Indian Institute of Technology Guwahati

Overview of India-Fermi Lab Collaboration in Neutrino Physics

Bipul Bhuyan

DUNE-India Workshop, TIFR

June 6, 2025

Phase I & II: 2012 - 2026

- An on-going collaboration with Fermi Lab Neutrino Physics experiments since 2012.
- Department of Science and Technology (DST, GoI) has provided the necessary funding to the Indian institutions for collaboration on Neutrino Experiments at Fermi Lab under Mega Science Scheme.
  - Fermi Lab contributed 2 M USD to support our students at Fermi Lab on 50% cost sharing basis. Long stay of Indian students was possible.
  - Participation in: MINOS, MINOS+, MIPP, MINERVA, NoVA and DUNE experiments during the first two phases.
  - 10/9 participating institutions: AMU, CUSB, CUST, DU, UoH, PU, IITG, IITH, NISER, JU (only phase I)
- Mandate was to develop human resources in cutting edge technology including detector construction and operation, data analysis in Neutrino Physics.
  - Very successful program. Graduated 20 Ph.D. students so far. 18 additional students will graduate by 2026-2027.
- Phase II is coming to an end on 31 March 2026. Initiated discussion to prepare for the next phase.

Phase III: 2026+

- Phase III of the collaboration with Fermi Lab on Neutrino Physics has be primarily on DUNE experiment.
  - Additional participation in the SBN program is a possibility depending on the interest.
- We have recently concluded a vision exercise similar to P5 in USA, led by the Office of the Principal Scientific Advisor (PSA) to the GoI.
  - Goal it to prepare a blueprint for the participation in and development of Mega Science projects by Indian scientists till 2035.

A. Scientific Recommendations:

1. ***Top priority projects:*** This includes those MSPs that are in progress and should be fully supported.

c) Participation in a top-of-the-line international neutrino experiments such as DUNE is strongly desirable, especially if the possibility of participation in building an important component of detector hardware is envisaged.

The vision document supports Indian contribution to the STT project.

ANNEXURE A.2

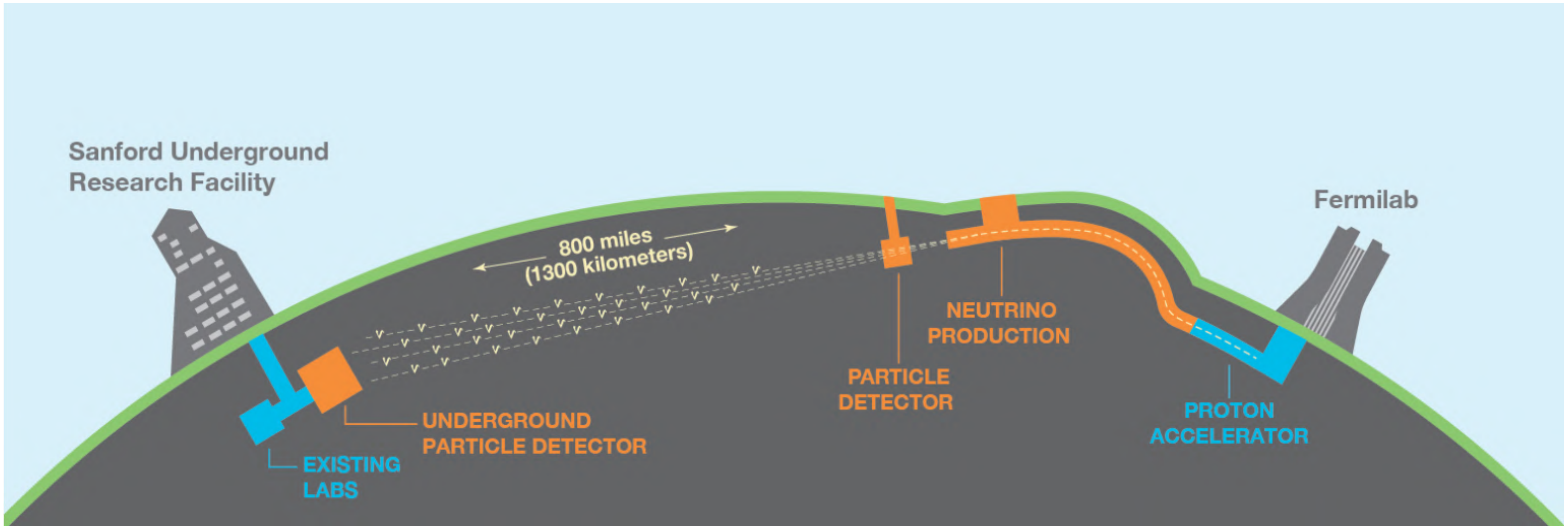
Tentative Assessment of Funding Requirements

		Years →	2021-2025		2025-2030		2030-2035	
Sec-tion	Name / Acronym of Project	Current/last sanctioned annual budget (Rs. Cr)	FTE personnel *	Funding (p.a.) (Rs. Cr)	FTE personnel *	Funding (p.a.) (Rs. Cr)	FTE personnel*	Funding (p.a.) (Rs. Cr)
3.2.3	DUNE	0	10	1	25	17	35	15

~ 20 M USD

Phase III Plan?

Deep Underground Neutrino Experiment



- $\nu_\mu\,(\bar{\nu}_\mu) \rightarrow \nu_e\,(\bar{\nu}_e)$ oscillations from Fermilab's PIP-II with 2.1×10^{21} POTs/yr.
- 40 kt fiducial Liquid-Argon in Far Detector 1300 km away from Fermilab at Sanford Underground Research Facility.
- Near Detector Complex 574 m away from Fermilab to reduce uncertainties.

δ_{CP} measurement;
Mass-hierarchy;
ν_τ oscillations;

Astrophysical Neutrinos;

Nucleon Decay;

Interest of the Indian Group on DUNE

- ✧ The Indian group on DUNE has shown interest in the Near Detector since LBNE era (~2010)
  - ✧ Interest has been on a **high resolution fine grained tracker with STT as the tracking volume**, 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

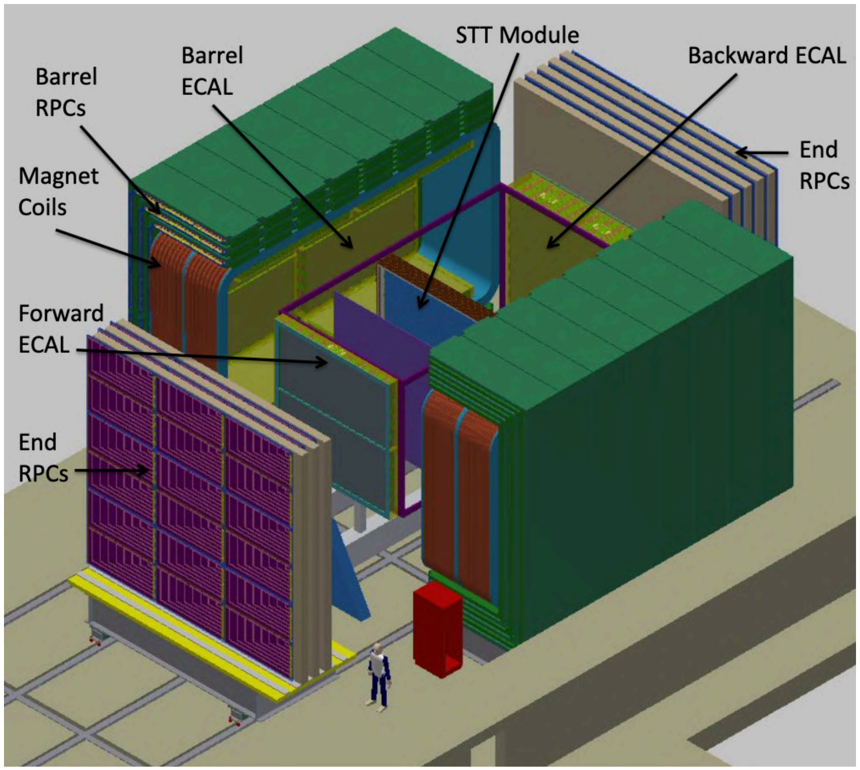
1. Detector technology for the Deep Underground Neutrino Experiment (DUNE), hosted by the United States
   a. Liquid Argon Time Projection Chamber (TPC) components
   b. Magnet design and fabrication
   c. High precision charged particle tracking
   d. Electromagnetic and hadron calorimeters
   e. Muon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

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.

An agreement based on reciprocity contribution of $US 10 million from DOE to INO project.

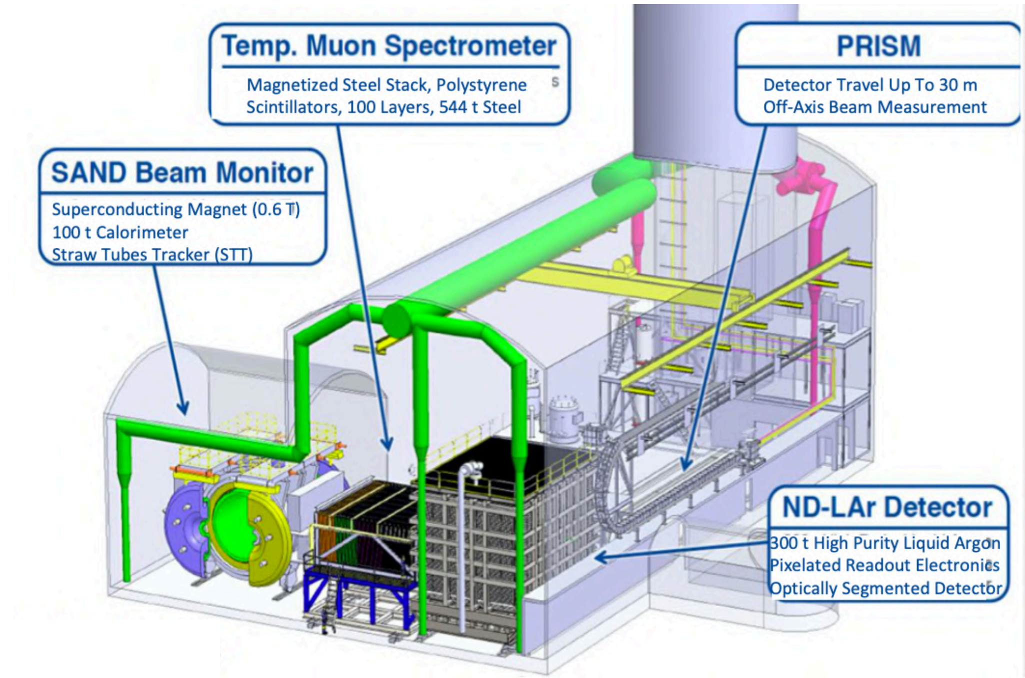
The Evolution of DUNE ND

- **The design of the DUNE ND has evolved significantly over the years:**



@ICHEP 2016, Chicago

✓ ND Hall Location:
- 574 m from the LBNF target
- ~ 60 m underground.



- An integrated system composed of multiple detectors:
  - Highly segmented LArTPC (ND-LAr): Same target as the FD.
  - Temp. Muon Spectrometer (TMS): Upgradeable to ND-GAr in Phase -II.
  - **System for On-Axis Neutrino Detection (SAND)**

STT remains as the baseline detector technology for the SAND tracking detector. We played a significant role in that decision making process in 2021.

Why SAND in the DUNE-ND system?

- The SAND detector is the only component within the near detector (ND) complex that will be permanently located on-axis along the neutrino beam from DAY-1, while ND-LAr and TMS/ND-GAr systems will move off-axis for about 50% of the time

- Crucial to have an on-axis beam monitoring to detect time-dependent spectral changes intrinsic to the beam, on a **weekly basis**

- The SAND system will continuously monitor the rate, spectrum and profile of the neutrino beam by measuring the event topology (energy+momentum) of the neutrino interactions on **event-by-event basis**.

- It will provide precision in-situ flux measurements of ν_μ , anti-ν_μ , ν_e , anti-ν_e (absolute and relative rates) for detailed fluxes determination and reduction of the DUNE-PRISM dependencies on neutrino beam modelling.

- Effectively, SAND will be able to perform many additional measurements, like improving the extrapolation of the ν and anti-ν fluxes to the far detector, constraining systematics from nuclear effects, neutron detection with ToF, being at very low risk against unknown unknowns

SAND in the ND hall

SAND will be permanently on-axis in a dedicated alcove

The schematic configuration is:

- a Superconducting Solenoid Magnet
- an Electromagnetic Calorimeter (ECAL)
- a Inner Tracker
- a thin active LAr target

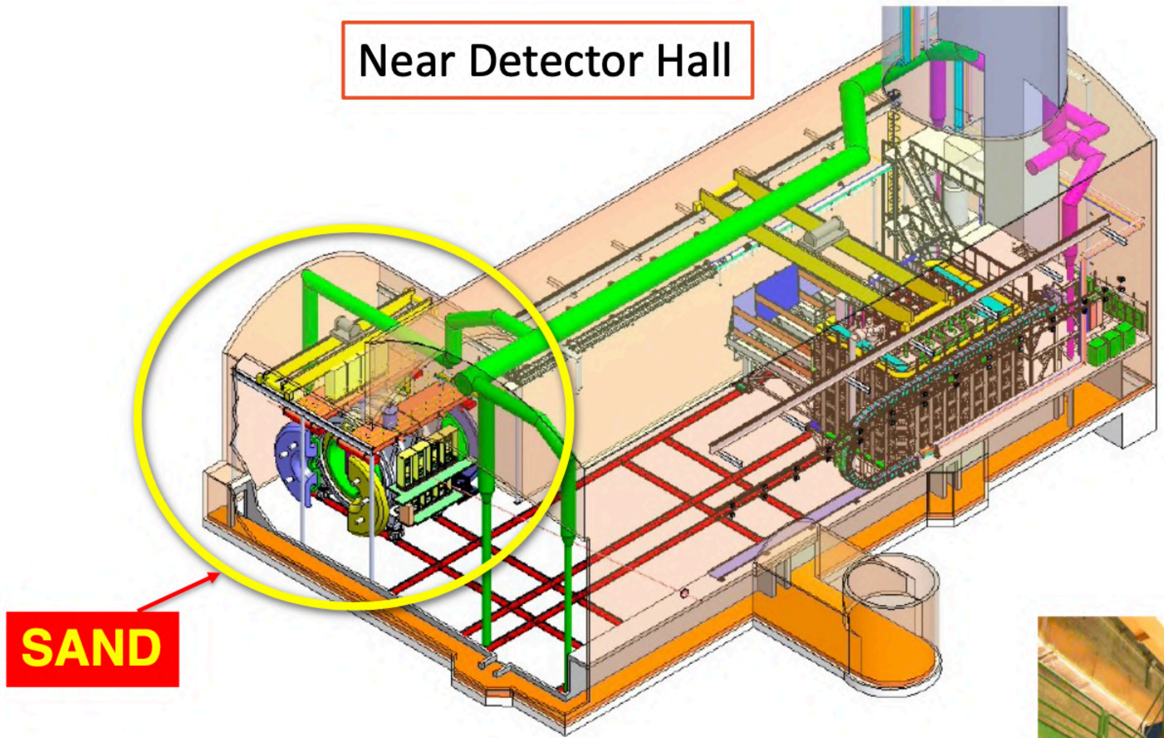
(Superconducting Solenoid Magnet and ECAL: in-kind from KLOE experiment (LNF-Italy))

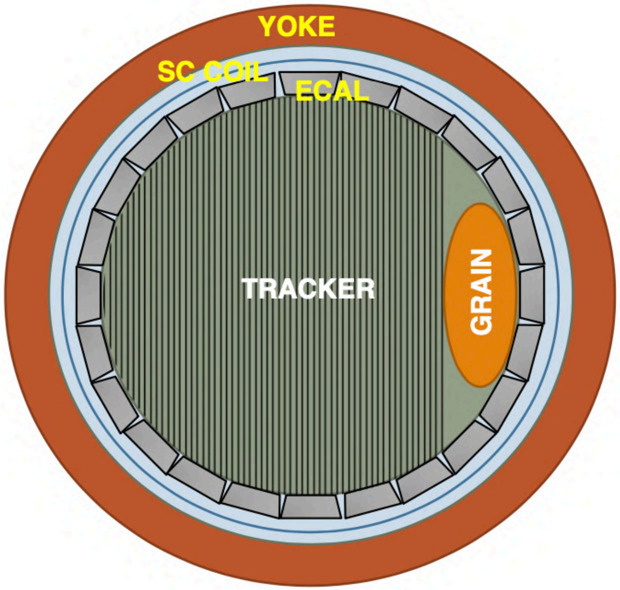
Inner Tracker

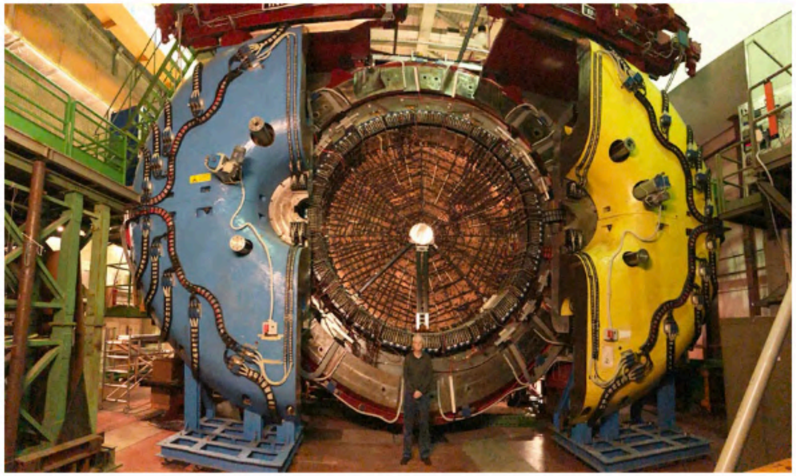
- 3 different detector concepts were under discussion for the inner tracker detector
  - a 3D projection scintillator tracker (3DST) as active neutrino target.
  - a low-density tracker (TPC) to measure particles escaping from the scintillator.
  - a Straw Tube Tracker (STT) providing low density tracker with integrated thin targets.
- After several review, the STT based tracking detector (with India as major proponent) has been accepted by the DUNE collaboration in an executive board meeting held on 2nd September, 2021, which was subsequently announced in the September DUNE collaboration meeting. Refer to the following talk by Gina Rameika for more details:

https://indico.fnal.gov/event/46504/contributions/223697/attachments/147324/188739/DUNE_Status_Rameika.pdf

SAND Detector



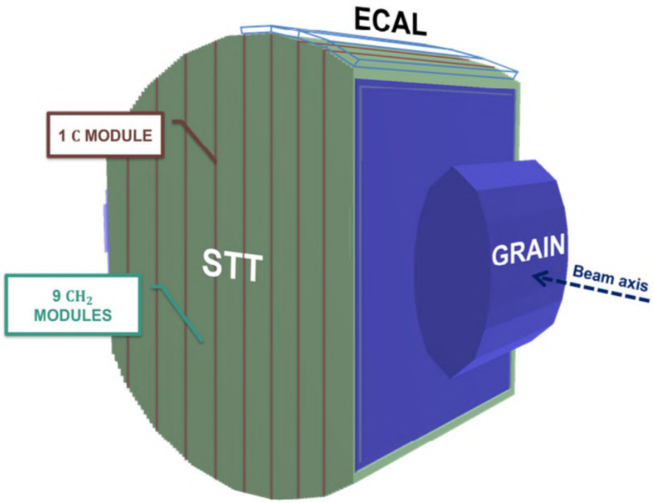




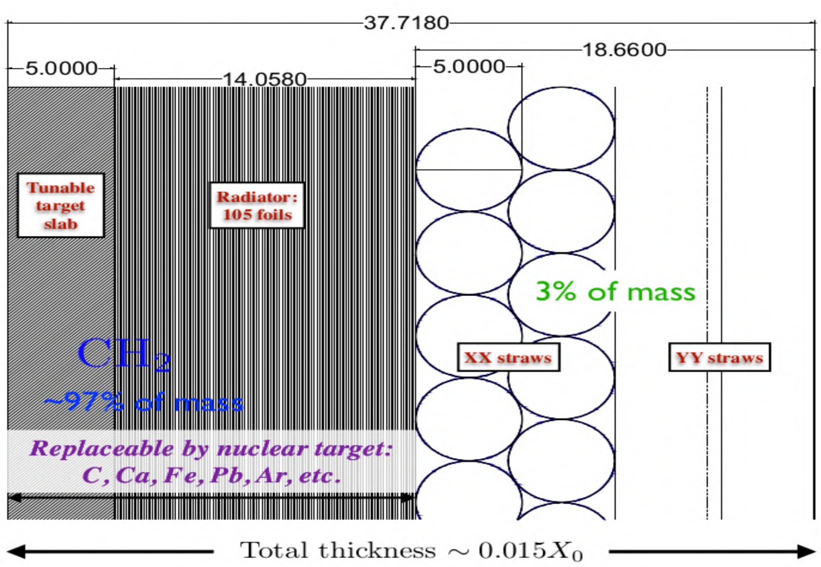
Repurposed from KLOE II experiment.

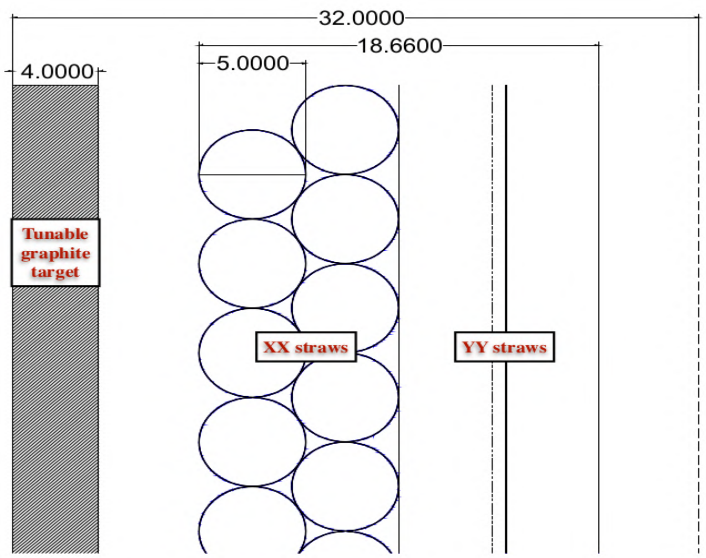
The superconducting magnet provides a 0.6 T uniform magnetic field over a Volume of about 45 m^3.

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 CH_2 radiator foils in CH_2 modules to allow Transition radiation for e/π separation.

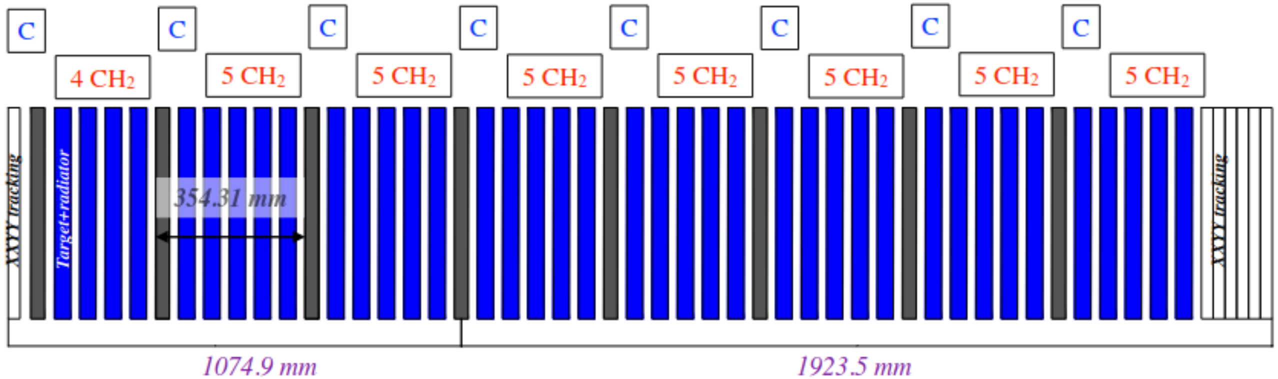




STT Configuration

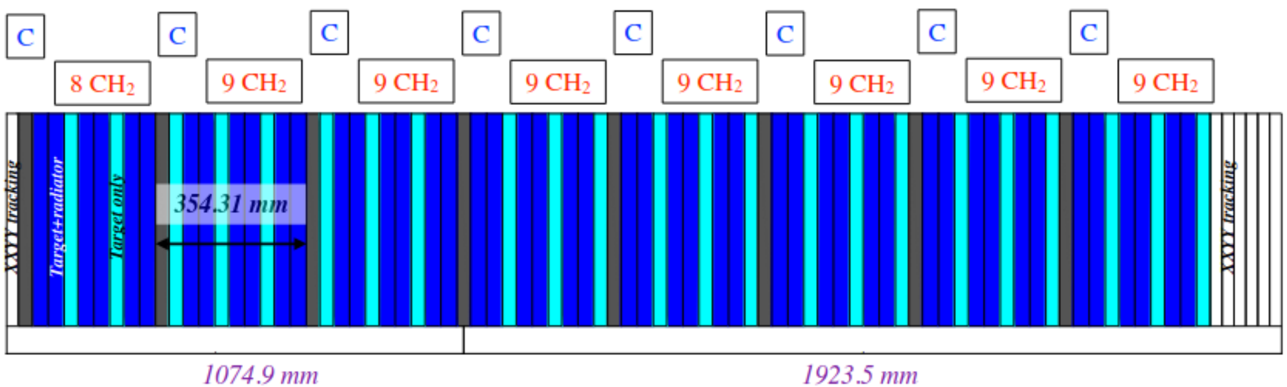
Initial STT config:

- **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:

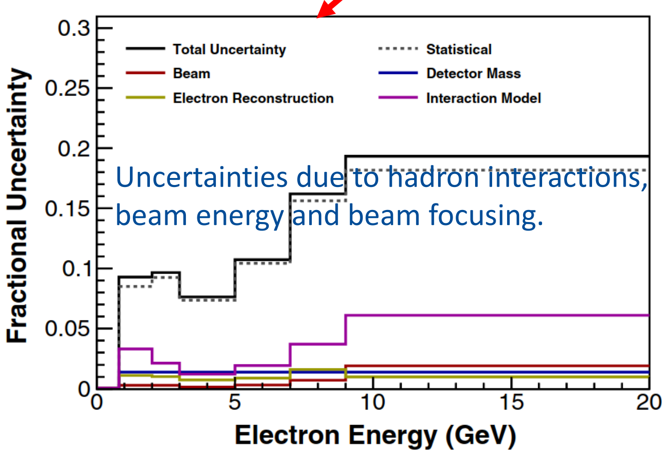
- **Total** - 86 modules
- **CH_2 with rad.** - 48
- **CH_2 target only** - 23
- **C** - 9
- **Trk** - 7
- **Total FV mass** - 4.407 tons



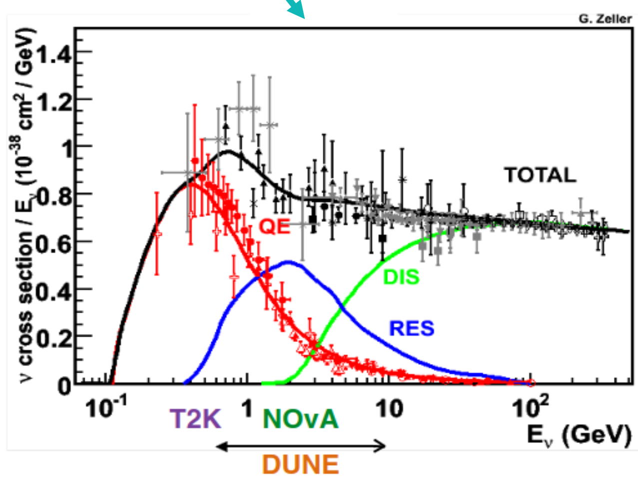
Neutrino counts

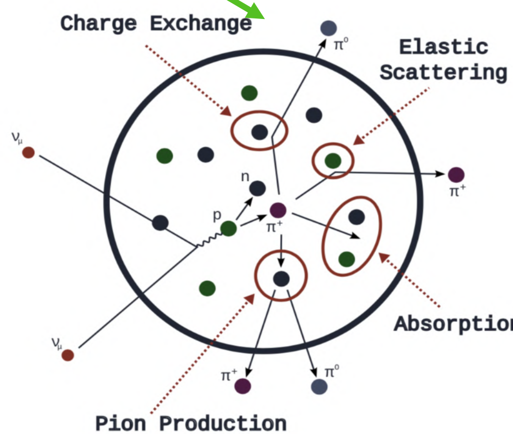
Neutrino event measurements are highly convoluted with the parameters having large uncertainties:

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



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





MINERvA measured uncertainties

Neutrino counts in SAND with STT

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

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

$\phi(E_\nu)$	$\sigma_X(E_\nu)$	$R_{phys}(E_\nu, E_{vis})$	$R_{det}(E_{vis}, E_{rec})$
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

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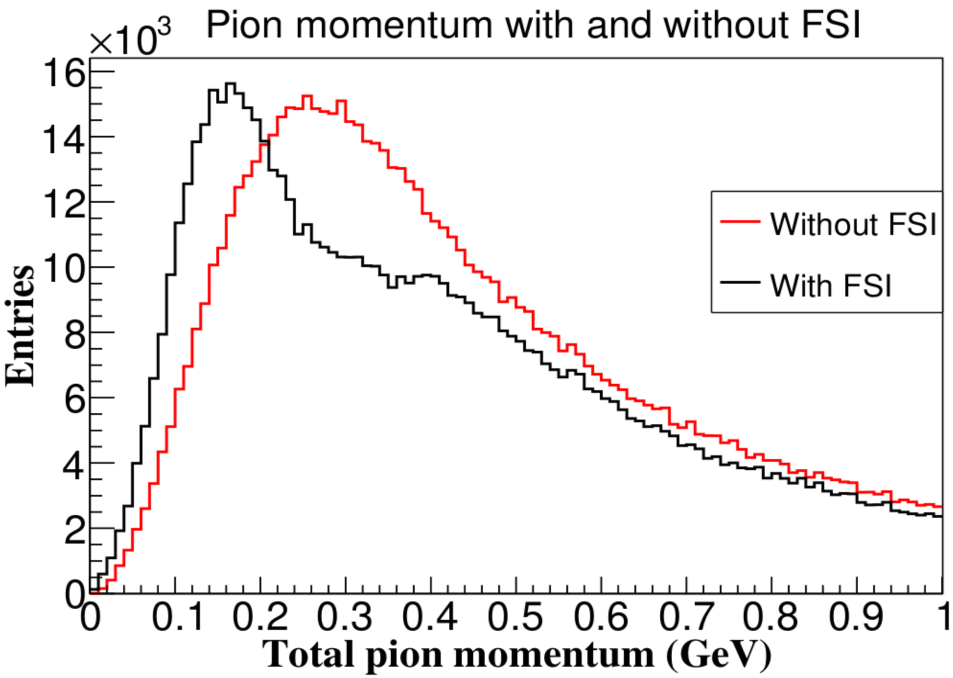
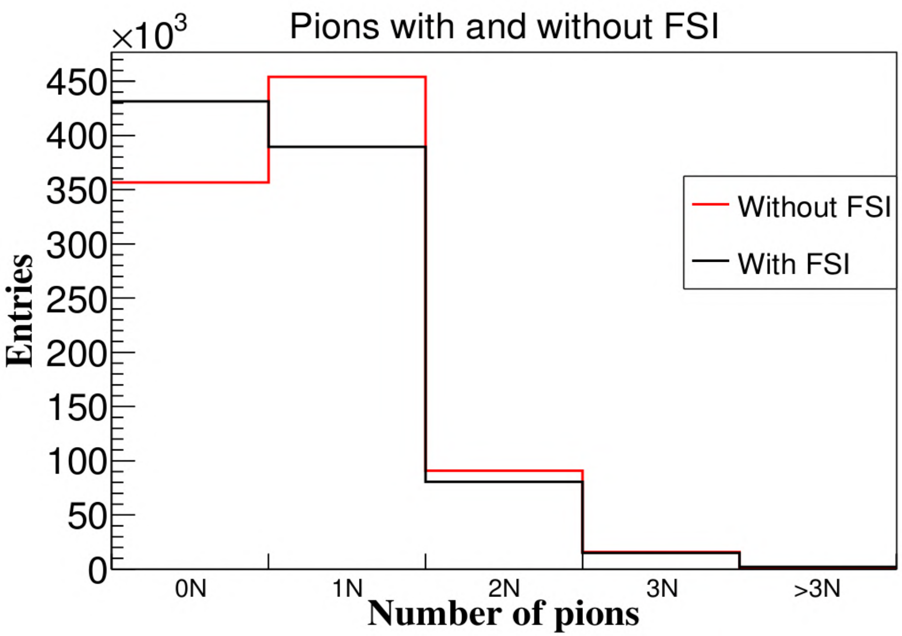
Primary/Without FSI pions ⇒ Pions produced at interaction;

Final State/With FSI pions ⇒ Pions coming out of nucleus.



Change in pion momentum due to FSI

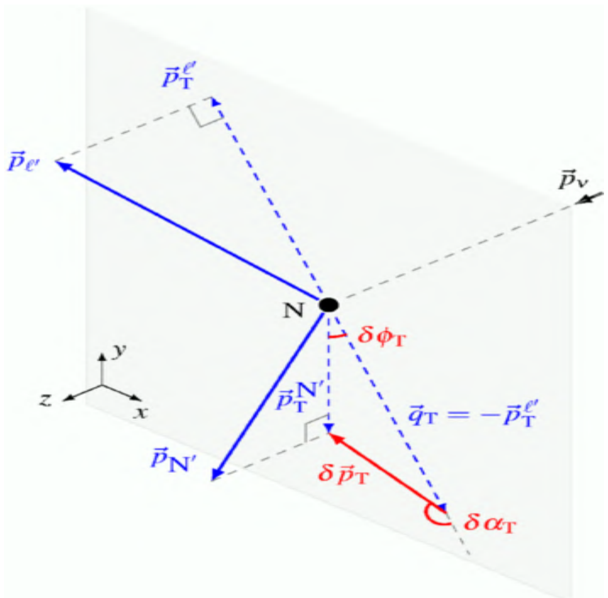


Pion absorption/production due to FSI

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 ν-H from ν-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), ν-H can be separated from ν-C.**



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

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

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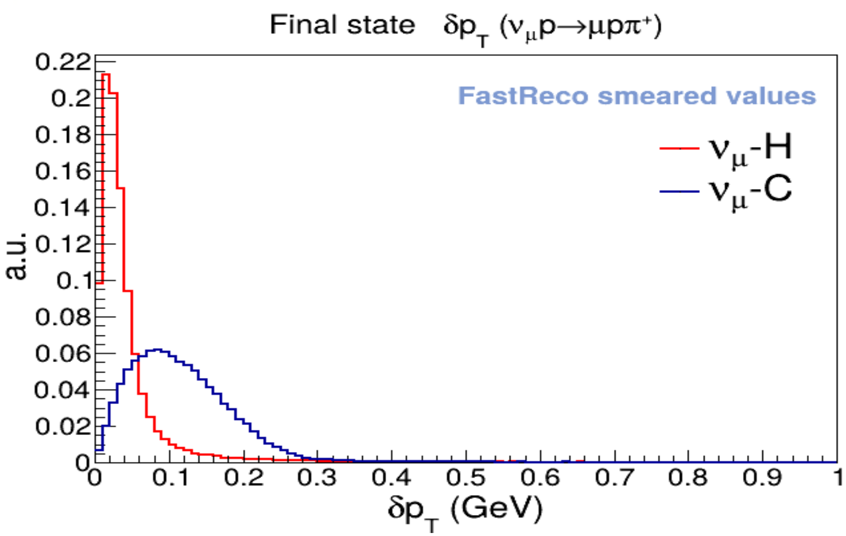
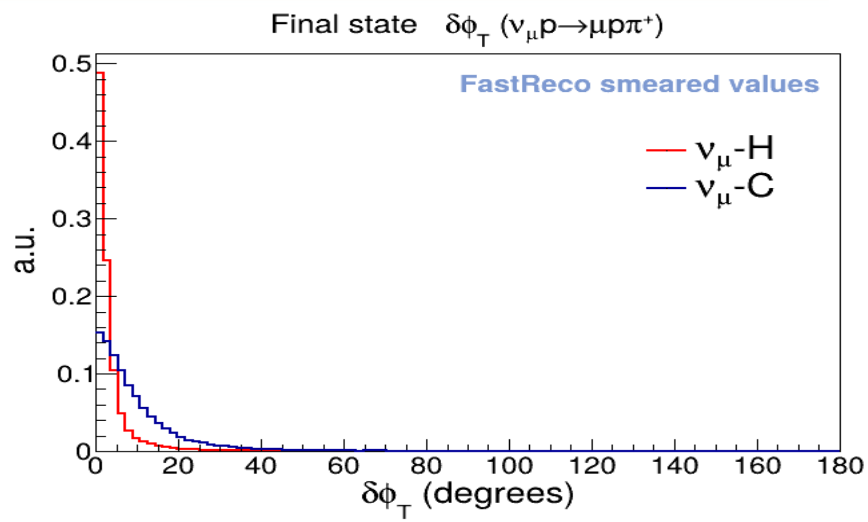
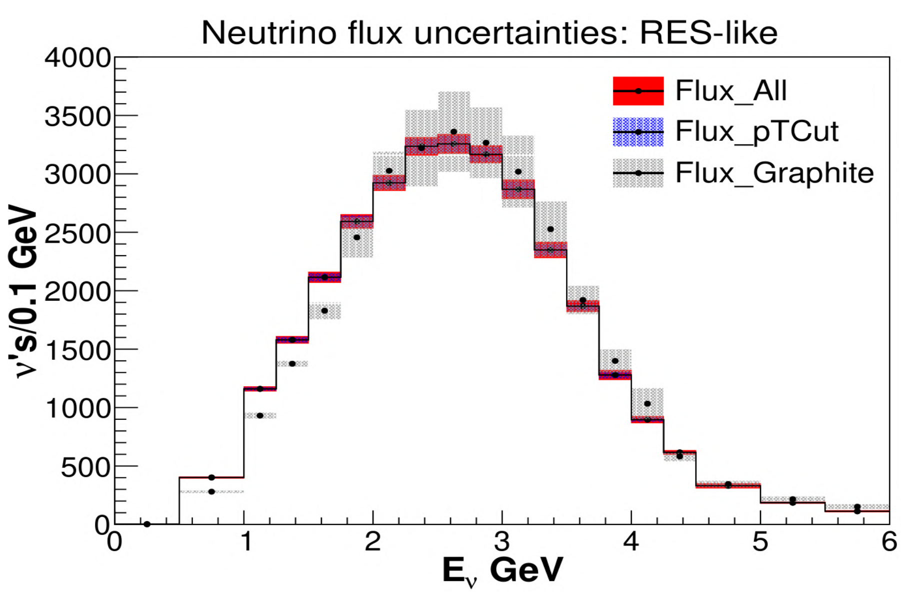
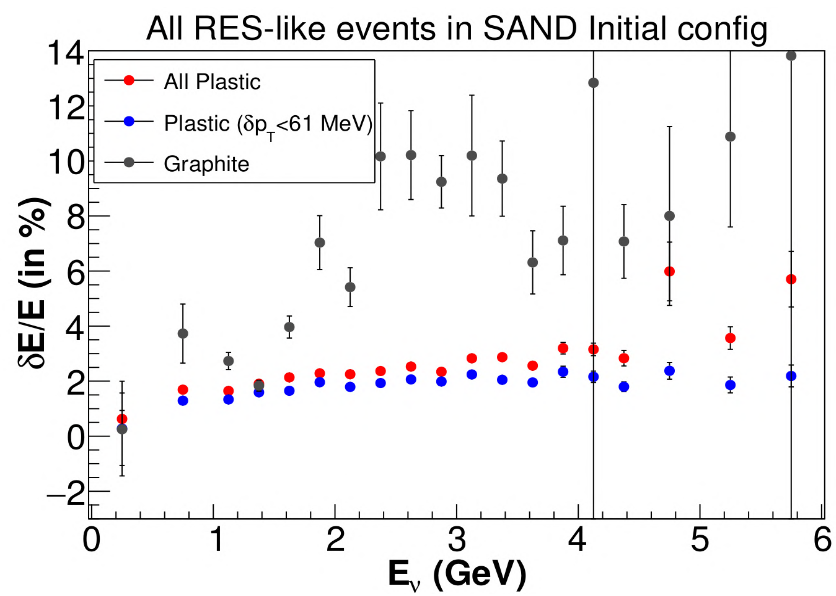






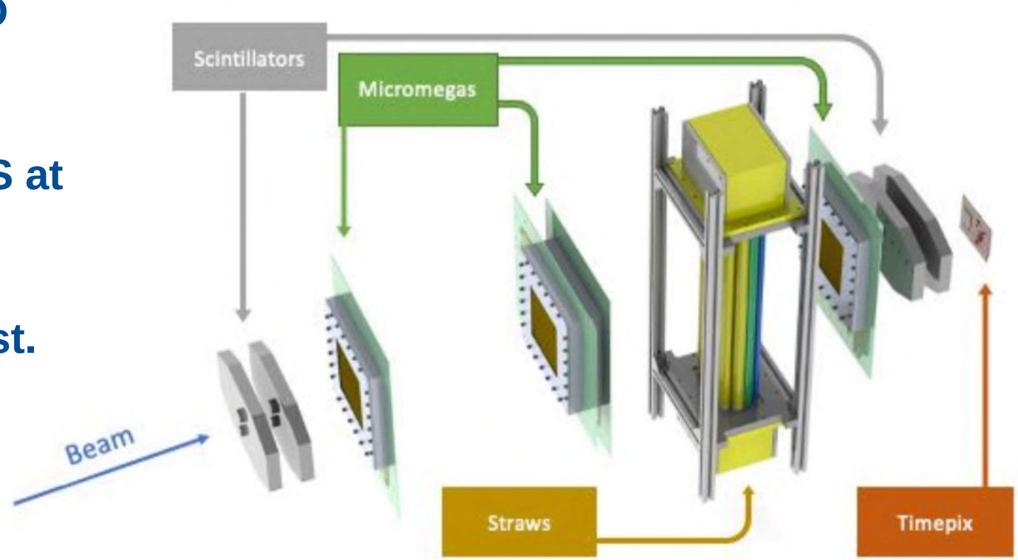


STT can bring down the flux uncertainties to below 2% using $\nu - H$ interaction sample . Using subtraction technique, the uncertainties can be brought down to 1% level.

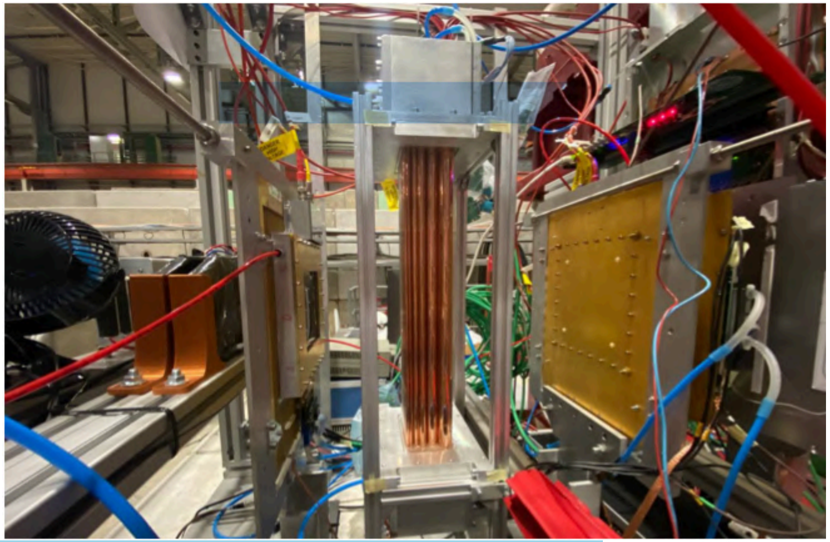
StrawTrackerRD setup for Test Beam Analysis

Shailesh Pincha, B. Bhuyan

- **A setup installed by StrawTrackerRD team studies STT performance.**
- **STT irradiated by a μ beam from SPS at CERN.**
- **5mm, 10mm, 20mm straws under test.**
- **μMegas gives the reference track coordinate for straw hits.**
- **Scintillators give the reference timing information for straw hits.**



We analyse the TB data from 2023 April and August runs to study spatial and timing resolution of 5 mm straws.



STT Test Beam Analysis Results

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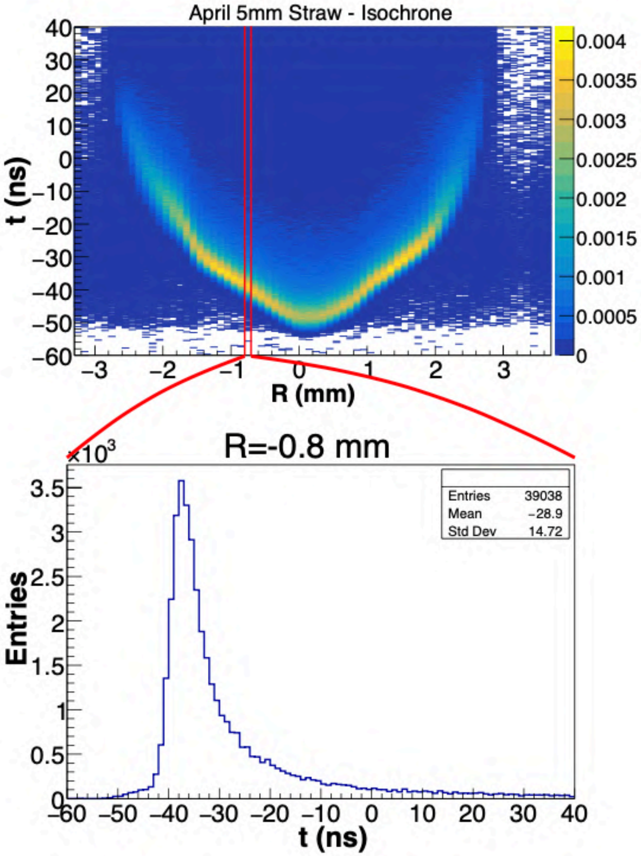
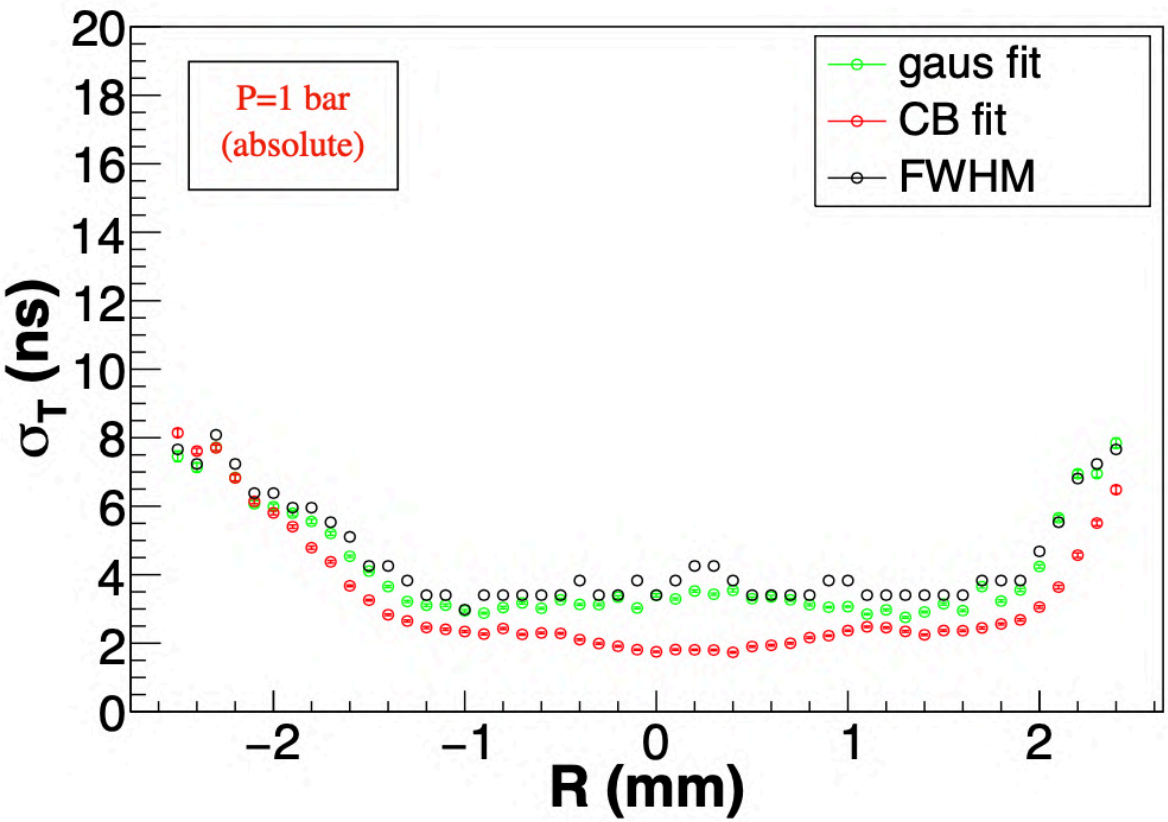
Preliminary timing resolution of straws measured at the SPS H4 test beam in 2023. Consistent with the expected single hit space resolution of $\leq 200\ \mu m$.





Participating Institutions from India

✧14 institutions currently. Other institutions are also most welcome to join the DUNE-India effort.

- ✧Indian Institute of Technology Guwahati (IITG)
- ✧Indian Institute of Technology Hyderabad (IITH)
- ✧Indian Institute of Technology Kanpur (IITK)
- ✧University of Hyderabad (HU)
- ✧Jawaharlal Nehru University (JNU)
- ✧Panjab University (PU)
- ✧Panjab Agricultural University (PAU)
- ✧University of South Bihar
- ✧Institute of Physics (IOP)
- ✧Physical Research Laboratory (PRL)
- ✧Lucknow University
- ✧HRI
- ✧NISER
- ✧Aligarh Muslim University (AMU)

* Institutions interested in hardware.

Current Activities and Future Possibilities

- **STT Prototyping, Test and Construction:**
  - **Straw production and module assembly sites at IITG, PU and NISER. Propose to build more than 50% of the total modules required for the initial STT configuration in the next five years.**
  - **Manpower are getting trained at JINR. IITG recently signed an MOU with JINR to jointly work on the STT project.**

2.0 m and 5.0 m Straws

✦ *Module Assembly unit at Fermilab*:

- *Total space around 150 m^2 including storage & handling;*
- *No strictly certified clean room required for assembly;*
- *Need 2 tables around 4m × 4m with flatness of about 100 μm: one table for assembly and one table for tests / spare;*
- *Need ceiling height exceeding 5 m for wiring in vertical position.*

⟹ *Required personpower: 7 people from institutions under Fermilab supervision*

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",

Signed on this date
07.10.2024
G.V. Trubnikov
Professor Devendra Jalihal
निदेशक
भारतीय प्रौद्योगिकी संस्थान गुवाहाटी
Director
Indian Institute of Technology Guwahati
Guwahati-781039

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

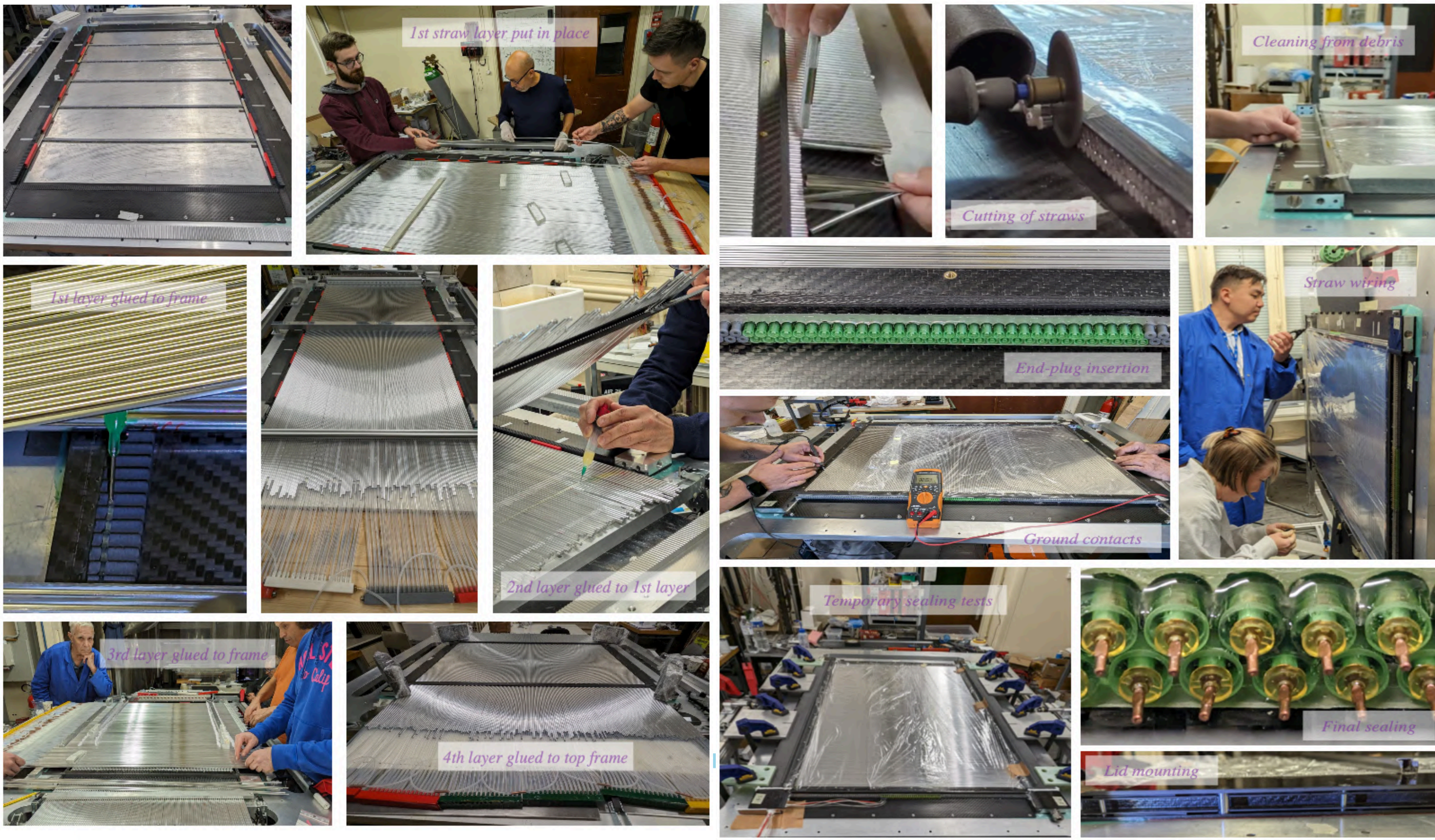
1. Cooperation

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;

Current Activities and Future Possibilities

- **STT Prototyping, Test and Construction:**
  - **Know how on the construction of the STT exists. Already build a 1.2 m x 0.8 m prototype at CERN. A second prototype is under construction at PISA.**

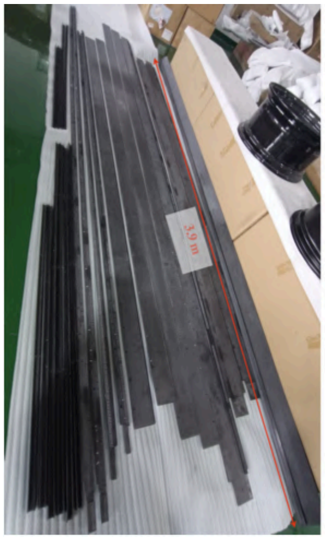


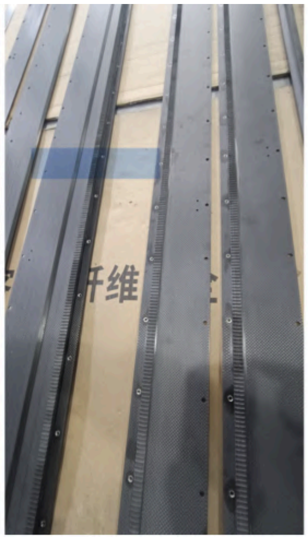
Current Activities and Future Possibilities

- **STT Prototyping, Test and Construction:**

Working on building the 0th module (3.9 m x 3.3 m) by the end of this year.

Most of the materials are already procured.





Independent Technical Review of the STT: 11-13 March, 2025

Reviewers: Hans Danielsson, Satoshi Mihara, Aseet Mukherjee, Anatoli Romaniouk, Peter Wintz.

Documented on Indico:https://indico.fnal.gov/event/68155/

2. Observations and recommendations

The chosen technology of ultrasonically welded straws appears suitable as a detector concept given the requirements. Furthermore, ultrasonically welded straws are today a well-established technology which minimize the risk to the project. The straw technology with welded straws is well advanced and under control.

Current Activities and Future Possibilities

- Development of ADC for the STT readout electronics.
  - IITK is taking the lead. Details in Navaneeth's talk.
- DUNE Distributed GRID Computing.
  - TIFR is already hosting small GRID site for DUNE computing. Possibility of setting up additional computing facility in other institutions for the distributed computing.
- Participation in the FD & ND installation and commissioning. Analyse protoDUNE data for physics studies, detector performance studies.
- Software development for event reconstruction, detector calibration and physics studies.
- Contribution to the design of the module 3 and 4 of the FD through physics studies.
- R&D for the design of the ND-GAr in Phase II.

Core Cost of the STT Project

ITEM	COST	SUPPLIER/SOURCE	QUOTE	DELIVERY TIME	VALIDATED
Procure mylar film (19 µm, double 70 nm Al)	$ 147,189	Fraunhofer FEP, Germany	Mar-24	3 months	✓
Procure endplugs (PC transparent)	$ 7,992	CLM Co. LTD, China	Apr-24	45 days	✓
Procure wire spacers (PC black)	$ 20,459	GJT Co. LTD, China	Apr-24	45 days	✓
Procure crimping pins (1.2 mm gold plated)	$ 13,375	SZLE Co. LTD, China	Feb-24	4 weeks	✓
Procure anode wire (W/Re 20 µm)	$ 201,369	Luma metall AB, Sweden	Feb-24	14 weeks	✓
Procure C-fiber frames	$ 581,073	DSNM Co. LTD, China	Jul-24	5 months	
Procure Al corner blocks	$ 1,296	PIM Co. LTD, China	Jun-24	2 weeks	✓
Procure gas and electrical connectors	$ 5,337	CERN store, Switzerland	Jun-24	4 weeks	✓
Procure STT tools	$ 340,000	JINR/GTU facilities			
Procure miscellaneous items & consummables	$ 125,000	STT prototypes			
Procure gas system (Xe/CO_2 + Ar/CO_2 + cooling)	$ 525,000	CERN DT, Switzerland	Jul-24	6 months	✓
Procure BOPP radiator film (18 µm, 3.3 m)	$ 4,050	HMNM Co. LTD, China	May-24	8 weeks	✓
Procure CH_2 targets (HDPE tiles)	$ 10,058	HJM Co. LTD, China	Jun-24	8 weeks	
Procure graphite targets (isostatic IFS-H7 tiles)	$ 15,066	CFCC Co. LTD, China	Mar-24	8 weeks	✓
Procure C-fiber frames for targets/radiators (T700)	$ 47,504	HRC Co. LTD, China	Jun-24	1 month	✓
Procure rods+nuts for super-module assembly	$ 3,237	PIM Co. LTD, China	Jul-24	3 weeks	✓
Procure VMM3a ASIC chips (existing masks)	$ 195,000	Globalfoundries, USA	Jun-24	8 months	✓
Procure VMM3a ASIC packaging	$ 109,000	Muse semiconductor, USA	Jun-24	5 months	✓
Procure integrated readout boards (MCU, ADC, SSR)	$ 92,298	PCBWay, China	Jul-24	7 weeks	✓
Procure flexible Kapton PCBs (PCIe connector)	$ 20,065	PCBWay, China	Jun-24	36 days	✓
Procure HV components	$ 38,012	CAEN, Italy	Jun-24	3 months	✓
Procure LV components	$ 63,271	CAEN, Italy	Jun-24	4 months	✓
Procure cables & connectors	$ 23,223	CERN store, Switzerland	Jul-24	4 months	✓
Procure LV distribution boards	$ 18,000	ATLAS NSW			
Procure DAQ/DTS interface boards	$ 45,000	DUNE DAQ group			
TOTAL	**$ 2,651,875**				

Average cost per module: $49,109

Average cost per channel: $19

Way forward: Critical Issues

- DAE is very supportive of our effort. Need to actively engage DST since a large number of DST institutions are involved in the project.
- For hardware contribution to the DUNE project, we need to have MOUs between the Indian funding agencies, Fermi Lab and DOE.
  - Though Annex-II was signed in 2018, due to the dis-continuation of INO project in India, the implementation of Annex-II is in question.
- Contribution to the DUNE CF by the Indian institutions remain a challenge. Individual institutions will not be able to contribute to the CF.
  - Should be part of the MOU with the funding agencies.
- Students exchange and support program by Fermi Lab should be continued. Has been quite successful in Phase –I and II of the India Fermi Lab Neutrino Collaboration.
  - Human resource development is one of the key mandates of the funding agencies.

Backup

Flux determination with ν-H interactions in SAND

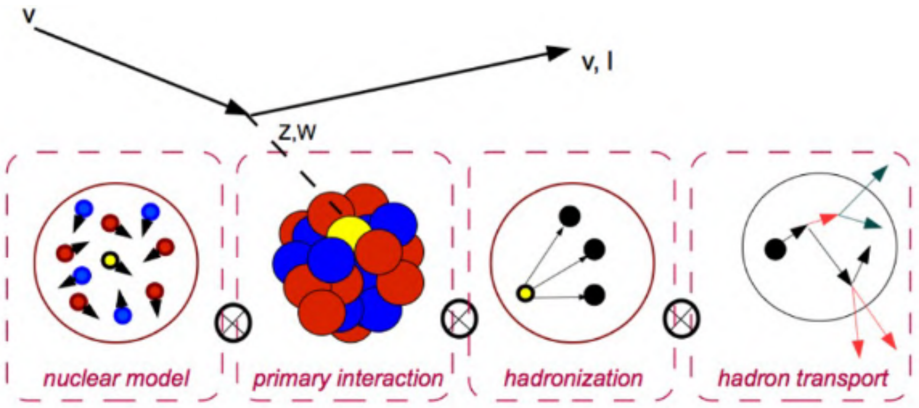
Shailesh Pincha, B. Bhuyan

- **Flux measurements in DUNE ND-SAND depend on Energy spectra reconstruction.**

- **Standard Candle for flux measurement: νe→νe elastic scattering. BUT,**

$$\frac{\sigma\left(\nu_\mu CC\right)}{\sigma\left(\nu_\mu e \rightarrow \nu_\mu e\right)} \approx 10^4$$

So, neutrino-nucleus interactions are statistically favourable. BUT again,



SAND provides a unique opportunity to study ν-H interactions, which are free of nuclear effects, risk-free.