Progetto DUNE a Fermilab

Discussione sulla European Strategy INFN

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Neutrino Physics

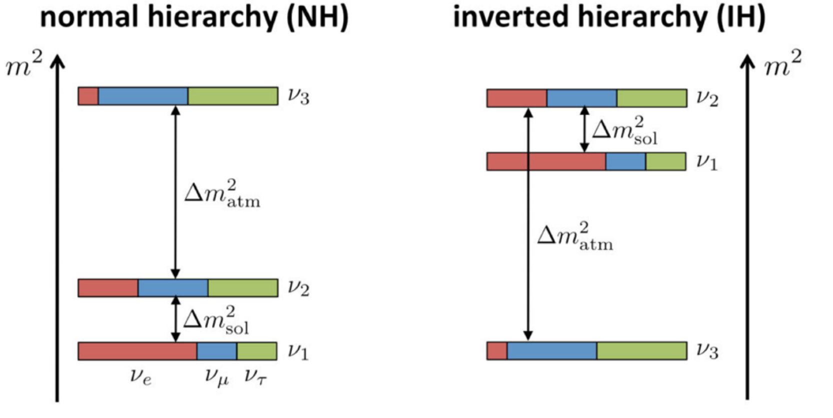
The PMNS Matrix describes the neutrino sector with 3 mixing angles (θ_{12}, θ_{13}, θ_{23}) and a complex phase (δ_{CP})

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{23}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

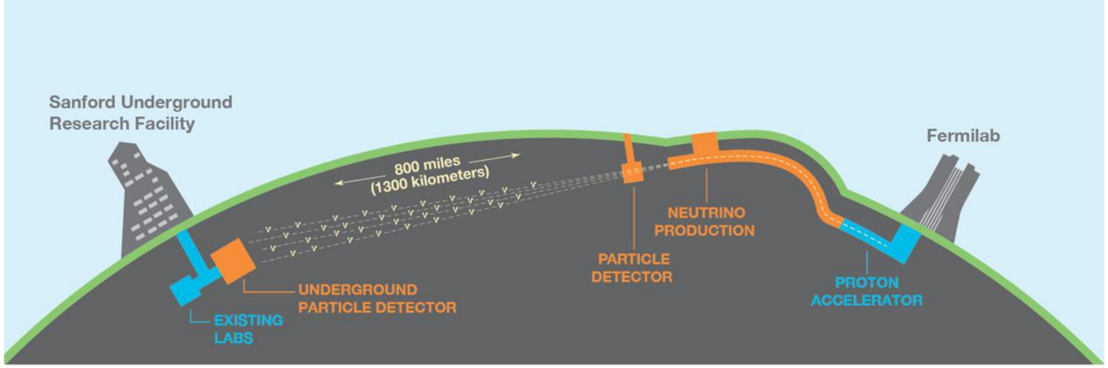
With $c_{ij} = cos\theta_{ij} \quad s_{ij} = sin\theta_{ij}$

Open questions:

- Neutrinos mass hierarchy
- Dirac or Majorana neutrinos?
- CP violation in leptons sector
- θ_{23} octant problem
- …

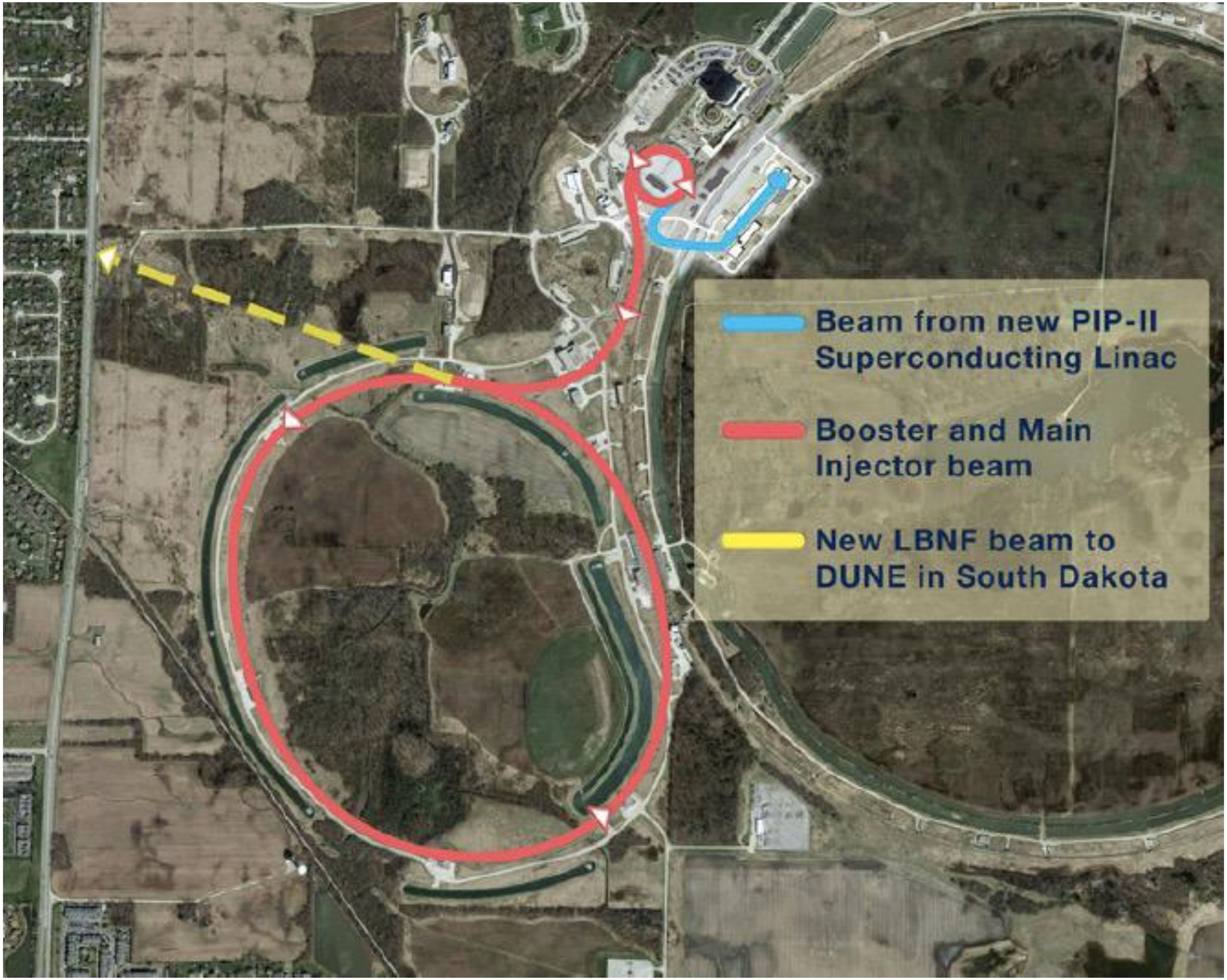


Deep Underground Neutrino Experiment (DUNE)



New generation «Long Baseline» experiment

- High intensity (anti)neutrino beam from Fermilab Main Injector (1.2 MW with an upgrade to 2.4 MW)
- 1-10 GeV Energy range
- Near Detector at 570 m from beam production point
- Far Detector: 2+2 Liquid Argon TPC modules (~17 kton each) at the SURF (Sanford Underground Research Facility) in Sud Dakota, 1300 km distance and ~1500 m deep



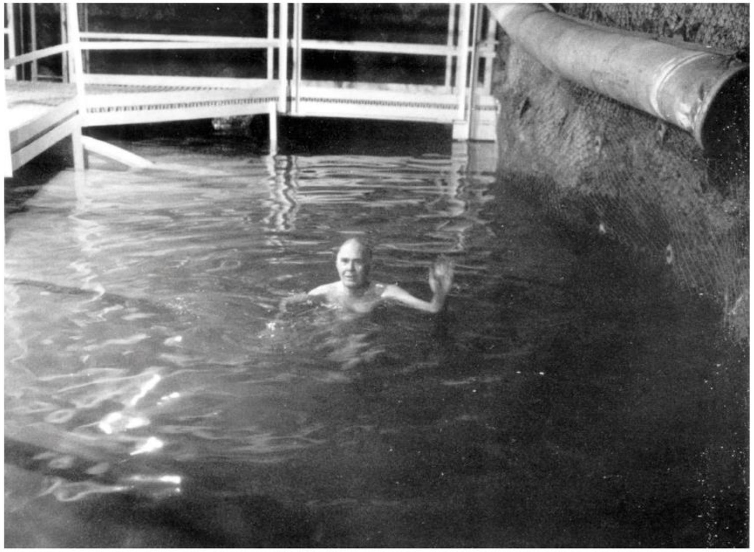
Beam from new PIP-II Superconducting Linac
Booster and Main Injector beam
New LBNF beam to DUNE in South Dakota

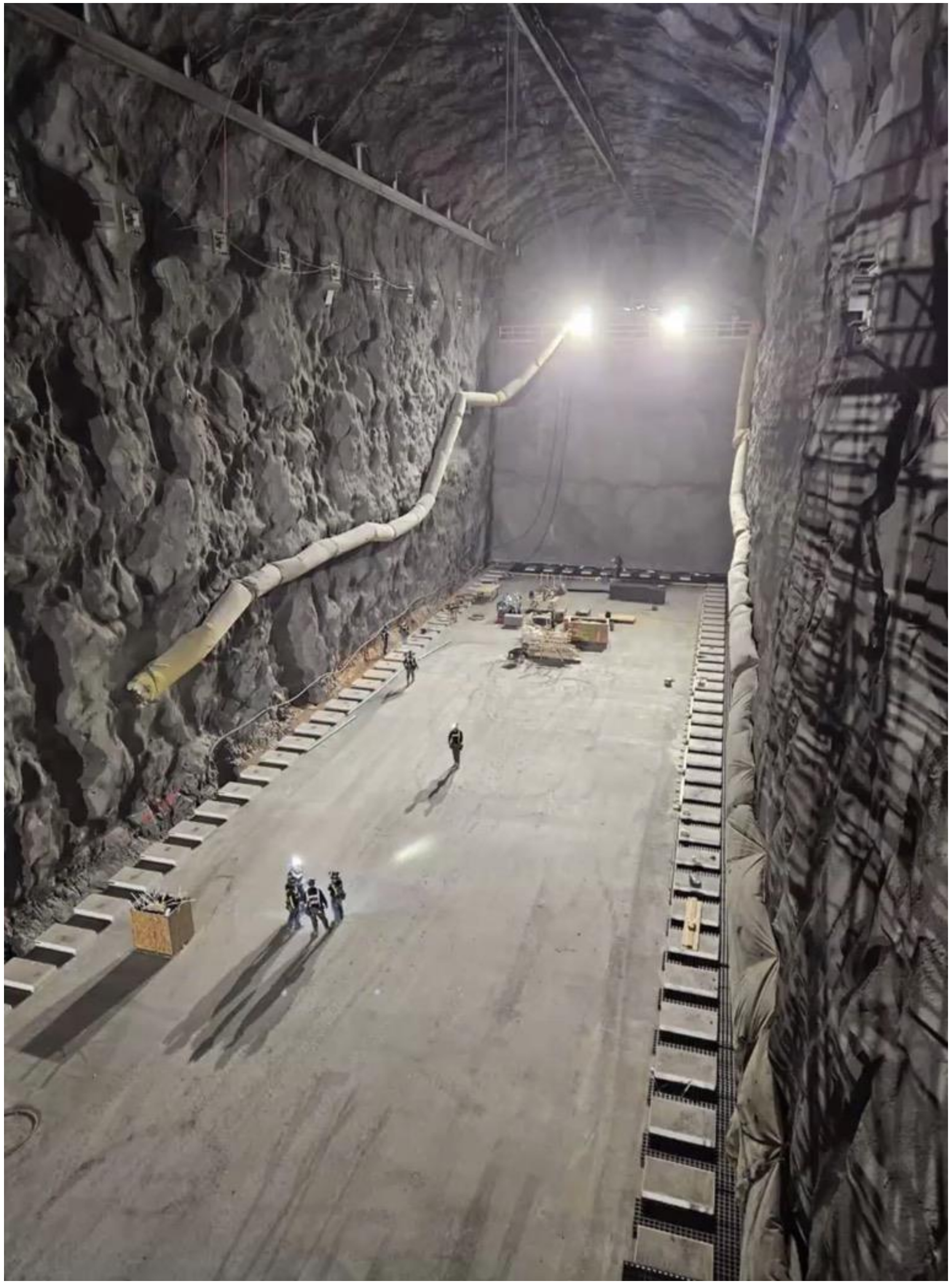
Physics program

- Neutrino Oscillations
  - CP violation phase in the neutrino sector
  - Neutrino Mass Hierarchy (measurement of Δm^2_{32})
  - Precise measurement of θ_{23}
- Neutrino Astrophysics
  - Neutrinos from supernovae
  - Solar neutrinos
- BSM physics
  - Nucleon decay (baryon number violation)
  - Dark matter
  - Non-standard interactions
  - Heavy Neutral Leptons
  - Sterile Neutrinos

Far Detector

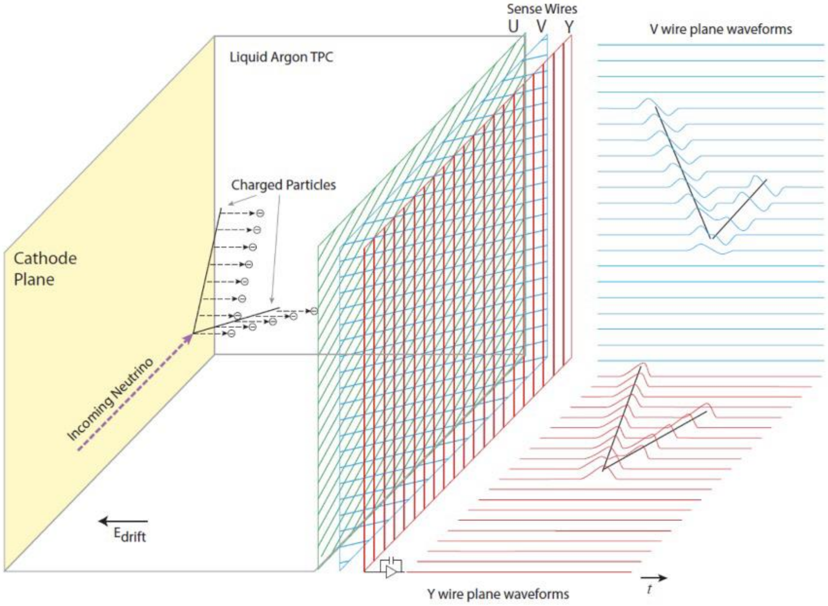
- Homestake gold Mine in South Dakota

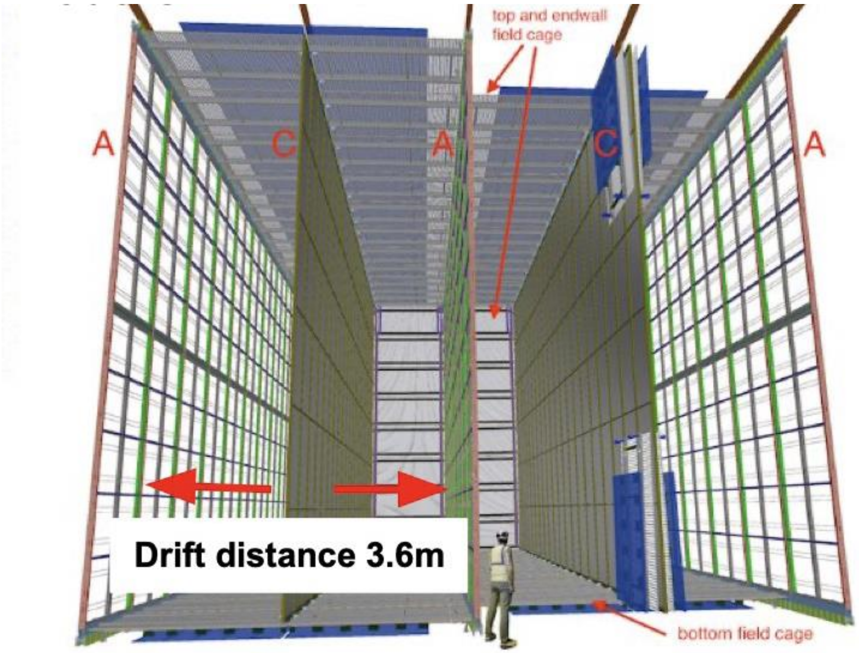




Far Detector

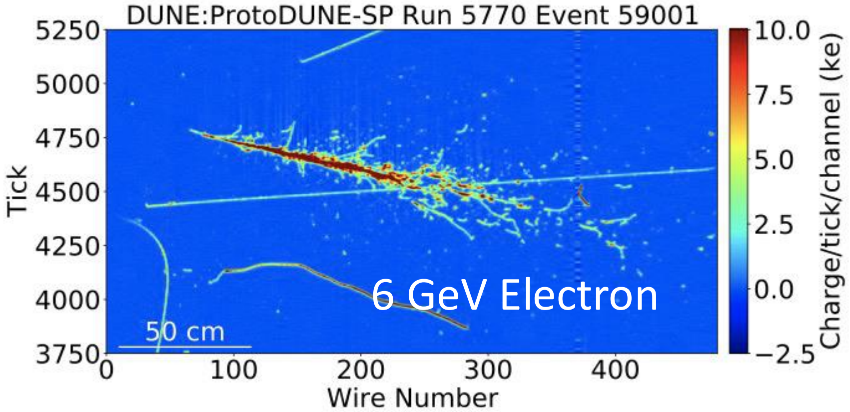
- Homestake gold Mine
- 2+2 Modules Liquid Argon TPC
- Module 1:
  - Horizontal Drift TPC
  - Vertical anode wire planes
  - X-ARAPUCA light sensors on vertical anode planes
- Module 2:
  - Vertical drift TPC
  - Charge signal collected by strips printed on a circuit board
  - X-ARAPUCA light sensors on the horizontal cathode and on the cryostat walls

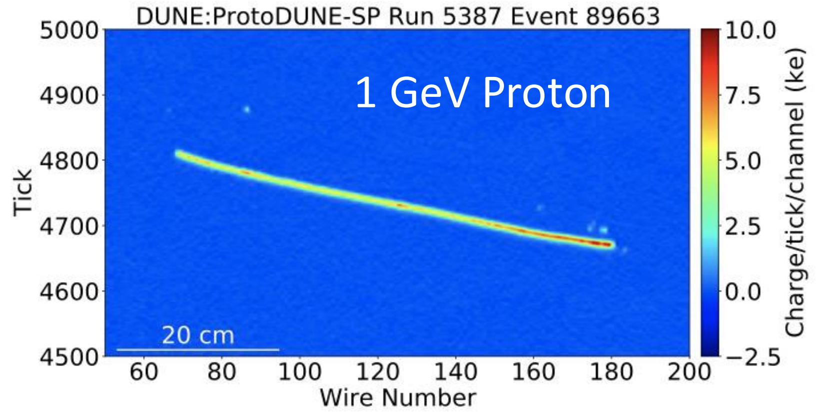


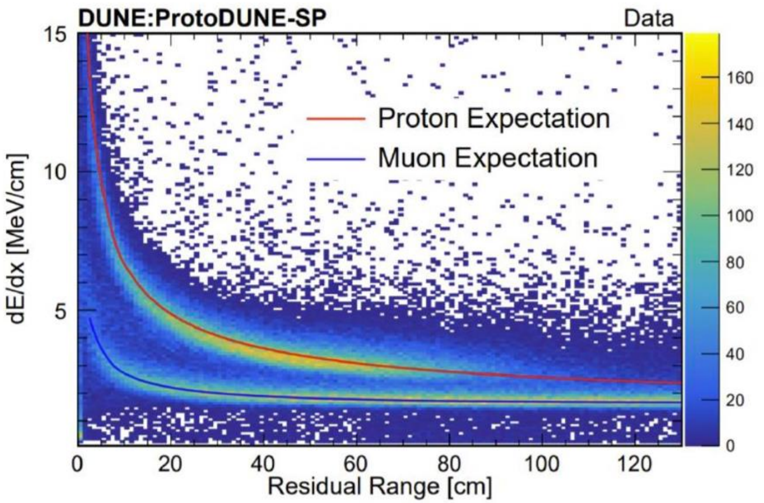


ProtoDUNE

- Demonstrators for the Far Detector Module 1 and 2 built and tested at CERN
- Neutrino Platform at CERN
- Vertical Drift prototype tested with cosmic rays in 2024
- Horizontal drift prototype tested in 2018-2020 with charged beams + cosmic rays; new run in 2024

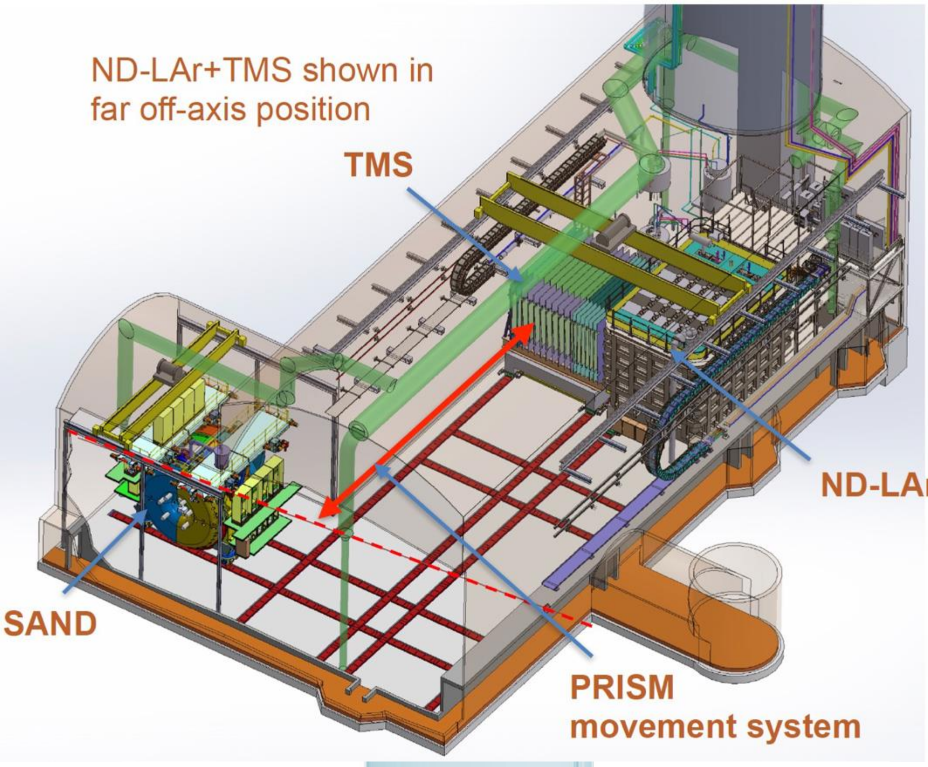


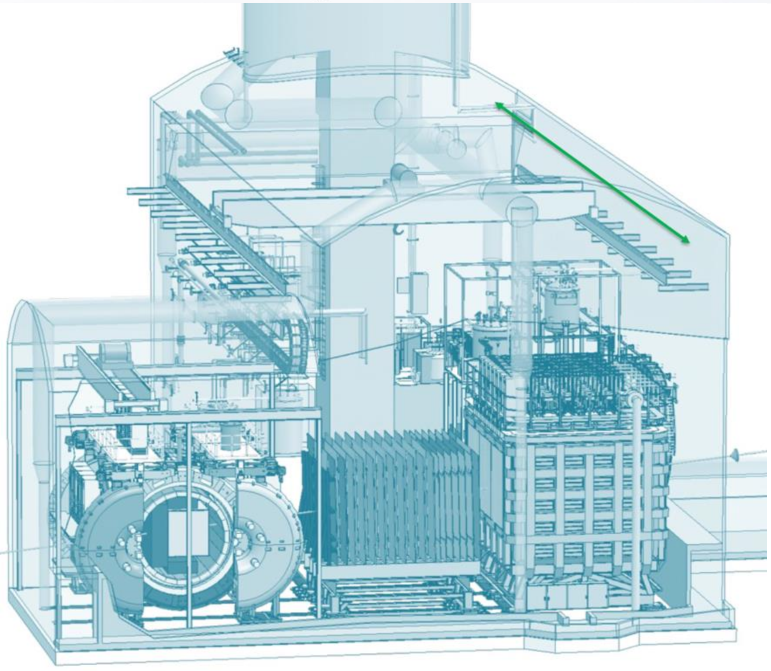




Near Detector

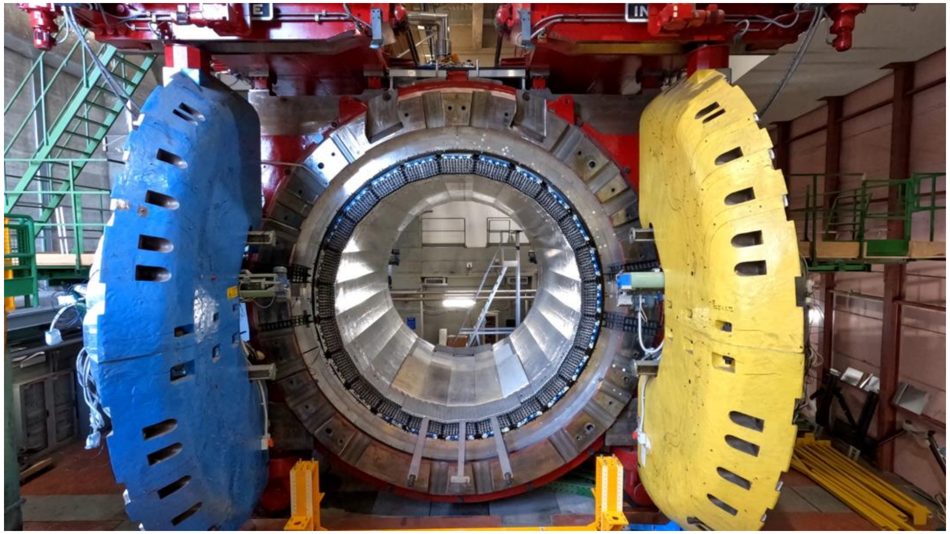
- Near Detector complex:
  - Liquid Argon TPC (ND-LAr)
  - The Muon Spectrometer (TMS)
  - Magnetic Tracker (SAND)
- Near Detector purpose:
  - Flux measurement
  - Cross sections of (anti)neutrino - Argon, C, CH2
  - Reduce beam-related systematics
- System for on Axis Neutrino Detection (SAND):
  - Monitor beam on-axis
  - Beam composition and spectrum
  - $p - \bar{\nu}$ cross section

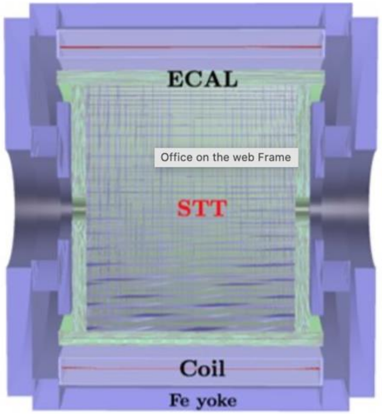


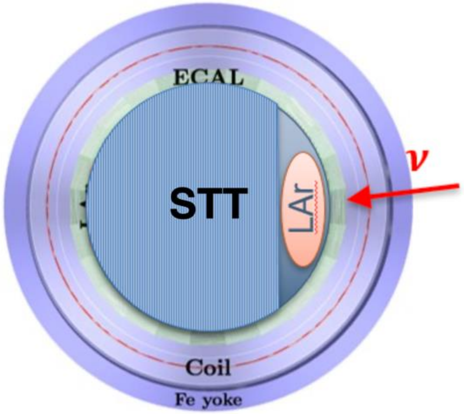


SAND

- Repurposed KLOE magnet and E-Cal:
  - 0.6 Tesla field
  - 24 barrel modules + 2 endcaps for 4π coverage
  - Lead + Scintillating Fibers (and 4880 PMTs)
  - Energy res: 5.7%/√E
  - Time res: 54 ps / √E
- Tracker detector
  - Two designs: straw tubes and drift chamber
  - Accurate reconstruction of the tracks, particle kinematics and particle ID
- GRAIN: 1 ton LAr active target
  - Measure nuclear effects in the neutrino-Argon interaction
  - Light collected with SiPMs







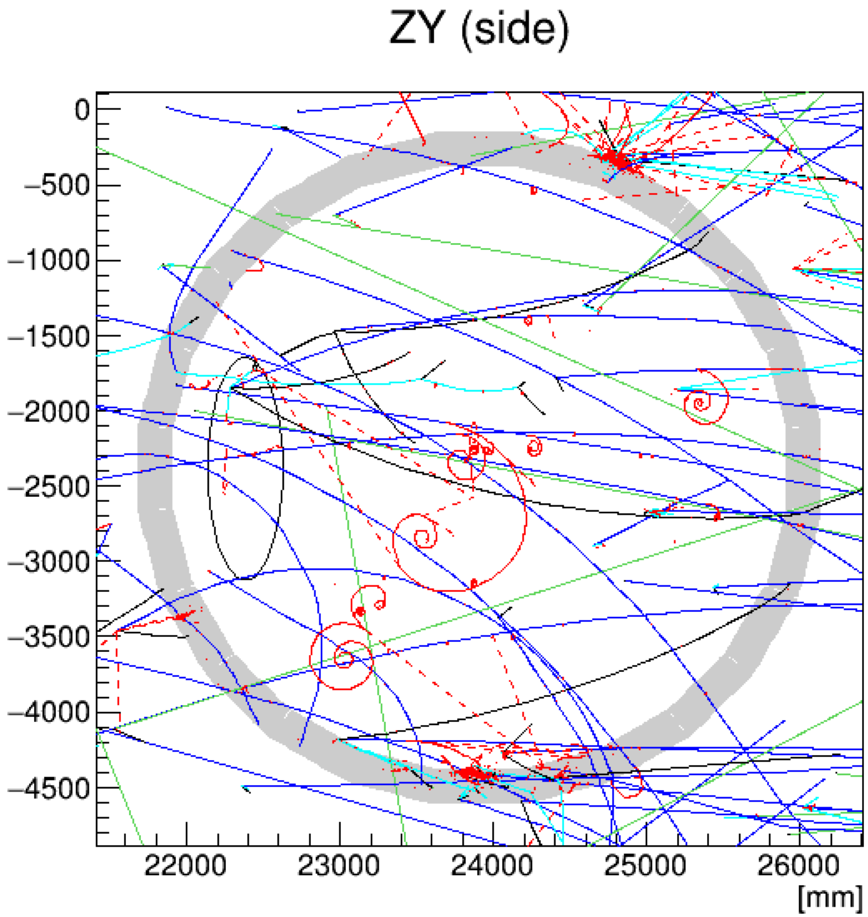
Timeline

- 2024: Completed the Far Detector excavation
- 2025-2026: KLOE eCal + magnet testing and shipping
- 2028: Near Detector Hall completed, ready for installation of the detectors (SAND goes in first)
- 2029: Far Detector starts physics with atmospheric and astrophysics neutrinos
- 2031: Beam checkout, begin physics with neutrino beams
- 2037-2038: Phase 2 (FD upgrade to 4 modules, ND upgrade with GAr TPC, beam to 2.4 MW)

Local Activities @ RM2

Montecarlo analysis of the two different tracker designs to determine the best solution to achieve the DUNE physics goals.

- Implemented the track reconstruction in the official software
- Compare the different tracker designs to base the decision on:
  - Efficiency
  - Momentum resolution
  - Energy resolution



Local Activities @ RM2

Testing the calorimeter modules at LNF to ensure correct operations after dismounting

- Old KLOE electronics is being repurposed to read the PMT signals and perform a first funcitonality test of the modules
- The KLOE DAQ will interface with a CAEN VME Bridge
- Developement of the DAQ software for the bridge
  - Based on C++/CAEN Libs for boards reading and on ROOT for the analysis files production
- Run a full scale test on all the 24 calorimeter barrel modules + the 2 endcaps
- Same test will be performed at Fermilab after shipping of the modules

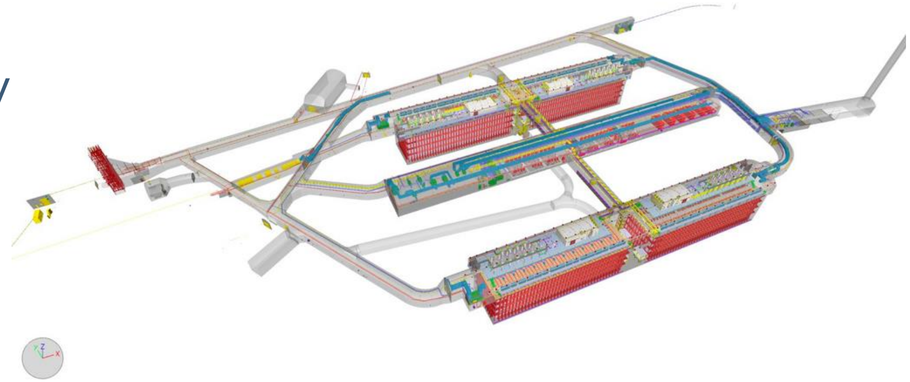
Summary

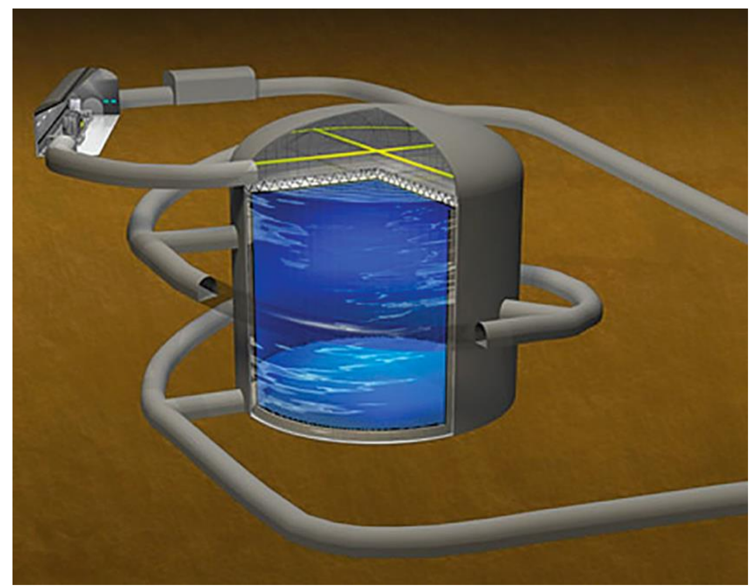
- DUNE è progettato per misure di alta precisione sui parametri della matrice PMNS con un programma di fisica molto ricco
- L'inizio delle operazioni con il fascio è previsto per il 2031
- Ci sono ottime opportunità sia nell'ambito hardware che in quello software
  - Analisi montecarlo per la ricostruzione degli eventi
  - Studio delle prestazioni del tracciatore
  - Caratterizzazione dei SiPM per il sotto-detector GRAIN
  - Test dei moduli del calorimetro
  - Sviluppo dell'elettronica di acquisizione per il calorimetro di SAND
- L'INFN vanta un'ottima collaborazione con il Fermilab, in particolare la sezione di TV è stata protagonista dell'esperimento Muon g-2 iniziato nel 2013

Backup

DUNE vs Hyper-K

- DUNE:
  - Very long baseline → large matter effect → unambiguous mass ordering and CPV
  - Broadband neutrino beam → high statistics over full oscillation period
  - Reconstruct energy over broad range → imaging + calorimetry → LArTPC technology
  - Highly-capable ND to constrain uncertainties
- Hyper-K:
  - Shorter baseline → small matter effect
  - Off-axis location & narrowband beam → very, very high statistics at oscillation maximum, less feed-down
  - Lower energy and mostly CCQE → very large water Cherenkov detector
  - Highly-capable ND to constrain systematic uncertainties





Oscillation Probabilities

ν_e appearance : mass ordering, δ_{CP} , octant of θ_{23}

$$P_{\nu_\mu\to\nu_e,(\bar\nu_\mu\to\bar\nu_e)} \approx 4\sin^2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\,J_{CP}^{max}\cos(\Delta\pm\delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{1-A}$$

$$J_{CP}^{max} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu} \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}} \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \qquad V_C = \sqrt{2}G_F n_e\,.$$

for $\bar\nu$
- «minus» sign
- V→ -V

α, Δ , A are sensitive to the sign of Δm^2_{31}

ν_μ disappearance: $|\Delta m^2_{32}|$, $\sin\vartheta^2_{23}$, constrain octant

$$P_{\nu_\mu\to\nu_\mu} \approx 1-\sin^2 2\theta_{\mu\mu}\sin^2\frac{\Delta m^2_{\mu\mu}L}{4E_\nu} \approx 1-\cos^2\theta_{13}\sin^2(2\theta_{23})\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} + \mathcal{O}(\alpha, s^2_{13})$$

$$\begin{aligned}\sin^2\theta_{\mu\mu} &= \cos^2\theta_{13}\sin^2\theta_{23}\,,\\ \Delta m^2_{\mu\mu} &= \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32}\\ &\quad + \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}\end{aligned}$$