

Precision measurements of (anti)neutrinos interactions with the SAND detector at the DUNE near site

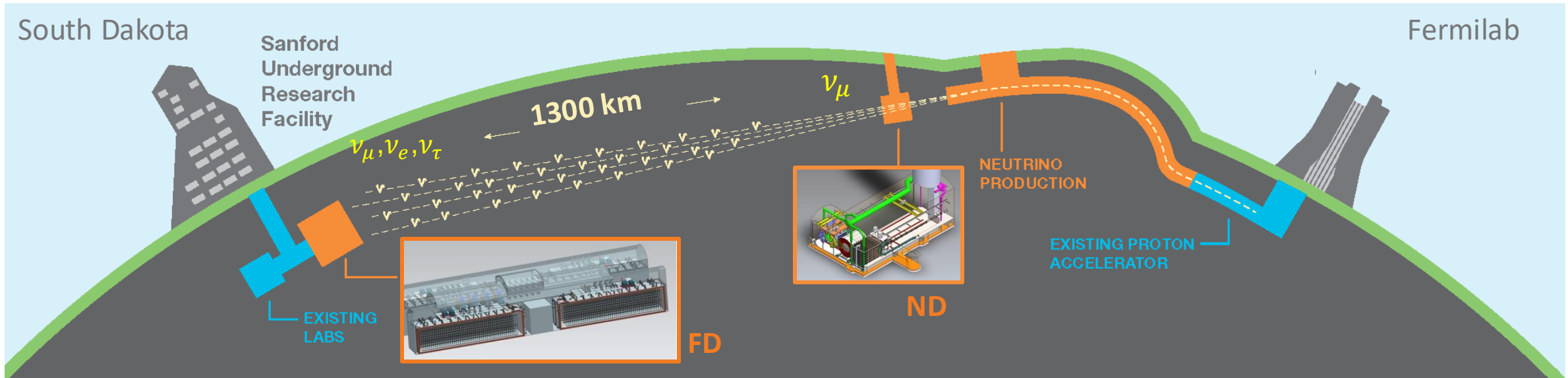
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for the DUNE Collaboration

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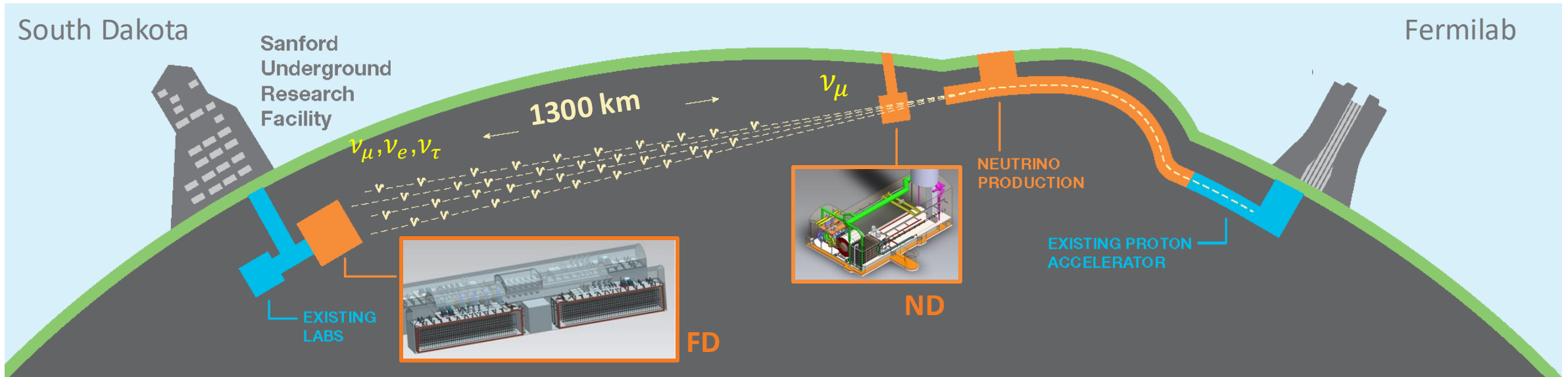


DUNE: Deep Underground Neutrino Experiment



- A new generation Long Baseline neutrino oscillation experiment
 - High precision measurements of the neutrino oscillation parameters: δ_{CP} , mass ordering, θ_{23}
 - Supernova and solar neutrinos detection
 - Beyond the Standard Model Searches

DUNE: Deep Underground Neutrino Experiment



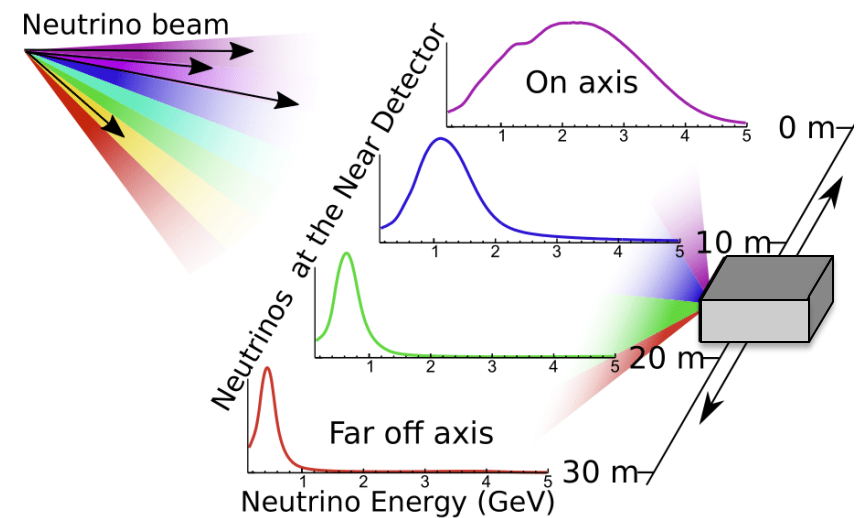
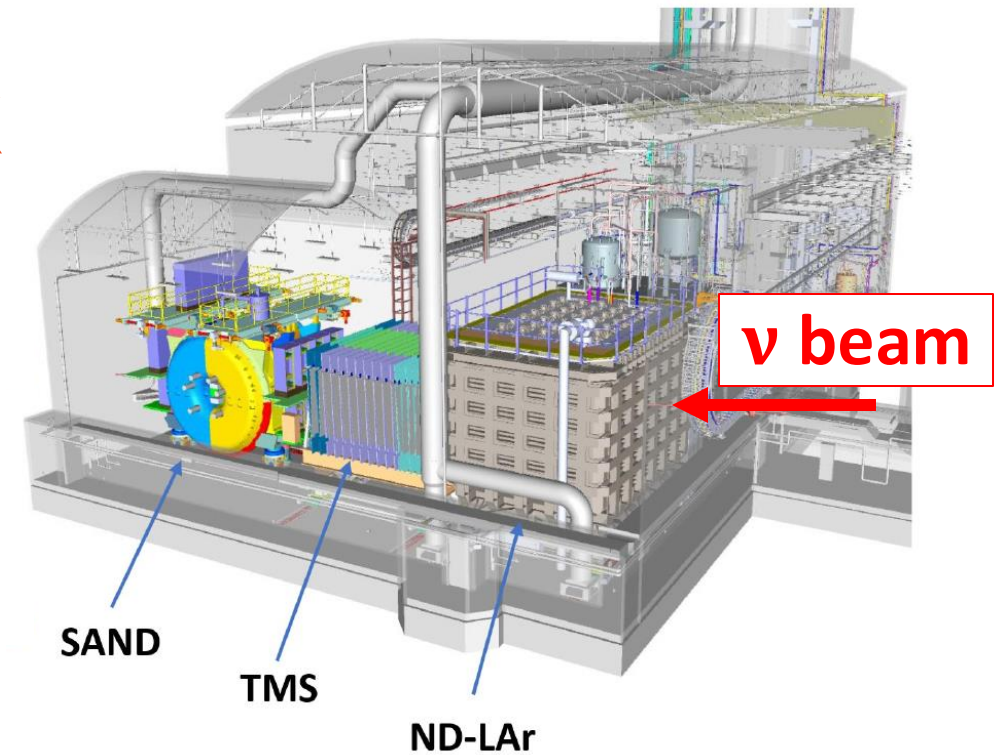
- An intense **wide band $\nu/\bar{\nu}$ neutrino beam** produced at Fermilab, peak flux at 2.5 GeV high intensity 1.2 MW ($1.1 \cdot 10^{21}$ pot/year) upgradable to 2.4 MW
- Two neutrino detector complexes:
 - a **Far Detector (FD)** in South Dakota, 1.5 km underground and 1300 km away from neutrino source consisting of four modules, 17 kton each
 - a **Near Detector complex (ND)** at Fermilab

The Near Detector complex

Near Detector will be located 574 m downstream of the neutrino beam and will include three main detectors:

- **ND LAr:** a 67 ton LArTPC
- **TMS:** The **Muon Spectrometer**
- **SAND:** **S**ystem for on **A**xis **N**eutrino **D**etection - a magnetized multi-purpose detector

ND-LAr and TMS will move in order to “scan” over the spectrum of ν energies



The Near Detector physics goals

To extract oscillation parameters DUNE will measure neutrino interactions rates both at FD and ND

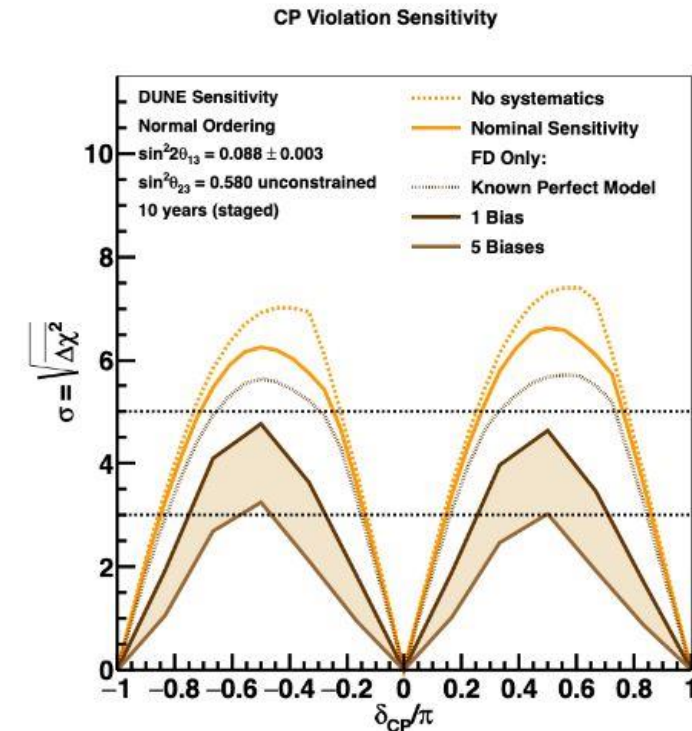
$$N_X(E_{rec}) = \int P_{osc}(E_\nu) * \phi(E_\nu) * \sigma_X(E_\nu) * R_{phys}(E_\nu, E_{vis}) * R_{det}(E_{vis}, E_{rec}) dE_\nu$$

To predict the expected oscillating ν_μ and ν_e spectra at FD the measurements done at ND must be propagated to FD.

Existing **systematic uncertainties** on modeling of cross section, nuclear effects and fluxes **are not consistent with the precision required by DUNE** (< 2-3%).

The ND will:

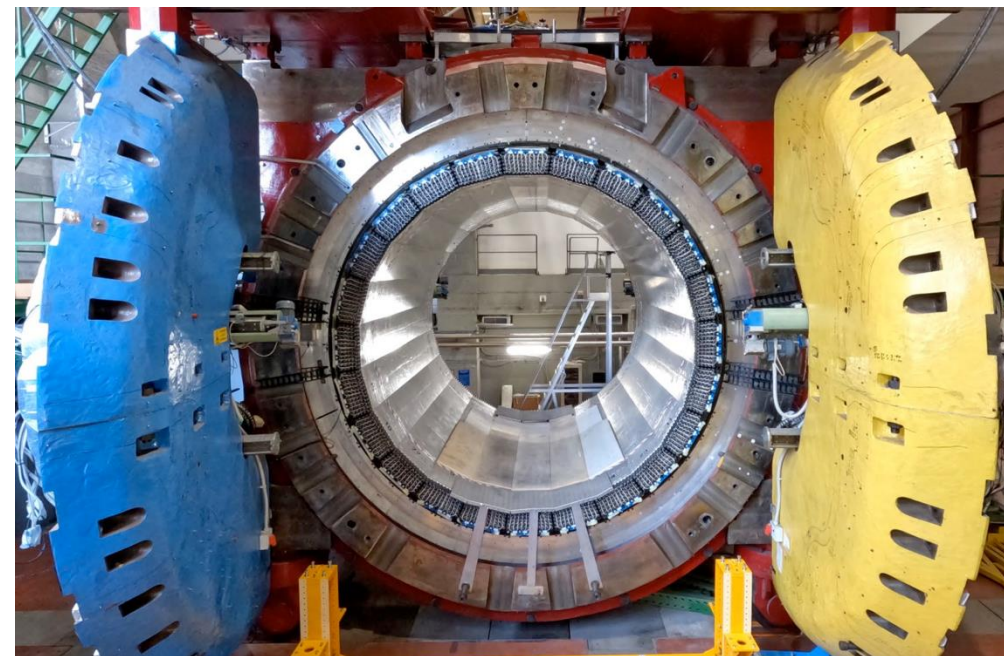
- measure with high precision:
 - Flux $\phi(E_\nu)$ → low density detector to provide high resolution and precise energy scales
 - cross section $\sigma_X(E_\nu)$ and calibrate detector response R_{det} → same Ar target as FD
- constrain nuclear effects R_{phys} → using both Ar and lighter targets



SAND

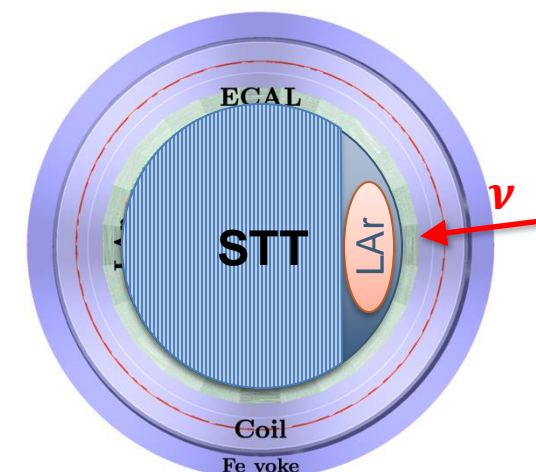
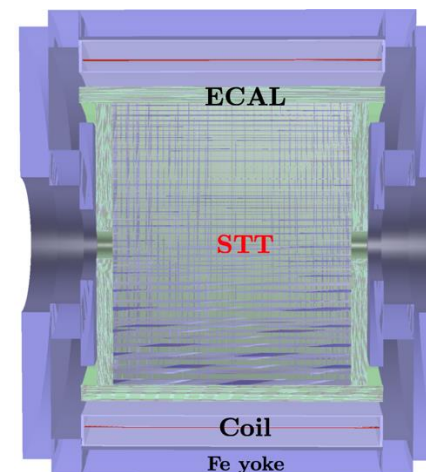
The only component of the ND that will be permanently located **on-axis**. It aims at:

- On-axis ν **spectrum monitor**
- Provide an independent in situ **measurements** of $\nu_{\mu,e}/\bar{\nu}_{\mu,e}$ **fluxes and energy spectra**
- **Constrain** systematics from **nuclear effects**
- Perform a **rich physics program besides oscillations**



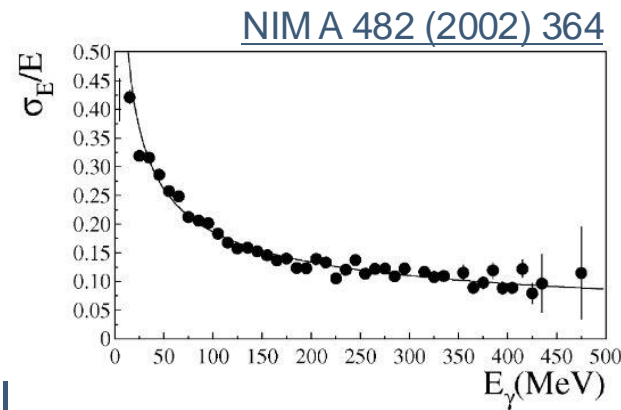
SAND consists of:

- **Superconducting magnet (0.6 T)**
 - **Electromagnetic Calorimeter (ECAL)**
 - **Straw-Tube-Tracker and CH₂, C target**
 - **1-ton LAr Active target (GRAIN)**
- } formerly KLOE

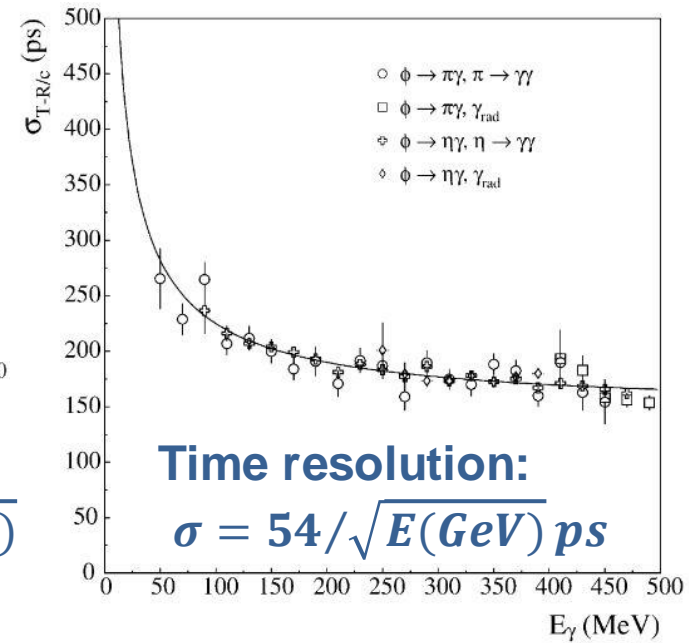


SAND – ECAL

- **Electromagnetic calorimeter:** lead and scintillating fiber sampling calorimeter
 - 24 modules, 4.3 m long, 23 cm thick barrel + C-shaped modules for the endcaps
 - 4880 PMTs, $\sim 4\pi$ coverage, $\sim 15 X_0$

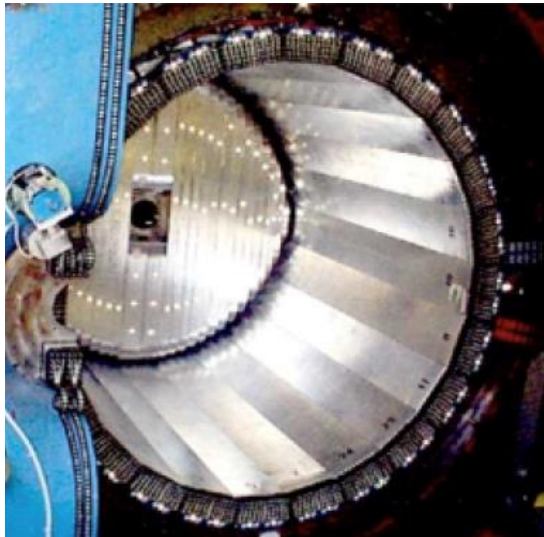


Energy resolution:
 $\sigma/E = 5.7\%/\sqrt{E(\text{GeV})}$



Time resolution:
 $\sigma = 54/\sqrt{E(\text{GeV})} \text{ ps}$

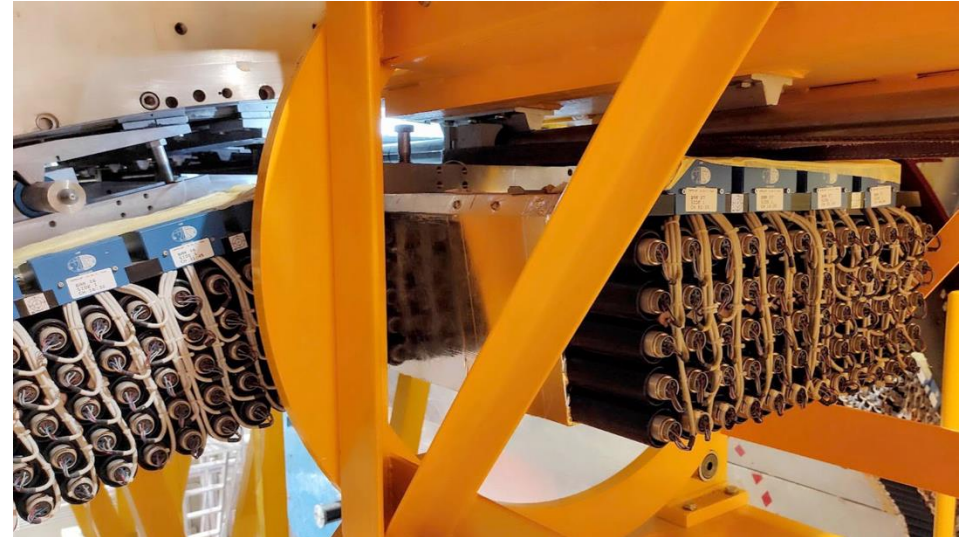
BARREL MODULES



ENDCAPS MODULES



SINGLE MODULE PMTs

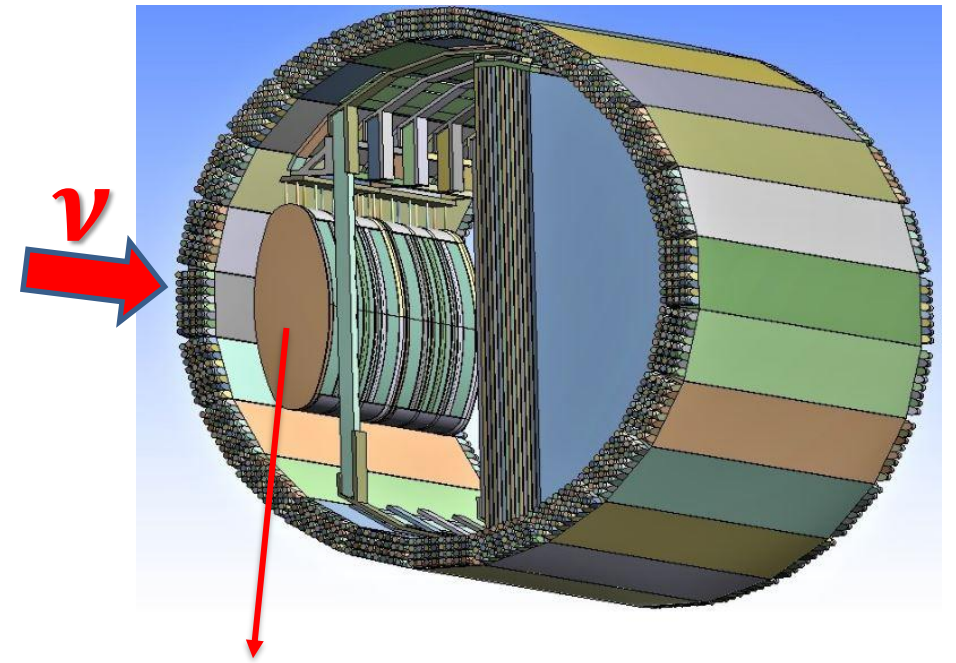


SAND – GRAIN

Its role is **constraining nuclear effects on argon** and have a **complementary Ar target permanently located on-axis** for cross-calibration.

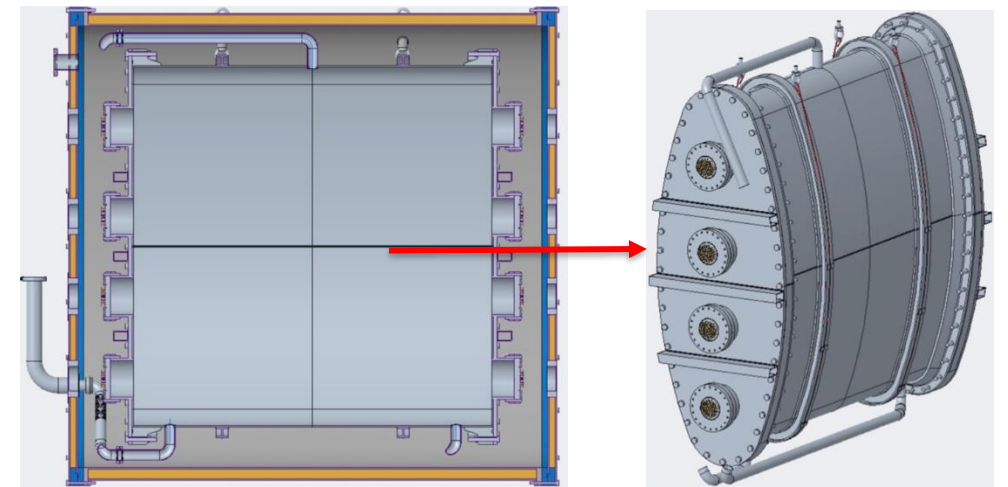
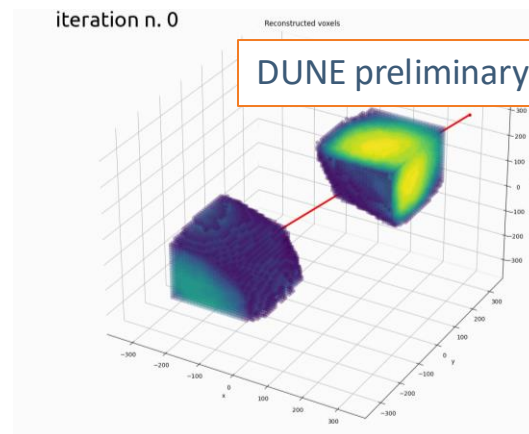
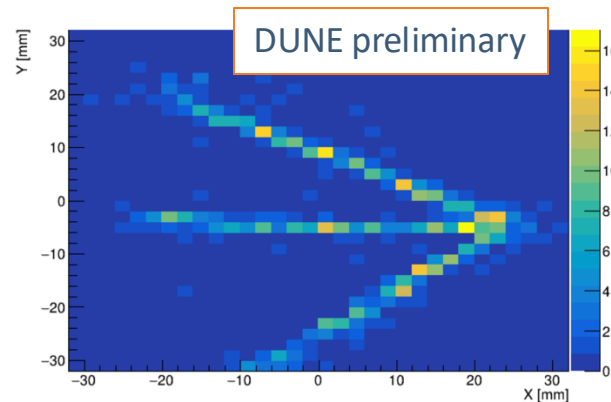
- Outer vacuum vessel made of C-composite material
- Inner vessel containing the LAr made of Al.
- $\sim 1 X_0$ overall radiation length

It will be equipped with an **optical** system to collect UV **scintillation light** on fine segmented focal planes and perform track reconstruction



OUTER VESSEL

INNER VESSEL



SAND – STT Inner tracker

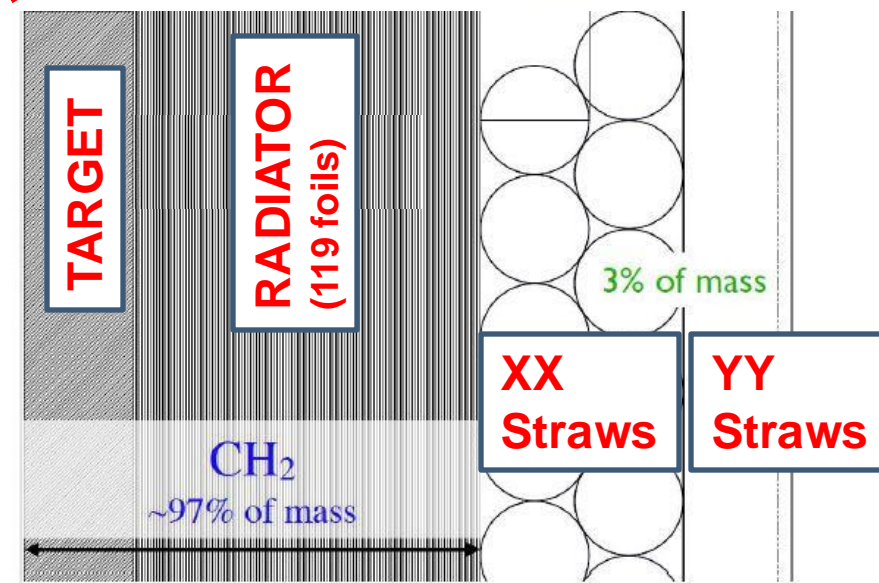
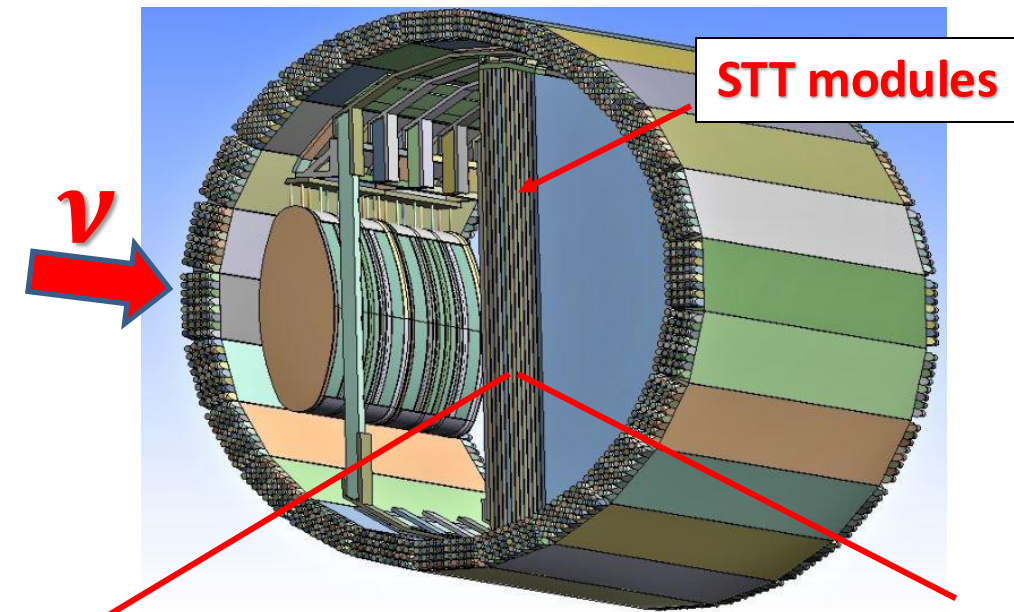
The design provides accurate control of **configuration**, **chemical composition**, and **mass** and allows to:

- **Accurate** reconstruction of **transverse plane kinematics** variables ($\delta p/p \leq 3\%$, $\delta\theta/\theta \leq 1.5\%$)
- separate neutrino and antineutrino events (**charge ID**),
- identify primary leptons (**beam flavor composition**)

Design

73 modules each made of:

- ~ 5 mm of passive target (CH₂, H, ...)
- radiator (105 polypropylene foils)
- 5 mm diameter straw tubes (Xe/CO₂ gas at 1.9 atm) arranged in XXYY layers



fiducial volume mass 4.7 t CH₂, 557 kg C

Beam monitoring capability

- Continuous beam monitoring on a weekly basis (3.78×10^{19} POT) is crucial
- Beam is monitored by measuring **variations of ν_μ CC interaction energy spectrum and event distribution in space**
- Sensitivity on a list of possible variations was obtained from simulation comparing expected spectra with:

$$\Delta\chi^2 = \sum_{i=1}^n \frac{(N_i^{norm} - N_i^{alt})^2}{N_i^{norm}}$$

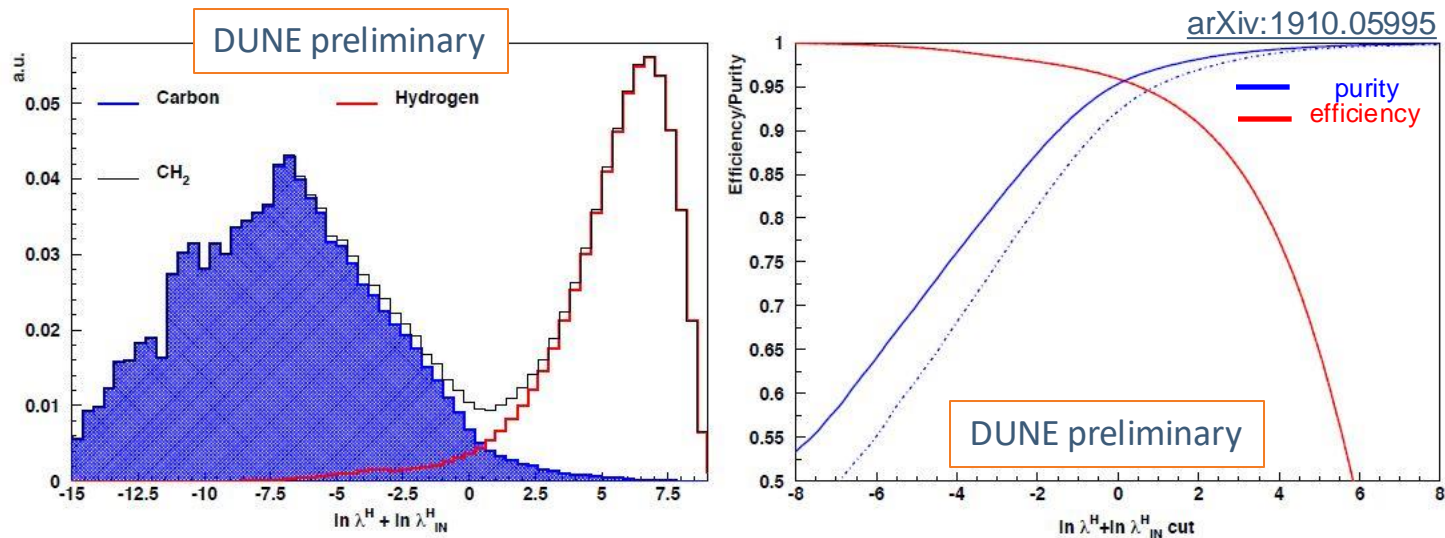
1 week FHC data taking

Proton beam parameter	1 σ deviation as given by beam group	Significance	
		$\sqrt{\Delta\chi^2}(E_\nu)$ true	rec
Horn current	+3 kA	12.57	9.44
Water layer thickness	+0.5 mm	4.69	3.58
Proton target density	+2%	5.28	4.07
Beam sigma	+0.1 mm	4.41	3.53
Beam off set X	+0.45 mm	5.11	3.54
Beam theta phi	0.07 mrad θ , 1.57 ϕ	0.62	0.28
Beam theta	0.070 mrad	0.91	0.58
horn 1 X shift	+0.5 mm	4.70	3.42
horn 1 Y shift	+0.5 mm	5.27	3.87
horn 2 X shift	+0.5 mm	1.18	0.69
horn 2 Y shift	+0.5 mm	1.31	0.77

SAND has enough sensitivity ($\sqrt{\Delta\chi^2} > 3$) to detect most of beam variations in one week.

SAND physics program - “solid” hydrogen concept

Model independent subtraction of measurements on dedicated graphite (pure C) targets from main CH₂ target to extract high statistics samples of ν ($\bar{\nu}$) CC interactions on H by a kinematic analysis



5y (FHC) + 5y (RHC)	Eff.	Purity	Size
ν_μ CC inclusive	93%	93%	2.9M
$\nu_\mu p \rightarrow \mu^- p \pi^+$	96%	95%	2M
$\nu_\mu p \rightarrow \mu^- p \pi^+ X$	89%	93%	760k
$\nu_\mu p \rightarrow \mu^- \pi^+ \pi^+ X$	75%	70%	93k
$\bar{\nu}_\mu$ CC inclusive	80%	84%	1.6M
$\bar{\nu}_\mu p \rightarrow \mu^+ n$	75%	80%	860k
$\bar{\nu}_\mu p \rightarrow \mu^+ p \pi^-$	94%	95%	300k
$\bar{\nu}_\mu p \rightarrow \mu^+ n \pi^0$	84%	84%	210k
$\bar{\nu}_\mu p \rightarrow \mu^+ p \pi^- X$	85%	94%	135K
$\bar{\nu}_\mu p \rightarrow \mu^+ n \pi \pi X$	82%	84%	156k

Interaction on Hydrogen can be exploited to perform:

- Flux measurements
- Constrain models on nuclear effects

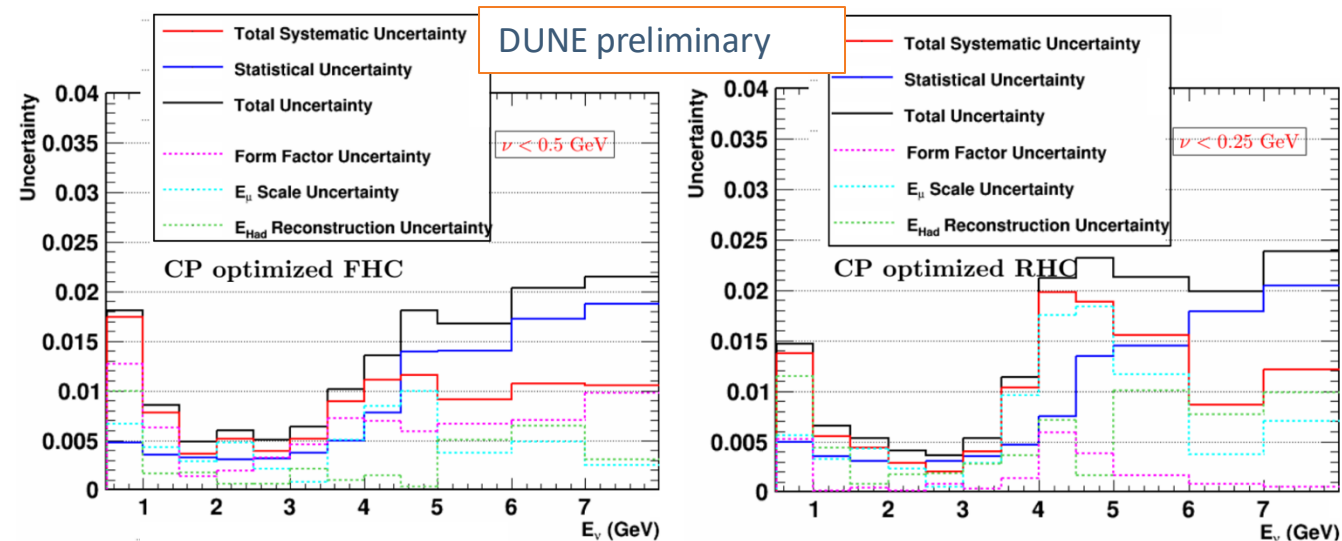
SAND physics program - Flux measurements

The measurement of ν flux $\phi(E_\nu)$ is a mandatory condition to extract oscillation probability from measured neutrino interactions

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

A **large sample** of ν (anti- ν) on H allows an accurate **determination** of absolute and relative ν **fluxes** using $\nu_\mu p \rightarrow \mu^- p \pi^+$, $\bar{\nu}_\mu p \rightarrow \mu^+ p \pi^-$ and $\bar{\nu}_\mu p \rightarrow \mu^+ n$ processes on hydrogen

- **interactions on H** are free from typical problems arising from nuclear smearing
- selecting **small momentum transfer** (cut on $\nu < 0.25$ GeV) flattens cross sections allowing to measure the flux



SAND physics program - constrain nuclear effects

DUNE will face the **challenge of modelling neutrino-nucleus interaction** which requires the knowledge of large and complex nuclear effects on Ar affecting the **re-scattering of final state particles** within the nucleus

This smearing introduces **uncertainties** on the reconstruction of neutrino energy

- **Argon detector alone** cannot resolve nuclear smearing and related systematics
- **H + Ar target** integrated with the SAND detector offers **valuable information** to reduce systematics:

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

1 % on H Measured from high statistic sample $R_{phys} \equiv 1$ $\delta p/p$ 0.2% calibrated in-situ from $K_0 \rightarrow \pi^+ \pi^-$ in STT volume

constrain the product $\sigma_X R_{phys}$ on Ar from a direct comparison between Ar and H interactions **within the same detector**

→ help DUNE PRISM to reduce beam model uncertainties

Conclusions

SAND is an excellent beam monitoring for changes that would impact long-baseline measurements

SAND can explore many different physics topics within the ND complex, from precise measurements of high statistics samples of (anti)neutrino interactions in hydrogen and other nuclear targets (including argon) to searches for new physics

SAND measures the flux and constrains nuclear effects, it is capable of controlling systematics uncertainties on ν spectrum to provide the initial state of the beam and to compare it with the observations at the Far Detector