DUNE Phase-II Physics and Technology

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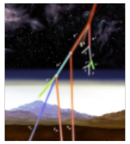
on behalf of the DUNE Collaboration

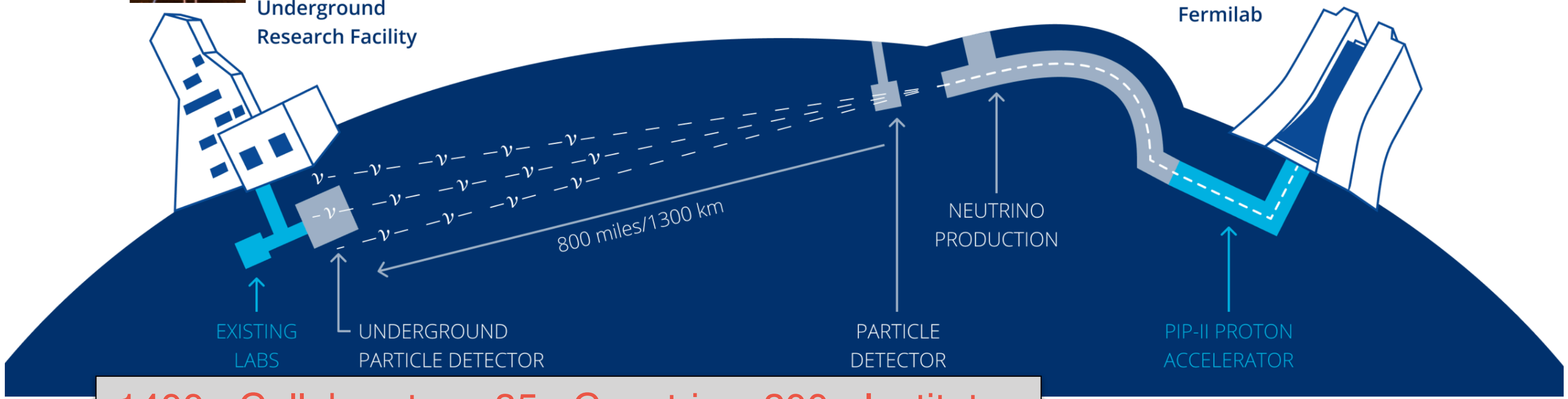
Workshop on Neutrinos@CERN
23-24 January 2025

IMPERIAL DUNE

The Deep Underground Neutrino Experiment (DUNE)



MW-scale beam from Fermilab to South Dakota



1400+ Collaborators, 35+ Countries, 200+ Institutes

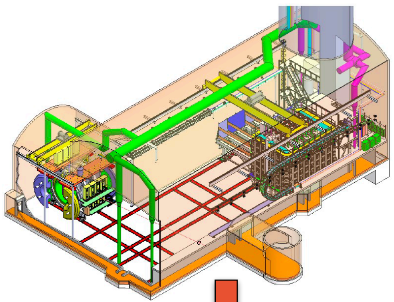
- A 70-kt total mass liquid argon equivalent far detector a mile underground at Sanford Underground Research Facility (SURF)
- A capable near detector at Fermilab comprising multiple technologies.
- A high-power, wide-band **neutrino beam** (~ GeV energy range)

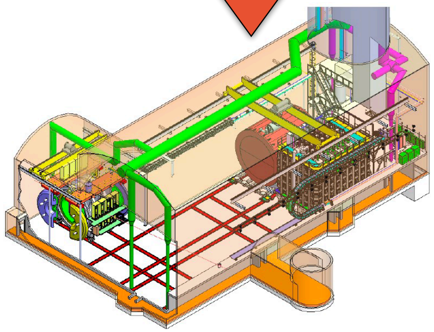
Rich physics programme: Charge-Parity (CP) Violation, mass ordering, precision measurement of oscillation parameters, neutrino astrophysics, and Beyond the Standard Model (BSM) physics

DUNE Cavern has been excavated

DUNE to built in two phases

Near Detector (ND)

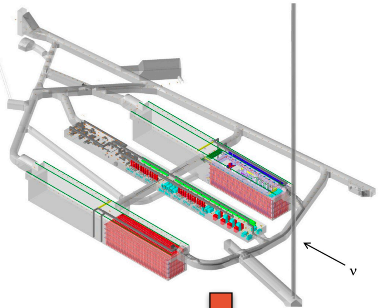


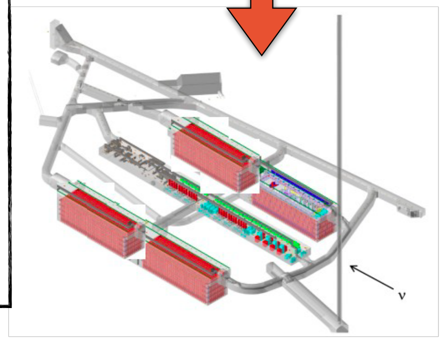


Phase I
- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)

Phase II
- **FD:** 2 additional modules (total: 4 x 17 kt LAr-equivalent)
- **MCND:** ND-LAr+ND-GAr (with PRISM) + SAND
- **Beam:** > 2 MW beam line (ACE Upgrades)

Far Detector (FD)





The LBNF facilities at the near and far sites support Phase II beam and detectors from the start (part of Phase-I scope) — ***simplifying Phase-II implementation***

LArTPC: *Liquid Argon Time Projection Chamber*
ND-LAr: *Liquid argon-based ND*
TMS: *Temporary Muon Spectrometer*
SAND: *System for on-axis ND*
MCND: *More Capable ND*
ND-GAr: *Gaseous argon-based ND*
PRISM: *movable ND capability for off-axis beam measurements*
PIP-II: *Proton Improvement Plan-II*
ACE: *Accelerator Complex Evolution at Fermilab*

Parameter	Phase I	Phase II	Impact
FD mass	2 FD modules (20 kt fiducial)	4 FD modules (40 kt fiducial LAr equivalent)	FD statistics
Beam power	1.2 MW	Up to 2.3 MW	FD statistics
ND configuration	ND-LAr+TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

**Non-argon options currently under consideration for Phase-II near and far detectors not listed*

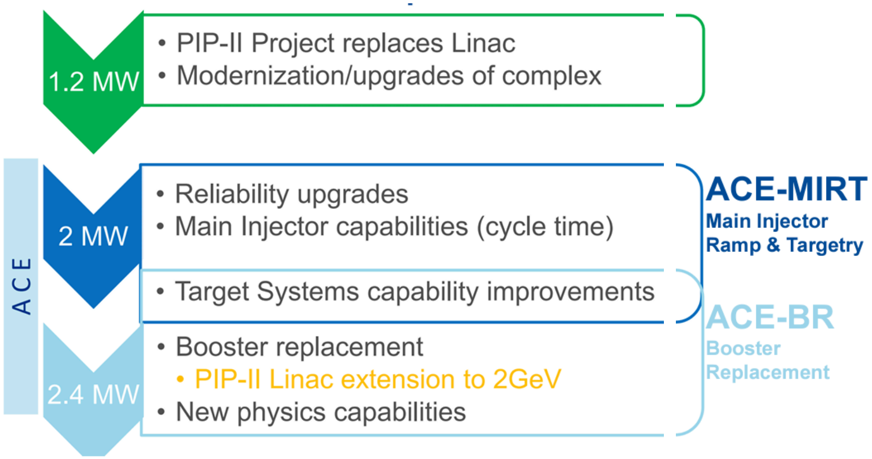
Accelerator upgrades

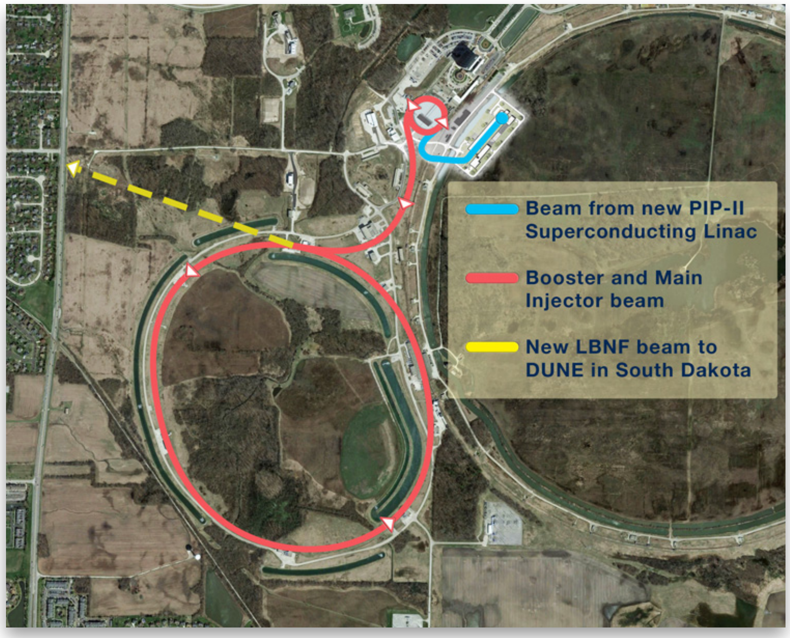
Proton Improvement Plan (PIP-II)

- New PIP-II linac (to be completed in 2029) provides beam for injection into Booster at energy increased to 800 MeV from present 400 MeV
- Proton flux at 8 GeV increases by factor of two resulting in beam power from Main Injector of up to 1.2 MW

Accelerator Complex Evolution (ACE)

- The ACE plan has two main components, ACE-MIRT and ACE-BR, to achieve > 2 MW beam power.





PIP-II creates a platform for next-generation upgrades

DUNE Science Drivers

- DUNE will precisely determine the level of CP violation in neutrino oscillations, as part of a much *broader programme of searches for new physics.*

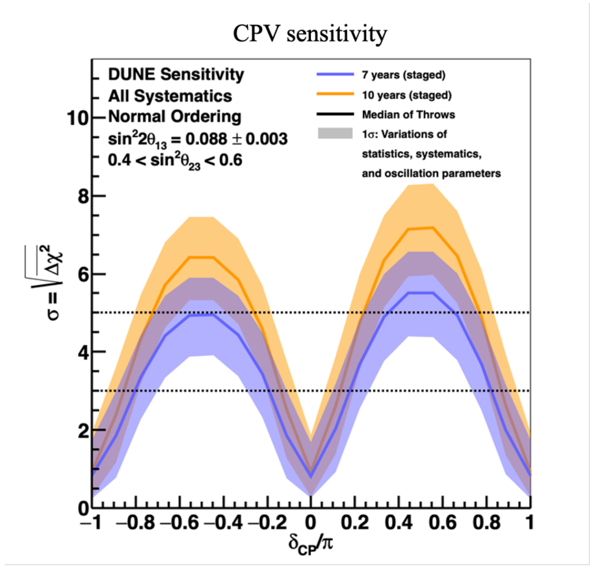
- **Long-baseline Physics**: DUNE will provide ultimate measurement of 3ν oscillation parameters (Δm^2_{32}, θ_{13}, θ_{23}, and δ_{CP}) with ~1000 kt·MW·yr exposure and few-percent-level systematic uncertainties (beam and atmospheric neutrinos).
- **Neutrino Astrophysics**: Expand MeV-scale neutrino astrophysics reach (supernova, solar).
- **BSM Physics**: Sensitive searches for long-lived particle decays and tests of 3-flavour paradigm at ND and FD, baryon number violation, and much more

*Phase-II elements **(ACE-MIRT, FD3, FD4, and MCND)** essential to achieve DUNE's full physics potential as part of this broader programme*

Oscillation Physics with DUNE

DUNE (Phase I+II) will enable

- *high precision measurements of all 4 parameters governing long-baseline oscillations (Δm^2_{32}, θ_{13}, θ_{23}, and δ_{CP})*
- *Establish CP violation at high significance over a broad range of possible values of δ_{CP}, and test the 3-flavour paradigm as a way to search for and constrain νBSM*

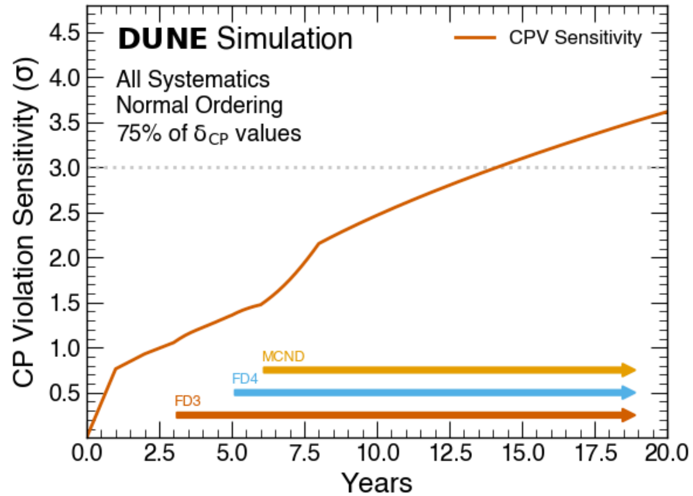


Impact of Phase II:

- Far Detectors 3/4 will increase fiducial mass by a factor of two.
- ACE-MIRT increases beam intensity right away, and throughout the DUNE programme.

Both will enable much faster resolution to mass ordering and much faster significance to maximal CPV

- MCND provides important systematic constraints to match the ~1% precision goal.



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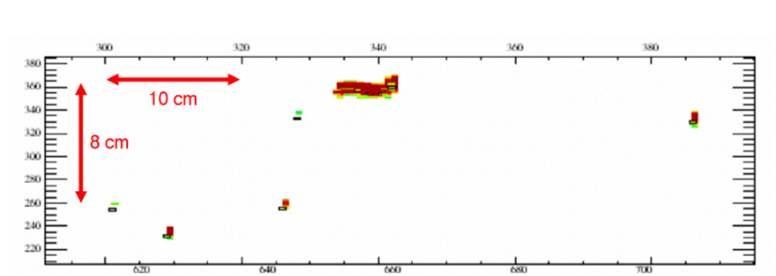
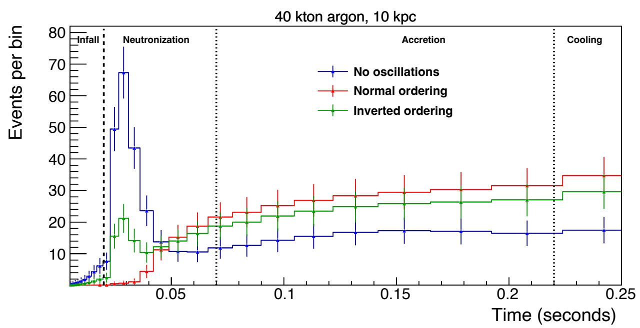
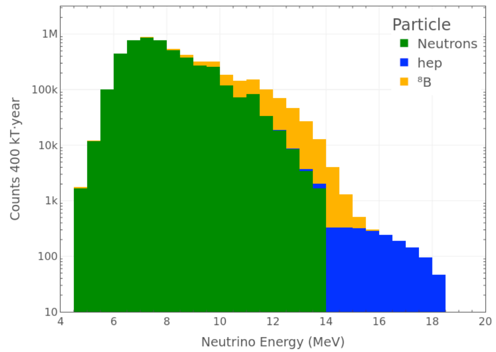
Supernova and solar neutrinos in DUNE

- Full Phase I+II FD mass, as well as potential improvements in energy resolution and background levels, are key to improve detection of neutrinos at low thresholds from astrophysical sources in the MeV energy range (e.g., solar and supernovae neutrinos).
- Different challenges from beam neutrinos (GeV range) in terms of triggering, read-out, reconstruction.
- DUNE sensitivity to electron neutrinos complementary to Hyper-K and JUNO.

$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ CC, 20 MeV

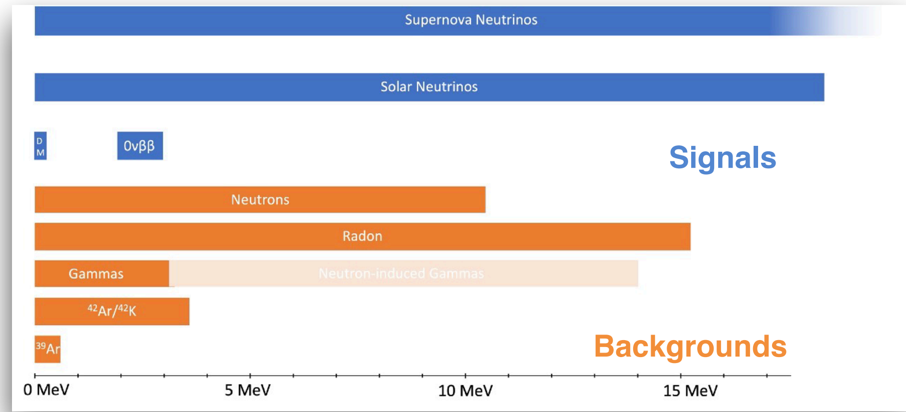


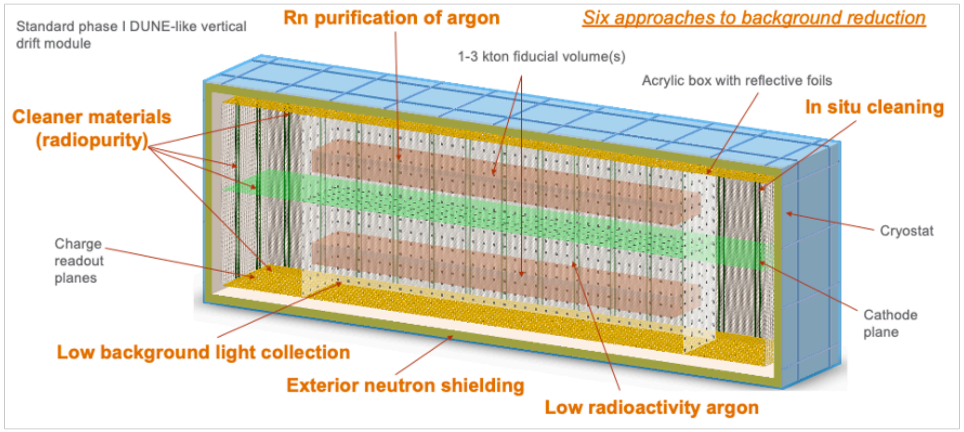




Background control is key for low-energy physics

- Realistic background target extends threshold down to 5 MeV, just above the ^{42}K beta endpoint from ^{42}Ar
- Most significant radioactive backgrounds and mitigation strategies being explored
  - *External neutrons and gammas → passive shielding (e.g., water)*
  - *Internal backgrounds from detector materials → careful material selection programs*
  - *Radon gas → inline radon trap, detector materials with low radon emanation*
  - *Intrinsic argon backgrounds (^{39}Ar, ^{42}Ar) → argon from underground sources*
  - *use underground argon in an acrylic vessel, reduce background (e.g., SLoMo)*

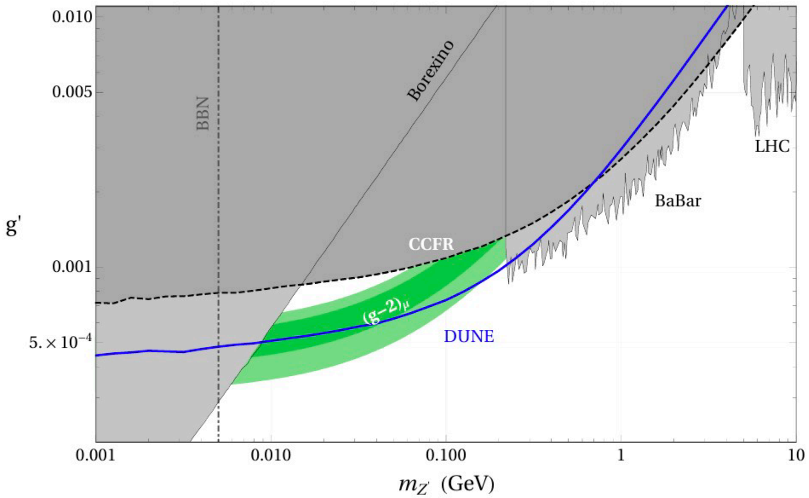


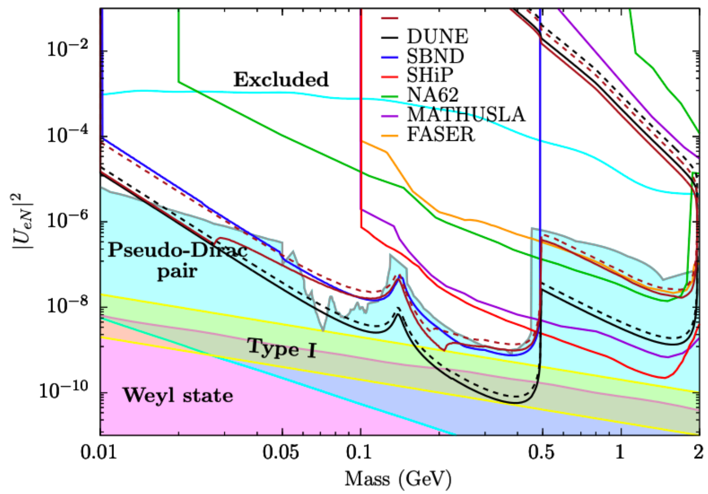


SLoMo Concept

BSM Physics

- A low-density gas argon TPC (ND-GAr) adds unique sensitivity to BSM search involving neutral particles produced in the beam and decaying in the ND (e.g., Heavy Neutral Leptons, Axion-Like Particles)
- Phase-II FD beneficial for searches that are expected to be nearly background-free (e.g., baryon number violation through proton decay)
- Phase-II improves ν_τ detection capabilities at both ND and FD
  - a promising tool to search for non-standard oscillations, for example created by light or heavy sterile neutrino mixing, or by Non-Standard Interactions (NSIs)





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Phase-II White Paper

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DUNE Phase II: scientific opportunities, detector concepts, technological solutions

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Authors References

Article information

Abstract

The international collaboration designing and constructing the Deep Underground Neutrino Experiment (DUNE) at the Long-Baseline Neutrino Facility (LBNF) has developed a two-phase strategy toward the implementation of this leading-edge, large-scale science project. The 2023 report of the US Particle Physics Project Prioritization Panel (P5) reaffirmed this vision and strongly endorsed DUNE Phase I and Phase II, as did the European Strategy for Particle Physics. While the construction of the DUNE Phase I is well underway, this White Paper focuses on DUNE Phase II planning. DUNE Phase-II consists of a third and fourth far detector (FD) module, an upgraded near detector complex, and an enhanced 2.1 MW beam. The fourth FD module is conceived as a "Module of Opportunity", aimed at expanding the physics opportunities, in addition to supporting the core DUNE science program, with more advanced technologies. This document highlights the increased science opportunities offered by the DUNE Phase II near and far detectors, including long-baseline neutrino oscillation physics, neutrino astrophysics, and physics beyond the standard model. It describes the DUNE Phase II near and far detector technologies and detector design concepts that are currently under consideration. A summary of key R&D goals and prototyping phases needed to realize the Phase II detector technical designs is also provided. DUNE's Phase II detectors, along with the increased beam power, will complete the full scope of DUNE, enabling a multi-decadal program of groundbreaking science with neutrinos.

DUNE Phase II

Contents

DUNE Phase II

https://iopscience.iop.org/article/10.1088/1748-0221/19/12/P12005

Community Endorsements

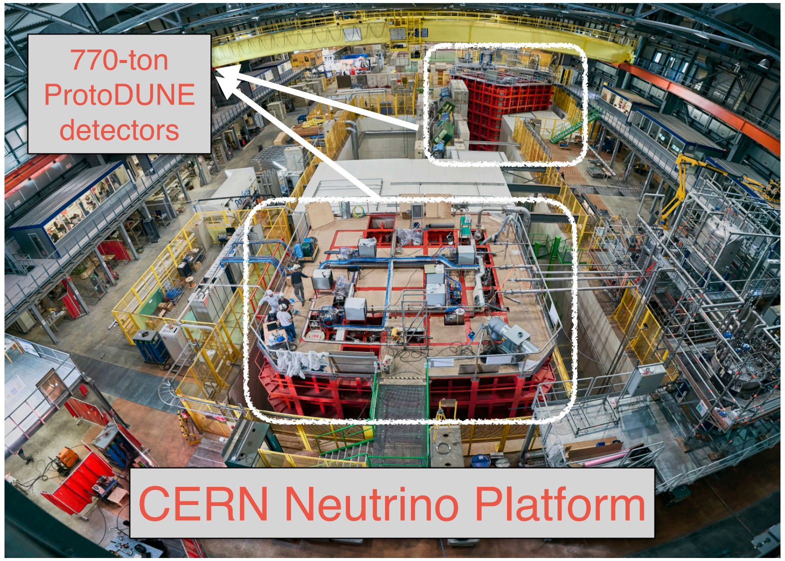
- The U.S. Particle Physics Project Prioritization Panel (**P5)** strong endorsed DUNE Phase-II elements (2.1 MW beam ACE-MIRT, FD3, and MCND) as second highest priority (**Recommendation 2**), *"as the definitive long-baseline neutrino oscillation experiment of its kind"*
- P5 also endorsed the DUNE FD4 concept as a "Module of Opportunity" and recommended an accelerated/expanded R&D programme in the next decade and if budget scenarios are favourable, also initiating construction of FD4
- Likewise, the 2013 Update of the **European Strategy for Particle Physics** and its 2020 update recommended that *Europe and CERN continue to collaborate towards the successful implementation of <u>full scope</u> of LBNF and DUNE*

Endorsement by the EPPSU will provide further crucial support.

A global R&D effort built around CERN

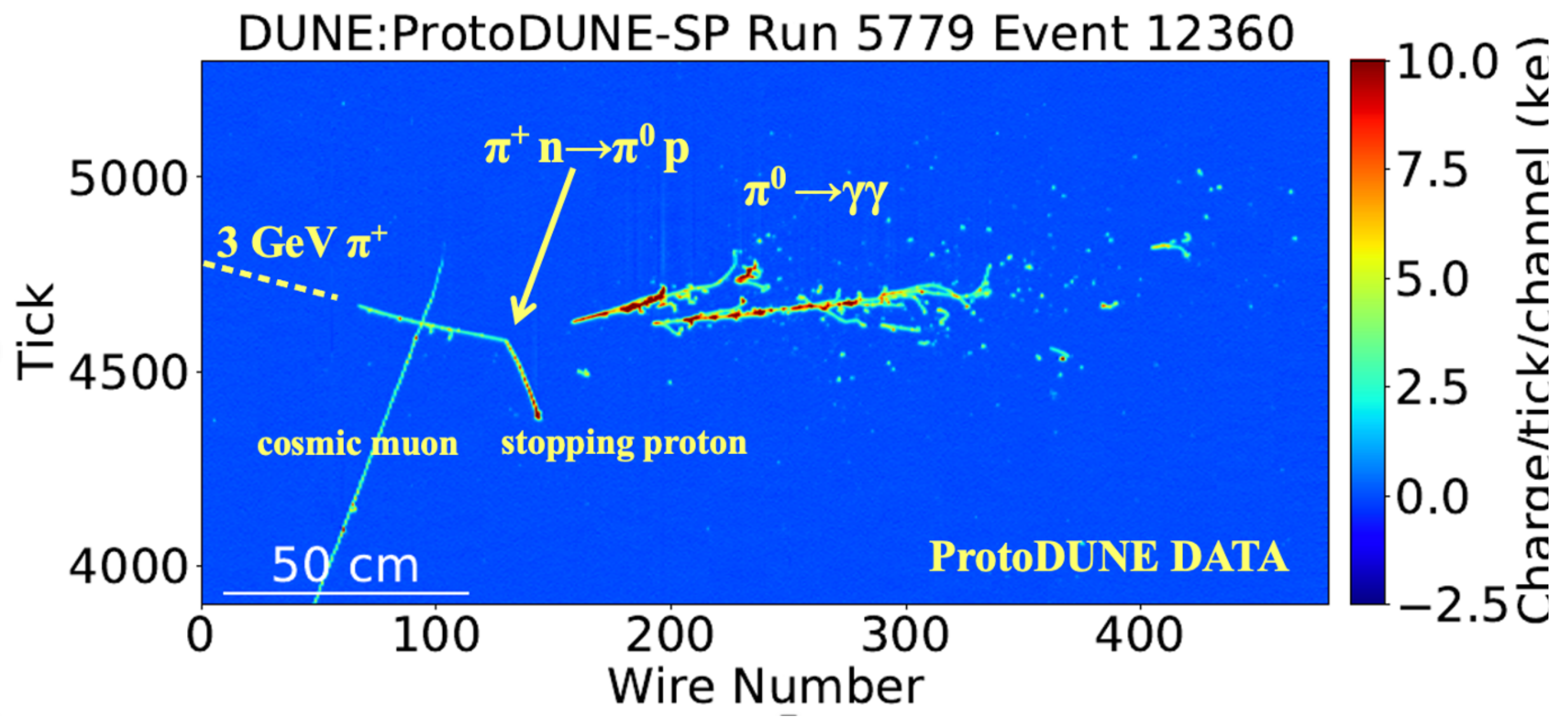
- CERN plays a central role in leading the R&D efforts
- Ongoing coordination between U.S. R&D Collaborations (RDCs) and non-U.S. Detector R&D (DRD) groups on synergistic areas of R&D and towards achieving common DUNE Phase-II goals
  - ***DRDs:*** *Liquid Detectors (DRD2); Gaseous Detectors (DRD1)*
  - ***RDCs:*** *Noble Element Detectors (RDC1); Photodetectors (RDC2); Readout & Electronics (RDC4); Gaseous Detectors (RDC6); Calorimetry (RDC9);*

The CERN neutrino platform for Phase-II R&D is at the centre of this global effort



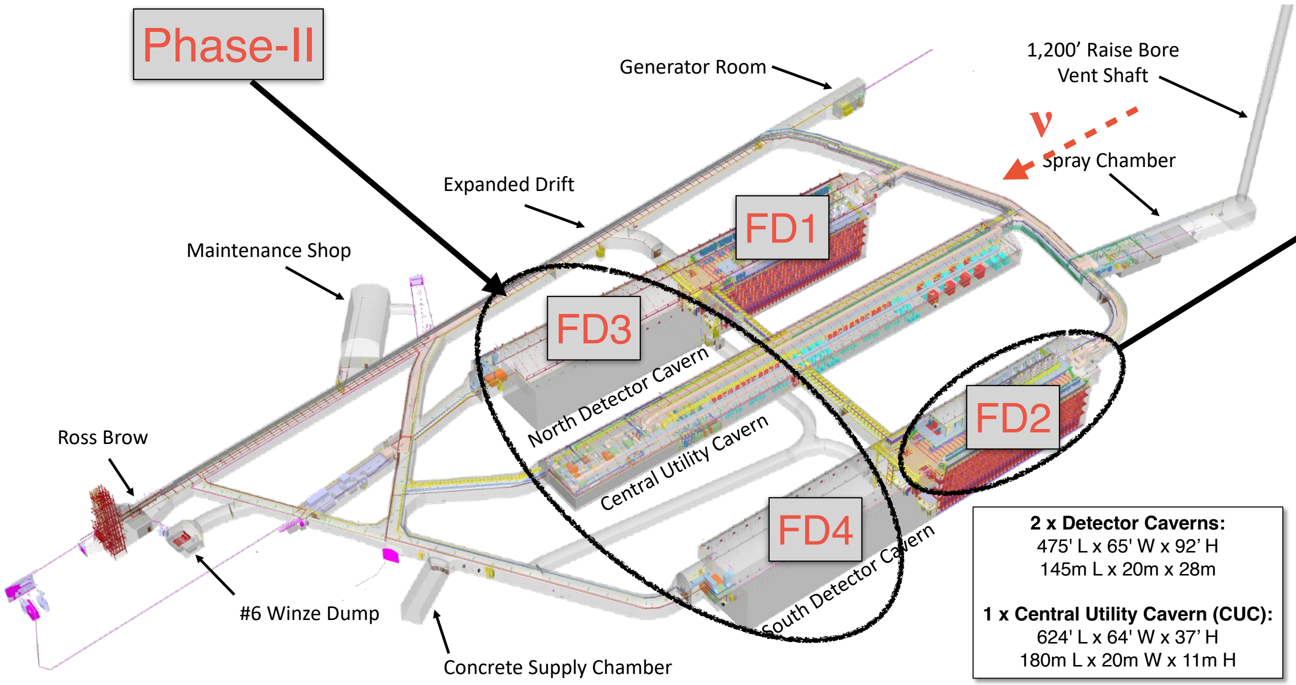
see talk by C. Touramanis

A beautiful ProtoDUNE data event

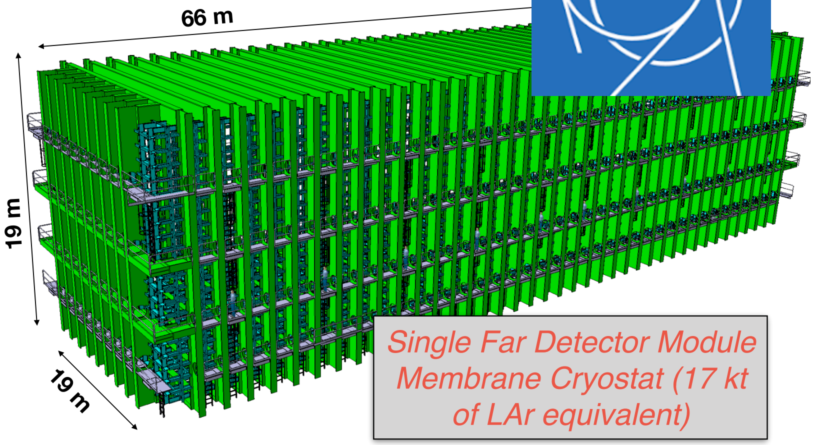


ProtoDUNE data has also led to several DUNE physics publications.

The DUNE Far Detector



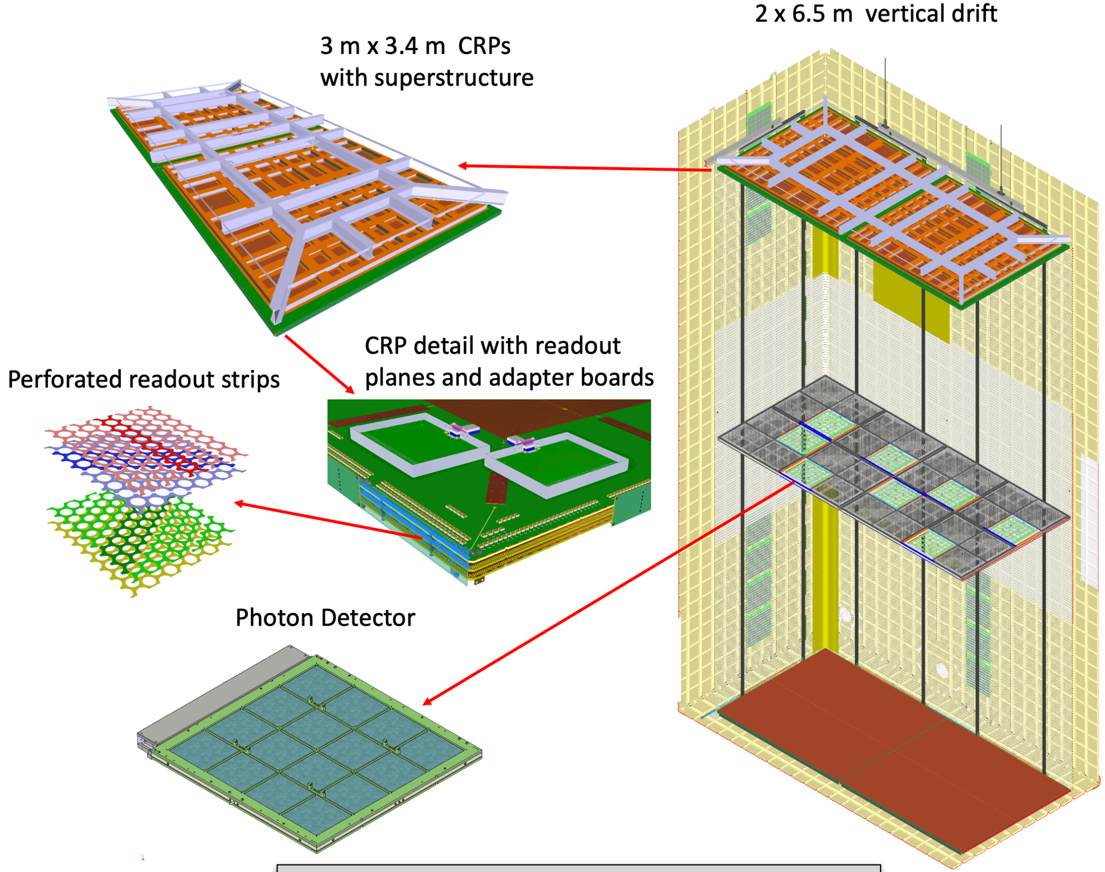
Cryostats funded by CERN



- **FD1**: Horizontal Drift (HD)
- **FD2**: Vertical Drift (VD)
- **FD3**: Improved VD-LArTPC
- **FD4:** Module of opportunity

Vertical Drift as a Starting Point for Phase-II Far Detectors

- Charge Readout Planes (CRPs) provide three-view charge readout: two induction planes and one collection plane.
- Technology developed at CERN
- Cathode plane at mid-height, two drift volumes of 6.5 m each.
- X-ARAPUCA-based Photon Detector System (PDS) on cathode and membrane walls.



LArTPC Vertical Drift Concept

Optimized Charge & Light Readouts for Phase-II

- FD3/4 R&D aimed at optimizing or upgrading VD designs for charge and light readout to broaden the physics programme towards expanded sensitivity for MeV-scale physics
- All technologies can be combined or integrated.

Energy Deposits in LArTPC

Observables in drift volume

- Ionization electrons
- Primary scintillation light

Detected signal carriers

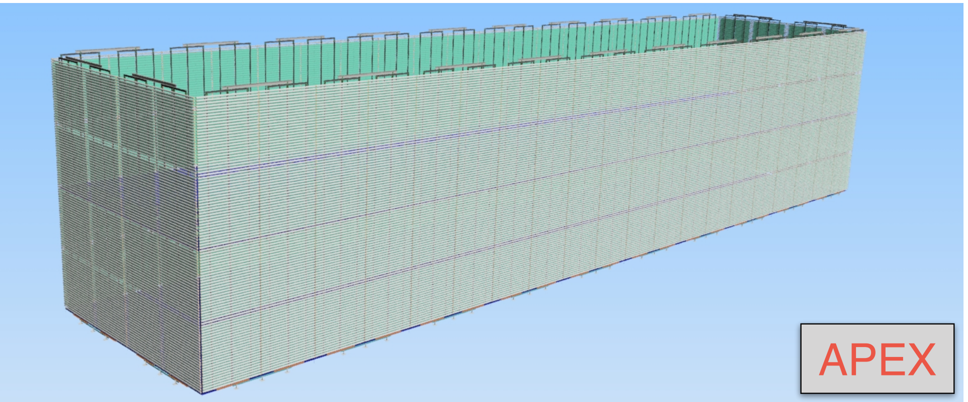
- Ionization electrons → Electrons
- Ionization electrons → Photons
- Primary scintillation light → Photons

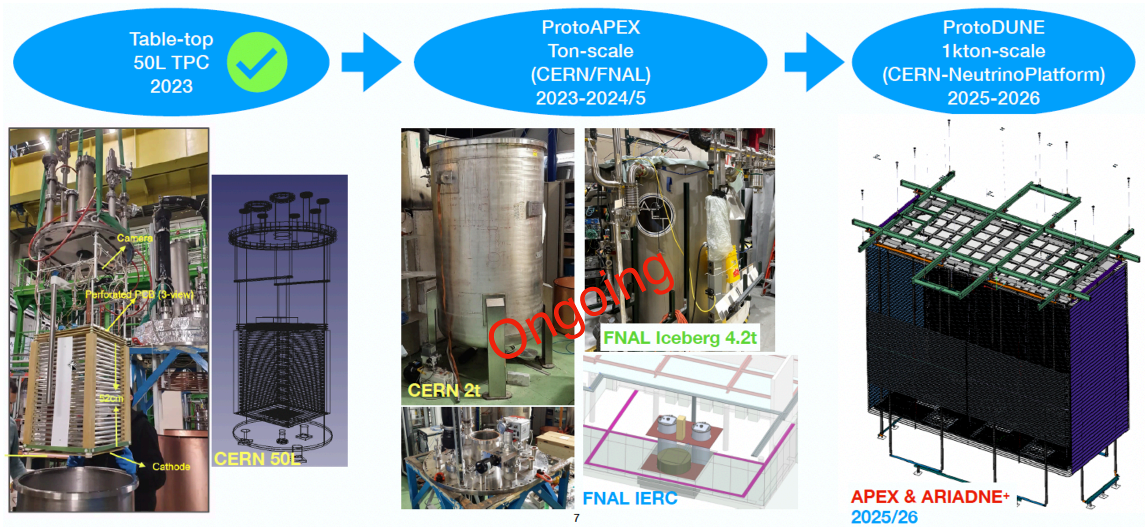
Readout options

- Electrons:
  - Improved 2D strip R/O (CRPs)
  - 3D pixel R/O (LArPix, Q-Pix, SoLAr)
- Photons (from ionization electrons):
  - 3D camera R/O (ARIADNE)
- Photons (from primary scintillation light):
  - Field cage X-ARAPUCAs (APEX)
  - PEN with enhanced reflection (PoWER)
  - Bare SiPMs (LightPix, SoLAr)
  - Photo-conductors (Q-Pix LiLAr)

Detector Concepts: FD3 Reference Design

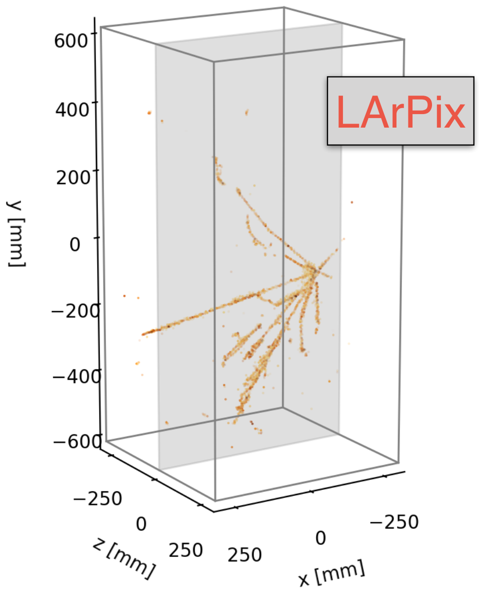
- VD-like, with improvements to CRP charge readout and X-ARAPUCA light readout
  - Single-phase and two vertical drift volumes, 6.5 m each
  - **Possible CRP optimizations:** strip pitch, simpler construction techniques, ASIC upgrade
  - **Possible PDS optimizations (via APEX R&D):** Photon detector system on field cage, larger (up to x10) coverage compared to VD (~60% optical coverage of LAr active volume), digital optical transmission

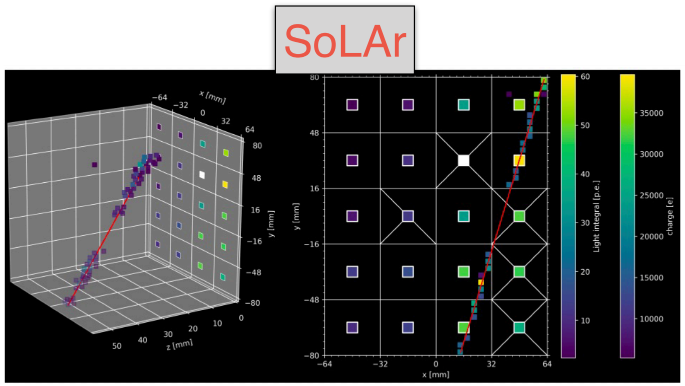


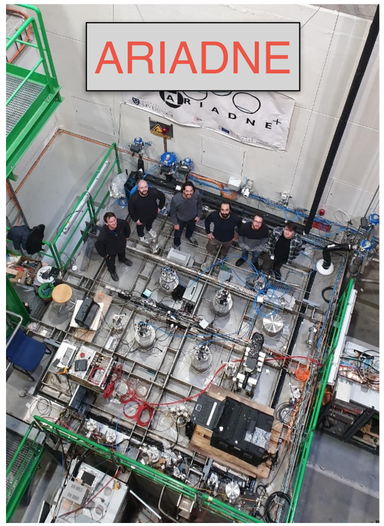


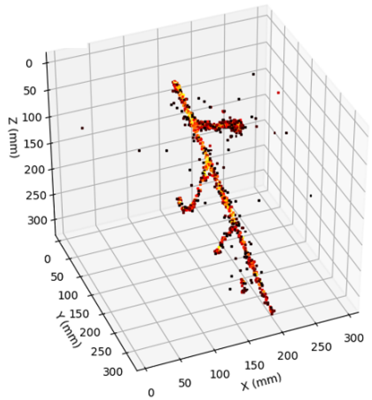
Detector Concepts: FD4 Reference Design

- VD-LArTPC with central cathode, and native 3D anode readouts
  - Either charge pixels (LArPix or Q-Pix) or optical-based readout (ARIADNE)
  - Pixels may also serve for integrated charge/light readout (SoLAr, LightPix or Q-Pix LiLAr)
  - Different solutions for top/bottom anodes in principle possible. Compact shield design







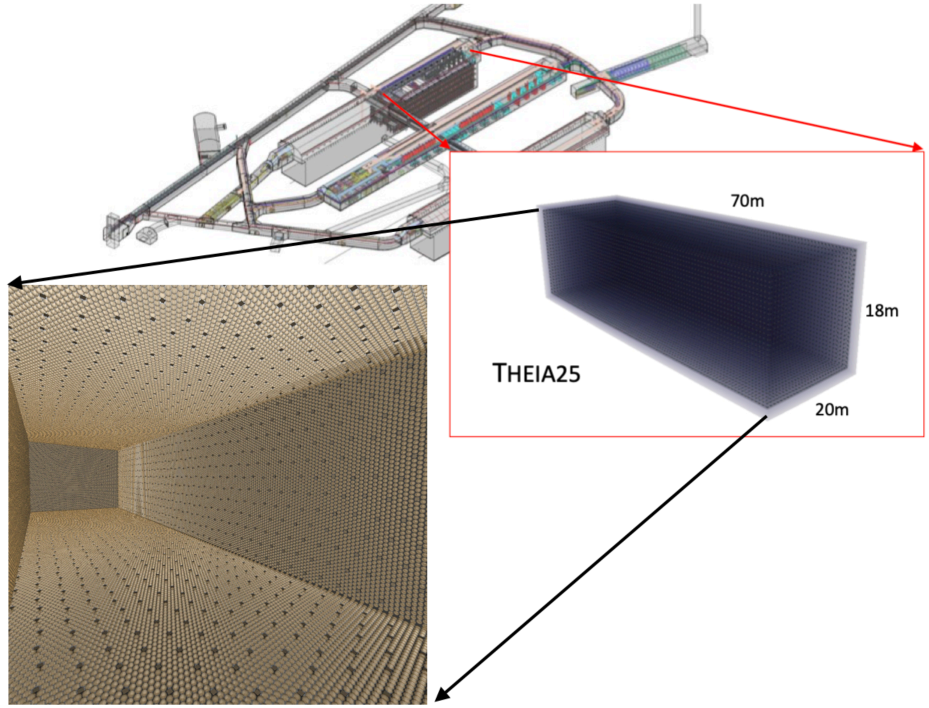


see talk by K. Mavrokoridis

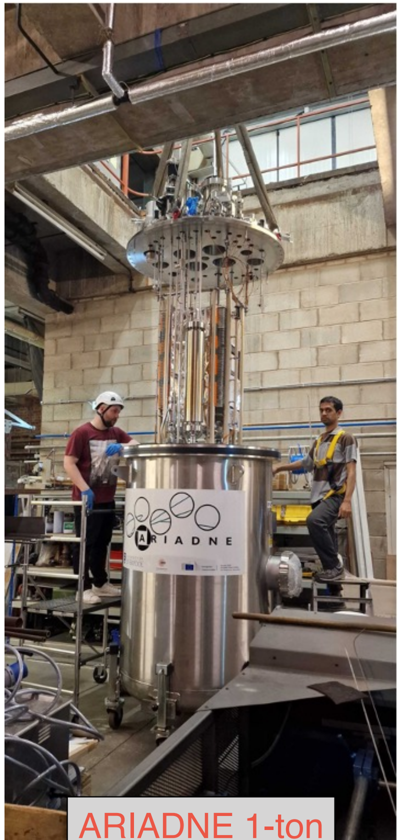
Detector Concepts: FD4 non-argon

THEIA

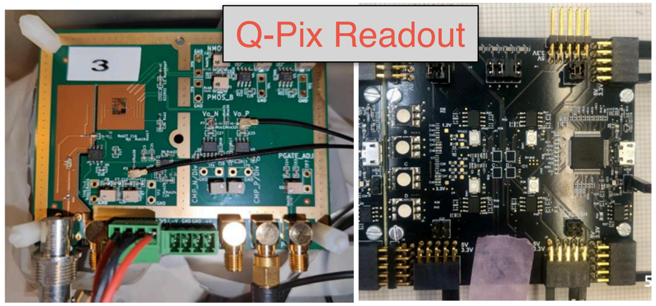
- Water-based liquid scintillator module measuring scintillation and Cherenkov light separately (**THEIA**)
- Cherenkov light offers e/μ discrimination via ring imaging, and sensitivity to particle direction
- Scintillation light offers improved energy and vertex resolution.
- Requires corresponding modifications to ND to carry out long-baseline oscillation programme,



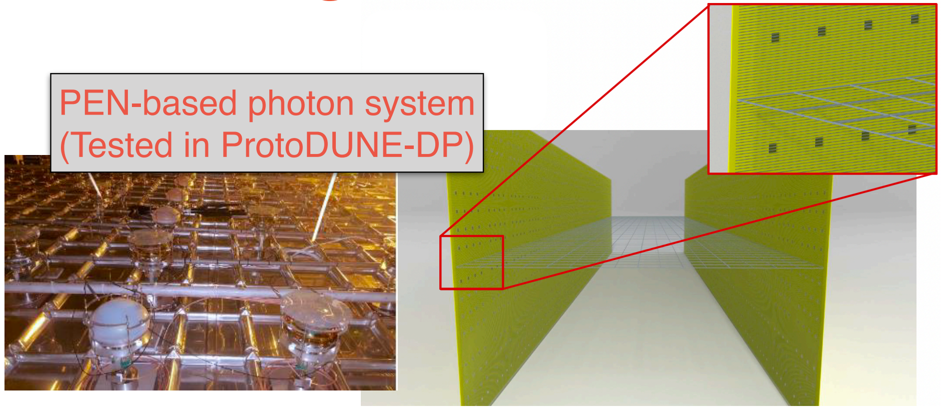
Active prototyping underway across all technologies



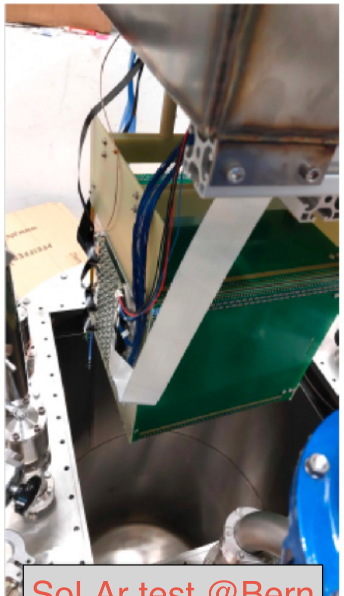
ARIADNE 1-ton Test @Liverpool



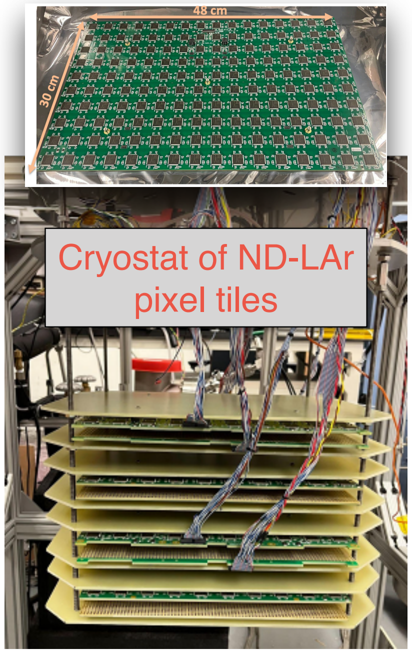
Q-Pix Readout



PEN-based photon system (Tested in ProtoDUNE-DP)

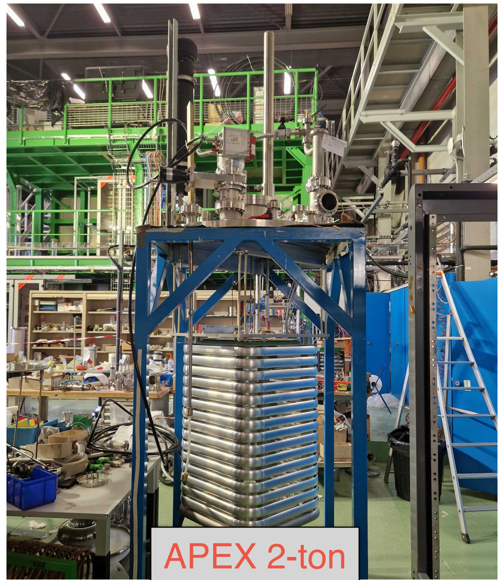


SoLAr test @Bern



Cryostat of ND-LAr pixel tiles

THEIA Demonstrator (EOS)



APEX 2-ton prototyping

FD prototyping plans and key R&D goals

- Technology Readiness Levels (TRL) currently achieved: TRL ≥ 3 on all items
- Small- and medium-scale prototypes in operation or planned

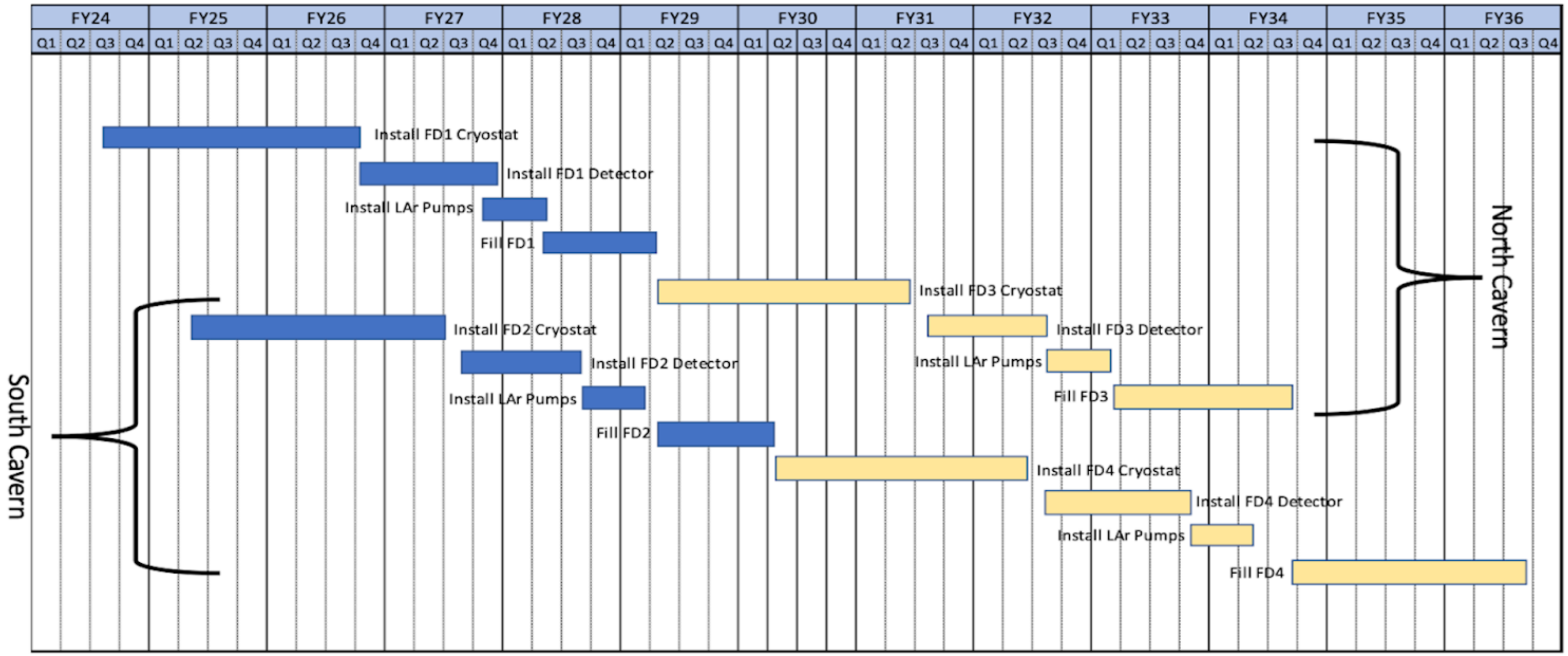
The ProtoDUNEs at CERN will continue to serve as an important platform to demonstrate these technologies and their potential for integration.

Technology	Prototyping Plans	Key R&D Goals
CRP	**2024:** Cold Box tests at CERN. **2025-2026:** ProtoDUNE-VD at CERN.	Port LArASIC to 65 nm process
APEX	**2024:** 50lt & 1-ton prototypes at CERN. **2024-25:** $\mathcal{O}(100)$-channel demonstrator at Fermilab. **2025-28:** ProtoDUNE-VD at CERN.	Mechanical integration of APEX PD in FC
		Signal conditioning, digitization and multiplexing in cold
LArPix, LightPix	**2024:** 2x2 ND demonstrator at Fermilab. **2024-25:** Cold Box tests at CERN. **2026-28:** ProtoDUNE at CERN.	Micropower, cryo-compatible, detector-on-a-chip ASIC
		Scalable integrated 3D pixel anode tile
		Digital aggregator ASIC and PCB
Q-Pix, Q-Pix-LILAr	**2024:** Prototype chips in small-scale demonstrator. **2025-26:** 16 channels/chip prototypes in ton-scale demonstrator at ORNL. **2026-27:** Full 32-64 channel "physics chip".	Charge replenishment and measurement of reset time
		Power consumption
		R&D on aSe-based devices and other photoconductors
ARIADNE	**2024:** Glass THGEM production at Liverpool. **2025-26:** ProtoDUNE-VD at CERN.	Custom optics for TPX3 camera
		Light Readout Plane design with glass-THGEMs
		Characterization of next-generation TPX4 camera
SoLAr	**2024:** Small-size prototypes at Bern. **2025-2028:** Mid-scale demonstrator at Boulby.	Development of VUV-sensitive SiPMs
		ASIC-based readout electronics
WbLS	**2024-25:** Prototypes at BNL (1- & 30-ton), LBNL (EOS), Fermilab (ANNIE). **2025-26:** BUTTON at Boulby.	WbLS organic component manufacturing
		WbLS *in situ* purification
		Spectral photon sorting (dichoicons)

Technically Limited FD3/4 Schedule

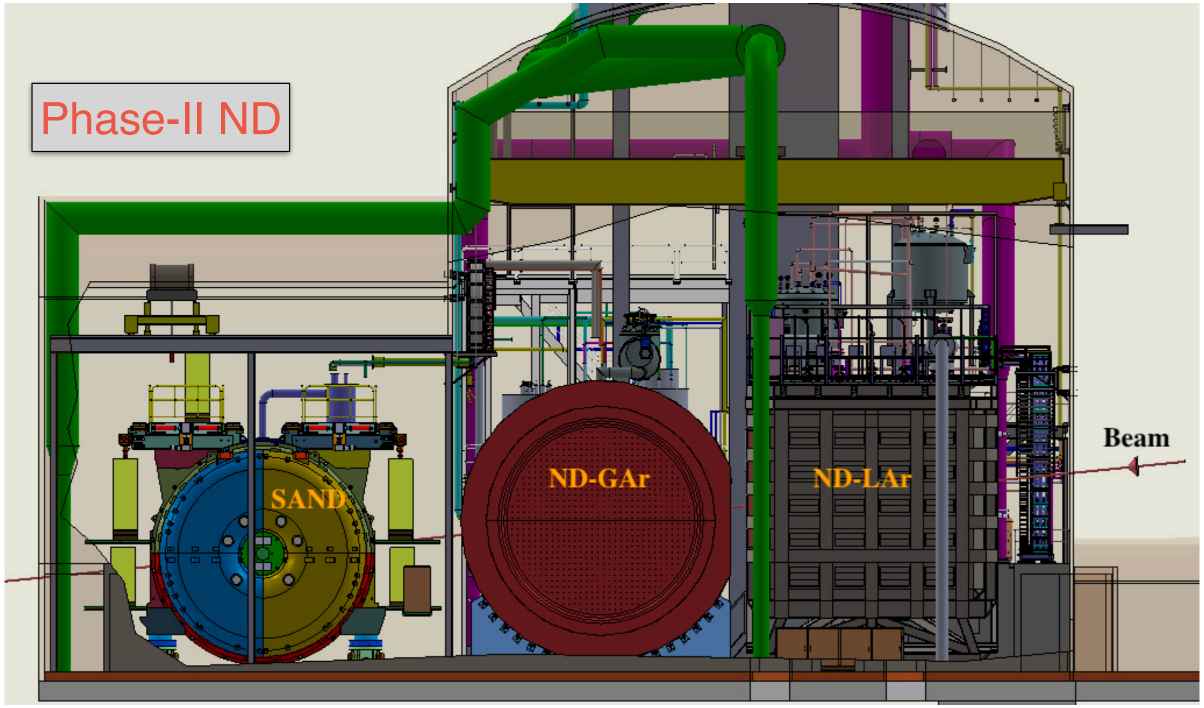
- Installation start in 2029 with FD3 completed in 2034 and FD4 in 2036
- The final schedule for FD4 will be driven by the technology choice and extent of upgrades planned in the case of a LArTPC

__Figure:__ A notional, technically limited schedule for FD3/4 assuming it is a vertical drift LArTPC similar to FD2

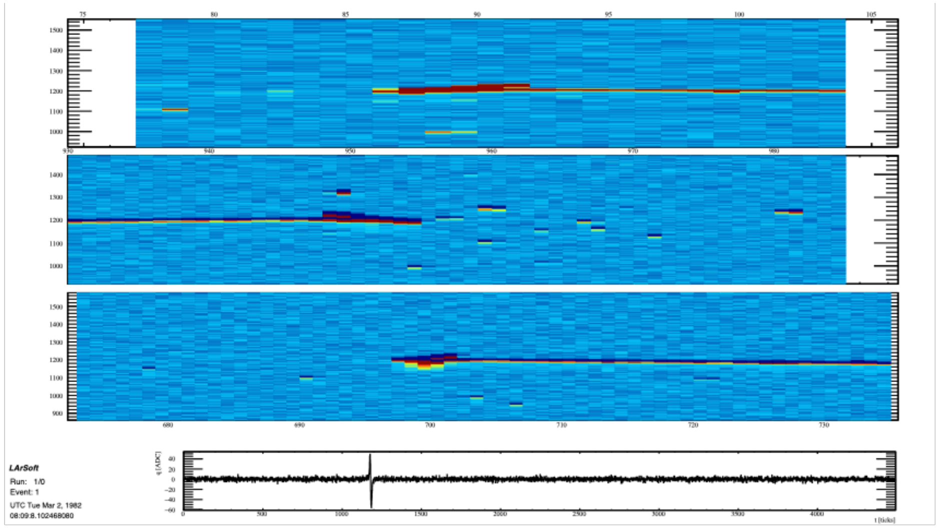


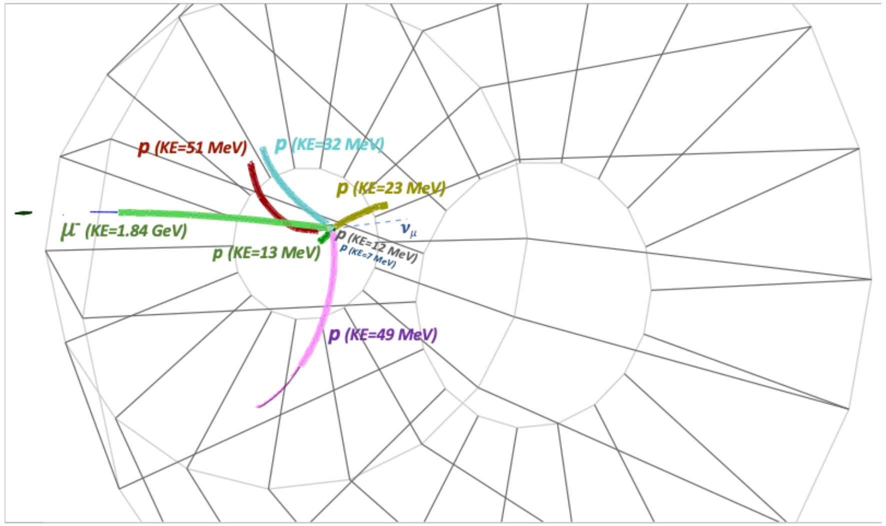
Near Detector requirements for high-statistics operation

- The More Capable Near Detector (MCND) ensures that DUNE is not systematics limited,
- MCND should expand the physics capabilities of the liquid-argon ND (ND-LAr).
- Phase-II ND Requirements for an argon target
  - *Argon as primary target nucleus*
  - *Very high particle ID efficiency*
  - *Low thresholds for protons and pions*
  - *4π acceptance over a wide range of momenta and angles*
  - *Magnetization for sign selection*



Why a gas detector for DUNE?

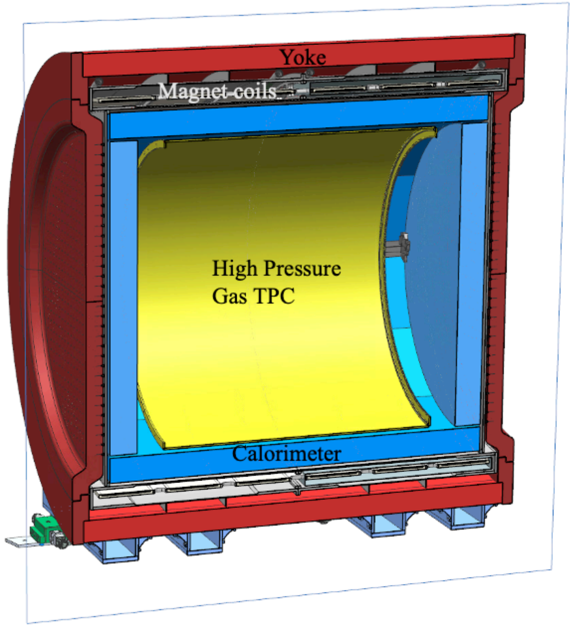


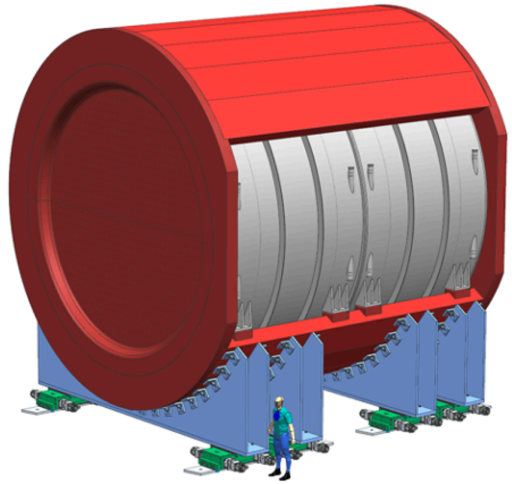


Looking at the same event in liquid argon and argon gas!

ND-GAr Baseline Concept

- Cylindrical volume of 5 m linear dimensions filled with gas at 10 bar (~1 ton of Ar)
- Baseline concept includes:
  - *Pressurized gaseous argon TPC*
  - *Surrounding calorimeter*
  - *Magnet: solenoid with partial return yoke*
  - *Muon-tagging system*
- Light detection system maybe necessary to reduce pileup, and to provide the event t0 in events that do not reach the calorimeter
- Will move perpendicularly to beam with ND-LAr (DUNE-PRISM concept)

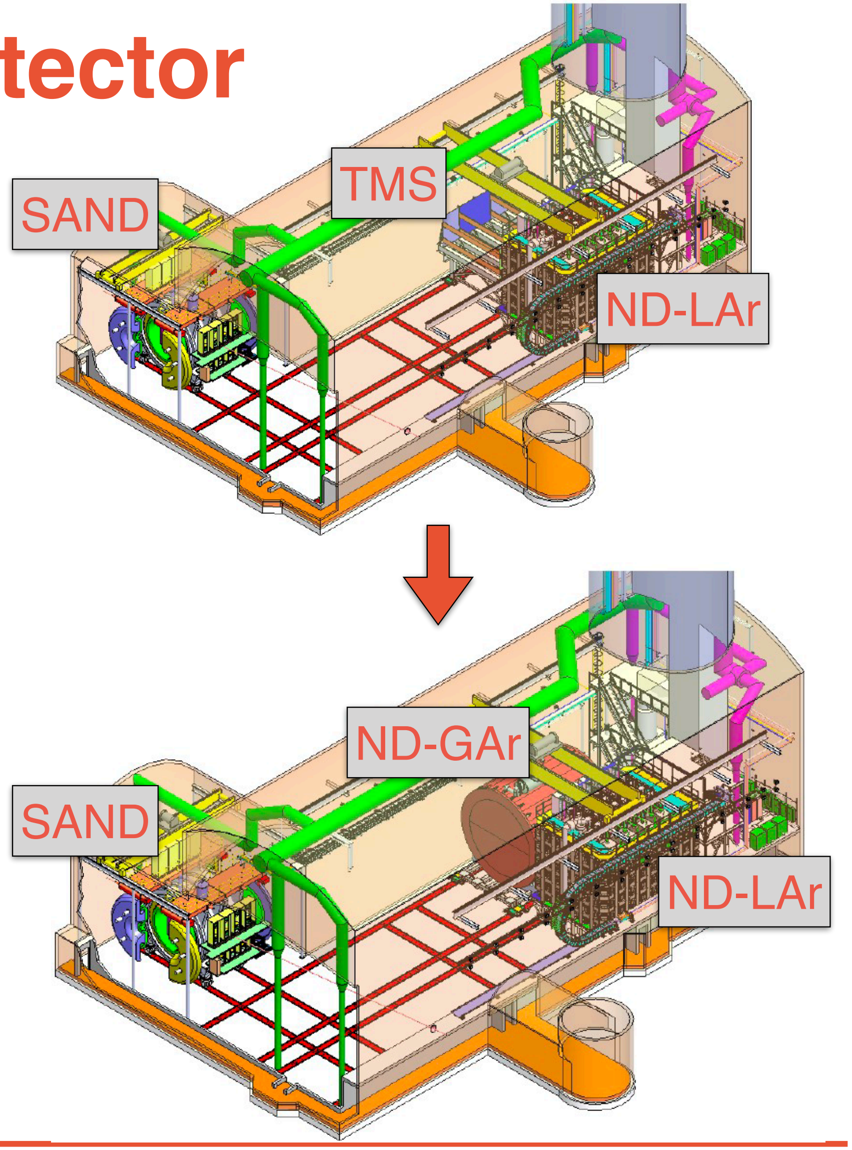




see talk by T. Mohayai

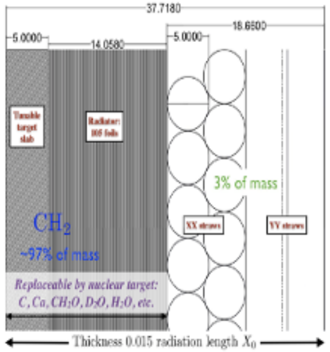
Phase-I to Phase-II Near Detector

- Gaseous argon detector (ND-GAr) will replace the Temporary Muon Spectrometer (TMS) in Phase II,
- Upgrades to ND-LAr and SAND are also possible.
- If FD4 neutrino target is not argon (e.g., THEIA), Phase-II ND would need to measure neutrino interactions on other targets.
  - *Several options under consideration*

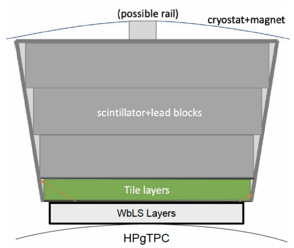


ND pptions for a non-argon target

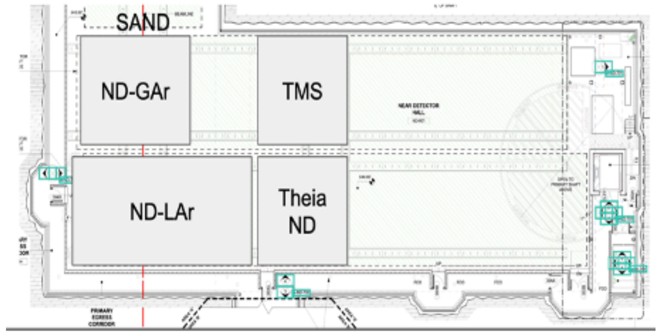
Additional nuclear targets in SAND



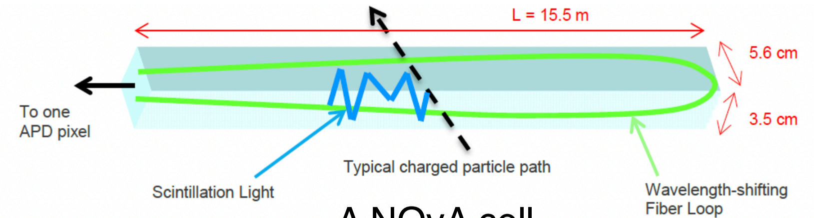
WbLS targets in ND-GAr ECAL



Dedicated Theia ND



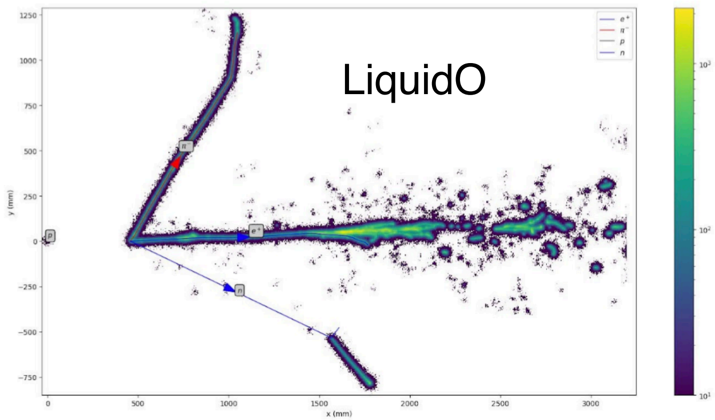
Complexity



A NOvA cell

Options for a dedicated WbND

- **NOvA-style ND** (replace NOvA scintillator with WbLS)
- **LiquidO ND** (use opaque scintillators with mm-scale scattering length to produce high resolution images of ν interactions)



CERN's leading role on DUNE

- Support of European participation as DUNE's leading co-host Laboratory, enabling collaboration.
- Neutrino Platform providing infrastructure, technical expertise, resources, support for DUNE R&D and detector technology validation.
- Technical support during DUNE construction phase (e.g., QA & QC).
- CERN Support and coordination of the DRD collaborations.
- Unique ability to perform beam tests for detector R&D at CERN.
- Leading contribution to LBNF through procurement of Far Detector cryostats.
- CERN's neutrino group providing important physics leadership.

A bright light at the end of the tunnel!

- DUNE as a global neutrino observatory will provide unique potential for discoveries and precision measurements in the neutrino sector.
- Phase I construction underway and Phase II preparation has started - both strongly supported by US and European communities.
- CERN's leading role on DUNE is crucial for its success.