Indian Institute of Technology Guwahati

LBL Neutrino Physics Activities in India: Collaboration with JINR on Associated Detector Technology Development

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Neutrino: A new Identity in the last 25 years!

Standard Model

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

Neutrino oscillations (confirmed by SNO, SuperKamiokande, T2K, NOvA etc.)

- Indicates massive neutrinos.
- Neutrino mass states are different from flavor states.
  - As neutrinos travel, they change flavor
- Beyond standard model.

Indian institutions have been Participating in the FNAL based Neutrino experiments since 2009.

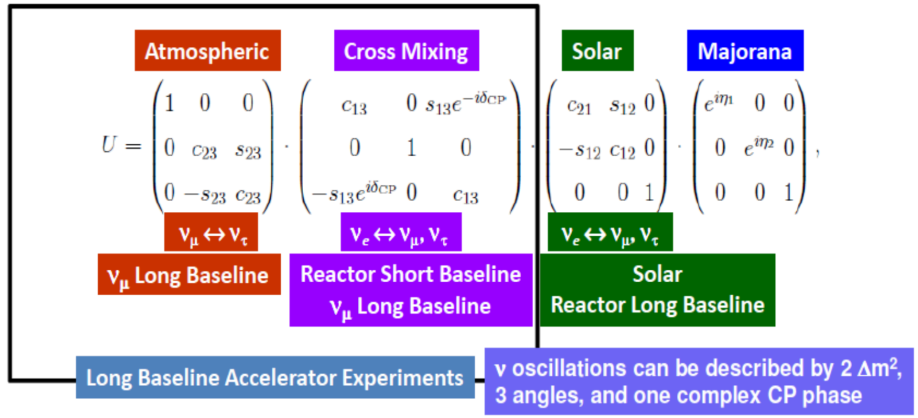
Neutrino Mixing

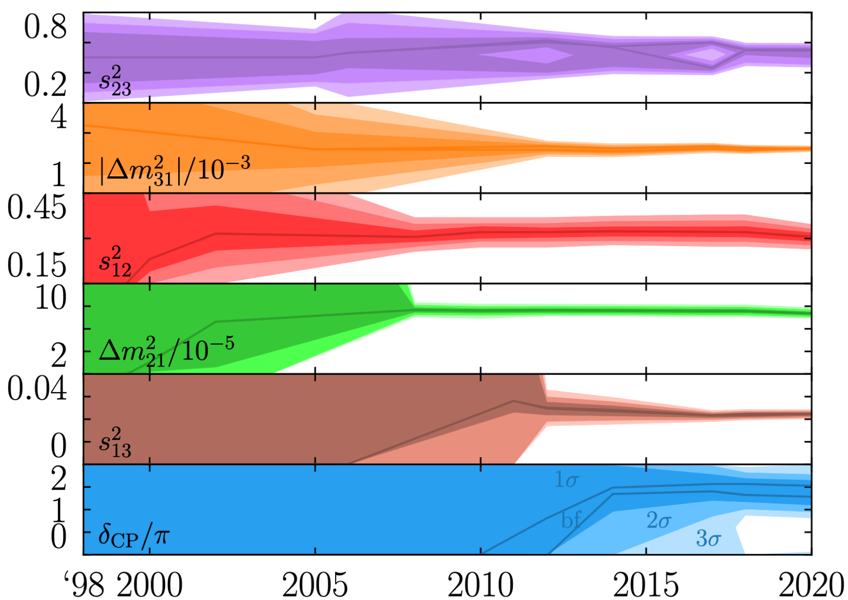
- Neutrinos mix, just like the quarks

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

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

- PMNS matrix. CKM matrix for quarks





ArXiv: 2212.00809

- Mixing results in oscillation; Probability of oscillation depends on:
  - ✓ Values of the parameters: $\delta_{CP}, \theta_{12}, \theta_{13}, \theta_{23}$
  - ✓ $\Delta m^2_{ij} = m^2_i - m^2_j$
  - ✓ Energy of the neutrino: E
  - ✓ Distance travelled (baseline): L

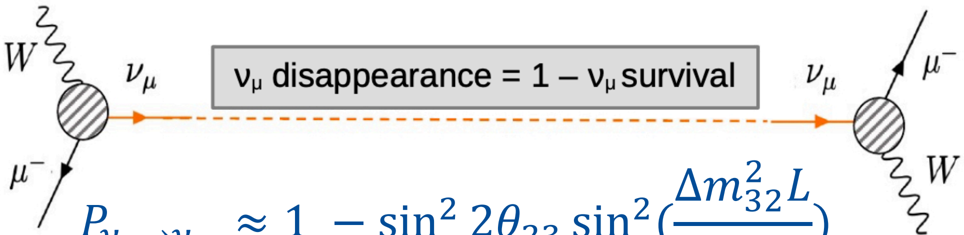
Two flavor approximation:

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

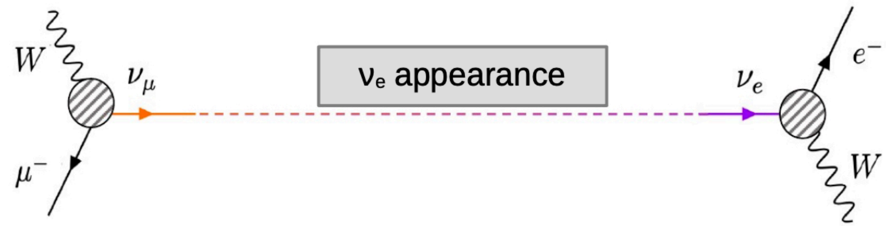
Neutrino Oscillation at LBL Experiments

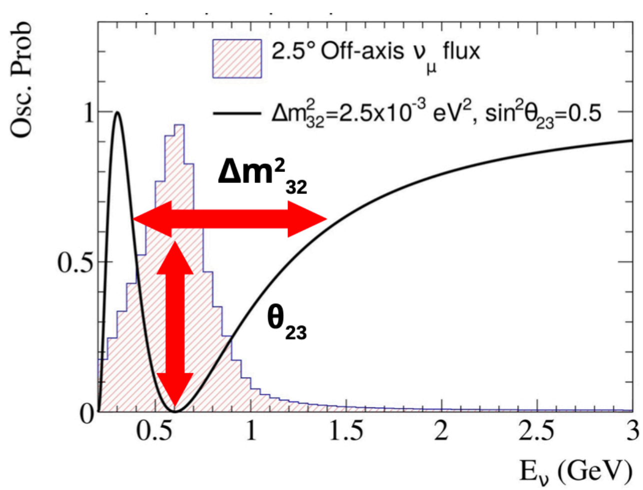
- Measure neutrino oscillations by sending neutrino beam across several hundreds of kms. Uses both ν_μ and $\bar{\nu}_\mu$ beam.

Study both $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance in the Far detector.



$$P_{\nu_\mu\to\nu_x} \approx 1 - \sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)$$





$$\begin{aligned} P_{\nu_\mu\to\nu_e} \approx\ & \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2((1-x)\Delta)}{(1-x)^2} \\ -\ & \alpha\sin 2\theta_{13}\sin\delta\sin 2\theta_{12}\sin 2\theta_{23}\sin\Delta\frac{\sin(x\Delta)}{x}\frac{\sin((1-x)\Delta)}{(1-x)} \\ +\ & \alpha\sin 2\theta_{13}\cos\delta\sin 2\theta_{12}\sin 2\theta_{23}\cos\Delta\frac{\sin(x\Delta)}{x}\frac{\sin((1-x)\Delta)}{(1-x)} \\ +\ & \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(x\Delta)}{x^2} \end{aligned}$$

$$x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31}L}{4E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Leading order dependence on $\sin^2 2\theta_{23}, \Delta m^2_{32}$ *and* L/E

Sensitive to $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$, δ_{CP}, magnitude and sign of Δm^2_{32}

Matter effects modify oscillation probability.

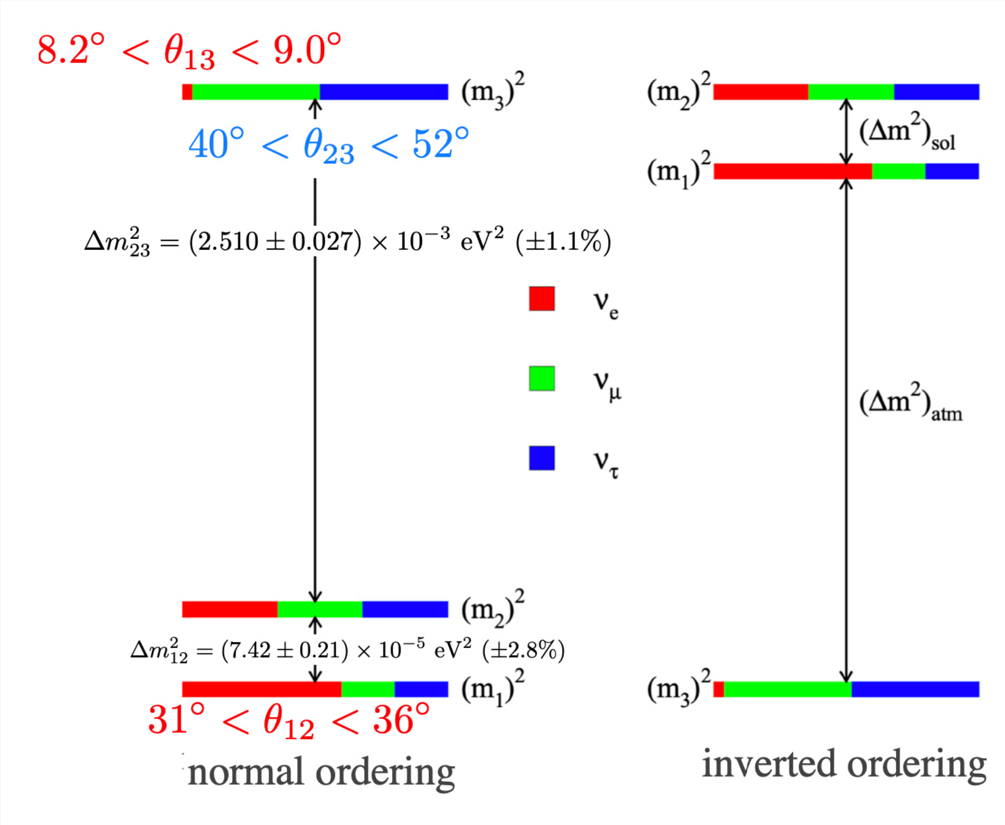
Opposite impact of matter effects and δ_{CP} for ν and $\bar{\nu}$

- $\delta_{CP} = \frac{\pi}{2}$: fewer neutrinos, more anti-neutrinos
- $\delta_{CP} = \frac{3\pi}{2}$: more neutrinos, fewer anti-neutrinos.

Key Questions for LBL Experiments

- 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?



arXiv:2102.00594 NuFit, arXiv:2111.03086

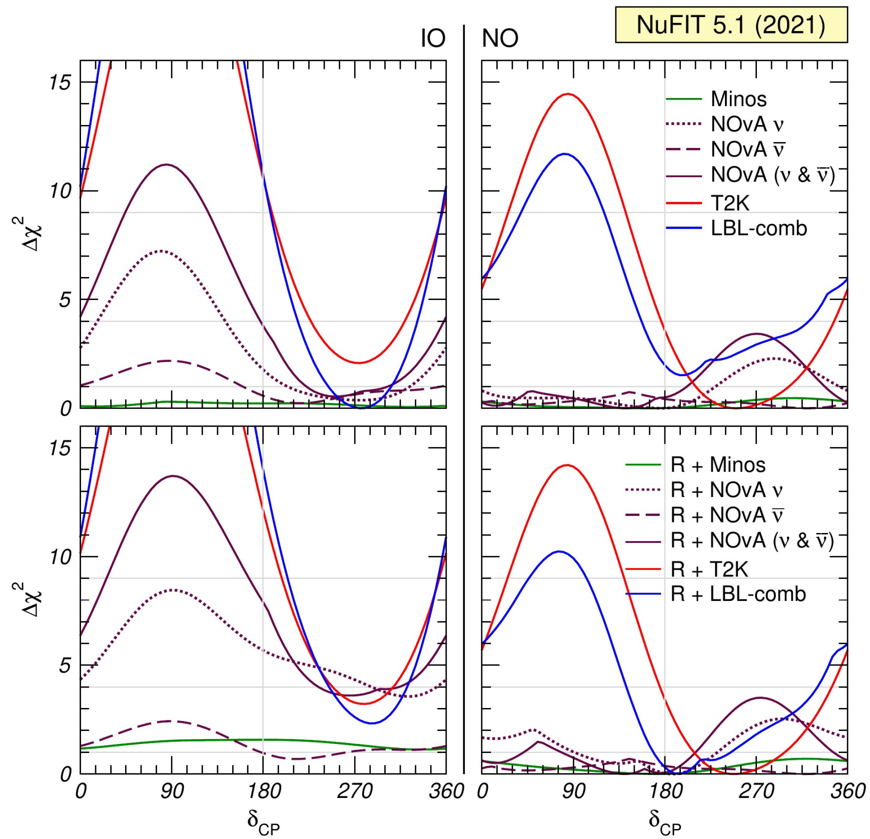
- No concrete evidence of mass ordering from individual experiments such as T2K, NoVA and SuperK.
- Global fit seems slightly prefer Normal Ordering $(< 3\sigma)$

Key Questions for LBL Experiments

- Discovery of CP violation in the lepton sector ($\delta_{CP} \neq 0 \; or \; \pi$)
  - Important for theories of lepto-genesis.
  - The observed CP violation in the quark sector is too small to explain all the matter anti-matter asymmetry in the universe.
  - CP violation in the lepton sector will shed more light on the problem
    - Measurement of δ_{CP} is critical.

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

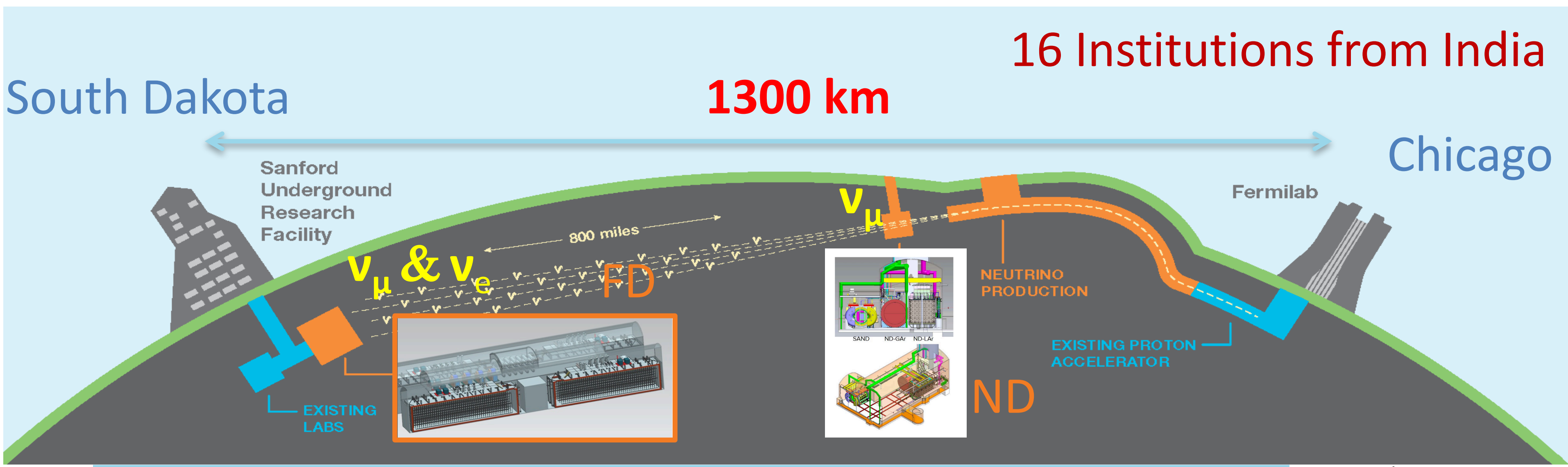
Combined results from Reactor +LBL Experiments is far from stable.



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

Deep Underground Neutrino Experiment

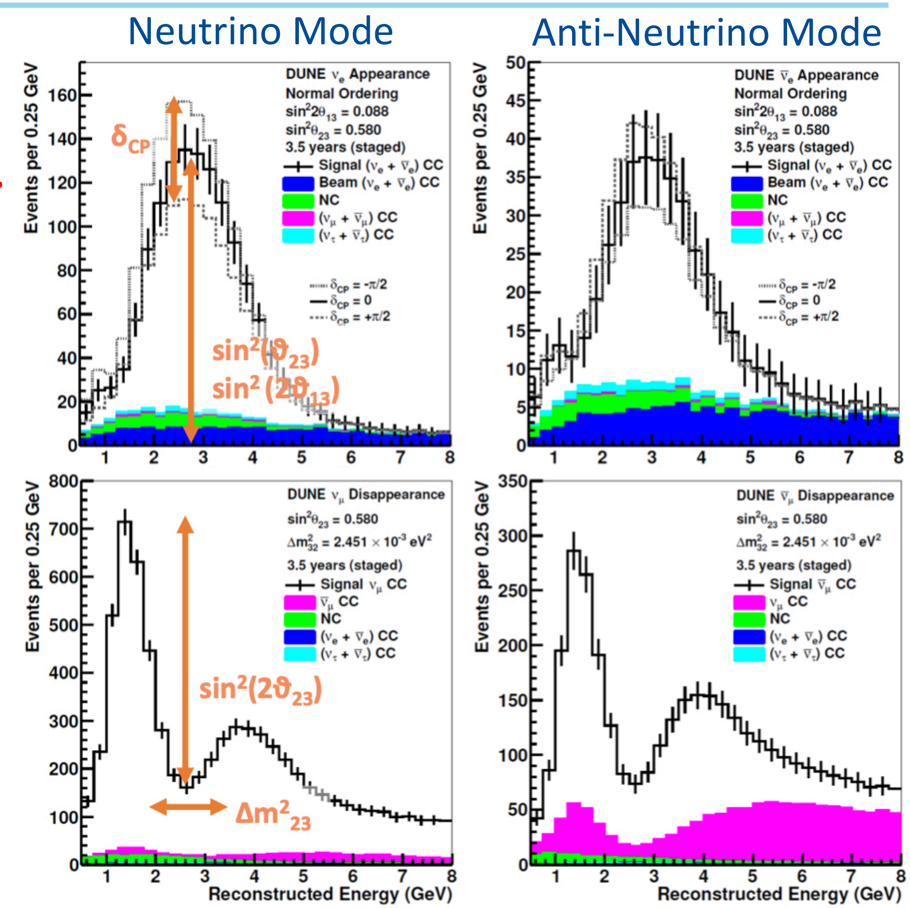
- Muon neutrinos/antineutrinos from high-power proton beam
  - ✓ 1.2 MW from day one; upgradeable to 2.4 MW
- A Massive Liquid Argon TPC Far Detector in South Dakota, located ~ 1.478 km underground in a former gold mine.
  - ✓ 4 modules, 70 kton of liquid Argon.
- A Near detector complex with multiple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



Oscillation Sensitivity for DUNE

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

- ν_e appearance probability depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects.
  All four can be measured in a single expt.
- Reconstructed energy sprectra. 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 $\nu_\mu/\bar{\nu}_\mu$ events in 7 years
- Simultaneous fit to four spectra to extract oscillation parameters

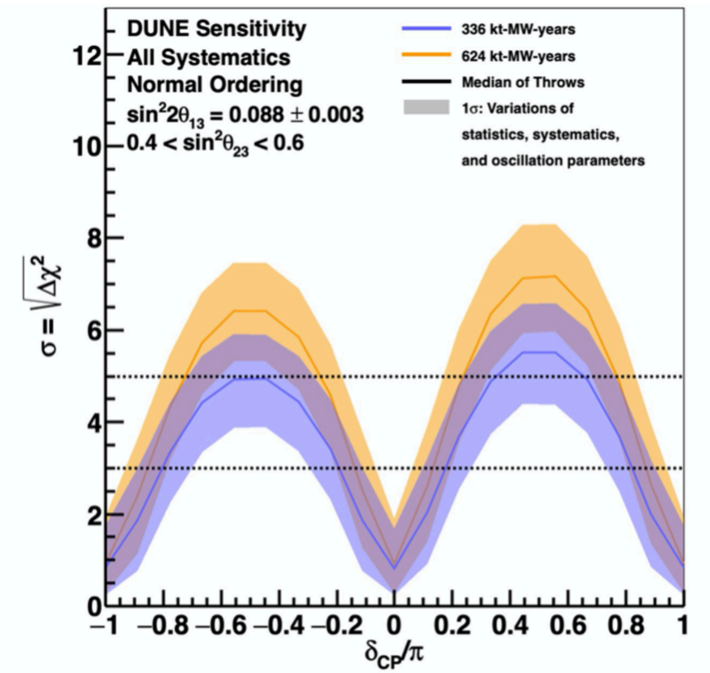


	$\nu_\mu \rightarrow \nu_e$		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Observed Events	169	12 (low energy)	32
Expected Background	55	7	12

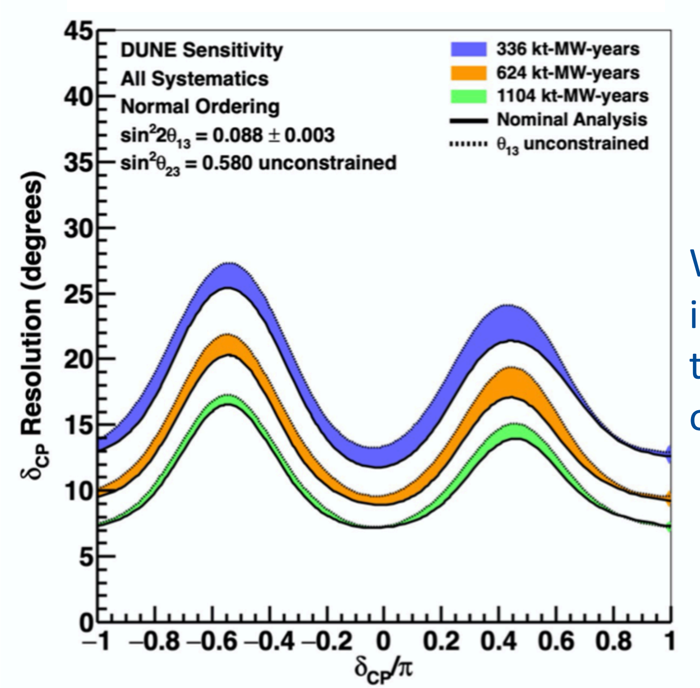
Latest results from NOvA.

CP Violation Sensitivity

CP Violation Sensitivity



δ_{CP} Resolution

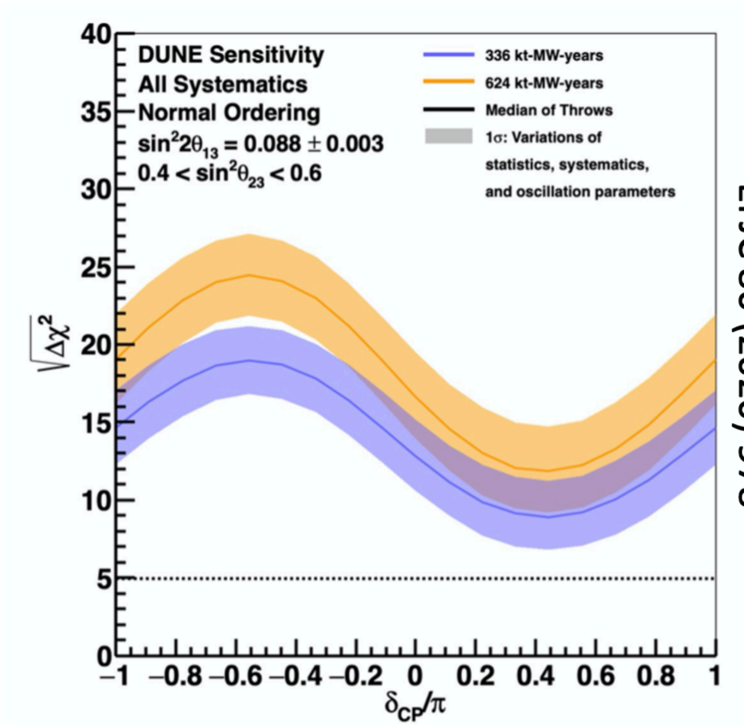


Width of the band indicates variation in the possible values of θ_{23}

- 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

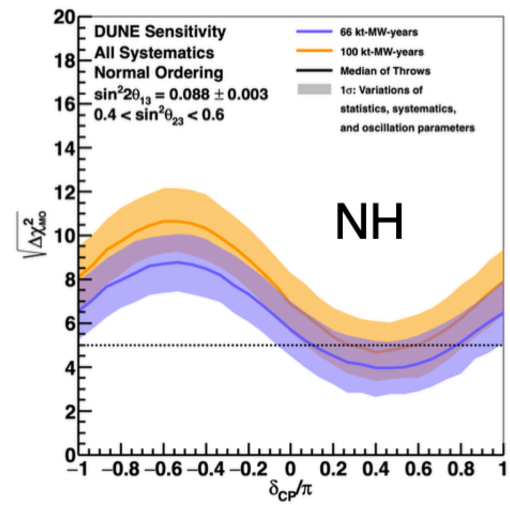


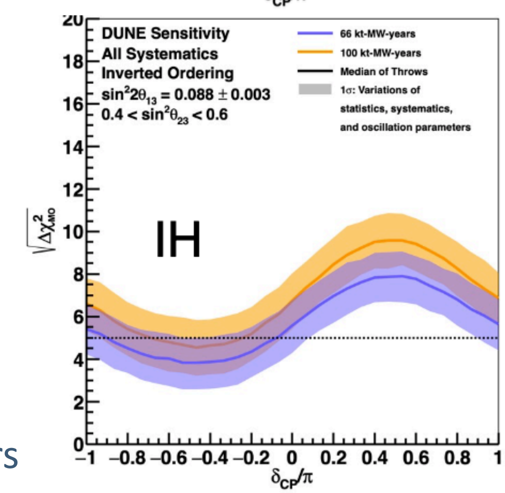
EPJC 80 (2020) 978

100 kt

66 kt

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

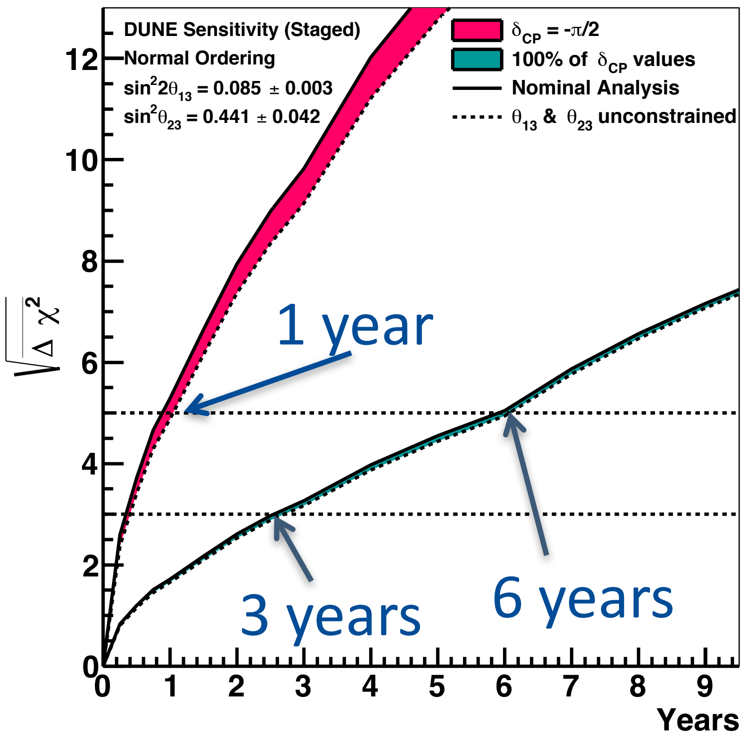




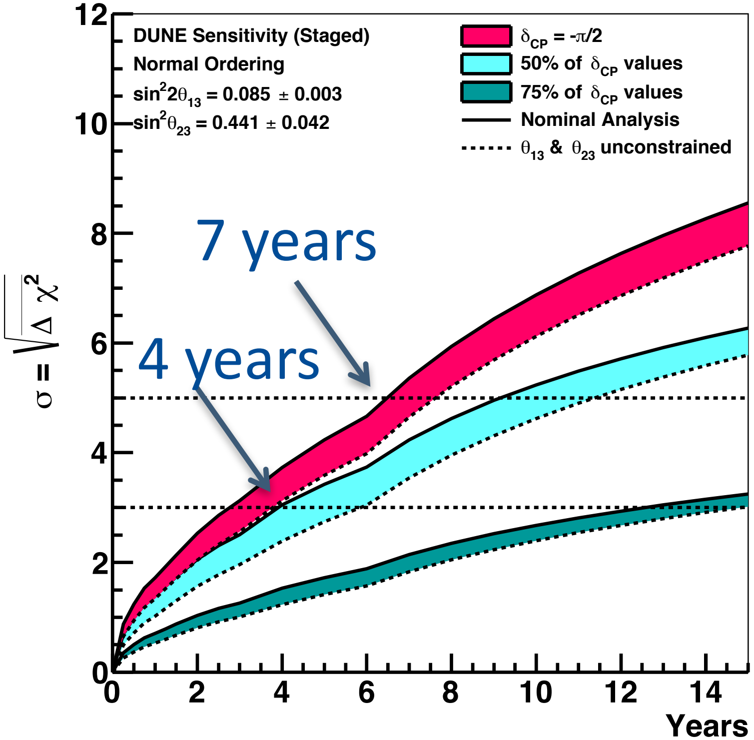
- Mass hierarchy determination: > 5σ for all parameter values
- Even by exposure of 66 kt-MW-yr, probability to extract wrong ordering < 0.01
- With 1.2 MW beam running, DUNE will need only 1 -2 years to measure mass ordering definitely.

Sensitivity vs. time

Mass Hierarchy Sensitivity



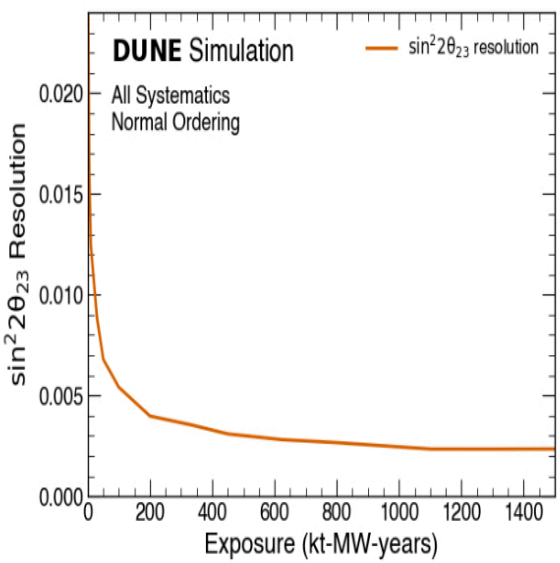
CP Violation Sensitivity

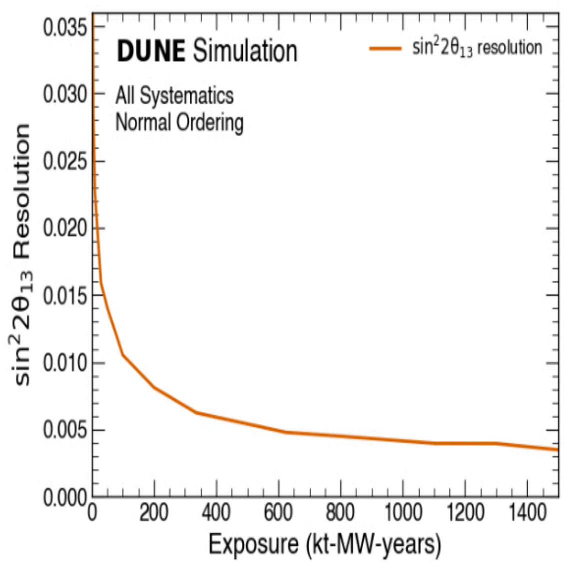


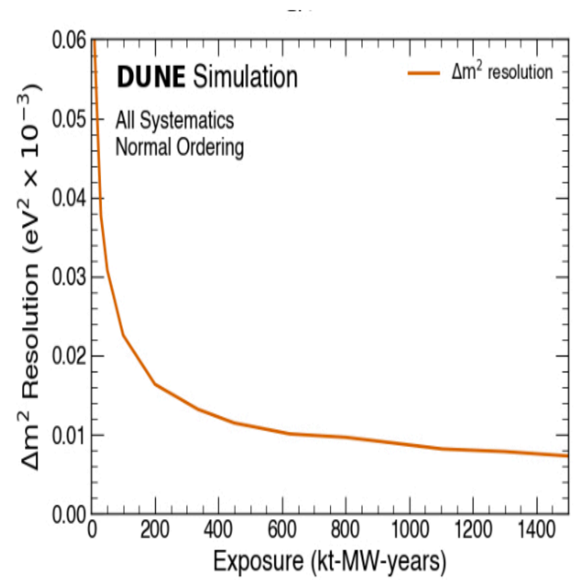
Important sensitivity milestones throughout beam physics program

Precision Measurement of Oscillation Parameters

- Sub-percent precision for $\Delta m^2_{32}, \theta_{23}$, and θ_{13} from accelerator neutrino experiments.
  - DUNE is entering the PMNS precision era.
  - Comparison with reactor measurements will be interesting to unveil new physics.

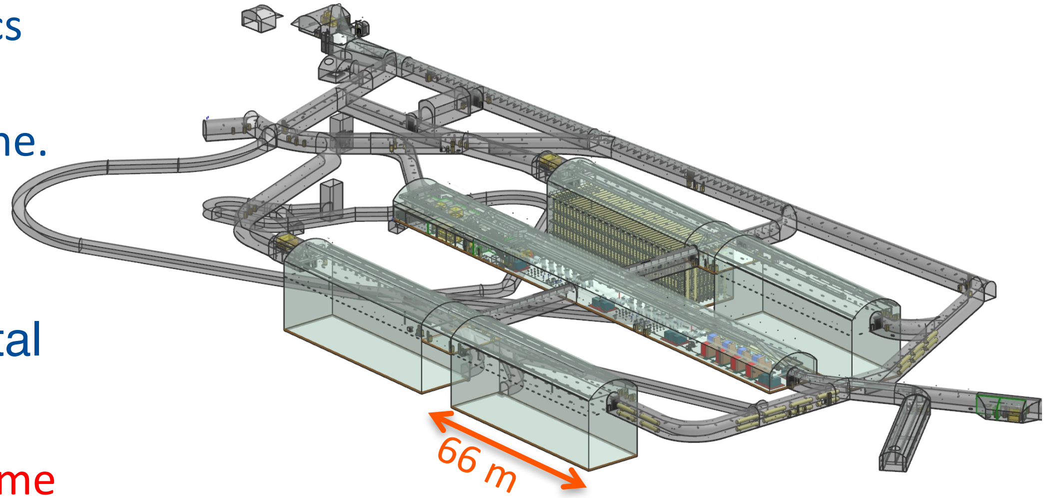






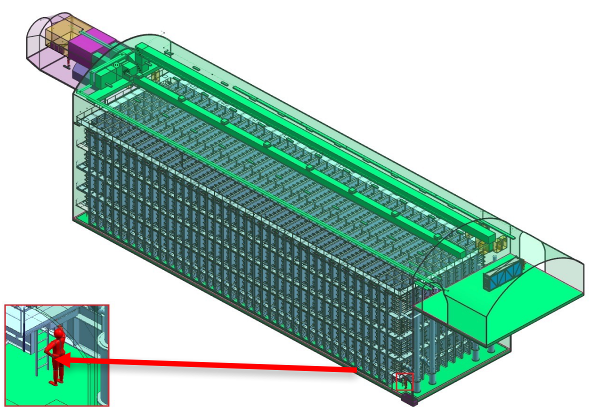
DUNE Far Detector

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

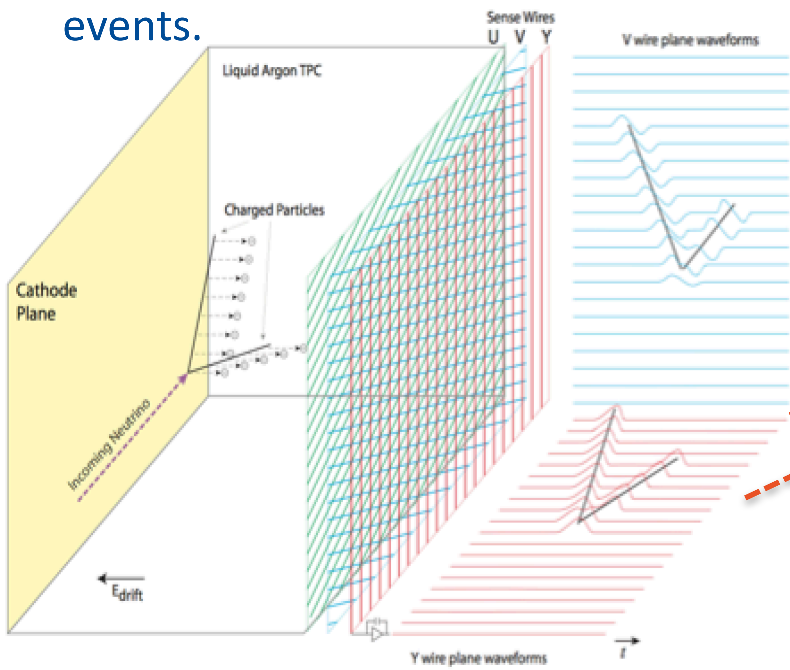
DUNE Phase-I



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

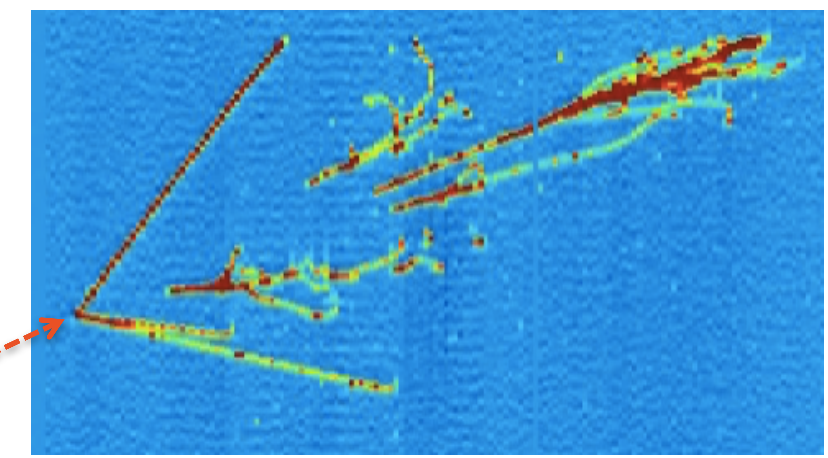
DUNE Far Detector: LAr TPCs

- Argon scintillates, light is detected by photon detectors
- Neutrinos interact in Argon producing charged particle
- 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

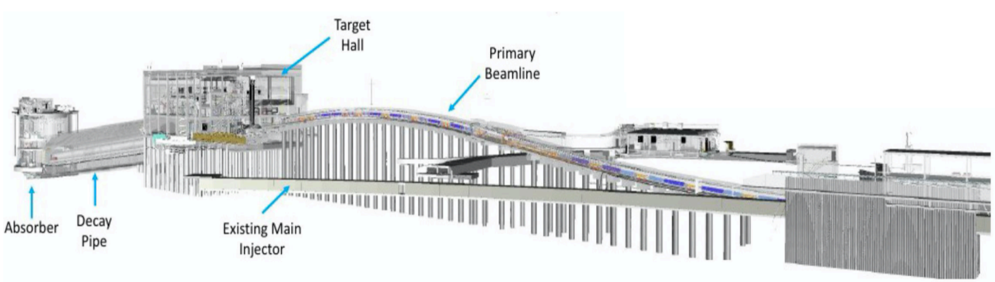
Far Detector Site Readiness

- ✓ All cryostat material delivered to SURF and being prepared for underground transport in January 2026.
- ✓ Cavern outfitting and final safety checks are ongoing
- ✓ Cryostat construction anticipated at the end of April 2026
- ✓ First physics run using the FD only in 2029

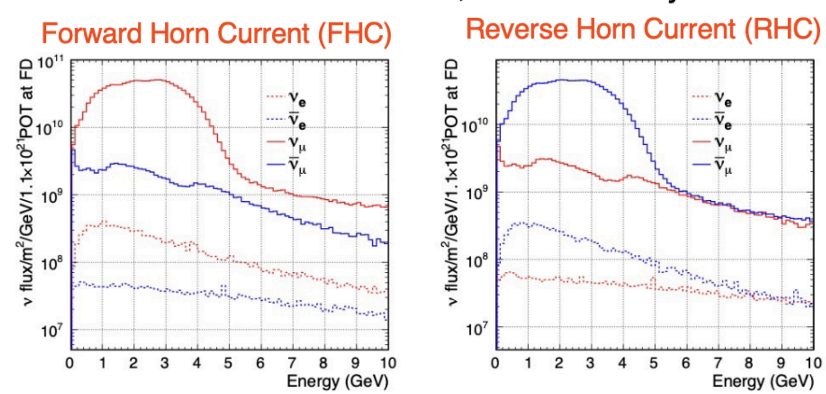
The LBNF Beam: PIP II

- 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.



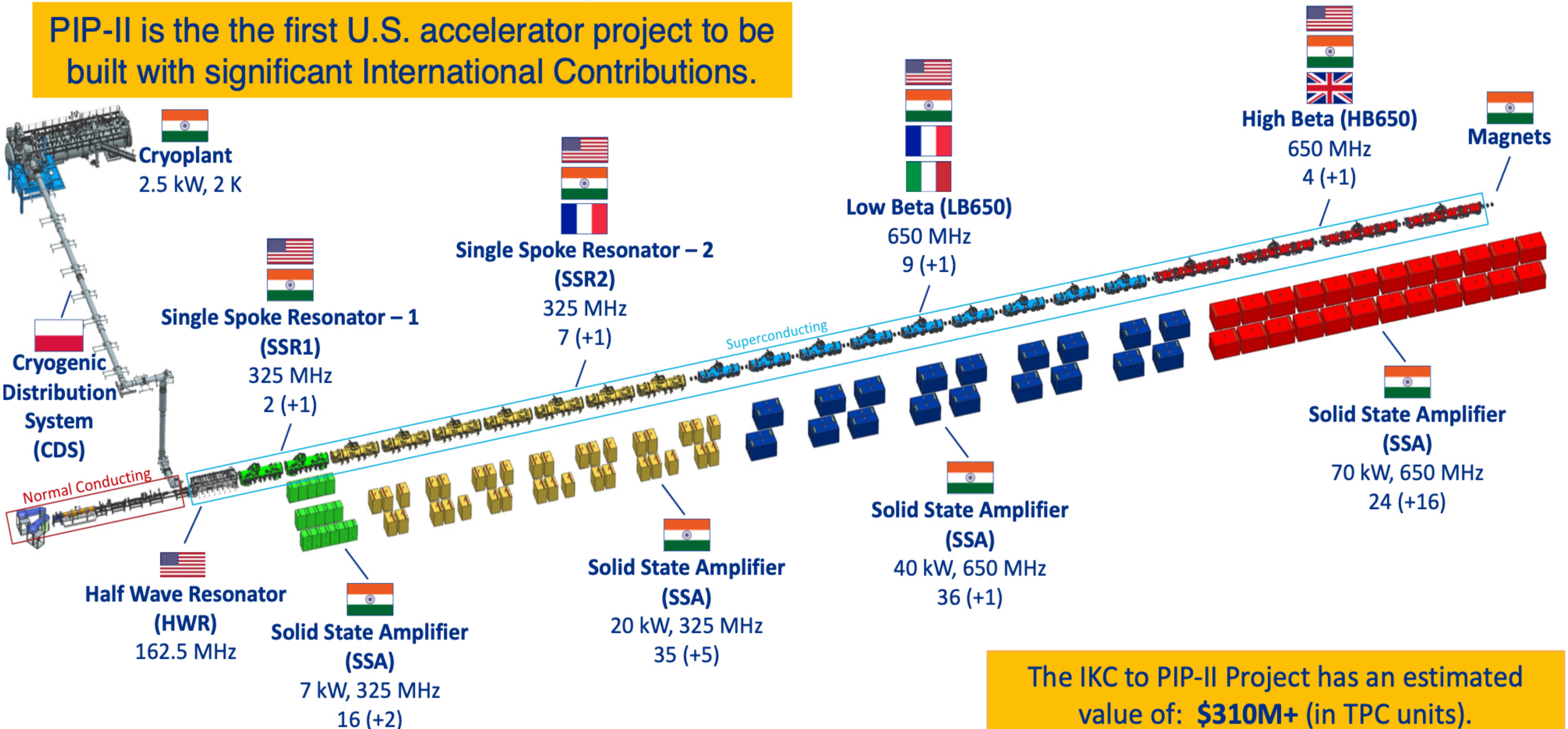
Neutrino Flux at SURF, 1300 km away



PIP II: Indian Contribution

In-Kind Contribution Scope Overview

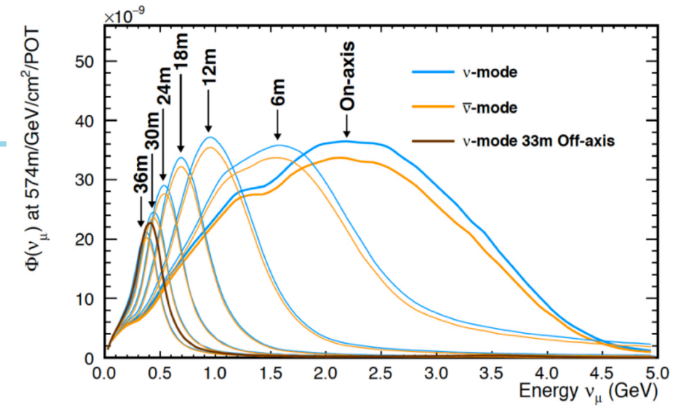
PIP-II is the the first U.S. accelerator project to be built with significant International Contributions.



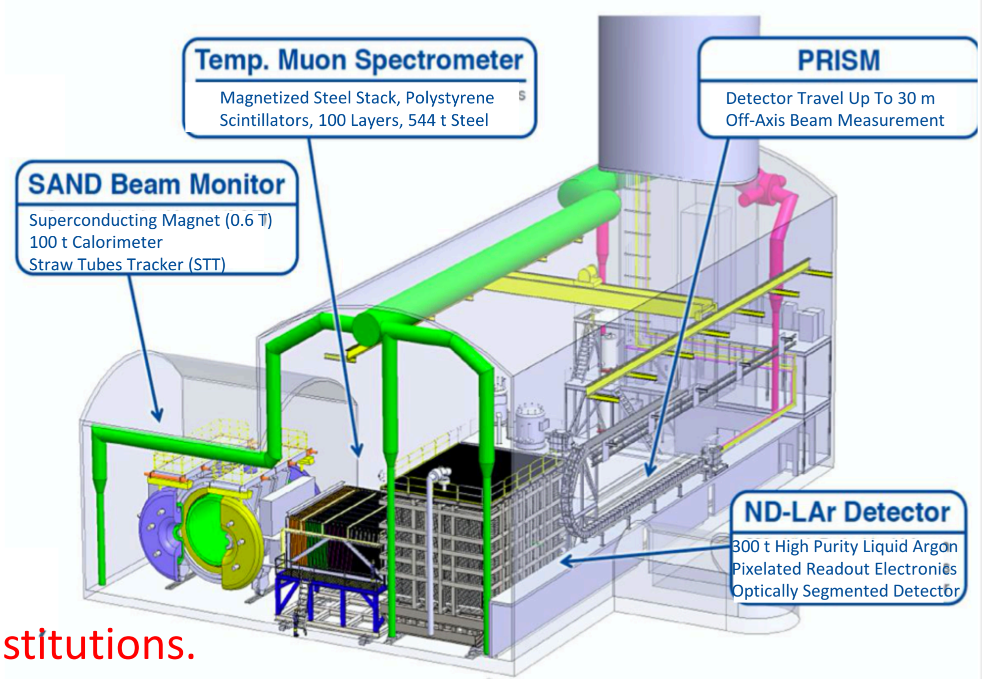
The IKC to PIP-II Project has an estimated value of: **$310M+** (in TPC units).

India must reap the science benefit from such a significant investment in PIP-II that will provide the neutrino beam for DUNE.

Near Detector (ND) – Phase I

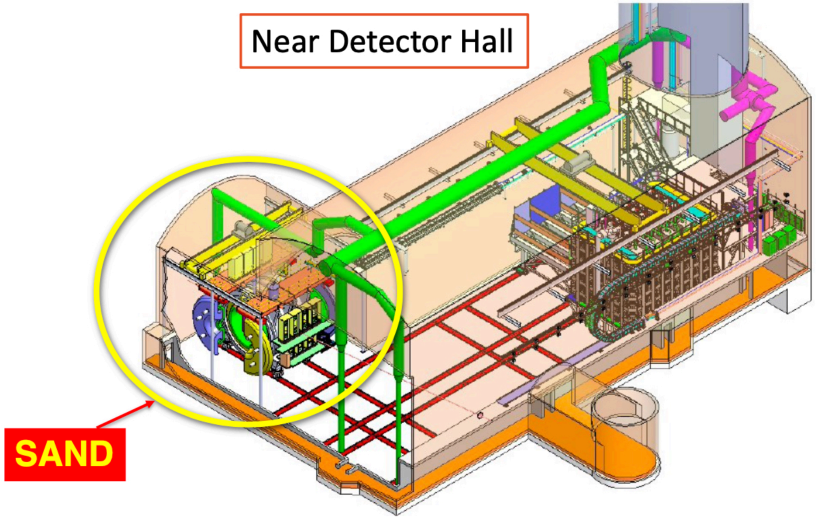


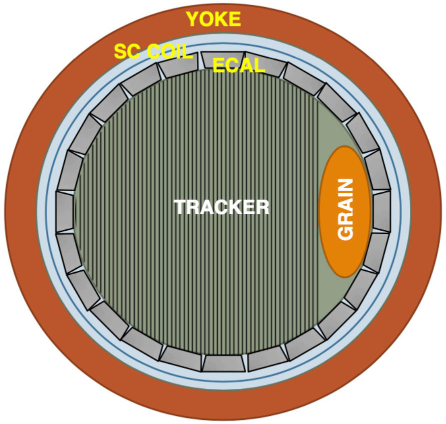
- ✓ Role: constrain systematic uncertainties needed in oscillation analyses
  - Precisely measure un-oscillated beam neutrino flux
  - Measure multiple interaction cross-section channels.
- ✓ ND Hall location
  - 574 m from LBNF target
  - ~ 60 m underground
- ✓ An integrated system composed of multiple 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.

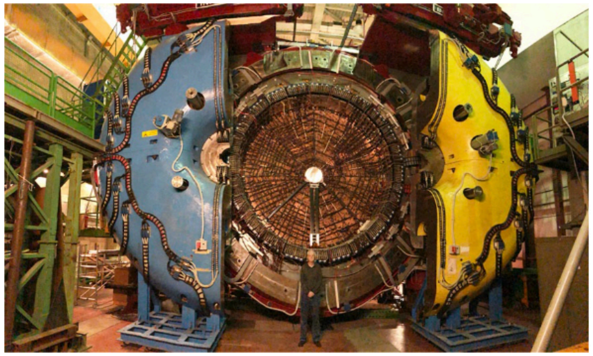


- ✓ Moving ND Detectors (ND-LAr & TMS) by 30 m results in different measured energy spectra
  - ✓ Linear combination of these spectra better reproduces oscillated FD spectrum, that reduces uncertainties.

SAND Detector

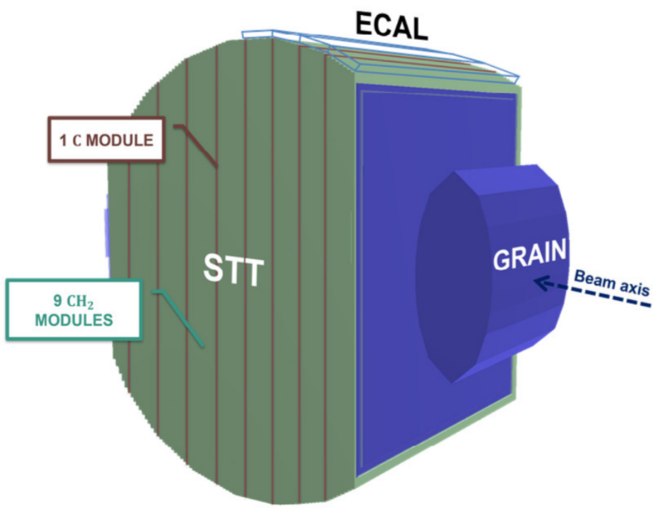




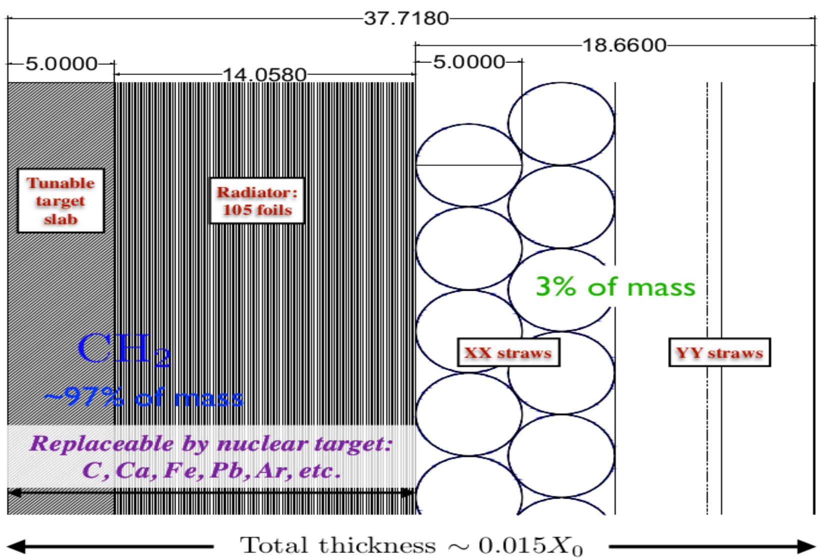


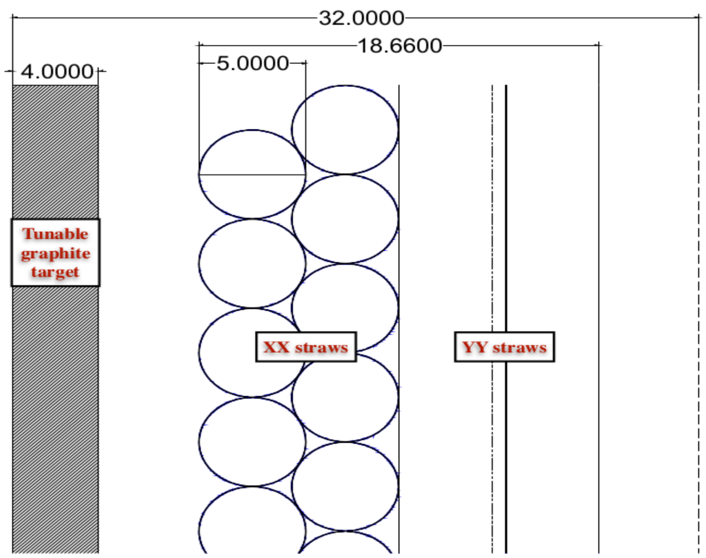
- Repurposed from KLOE II experiment. The superconducting magnet provides a 0.6 T uniform magnetic field over a volume of about 45 m^3.
- Permanently located on-axis along the neutrino beam from day 1 to monitor the beam to detect time-dependent spectral changes intrinsic to beam, while ND-LAr and TMS/ND-GAr system will move off-axis for about 50% of the time.
- Will provide in-situ flux measurements (absolute and relative) for ν_μ, anti-ν_μ, ν_e and anti-ν_e and will reduce dependency on DUNE-PRISM for neutrino beam modelling.

Tracking Volume of SAND



- 1 ton LAr upstream to cross-verify ν-Ar interactions for FD.
- C/CH_2 modules interleaved with XXYY STT layers to separate the targets physically.
- Target thickness (C: 4 mm; CH_2: 5 mm) to have equivalent radiation length, hence similar acceptance.
- 105 adiator foils in CH_2 modules to allow Transition radiation for e/π separation.

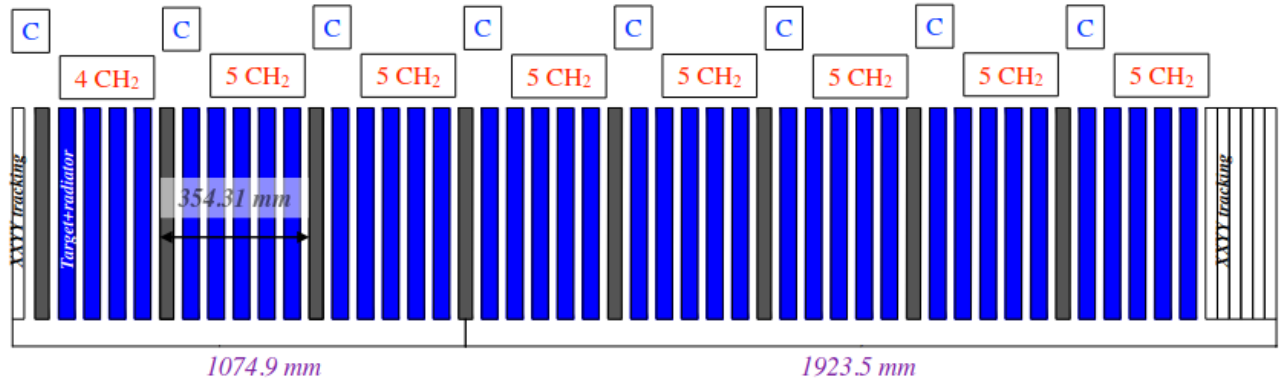




STT Configuration

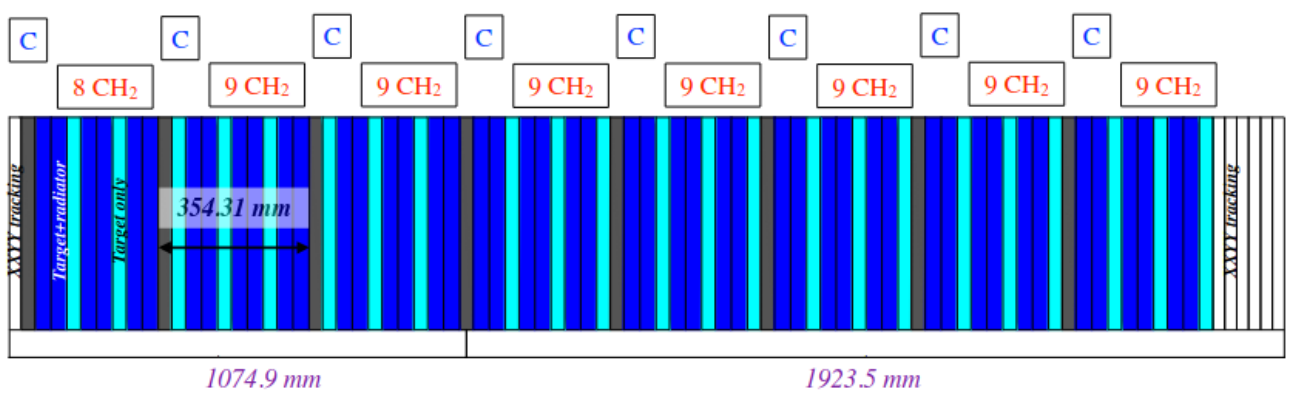
Initial STT config:

- **Total** - 54 modules
- **CH_2 with rad.** - 39
- **CH_2 target only** - 0
- **C** - 9
- **Trk** - 7
- **Total FV mass** - 2.878 tons



Maximal STT config:

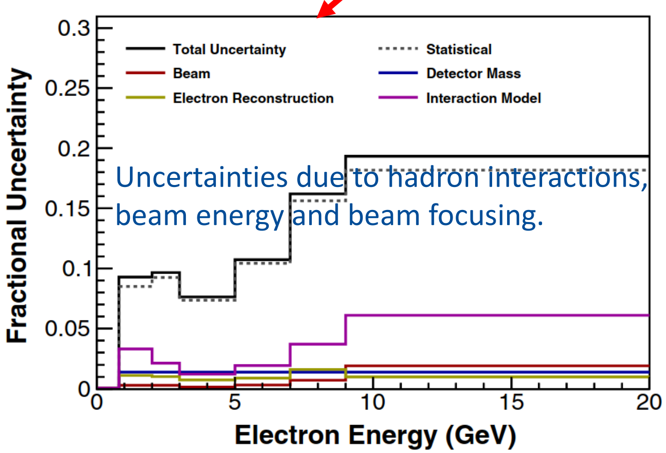
- **Total** - <u>86 modules</u>
- **CH_2 with rad.** - <u>48</u>
- **CH_2 target only** - <u>23</u>
- **C** - 9
- **Trk** - 7
- **Total FV mass** - <u>4.407 tons</u>



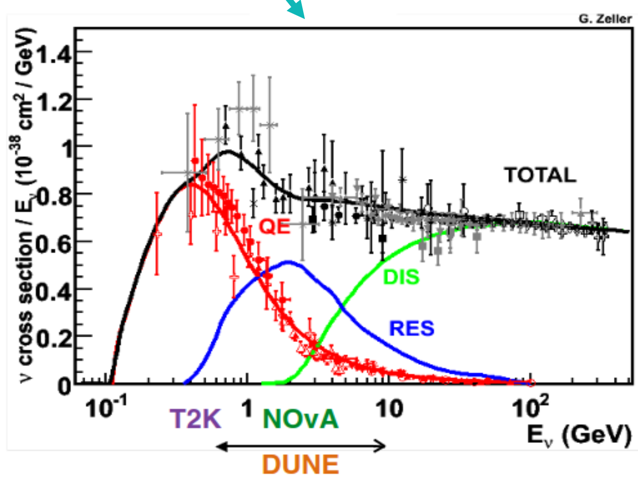
Neutrino counts

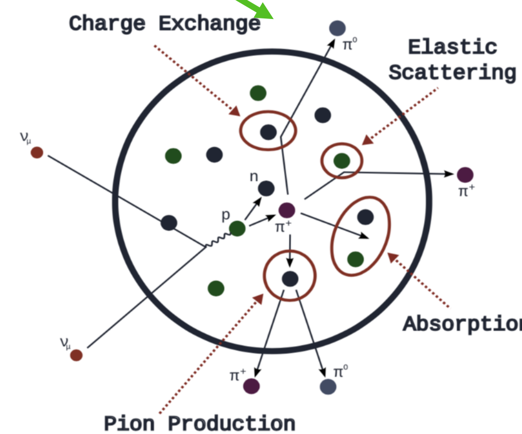
Neutrino event measurements are highly convoluted with the parameters having large uncertainties:

$$N_X = \int P_{osc}(E_\nu) * \boxed{\phi(E_\nu)} * \boxed{\sigma_X(E_\nu)} * \boxed{R_{phys}(E_\nu, E_{vis})} * R_{det}(E_{vis}, E_{rec})\, dE_\nu$$



Uncertainties due to hadron interactions, beam energy and beam focusing.





MINERvA measured uncertainties

Neutrino counts in SAND with STT: Solid H Concept

Neutrino event measurements are highly convoluted with the parameters having large uncertainties:

$$N_X = \int P_{osc}(E_\nu) * \boxed{\phi(E_\nu)} * \boxed{\sigma_X(E_\nu)} * \boxed{R_{phys}(E_\nu, E_{vis})} * \boxed{R_{det}(E_{vis}, E_{rec})} dE_\nu$$

known to 1% on H

Measured with large statistic

$R_{phys} \equiv 1$

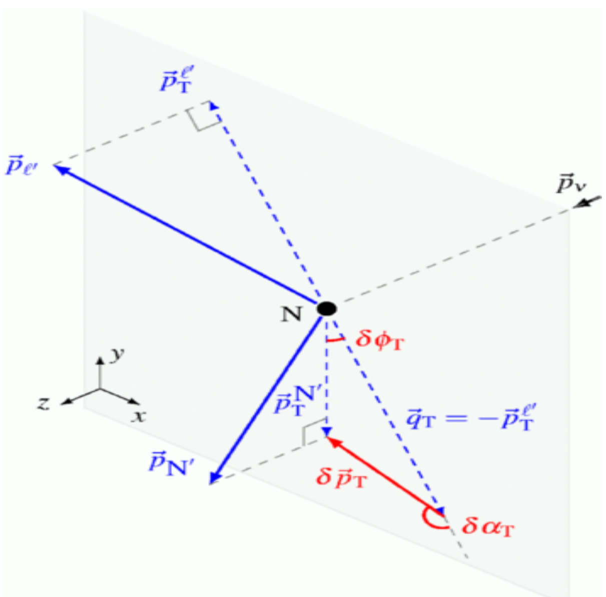
$\delta p/p$ 0.2% *calibrated from* $K_0 \longrightarrow \pi^+ \pi^-$ *in STT volume*

- **Primary task is to extract ν-H interactions from CH_2 target and separate them from the rest.**
- **Excellent timing, vertex, momentum, angular resolution needed.**
- **This is achieved with the help of Straw Tube Trackers.**

Nuclear Effects are significant

Shailesh Pincha, B. Bhuyan

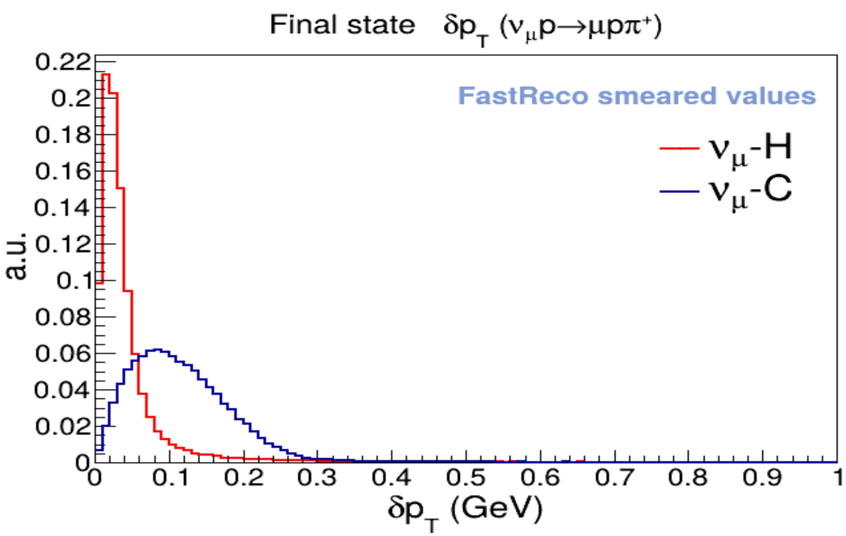
- **Nuclear effects are hard to model. Different neutrino event generators use different nuclear models/effects, different Initial-State and Final-State modelling, etc.**
- **Hydrogen doesn't have nuclear effects, but Hydrogen is sitting inside Plastic (CH_2). So, separation of v-H from v-C is required.**
- **Any interaction obeys energy-momentum conservation. Initially, transverse momentum is zero. Due to nuclear effects, final transverse momentum may not be zero. Using such Transverse Kinematic Imbalance (TKI), v-H can be separated from v-C.**

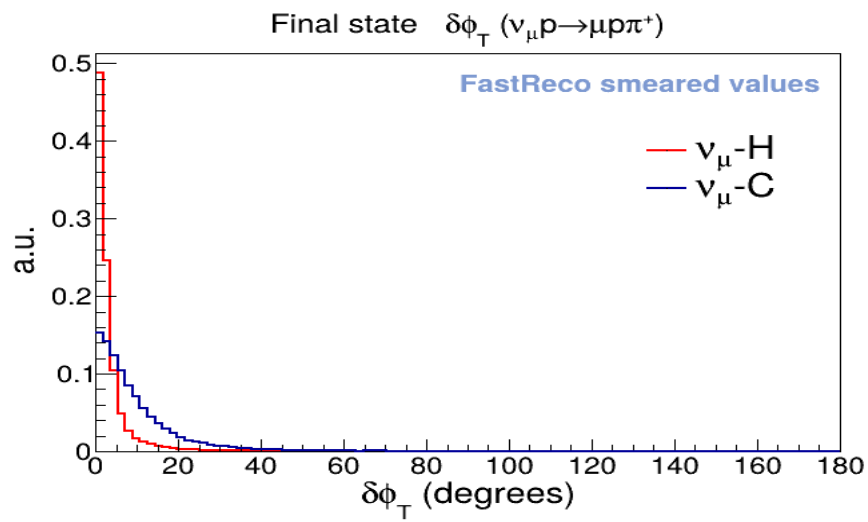


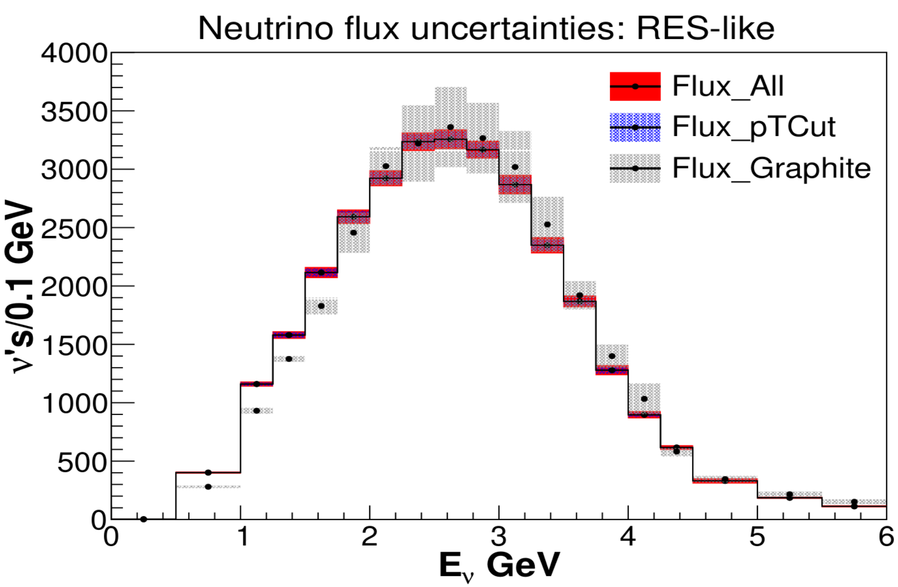
δp_T	Missing transverse momentum:- $\delta p_T = \lvert\vec{p}_T^{\ell} + \vec{p}_T^{had}\rvert$	Spread upto 1 GeV for v-C. Delta peak at 0 for v-H.
$\delta \varphi_T$	Angle between $-\vec{p}_T^{\ell}$ and $\vec{p}_T^{had}$.	Spread in 0-180° region for v-C. Delta peak at 0° for v-H.
$\delta \alpha_T$	Accelerating/Decelerating FSI:- Angle between $\delta\vec{p}_T$ and $-\vec{p}_T^{\ell}$.	Spread in 0-180° region for v-C. N.A. for v-H.

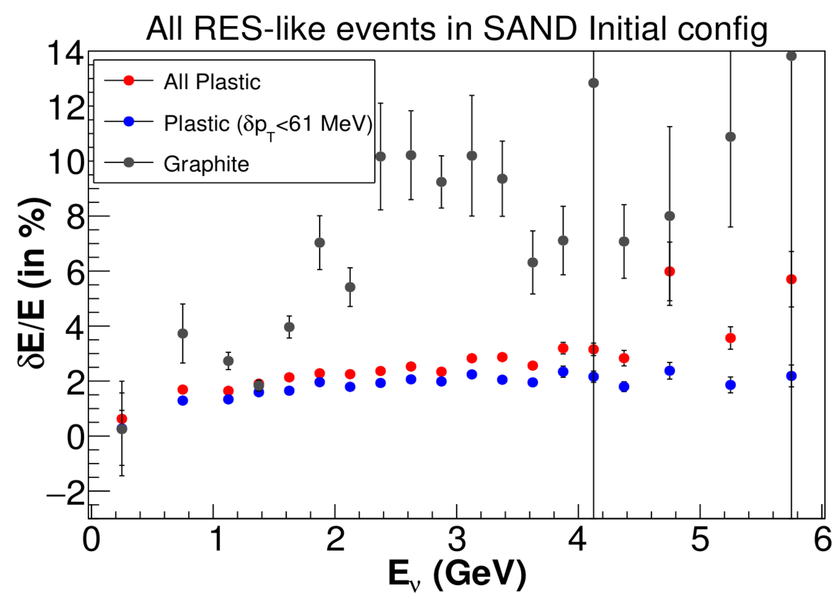
STT: Separation of $\nu - H$ from $\nu - C$

Shailesh Pincha, B. Bhuyan





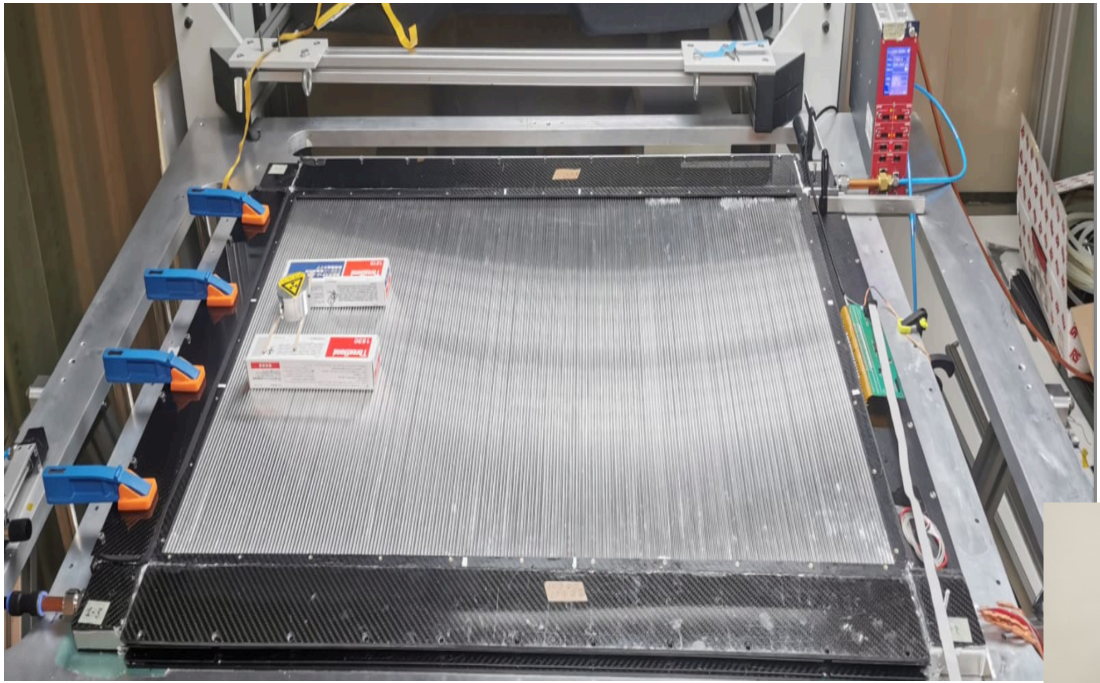




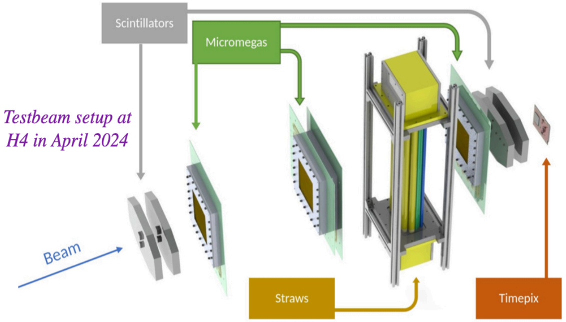
STT can bring down the flux uncertainties to below 2% using $\nu - H$ interaction sample . Using subtraction technique, the uncertainties can be brought down to 1% level.

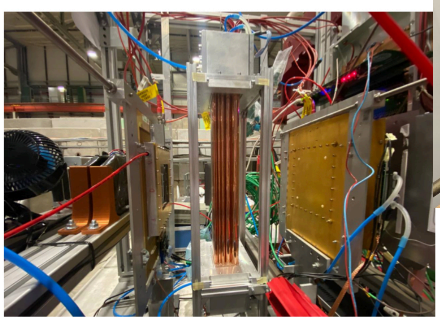
STT Prototyping in Collaboration with JINR and DRD1

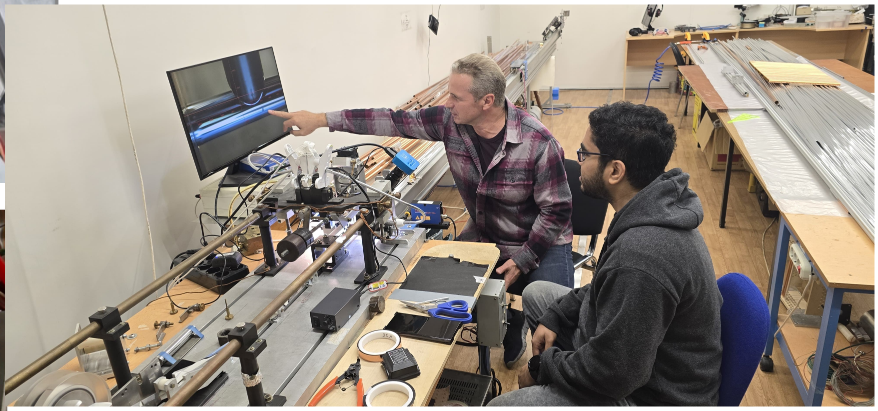
- **To demonstrate the technology, we have collaborated with JINR colleagues to build a 1.2 m x 0.8 m prototype (5 mm diameter, 2 μm wire) at CERN.**



- Test beam exposure in H4 SPS at CERN (April – Oct, 2024)
  - 4 MicroMega external trackers (3 X +1 Y) with pitch 250 μm.
  - Coincidence of 2 scintillators for time reference.
  - External Si-pixel tracker (50 μm x 50 μm)
  - Common readout based on both Tiger and VMM3 ASIC for all sub-detectors.





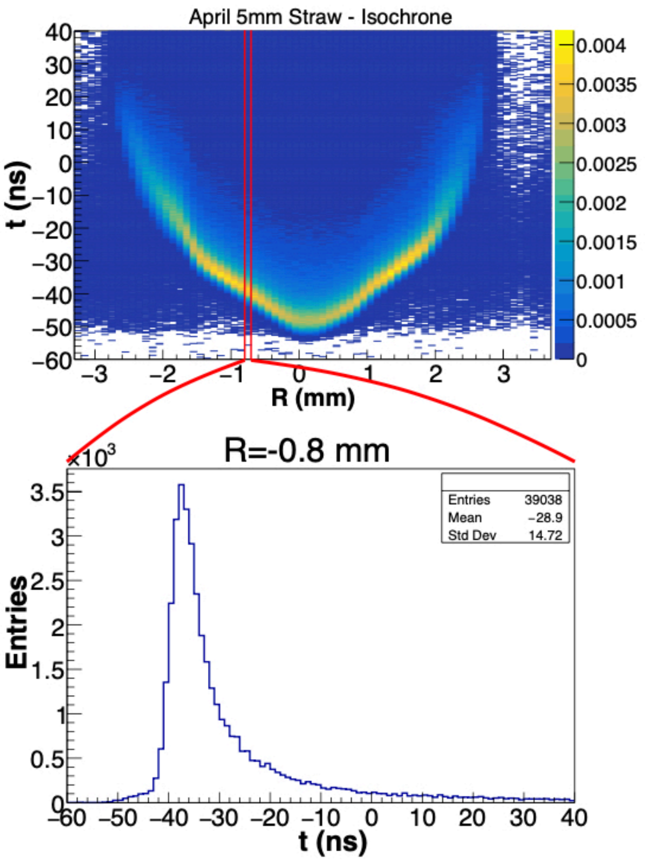


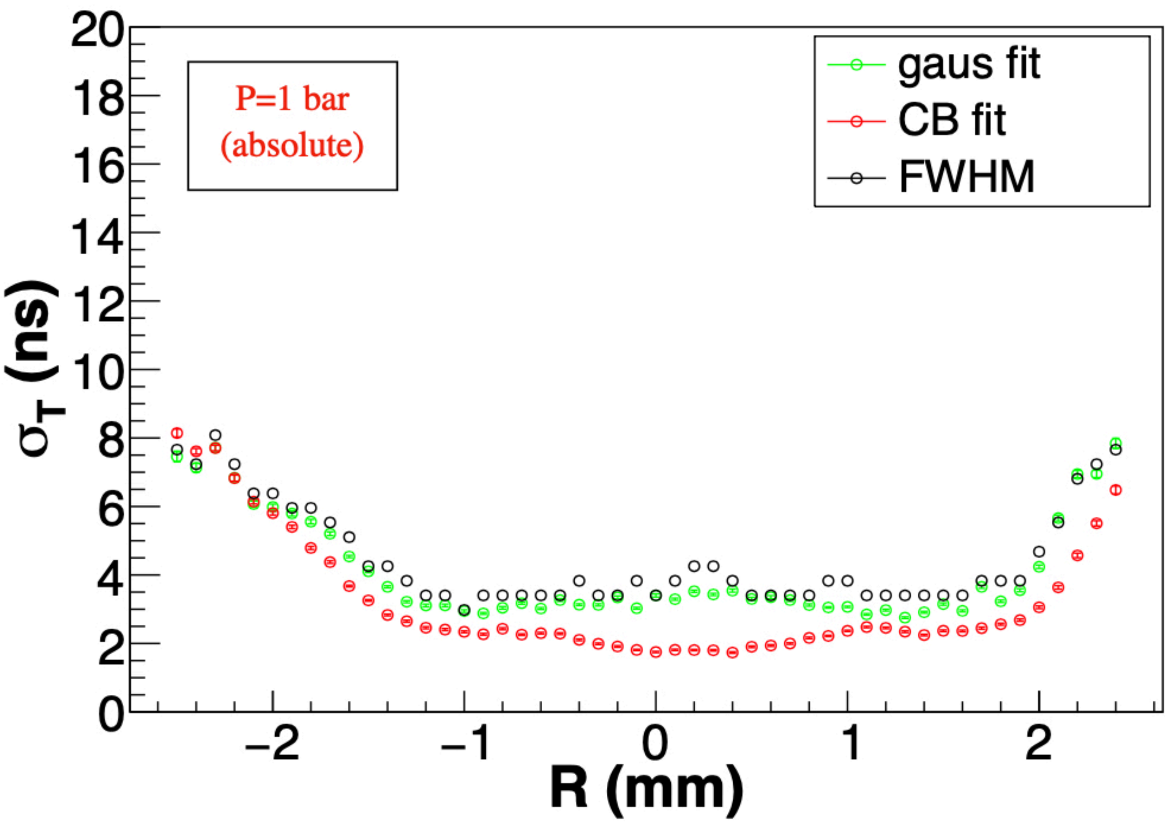
See Shailesh Pincha's poster on Test Beam data analysis from the STT prototype.

STT Test Beam Analysis Results

Shailesh Pincha, B. Bhuyan

Preliminary timing resolution of straws measured at the SPS H4 test beam in 2023. Consistent with the expected single hit space resolution of $\leq 200\ \mu m$.





MOU with JINR for the Development of STT Detector

Cooperation agreement
№ 426
Between

Joint institute for nuclear research,
Address: 6, Joliot-Curie str., Dubna, Moscow region, 141980, Russia,
represented by:
Position: Director
Name: Trubnikov Grigoriy Vladimirovich
Acting by virtue of: Statute
hereinafter referred to as "JINR",
and

Indian Institute of Technology Guwahati
Address: North Guwahati, Assam, India
Position: Director
Name: Professor Devendra Jalihal
Acting by virtue of: Statute
hereinafter referred to as "IITG",

Hereinafter JINR and IITG are jointly referred to as the "Parties" and each individually as a "Party"

On the following:

1. Cooperation

1.1. This agreement provides a framework and main course of cooperation between the Parties in relation to:
Subject area of cooperation: Research and Development of Straw Technologies
Theme in accordance with the Topical plan for JINR research (if any): 02-1-1065-4-2020/2024, 02-2-1099-2010
The Parties acknowledge that their intention is to achieve the following results of cooperation:

- Exchange of scientists, engineers and students for short-term and long-term periods;
- Joint supervision of PhD students;
- Production of straw tubes and assembly of the SPD Straw Tracker Prototype at the JINR facility;
- Assembly of the large scale (4 by 3.2 m) Straw Tracker Prototype at the JINR facility, for future possible large scale neutrino and high energy physics experiments;
- Other forms of cooperation as may be mutually decided upon;

1.2. This agreement shall be effective from the date when signed by the last Party for a five (5) year period unless earlier discontinued. If either Party wishes to terminate the agreement, it must notify the other Party in writing of its intention to terminate the agreement at least 30 days prior to the end of the then current term.

1.3. The Parties appoint the following representatives to coordinate the works hereunder:
At JINR:
Name: Temur Enik
Position: Group Leader
E-mail: temuren@jinr.ru, temur.enik@cern.ch
Tel.: +79166700784

At the IITG:
Name: Bipul Bhuyan
Position: professor
E-mail: bhuyan@iitg.ac.in
Tel.:. +913612582710

2. Common provisions

2.1. This agreement shall not form any financial liabilities of the Parties and does not provide for any contributions to be made by the Parties. This agreement forms a basis for conclusion of additional agreements in the scope of this agreement.

2.2. Each Party bears its own costs and expenses in respect hereto.

2.3. Nothing in this Agreement shall be construed as authorization of any of the Parties to act as agent for the other Party or to transact business on behalf of that Party or to make representations, warranties or representations to third parties. Nothing in this Agreement may be construed as creating any joint venture or partnership between the Parties.

2.4. The Parties undertake to keep the results of joint researches confidential and to disclose them to third parties only by mutual agreement.

2.5. The Parties mutually do not give each other any express or implied guarantees as to the achievement of any results in the implementation of the joint work.

2.6. The Parties acknowledge that, by entering into this agreement, they did not intend to create obligations, the fulfilment of which may be enforced by a court or for the failure to fulfil which the party may be held liable.

2.7. All amendments and additions to this agreement shall only be valid if made in writing and signed by authorized signatories of both parties. This Agreement is drawn up in two copies with equal legal force, one for each party. This Agreement is drawn up in two languages - Russian and English. The text in both languages shall be equally authentic.

2.8. All disputes that may arise in connection with the conclusion, performance or termination of this agreement shall be settled exclusively by negotiation between the Parties.

Signed on this date

07.10.2024

G.V. Trubnikov　　　　Professor Devendra Jalihal

निदेशक
भारतीय प्रौद्योगिकी संस्थान गुवाहाटी
गुवाहाटी-७८१०३९
Director
Indian Institute of Technology Guwahati
Guwahati-781039

Объединенный институт ядерных исследований

Continuation of an earlier MOU from 2015

Signed on October 7, 2024

Salient points of the MOU:

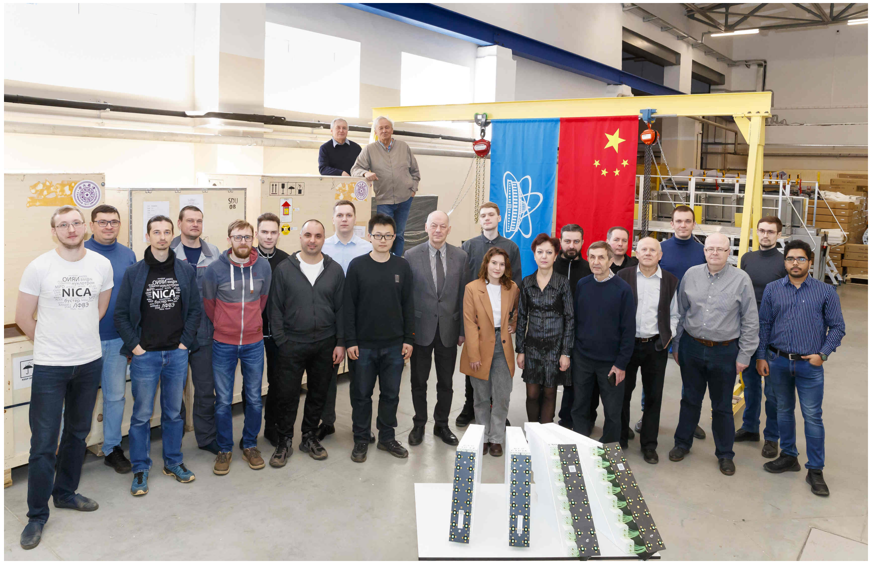
- Exchange of scientists, engineers and students for short-term and long-term periods;
- Joint supervision of PhD students;
- Production of straw tubes and assembly of the SPD Straw Tracker Prototype at the JINR facility;
- Assembly of the large scale (4 by 3.2 m) Straw Tracker Prototype at the JINR facility, for future possible large scale neutrino and high energy physics experiments;

Collaboration with JINR during the first MOU Period

NICA MPD-ECAL:

- ECAL shashlik tower (cell): ~40 cm length, 220 scint.+Pb layers, ~40 mm² cross-section, WLS fibers
- ECAL module: 8x2 tower config, 8 module types due to projective geometry
- Good modules → glued into clusters (8×2 modules), then baskets (8×6, 48 modules). Installation of readout plates (each with 16 SiPMs in 8x2 config), ADC electronics, cooling pipes, power/data cables completes a basket
- 50 baskets (25 per half) constitute the entire barrel ECAL for MPD of NICA

- Maharnab's contribution:
  - Test & analysis of LED calibration data, derived temperature corrected operating voltages for SiPMs.
  - Cosmic muon test and analysis for more than 2100 modules, developed analysis methods for e-beam data.
  - final assembly of readout plates, connectors, sealing, baskets post-testing.
  - LED+ cosmic muon tests and analysis of the runs for 24 of 42 assembled baskets.



At ECAL assembly and testing hall with members of MPD team, JINR

Presenting ECAL status at XI MPD meeting (JINR, 2023)

Summary

- DUNE will use a broadband beam and long baseline (1300 km) to make precise and simultaneous measurements of the mass ordering, the CP-violation phase, and the neutrino mixing angles.
- Successful run with the protoDUNE since 2018 at CERN.
- Expect first DUNE FD data in early 2029, 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.
  - **It is important that India reaps the benefit by actively participating in the DUNE science program**
  - **Indian institutions are engaged in the development of the STT based tracker for the SAND ND.**

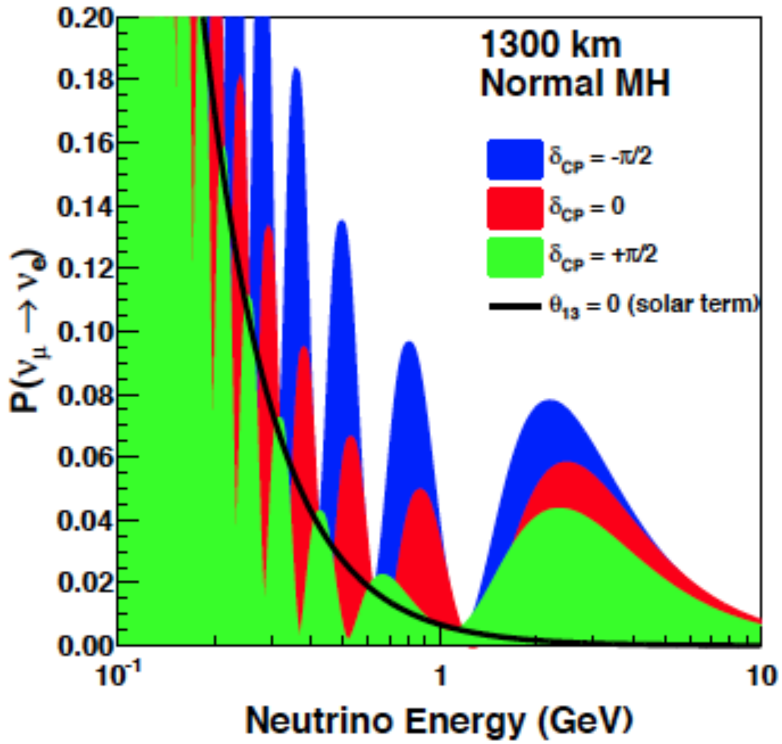
- Looking forward to a continued productive collaboration with JINR on the development of advanced detector technologies for future applications in HEP.

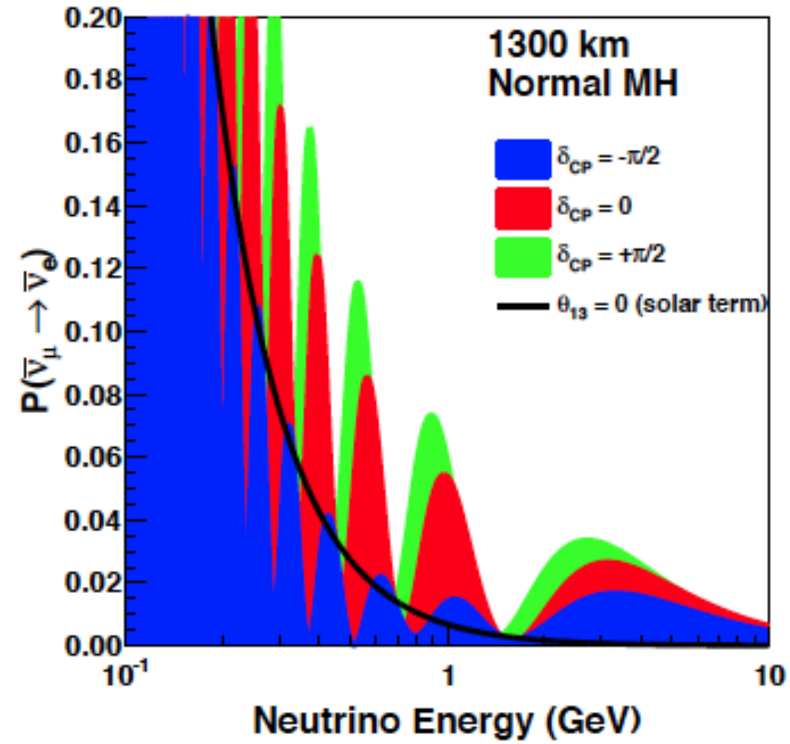
Backup

DUNE Neutrino Oscillation Strategy

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

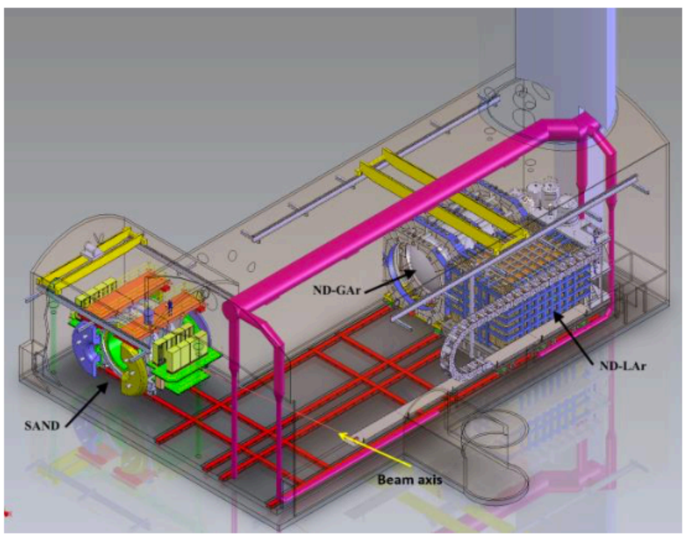
- ν_e appearance probability depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects. All four can be measured in a single experiment.
- Wide-band beam covers 1st and 2nd oscillation maxima

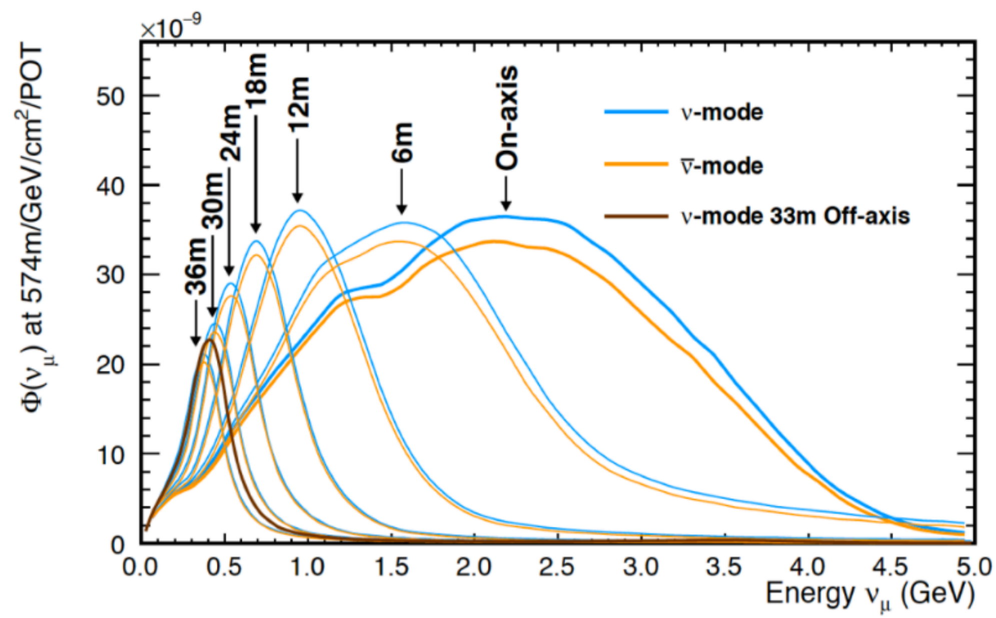




Near Detector (ND) – PRISM Concept

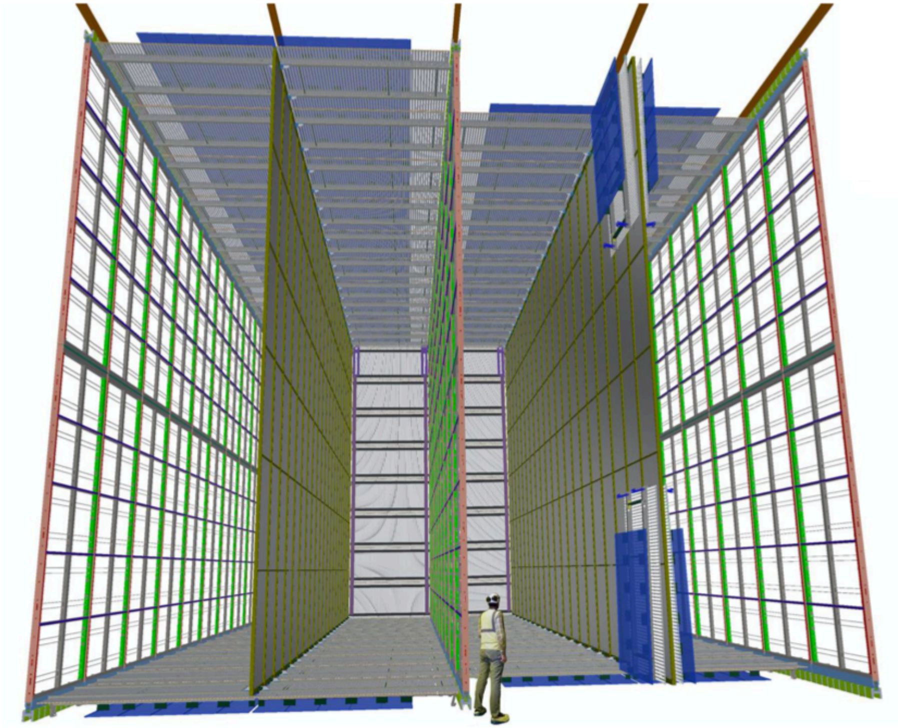
- ✓ Precision Reaction-Independent Spectrum Measurement
- ✓ Moving ND Detectors (ND-LAr & TMS) by 30 m results in different measured energy spectra
  - ✓ Linear combination of these spectra can better reproduce oscillated FD spectrum, which will reduce uncertainties.



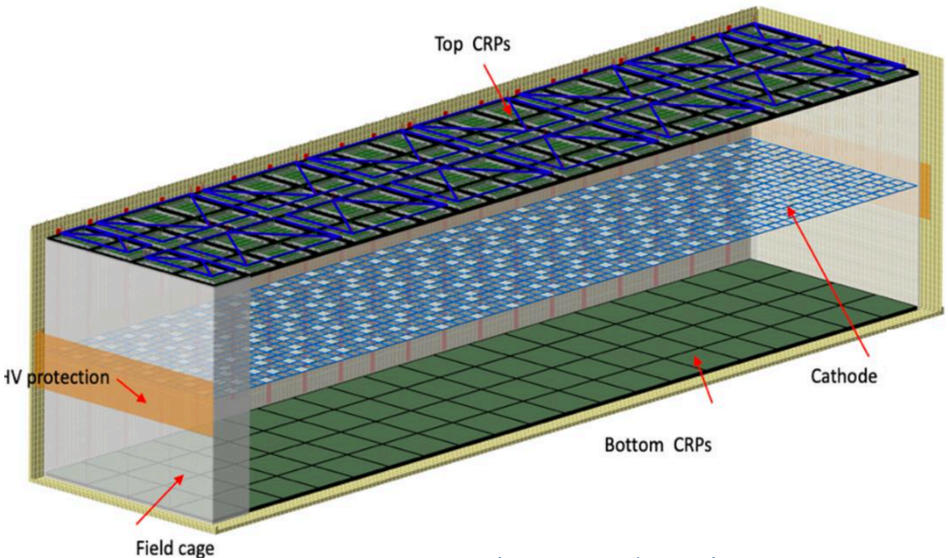


Two Far Detector Modules

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



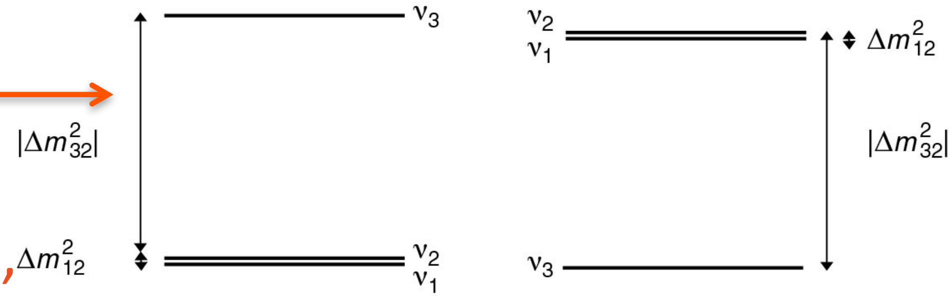
- **Vertical Drift Module**
  - Evolved from dual-phase design
  - 6.5 m vertical drift
  - Anode-cathode-anode geometry
- Charge readout via printed circuit boards
- Photon detector in cathode plane



CRP: Charge Readout Plane

DUNE Science Program

- Neutrino Oscillation Physics
  - **Search for leptonic (neutrino) CP Violation**
  - Resolve the mass ordering ($m_3 > m_{1,2}$ or $m_{1,2} > m_3$)
  - Precision oscillation physics
    - ✓ Parameter measurements,
    - ✓ **Testing the current 3-neutrino model, non-standard interactions, …**

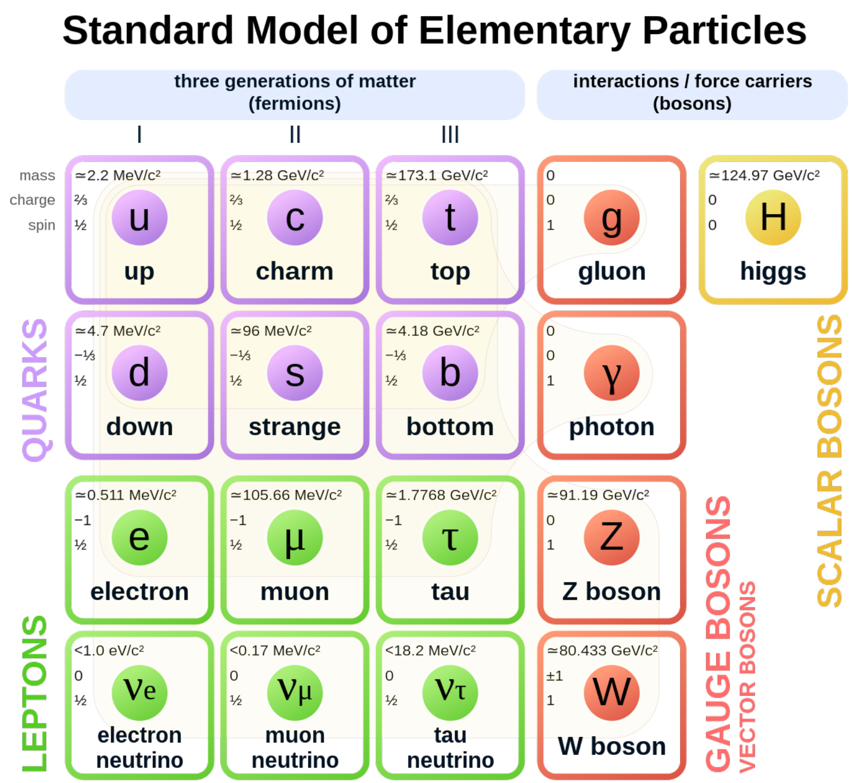


- Supernova burst physics and astrophysics
  - 3000 ν_e events in 10 sec from SN at 10 kpc
- Nucleon Decay

+ many other topics (ν interaction physics with near detector, atmospheric neutrinos, sterile neutrinos, WIMP searches, Lorentz invariance tests, etc.)

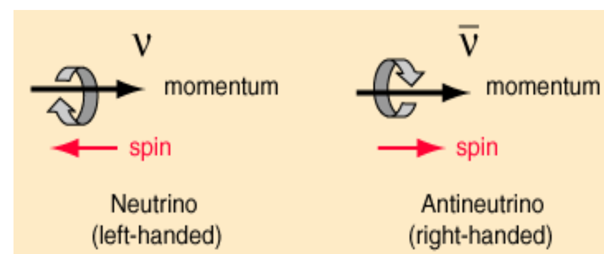
Neutrinos in the Standard Model

✓3 generations of Quarks and Leptons:



- 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



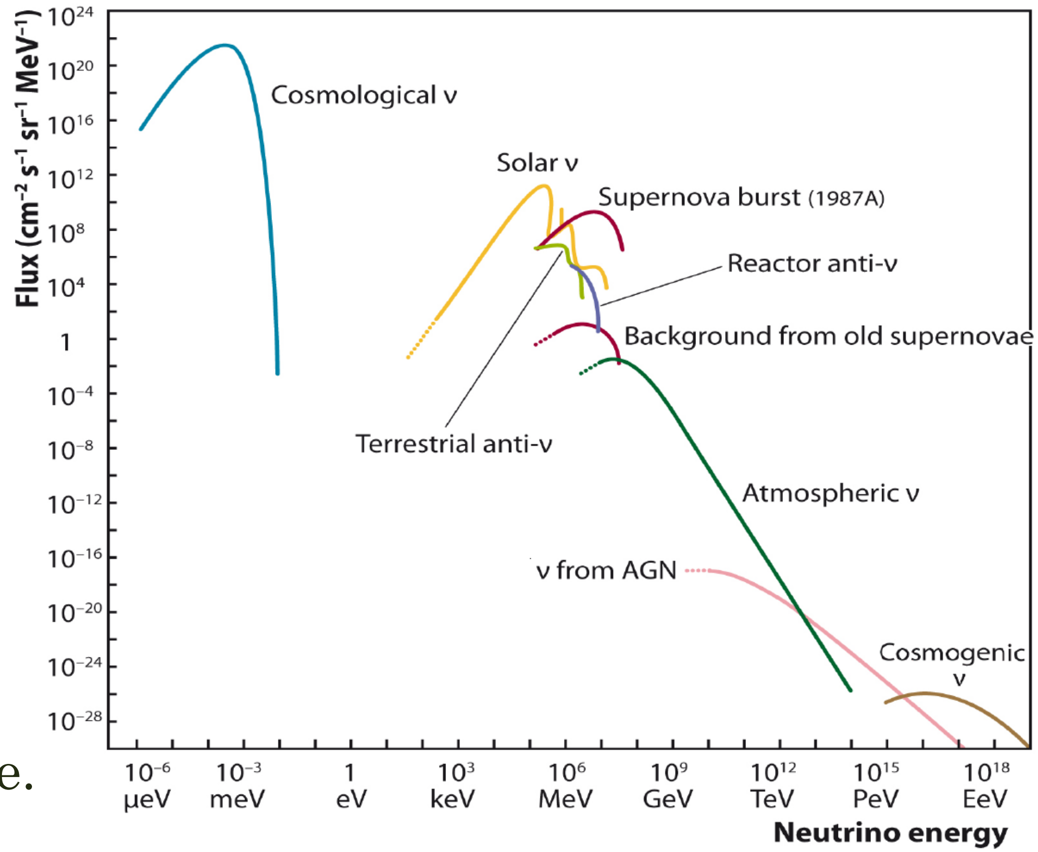
✓Neutrino interaction cross sections are small, $\mathcal{O}(10^{-38}\ cm^2/nucleon)$ at 1 GeV.

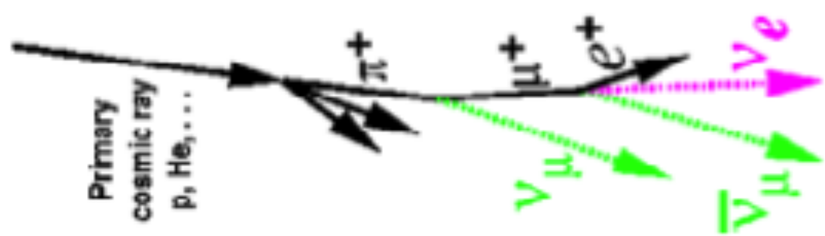
✓100,000 billion pass through your body each second from the sun.

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

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.

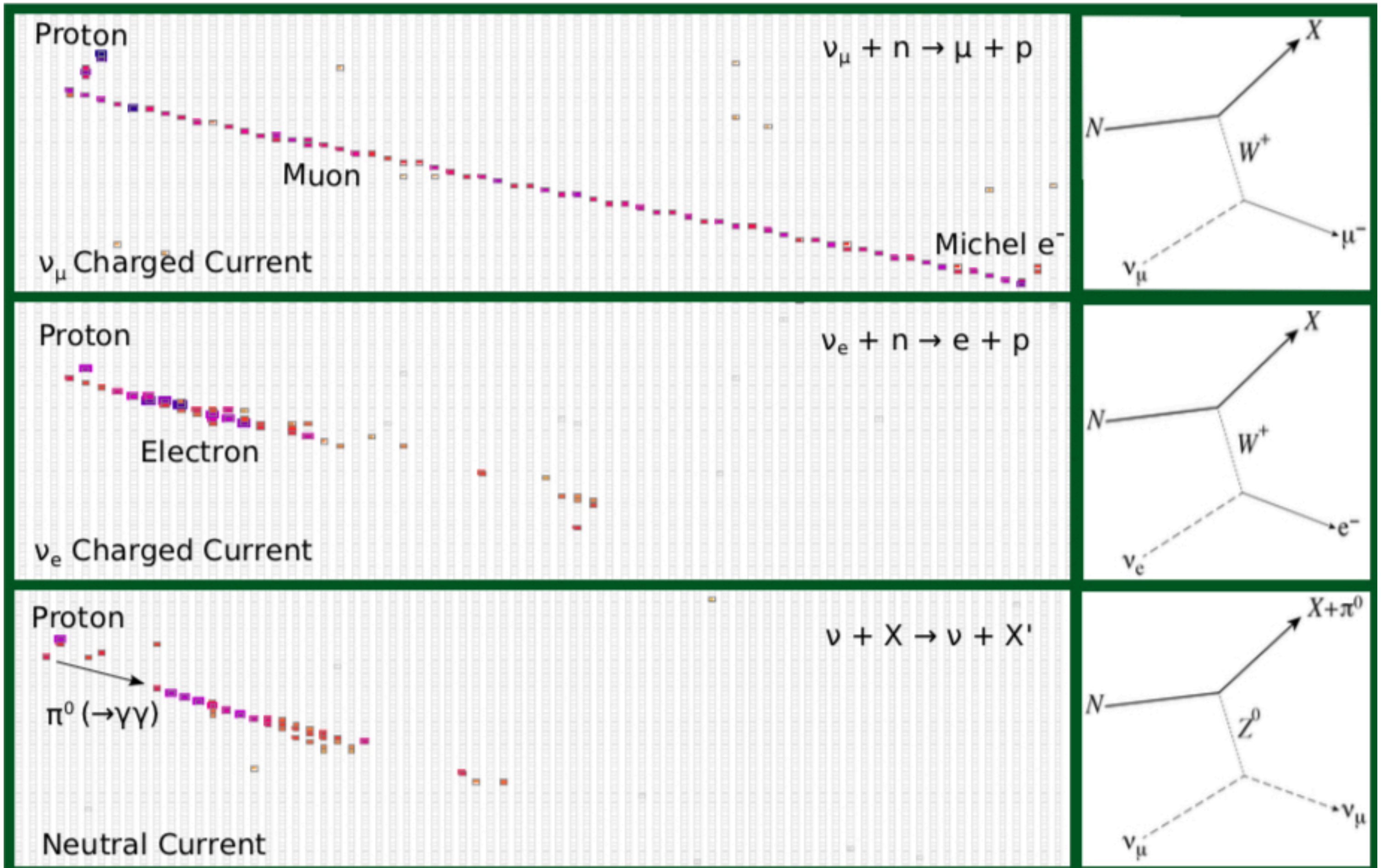




On Average 2 muon neutrinos are produced for every electron neutrino in the atmosphere.

How to detect a Neutrino?

- ✓ Neutrinos do not have electric charge. They only interact weakly.
  - So, we see only the by products of the weak interactions.



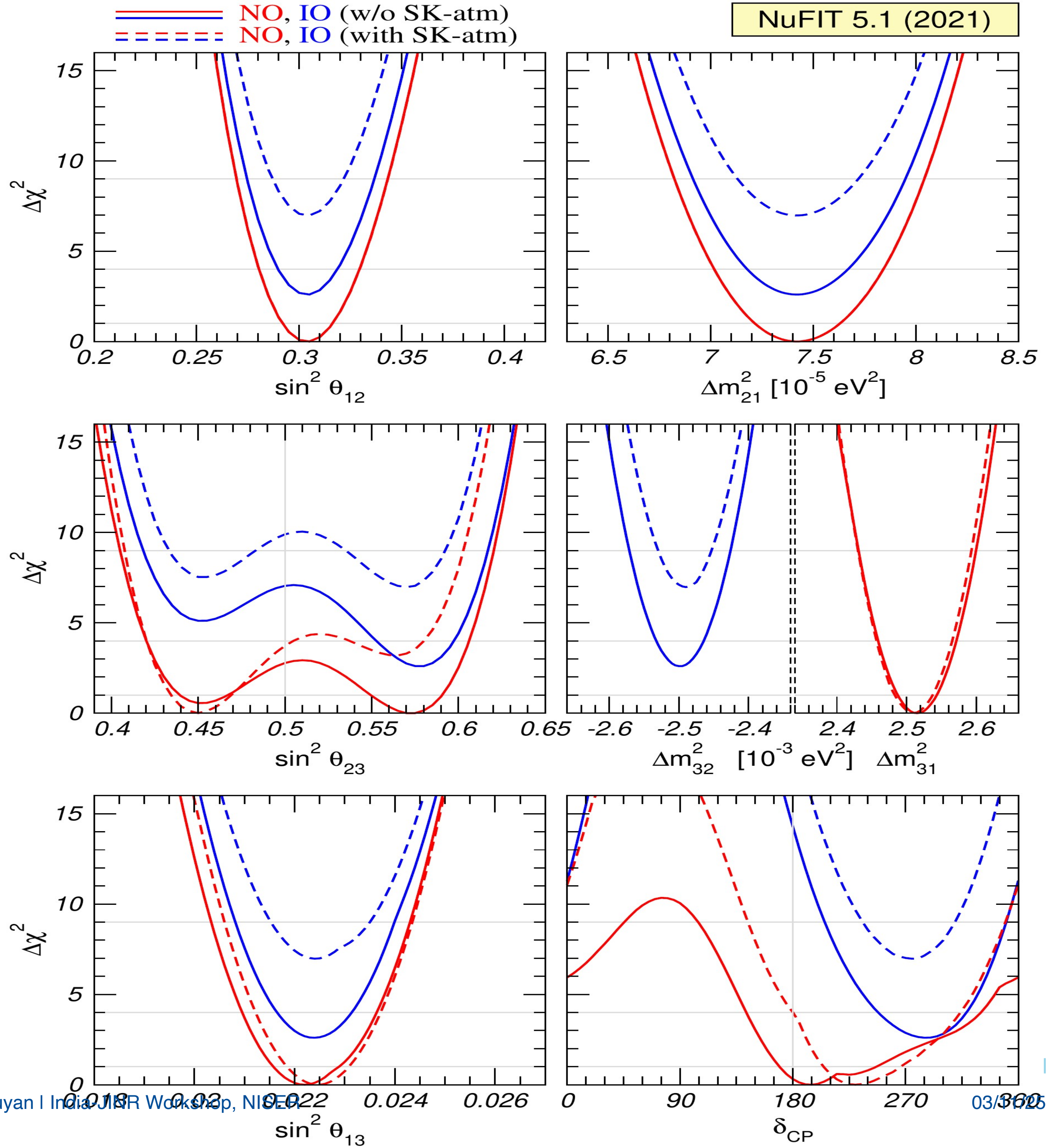
NuFIT 5.1 (2021)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{\rm CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

with SK atmospheric data

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

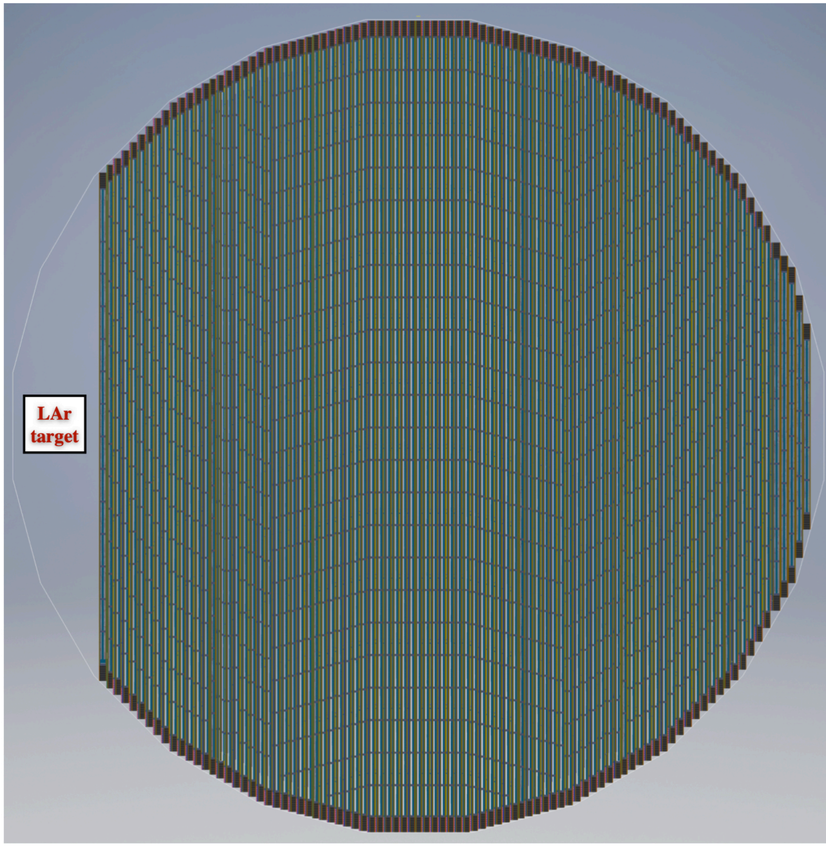


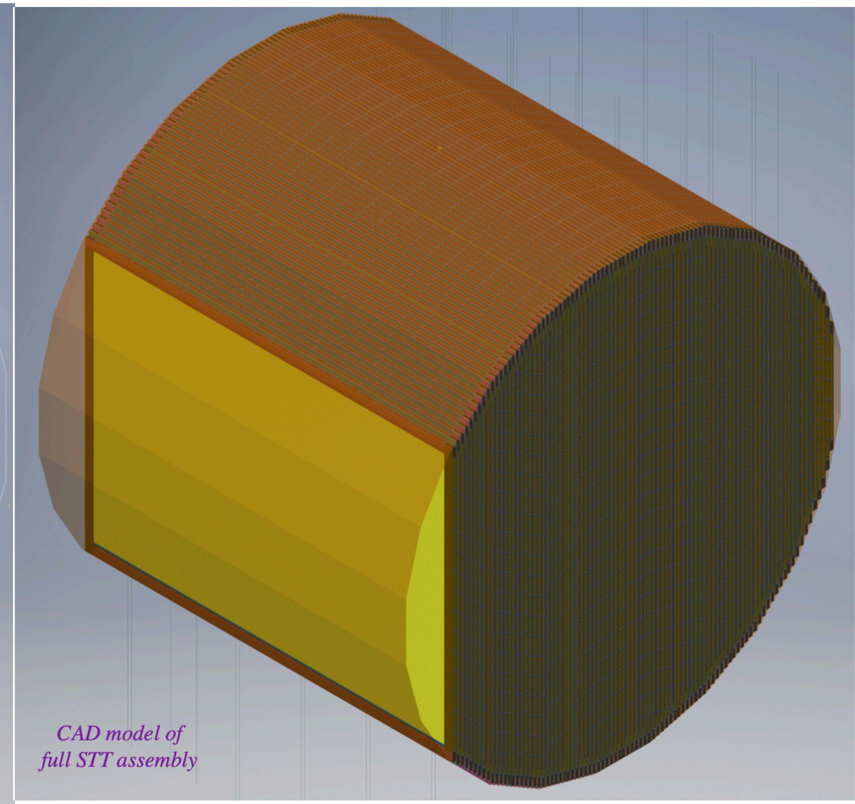
NO, IO (w/o SK-atm)
NO, IO (with SK-atm)
NuFIT 5.1 (2021)
$\Delta\chi^2$
$\sin^2\theta_{12}$
Δm^2_{21} [10^{-5} eV^2]
$\sin^2\theta_{23}$
Δm^2_{32} [10^{-3} eV^2] Δm^2_{31}
$\sin^2\theta_{13}$
δ_{CP}

CAD model of full STT assembly:

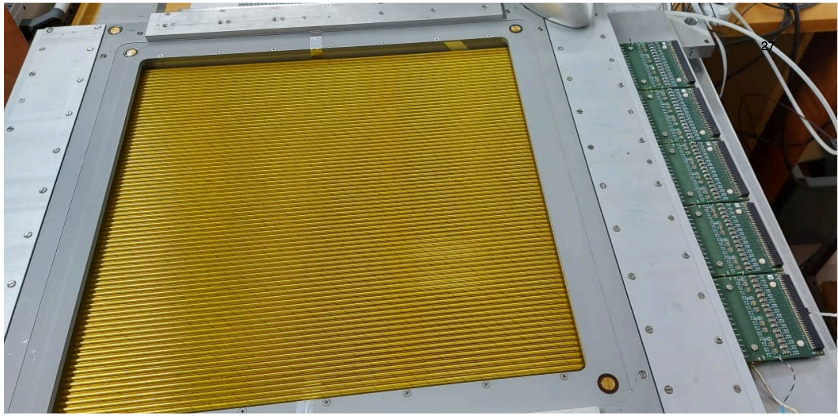
78 CH_2 modules
7 C modules
5 tracking modules

FV mass:
4.7 t CH_2
557 kg C





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

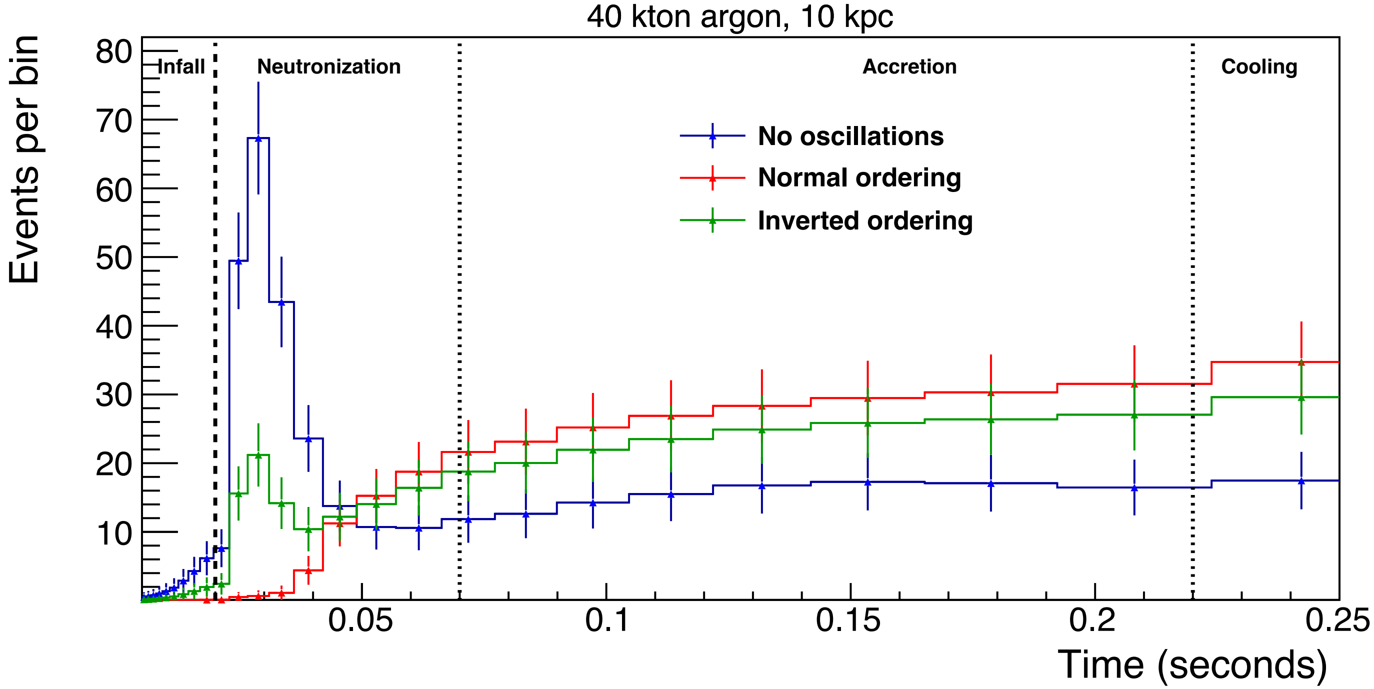
- Ratio of ν_e/ν_μ AND $\bar{\nu}_e/\bar{\nu}_\mu$ vs. E_ν from CH_2 (& H) targets
  $\Longrightarrow$ Excellent $e^\pm$ charge measurement and $e^\pm$ identification ($\sim$ 75k $\bar{\nu}_e$ CC in FHC)

- 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

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



SN Neutrinos in DUNE

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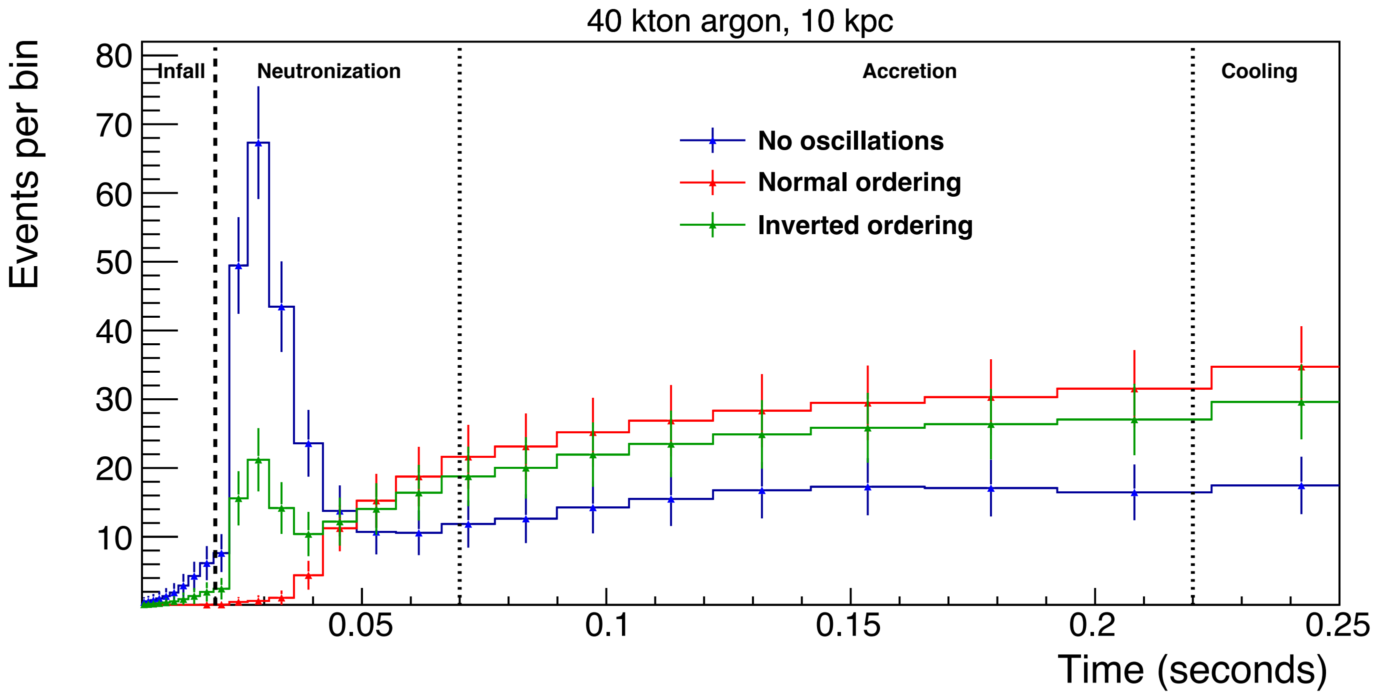
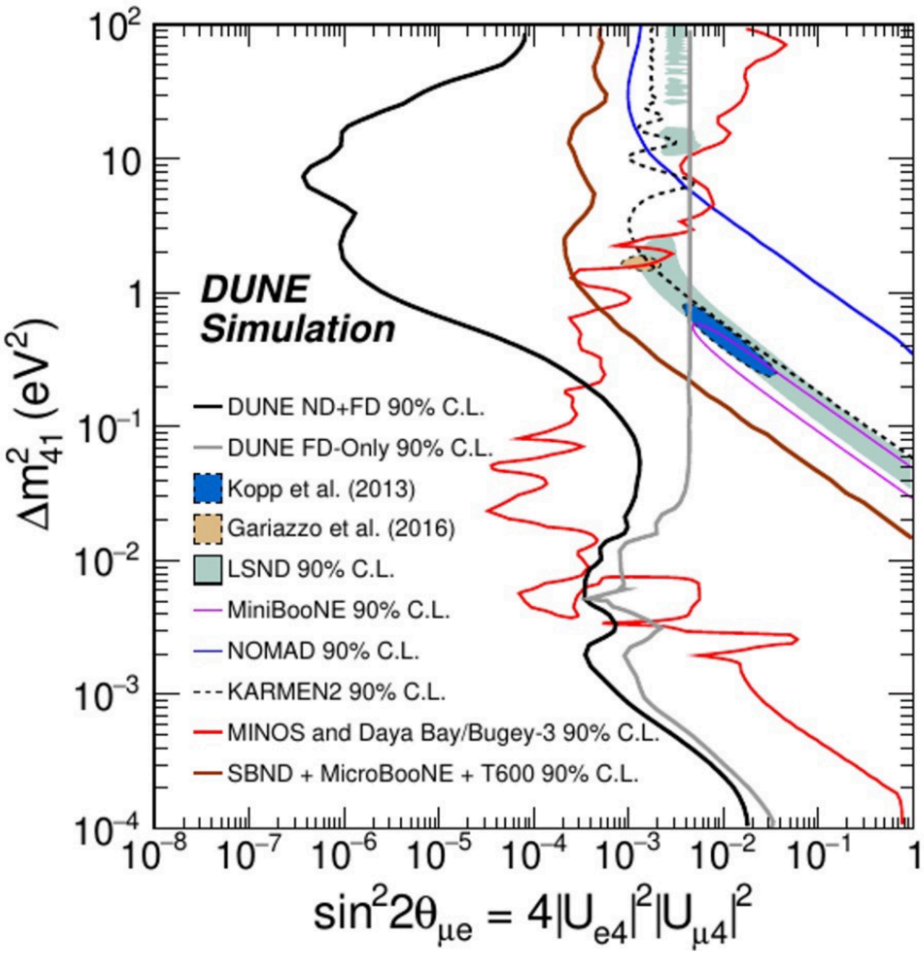


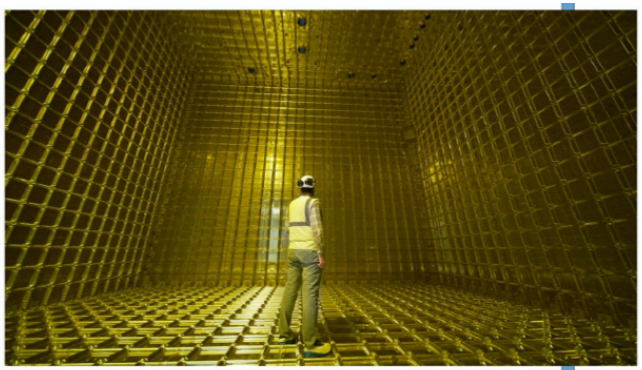
BSM Searches

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

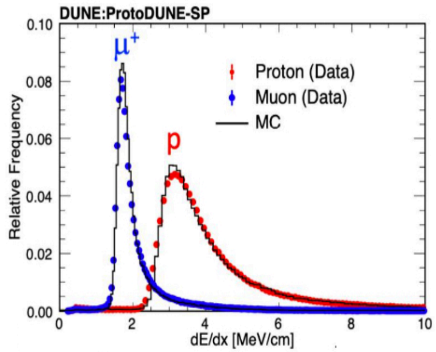
Sterile Neutrino Sensitivity
(ν_e CC appearance at ND)

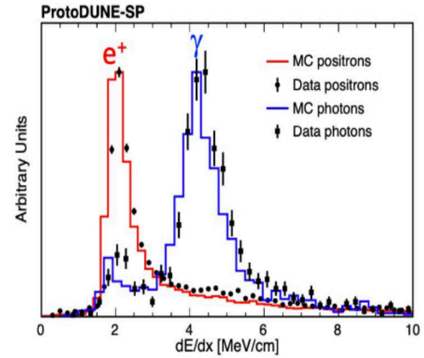


DUNE FD Prototypes at CERN



- Two 6 x 6 x 6 m^3 Module-0 currently at the CERN Neutrino Platform, CERN's beam in the North Area.
  - ✓ Beam (0.3- 7 GeV hadrons, 4 x 10^6 triggers) & cosmics collected in ProtoDUNE-HD during 10/2018 – 07/2020.
  - ✓ High $\epsilon_{reco}(\sim 100\%)$ & beam particle ID (~80%), excellent e/γ and μ/p separation.
- ProtoDUNE Phase-I (2018-2020)
  - ✓ Successfully demonstrated the horizontal drift technology, reaching or exceeding DUNE specifications.
  - ✓ Several analyses ongoing (h-Ar cross sections, calibrations, detector response.
- ProtoDUNE Phase-II (2020-)
  - ✓ Two modules, an upgraded horizontal and a vertical drift constructed.
  - ✓ Run-II of the HD completed in September, Run-I for the VD starting in early 2025 (transferred argon already).



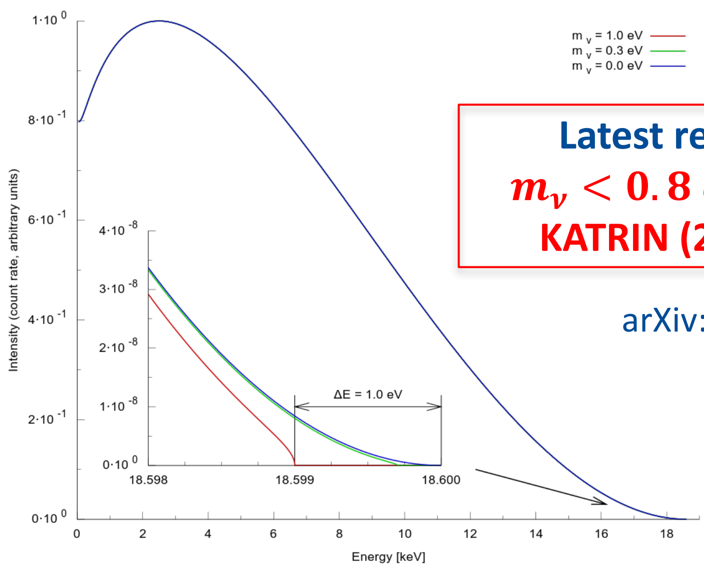


First R&D and physics results [JINST 15 (2020) 12, P12004

Known Unknowns: Neutrino Mass

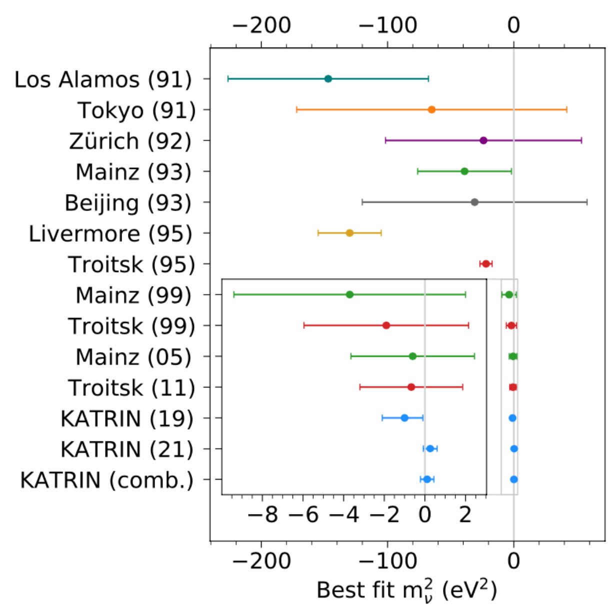
- Yet to be measured. Exisitng limits:
  - Cosmological observations: $\sum m_i < 0.12\ eV\ (95\%\ CL)$. Strongly relies on the underlying cosmological assumptions
  - Neutrinoless double β-decay experiments: $m_{\beta\beta} < 0.08\ - 0.18\ eV\ (90\%\ CL)$, depending the on the nuclear matrx element 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)

- 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



Progress in Neutrino Physics and the Nobel Prizes

Credit to APS

The Growing Excitement of Neutrino Physics

- 1930: On-paper appearance as "desperate" remedy by W. Pauli
- 1956: $\bar{\nu}_e$ first experimentally discovered by Reines and Cowan
- 1962: ν_μ existence confirmed by Lederman *et al.*
- 1998: Atmospheric neutrino oscillations discovered by Super-K
- 2000: ν_τ first evidence reported by DONUT experiment
- 2001: Solar neutrino oscillations detected by SNO (KamLAND 2002)
- 2011: $\nu_\mu \rightarrow \nu_\tau$ transitions observed by OPERA
- 2011-13: $\nu_\mu \rightarrow \nu_e$ by T2K, $\bar{\nu}_e \rightarrow \bar{\nu}_e$ deficit observed by Daya Bay(2012)
- 2015: Nobel prizes for ν oscillations, Breakthrough prize (2016)

Nobel & Breakthrough for ν oscillations
T2K observe $\nu_\mu \rightarrow \nu_e$ appearance
Daya Bay observe theta 13 at 5 sigma
K2K confirms atmospheric oscillations
KamLAND confirms solar oscillations
Nobel Prize for neutrino astroparticle physics!
SNO shows solar oscillation to active flavor
Super K confirms solar deficit and "images" sun
Super K sees evidence of atmospheric neutrino oscillations
Nobel Prize for ν discovery!
LSND sees possible indication of oscillation signal
Nobel Prize for discovery of distinct flavors!
Kamioka II and IMB see supernova neutrinos
Kamioka II and IMB see atmospheric neutrino anomaly
SAGE and Gallex see the solar deficit
LEP shows 3 active flavors
Kamioka II confirms solar deficit

Pauli predicts the Neutrino
Fermi's theory of weak interactions
Reines & Cowan discover (anti)neutrinos
2 distinct flavors identified
Davis discovers the solar deficit

1930 — 1955 — 1980 — **2015**