The SAND detector at the DUNE near site

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INFN BOLOGNA

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

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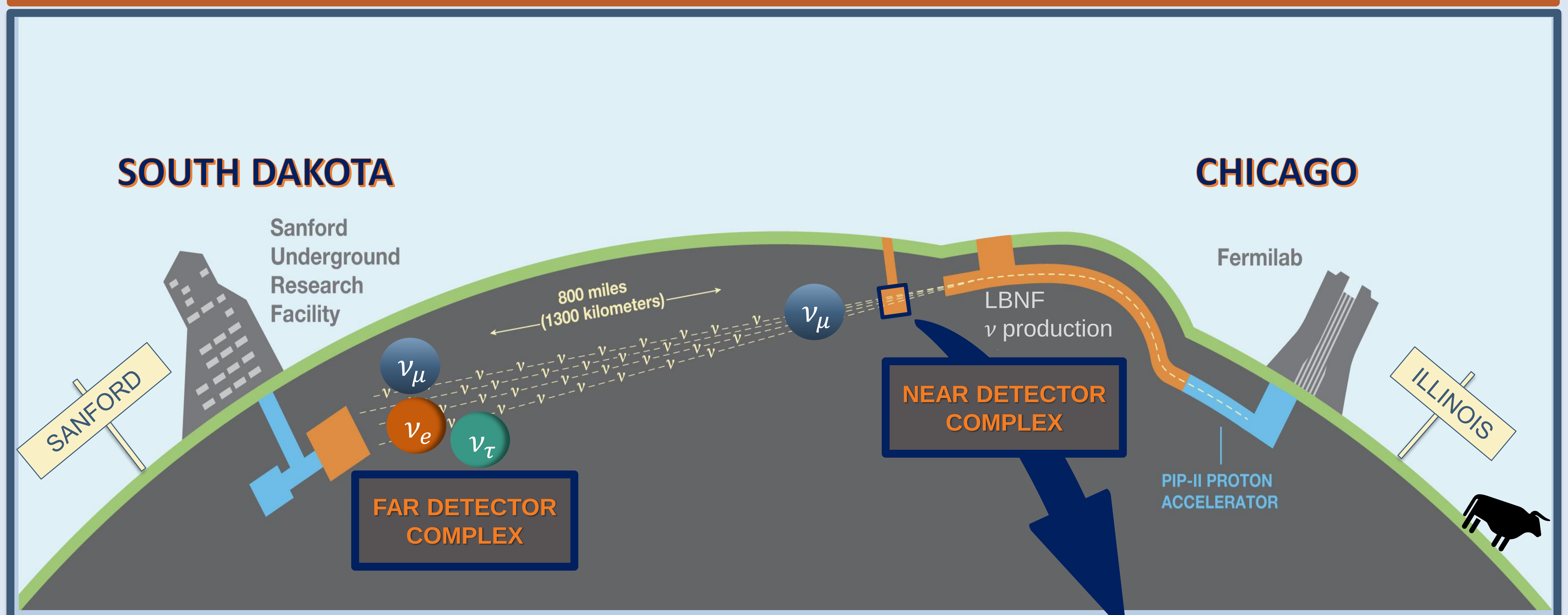
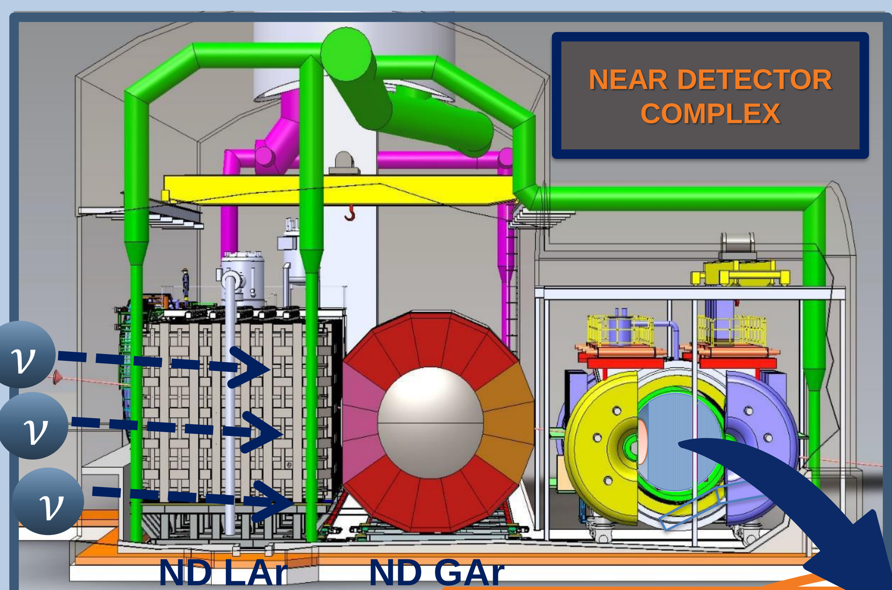
THE DUNE EXPERIMENT



NEAR DETECTOR COMPLEX

- **ND-LAr**: 67 t modular LArTPC
- **ND-GAr**: high pressure GArTPC surrounded by an electromagnetic calorimeter in 0.5 T magnetic field
- **SAND**: (System for on Axis Neutrino Detection) magnetized high-capability multi-purpose detector

PURPOSE: measure the flavour composition of the unoscillated neutrino spectrum and reduce systematics affecting the oscillation analysis.

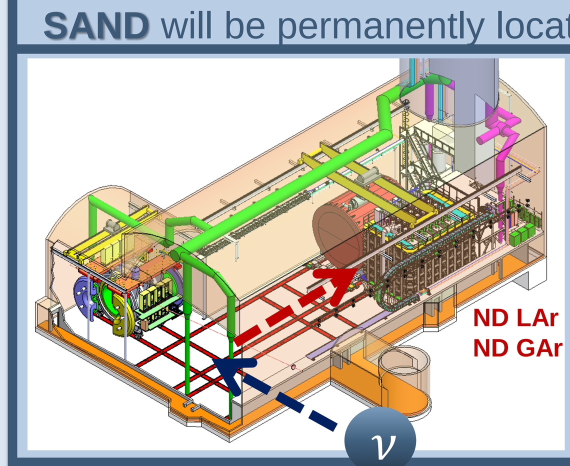


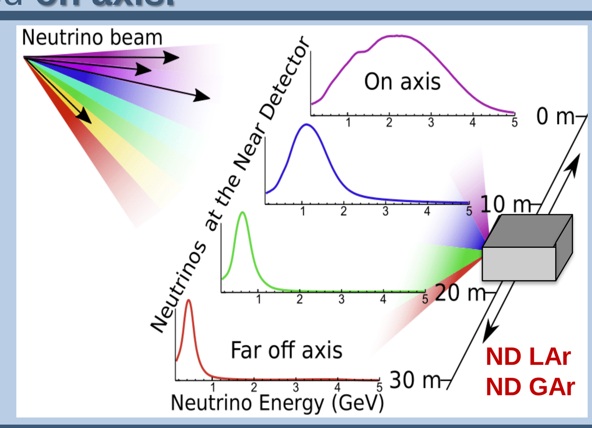
FAR DETECTOR COMPLEX

Located at SURF 1.4 km underground consisting of 4 LArTPC modules 17 kt each. Its purpose is the measure of the oscillated $\nu_\mu/\nu_e(\bar{\nu})$ energy spectra to be compared with the unoscillated ones.

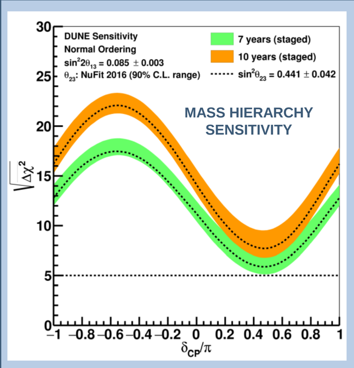
DUNE PRISM CONCEPT

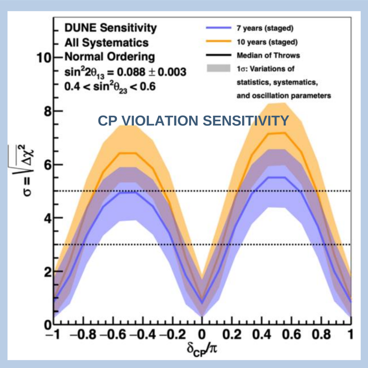
ND-LAr and **ND-GAr** will move **off axis**, with respect to the neutrino beam direction, as neutrino energy peak and detector position correlation set constrains on detector-related systematics uncertainties. **SAND** will be permanently located **on axis.**





DUNE PHYSICS GOALS





Sensitivity to MH (left) and CP (right) determination as function of the true value of δ_{CP} for 7 and 10 years of exposure assuming normal ordering. The shaded regions represent the range in sensitivity corresponding to different true values of θ_{23}.

NEUTRINO OSCILLATIONS

- Measurement of the CP violating phase δ_{CP}
- Determination of the neutrino mass ordering

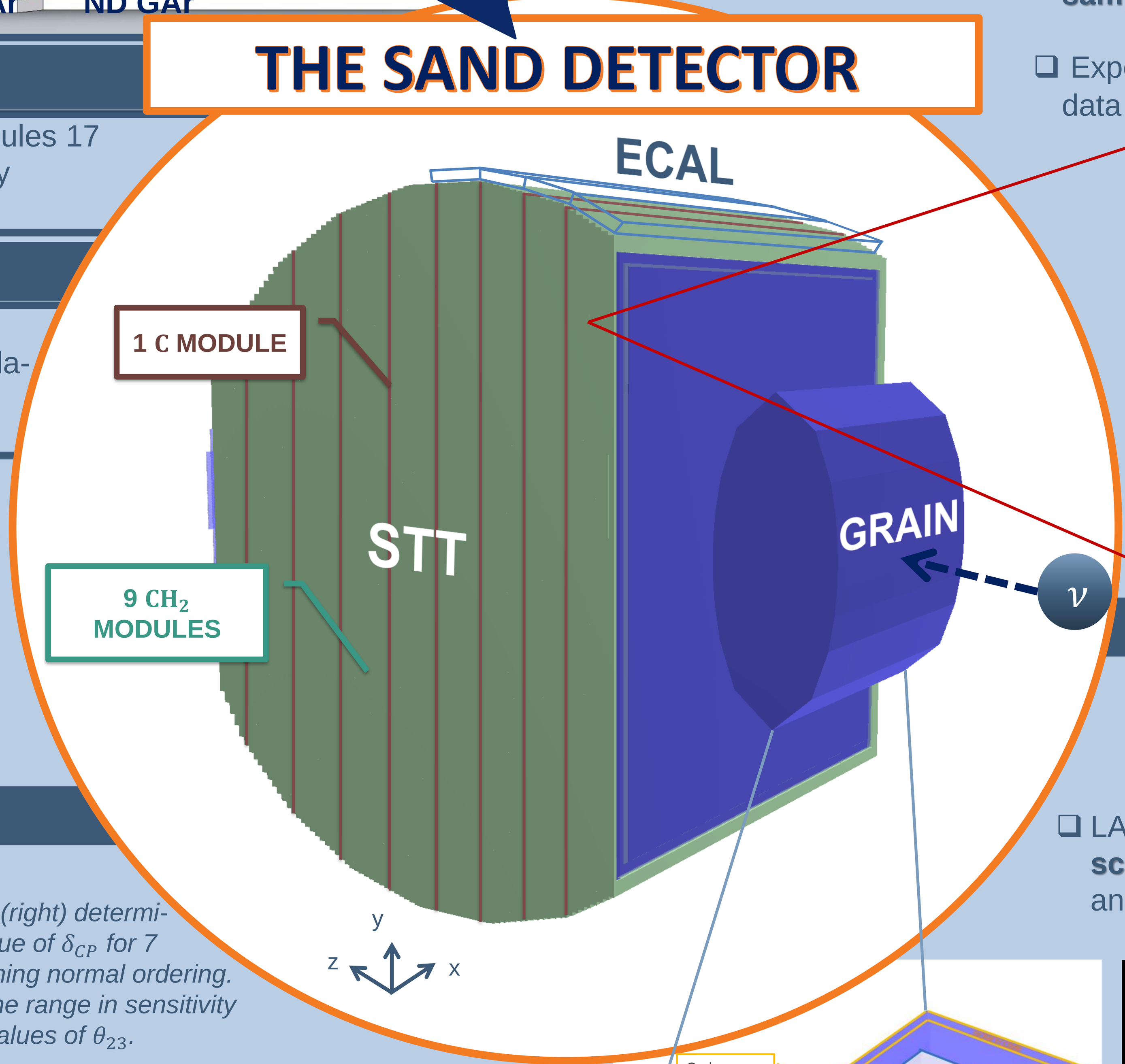
SUPERNOVA PHYSICS

- Observation of neutrinos from core collapse supernovas to investigate the astrophysics core collapse

BSM PHYSICS

- Search for proton decay channels (e.g. $p \to K^+ \bar{\nu}$)

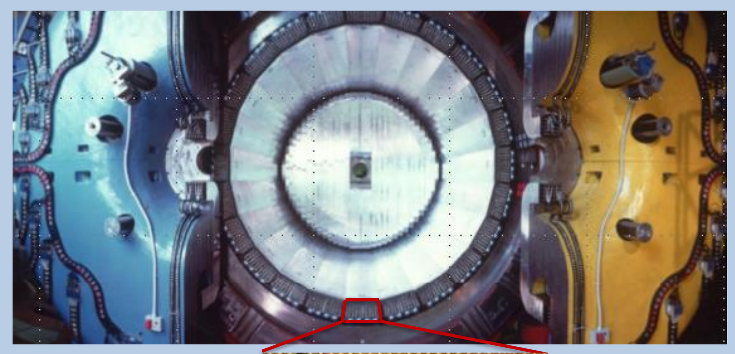
THE SAND DETECTOR



SAND COMPONENTS

SOLENOIDAL MAGNET & ELECTROMAGNETIC CALORIMETER

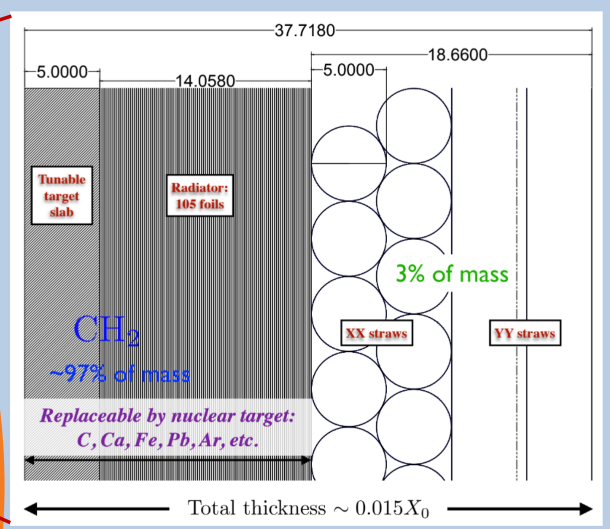
- Solenoidal superconducting magnet of 475 t, 4.3 m long and 4.8 m diameter refurbished from KLOE experiment;
- **Lead/scintillating fiber** 4π-coverage ECAL ($\sim 15\, X_0$) made of 24 barrels with trapezoidal cross-section + 2 end-caps of 32 verticals modules 23 m thick
- ECAL Read out: **photomultiplier tubes** placed at both ends of each barrel module for a total of 4880 channels
- Energy and time resolution: $\sigma/E = 5.7\%/\sqrt{E(GeV)}$, $\sigma = 54/\sqrt{E(GeV)}$ ps [2]



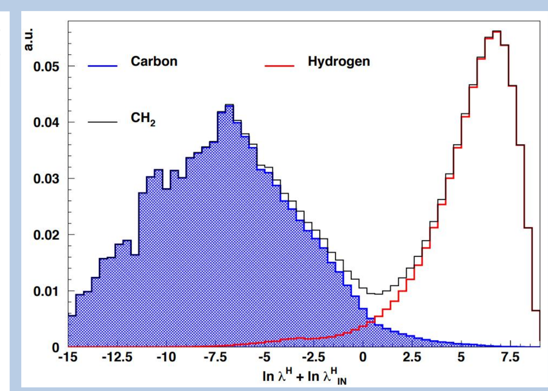
Lead scintillating fibers in the ECAL barrel

STRAW TUBE TARGET TRACKER (STT)

- **Diffuse target tracker system:** trade-off between the need of large mass (enough statistics) and overall low density (high momentum resolution $\sigma(1/p)/(1/p) \sim 4\%$ for 1 GeV μ);
- Fiducial mass of ~ 5 t made of 84 modules (8 C modules + 70 CH_2 modules + 6 tracking modules)
- Module composition: (i) **tunable target** (C or CH_2) making 97% of the module mass, (ii) **TR radiator** for e/π discrimination and (iii) 4 planes of **straw tubes** (Xe/CO_2 gas at 1.9 atm) arranged in *XXYY* layers;
- Module average **density and chemical composition variable** ($0.005 < \rho < 0.18\, g/cm^3$) by replacing, during data taking, the targets with a wide range of materials (CH_2, C, Ca, Ar, Fe, Pb);
- High statistic, nuclear model independent $\nu(\bar{\nu}) - H$ **CC interaction sample** from subtraction technique between CH_2 and C interactions [3].
- Expected statistics in STT with LBNF beam power 2.4 MW and 2 yr of data taking is about 66×10^6 ν_μ CC in CH_2 and $6,5 \times 10^6$ ν_μ CC in H



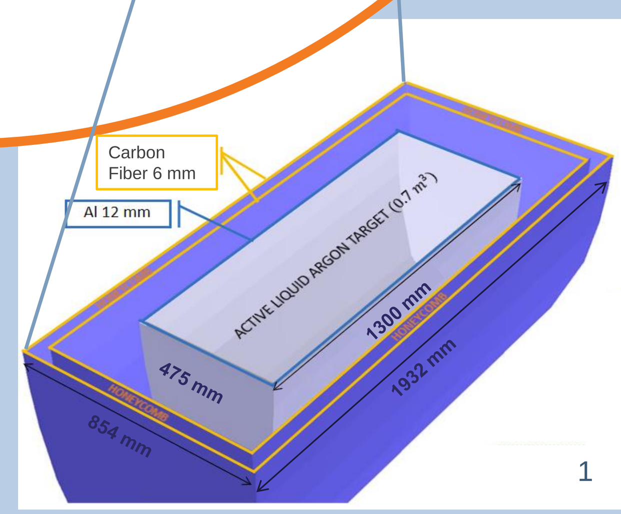
YZ section of STT module (length in mm)

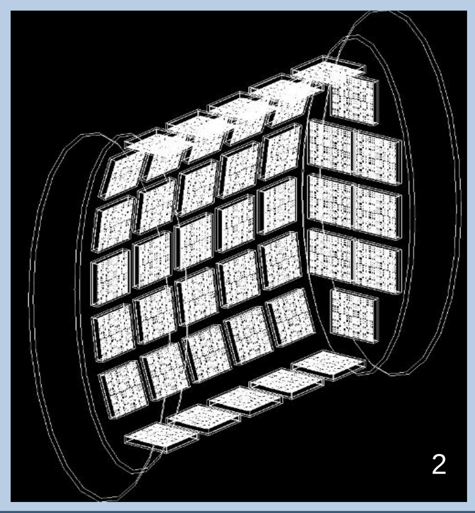


Likelihood function incorporating multi-dimensional correlations among kinematic variables to separate C and H samples [3]

GRAIN: A LIQUID ARGON ACTIVE TARGET

- **GRAIN** (**GR**anular **A**rgon **I**nteractions of **N**eutrinos): ~1 t LAr active target provides a sample of $\nu(\bar{\nu}) - Ar$ to reduce nuclear model systematic uncertainties.
- LAr volume walls equipped with an **optical system to collect UV scintillation light.** Current design foresees a combination of lenses and Hadamard masks [4].





1. *GRAIN cryostat:*
   - *Internal vessel in Al (still under optimization);*
   - *External vessel combination of honeycomb + carbon fiber*
2. *In this sketch the light detection system is based on Hadamard masks*

SAND PHYSICS PROGRAM

$\nu/\bar{\nu}$ BEAM MONITORING

- **Continuous monitoring:** one of the main purposes of SAND will be the neutrino beam monitoring to spot potential variations that would directly affect the FD oscillation analysis.
- The beam is monitored by reconstructing the neutrino energy from the measurement of the particles momenta produced in ν_μCC interactions.
- **Momentum reconstruction** of particles is obtained requiring a minimum number of STT hits in the *YZ* plane: ≥ 6 for interaction in ECAL and GRAIN, ≥ 4 for interactions in STT.
- **Reconstructed Neutrino Energy:**

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

Visible E in ECAL | Visible E in GRAIN | Reconstructed track Kin E

- **Expected sensitivity** to the beam variation is evaluated comparing the reconstructed neutrino energy distribution E_ν^{rec} expected from nominal (N_i^{nom}) and varied beam (N_i^{var}), using the test statistic T:

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

Proton beam parameter	1σ deviation as given by beam group	New $\sqrt{\Delta\chi^2(E_\nu)}$ true	New $\sqrt{\Delta\chi^2(E_\nu)}$ 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 will have enough sensitivity ($\sqrt{\Delta\chi^2} > 3$) to detect most of beam variations on **1 week of data taking**

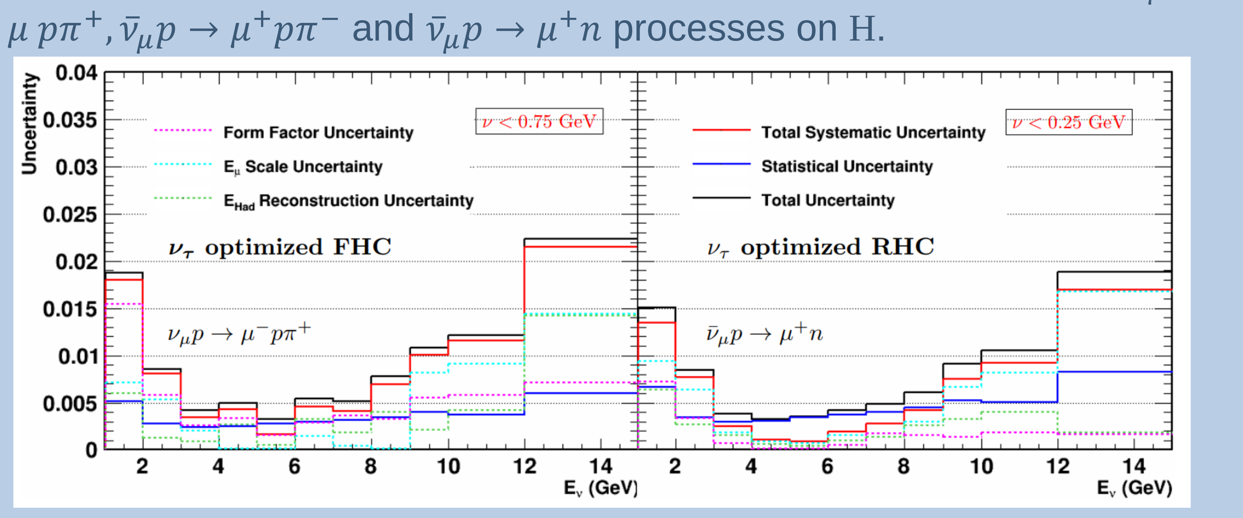
FLUX MEASUREMENTS

- **Measurement of ν flux $\phi(E_\nu)$** is mandatory to extract oscillation probability from measured neutrino interactions $N_x(E_{rec})$ for a process x:

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

ν flux | Nuclear smearing | Detector response

- Large sample of $\nu - H$ **CC interactions** in STT allows an accurate **determination** of absolute and relative ν **fluxes** using $\nu_\mu p \to \mu p \pi^+$, $\bar{\nu}_\mu p \to \mu^+ p \pi^-$ and $\bar{\nu}_\mu p \to \mu^+ n$ processes on H.



Systematic uncertainties on flux measurement (5 year data taking, STT-only) [1]

NUCLEAR EFFECT CONSTRAINS

- **Constrains of nuclear smearing** on Ar, crucial to reduce systematics at FD, can be done from a direct **comparison between Ar and H** interactions within the same detector. For $\nu - H$ interactions:

✓ $\phi(E_\nu)$ known at level of 1%;
✓ $\sigma_X(E_\nu)$ measured from high statistic sample;
✓ $R_{phys} \equiv 1$ (no nuclear smearing for H target)
✓ R_{det} $\delta p/p \sim 0.2\%$ calibrated in-situ from $K_0 \to \pi^+\pi^-$ in STT

BACKGROUND REJECTION

- **Cosmic radiation and ambient radioactivity** backgrounds are suppressed requiring a time coincidence with the beam spill;
- The most critical background source are **beam related neutrino interactions** in the material surrounding the detector
- **External bkg rejection**: selection and neutral network jointly applied to timing and topological information from subdetectors

Selection	STT FV Signal ε (%)	Ext bkg Tot ε (%)	Purity (%)
STT hits in FV > 15	98.32	7.24	9.98
Pre-selection	95.32	1.94	28.59
NN > 0.95 cut	92.89	0.02	98.01
E_{vis} > 0.5 GeV	92.71	0.01	99.65

CONCLUSIONS

SAND is capable of: (*i*) **spot beam changes** on few days basis, (*ii*) accurately **measure the $\nu(\bar{\nu})$ flux**, (*iii*) **constraining nuclear effects** reducing the systematics uncertainties affecting the oscillation analysis. Additionally, SAND will have its own program of **searches for new physics** exploiting a high statistics sample of $\nu - H$.

[1] "DUNE Near Detector CDR", The DUNE collaborations, arXiv:2103.13910;
[2] The KLOE calorimeter, NIM A 482 (2002) 364;
[3] "Precision Measurements of Fundamental Interactions with (Anti)Neutrinos", arXiv: 1910.05995
[4] R. Accorsi, "Design of a near-field coded aperture cameras for high-resolution medical and industrial gamma-ray imaging", 08 2005.