System for on Axis Neutrino Detection (SAND)

Status and Outlook

Sergio Bertolucci
University of Bologna and INFN

DUNE ND today

- The decision of DUNE to adopt the PRISM concept implies the need of **two** detectors, one staying on axis and the other moving across the beam.
- Both detectors should have a magnetic field
- Current understanding is that the moving detector consists of a large volume of LAr (Argoncube) followed by a large magnetized volume of ~.5 T produced by a 'transparent' magnet and filled by a large HPTPC surrounded by an hermetic e.m. calorimeter (+ a possible muon detector)
- In the last few months the idea to use the KLOE magnet and the KLOE e.m. calorimeter, hosting a suitable tracker in its inner volume (~ 43 m^3), has gained consensus.

- So **KLOE** has evolved into **SAND**

Primary goals of SAND

Monitoring of the beam stability on a few-days basis

- Event rate: requires a large-mass active detector
- Beam profile: requires relatively large width and segmentation
- Spectrum: requires a spectrometer to measure the particle momenta

Precision in-situ flux measurements of ν_μ , a-ν_μ , ν_e , a-ν_e

- Absolute ν_μ and a-ν_μ flux
- Relative ν_μ and a-ν_μ (E) flux
- Ratios ν_e/ν_μ (E), a-ν_μ/a-ν_e (E)

Constraining systematics from nuclear effects and related smearing

- Measurements complementary to the other Ar-based ND detectors (Lar+MPD) using different nuclear targets
- Possibility of a solid hydrogen target free from nuclear effects

Provide the necessary redundancy and resolution to achieve a ND complex robust against unknown unknowns

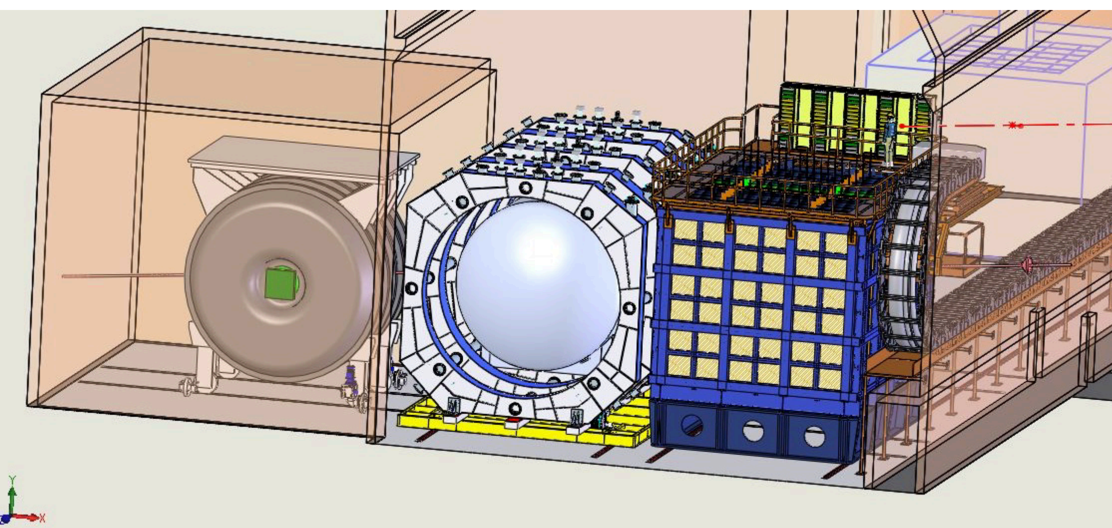
SAND within the ND complex

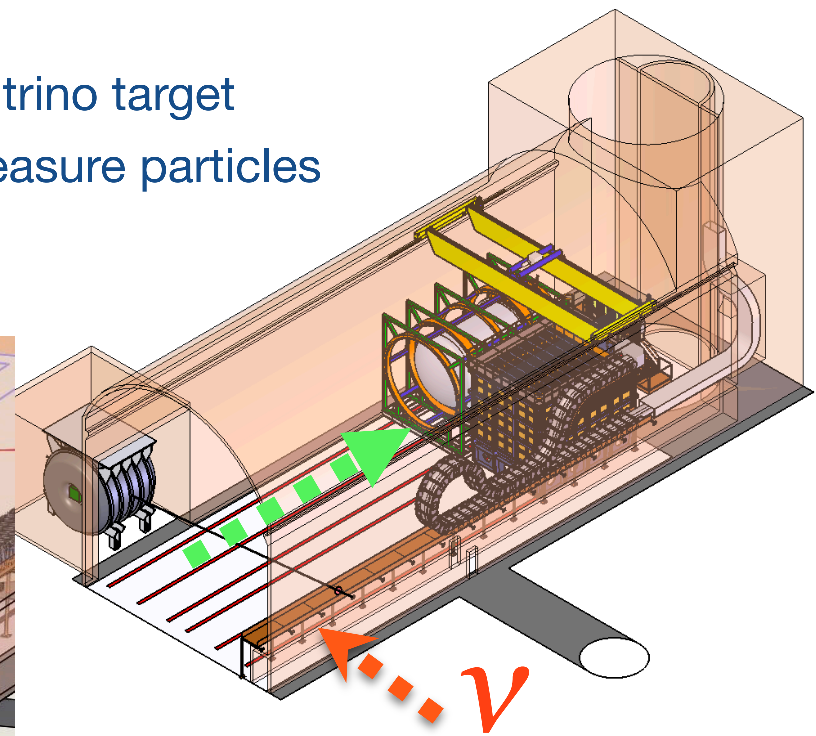
ArCube and MPD detectors will move off-axis (DUNE-PRISM) for about 50% of the time

SAND will be permanently on-axis in a dedicated alcove

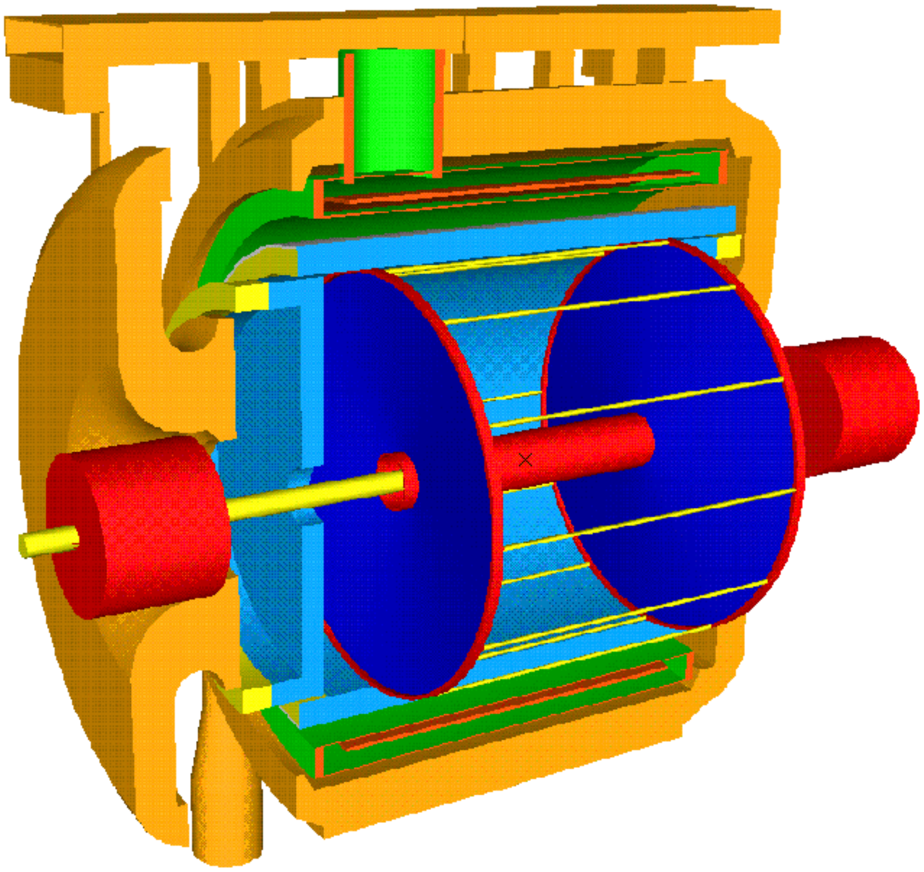
It will consist of:

- a superconducting solenoid magnet
- an Electromagnetic Calorimeter (ECAL)
- a thin active Lar target
- A 3D scintillator tracker (3DST) as active neutrino target
- and/or a Low-density tracker to precisely measure particles escaping from the scintillator



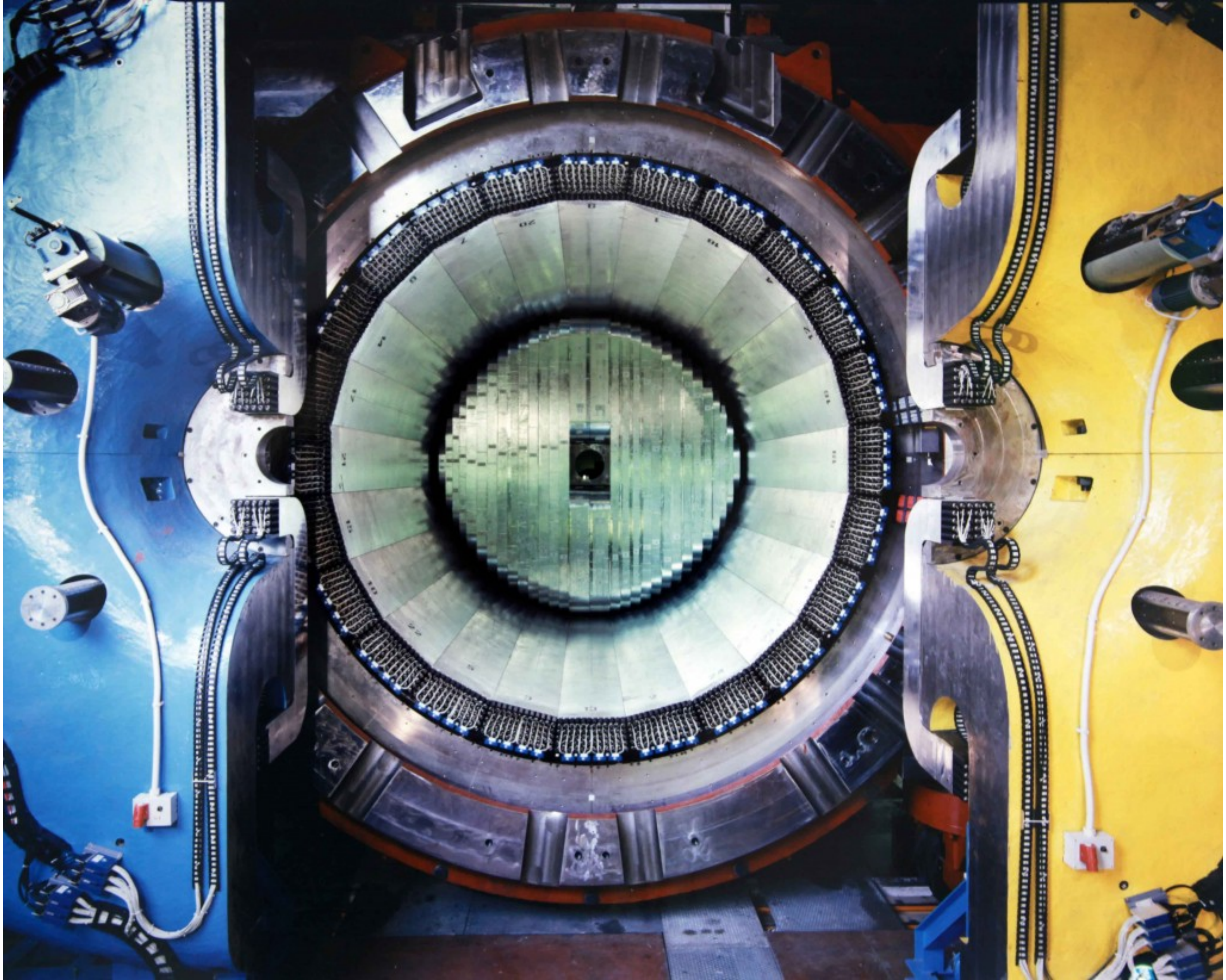


The KLOE Detector



Electromagnetic calorimeter
Lead/scintillating fibers
4880 PMT's

Superconducting coil (5 m bore)
$B = 0.6$ T ($\int B\, dl = 2.2$ T·m)




PICCOLI

Coil parameters

Layers	2
Turns/layer	368
Ampere-turns	2.14 MA-T
Operating current	2902 A
Stored energy	14.3 MJ
Inductance at full field	3.4 H
Discharge voltage	250 V
Peak quench temperature	80 K

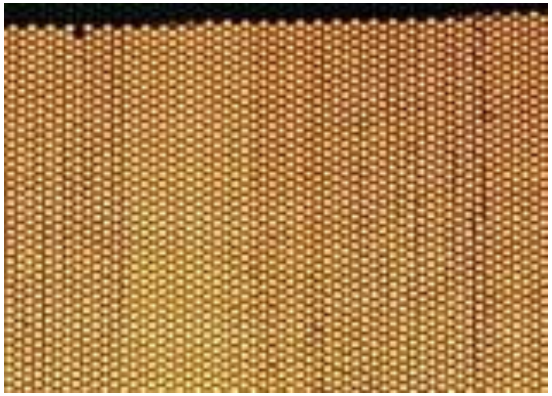
Guaranteed heat loads

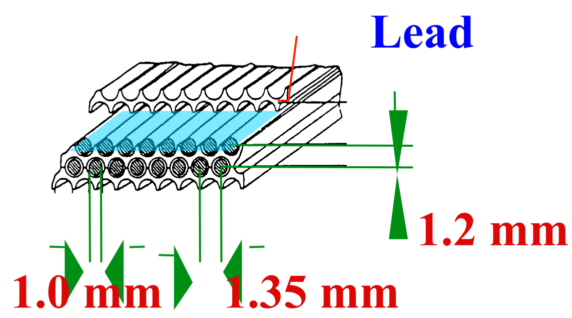
Source	**Heat load**
Current leads	0.6 g/s
4 K Radiation and conduction	55 W
70 K Radiation and conduction	530 W

The KLOE calorimeter

Pb - scintillating fiber sampling calorimeter of the KLOE experiment at DAΦNE (LNF):

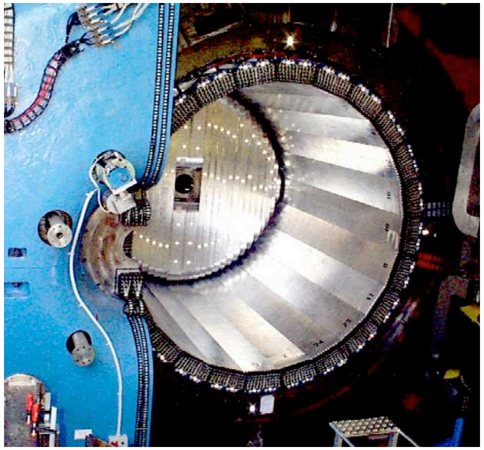
- 1 mm diameter sci.-fi. (Kuraray SCSF-81 and Pol.Hi.Tech 0046)
  - Core: polystyrene, ρ =1.050 g/cm^3, n=1.6, λ_{peak} ~ 460 nm
- grooved lead foils from molding .5 mm plates
- Lead:Fiber:Glue volume ratio = 42:48:10
- X_0 = 1.6 cm ρ=5.3 g/cm^3
- Calorimeter thickness = 23 cm
- Total scintillator thickness ~ 10 cm

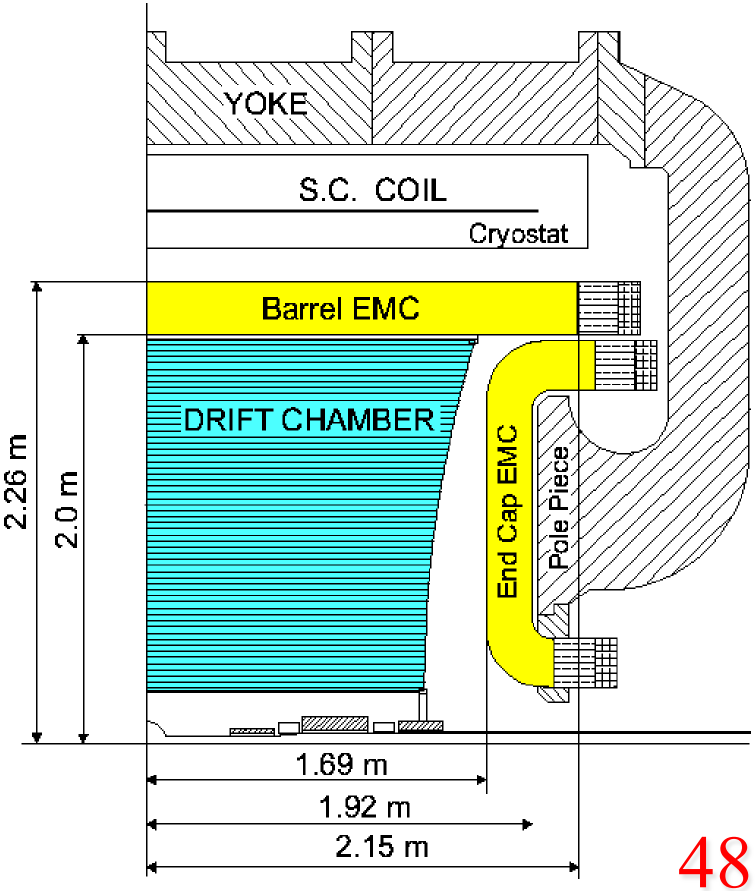




Electromagnetic calorimeter

24 barrel modules
60 cells (5 layers)
4.3m length





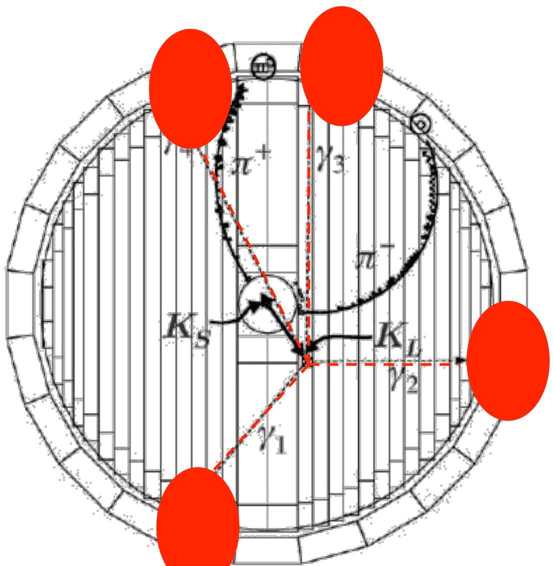
2 × 32 endcap modules
10/15/30 cells

2440 cells total

4880 channels

The KLOE calorimeter

- Operated from 1999 till March 2018 with good performances and high efficiency for electron and photon detection, and also good capability of $\pi/\mu/e$ separation

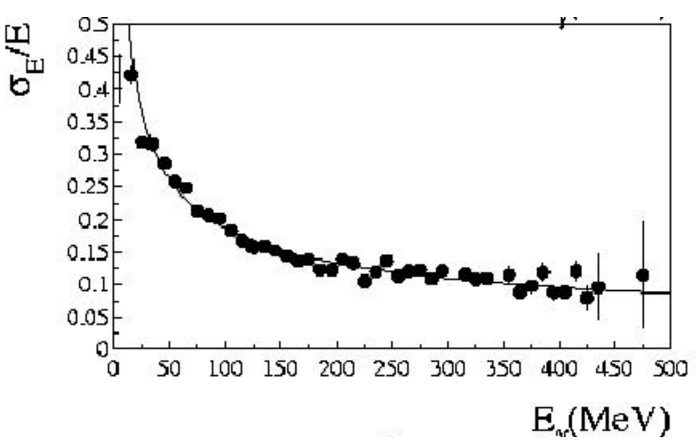


($\phi \to K_S K_L$; $K_S \to \pi^+\pi^-$; $K_L \to 2\pi^0$)

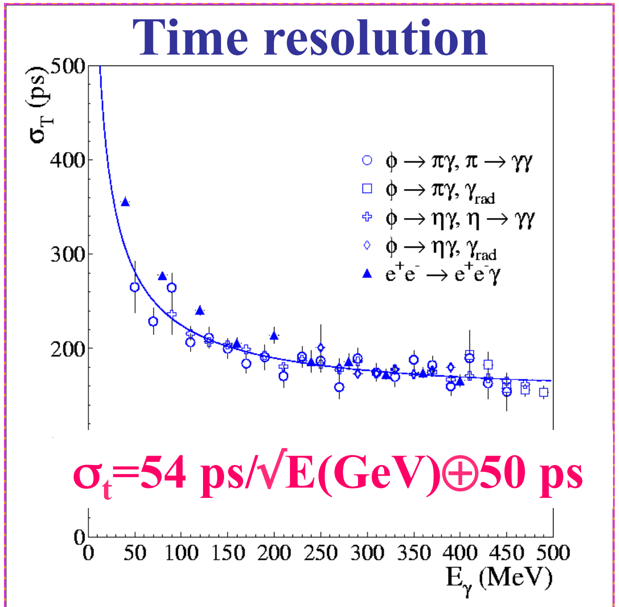
4γ

Energy resolution:

$\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$



(see KLOE Collaboration, NIM A482 (2002),364)



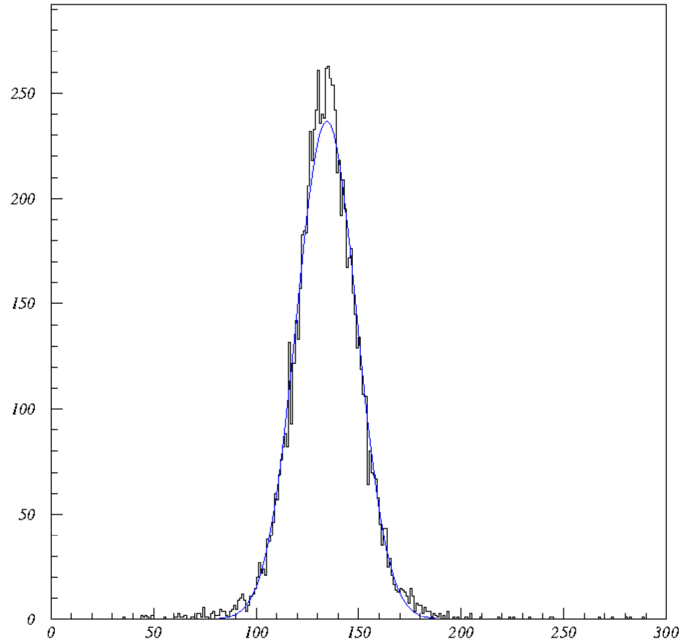
EMC mass reconstruction

$\phi \rightarrow \pi^+\pi^-\pi^0$

$M(\pi^0 \rightarrow \gamma\gamma)$

$M = 134.5$ MeV

$\sigma_M = 14.7$ MeV

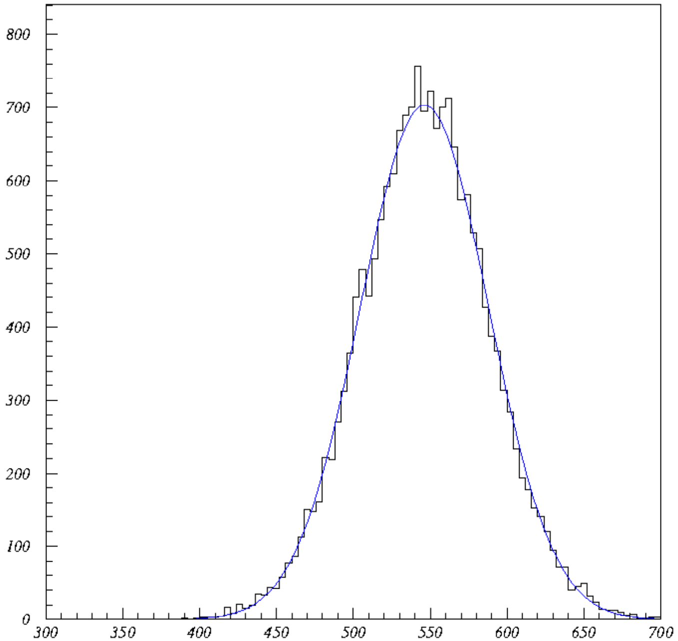


$\phi \rightarrow \eta\gamma$

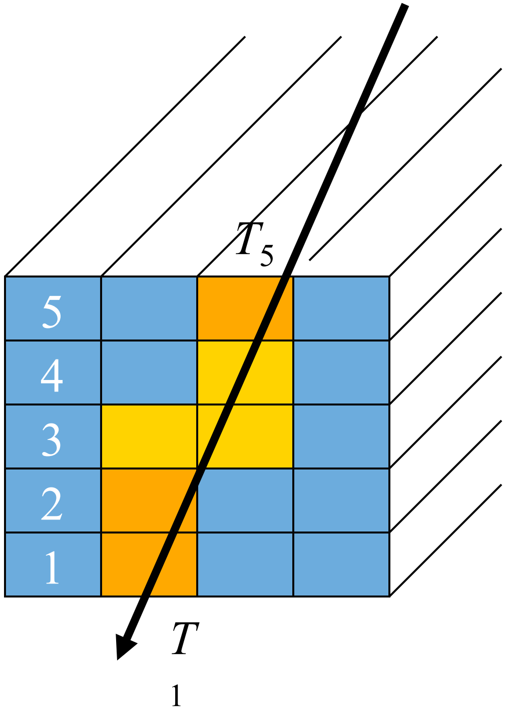
$M(\eta \rightarrow \gamma\gamma)$

$M = 546.3$ MeV

$\sigma_M = 41.8$ MeV

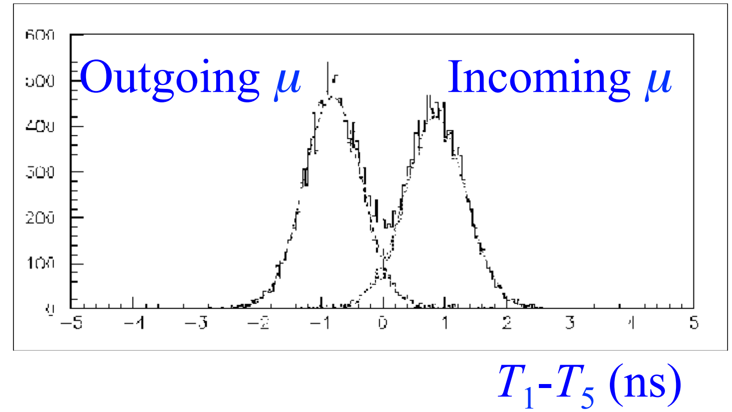


EMC time-of-flight measurement



T_1-T_5 distribution can distinguish incoming/outgoing μ' s

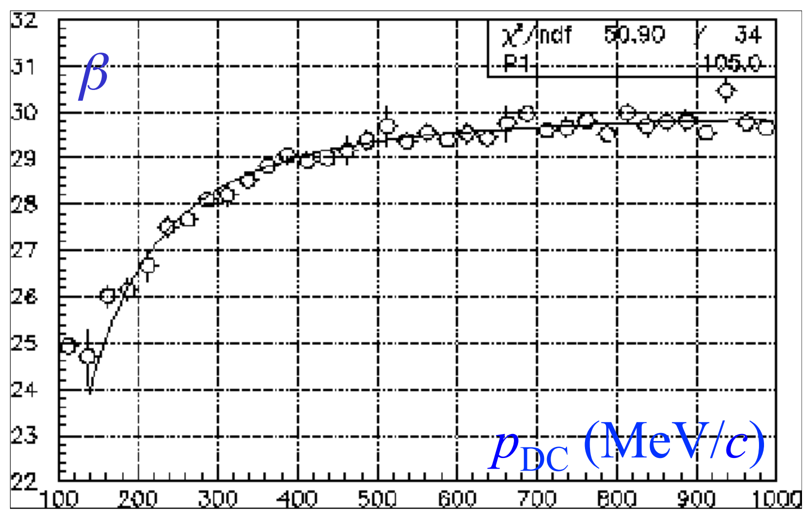
Used to reject cosmic rays



μ mass from TOF

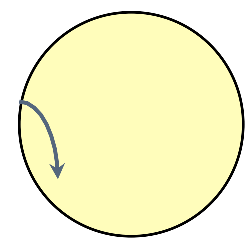
Fit to β vs p_{DC} gives

$m_\mu = 105\ \mathrm{MeV}/c^2$



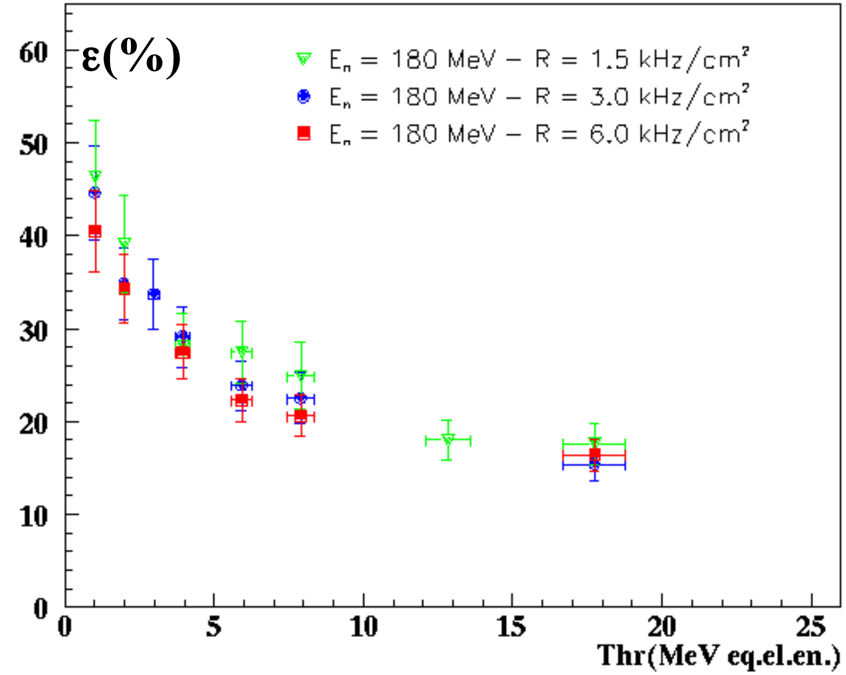
$\beta = L/\Delta T$

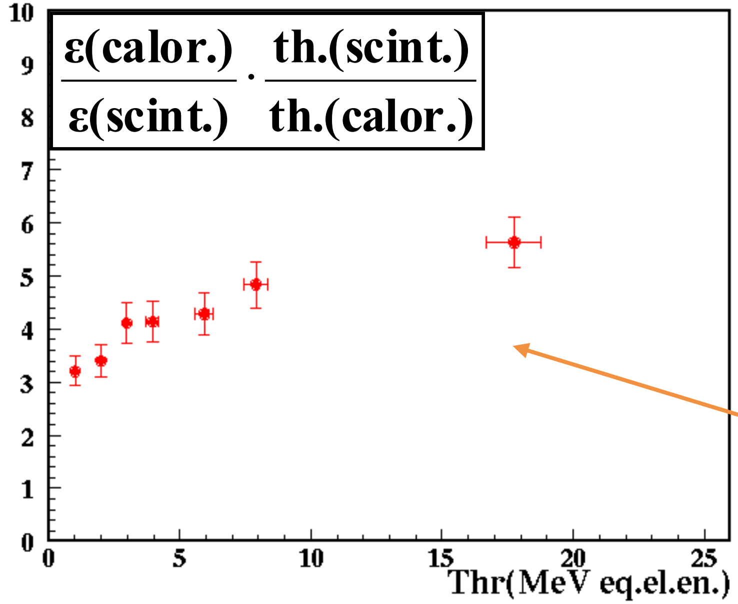
L from DC



Calorimeter efficiency for neutrons

- E_{peak} = 180 MeV
- Very high efficiency w.r.t. the naive expectation (~ 10% @ 2 MeV thr.)

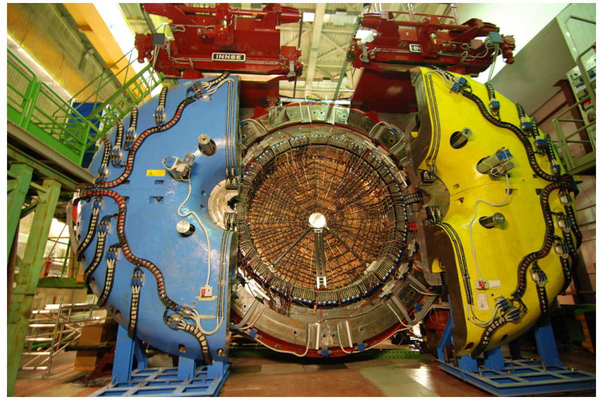


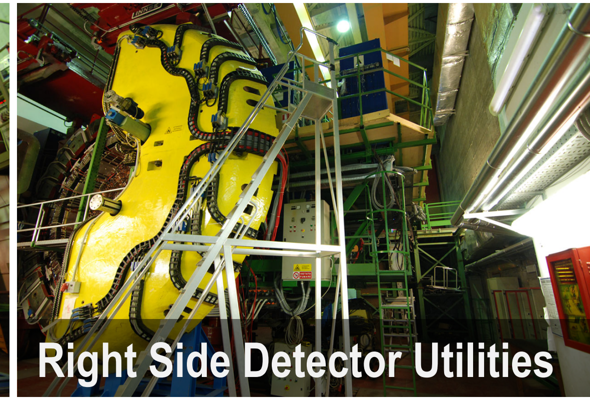


Comparison with a scintillator normalized to the same active material thickness

November 2019: Two DUNE Near Detector Engineers Visited INFN Frascati To Collect Cavern Design Requirements For SAND Detector


Left Side Detector Utilities




Right Side Detector Utilities


Detector Movement System


Protrusions From Detector Have Been Recorded In Detail To Ensure Detector Will Fit Within Allocated Alcove Size

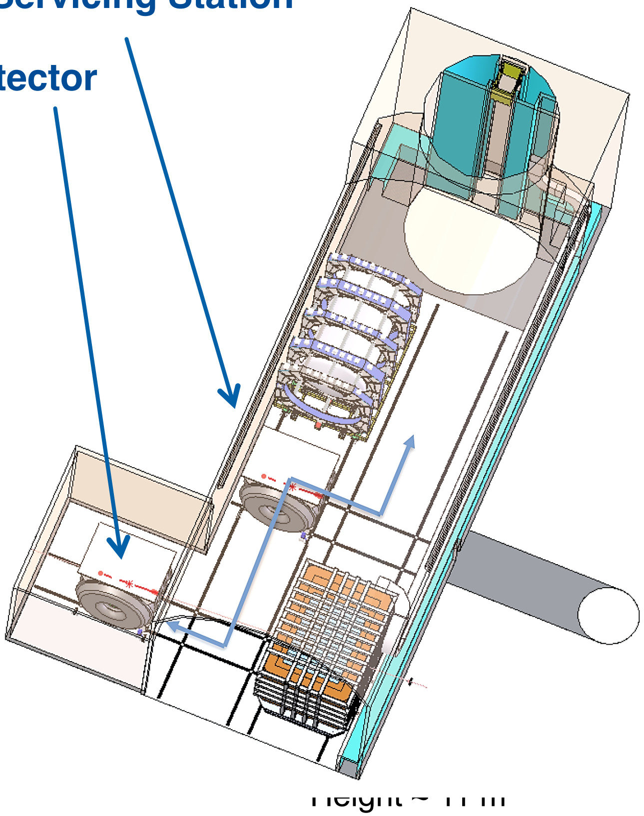
DUNE Engineer Bob Flight

Topics Covered During Visit:
- Cavern Interfaces
- Electrical Interfaces
- Cryogenic Interfaces
- Handling Procedures
- Detector Assembly

SAND Detector Will Serve As Stationary Beam Monitor, But Movement During Installation And Servicing Must be Planned

Floor Guides To Assembly And Servicing Station

KLOE Stationary Detector Inside Alcove

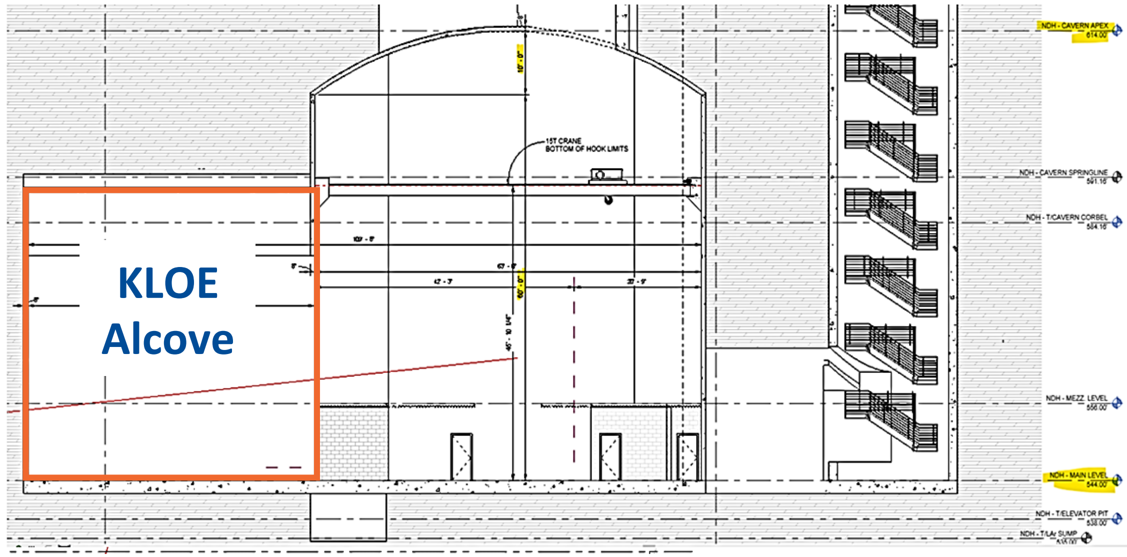


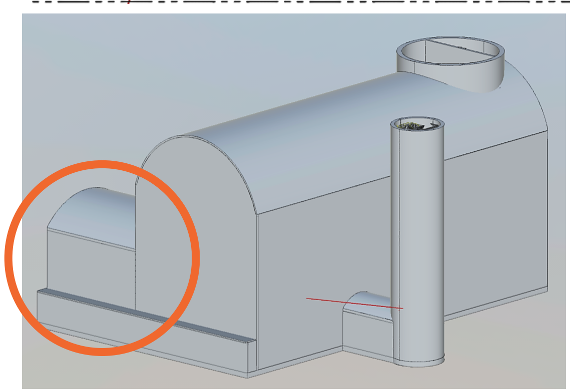
November 2019: Two DUNE Near Detector Engineers Visited INFN Frascati To Collect Cavern Design Requirements For KLOE Detector

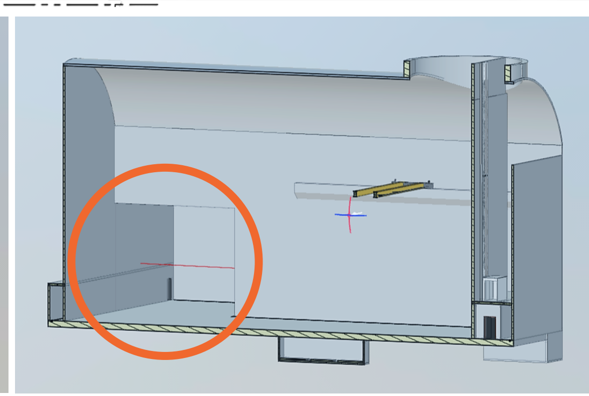
- Detector as-built physical sizes verified
  - Including supporting equipment on rack platforms
  - Including service space for open end yoke plates
- Utility requirements verified
  - Electrical power
  - Cooling water
- Exchanged cryogenics process flow diagrams, cryostat cool-down procedures, cryogenic connection interface details
- Validated crane requirements
- Discussed detector hydraulic lifting and movement procedures
- Evaluated future storage/staging needs at FNAL

KLOE Engineering Information Required To Finalize LBNF Conventional Facility Design Has Been Successfully Transferred To DUNE

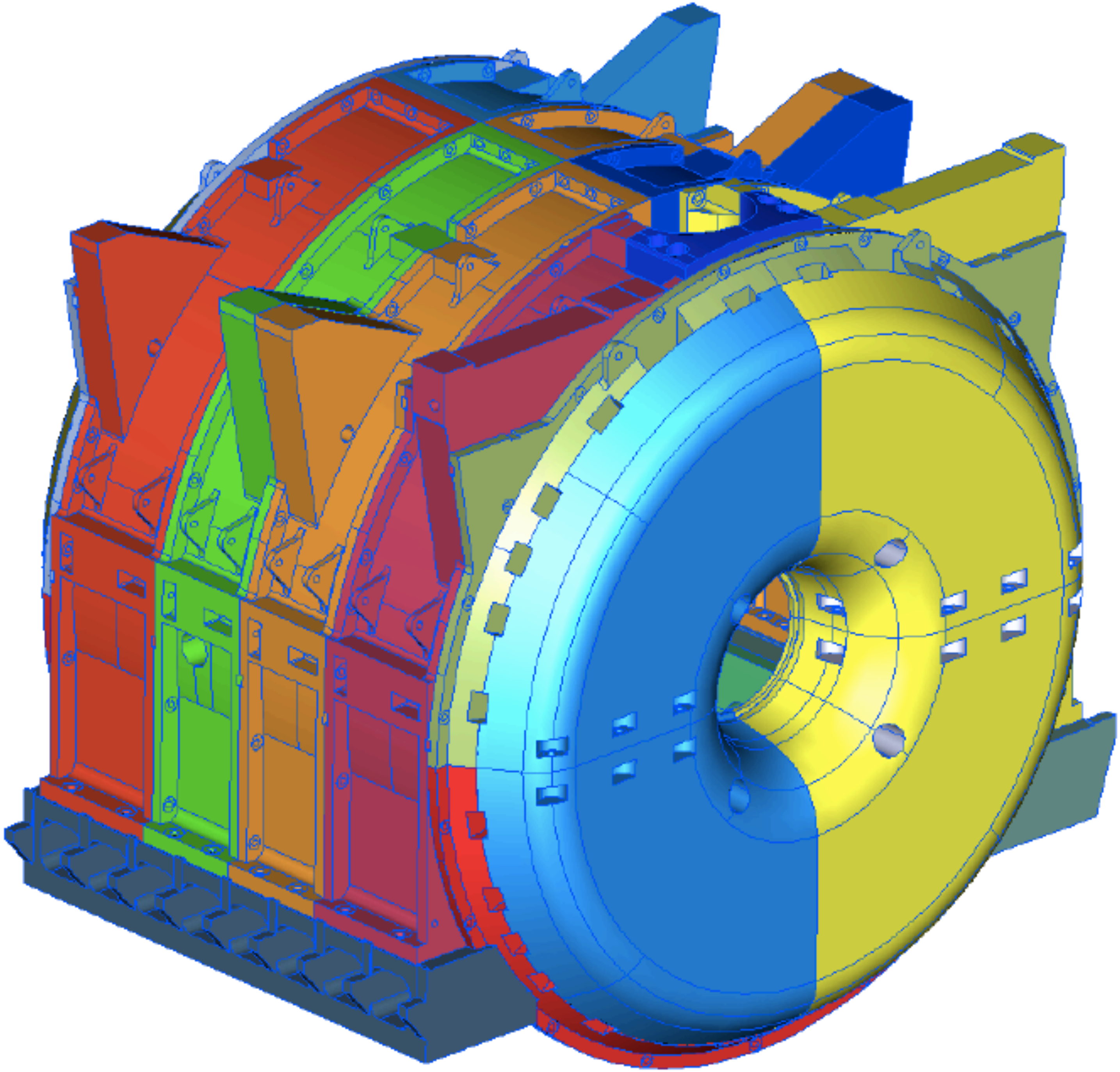
DUNE/LBNF Is Currently Completing The Preliminary Design Of The Near Detector Cavern: SAND Space Needs Are Now Finalized

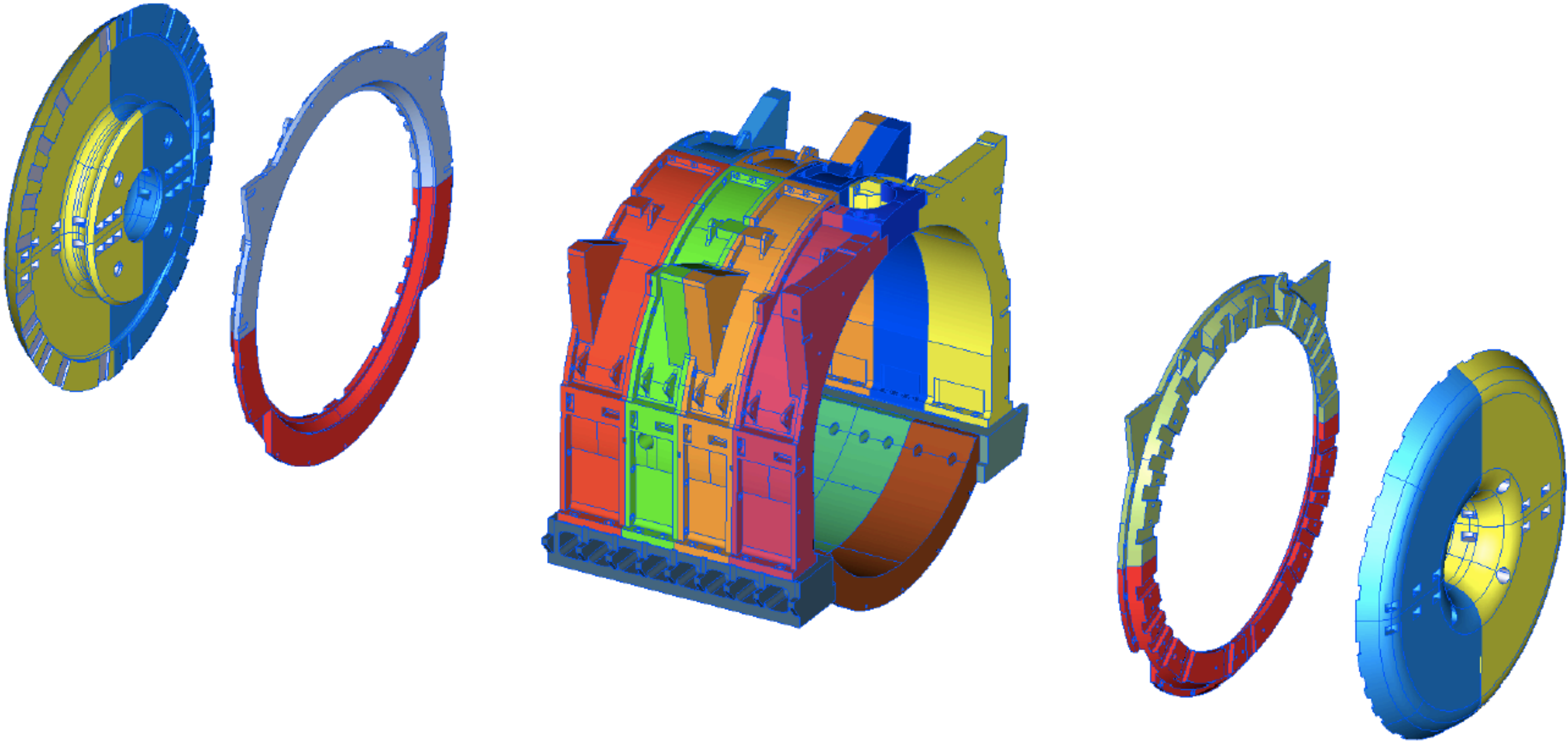






SAND Detector Now Integrated Into
LBNF Conventional Facility Preliminary Design Submittal





INFN and the ND

- Following the decision of the DUNE Collaboration of the two detectors configuration, **INFN is willing to provide all the needed resources** to dismount, refurbish, deliver, reassemble and commission a fully functional magnet + e.m. calorimeter+ LAr active target (~1.5 t)

- INFN has also started to contribute to the design of the magnet for the new detector, and is considering to contribute to its construction.

SAND as a component of the ND system

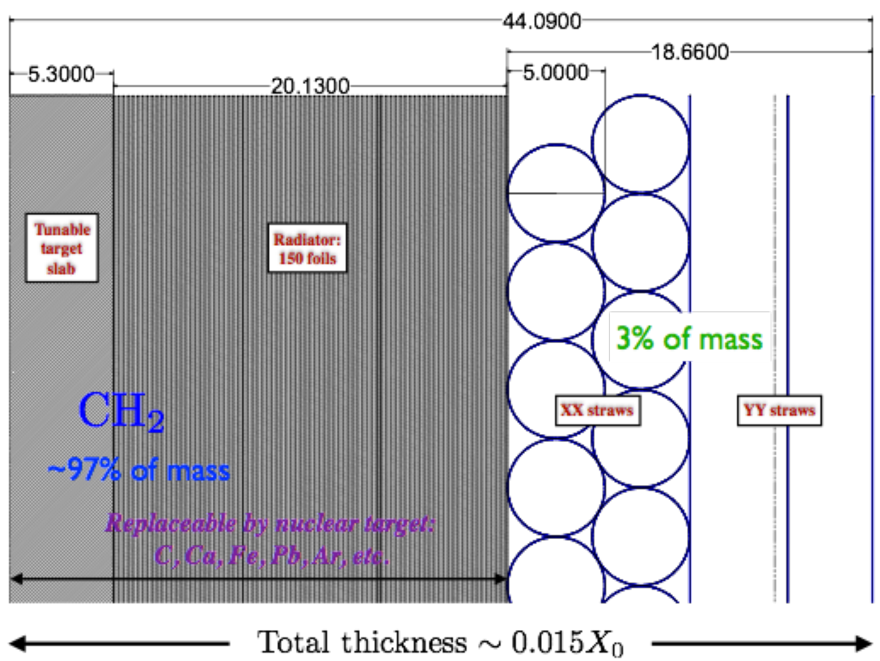
- Detailed simulations/analyses have been performed based on KLOE and a tracker composed by **straw tubes (STT)** interspersed with TRD foils and/or interchangeable targets of different materials.
- The study has shown that such a configuration has a great potential to complement the information coming from the moving detector, providing redundancy in the assessment of the systematics. **We will use it as a starting point and as a reference.**

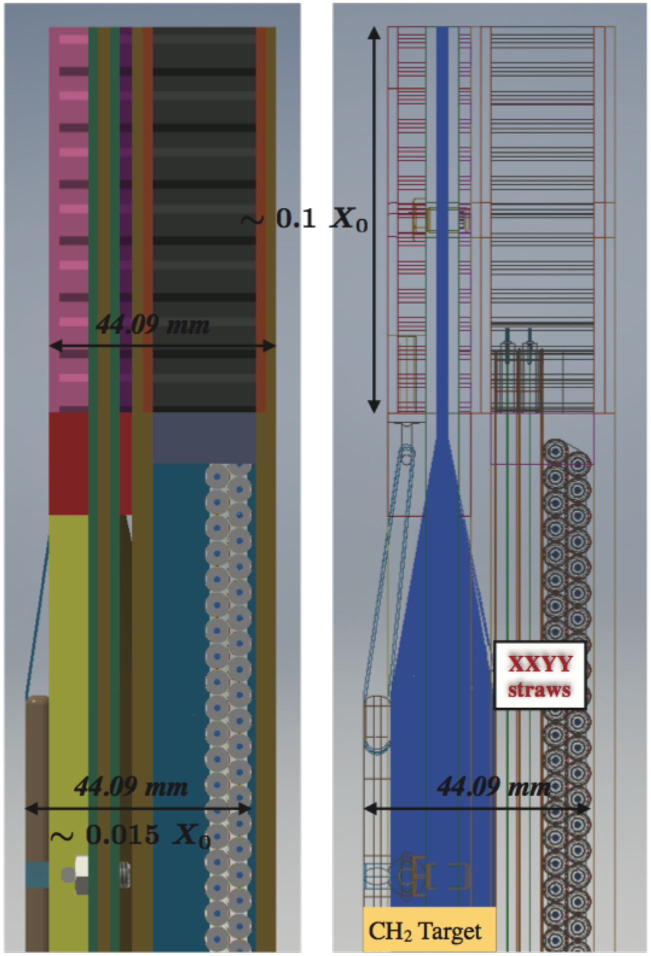
  (A comprehensive set of results is described in DUNE-DOC- 13262:
  https://docs.dunescience.org/cgi-bin/private/RetrieveFile?docid=13262&filename=A_Near_Detector_for_DUNE.pdf&version=4)

- Lately, as a consequence of a fruitful discussion, **an hybrid tracker** configuration has been implemented, which consists of a large **3DST** volume surrounded by a **gaseous tracker**. The proponents of the two instances merged in a **single working group.**

The Straw Tube Tracker (STT)

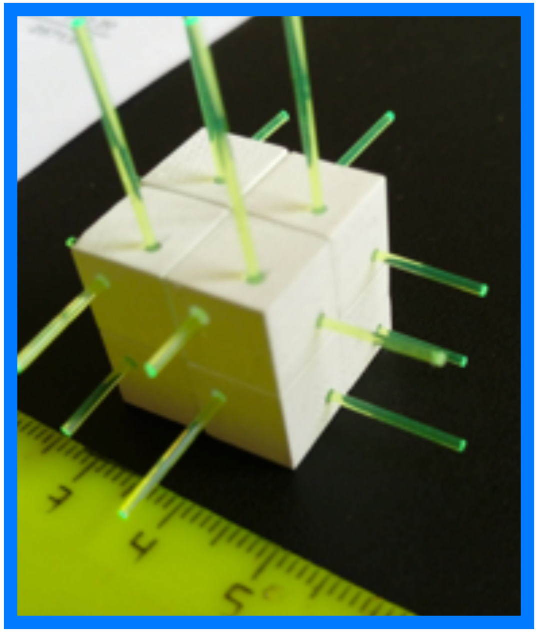
- Thin passive targets (100% purity) physically separated from active tracker (straws ~3% of total mass)
- Tunable target mass & density by varying thin targets (~97% of total mass) with average density 0.005<= rho <=0.18 g/cm^3
- A variety of thin (<0.1 X_0) nuclear targets can be installed & replaced during data taking: C, Ca, Fe, Pb,etc





Modular design (flexible) offering a control of the configuration, chemical composition, and mass of targets comparable to e-scattering experiments

The 3D Scintillator Tracker



2018 *JINST* **13** P02006
NIM A936 (2019) 136-138

Prototype funded under the US-Japan program

- Detection efficiency at 4π (>90% for muons)
- Muon p resolution by range ~2-3%
- Detect protons above ~300 MeV/c
- Time resolution ~ 0.9ns per channel (MIP), i.e. ~0.5ns per cube (MIP)
- Very good neutron detection capability

It will be installed in the T2K Near Detector in fall 2021 (arXiv:1901.03750)

CERN-SPSC-2018-001

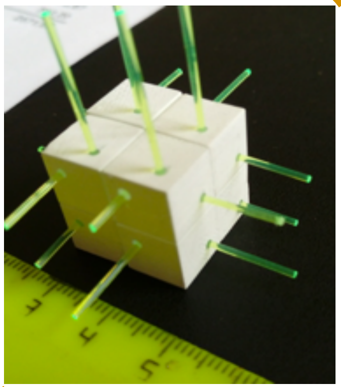
SPSC-P-357

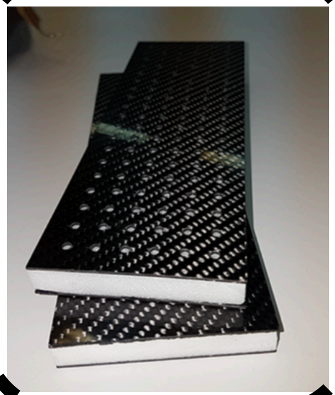
arXiv:1901.03750

The 3D Scintillator Tracker

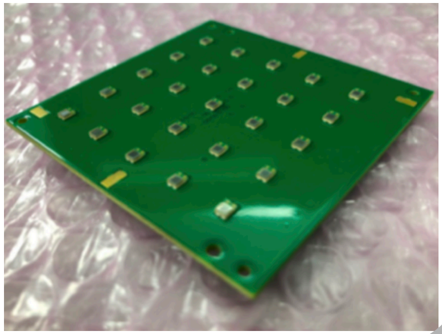
The design is based on the R&D performed for the T2K SuperFGD detector

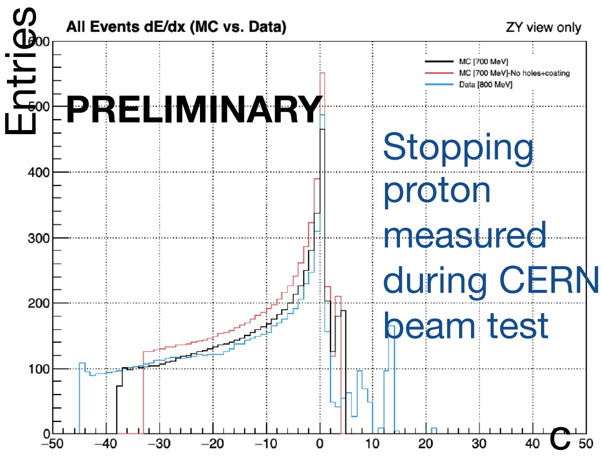
Optimization of the box thickness will depend on FEA results and internal cube structure





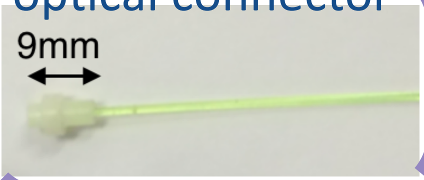
Hamamatsu MultiPixel PhotoCounters

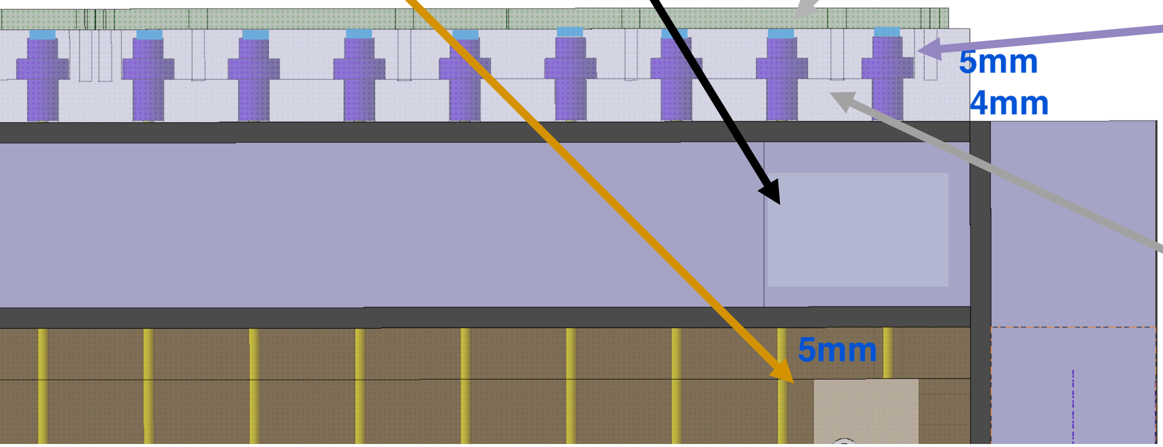




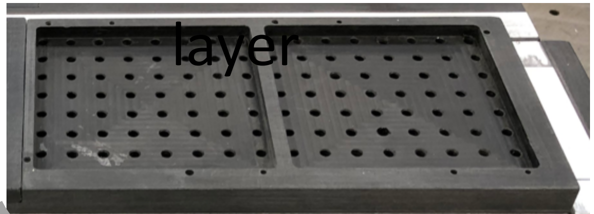
Stopping proton measured during CERN beam test

optical connector





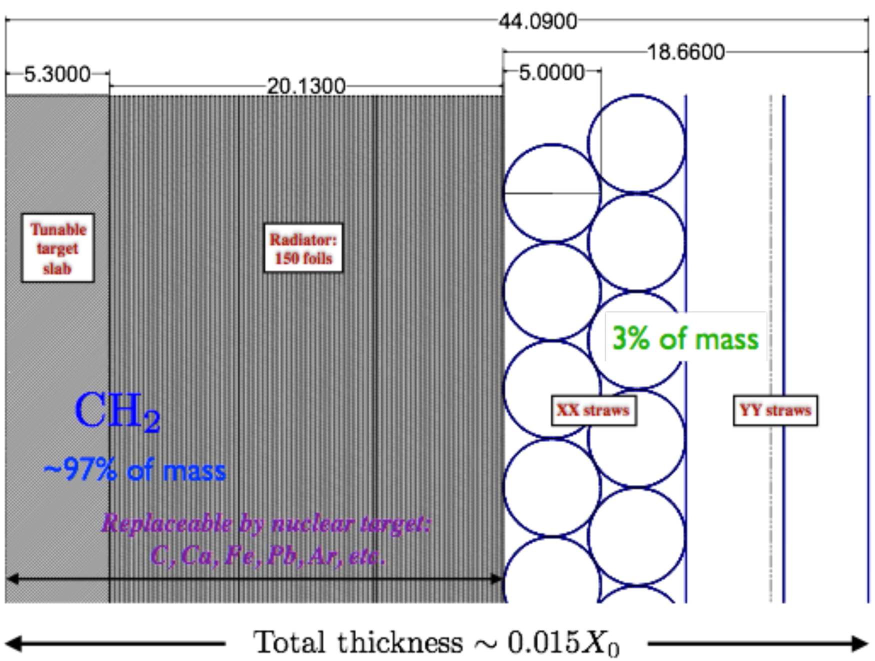
Plastic layer

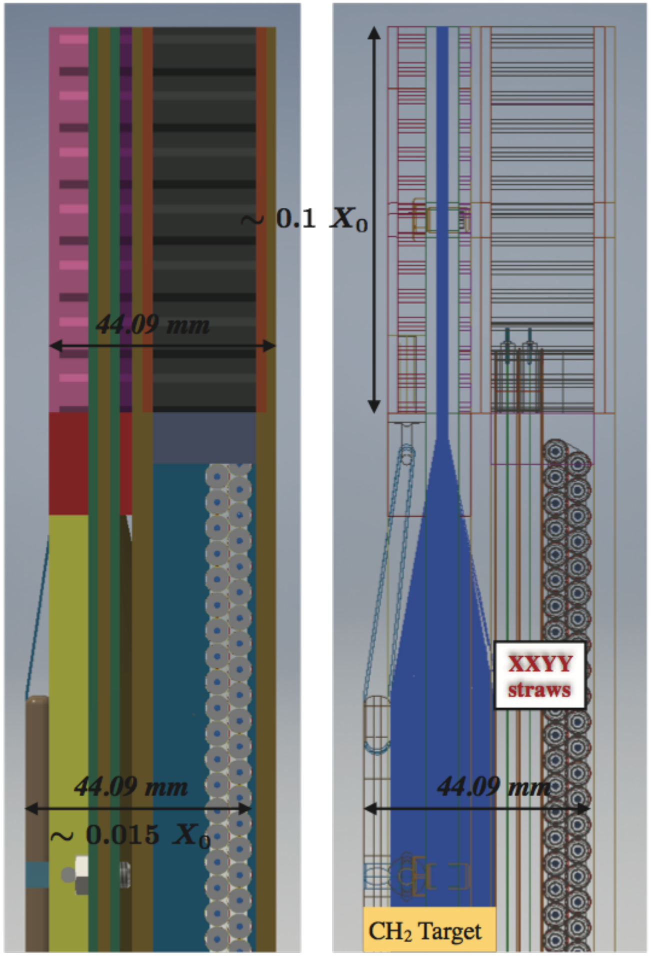


Option 3DST + Straw Tubes

Possible STT configurations:

- Straw Pure tracking in STT: remove most density & mass
- Physics measurements in STT: multiple nuclear targets, increase density & mass





Detailed studies and optimization are ongoing to evaluate performance: find optimal compromise between target mass (statistics) & resolution

Simulation

Since the beginning, we decided to use two simulation packages, **Fluka** and **G4** and to **validate** them on **KLOE data**.

Common Features:

- Flux: Optimized 3-Horn Design: https://home.fnal.gov/~ljf26/DUNEFluxes/
- KLOE Iron/coils/magnetic field from drawings. B=0.6 T in the inner volume + Ecal, 1.5T in the yoke.
- KLOE ECAL: Layered in G4. In FLUKA, exact barrel description, endcap with homogeneus material, segmented readout
- Lar meniscus ~ 1.5 t, upstream
- 3DST: dimensions/materials as provided by Davide Sgalaberna
- STT: dimensions/materials as provided by Roberto Petti,
- 3DST+ Gaseous Tracker (STT or TPC's), evolving configuration

Fluka simulation

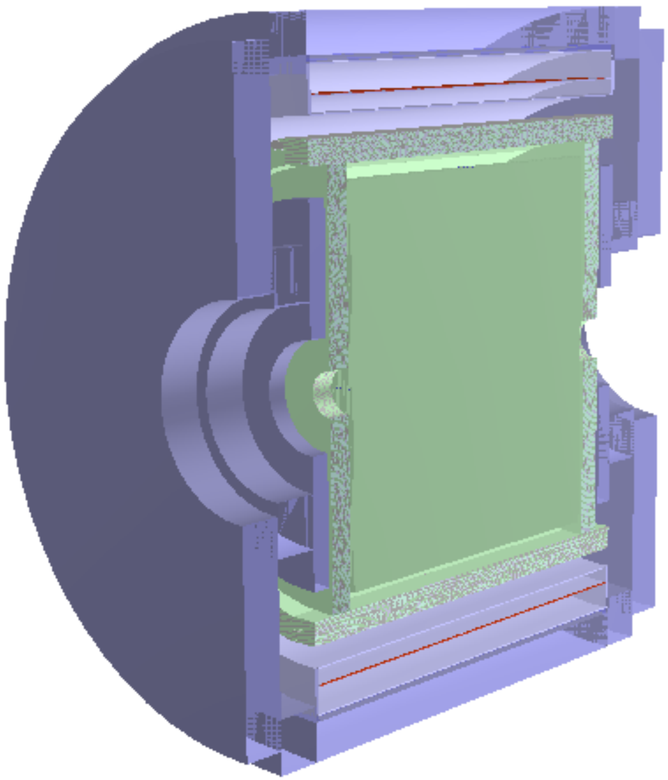
- Includes internal generation of neutrino events
- Output in ROOT trees:
- Information on
  - boundary crossing
  - energy depositions in
    - STT gas
    - 3DST 1x1cm cells, with and w/o Birks quenching
    - Ecal fibres with and w/o Birks quenching
    - Ecal “cells” (corresponding to readout granularity)
    - LAr meniscus
  - Associated particle type, energy, origin (parent from primary neutrino interaction) , time

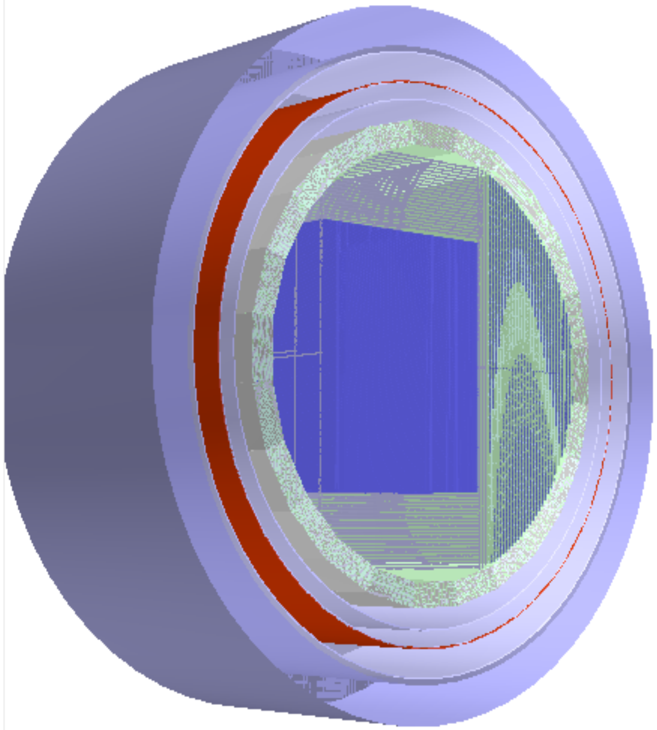
Geant4 simulation

Ingredients:

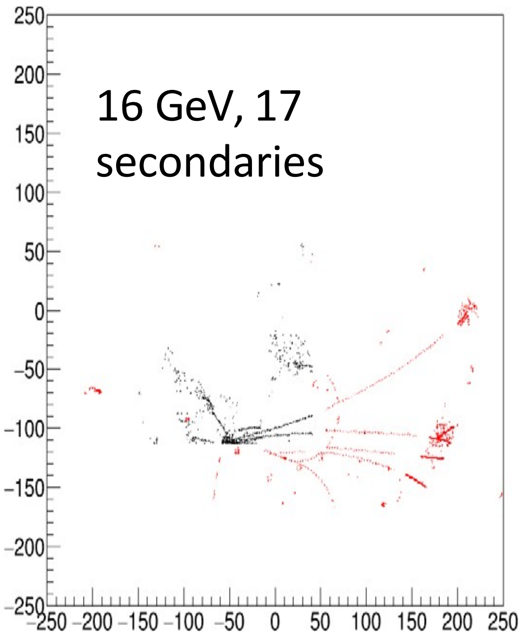
- Geometry: based on https://github.com/gyang9/dunendggd
- Neutrino Event Generator: GENIE
- Energy Deposition: Edep-sim
  https://github.com/ClarkMcGrew/edep-sim
- Digitization, Reconstruction and Analysis: independent tools: (https://baltig.infn.it/dune/kloe-simu)

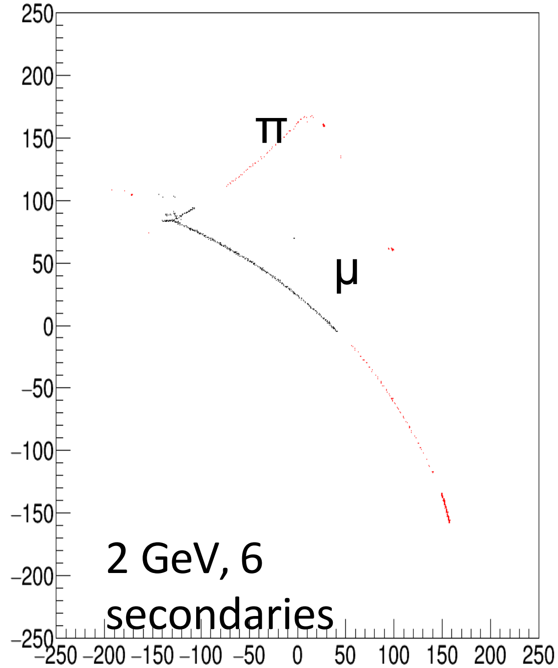
SAND Geometries (STT, 3DST+STT)



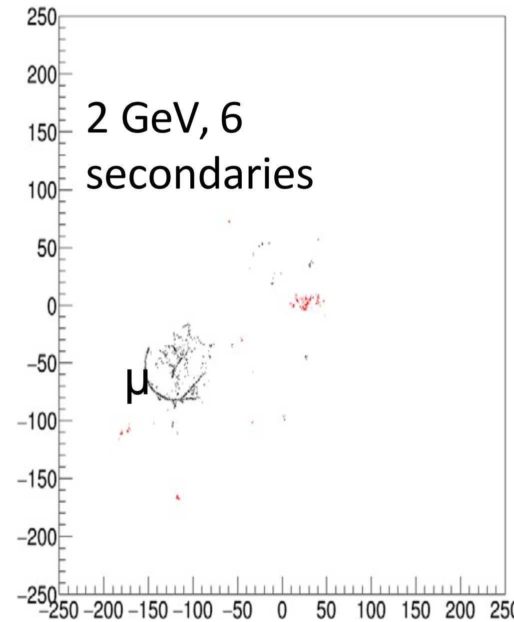


Example events





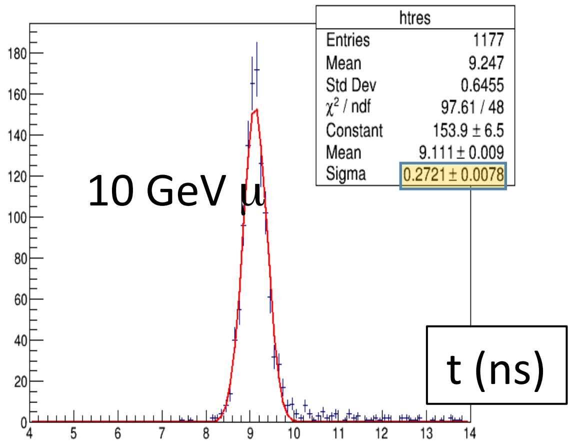
Output: energy in 1cm cubes, and time
Will reuse 3DST software for light yield and digitization.



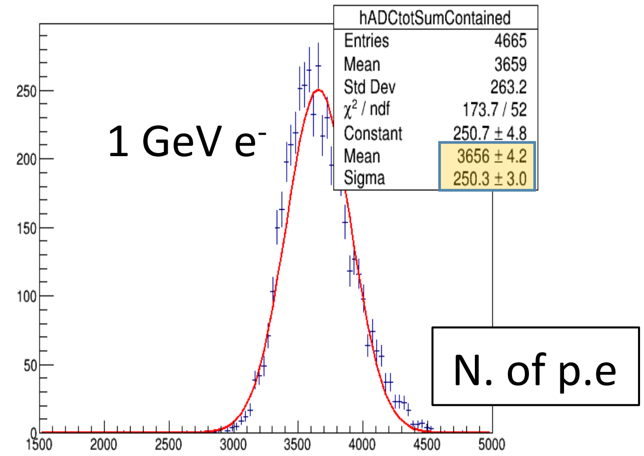
Black: Edep in 3DST
Red: tracker and Calo

G4: Calorimeter simulated performances

- Time and e.m. energy resolution measured by KLOE collaboration are well reproduced by MC simulation with muons and electrons.



The resolution is 260 ps, in agreement with a scaling law of $\sim 54\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})}$ considering a 40 MeV equivalent energy release.



an energy resolution of $5.7\%/\sqrt{E(\mathrm{GeV})}$

10.1016/S0168-9002(01)01502-9

Fluka Digitization

- The hits from simulations are grouped in cell
- Generation and propagation of light from the interaction point to the PMTs, taking into account scintillation time and attenuation length for different planes
- The visible energy is converted in Npe
- The Npe are propagated inside the fiber

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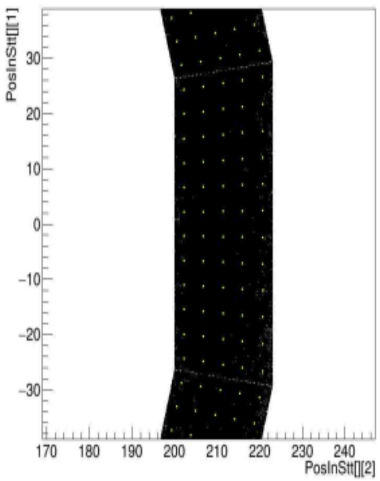
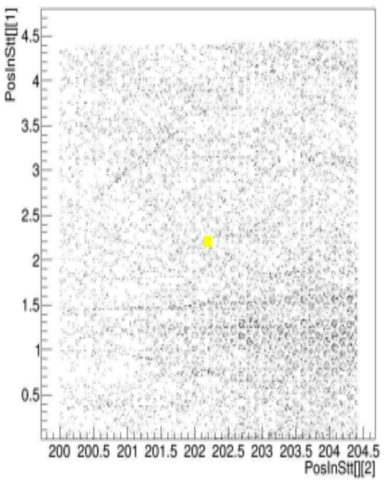
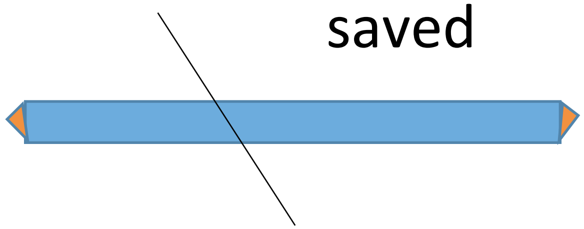




Only the hit in the fibers are saved



- Final information:

average time and Npe at each pmts

Reconstructed information:

interaction time

$$t\ (\mathrm{ns}) = \frac{t^A + t^B}{2} - \frac{t_0^A + t_0^B}{2} - \frac{L}{2v}$$

interaction position along the cell

$$s\ (\mathrm{cm}) = \frac{v}{2}(t^A - t^B - t_0^A + t_0^B)$$

π^0 from ECAL (Fluka)

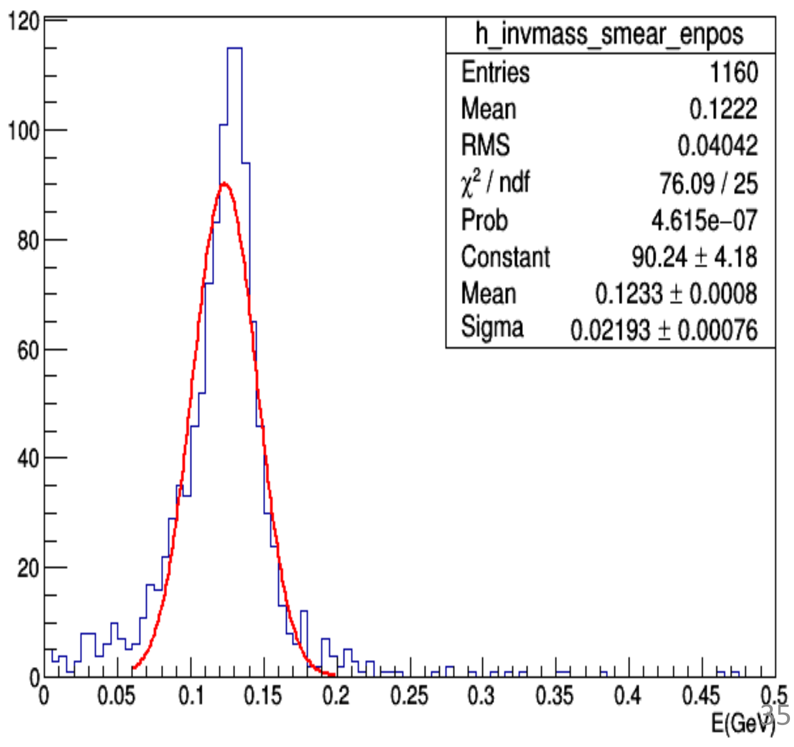
Reconstructed CC sample: 20000 events

1 π^0 27% of events

2 π^0 8% of events

> 2 π^0 2.5 % of events

2 π^0 sample: π^0 invariant mass,
Considering only 4-cluster events



Resolutions:

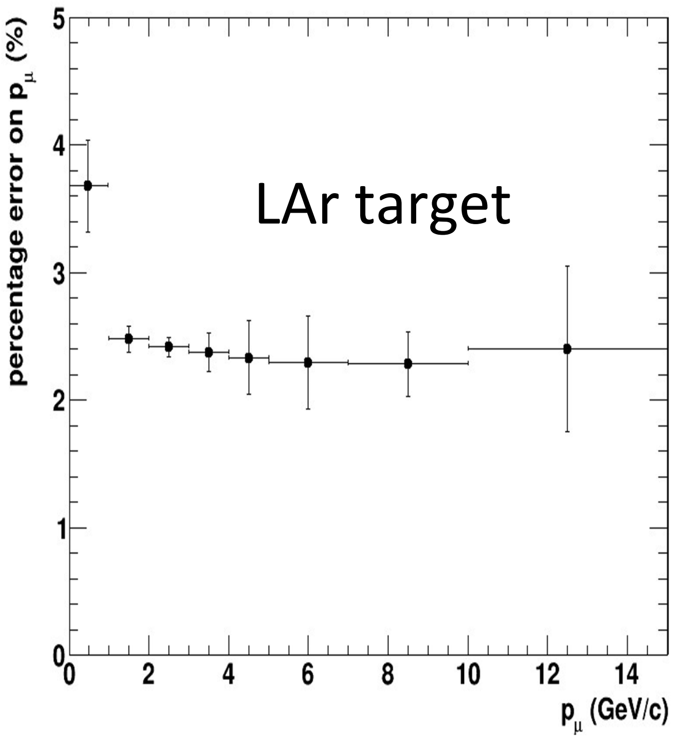
1 π^0 16.8%

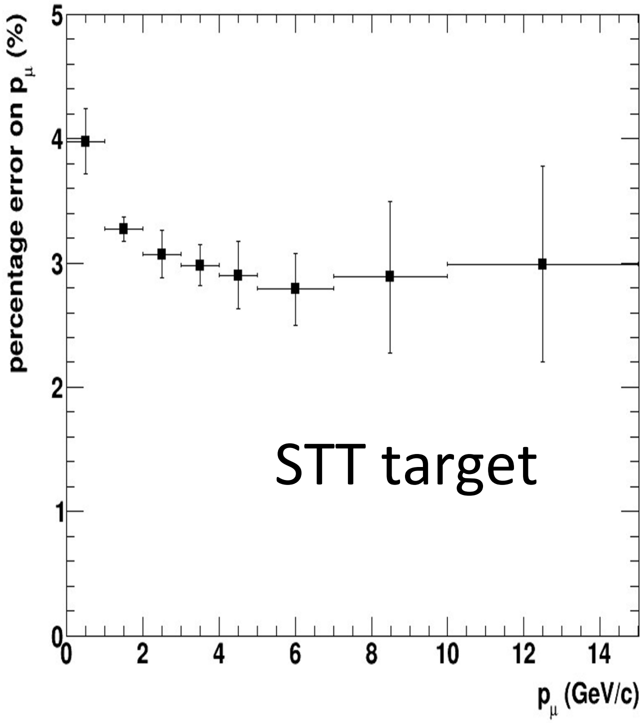
2 π^0 17.7%

3DST signal

- Work in progress to include 3DST response in the Fluka-based software
- For the moment:
  - Energy deposition in $1cm^3$ cells
  - Same, with quenching of the signal according to “reasonable” Birks parameters for plastic scintillator

STT results: muons





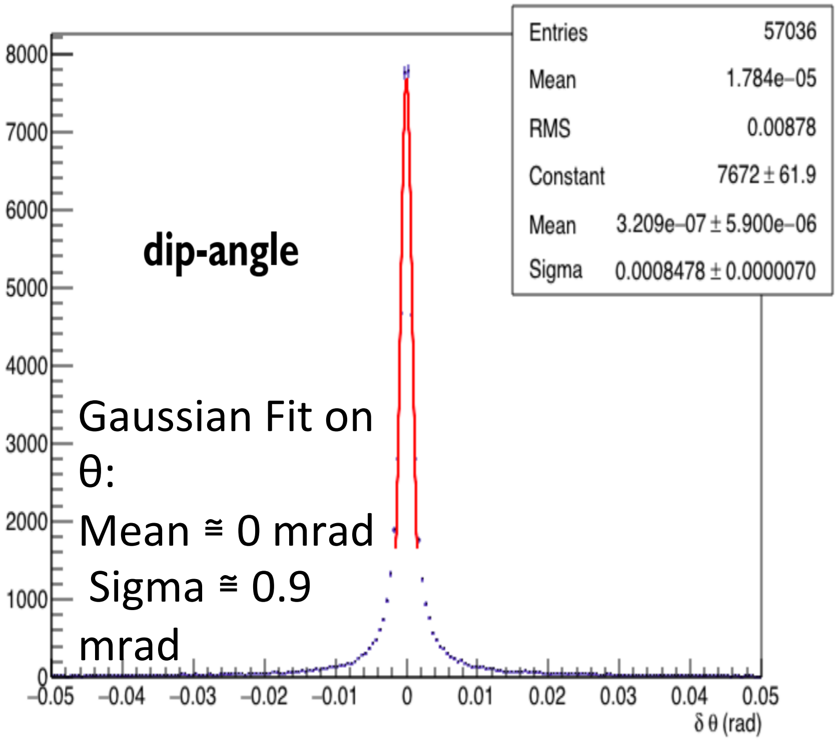
Good resolution on p (~3%) for both targets
Good resolution on dip angle ~1.7 mrad

Charge mis-id ~0.02%

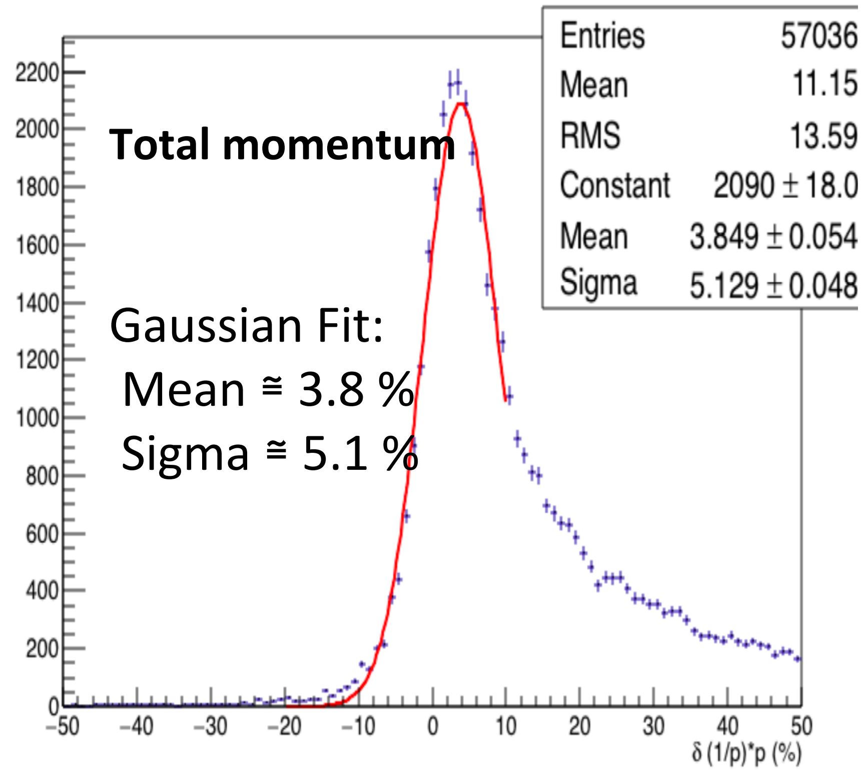
Same results with GEANT4

STT results: electrons

Generated in STT with GENIE+GEANT4. Very good resolutions, tails due to circular fit approximation to be improved i.e. with Kalman filter.



Wrong sign 1.3%



Same results with FLUKA

Fluka based full reconstruction –no MC truth

- Interaction Vertex based on STT-hit topology (Step 0)
- Track finding (Global transform method)
- Linear or circle fits to track
- Vertex reco from crossing on two most rigid tracks (Step 1)
- Iteration…

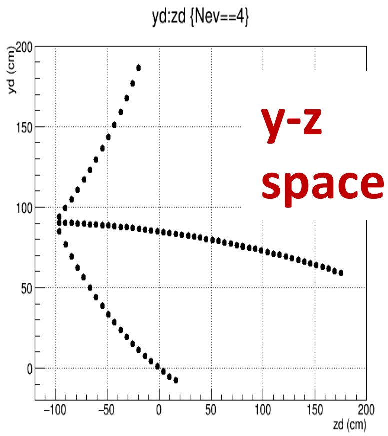
On two views

- Matching of tracks in the two views → tracks in 3D
- Evaluation of $p_{\perp}$ and dip-angle ➔ p estimate
- Ecal hit compatible with tracks ➔ ToF measurement ➔ β estimate➔ PiD

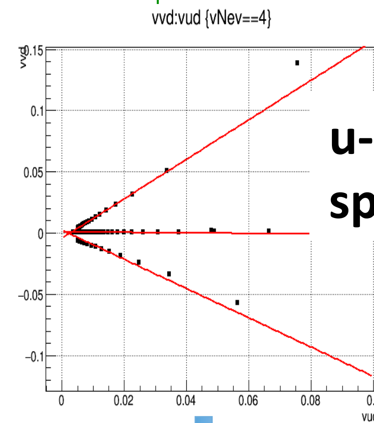
From Vertex to Track reconstruction, no MC truth

Coordinate transformation by using reco-Vertex (z_V,y_V):

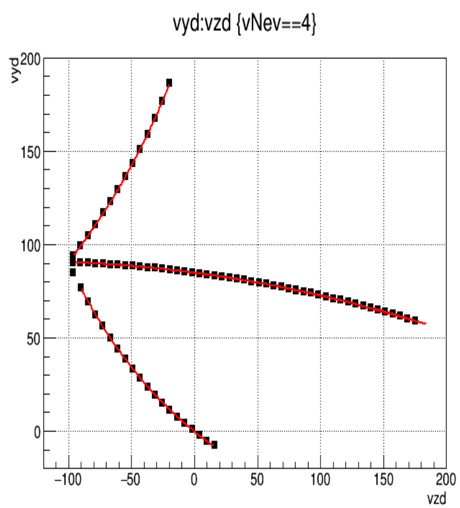
$$u = +(z-z_V) / [(z-z_V)^2 + (y-y_V)^2]^{1/2}$$
$$v = -(y-y_V) / [(z-z_V)^2 + (y-y_V)^2]^{1/2}$$



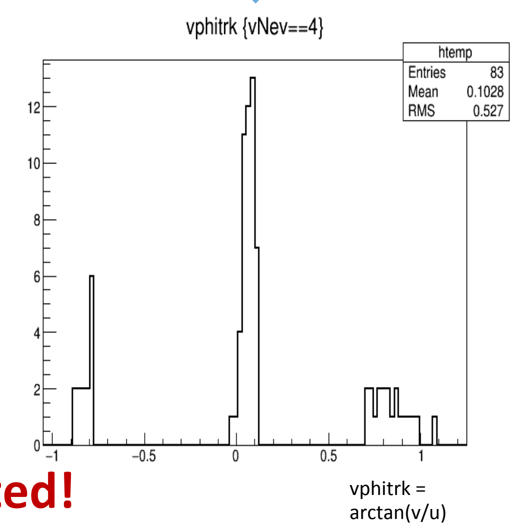
Curved trajectories become straight lines



Two-step method: first rough vertex finding, allows for coordinate transform peaks in ϕ correspond to tracks Second vertex finding from track intersection



Track finding and fits

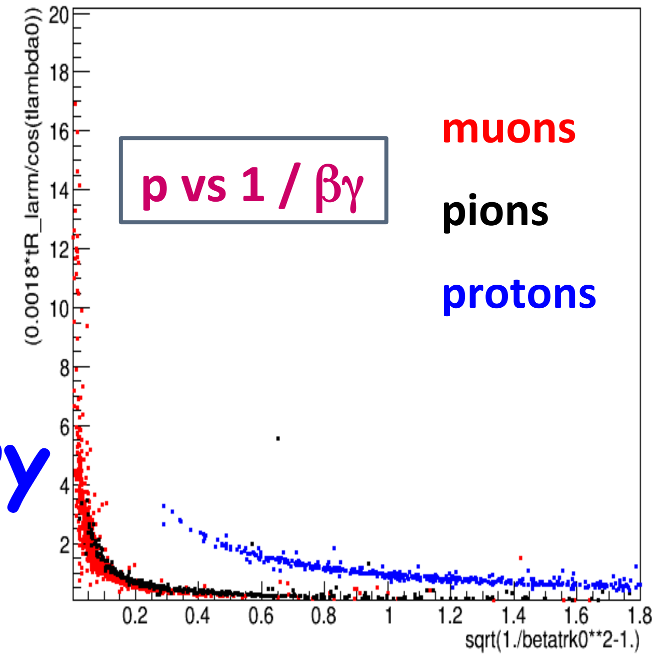


ϕ=arctan(v/u)

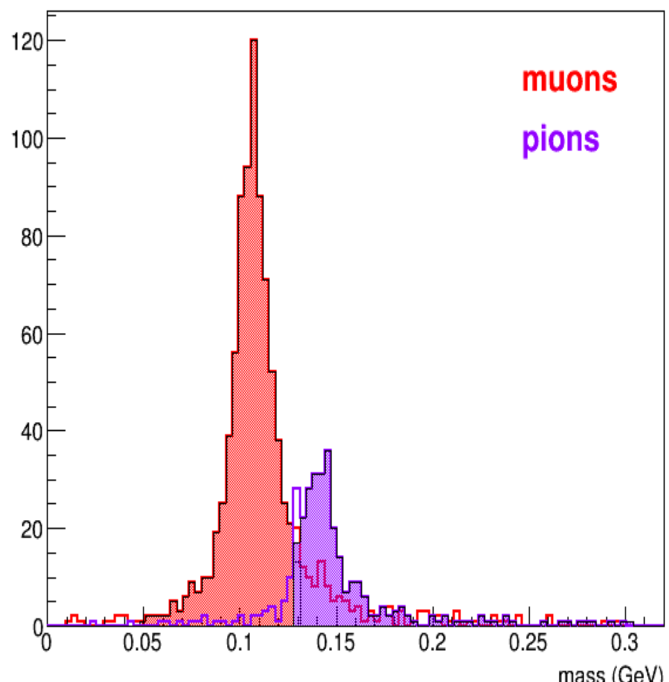
Each peak identifies a track

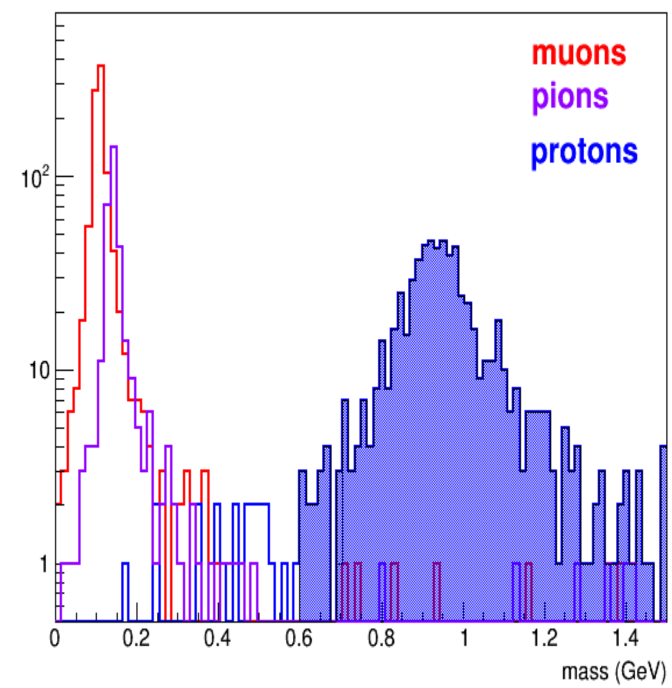
Each trajectory is fully reconstructed!

Mass reconstruction and PiD

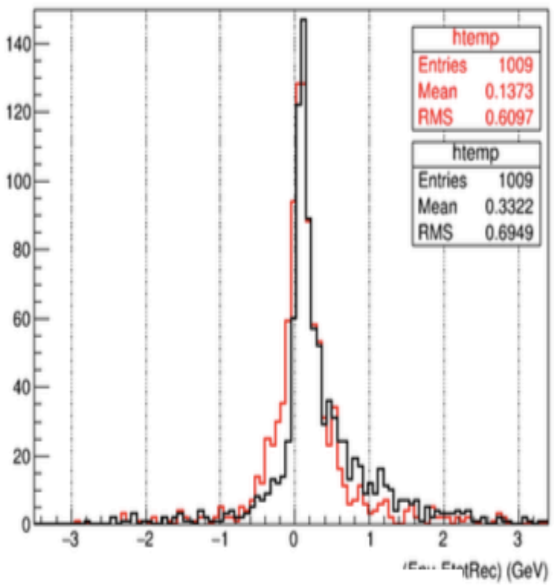


preliminary





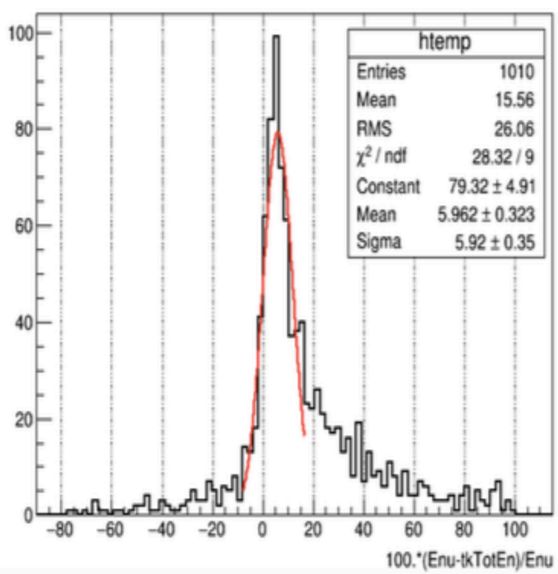
ν energy reconstruction (preliminary)

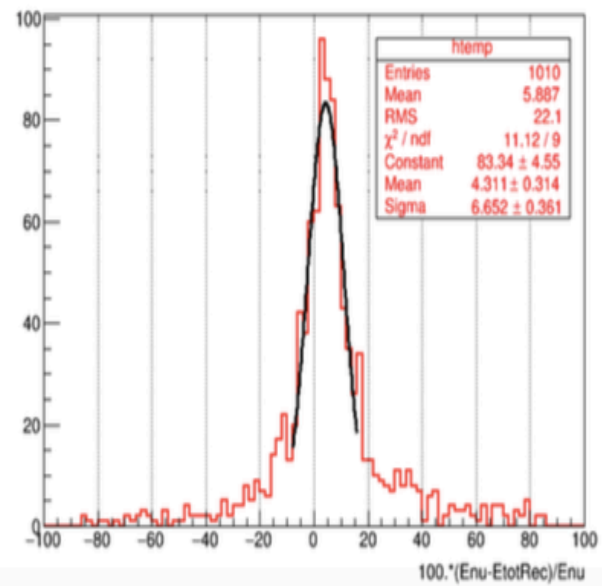


'All-tracks' energy only

'All-tracks' energy +
Off-track Calo energy

NO MC truth
$\sigma/E = 6.6\%$



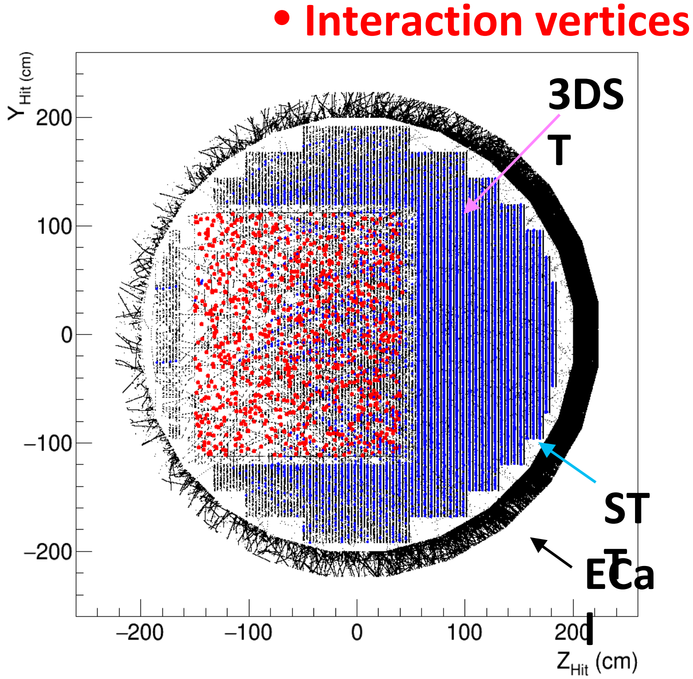


Preliminary background estimate from CC external interactions for SAND detector

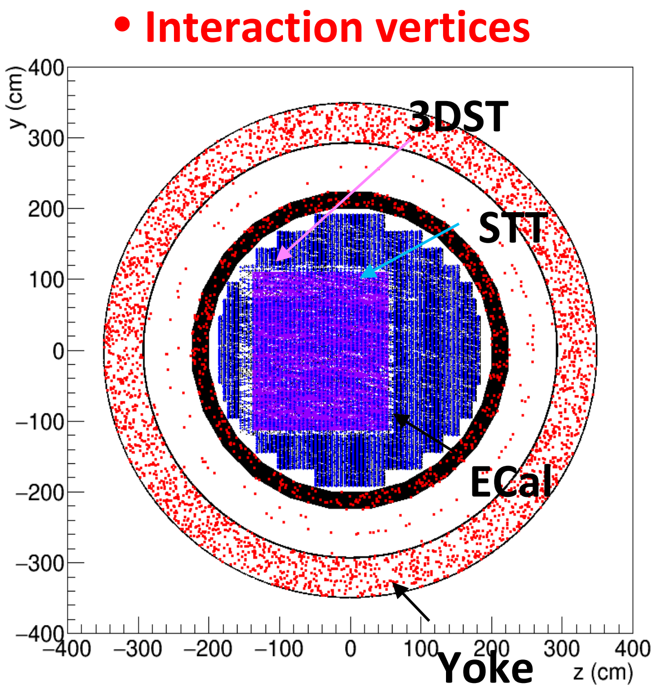
MC samples by FLUKA

"Internal" events: ν_μ (CC) interactions inside 3DST

"External" events: ν_μ (CC) interactions inside KLOE magnet+Calorimeter (ECal)



Target mass: 10.6 tons



Target mass: 770 tons

Selection of internal events

- Based on Relative time between ECal and 3DST (difference $\Delta T_{1st} = T_{1st}^{Cal} - T_{1st}^{Sc}$)

- Expected background from external interactions:

  Bck_1: Time " reversal" ($T_{1st}^{Cal} > T_{1st}^{Sc}$)

  Bck_2: T^{Cal} missing in the event

- Background rejection cuts

  1) Fiducial Volume cut on 1st 3DST-hit position

  2) Cut on 3DST-hit multiplicity

Results (preliminary)

Preliminary background estimate using:

1) $\Delta T_{1st} = T_{1st}^{Cal} - T_{1st}^{Sc} > 1ns$

2) Fiducial Volume cut on 3DST (1st hit position)

(10cm cut on X sides) ⊗ (15cm cut on Y sides) ⊗
(20cm cut on Z front side and 10cm cut on Z rear side)

68%

3) ($N_{Scin} > 30$) (negligible effect on signal after FV)

$Bck_{beam} \sim (1.4 \pm 0.4)$ %
(from CC interactions in magnet and Calorimeter)

What next?

- Study the performances of the tracker configurations, assessing their merits and their potential shortcomings for the physics signals and the backgrounds.
- Validate simulations with the ongoing and future prototypes data.
- Provide a realistic engineering design, evaluate tracker cost
- Provide a complete set of KLOE drawings, operation manuals, specs to the FNAL engineers. Harmonize and update all the relevant certifications, safety codes, etc.
- Decide what to keep and what to change in the KLOE electronics and DAQ. Do a detailed spare inventory.
- Contribute to the write-up of the CDR.

THANK YOU