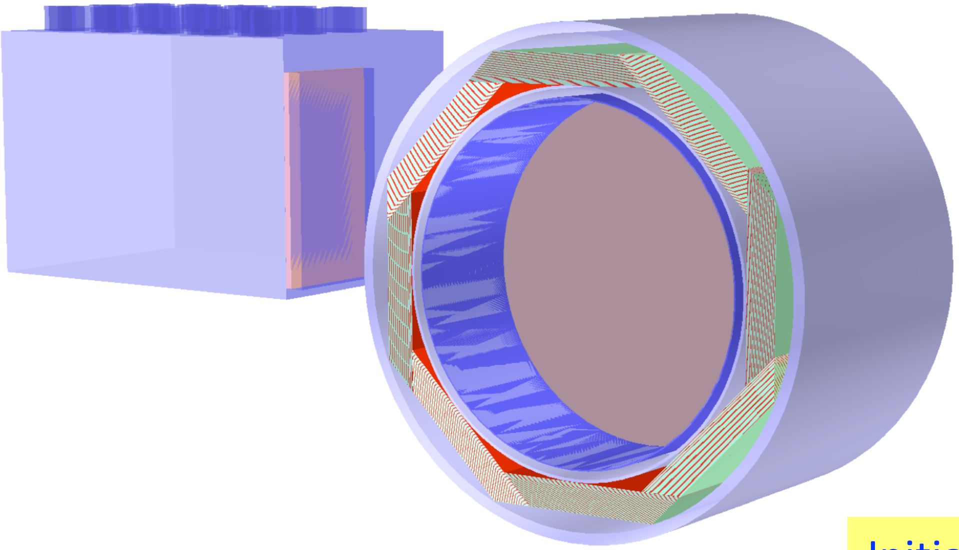
$\nu_e + Ar \rightarrow e^- + \pi^+ + p + n$

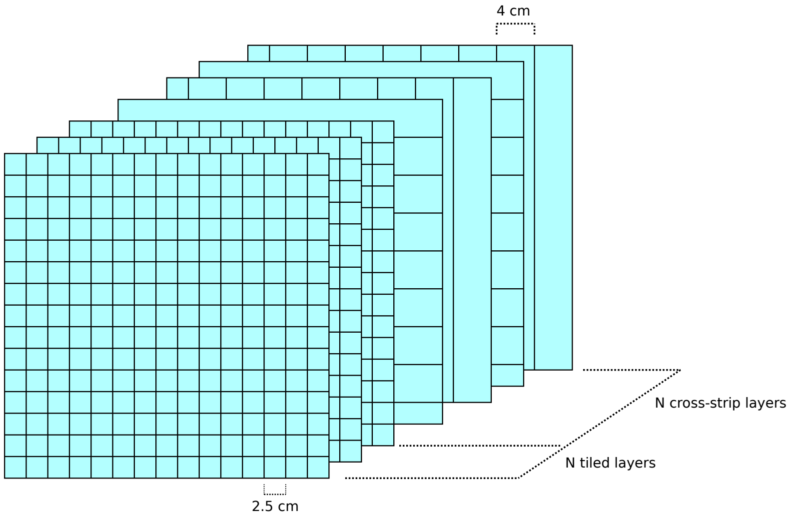


Neutron with p = 0.23 GeV/c at the P.V. not shown

ECAL

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

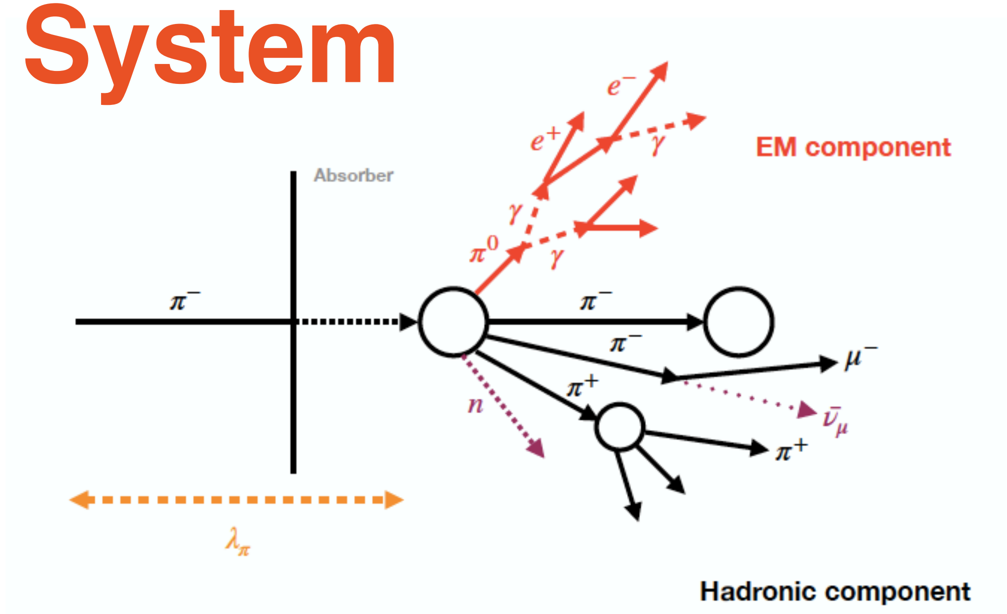


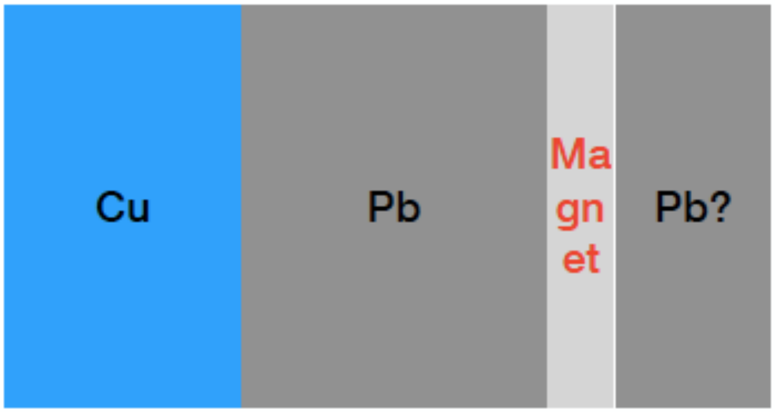


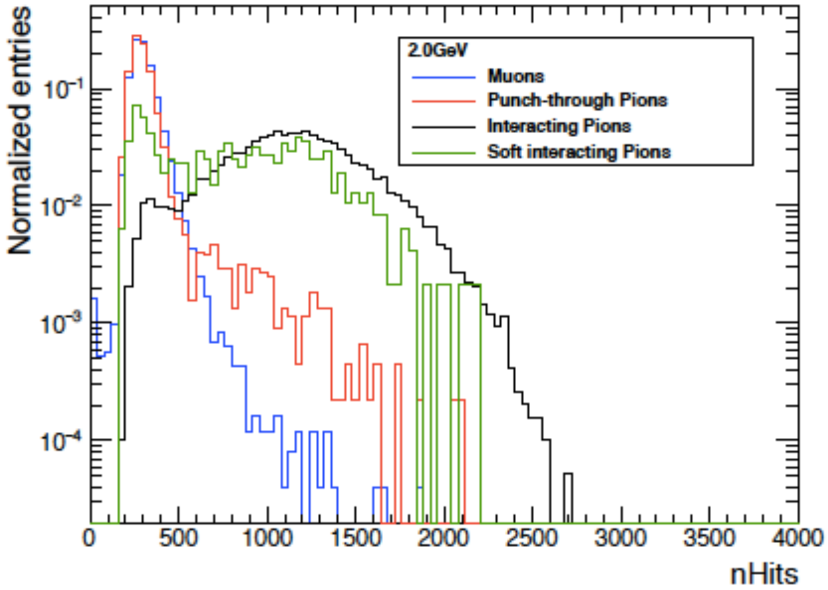
Initiated detailed optimization study

Need for Muon System

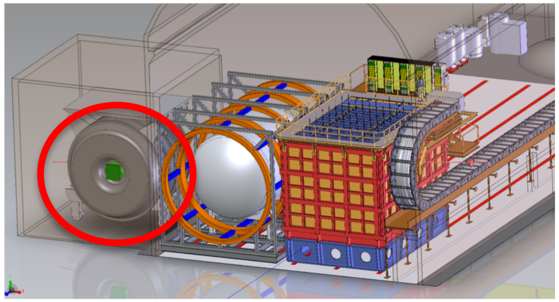
- ECal thickness ~ 1 λ
- 1/3 of pions don't interact in ECal
- Solution
  - additional absorber
  - Muon system

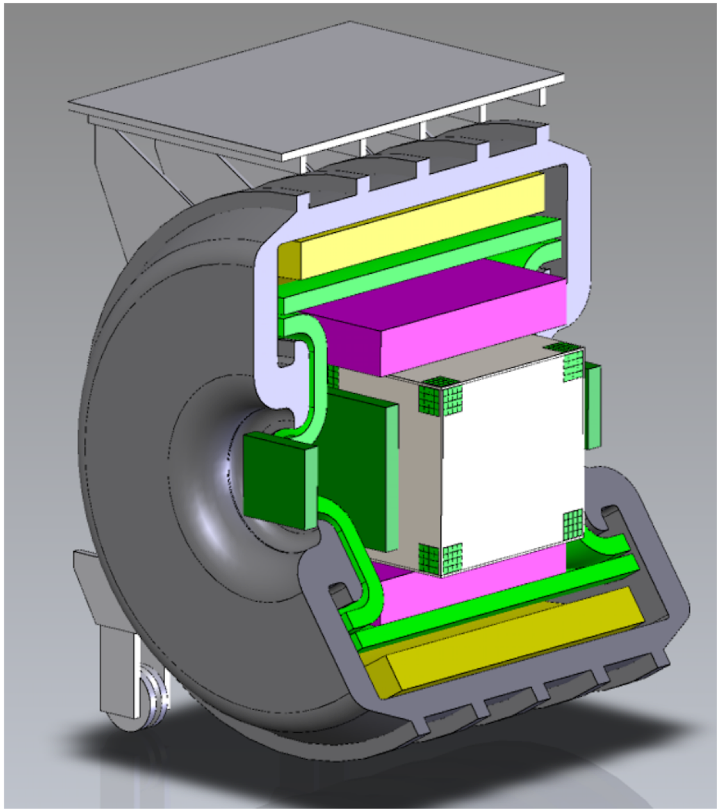






3DST-S+KLOE Overview





- 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

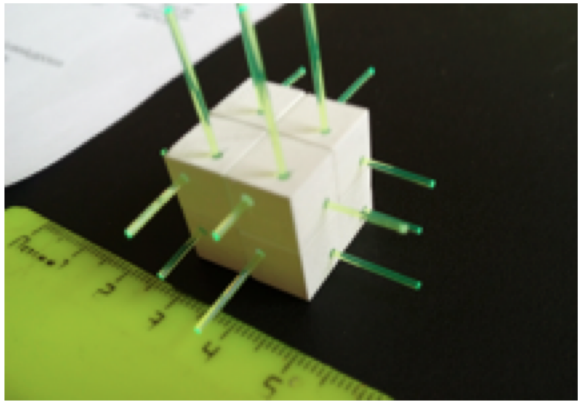
3DST-S+KLOE Details

- Active scintillating target composed of $1\text{x}1\text{x}1\text{cm}^3$ 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)



3DST-S+KLOE 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

Timeline

- May 2018: Conceptual design of ND
- May 2018: FD IDR
- July 2018: Completion of ProtoDUNE-SP construction
- July 2019: Commissioning of ProtoDUNE-DP
- Dec 2019: ND CDR
- Early 2020: baseline LBNF & DUNE-US (CD2/3a)
- Dec 2020: ND TDR, 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!

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 3DST-S+KLOE
    - 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

BACKUPS