The SAND detector in the DUNE near detector system

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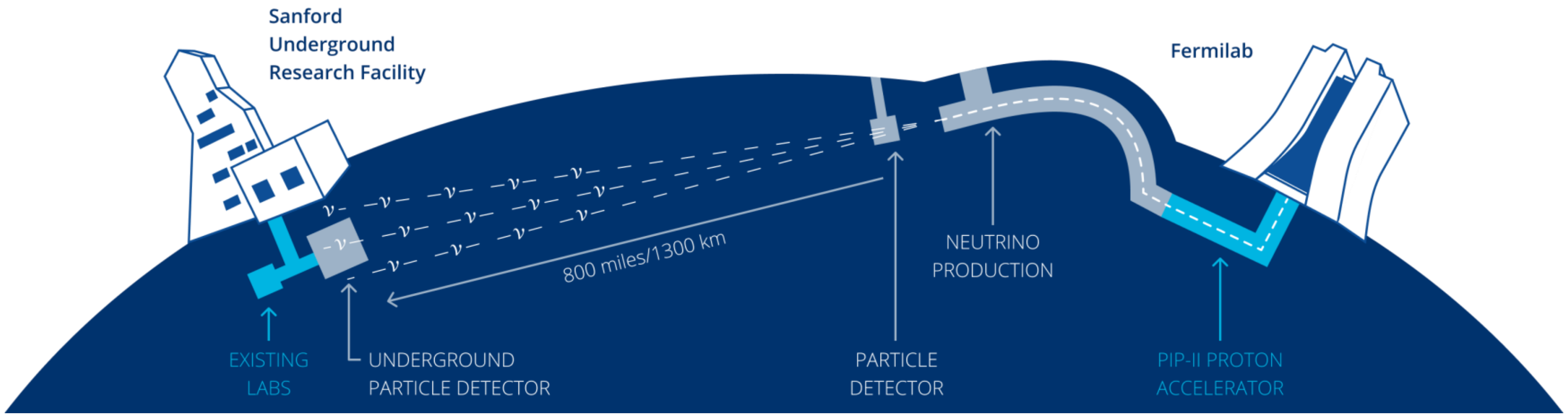
The Deep Underground Neutrino Experiment



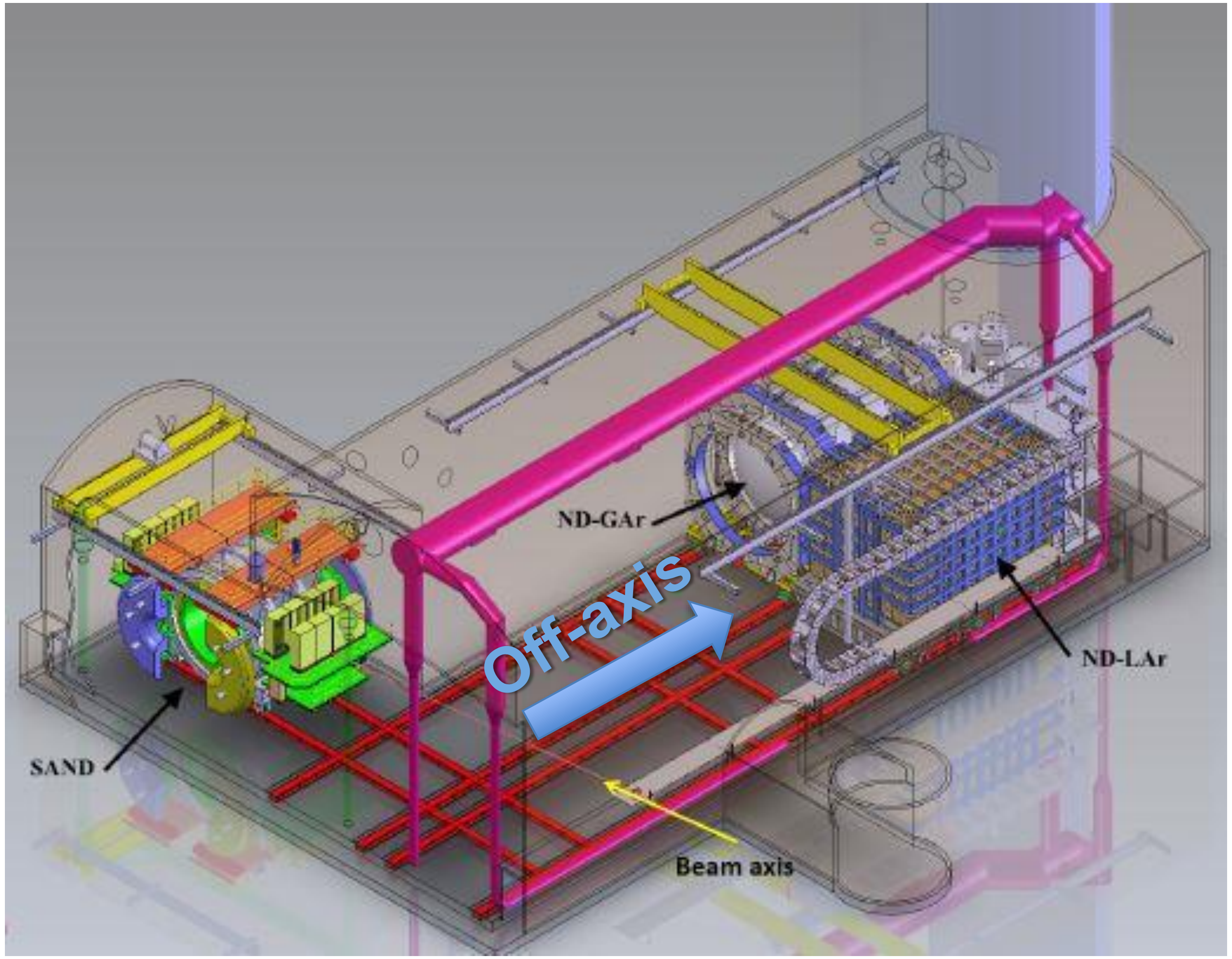
DUNE Far Detector **DUNE Near Detector and neutrino source**

- A new generation Long Baseline oscillation experiment with a rich physics research program: three flavor oscillation measurements, supernovae, BSM studies
- An intense **wide-band $\nu_\mu / \overline{\nu}_\mu$ neutrino beam** 1.2 MW (1.1 x 10^{21} pot/year), upgradable to 2.4 MW high-intensity produced at Fermilab
- Two neutrino detectors are foreseen: a **Near Detector complex (ND)** at Fermilab and a **Far Detector**, consisting of four Liquid Argon Time Projection Chamber (LArTPC) modules 17 kton each, located 1.5 km underground and 1300 km away from neutrino source at Sanford Underground Research Facility in South Dakota

The Near Detector complex

Near Detector will be located 574 m downstream of neutrino beam and will include three main components with standalone features:

- **ND-LAr**: a 67 ton LArTPC
- **ND-GAr**: a high pressure gaseous argon TPC surrounded by an electromagnetic calorimeter in a 0.5 T magnetic field
- **SAND**: the System for on-Axis Neutrino Detection



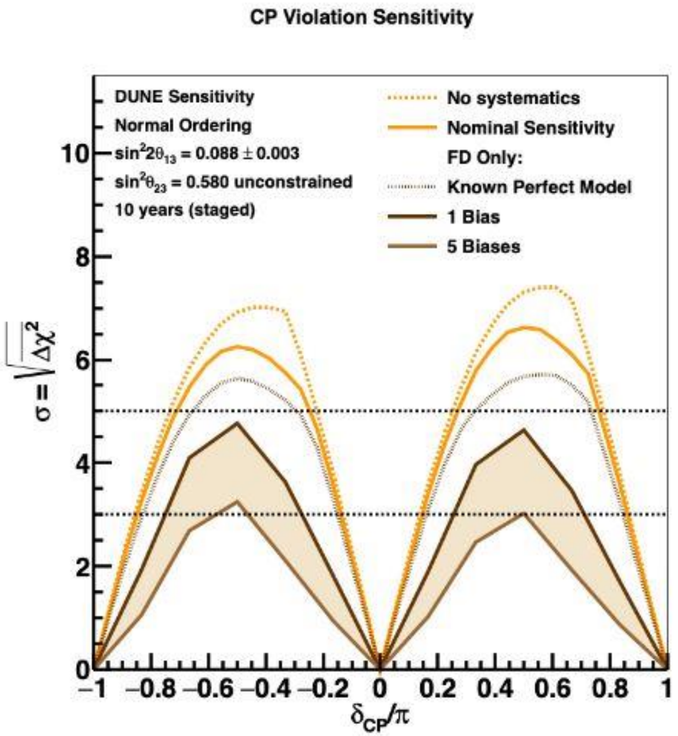
arXiv:2103.13910

The Near Detector physics goals

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

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

To predict the expected oscillating ν_μ and ν_e spectra at FD the measurements done at ND must be propagated to FD but systematic uncertainties on modeling of cross section, nuclear effects and fluxes are not consistent with the precision required by DUNE

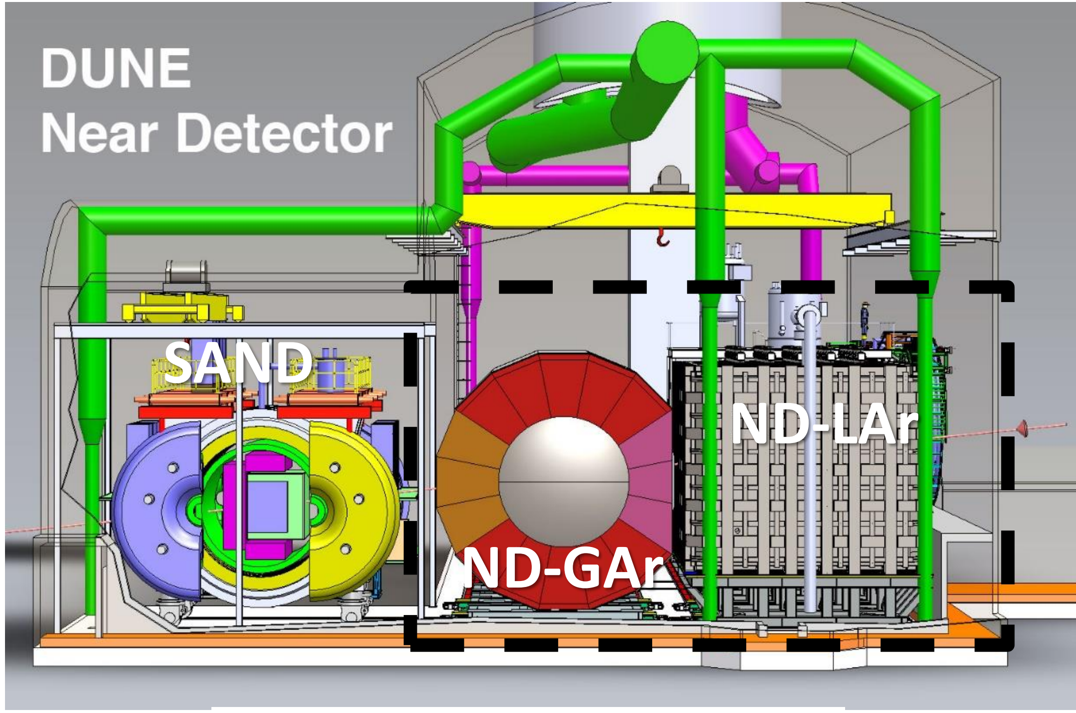


The ND will play the role of:

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

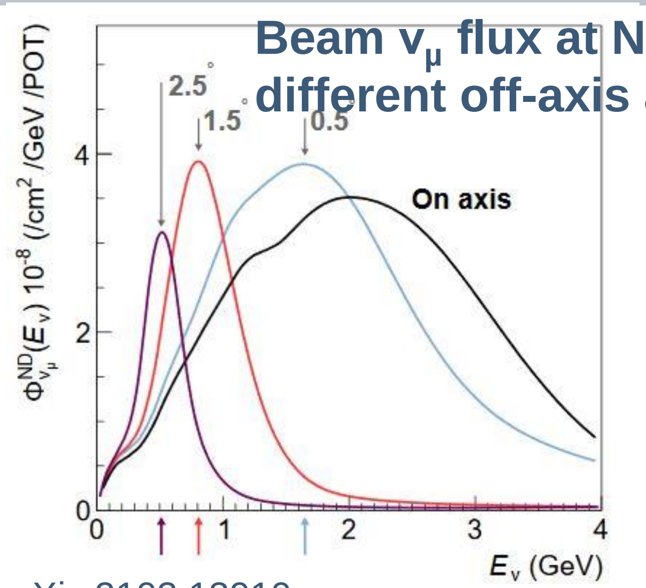
DUNE PRISM

PRISM (Precision Reaction-Independent Spectrum Measurement) concept to control systematic uncertainties on neutrino-argon interactions model →ND-LAr + ND-Gar will move to collect data at different off-axis positions:



- disentangle effects due to mismodeling of neutrino flux and interaction cross-section, as well as mapping of reconstructed vs true neutrino energy response of the detector

- predict oscillated neutrino event spectra at FD with reduced model dependence



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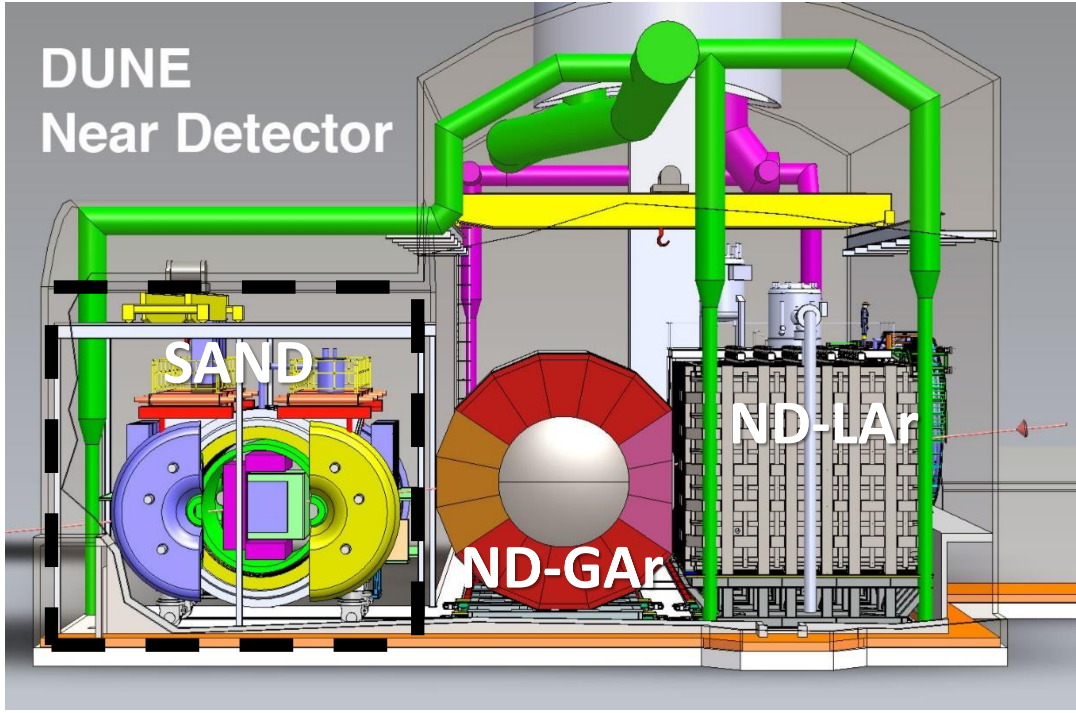
SAND

The only component of the ND that will permanently be located **on-axis**

SAND consists of:

- **Electromagnetic Calorimeter (ECAL)**
- **Superconducting magnet**
- **Lar active target**
- **Inner tracker**

inherited from KLOE experiment

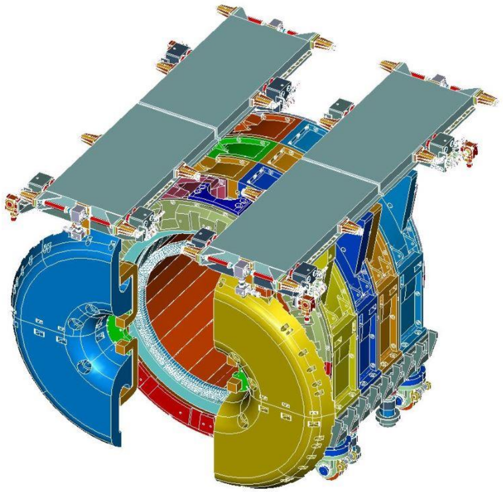


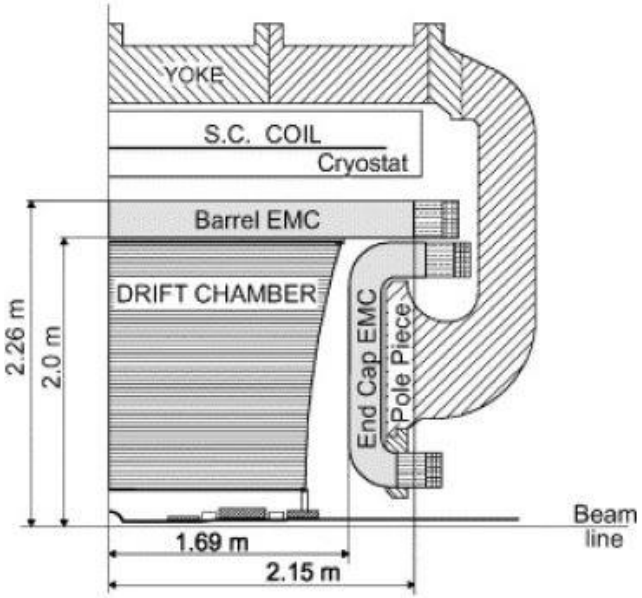
SAND primary goals

- On-axis ν-spectrum monitor to detect any potential changes in the beam over time on a weekly basis that can affect the FD oscillation analysis
- Provide an independent in-situ measurements of ν_{μ}, anti- ν_{μ}, ν_e, anti- ν_e fluxes and energy spectra
- Constrains systematics from nuclear effects by measuring the ν and anti-ν cross sections on nuclei other than argon (carbon and hydrocarbons)
- Exploit the unprecedented high statistics to perform a rich physics program besides the oscillation program

The KLOE detector

- SAND is largely based on a reuse of the magnet and calorimeter of the KLOE experiment which took data from 1999 to 2018 with a very stable detector performance to study CP violation in neutral kaon decays at the DAFNE Φ-factory in Frascati

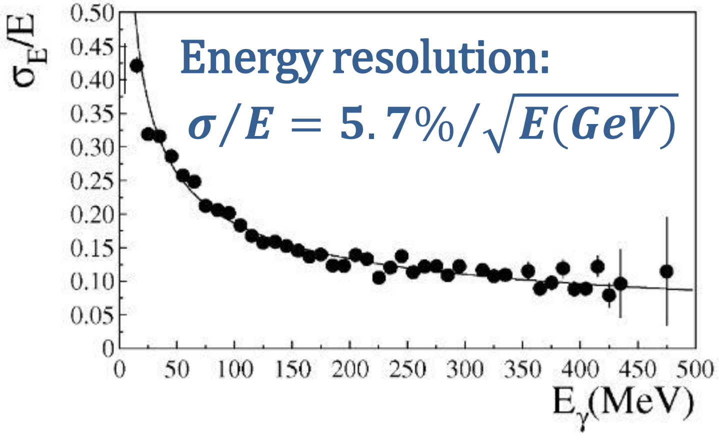


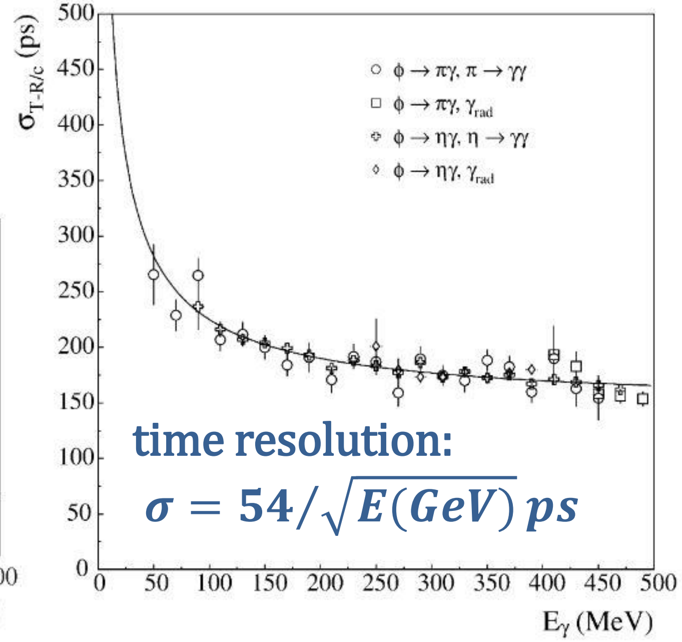


- Drift chamber in the inner volume will be replaced by a target/tracker system

- Electromagnetic calorimeter: lead and scintillating fiber sampling calorimeter + 4880 PMTs

- Magnet: superconducting coil (5 m bore) inside the yoke produced B= 0.6 T





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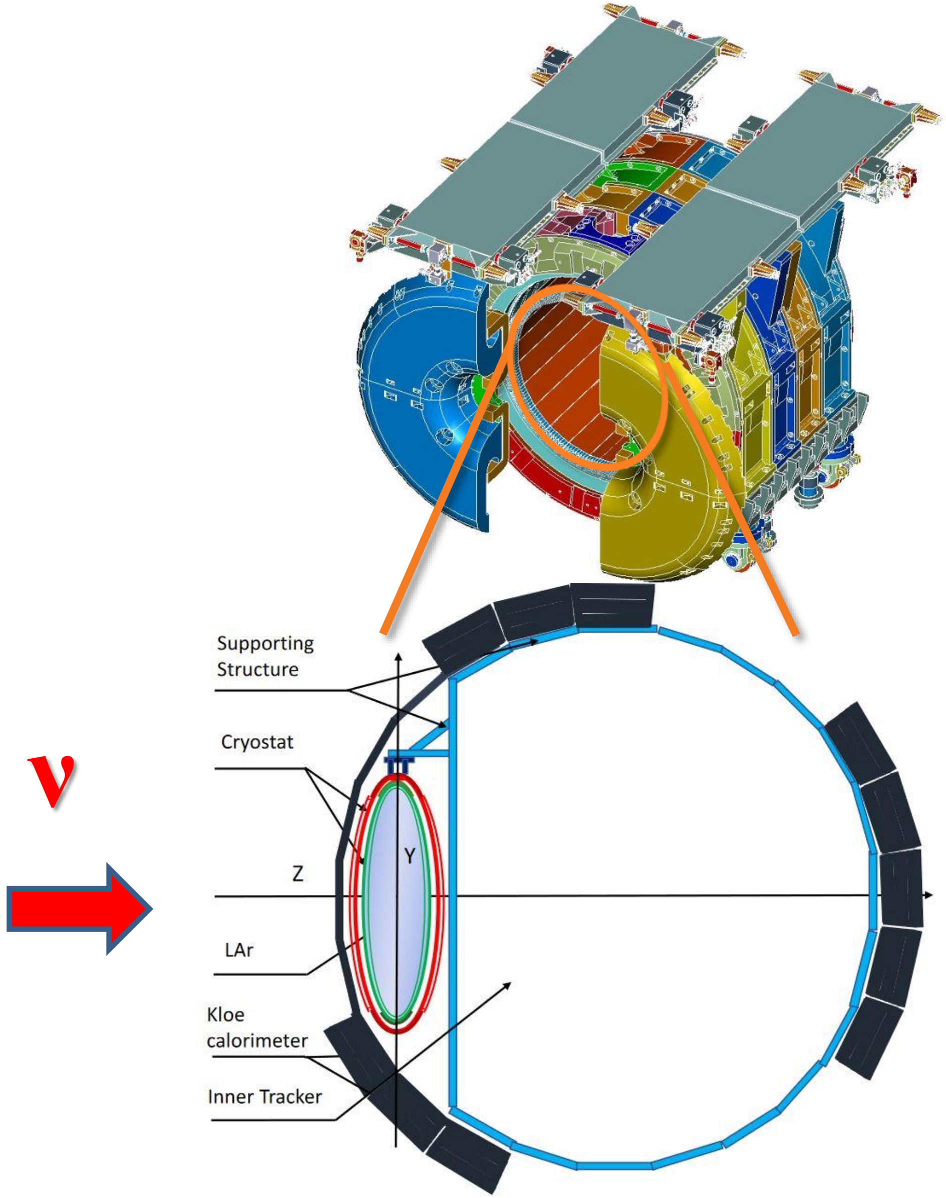
Liquid Argon Active volume

- The upstream part of SAND will be instrumented with 1-ton LAr active target, so called “LAr meniscus”
- It will be instrumented with an optical system to collect UV scintillation light on fine segmented focal planes
- The outer vacuum vessel of the cryostat will be made of C-composite material reinforced with an internal Al foil, the inner vessel containing the LAr will be made of Al, to keep the overall radiation length ~ 1 X_0
- It will reconstruct the events in combination with the ECAL and the tracker
- Its role is constraining nuclear effects on argon and have a complementary Ar target permanently located on axis for cross-calibration

SAND detector



preliminary CADs

SAND inner tracker

The internal magnetized volume of SAND will be instrumented with an Inner Tracker to: separate neutrino and antineutrino events (charge ID), identify primary leptons(beam flavor composition), reconstruct event-by-event and all charged and neutral (π^0, n) particles tracks

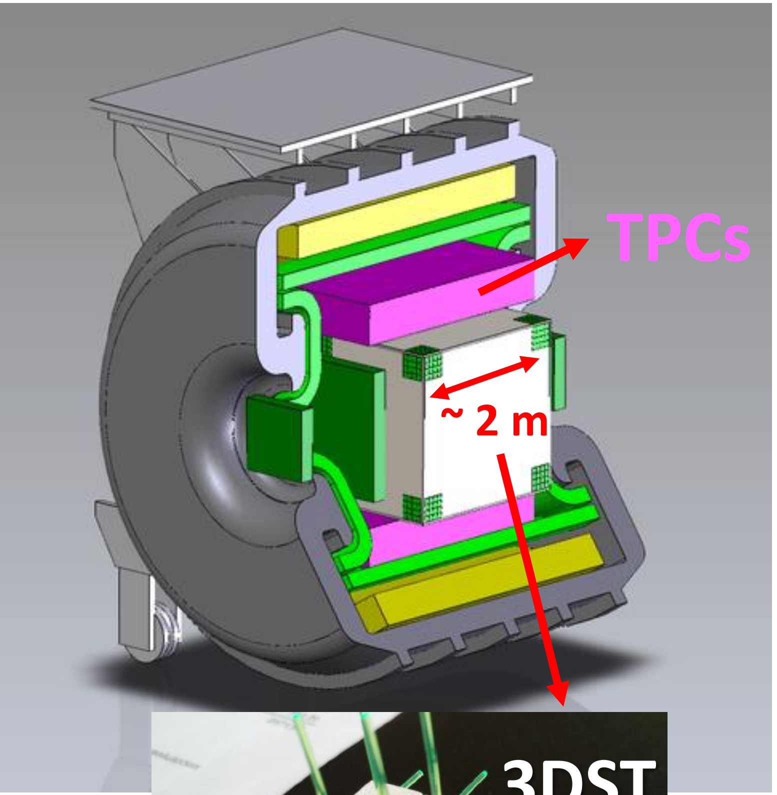
Three different detector technologies are under investigation for the inner tracker:

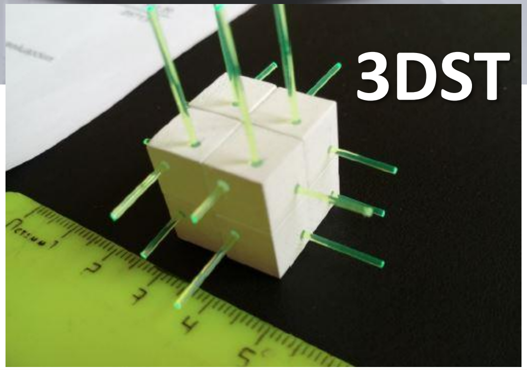
- **3-Dimensional projection Scintillator Tracker (3DST)** as active neutrino target
- **TPCs** as low density tracker to measure particles escaping the scintillator
- **Straw Tube Trackers (STT)** as low density tracker interleaved with carbon or hydrocarbon layers as target

The possible main configurations with these detectors are:

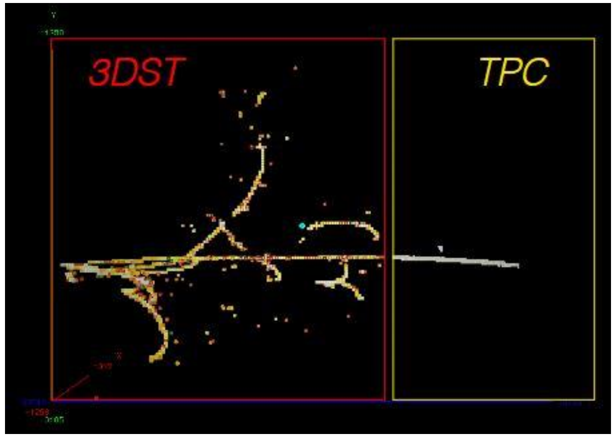
- 3DST + TPCs
- STT only

SAND inner tracker – 3DST+TPC





- 3DST (active target) is made of many 1.5 x 1.5 x 1.5 cm^3 plastic scintillator cubes each readout by three orthogonal wavelength-shifting fibers optically coupled to SiPMs
- TPCs are rectangular chambers surrounding the 3DST filled with an optimized gas mixture and instrumented with resistive Micromegas detectors (200-600 μm spatial resolution → 2-4% momentum resolution)
- 3DST: particle identification by energy deposit and momentum reconstruction by range ($\Delta p/p$ < 4% for μ and p) + event-by-event neutron kinetic energy measurement with Time of Flight



- Momentum reconstruction of particles leaving 3DST by TPCs
- Fully active target (11.8 ton mass)

SAND inner tracker – STT

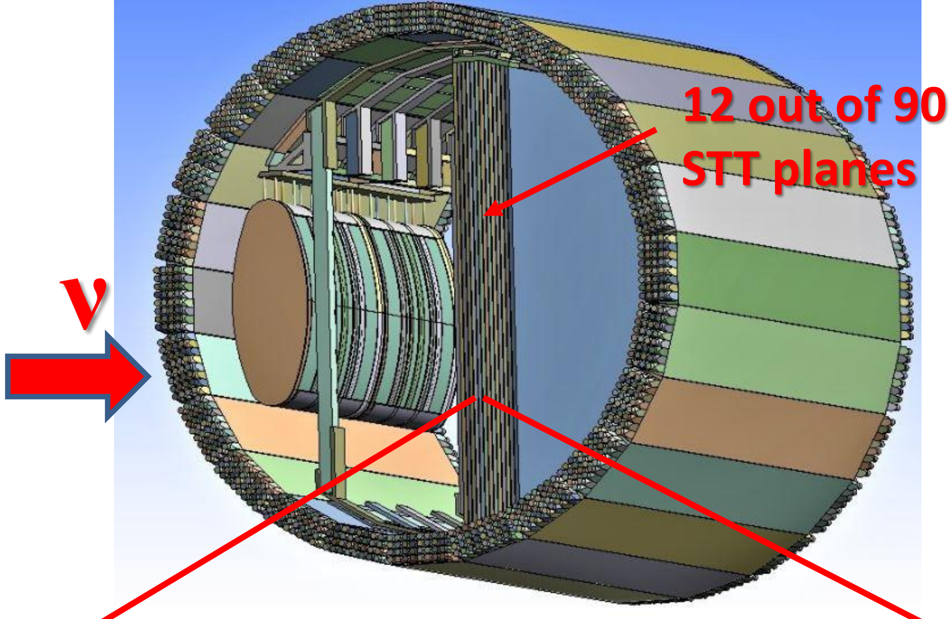
90 modules with planes of 5 mm diameter straw tubes (Xe/CO_2 gas at 1.9 atm) arranged in XXYY layers, radiator of polypropylene foils and a target (CH_2, C,…)

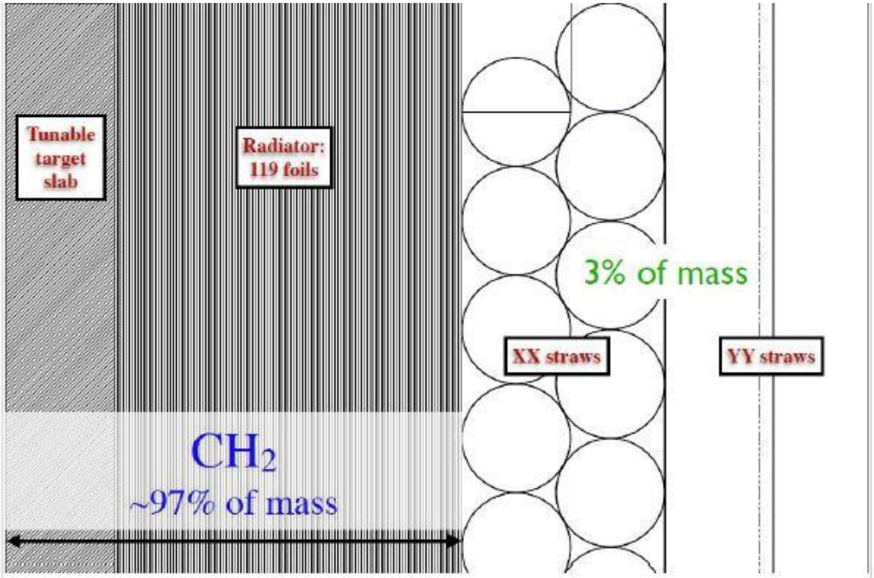
This design provides:

- Accurate reconstruction of transverse plane kinematics variables from particle 4-momenta

  ($\Delta p/p \leq 3\%$, $\Delta\theta/\theta \leq 1.5$ % mrad)

- e/π separation via transition radiation (e/π ~ 10^{-3}) and p/π/K identification with dE/dx and range
- 4π detection of π^0 from γ conversion (~ 49 %) within STT volume
- Neutron detection is ensured by combination of STT with ECAL





fiducial volume mass 4.7 t CH_2, 557 kg C

Background rejection

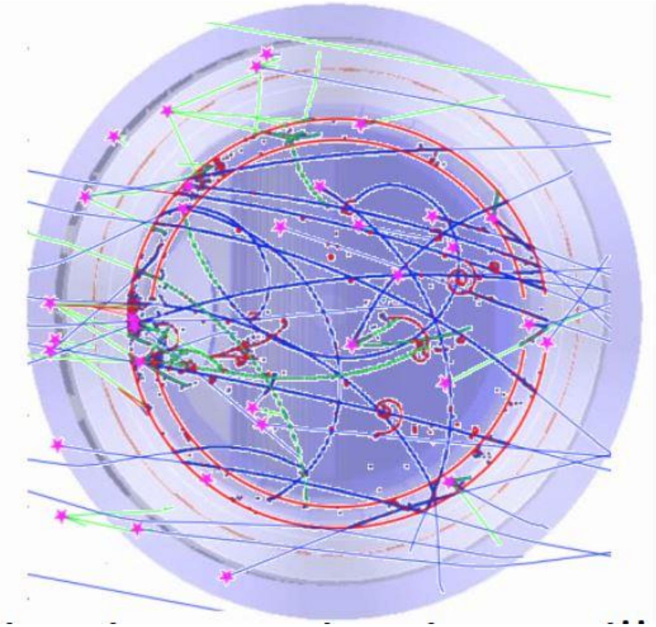
Backgrounds at ND site arise mainly from:

- cosmic radiation and ambient radioactivity → suppressed to negligible level requiring a time coincidence with the beam spill
- beam related neutrino interactions in the material surrounding the detector → most critical background source

Expected CC + NC event rate per beam spill are 84 events/spill (ν) and 45 events/spill ($\bar{\nu}$)

External background is rejected using a combination of simple cuts and a neural network jointly applied to timing and topological information from the subdetector and reconstructed quantities

simulation of ν interaction in a spill



STT option

Signal efficiency (%)	Background efficiency (%)	Purity (%)
92.8	0.003	99.6

Beam monitoring capability

- The beam is monitored by measuring variations of ν_μ CC interaction energy spectrum and event distribution in space
- Expected sensitivity are evaluated comparing the distribution of reconstructed neutrino energy expected from nominal (N_i^{norm}) and varied (N_i^{var}) beam using the test statistic T:

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

1 week data taking

ECAL+3DST option Beam parameter	Parameter description Nominal	Changed	Significance, $\sqrt{\chi^2}$ Rate-only	FHC	RHC
proton target density	1.71 g/cm^3	1.74 g/cm^3	0.02	8.51	5.65
proton beam width	2.7 mm	2.8 mm	0.02	4.67	2.93
proton beam offset x	N/A	+0.45 mm	0.09	2.84	1.70
proton beam θ	N/A	0.07 mrad	0.03	0.50	0.42
proton beam (θ, ϕ)	N/A	(0.07,1.571) mrad	0.00	0.51	0.35
horn current	293 kA	296 kA	0.2	12.64	7.97
water layer thickness	1 mm	1.5 mm	0.5	5.30	3.20
decay pipe radius	2 m	2.1 m	0.5	7.45	4.20
horn 1 along x	N/A	0.5 mm	0.5	4.77	2.94
horn 1 along y	N/A	0.5 mm	0.1	3.53	2.27

ECAL+STT option Beam parameter	Parameter description Nominal	Changed	Significance, $\sqrt{\chi^2}$ Rate-only	ECAL+STT
proton target density	1.71 g/cm^3	1.74 g/cm^3	0.02	4.4
proton beam width	2.7 mm	2.8 mm	0.02	6.1
proton beam offset x	N/A	+0.45 mm	0.09	4.7
proton beam θ	N/A	0.07 mrad	0.03	0.5
proton beam (θ, ϕ)	N/A	(0.07,1.571) mrad	0.00	0.4
horn current	293 kA	296 kA	0.2	10.3
water layer thickness	1 mm	1.5 mm	0.5	4.7
decay pipe radius	2 m	2.1 m	0.5	6.9
horn 1 along x	N/A	0.5 mm	0.5	3.8
horn 1 along y	N/A	0.5 mm	0.1	4.2

- In one week SAND has enough sensitivity ($\sqrt{X^2} > 3$) to detect the majority of beam variations and the cases with less sensitivity don't contribute significantly to the beam spectrum

SAND physics program

- Reducing systematics for long baseline oscillation analysis:
  - Flux measurements
  - Constraints on the nuclear effects in Ar using a combination of different nuclear targets
- SAND will turn the ND site to a physics facility for precision measurements and searches exploring many different topics:
  - Precision isospin physics
  - Measurements of $\sin^2\theta_W$ and electroweak physics
  - Measurements of strangeness content of the nucleon ($s(x)$, $\bar{s}(x)$, Δs, etc)
  - Study of QCD and structure of nucleons and nuclei
  - Measurements of nuclear physics and ν-nucleus interactions
  - Search for new physics: sterile neutrinos, NSI, etc…

arXiv:1910.05995

Nucl. Phys. A765, 126(2006), hep-ph/0412425

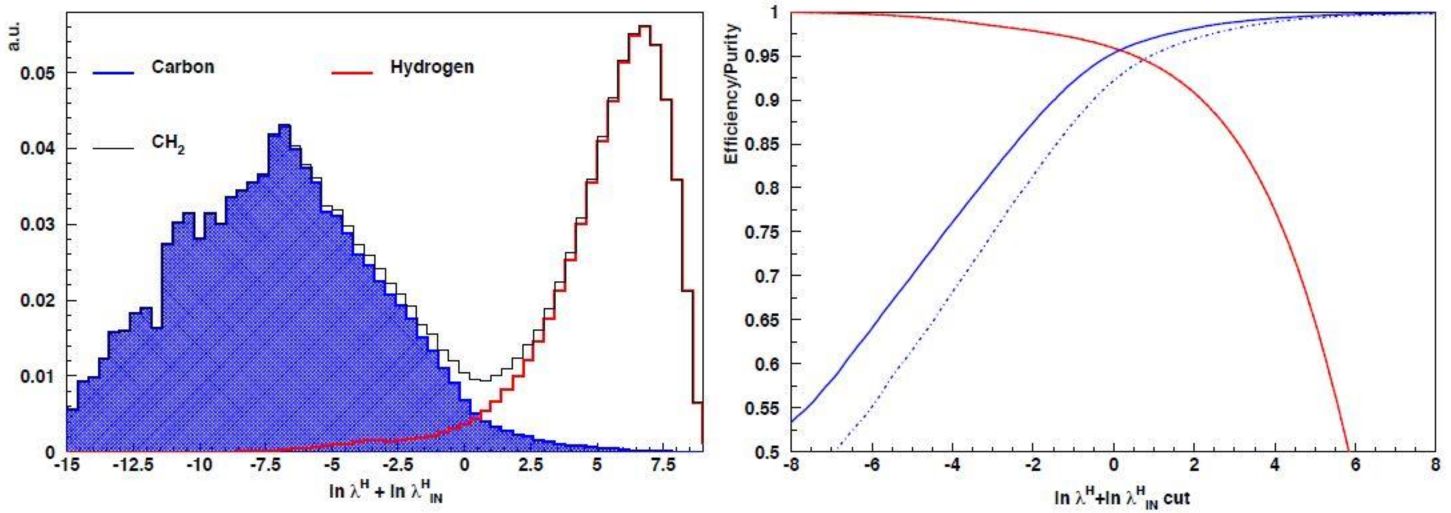
Phys. Rev. D76, 094023 (2007), hep-ph/0703033

SAND physics program
“solid” hydrogen concept

STT option provide a compact modular layout with a flexible design to control configurations, chemical composition and mass of neutrino targets similar to e$^{\pm}$ DIS experiments will provide a “solid” hydrogen concept:

arXiv:1910.05995

model independent subtraction of measurements on dedicated graphite (pure C) targets from main CH_2 target to extract high statistics samples of ν(anti-ν) CC interactions on H by a kinematic analysis



Keep under control systematic uncertainties:
- Flux measurements
- Constrain models on nuclear effects

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

SAND physics program - flux measurements

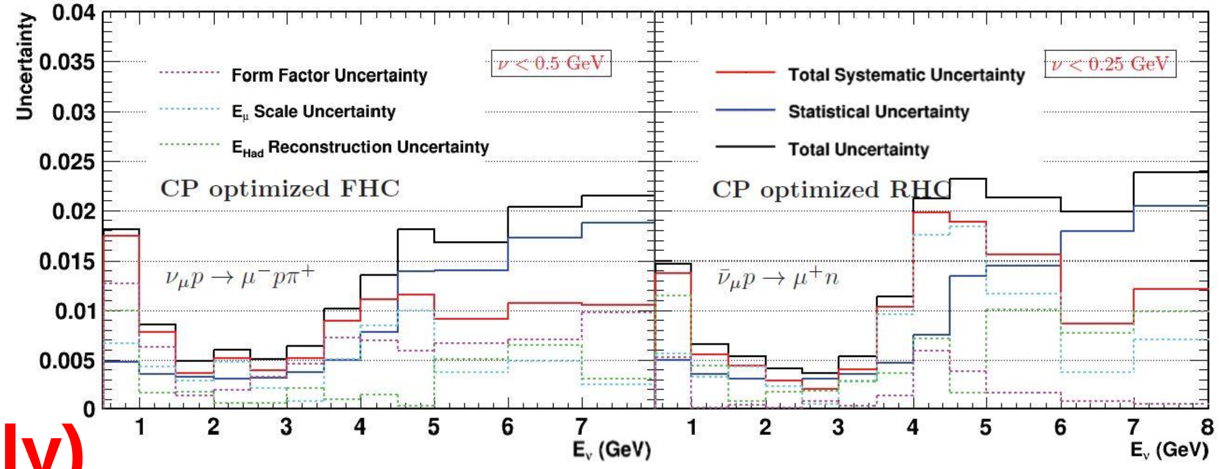
The measurement of ν flux is a mandatory condition to extract oscillation probability from measured neutrino interaction

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

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 $\bar{\nu}_\mu p \rightarrow \mu^+ n$ process on hydrogen

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

systematics uncertainties for the flux measurement



5 years (STT-only)

arXiv:2103.13910

SAND physics program - flux measurements

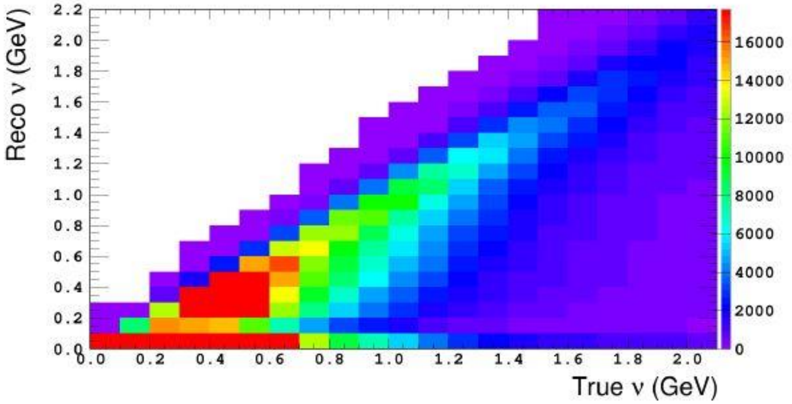
Relative ν_μ and $\bar{\nu}_\mu$ fluxes can be measured by selecting inclusive CC interactions with small energy transfer (< 0.25 GeV) in the 3DST (CH)

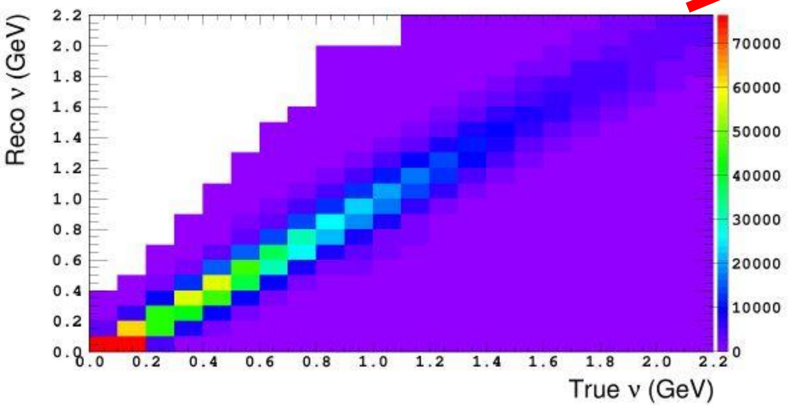
- large target mass provides sizable number of interactions (1.5×10^7 ν_μ CC and 5.5×10^6 $\bar{\nu}_\mu$ CC / year)
- uncertainties introduced by nuclear effects and by corresponding smearing on the reconstructed hadronic energy can be partially mitigated by the neutron reconstruction with ToF

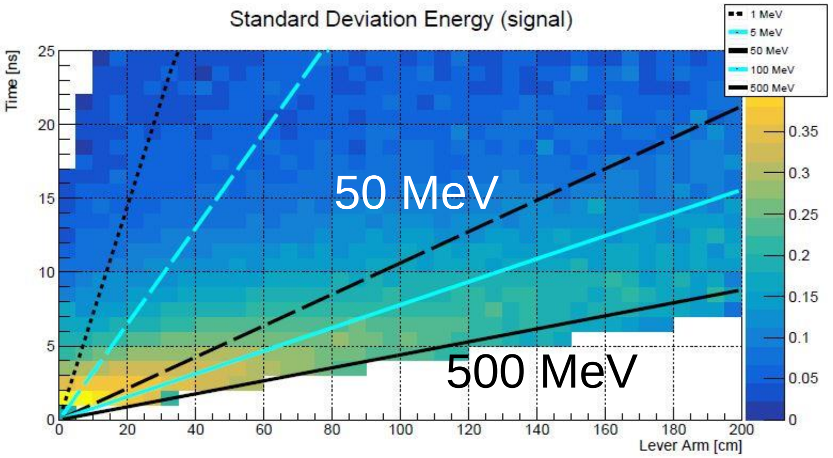
3DST + TPC

Reconstructed versus true ν energy

neutron energy reconstructed with ToF







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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 with STT option offers valuable information to reduce systematics:

$$N_X(E_{rec}) = \int_{E_\nu} dE_\nu \underbrace{\boxed{\Phi(E_\nu)}}_{\text{1 \% on H}} P_{osc}(E_\nu) \underbrace{\boxed{\sigma_X(E_\nu)}}_{\text{Measured from high statistic sample}} \underbrace{\boxed{R_{phys}(E_\nu, E_{vis})}}_{R_{phys} \equiv 1} \underbrace{\boxed{R_{det}(E_{vis}, E_{rec})}}_{\delta p/p \text{ 0.2 \% calibrated in-situ from } K_0 \to \pi^+\pi^- \text{ in STT volume}}$$

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

→ reduce beam model uncertainties affecting DUNE PRISM

Conclusions

- SAND is an excellent beam monitoring to spectral changes that would impact on long-baseline measurements

- SAND adds robustness to the ND complex: measuring the flux and constraining nuclear effects, is capable of control systematics uncertainties on ν spectrum in order to provide the initial state of the beam and to compare it with the observations at the Far Detector

- SAND can explore many different physics topics within the ND complex, from precision measurements to searches for new physics

- Dedicated studies were carried out to finalize the design of SAND as an integrated on-axis detector and currently the choice between the different technologies is under decision process

Thank you for your attention!

Backup

SAND physics – test of isospin

- The Adler integral provide the ISOSPIN of the target:

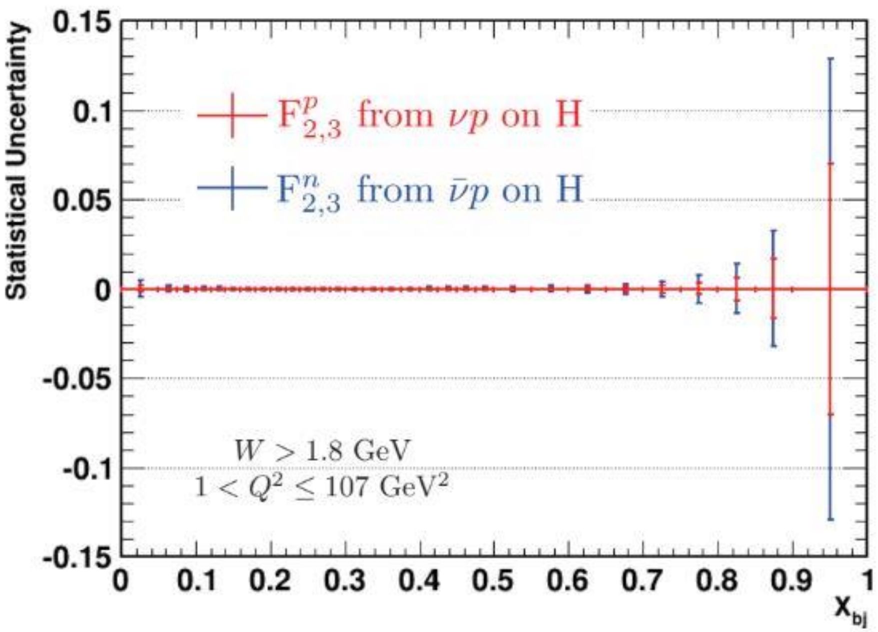
$$S_A(Q^2) = \int_0^1 \frac{dx}{2x}\left(F_2^{\bar{\nu}p} - F_2^{\nu p}\right) = I_p$$

- Large statistics of ν interaction on H will provide precision test of S_A at different Q^2 values

- Only measurements available fro BEBC based on 5000 νp and 9000 $\bar{\nu}$p (D. Allasia et al., ZPC 28 (1985) 321)

- Direct measurements of $F_{2,3}^{\nu n}/F_{2,3}^{\nu p}$ free from nuclear uncertainties

Process	$\nu(\bar{\nu})$-H
Standard CP optimized:	
ν_μ CC (5 y)	3.4×10^6
$\bar{\nu}_\mu$ CC (5 y)	2.5×10^6
Optimized ν_τ appearance:	
ν_μ CC (2 y)	6.5×10^6
ν_μ CC (2 y)	4.3×10^6



SAND physics – electroweak measurements

Complementary with colliders & low energy measurements: DUNE ND can determine $\sin^2\theta_W$ from the ratio of NC and CC interactions induced by neutrinos in different channels:

- $R^{\nu} = \sigma_{NC}^{\nu} / \sigma_{CC}^{\nu}$ in ν-N DIS (~ 0.35 %)
- $R_{\nu e} = \sigma_{NC}^{\nu} / \sigma_{NC}^{\nu}$ in ν-e⁻ NC elastic (~ 1 %)

Independent cross-check of NuTeV $\sin^2\theta_W$ anomaly (3σ from SM prediction) in a similar Q^2 range