DUNE: Physics I Plans I Progress

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56th Fermilab Users' Meeting
June 30, 2023

Caltech

56th Fermilab Users Meeting
NEW IDEAS FOR FUTURE PROJECTS
at Fermilab

DUNE

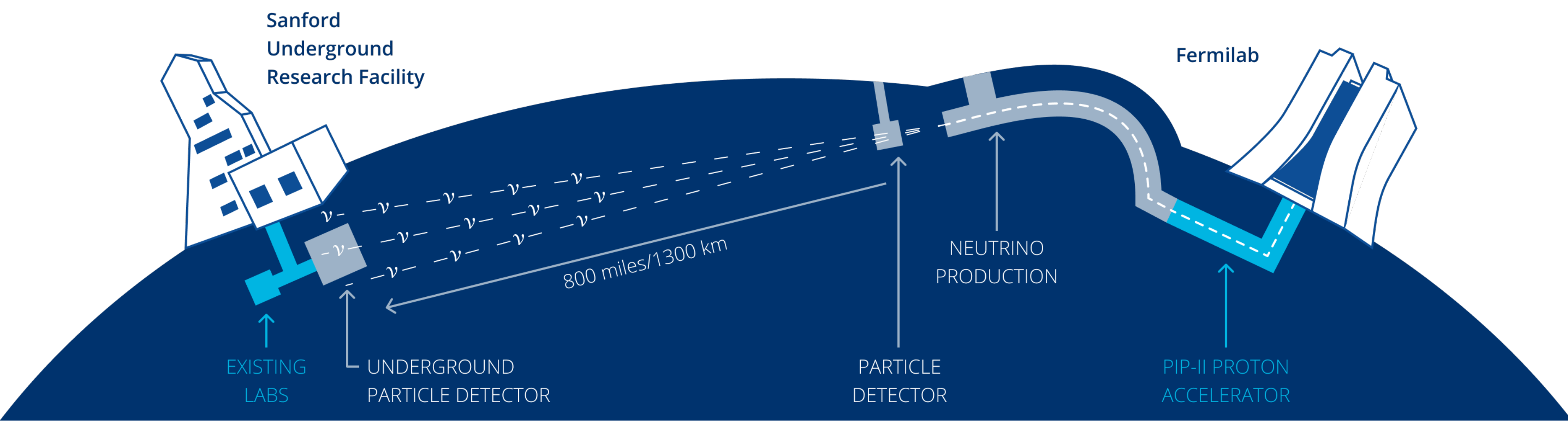
Why build it? Where do we stand?

DUNE: Physics I Plans I Progress

What and When?

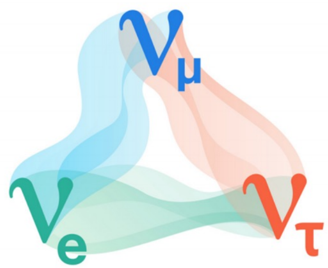
From the Director's report at Users' Meeting 23

Delivering on LBNF/DUNE is Fermilab's highest priority

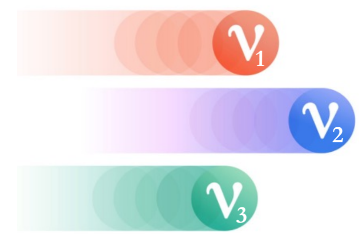


Neutrino Oscillations

Image by Symmetry Magazine



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Flavor Eigenstates

Mixing Matrix

Mass Eigenstates

$$U_{\mathrm{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

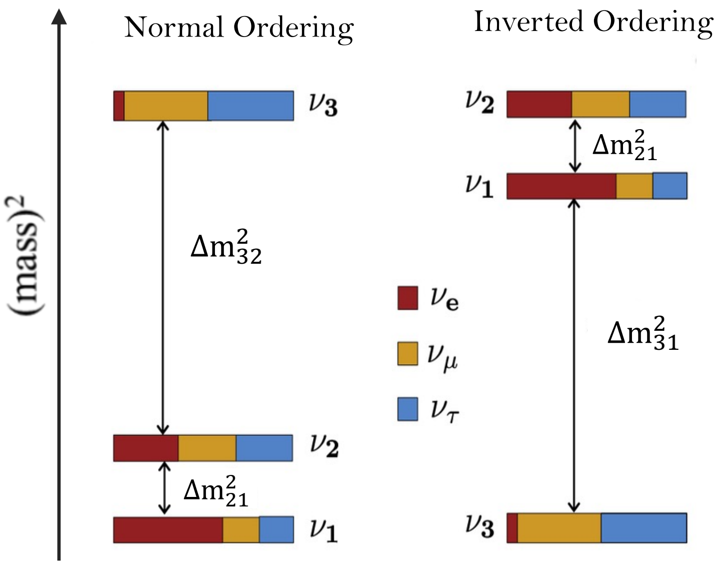
- The mixing angles determine the amplitude and the mass-splitting control the frequency of the oscillations.
- L and E are experimental design parameters.

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

L : distance (baseline)
E : neutrino energy

Open Questions

1. Which neutrino is the heaviest?

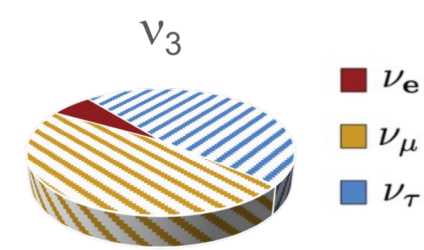


ν Mass Ordering (MO):
Normal or Inverted?

2. Is the θ_{23} mixing maximal?

Current Measured Value : $\theta_{23} \sim 45°$

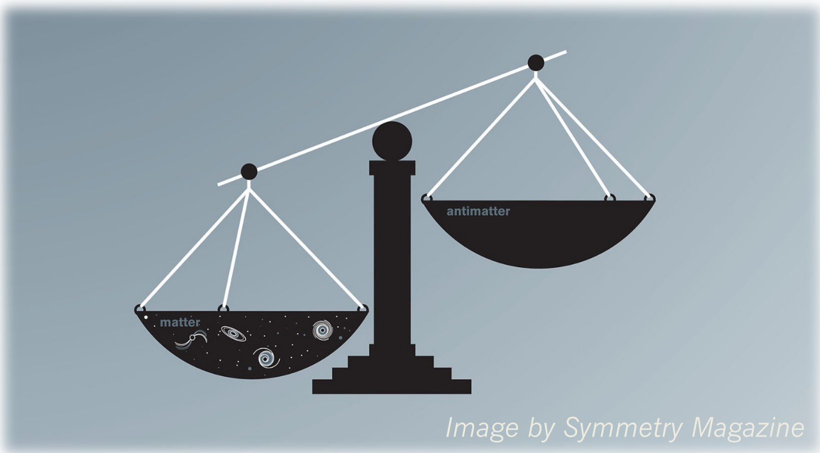
Precision : $\sin^2\theta_{23} \sim 5\%$



If $\theta_{23} = 45° \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$

Open Questions

3. Why is there more matter than anti-matter in the Universe?



Do neutrinos and anti-neutrinos oscillate differently violating the CP symmetry?

Is sin δ_{CP} = 0?

4. Is the 3-flavor neutrino picture complete?

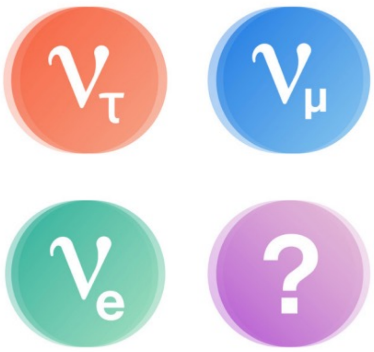
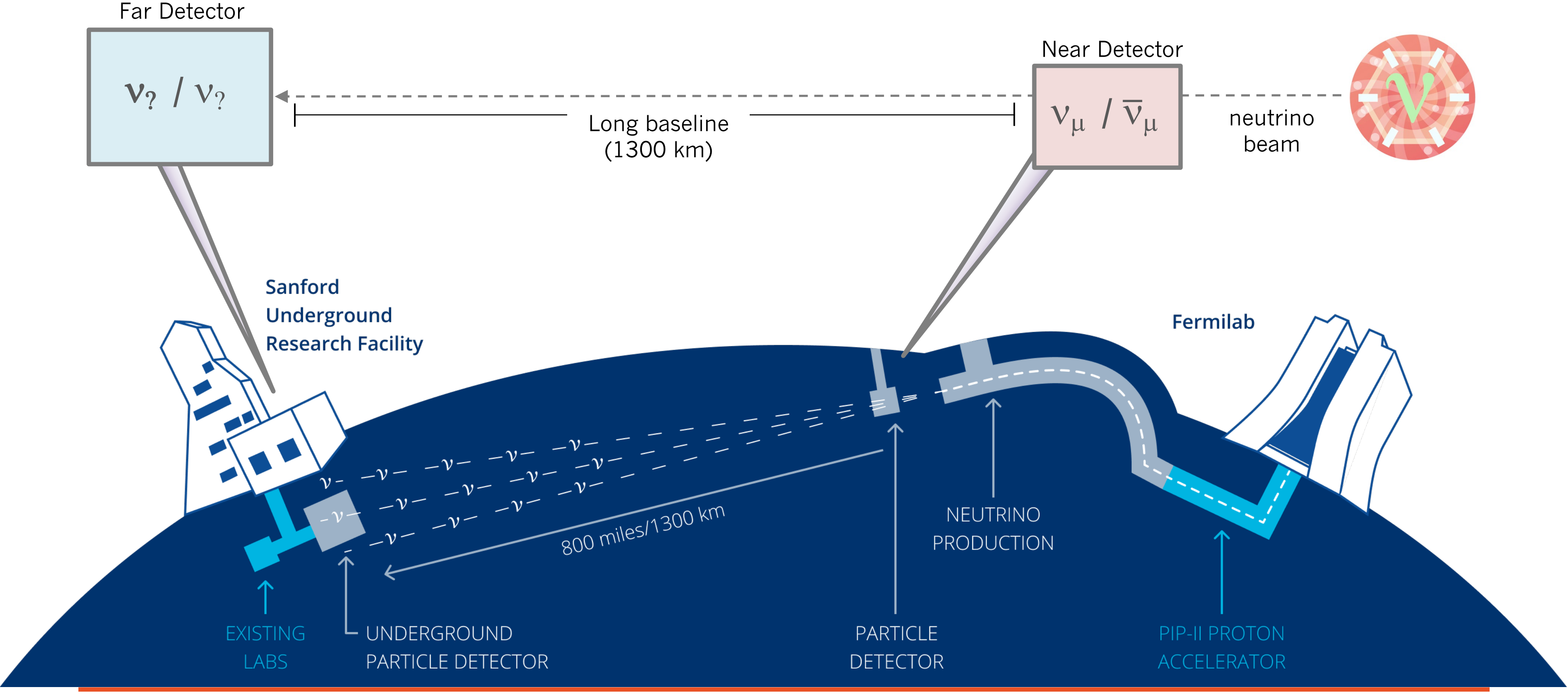


Image by Symmetry Magazine

- Are there only 3 neutrino flavors?
- Is νSM complete?
- Is PMNS matrix unitary?

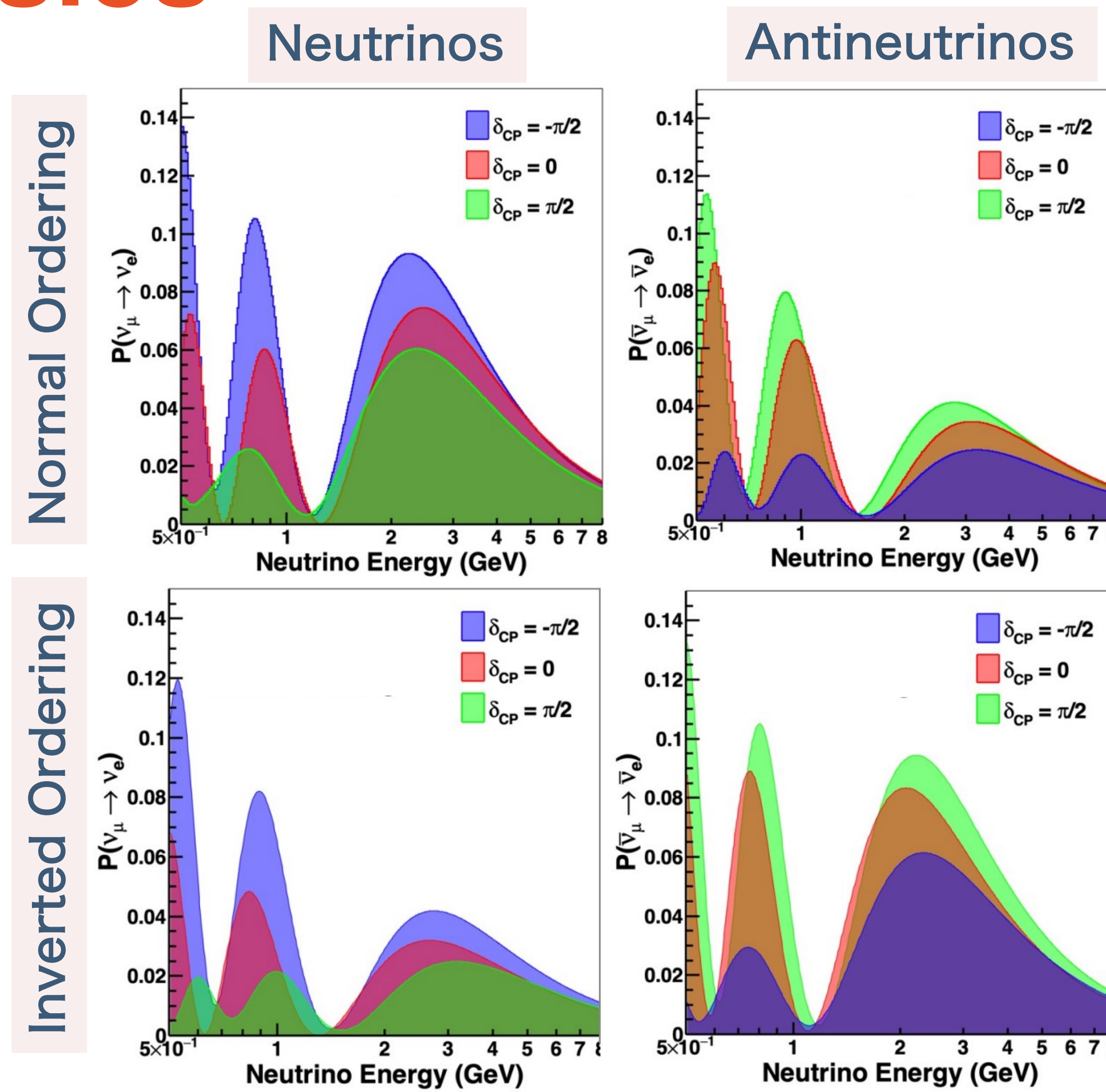
DUNE

- The Deep Underground Neutrino Experiment (DUNE) is next-generation international neutrino experiment hosted in the US.
- DUNE will feature a wideband beam of muon neutrinos and utilize large LArTPC detectors at SURF ~1300 kms to detect neutrino oscillations.

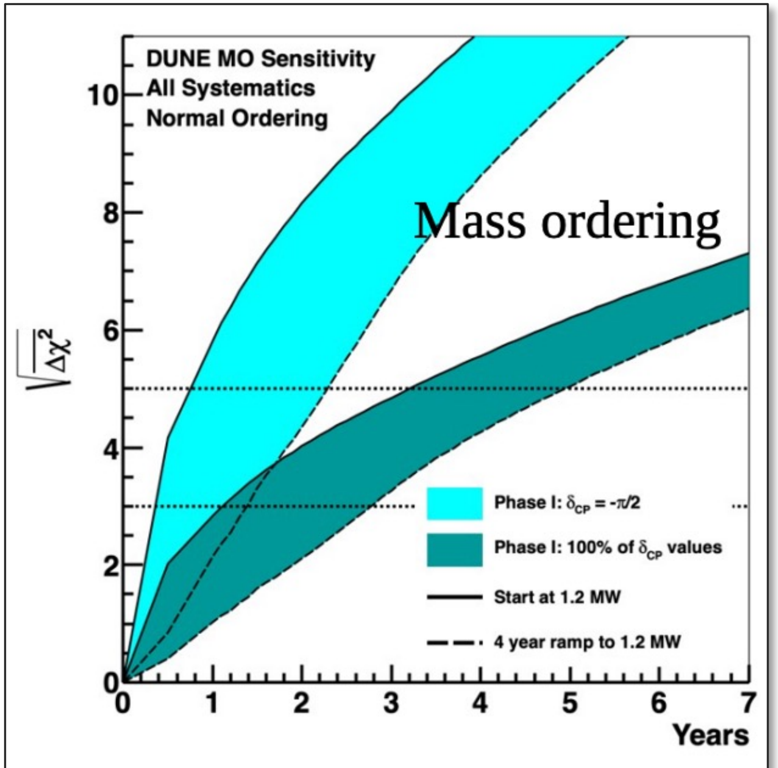


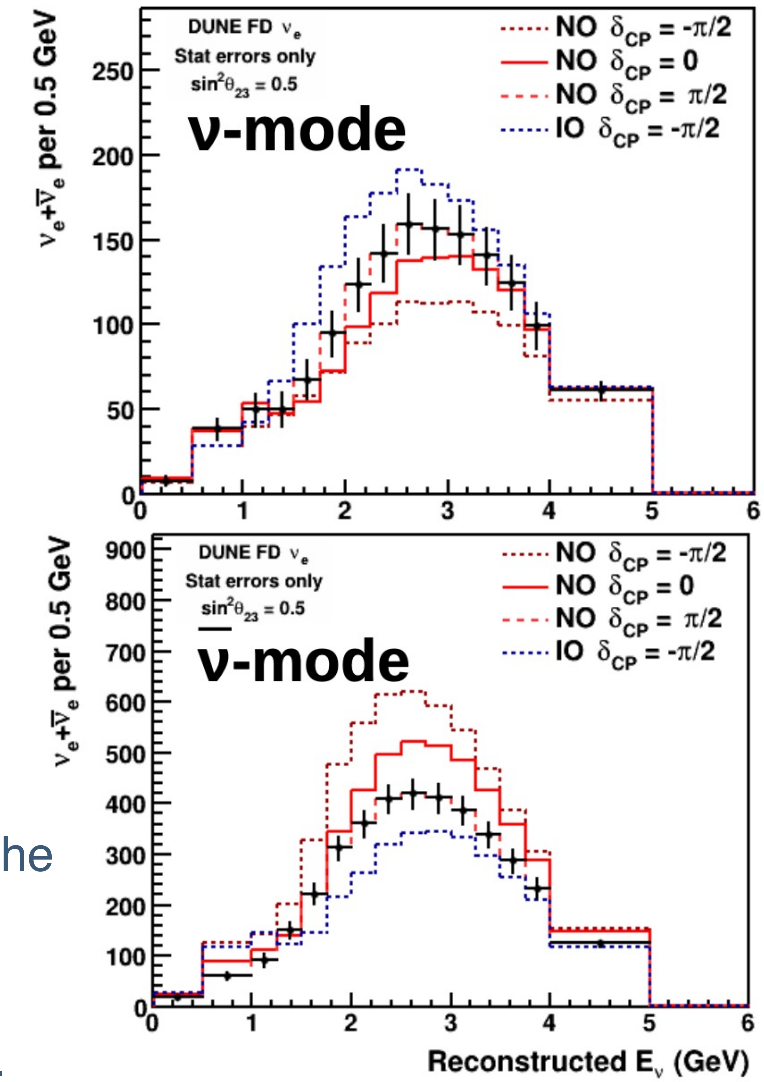
DUNE: Physics

- Asymmetry in $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ as a continuous function of neutrino energy (at L = 1285 km) gives DUNE its *strong* discriminating power to measure
  - mass ordering,
  - θ_{23} octant, &
  - CP violation



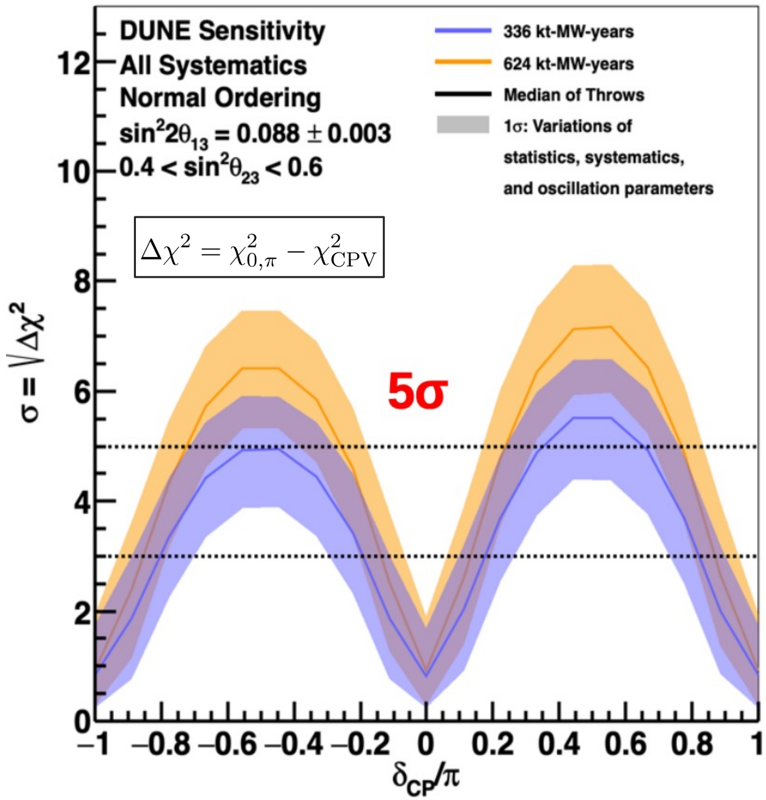
Goals: Mass Ordering



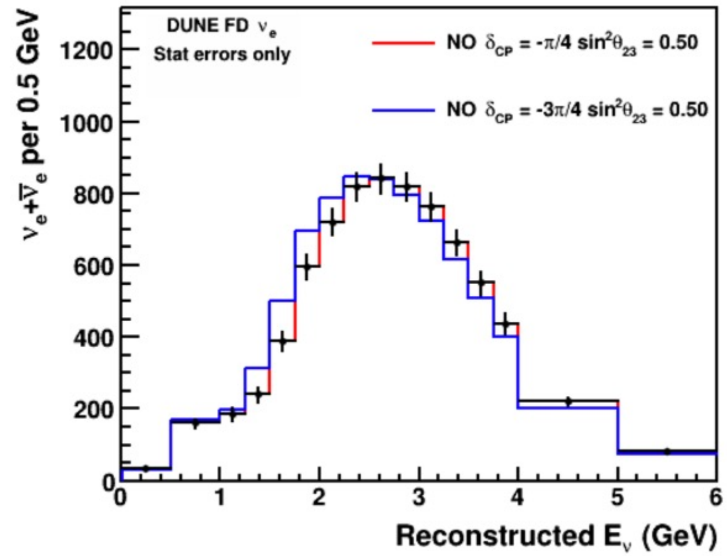


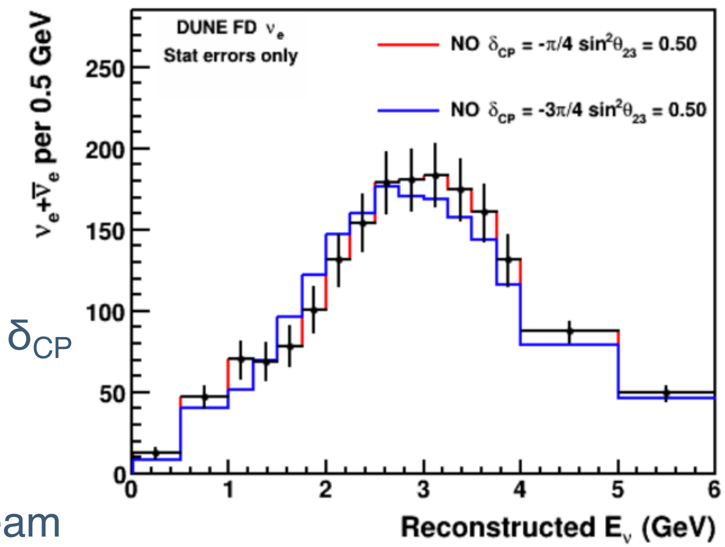
- Unrivaled sensitivity to resolve MO for any values of other oscillation parameters due to the enormous difference between NO & IO expectations for any value of δ_{CP}.
- Early science milestone soon after turning-on.

Goals: CP violation



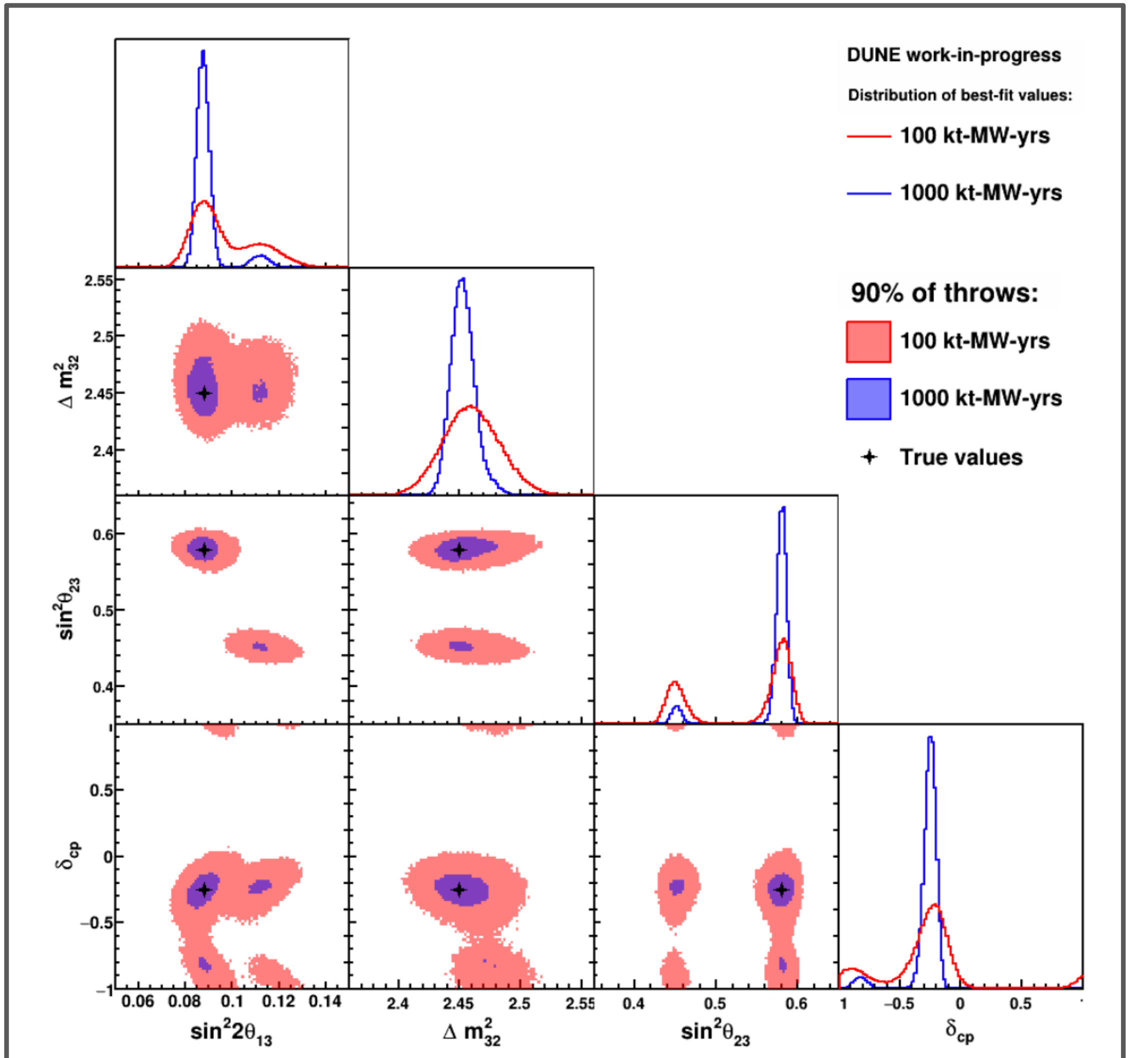
EPJC 80 (2020) 978





- DUNE has > 5σ discovery potential for > 50% of δ_{CP} values for either MO.
- Incomparable capability to resolve critical degeneracies in δ_{CP} using the broad-spectrum beam and superior energy resolution.

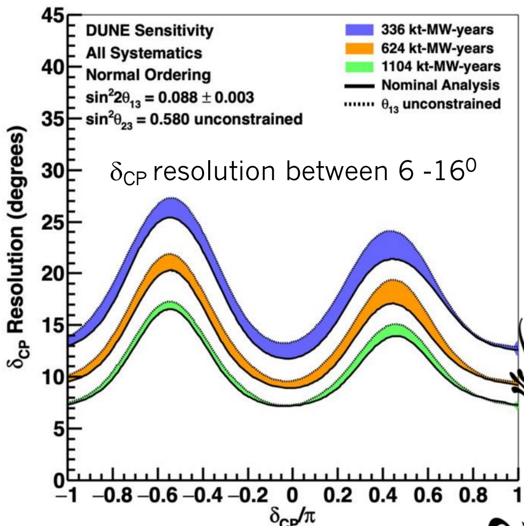
Goals: CPv and Mixing Angles

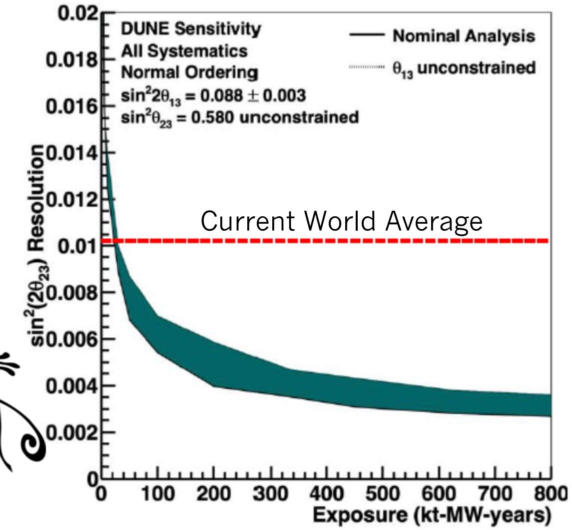


- Long-baseline oscillations are highly degenerate not only in CPv and νMO but also with mass-splitting and mixing angles.
- DUNE can utilize the spectral information from its broad-band beam to measure all these parameters.

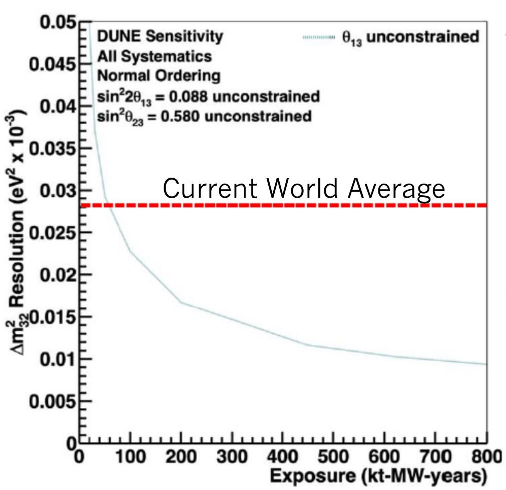
Goals: Precision

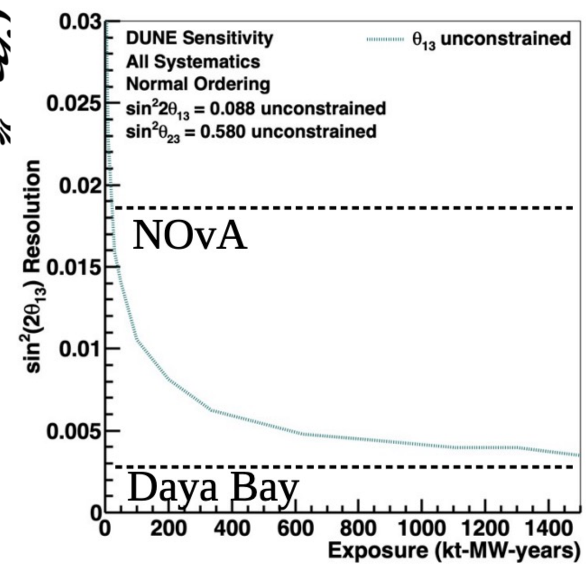
World Average from NuFit5: JHEP 09 (2020) 178





DUNE is the best-in-class experiment that will make unambiguous high precision measurements of Δm^2_{32}, δ_{CP}, θ_{23} and θ_{13} with a single experiment.

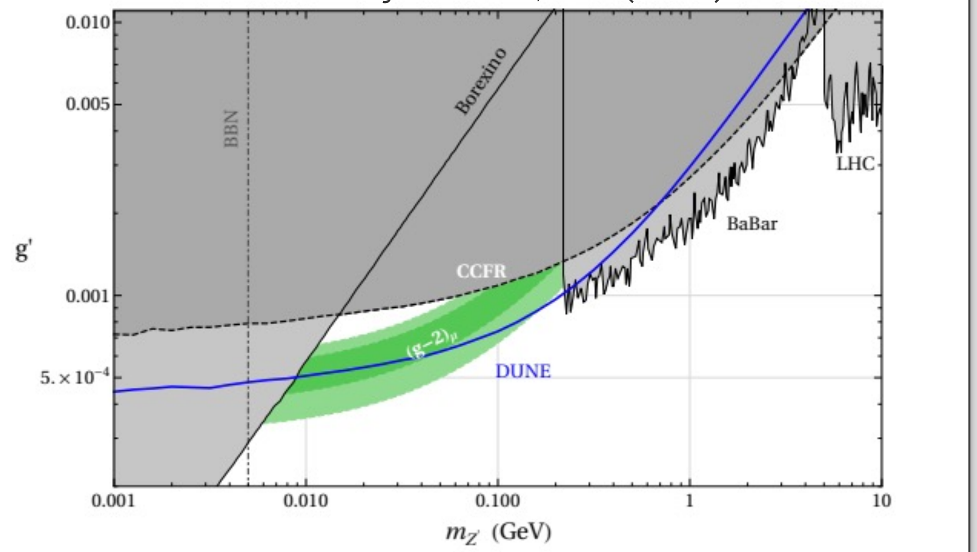


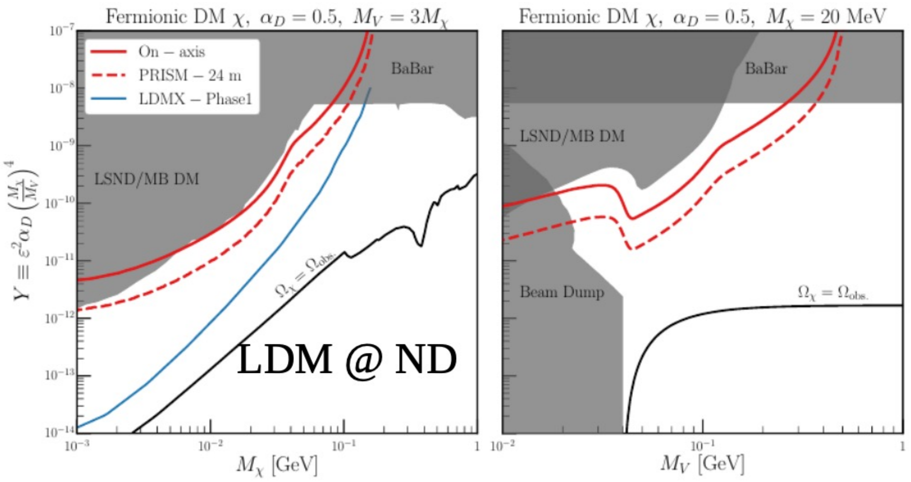


Beyond νSM

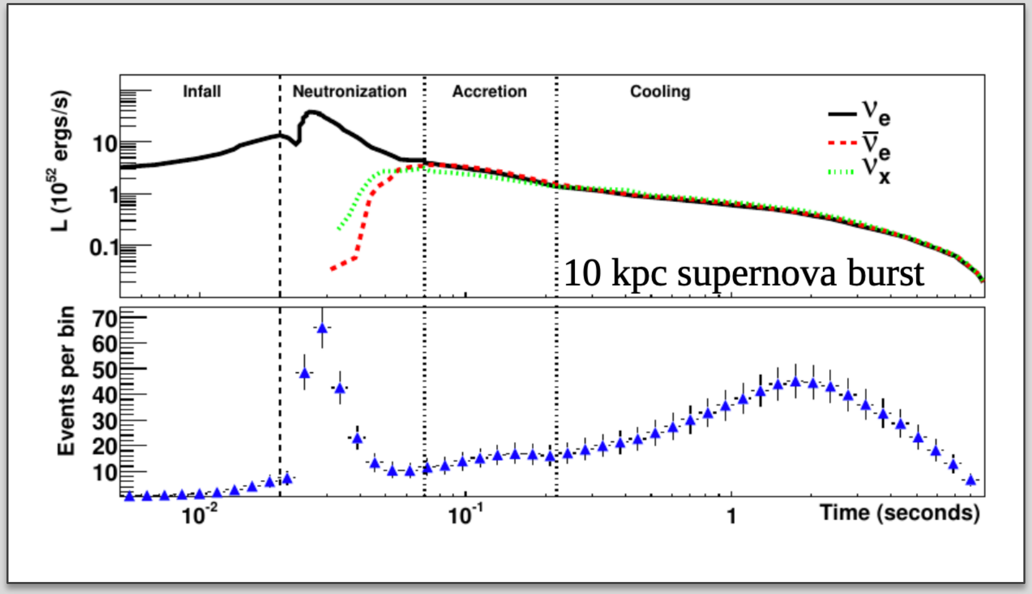
- Due to it large mass, underground location, high resolutions, low thresholds and intense beam DUNE has the potential to probe many BSM models such as
  - Existence of Sterile neutrinos
  - Dark Matter searches
  - Neutrino Tridents
  - Heavy neutral leptons (HNL)
  - Non-standard interactions (NSIs)
  - CPT symmetry violation

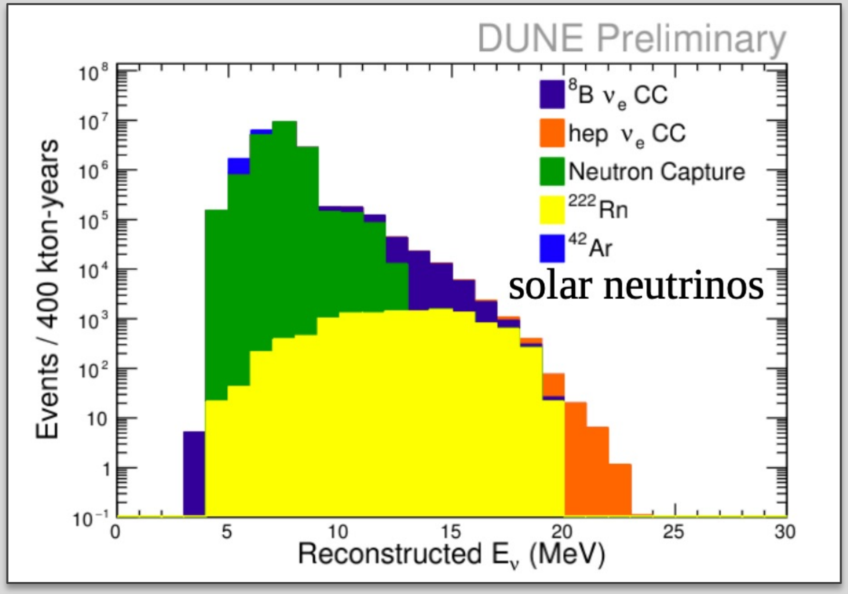
Eur. Phys. J. C **81**, 322 (2021)





Non-beam ν's



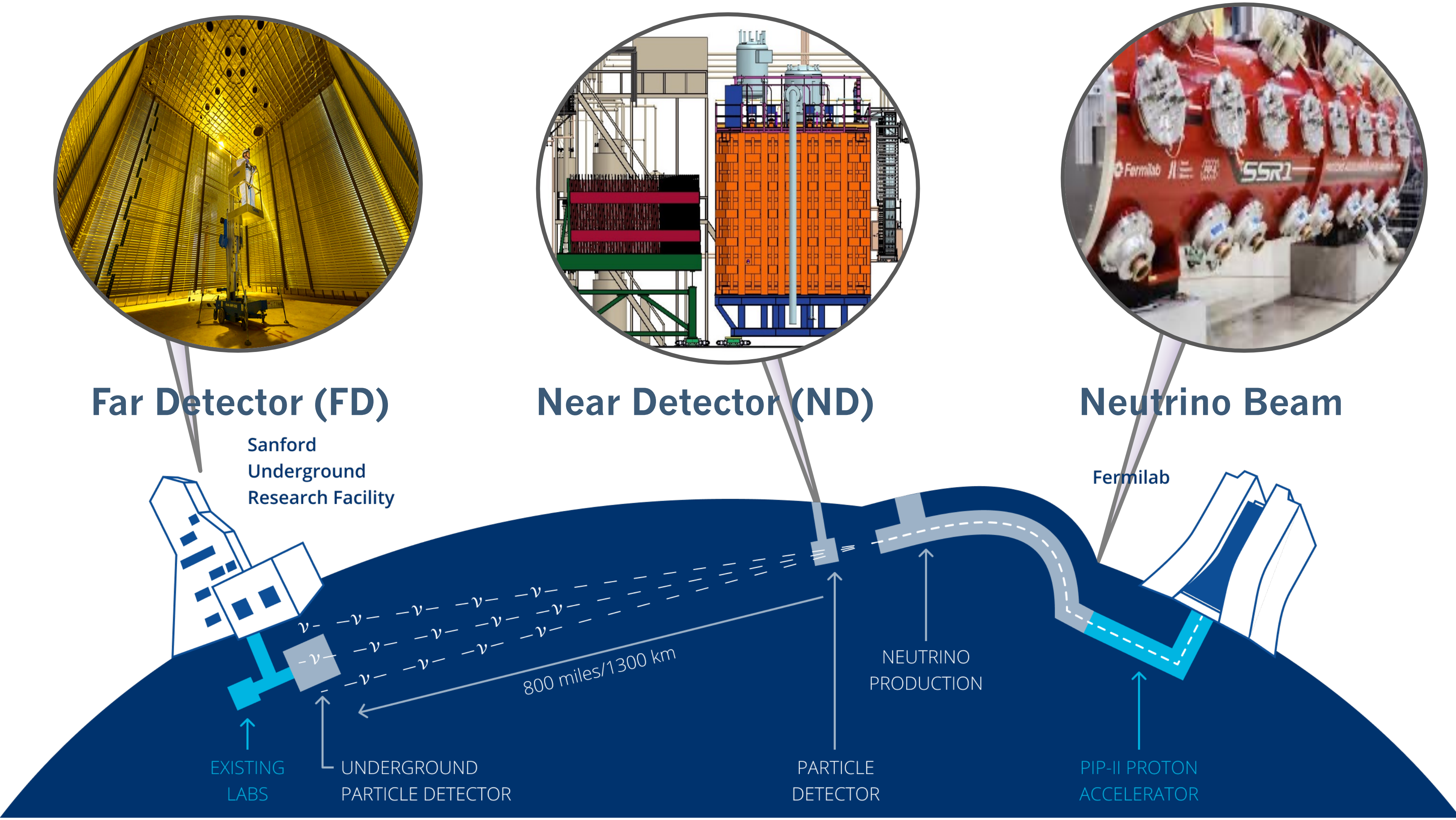


	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

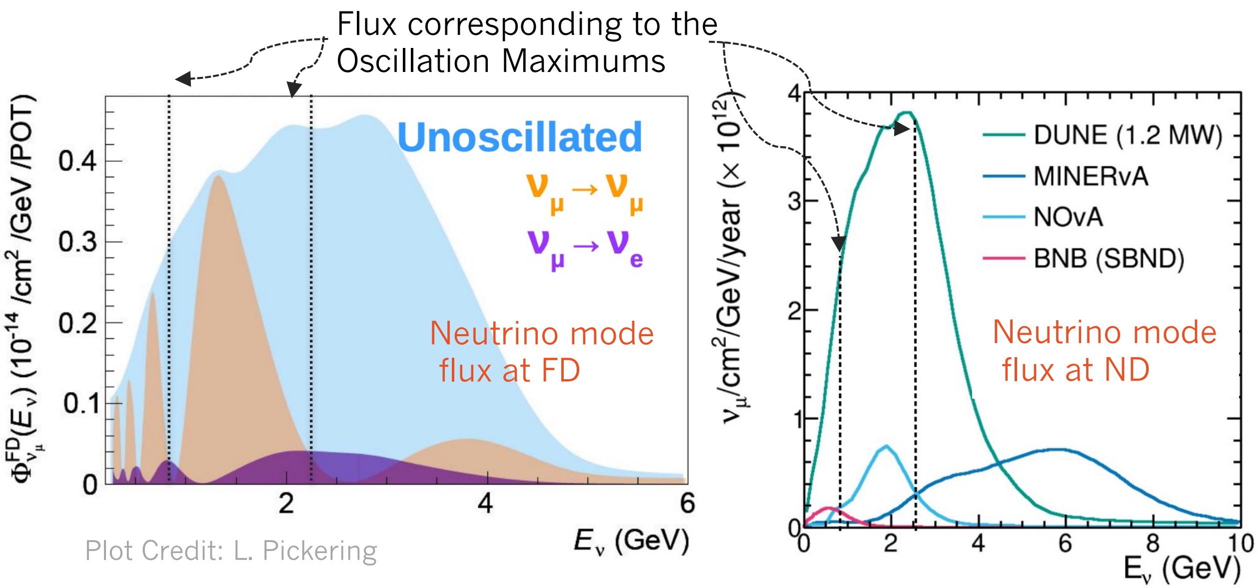
[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

- DUNE will see SN ν_es adding a nice complementarity to the other large detectors.
- Solar neutrino sensitive to the ^{8}B and potential to measure the hep flux and solar mixing parameters.

DUNE: The Experiment

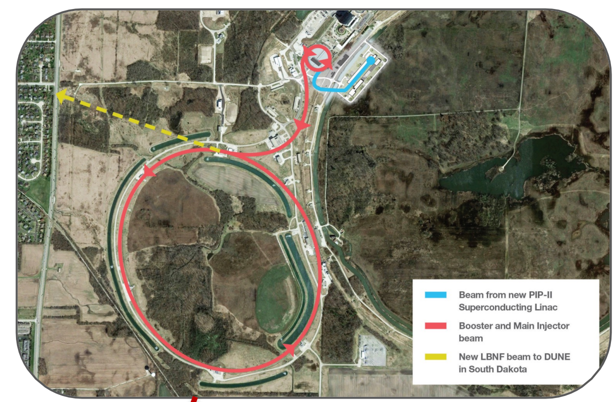


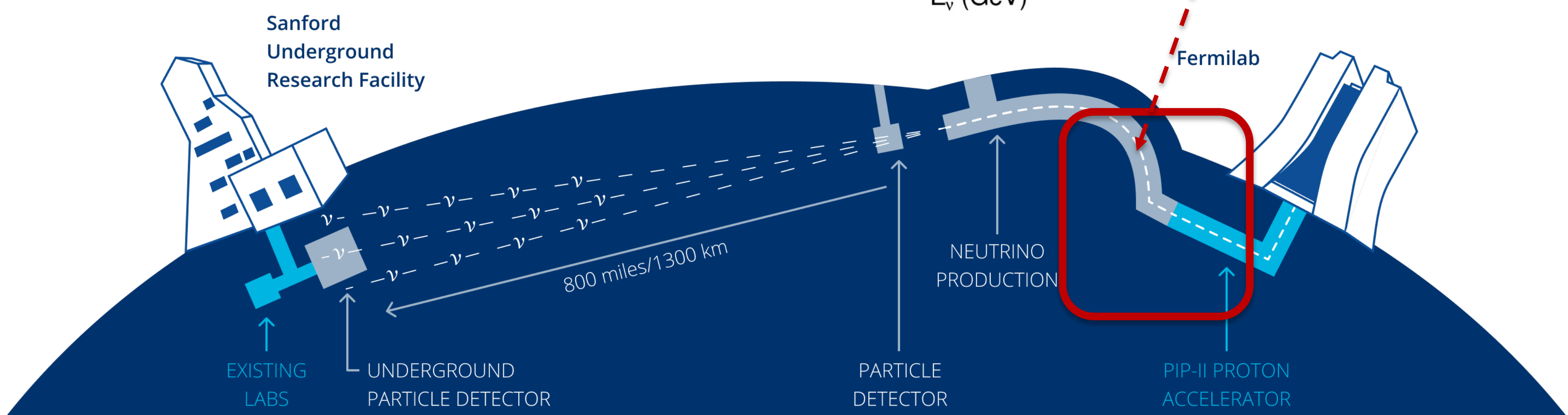
Neutrino Beam



Plot Credit: L. Pickering

Building the world's most intense neutrino beam!





DUNE: Driven by LBNF and PIP-II

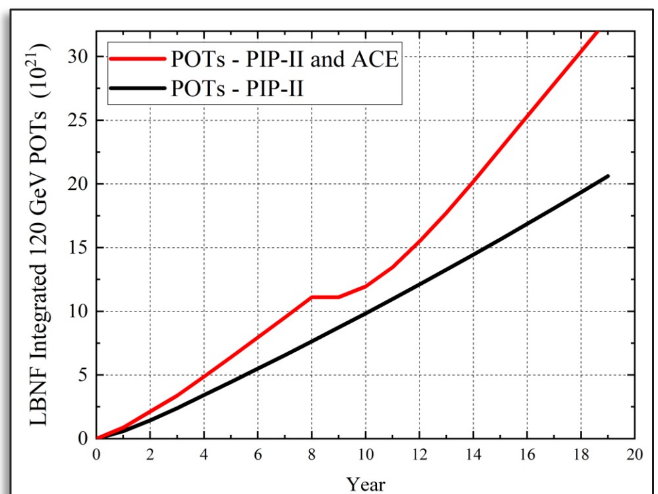
Detailed technical and timeline updates available at:
Accelerator Session on Wednesday & ACE talk later in this session!

From Valishev's ACE Workshop Introduction:

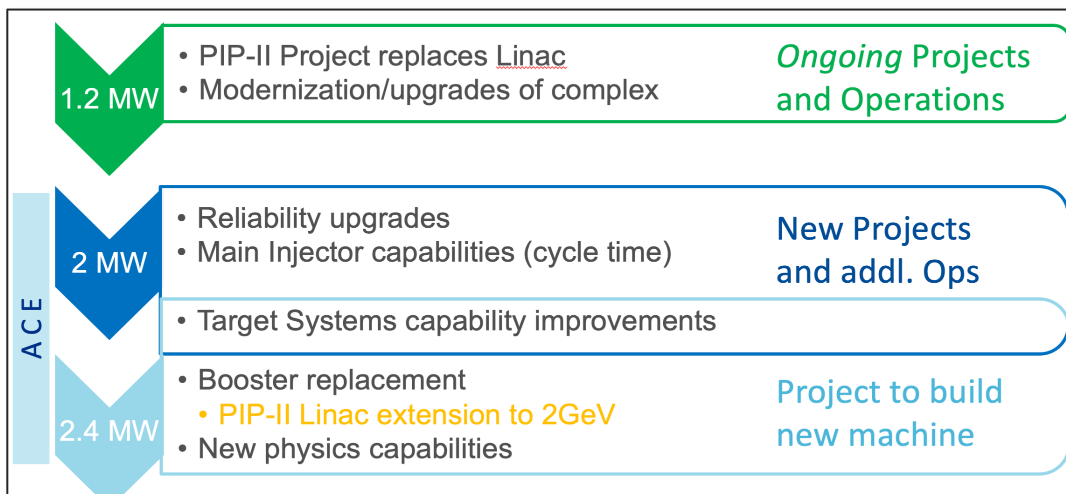
DUNE: The world's most capable neutrino experiment, driven by LBNF and PIP-II

Delivering on LBNF/DUNE is Fermilab's highest priority

Slide from Adam Schreckenberger



Plot from Mary Convery



Slide from Ralitsa Sharankova

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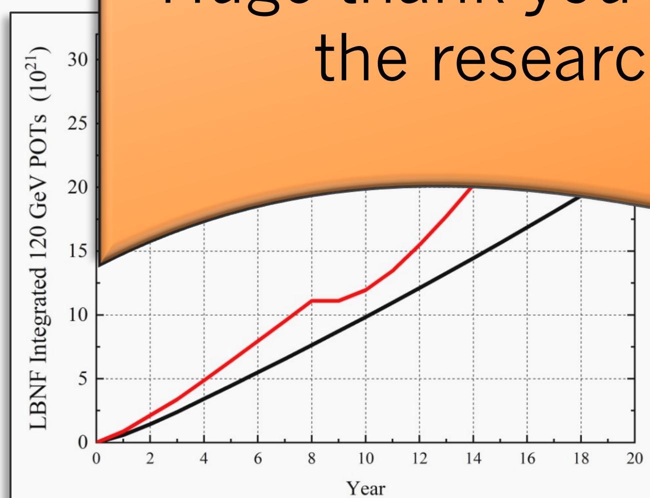
From Valishev's ACE Workshop Introduction:

DUNE ... ost capable neutrino experiment, driven by ... nd PIP-II

Huge thank you to the Accelerator Division, for all the research, innovations, and services!



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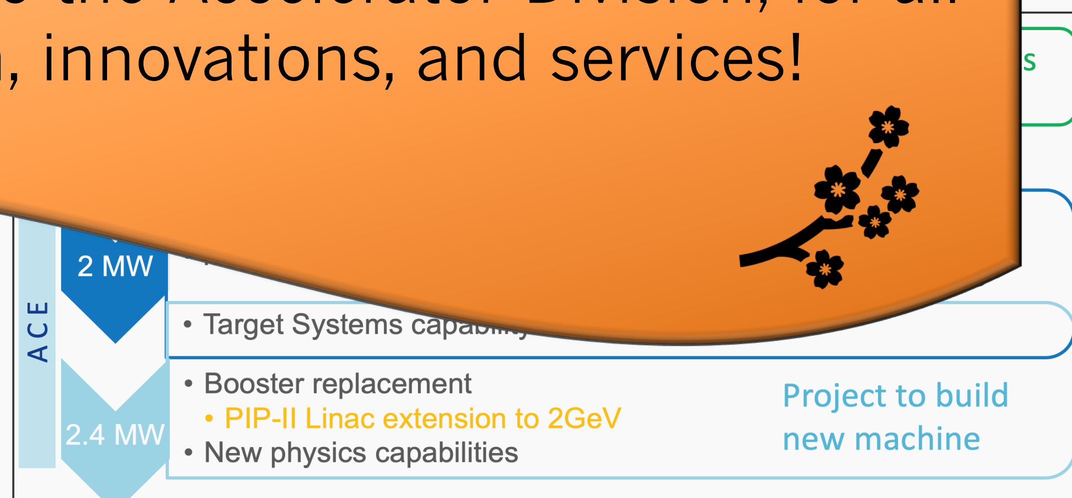
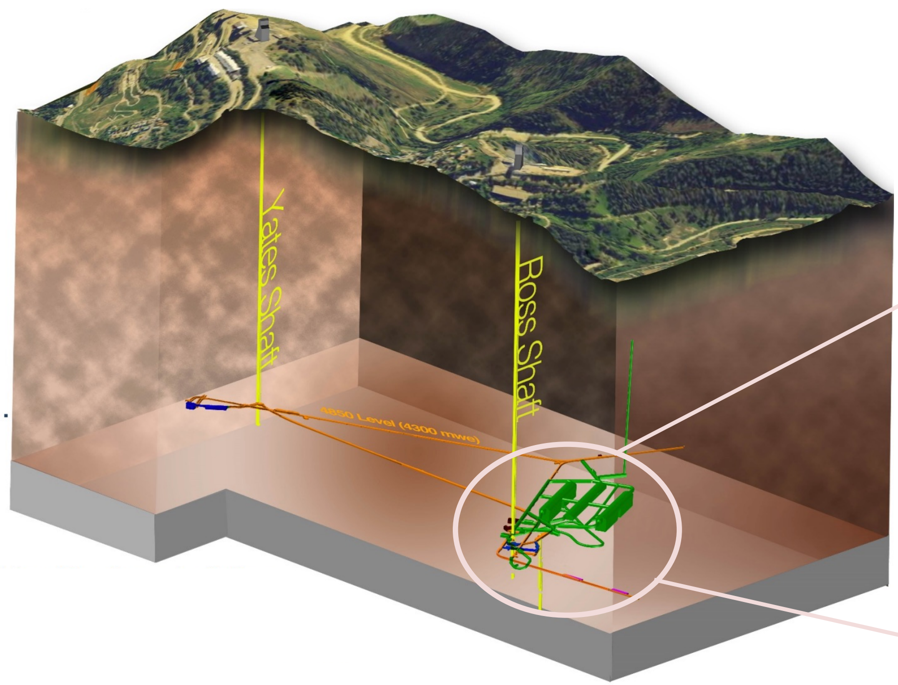
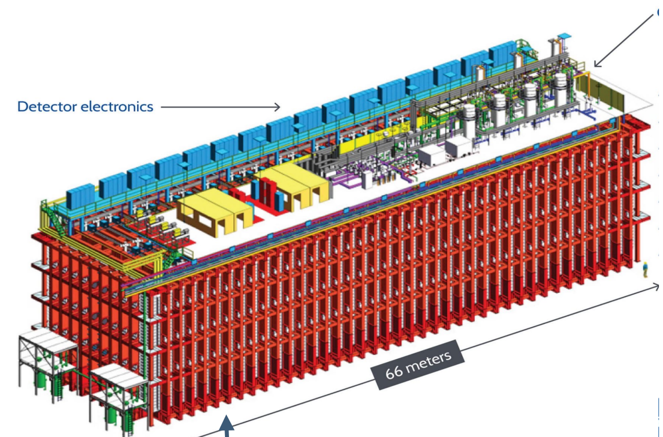
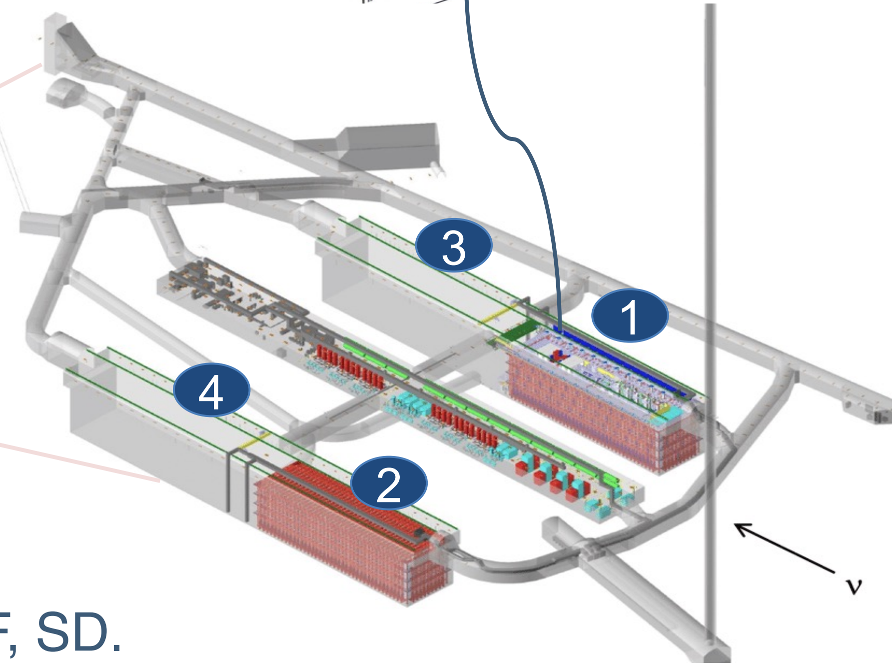


Slide from Ralitsa Sharankova

DUNE FD



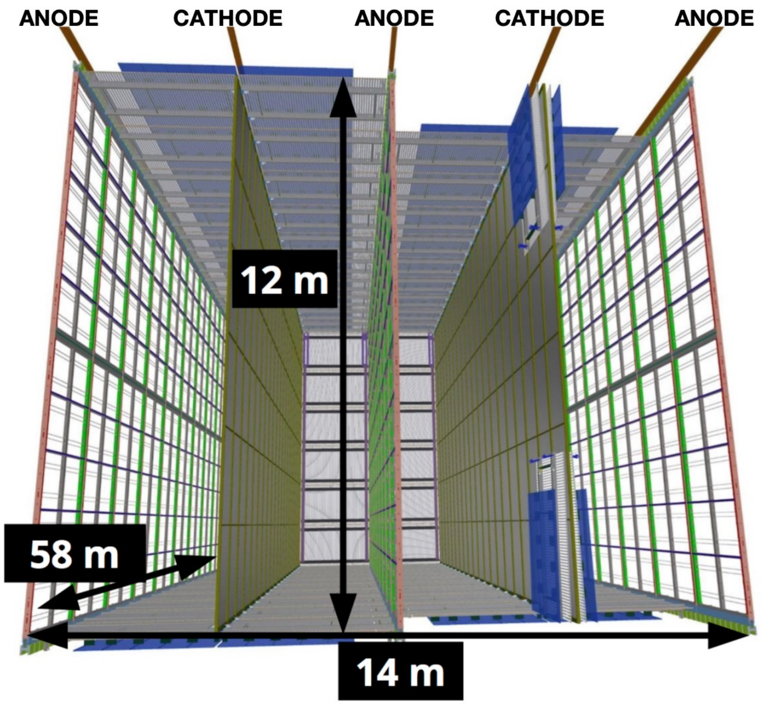




- 4 modules of 17 kt LArTPC detector
- Located 1.5 km underground at SURF, SD.
- Design of FD-I and FD-II has been frozen.
- Discussions and R&D for the remaining module design is ongoing.

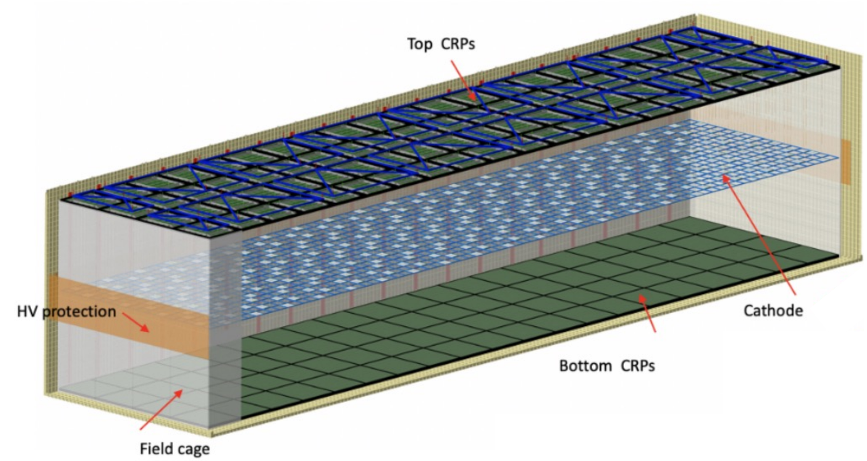
FD: Horizontal and Vertical Drift LArTPCs

TDR: JINST 15 T08010 (2020)



- First module will use horizontal drift technology.
- 150 Anode Plane Assemblies (APAs) with 384,000 readout wires
- 3.5 m drift; Cathode at -180 kV; 500 V/cm field

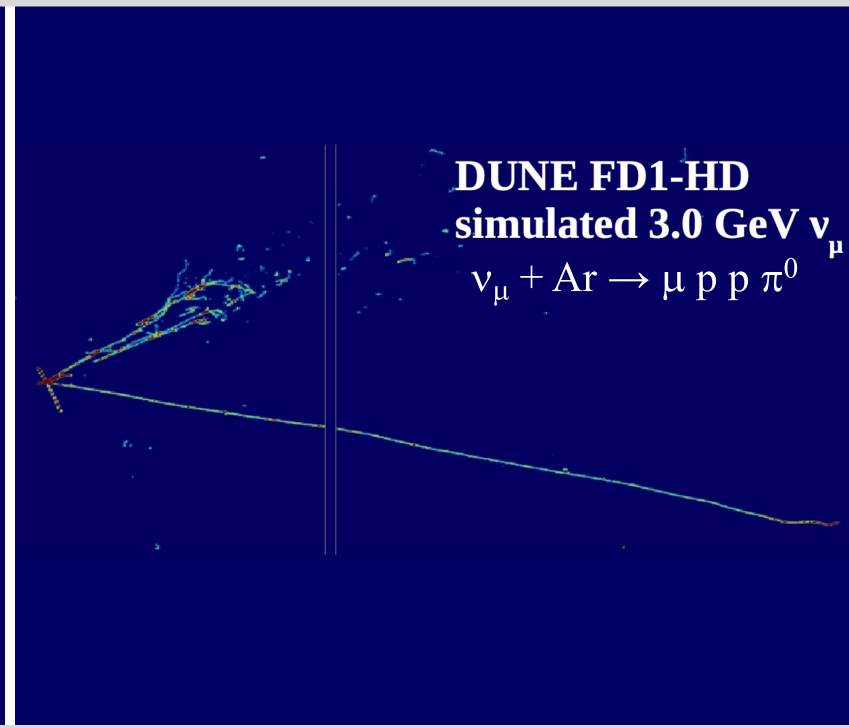
Two Posters at UM - Alex Heindel and Sarah Choate



- Second module will use vertical drift technology. TDR coming out soon!
- Charge readout planes (CRPs) are at the top and bottom with the Cathode in the middle. The photon detectors are integrated on cathode and on cryostat walls.
- 6.5 m drift; -300kV on cathode; 450 V/cm field

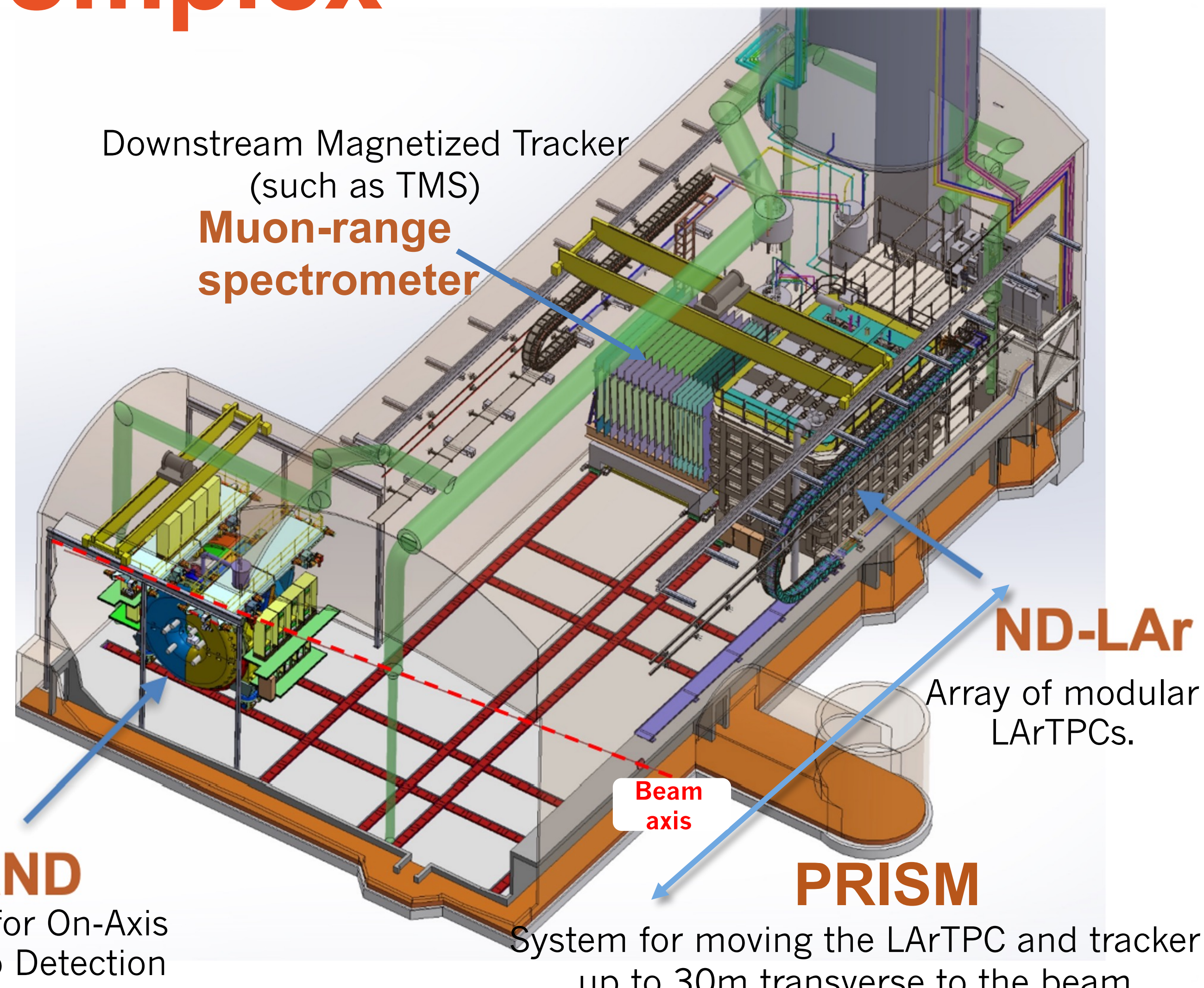
Why LArTPCs?

- Excellent imaging for neutrino flavor ID and energy reconstruction with high resolution.
- Low thresholds for charged particles enables precise reconstruction of lepton and hadronic energy over a broad energy range.



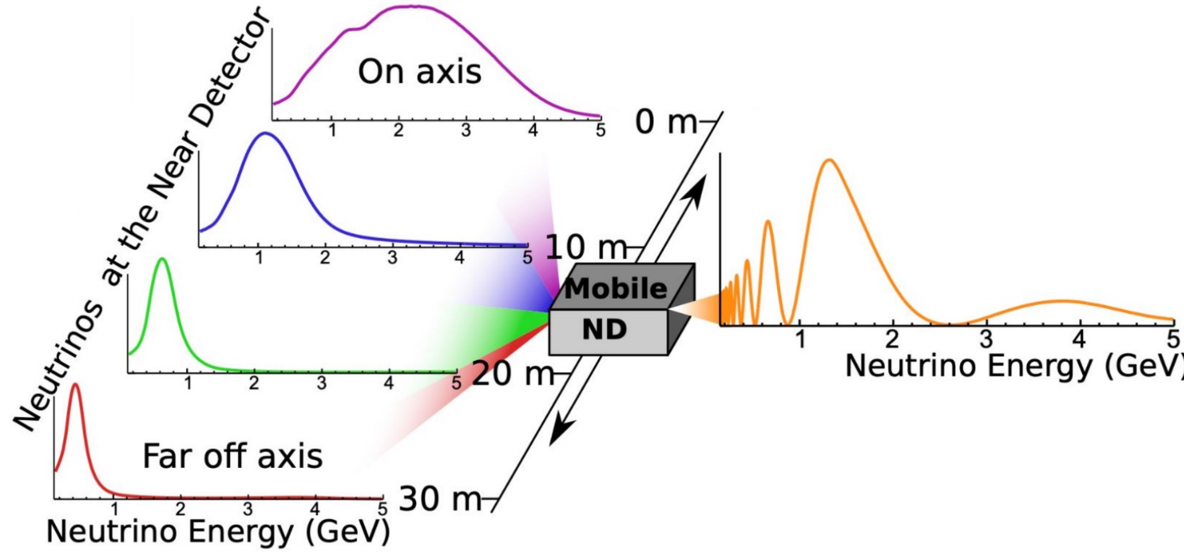
The ND Complex

- To achieve its ambitious physics goals, DUNE will need to constrain its systematics to a few percent level.
- **A suite of near detectors** are designed to robustly constrain systematics and achieve required sensitivities.

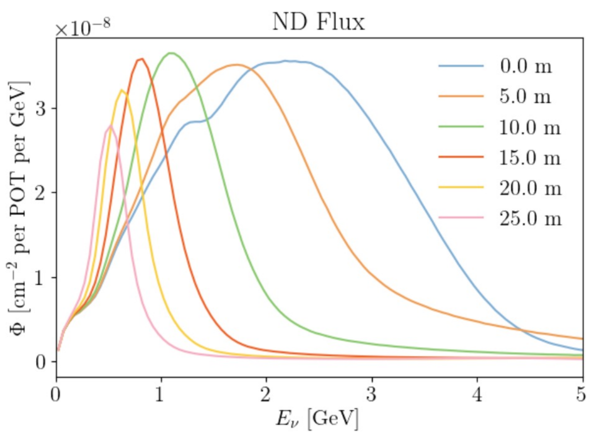


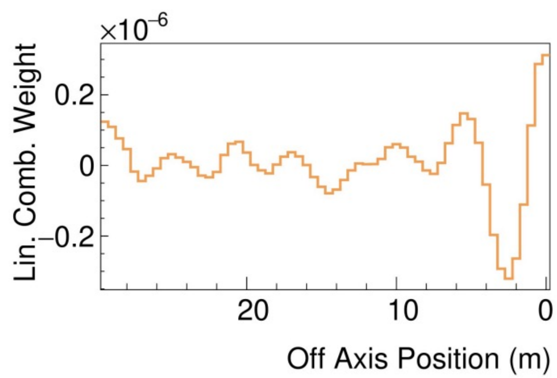
PRISM

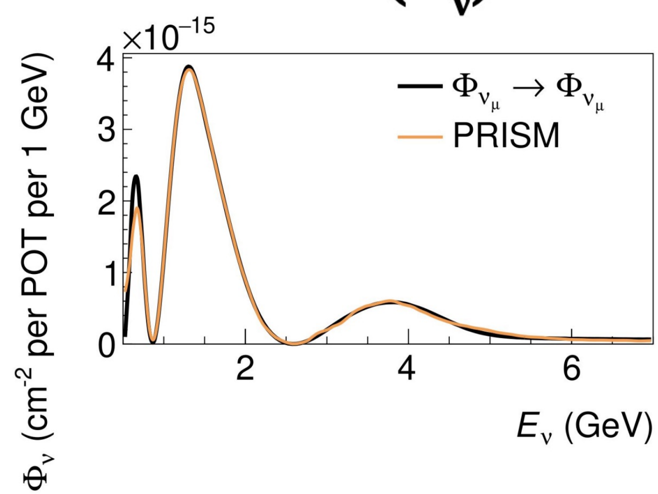
- Using a linear combination of ND flux at various off-axis position, we can construct a prediction for the oscillated FD flux.



$$\Phi^{ND}(E_\nu,x) \cdot C(x) = \Phi^{FD}(E_\nu)$$



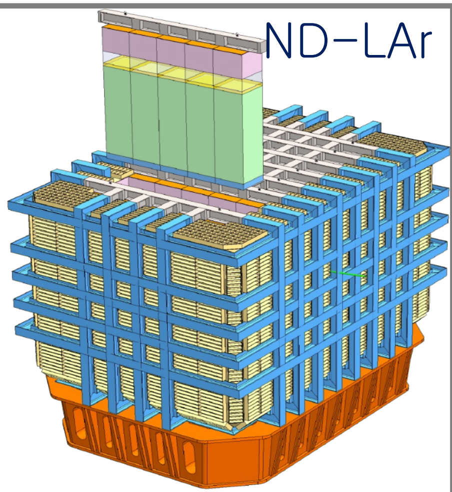




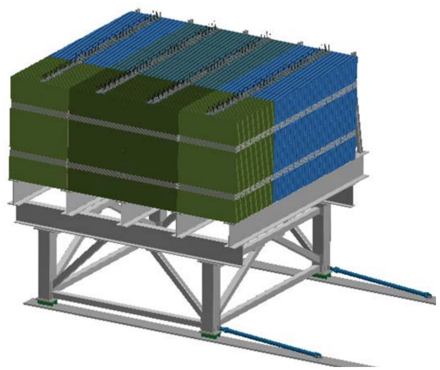
ND Requirements

DUNE PRISM

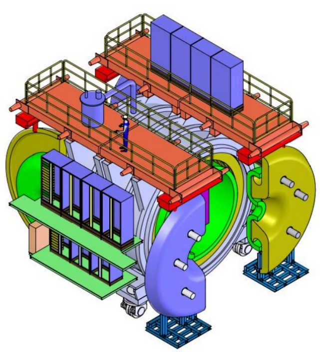
ND-LAr



TMS



SAND



- ✓ Measurements transferable to the FD
- ✓ Constrain the cross-section model
- ✓ Measure the neutrino flux
- ✓ Obtain measurement with different fluxes
- ✓ Monitor time variations of the neutrino beam
- ✓ Operate in high-rate environment
- \+ New exciting physics measurements to test BSM, sterile and dark-matter models.

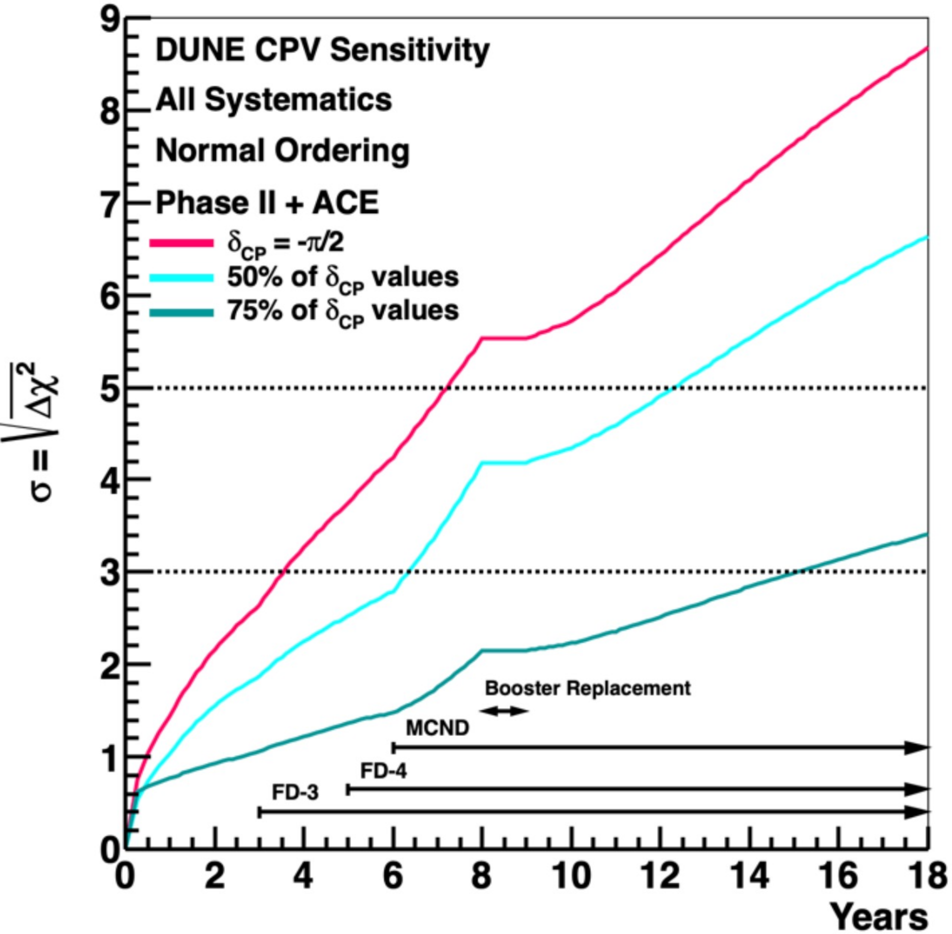
DUNE: Phased Construction

Phase I

- FD mass: 17 kt x 2 modules
- Beam: 1.2 MW
- ND: ND-LAr, TMS, SAND

Phase II

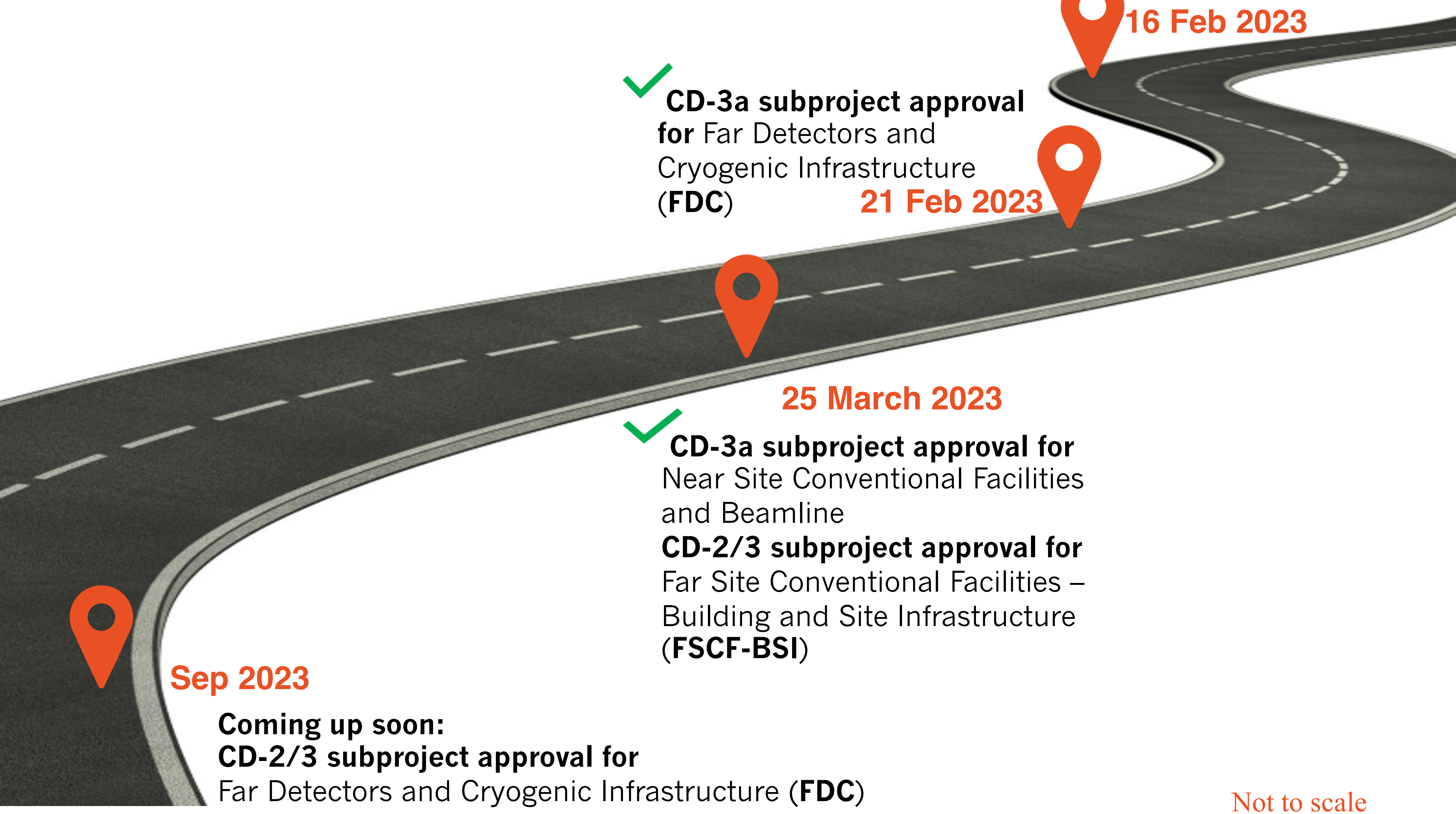
- FD mass: 17kt x 4 modules
- Beam: 2.4 MW
- ND: TMS to be replaced by a more capable ND such as Gas-Ar TPC



DUNE needs the full detector scope to achieve its science goals!

DUNE: Progress

Milestones in 2023



CD-1RR approved by DOE.
- Reaffirmed science objectives
- Reset point estimate and cost range
- Implemented subprojects.

16 Feb 2023

CD-3a subproject approval for Far Detectors and Cryogenic Infrastructure (**FDC**)

21 Feb 2023

25 March 2023

CD-3a subproject approval for Near Site Conventional Facilities and Beamline

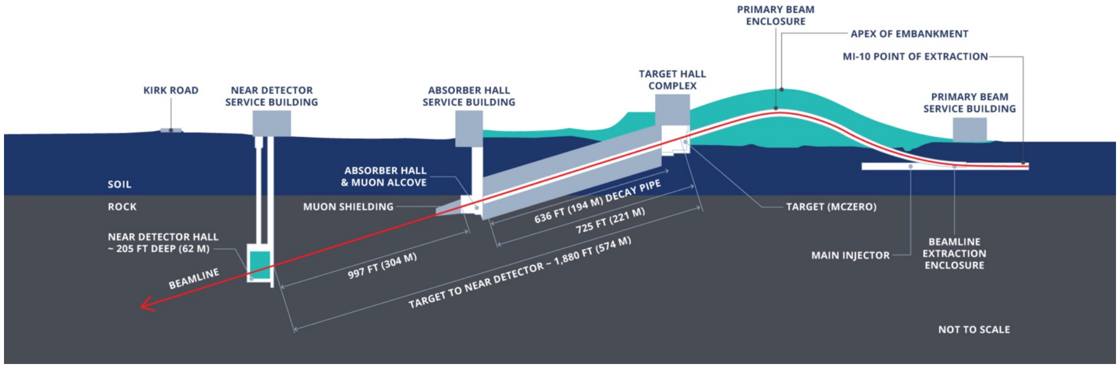
CD-2/3 subproject approval for Far Site Conventional Facilities – Building and Site Infrastructure (**FSCF-BSI**)

Sep 2023

Coming up soon:
CD-2/3 subproject approval for
Far Detectors and Cryogenic Infrastructure (**FDC**)

Not to scale

Near Site Facilities & Beamline @Fermilab

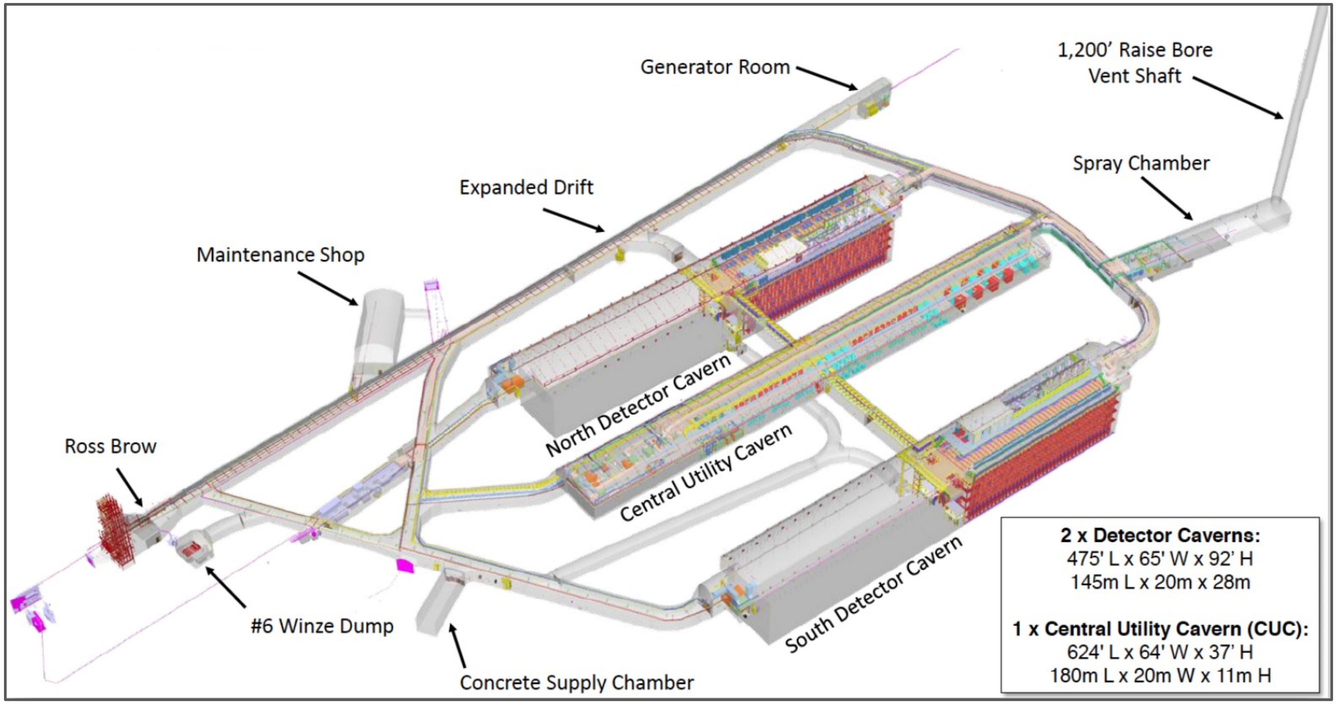


Groundbreaking for PIP-II Accelerator Building


Cryogenics Plant Building is complete

- Beamline design at 70% final design status and prototyping is in advanced stages.
- Conventional Facilities design remains at 100% final design status.
- Near site facilities construction starts in 2025.

Far Site Facilities @SURF



- Excavation of caverns for the far detector is ongoing at SURF, SD.
  - ~ 70% completed by May 2023

FD-I Construction

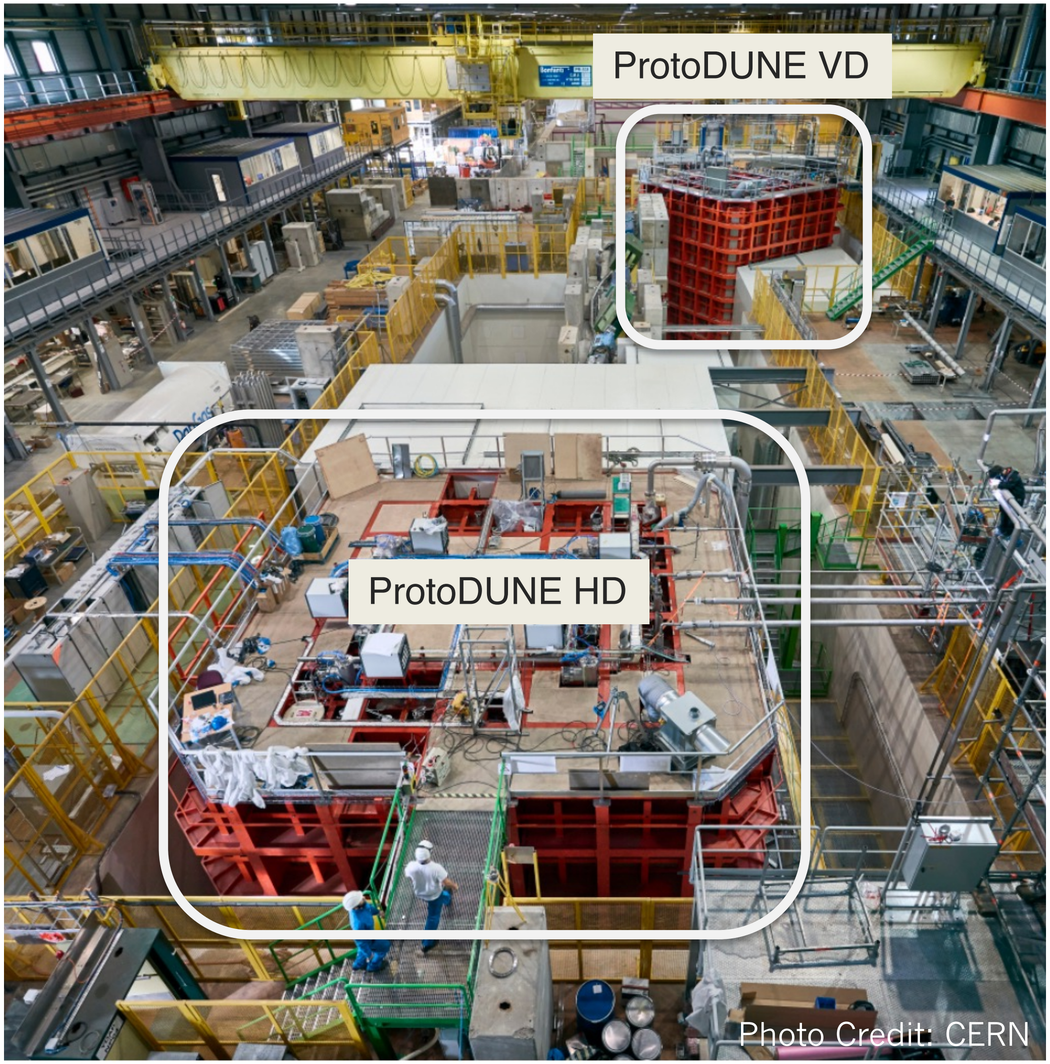
Production of APAs

Testing assembly of cryostat components

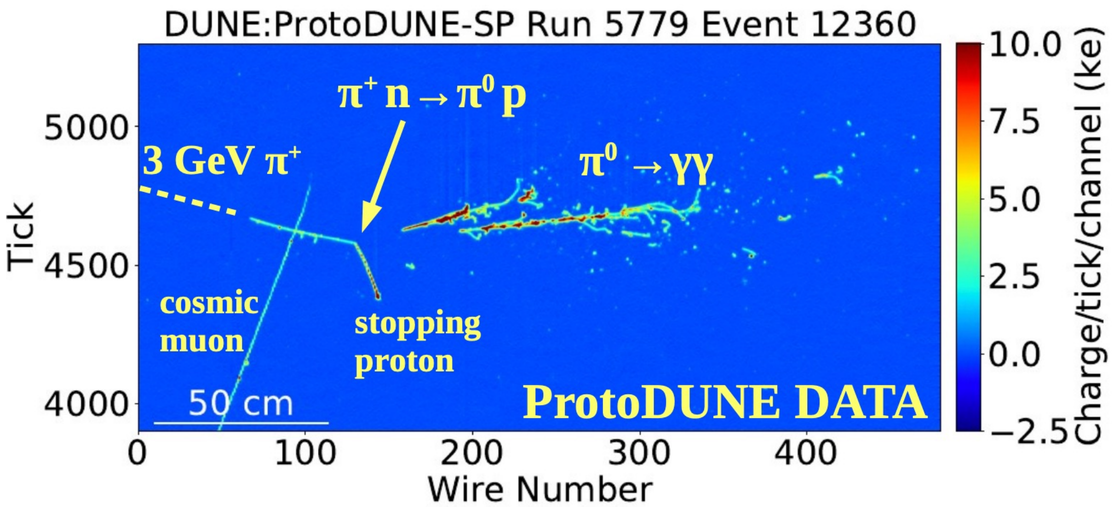
- APAs are being built primarily in the UK and the test APAs have arrived at SURF.
- CERN has started fabrication of cryostat-I.
- Aim to have FD-I and FD-II taking physics data by 2029.

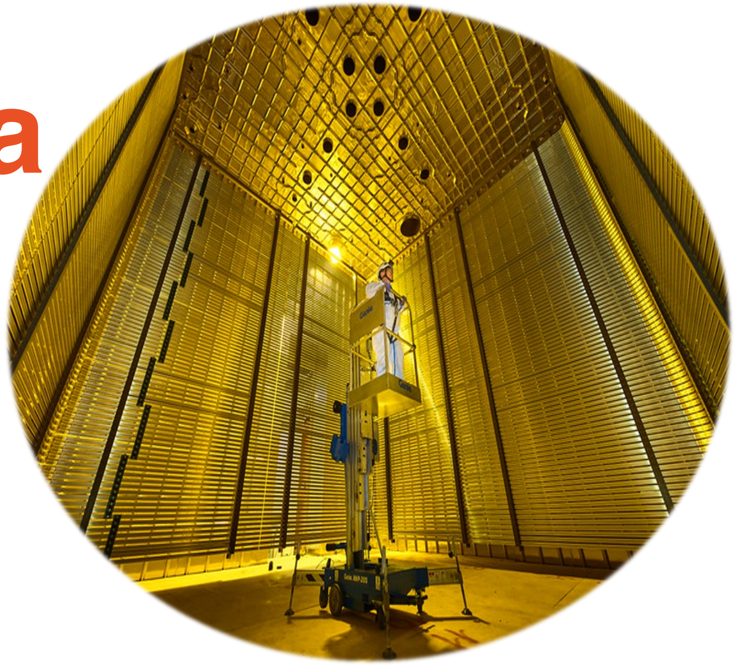
FD Prototypes: ProtoDUNEs @CERN

- Two 770-ton prototypes of DUNE FD have been built at CERN for a test-beam run with charged particles.
- ProtoDUNE- Horizontal Drift (HD) collected over 4 million events in a successful run from 2018- 2020.
- A run of ProtoDUNE VD and a second run of ProtoDUNE HD is anticipated early next year.

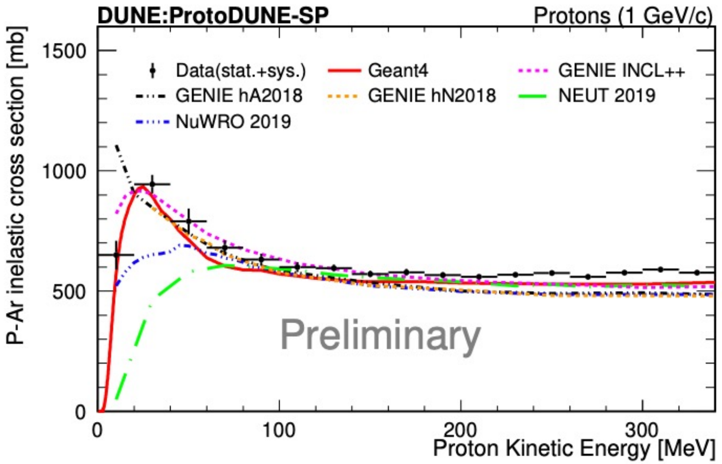


ProtoDUNE-HD Data



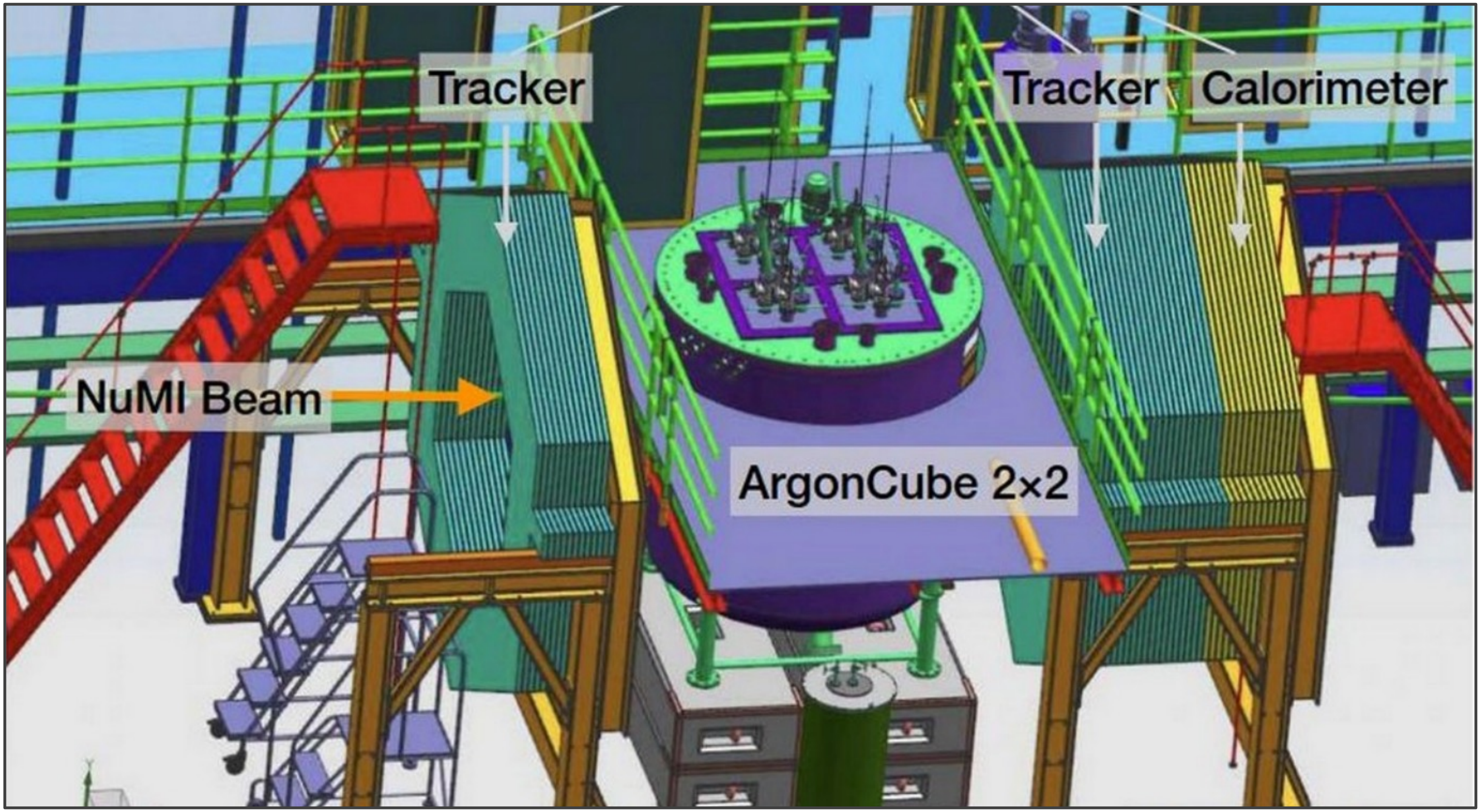


p-Ar cross section



- Rich test-beam data collected with charged particles (charged pions, kaons, protons, muons and electrons) with different momentum modes at CERN.
- Multiple papers on calibration, detector physics measurements and reconstruction have been published since 2020.
- Hadron-Ar cross-section measurements coming out soon!

ND Prototypes



See next talk by Zach Hulcher!

Summary

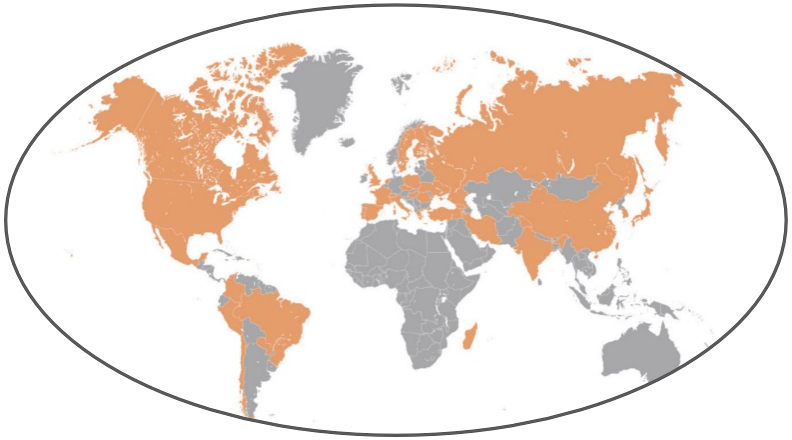
- DUNE has excellent physics sensitivities:
  - Resolve the neutrino mass ordering and the potential to measure CP violation over a broad range of δ_{CP}
  - Unique and complementary sensitivity to low-energy neutrinos from supernova burst and to physics beyond the SM
- DUNE is making good progress on all fronts:
  - Far site excavation is **~70% finished** and first components of the FD are being shipped to SURF.
  - PIP-II is advancing rapidly and Near site design has finished
- Both Near and Far detector prototyping is progressing successfully.
  - Rich test-beam data collected in the first ProtoDUNE run.
  - **First ν-beam test with a DUNE prototype detector is coming this year!**

Thank You!

DUNE Collaboration Meeting, Fermilab, May 2023

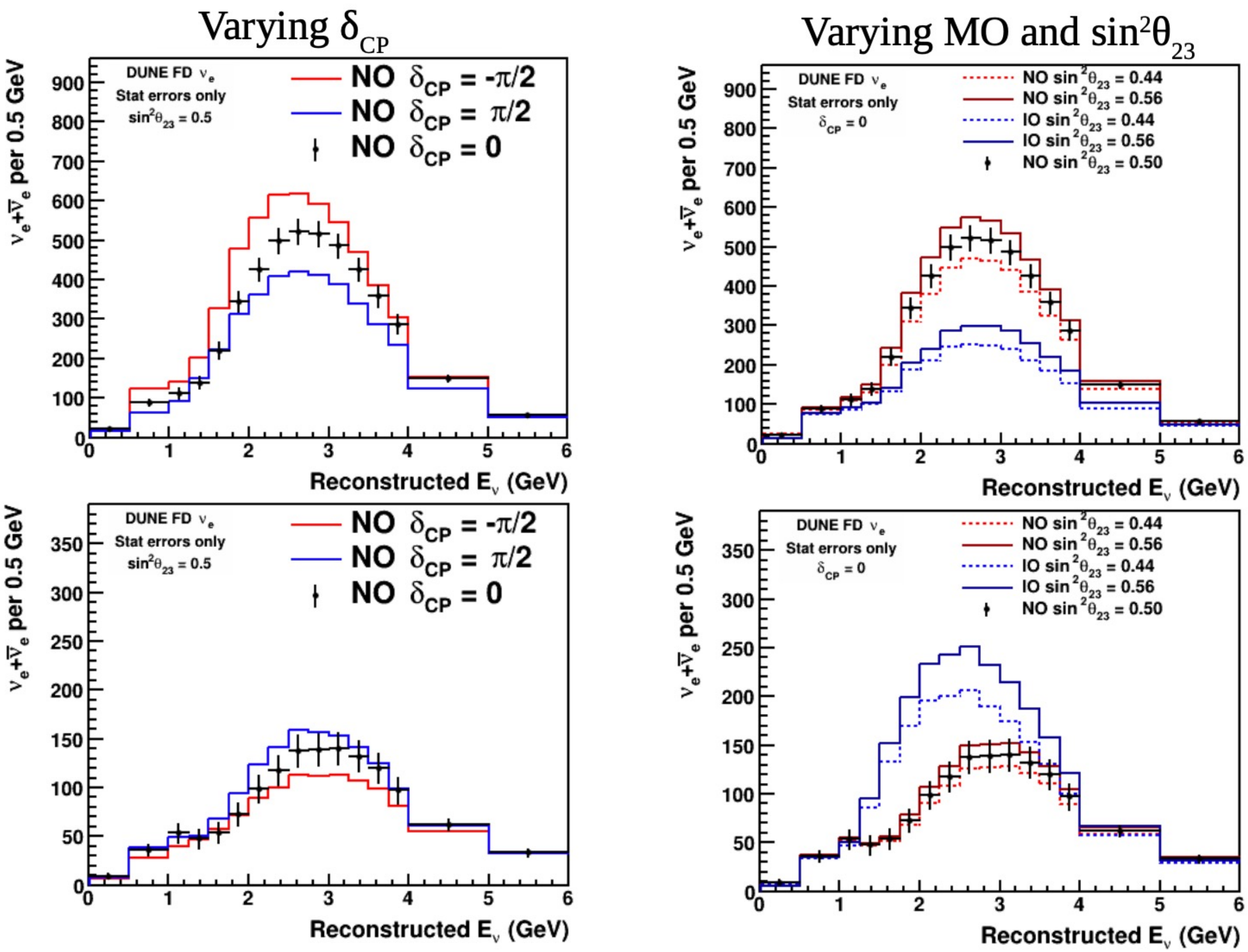
HUMANS OF DUNE

- ◎ **1400+ collaborators**
- ◎ **200+ institutions**
- ◎ **37 countries (including CERN)**

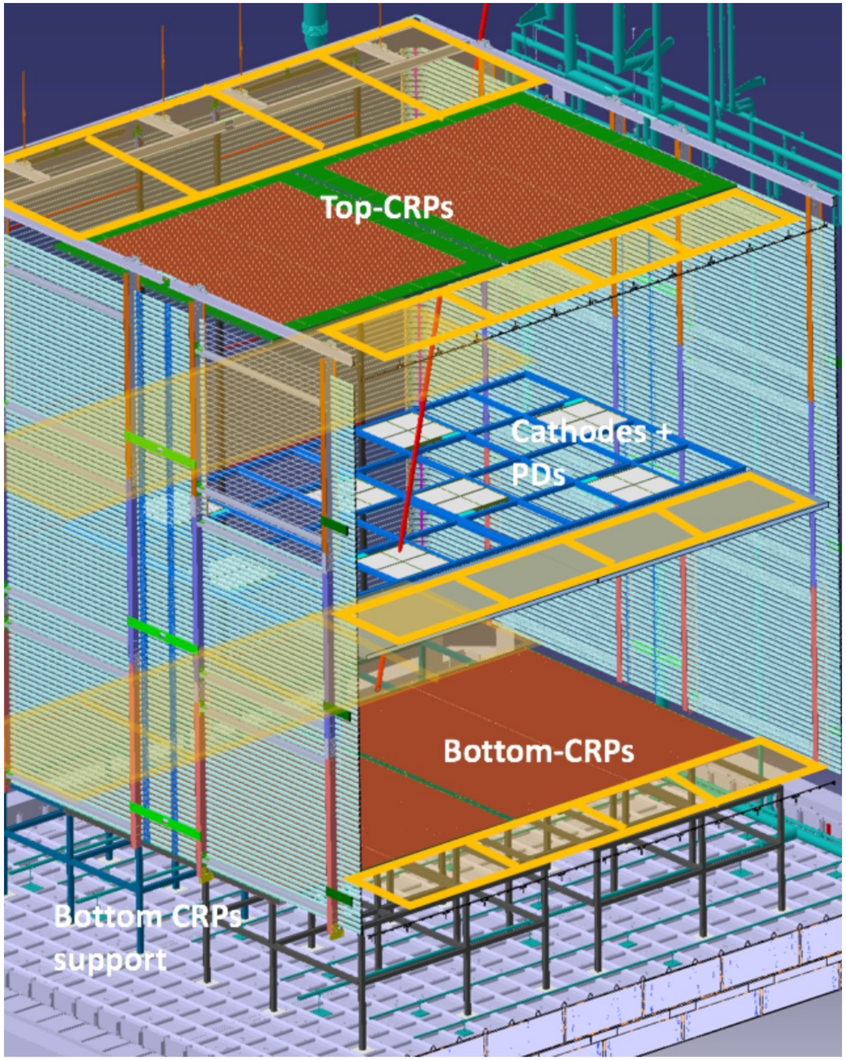


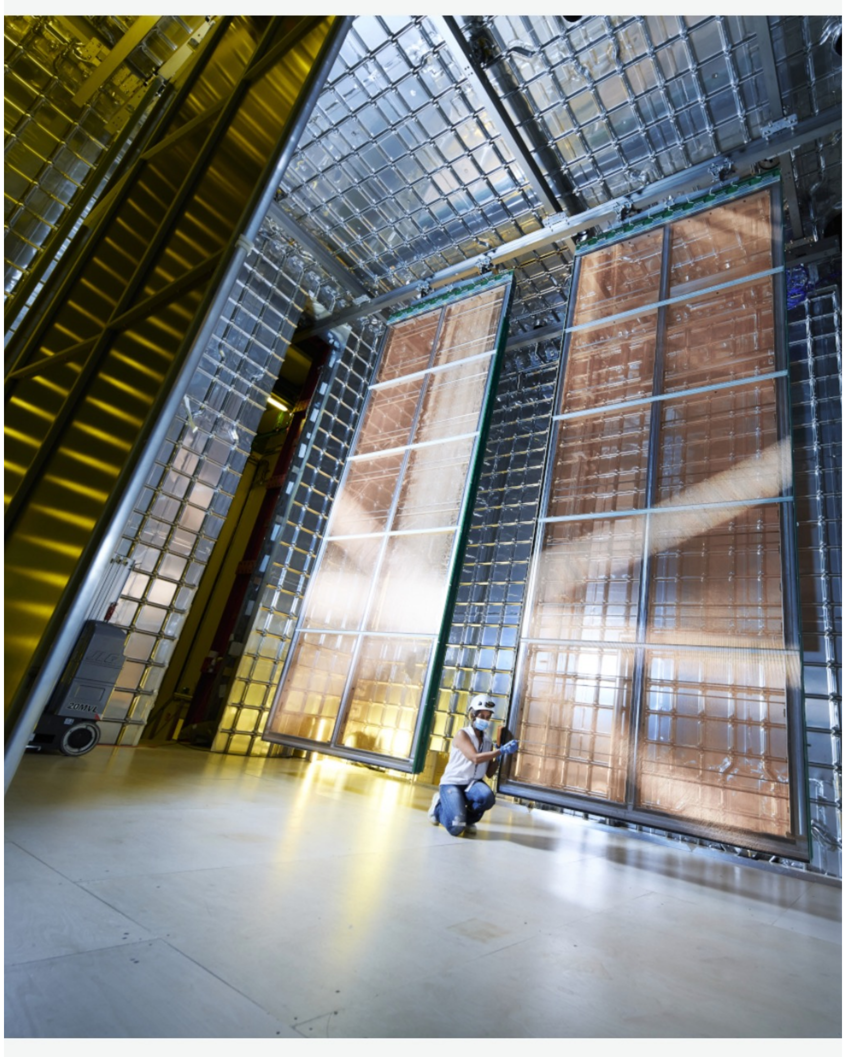
Supplemental Materials

DUNE: Physics



FD Prototypes

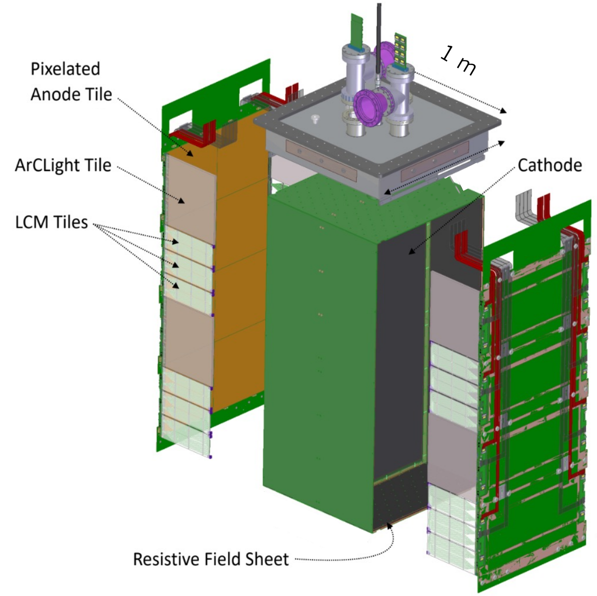




ND-LAr

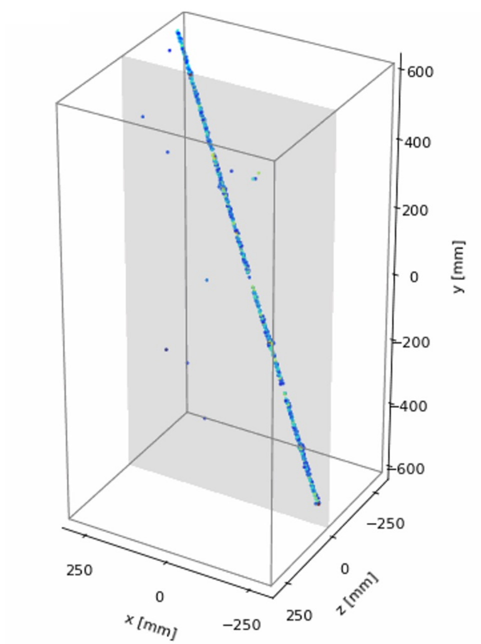
Core Requirements :

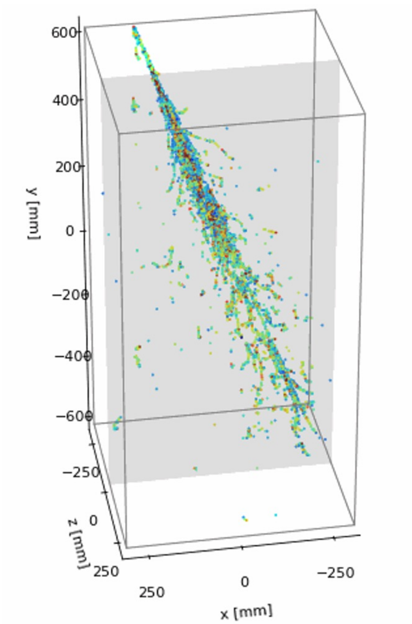
- Liquid Ar target and similar detector technology as FD.
- Constrain flux via ν+e elastic scattering.
- Precise constraints on event rates (flux × cross sections) in LAr

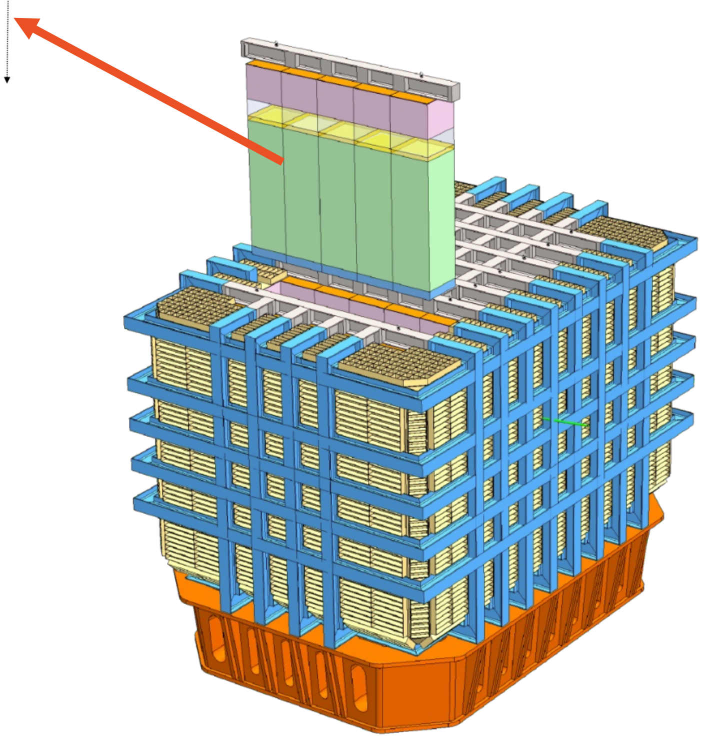


Design :

- 5 x 7 array of 1m x 1m x 3m TPC modules with ~50t fiducial volume
- Modular design to tolerate high event rate environment.
- Pixelated charge readout for true 3D imagining of particle tracks.





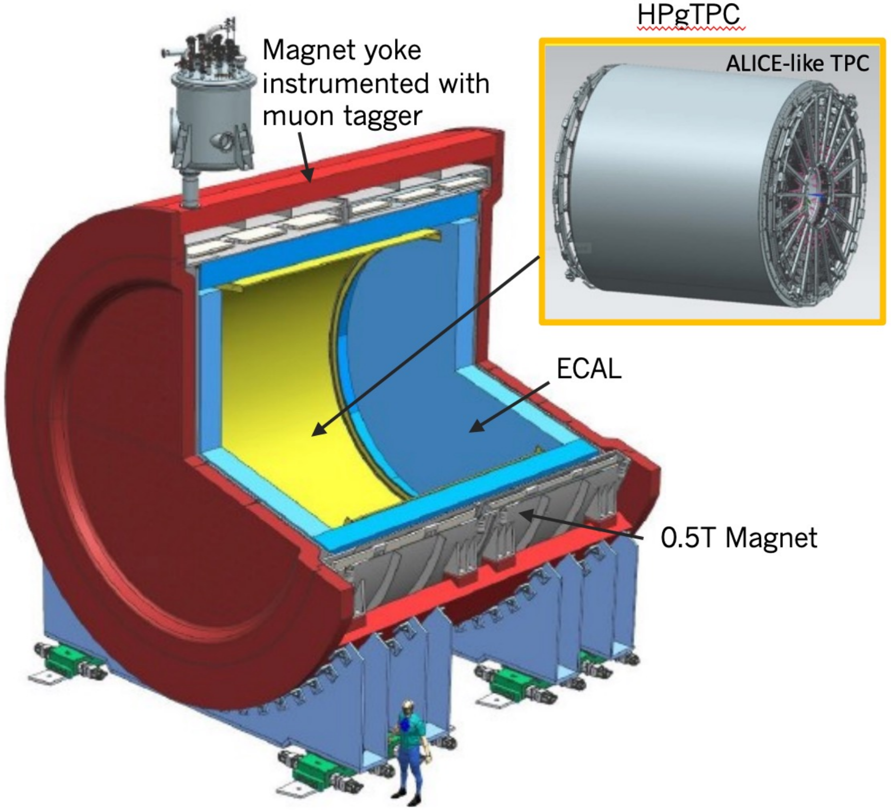


ND-GAr

Core Requirement : Downstream tracking of muon tracks exiting ND-LAr + low threshold tracking of hadronic system providing fine tuning of cross-section measurements

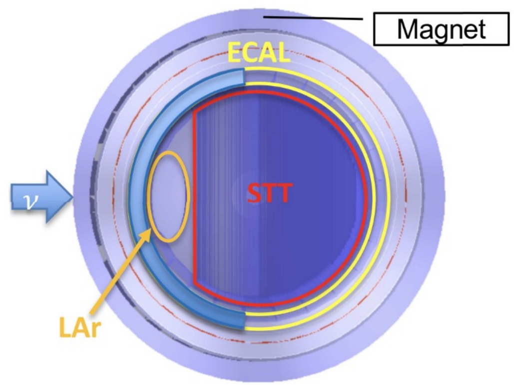
Main design capabilities:

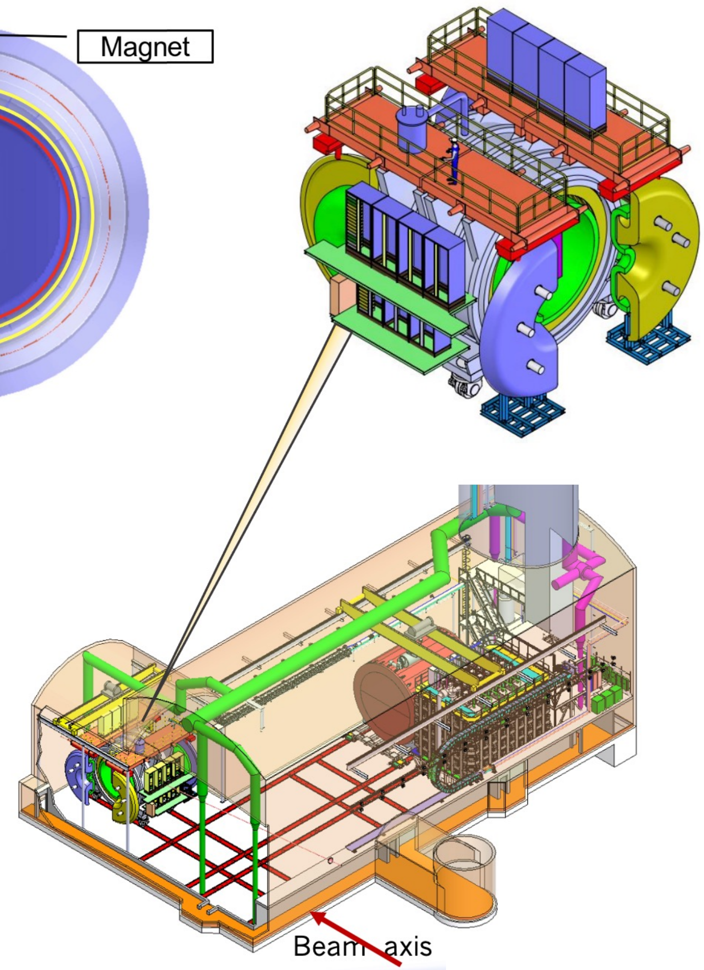
- Excellent PID,
- tracking efficiency,
- momentum resolution
- 4π coverage
- Minimal secondary interactions
- Low threshold : high sensitivity to low energy protons or pions
- Measure exclusive final-state topologies



SAND

Core Requirement : Continuous monitoring of the on-axis flux to determine flux stability and trigger quick response to any beamline geometry change.





Design:

- Inner straw-tube tracker (STT) surrounded by an electromagnetic calorimeter (ECAL) inside a large solenoidal magnet.
- STT provides CH_2 and C targets for a model-independent measurement of (anti)neutrino interactions on hydrogen and comparison with world cross section data.
- Inner Liquid Ar target provides constraints of nuclear effects in Ar and cross-check for ND-LAr.