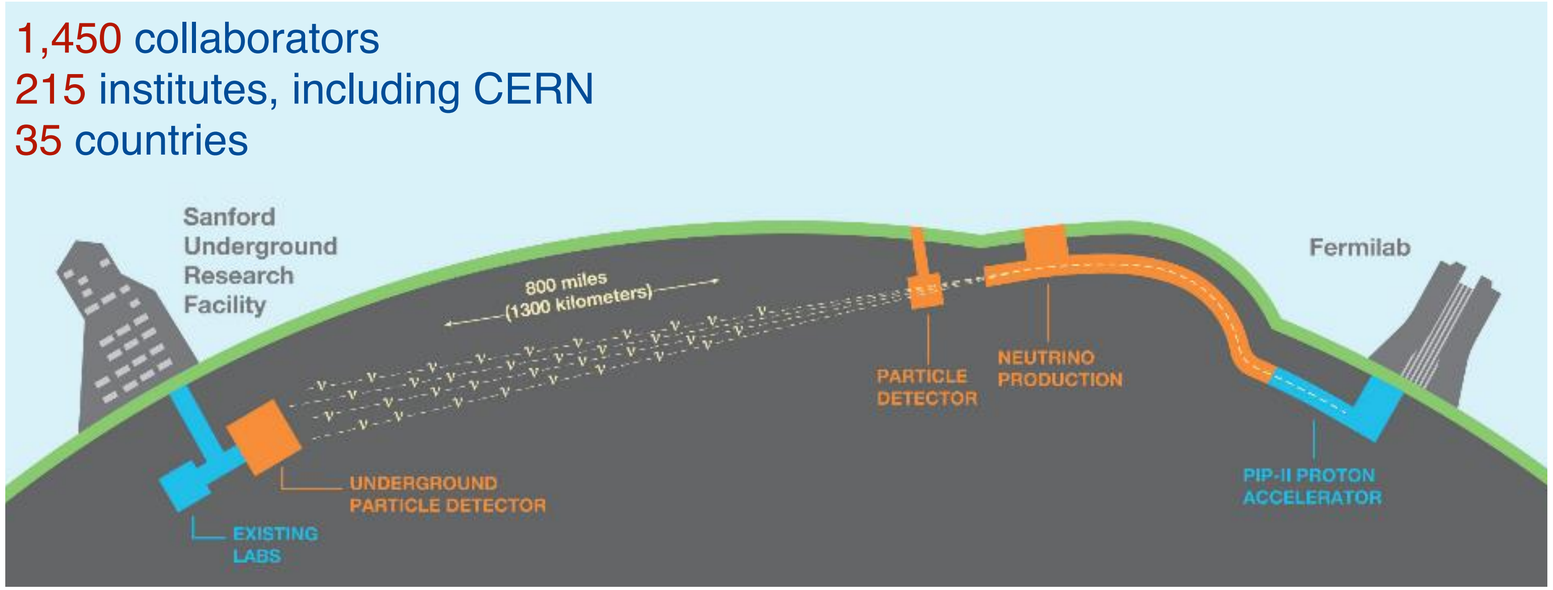
Status and Prospects of the DUNE Experiment

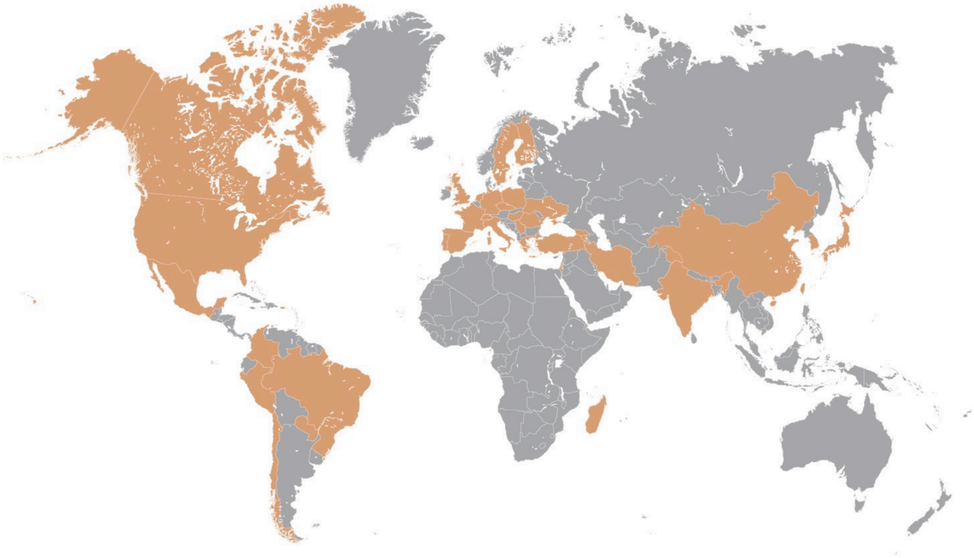
Wei Shi
Stony Brook University
for the DUNE Collaboration

DPF-PHENO 2024
May 13
Pittsburgh

DUNE Collaboration

1,450 collaborators
215 institutes, including CERN
35 countries





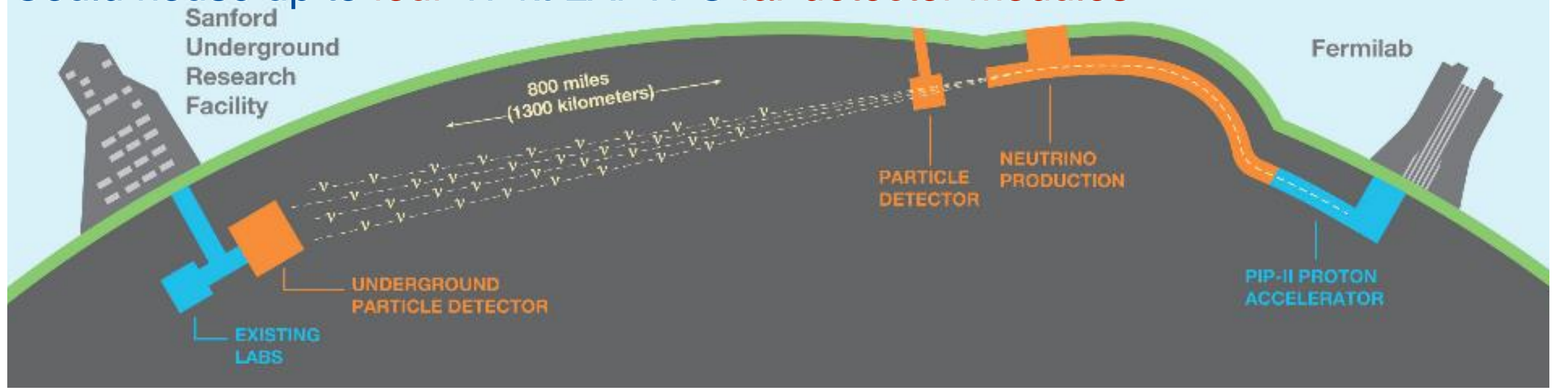
DUNE Far Site

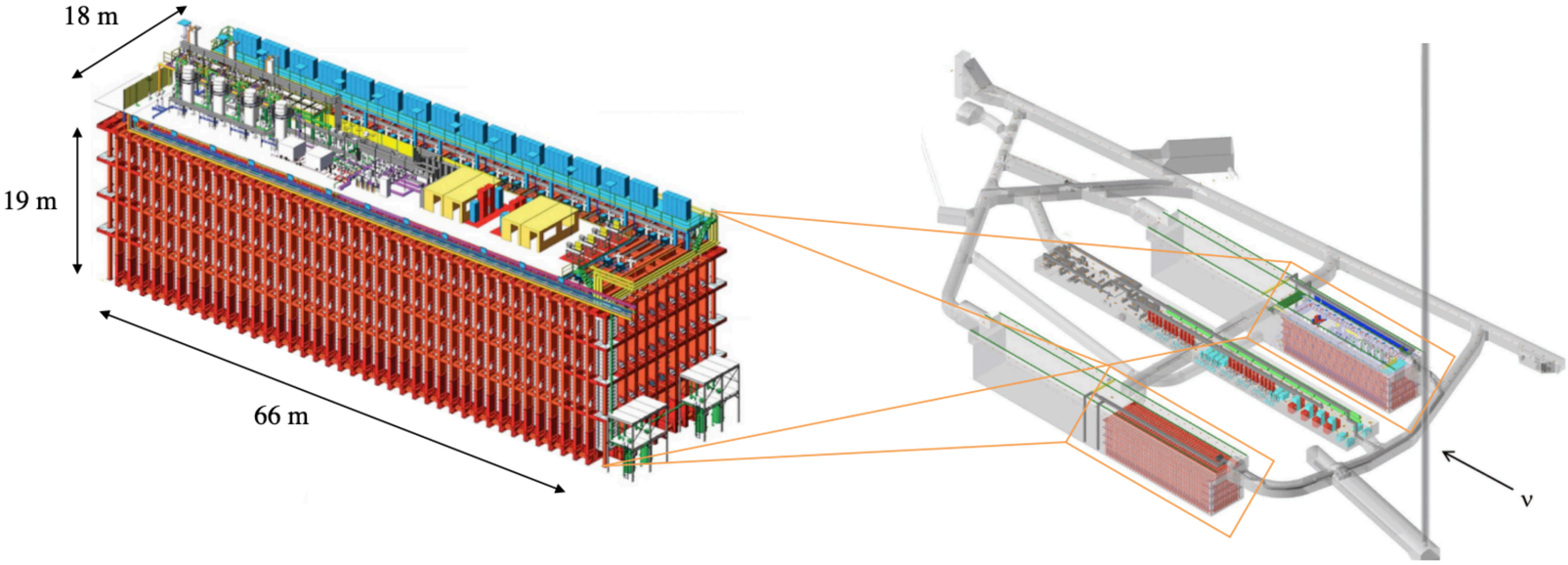
SURF in Lead, South Dakota

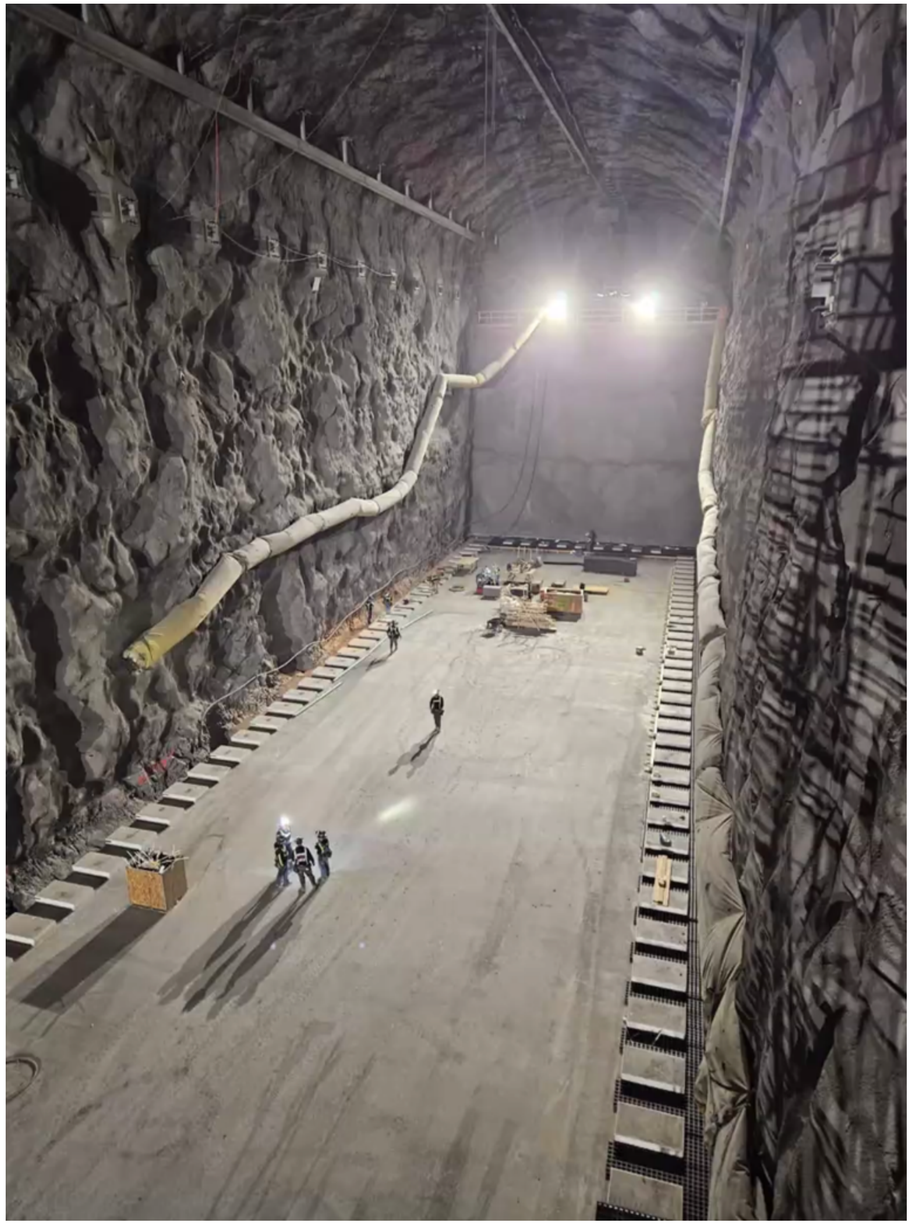
Cavern excavation completed Feb 1, 2024 - outfitting & receive cryostats

4850 ft underground, 8 soccer fields, 800 ktons of rock

Could house up to four 17 kt LAr TPC far detector modules



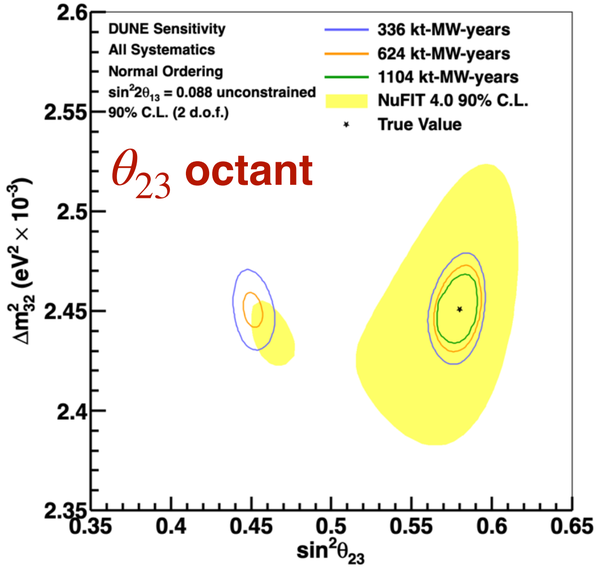




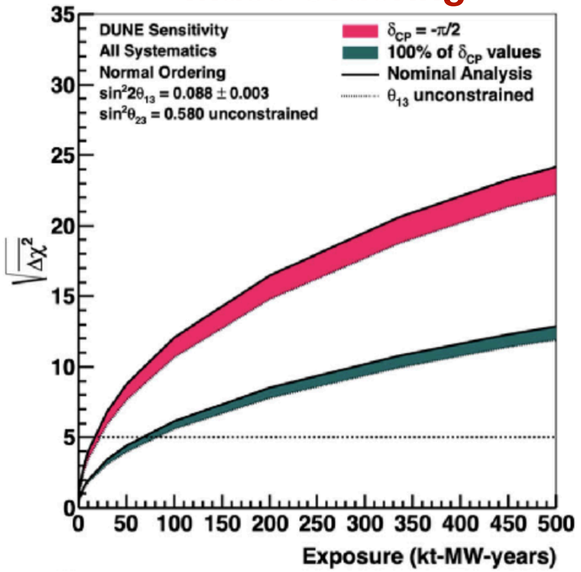
Flagship Program: long-baseline neutrino oscillation physics

High precision measurements of neutrino mixing in a *single* experiment

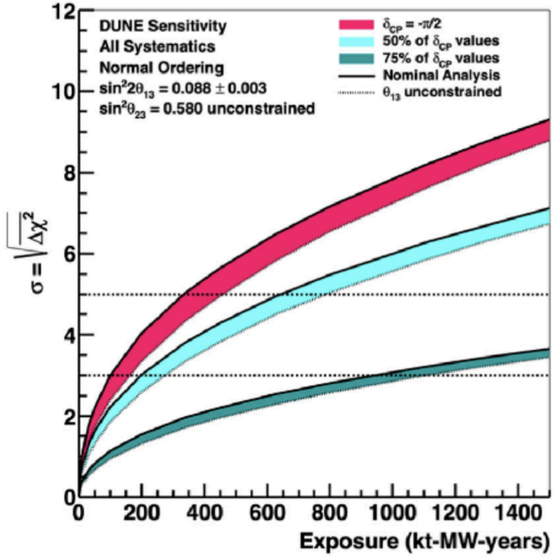
- First year data taking: oscillated ν_e approximately sum of T2K & NOvA
- Neutrino mass ordering: unambiguous discovery@66kt-MW-yr (<3yr)
- Observation and measurement of CPV in lepton sector
  - Max CPV: 3σ evidence@100kt-MW-yr (<5yr, Nature kindness)
- Wide-band beam
  - Resolves degeneracies: non-max-CPV, θ_{23} octant (anti-correlation to $\sin^2 2\theta_{13}$)
  - Offers 2nd oscillation peak: stronger CPV effect & lower E (separate measurement)
- Indirect and direct tests of the 3-ν paradigm (PMNS unitarity)
  - Direct test precision dominated entirely by ν_τ appearance data (possible with re-optimized high E beam)



Mass Ordering

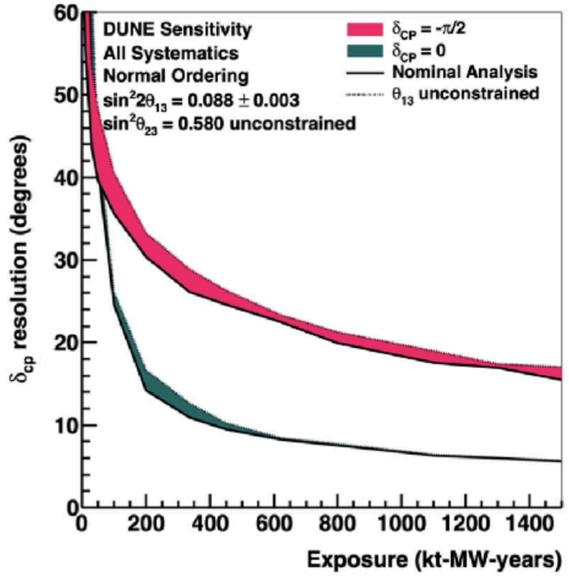


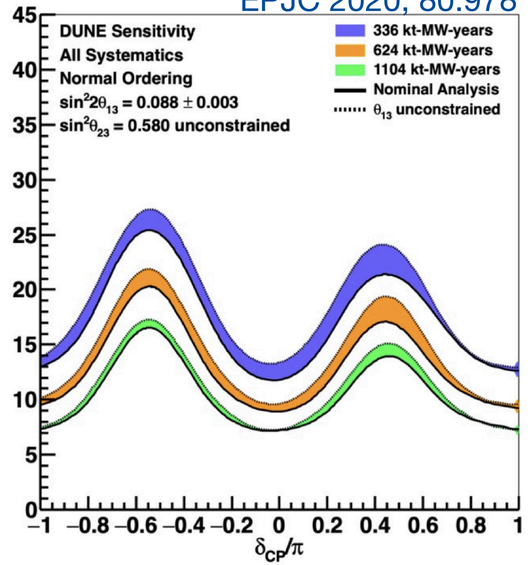
CPV



δ_{CP} resolution

EPJC 2020, 80:978

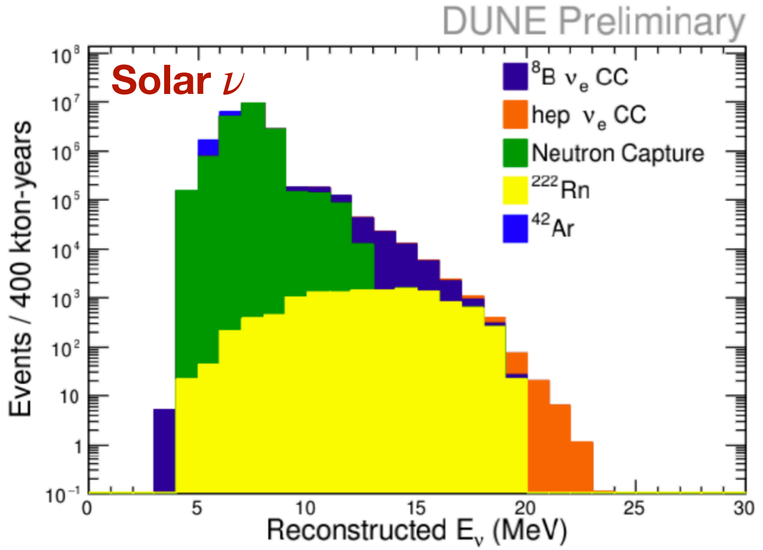


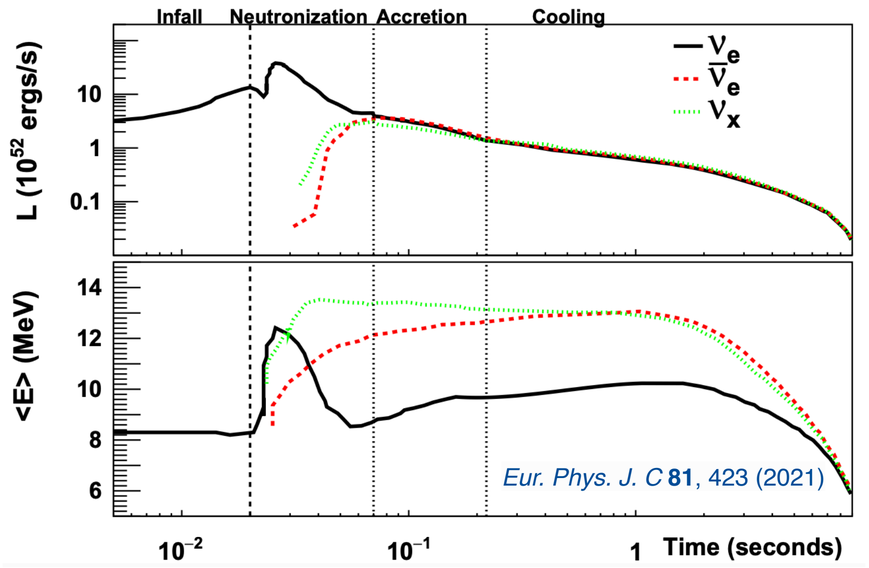


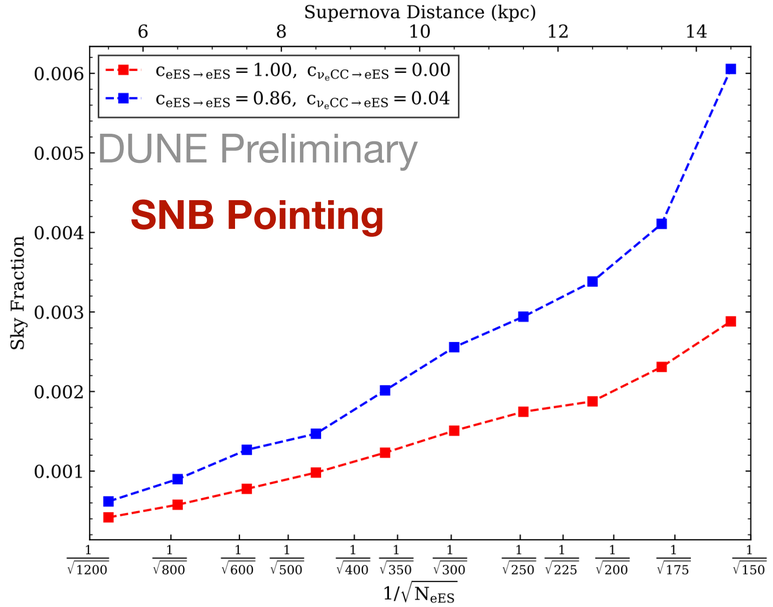
Low Energy Physics

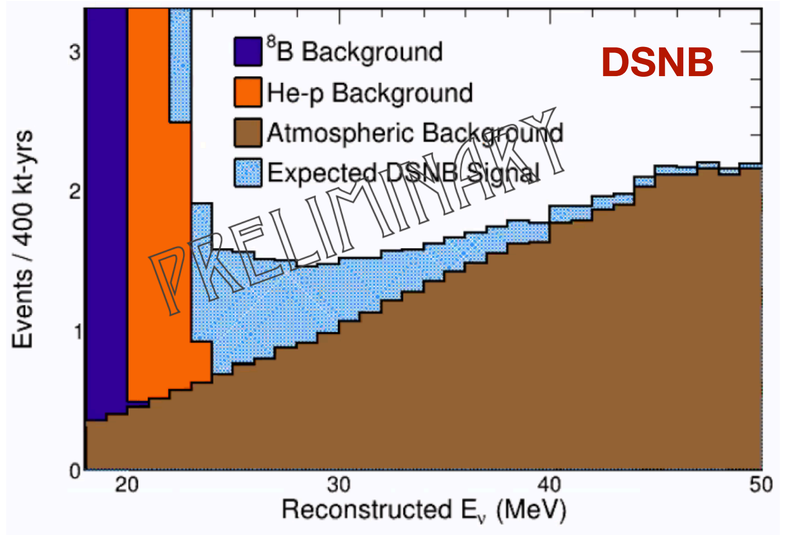
Observatory for astrophysical neutrino sources

- Solar
  - **5σ** sensitivity to Hep flux in Phase I
  - Sensitive to ^{8}B flux
- Galactic supernova neutrino burst
  - Unique sensitivity to (thousands of) ν_e, complementary to HK, JUNO ($\bar{\nu}_e$ IBD)
  - Triggering: > 95% efficiency at 20 kpc
  - Pointing capability: 5-7 degrees at 68% coverage (40kt LAr)
- Diffuse supernova neutrino background (guaranteed signal!)
  - 22 - 33 MeV window
  - 2.2σ significance after 400kt-yr (assume 8.8% energy resolution)







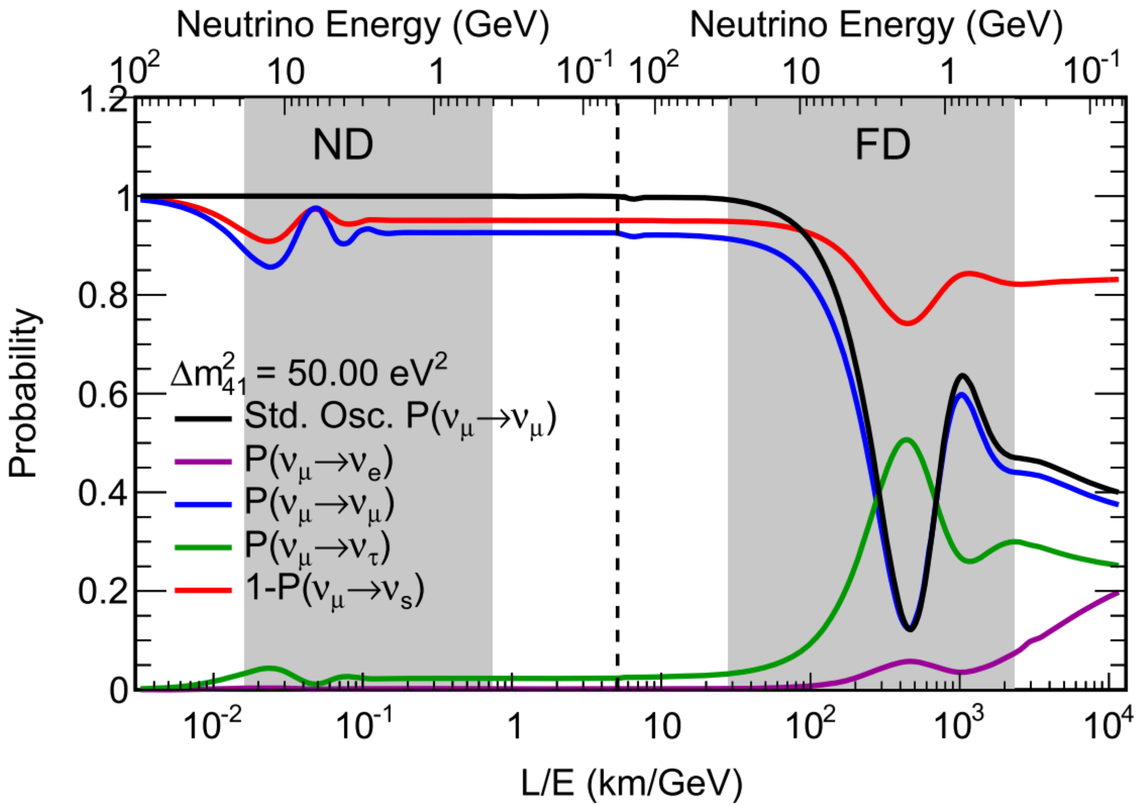


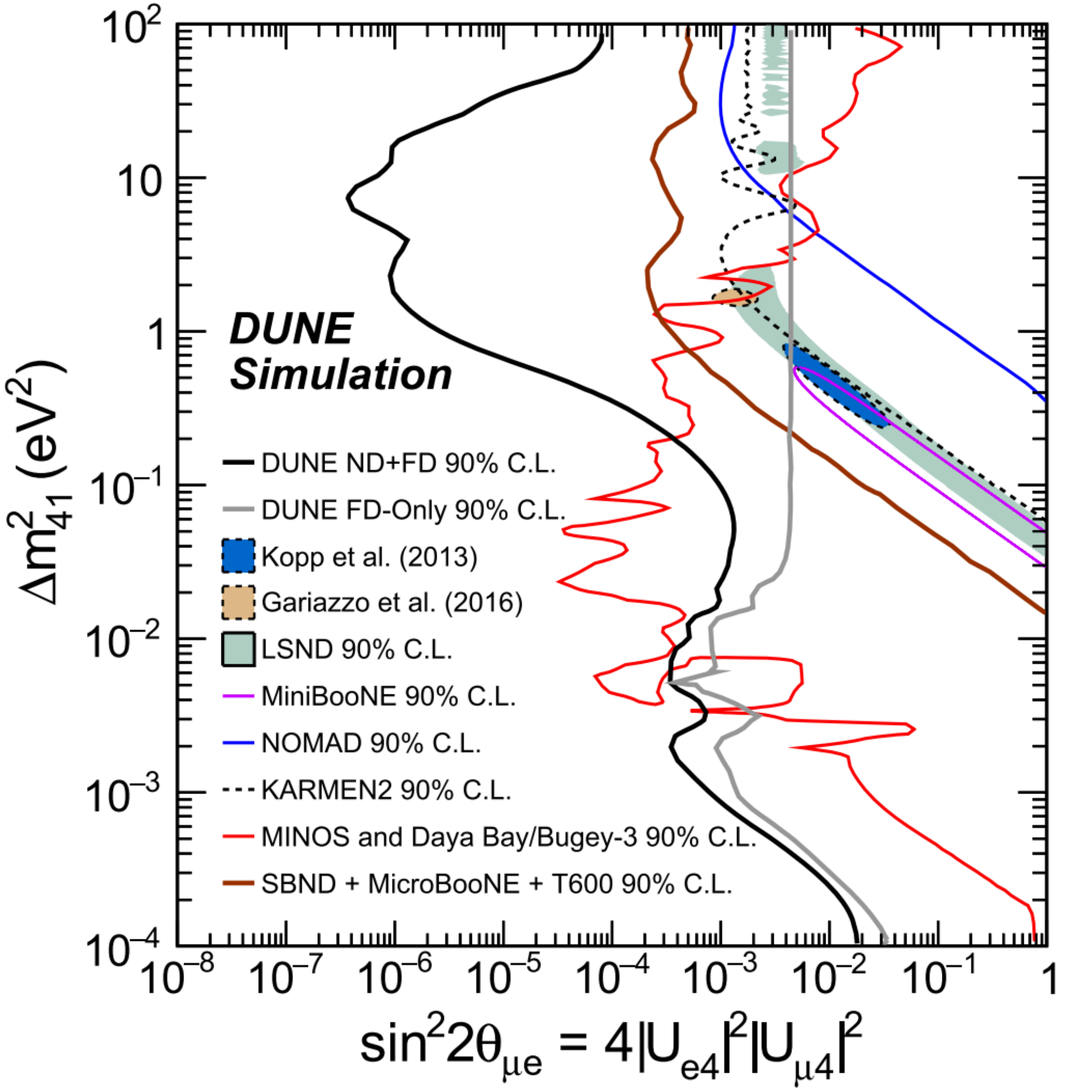
BSM and More

Eur. Phys. J. C 81 (2021) 4, 322

BSM physics

- Beyond 3-ν paradigm: sterile neutrino mixing
- Baryon number violating processes (400 kt-yr)
  - Unique at DUNE: $p \rightarrow K^+ + \nu$
    - p lifetime > 1.3×10^{34}yr (90% CL)
  - $n - \bar{n}$ oscillation
    - Free n: > 5.53×10^{8}s (90%CL)



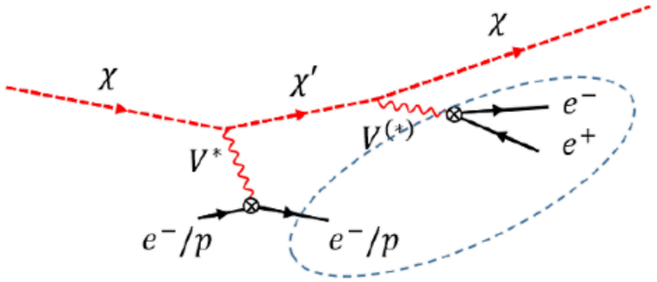


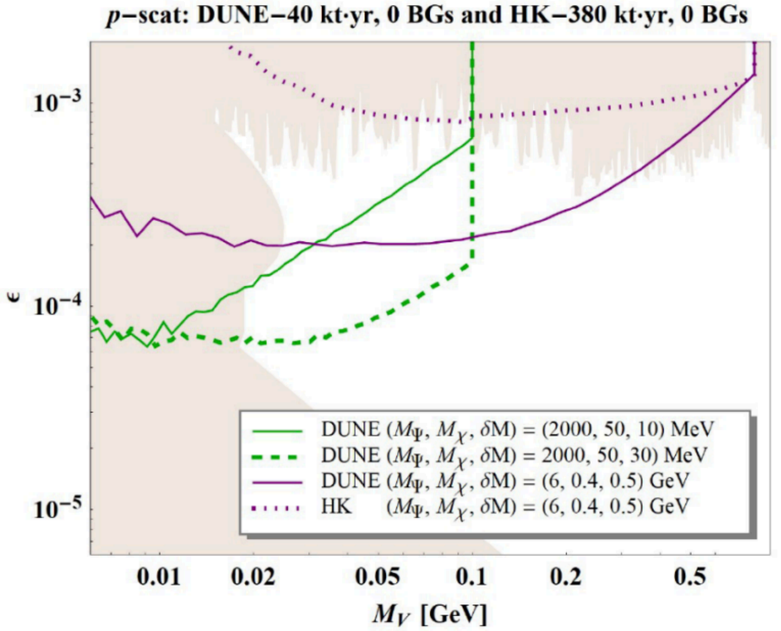
BSM and More

Eur. Phys. J. C 81 (2021) 4, 322

BSM physics

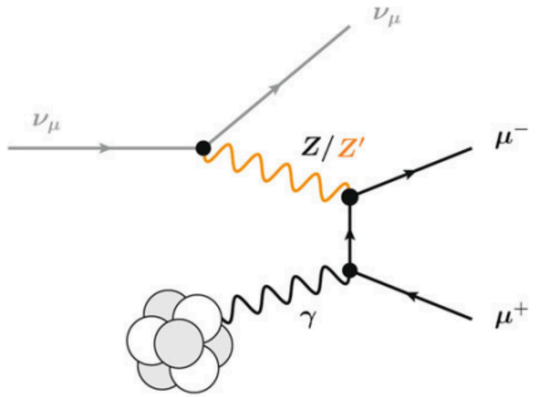
- World leading sensitivity on inelastic boosted dark matter at low mass in early years:
  - Capability to resolve low-energy electron/ proton tracks
- Neutrino trident production (ND)
  - New gauge boson probes gauged $L_\mu - L_\tau$

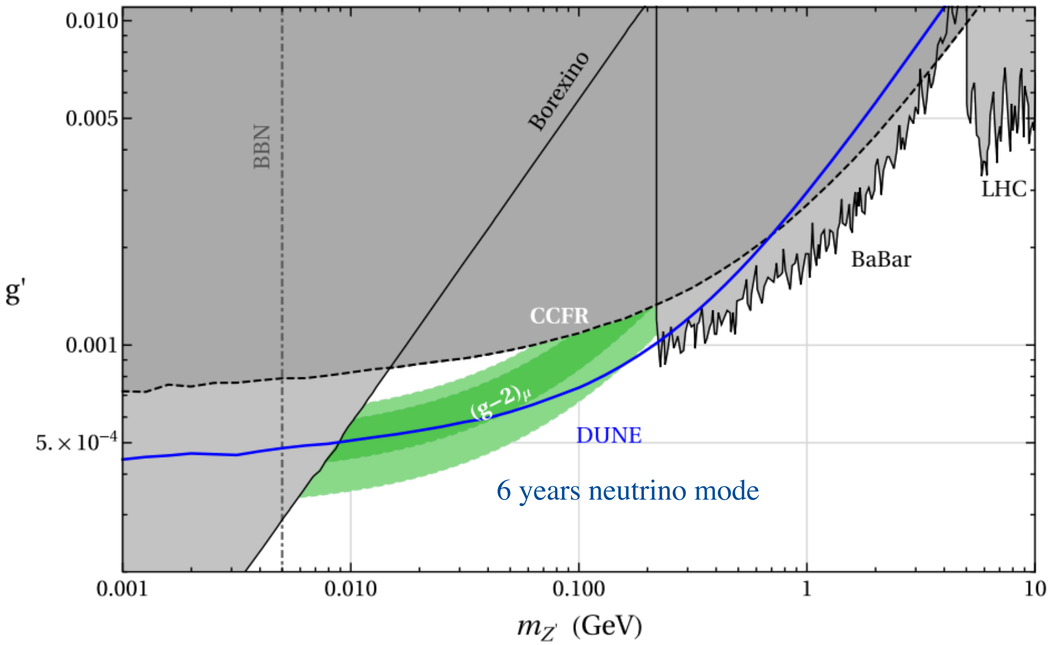




More…

- Atmospheric neutrino oscillation
- Non-standard neutrino interactions
- Non-unitary PMNS
- CPT and Lorentz violation
- Large-extra dimensions
- Heavy neutral leptons
- Neutrino magnetic moment
- Millicharged particles



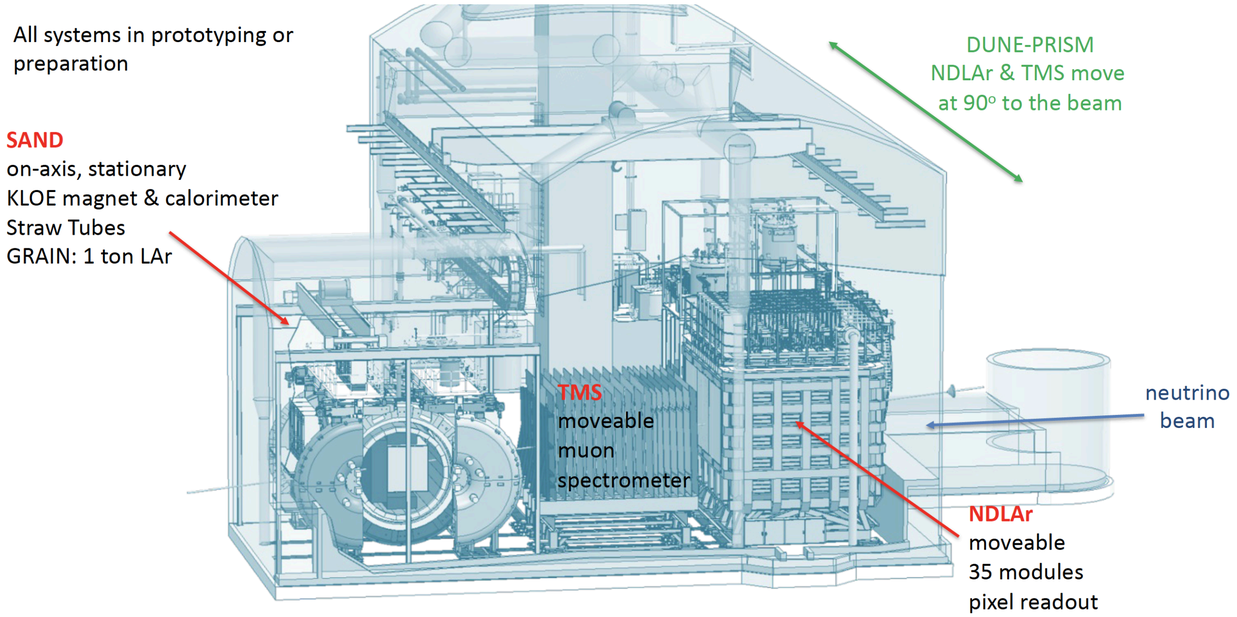


DUNE Near Detector

ND measurements shall be of sufficient precision to ensure that when extrapolated to predict the FD event spectra, the **associated systematic error must not dominate the measurement precision**

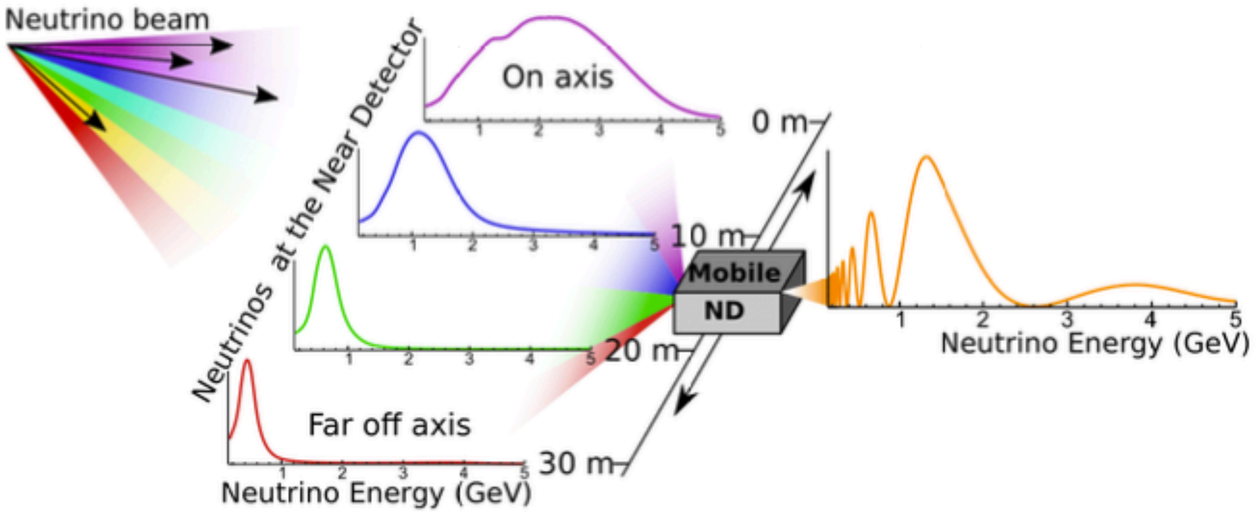
Day 1:

- **ND-LAr**: 7x5 array of 1x1x3 m^3 LArTPCs
  - Active LAr 130t, expect ~50 ν events/10 μs beam spill
- **TMS**: magnetized steel range stack to measure muons
- **SAND:** multi-purpose on-axis magnetized detector primarily for beam monitor
- Preliminary Design Review: late 2024 - early 2025



A special physics program: DUNE-PRISM

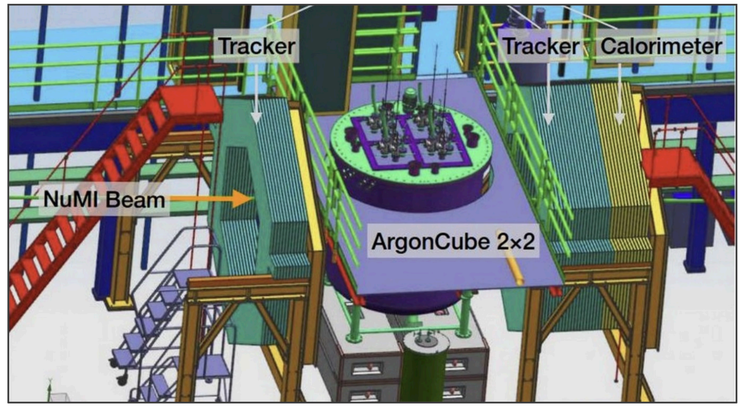
- **P**recision **R**eaction-**I**ndependent **S**pectrum **M**easurement
- NDLAr + TMS can move **up to 28.5m off axis**
- Measure a variety of neutrino energy spectra
  - Constrain standard oscillation analysis systematics
  - Linearly combine DUNE-PRISM data to predict the FD oscillated data allows any unknown or poorly modeled cross-section effects to be naturally included in the prediction

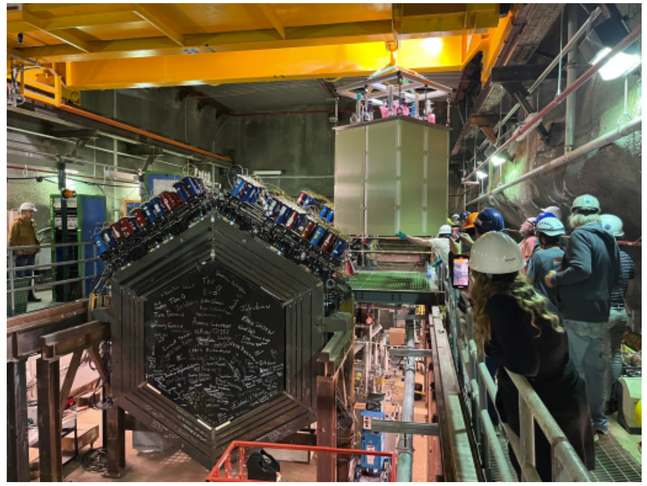


ND prototypes

NDLAr 2x2 demonstrator at NuMI neutrino beam

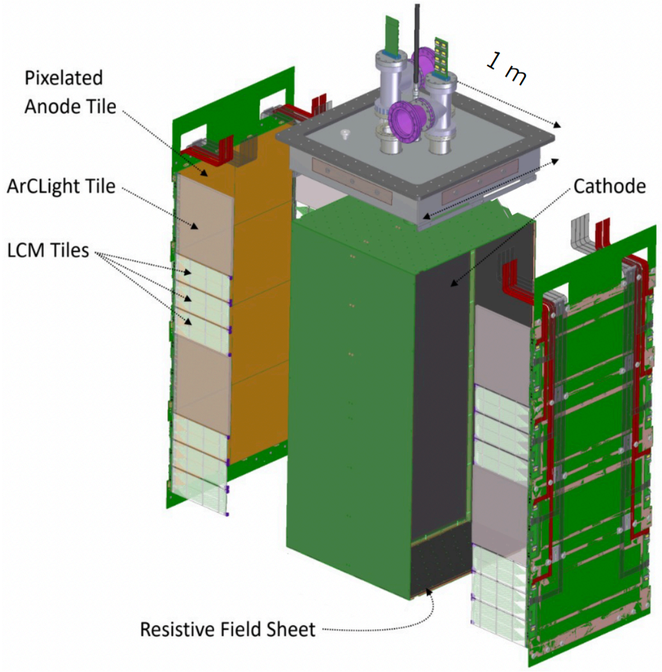
- Four TPC modules installed in former location of MINOS-ND
- Includes upstream/downstream trackers, repurposed from MINERvA
- **Goals**:
  - Demonstration of performance in a GeV neutrino beam
  - Develop neutrino signal analysis and reconstruction techniques
    - 3D signals, charge-light correlation, pileup, track matching
- Expect to run in FY2024





A Full Scale Demonstrator (1x1x3 m^3) at Bern

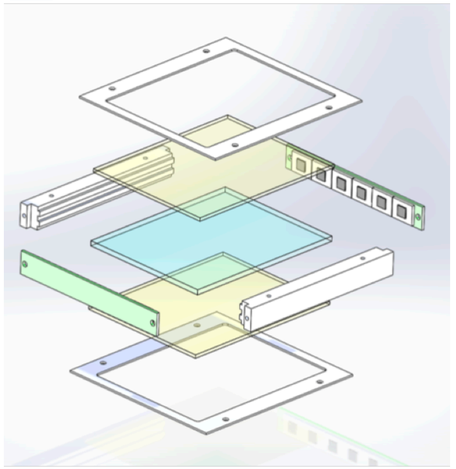
- 410k pixels, 3.7mm pitch, 30% optical coverage
- **Goals**:
  - Validate full-scale TPC assembly and integration
  - Exercise ND-LAr component production and testing program
  - Demonstrate design meets ND-LAr system-level requirements
  - Inform ND-LAr Final Design Review
  - Expect to run in August 2024

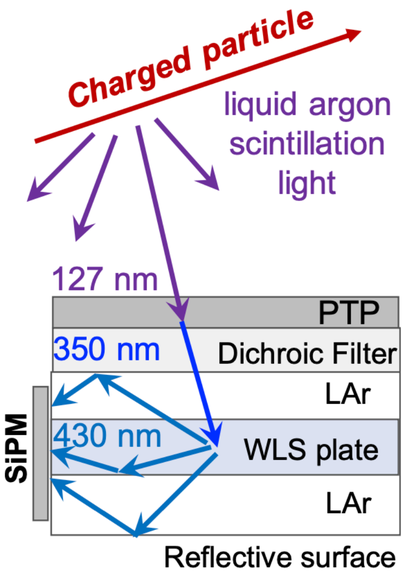


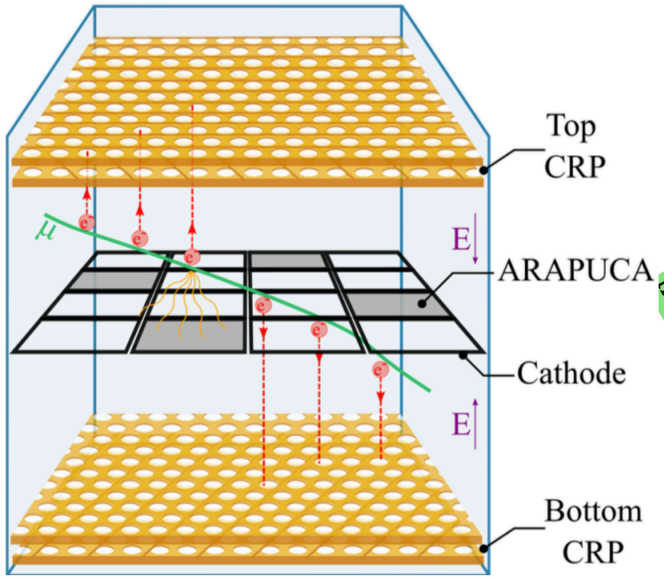
DUNE Far Detector 2

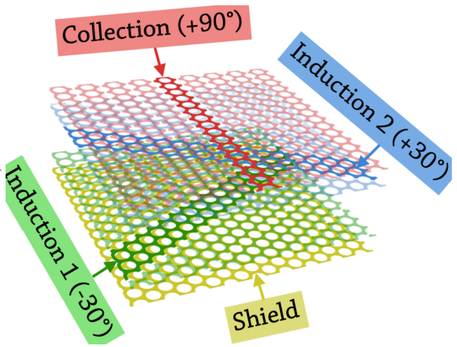
FD2 features

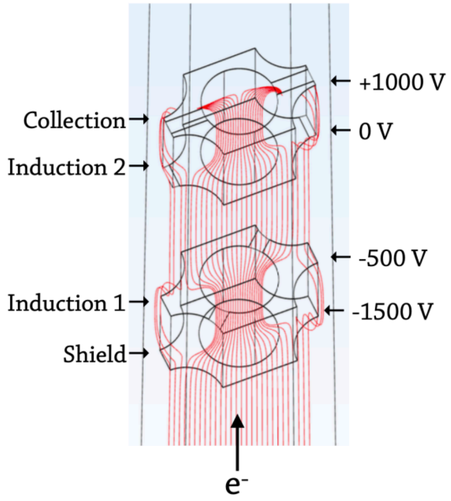
- First FD to be installed: **cryostat install Q3 2024**!
- The **state-of-the-art**: draws from the strengths of many liquid argon prototypes and experiments
- **6.5 m vertical drift distance**, maximized active volume 14,190 ton
- Simplified charge readout plane (CRP) perforated PCB, reducing overall costs to FD1
- **Power-over-Fiber (PoF)** technology enables **photodetectors** (X-Arapuca) deployed on **300 kV** high voltage surface **in LAr**
  - Noise immunity, voltage isolation and spark free
  - **First-ever** realization in cryogenics and particle physics

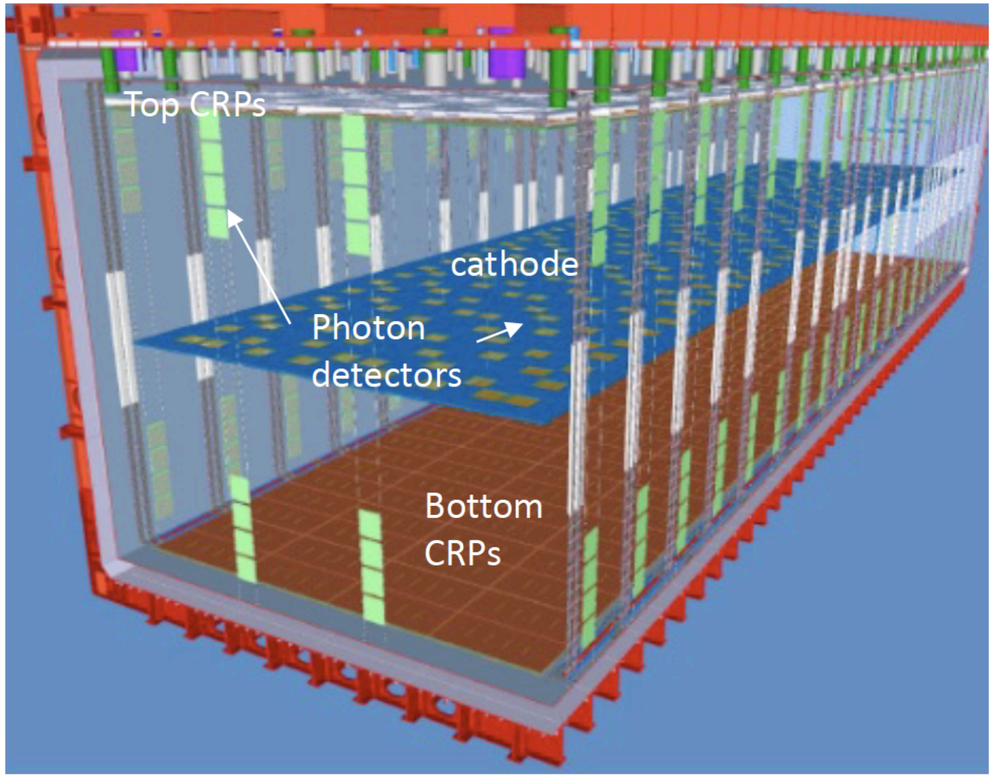








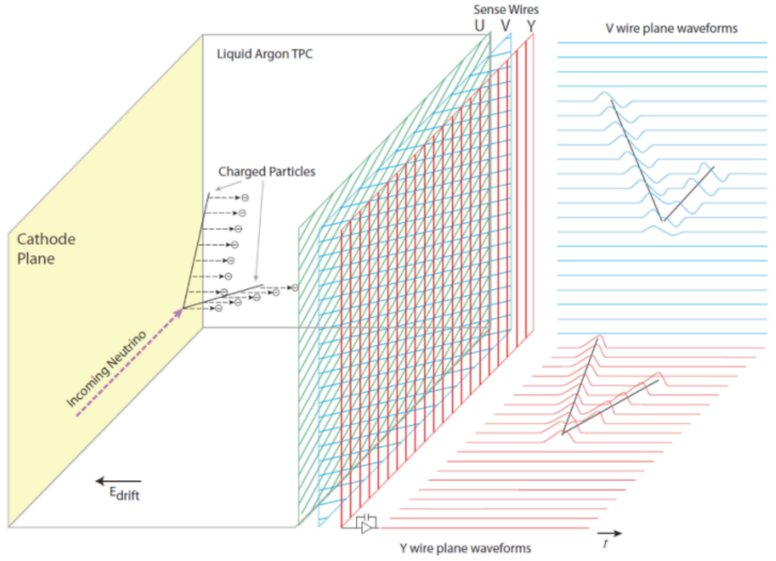


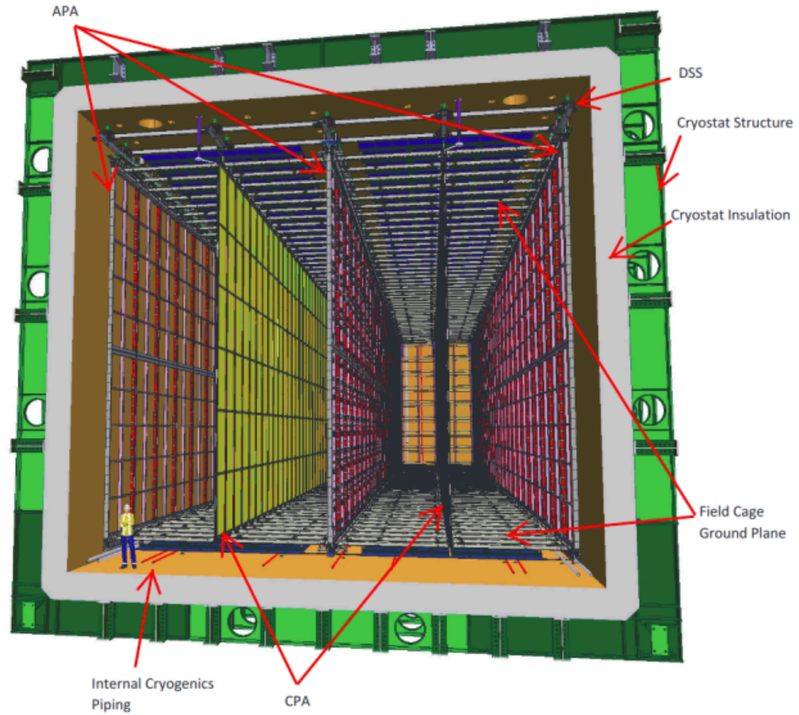


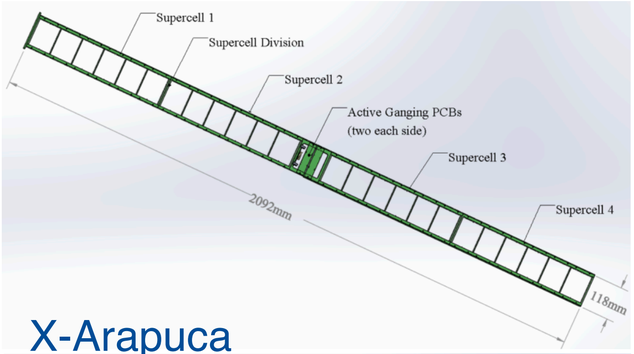
DUNE FD1

FD1 features

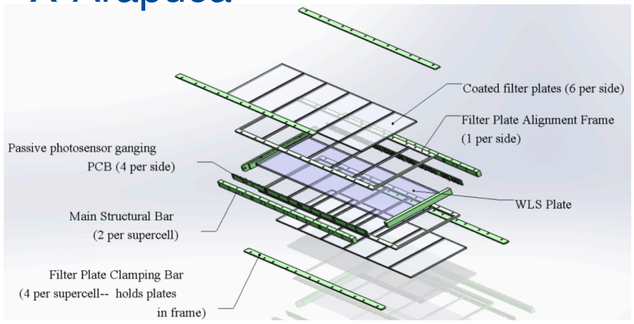
- **3.5 m** horizontal drift distance (180 kV cathode), 4 drift volumes
- Active volume 13,661 ton
- Charge readout: wire planes (3 layers)
- Photodetectors (X-Arapuca) behind anode
  - PDE 2-3%
  - Mean light yield ~30PE/MeV

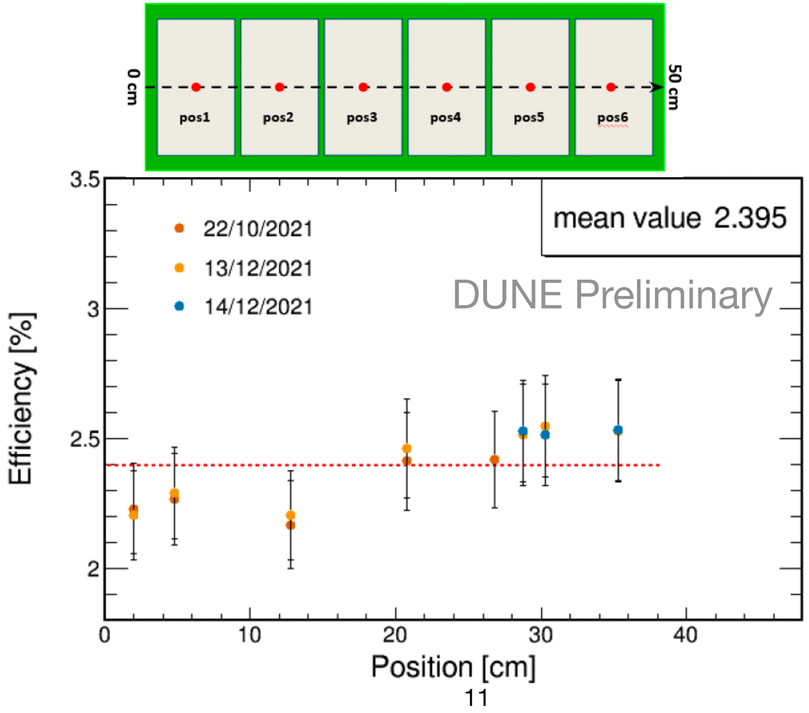




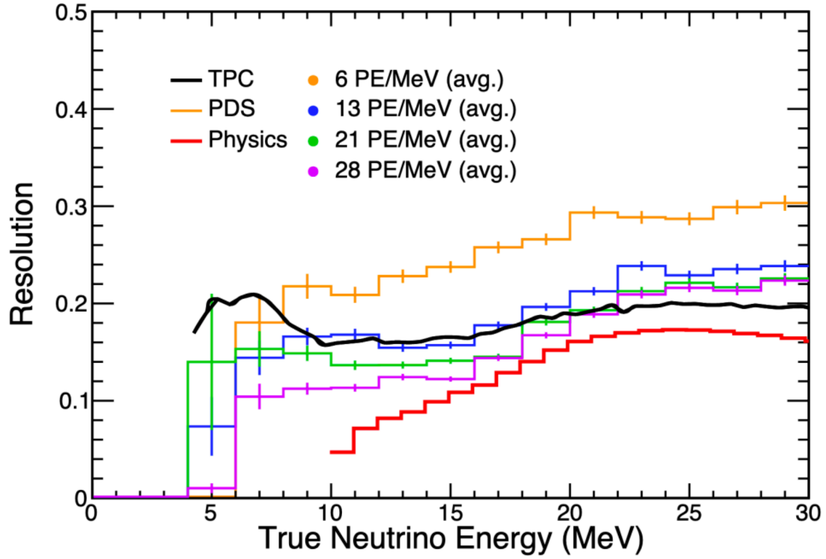


X-Arapuca





DUNE FD1-HD TDR
(For SN neutrino events)

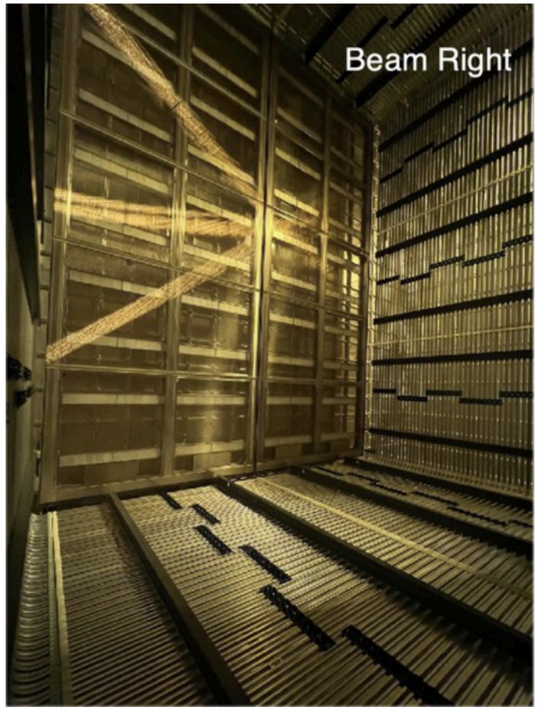


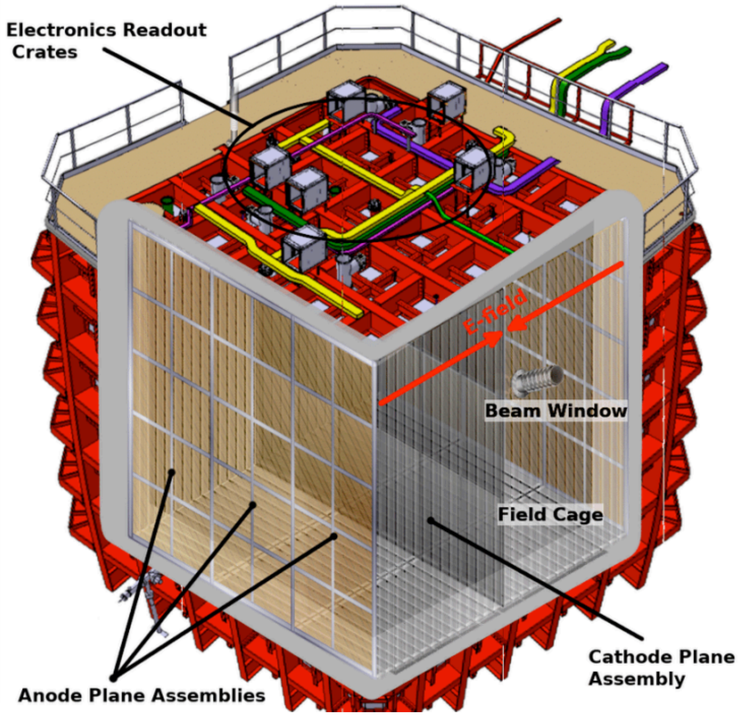
FD Prototypes

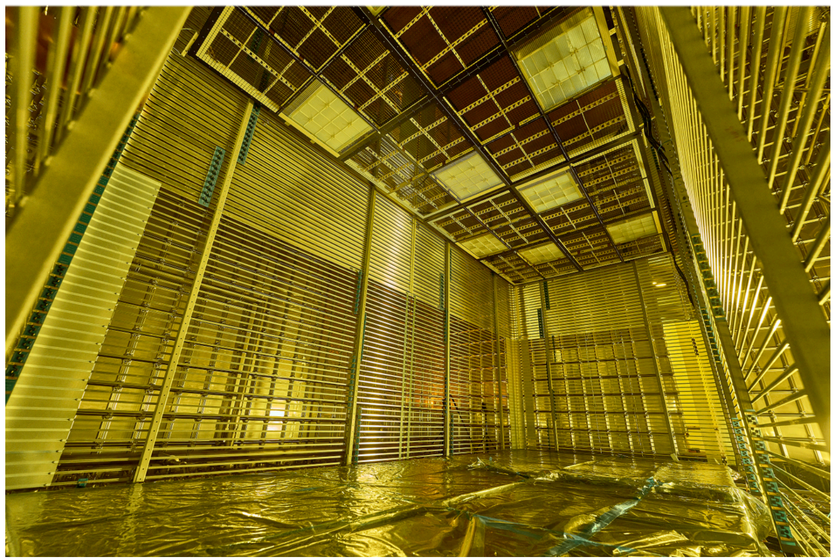
ProtoDUNE-HD (FD1)
- Beam run 2024 July-August 8 weeks
- Topics: **(More in Matthew's talk next)**
  - Focus on negative polarity and lower energy beam (complement 2018 PD-SP program)
  - Precise measurement of hadron-argon cross sections
  - Dual calorimetry for PID and event reconstruction

ColdBox (VD)
- Many prototypes before final design, fast turnaround (1 month)

ProtoDUNE-VD (770t LAr)
- Cosmic run in Oct following LAr transfer from ProtoDUNE-HD
- Beam run expected early 2025
- Topics:
  - Neutron tagging (capture)
  - Xe-doping program
  - Light propagation
  - Track timing
  - Dual calorimetry for PID and event reconstruction





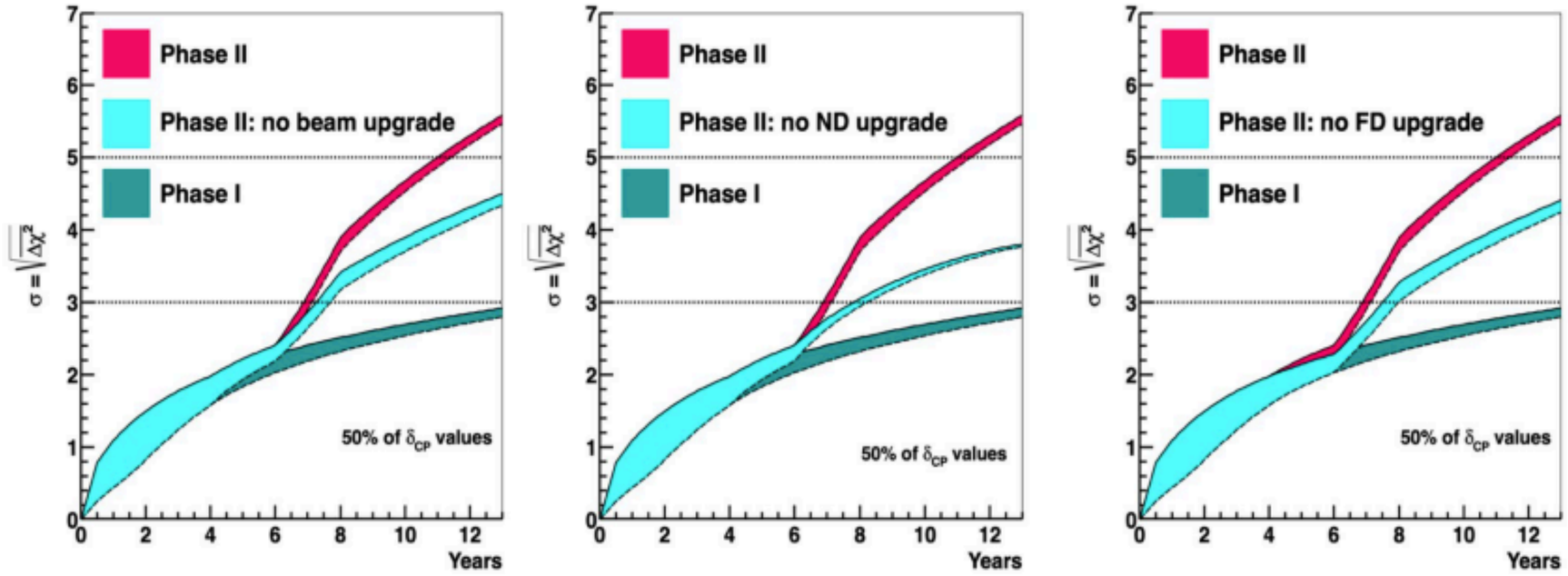


DUNE Phase II Scope

Phase I (day 1)
- FD (approved): two 17 kt (total) LAr TPCs - one Horizontal Drift, one Vertical Drift.
- ND (baseline TBC and approve by 2025): NDLAr with TMS; DUNE-PRISM; SAND on-axis.

Phase II - open to new (non-DUNE) collaborators!
- **Two additional 17 kt FD modules**
- **More Capable Near Detector (MCND) including ND-GAr**
- > 2MW beam (not covered in this talk)

Phase-II is not optional - All necessary to complete the core CPV program of DUNE and more



DUNE Phase II FD

FD3 vision

- Similar in concept to FD2 - optimized VD
- Proposed upgrades:
  - **Major upgrade: light detection system - APEX**
  - Xe-doping
  - Modest optimization on charge readout
- Incremental background control
- **Construction fully endorsed by the 2023 P5**

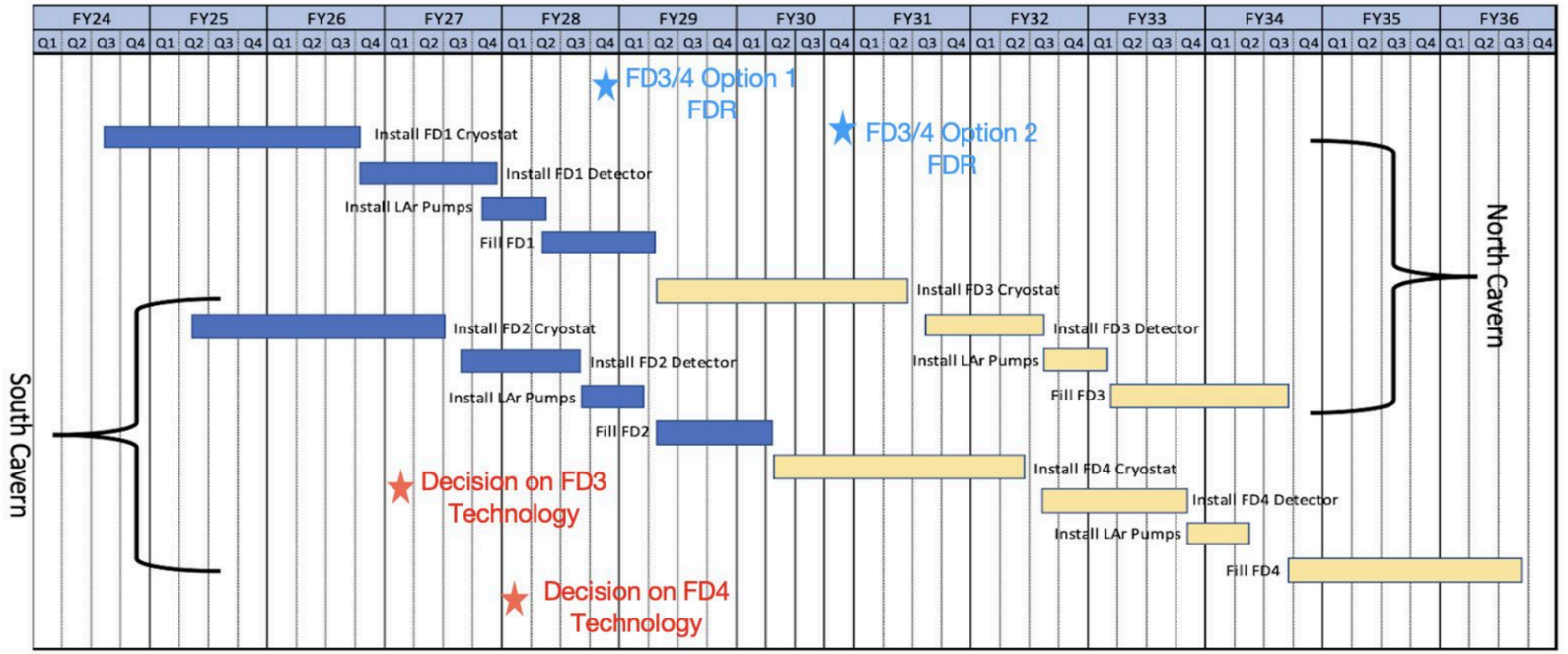
FD4 vision

- **Goal:** push E threshold to **MeV or lower**
- **Baseline** concept: similar to FD2
  - Several options being explored: upgrade to **pixel-based 3D charge readout** or **optical-based charge readout**
  - **Dedicated** compact **background shield** design
- **Alternative** concept: water-based liquid scintillator
- **Endorsed by P5** as a **"Module of Opportunity"** and recommended an accelerated/expanded R&D program in the next decade if budget scenarios are favorable

FD technically limited schedule

Earliest installation:
FD3: 2029
FD4: 2030

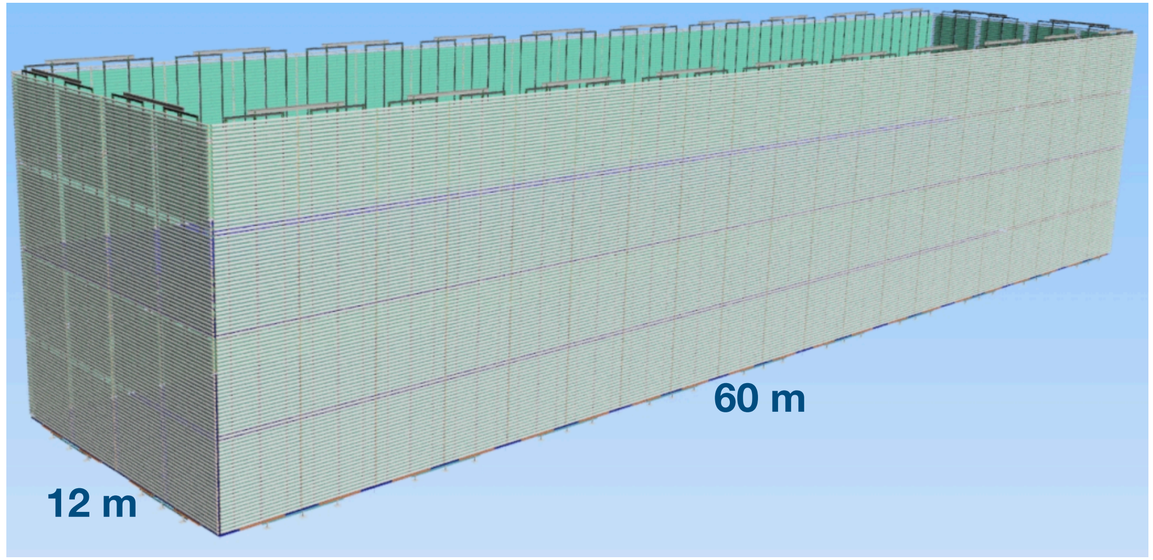
Earliest completion:
FD3: 2034
FD4: 2036

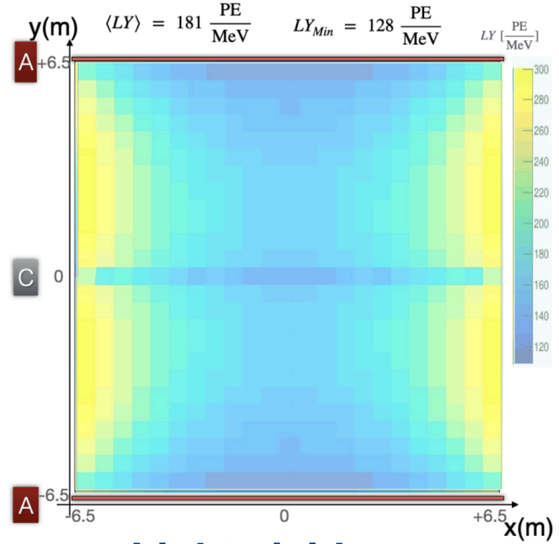


DUNE FD3 APEX (Aluminum Profiles with Embedded X-Arapucas): A fully integrated LArTPC field cage + photodetector system

Features

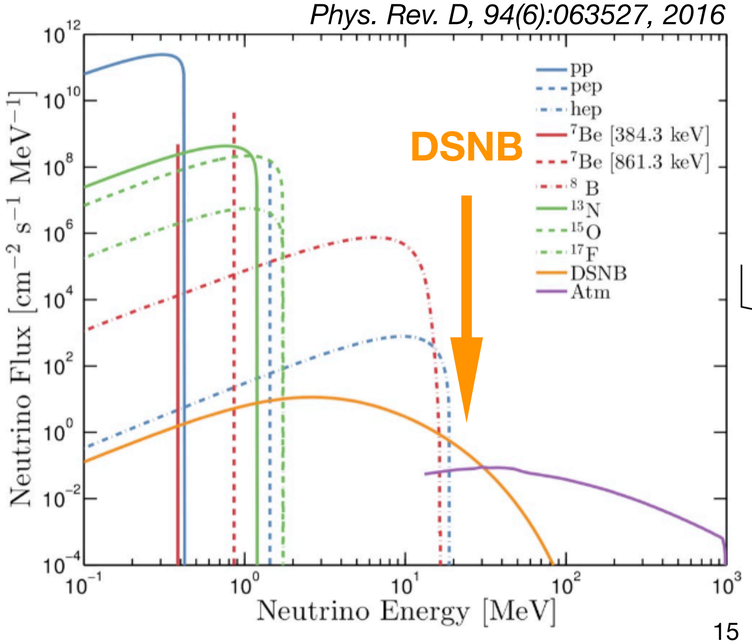
- ~60% optical coverage of LAr (active) volume (**2000** m^2 scaled-up surface PDS): 10 times of FD2 (cathode & behind FC)
- **Min** (avg.) **light yield** x**6** (x4) times higher wrt FD2, higher uniformity
- Lower detection thresholds, better timing and energy resolution extend frontiers of neutrino oscillation and low energy astroparticle physics from GeV to MeV
  - Diffused supernova neutrino background
  - CPV in neutrino 2nd oscillation peak
  - Background tagging (e.g. neutron capture) and rejection
    - Enhance supernova & solar neutrinos sensitivity
  - BSM/dark matter



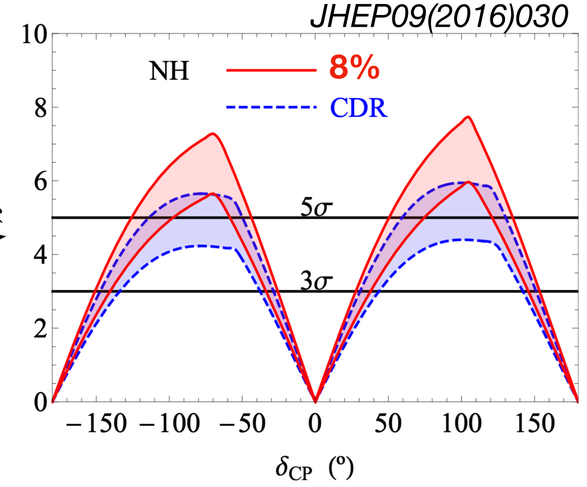


Light yield map

Phys. Rev. D, 94(6):063527, 2016



JHEP09(2016)030



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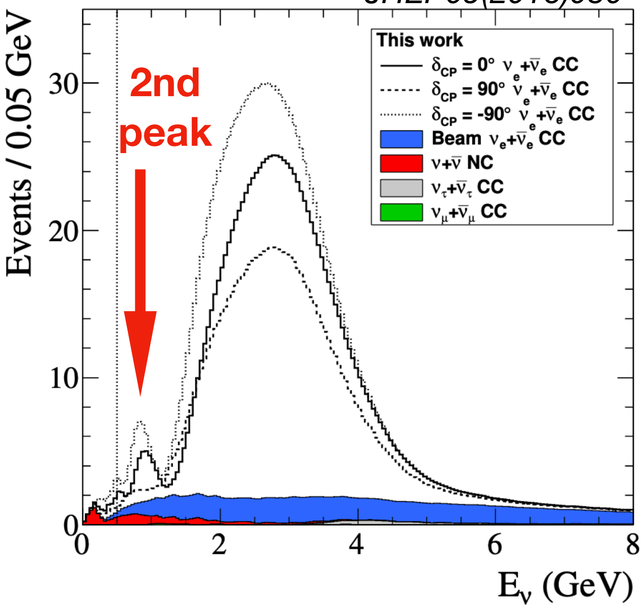
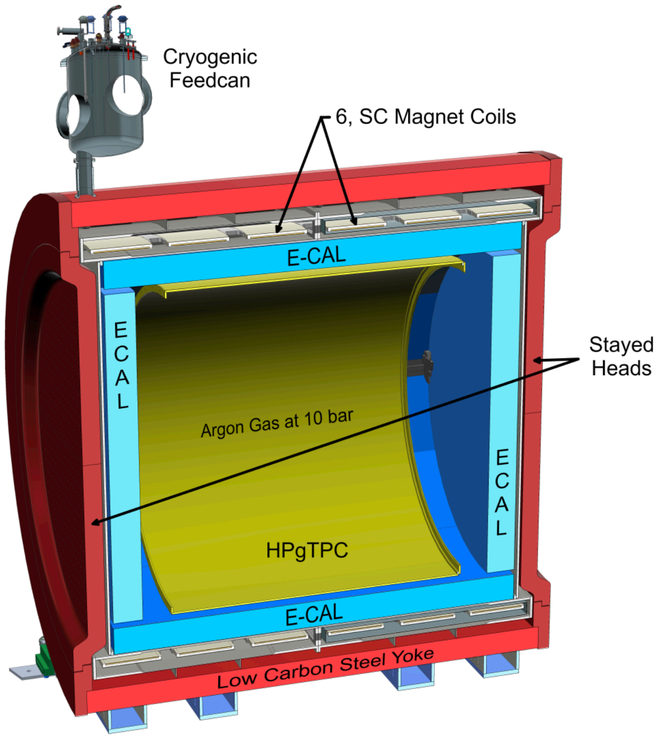
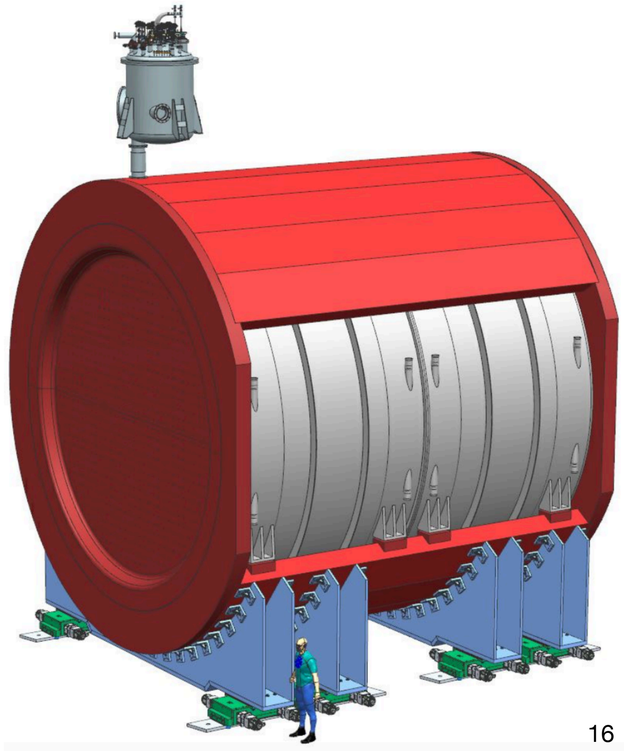


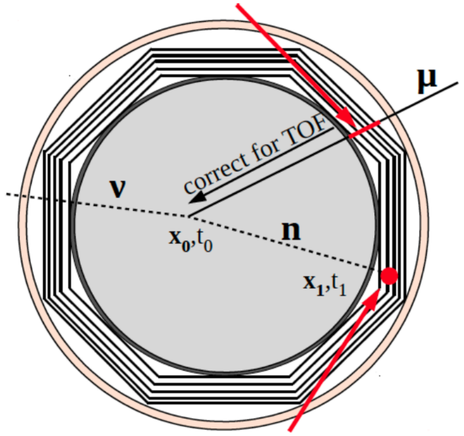
DUNE Phase II ND

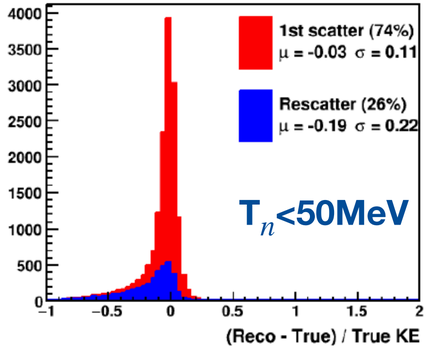
Major upgrade: a gaseous argon detector (ND-GAr) will replace the Phase I muon tracker TMS

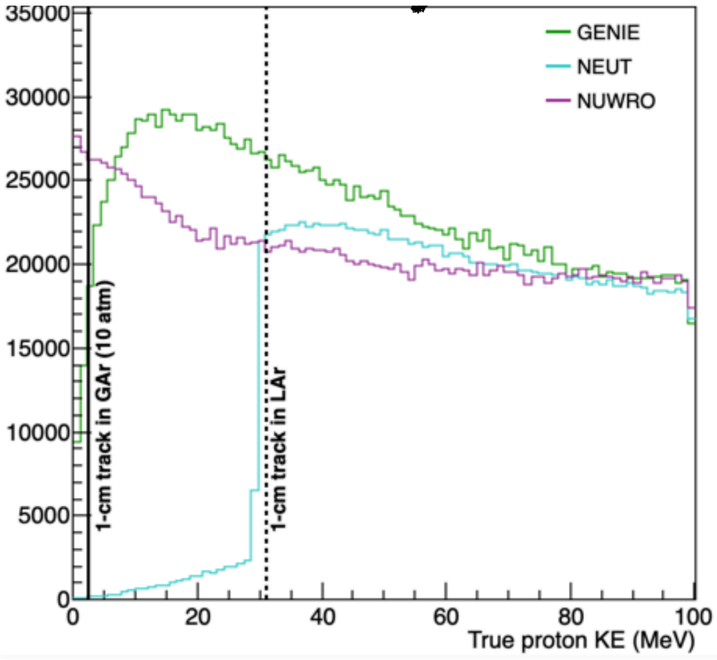
- A **high pressure** (10 bar) gaseous TPC: **Ar-based gas mixture**
- **Dual readout**: charge (multiwire/GEMs/MicroMegas) + light (commercial Timepix3 cameras)
- **ECAL** (scintillator + lead sandwich): E&M (5% Eres @1GeV), **neutron ToF** (50% purity, 20-40% efficiency), μ/π PID (hadronic interaction of pion in ECAL helps PID)
- Superconducting magnet **0.5T**: partial return yoke facing ND-LAr to reduce dead region
- **Lower energy** and tracking **threshold** + sub-mm spatial resolution + better PID and momentum resolution
- Address systematic challenges in oscillation physics by providing precise measurements
- **P5 endorsed construction** in baseline and favorable budget scenarios: construction timeline similar to FD3











Summary

DUNE is a world-class neutrino experiment
- High precision measurements of neutrino mixing in a *single* experiment
- Observatory for astrophysical neutrino sources
- Offers many BSM physics topics

Phase I - Day 1 FD: FD2 (2029) + FD1 (2030)
- FD prototypes: ProtoDUNE-HD (FD1), ProtoDUNE-VD (FD2) - both will run at CERN NP in 2024!!!

Phase I - Day 1 ND: ND-LAr + TMS + PRISM + SAND (2031)
- ND prototypes: 2x2 demonstrator (FNAL), full scale demonstrator (Bern) - both expected to run 2024!!!

DUNE Phase II is essential to DUNE core physics and received strong endorsement from P5
- Two additional 17 kt FD modules
- More Capable Near Detector (MCND) including ND-GAr
- > 2MW beam
- Open to new (non-DUNE) collaborators!