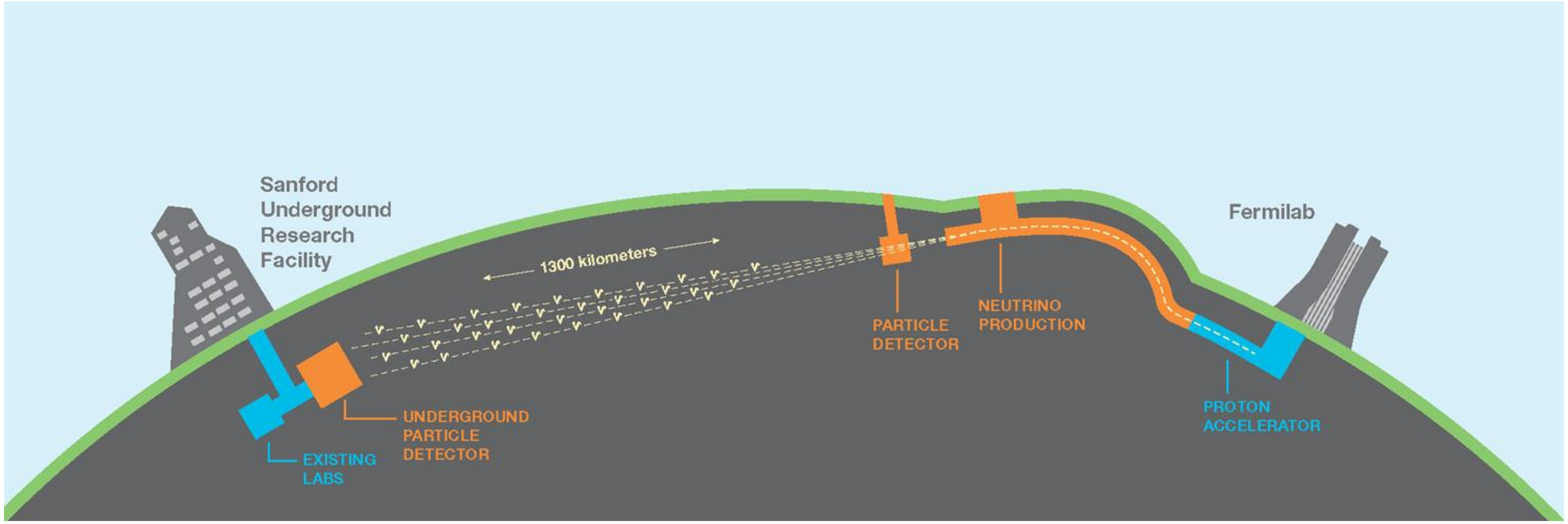
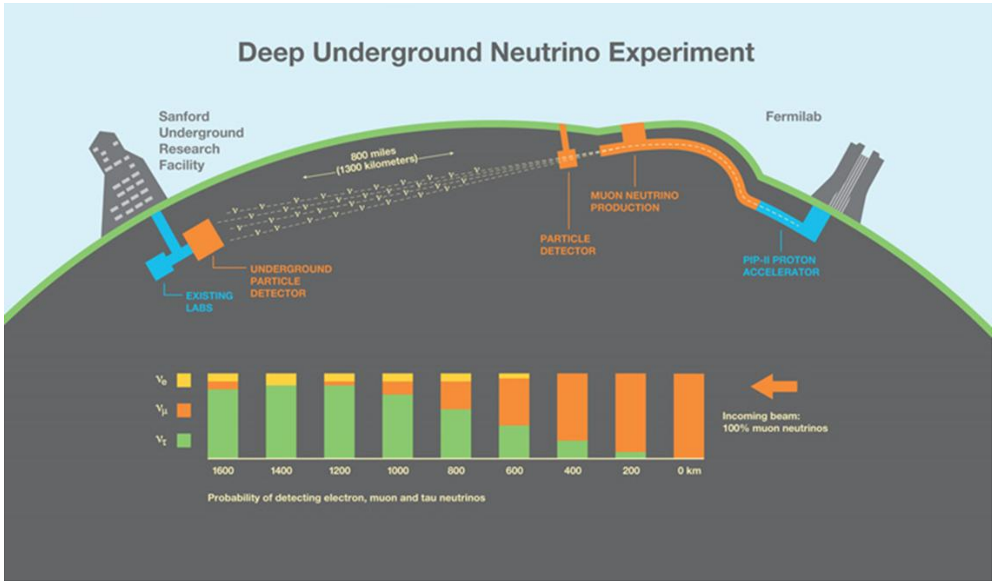
Deep Underground Neutrino Experiment

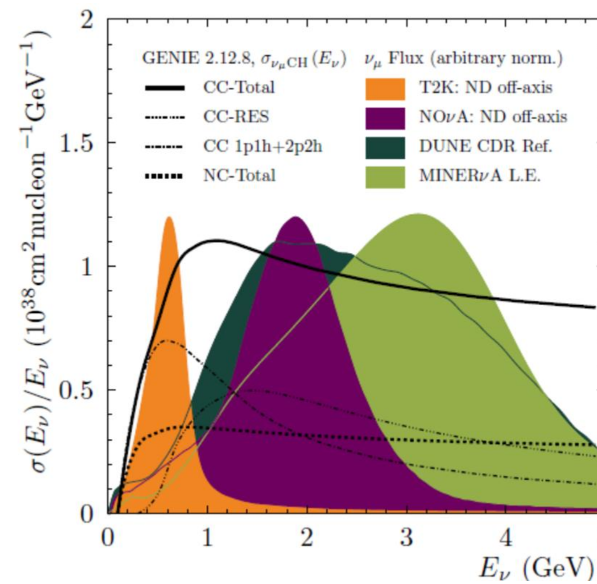


Kim Siyeon
Chung-Ang University

CPNR Workshop
October 24~27, 2025

• Long-baseline oscillation

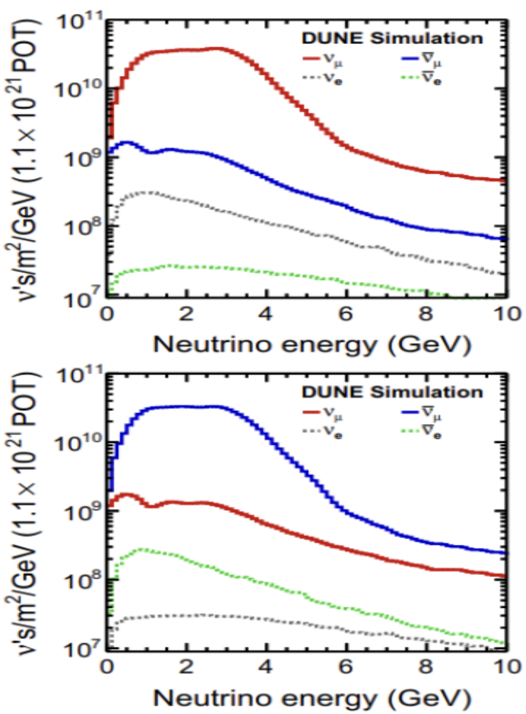




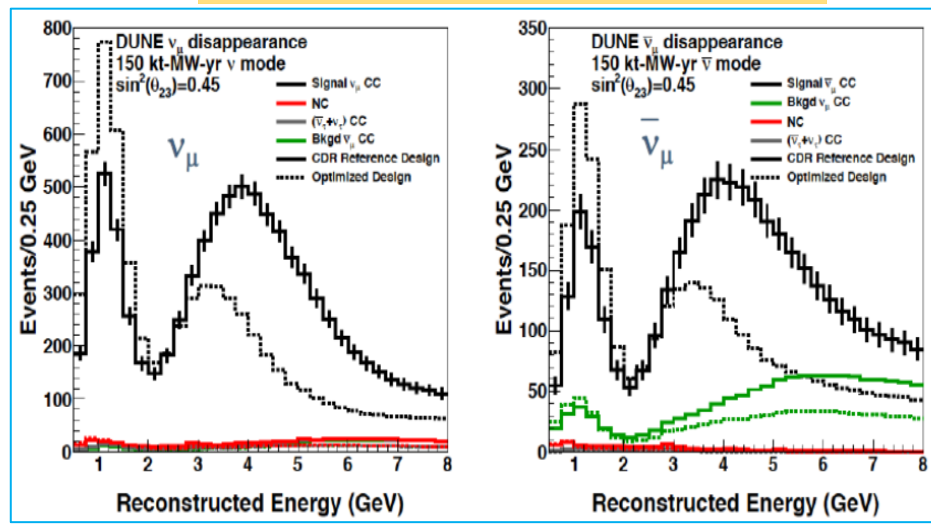
Experiment	Beam Source	Detector (threshold)	Interaction	Flavors	Physics	Status
DUNE	PIP-II NuMI (0.5~10 GeV)	L-Ar Time Projection Chamber, (a few MeV)	NC, CC, ES	all	Oscillation Interaction	Construction

Long-baseline oscillation

- 1285-km baseline
- Neutrino energy range Sub GeV ~ 10 GeV
- Neutrino mode(FHC) and antineutrino mode(RHC)
- Appearance of $\nu_e(\overline{\nu_e})$ and disappearance of $\nu_\mu(\overline{\nu_\mu})$ at FD

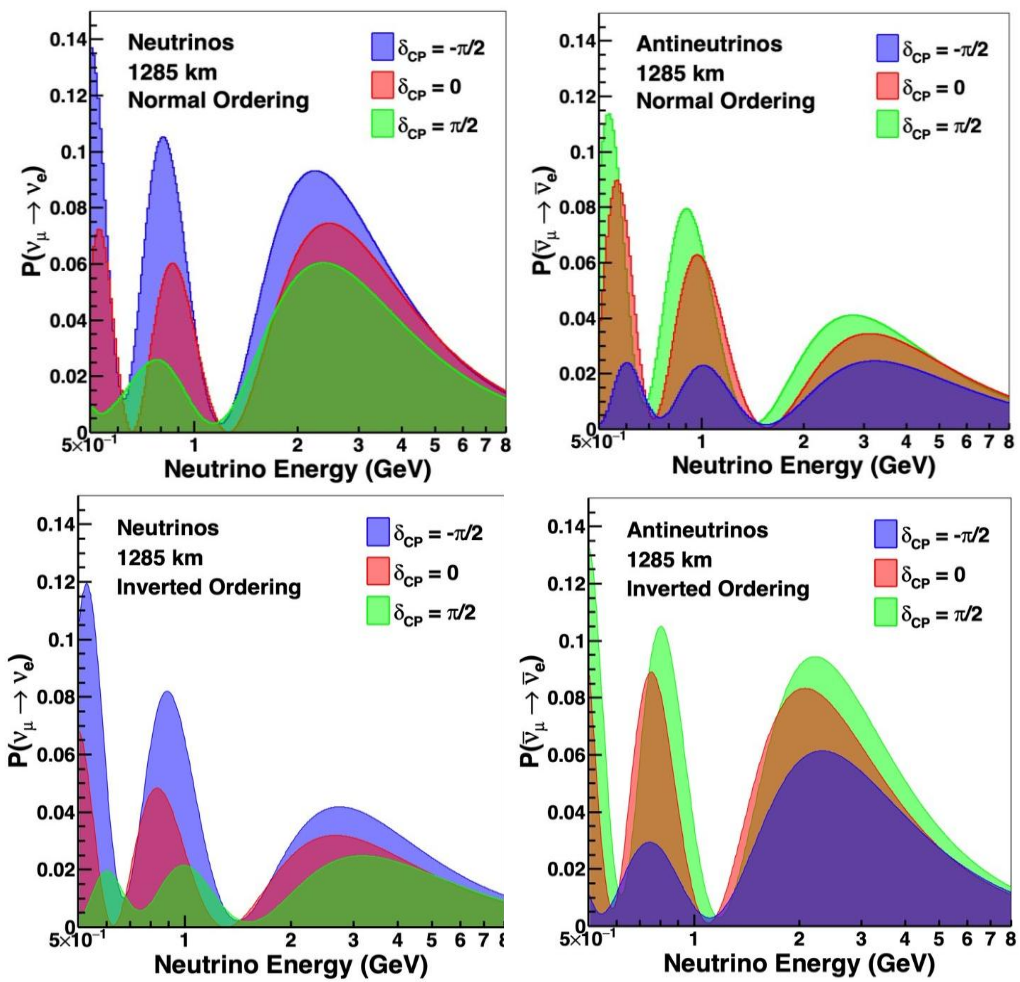


Beam Optimization

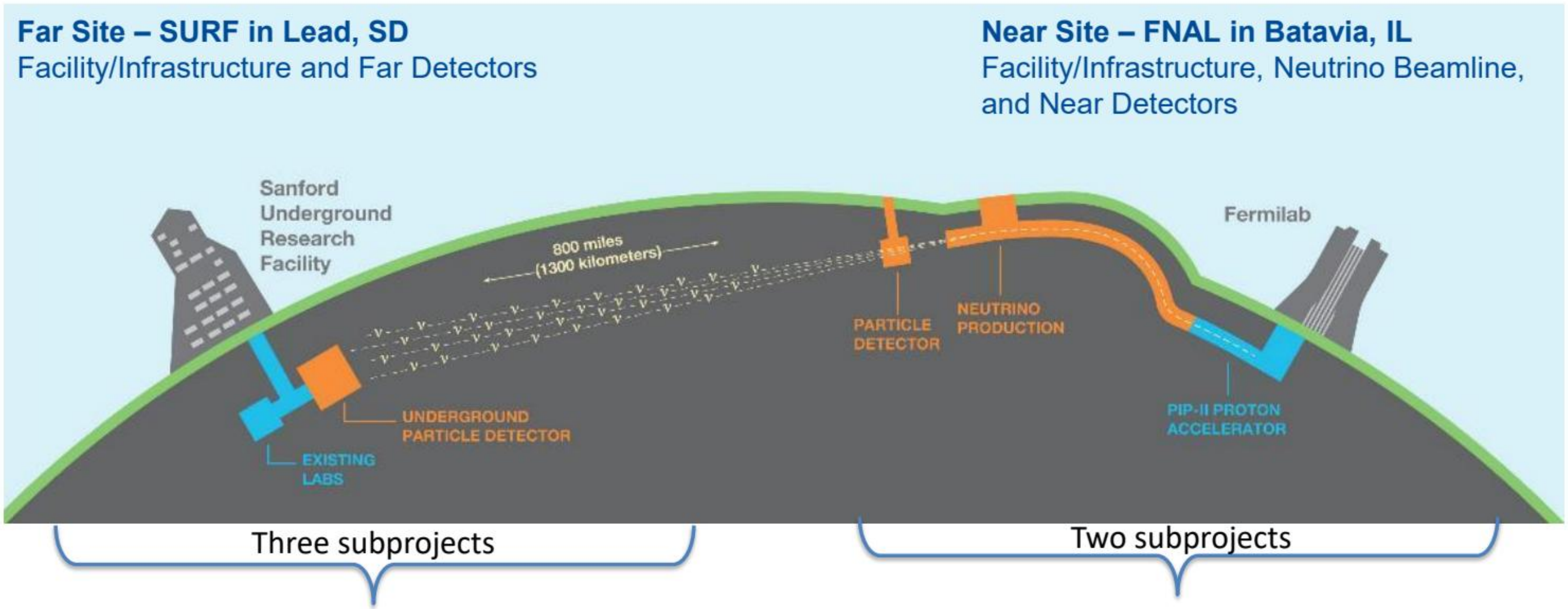


Neutrino-antineutrino asymmetry: P($\nu_\mu \to \nu_e$) vs. P($\nu_\mu \to \nu_e$)

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{\rm CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$



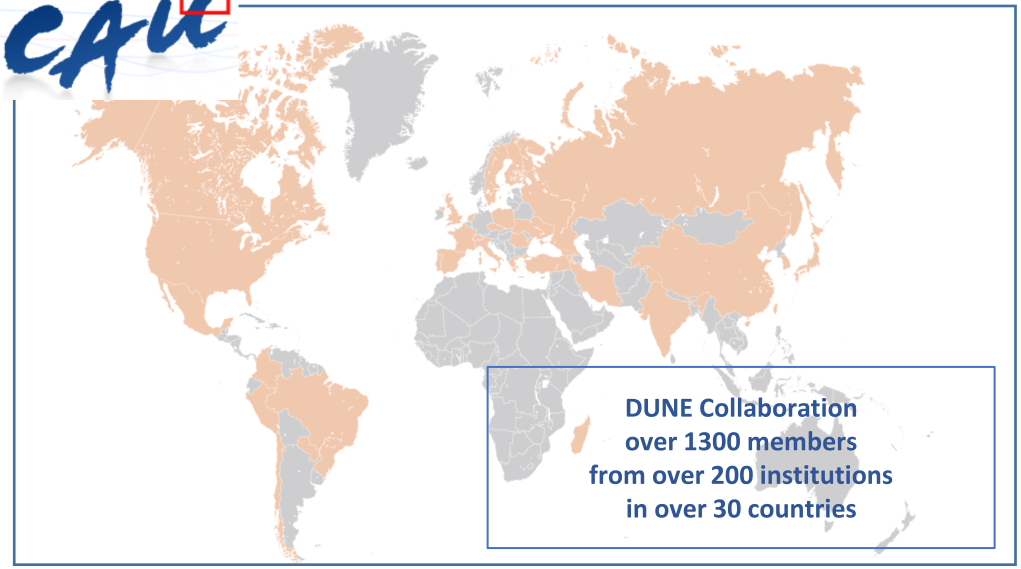
LBNF/DUNE Project - Delivered at Two Sites through Five Subprojects



- **FSCF-EXC** – Far Site Excavation
- **FSCF-BSI** – Far Site Building & Site Infrastructure
- **FDC** – Far Detectors and Cryogenic Infrastructure

- **NSCF+B** – Near Site Conventional Facilities + Beamline
- **ND** – Near Detectors

Construction Timeline



DUNE Management Group

Technical Coordination & Consortia

FD1: Eric James
FD2: Steve Kettell
DAQ | APA | Photon Detector
HV | **TPC Electronics** | CRP
Top Drift Electronics | Calibration

ND: Hiro Tanaka
ND LAr | TMS | SAND

Korean members of DUNE Collaboration
(2025년 10월 현재)

Chung-Ang University

: Kim, Siyeon (Professor, IR)
: Gwon, Sunwoo (Research Fellow)
: Masud, Mehedi (Research Fellow)

: Park, Juseong (Grad Student)
: Kim, Sunhong (Grad Student)
: Nam, Hokyeong (Grad Student)
: Park, Yujin (Undergraduate)

Jeon-Buk National University
: Shin, Seodong (Professor, IR)

Jeju National University
: Ko, Young Ju (Professor, IR)

Seoul national Univ. of Technology
: Park, Myeonghun (Professor, IR)

Physics Coordination & Working Group

Long-baseline | Atmospheric & Exotics

FD sin/reco | ND Prototype analysis

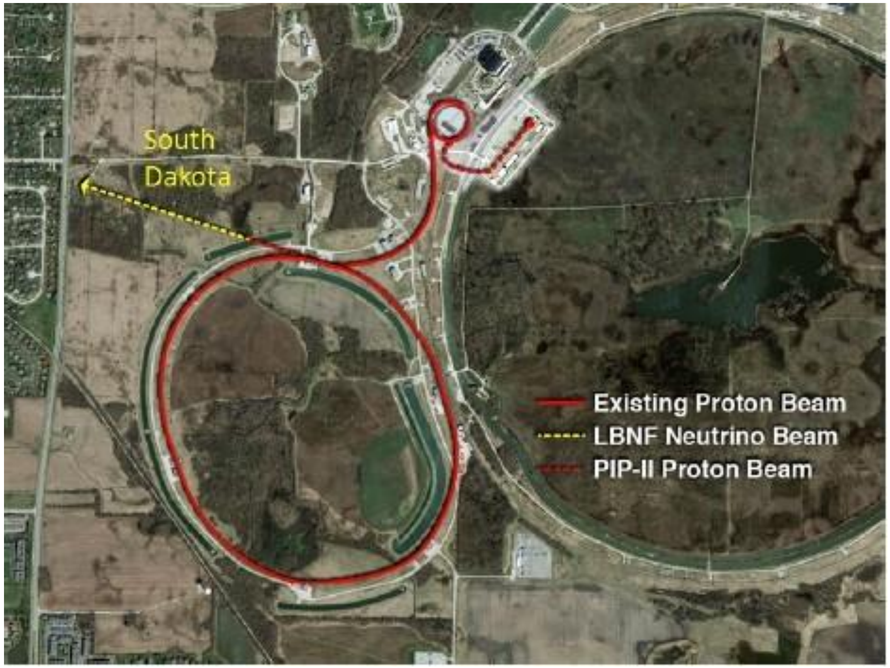
Neutrino Interactions + Uncertainties

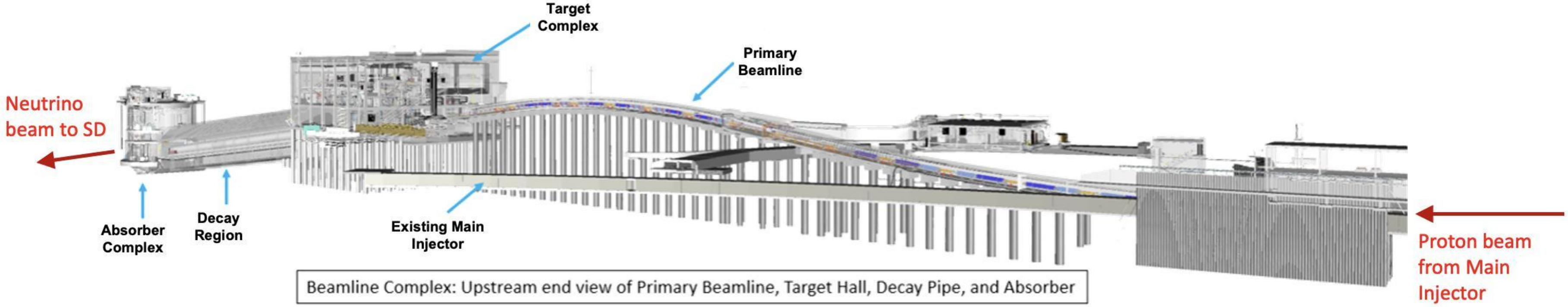
Beam BSM | ND sim/reco | Low Energy

Calibration | **ProtoDUNE Analysis**

LBNF: intense beam, underground facilities and infrastructure

- Construction of the beamline enclosure and the ND enclosure begins in 2025.
- Conventional facilities design is completed.
- Initial site work is completed.
- 1.2 MW neutrino beam from PIP-II proton beam, upgradeable to 2.4 MW

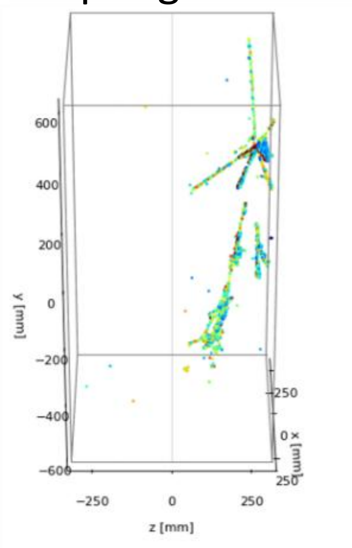




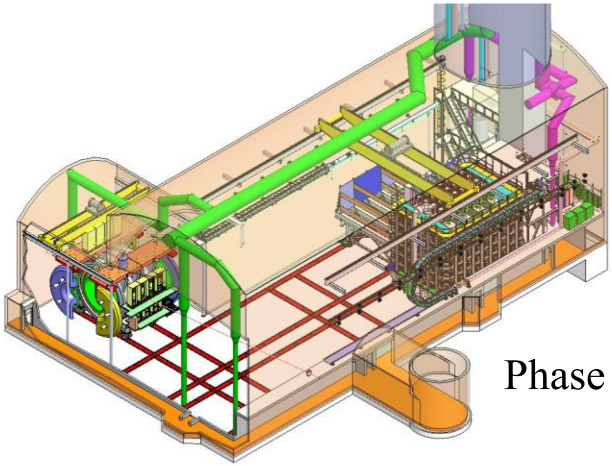
Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

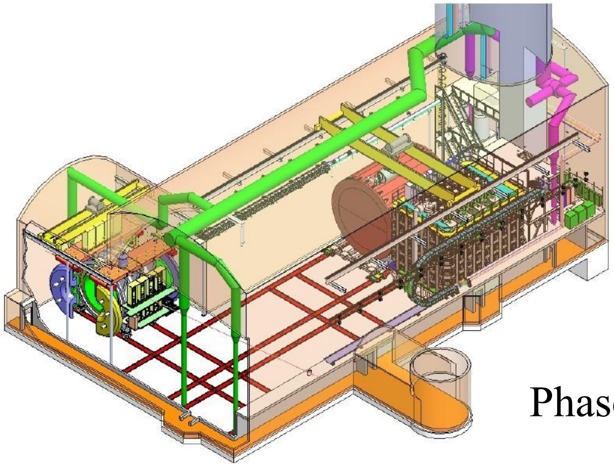
Near Detector

- Innovative design enables the first-ever operation of a liquid argon near detector in the world's most intense neutrino beam.
- Near detector critical to precision neutrino science.
- Near detector prototype installed in neutrino beam at Fermilab. Taking data this spring.

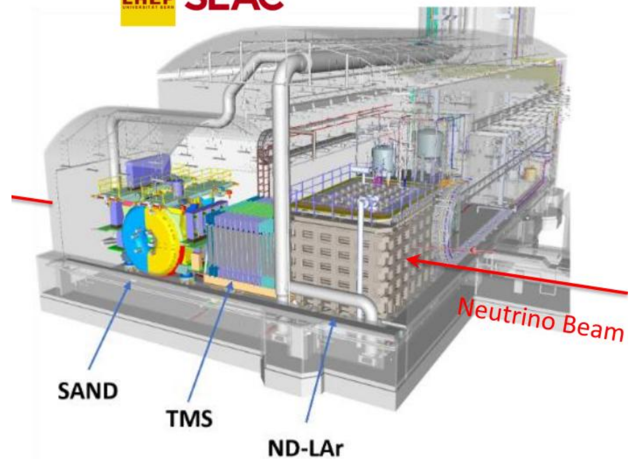


Cosmic data in ND-LAr prototype in Switzerland


Phase I ND


Phase II ND

- **Phase 1 Detector:**
  - Moveable LArTPC + Muon Spectrometer:
    - ND-LAr**:** 7x5 array of modular 1x1x3 m^3 LArTPCs with pixel readout
    - TMS: Magnetized steel range stack
    - DUNE-PRISM: ND-LAr+TMS move up to 28.5 m off-axis
  - SAND**:** On-axis magnetized detector
    - KLOE solenoid + electromagnetic calorimeter
    - GRAIN (LAr target with optical readout) + Inner Tracker



Far Detector Cryostat

- Departed Spain in May Arrive in Houston in June
- Warm structure 2,500 ton (3rd barrier, fastens and fittings)

Black Hills Pioneer

Friday, January 19, 2024 Vol. 148 No. 161 Since 1876 $1.50

First components for DUNE experiment in Lead

The first of what will eventually be 2,000 pieces of the cryostats for the deep underground neutrino experiment arrived in Lead last week. This spring members of the LBNF/DUNE team will work with Sanford Lab employees to begin tests to ensure the massive pieces can be safely and efficiently lowered down the Ross Shaft.
Photo by Stephen Kenny

By Wendy Pitlick
Black Hills Pioneer

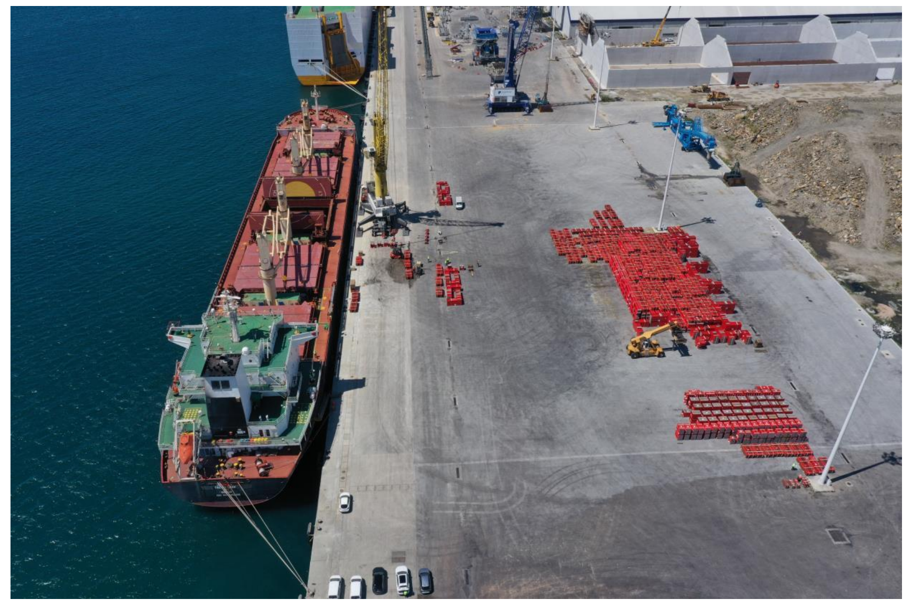
LEAD — The first components for the deep underground neutrino experiment have arrived in Lead, and starting this spring the LBNF/DUNE project team and officials with the Sanford Lab will begin tests to ensure cryostats for the experiment can be safely lowerd down the Ross Shaft.

That's because the components are massive. The first piece is more than 8 tons and 40 feet by 3 feet by 1.5 feet. The second piece is nearly 6 tons and 18 feet by 11 feet. Both pieces form just a corner of the massive cryostat for the deep underground neutrino experiment. When they're lowered down the Ross Shaft, they will have a clearance of about 3 inches on each side.

Jolie Macier, DUNE far detector and cryogenics project manager from Fermilab, said the size of the pieces present challenges that members of the collaboration wanted to work out before it is time to actually assemble the cryostats underground. Besides the massive size of the first piece, the smaller piece, referred to as the "L beam," has its own set of complications, Macier said.

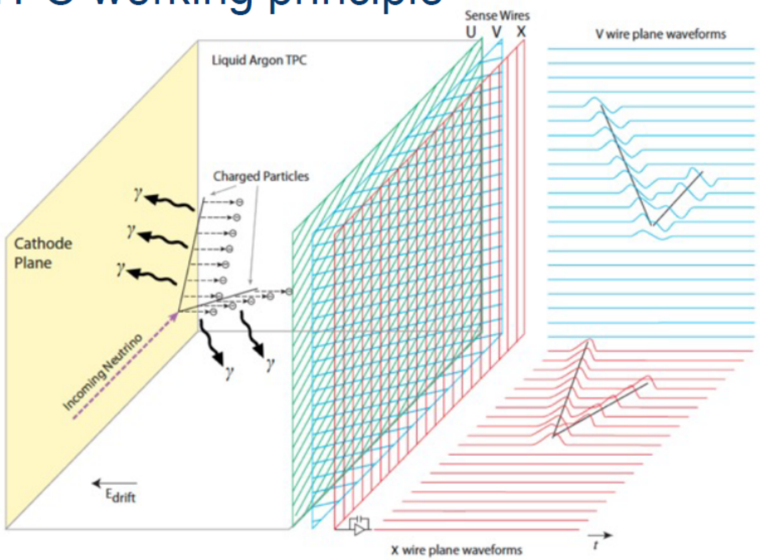
"It has a center of gravity that is a challenge," she said. "That's why we wanted some extra time to be able

DUNE COMPONENTS Pg 6



The Single-Phase LAr-TPC

TPC working principle



- Ionization electrons [~5 fC/cm] drift to the anode in pure LAr & uniform E-field (~500 V/cm)
  - Few mm pitch and ~MHz sampling frequency
  - 3D via multiple 2D view (wire# vs drift time)
  - high imaging capabilities → kinematic reconstruction with mm-scale spatial resolution
  - Intrinsically excellent Calorimetry and Particle Identification (dE/dx) capability
- Prompt scintillation light (@128 nm)
  - T = 0, trigger, calorimetry

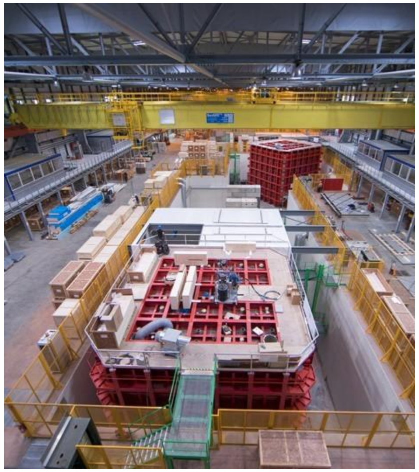
LAr as radiation detection medium

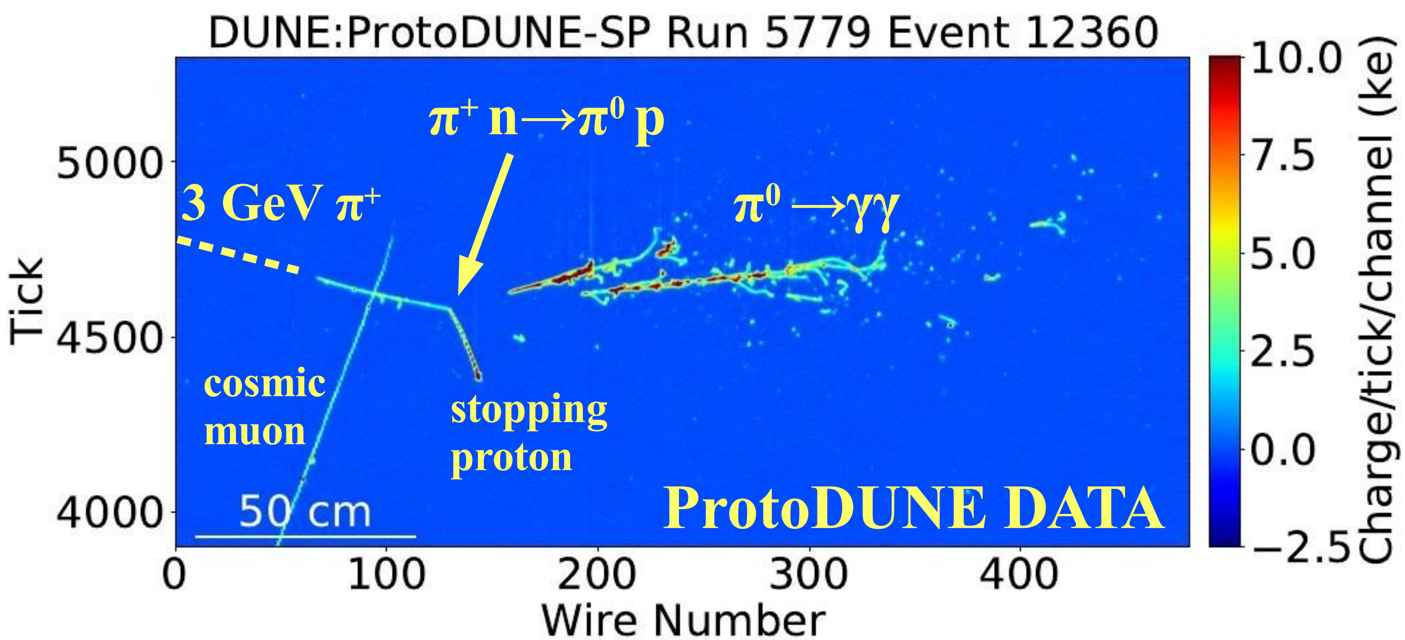
- Dense: 40% more than water
- Abundant primary ionization: 42 000 e^-/MeV
- High electron lifetime if purified → long drifts
- High light yield: 40k γ/MeV
- Easily available: ~1% of the atmosphere
- Cheap: $2/L ($3000/L for Xe, $500/L for Ne)

- Technological challenges
  - LAr continuous purification << 0.1 ppt O_2 eq. (>> 3 ms electron lifetime) for long drift
  - Imaging & anode planes
  - Very low noise front end amplifiers to detect ~ fC primary charge deposition
  - Large area photon detectors sensitive to 128 nm wave length
  - HV system to provide uniform/stable E-field in large drift volume
- Pioneered by ICARUS and adopted in present and next generation neutrino ezperiment (μBoone, SBND, DUNE)
  - DUNE: scaling to multi-kt size

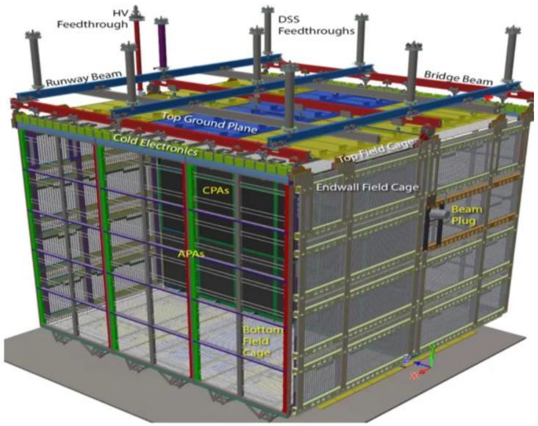
LArTPC technology provides exquisite resolution

- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- High Resolution & Low thresholds:
  - sensitivity to few-MeV neutrinos, hadrons
  - excellent for LE neutrino and BSM Search



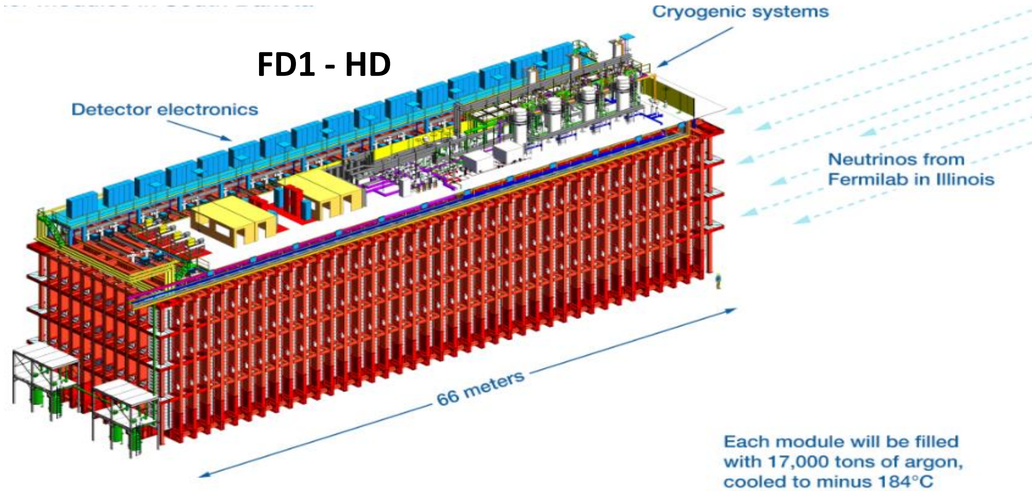


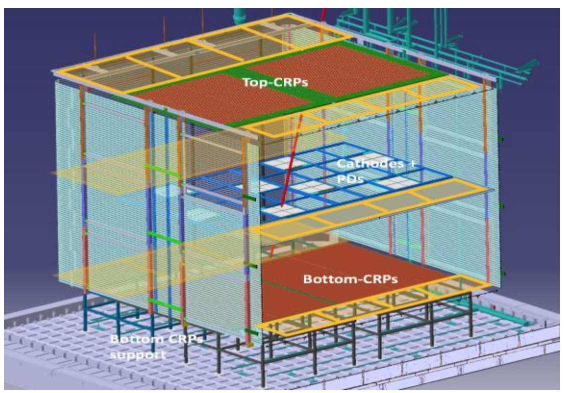
Liquid Argon Time Projection Chamber in ProtoDUNE



ProtoDUNE - HD

FD1 - HD

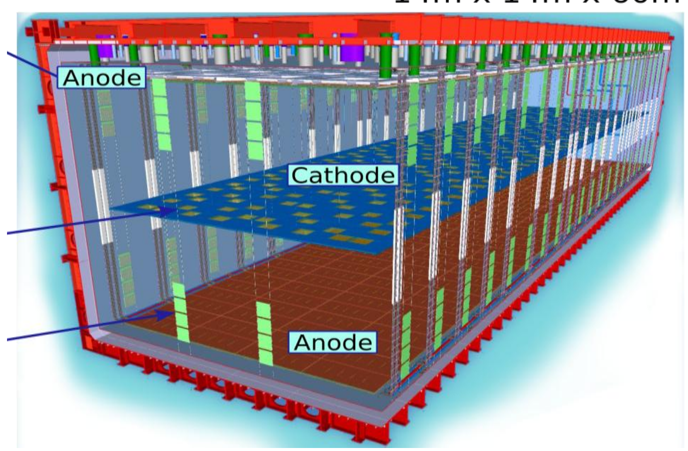


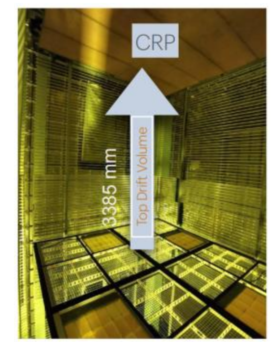


ProtoDUNE - VD

FD2 - VD

14m x 14m x 60m





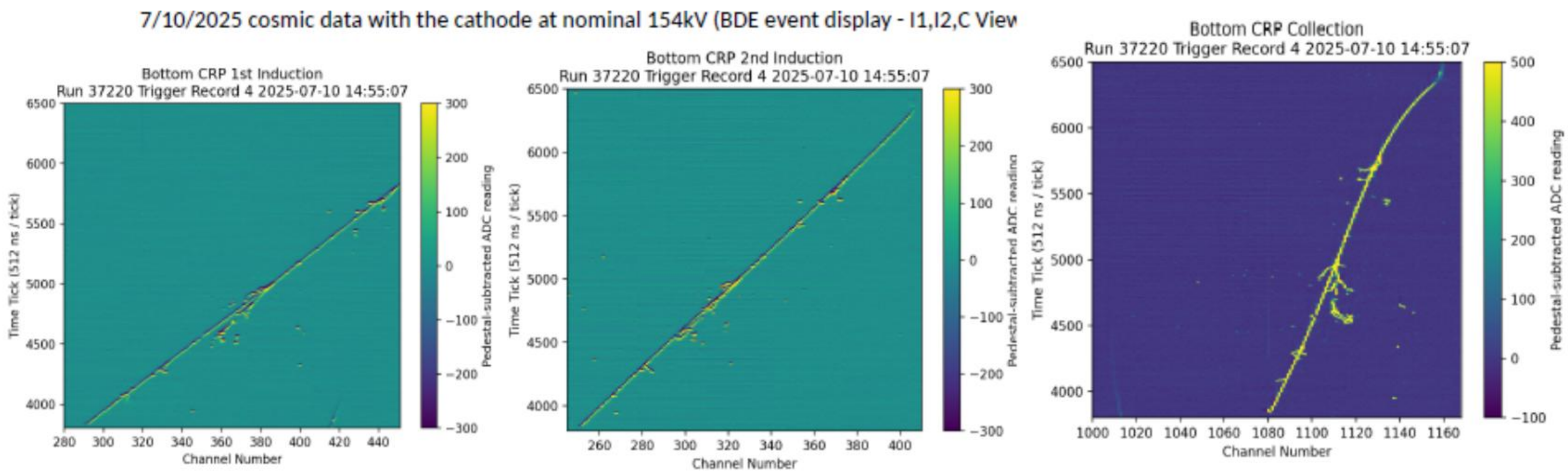
2025 ProtoDUNE Run-II (2단계) 가동, 실제 검출된 데이터 분석 실행
2026-2027 DUNE FD(원거리 검출기) 설치
2027-2028 DUNE FD 데이터 분석 실행

ProtoDUNE, DUNE FC as of Sept.2025

- NP04: Both beam and cosmic data available.
  2024 data being prepared for X-section and other physics.

- FD1 APA Production in UK and US | Cold electronics FEMB | HVS |
  PDS cold electronics | Photon Detector Module

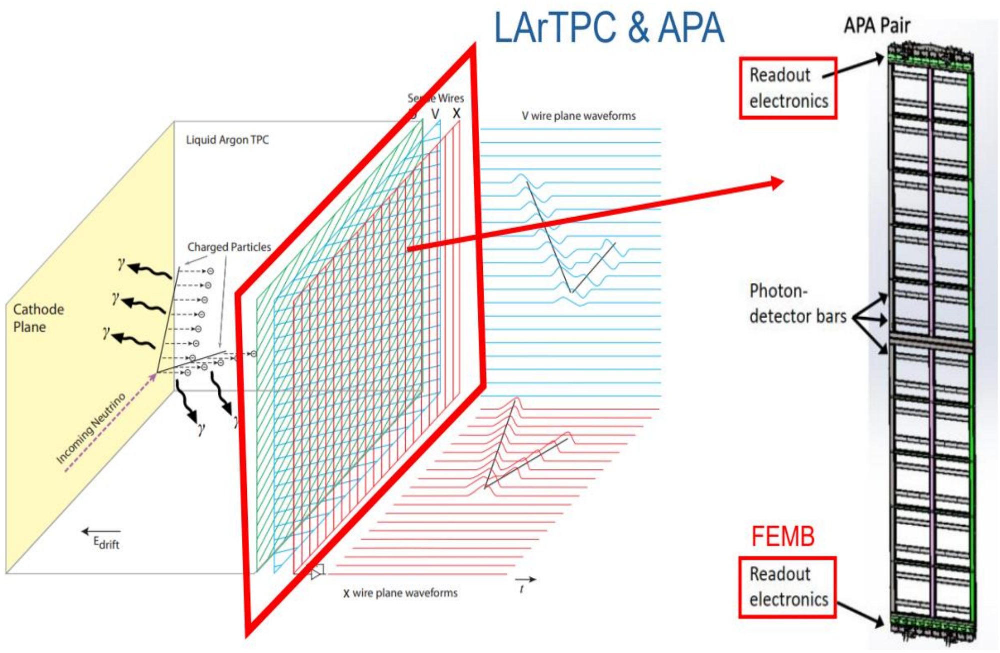
- NP02 and FD2:
  NP02 operating, exposed to charge-particle beam, commissioning e-noise investigations, beam plug, PDs, PMT’s, etc
  FD2 Started productions in France and US, Progress in PRRs

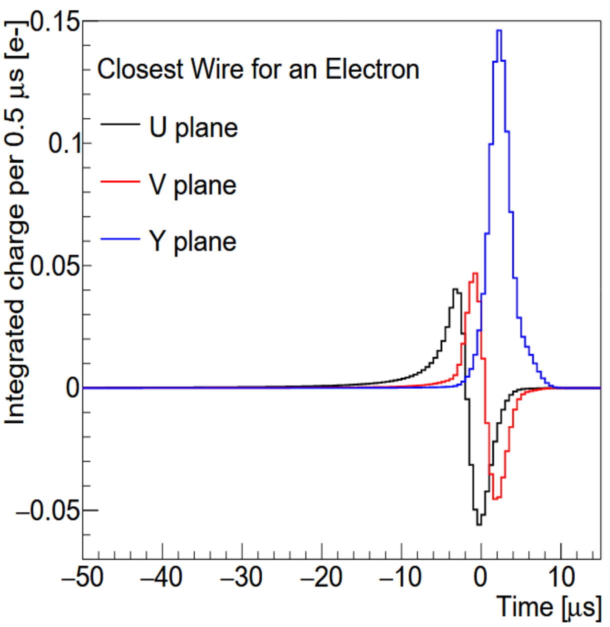


From Detection to Analysis

LArTPC U, V, X wires → Cold Electronics → Warm Electronics → DAQ → Data Processing → Event Selection → Reconstruction → Physics Analysis

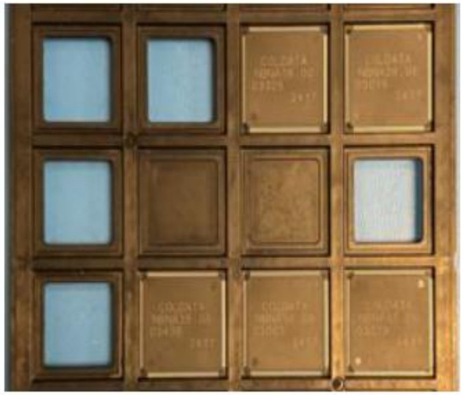
Event Generation → Simulation → Data Processing → Event Selection → Reconstruction → Physics Analysis



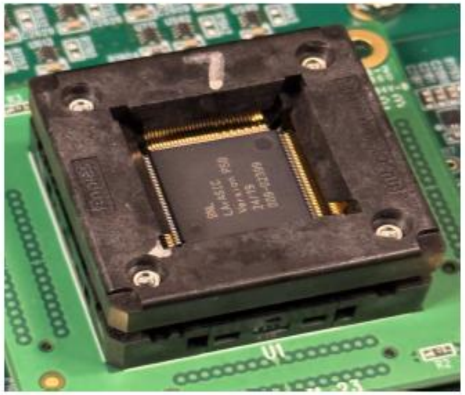


Cold Electronics Readout

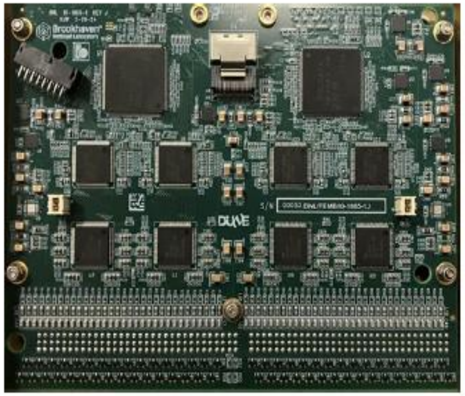
❖ COLDATA



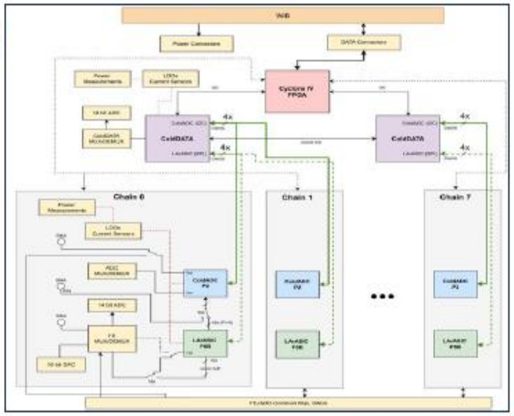
❖ LArASIC

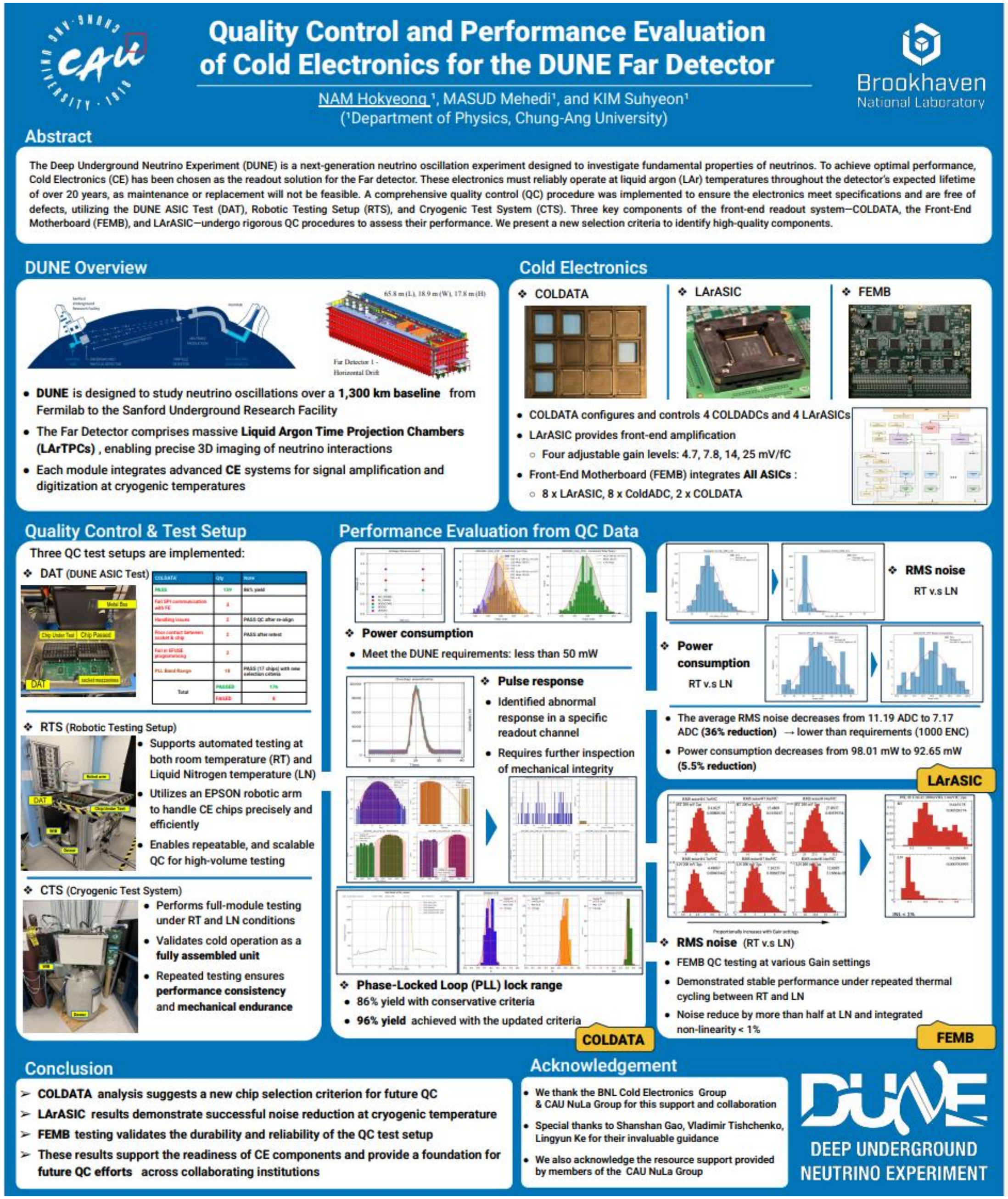


❖ FEMB



- COLDATA configures and controls 4 COLDADCs and 4 LArASICs
- LArASIC provides front-end amplification
  - Four adjustable gain levels: 4.7, 7.8, 14, 25 mV/fC
- Front-End Motherboard (FEMB) integrates **All ASICs** :
  - 8 x LArASIC, 8 x ColdADC, 2 x COLDATA





- CAU NULA

  Finalizing an internal report on performance evaluation

  Cold Electronics Working Group making a paper for publication

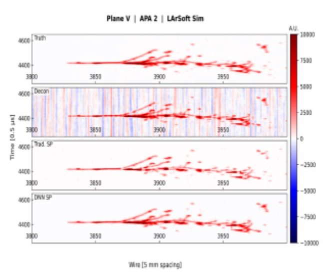
Wire-Cell and DUNE/ProtoDUNE Analysis

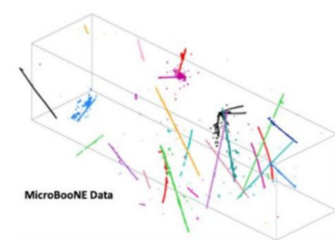
NAM Hokyeong[1], PARK Yujin[1], PARK Juseong[1], KIM Sunhong[1], SIYEON Kim[1]
([1]Department of Physics, Chung-Ang University)

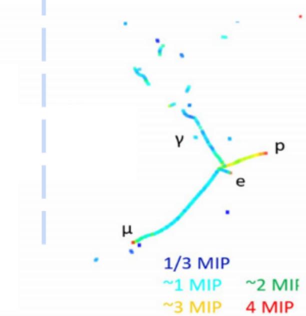
Brookhaven National Laboratory

Wire-Cell Toolkit

Part 1:	Part 2:	Part 3:
Simulation	3D imaging	3D vertexing
Noise Filtering	Clustering	Particle Identification
Signal Processing	Charge-Light Matching	3D Pattern Recognition
	Neutrino Event Selection	







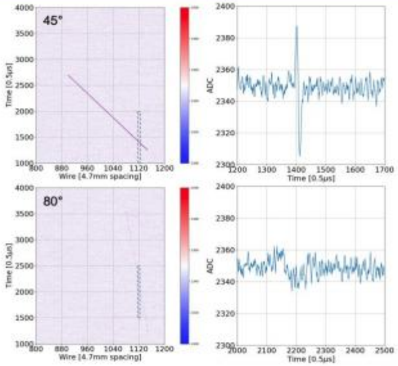
MicroBooNE → SBND, ProtoDUNE-HD, ProtoDUNE-VD, DUNE FD

Liquid Argon Software:

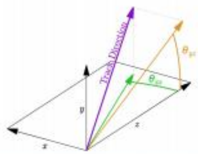
Simulation and reconstruction packages for LArTPC detectors

- **Event generation: Genie, CORSIKA, CRY, SingleGen module**
- **Simulation: GEANT4, FLUKA**
- **Reconstruction: Wire-Cell, Pandora**

DNN Signal Processing Motivation

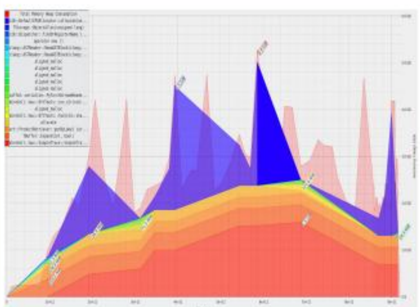


- Object with large θ_xz angles
  → **Prolonged topology**
- Object with small θ_xz angles
  → Isochronous topology
- Prolonged topologies lead:
  - Poor S/N ratio in induction wire planes
  - Disconnected objects in reco.
    & issues in 3D imaging and clustering



X axis - electric field direction
Y axis - vertical upward
Z axis - beam direction
arXiv: 2007.06722

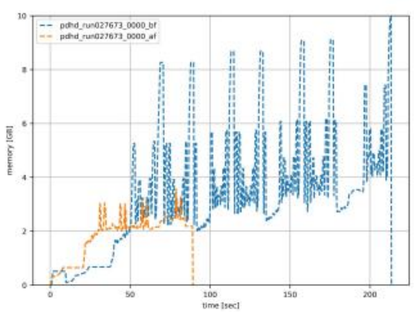
Memory Usage Optimization



- Memory profiling using Valgrind Massif tool
- The cause of excessive memory usage
  - ML inference peak (blue)
  - duplication of data saving pipeline (red)

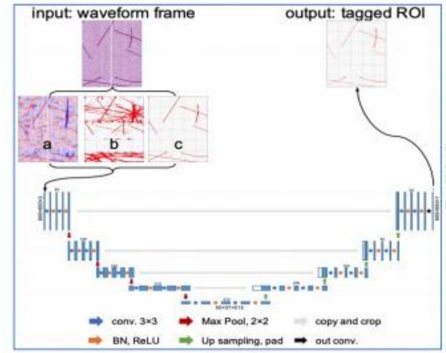
Strategy

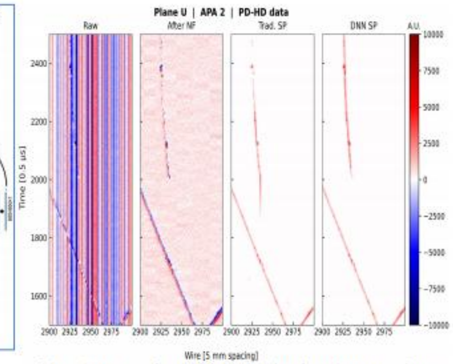
1. Lightweight *MobileNetV3* architecture as backbone
   → less number of parameters
2. Dedicated filter for duplicated pipeline
   → Keep only the necessary data



- DUNE computing environment recommends keeping memory usage below 4 GB
  → DNN SP was not applicable yet
- After the optimization, the memory usage is reduced from 10.0 GB to 3.6 GB
- Through an additional memory optimization (chunking for ML inference), the memory usage can be further reduced

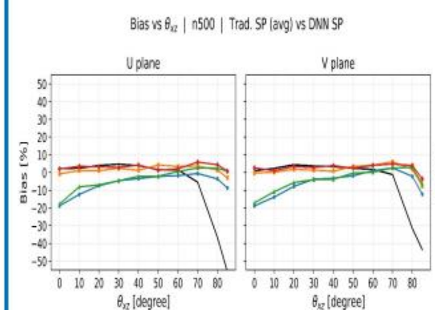
DNN Signal Processing Results

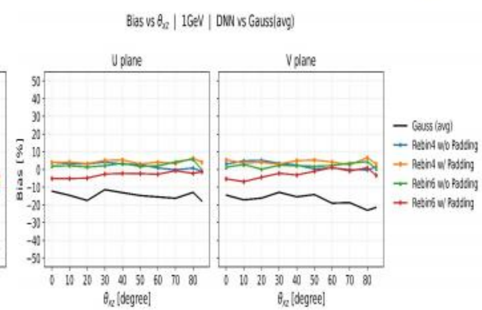




❑ DNN-based ROI finding ❑ 2D waveform evolution in signal processing

- Input features for ML training: loose low frequency filter - noise, multi-plane coincidence
- U-Net like architecture: encoder - decoder
- DNN-based signal processing (DNN SP) demonstrated
  - better charge reconstruction performance in prolonged topology
  - capability to truncate "tear drop"
- Performance evaluation showed the DNN SP could be a better option specifically in prolonged topology





❑ Single track evaluation ❑ Single shower evaluation

Conclusion

- Wire-Cell Toolkit has been actively developed for LArTPC experiments
- DNN SP showed better charge reconstruction performance
- Memory optimization made it possible to use the DNN SP in the actual DUNE workflow
- DNN SP becomes more important as cosmic backgrounds are prolonged in ProtoDUNE-VD

Special Welcome

- New member Institutes in 2025
  - Jeju National University
    (IR: Ko, Young Ju)
  - Seoul National University of Technology
    (IR: Park, Myeonghun)

- Expecting a transition in DUNE experiment and a promotion in K-DUNE in upcoming years,

  Please do not postpone joining DUNE.