Indian Institute of Technology Guwahati

Deep Underground Neutrino Experiment (DUNE): Possible Indian Collaboration with JINR on Detector Development

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India-JINR Workshop on Elementary Particle and Nuclear Physics,
and Condensed Matter Research

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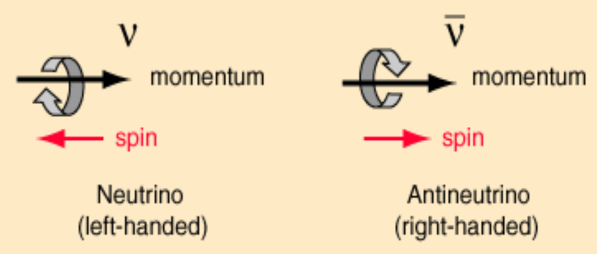
Neutrinos in the Standard Model

- Neutrinos
  - ✓ ν_e, ν_μ, ν_τ
  - ✓ $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
- Interacts only through weak force
  - ✓ Mediators: $W^{\pm}, Z^0$

✓ $m_\nu \approx 0$

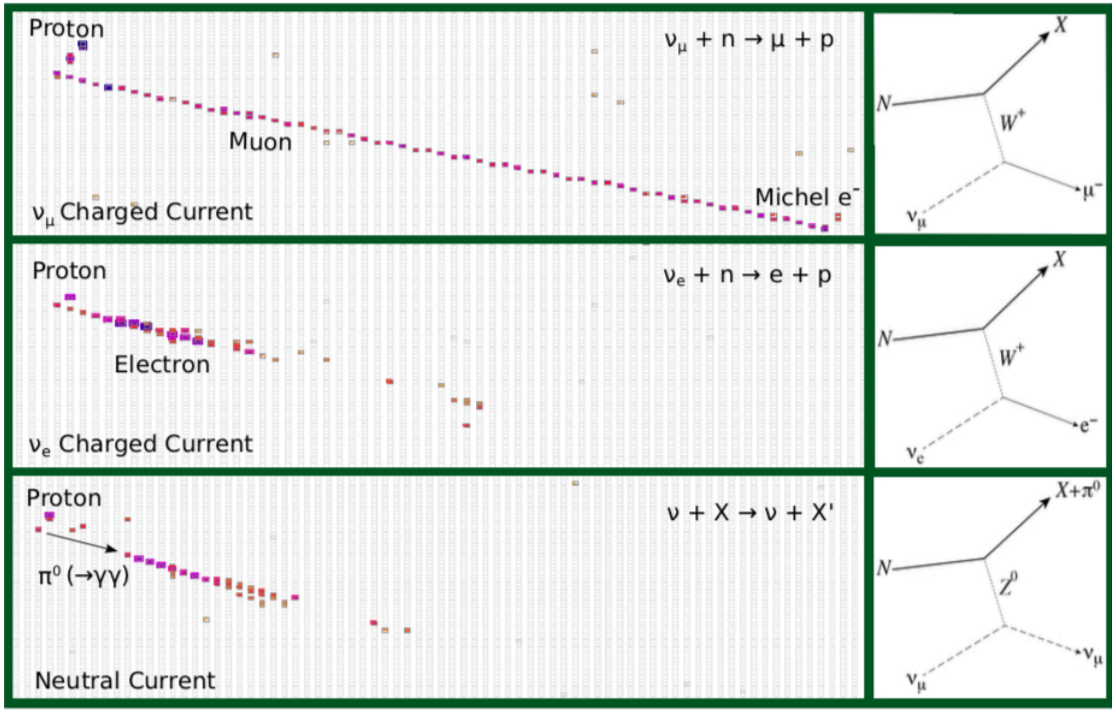
✓Neutrinos are left handed

- anti-neutrinos are right handed



✓ Neutrinos do not have electric charge. They only interact weakly.

- So, we see only the by products of the weak interactions.



✓Quite abundant: 100,000 billion pass through your body each second from the sun.

-Will stop ~1 neutrino which passes through it in a lifetime!

Neutrino interaction cross sections are small, $\mathcal{O}(10^{-38}\ cm^2/nucleon)$ at 1 GeV.

Neutrino Sources

✓Solar: 0.1 – 15 MeV

- from fusion inside the stars
- 85% from $p + p \rightarrow d + e^- + \nu_e$

✓Man-Made: ~few MeV

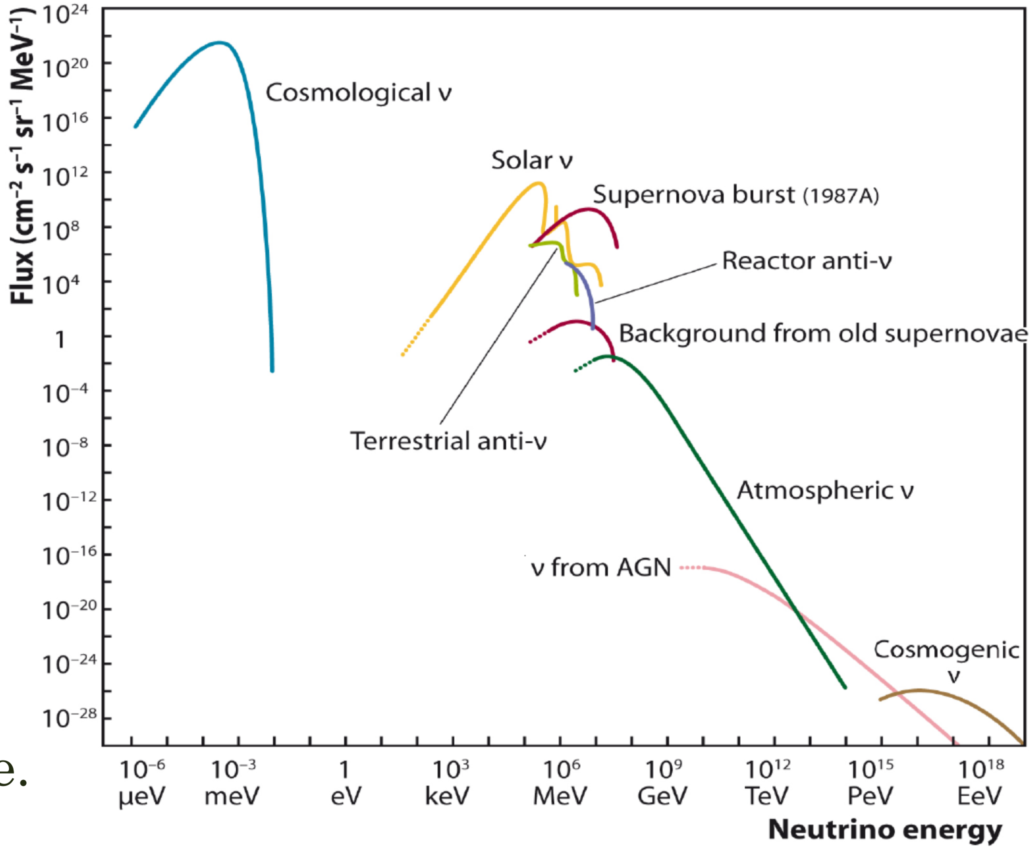
- Nuclear reactors - byproduct

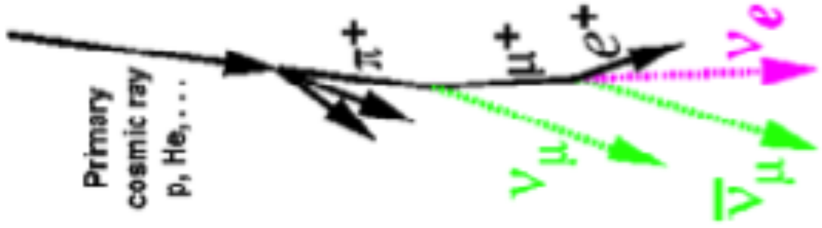
✓Man-Made: ~0.5 MeV – 18 GeV

- Particle Accelerators

✓Atmospheric: ~ MeV– 200 TeV

- Proton (from outer space) interaction with the atmosphere.





On Average 2 muon neutrinos are produced for every electron neutrino in the atmosphere.

Neutrino: A new Identity in the last 25 years!

Standard Model

- Neutrinos interact through weak interaction.
- Lepton flavour is strictly conserved.
- Neutrino have zero mass.

Neutrino oscillations & Relative Neutrino Masses (confirmed by SNO, SuperKamiokande, T2K, NoVA etc.)

- Observed neutrino oscillation itself is a great triumph
  - Macroscopic manifestation of quantum effects.
- Indicates non-zero mass for neutrinos
  - Huge impact in particle physics & cosmology
- Neutrino mass states are different from flavor states.
  - As neutrinos travel, they change flavor
- Beyond standard model.

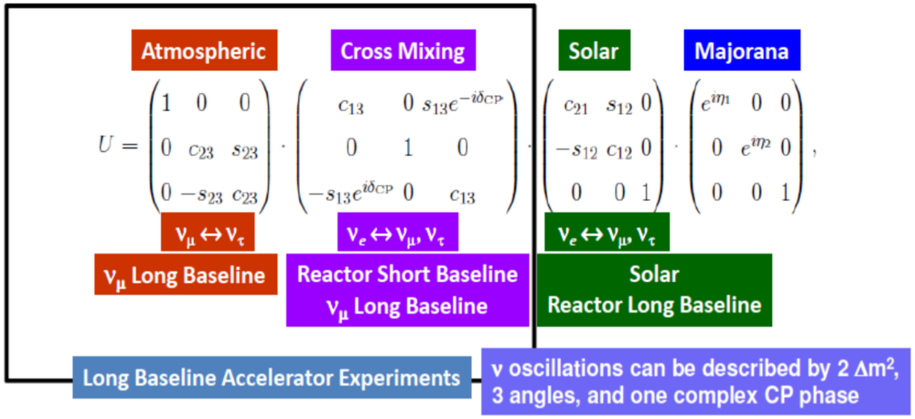
Neutrino Mixing

- Neutrinos mix, just like the quarks

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\,|\nu_k\rangle$$

with $\alpha = e, \mu, \tau$ and $U^*_{\alpha k}$ is the unitary matrix.

- PMNS matrix. CKM matrix for quarks
- Unlike the quarks, mixings are large
  - All mixing angles and mass splitting have been measured.



Atmospheric

Cross Mixing

Solar

Majorana

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$\nu_\mu \leftrightarrow \nu_\tau$

$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

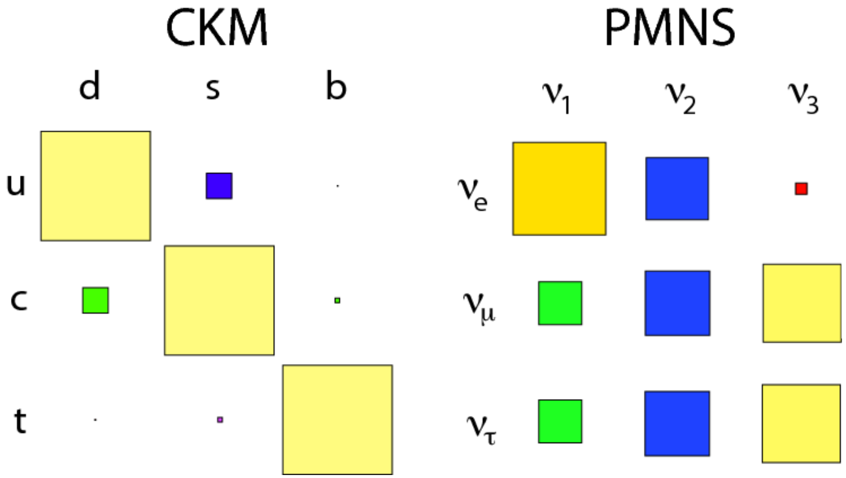
ν_μ Long Baseline

Reactor Short Baseline
ν_μ Long Baseline

Solar
Reactor Long Baseline

Long Baseline Accelerator Experiments

ν oscillations can be described by 2 Δm^2, 3 angles, and one complex CP phase



Parameter	Main method(s)	Source(s)	Status
θ_{12}	Oscillations	solar, reactor	known
θ_{23}	Oscillations	atmospheric, accelerator	known
θ_{13}	Oscillations	reactor, accelerator	known
δ_{CP}	Oscillations	accelerator	hints
α, β	Rare processes	double beta decay	unknown
Δm^2_{21}	Oscillations	reactor, solar	known
$\lvert\Delta m^2_{32}\rvert$	Oscillations	reactor, accelerator, atmospheric	known
Ordering (sgn Δm^2_{32})	Oscillations	reactor, accelerator, atmospheric	hints
$m_{1,2,3}$	Kinematics	β decay, cosmology	limits

θ_{23} and $|\Delta m^2_{32}|$

- Atmospheric neutrino oscillations are sensitive to Δm^2_{32} and θ_{23}.
- Signature: disappearance of upward-going muon like interactions and the subsequent appearance of tau-like interactions, if the tau can be reconstructed

Experiment	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ $[10^{-3}\mathrm{eV}^2]$
Antares	$0.50^{+0.2}_{-0.19}$	$2.0^{+0.4}_{-0.3}$
IceCube	$0.51^{+0.07}_{-0.09}$	$2.31^{+0.11}_{-0.13}$
Super-Kamiokande (Super-K)	$0.588^{+0.031}_{-0.064}$	$2.50^{+0.13}_{-0.20}$

New results from IceCube and Super-K using atmospheric neutrinos

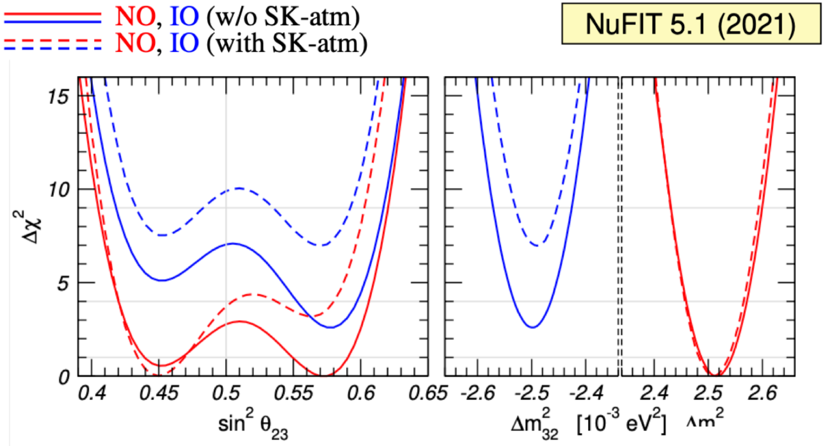
- T2K and NOvA also reported new results from accelerator

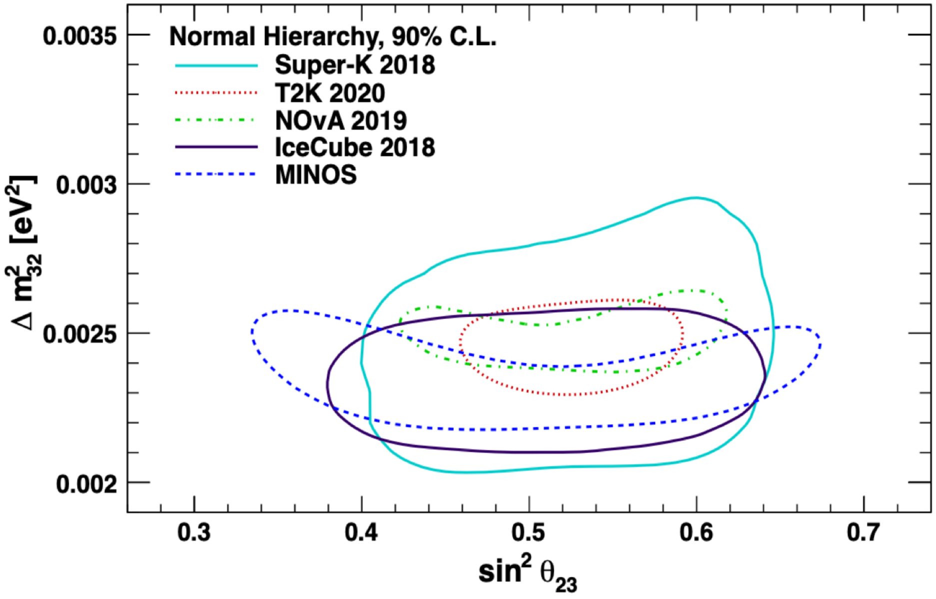
Nova best fit: Normal hierarchy

$\Delta m^2_{32} = (2.41\pm0.07)\times10^{-3}$ eV^2 2.9%

$\sin^2\vartheta_{23} = 0.57^{+0.04}_{-0.03}$ ~6%

$\delta = 0.82\pi$





All measurements are consistent with maximal mixing, though Super-K has a weak ($\sim1\sigma$) preference for the second octant.

θ_{12} and Δm^2_{21}

- Solar neutrino measurements have the best sensitivity to constrain the so-called solar mixing angle θ_{12} and to a lesser degree, the Δm^2_{21} mass splitting.
    - Relies on the validity of the SSM predictions for solar neutrino fluxes.
    - Electron-neutrino survival probability (P_{ee}) of solar neutrinos is measured in the energy range of ~ 1 MeV to about 15 MeV.

High-precision measurements of 8_B solar neutrinos by Super-K and SNO dominate the combined fit to all solar neutrino data.

- Reactor anti-neutrino data from KamLAND provides complimentary measurements.
- Tension between solar and reactor result, **1.5 σ**

$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$$

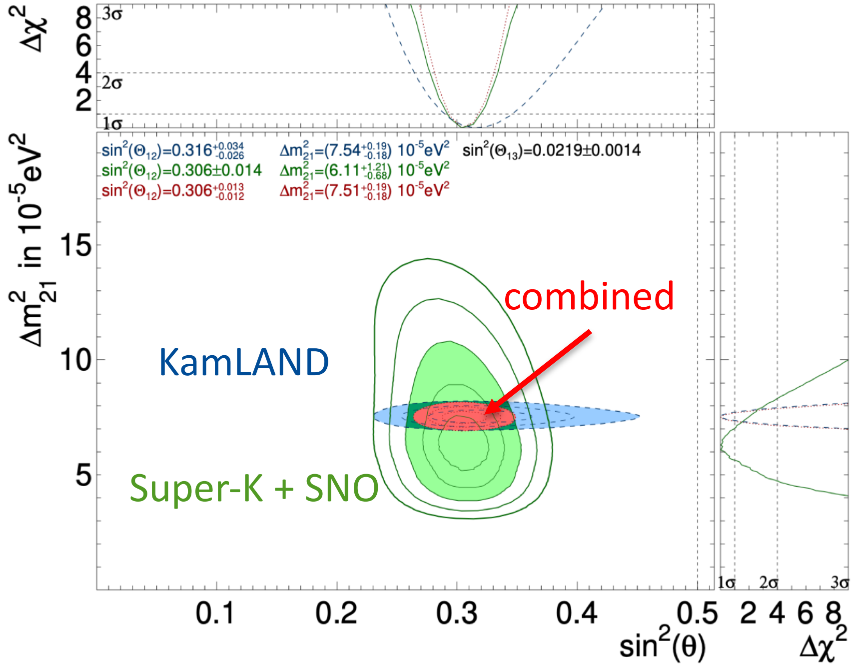
$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$

$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$$

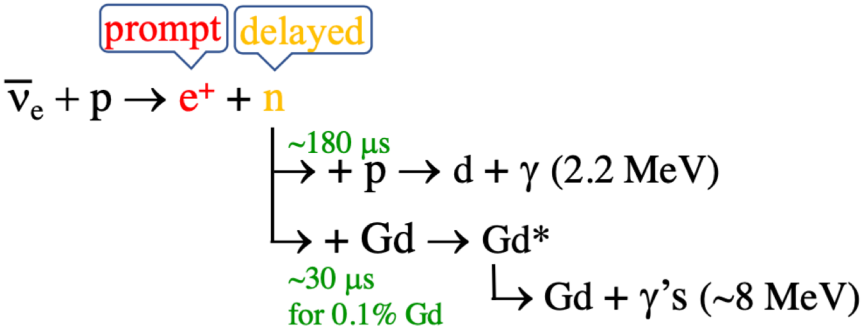
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$$

- **JUNO** can simultaneously measure Δm^2_{21} and θ_{12} using reactor anti-neutrinos and solar neutrinos
- **Hyper-K** will improve the solar results.



θ_{13} and Δm^2_{32}

- Reactor experiments use the inverse β −decay reaction with prompt and delayed γ signal to detect anti-neutrinos with liquid scintillator target



$$\underbrace{\bar{\nu}_e + p \rightarrow \overset{\text{prompt}}{e^+} + \overset{\text{delayed}}{n}}$$

~180 μs: $\rightarrow + p \rightarrow d + \gamma\ (2.2\ \text{MeV})$

$\rightarrow + Gd \rightarrow Gd^*$

$\hookrightarrow Gd + \gamma\text{'s}\ (\sim 8\ \text{MeV})$

~30 μs for 0.1% Gd

- Event rate without oscillation ~ 1 $(\text{ton.GW}_{th}.\text{day})^{-1}$
- Survival Probability: θ_{12}term is negligible at DayaBay baseline.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \boxed{sin^2 2\theta_{13}\left[cos^2\theta_{12} sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + sin^2\theta_{12} sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]}$$
$$- \boxed{cos^4\theta_{13} sin^2 2\theta_{12} sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)}$$

- New results from DayaBay using neutron-Gadolinium (nGd) capture.

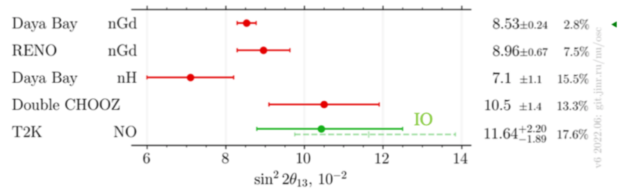
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024} \qquad \text{(2.8\% precision)}$$

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$

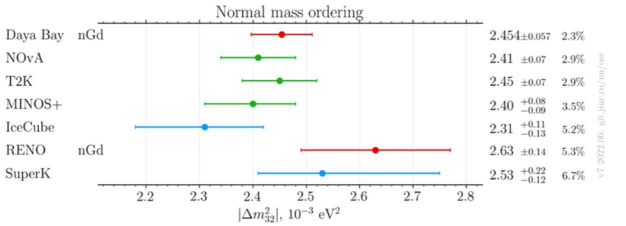
Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$

(2.3% precision)

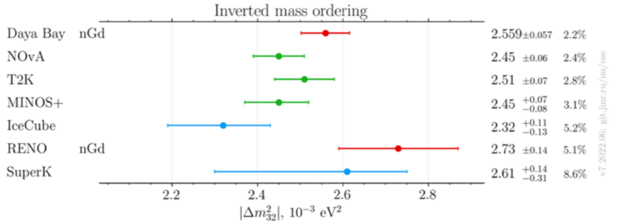
$\sin^2 2\theta_{13}$

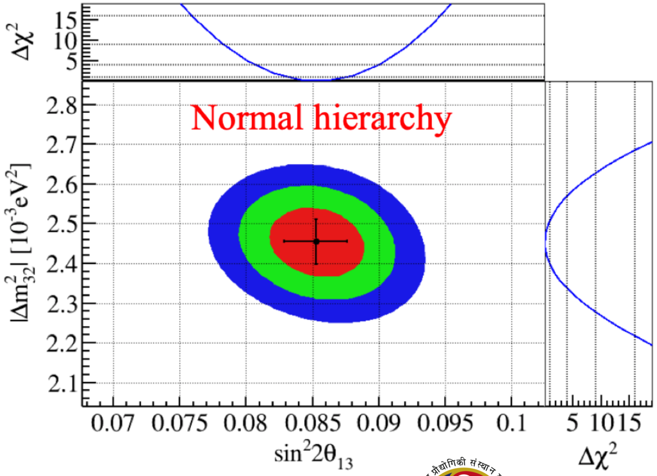


Δm^2_{32} (NO)



Δm^2_{32} (IO)



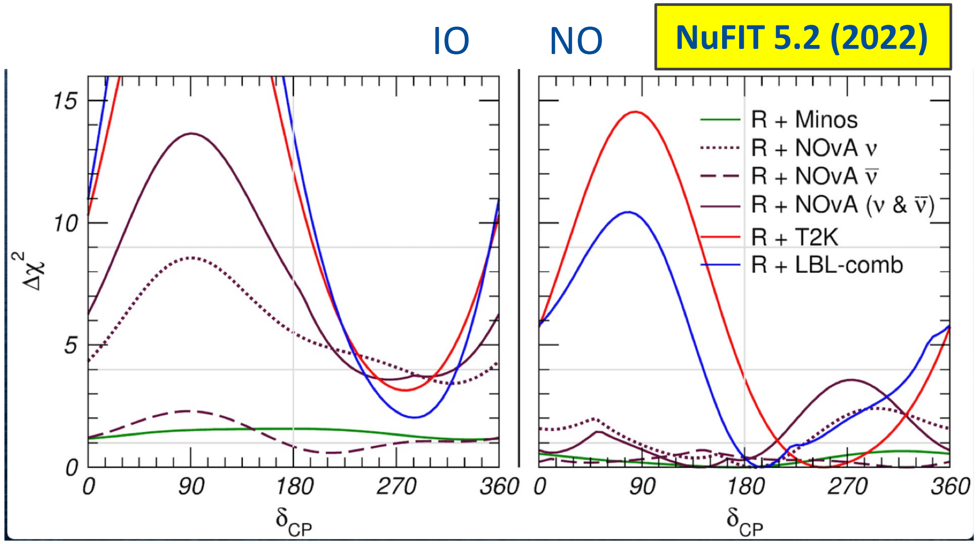


Known Unknowns: CP Violation

- One of the major questions in physics which is yet to be understood
  - Why the universe is mostly matter? Where is anti-matter?
- Possible answer is CP Violation
  - The observed CP violation in the quark sector is too small to explain this
  - CP violation in the lepton sector will shed more light on the problem
    - Measurement of δ_{CP} is critical.

Some experiments slightly favor ($< 3\sigma$) $\delta_{CP} \sim 270° \ (-90°)$

Combined results from Reactor +LBL Experiments is far from stable.



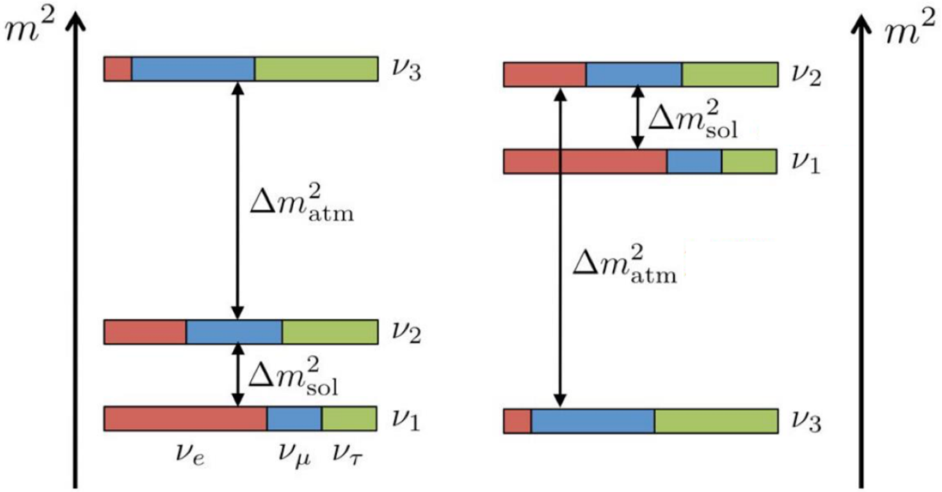
✓ DUNE and HyperK can provide a definite answer.

✓ Further improvement may come from KNO, ESSnuSB and THEIA.

Known Unknowns: Neutrino Mass Ordering

- So far only the mass squared difference between neutrino mass states have been measured
  - Two states have similar mass, one is different

- Is it 2 light states + 1 heavy state or 2 heavy states + 1 light state?



Normal Hierarchy (NH) Inverted Hierarchy (IH)

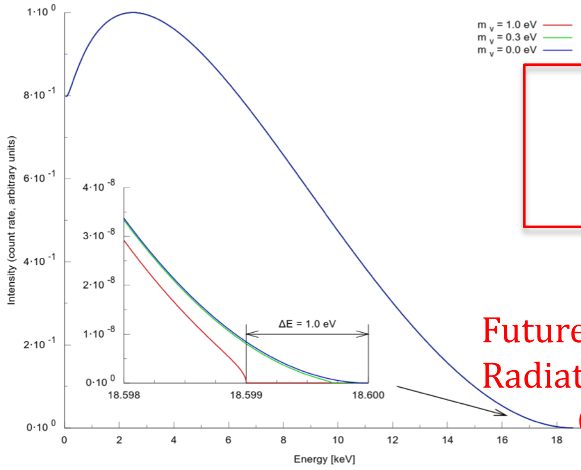
- No concrete evidence of mass ordering from individual experiments such as T2K, NoVA and SuperK.

- Global fit seems slightly prefer Normal Ordering $(< 3\sigma)$

- Definite answer will come from DUNE, JUNO, HyperK, ORCA and IceCube.

Known Unknowns: Neutrino Mass

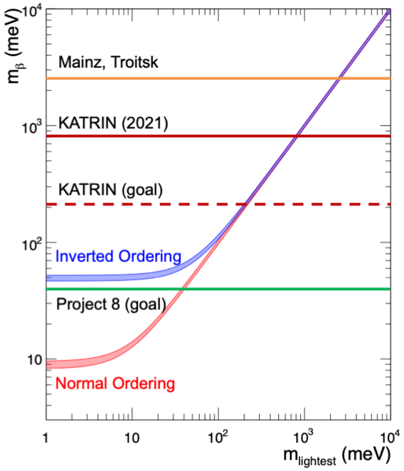
- Yet to be measured. Exisitng limits:
  - Cosmological observations: $\sum m_i < 0.12\ eV\ (95\%\ CL)$. Strongly relies on the underlying cosmological assumptions
  - Neutrinoless double β-decay experiments: $m_{\beta\beta} < 0.04\ - 0.16\ eV\ (90\%\ CL)$, depending the on the nuclear matrx element calculation.
    - In contrast to m_ν, the effective mass in double-beta decay is given by $m_{\beta\beta} = |\sum_i U_{ei}^2 m_i\,|$
    - Limit is only valid under the assumption that neutrinos are their own anti-particle (Majorana particle)
    - Search for $0\nu\beta\beta$ decays is a no loss game:
      - If $0\nu\beta\beta$ decays are seen → Majarona neutrinos, lepton number violation
      - If no $0\nu\beta\beta$ decays upto $|M_{\beta\beta}| \sim 0.001\ eV$ → lightest neutrino mass can be determined to be ~5 meV.
- Sophisticated experiments to measure the end point of the beta decay spectrum.
  - Independent of cosmological model or the nature of the neutrino particle (Majorana or Dirac)



Latest result:
$m_\nu < 0.8\ eV$ from KATRIN (2022)

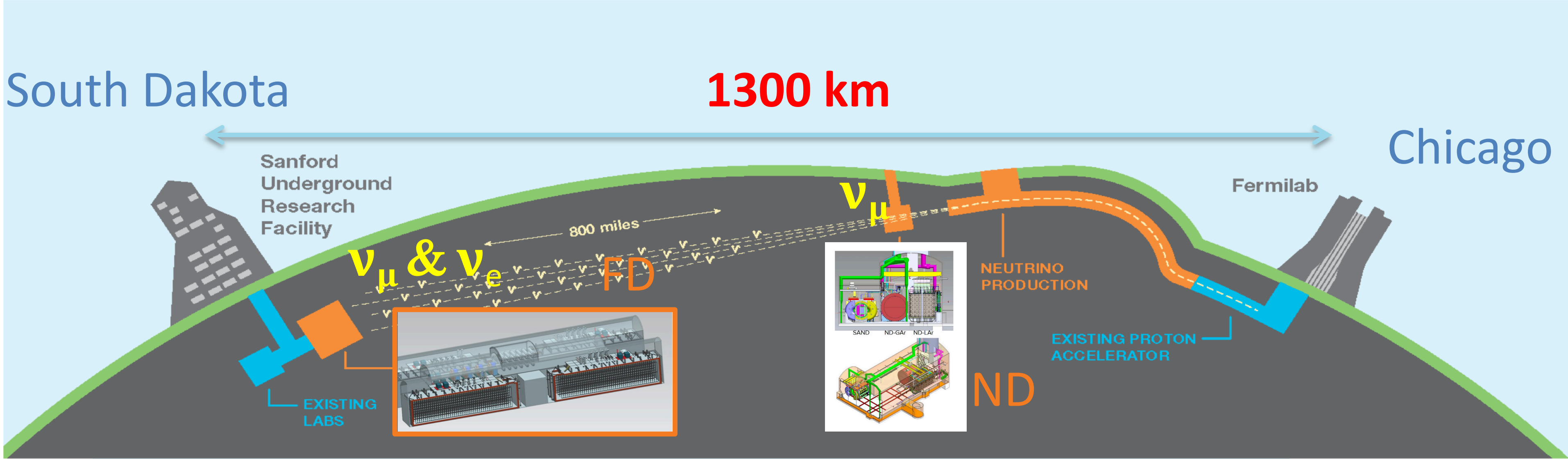
arXiv:2105.08533

Future of β-decays: Project 8: Cyclotron Radiation Emission Spectroscopy (CRES) Goal: $m_\beta < 0.04\ eV$.



Deep Underground Neutrino Experiment

- Muon neutrinos/antineutrinos from high-power proton beam
  - ✓ 1.2 MW from day one; upgradeable to 2.4 MW
- A Massive Liquid Argon TPC Far Detector in South Dakota, located ~ 1.478 km underground in a former gold mine.
  - ✓ 4 modules, 70 kton of liquid Argon.
- A Near detector complex with multiple detectors, located approximately 575 m from the neutrino source at Fermi Lab
  - ✓ Characterize the beam with 100s of millions of neutrino interactions.



The DUNE Collaboration

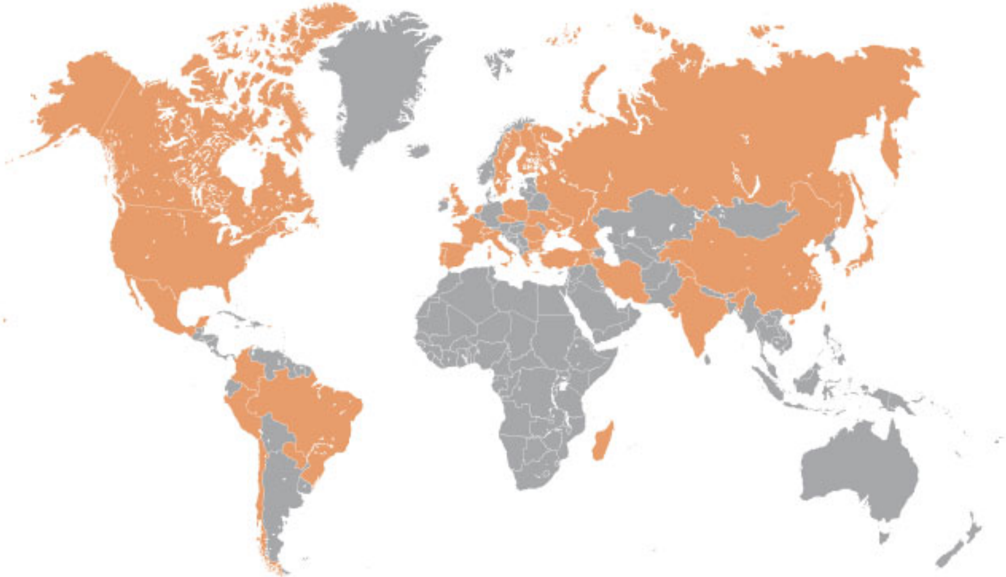
As of today:

60 % non-US

$\overbrace{\hphantom{200 institutions}}$

1400+ collaborators from 200 institutions in 32 nations

Armenia, Brazil, Bulgaria, Canada CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, **India,** Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Portugal, Romania, Russia, Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA

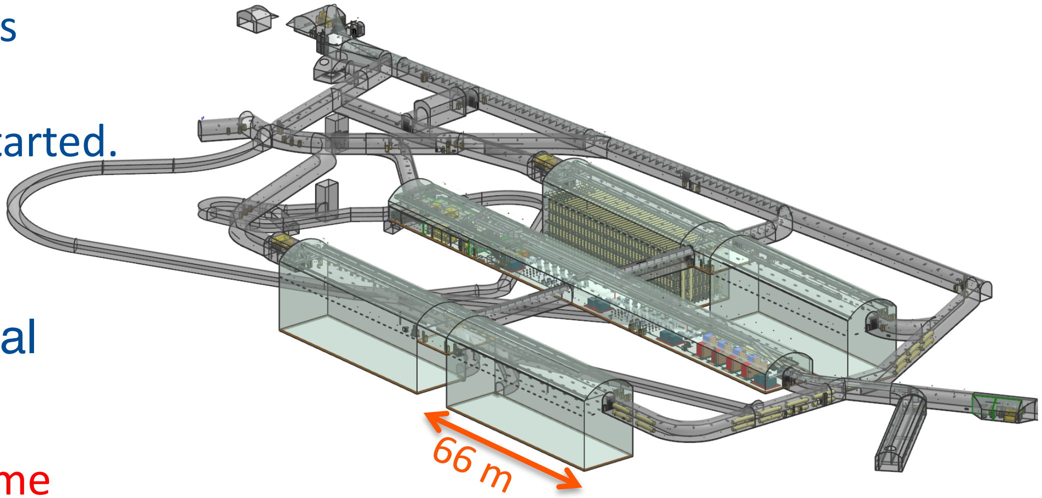


DUNE: a fully international science collaboration

LBNF (Long Baseline Neutrino Facility): US(DOE)-hosted project with international contributions

DUNE Far Detector

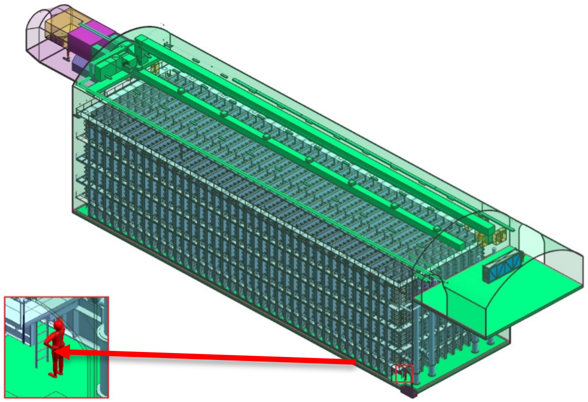
- Located at Sanford Underground Research Facility (SURF)
  - 1 mile underground at Homestake mine in South Dakota
  - SURF already hosts particle physics experiments
  - Excavation for DUNE has already started.
    - Requires excavation of 875,000 tons of rock



- 4 modules with 70-kt LAr-TPC in total
  - Each module contains 17 kt of liquid argon, 18 x 19 x 66 m^3 volume

DUNE Phase-I

  - 1 Horizontal Drift (HD) Module (like ICARUS and MicroBooNE)
  - 1 Vertical Drift (VD) Module
  - 2 Modules of Opportunity: Yet to decide on the design



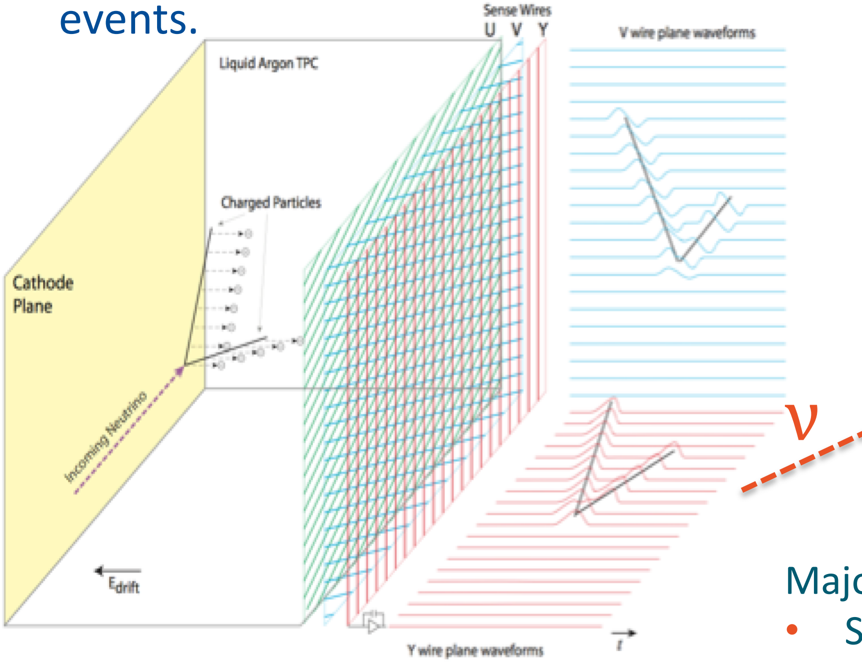
- Why liquid Argon?
  - Argon scintillates: 20,000 photons/MeV @500 V/cm
  - Argon can be easily ionized: 55,000 electrons/cm

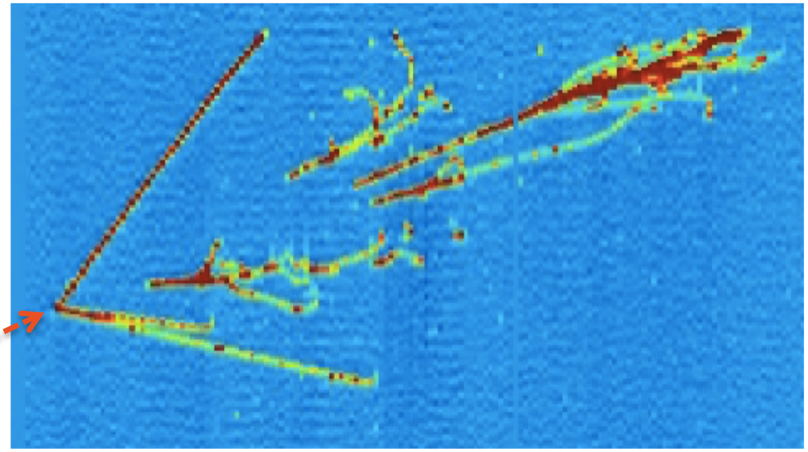
DUNE Far Detector: LAr TPCs

- Neutrinos interact in Argon producing charged particle
- Argon scintillates, light is detected by photon detectors
- Charged particles ionize Argon, electrons slowly drift to anode
- Anode is instrumented (readout wires)
  - Combining with light, reconstruct 3D events.

LAr TPC provides:

- Excellent 3D imaging
  - few mm resolution over large volume
- Excellent energy measurement
  - Fully active calorimeter
- Allows particle ID by dE/dx, range, event topology
- Excellent at imaging neutrino interactions
  - Both high energy (~ GeV) and low energy (~ 10 MeV)





Major (and exciting) challenges

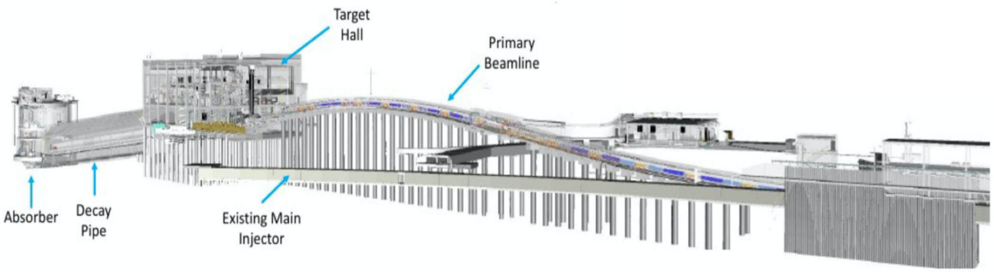
- Scaling technology to very large detector volumes

The LBNF Beam: PIP II

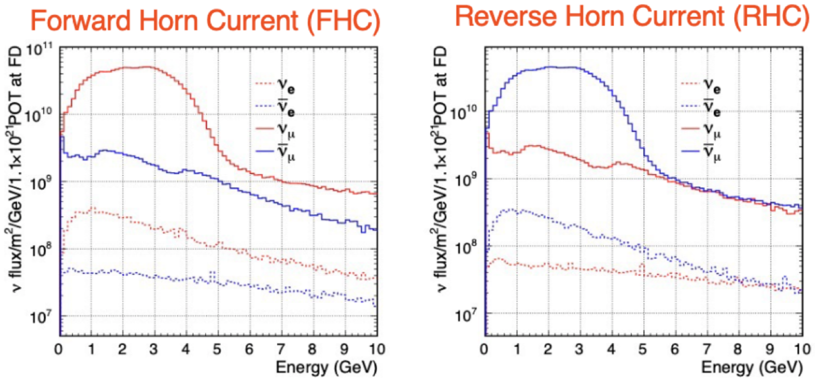
- Goal: Deliver world-leading beam power to the U.S. neutrino program while providing a flexible platform for the future
  - 1.2 MW (~10^{14} POT/s) to LBNF over 60-120 GeV; upgradable to 2.4 MW
- Scope
  - 800-MeV SC Linac
  - Modifications to Booster, Recycler, Main Injector
- Broad international effort
  - India is deeply involved in R&D and construction phases

✓ Horn focused neutrino beam line optimized for CP violation sensitivity

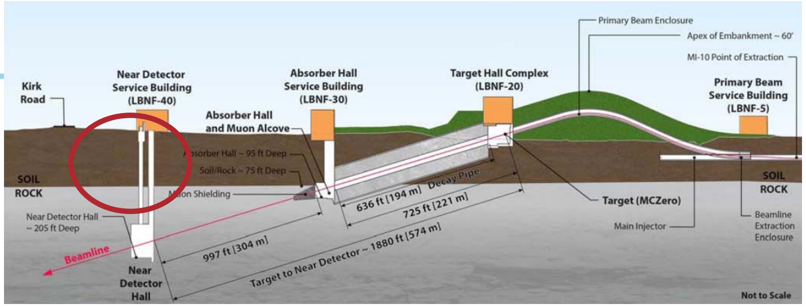
- Both neutrino (FHC) and anti-neutrino (RHC) modes.
- $\nu/\bar{\nu}$ energies between 0 to 8 GeV.



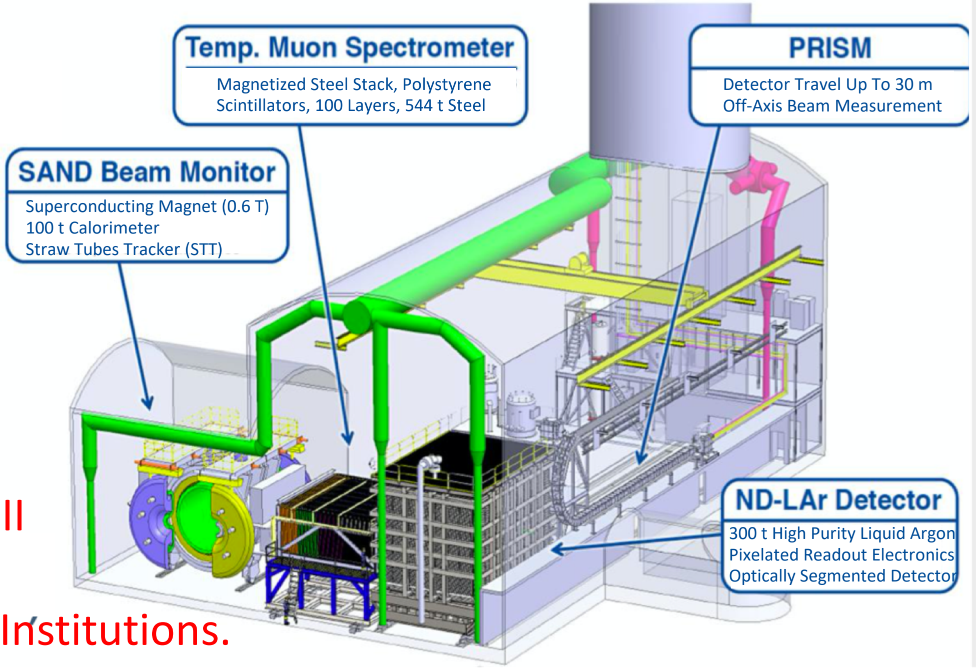
Neutrino Flux at SURF, 1300 km away



Near Detector (ND) – Phase I



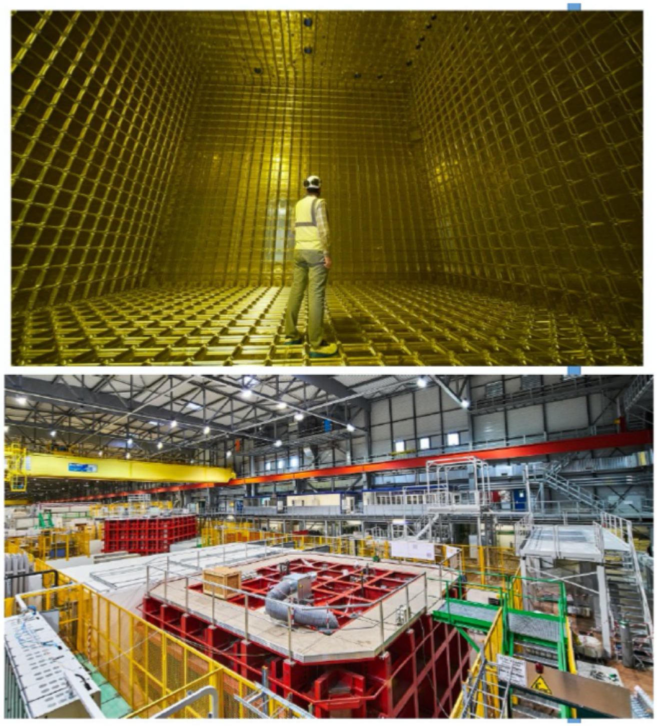
- ✓ Role: constrain systematic uncertainties needed in oscillation analyses
  - Precisely measure un-oscillated beam neutrino flux
  - Measure multiple interaction cross-section channels.
- ✓ ND Hall location
  - 574 m from LBNF target
  - ~ 60 m underground
- ✓ An integrated system composed of multiple detectors:
  - Highly segmented LArTPC (ND-LAr)
    - Same target as FD
  - Temp. Muon Spectrometer (TMS)
    - Upgradeable to ND-GAr, Phase-II
  - System for on-Axis Neutrino Detection (SAND): Interest of Indian Institutions.



- ✓ Capability to move part of ND for off-axis measurements, sampling different E_ν spectra ➡ DUNE PRISM Concept

DUNE Prototypes

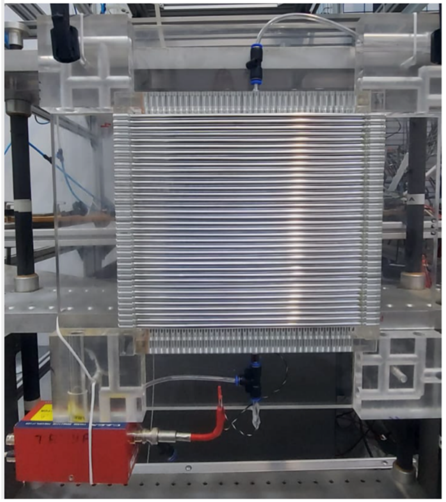
- ✓ DUNE prototypes are being built at CERN and tested with charged particle beam
- ✓ 2x1 kton cryostats used to validate FD components at full scale.
  - ✓ Successful run from 2018 – 2020 and spring 2023.



First R&D and physics results
[JINST 15 (2020) 12, P12004

ArgonCube 2 x 2
ND-LAr Demonstrator

4 independent modules,
Test in NuMI beam
scheduled in 2022



STT Prototype
@ JINR

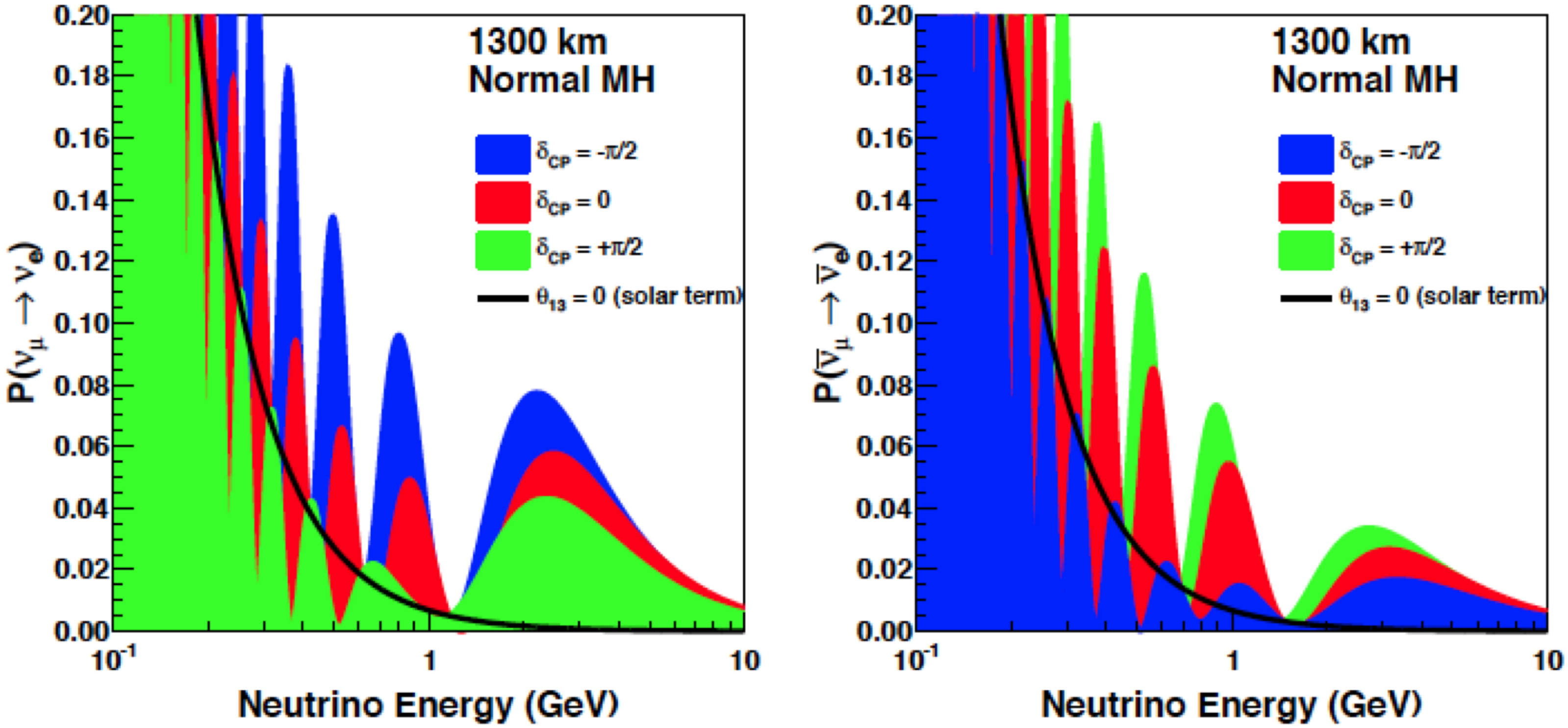
Instrumented one straw with 20 μm wire (50 g tension) and tested with ^{55}Fe source at STT operating conditions

2.0 m and 5.0 m Straws

DUNE Neutrino Oscillation Strategy

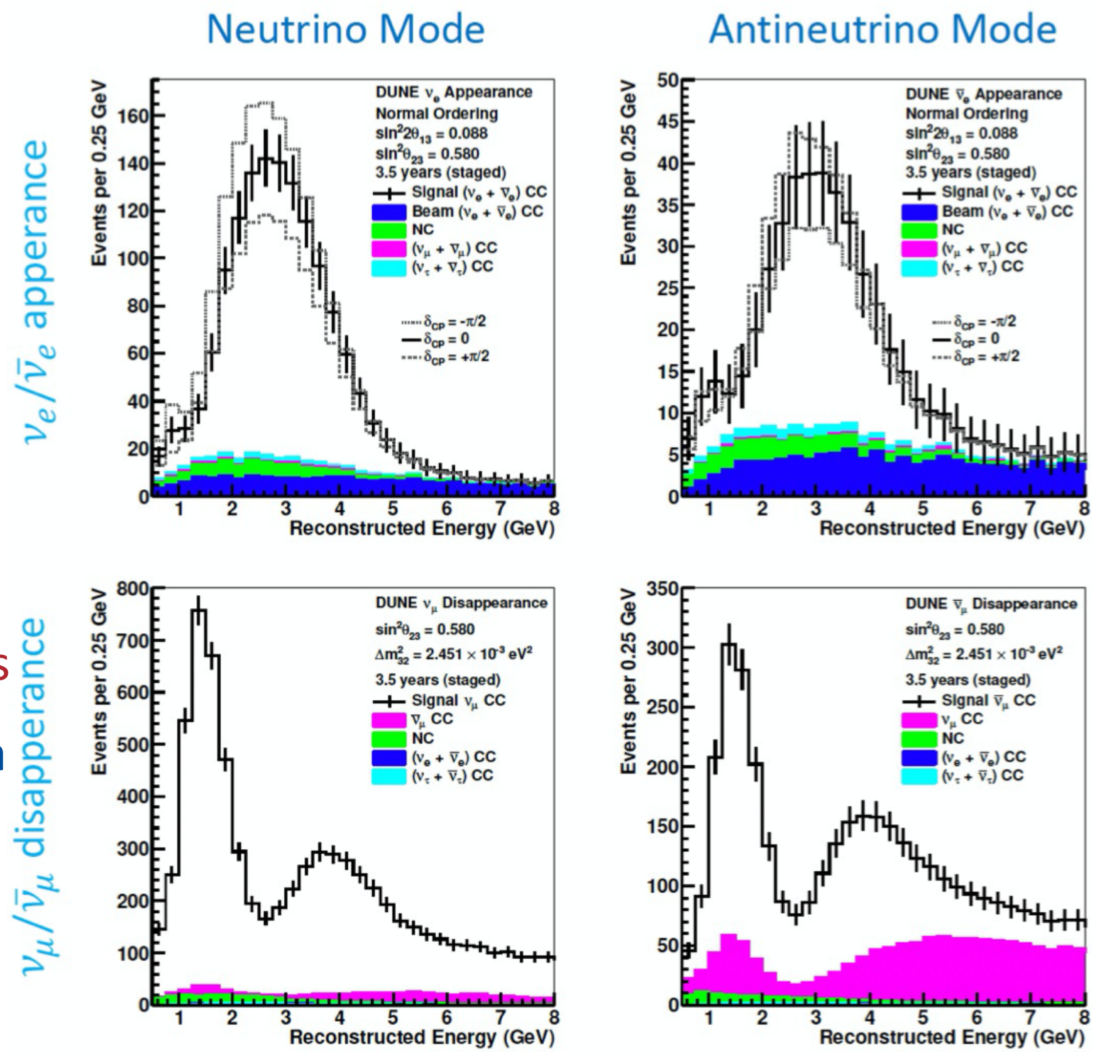
Measure neutrino spectra at 1300 km in a wide-band beam

- ν_e appearance probability depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects. All four can be measured in a single experiment.
- Wide-band beam covers 1st and 2nd oscillation maxima



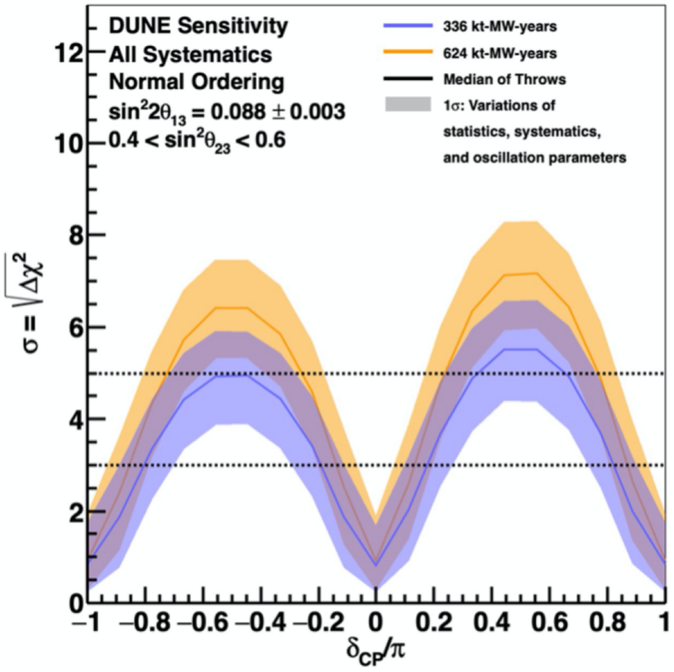
Oscillation Sensitivity for DUNE

- Reconstructed spectra of selected CC-like events
- Includes full FD systematics
- 3.5 years neutrino beam mode
- 3.5 years anti-neutrino beam mode
- ~ 1000 $\nu_e/\overline{\nu_e}$ events in 7 years
- ~10,000 $\nu_\mu/\overline{\nu_\mu}$ events in 7 years
- Simultaneous fit to four spectra to extract oscillation parameters

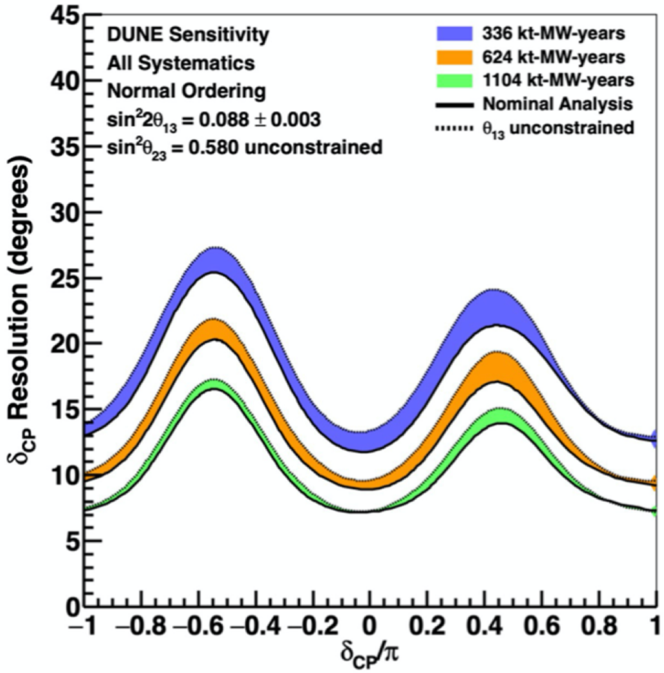


Eur. Phys. J. C 80 (2020) 10, 978

CP Violation Sensitivity



CP Violation Sensitivity



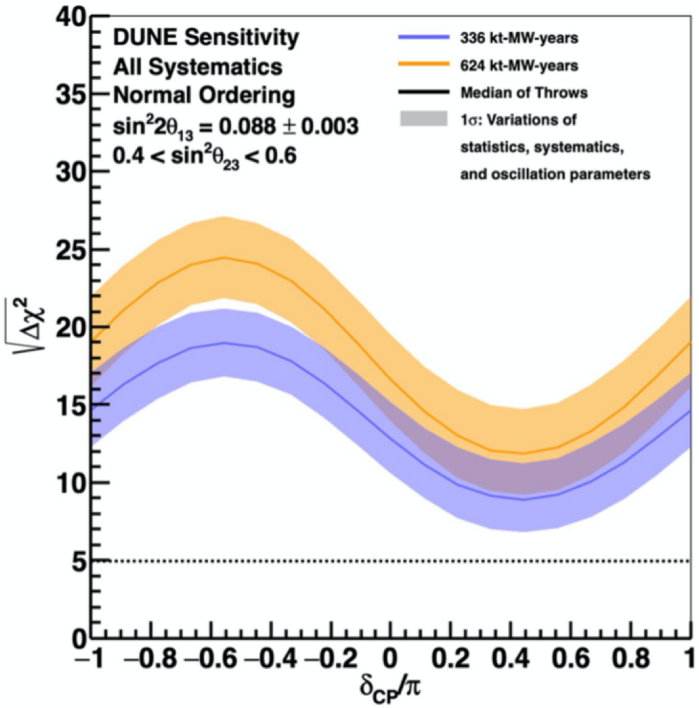
δ_{CP} Resolution

Width of the band indicates variation in the possible values of θ_{23}

- 5σ discovery potential for CP violation over > 50% of δ_{CP} values
- $7 - 16^{\circ}$ resolution to δ_{CP}, with external input only for solar parameters.
- Simultaneous measurement of neutrino mixing angles and δ_{CP}

Mass Hierarchy

Mass Hierarchy Sensitivity



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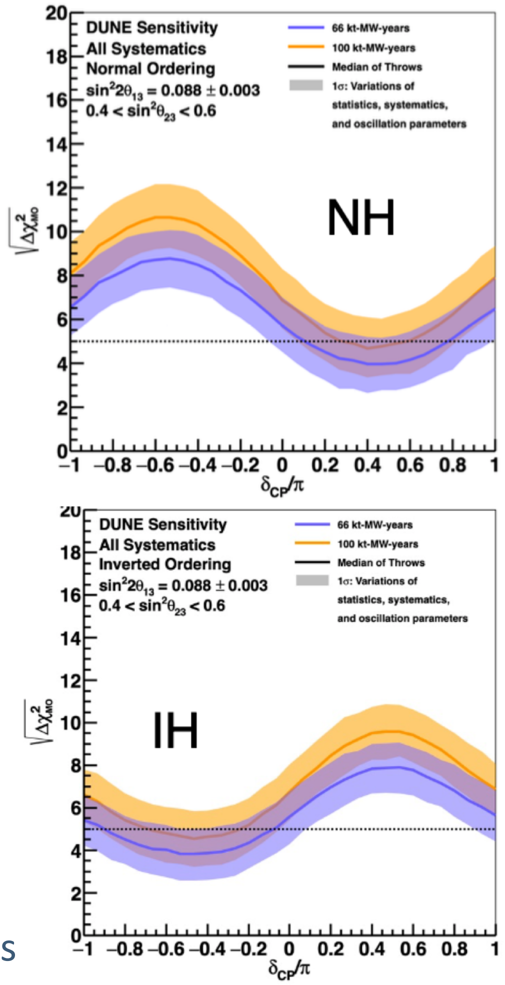
DUNE low exposure, PRD 105, 7, 072006 (2022)

100 kt

66 kt



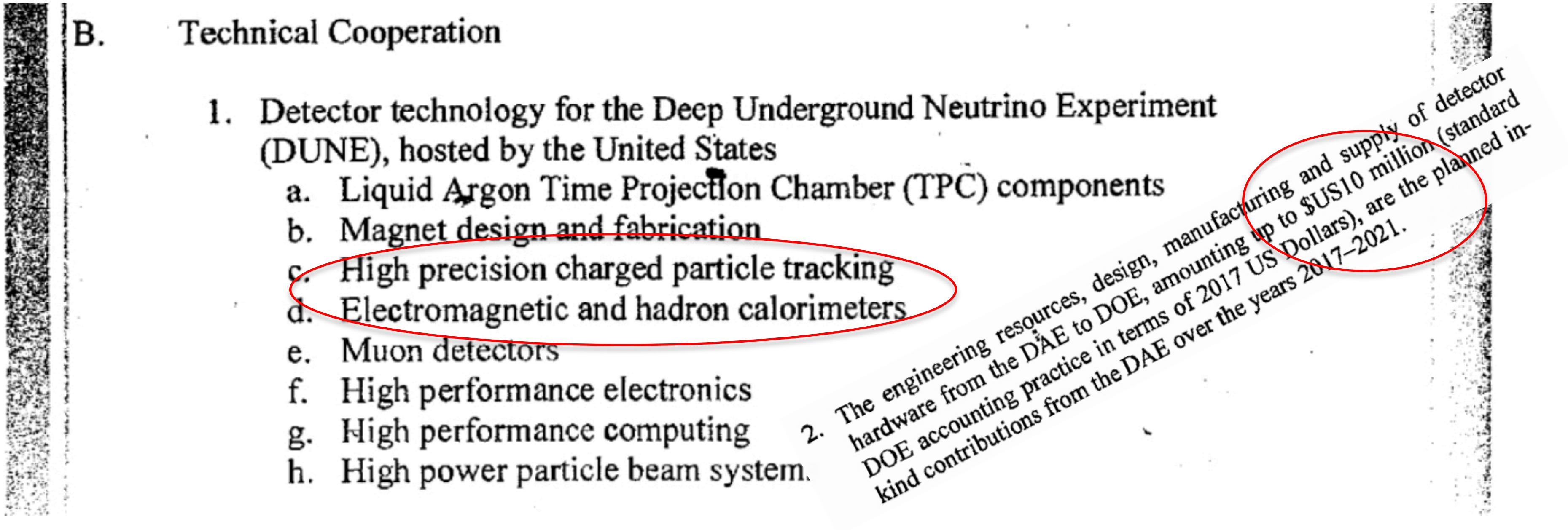
- Mass hierarchy determination: > 5σ for all parameter values
- Even by exposure of 66 kt-MW-yr, probability to extract wrong ordering < 0.01
- With 1.2 MW beam running, DUNE will need only 1 -2 years to measure mass ordering definitely.

DUNE Near Detector: Indian Interest

- ☐ The Indian group on DUNE has shown interest in the Near Detector since LBNE era.
  - ✧**Interest has been on a high resolution STT tracker, surrounded by an plastic scintillator based ECAL, and a RPC based muon detector inserted in a dipole magnet.**

The signing of the Annex-II of the agreement between DAE (India) and DOE (USA) in April 2018 is the result of such interest by the Indian physicists.

Annex II (operative part of agreement signed between Secretaries of DoE and DAE)



B. Technical Cooperation

1. Detector technology for the Deep Underground Neutrino Experiment (DUNE), hosted by the United States
   a. Liquid Argon Time Projection Chamber (TPC) components
   b. Magnet design and fabrication
   c. High precision charged particle tracking
   d. Electromagnetic and hadron calorimeters
   e. Muon detectors
   f. High performance electronics
   g. High performance computing
   h. High power particle beam system.

2. The engineering resources, design, manufacturing and supply of detector hardware from the DAE to DOE, amounting up to $US10 million (standard DOE accounting practice in terms of 2017 US Dollars), are the planned in-kind contributions from the DAE over the years 2017–2021.

DUNE-India

✧DUNE-India group proposes major contribution to the STT construction for the SAND Detector under Annex II of the agreement between DAE and DOE:

- ✧STT is the central tracking detector of SAND. Core cost of the detector is about 6.5 M USD including the contingency.

- ✧Propose to setup STT production facility at IITG, PU and NISER. Closely working with our colleagues at JINR on the ongoing prototyping activities and analysis of the test beam data at CERN.

  - ✧Possibility of further expansion of the collaboration with JINR with adequate resources.

Summary

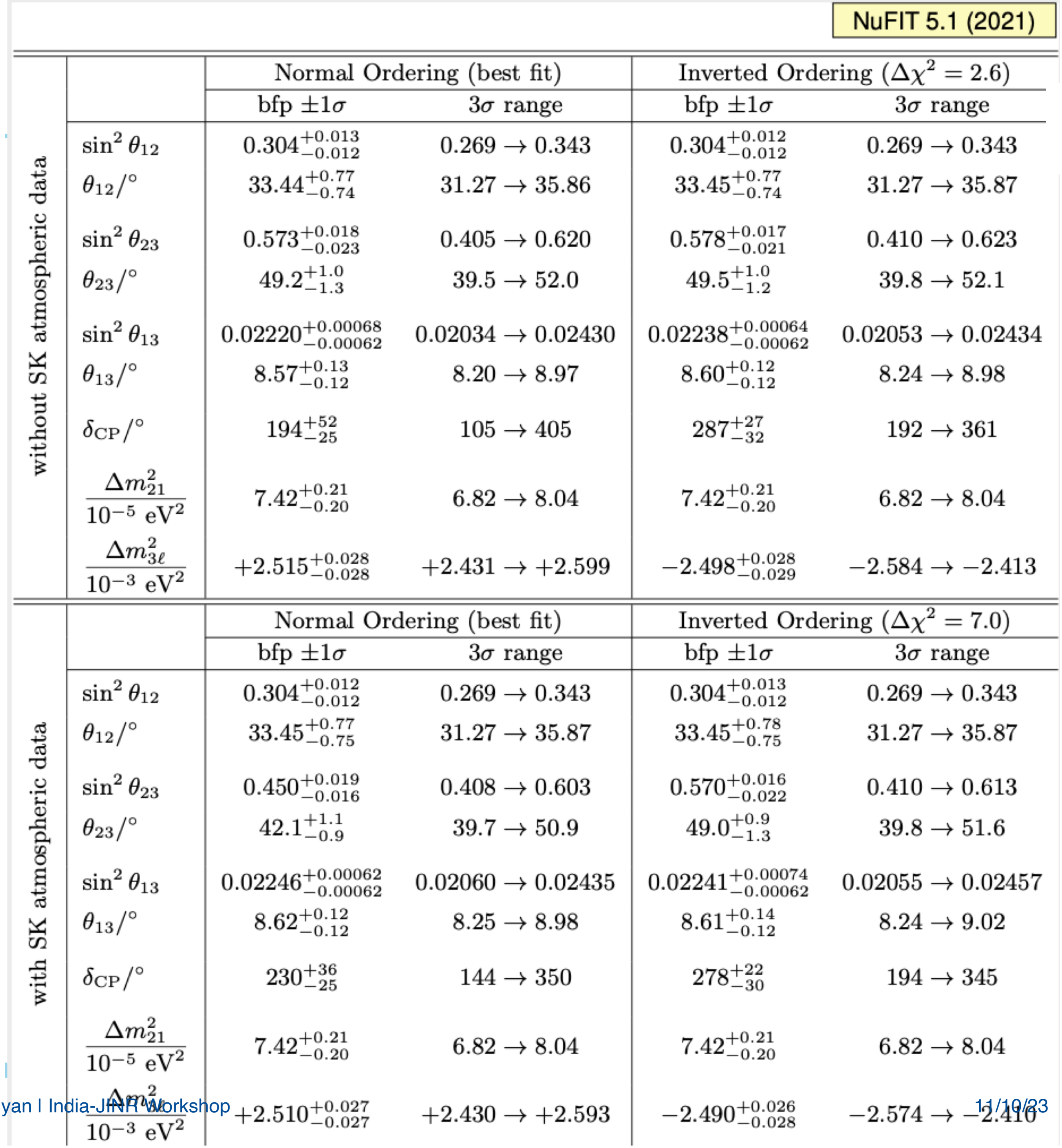
- ☐ DUNE will use a broadband beam and long baseline (1300 km) to make precise, simultaneous measurements of the mass ordering, the CP-violation phase, and the neutrino mixing angles.

- ☐ The large mass, high granularity, and deep underground location of the DUNE far detector also provide good sensitivity to BSM physics.

- ☐ Several successful run with the protoDUNE. Expect first DUNE FD data in 2028, oscillation physics starts at the end of this decade.

- ☐ India is playing a major role in the PIP-II accelerator upgrade program at Fermi Lab.
  - ☐ **India is set to reap the benefit by actively participating in the DUNE science program.**
  - ☐ **Active collaboration with JINR for the construction of the STT based tracking detector for SAND.**

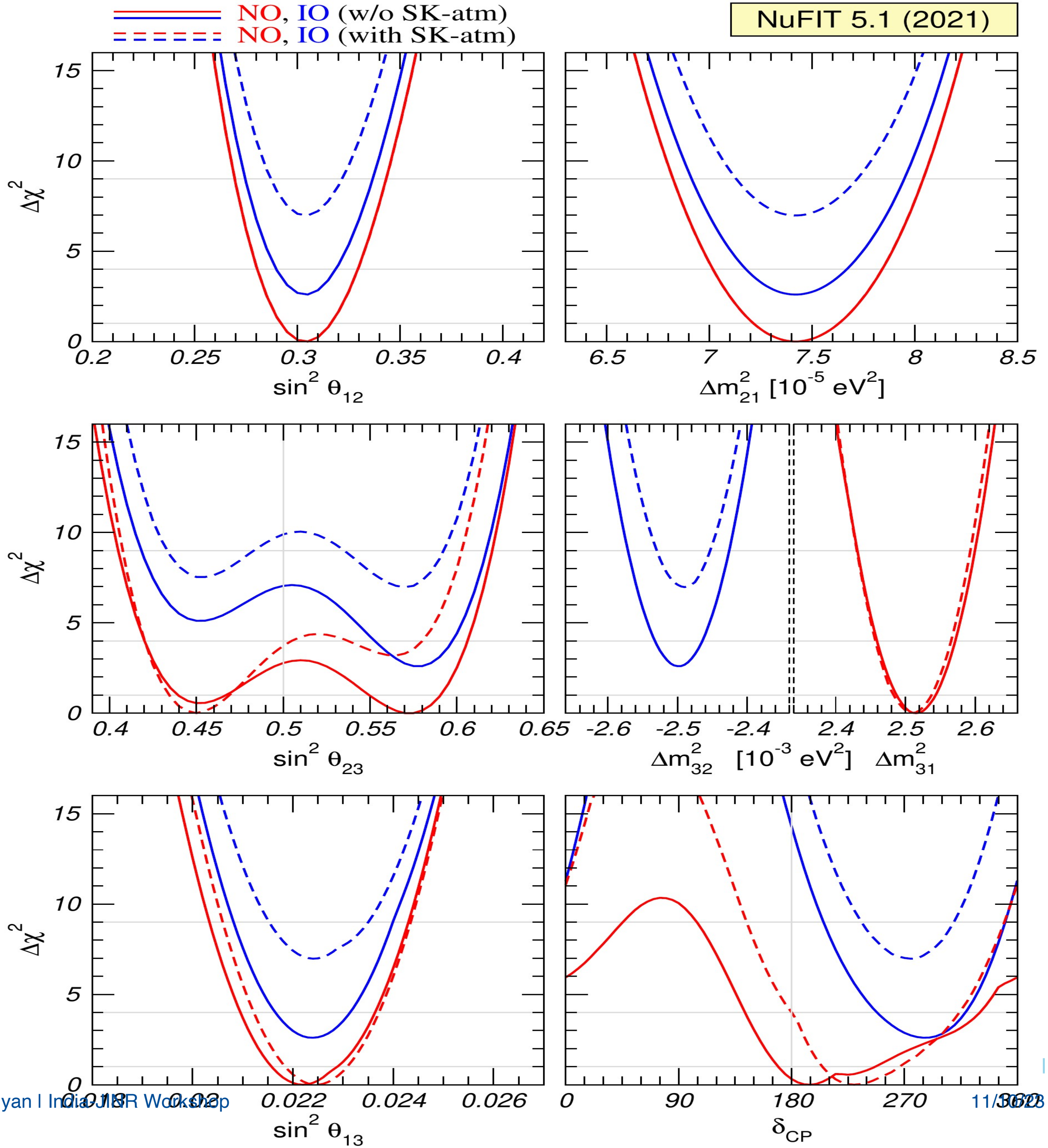
Backup



NuFIT 5.1 (2021)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
	$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{\rm CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

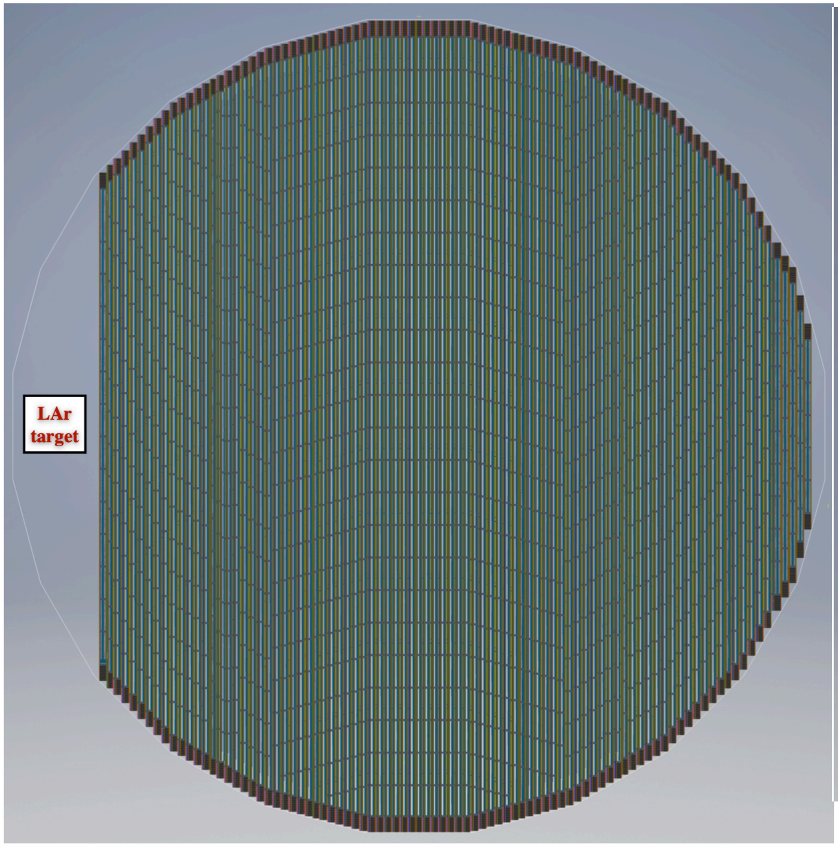
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{\rm CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

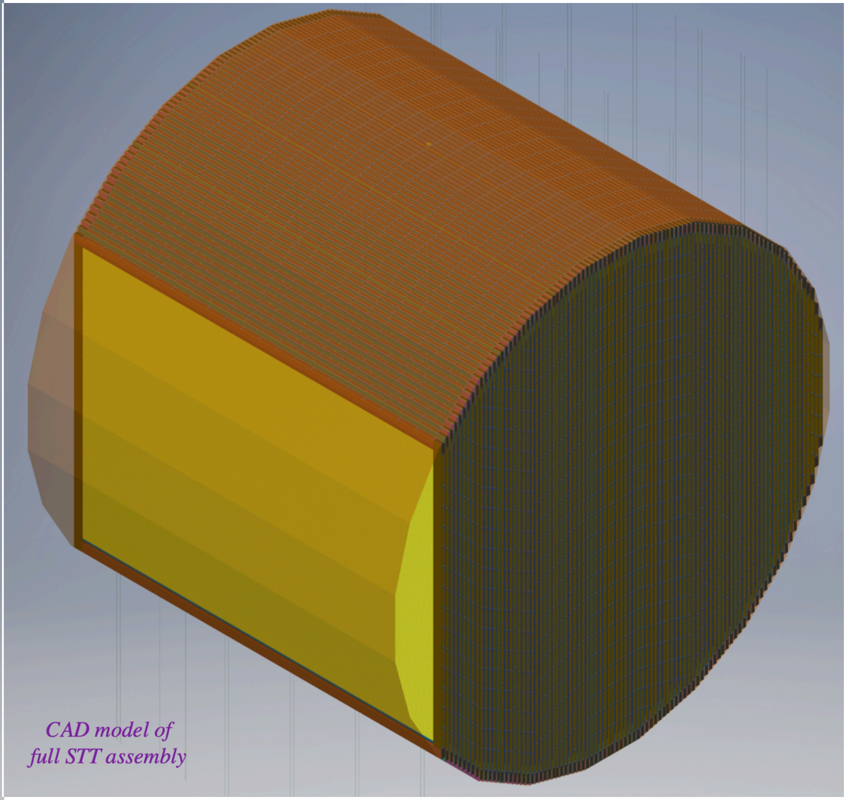

NO, IO (w/o SK-atm)
NO, IO (with SK-atm)
NuFIT 5.1 (2021)
$\Delta\chi^2$
15
10
5
0
0.2
0.25
0.3
0.35
0.4
$\sin^2\theta_{12}$
6.5
7
7.5
8
8.5
Δm^2_{21} [10^{-5} eV^2]
0.4
0.45
0.5
0.55
0.6
0.65
$\sin^2\theta_{23}$
-2.6
-2.5
-2.4
2.4
2.5
2.6
Δm^2_{32} [10^{-3} eV^2] Δm^2_{31}
0.018
0.02
0.022
0.024
0.026
$\sin^2\theta_{13}$
0
90
180
270
360
δ_{CP}

CAD model of
full STT assembly:

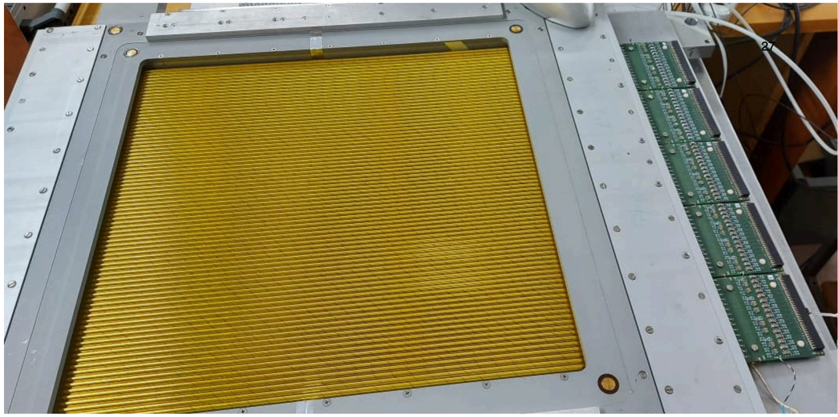
78 CH_2 modules
7 C modules
5 tracking modules

FV mass:
4.7 t CH_2
557 kg C




CAD model of full STT assembly

Number of straws	*234,272*
Total straw length (m)	*753,073*
Straw outer diameter (mm)	*5*
Average straw length (m)	*3.21*
Maximal straw length (m)	*3.87*
Total straw film area (m^2)	*11,823*
Total straw internal volume (m^3)	*15*
Total length of C-composite frames (m)	*1,207*
Number of modules	*90*
Number of modules with CH_2 target	*78*
Number of modules with graphite target	*7*
Number of tracking modules (no target)	*5*
Number of straw planes	*372*
Number of FE boards	*458*
Number of HV channels	*372*
Number of LV channels	*115*


Prototype 50cm x 50cm tested at JINR with
VMM3 readout FE boards from Mu2e (BNL)

SUMMARY OF FLUX MEASUREMENTS

- Relative ν_μ flux vs. E_ν from exclusive $\nu_\mu p \to \mu^- p \pi^+$ on Hydrogen: $< 1\%$
  $\boxed{\nu < 0.5\ \text{GeV}}$ flattens cross-sections reducing uncertainties on E_ν dependence.

- Relative $\bar{\nu}_\mu$ flux vs. E_ν from exclusive $\bar{\nu}_\mu p \to \mu^+ n$ QE on Hydrogen: $< 1\%$
  $\boxed{\nu < 0.25\ \text{GeV}}$: uncertainties comparable to relative ν_μ flux from $\nu_\mu p \to \mu^- p \pi^+$ on H.

- Absolute ν_μ flux from $\nu e^- \to \nu e^-$ elastic scattering: $< 2\%$
  $\Longrightarrow$ Complementary to measurement in LAr TPC with small systematics

- Absolute $\bar{\nu}_\mu$ flux from QE $\bar{\nu}_\mu p \to \mu^+ n$ on H with $\boxed{Q^2 < 0.05\ \text{GeV}^2}$: $\sim$ 135k in RHC

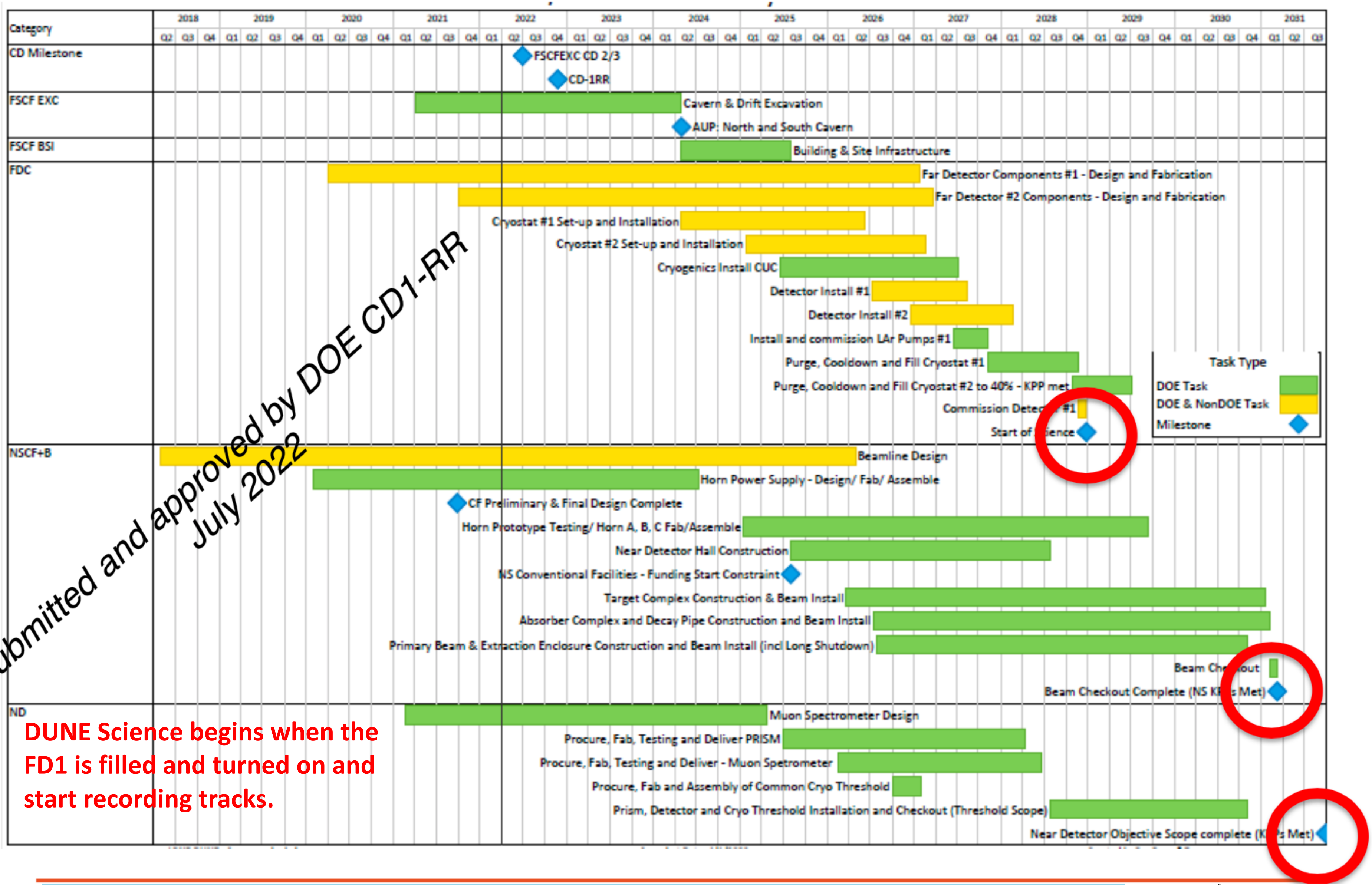
- Ratio of ν_e/ν_μ AND $\bar{\nu}_e/\bar{\nu}_\mu$ vs. E_ν from CH_2 (& H) targets
  $\Longrightarrow$ Excellent $e^\pm$ charge measurement and $e^\pm$ identification ($\sim$ 75k $\bar{\nu}_e$ CC in FHC)

- Ratio of $\bar{\nu}_\mu/\nu_\mu$ vs. E_ν from coherent π^-/π^+ on C (CH_2 and C): 3.5-7%
  $\Longrightarrow$ Excellent angular resolution (t variable) and light isoscalar target

- Determination of parent $\mu/\pi/K$ distributions from $\nu(\bar{\nu})$-H (& CH_2) at low-ν
  $\Longrightarrow$ Direct in-situ measurement for flux extrapolation to FD

Schedule summary: LBNF/DUNE

2028 2031

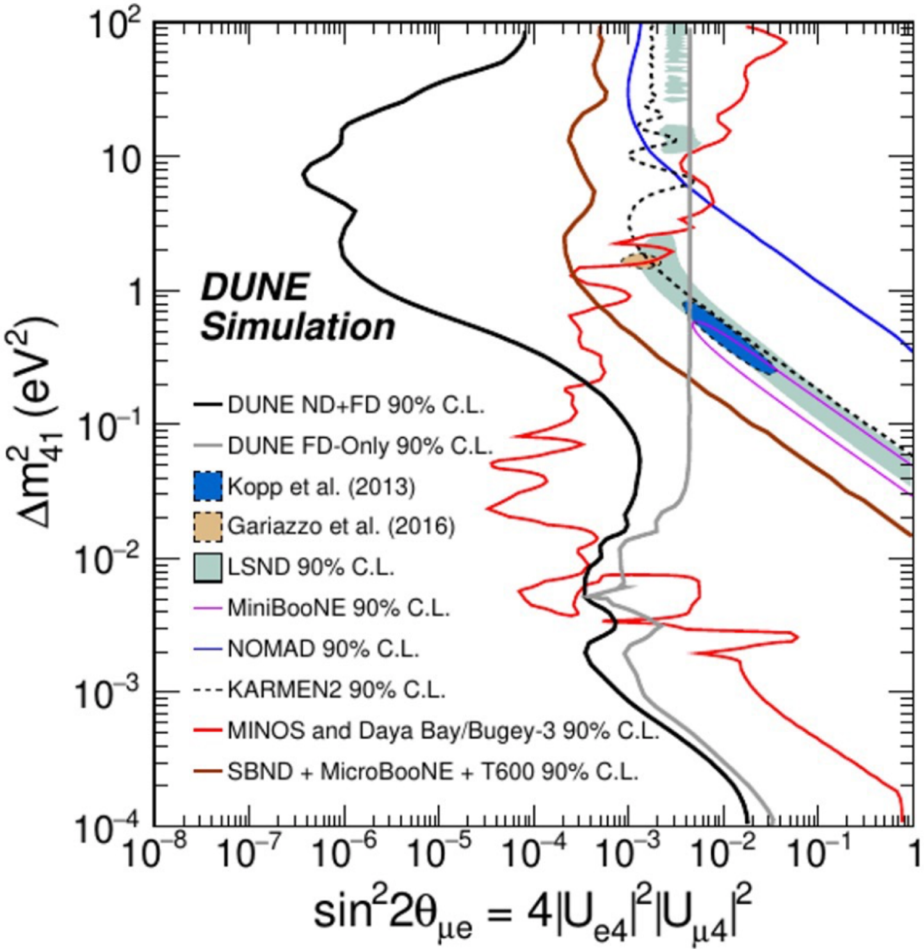


Submitted and approved by DOE CD1-RR
July 2022

DUNE Science begins when the FD1 is filled and turned on and start recording tracks.

BSM Searches

- DUNE can also look for beyond Standard Model (BSM) physics
  - Non-standard neutrino interactions
  - Sterile neutrinos
  - Dark-matter searches
  - Nucleon decay
  - Many others

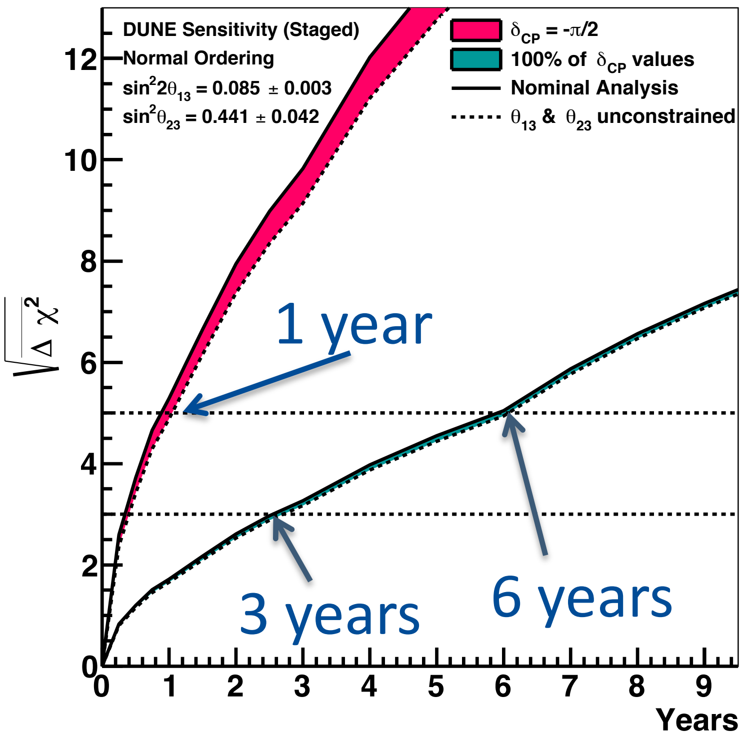


Sterile Neutrino Sensitivity

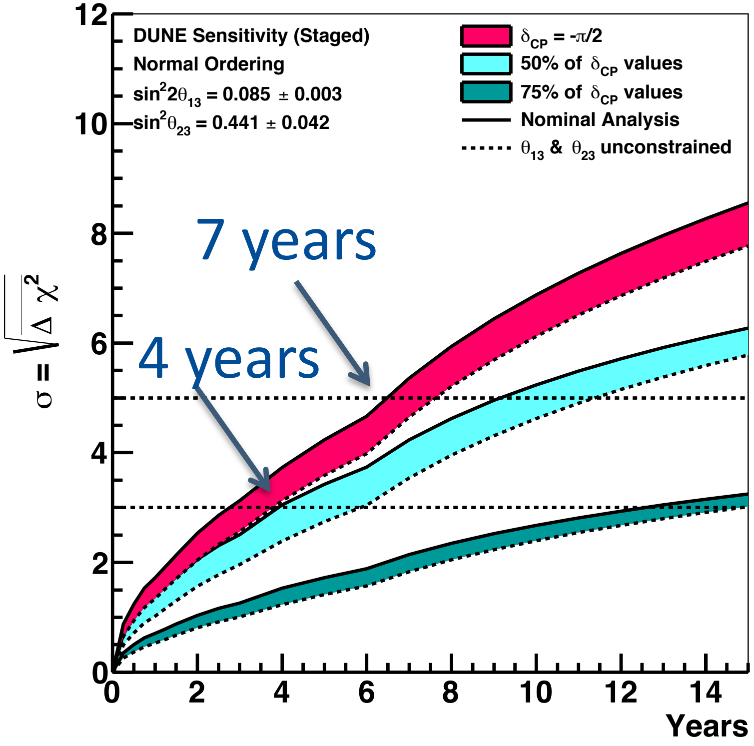
(ν_e CC appearance at ND)

Sensitivity vs. time

Mass Hierarchy Sensitivity



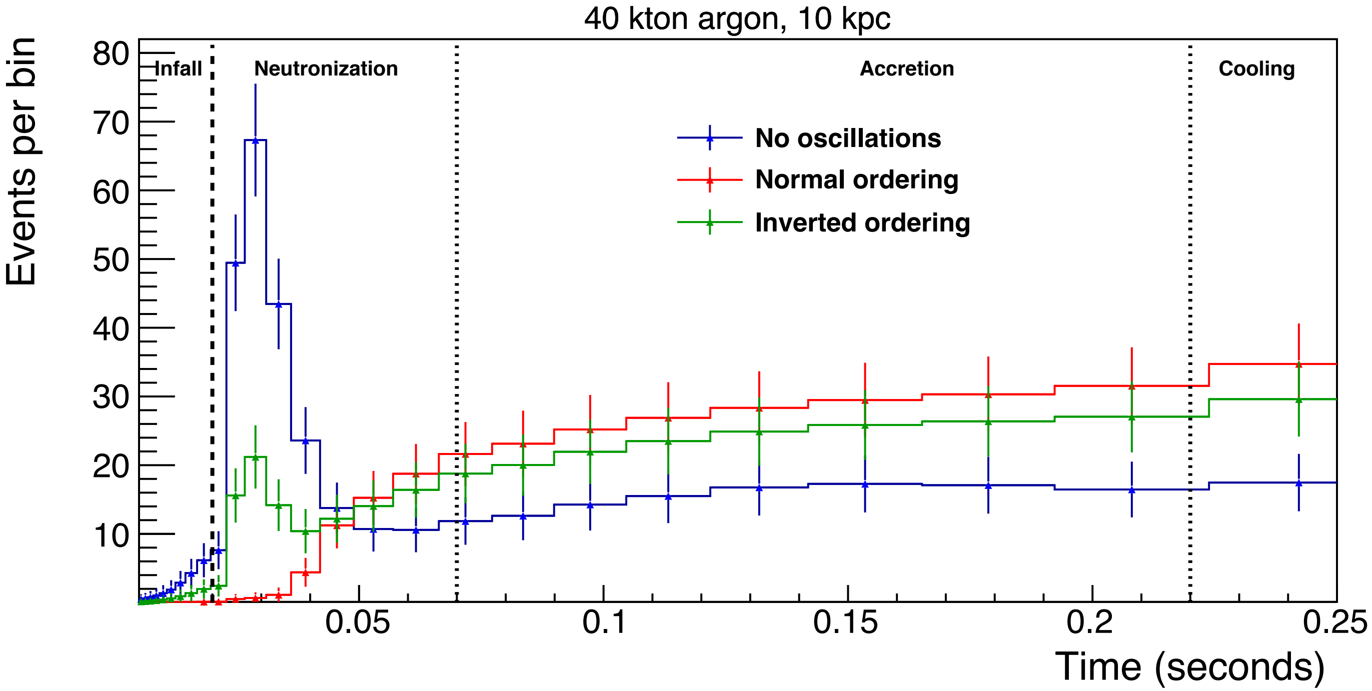
CP Violation Sensitivity



Important sensitivity milestones throughout beam physics program

SN Neutrinos in DUNE

- LAr provides unique sensitivity to ν_e: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
- About 3000 ν_e events in 10 sec from SN at 10 kpc
- The time structure of the SN signal during the first few tens of ms after the core bounce can provide a clear indication if the ν_e burst is present, and makes it possible to distinguish between different mixing scenarios



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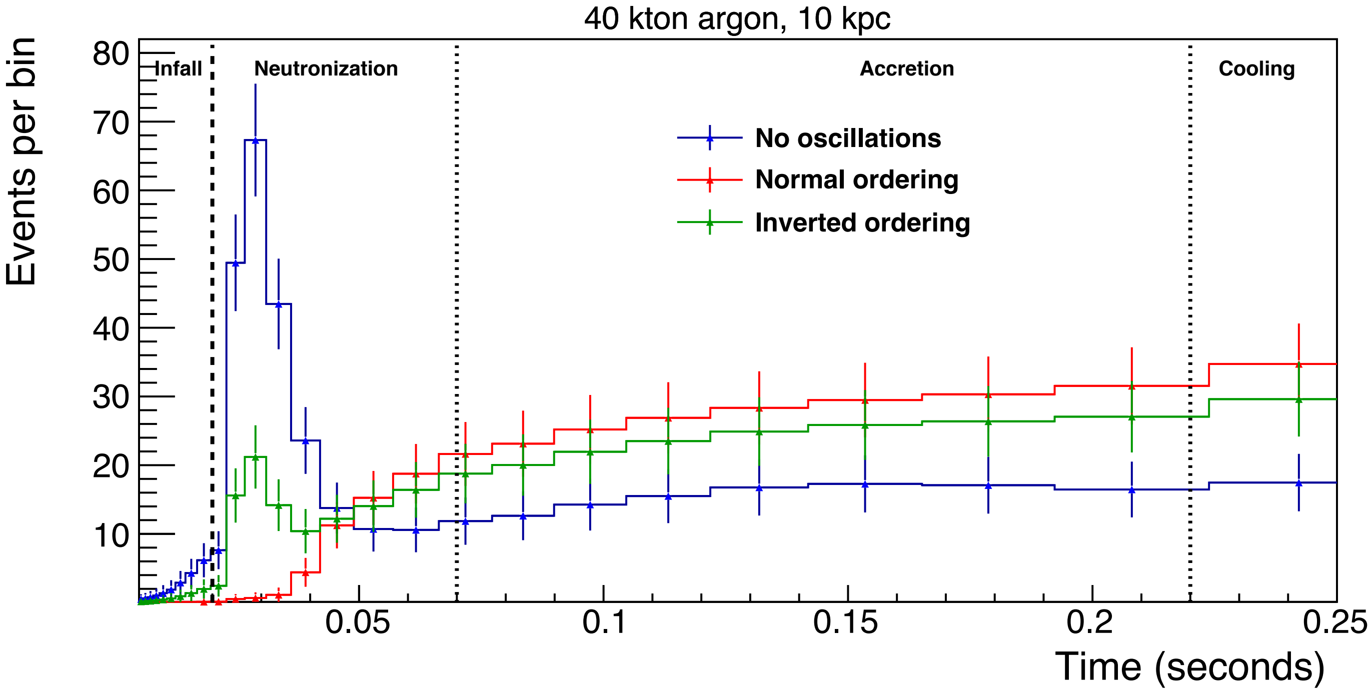
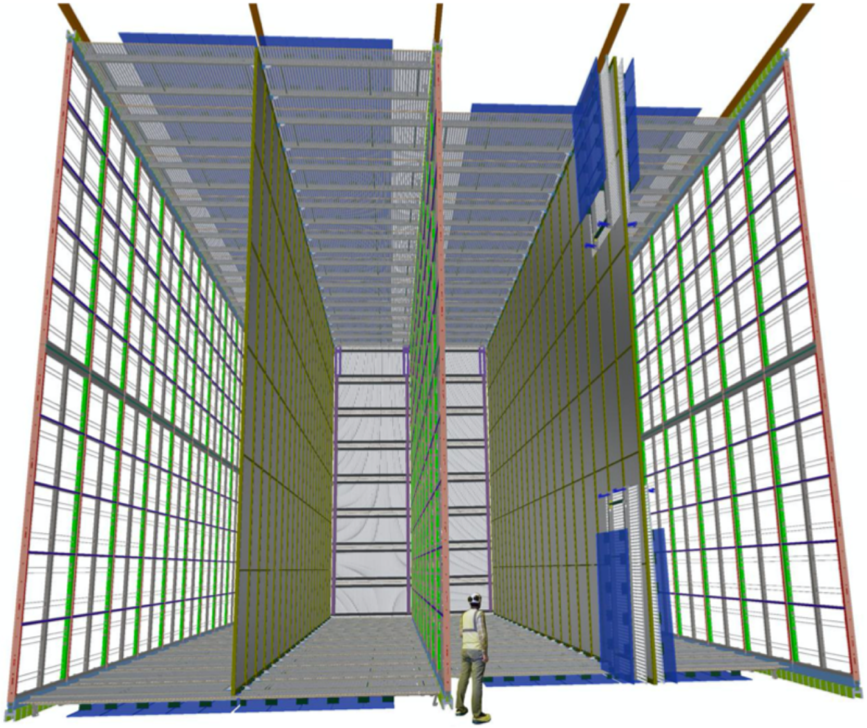
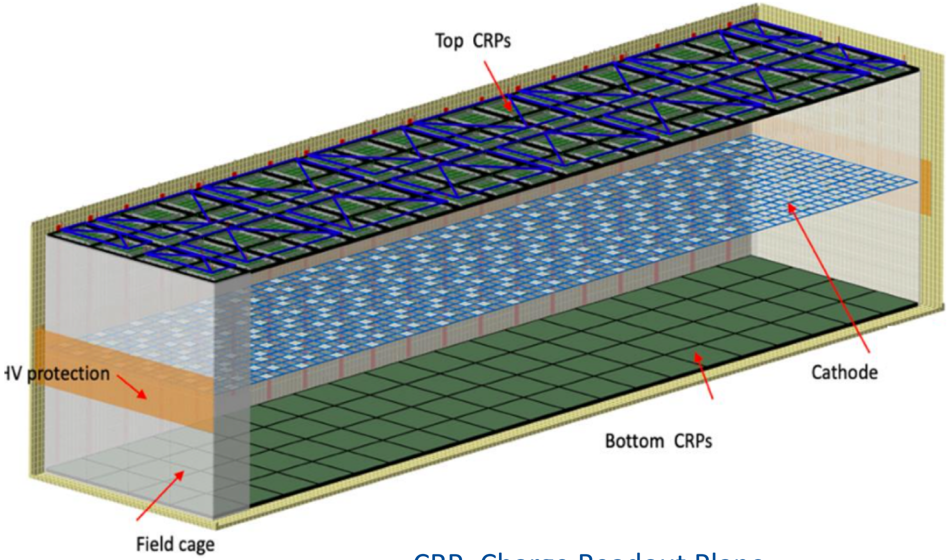


Two Far Detector Modules

- **Horizontal Drift Module**
  - 3.6 m horizontal drift
  - Anode-cathode-anode-cathode-anode geometry
- Charge readout with wires
- Photon detectors in anode planes



- **Vertical Drift Module**
  - Evolved from dual-phase design
  - 6.5 m vertical drift
  - Anode-cathode-anode geometry
- Charge readout via printed circuit boards
- Photon detector in cathode plane



CRP: Charge Readout Plane