The System for on-Axis Neutrino Detection of the DUNE Near Detector complex

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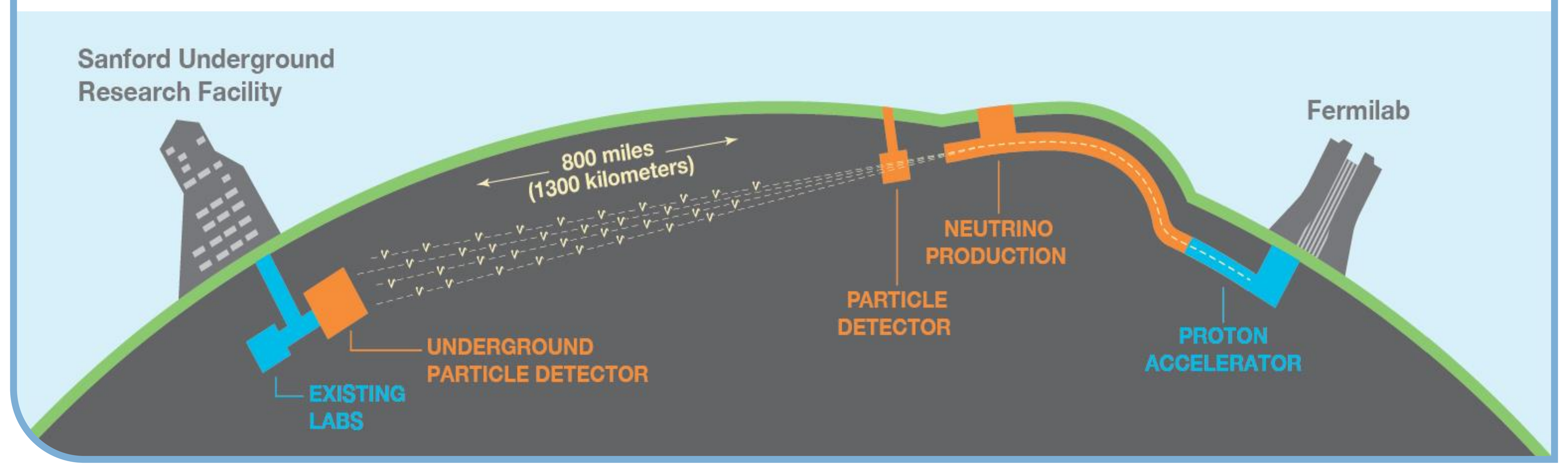
The DUNE experiment

The **Deep Underground Neutrino Experiment** is a long-baseline neutrino oscillation experiment. Its physics program includes:

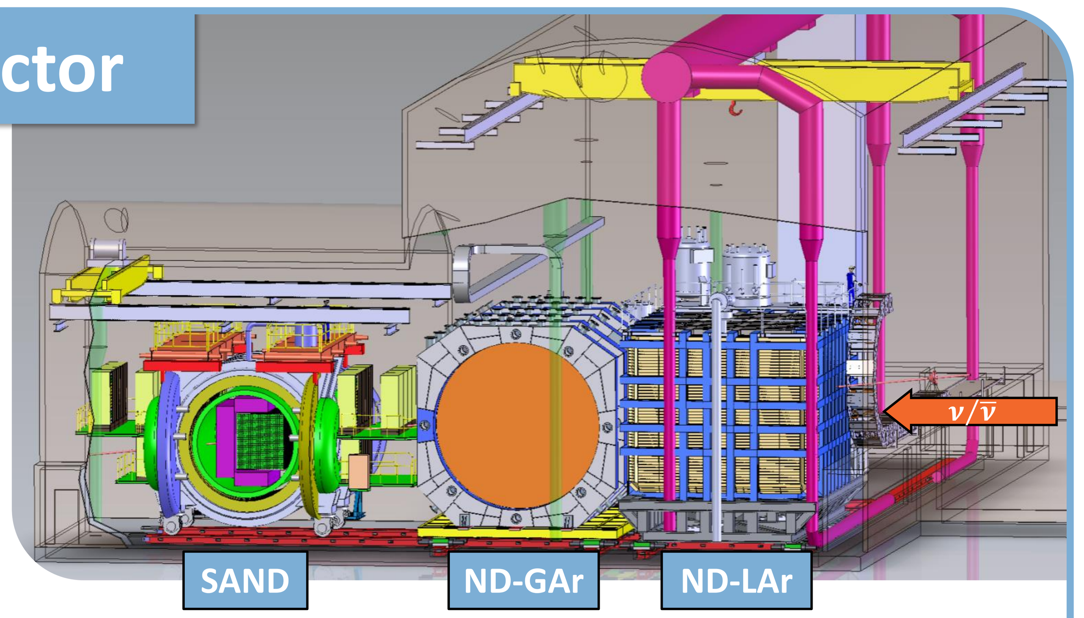
- high precision measurements of the neutrino oscillation parameters
- searches for beyond standard model physics
- supernova neutrino detection

DUNE will be composed by a massive liquid argon far detector (FD) composed by 4 modules, 17 kt each (1300 km from the neutrino beam source) and a near detector (ND) complex (about 500 m from the neutrino beam source).



The Near Detector

Its main goals are constraining systematic uncertainties and monitoring the variation of the neutrino beam.



The DUNE Near Detector is composed of three apparatus:

- Pixelated, modular, 50 fiducial mass, Liquid Ar TPC (ND-LAr)
- Multi-Purpose Detector based on magnetized high pressure Ar gas TPC, 1.8 t active mass
- System for on-Axis Neutrino Detection (SAND)

SAND: Background sources

At the ND site the most critical background sources are beam related neutrino interactions in the material surrounding the detector. Mostly:

- neutrons
- external neutrino interactions

Expected CC+NC event rates per beam spill in SAND components

Detector element	Mass	FHC	RHC
Magnet	511 t	68.9	36.6
ECAL	100 t	13.5	7.2
LAr+STT	8.2 t	1.1	0.59
STT fiducial	5.5 t	0.74	0.39
Total	619.2 t	83.5	44.39

Simulated $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ interactions using GENIE and Geant4.

7.6×10^6 ν_μ CC interaction in FHC mode
4.9×10^6 $\bar{\nu}_\mu$ CC interaction in RHC mode
} In ECAL, STT + LAr target and magnet

SAND

The **System for on-Axis Neutrino Detection** is a multipurpose detector, capable of precision tracking and calorimetry. It is composed of:

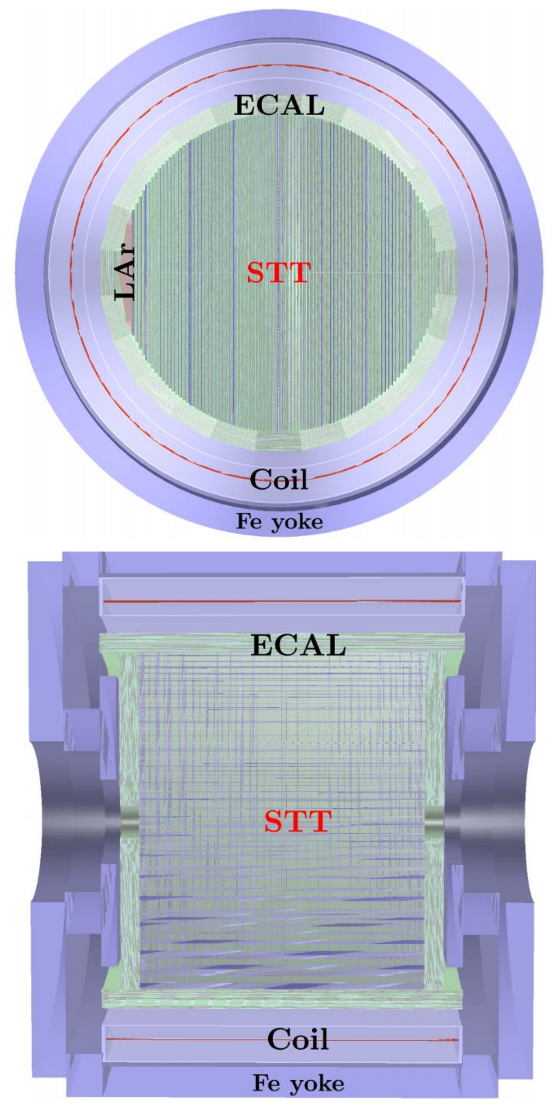
Superconducting magnet
0.6 T over a 4.3 m long, 4.8 m diameter volume

Liquid Argon volume
1 t, optical readout

Electromagnetic calorimeter
lead-scintillating fibers, 24 modules, 4.3 m long, 23 cm barrel + endcap

Energy resolution
$\sigma/E = 5\%/\sqrt{E(\mathrm{GeV})}$

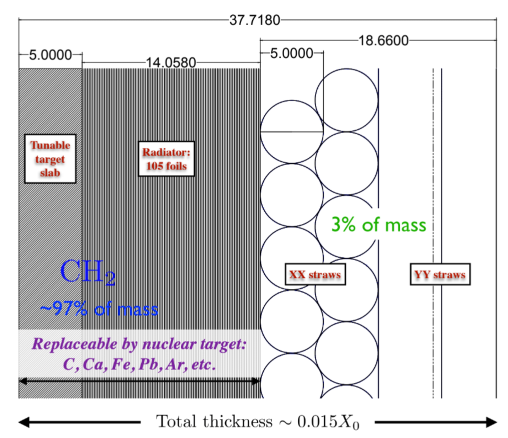
Time resolution
$54/\sqrt{E(\mathrm{GeV})}$ ps



Inner tracker
two designs are being considered
3D scintillator tracker (3DST +TPC)
or
Straw Tube Tracker (STT)
(configuration sketched in the figure)

Four straw layers in a XXYY arrangement alternated with CH_2 radiator and pure C target.

Possibility to change the target with different materials

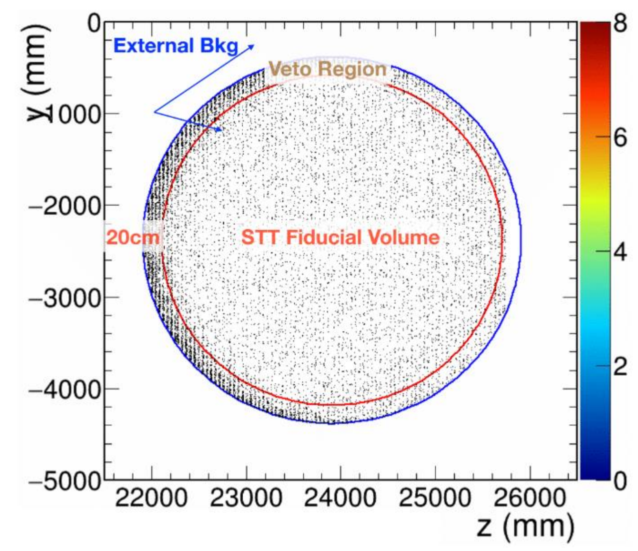


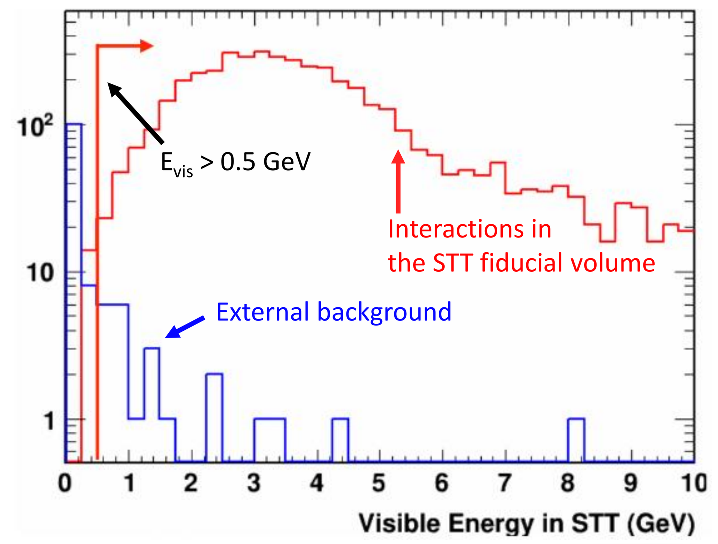
Background Rejection

Rejection of External Neutrino Interactions in the STT

- at least one reconstructed track in the STT
- ≥ 4 hits in the YZ bending plane
- reconstructed visible energy > 0.5 GeV

Selection	STT FV Signal ε (%)	Ext. bkg Total ε (%)	Purity (%)
STT hits in FV > 15	98.32	7.238	9.98
Pre-selection	95.32	1.944	28.59
NN>0.95 cut	92.89	0.015	98.01
$E_{vis} > 0.5$ GeV ≥ 1 track	92.71	0.003	99.65



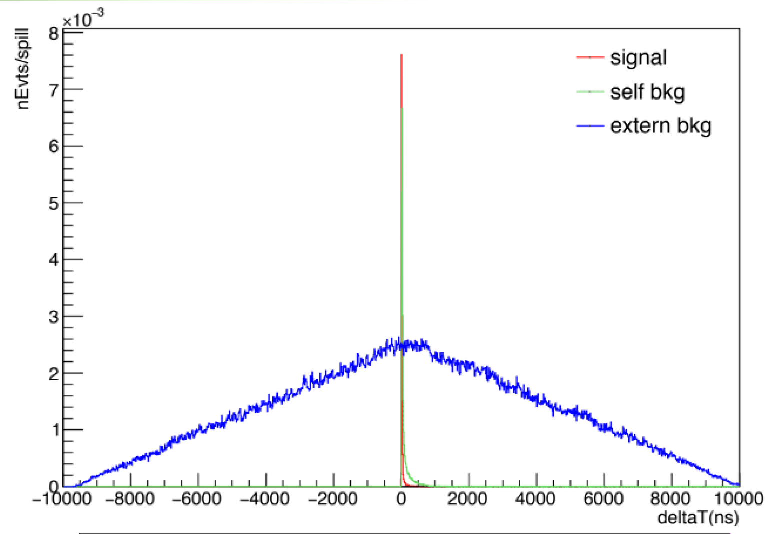


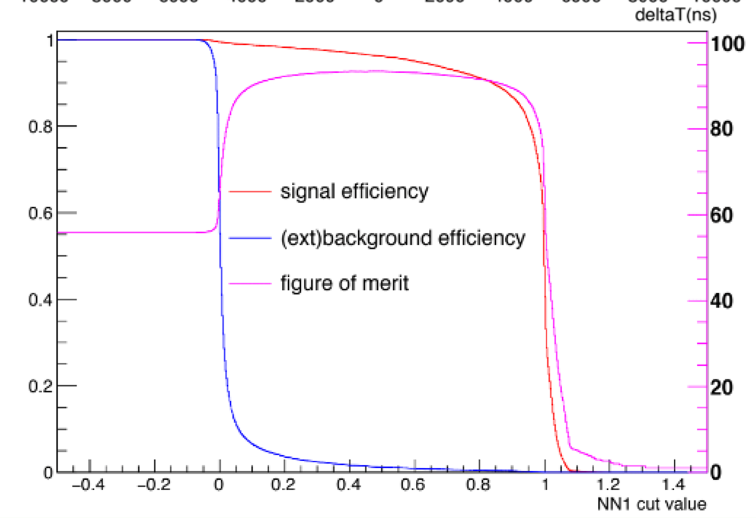
Rejection of Random Neutron Background
$\bar{\nu}_\mu\, p \to \mu^+ n$ in QE interactions in Hydrogen

Neutron candidate if:

- clustering with $E_{rec} > 250$ eV in STT and 1.1 p.e. in ECAL
- no charged particle connected to the cluster

Selection based on ToF of "measured" neutron candidate or using Neural Network to correlate neutron candidate with overlapping detected activity





Selection	$\bar{\nu}_\mu\, p \to \mu^+ n$ on H: Primary neutron ε (%)	$\bar{\nu}_\mu\, p \to \mu^+ n$ on H: Secondary neutron ε (%)	External events ε (%)
No cut	100	100	100
$-2 < \Delta t < 300$ ns	81	33	0.6
NN cut	85.4	8.5	6.0

Beam Monitoring with SAND

Continuous monitoring of the neutrino beam is needed to detect potential variations over time affecting the FD oscillation analysis.

The beam is monitored by measuring the momentum and energy distributions of particles produced in ν_μ CC interactions.

The goal is to monitor the beam spectrum, profile, and event rate in a statistically significant way over a 7 days basis ($\sim 3.78 \times 10^{19}$ pot).

Simulated samples: $\sim 1.5 \times 10^6$ ν_μ CC inteactions in ECAL, STT, LAr target (GENIE + GEANT) in FHC mode.

Momentum reconstruction: a minimum number of STT digits in the YZ bending plane is required to reconstruct particle's momentum

- for interaction in the ECAL and LAr target: ≥ 6 digits
- for interaction in STT: ≥ 4 digits

Neutrino energy:

$$E_\nu^{rec} = E^{ECAL} + E^{LAr} + \sum_{tracks} K^{STT}$$

E^{ECAL} and E^{LAr} being the visible energy in SAND ECAL and LAr target and K^{STT} kinetic energy associated to reconstructed tracks.

Beam monitoring sensitivity

Sensitivity to different beam variations evaluated comparing the distributions of E_ν^{rec} expected for nominal and varied beam conditions using the test statistic:

$$T = \Delta\chi^2 = \sum_{i=1}^{N} \frac{(N_i^{nom} - N_i^{var})^2}{N_i^{nom}}$$

- nominal distribution obtained from full Monte Carlo simulation
- varied distribution obtained by re-weighting the nominal one
- weights obtained from MC simulations, versus neutrino energy and shift of the beam axis

Shift of Beam Direction

Significance $\Delta\chi^2 = 9$ in one week

Component	X shift (cm)
ECAL	107.6
STT	21.1
Combined	34.9

Significance > 3 with ECAL+STT in one week for a 0.13 mrad change in beam direction.

Beam Parameters

Results (some)	$T \sim \Delta\chi^2$ ECAL		$T \sim \Delta\chi^2$ ECAL+STT	
Beam parameter	E_ν^{true}	E_ν^{rec}	E_ν^{true}	E_ν^{rec}
Horn current	107.6	76.1	158.2	105.6
Water layer thick.	21.1	16.2	30.2	22.2
p beam radius	34.9	27.6	13.5	9.8
p beam offset X	24.6	16.9	34.1	22.2
p target density	18.0	14.3	25.6	19.6
p beam θ	0.7	0.2	1.1	0.3
Horn1 X shift	16.2	10.7	23.4	14.6
Horn2 X shift	0.4	0.2	0.6	0.3

Conclusions

The SAND ECAL and STT provide large rejection factors exceeding 3×10^{-5} against external backgrounds with minimal efficiency losses.

A significance exceeding $\Delta\chi^2 > 9$ achieved in one week of data taking for the detection of different changes in the beam parameters.

[1] B. Abi et al. [DUNE], '*Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I Introduction to DUNE*,' JINST 15, no.08, T08008 (2020) doi:10.1088/1748-0221/15/08/T08008
[2] Nucl.Instrum.Meth.A614 (2010) 87-104; arXiv:1510.05494
[3] Nucl.Instrum.Meth.A506 (2003) 250-303