A high-performance electromagnetic calorimeter for neutrino physics in the DUNE Near Detector complex

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on behalf of the DUNE collaboration

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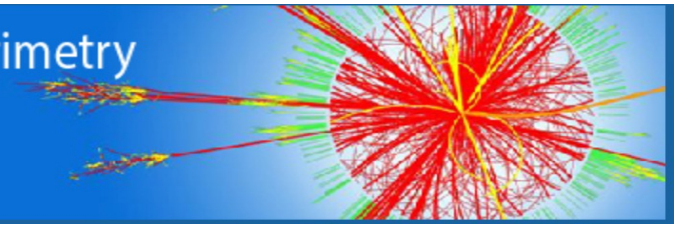

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Overview

- The KLOE electromagnetic calorimeter
  - general description
  - achieved performance

- The DUNE experiment and the Near detector complex
  - the role of the electromagnetic calorimeter in SAND
  - the expected performance
  - DUNE sensitivity

Some history

- **KLOE** was designed for high precision Kaon and hadron physics at DAFNE Φ factory of the Laboratori Nazionali di Frascati (Italy)
- Data taking:
  - KLOE (1999 – 2006), KLOE- 2 (high lum.) (2014- 2018)
- A lot of **very important results** based on K and η decay observation:
  - **CPT symmetry test:** by measuring the $K_S \rightarrow \pi e \nu$ decay charge asymmetry

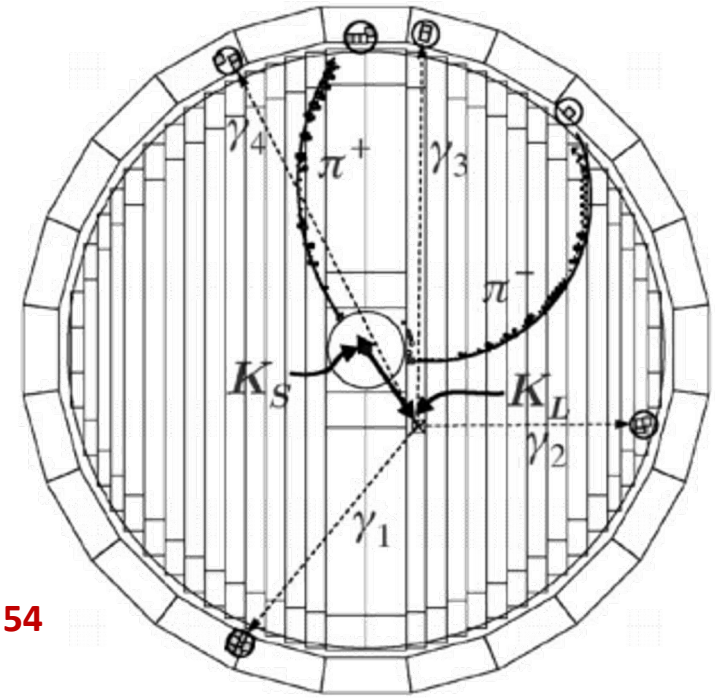
$$BR(K_S \rightarrow \pi e \nu) = (6.91 \pm 0.37) \times 10^{-4}$$

  - **CP violation**:
    - by the experimental limit on the $K_S \rightarrow \pi^0 \pi^0 \pi^0$ decay **JHEP12(2006)011**
    - by measuring the branching ratio of the $K_L \rightarrow \pi^+ \pi^-$ decay **PLB 723 (2013) 54**
    - by searching for the decay $\eta \rightarrow \pi^+ \pi^-$ **JHEP10(2020)047**
- High precision (0.1%) test of **unitarity of CKM matrix**

$$1 - |V_{ud}|^2 - |V_{us}|^2 = 0.0004 \pm 0.0007$$

JHEP04(2008)059

L=8 fb^{-1} => 2.4 10^{10} ϕ decays
O(8 10^9) K_s K_L pairs

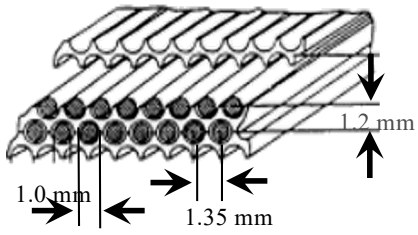


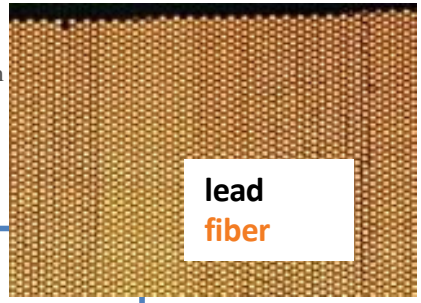
$\Phi \rightarrow K_S K_L$
$K_S \rightarrow \pi^+\pi^-$ $K_L \rightarrow \pi^0\pi^0$

The KLOE ecal

- **Structure**: made by an optimized composite of scintillating fibers (∅ 1.0 mm, λ_{Peak} ≈460nm) immersed in 200 grooved lead foils 0.5 mm thick

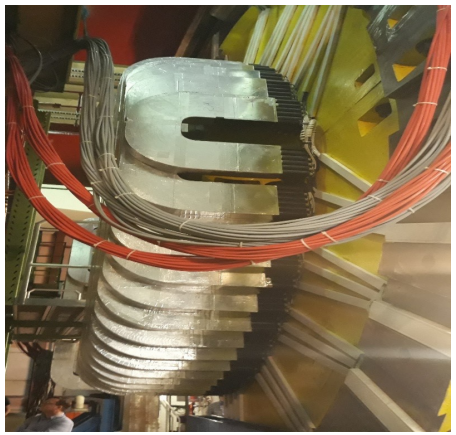
Volumetric ratio: lead: fiber:glue = 42:48:10

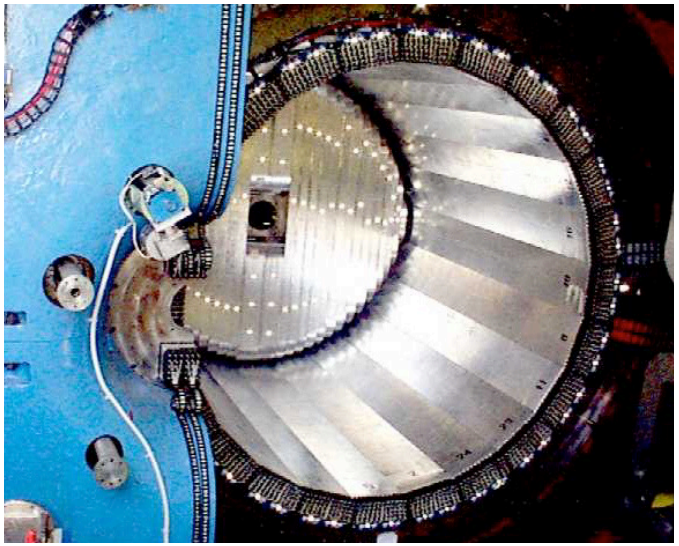




Average density: 5 g/cm^3
Radiation length: 1.5 cm
Total width ≈ 15 radiation lengths

- **Dimensions**: ∅ $4m$, L=3.4 m
  - 4 π coverage
  - Total thickness: 23 cm
  - Barrel: 24 modules
    - 60 cells each
    - 5 planes
    - H:4.4-5.3 cm – W:4.4 cm – L:4.3 m
  - Endcap: 32 modules
    - 10-15-30 cells each



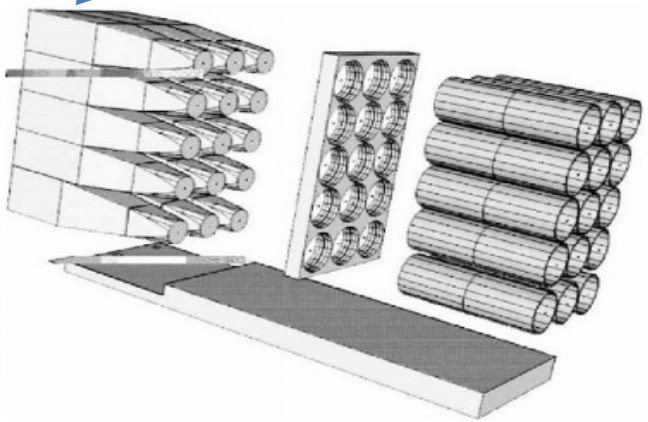


NIM A482, 1-2 (2002)

The readout

- 2 PMTs (1,5 inch) for each cell on both sides
  - 2880 channels for barrel
  - 2000 channels for endcaps
- ADC for charge signals and TDC for time signals
- Energy threshold: (100 keV)

Light guides for matching with cylindrical PMTs



4880 Photomultipliers
very stable in low magnetic field

HAMAMATSU | PHOTOMULTIPLIER TUBE R5946

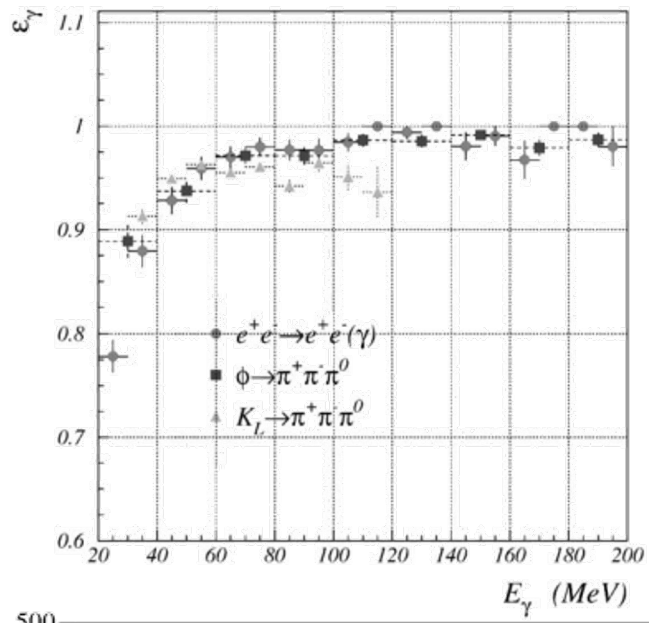
Stable Operation in High Magnetic Fields beyond 1 Tesla
38mm(1–1/2 Inch) Diameter, Proximity Photocathode and Fine Mesh Dynodes

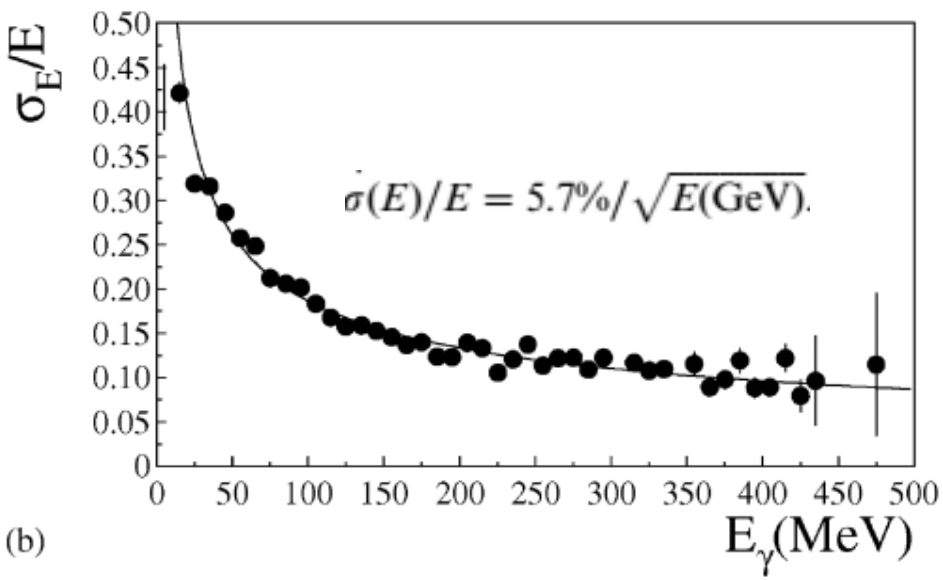
- Reconstructed time $$t\ (\mathrm{ns}) = \frac{t^A + t^B}{2} - \frac{t_0^A + t_0^B}{2} - \frac{L}{2v}$$
- Reconstructed position $$s\ (\mathrm{cm}) = \frac{v}{2}(t^A - t^B - t_0^A + t_0^B)$$

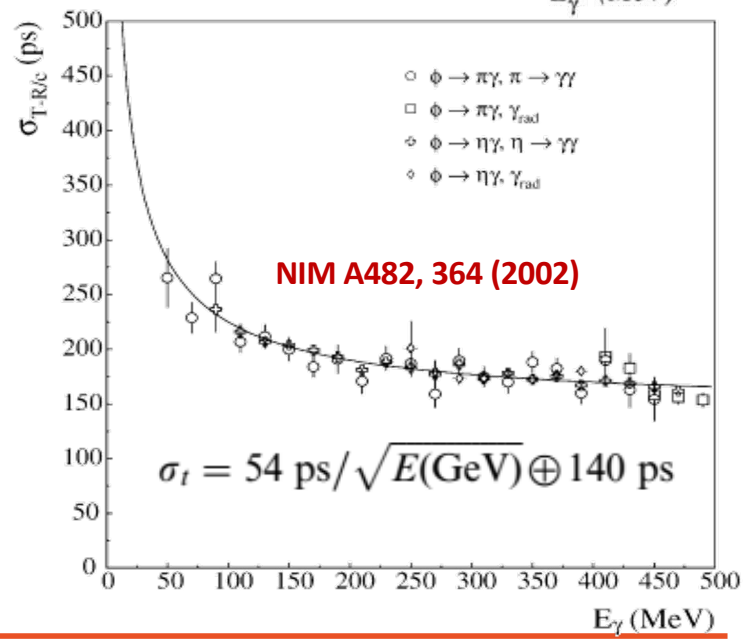
v and t_0 precisely calibrated with muons

Demonstrated performances in KLOE

- high efficiency for gamma detection
- high resolution for shower vertex identification (due to the high granularity)
- excellent time resolution
- excellent energy resolution (25 p.e/MeV for MIP)

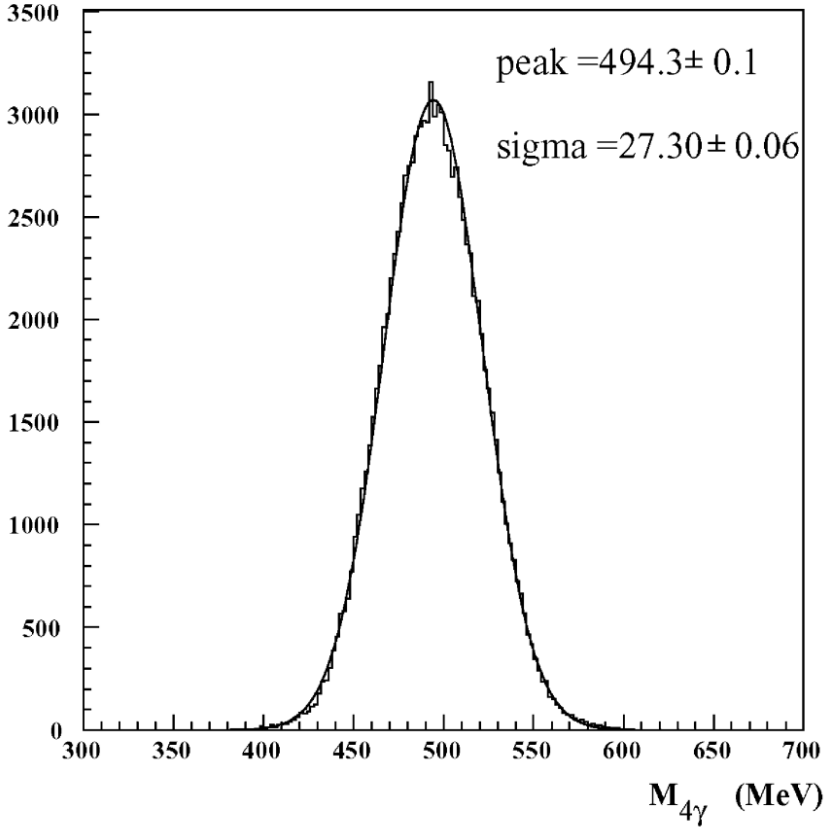






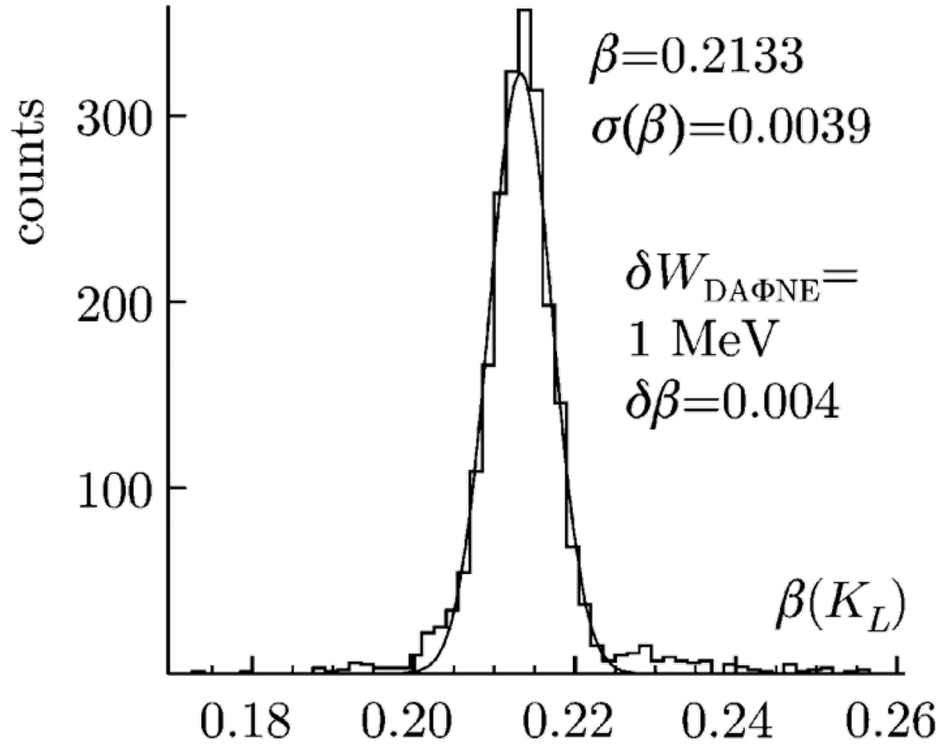
Demonstrated performances in KLOE

K_S mass from photon energy in $K_s \rightarrow \pi^0\pi^0$ events



NIM A482, 364 (2002)

β spectrum of K_L interacting in the ecal (by time-of-flight)

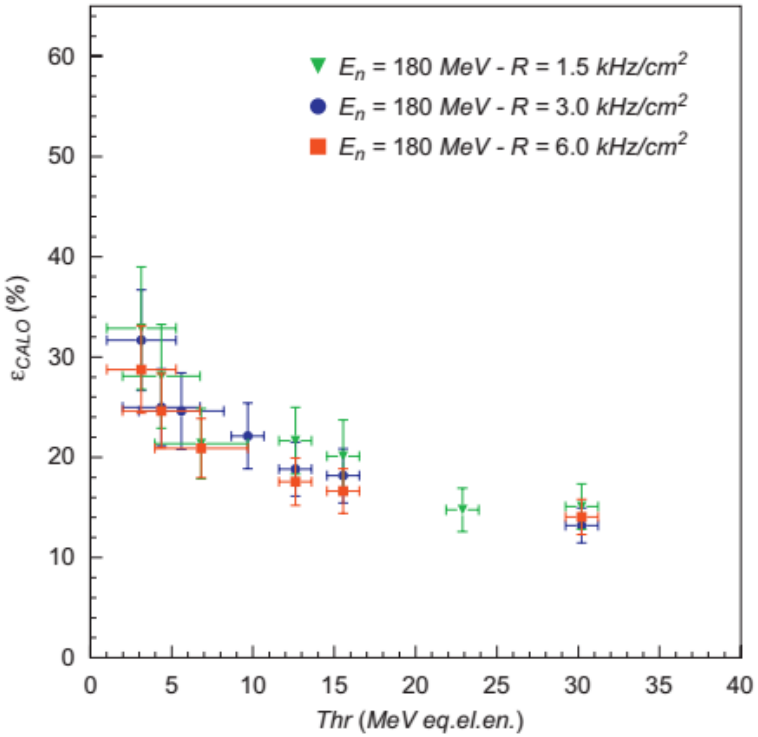


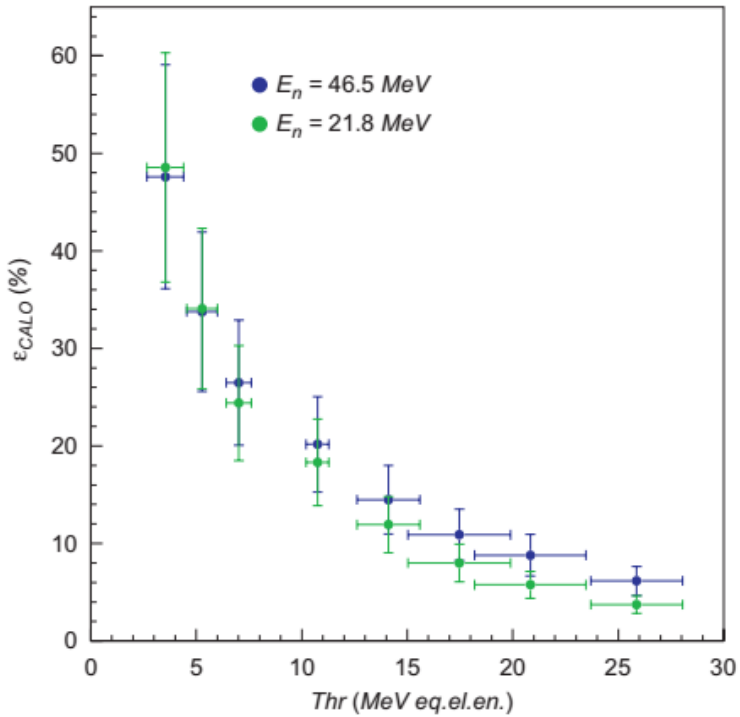
useful for detecting K_L and

to monitor the variations in the center of mass energy of DAFNE

Neutron detection efficiency

- Tested with neutrons in 20-200 MeV energy range



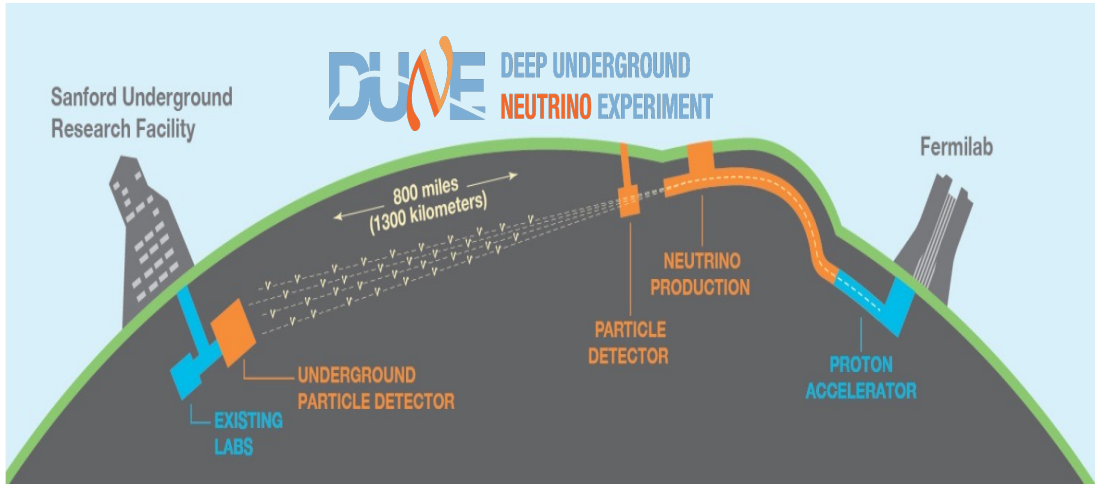


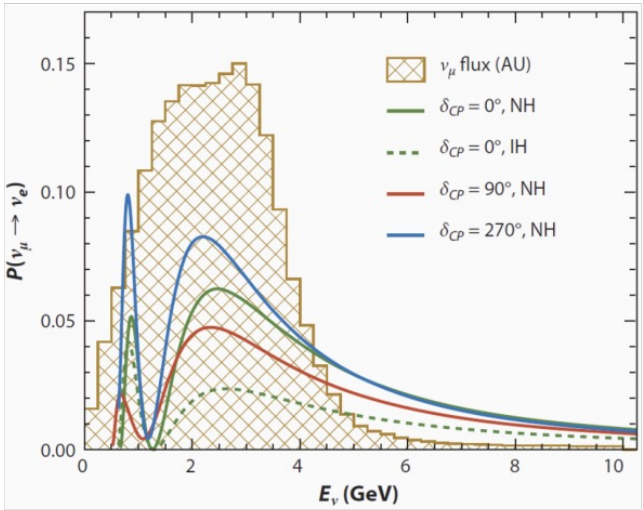
NIM A 598 (2009) 244–247

- huge inelastic production of neutrons on the lead planes
- secondary neutrons, protons and photons that contribute to the visible energy thanks to the fine granularity structure

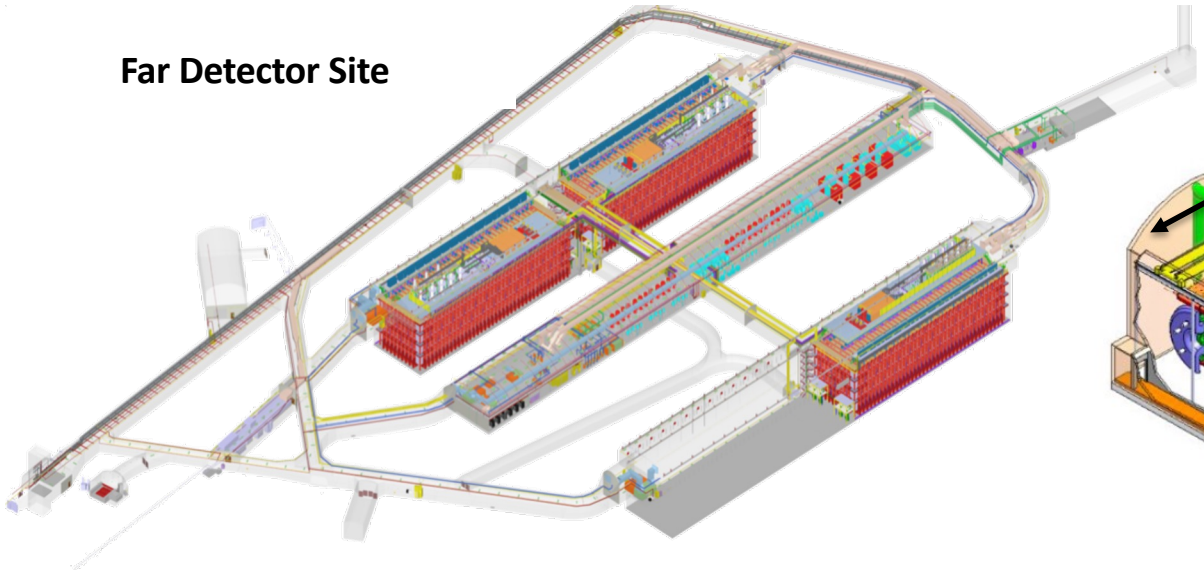
DUNE: Deep Underground Neutrino Experiment

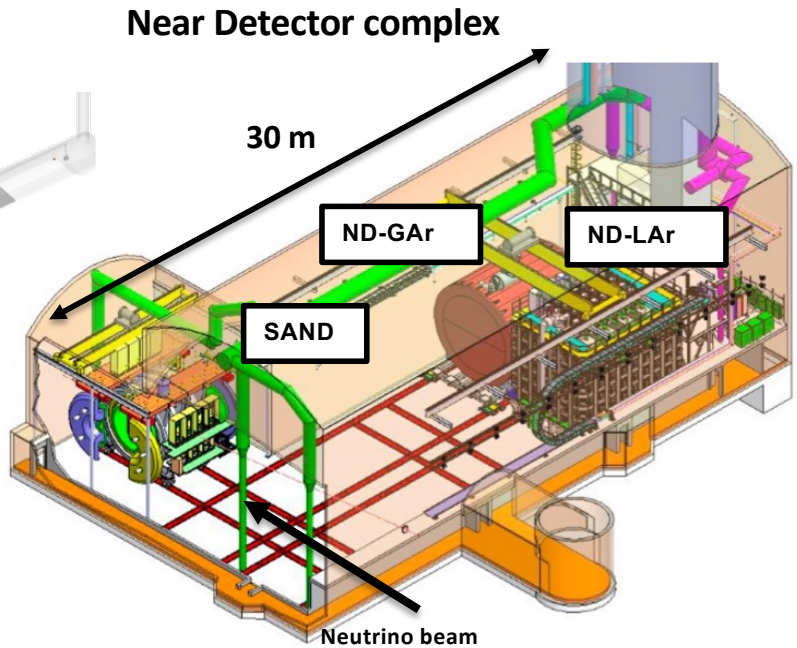
- **Main goals:**
  - Precisely measurement of the $\nu_\mu/\bar{\nu}_\mu$ oscillation probability to discover CP violation in neutrino sector, mass hierarchy, θ_{23} angle octant
  - Observation of supernovae neutrinos
  - Obervation of proton decay
- **Experimental apparatus:**
  - Long-baseline Neutrino Facility al Fermilab:
    - **high intense neutrino beam** 1.2 MW – 1.1 x 10^{21} POT/year (upgrade to 2.4 MW**)** with **wideband** spectrum (energy peak at 2.6 GeV)
  - **Far Detector** at 1300 km from **Near Detector:** to uniquely identify the different effects (mass hierarchy and CP violation) in the oscillations





The experimental apparatus



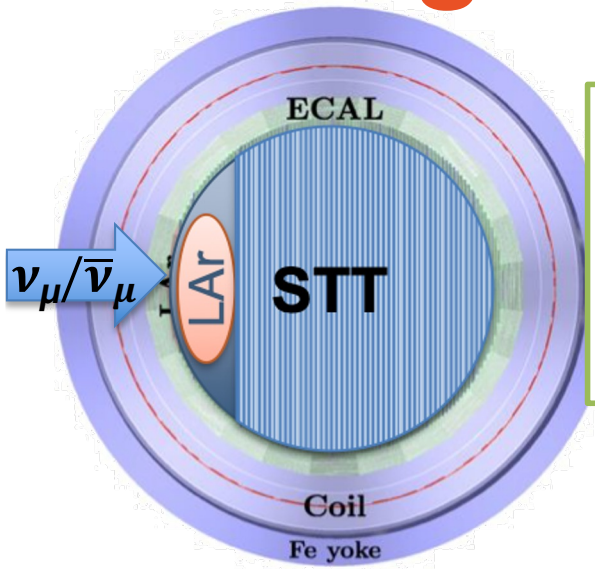


- → **4 modules**: liquid Argon time projection chamber, 17 kton mass each (15 m X 15 m x 64 m)
- → They will be installed at **Sanford Underground Facility** in South Dakota, 1.5 km underground
- → EVENTS: 3000 ν_μCC/year, 250 ν_eCC/year

- → Near Detector complex at **Fermillab** (600 m far from the beam target).
- → 3 detectors:
  - → ND-LAr, ND-GAr movable out of axis
  - → SAND permamently on-axis
- → EVENTS: O(10^8) CC events/year in ND-LAr, O(10^6) CC events/year in ND-GAr/SAND

The KLOE calorimeter and magnet will be re-used in the SAND detector

SAND geometry: GRAIN+ECAL+STT



→ **ECAL** +

→ **MAGNET**

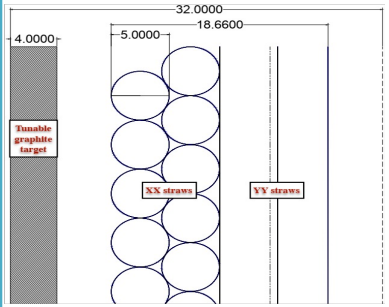
superconducting coil B = 0.6 T

mass: 475 tons

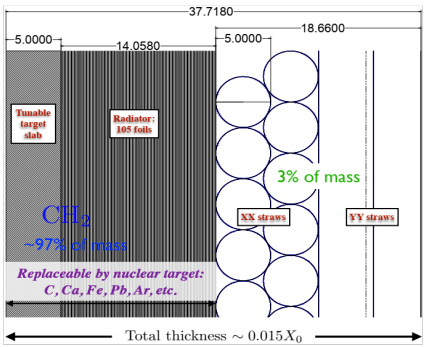
→ **Straw Tube Tracker (STT)** ∅ 5 mm

90 modules interleaved by carbon target or CH_2 target (**5 ton**) + transition radiator detector

Carbon target module

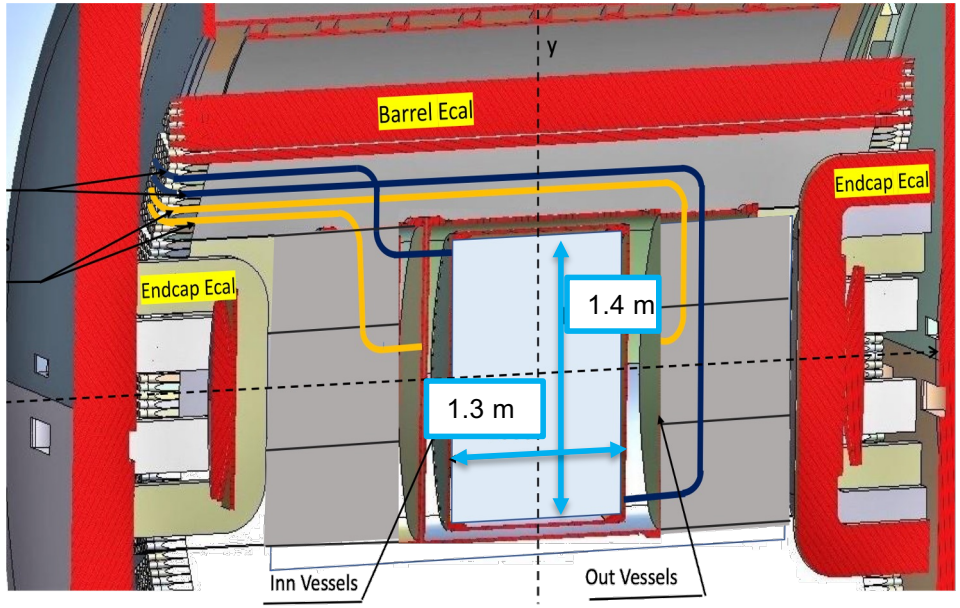


CH_2 target + radiator module



→ **GRAIN**: GRanular Argon for Interactions of Neutrinos

1 ton LAr cryostat in the upstream volume



instrumented with :

- SiPMs only
- or with SiPM matrix coupled to an optical focusing system (R&D under development)

The role of the ecal in SAND

SAND main goals:

- monitor for beam parameter changes on a weekly basis

by using **interactions in ecal** (23 ton) in the upstream part

- collect **interactions on Carbon** and on **CH_2** target in STT
- collect interactions **on Argon**
- for cross-section studies on different targets (C, H, Ar)
- for ν_μ , ν_e , $\bar{\nu}_\mu$, $\bar{\nu}_e$ on-axis flux measurement

ecal fundamental for:

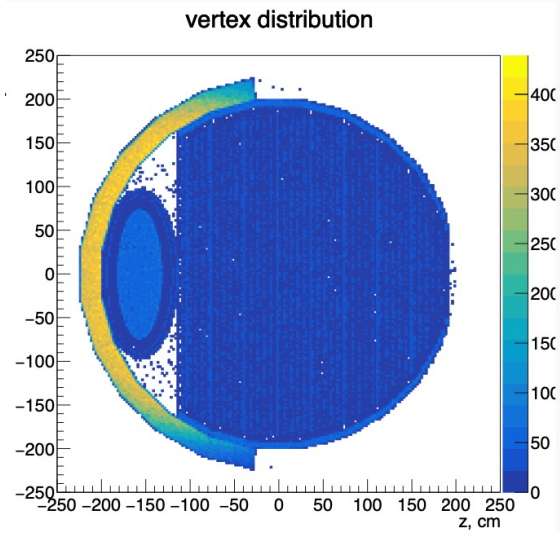
- **neutral particles** detection (neutrons, gamma),
- for **particle** identification
- for **time information** for background reduction

Target	CP optimized FHC (1.2MW, 2y)				CP optimized RHC (1.2MW, 2y)			
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC
CH_2	13,010,337	624,330	192,118	31,902	2,035,973	4,870,562	91,004	69,278
H	1,222,576	111,574	18,396	5,557	194,216	906,130	8,712	12,434
C	1,547,011	67,294	22,799	3,458	241,710	520,287	10,800	7,460
Ar	3,114,331	121,506	46,384	6,503	480,862	936,489	21,932	13,867
Pb	62,127,600	2,507,940	923,012	130,680	10,375,400	18,222,200	437,284	265,304

The ecal as a target

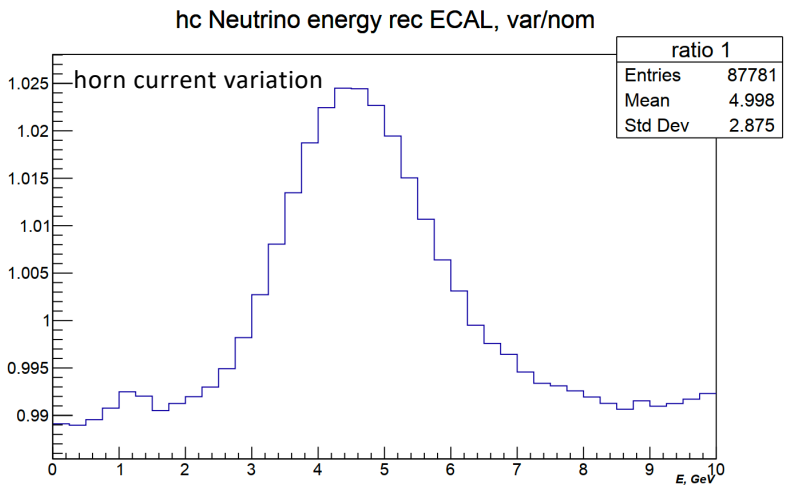
for beam monitoring

- Interactions on **front-ECAL** + STT + GRAIN
  - → for beam monitoring on a **weekly basis**
  - → by studying the neutrino spectrum variations



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

Detector	Simulated events	Reconstructed events	Efficiency
STT	299363	299152	~1
GRAIN	79715	71104	0.9
ECAL	1071508	647045	0.60



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

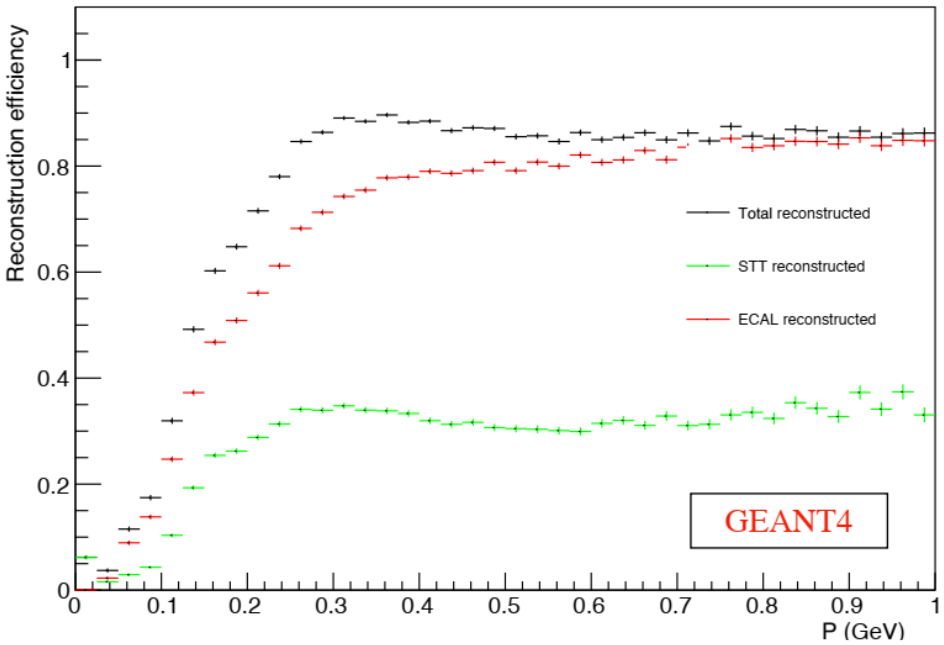
SAND is also sensitive to 0.13 mrad changes in neutrino beam direction

DUNE DocDB:13262-v7

SAND expected performances

an interplay between ecal and STT

Neutron detection efficiency



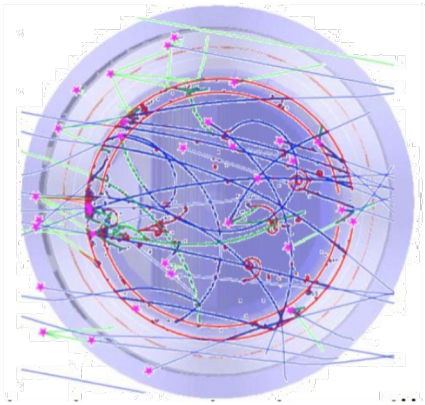
Target	QE	RES	DIS	Total
Carbon	64.8 %	76.5 %	80.1 %	73.6 %
Hydrogen	80.5 %	85.0 %	87.4 %	82.3 %

- Good detection efficiency for neutrons in the **ecal and STT**:
  - energy evaluation by time of flight measurement
- Good **p/π/K** identification capability by dE/dx and range in **ecal and STT**
- High **π^0 detection efficiency** from gammas detection in **ecal and STT**
- High **detection efficiency** for charged particle tracks in the bending plane by **STT** $\Delta p/p \leq 3\%$, $\Delta\theta/\theta \leq 1.5$ % mrad
- Good **e/π** identification capability thanks to the transition radiation detector ($e/\pi \sim 10^{-3}$)

Background rejection and event time identification

$\nu/\bar{\nu}$ interactions induced by the beam in the materials result in:

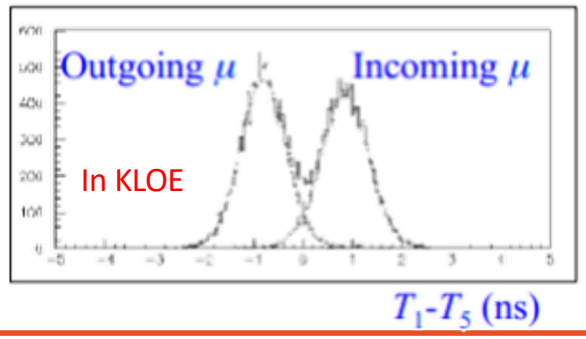
- random particles (mainly neutrons) overlapping with a (anti)neutrino interaction in SAND within a single beam spill (10 us)
- external neutrino interactions misidentified as internal interactions

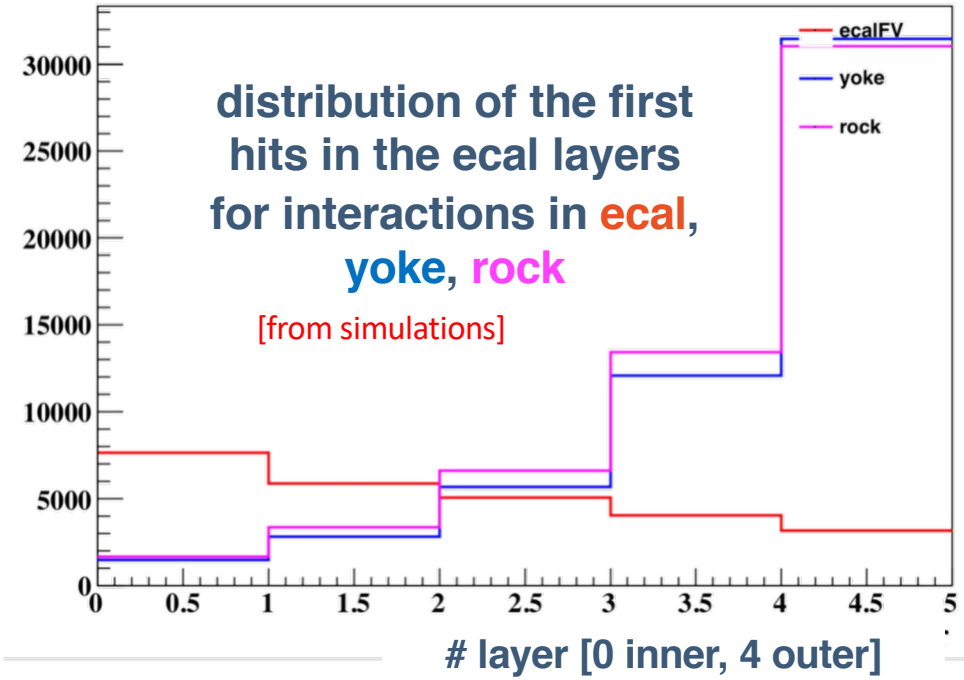


simulation of ν interaction in a spill

Detector element	Mass	FHC	RHC
Magnet	511 t	68.9	36.6
ECAL	100 t	13.5	7.2
LAr+STT	8.2 t	1.1	0.59
STT fiducial volume	5.5 t	0.74	0.39
Total	619.2	83.5	44.39

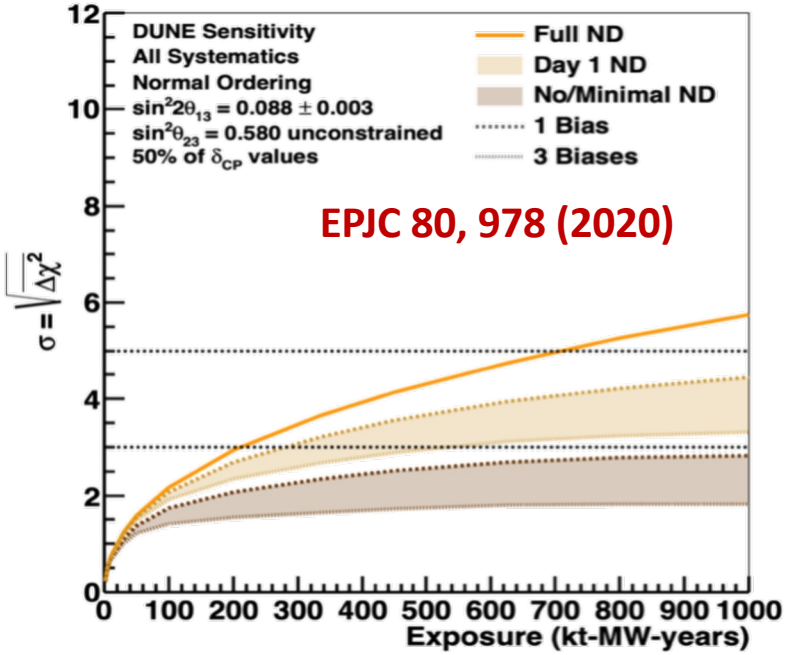
but the events are well separated in time!
the **ecal is fundamental to identify external tracks!**

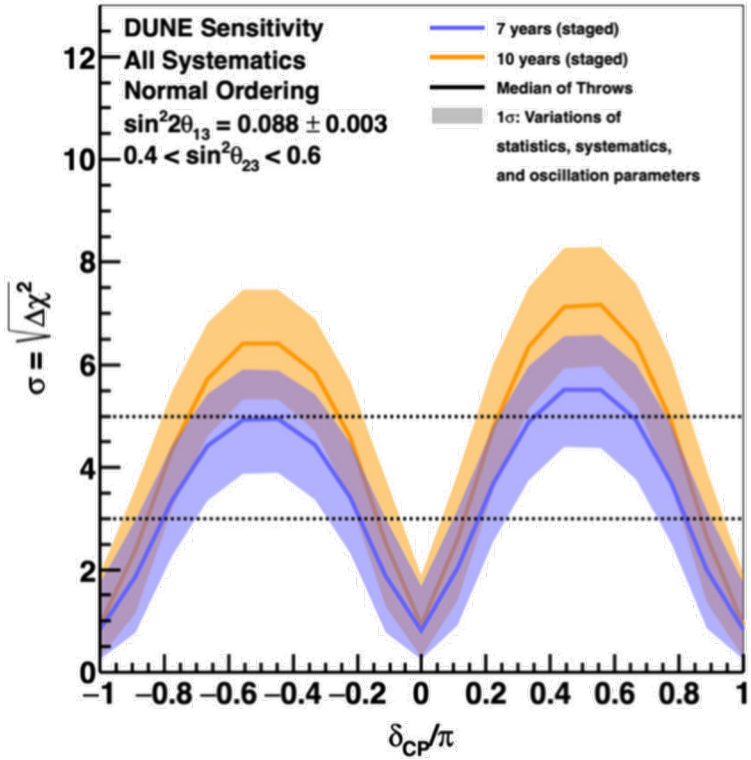




Expected DUNE sensitivity

The Near Detector Complex is designed to provide **robust and complementary** measurements of **flux and spectrum** of all neutri**no flavour** for constraining **nuclear effect** and **tune** neutrino interaction **model at GeV energy**





FD flux — Cross-section — detector response

$$\frac{dN_x^{FD}}{dE_{rec}}(E_{rec}) = \int \Phi_{\nu_\mu}^{FD}(E_\nu) P_{\nu_\mu \to x}(E_\nu) \sigma_x^{Ar}(E_\nu) T_x^{FD,Ar}(E_\nu, E_{rec}) dE_\nu$$

Oscillation probability

in order to reduce systematics to few % level for a **data driven** long-baseline oscillation analysis for measuring δ_{CP} **in 7-10 years of data taking**

Conclusions

- The KLOE electromagnetic calorimeter has shown **high performance** in term of:
  - energy resolution
  - time resolution
  - neutral particle detection
- all of these are fundamental properties for **neutrino interaction detection** in SAND

- Currently the SAND consortium is planning to dismounting the apparatus and to refurbish the magnet and the electromagnetic calorimeter
- for preparing the **future installation within the SAND** detector in the DUNE Near Detector complex

Start of the operations

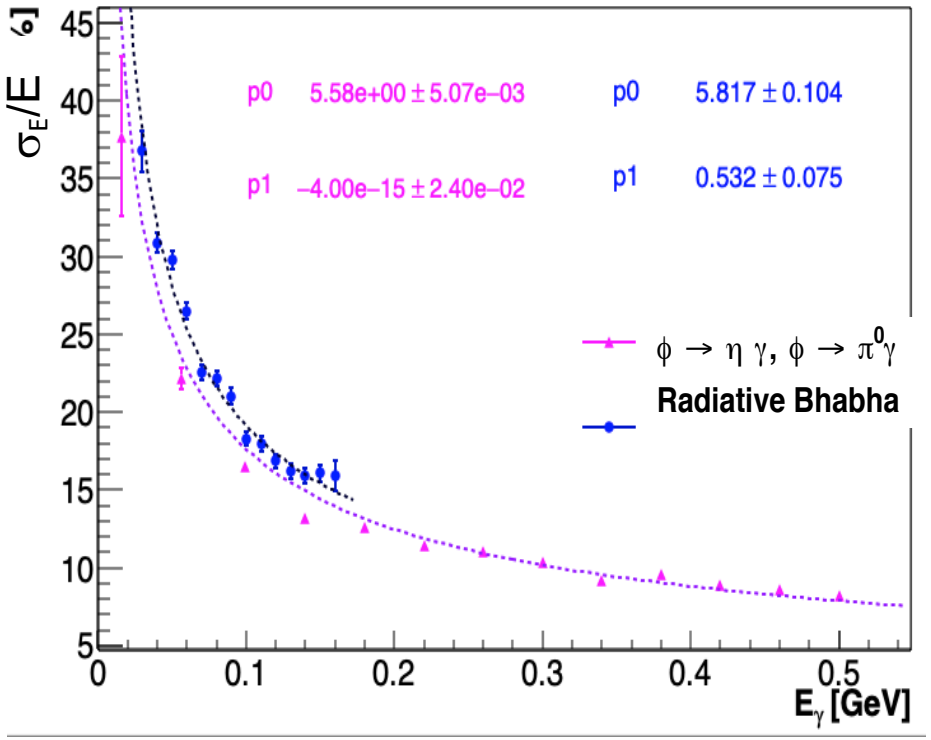
backup

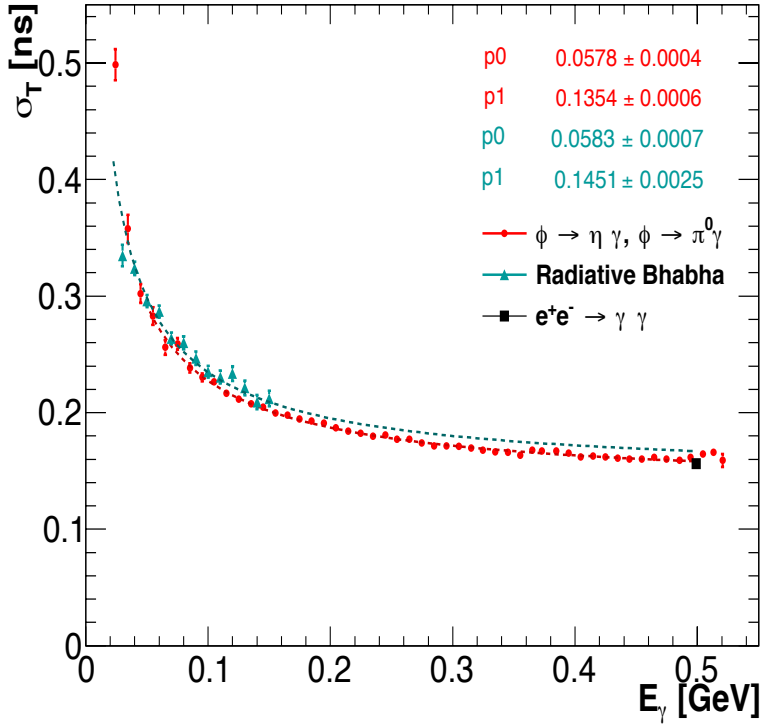
KLOE stability during the years

Check e.m. calorimeter performance
during KLOE-2 data taking (2015-2018):
compatible with known performance.

$\sigma_E/E \cong 5.6\% / \sqrt{E(GeV)}$
$\sigma_t \cong 58\ ps / \sqrt{E(GeV)} \oplus 135\ ps$

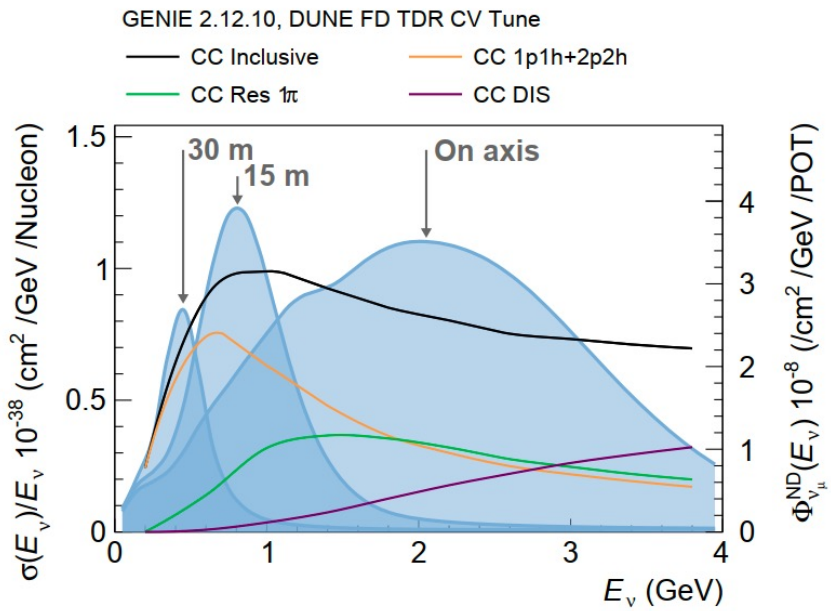
E. Diociaiuti et al. KLOE-2 note





DUNE-PRISM

- Method:
  - 50% data taken with ND-LAr+ND-GAr off-axis at various position (8 steps 12 day each)+ horn variation



- Goal:
  - create a ND data sets with flux spectra very similar to the oscillated FD fluxes,
    - minimizing errors arising from the near-to-far flux difference,
    - minimizing errors related to the neutrino interaction model