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

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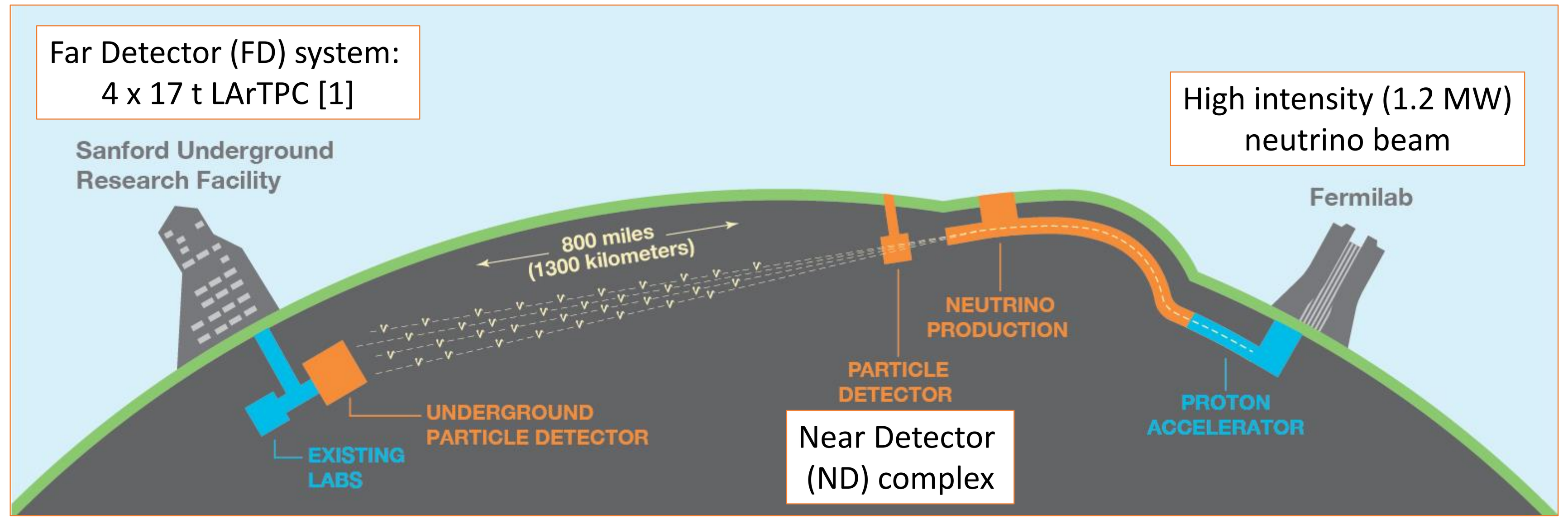
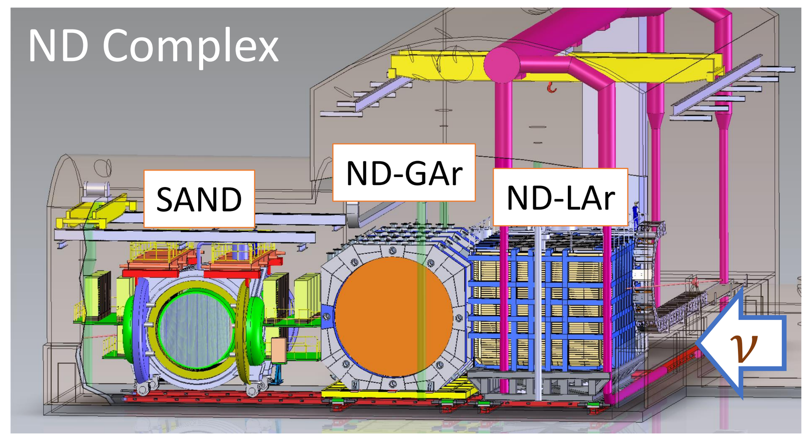
DUNE – Deep Underground Neutrino Experiment

DUNE Experiment

The Deep Underground Neutrino Experiment (**DUNE**) is a long-baseline neutrino oscillation experiment. Its major aims are:

- Measure the **leptonic CP violating phase** and the neutrino **mass hierarchy**
- Search for **proton decay**
- Detection of **supernova neutrinos**





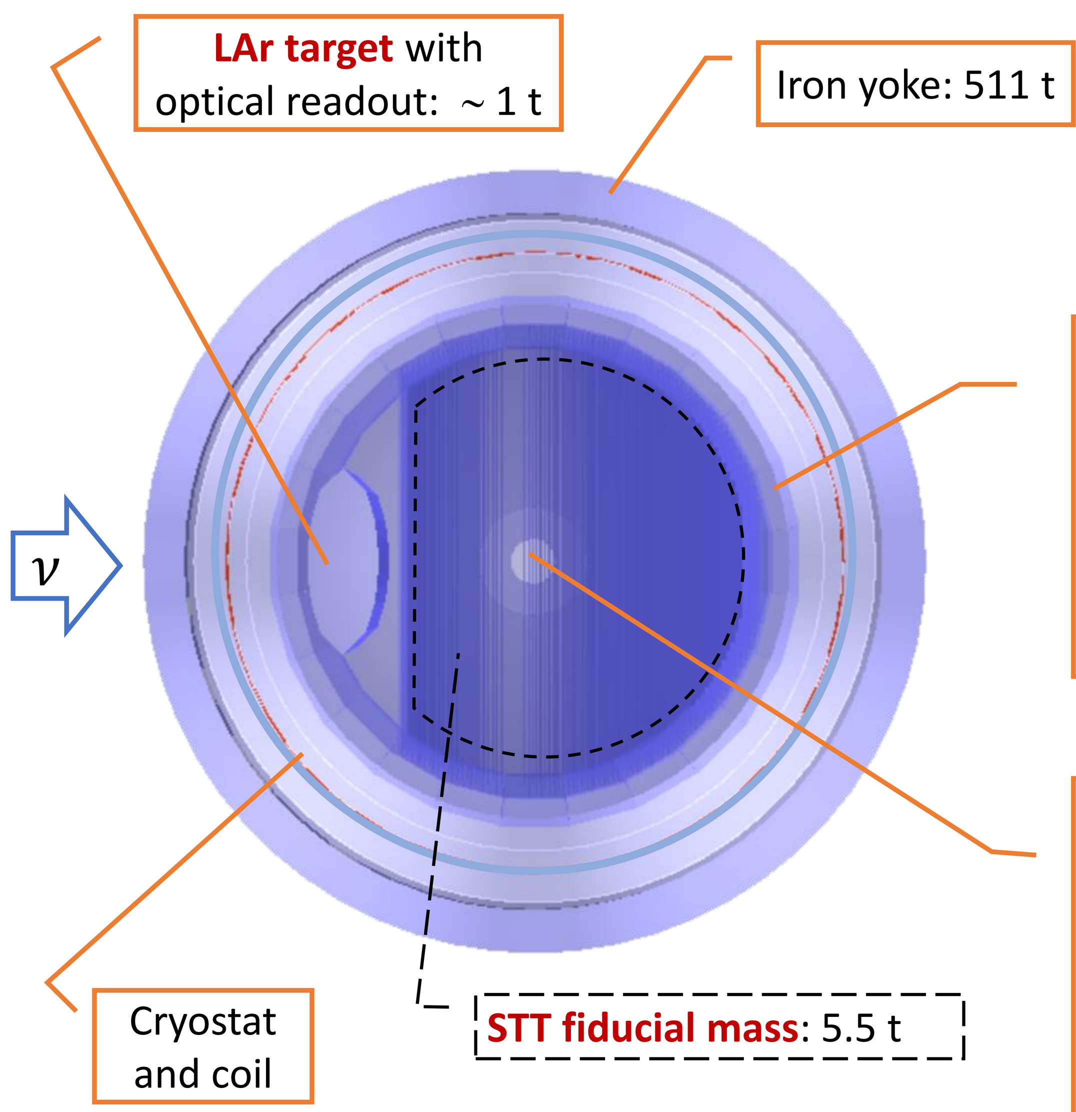
ND-LAr: modular 67 t LArTPC

Multi-Purpose Detector (**ND-GAr**): magnetized (0.6 T) high pressure GArTPC surrounded by electromagnetic calorimeter

System for on-Axis Neutrino Detection (**SAND**)

ND provides input for the neutrino interaction model, measures and monitors the beam, and constrains systematic uncertainties

A SAND design*



Side view of the **solenoidal superconducting iron magnet** (B = 0.6 T)

Lead/scintillating fiber 4π-coverage e.m. calorimeter (ECAL): 24 barrel modules and 2 endcaps.

- Total mass: 100 t
- $\sigma_E/E = 5\%/\sqrt{E(GeV)}$
- $\sigma_t = 54\ ps/\sqrt{E(GeV)}$

Straw Tube Tracker (STT): modules of CH2 or C targets interleaved with horizontal and vertical planes of straw tubes.

- Total mass: 7.4 t
- $\sigma(1/p)/(1/p) \sim 4\%$ (1 GeV μ)
- $\sigma_{ang} \sim O(few\ mrad)$ (1 GeV μ)

* *This is one of the alternative designs currently being studied*

Background Rejection

At the ND site the most critical **background source is beam related neutrino interactions** in the material surrounding the detector.

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	0.6
STT fiducial	5.5 t	0.74	0.4
Total	**619 t**	**83.5**	**44.4**

The external background is rejected using a combination of **selections and a neural network** jointly applied to timing and topological information from the subdetector and reconstructed quantities.

Selction	Signal Efficiency (%)	Background Efficiency (%)	Purity (%)
STT hits in FV > 15	98.3	7.2	10.0
Pre-selection cuts	95.3	1.9	28.6
NN > 0.95	92.9	0.015	98.0
Evis > 0.5 GeV and ≥ 1 track	92.7	0.003	99.6

Beam Monitoring

Continuous monitoring of the neutrino beam is mandatory to detect potential variations over time directly 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 Sample: $\sim 1.5 \times 10^6$ ν_μ CC interactions in ECAL, STT and LAr target (GENIE + GEANT4) in FHC mode.

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

- For interactions in ECAL and LAr target: ≥ 6 digits
- For interactions 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 ECAL and LAr target, respectively, and K^{STT} the kinetic energy associated to reconstructed tracks.

Expected sensitivity to each considered beam variations is evaluated comparing the distribution of E_ν^{rec} expected from ***nominal*** (N_i^{nom}) and ***varied*** (N_i^{var}) beam, using the **test statistic** T:

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

The nominal distribution is evaluated using a full Monte Carlo (MC) simulation, while the varied one is derived from the former one applying a **re-weighting technique**. The weights, evaluated versus neutrino energy and off axis position, were based on MC simulations.

Shift of Beam Direction

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

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

Significance > 3 with ECAL+STT in one week of data taking (3.78 x 10^{19} pot) for a 0.13 mrad change in beam direction.

Sensitivity to beam parameter variations

Results (some)	Test Statistic: $T \sim \Delta\chi^2$			
	ECAL		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

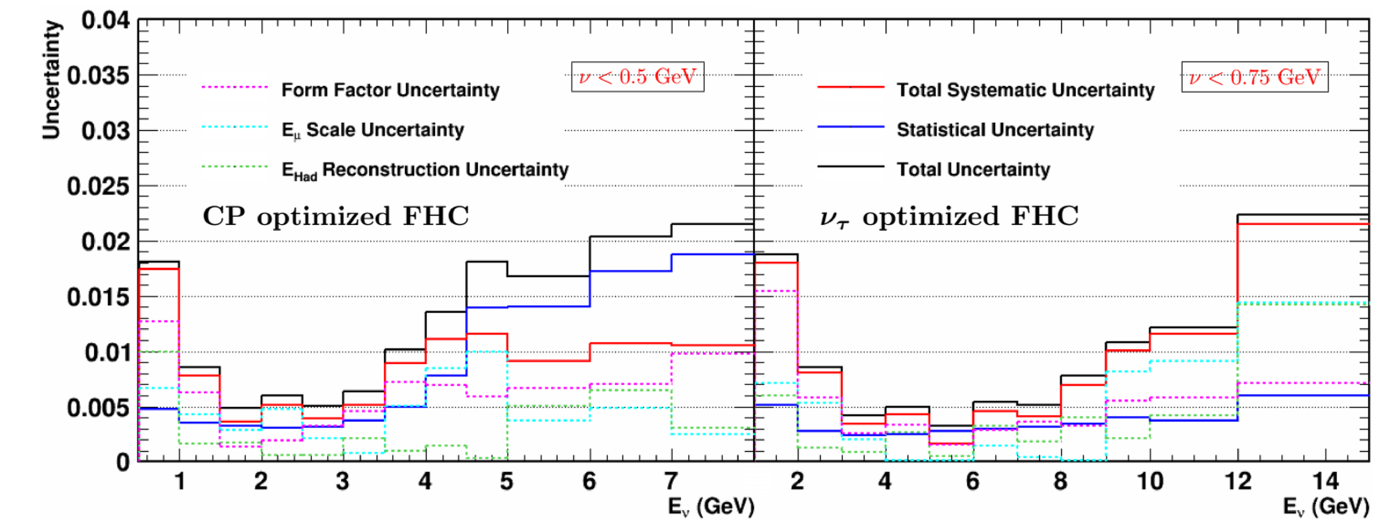
Flux Measurements

The measurement of the neutrino flux is a mandatory condition to extract oscillation probability from measured neutrino interactions

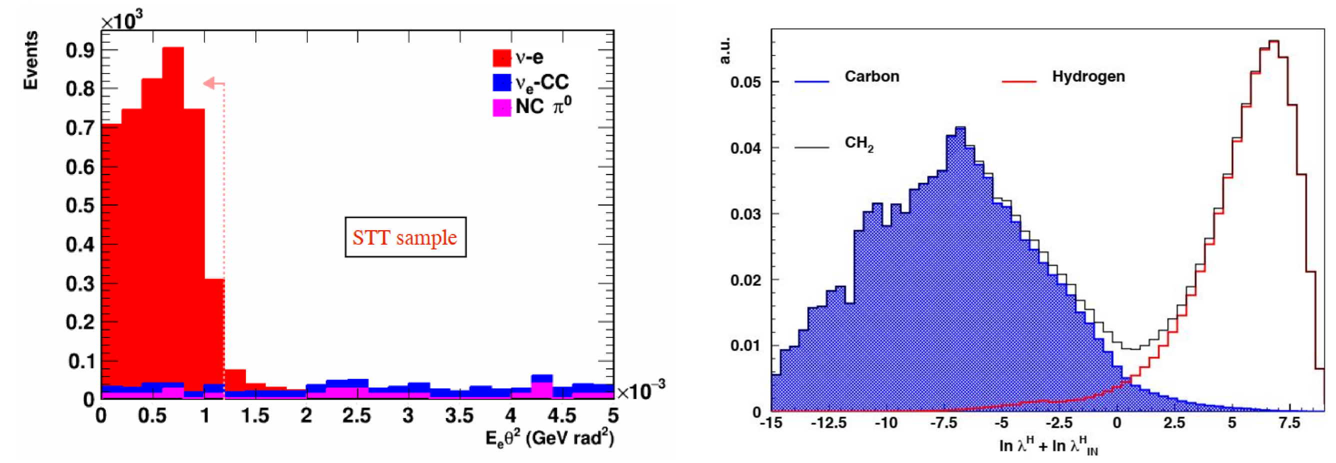
$$N_X(E_{rec}) = \int_{E_\nu} dE_\nu\, \Phi(E_\nu)\, P_{osc}(E_\nu)\, \sigma_X(E_\nu)\, R_{phys}(E_\nu, E_{vis})\, R_{det}(E_{vis}, E_{rec})$$

SAND will determine the **absolute $\nu_\mu, \bar{\nu}_\mu$ and the relative $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ fluxes** at the ND Site using different complementary physics processes:

- Absolute ν_μ flux from $\nu e \to \nu e$ ES: 2% accuracy
- Absolute $\bar{\nu}_\mu$ flux from $\bar{\nu}_\mu p \to \mu^+ n$ QE on H with $Q^2 \leq 0.05\ GeV^2$
- Relative $\bar{\nu}_\mu$ flux vs. E_ν from $\bar{\nu}_\mu p \to \mu^+ n$ QE on H with $\nu < 0.25\ GeV$: < 1% accuracy
- Relative ν_μ flux vs. E_ν from $\nu_\mu p \to \mu^- p \pi^+$ on H with $\nu < 0.5\ GeV$: 1% accuracy



About 1k events/year of **νe ES interactions** in STT fiducial volume will be collected selecting single electron track event with $E_e > 0.15\ GeV$ and $E_e\theta^2 < 0.0012\ GeV \cdot rad^2$ (efficiency: 84%, purity: 95%)



Large sample of **νH CC interactions** are statistically and model-independently obtained by subtraction of neutrino interactions in CH$_2$ and C targets.

Kinematic selection provides νH samples of all inclusive and exclusive CC topologies with 80 - 95% purity and 75 - 96% efficiency before subtraction.

Additional improvements are obtained with the use of **likelihood functions** incorporating multi-dimensional correlations among kinematic variables.