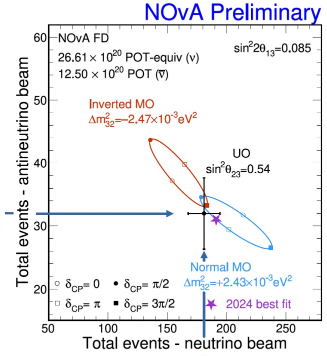
Preamble

Why DUNE?

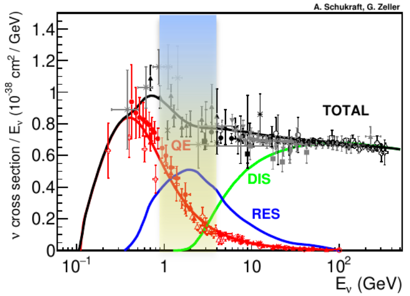
Neutrino2024

32 $\overline{\nu}_e$ data candidates



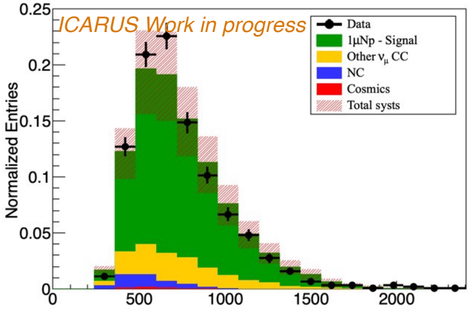
181 ν_e data candidates

Till now, rather fuzzy results about closure of PMNS
→ need for a high mass and high performant detector (neutrino energy measurement)



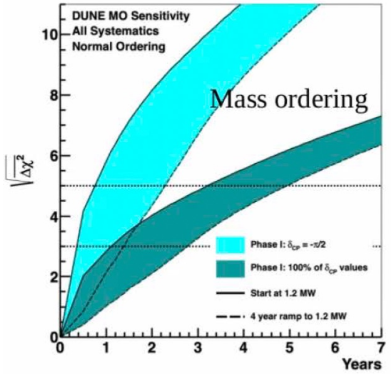
Why detectors at the Near site?

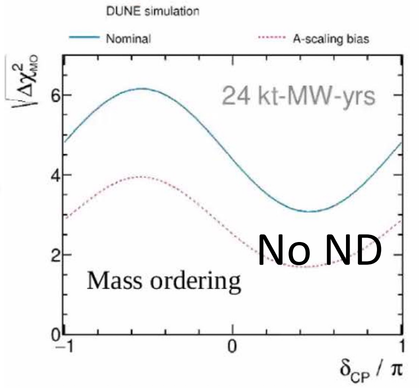
Neutrino2024

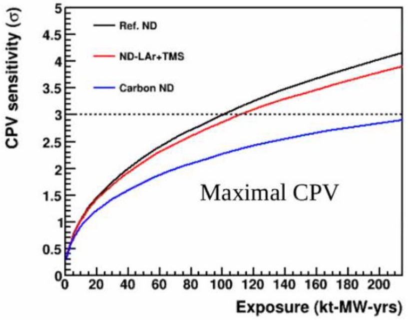


SBN without Near detector
→ about 25% systematics

DUNE: first robust measurement of the MO





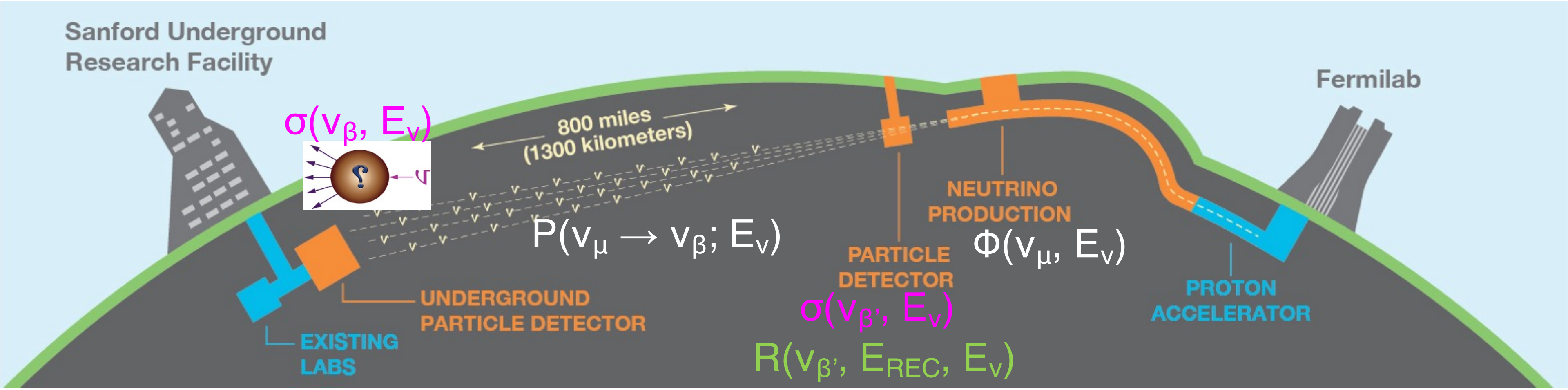


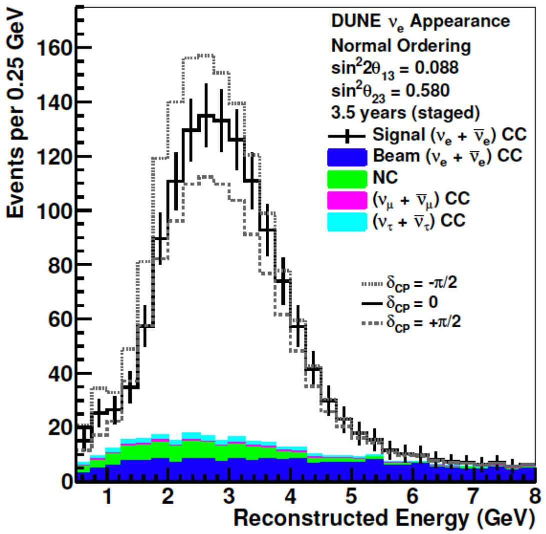
Why SAND?

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

- P_{osc}: about 1
- R_{det}: LAr detectors
- Φ: SAND
- σ_X: SAND LAr interactions
- R_{phys}: SAND multi-target (long shot)

DUNE at work





ν_e appearance from ν_μ beam after 3.5 years (staged)

Need maximal control of prediction under PMNS parameters:
fluxes, cross-sections, detector responses

To maximize deconvolution of intrinsic degeneracies perform single measurements for as many as possible sources of systematics effects ☞ Near Detector complex

DUNE-SAND

… general updates on status, progress, and planning…

Luca Stanco

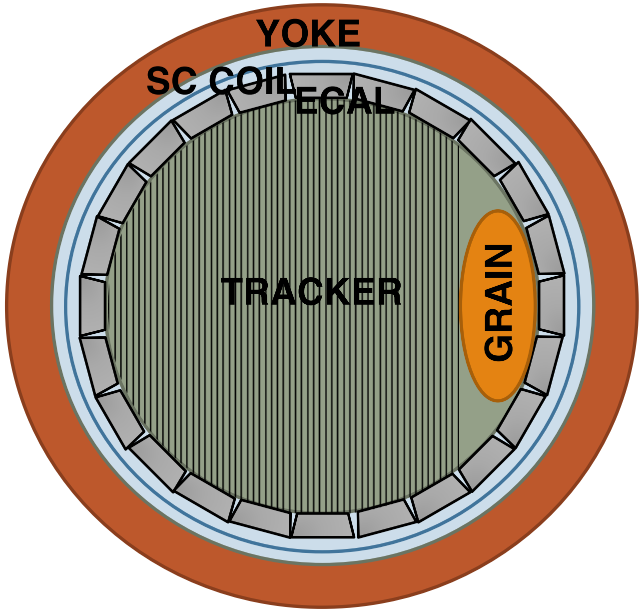
- ECAL/Magnet
- Tracker
- GRAIN
- DAQ
- Software/Physics

MAGNET – KLOE 0.6T superconductive coil + Fe Yoke

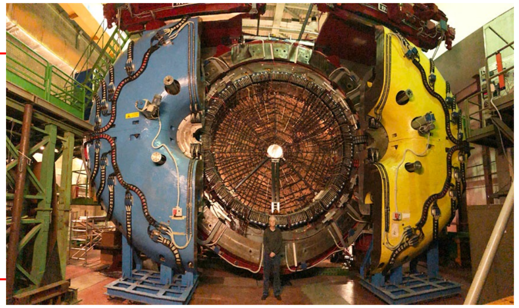
ECAL - KLOE Lead Scintillating Fibers calorimeter (Barrel ~85 t + EndCaps ~40 t)

TRACKER (STT) – 5 ton Straw-Tube tracker with "solid-H" target CH_2 and C interleaved foils (Drift Chamber, DCH, similar)

GRAIN – 1 ton liquid Argon target with VUV imaging system (fully optical read-out)



SAND, a multipurpose detector with a high-performant ECAL, light-targeted tracker, LAr target, <u>all of them in a magnetic field</u>



Our first commitment: be ready to start installation in September 2028

SAND configuration

SAND will be permanently on-axis in a dedicated alcove

The schematic configuration is:

- a Superconducting Solenoid Magnet
- an Electromagnetic Calorimeter (ECAL)

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

- an Inner Tracker, including a thin active LAr target

Inner Tracker

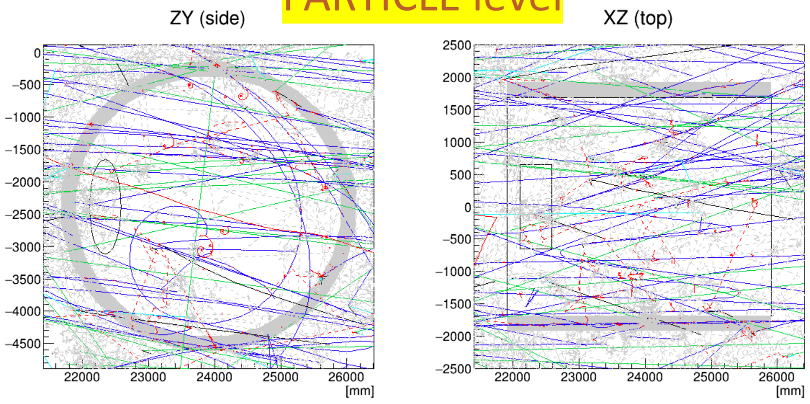
- **Why SAND needs a dedicated tracker system inside the magnet?** Separation of neutrino and anti-neutrino fluxes (charge ID),
  event-by-event reconstruction,
  neutron identification (with ECAL),
  subtraction analysis to isolate free proton interactions.

- a StrawTubeTracker (STT) providing a low density tracker with integrated thin targets as first option
- a Drift Chamber (DCH) backup-option is under study with the exactly the same configuration and geometry

Events in SAND for an entire spill

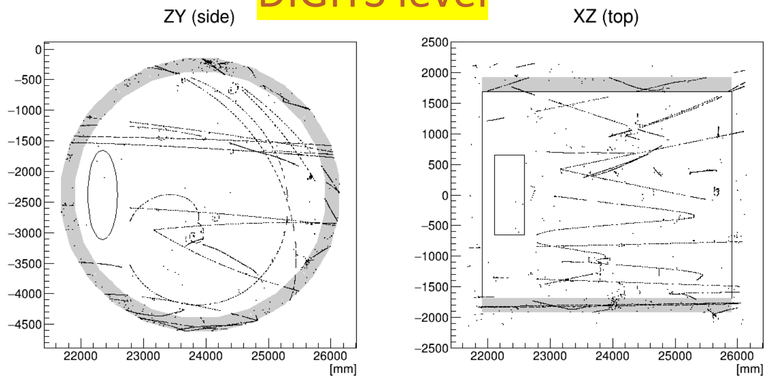
PARTICLE level

(not time-gated)

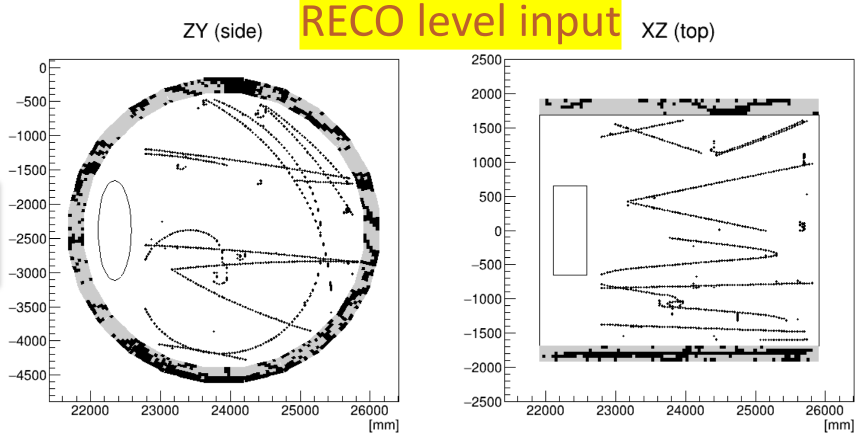


SAND + TMS + NDLAR (no rock-muon)

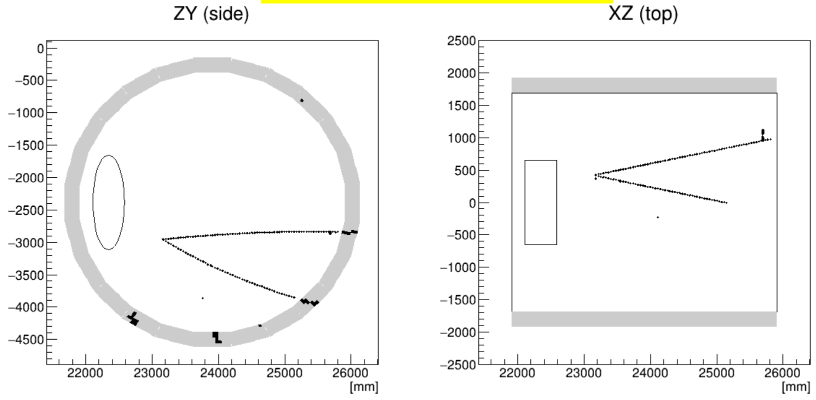
DIGITS level



RECO level input



time-gated 100 ns



Identified Event

Certainly, one of the best detectors ever placed in a neutrino beam

SAND commitments and interplay

- SAND is out of DUNE-US project. However, a bilateral DOE-INFN MoU has been signed on April 9, 2024, defining, among others, the respective contributions and responsibilities to SAND’s construction, verification and installation.

- SAND Consortium provides the detector components, expertise and resources for testing, assembling, installation, commissioning

- Fermilab provides logistics, technical coordination, technical support and engineering for the pre-assembly activities, pre-shipping and post-shipping acceptance tests, occurring at Fermilab and support to installation at the DUNE-ND site

Details of MoU

Addendum 2 of the Implementing Arrangement between the USA Department Of Energy and the Italian Ministry of Education, University and Research (MUR) for Cooperation in Areas of Astroparticle and Nuclear Physics defines the areas of cooperation and reciprocal responsibilities of DOE (through Fermilab) and MUR (through INFN) in DUNE.

Among other contributions, it covers the deliverables and the support for the installation of SAND in the DUNE ND facilities that, although it is understood to be "*outside the current U.S. LBNF/DUNE project*", it "*is planned to be coordinated with Fermilab and the DUNE Program*".

Excerpt MoU DOE-INFN

… the DUNE experimental detector systems to which INFN shall contribute include:

…

A DUNE ND assembly which will include an on-axis neutrino detector identified as System for on-Axis Neutrino Detection (SAND), it being understood that:

a) INFN's contribution to SAND is a critical part of the overall international DUNE Program though it is outside the current U.S. LBNF/DUNE project (and its associated project completion), which is being undertaken by DOE in accordance with DOE Order 413.3B regarding project management for the acquisition of capital assets;
b) and the SAND installation schedule is planned to be coordinated with Fermilab and the DUNE Program.

Fermilab shall contribute resources as follows:

1. Provide facilities for the execution of the DUNE Program, including:
i. Accelerators and the associated neutrino beamline for DUNE;
ii. Experimental halls including infrastructure such as AC power distribution, computer and data networking, and building cranes;
iii. Safe working environments to conduct activities; and
iv. Engineering support for external cryogenic systems, cryogenic system integration, and process control systems to be built, installed by INFN, and operated in collaboration with INFN.

2. Support for the installation of the DUNE ND and FD in their respective experimental halls. This support include:
i. Providing technical coordination for each detector and associated subsystems; and
ii. Providing certain specialized technical services such as crane operation and welding services.

3. Along with the DUNE Collaboration, support for the commissioning, experimental, and physics operation of DUNE that shall include:
i. Technical staff to operate the cryogenics systems; and
ii. Physics control room facilities located near the DUNE ND and FD experimental halls.

4. Provide oversight of activities regarding environmental and safety standards; provide support for carrying out safety reviews and obtaining necessary operational readiness clearances; and provide the necessary training for users to carry out the functions of installation, maintenance, and operation of the detectors.

as a result…

Fermilab has formed an engineering group to support the SAND consortium in developing designs and procedures in accordance with standards and regulations in use at Fermilab.

For the moment, the group, lead by SAND's Technical Leader, consists of a cryogenic, two electrical and a mechanical engineers, and a logistic coordinator shared with DUNE ND. The group is planned to be expanded as needed and to cover safety, onsite preinstallation and QA/QC activities and the final installation and commissioning of the detector.

Integration and Installation processes and schedules are being developed in close collaboration with DUNE-ND's I&I team.

SAND Consortium is preparing a TDR, to be completed by end of 2024 and to be included in the DUNE-ND TDR.

Preliminary Design Reviews are coherently being planned with DUNE's review office.

SAND Working Groups

Activities / Sub-systems	Chair(s)
1) **Magnet and Yoke**	*G. Delle Monache*
2) **ECAL**	*D. Domenici, A. Di Domenico*
3) **STT**	*G. Sirri, S. Di Falco, R. Petti*
4) **GRAIN**	*A. Montanari, L. Di Noto*
5) **DAQ/Trigger & Timing/Slow Controls**	*S. Di Domizio, C. Mariani, N. Tosi*
6) **Software/Physics**	*M. Tenti*
7) **Calibration**	*P. Gauzzi*
8) **TDR editor chair**	*P. Bernardini*

SAND status in a nutshell

- **Activity in Frascati going on quite smoothly**:
  continuing preparation for tools and test operations;
  dismounting of calorimeter modules, done for the Barrel ones, ready for the Endcap !
  Active involvement of Fermilab engineering group for re-installation planning and preparation
  Getting ready for the DUNE PDR, on July 22nd and 23rd.
- **LAr-GRAIN detector**: key issue on ASIC read-out under vibrant studies (defined roadmap towards design and production of 1024 channels ASIC),
  first cold test in Genova of coded masks and lenses prototypes almost ready to start;
  major advances in cryogenics and preparation of a full-scale test facility in INFN Legnaro Lab
- **Tracker**: advanced prototyping activities at CERN, Pisa and Bologna (plus other sites, installing and testing machines for straws production). Discussion in progress on tracker selection (STT vs DCH).
- **DAQ, Trigger, Timing and Slow Controls**: significant progress on integration with DUNE-DAQ and on timing.
- **Calibrations**: newly formed group; already developed a plan for calibrating ECAL and GRAIN
- **TDR writeup**: writeup progressing; more than 140 pages written
- **Physics**: part of the task force for re-evaluation and re-enforcement of the SAND detector
- **All schedules**: already rather detailed (see next presentations)

Undergoing TDR elaboration

SAND strategy

(from the DUNE management)

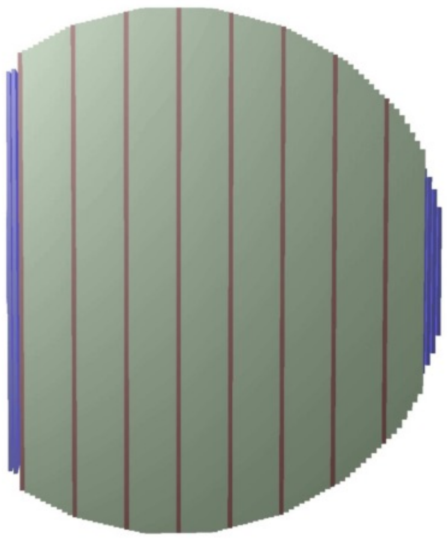
«SAND is special in that a large component of SAND is not being designed to a minimum required specification; the magnet and calorimeter already exist

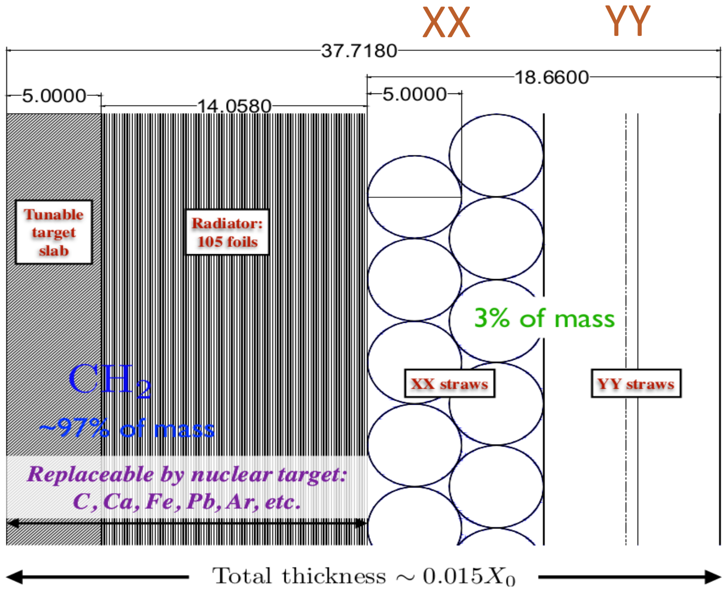
- *Identify the physics drivers that motivate the conceptual design of a low-density, high-resolution, hydrogen-rich inner tracker, with additional nuclear targets*
- *ν_μ/ν_e/anti-ν_μ/anti-ν_e, HNL → low X0, low density*
- *ν-H measurements → hydrogen rich + passive C*
- *ν-Ar/ν-H measurements → argon target*
- *etc.»*

SAND physics goals

Label	Name	Requirement	Rationale	System	Ref. Goal
ND-X5	Measure free proton cross sections	ND should measure $\nu - p$ cross sections	$\nu - p$ measurements, free of nuclear effects, constrain nucleon-level cross section predictions, and can be achieved via the "solid hydrogen" concept	SAND	ND-G2, ND-G3
ND-X6	Measure $\nu -$ Ar/$\nu -$ H σ ratios	ND should measure the ratio of ν cross sections on Ar and H(p).	Measuring cross section ratios to free nucleon is directly sensitive to nuclear effects, and could guide theory to improved nuclear models	SAND	ND-G2
ND-X7	Measure cross sections on various targets	ND should measure neutrino cross sections on various nuclear targets with the same detector	Studying the A-dependence of various inclusive and exclusive neutrino cross sections can inform nuclear models.	SAND	ND-G2
ND-X8	Measure $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ interactions	ND should separately measure interactions of each neutrino flavor in the neutrino beam	SAND can complement the wrong-sign and intrinsic ν_e measurements of ND-LAr with additional information from sign-selecting the $e^\pm$ samples	SAND	ND-G2
ND-X9	Inverse μ decay measurement	ND should identify and measure the rate of inverse μ decay events	Similar to ND-M1, the high-energy tail can be constrained with inverse muon decay. However the μ in preocess are too energetic to analyze in TMS.	SAND	ND-G3
ND-X10	Continuous on-axis beam monitoring	ND should have continous on-axis neutrino monitoring	With a fixed on-axis detector, ND-LAr+TMS does not need to return to the on-axis position monthly, and can take extended off-axis data, reducing the required movement rate and reducing the possibility of overlooking a variation in the beam conditions	SAND	ND-G4

SAND tracker (US, INDIA, INFN,…)





1 module is made of:
- 1 target slab
- (optional) radiator for TR
- 2 XX straw layers
- 2 YY straw layers

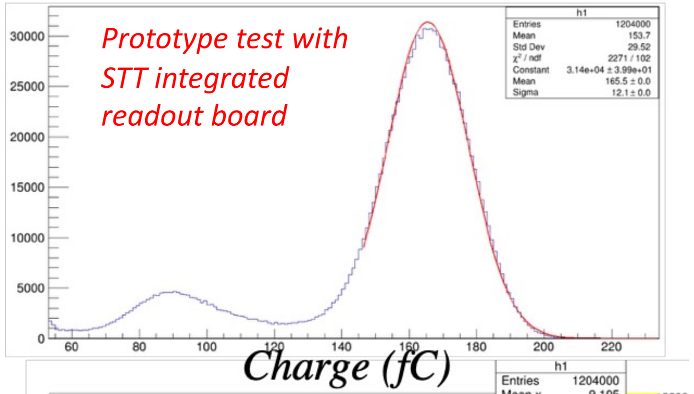
70 CH_2 modules
8 C modules
→ Solid H target!

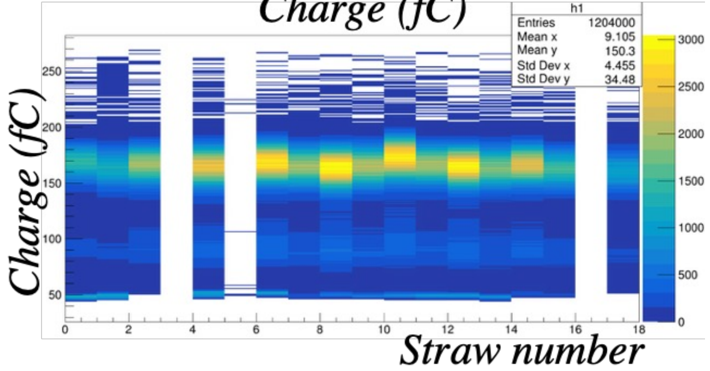
220,000 straws
Average length 3.2 m
Internal gas volume 14 m3
Nominal gas pressure 2 atm

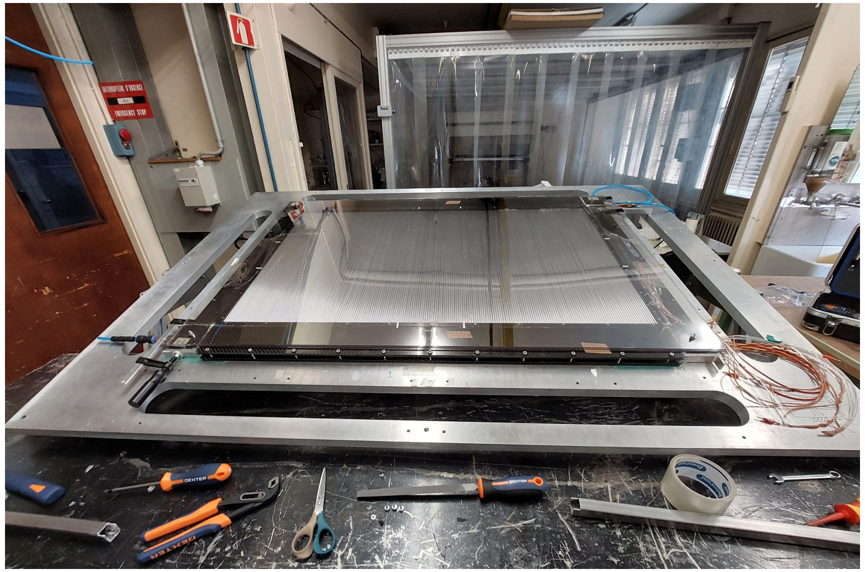
Quite challenging project (never realized before):
all the requested performances in a single detector

STT Activities

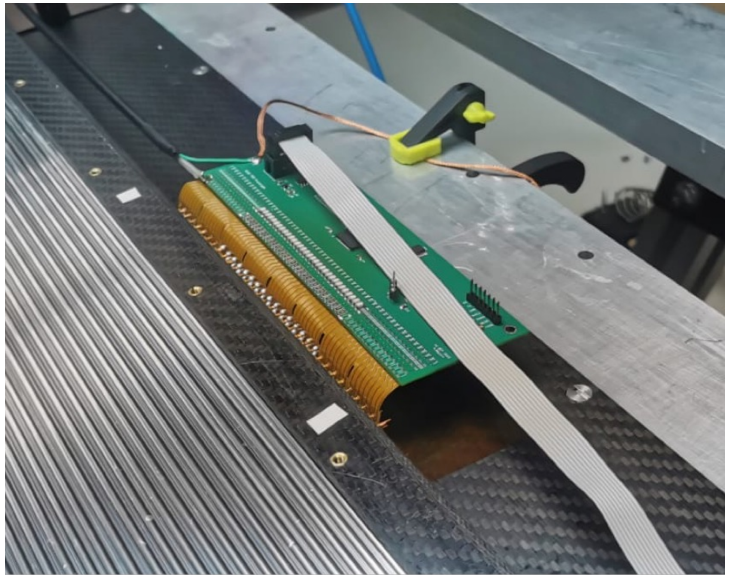
- *Successful completion and test of 1.2m 0.8m STT prototype at CERN in Nov. 2023*
- *Demonstration of integrated STT readout boards with C-fiber prototype at CERN*
- *Established end-to-end assembly procedure and validation of the design*
- *Validation of thermal studies with mockup cooling prototype at CERN*
- *Measurement of straw creep rate as a function of time*
- *Analysis of dE/dx from August 2023 testbeam and implications for STT performance*
- *Tooling for assembly of 4m STT modules*
- *Preparation for STT production: INP Kazakhistan, IIT Kanpur, Panjab University*
- *Plans for STT production: straw production & module assembly*
- *Drift chamber study*







1.2m 0.8m STT prototype



Integrated STT readout board

STT involvements/interests

USA: Duke University, University of South Carolina, BNL, Virginia, …
Italy: INFN/Univ. Bologna, Genova, Padova, Pavia, Pisa; INFN/Lab. Frascati, Catania
India: IIT Guwahati, NISER, Panjab University, University of Lucknow, …
Georgia: Georgian Technical University (GTU)
Joint Institute for Nuclear Research (JINR), Dubna
Kazakhistan, INP (Almaty) - **new entry** -
(Germany: University of Hamburg)
…

e.g. GTU contribution for DUNE STT

1. For the first time created & developed straw tubes with a diameter of 20 μm and 5 mm using ultrasonic welding technology, including double-coated straws.
2. Study of straw mechanical properties, including requirements for detector assembly.
3. First mass production of straws for mock-up
4. The first production of 4 m long straws in Tbilisi and Dubna, study their properties
5. First mass production of 1000 straws tested and verified by quality control. Used for the first prototype assembled at CERN.
6. Special extra straws for distribution between institutions (requirement for distribution is that all data measurement to be shared)
7. Production of endplags used in the prototype
8. Frame design and modeling, study of electronics cooling
9. Spacer design R&D for wiring

Issue corresponds to the schedule as driven by the current DUNE schedule that foresees the ND beneficial occupancy in 2028, on top of engineering fulfilment and funding

SAND Tracker activities for 2024

- Construction of a 1200 x 800 mm2 drift chamber prototype.
- A second STT one in Pisa is also foreseen.

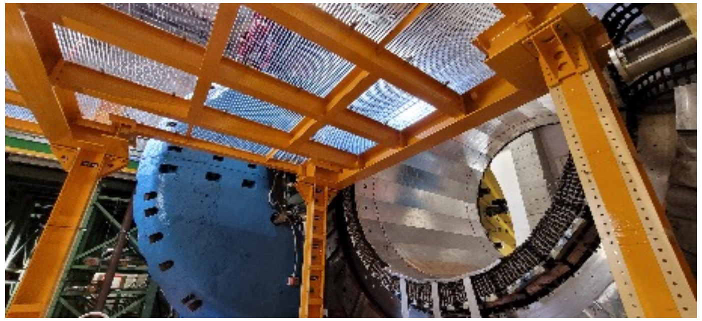
- Beam test to compare the performance of two technologies (STT, drift chamber)

- Building a telescope to evaluate accuracy in position:
  - mupix20 sensors (active area 2cm x 2cm).
  - Readout: Cyclone10 cards.
  - Mechanical table and handling system, dedicated PC for acquisition.
  - Test of different ASIC chips.

- Design and procurement for Module 0 of the tracker (SJ for the choice of technology, physics driven)

PDR/TDR: key corner to clarify working feasibility (schedule, engineering, funding)

KLOE-to-SAND Operation Activities at LNF



- ✓ Removal of all the cables and the FEE+HV racks
- ✓ Extraction of the Drift Chamber

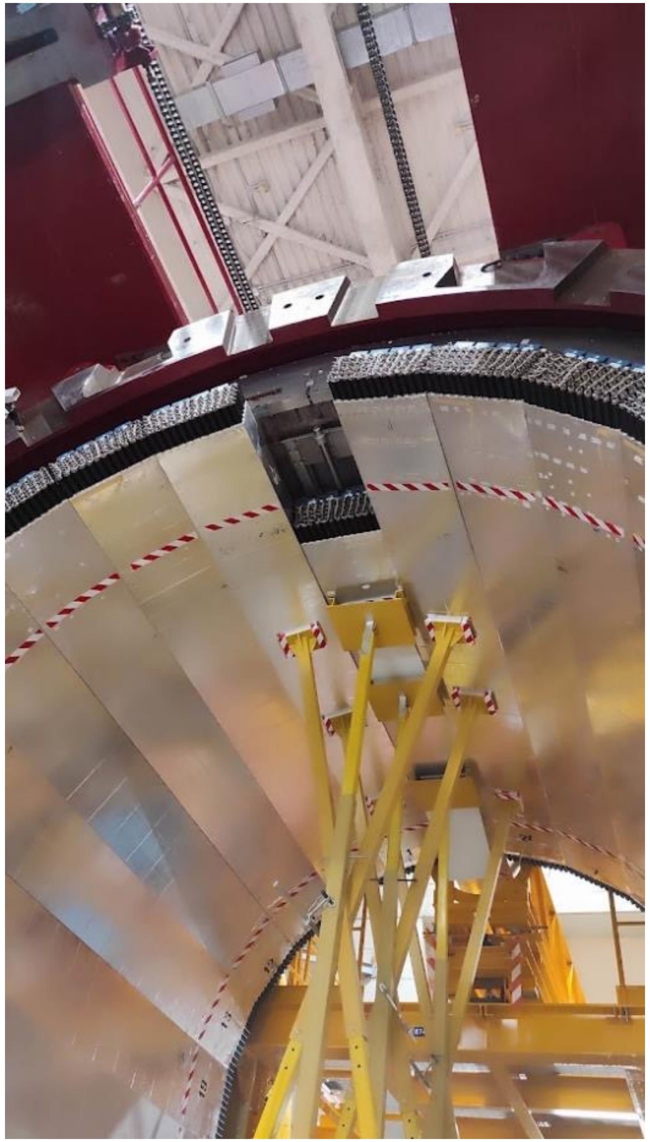
CALORIMETER

- ✓ Laser Tracker survey
- ✓ Extraction of Barrel (24 modules)
  - ✓ Variable height platform design and construction
  - ✓ Insertion/extraction machine refurbishment
  - ✓ Dismounting of PMTs
- Dismounting of 4 End-Caps
  - Tools refurbishment and construction
- Modules consolidation
- Operational test

MAGNET AND YOKE

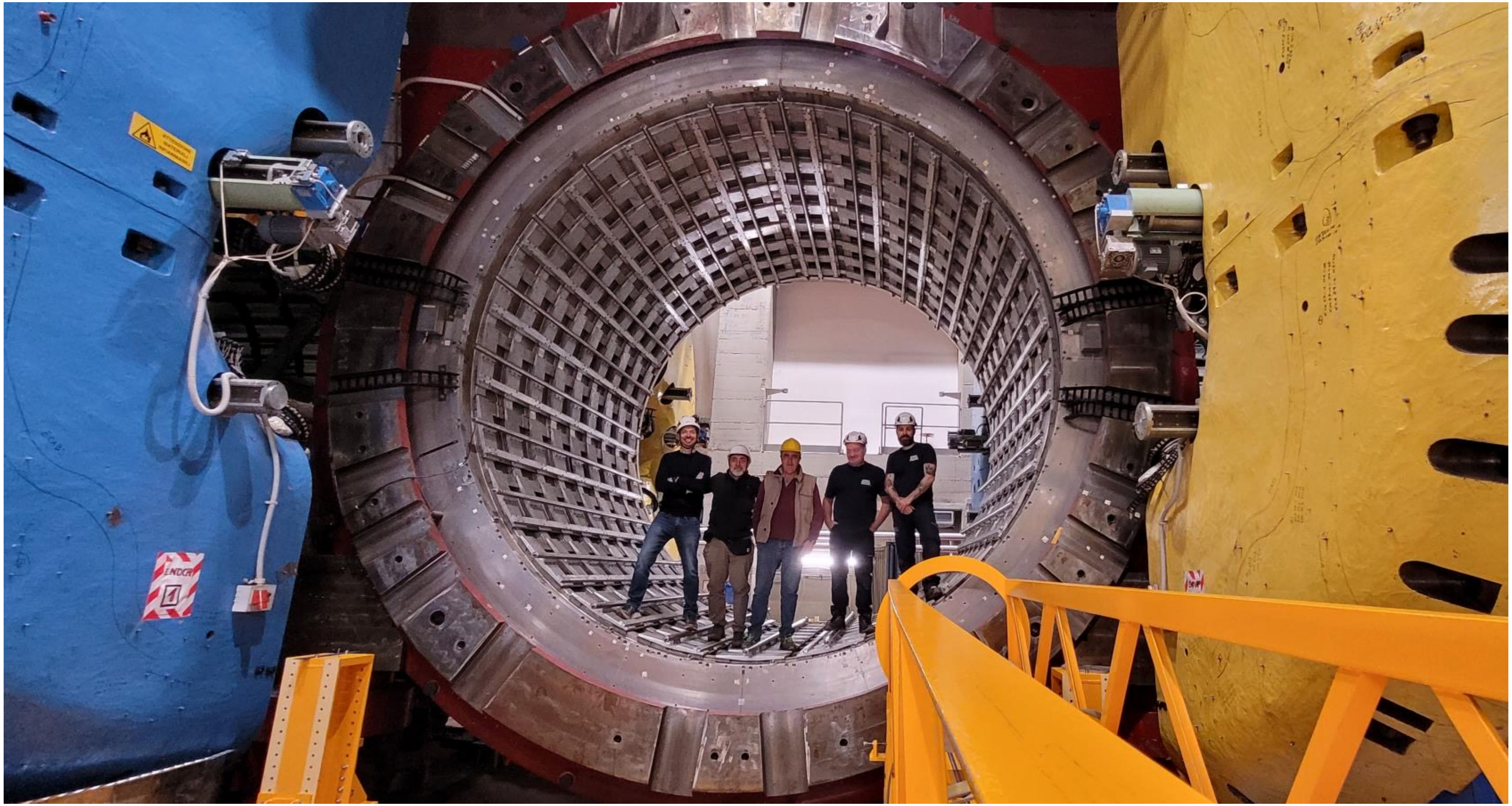
- Installation of new Power Supply
- Colling and operational test
- Extraction of the Cryostat
- Dismounting of the Iron Yoke
- Packaging and Shipping

Extraction of the Barrel Modules



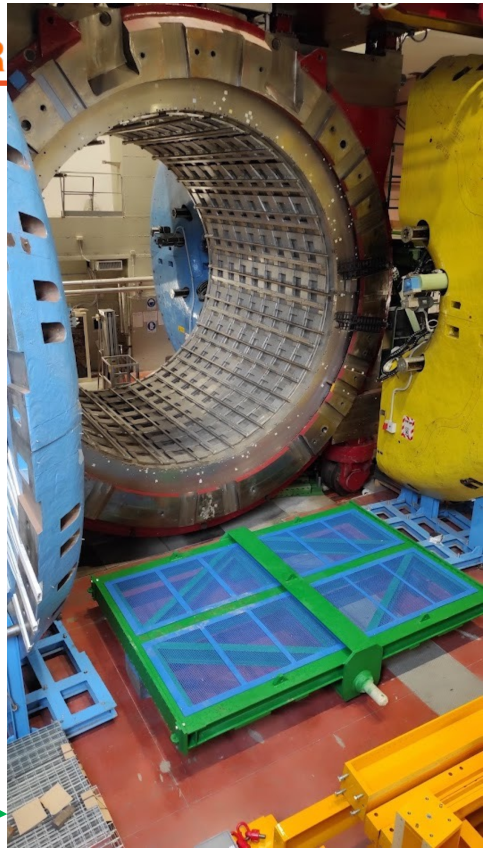
INFN DUNE

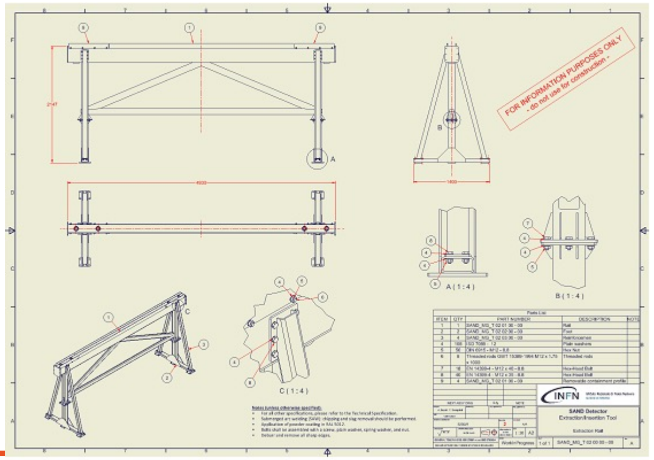
Barrel Extraction completed

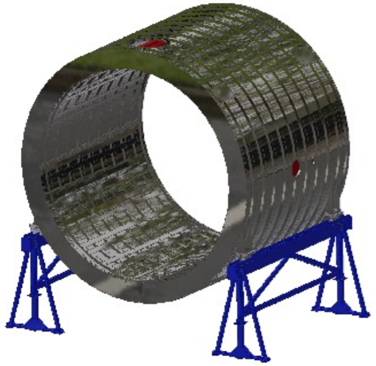


ECAL Dismounting Summary

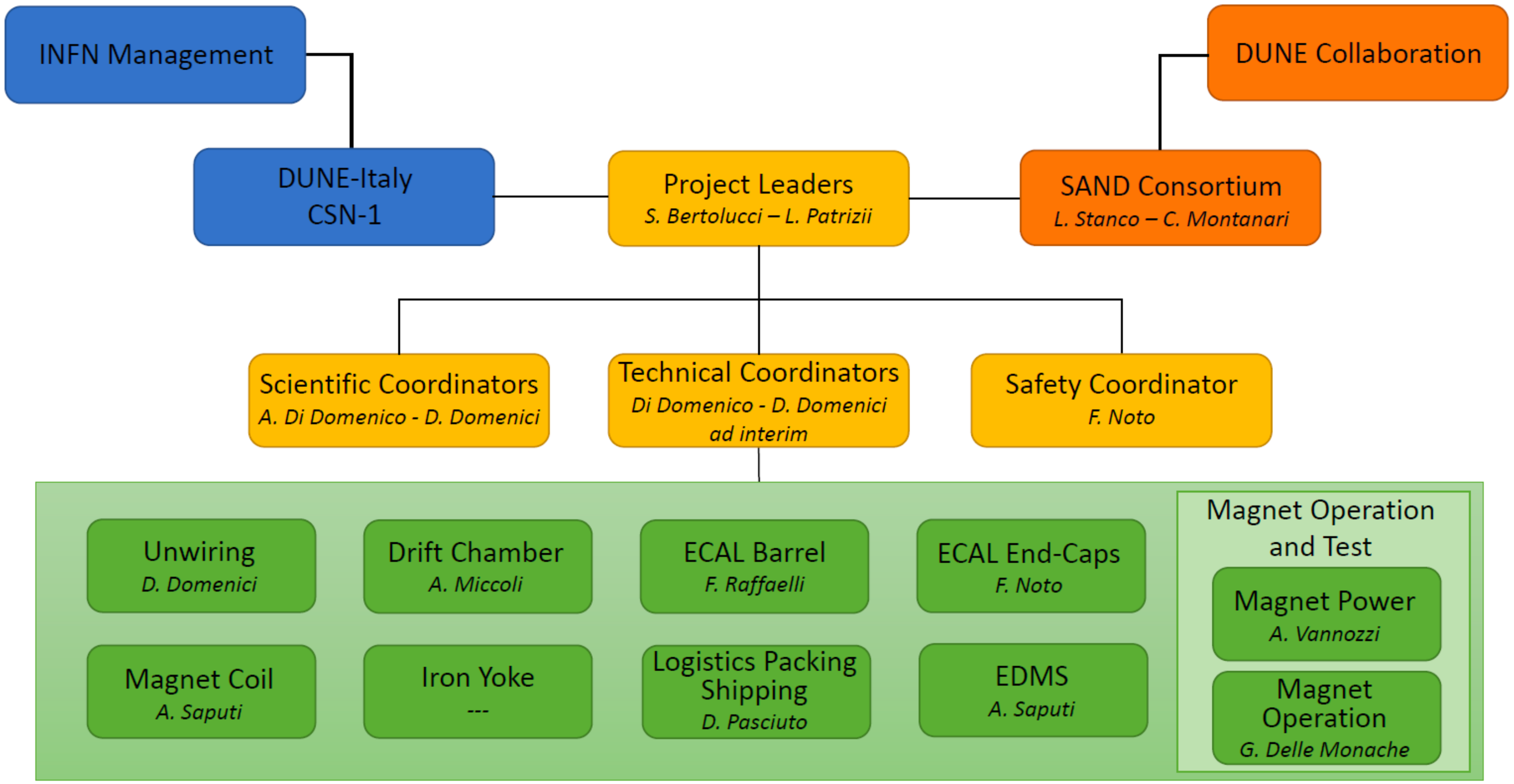
- The **24 modules** (3500 kg each) of the KLOE ECAL Barrel have been successfully extracted.
- The operations started at the beginning of February and ended in mid-May, with a net working time of 60 days.
- In view of the future insertion at FNAL a list of improvements of the tools has been already agreed
- Meanwhile, the tools for the End-Caps dismounting are under preparation
- Progresses have been made with OCEM on the technical solution for the magnet power supply, but delivery time is expected May 25
- Magnet cryostat extraction tools design is completed. Procedures are under definition.







KLOE-to-SAND Organizational Breakdown Structure



KLOE ECAL Performance/refurbishing

Lead-Scintillating Fibers
4880 PMTs read-out
98% solid angle coverage
24 Barrell modules
64 C-shaped EndCaps modules

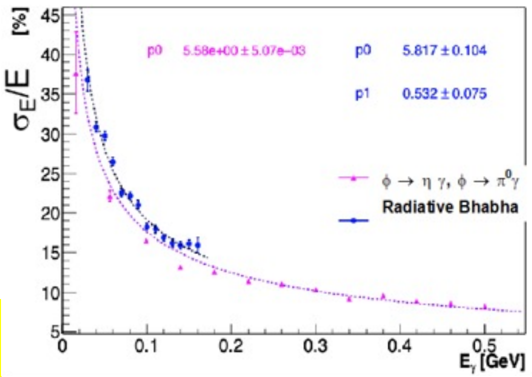
Neutron response of the ECAL is a key feature for SAND

Spare PMTs

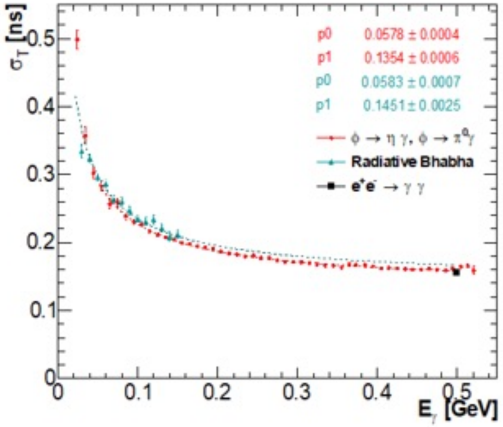
ECAL has 4880 Hamamatsu mesh PMT developed with KLOE. Since the production line is being discontinued, we purchased 150 spare tubes. A sample of 25 PMTs of the new batch have been tested at LNF showing very good performance. The whole batch is now at FNAL

HV system and new FE electronics

- HV system selected, ready to go for tender
- Studies and test for the dynamic range of PMT signals in SAND are going to be finalized. Final choice for the charge and time readout chain, in tight collaboration with CAEN, expected by mid 2025.



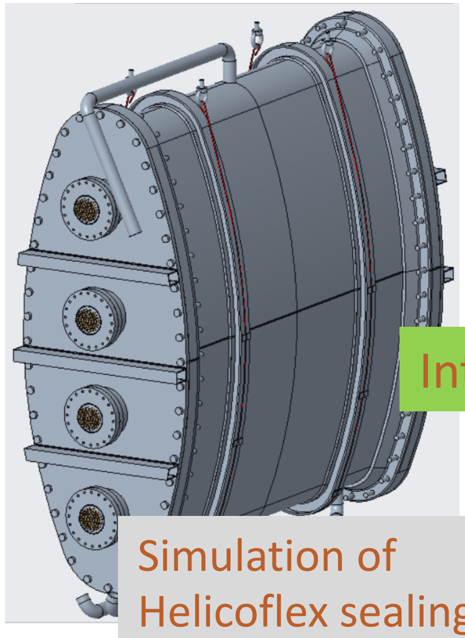
Energy and Time resolution measured in 2015-2018 run



$\sigma_E/E = 5.6\% / \sqrt{E(GeV)}$
$\sigma_t = 58$ ps $/ \sqrt{E(GeV)} \oplus 135$ ps

Updates on GRAIN

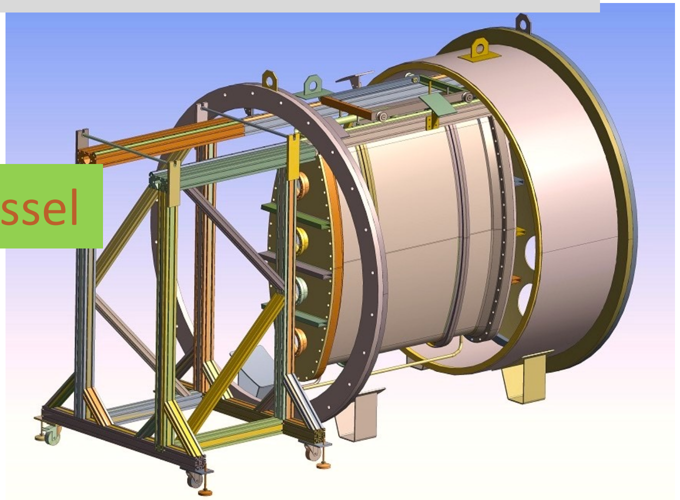
DEEP

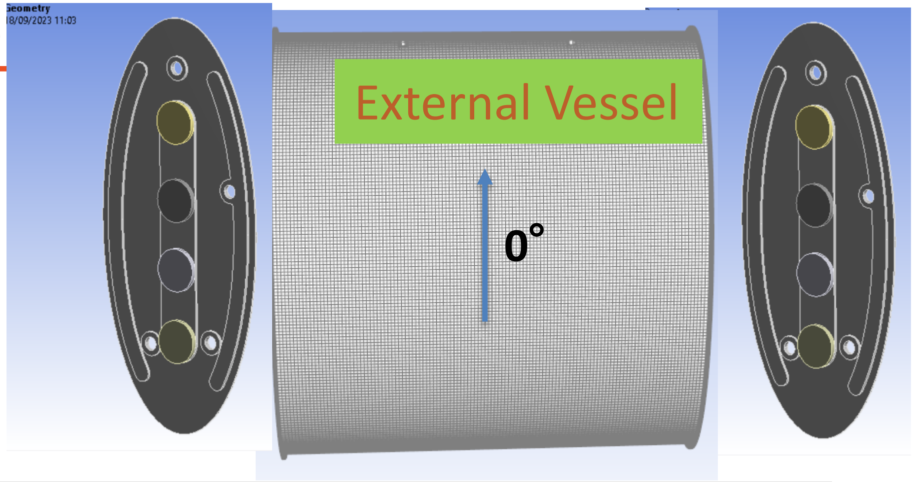


Internal Vessel

Simulation of Helicoflex sealing under way

Vacuum tank for Inner Vessel test at INFN-Legnaro almost ready for tender

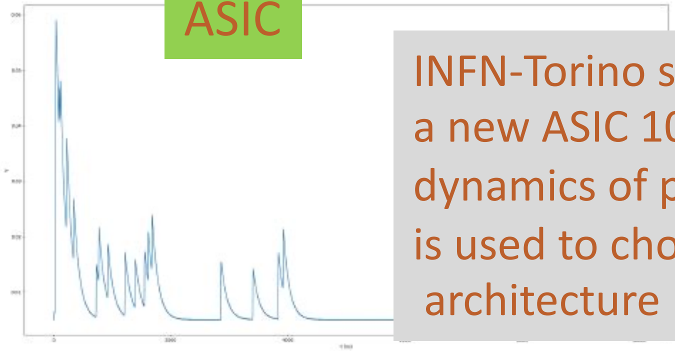




External Vessel

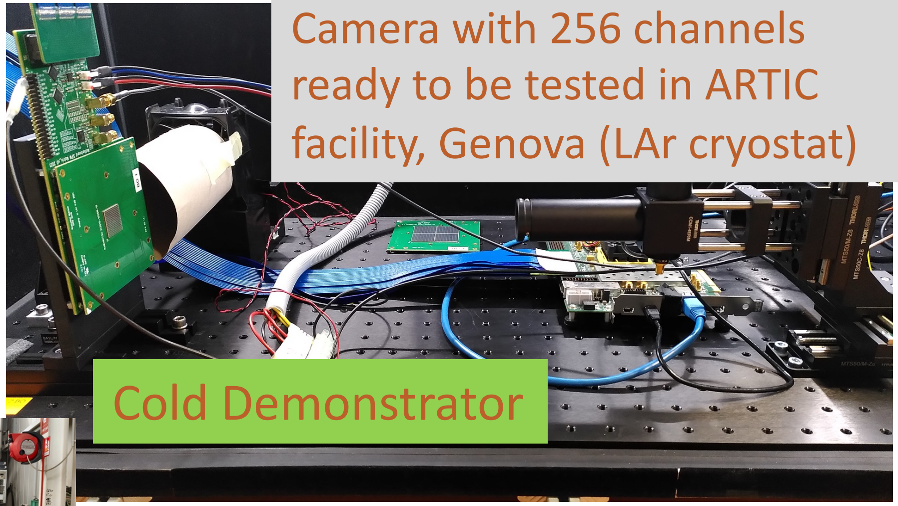
Test degassing and permeability of different samples of Carbon Fiber composites in INFN-Frascati

ASIC



INFN-Torino started the design of a new ASIC 1024 channels. Expected dynamics of photon arrival on SiPMs is used to choose optimized frontend architecture

Camera with 256 channels ready to be tested in ARTIC facility, Genova (LAr cryostat)



Cold Demonstrator

LNL-setup

INFN DUNE

DAQ Trigger - Timing - Slow Monitor updates

- Made progress in the definition of the timing requirements of SAND
  - We need timing alignment of few O(10) / < 100 ps RMS, depending on the subdetector
  - These are probably the most stringent requirements within the ND complex
  - These requirements apply to both between subdetectors and within each subdetector
  - However we only need them to be met within each single spill
- There are good chances that the DUNE-TIMING system can fit our needs
  - On the long term that system guarantees a timing alignment of O(100) ps RMS
  - On the short-term (a spill) and within a small subset of endpoints, the performances are significantly better
  - We are trying to identify a few measurements that can help us deciding whether to adopt the DUNE-TIMING system in SAND

PLL BW	Skew stdev
100Hz	31 ps
400Hz	6.9 ps
1kHz	2.8 ps
4kHz	1.8 ps

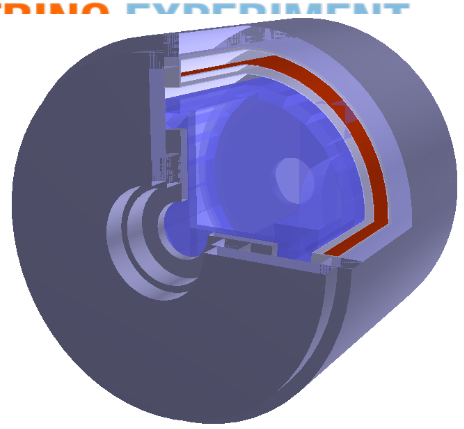
https://indico.fnal.gov/event/61796/

One important point about the timing is the synchronization with the beam

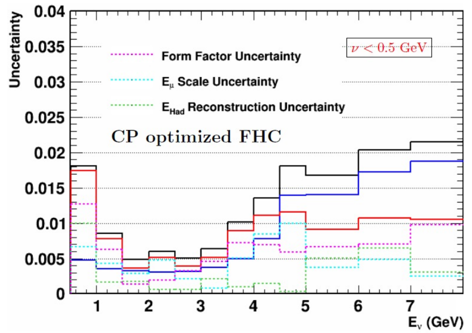
- In SAND we aim at ~ns timing accuracy, to disentangle the bunch structure in each spill
- The options proposed by the accelerator group are not fully satisfactory
- We are considering the possibility to implement a custom instrumentation to pickup a signal directly from the proton beam
- This would require a discussion with the accelerator group
- We also started discussing about this topic with the TMS group

Nicolò Tosi has replaced Michele Pozzato as co-coordinator of the WG, together with Camillo Mariani and Sergio Di Domizio

Software/Physics



- ECAL:
  - Detailed ECAL endcap geometry + its digitization
  - Validation and test of the ECAL clustering algo + Study of Particle ID
- Tracker:
  - Validation and test of Kalman Filter for track reconstruction
  - Development of fast track recostruction algorithms
- GRAIN:
  - Improvement of 3D reconstruction with masks
  - ML-based filter for coded aperture camera raw data
- *sandreco* integration with DUNE SW framework



Breakdown of expected uncertainties on flux determination

A summary of the analyses and results is here

SAND: conclusions

- ✓ The SAND detector is a key element of the ND-complex (and DUNE)
  (formally based also on the MoU just signed off)
- ✓ Our plan is compatible with the first day of ND-hall allowance to start installation (Sept. 2028),
  (thanks also to FNAL interplay)
- ✓ Disassembly of KLOE in Italy is actively and wonderfully going on
  (two months delay will be shortly recovered)
- ✓ Robust R&D program underway for the Tracker and GRAIN
  (PDR/TDR will be a disentangling milestone)
- ✓ The physics potentials are huge, for oscillation physics and beyond
  (undergoing Task Force mission)