The SAND detector of the DUNE experiment

Denise Casazza on behalf of the DUNE collaboration.

The XIX International Conference on Topics in Astroparticle and Underground Physics - TAUP 2025.

Xichang, 24th-30th August 2025.

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The Deep Underground Neutrino Experiment (DUNE)

DUNE **main physics goals**:

Long baseline neutrino oscillation:
- establish whether nature violates CP in the lepton section and if so measure δ_{CP},
- improve accuracy on θ_{23} and determine the octant $\theta_{23} < \pi/4$ vs. $\theta_{23} > \pi/4$,
- determine the neutrino mass ordering at high confidence level.

Astrophysics via MeV-scale ν_es at FD:
- supernova pointing and neutrino property measurement via SNB detection,
- solar neutrino measurements of *hep* flux, ^8B channel and Δm^2_{21}.

Beyond Standard Model (Light Dark Matter, proton decay, sterile neutrinos…).

Far Detector:

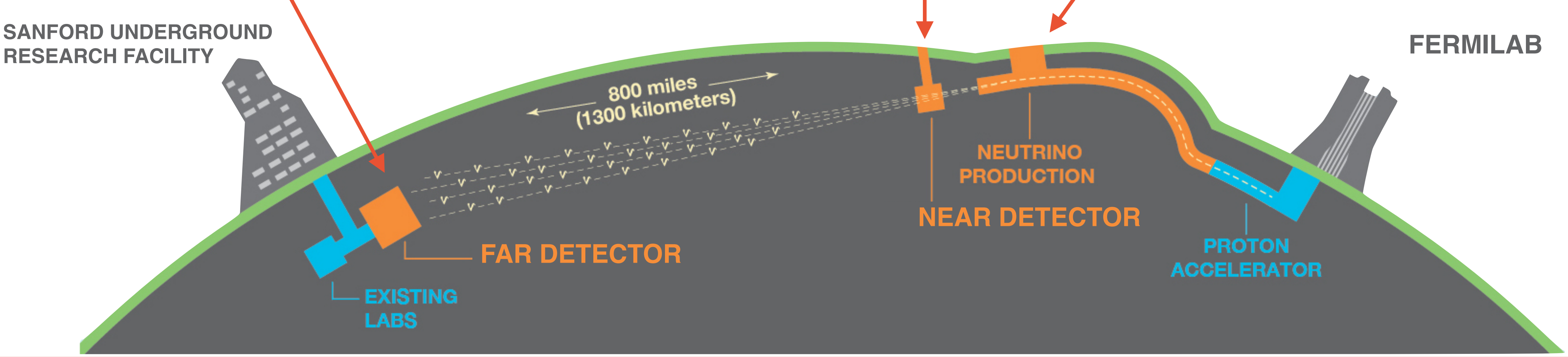
- 4 modules,1.5 km underground: 3 LArTPCs (17 kton each) + 1 module of opportunity (FD4).
- Horizontal (FD2) and vertical (FD1) technologies.

Near Detector:

- Configuration: ND-LAr, TMS(→ ND-GAr), SAND.

LBNF beam:

- Both neutrino-enriched and antineutrino-enriched configurations.
- Wide-band neutrino beam: 1.2MW(→2.4MW), peaked at ~ 2.5GeV.



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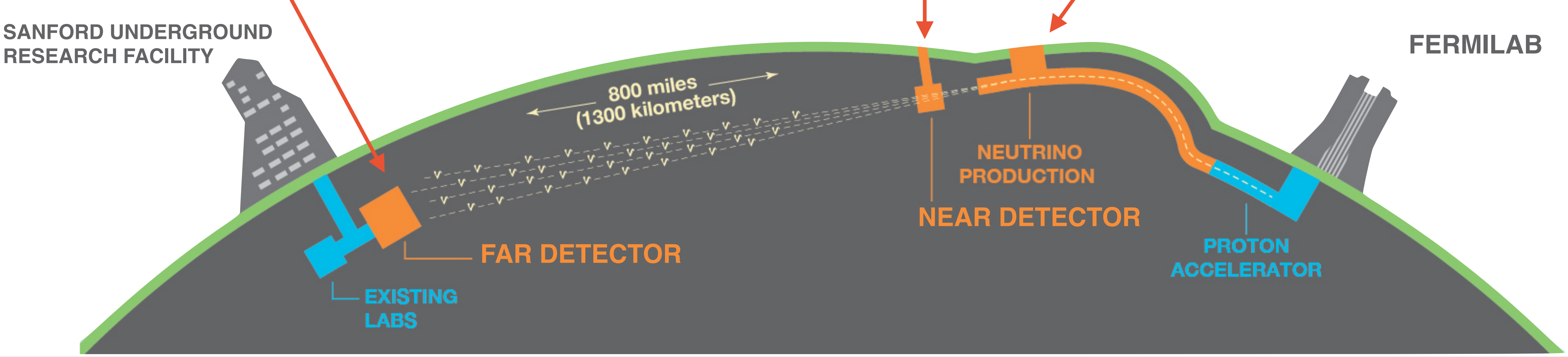

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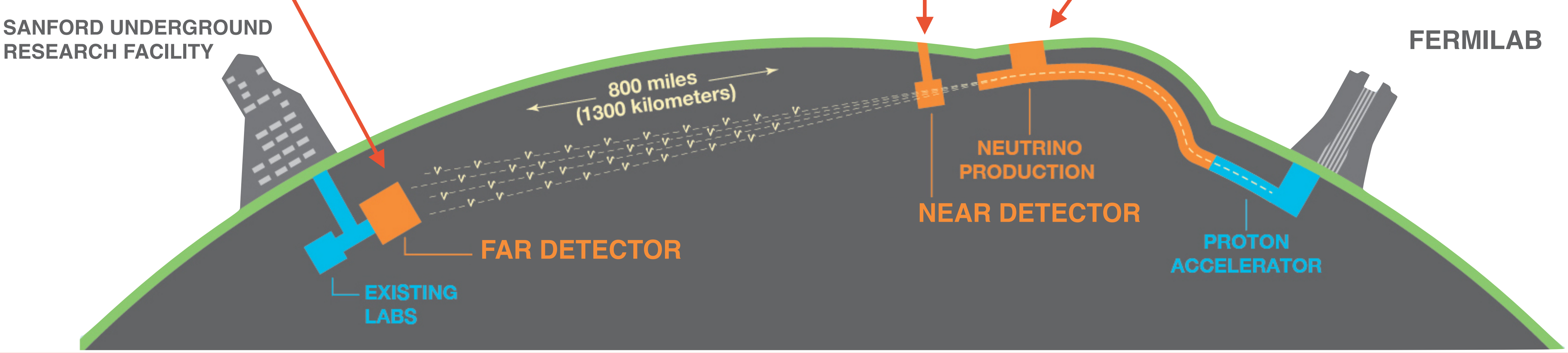

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See Luis's talk!

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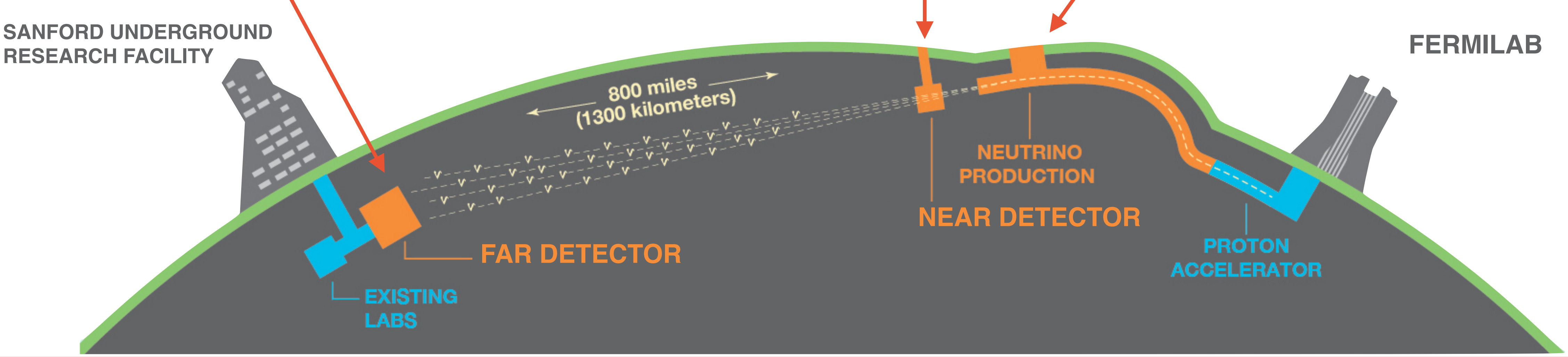
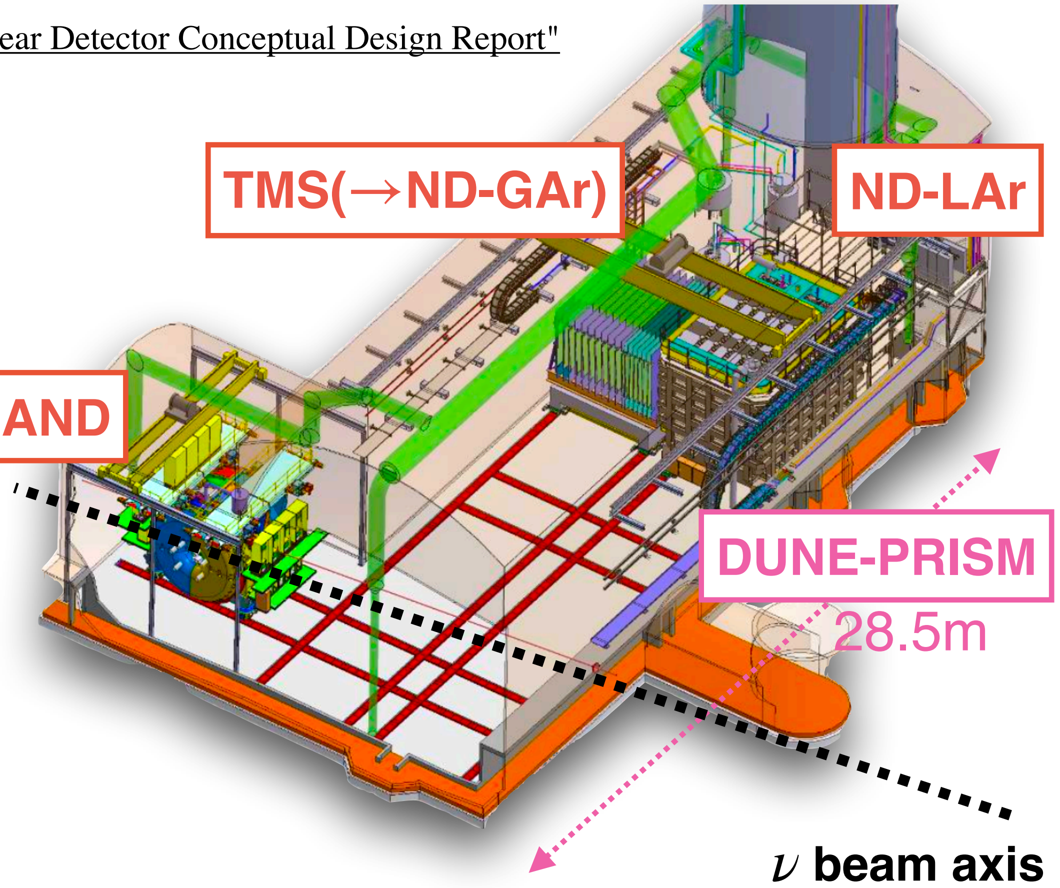


Near detector complex

"Near Detector Conceptual Design Report"



The DUNE near detector 574 m downstream the beam target and 60 m underground will have three components:

- **ND-LAr**: 67 ton liquid argon TPC based with pixelated readout coupled with:
  - **TMS** (phase I): muon spectrometer,
  - **ND-GAr** (phase II): magnetised high pressure gaseous argon TPC surrounded by an ECal.
- **SAND:** On-axis magnetised detector with LAr active target, a low-density tracker and an ECal.

  DUNE-PRISM: up to 28.5 m off-axis movable system composed of ND-LAr+TMS/ND-GAr to scan different neutrino energies.

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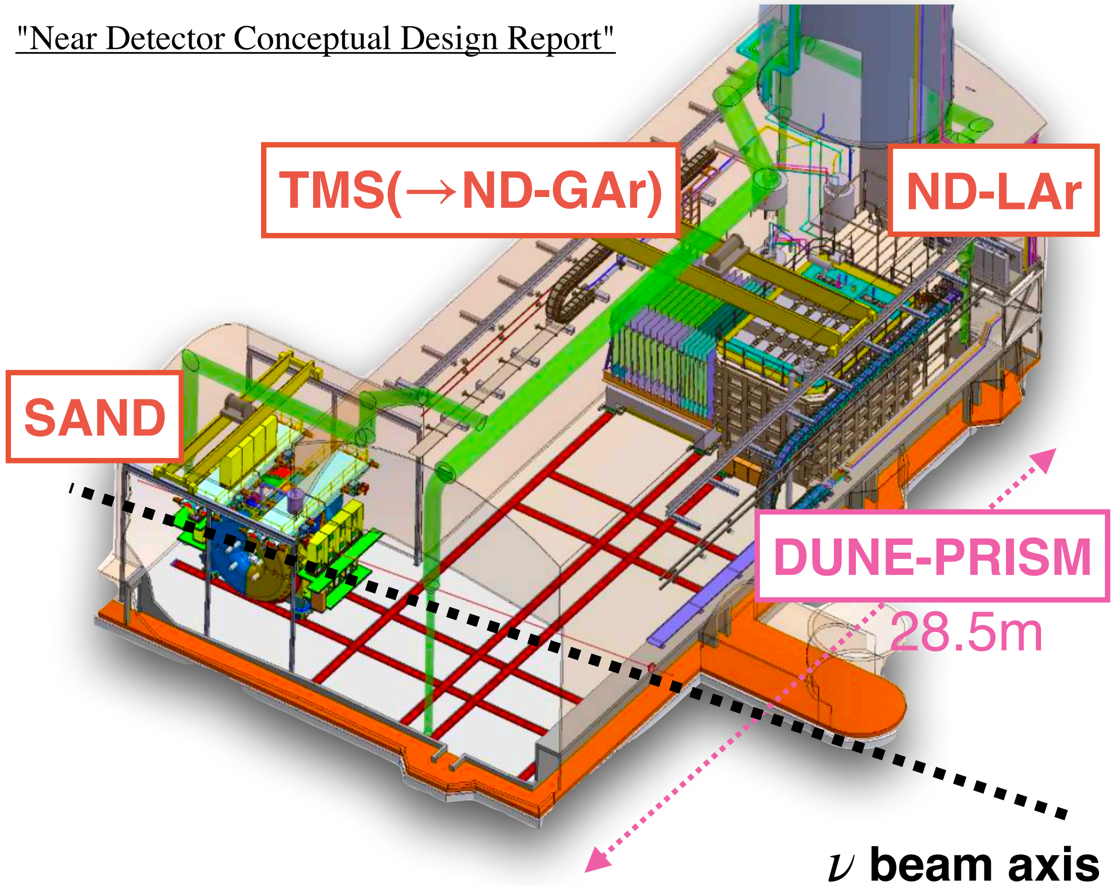

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The DUNE near detector role:

- Measure the ND beam rate spectrum before oscillation for the prediction at FD.

$$N_{ND}^{\nu_\mu}(\mathrm{p}_{reco}) = \sum_i \Phi_{\nu_\mu}(E_{true}) \cdot \sigma^i_{\nu_\mu}(\mathrm{p}_{true}) \cdot \epsilon_{\nu_\mu}(\mathrm{p}_{true}) \cdot R_i(\mathrm{p}_{true}; \mathrm{p}_{reco})$$

i = interaction, $p = (E, \vec{p})$

- Measure the flux at ND.
- Constrain systematic uncertainties measuring cross sections, detector response and efficiency.

- Independent physics programme for cross sections and BSM.

$$N_{FD}^{\nu_\mu \to \beta}(\mathrm{p}_{reco}) = \sum_i \Phi_{\nu_\mu}(E_{true}) \cdot P_{\nu_\mu \beta}(E_{true}) \cdot \sigma^i_{\beta}(\mathrm{p}_{true}) \cdot \epsilon_{\beta}(\mathrm{p}_{true}) \cdot R_i(\mathrm{p}_{true}; \mathrm{p}_{reco})$$

i = interaction, $\beta = \nu_\mu, \nu_e$, $p = (E, \vec{p})$

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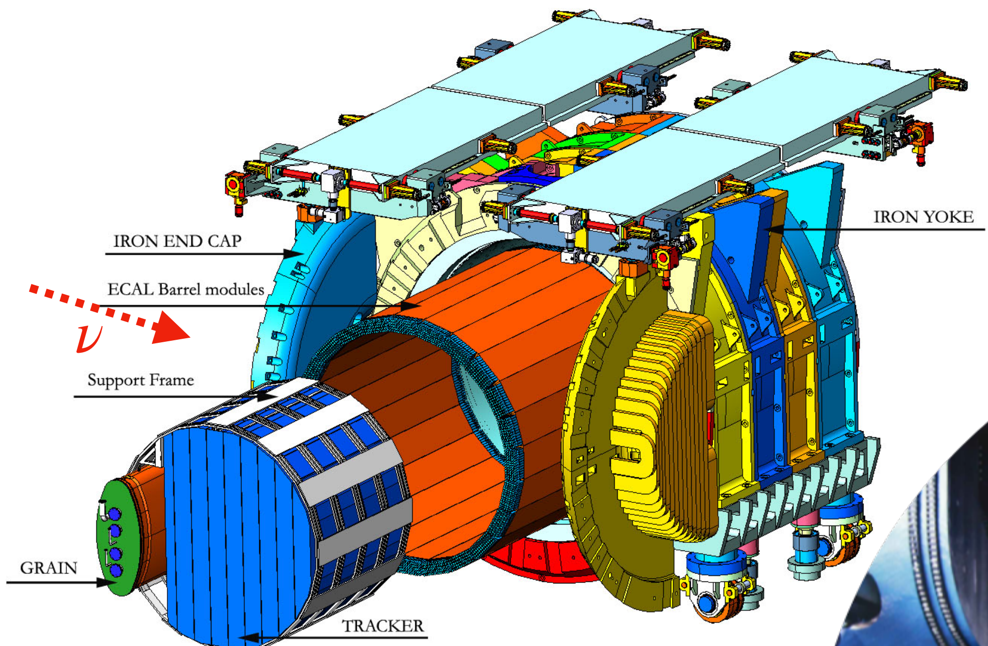
SAND in a nutshell

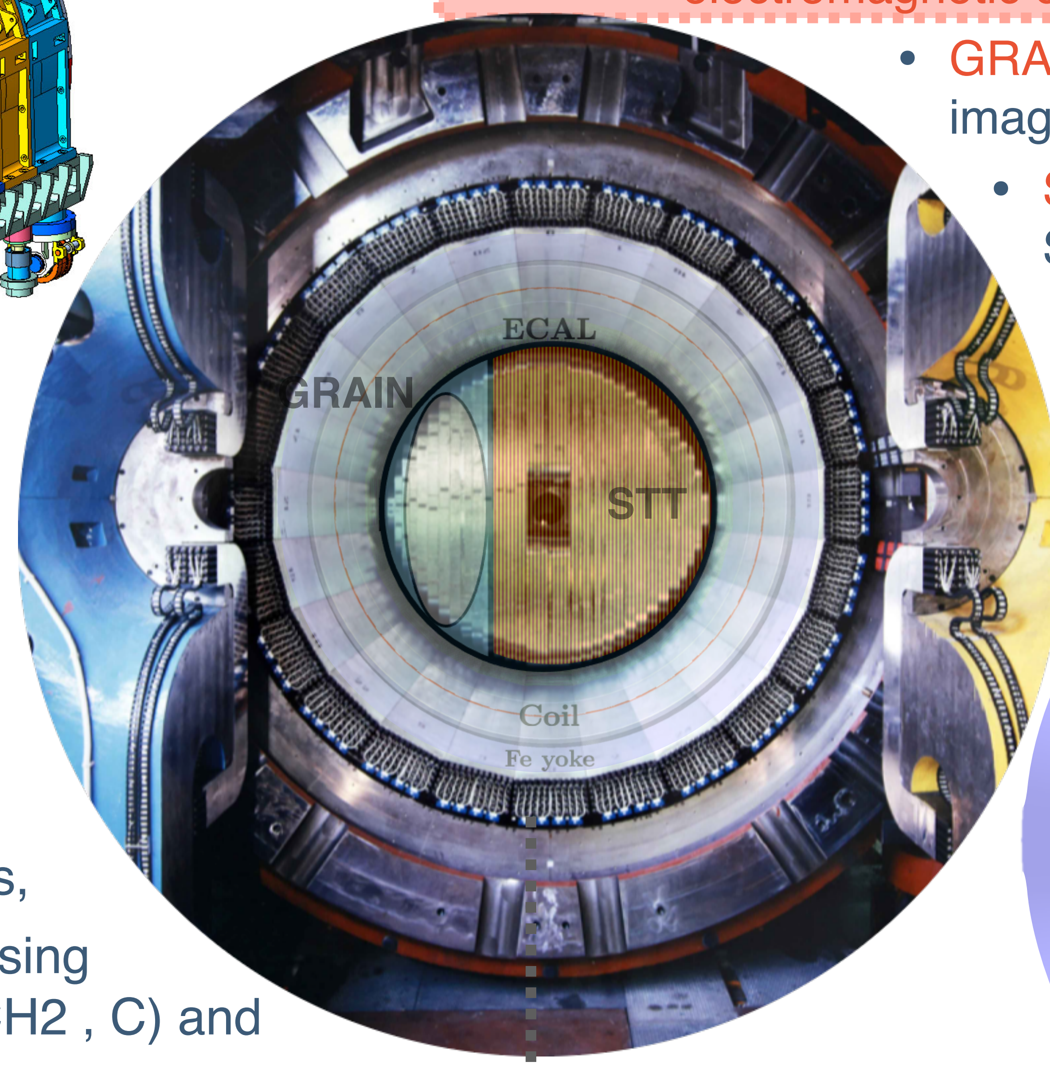


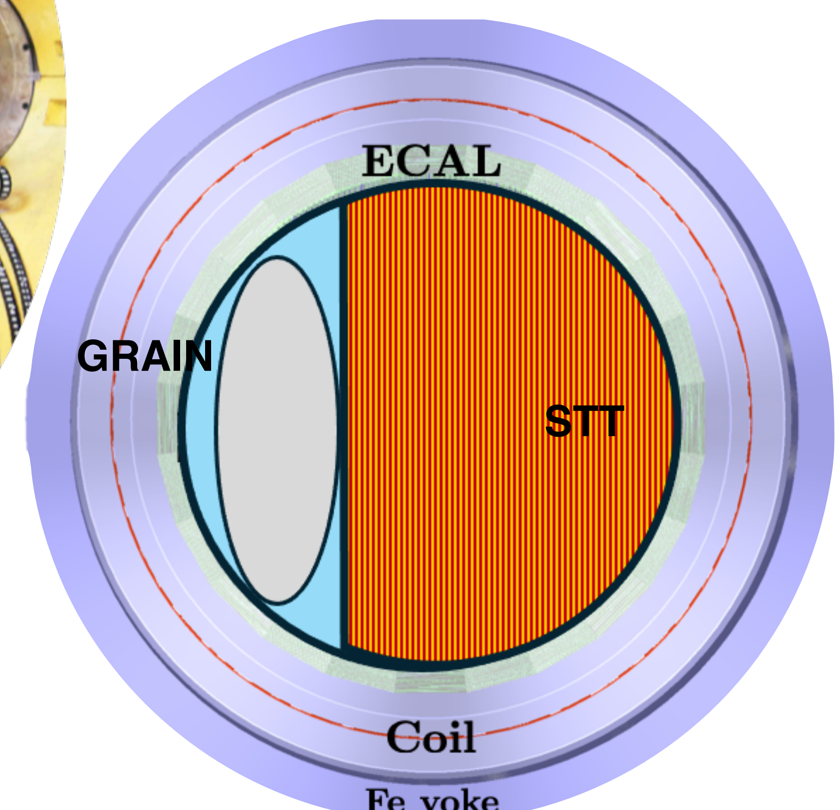
SAND (System for on-Axis Neutrino Detection) is a multi-purpose detector, permanently on-axis, capable of precision tracking and calorimetry, featuring:

- 0.6 T superconducting magnet,
- electromagnetic calorimeter (ECal),

KLOE experiment!

- GRAIN: a LAr active target (~1 ton), with imaging system.
- STT: a low-density tracker based on Straw Tubes with distributed target mass.





SAND goals

- Monitor beam changes continuously with high significance on a weekly basis,
- Constrain nuclear effects by using different nuclear targets (Ar, CH2 , C) and "solid Hydrogen" technique.
- Perform independent $\nu/\bar{\nu}$ flux measurements
- BSM physics program

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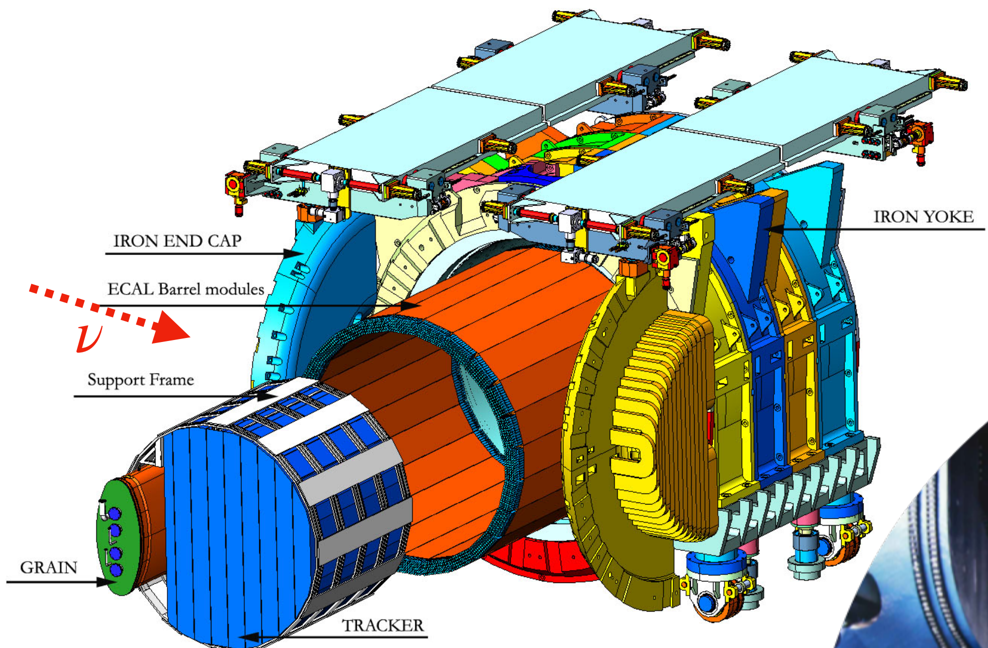

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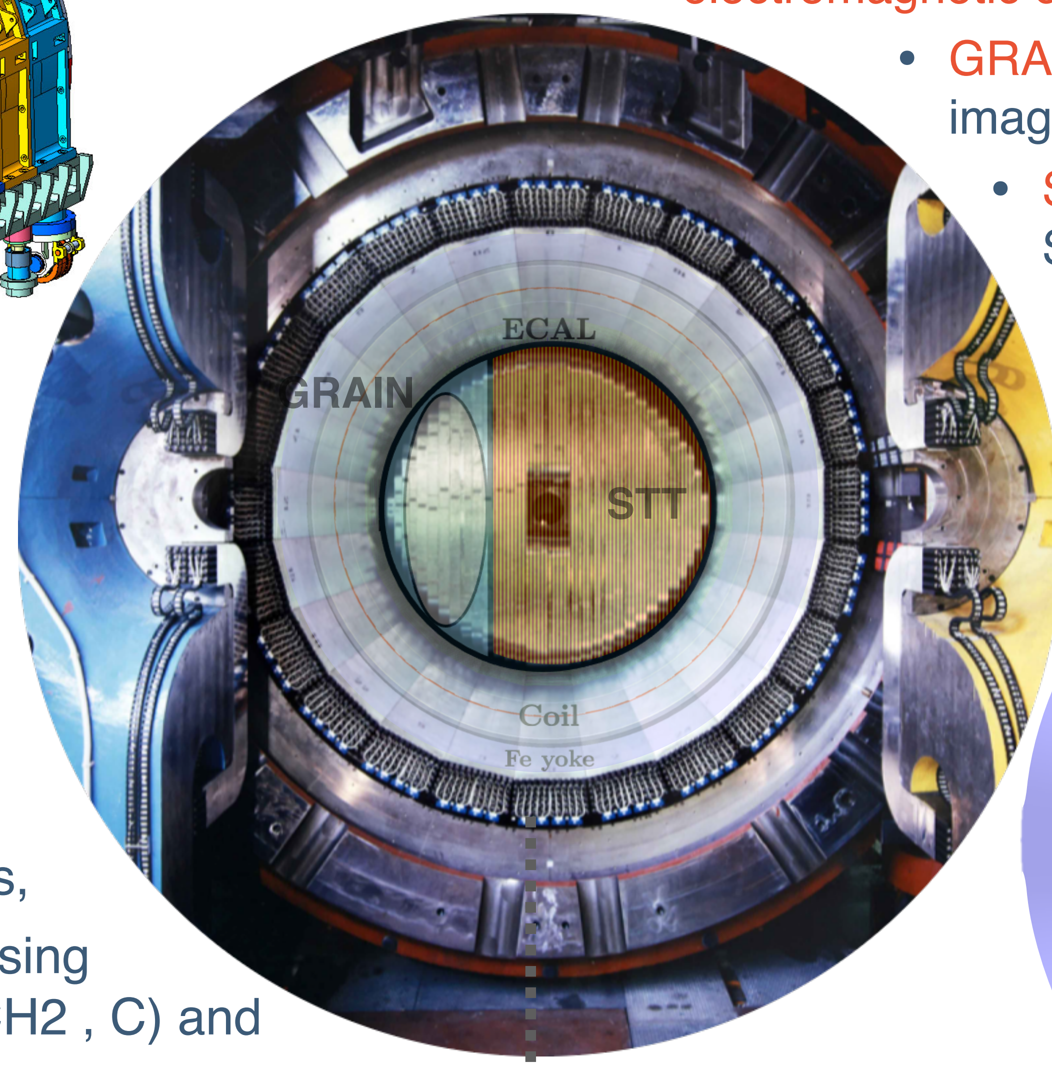

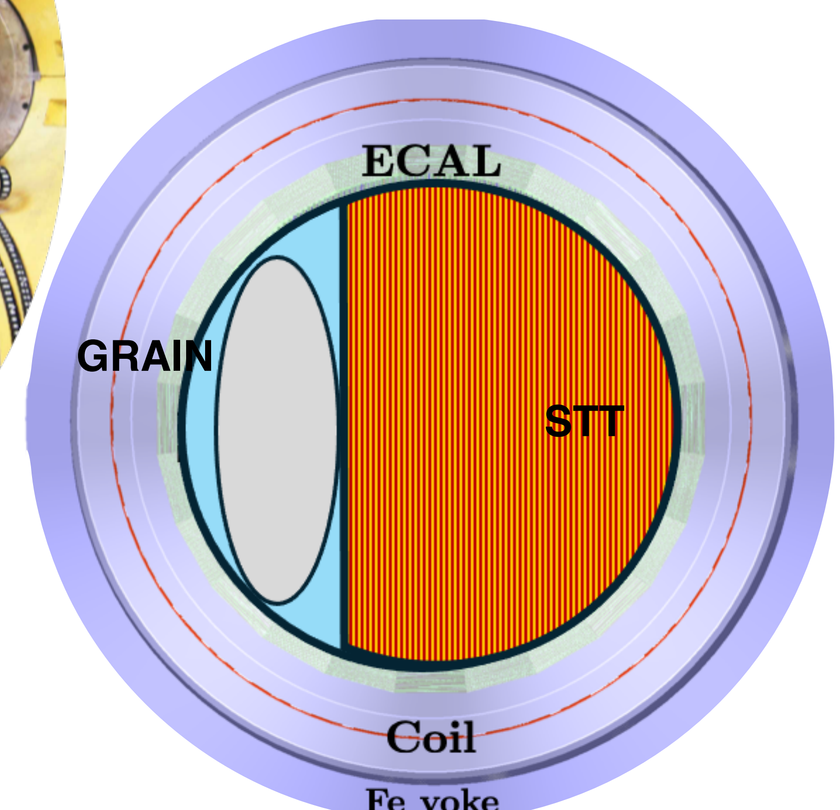

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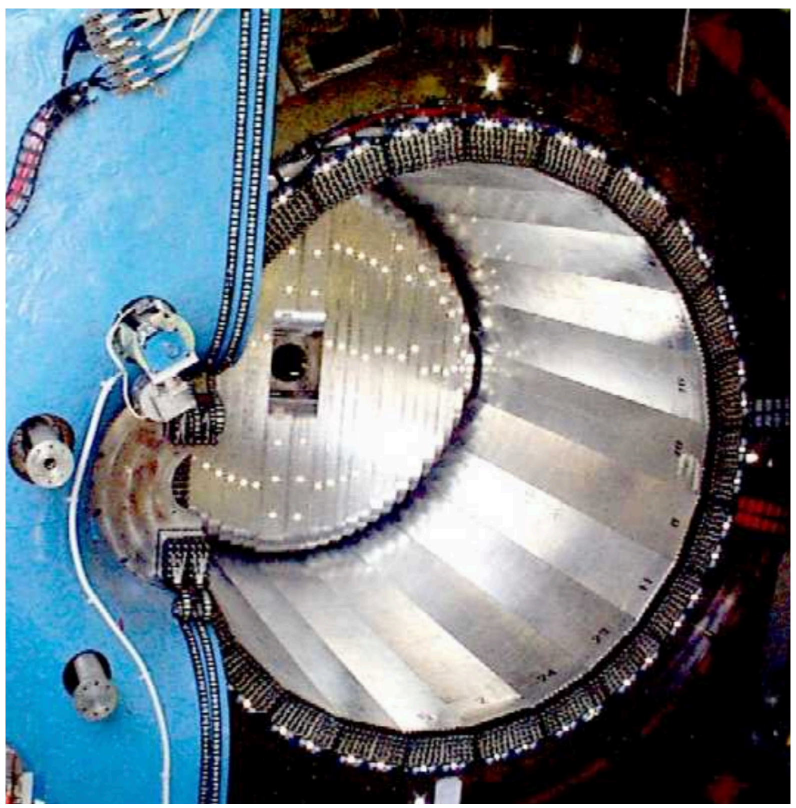
The SAND ECal

- $\sim 4\pi$ **lead-scintillating fiber longitudinal sampling EM** calorimeter.
- 4880 channels (cells) in barrel (24)& two-endcap (32 + 32) modules.
- Each module: 15 X_0 thick, composed of 200 lead foils 0.5 mm thick, grooved to host fibers + 200 layers of cladded scintillating fibers, 1mm ⌀. 5 layers with a cell granularity $\sim 4.4 \times 4.4\ cm^2$.
- Singe cell readout at both ends via PMTs.

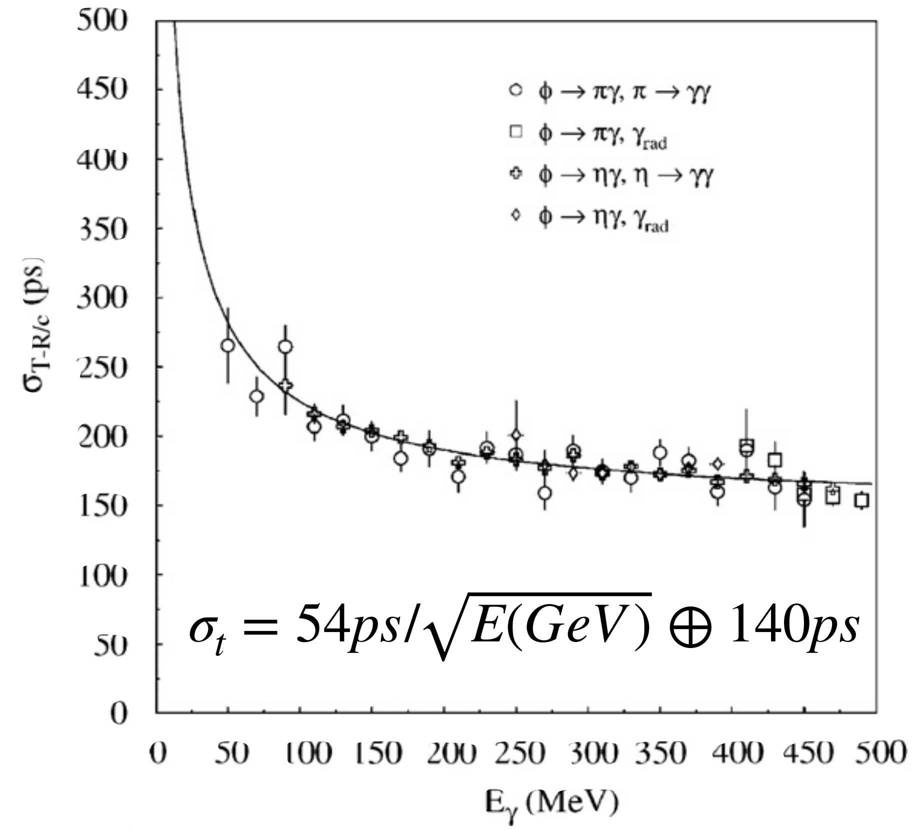


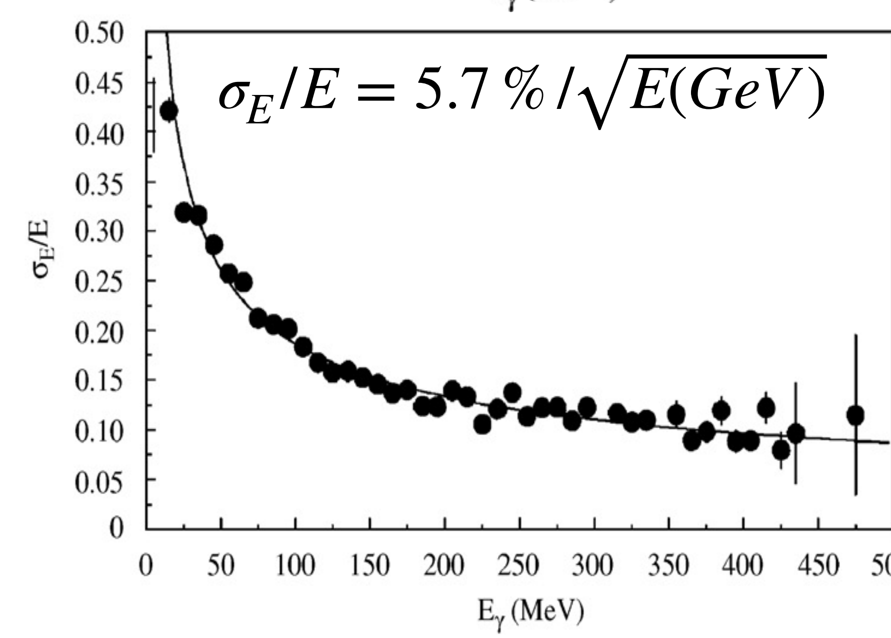
BARREL MODULES

ENDCAP MODULES

PMT VIEW - single barrel module

"ECAL Overview and performance "





"Calibration and performances of the KLOE calorimeter."

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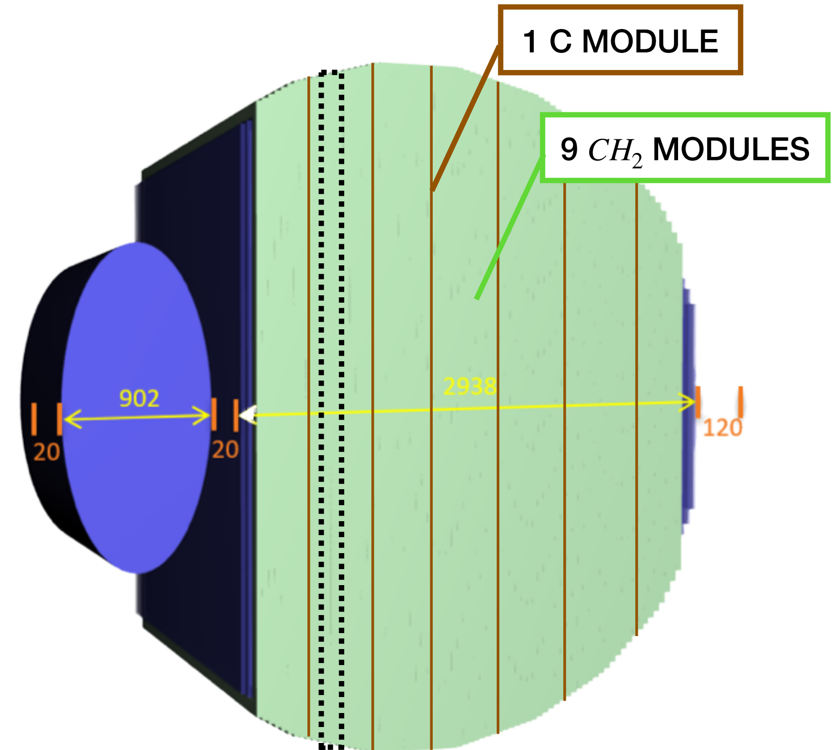
The SAND Straw Tube Tracker

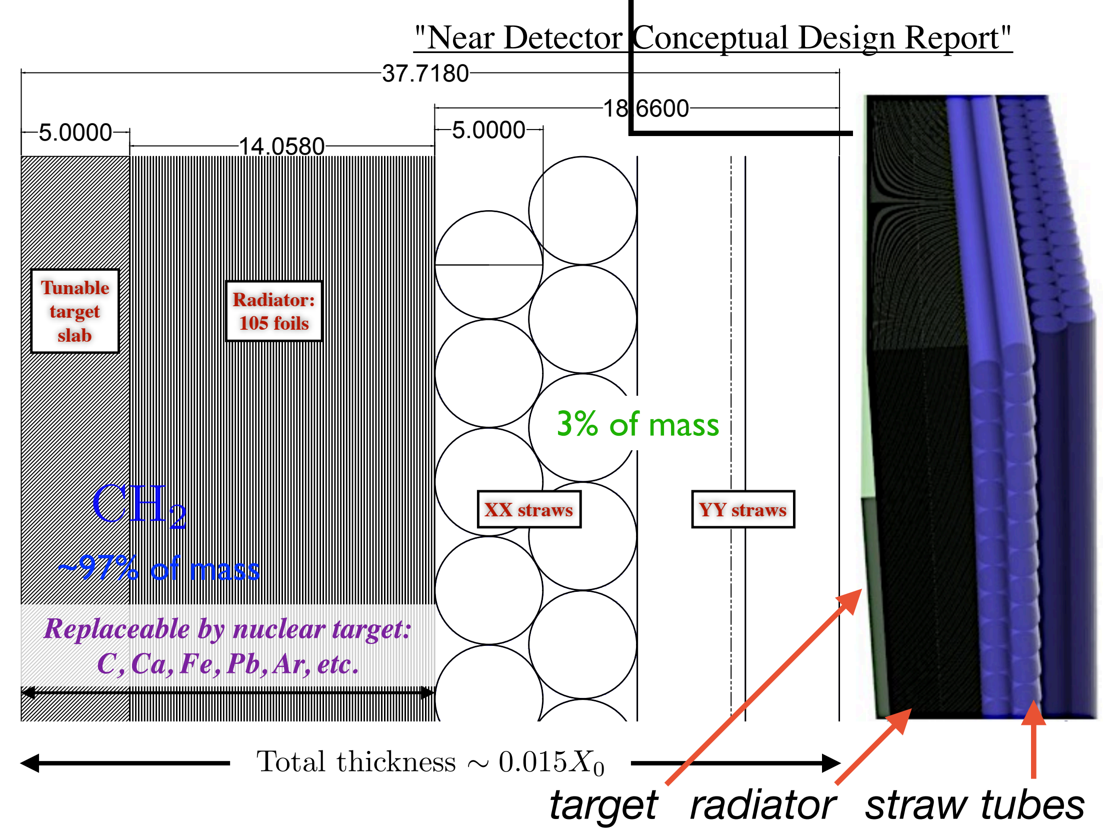
DESIGN:

- Low-density tracker based on 5 mm diameter straw tubes, 84 modules.
- Each module:

  1. target material $(1-2\,\%\,X_0)$,
  2. transition Radiation Detector,
  3. four straw tube layers in XXYY configuration.

- Basic configuration: one layer of C (graphite) every nine of CH_2 (polypropylene). Gas mixture: Xe/CO_2 $(70\,\%/30\,\%)$ at 1.9 atm.



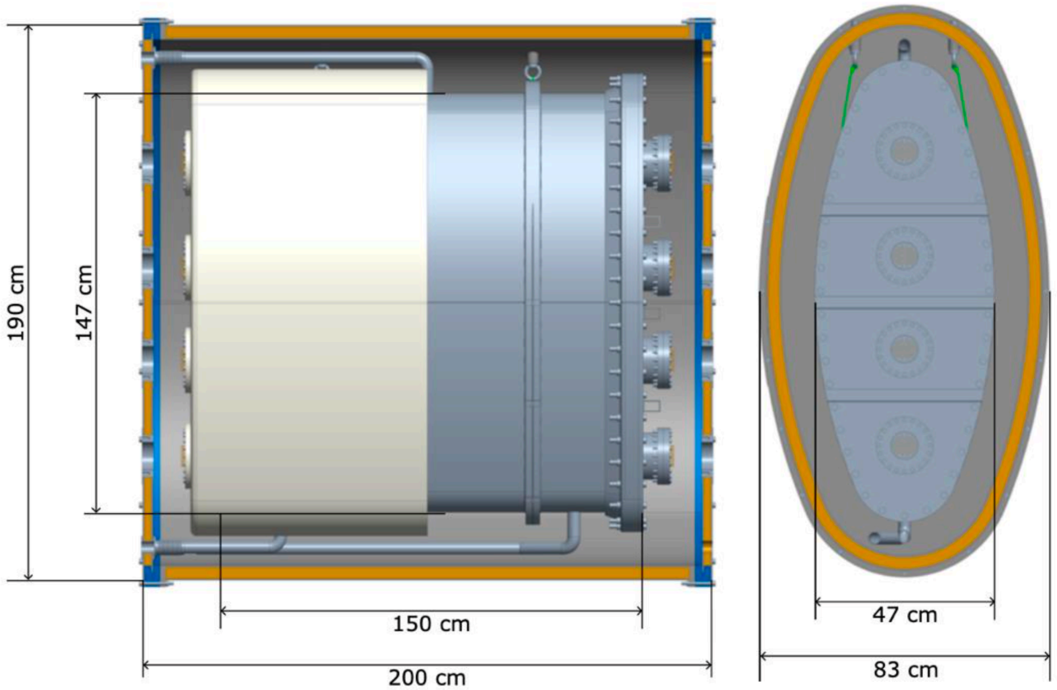


FEATURES:

- Modular layout with tuneable average density and availability for new targets.
- Accurate reconstruction of kinematics variables: momentum ~ 3.5 %, angular ~ 2 mrad and time ~ 1 ns resolutions,
- Single hit space resolution < 200 μm,
- Particle identification for charged particles via p + dE/dx.

GRAIN: GRanular Argon for Interactions of Neutrinos

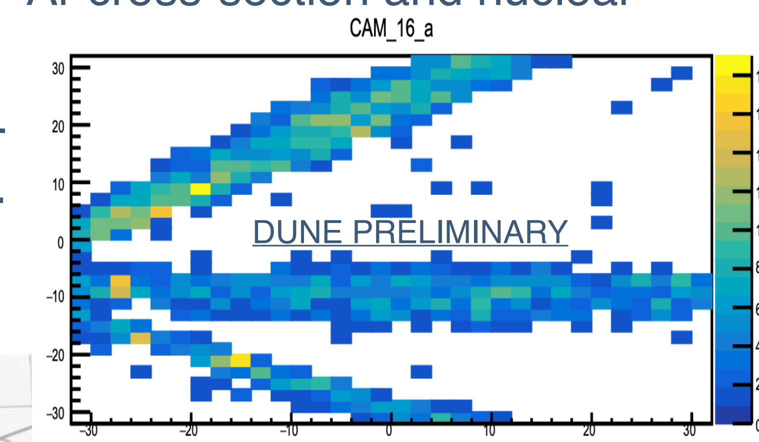
LAr active target with an optical readout system that allow **particle reconstruction** using **scintillation light.**

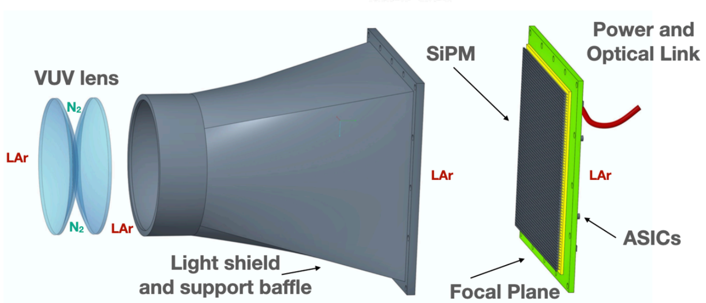


- 1-ton LAr target,
- inner cryostat made of steel, operated at 1.5 bar,
- outer vacuum vessel made of composite materials, maintained at $10^{-5} bar$.

Main motivations

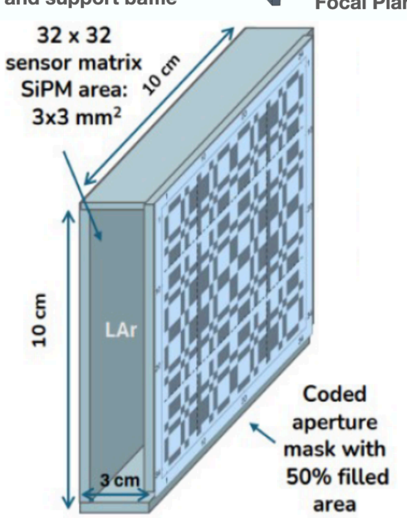
- Constraint on systematics for the ν–Ar cross-section and nuclear effects,
- Complementary Ar target for cross-calibration with other ND detectors.





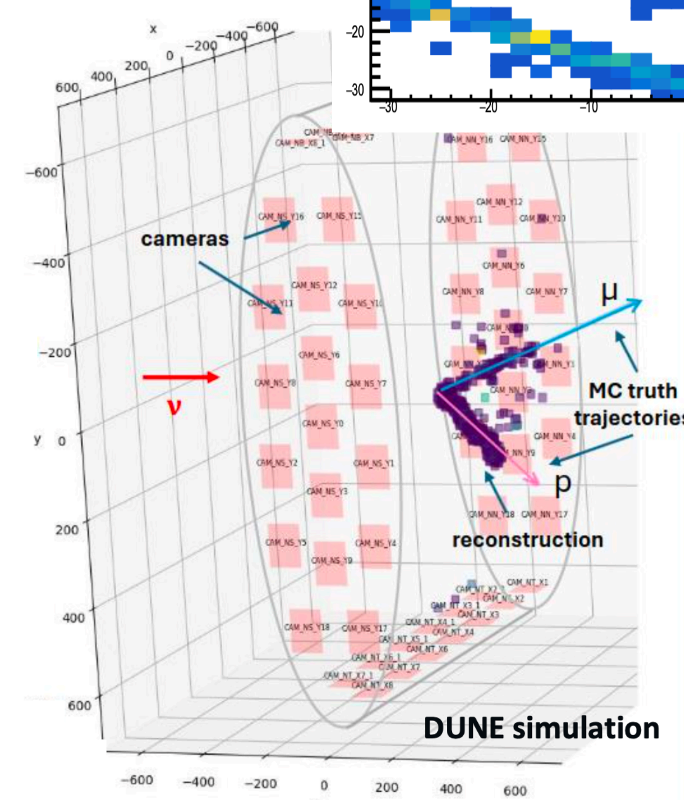
Lens

53 cameras, SiPM matrix 32 x 32 SiPMs, surface $2x2mm^2$.



Coded aperture masks

60 cameras, SiPM matrix 32 x 32 SiPMs, surface 3x3 mm^2.



"V. Cicero's talk"

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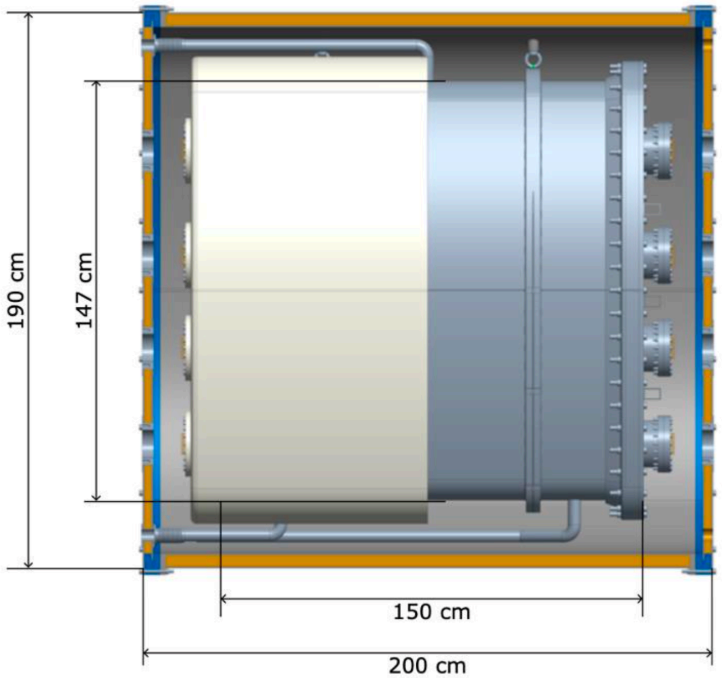

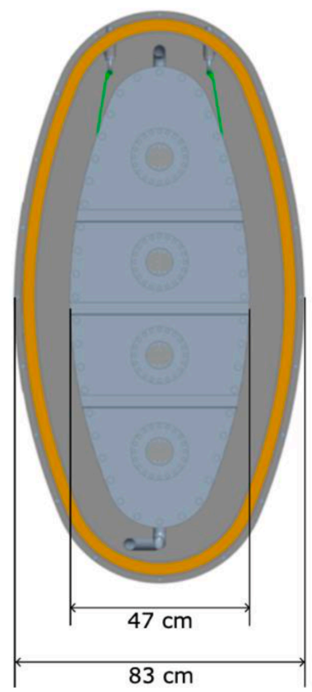

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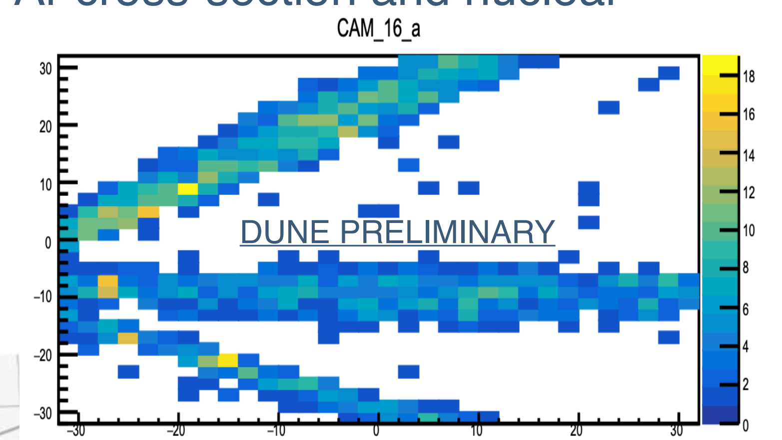

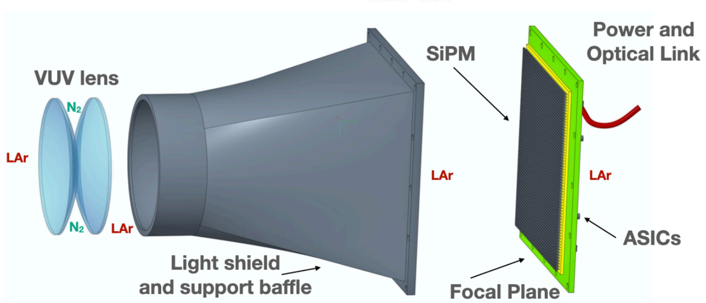

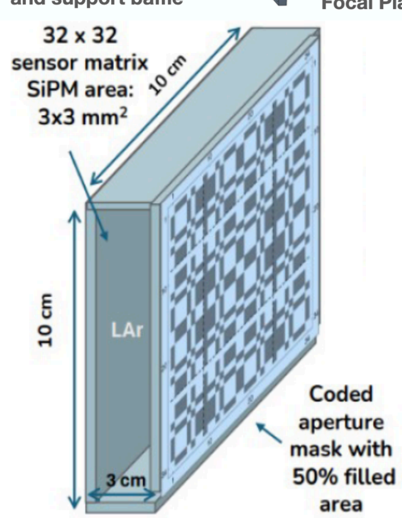

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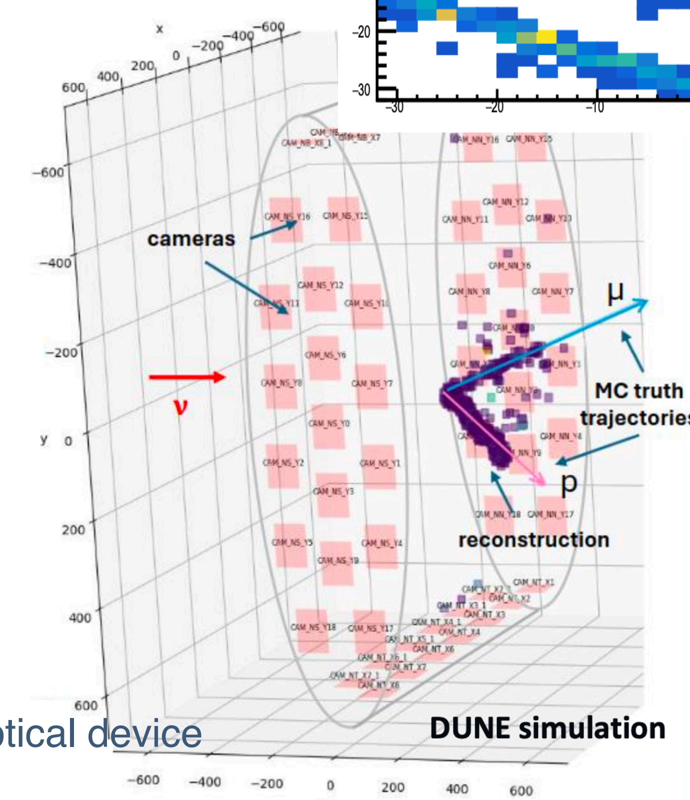


CAMERA: array of Silicon Photo-Multipliers (SiPM) + optical device

"V. Cicero's talk"

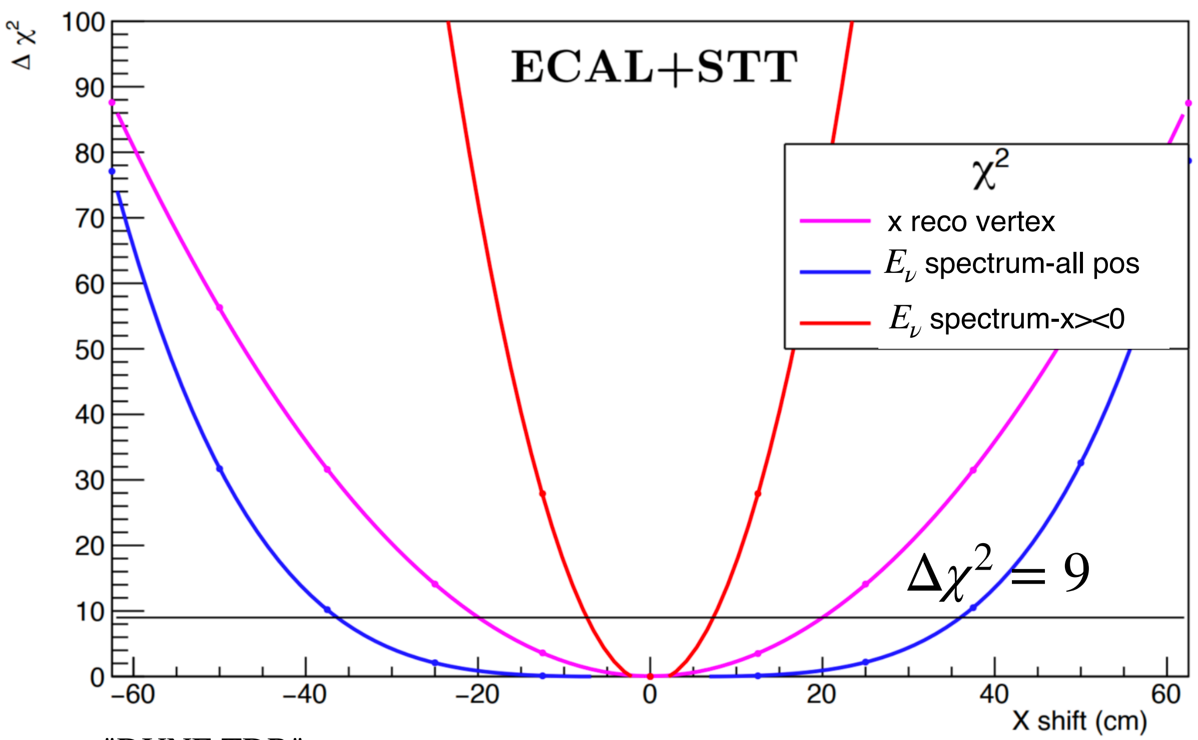
Beam monitoring capability

SAND is permanently located on-axis for continuous beam monitoring to:

- track changes in the beam necessitating changes in the beam model,
- diagnose the reasons for unanticipated changes in the beam spectra.

Detecting variations in the **energy spectrum** and **spatial distribution** of ν_μ-CC events on a weekly basis ($3.78 \cdot 10^{19}$ proton-on-target).

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



"DUNE TDR"

DUNE PRELIMINARY

Beam parameter	1σ variation	$\sqrt{\Delta\chi^2(E_\nu^{\text{true}})}$	$\sqrt{\Delta\chi^2(E_\nu^{\text{rec}})}$
Horn current	+3kA	12.57	9.44
Water layer thickness	+0.5 mm	4.69	3.58
Proton target density	+2%	5.28	4.07
Proton beam radius	+0.1 mm	4.41	3.53
Proton beam offset X	+0.45 mm	5.11	3.54
Proton beam θ,ϕ	0.07 mrad θ, 1.57 ϕ	0.62	0.28
Proton beam θ	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 X shift	+0.5 mm	1.31	0.77

"A Proposal to Enhance the DUNE Near Detector Complex"

- $\sqrt{\Delta\chi^2} > 3$ for **7 beam parameters**.
- $\sqrt{\Delta\chi^2} > 3$ for beam x-axis direction shifts down to 8.4cm

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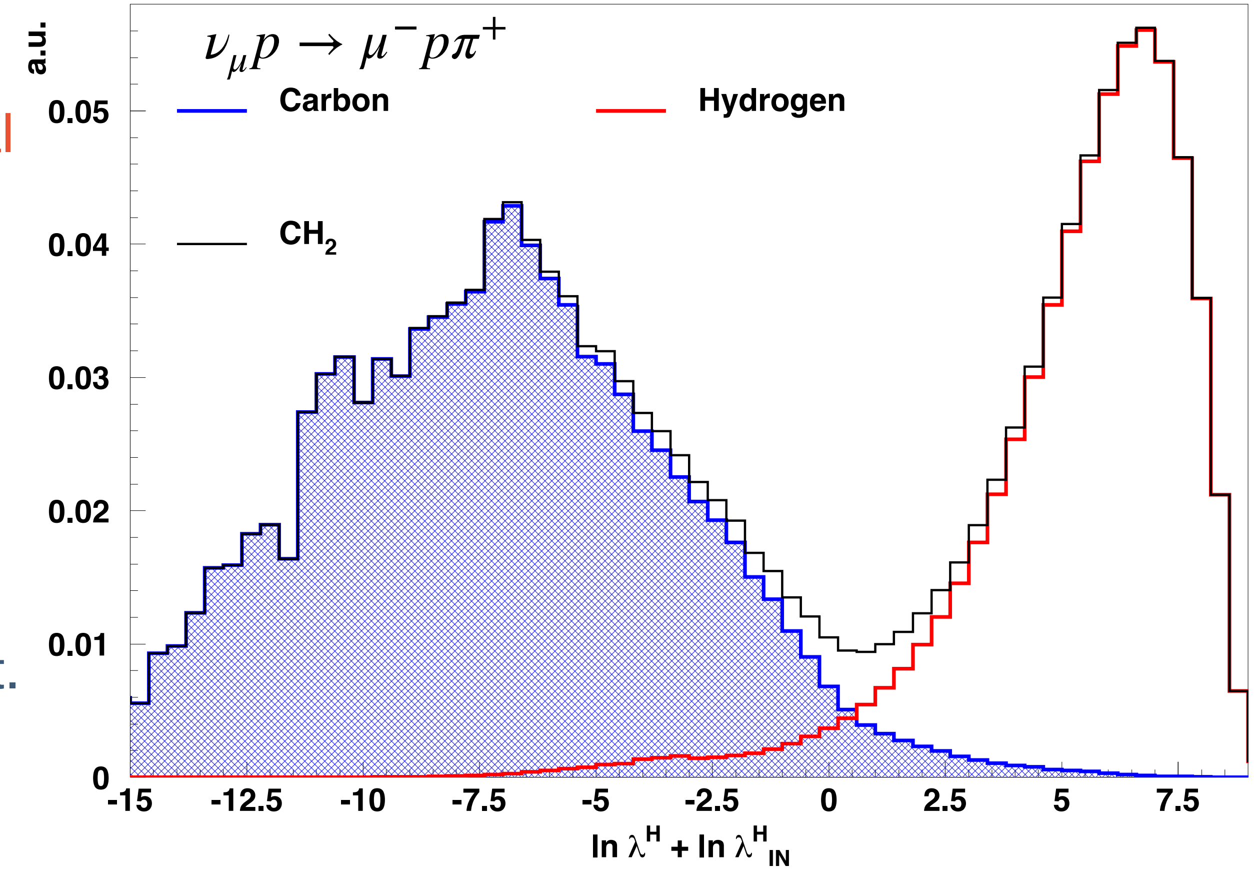
Solid hydrogen concept

The modular design of the STT offers the opportunity to extract $\bar{\nu}/\nu$ interactions on hydrogen (H) by the **subtraction** of samples interacting on the **polypropylene (CH_2)** and **graphite** (C) targets.

ν-H interactions are free from nuclear effects and final state interactions.

1. **Kinematic variables** can then be used to select interactions using a multi-dimensional likelihood function.
2. The **residual** C backgrounds are subtracted with data-driven procedure, thanks to the graphite target.



"A precise determination of (anti)neutrino fluxes with (anti)neutrino-hydrogen interactions."

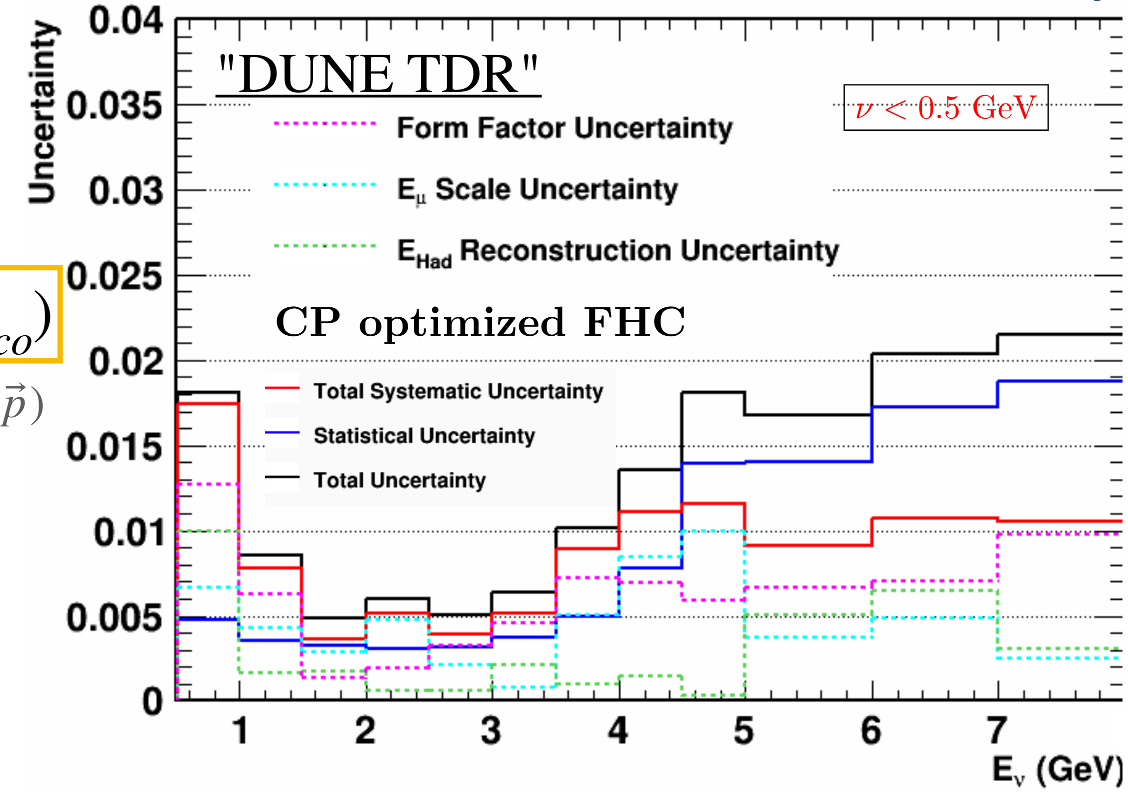
Use cases:
Cross-section and nuclear effects systematic uncertainties control.
Flux measurements.

Flux measurements

The capability of SAND to identify and reconstruct different types of interactions will enable flux measurements, necessary to predict the FD rate.

$$N_{ND}^{\nu_\mu}(\mathrm{p}_{reco}) = \sum_i \boxed{\Phi_{\nu_\mu}(E_{true})} \cdot \boxed{\sigma^i_{\nu_\mu}(\mathrm{p}_{true})} \cdot \epsilon_{\nu_\mu}(\mathrm{p}_{true}) \cdot \boxed{R_i(\mathrm{p}_{true}; \mathrm{p}_{reco})}$$

i = interaction, $p = (E, \vec{p})$

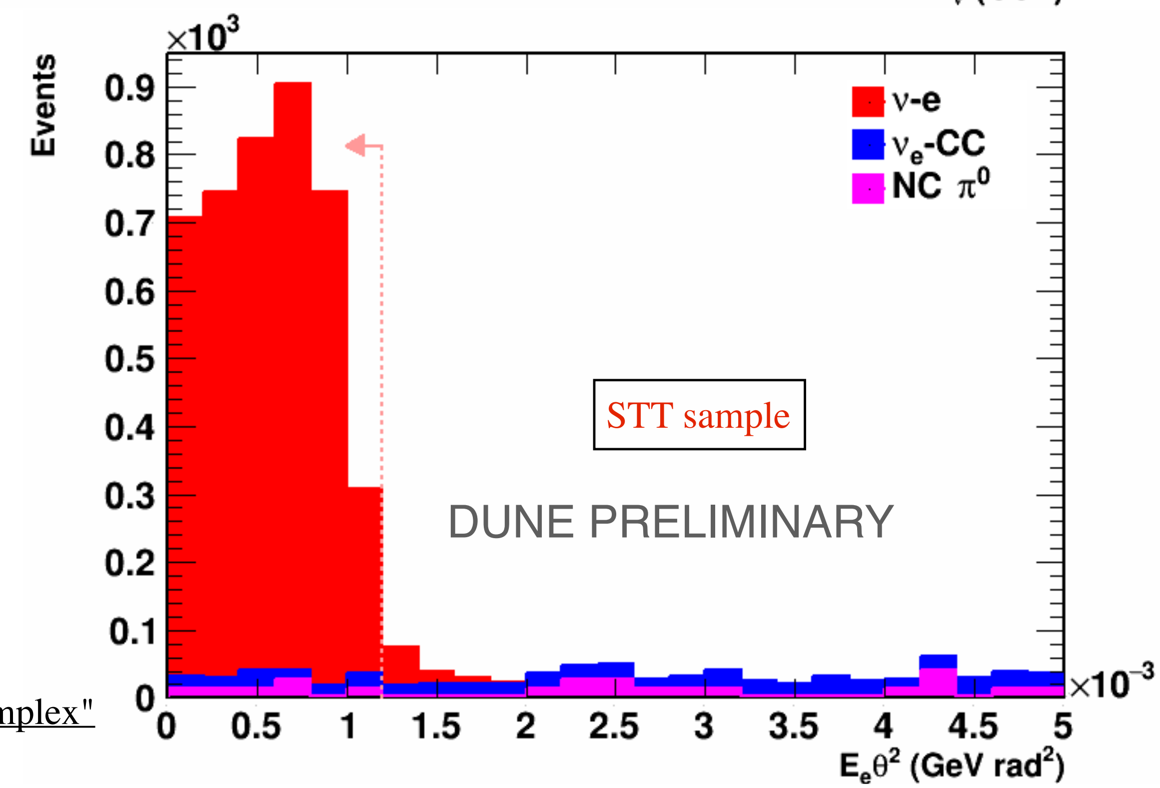


Absolute and relative **fluxes** with uncertainties < 1% using $\nu_\mu p \to \mu^- p \pi^+$ and $\bar{\nu}_\mu p \to \mu^+ n$ processes on **hydrogen**.

Clean selection with solid H technique

$R_i(\mathrm{p}_{true}; \mathrm{p}_{reco})$ without nuclear smearing

Flattening of cross section energy dependence in low energy region



Absolute $\nu e \to \nu e$ on **STT** and **GRAIN** for FHC and RHC modes.

"A Proposal to enhance the DUNE Near-Detector Complex"

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Constrain nuclear effects

Argon targets brings intrinsic limitations in oscillation analysis due to substantial **nuclear effects** which remain folded in $R_i(\mathrm{p}_{true};\mathrm{p}_{reco})$.

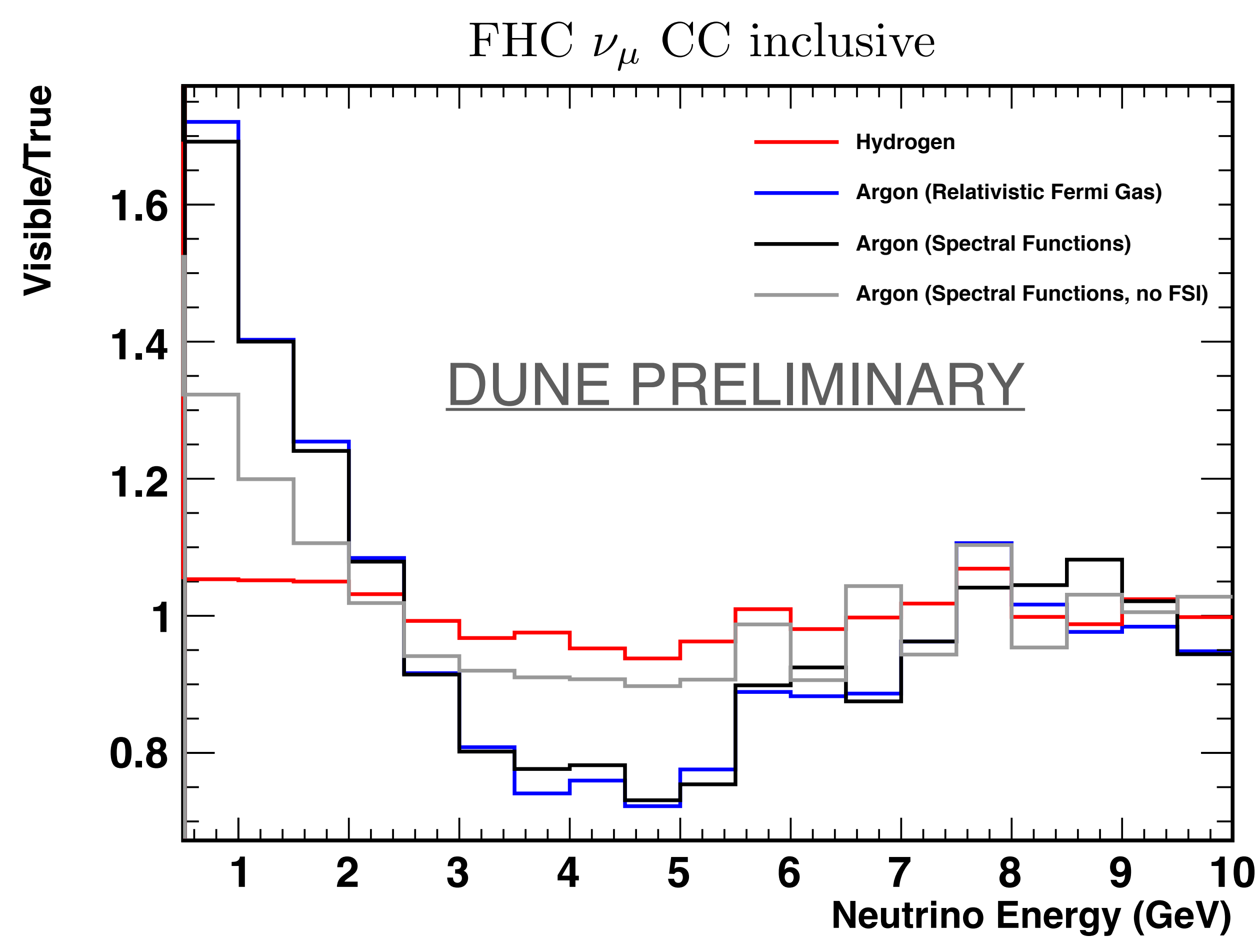
$$N_{ND}^{\nu_\mu}(\mathrm{p}_{reco}) = \sum_i \Phi_{\nu_\mu}(E_{true}) \cdot \sigma^i_{\nu_\mu}(\mathrm{p}_{true}) \cdot \epsilon_{\nu_\mu}(\mathrm{p}_{true}) \cdot R_i(\mathrm{p}_{true};\mathrm{p}_{reco})$$

i = interaction, $p = (E, \vec{p})$

$$R_i(\mathrm{p}_{true};\mathrm{p}_{reco}) = R_{phys} R_{det}(\mathrm{p}_{true};\mathrm{p}_{reco})$$

1% on H | Meas on H | R_{phys}=1 on H, R_{det} calibrated

- $\sigma^i_{\nu_\mu}(\mathrm{p}_{true}) \cdot R_{phys}(\mathrm{p}_{true};\mathrm{p}_{reco})$ on **Ar** can be constrained from **Ar - H** comparison.
- Results can then be compared with similar analyses of different targets in STT.



Conclusions

- DUNE will address exciting neutrino physics open questions with the conjunct work of near and far detectors.
- SAND sub-detectors in combination with the other ND allows for high resolution particle identification and reconstruction for neutrino interactions.
- SAND is an excellent beam monitor for changes that would impact long-baseline measurements.
- Solid Hydrogen measurements will allow for a significant reduction of the systematics due to neutrino-nucleus interactions.
- SAND will perform complementary measurements of both the normalisation and energy dependence of the flux.

Thank you for your attention!