Reconstruction of neutrino interactions in SAND with an innovative liquid argon imaging detector

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for the DUNE Collaboration

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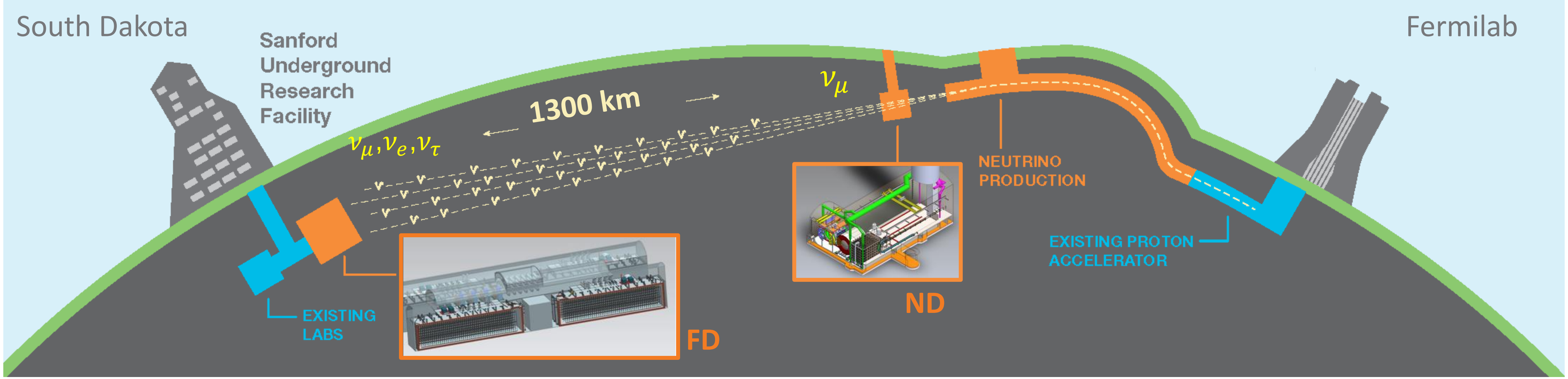
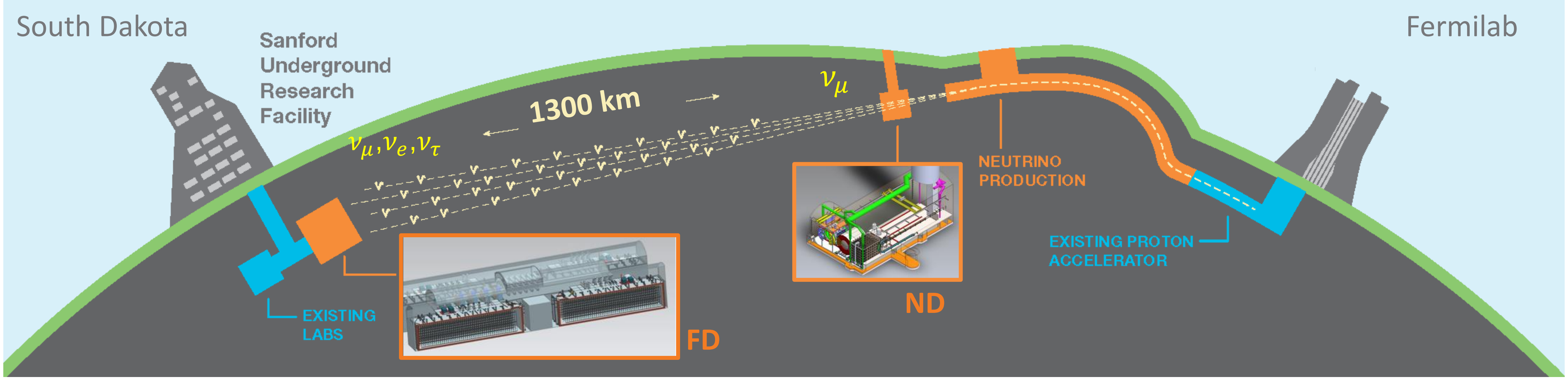
DUNE: Deep Underground Neutrino Experiment



- A new generation Long Baseline neutrino oscillation experiment
  - High precision measurements of the neutrino oscillation parameters: δ_{CP}, mass ordering, θ_{23}
  - Supernova and solar neutrinos detection
  - Beyond the Standard Model Searches

DUNE: Deep Underground Neutrino Experiment



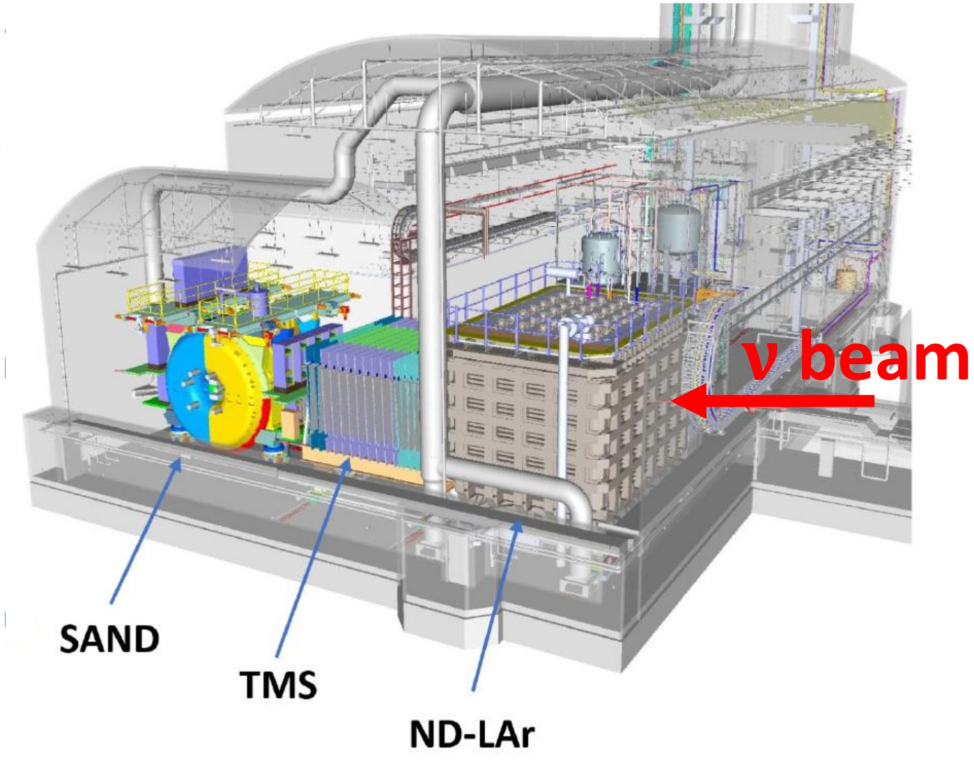
- An intense **wide band $\nu/\bar{\nu}$ neutrino beam** produced at Fermilab, peak flux at 2.5 GeV high intensity 1.2 MW ($1.1\ 10^{21}$ pot/year) upgradable to 2.4 MW
- Two neutrino detectors:
  - a **Far Detector (FD)** in South Dakota, 1.5 km underground and 1300 km away from neutrino source consisting of three Liquid Argon Time Projection Chamber (LArTPC) modules and a fourth module still under discussion, 17 kton each
  - a **Near Detector complex (ND)** at Fermilab

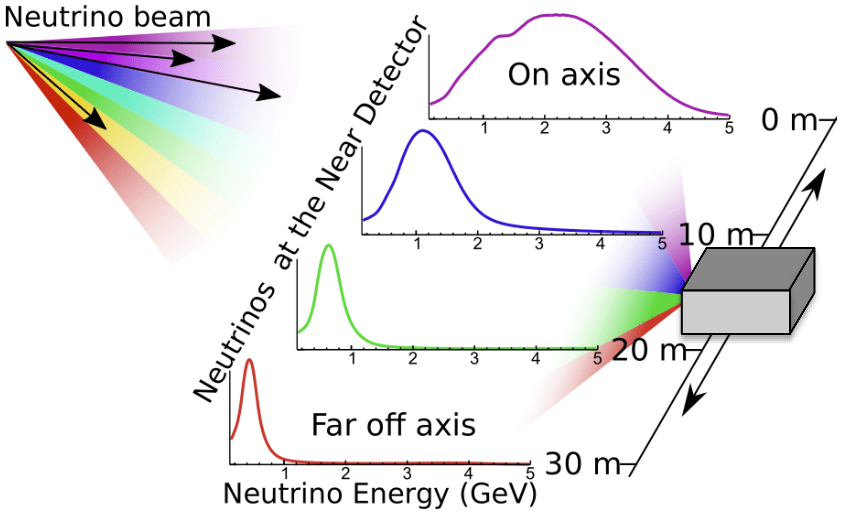
The Near Detector complex

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

- **ND LAr**: a 67 ton LArTPC
- **TMS**: The Muon Spectrometer
- **SAND**: System for on Axis Neutrino Detection - a magnetized multi-purpose detector

ND-LAr and TMS will move in order to "scan" over the spectrum of ν energies





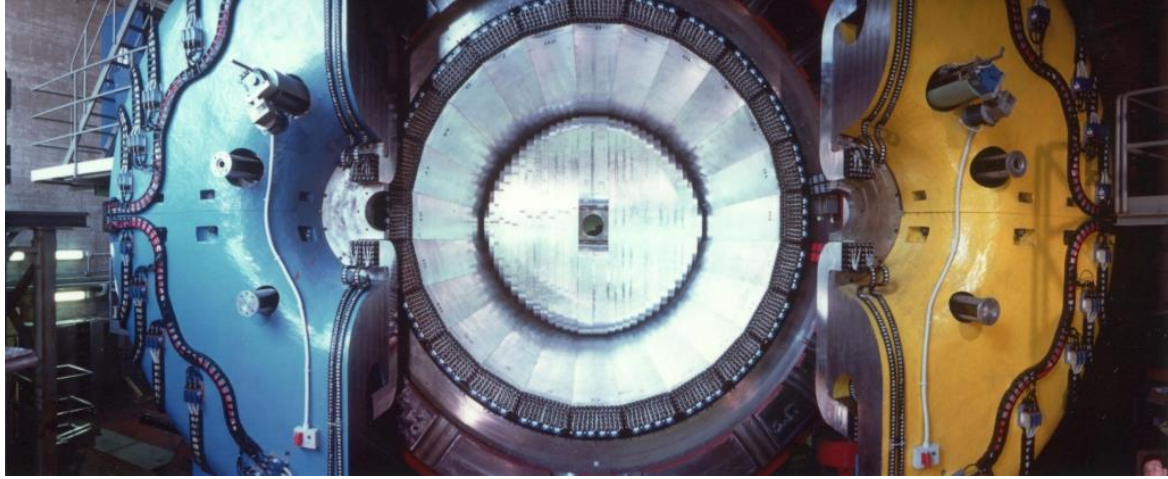
SAND

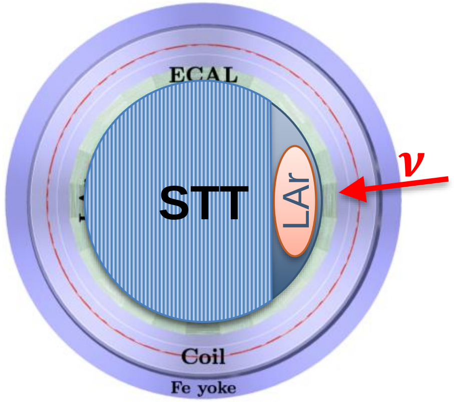
The only component of the ND that will be permanently located **on-axis.** SAND consists of:

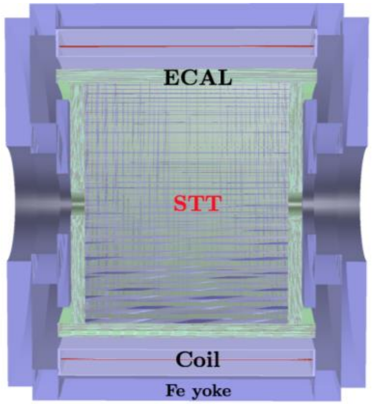
- **Superconducting magnet**
- **Electromagnetic Calorimeter (ECAL)** } (formerly KLOE)
- **Straw-Tube-Tracker and CH_2, C target**
- **1-ton LAr Active target (GRAIN)**

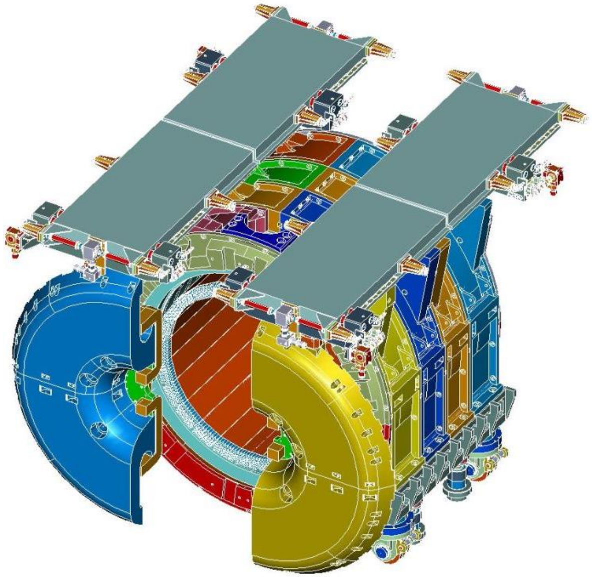
It aims at:

- Monitoring of the on-axis ν spectrum to detect beam variations on a weekly basis
- Flux measurements and characterization for both ν_e and ν_μ
- Cross-section measurements on different nuclear targets to constraint systematic effect from nuclear effects
- Exploit the unprecedented high statistics to perform a rich physics program besides oscillations







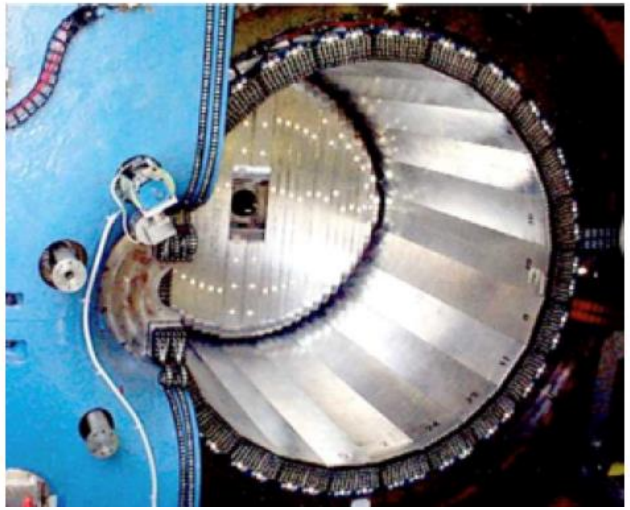


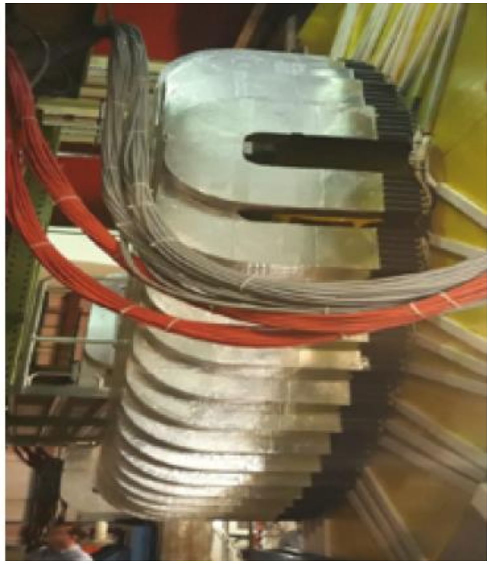
SAND – ECAL and STT

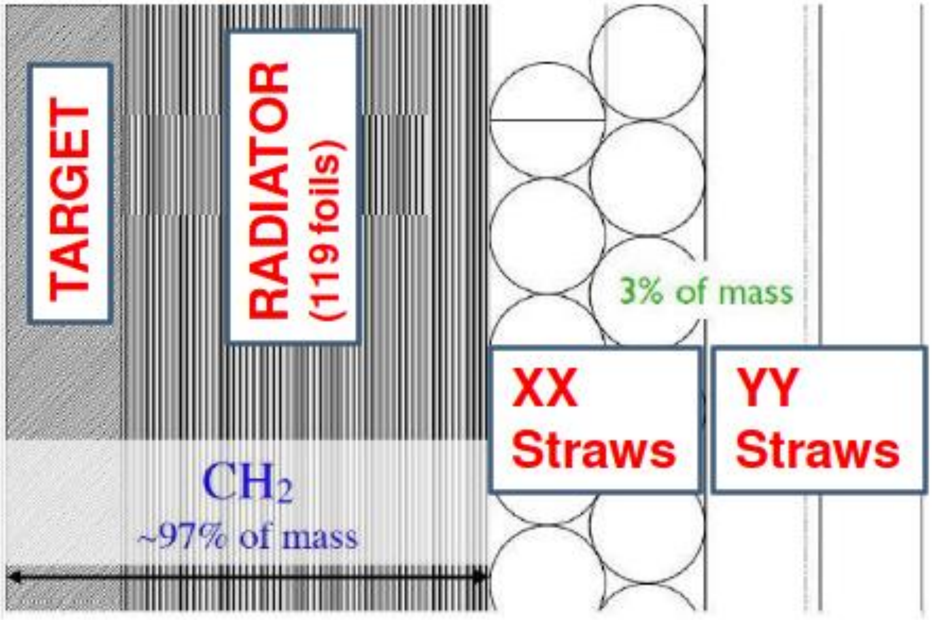
- Electromagnetic calorimeter: lead and scintillating fiber sampling calorimeter
  - 24 modules, 4.3 m long, 23 cm barrel + endcap
  - 4880 PMTs, ~ 4 π coverage, ~ 15 X0
  - Energy resolution: $\boldsymbol{\sigma/E = 5.7\%/\sqrt{E(GeV)}}$
  - time resolution: $\boldsymbol{\sigma = 54/\sqrt{E(GeV)}\,ps}$

- The tracker is made of Straw Tubes and passive target:
  - 90 modules with planes of 5 mm diameter straw tube (Xe/CO2 gas at 1.9 atm) arranged in XXYY layers
  - Radiator of polypropylene foils and a target (CH2, C,

- The STT design provides accurate **control of configuration, chemical composition, and mass**







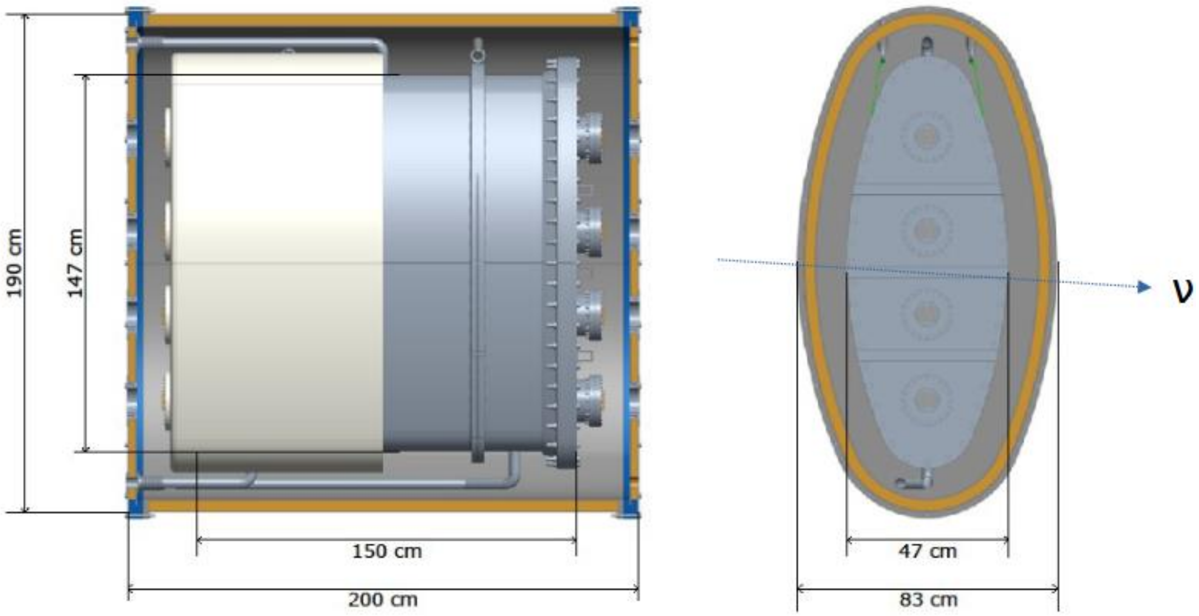
SAND – GRAIN

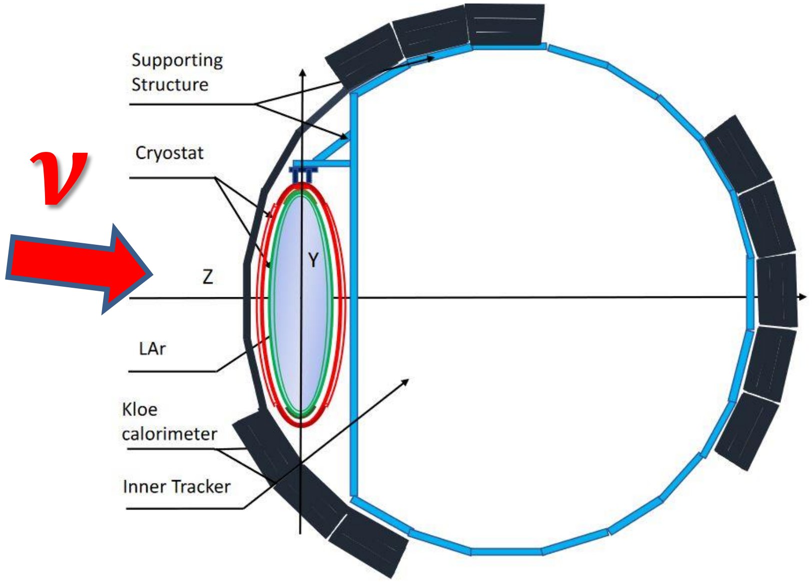
The upstream part of SAND will be instrumented with **1-ton LAr active target**: GRAIN (GRanular Argon for Interaction of Neutrinos)

- Outer vacuum vessel made of C-composite material
- Inner vesser containing the LAr made of Al.
- The overall radation length is ~1 X_0

Its role is **constraining nuclear effects on argon** and have **a complementary Ar target permanently located on-axis** for cross-calibration.

It will exploit an innovative technique to replace the TPC.



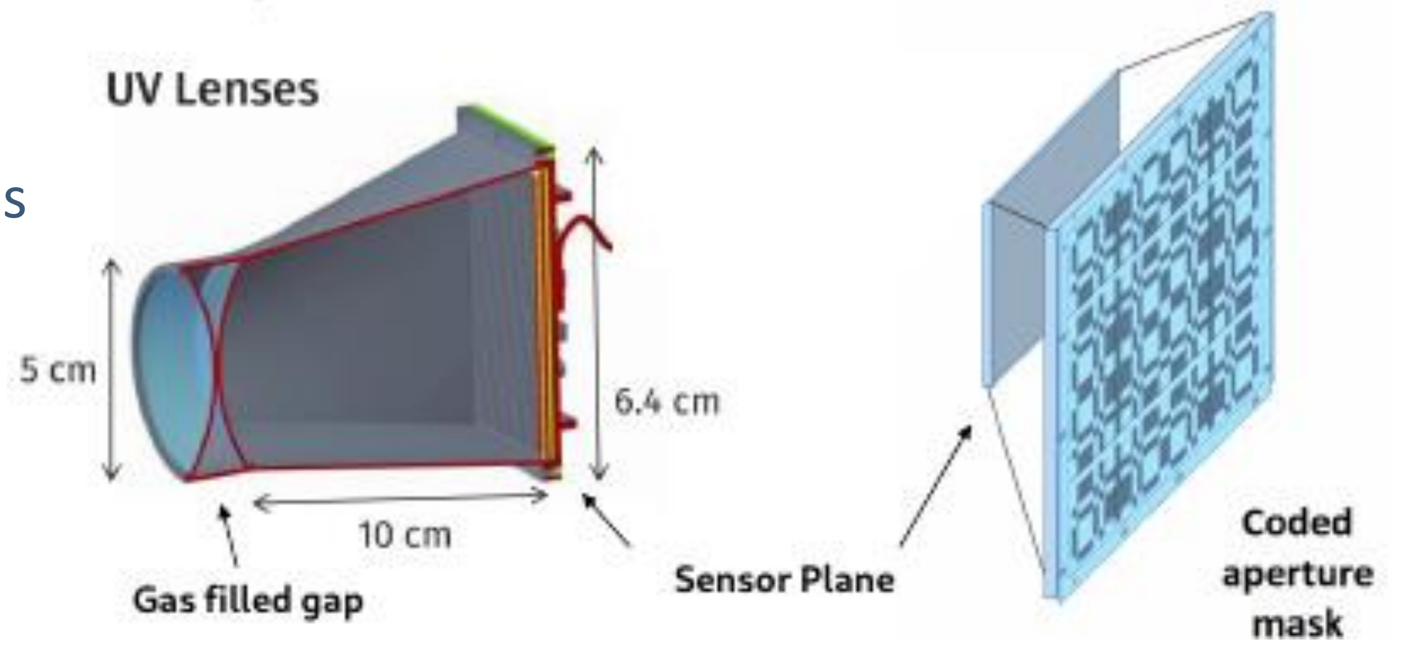


GRAIN – Optical Reconstruction

Equip GRAIN with an imaging device able to collect the scintillation light and perform a fast reconstruction of the events without collecting the charge.

Why

- High rate capability
- Possibility to work in magnetic fields
- Reduced electronic noise

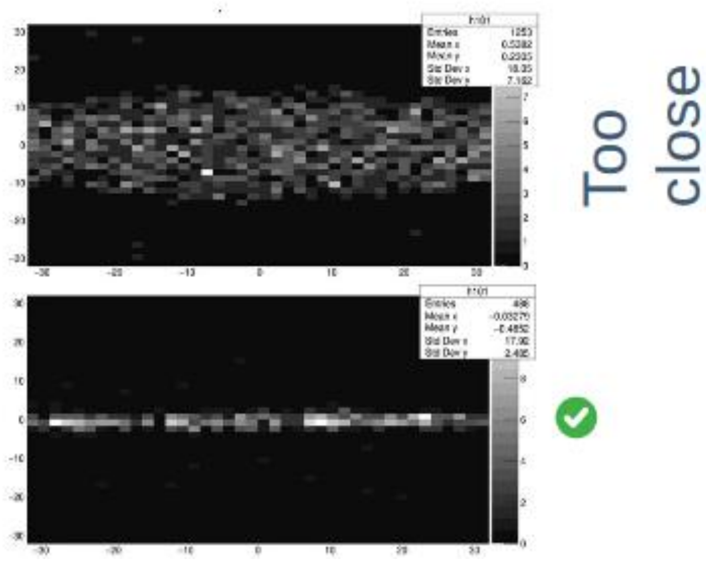


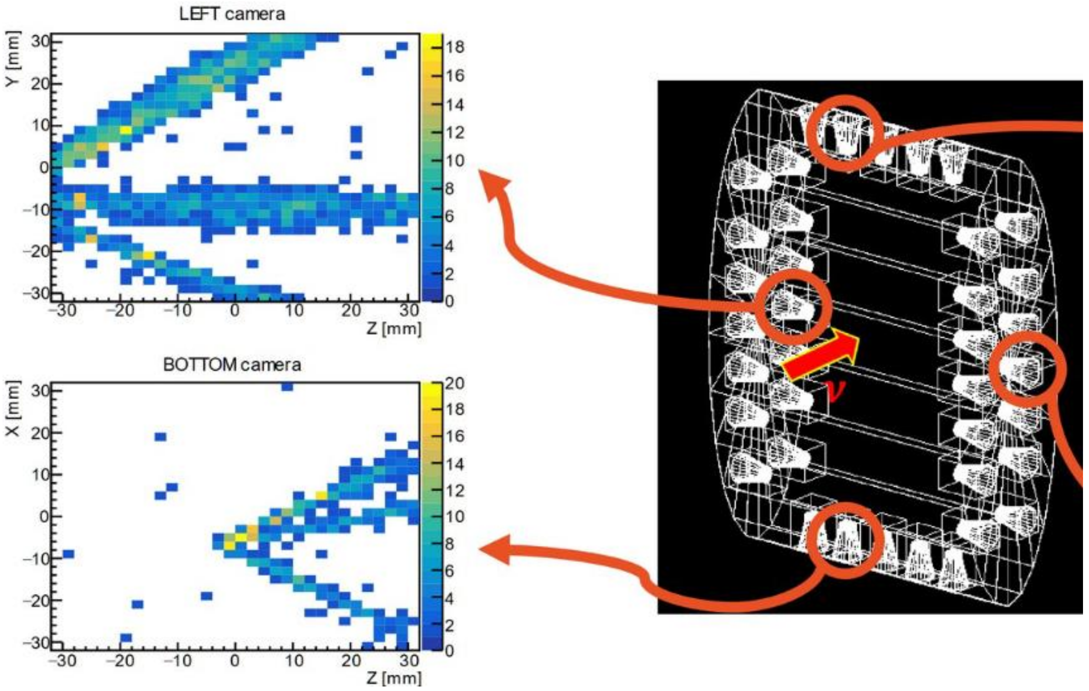
How

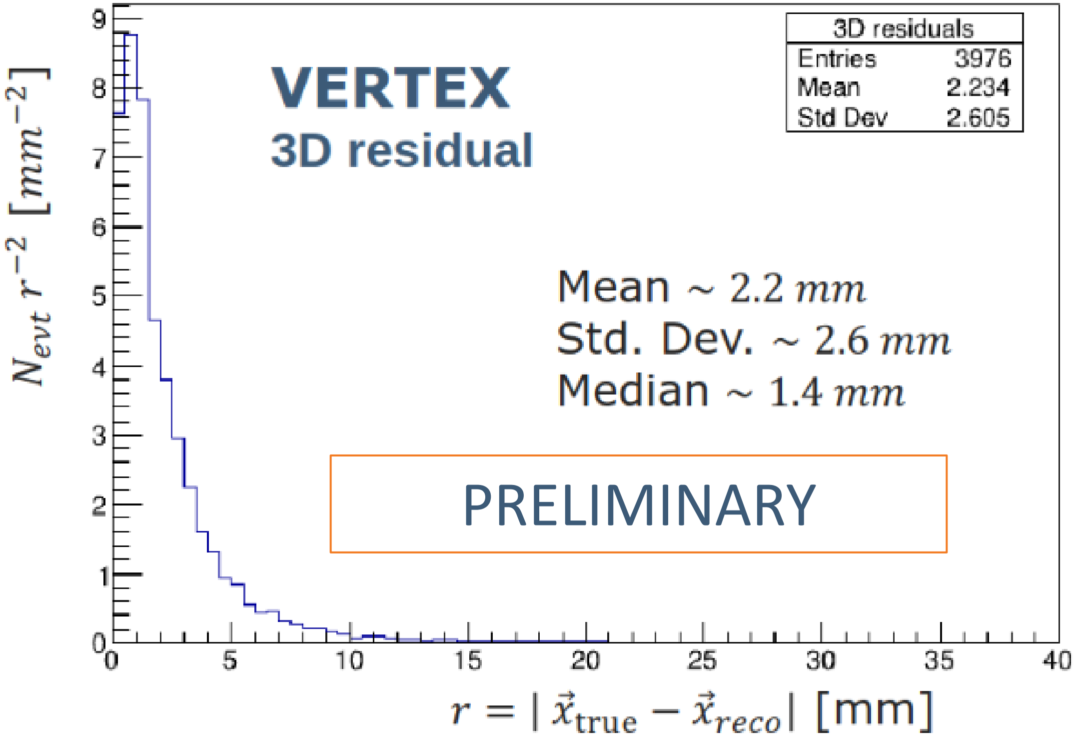
- SiPM matrix
- UV gas-filled lenses
- Coded Aperture masks

GRAIN – Gas Lens Cameras

- Inverted lens with gas-filled gap (N2) with n = 1
- Excellent resolution from simulation
- Limited depth of field
- Xe doping to shift the λ in a range with better transmission through lenses



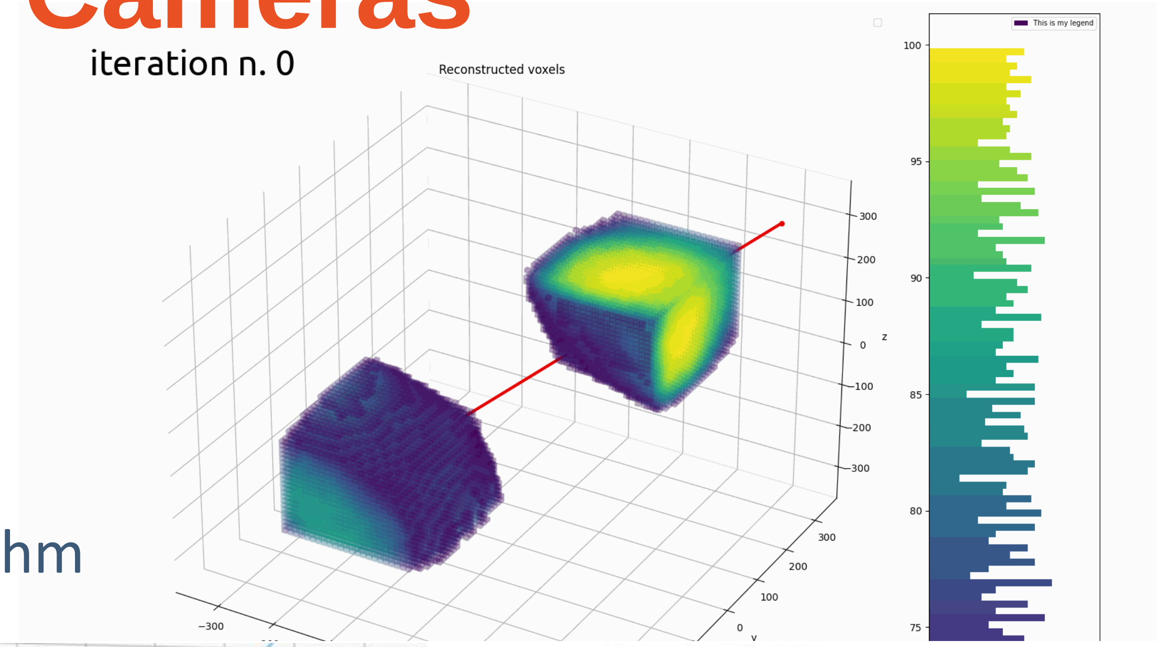


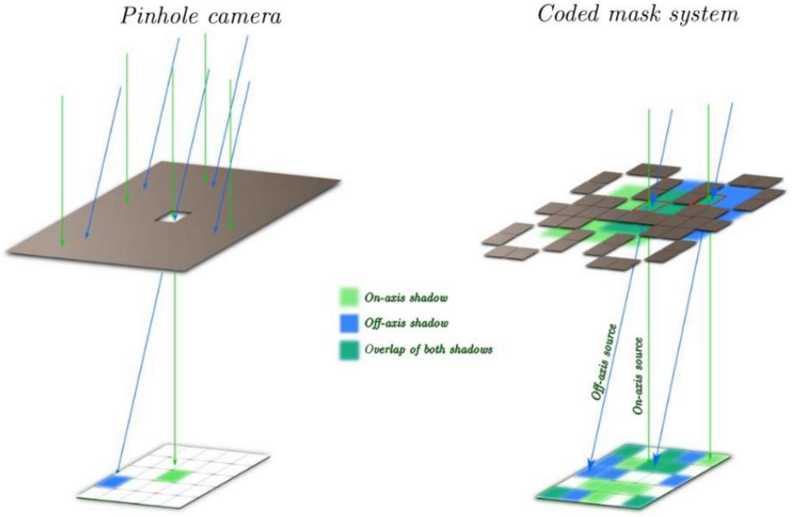


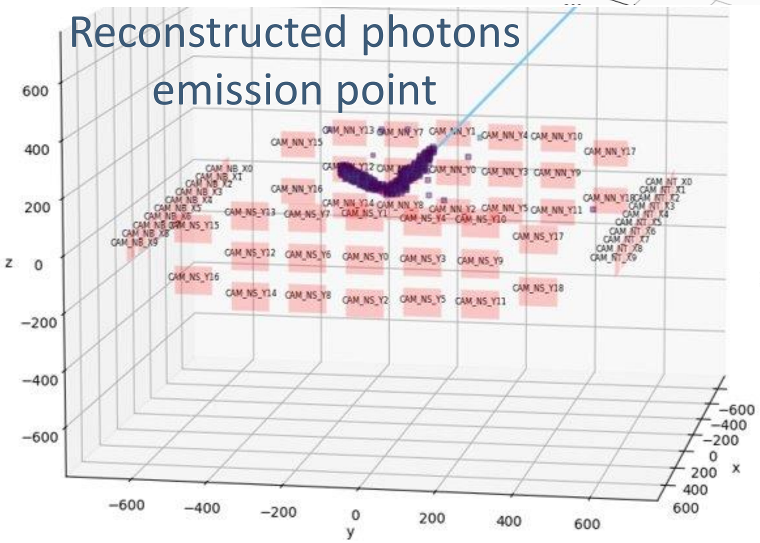
GRAIN – Coded Aperture Cameras

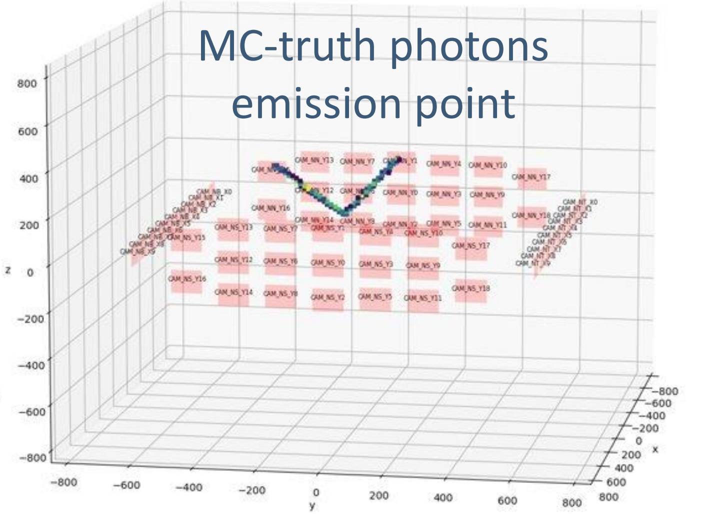
Alternative to traditional optical system used to avoid issues with argon λ and n.

- Compact and easy to build (extension of the pinhole camera)
- Good depth of field
- Worse resolution than lenses
- Computationally heavy reconstruction algorithm









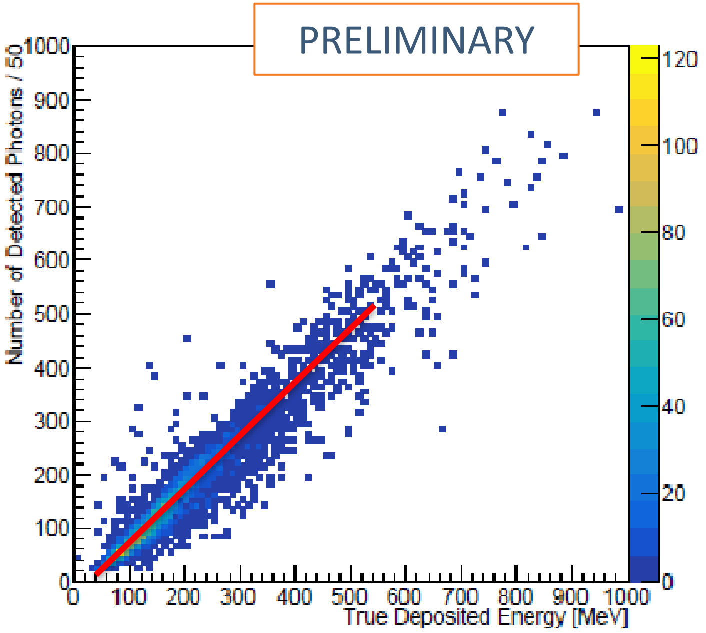
GRAIN – Calorimetric Measurements

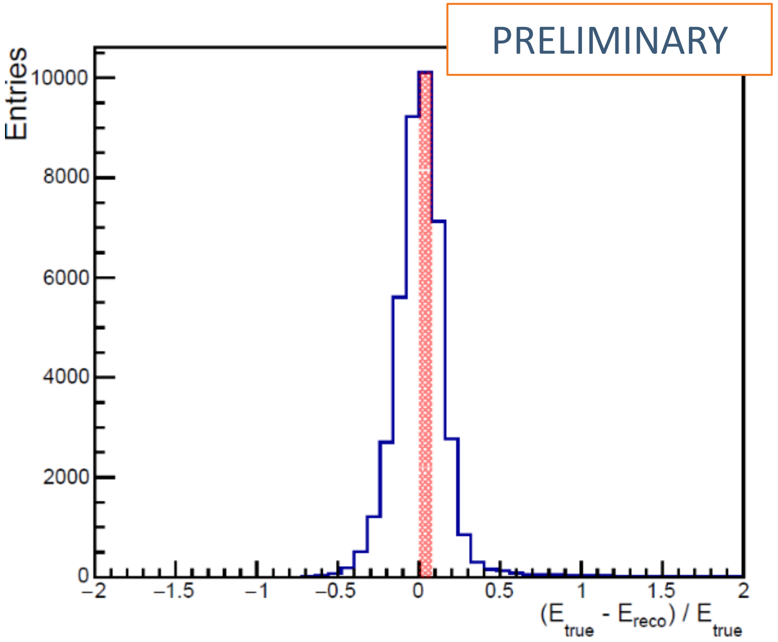
Calorimetric reconstruction in grain is possible by **exploiting the collected light on all the sensor planes**.

- A **calibration coefficient** must be obtained to convert the **collected light signal in deposited energy** by all the particles in GRAIN

- Calibration coefficient has **dependency on location, particle, camera arrangement, interaction type**
  - Multiple calibration coefficients could be needed

First coefficient obtained for the $Ar + \nu_\mu \rightarrow \mu^- + p + X$ interaction channel



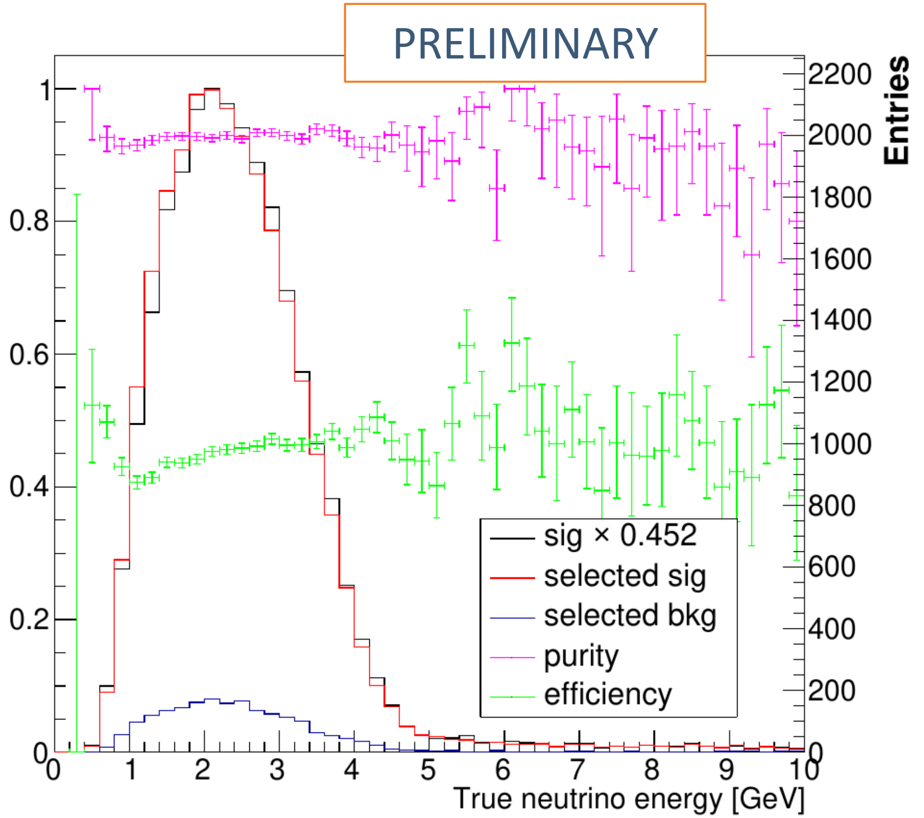


$Ar + \nu_\mu \rightarrow \mu^- + p + X$ selection

STT selection
Only one muon and one proton tracks reconstructed in STT fiducial volume (4+ hits in the STT)

ECAL selection
No unmatched clusters

GRAIN selection
Reconstructed energy in GRAIN compatible with the mean energy release expected by muon and a proton in GRAIN (from MC).



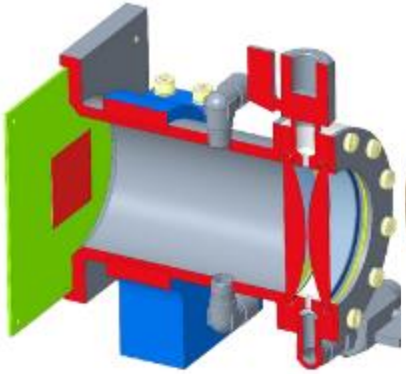
CCQE – like events are selected with efficiency > 45% and Purity > 90%

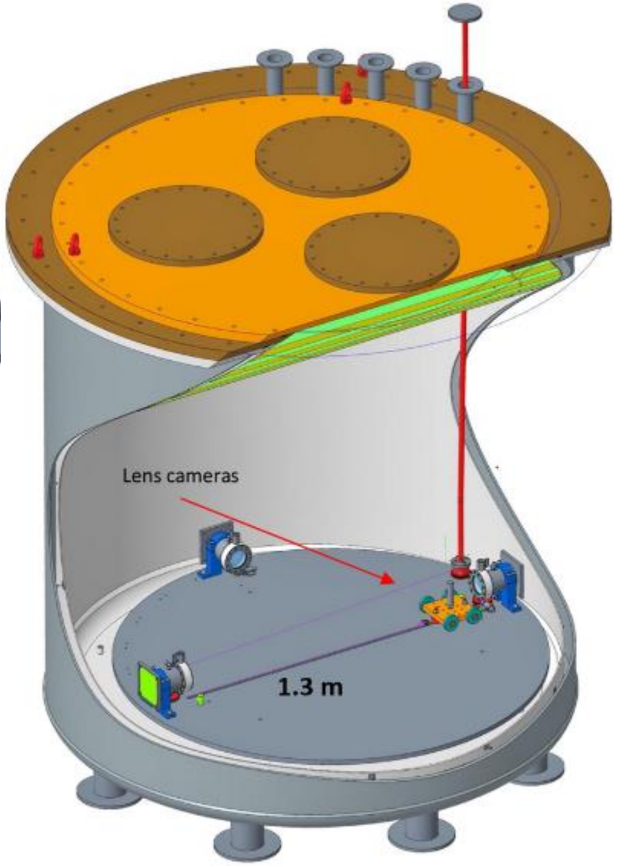
Selection of a single mu and p is expected to improve as soon as GRAIN track reconstruction is finalized.

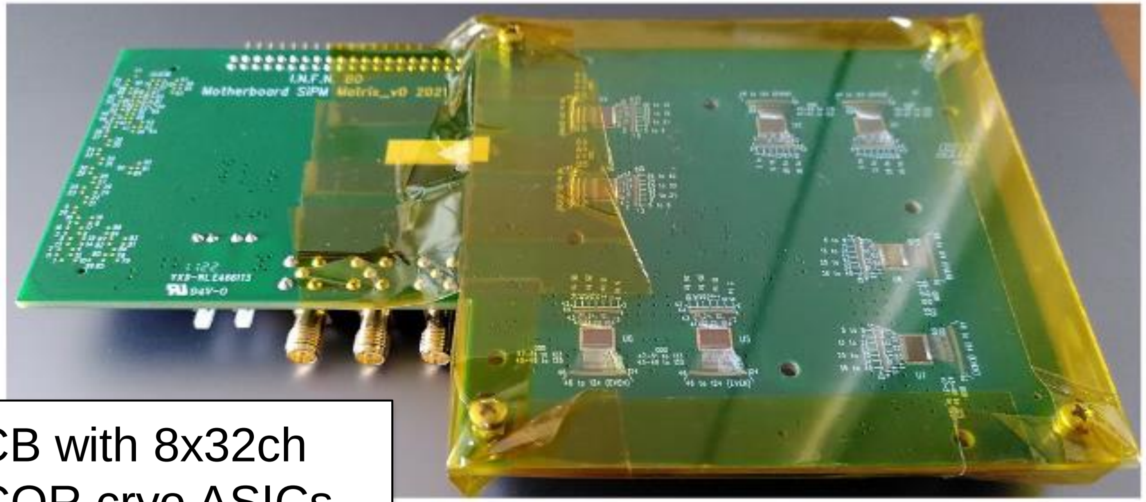
Hardware development

Ongoing activities on two facilities from GRAIN related R&D

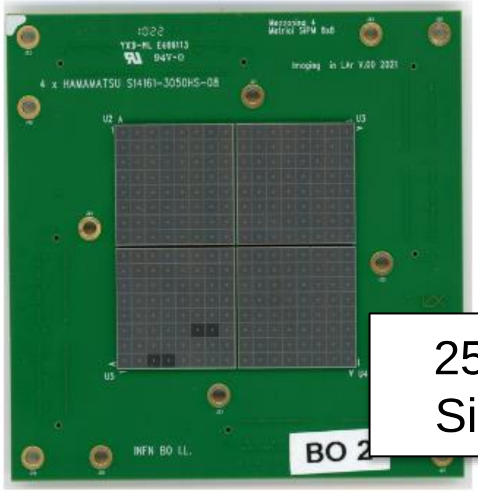
- **Artic in Genoa**, 1 ton LAr cryostat for studies on sensor performance, starting soon
- **Integration facility in LNL**, for vacuum integration studies. It'll host an inner vessel prototype, currently in design phase







PCB with 8x32ch ALCOR cryo ASICs



256 channel SiPM matrix

Conclusions

- SAND will **monitor and characterize** the neutrino beam while also performing **rich physics program besides oscillations**

- It will include an **innovative detector** (GRAIN) which will **exploit the argon scintillation light** to perform track and energy reconstructions.

- Two optical systems are being developed**: lens- and coded aperture-based cameras**

- GRAIN physics case has been addressed studying the performance of SAND (w/GRAIN) in selecting and reconstructing $\mu^- + p$ channel:
    - **Efficiency > 45% and Purity > 90%**

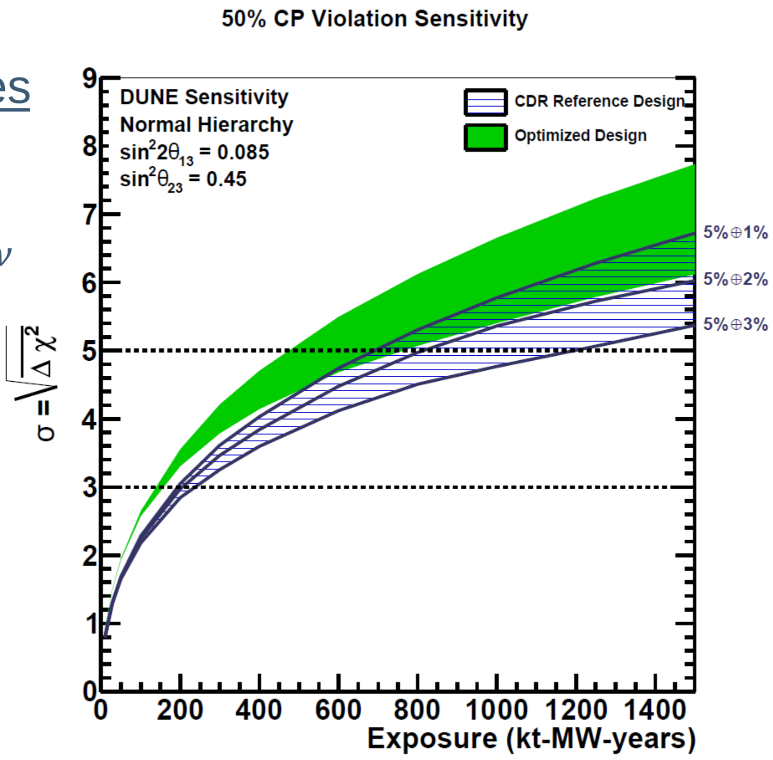
- Cryo demonstrator with 3x256 pixel cameras almost ready
- Cameras and ASIC with 1024 pixel under development
- **On track to be ready for first beams by 2029-30**

The Near Detector physics goals

DUNE ND CDR
arXiv:1512.06148

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

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



To predict the expected oscillating ν_μ and ν_e spectra at FD the measurements done at ND must be propagated to FD.

Existing systematic uncertainties on modeling of cross section, nuclear effects and fluxes are not consistent with the precision required by DUNE (<2-3%).

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 $\sigma_X(E_\nu)$ and calibrate detector response R_{det} → same Ar target as FD
- constrain nuclear effects R_{phys} → using both Ar and lighter targets

SAND – Reconstructions

STT

Digitization of signal as smearing of 200 um of the Montecarlo hits

Minimum of 4 hits in STT required to reconstruct the tracks

Reconstructed momentum from Gluckestern formula

ECAL

Digitization of the signal includes light attenuation, photo-electrons production, position of the hits in the detector

Iterative algorithm to cluster close hits

Energy, position, time, and direction extracted for each cluster

GRAIN

Deposited energy obtained from the total collected light exploiting the calibration coefficient

GRAIN – Optical Reconstruction

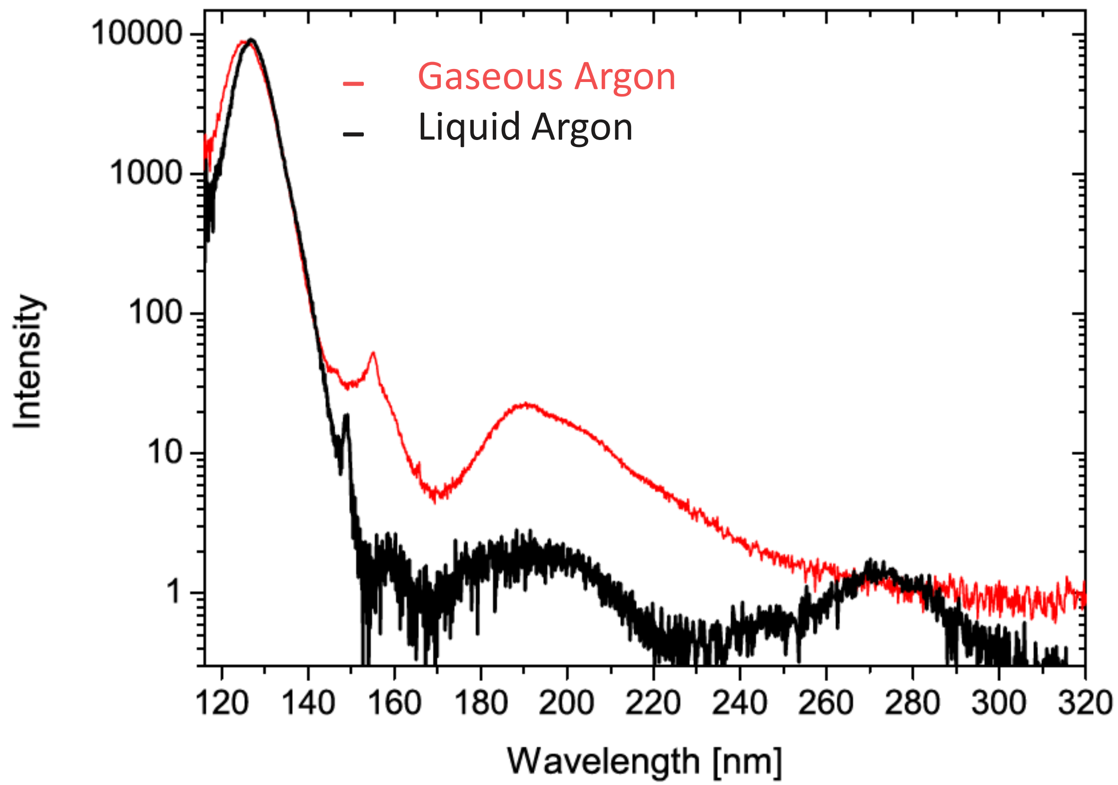
Equip GRAIN with an imaging device able to collect the scintillation light and perform a fast reconstruction of the events without collecting the charge.

What we need

- An optical system
- A sensor plane
- A readout chip

Why is difficult

- Argon emits in the VUV range
- Argon *n*
- Cryogenic temperatures



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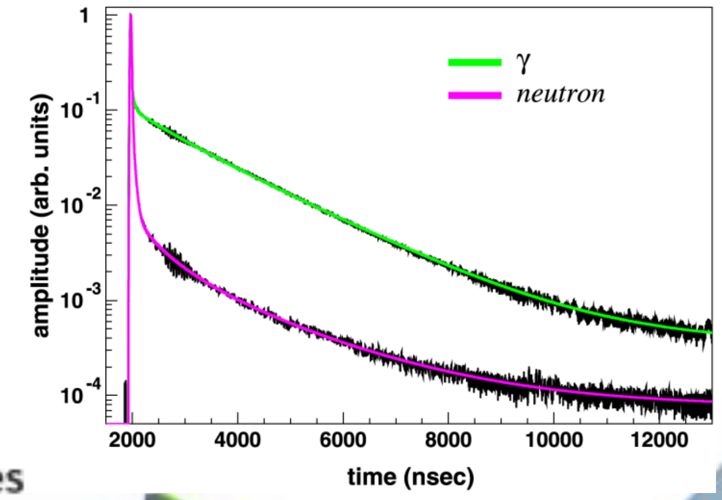
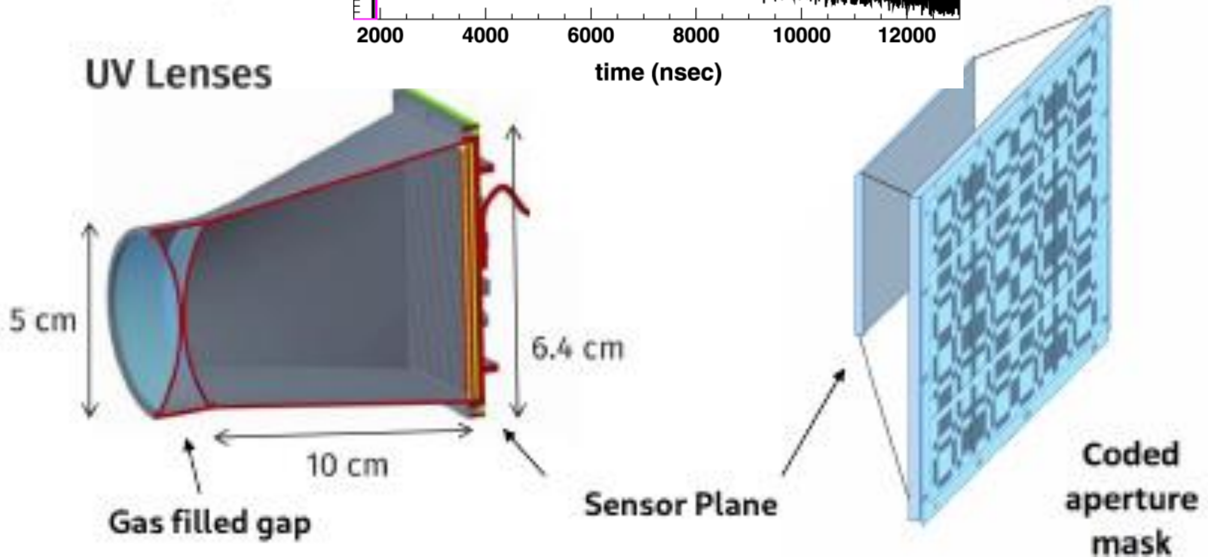


What do we get

- High rate capability
- Possibility to work in magnetic fields
- Reduced electronic noise

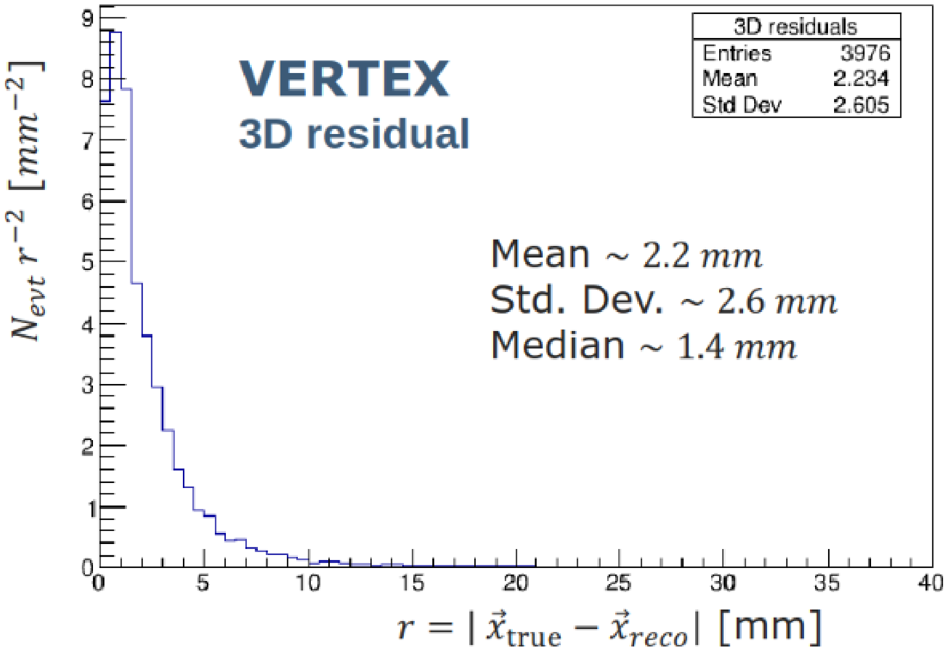
What can we use

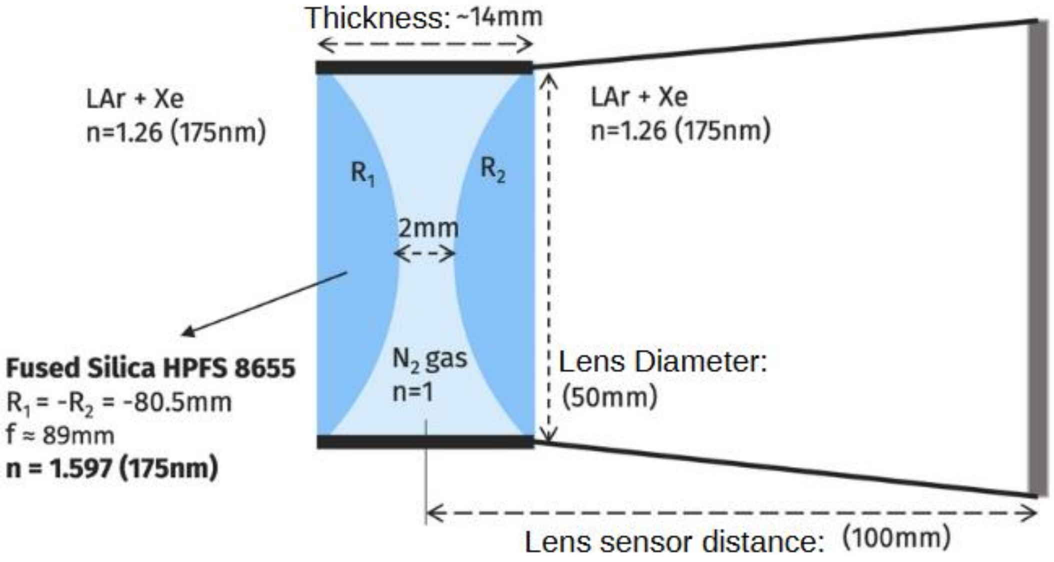
- UV gas-filled lenses
- Coded Aperture masks



GRAIN – Gas Lens Cameras

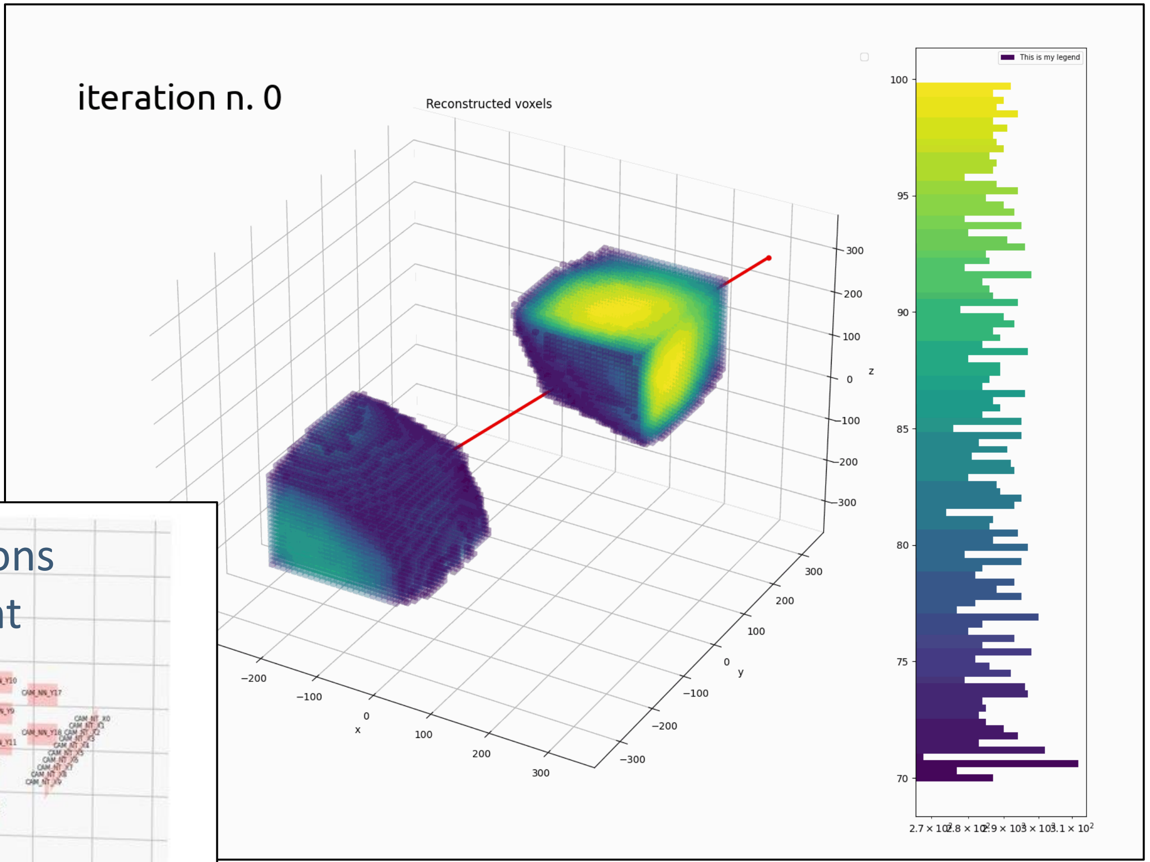
- Images from single views can be fitted and the full event reconstructed exploiting projection matrix-based methods.
- Limited depth of field
- Excellent resolution from simulation

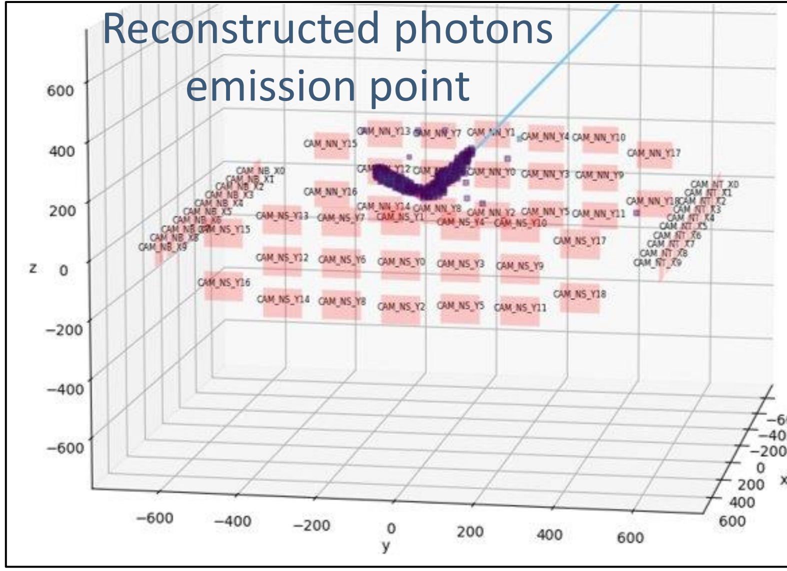


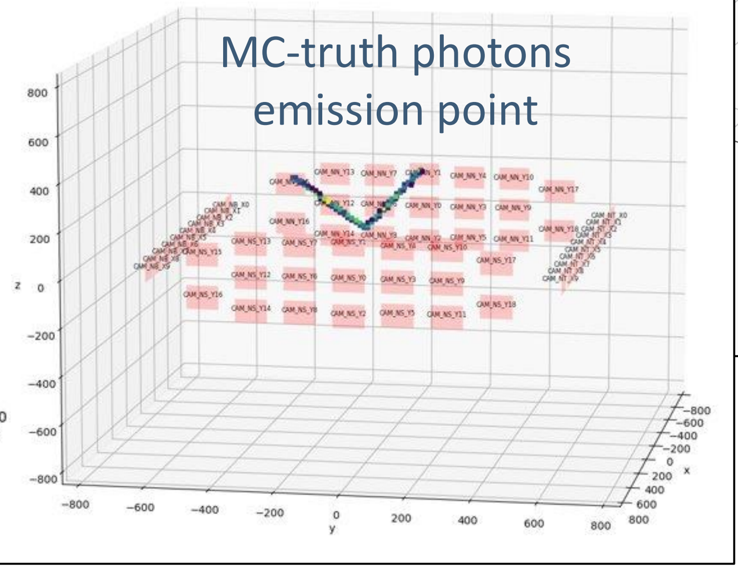


GRAIN – Coded Aperture Cameras

- Maximum Likelihood Expectation Maximization algorithm
- Iterative algorithm converges towards the correct solution
- Computationally expensive (about 3 s/iteration), needs GPUs and lots of RAM (hundreds of Gb)







Beam monitoring capability

- Beam is monitored by measuring variations of ν_μCC interaction **energy spectrum** and event **distribution in space**
- Sensitivity is evaluated comparing the distribution of reconstructed neutrino energy expected from nominal (N_i^{norm}) and altered (N_i^{alt}) beam using the **test statistic T**:

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

1 week data taking

Proton beam parameter	1σ deviation as given by beam group	New $\sqrt{\Delta\chi^2(E_\nu)}$ true	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 has enough sensitivity** ($\sqrt{\Delta\chi^2} > 3$) to detect **most of beam variations** in **one week.**
  Cases with less sensitivity don't contribute significantly to the beam spectrum

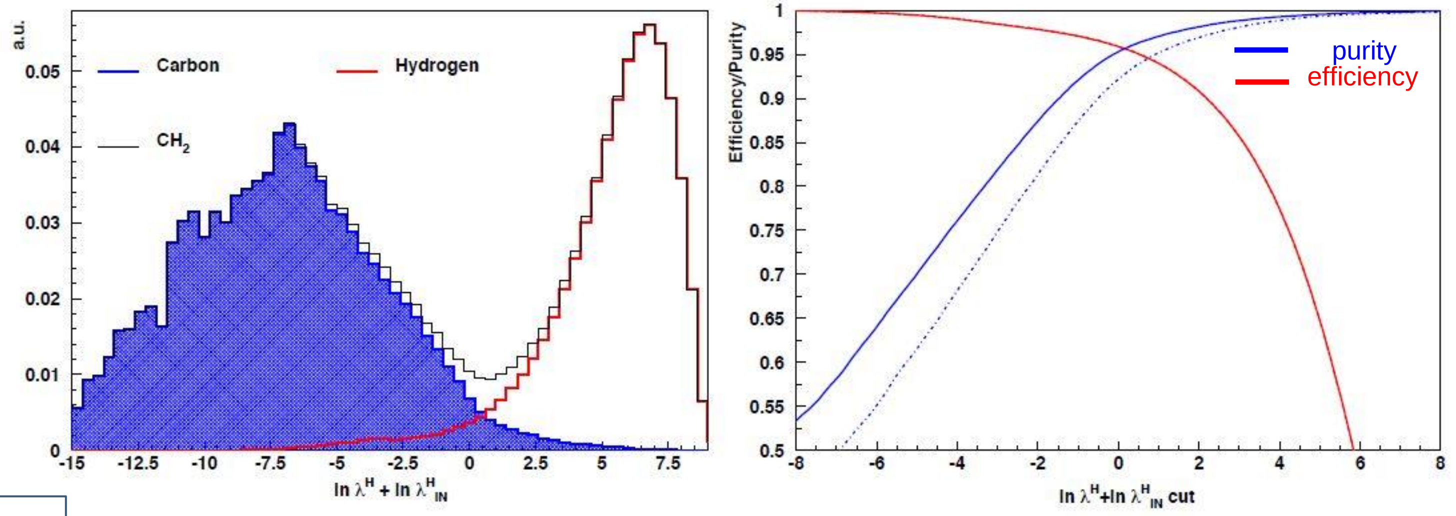
SAND physics program - “solid” hydrogen concept

STT provides a **compact modular layout** with a flexible design to control configurations, chemical composition and mass of neutrino targets similar to $e^{\pm}$ DIS experiments

“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 $(\overline{\nu})$ CC **interactions on H** by a kinematic analysis

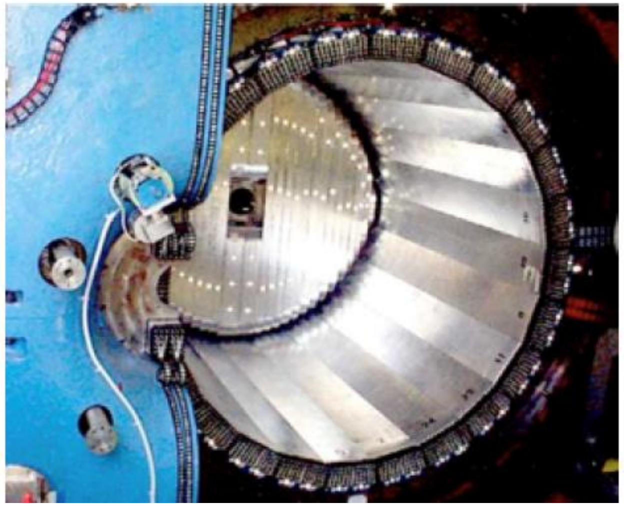


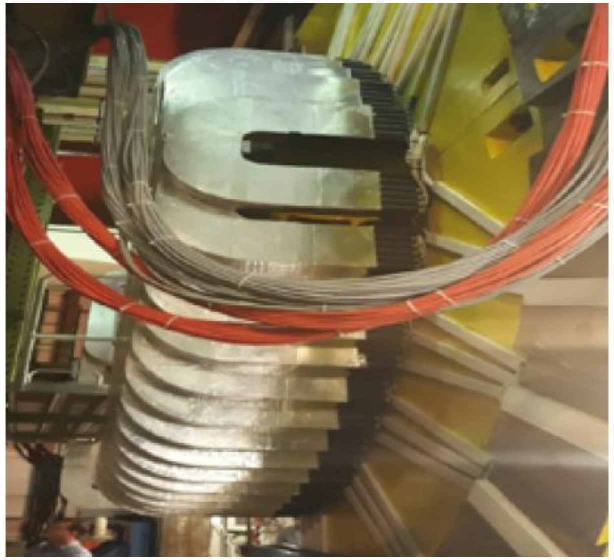
Keep under control systematic uncertainties:
- Flux measurements
- Constrain models on nuclear effects

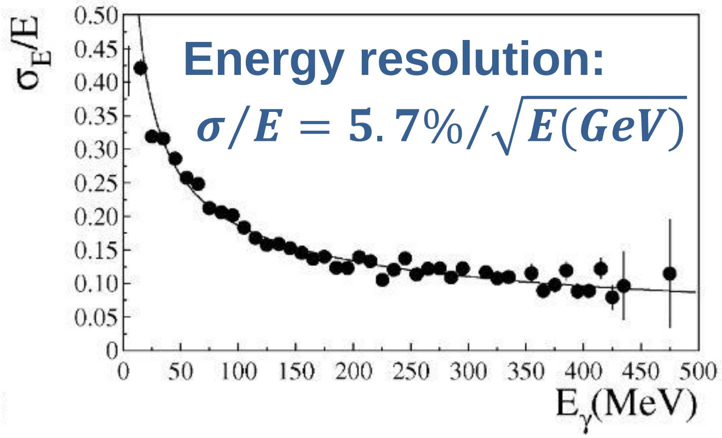
Likelihood function incorporating multi-dimensional correlations among kinematic variables to separate C and H samples

SAND – Magnet and ECAL

- Electromagnetic calorimeter: lead and scintillating fiber sampling calorimeter
  - 24 modules, 4.3 m long, 23 cm barrel + endcap
  - 4880 PMTs
  - ~ 4 π coverage
  - ~ 15 X0







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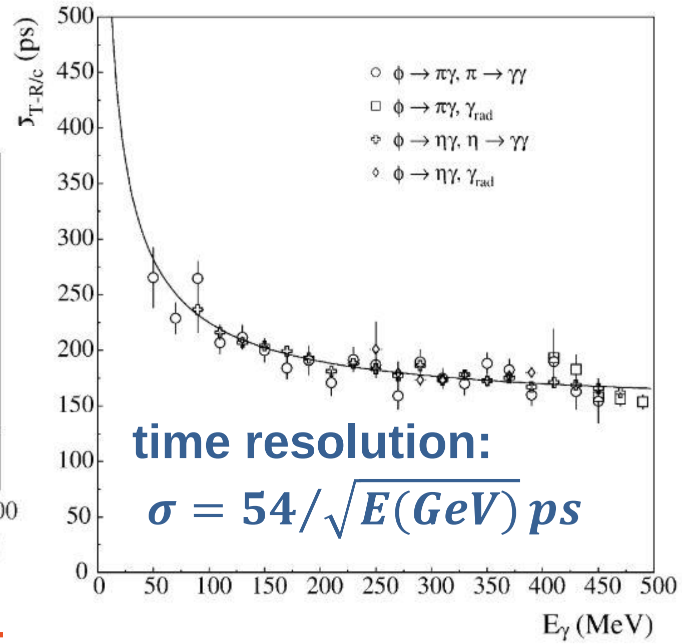


- Magnet:
  - superconducting coil, 0.6 T over a 4.3 m long, 4.8 m diameter volume
  - mass: 475 tons

SAND – STT

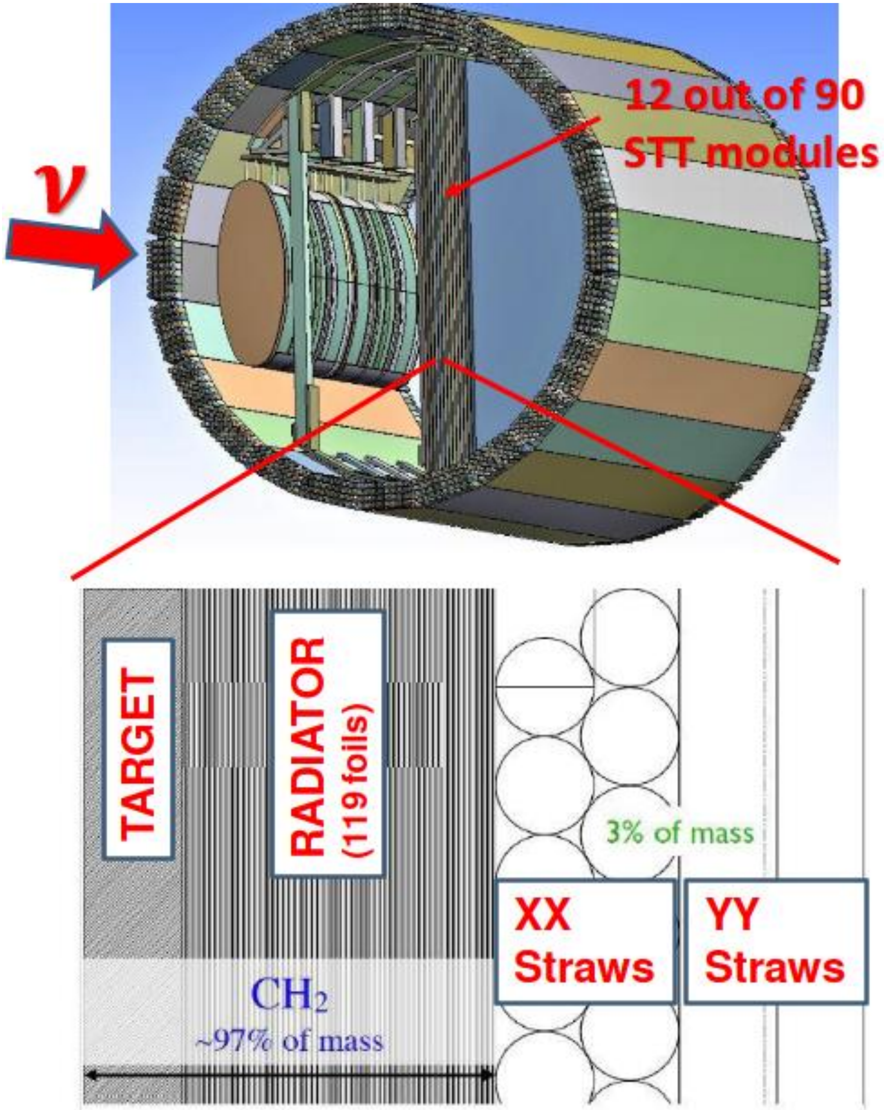
The internal magnetized volume of SAND will be instrumented with an Inner Tracker to:

- separate neutrino and antineutrino events (charge ID),
- identify primary leptons (beam flavor composition),
- reconstruct event-by-event and all charged and neutral (π0, n) particles tracks

The tracker is made of Straw Tubes and passive target:

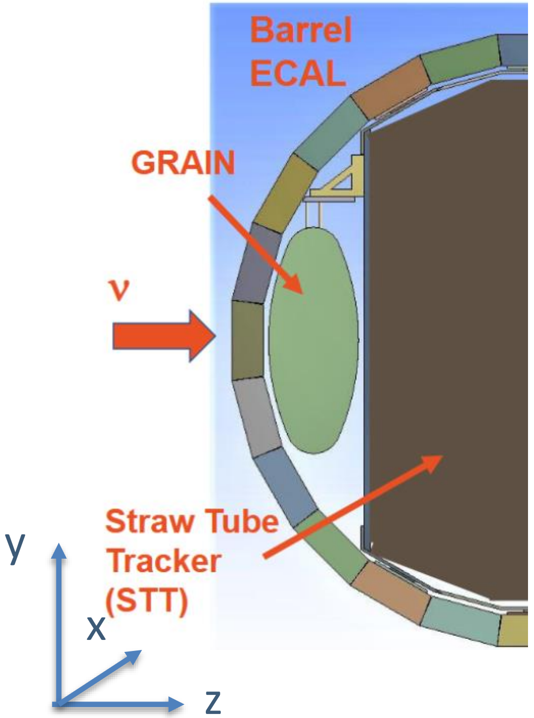
- 90 modules with planes of 5 mm diameter straw tubes (Xe/CO2 gas at 1.9 atm) arranged in XXYY layers
- Radiator of polypropylene foils and a target (CH2, C,...)

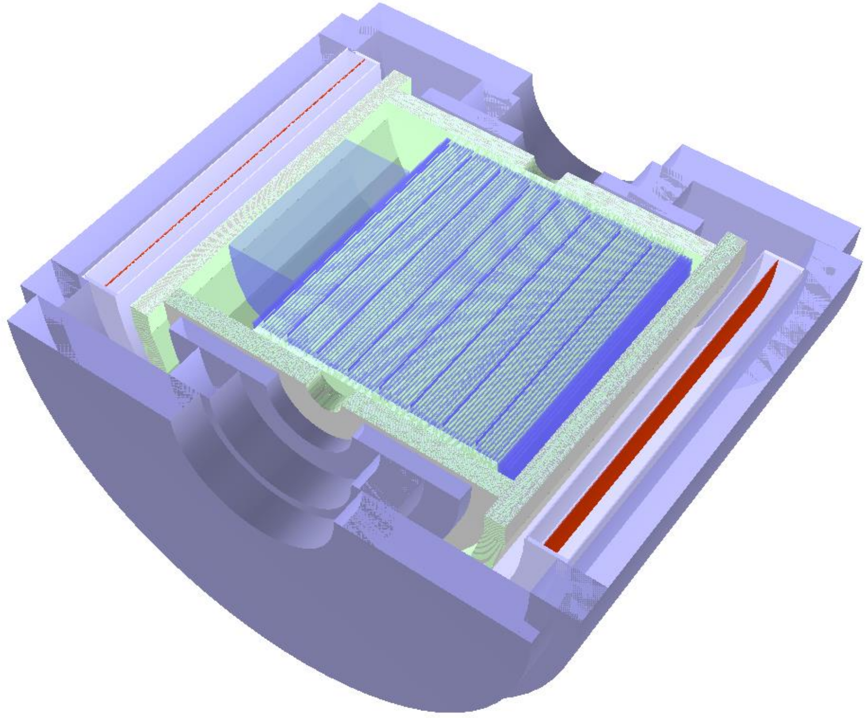
The design provides accurate **control of configuration, chemical composition, and mass**

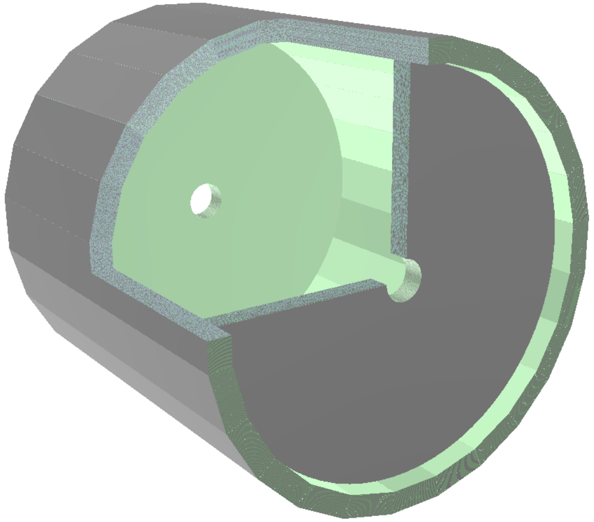


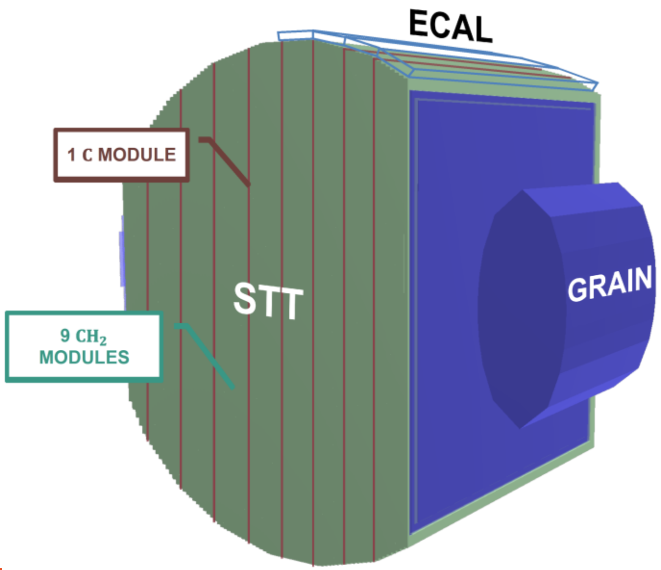
SAND detector

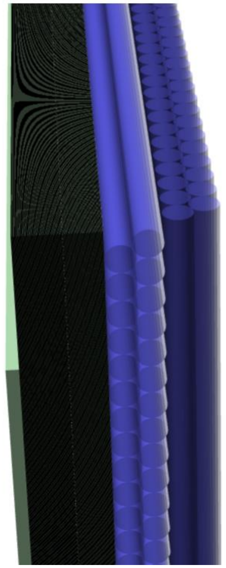
- Full SAND geometry simulated:
  - ECAL
  - STT
  - GRAIN

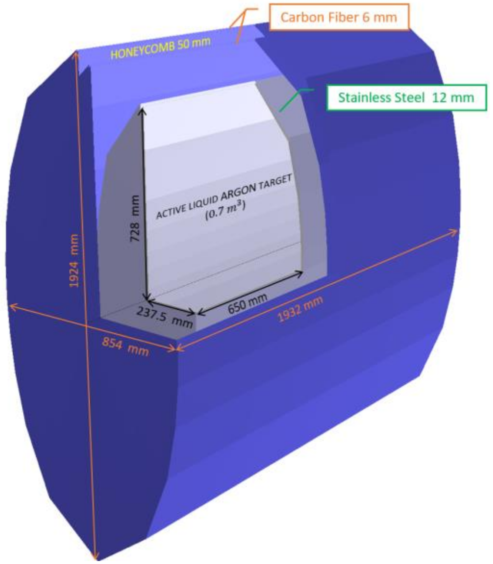






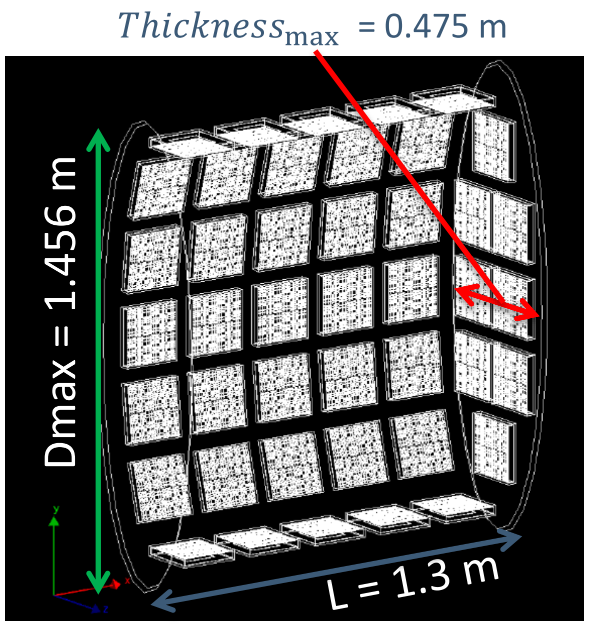


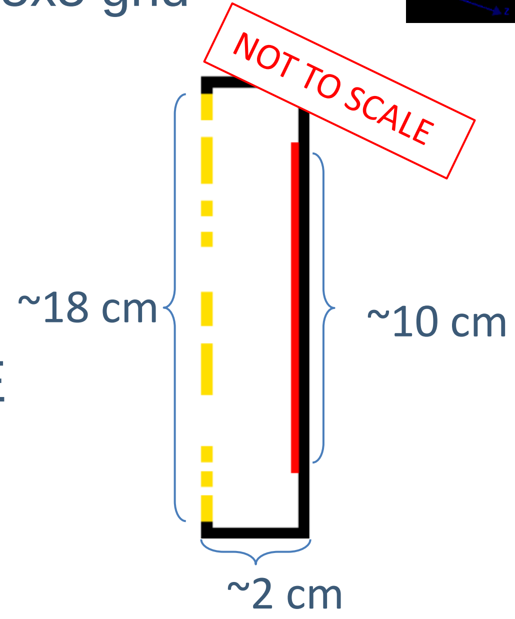


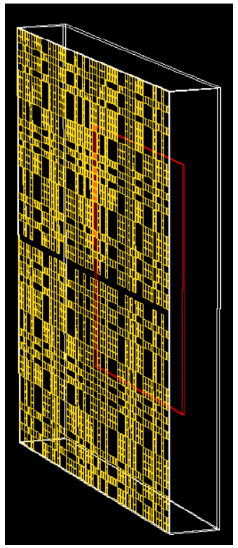


RECAP: mask geometry in GRAIN

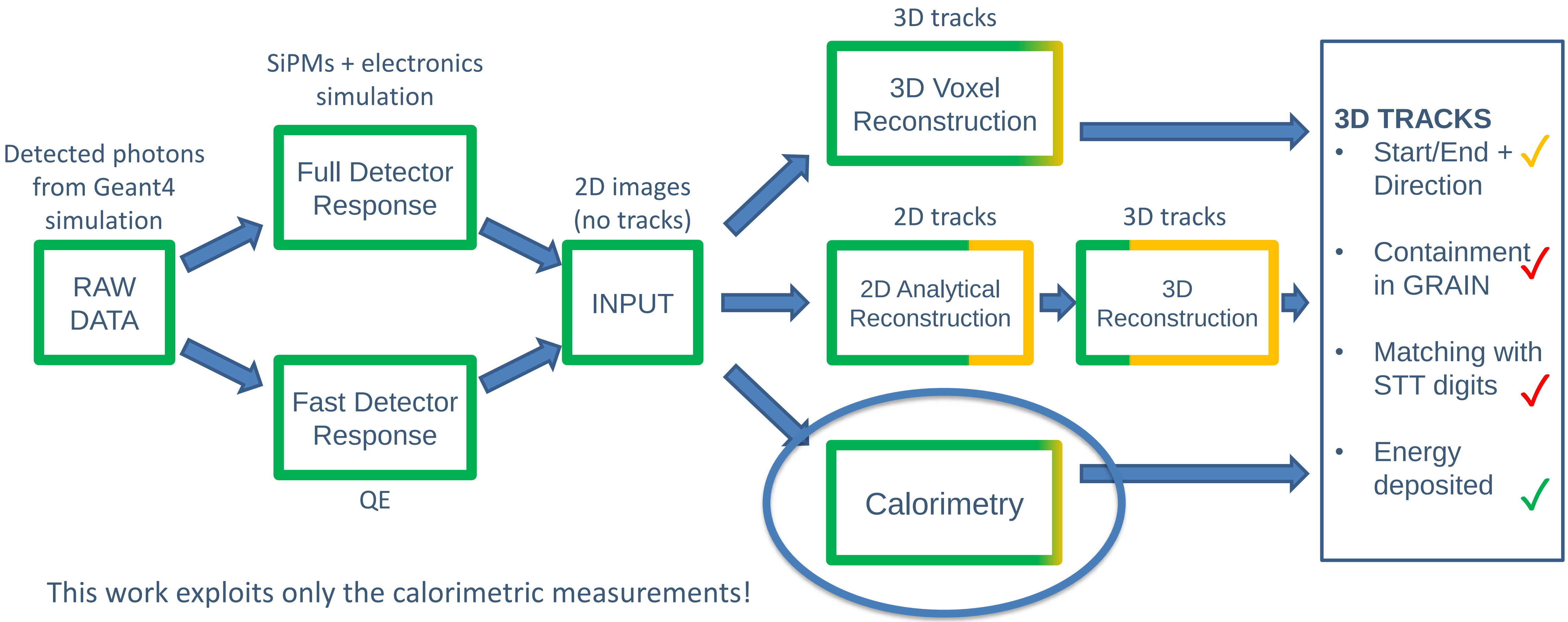
- Simulated GRAIN geometry:
  - x, y, z = 130 x 146 x 48 cm3
- 76 cameras, covering most of the available surface:
  - 25 cameras on each curved (YX) face arranged in a 5x5 grid
  - 5 cameras on top/bottom
  - 8 cameras on each side (YZ) face
- 32x32 matrix sensors, 3.2 mm pixels and 25% QE







RECAP: current status of the GRAIN simulation



This work exploits only the calorimetric measurements!

MC Sample

- 8.2M $\nu_\mu - Ar^{40}$ (CC+NC) interactions generated by GENIE 2.12.10
  - (2x10% training, 80% analysis)

- Muon neutrino energy spectrum: FHC

- Beam direction: along z

- Neutrino interactions are uniformly distributed in LAr volume inside GRAIN

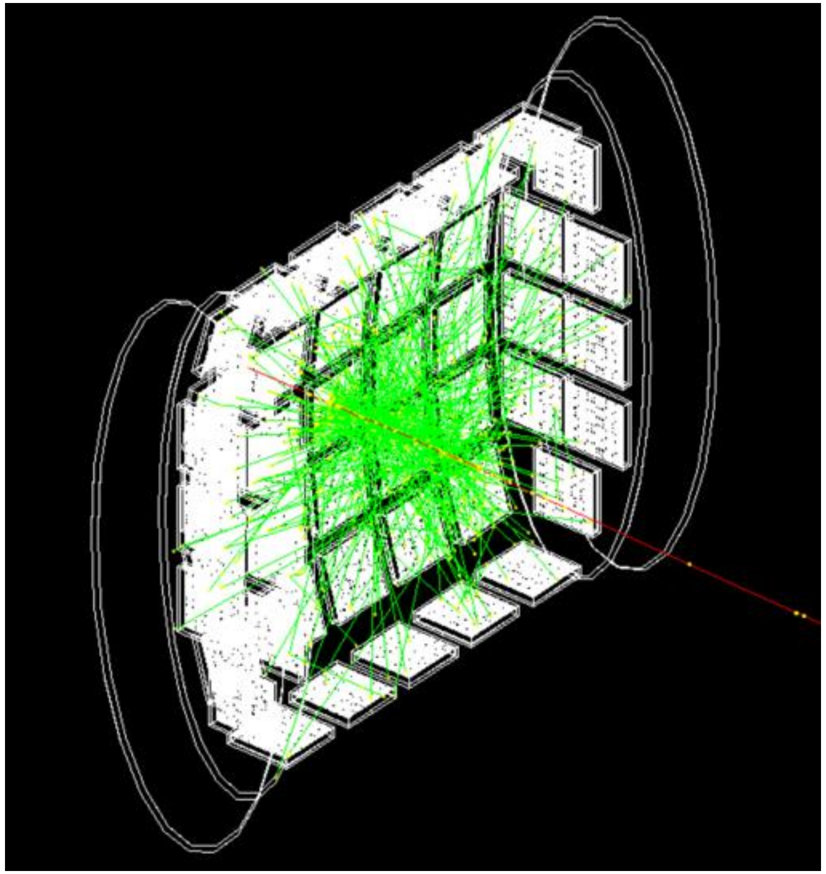
- Particles are propagated with edep-sim

GRAIN response simulation

- Simulation of Argon scintillation and light propagation with OptMen based on Geant4

- SiPM matrix response simulated as
  - 25% QE
  - 7% crosstalk
  - Possibility to simulate a full electronic response (repo)

- GRAIN response is the sum of all the SiPM matrix responses



Reconstruction

- STT tracks reconstructed by FastReco
  - Smearing of MC-truth, momentum reconstruction from smeared quantities

- ECAL clusters reconstructed by sand-reco
  - Digitazion of the signal, clustering of the hits

- Energy deposition in GRAIN reconstructed from its response
  - See next slides

- Particle ID is assumed

Kalman Filter - Ingredients

- Track state vector (a_k)

$$\begin{pmatrix} x \\ y \\ 1/\tilde{R} \\ \tan\lambda \\ \phi \end{pmatrix}$$

X coordinate
Y coordinate
Signed inverse radius
Tangent of dip angle
Rotation angle

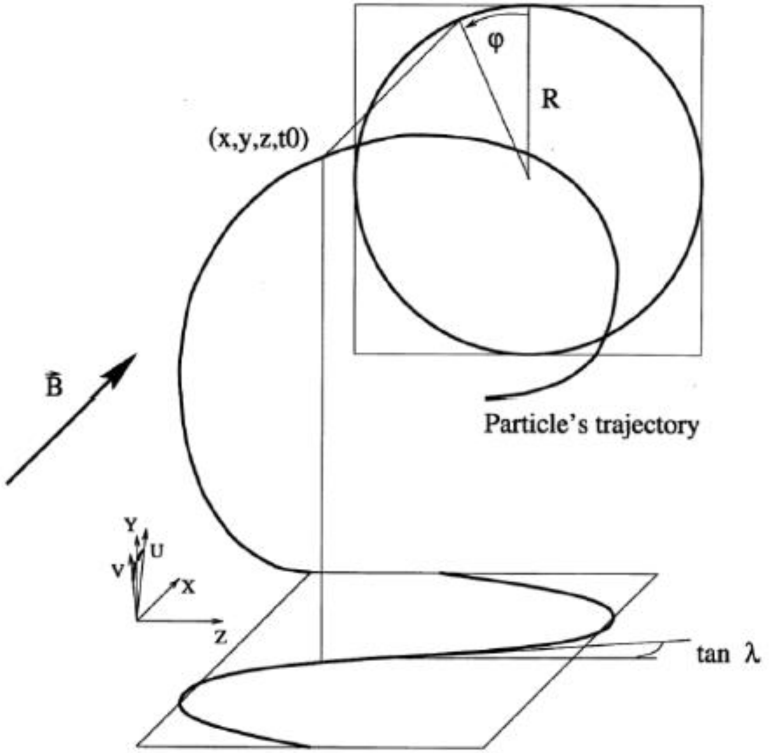
- Track model: helix
- Measurement vector:

$$m_k = \begin{pmatrix} x \\ \theta_{xz} \end{pmatrix} \quad \theta_{xz} = -\kappa \cdot \arctan\frac{\tan\lambda}{\sin\phi}$$

$$m_k = \begin{pmatrix} y \\ \theta_{yz} \end{pmatrix} \quad \theta_{yz} = \phi + \kappa \cdot \frac{\pi}{2}$$

Either one depending on the STT plane

- Energy loss and MCS taken into account



Pierre Astier et al. *Kalman filter track fits and track break point analysis*. Nucl. Instrum. Meth. A, 450:138–154, 2000.

Kalman Filter - Ingredients

- State projection from z_{k-1} to z_k :

$$f_{k-1} \quad \begin{aligned} x_k &= x_{k-1} + \tilde{R}_{k-1} \cdot \tan\lambda_{k-1} \cdot (\phi_k - \phi_{k-1}) \\ y_k &= y_{k-1} + R_{k-1} \cdot (\sin\phi_k - \sin\phi_{k-1}) \\ 1/\tilde{R}_k &= 1/\tilde{R}_{k-1} + \kappa \cdot \Delta(1/R_{k-1}) \\ \tan\lambda_k &= \tan\lambda_{k-1} \\ \cos\phi_k &= \cos\phi_{k-1} + (z_k - z_{k-1})/R_{k-1} \end{aligned}$$

$$\Delta(1/R) = -\frac{(1/R_{k-1})^2}{0.3 \cdot B} \cdot \frac{1}{\sqrt{1 + \tan^2\lambda_{k-1}}} \cdot \beta \cdot \Delta E$$

- The propagator matrix:

$$F_{k-1} = \frac{\partial f_{k-1}}{\partial a_{k-1}}$$

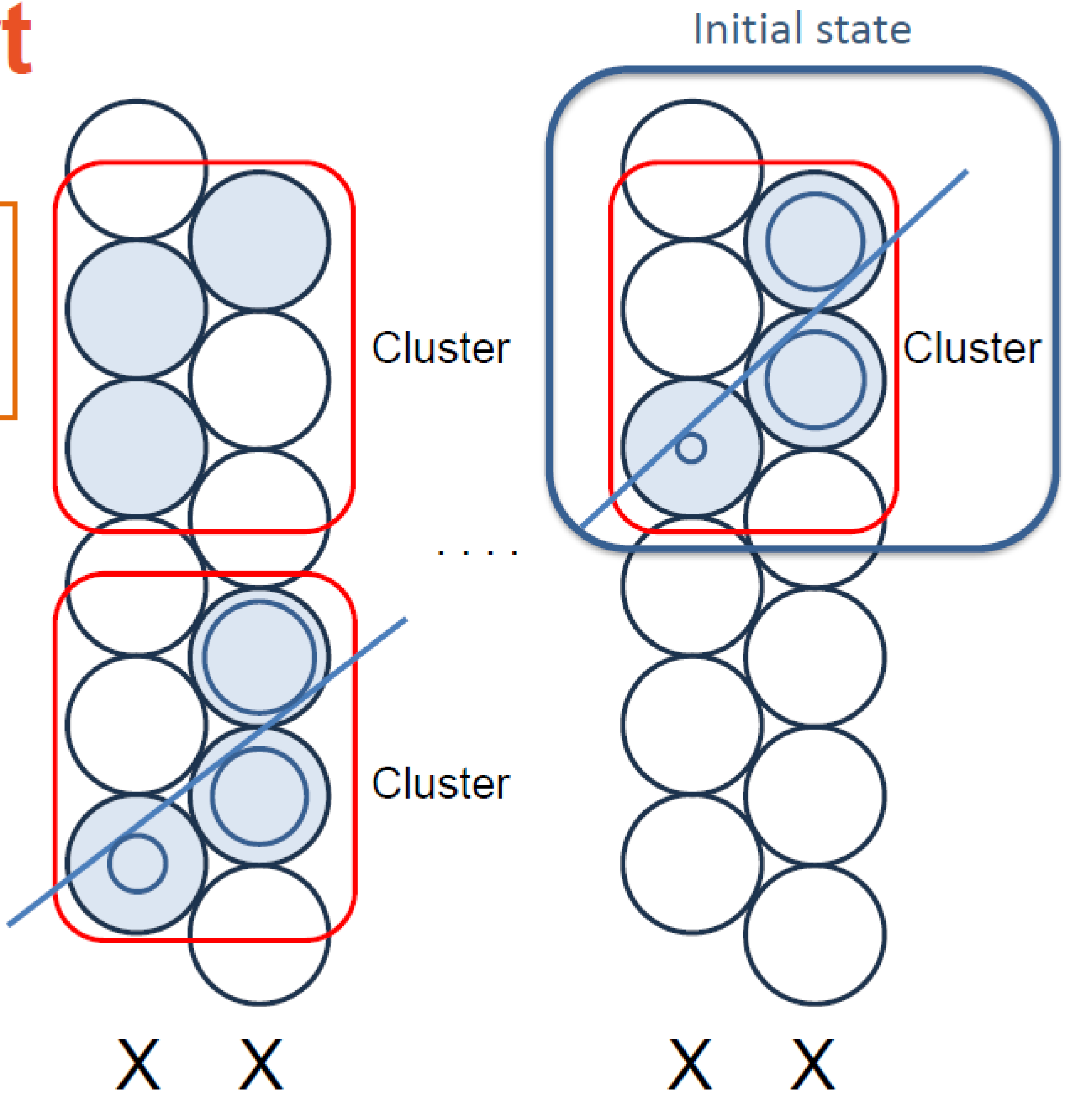
Other elements

- Projector
- Process noise matrix
- Measurement noise matrix
- Projector matrix

Kalman Filter - Flow-chart

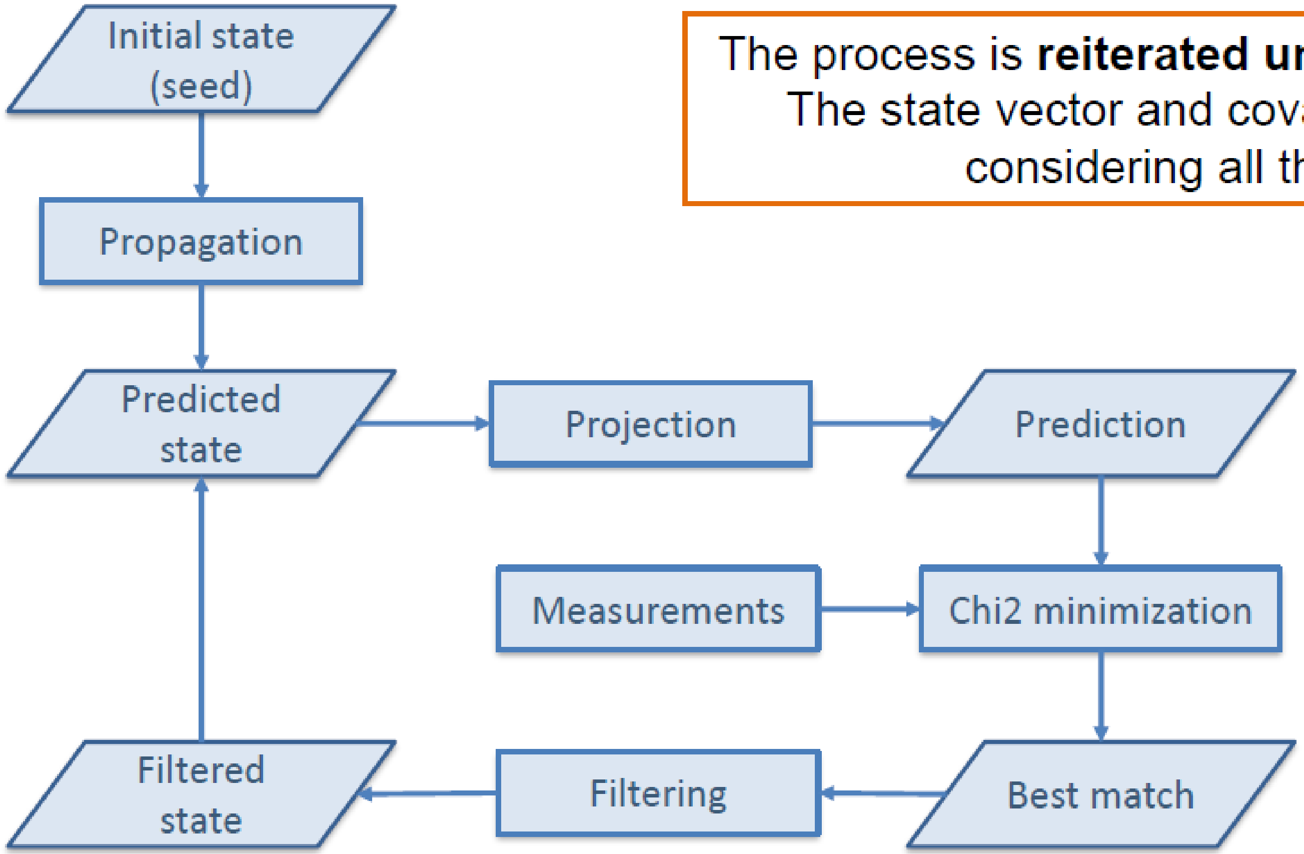
Initial state (seed)

Initial state vector and covariance matrix obtained from most downstream STT cluster



- Input geometry is read: tubes and planes info stored and organized
- Input tube-digits are grouped in plane
- Within plane adjacent tube-digits are clustered
- Reconstruct radius for tube-digits
- Evaluate common tangents and take the best one according to a likelihood
- **Clusters are reconstructed: m, q, t0, quality**
- **Most downstream cluster is the initial state for the Kalman filter**

Kalman Filter - Flow-chart



The process is **reiterated until no cluster can be added**. The state vector and covariance matrix are updated considering all the measurements.

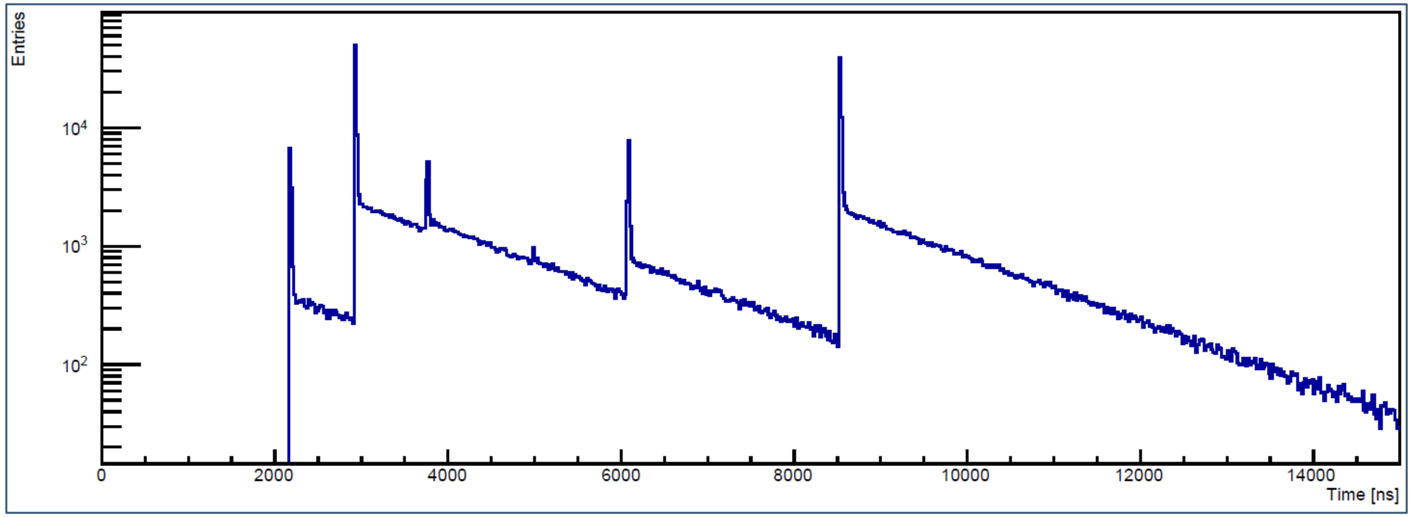
SPILL SIMULATION AND PILEUP

PILEUP
- overlaying of time-shifted GRAIN response of background events and of neutrino interactions in GRAIN

BACKGROUND EVENTS
- neutrino interaction in SAND (excluding GRAIN) with energy deposition in GRAIN
- mean number of background events per spill obtained from simulation.
- number of background events in a spill extracted from a Poisson distribution

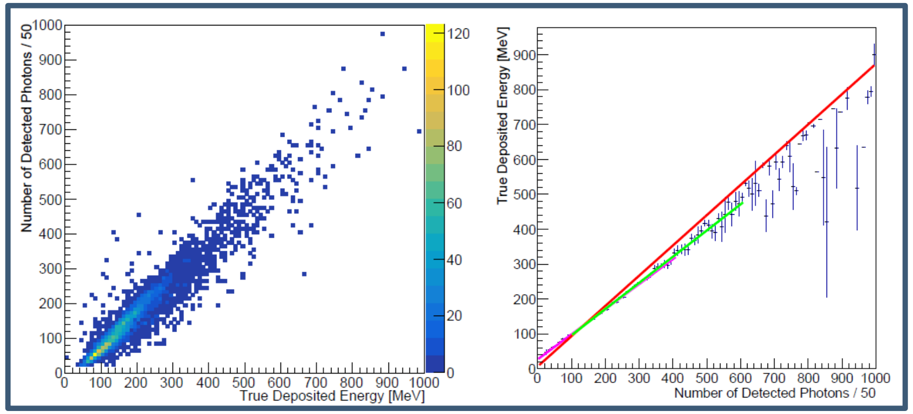
TIME SHIFTS
- According to the beam structure

Peak corresponding to signal event is assumed to be known



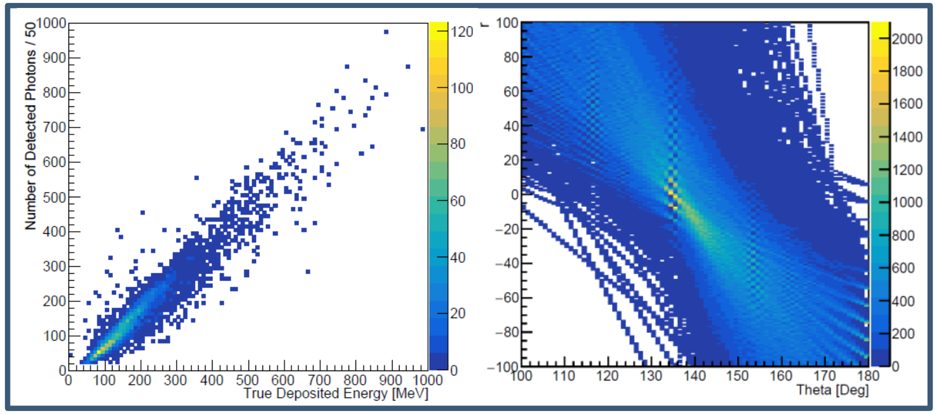
CALIBRATION COEFFICIENT COMPUTATION

Linear fit of the distribution's profile



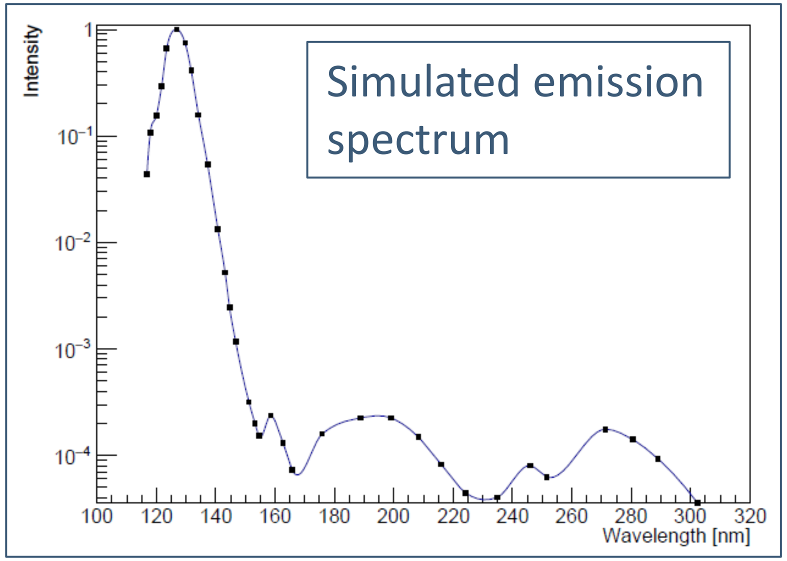
Range	Slope	Intercept
$0 - 400$	0.712 ± 0.005	27 ± 1
$100 - 600$	0.751 ± 0.006	1 ± 1
$0 - 1000$	0.868 ± 0.001	6 ± 1

Hough Transform of the distribution

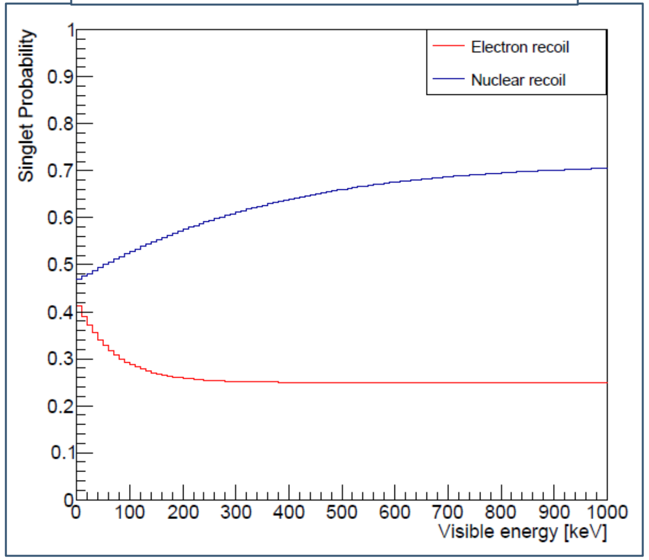


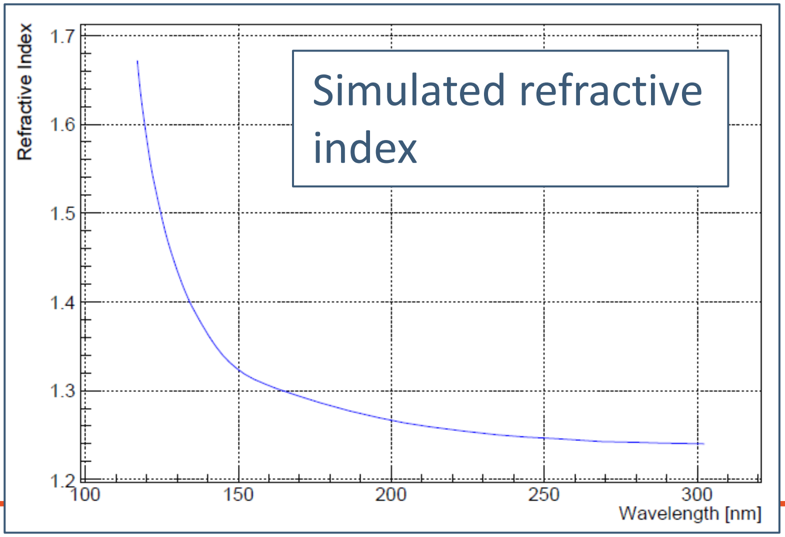
θ step	r step	max θ	max r
2°	2	135°	1.0
0.5	1	134.75	0.995
0.125	1	135.06	0.0
0.125	0.125	135.06	0.06
0.0625	0.0625	135.03	0.03

LIQUID ARGON SIMULATION



Simulated singlet/triplet ratio





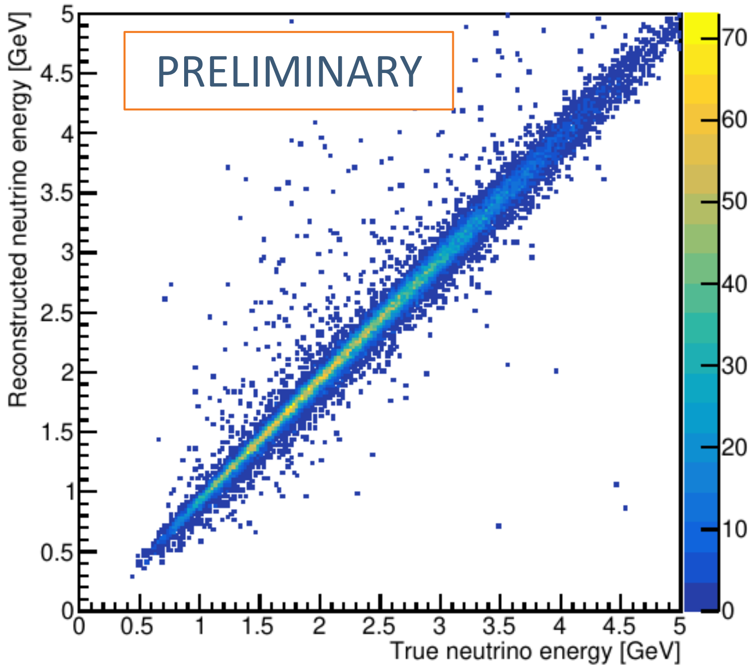
Liquid Argon properties are implemented from the latest experimental results.

The cryostat inner surface is simulated as 100% opaque to avoid unwanted reflections.

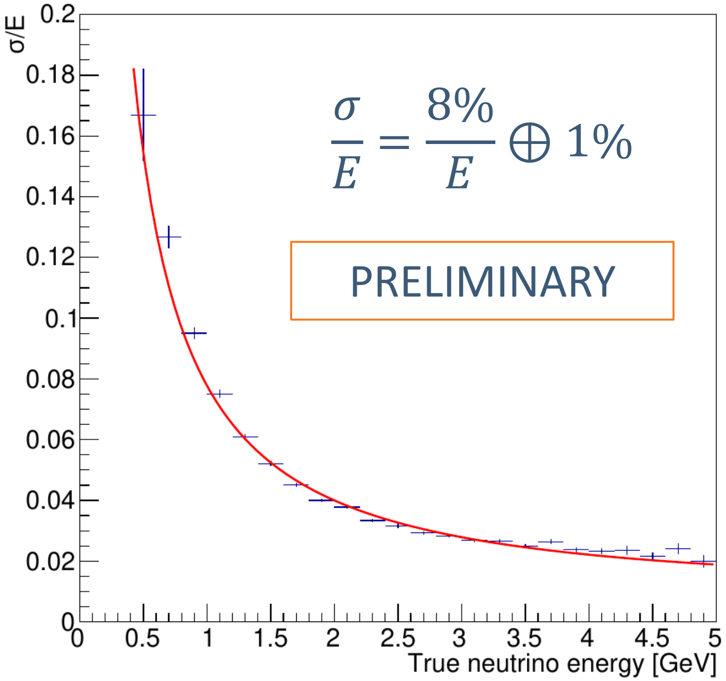
Light emission	
Light yield	40k ph/MeV
τ_s	7 ns
τ_3	1.6 μs
λ	127 nm
I_s/I_3	0.25 electron recoil 0.7 nuclear recoil
Light propagation	
λ_{RS}	90 cm
λ_{Abs}	5 m
Optical surface properties	
Model	glisur
Type	dielectric_dielectric
Finish	Polish
Reflectivity	0%
Absorption	100%

NEUTRINO ENERGY RECONSTRUCTION

Neutrino energy of selected events is reconstructed combining the information of all sand subdetectors



SAND energy resolution was computed as a function of the true neutrino energy and evaluated using the electromagnetic calorimeter equation:



$$\frac{\sigma}{E} = \frac{8\%}{E} \oplus 1\%$$