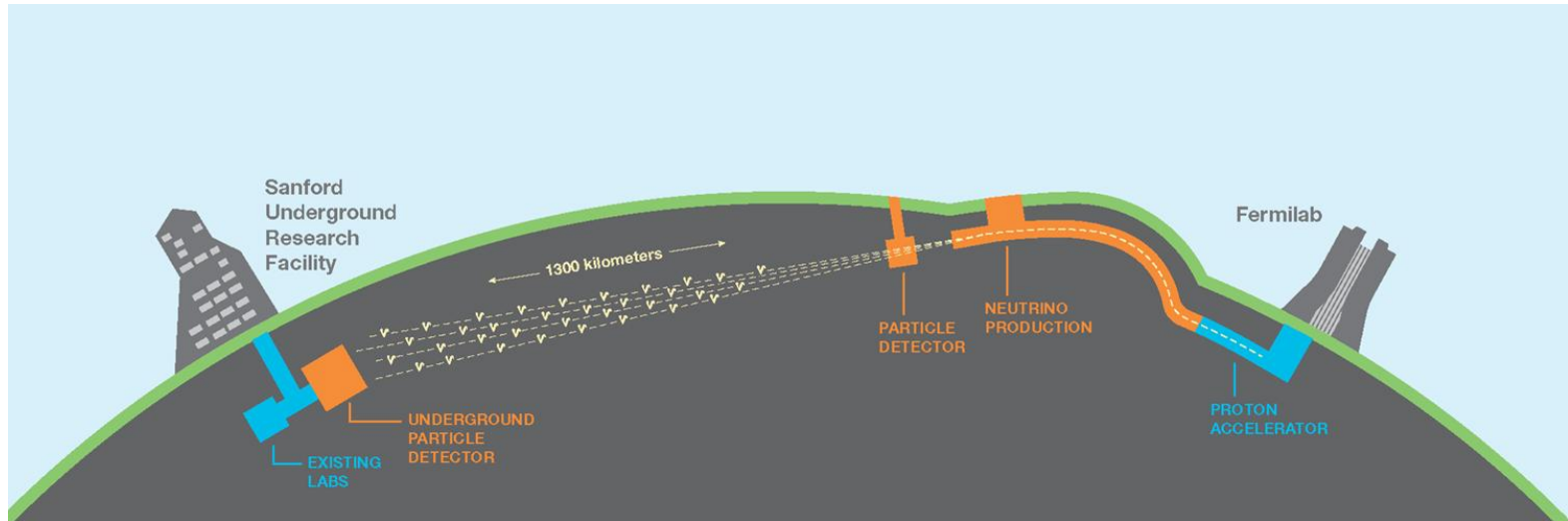


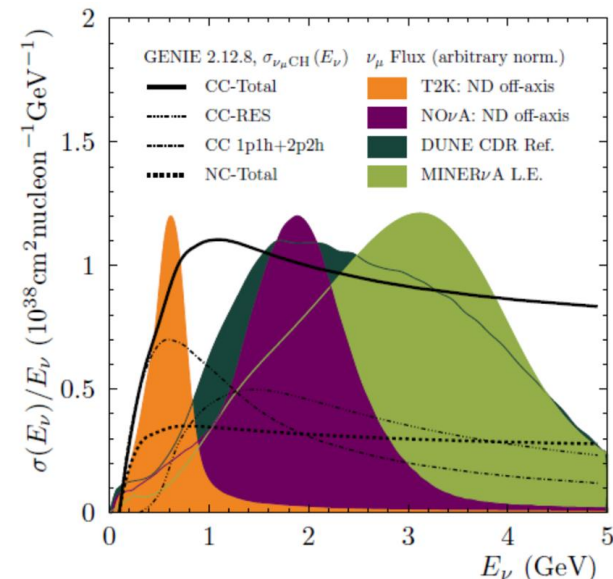
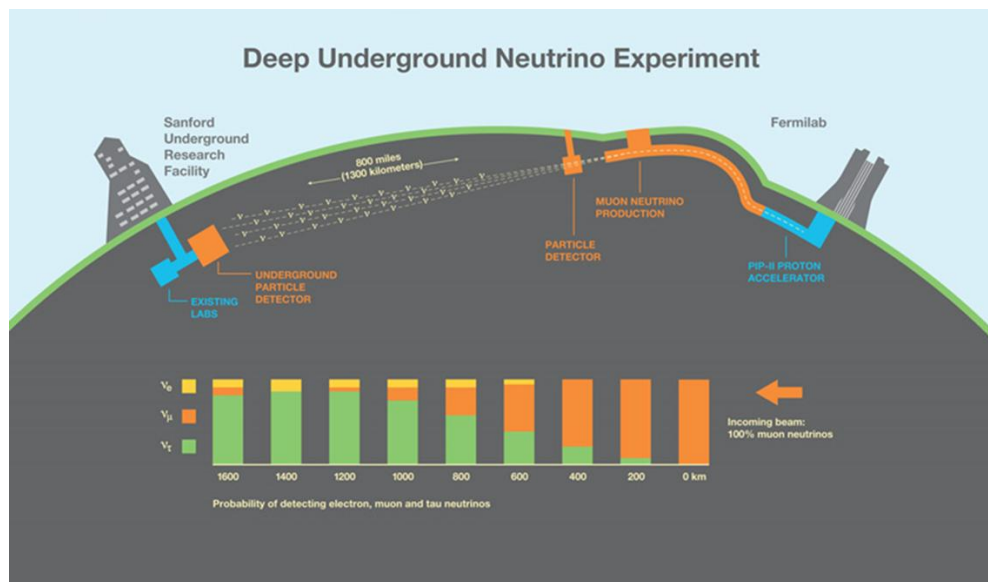
Deep Underground Neutrino Experiment



Kim Siyeon
Chung-Ang University

CPNR Workshop
October 24~27, 2025

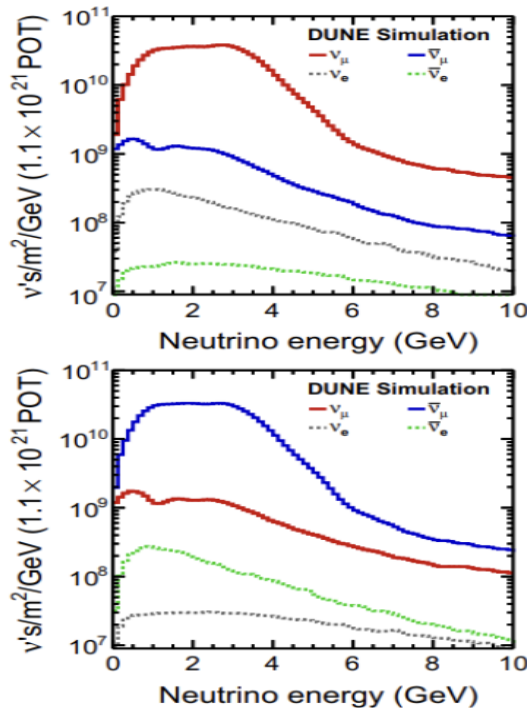
• Long-baseline oscillation



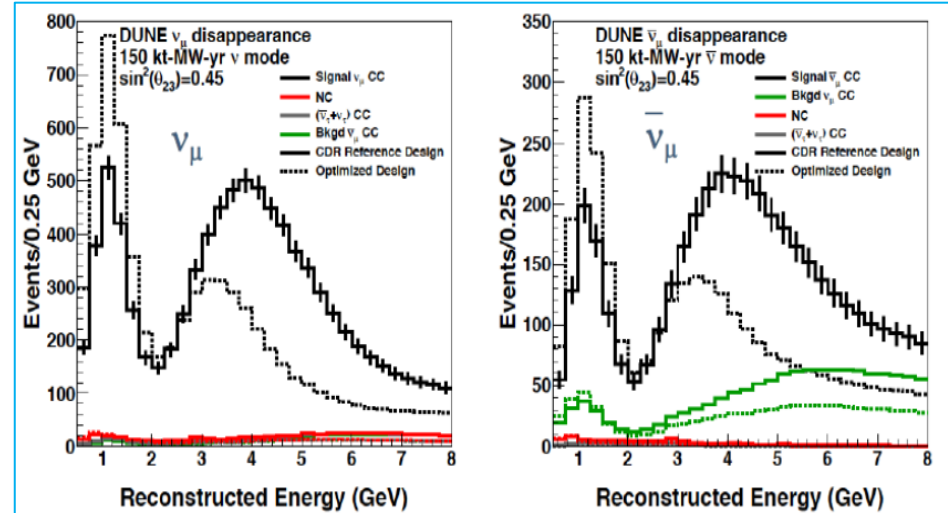
Experiment	Beam Source	Detector (threshold)	Interaction	Flavors	Physics	Status
DUNE	PIP-II NuMI (0.5~10 GeV)	L-Ar Time Projection Chamber, (a few MeV)	NC, CC, ES	all	Oscillation Interaction	Construction

Long-baseline oscillation

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

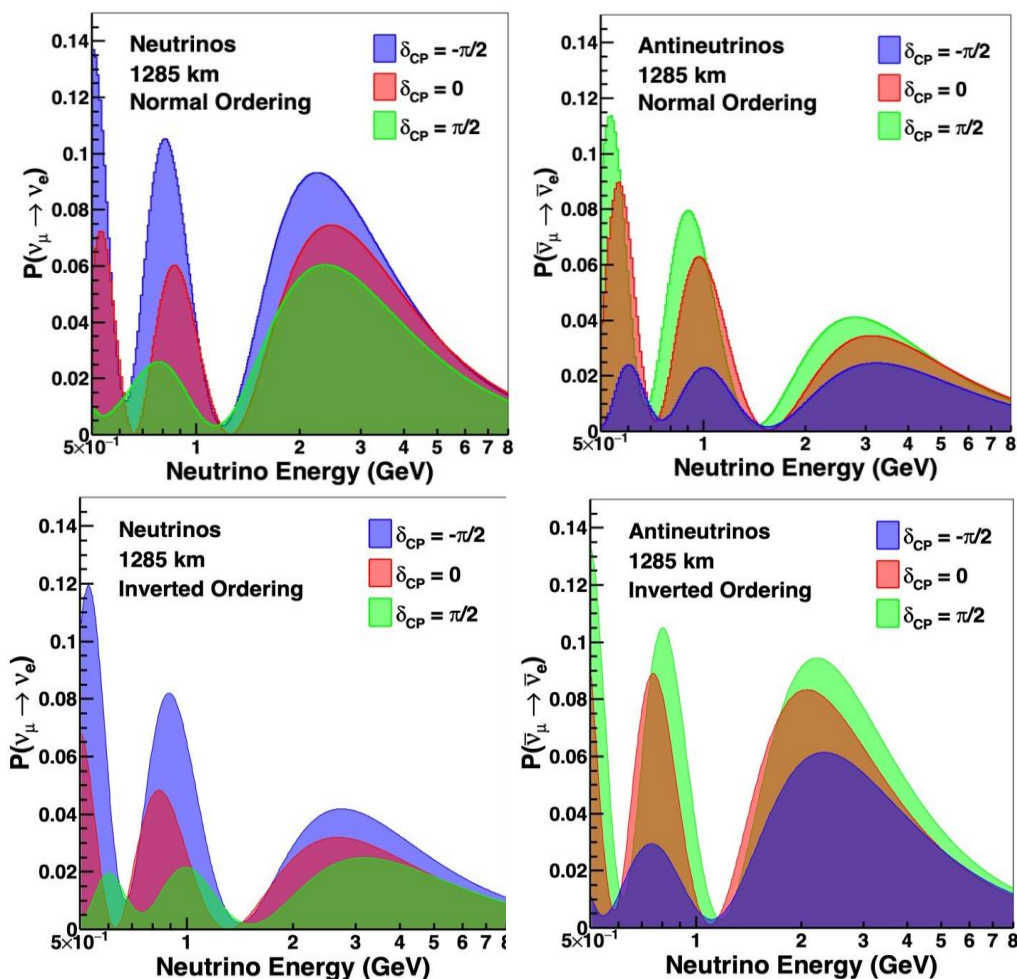


Beam Optimization

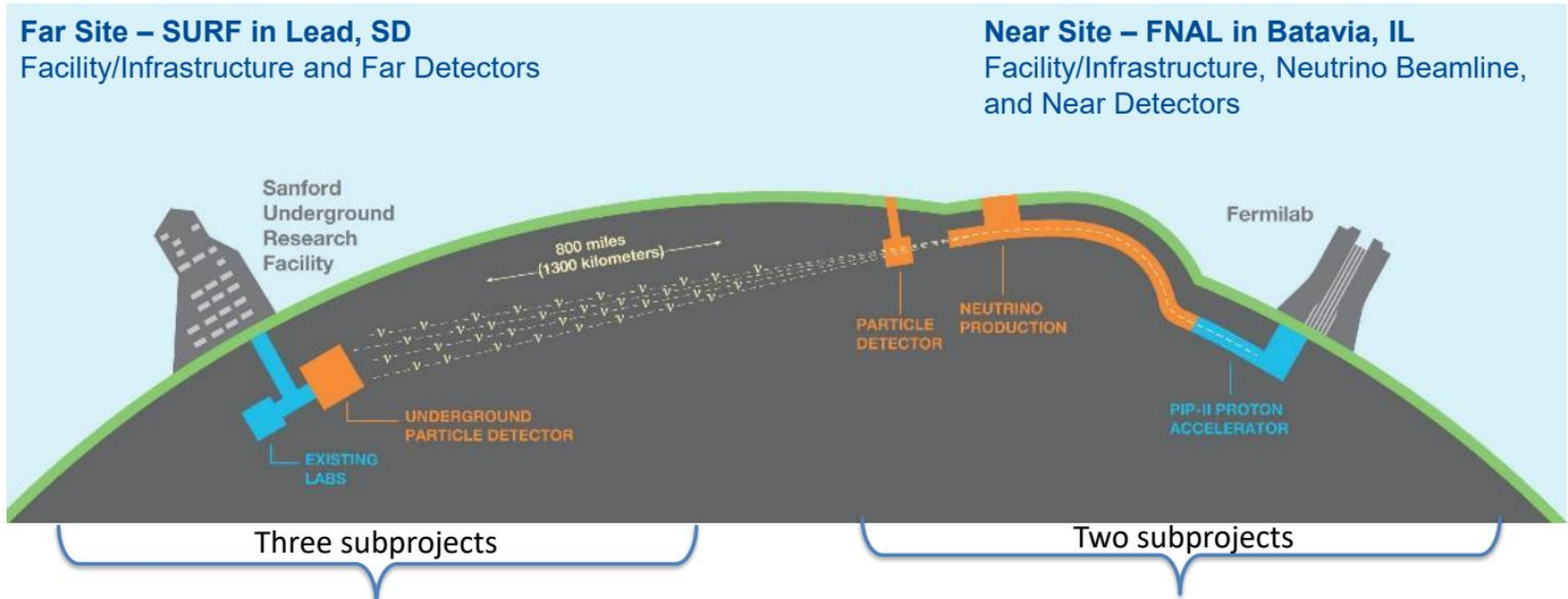


Neutrino-antineutrino asymmetry: $P(\nu_\mu \rightarrow \nu_e)$ vs. $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

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



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

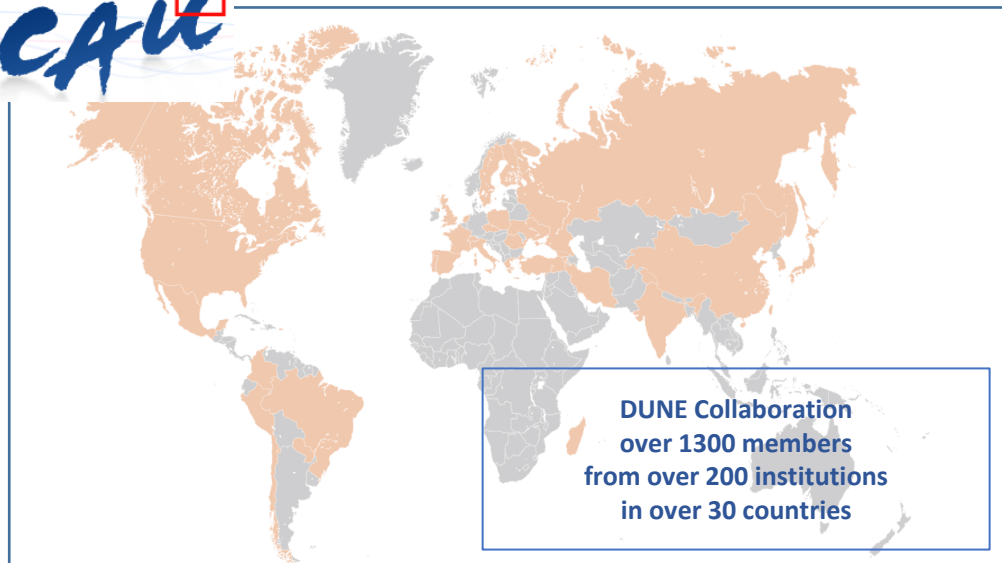


- **FSCF-EXC** – Far Site Excavation
- **FSCF-BSI** – Far Site Building & Site Infrastructure
- **FDC** – Far Detectors and Cryogenic Infrastructure

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

Construction Timeline





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)

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

Physics Coordination & Working Group

Long-baseline | Atmospheric & Exotics

FD sin/reco | ND Prototype analysis

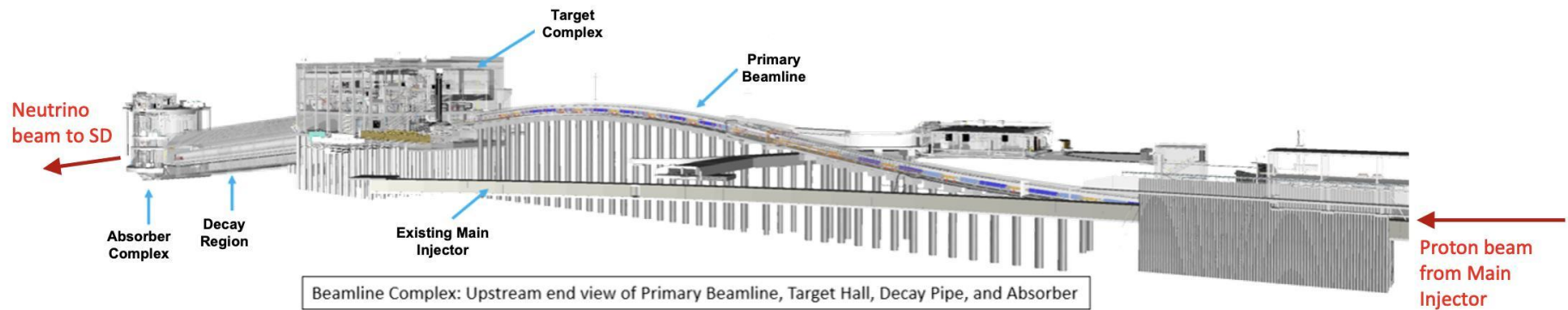
Neutrino Interactions + Uncertainties

Beam BSM | ND sim/reco | Low Energy

Calibration | **ProtoDUNE Analysis**

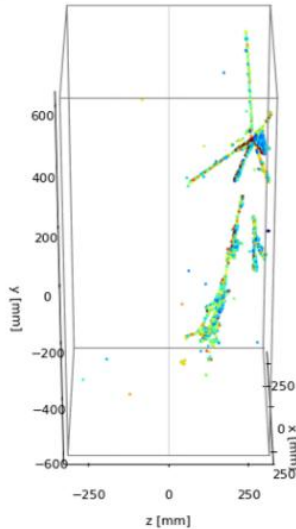
LBNF: intense beam, underground facilities and infrastructure

- 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

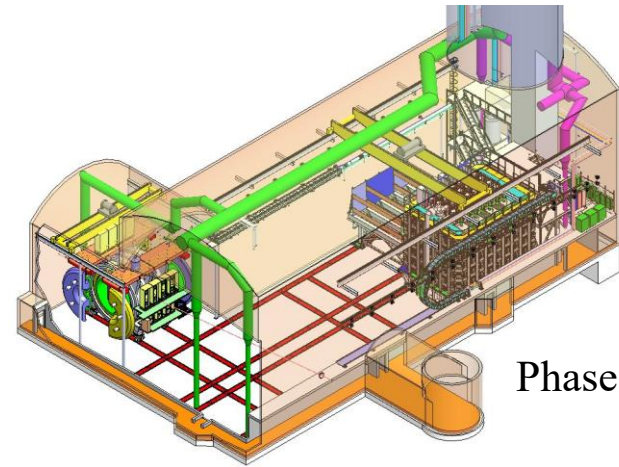


Near Detector

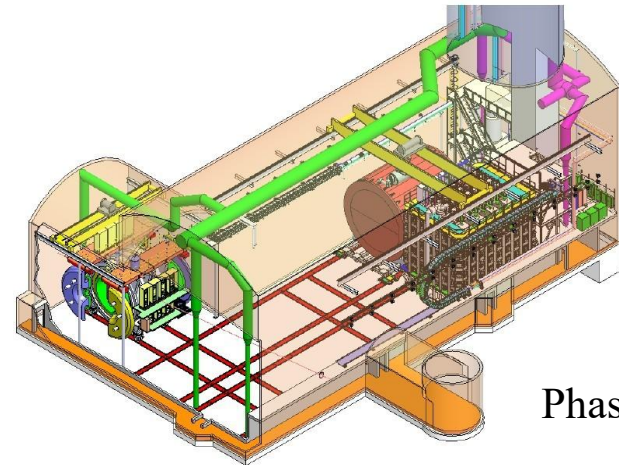
- Innovative design enables the first-ever operation of a liquid argon near detector in the world's most intense neutrino beam.
- Near detector critical to precision neutrino science.
- Near detector prototype installed in neutrino beam at Fermilab. Taking data this spring.



Cosmic data in ND-LAr prototype in Switzerland



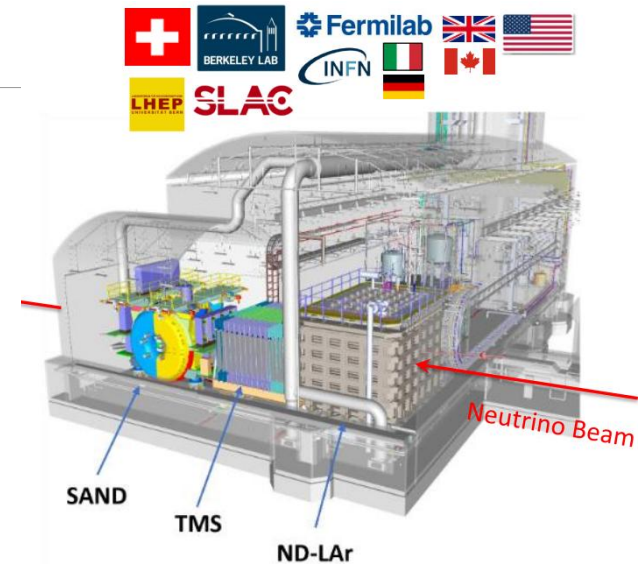
Phase I ND



Phase II ND

- **Phase 1 Detector:**

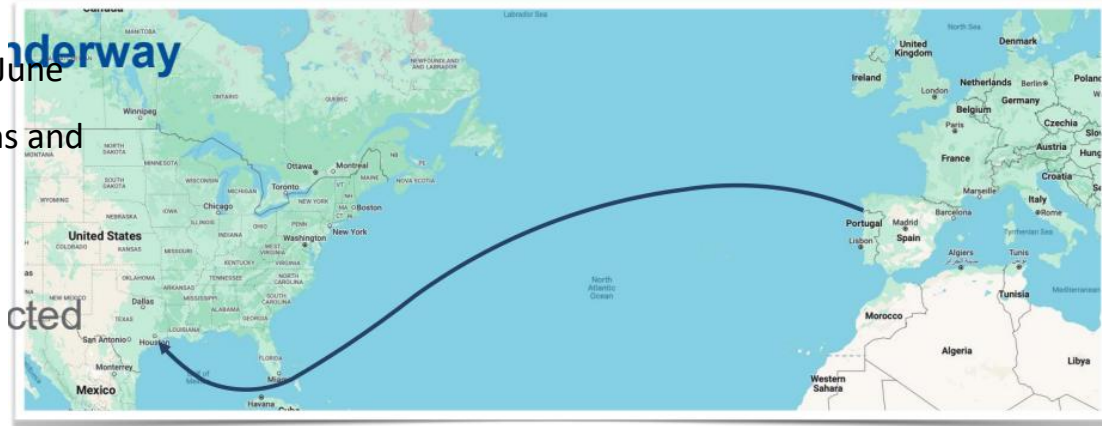
- Moveable LArTPC + Muon Spectrometer:
 - ND-LAr: 7x5 array of modular 1x1x3 m³ LArTPCs with pixel readout
 - TMS: Magnetized steel range stack
 - DUNE-PRISM: ND-LAr+TMS move up to 28.5 m off-axis
- SAND: On-axis magnetized detector
 - KLOE solenoid + electromagnetic calorimeter
 - GRAIN (LAr target 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 lowered down the Ross Shaft.

That's because the components are massive. The

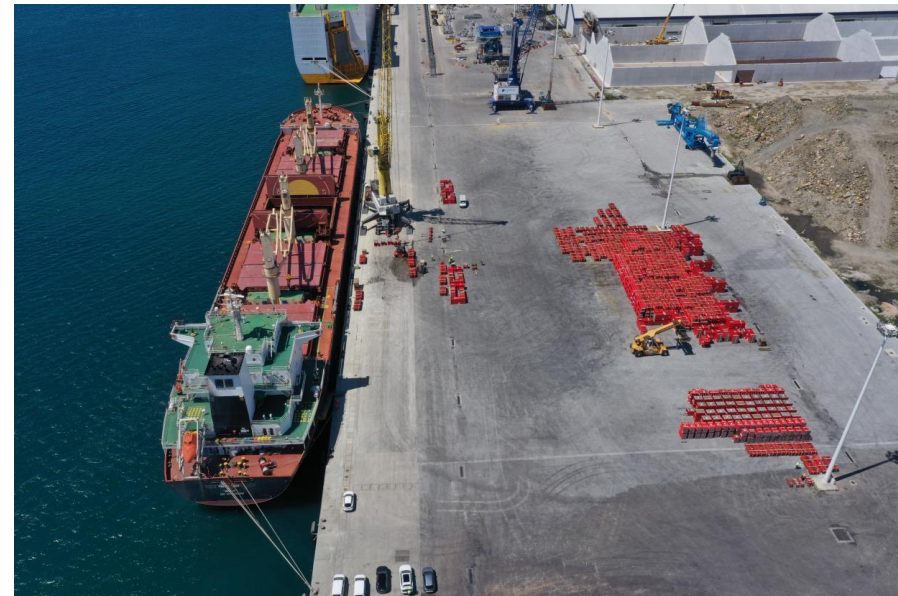
first piece is more than 8 tons and 40 feet by 3 feet by 1.5 feet. The second piece is nearly 6 tons and 18 feet by 11 feet. Both pieces form just a corner of the massive cryostat for the deep underground neutrino experiment. When they're lowered down the Ross Shaft, they will have a clearance of about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

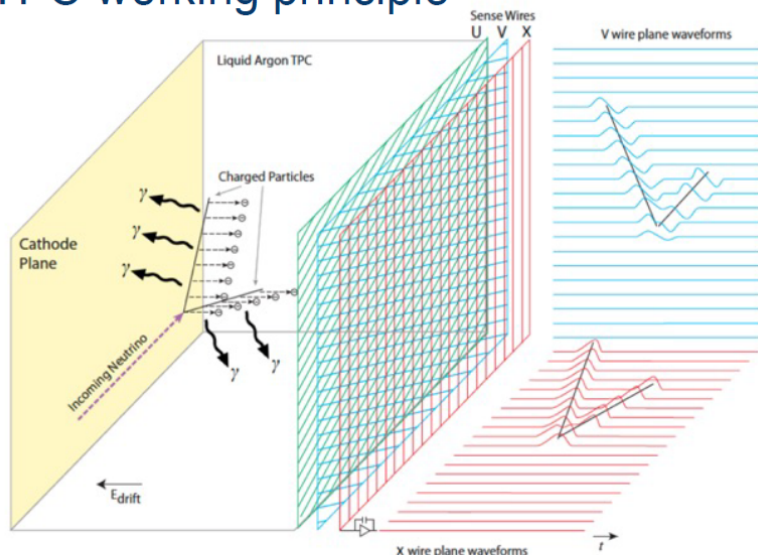
"It has a center of gravity that is a challenge," she said. "That's why we wanted some extra time to be able

DUNE COMPONENTS Pg 6



The Single-Phase LAr-TPC

TPC working principle



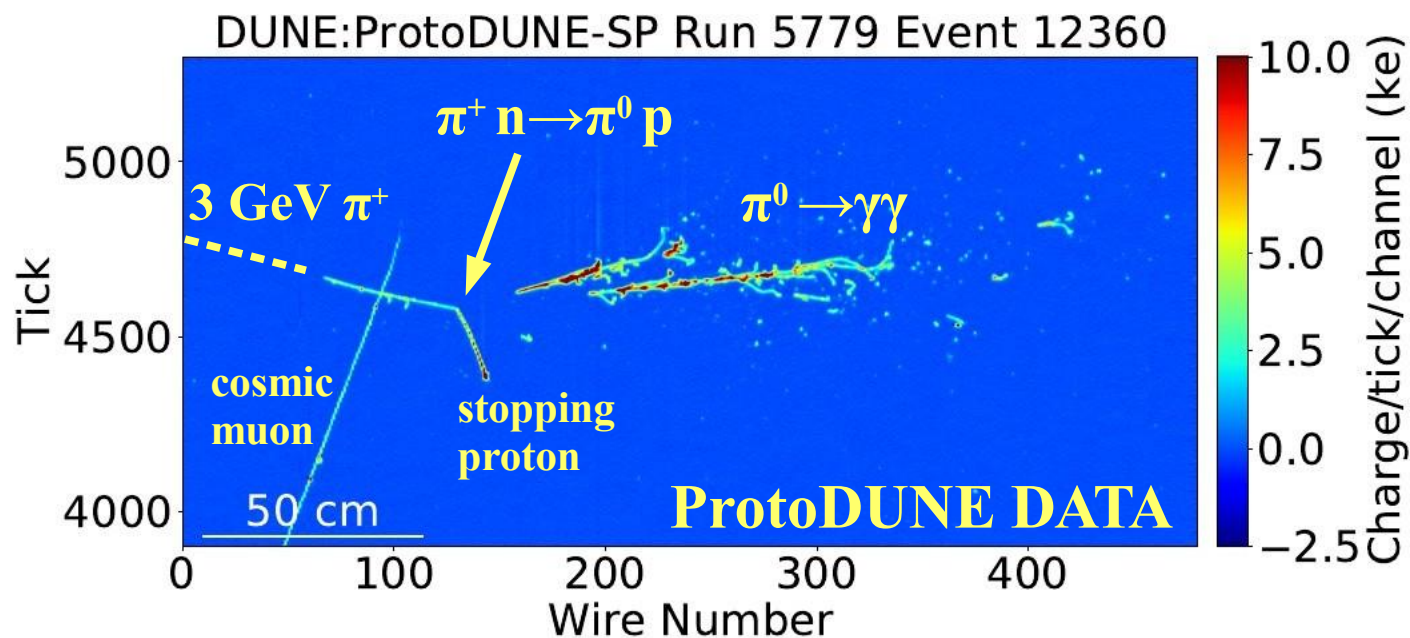
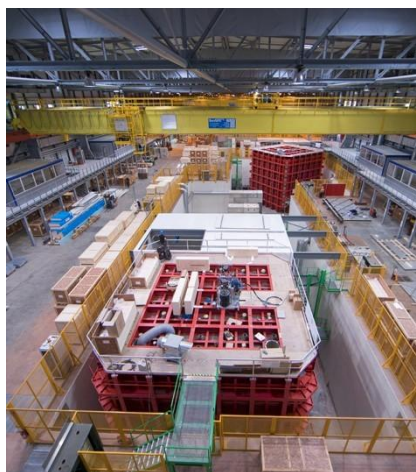
- Ionization electrons [~ 5 fC/cm] drift to the anode in pure LAr & uniform E-field (~ 500 V/cm)
 - Few mm pitch and $\sim$ MHz sampling frequency
 - 3D via multiple 2D view (wire# vs drift time)
 - high imaging capabilities $\rightarrow$ kinematic reconstruction with mm-scale spatial resolution
 - Intrinsically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

LAr as radiation detection medium

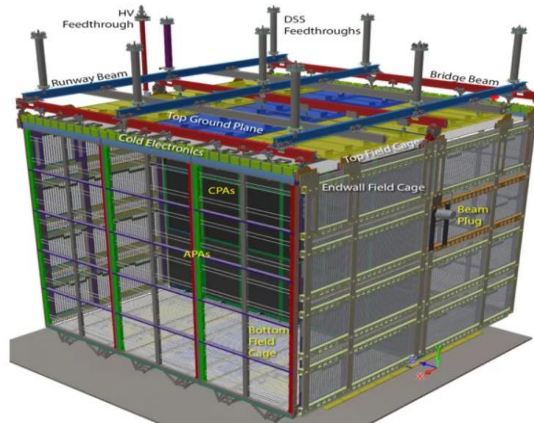
- Dense: 40% more than water
- Abundant primary ionization: 42 000 e^- /MeV
- High electron lifetime if purified $\rightarrow$ long drifts
- High light yield: 40k γ /MeV
- Easily available: $\sim 1\%$ of the atmosphere
- Cheap: \$2/L (\$3000/L for Xe, \$500/L for Ne)
- Technological challenges
 - LAr continuous purification $\ll 0.1$ ppt O_2 eq. ($\gg 3$ ms electron lifetime) for long drift
 - Imaging & anode planes
 - Very low noise front end amplifiers to detect $\sim$ 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 experiment (μ Boone, SBND, DUNE)
 - DUNE: scaling to multi-kt size

LArTPC technology provides exquisite resolution

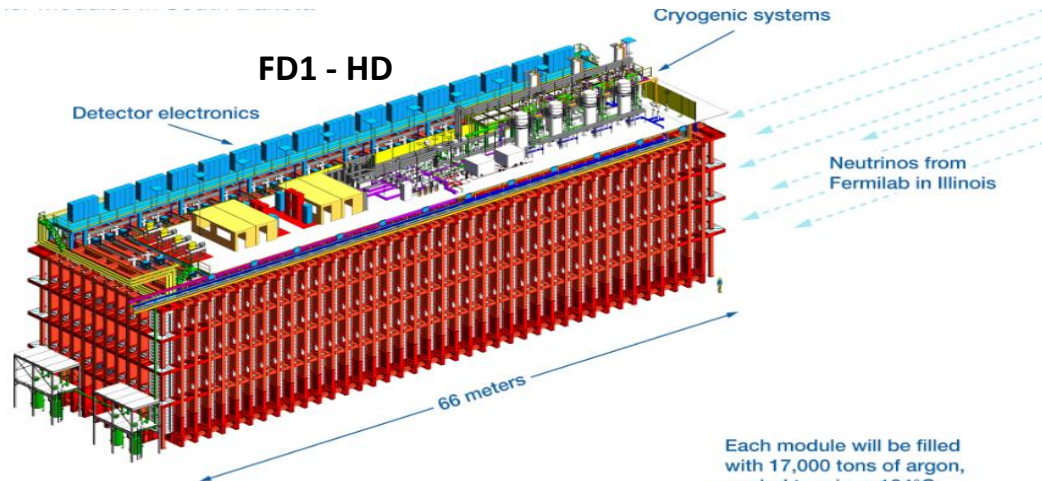
- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- High Resolution & Low thresholds:
 - sensitivity to few-MeV neutrinos, hadrons
 - excellent for LE neutrino and BSM Search



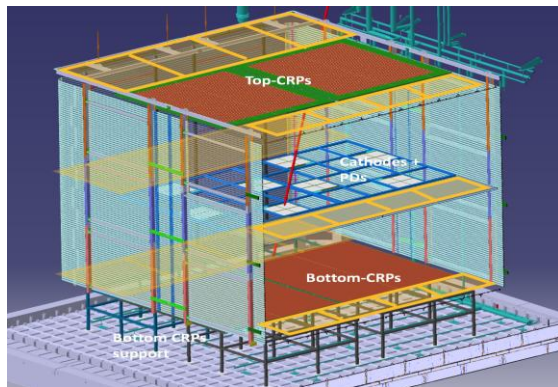
Liquid Argon Time Projection Chamber in ProtoDUNE



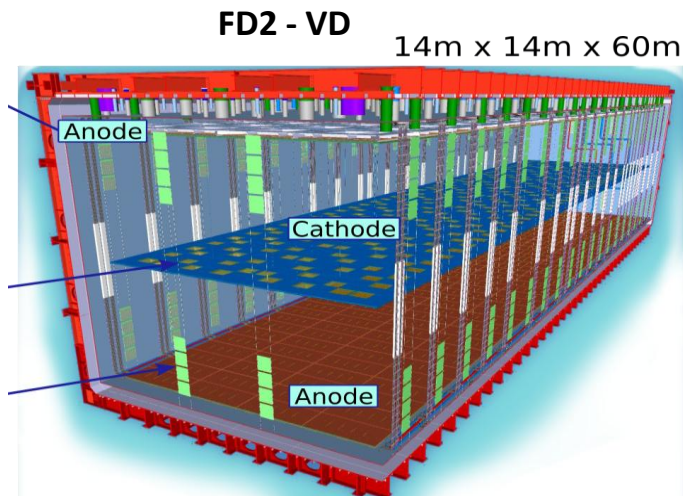
ProtoDUNE - HD



FD1 - HD



ProtoDUNE - VD



FD2 - VD

14m x 14m x 60m



2025 ProtoDUNE Run-II (2단계) 가동, 실제 검출된 데이터 분석 실행

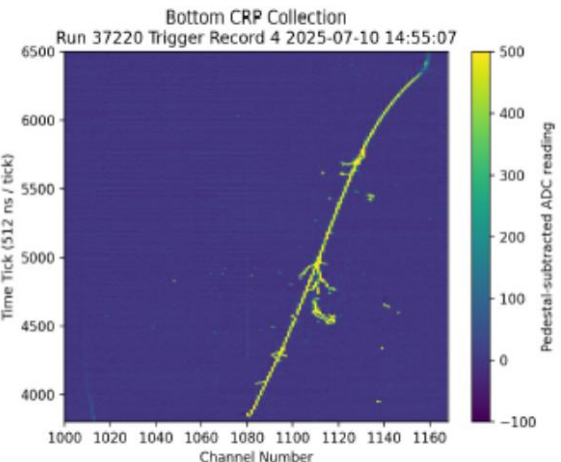
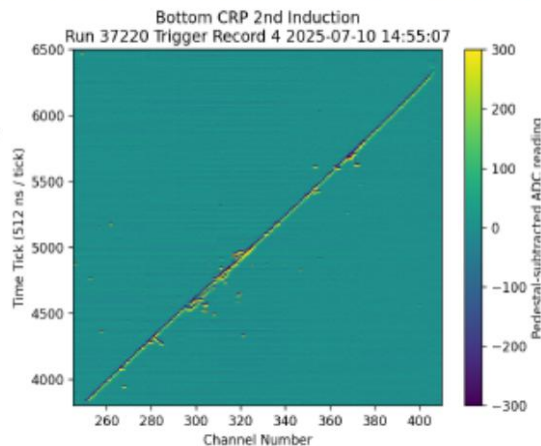
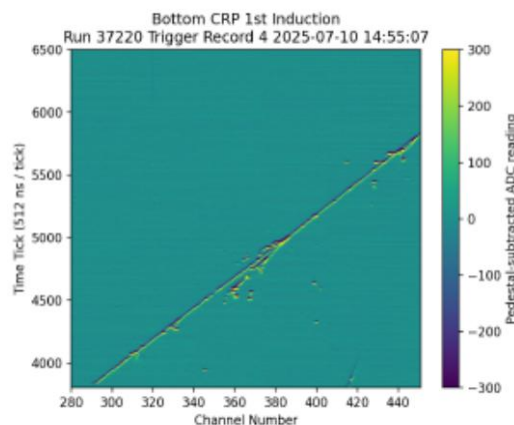
2026-2027 DUNE FD(원거리 검출기) 설치

2027-2028 DUNE FD 데이터 분석 실행 CPNR, CNU | Kim Siyeon

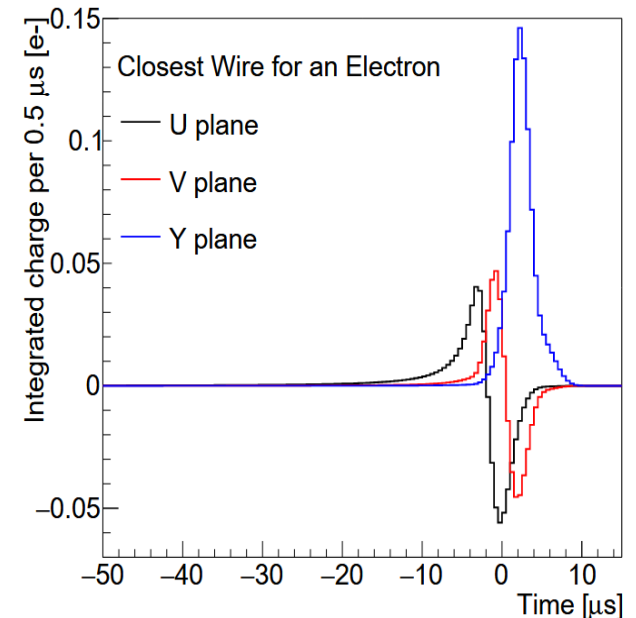
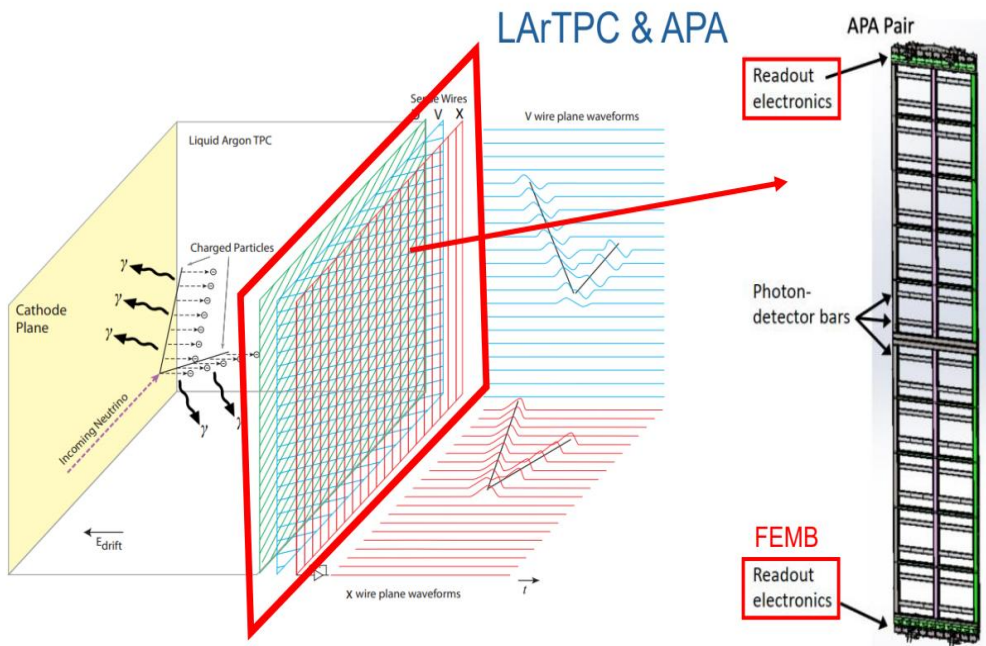
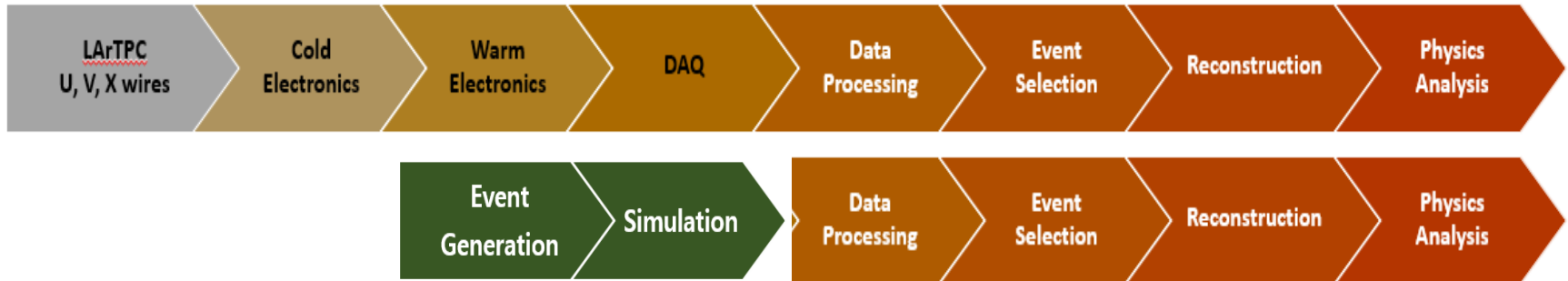
ProtoDUNE, DUNE FC as of Sept.2025

- 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

7/10/2025 cosmic data with the cathode at nominal 154kV (BDE event display - I1,I2,C View)

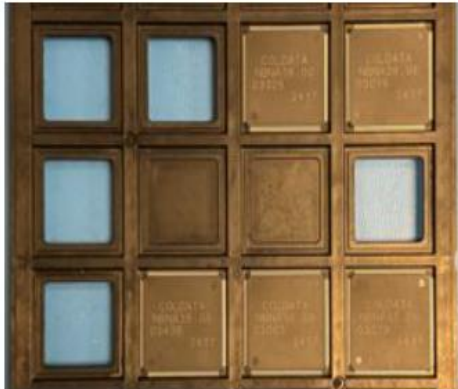


From Detection to Analysis



Cold Electronics Readout

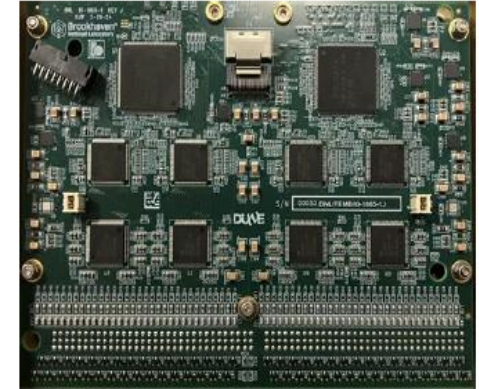
❖ COLDDATA



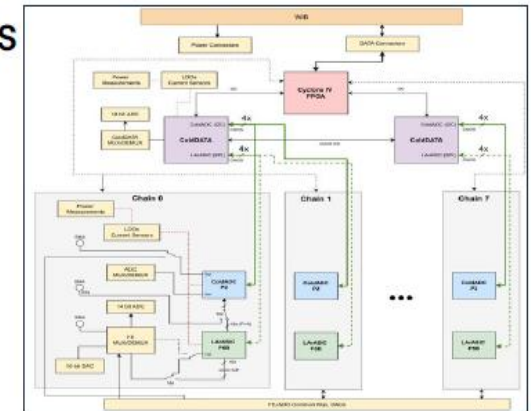
❖ LArASIC



❖ FEMB



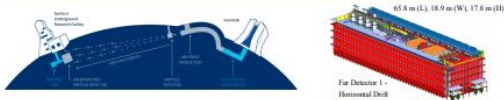
- COLDDATA configures and controls 4 COLDADCs and 4 LArASICs
- LArASIC provides front-end amplification
 - Four adjustable gain levels: 4.7, 7.8, 14, 25 mV/fC
- Front-End Motherboard (FEMB) integrates **All ASICs** :
 - 8 x LArASIC, 8 x ColdADC, 2 x COLDDATA



Abstract

The Deep Underground Neutrino Experiment (DUNE) is a next-generation neutrino oscillation experiment designed to investigate fundamental properties of neutrinos. To achieve optimal performance, Cold Electronics (CE) has been chosen as the readout solution for the Far detector. These electronics must reliably operate at liquid argon (LAr) temperatures throughout the detector's expected lifetime of over 20 years, as maintenance or replacement will not be feasible. A comprehensive quality control (QC) procedure was implemented to ensure the electronics meet specifications and are free of defects, utilizing the DUNE ASIC Test (DAT), Robotic Testing Setup (RTS), and Cryogenic Test System (CTS). Three key components of the front-end readout system—COLDATA, the Front-End Motherboard (FEMB), and the LArASIC—undergo rigorous QC procedures to assess their performance. We present a new selection criteria to identify high-quality components.

DUNE Overview



- **DUNE** is designed to study neutrino oscillations over a **1,300 km baseline** from Fermilab to the Sanford Underground Research Facility
- The Far Detector comprises massive **Liquid Argon Time Projection Chambers (LArTPCs)**, enabling precise 3D imaging of neutrino interactions
- Each module integrates advanced **CE systems** for signal amplification and digitization at cryogenic temperatures

Cold Electronics



- 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

Quality Control & Test Setup

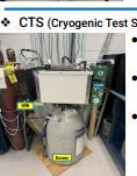
Three QC test setups are implemented:



CULDATA	QV	Name
PASS	100	88% yield
Fail QPC communication with FE	2	
Handling issues	2	PASS QC after re-align
Poor contact between column & chip	2	PASS after reset
Fail in QPCSS programming	2	
PLI Band Range	18	PASS (17 chips) with new selection criteria
Total	PASS=60 FAIL=2	17%

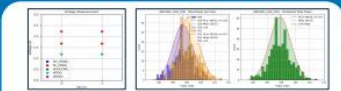
- ❖ **RTS (Robotic Testing Setup)**

- 
- Supports automated testing at both room temperature (RT) and Liquid Nitrogen temperature (LN)
 - Utilizes an EPSON robotic arm to handle CE chips precisely and efficiently
 - Enables repeatable, and scalable QC for high-volume testing



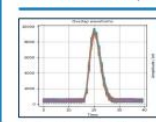
- Performs full-module testing under RT and LN conditions
- Validates cold operation as a **fully assembled unit**
- Repeated testing ensures **performance consistency and mechanical endurance**

Performance Evaluation from QC Data



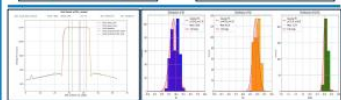
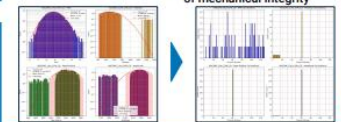
- ❖ **Power consumption**

- Meet the DUNE requirements: less than 50 mW



- ❖ **Pulse response**

- Identified abnormal response in a specific readout channel
- Requires further inspection of mechanical integrity



- ❖ **Phase-Locked Loop (PLL) lock range**

- 86% yield with conservative criteria
- 96% yield achieved with the updated criteria

COLDATA

Conclusion

- **COLDATA** analysis suggests a new chip selection criterion for future QC
- **LArASIC** results demonstrate successful noise reduction at cryogenic temperature
- **FEMB** testing validates the durability and reliability of the QC test setup
- These results support the readiness of CE components and provide a foundation for future QC efforts across collaborating institutions

Acknowledgement

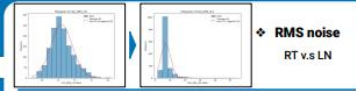
- We thank the BNL Cold Electronics Group & CAU NuLa Group for this support and collaboration
- Special thanks to Shanshan Gao, Vladimir Tishchenko, Lingyun Ke for their invaluable guidance
- We also acknowledge the resource support provided by members of the CAU NuLa Group



- CAU NULA

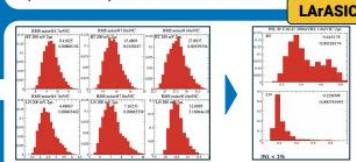
Finalizing an internal report on performance evaluation

Cold Electronics
Working Group
making a paper
for publication



- ❖ Power consumption

- The average RMS noise decreases from 11.19 ADC to 7.17 ADC (**36% reduction**) — lower than requirements (1000 ENC)
- Power consumption decreases from 98.01 mW to 92.65 mW (**5.5% reduction**)



❖ **RMS noise** (RT v.s LN)

- FEMB QC testing at various Gain settings
- Demonstrated stable performance under repeated thermal cycling between RT and LN
- Noise reduce by more than half at LN and integrated non-linearity < 1%

FEME



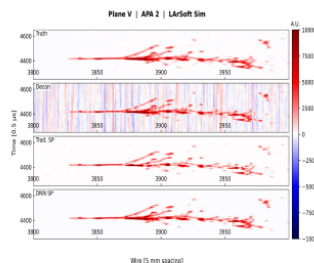
Liquid Argon Software:

Simulation and reconstruction packages for LArTPC detectors

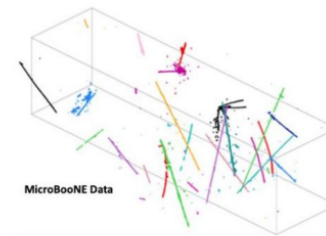
- Event generation: Genie, CORSIKA, CRY, SingleGen module
- Simulation: GEANT4, FLUKA
- Reconstruction: **Wire-Cell**, Pandora

Wire-Cell Toolkit

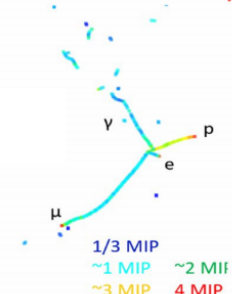
Part 1:
Simulation
Noise Filtering
Signal Processing



Part 2:
3D imaging
Clustering
Charge-Light Matching
Neutrino Event Selection

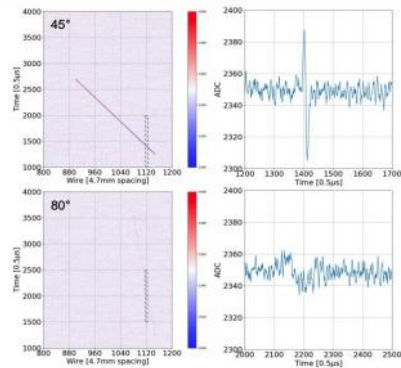


Part 3:
3D vertexing
Particle Identification
3D Pattern Recognition

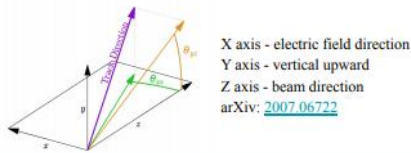


MicroBooNE → SBND, ProtoDUNE-HD, ProtoDUNE-VD, DUNE FD

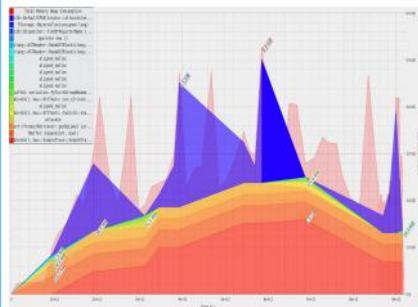
DNN Signal Processing Motivation



- 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.



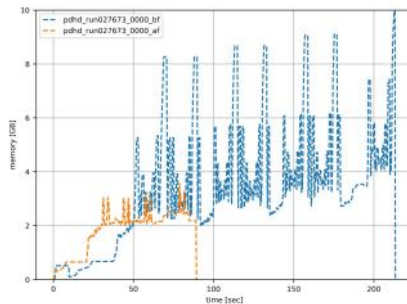
Memory Usage Optimization



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

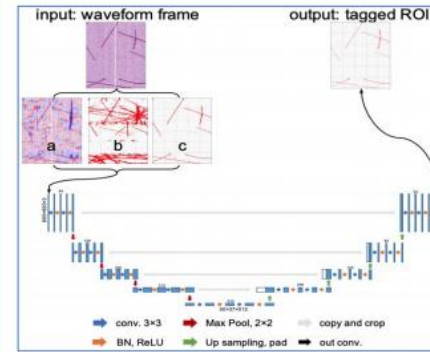
Strategy

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

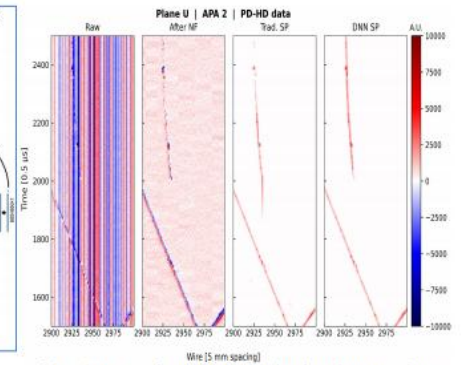


- DUNE computing environment recommends keeping memory usage below 4 GB
→ DNN SP was not applicable yet
- After the optimization, the memory usage is reduced from **10.0 GB to 3.6 GB**
- Through an additional memory optimization (chunking for ML inference), the memory usage can be further reduced

DNN Signal Processing Results



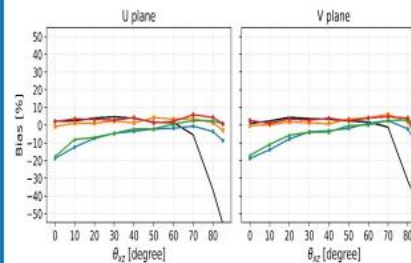
□ DNN-based ROI finding



□ 2D waveform evolution in signal processing

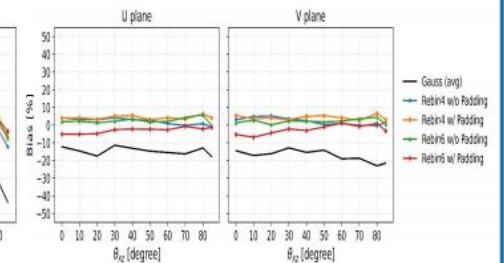
- Input features for ML training: loose low frequency filter - noise, multi-plane coincidence
- U-Net like architecture: encoder - decoder
- DNN-based signal processing (DNN SP) demonstrated
 - better charge reconstruction performance in prolonged topology
 - capability to truncate "tear drop"
- Performance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

Bias vs θ_{xz} | n500 | Trad. SP (avg) vs DNN SP



□ Single track evaluation

Bias vs θ_{xz} | 1GeV | DNN vs Gauss (avg)



□ 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.