ECAL Overview and performance

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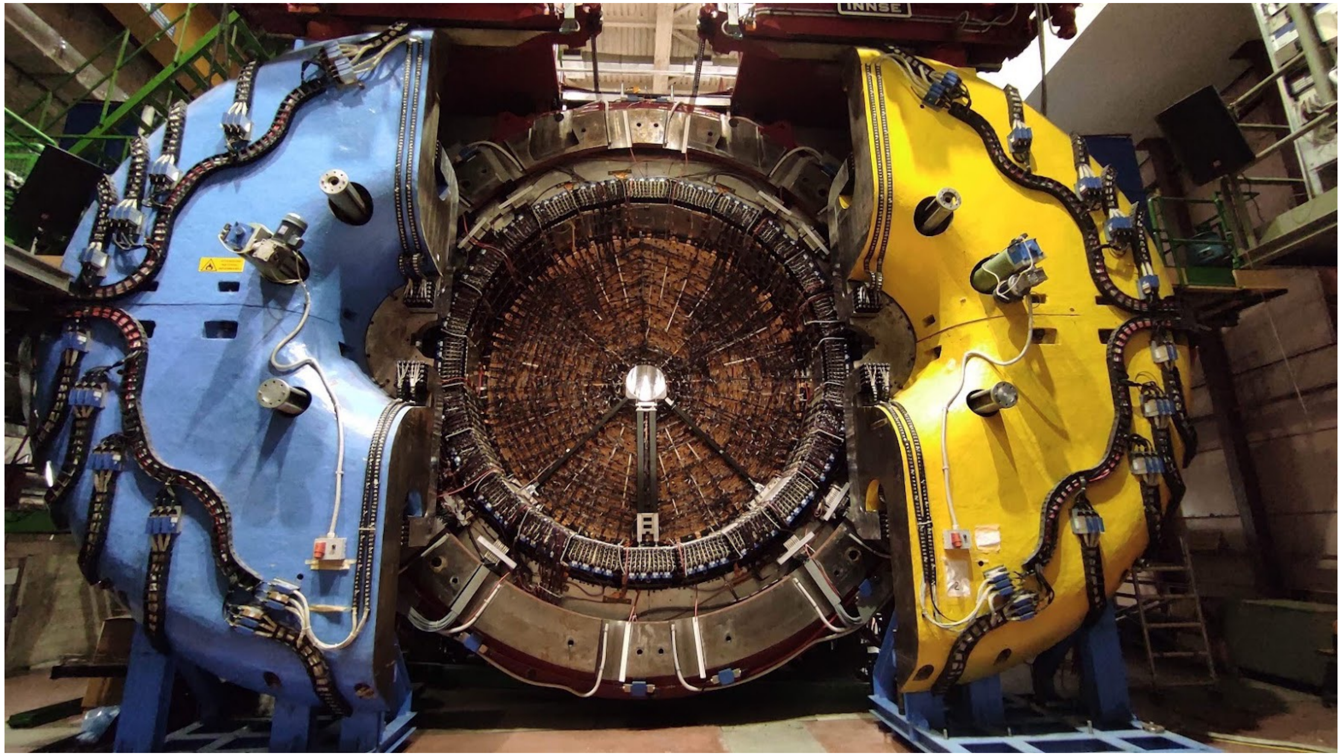


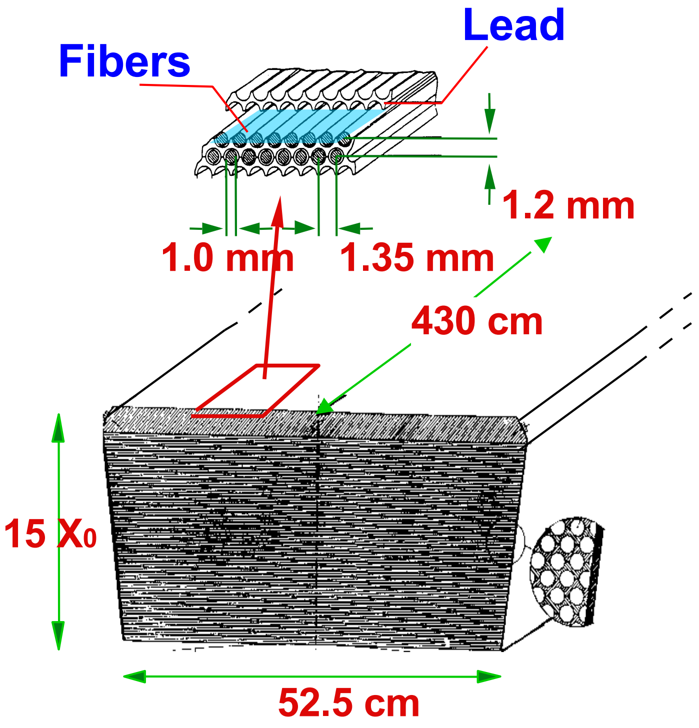
DUNE ND: ND-SAND KLOE Components PDR – 22-23 July 2024

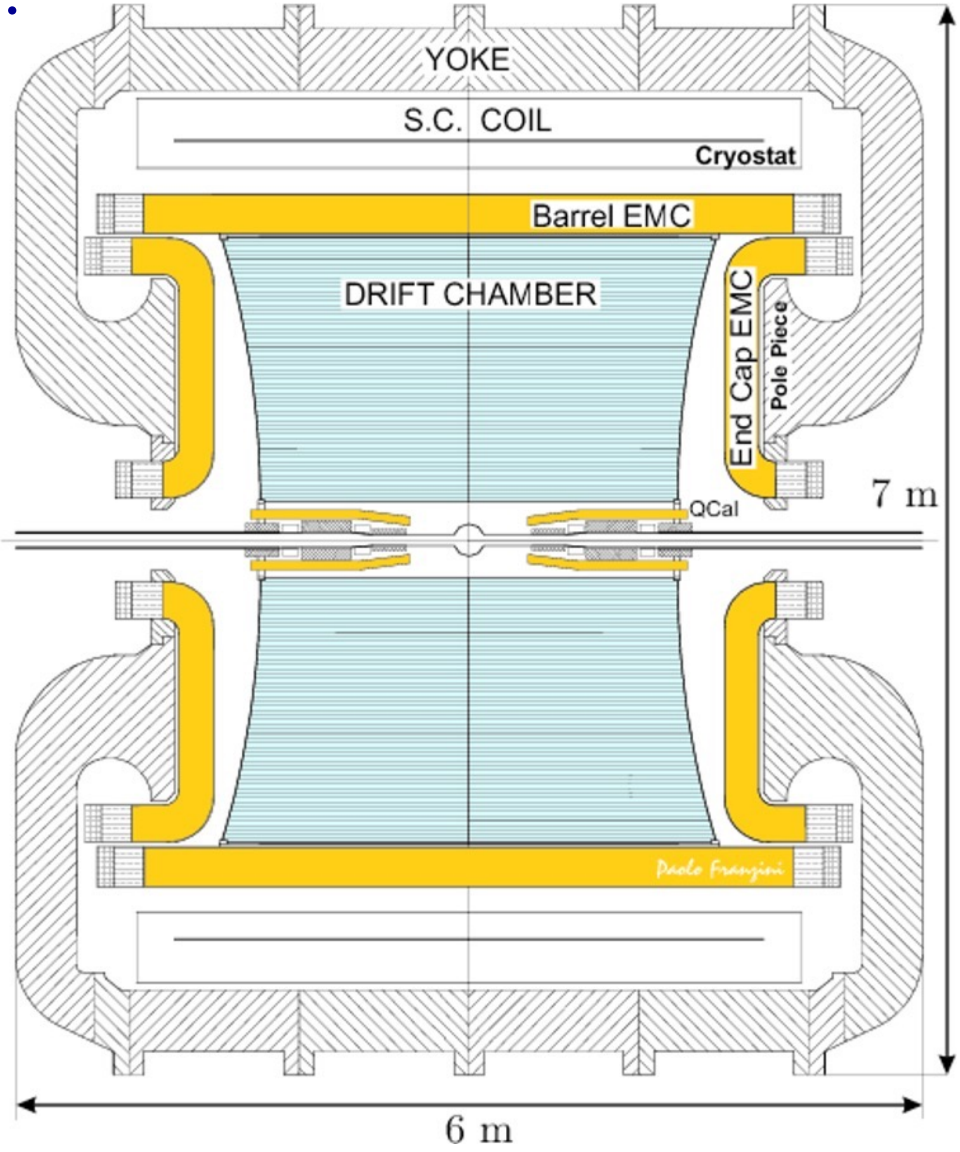
The KLOE e.m. calorimeter

Fine sampling lead/scintillating fibers calorimeter:

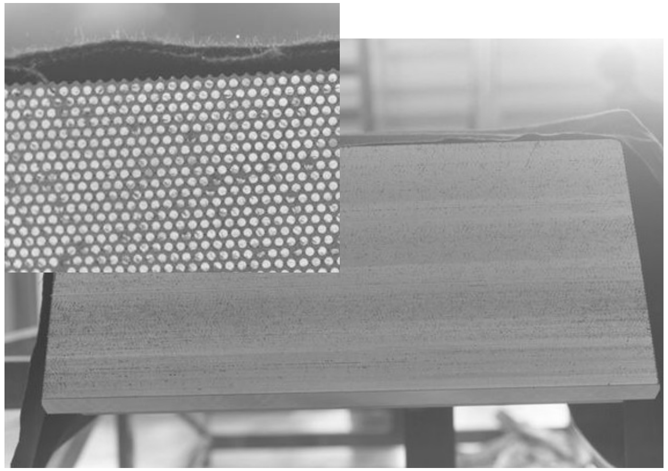
- **Volume Ratio (%) Fiber:Lead:Glue 48:42:10**
- **1 mm diameter scintillating fibers**
- **Average ρ = 5.3 g/cm^3**
- **X_0 = 1.6 cm (~15 X_0 depth)**
- **Sampling fraction 13 %**
- **Readout through fine mesh PMTs**

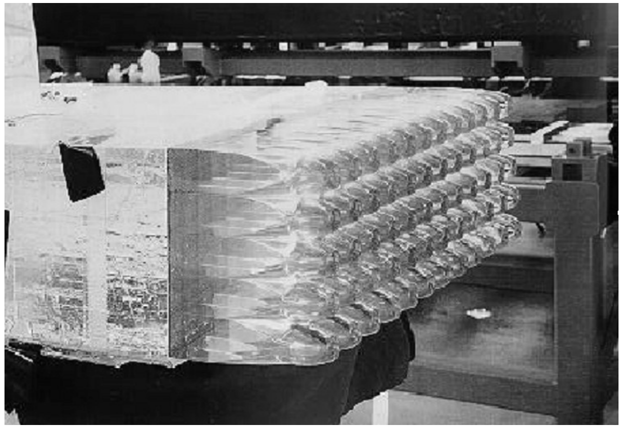
14000 km
of fibers in total

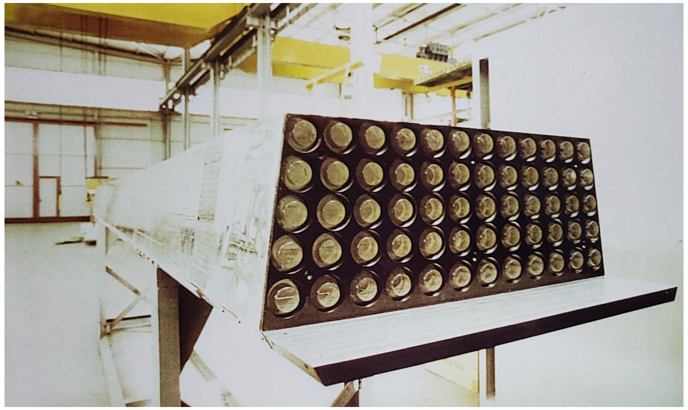




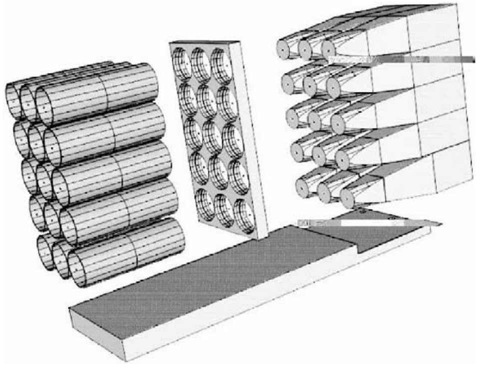
The KLOE e.m. calorimeter: light guides and PMTs







Light guide with Winston cone



PMT fine-mesh Hamamatsu R5946

The KLOE e.m. calorimeter

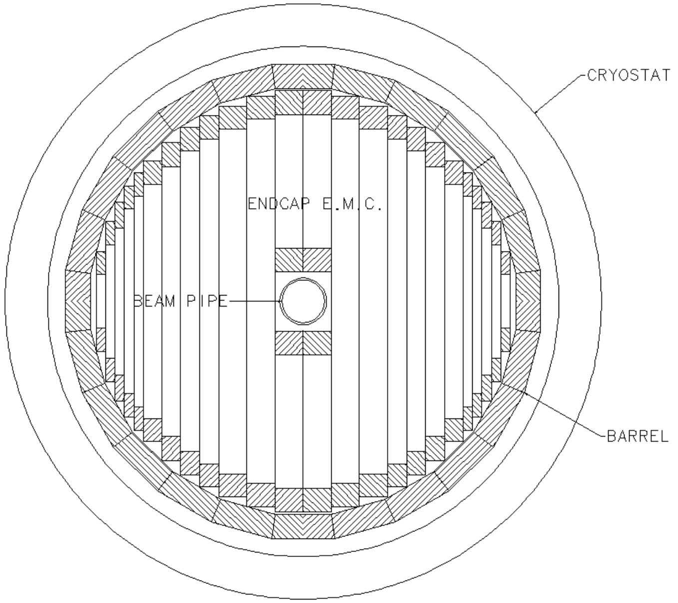
Barrel:

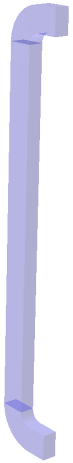
- 24 trapezoidal barrel modules of 4.3 m length
- fibers parallel to the barrel axis
- 60 readout cells/module
  (5 layers × 12 columns)
  ~ 4.4 × 4.4 cm cell granularity

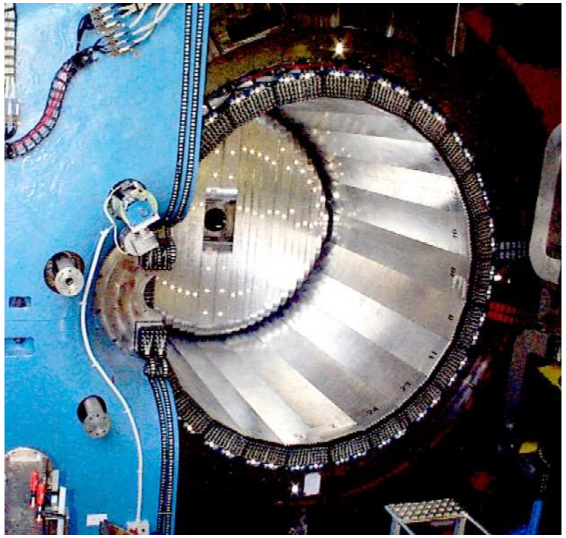
Endcaps:

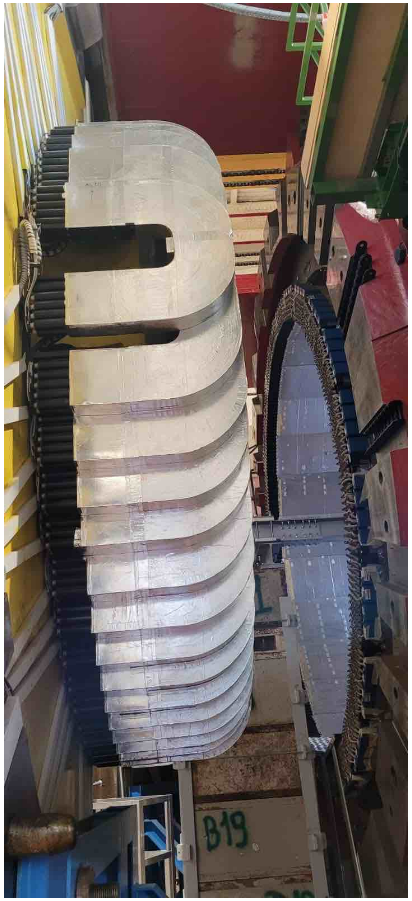
- 2 × 32 modules curved at both ends
- vertical fibers
- 15/20/30 readout cells

Total: 4880 PMT's
Charge and time readout
(with ADC's and TDC's)



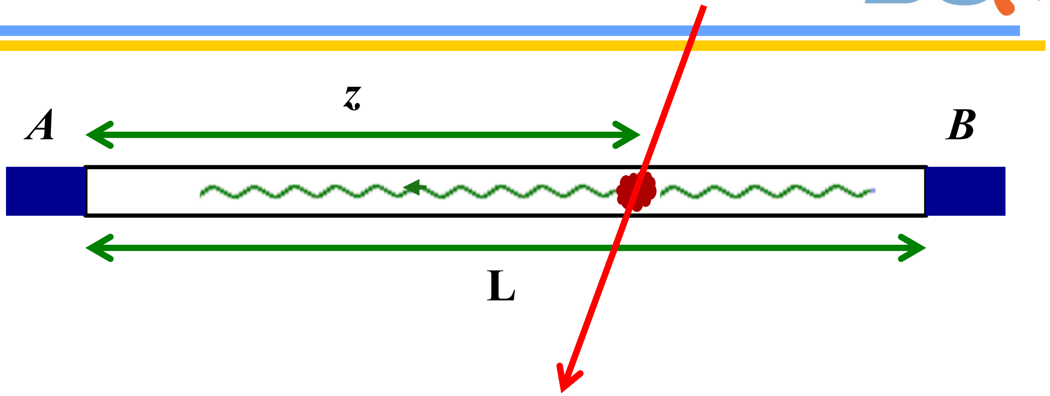






Energy reconstruction

- **Each cell readout at both ends ($Q^{(A)}, Q^{(B)}, T^{(A)}, T^{(B)}$)**



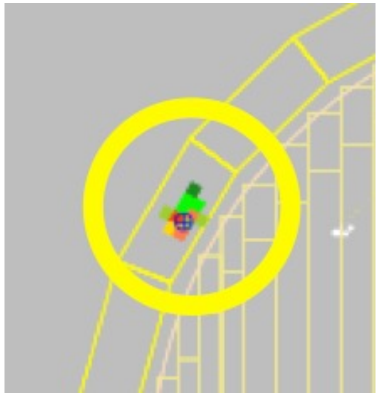
$$E_i^{(A,B)} = \frac{Q_i^{(A,B)} - P_i^{(A,B)}}{C_i} K$$

P_i = pedestal
C_i = calibration constant
K = absolute energy scale factor

$$E_i = \frac{1}{2}\left(\frac{E_i^{(A)}}{w_A(z)} + \frac{E_i^{(B)}}{w_B(z)}\right)$$

Cell energy, corrected for the attenuation along the fibers

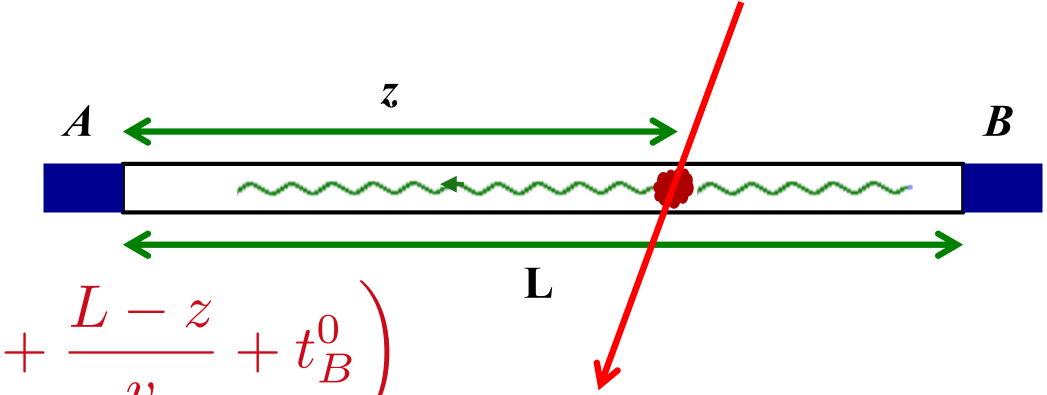
- **Contiguous cells in position and time are joined into *"clusters"* to reconstruct showers and particles in the calorimeter**



$$E_{cl} = \sum_i E_i \qquad t_{cl} = \frac{\sum_i t_i E_i}{\sum_i E_i} \qquad \vec{r}_{cl} = \frac{\sum_i \vec{r}_i E_i}{\sum_i E_i}$$

Time reconstruction

- **Each cell readout at both ends (Q_A, Q_B, T_A, T_B)**



$$\frac{1}{2}(t_A + t_B) = \frac{1}{2}\left(t + \frac{z}{v} + t_A^0 + t + \frac{L-z}{v} + t_B^0\right)$$

$t_{A,B}$ = arrival time at the PMTs
$t^0_{A,B}$ = offsets due to the electronics
v = light velocity in the fibers

$$t = \frac{1}{2}(t_A + t_B) - \frac{L}{2v} - t_0$$

- **Third coordinate reconstruction:**

$$\frac{1}{2}(t_A - t_B) = \frac{1}{2}\left(t + \frac{z}{v} + t_A^0 - t - \frac{L-z}{v} - t_B^0\right)$$

$$z = \frac{1}{2}v(t_A - t_B - \Delta t_0)$$

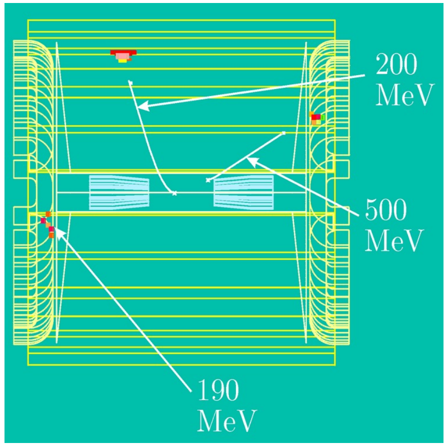
$$\left(\Delta t_0 = t_A^0 - t_B^0 - \frac{L}{v}\right)$$

Energy resolution

- **Linearity of the response and energy resolution measured with radiative Bhabha scattering ($e^+e^-\rightarrow e^+e^-\gamma$) by detecting the charged tracks in the drift chamber**

$$E_\gamma = \sqrt{s} - E_+ - E_-$$

E_+ and E_- measured in the Drift chamber (better resolution for charged tracks)



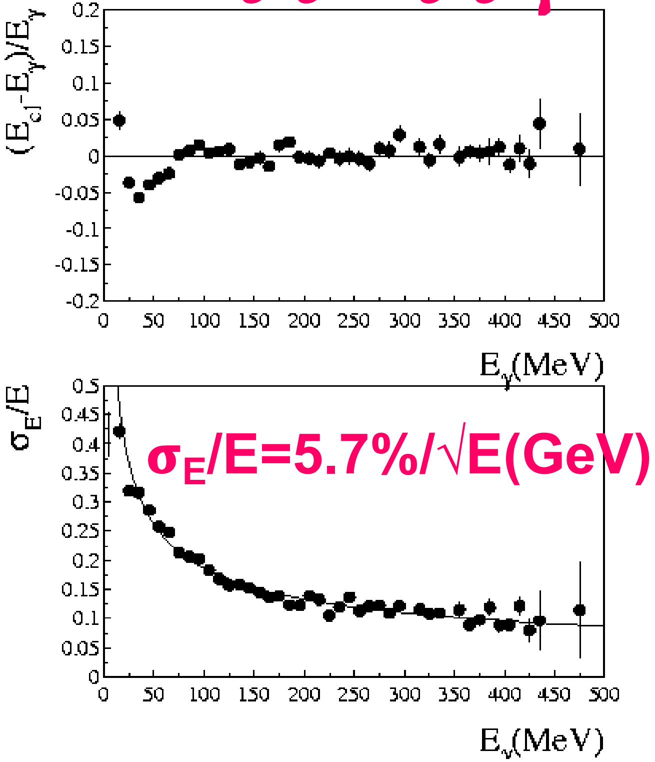
- **Linearity within 1% for E > 70 MeV**

$$\frac{E_{cl} - E_\gamma}{E_\gamma}$$

$$\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E[\mathrm{GeV}]}}$$

- **For $E = 100$ MeV $\Rightarrow \sigma_E = 18$ MeV**

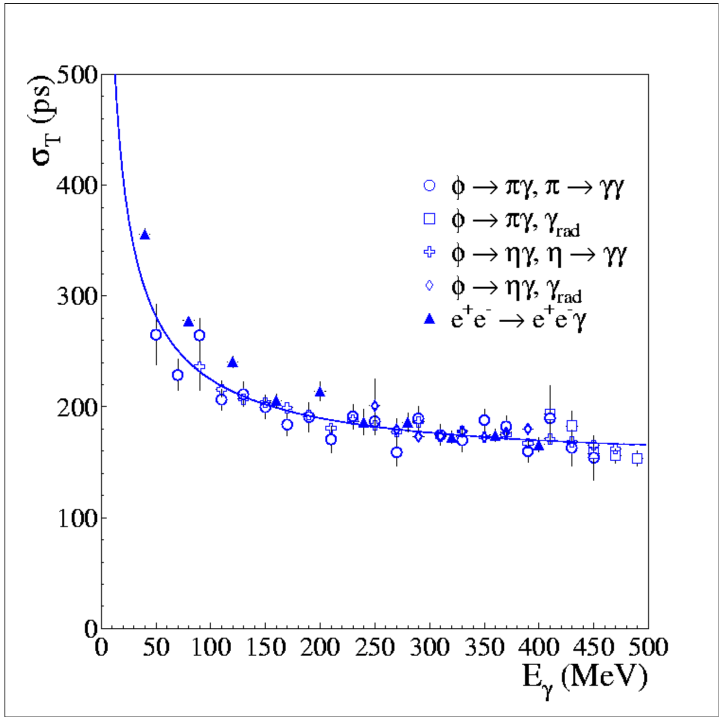
$e^+e^-\rightarrow e^+e^-\gamma$



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

Time resolution

- **Measured with different processes: $\phi\rightarrow\pi^0\gamma$ ($\pi^0\rightarrow\gamma\gamma$), $\phi\rightarrow\eta\gamma$ ($\eta\rightarrow\gamma\gamma$), $\phi\rightarrow\pi^+\pi^-\pi^0$, $e^+e^-\rightarrow e^+e^-\gamma$**

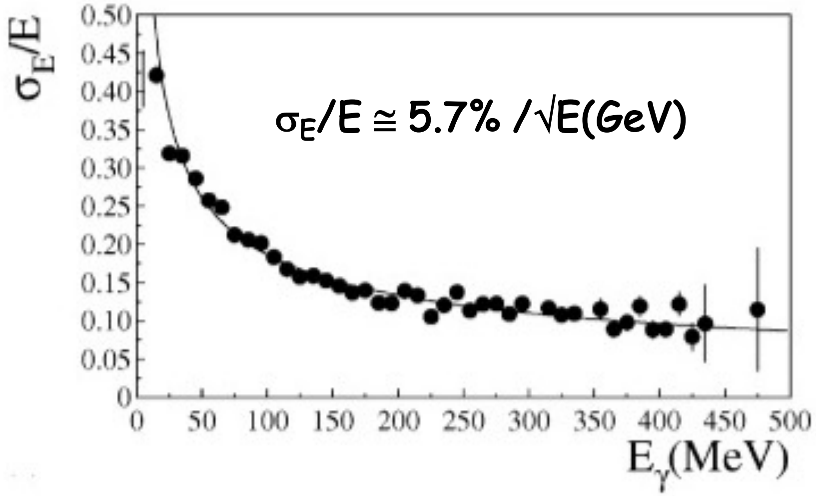


$$\sigma_t = \frac{54\,\mathrm{ps}}{\sqrt{E(GeV)}} \oplus 140\,\mathrm{ps}$$

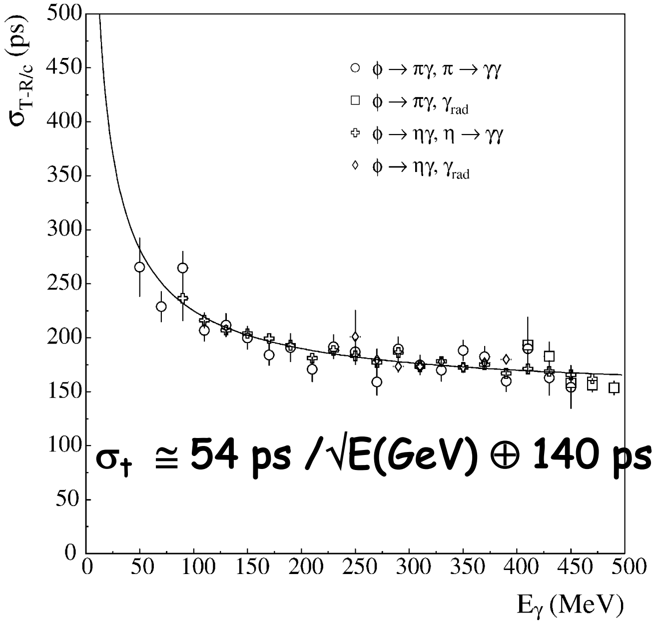
- **The constant term has two contribution: a term common to all the cells, due to the spread of the DAΦNE Interaction Point position (~100 ps), and a proper constant term, uncorrelated among cells, due to a residual miscalibration (~ 100 ps)**

ECAL resolutions in KLOE and KLOE-2

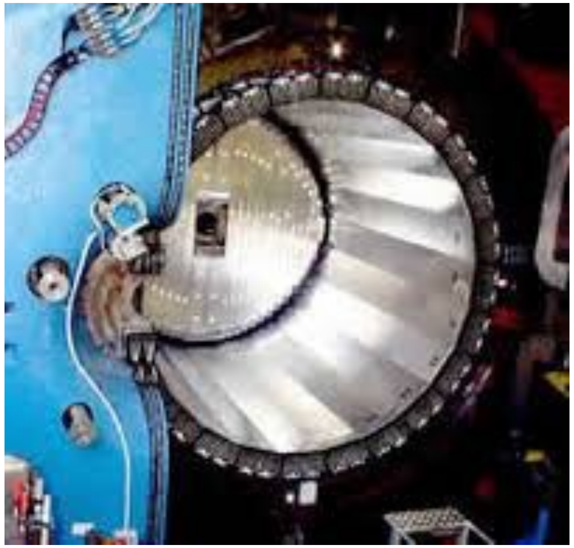
KLOE

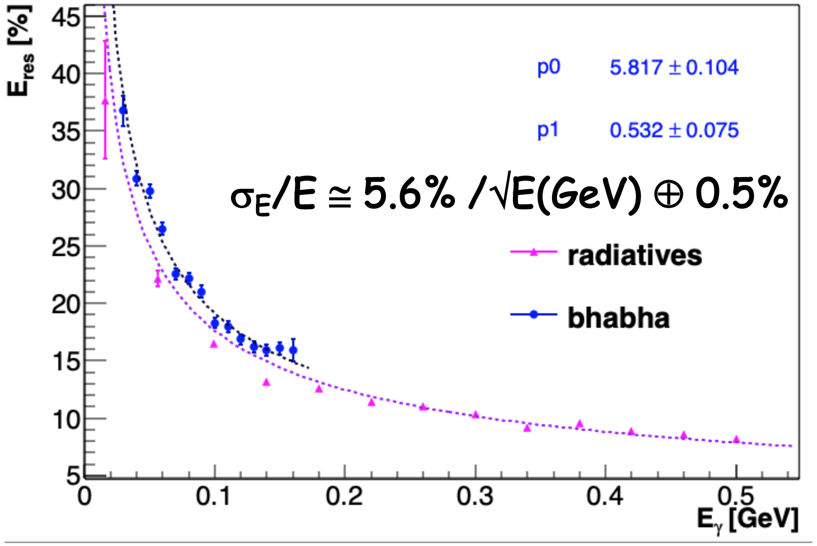


$\sigma_E/E \cong 5.7\% / \sqrt{E(GeV)}$



$\sigma_t \cong 54\ \text{ps} / \sqrt{E(GeV)} \oplus 140\ \text{ps}$

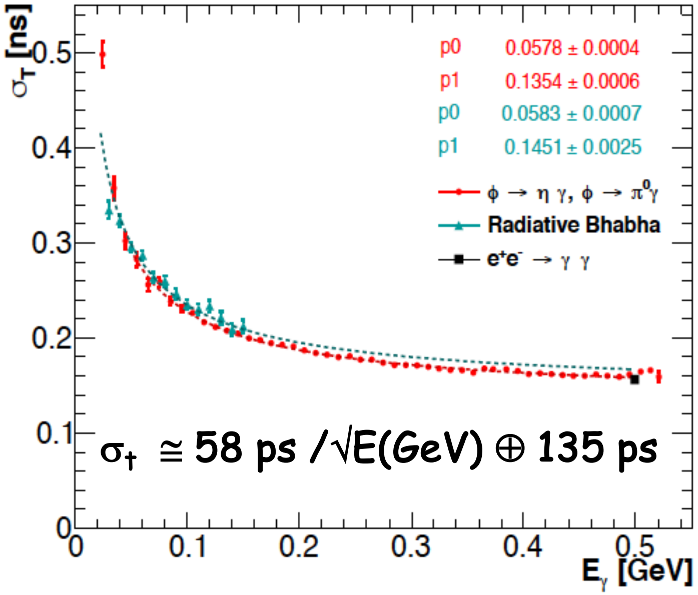




$\sigma_E/E \cong 5.6\% / \sqrt{E(GeV)} \oplus 0.5\%$

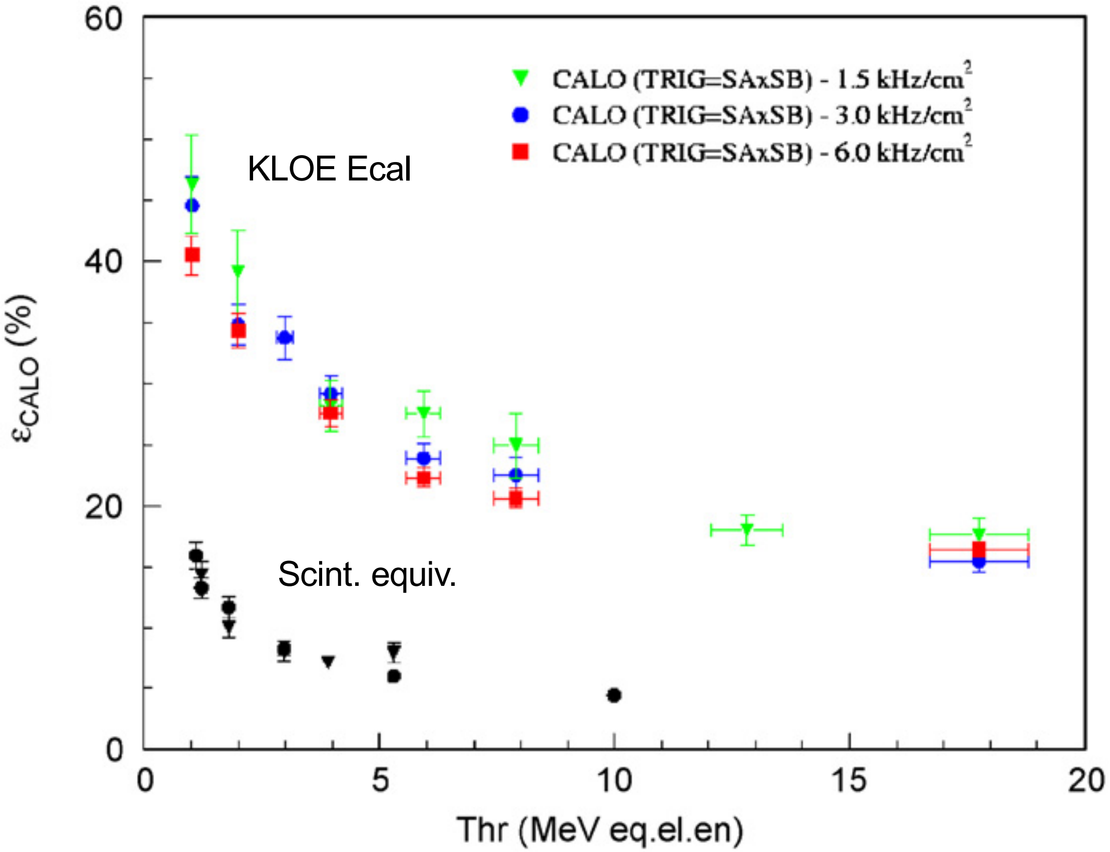
KLOE-2

~ 20 years later



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

Measurement of the neutron response of ECAL



Measurement of the neutron response of the KLOE Ecal

M. Anelli et al., *"Measurement and simulation of the neutron response and detection efficiency of a Pb-scintillating fiber calorimeter "*, NIM **A581** (2007) 368

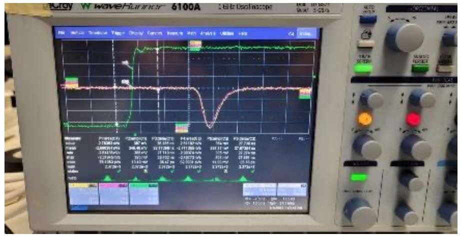
M. Anelli et al., *"Measurement of the neutron detection efficiency of a 80% absorber–20% scintillating fibers calorimeter "*, NIM **A626** (2011) 67

ECAL module refurbishment and test at LNF

- After dismounting operation, the special protective adesive tape of all barrel modules has to be replaced; gluing of delaminated modules, etc.
- check light tightness of module and PMT working;
- test basic performance with cosmics rays (light yield, E and T resol.)
- test FEE prototypes
  (comparison with old KLOE electronics)

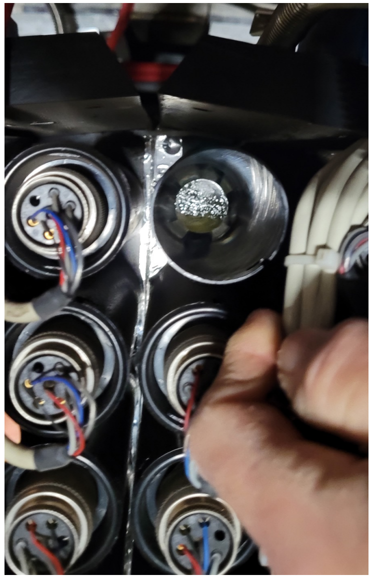
Shifts of trained technicians and physicists

Test box for testing PMTs



ECAL test at LNF

PMTs will be dismounted, light guides cleaned, new optical gel applied, and PMTs re-mounted.



ECAL test at LNF

For the ECAL module test the KLOE electronics will be reused

VME bridge

trigger distributor

NIM modules for trigger logic

CAEN HV power supply

KLOE ADC CAEN VX559 (30 ch.) 8 boards
KLOE TDC CAEN VX569 (30 ch.) 8 boards

KLOE Low Voltage power supply (380~V)
+/-6V (2x 300W) => PMT preamp, FEE etc.
+/- 5.2 (2x 280W) => digital circuitry

KLOE SDS 8 boards: spllitter +
discriminators on 30 ch./board
common tunable threshold(low+hign thr.)

ECAL: procurement of HV and LV power supply

HV

LV

CAEN
n° 102 board A7030P (48 ch.) H.V. channels +3 KV 1 mA (1.5 W) - Multipin Conn. common floating
n° 7 Sistem SY4527B Universal Multichannel Power Supply System - BASIC 600W
n° 7 Power supply booster A4533 - 1200W

n° 10+2 spare board A25251 8 full floating channels 8V/12A

Mapping of present HV cables 5x12ch on 48 ch. modularity not trivial (to be studied also for LV)
=> under study to minimize cost (custom connectors or patch panel)

ECAL test at FNAL

Upon arrival at Fermilab, ECAL modules will be stored in a proper area for barrel and equipped with a crane of 5 t maximum load for handling barrel modules, and 15-20 t for handling Endcap modules. A controlled temperature environment is required in the storage and test area of ECAL modules, avoiding thermal stresses and keeping temperature changes within about ±10^{o}C along the whole period.

The quality assurance (QA) and quality control (QC) operation will be performed repeating the tests on each module done at LNF. In particular, after re-installation of PMTs (shipped separately) in the ECAL modules, the ECAL module performance in terms of light yield, energy and time resolution using cosmic rays will be measured and checked again at a cosmic ray test stand, with the same equipment used at LNF, before installation in the SAND detector.

Storage area for barrel modules: ~50 m^2
Storage area for end-cap modules: ~60 m^2
Test area: 50-100 m^2 depending on the parallelization degree of the operations

Studies for the optimization of the ECAL working point

What is the expected dynamic range of ECAL PMT signals in terms of photoelectrons in SAND ?

Np.e. distributions and expected Np.e. dynamic range

- MC simulation of neutrino interactions in SAND
- sample of 118k evts corresponding ~ 30 minutes at 1.2 MW in FHC mode (or ∼15 min at 2.4 MW)
- Digitization of ECAL (as in KLOE MC): deposited energy in the cells propagated to PMTs and converted into p.e. number; constant fraction discriminator simulated

E_ν range $= [0,10]$ GeV

Events number	101,696
Events cells number	2,184,901

Fraction of events with at least one cell above PE threshold	[%]
1000 PE threshold	2.58
2000 PE threshold	0.49
3000 PE threshold	0.13
4000 PE threshold	$3.64 \cdot 10^{-2}$
Fraction of hit cells above PE threshold	**[%]**
1000 PE threshold	0.19
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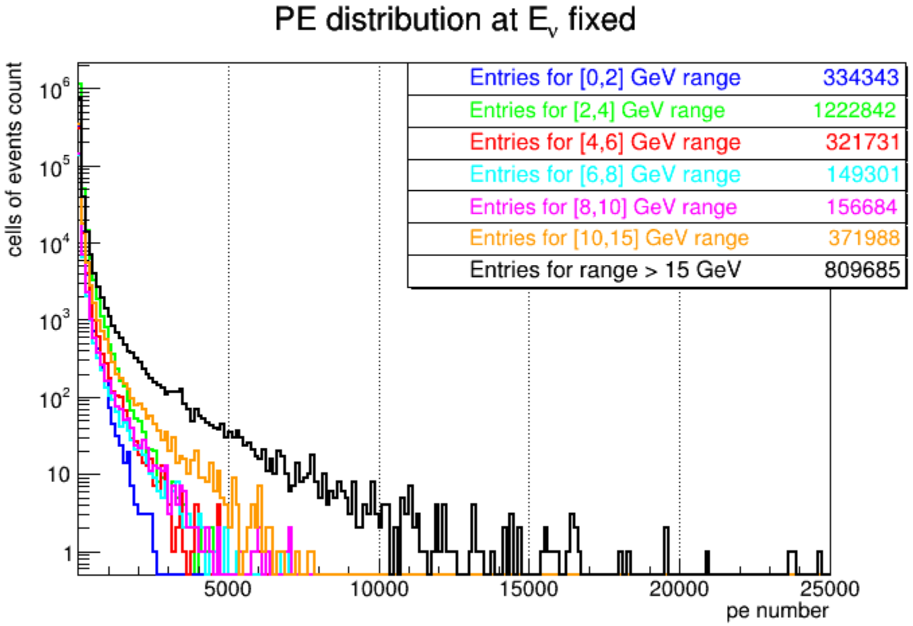

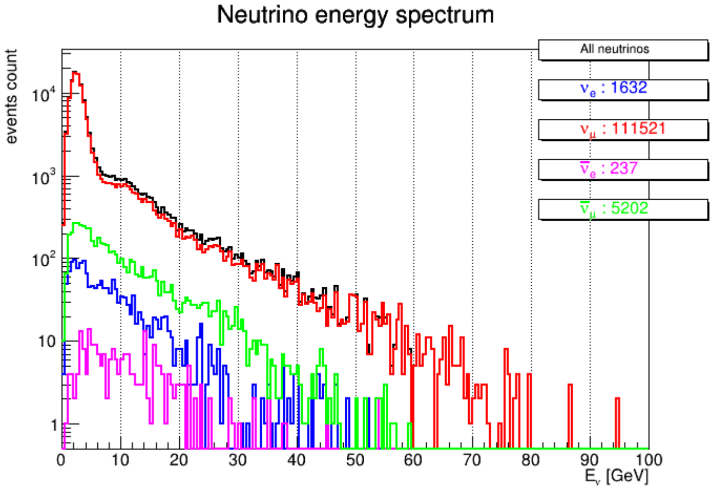

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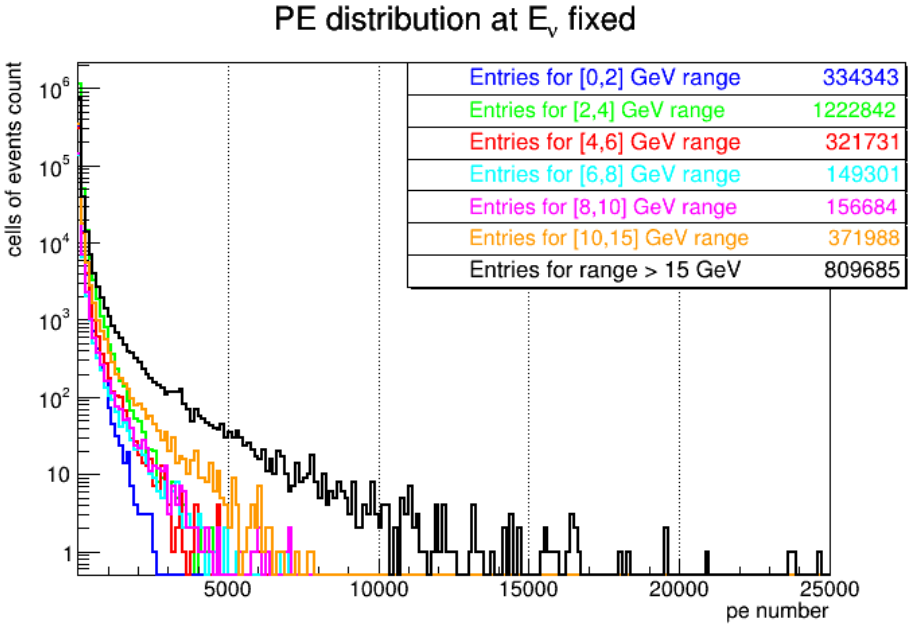

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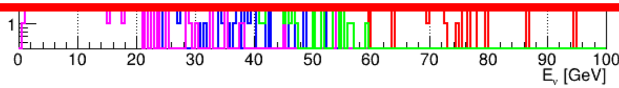
- Neutrino energy range of interest for oscillation analyses is [0,10] GeV
- In this range the MAXIMUM Np.e. that has to be treated by FEE can be safely set between 1000 and 2000
  => see next slides for the choice of the FEE dynamic range



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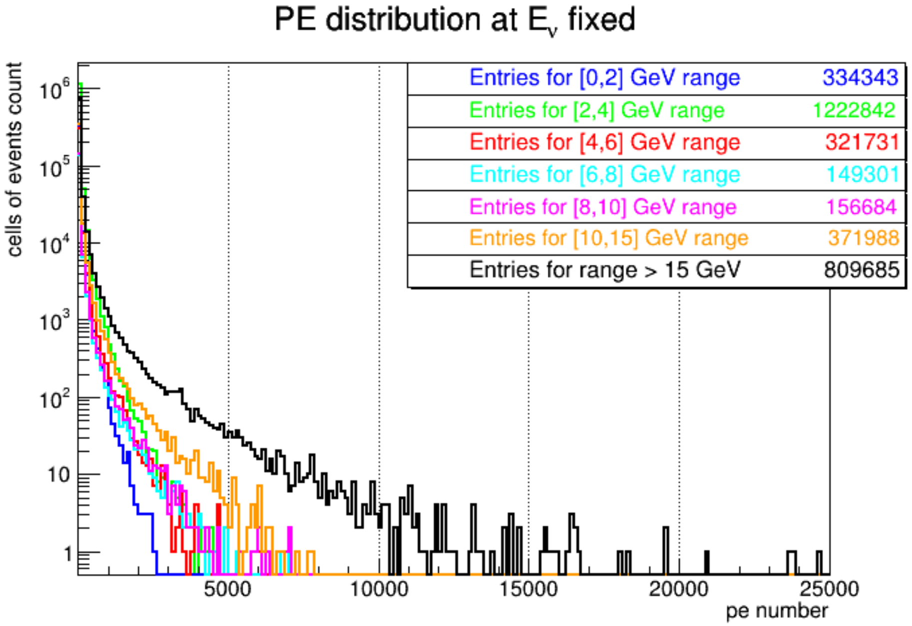

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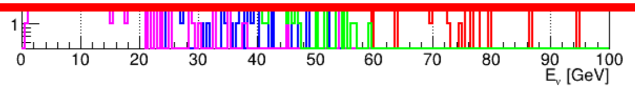
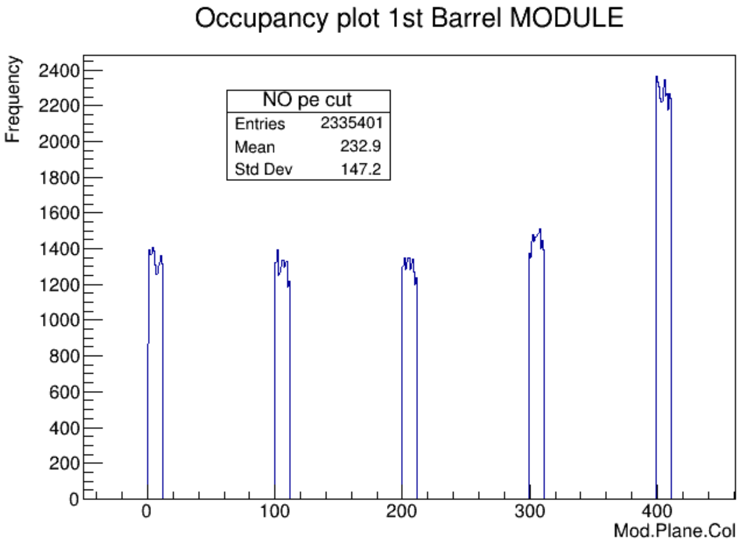


- to maximize the neutron detection efficiency by ECAL the MINIMUM Np.e. that has to be treated by FEE is the lowest possible, ideally 1-3 Np.e.

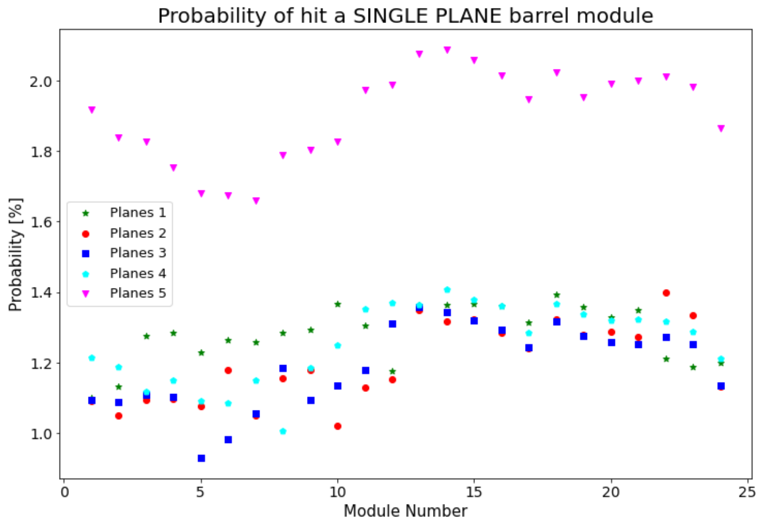
Studies for the optimization of the ECAL working point

What is the expected pile-up of ECAL PMT signals in SAND ?

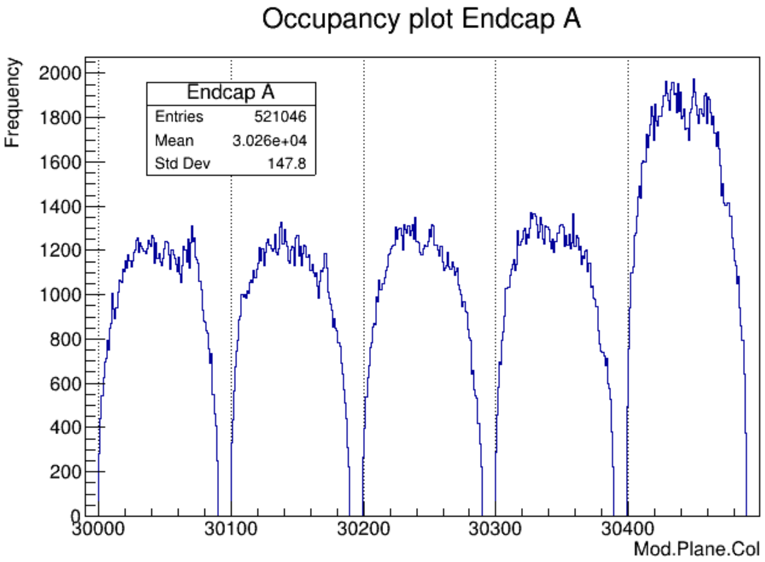
Cell occupancy plots and hit probability



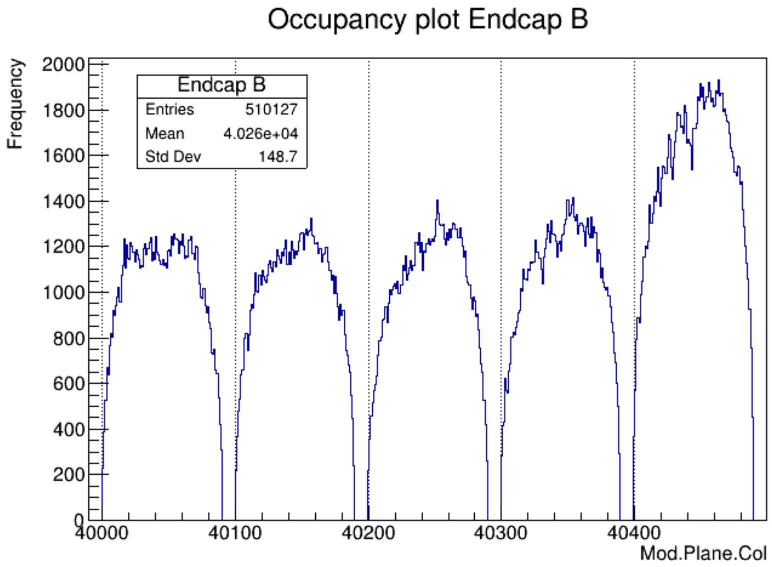
Barrel



Ecap A



Ecap B



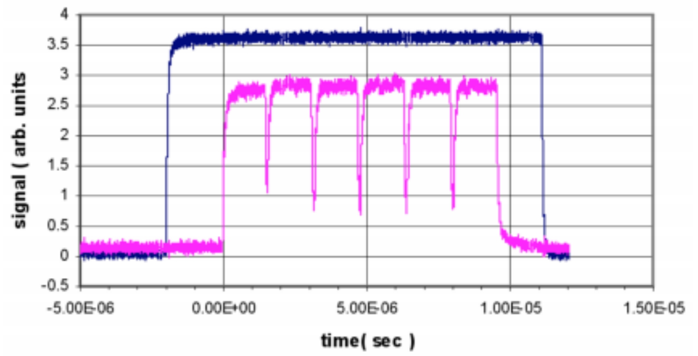
Average probability that a cell is fired/hit in a neutrino interaction event:

P_{barrel} = 1.37%
P_{ecapA} = 0.88%
P_{ecapB} = 0.86%

P_{cell} = 1.16%

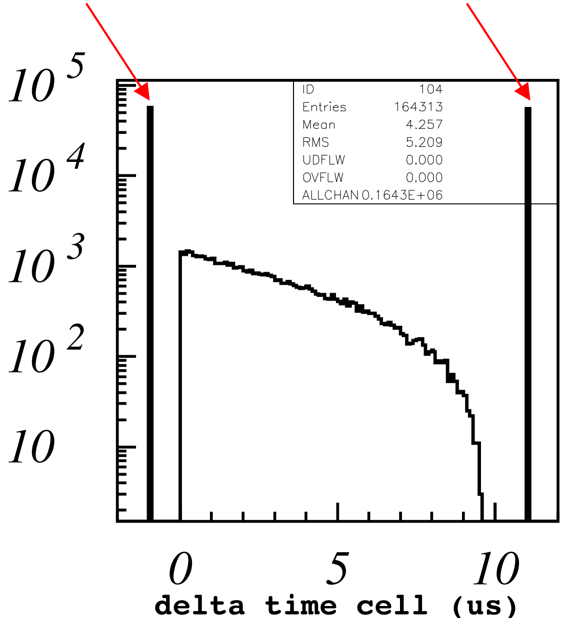
Pile-up probability

- The beam time structure (SPILL: 9.6 μs every 1.2 s) is reconstructed to simulate the time of the neutrino interaction event and calculate the pile-up probability that, given a PMT signal, a second signal arrives within a fixed time window (TW) after the first signal.
- In average **N=84** interactions per spill (1.2 MW beam). The time difference between two consecutive interactions in a spill is evaluated and from this, the **distribution of time differences for a single cell** with a probability to be hit of P_{cell} = 1.16%, 1.5%, 2% is evaluated.
- Time propagation/smearing of hits in a single neutrino interaction event is taken into account (=>negligible).
- Finally the pile-up probabilities for different time windows are evaluated, TW = 50, 100, 150, 200 ns.



spills with 0 hit

1 hit



P_{CELL} [%]	1.16	1.5	2.0
Time window [ns]	pile-up probability (%)		
50	0.64	0.86	1.36
100	1.32	1.71	2.56
150	1.91	2.60	3.78
200	2.52	3.48	4.93

$P_{pile-up}$ is O(1%) in 50 ns TW

Studies for the optimization of the ECAL working point

Can the present KLOE PMT-base configuration fit the expected dynamic range of signals in SAND?

PMT signal in KLOE and preamp linearity test

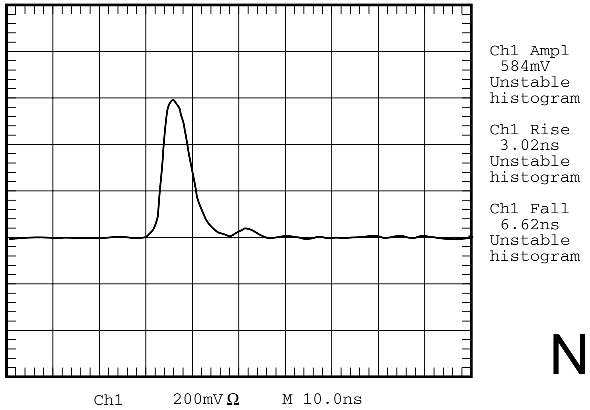
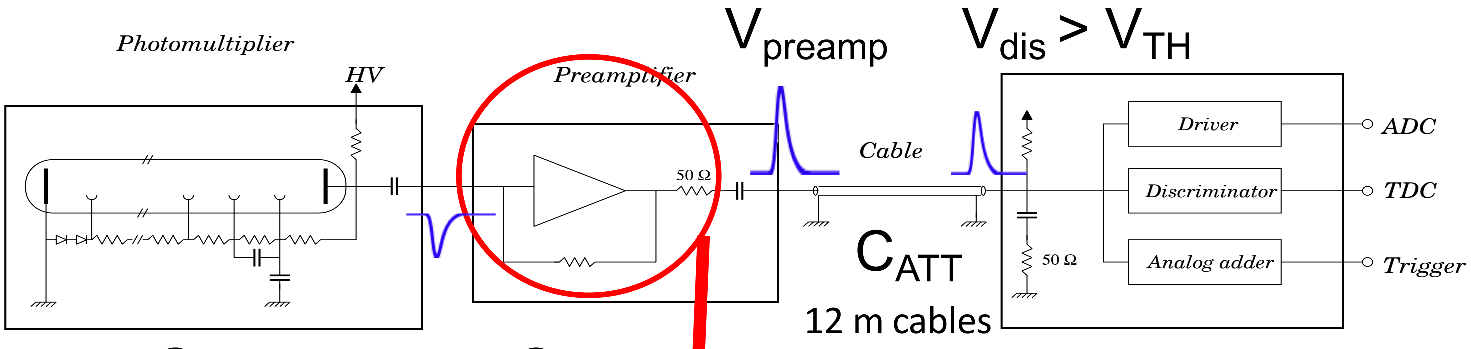
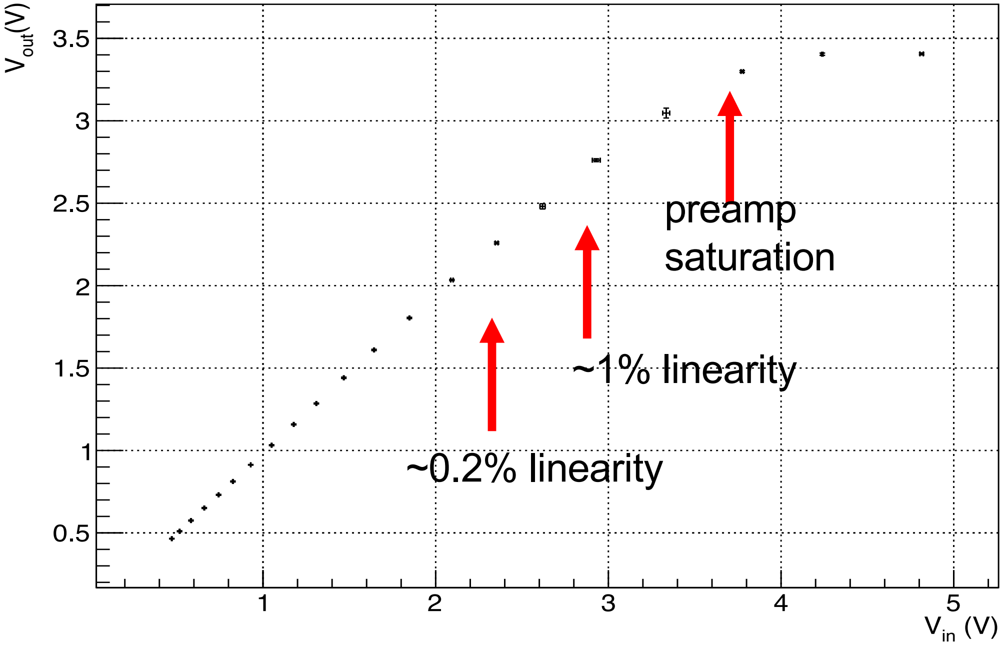


Figure 4: Typical signal from the PM base.

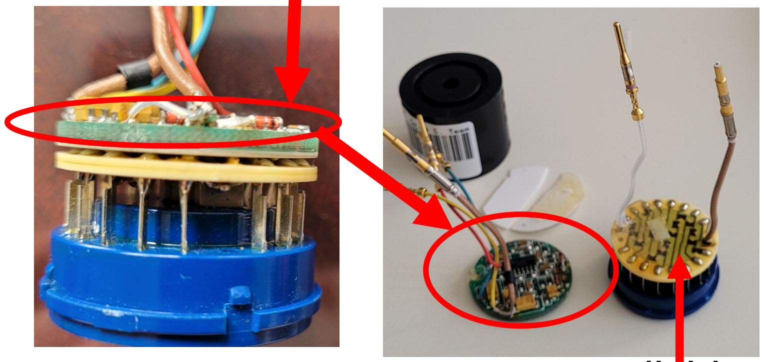


Constant fraction discriminators.
Effective thresholds in the range 4–5 mV:
correspond to signals originated
by 3–4 p.e. or a 3–4 MeV photon
at 2 m from PMT

preamp linearity test



divider and preamp in the PMT base



Conclusion:
the dynamic range of signals can be increased in SAND by accepting linearity at 1% level (instead of 0.2% as in KLOE)

Choice of the dynamic range

Assuming:

- to increase V_{preamp}(max) by 15% => V_{preamp}(max) = 5.4 V (G$_{preamp}$=2.5)
  (linearity from 0.2% to 1%)

- V_{dis}(max) = V_{preamp}(max) • 0.5 • C_{ATT}= 2.0 V (12m long cable attenuation: C_{ATT} = 0.74)
- to have a very low noise environment as in KLOE => lowering (halving) the minimum discriminator/digitizer threshold to V_{TH}= 2.5 mV

G_{PM} $(\times 10^5)$	G_{tot} $(\times 10^6)$	$N_{pe}(\mathrm{max})$	signal amplitude (mV/pe)	$N_{pe}(\mathrm{min})$ $V_{TH} = 2.5$ mV	MeV at module center
4.8	1.2	~ 2000	1.0	~ 3	3.0
6.4	1.6	~ 1500	1.3	~ 2	2.0
9.5	2.4	~ 1000	2.0	~ 1	1.0

- Different dynamic ranges can be implemented changing G_{PM} =>
  the final choice should be a compromise between an affordable level of events with energy saturated cells, depending on N_{pe}(max), and an acceptable neutron detection efficiency, depending on N_{pe}(min).

Preamp linearity test => saturation

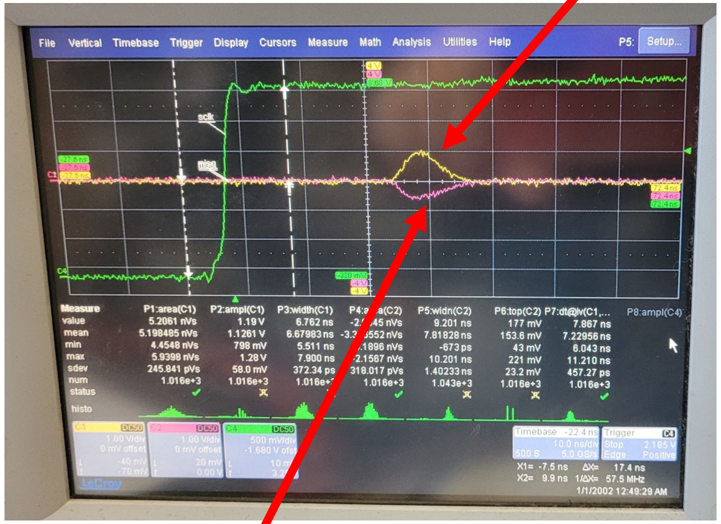
PMT2 HV=1700 V

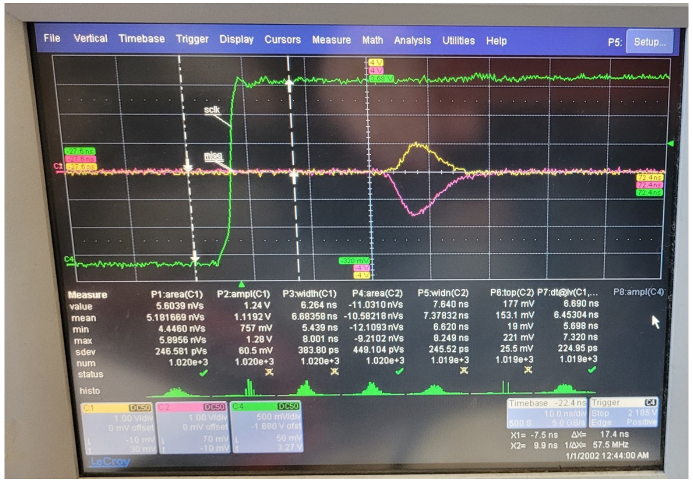
REF PMT1

HV=1900 V

fixed LED
intensity (full)

HV=2100 V





no preamp PMT2

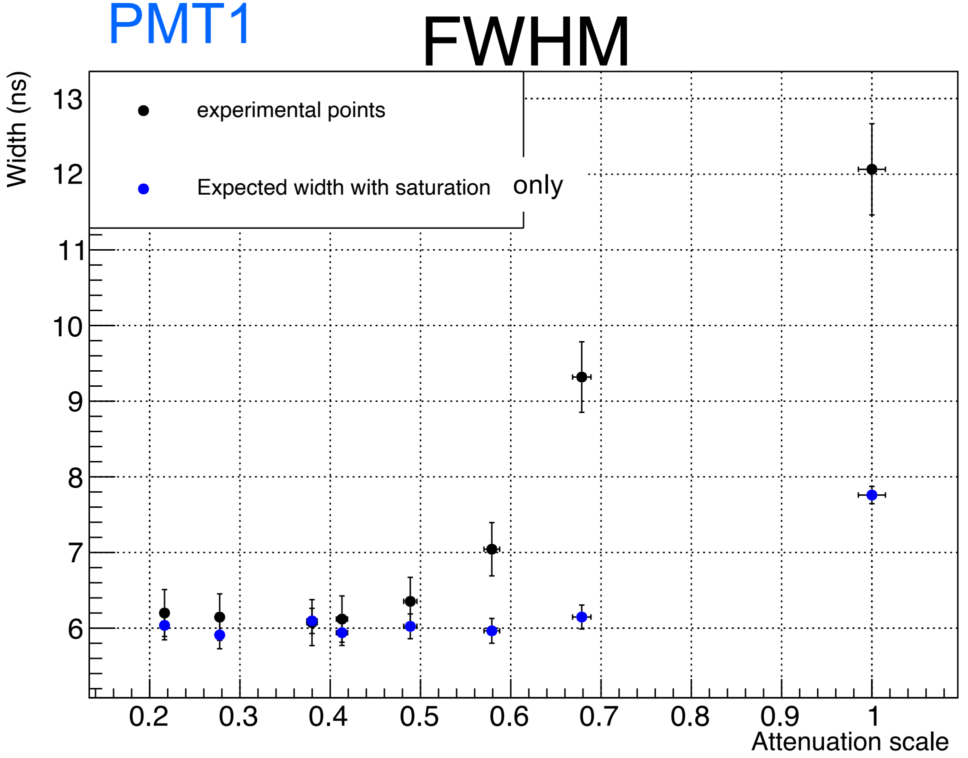
with preamp PMT2

preamp recovery time from saturation
depends on input amplitude signal

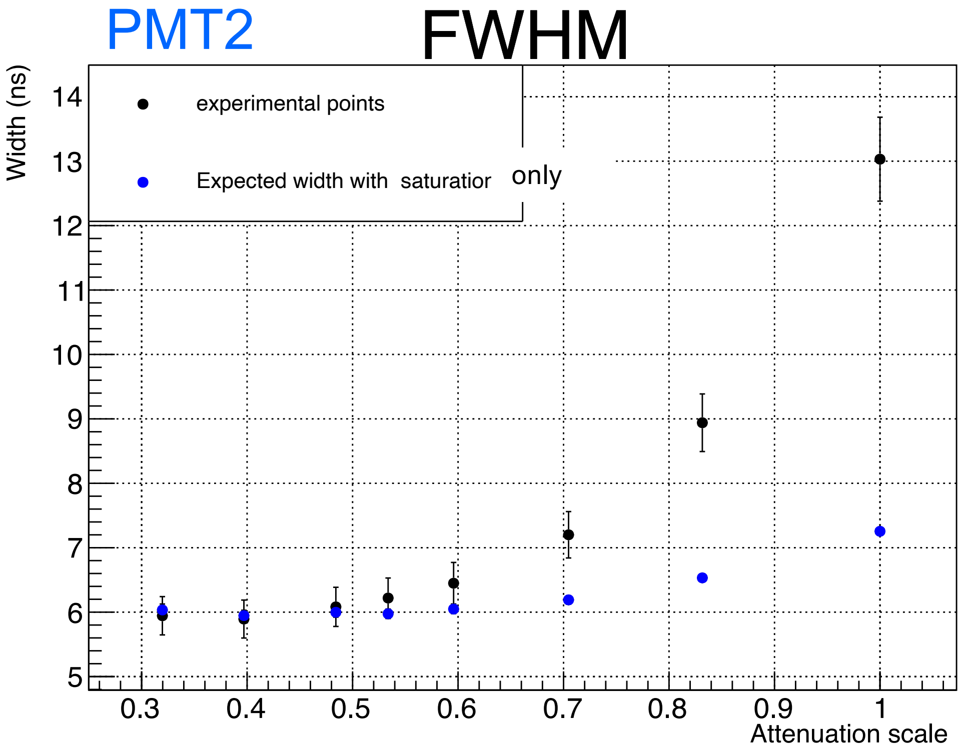
Preamp linearity test => saturation

- Two PMTs with their bases tested in the preamp saturation regime

PMT1


FWHM

PMT2


FWHM

- The time baseline is distorted during saturation. The recovery time from saturation to linear regime depends on the input signal amplitude.
- The input information is not fully lost during the saturation regime. The “over-linearity” of the integrated charge, or the signal width increase vs the input signal amplitude could be exploited to characterize signals beyond the preamp saturation regime.

=> amplitude of signals can be measured even in the saturation regime!
(precision to be studied)

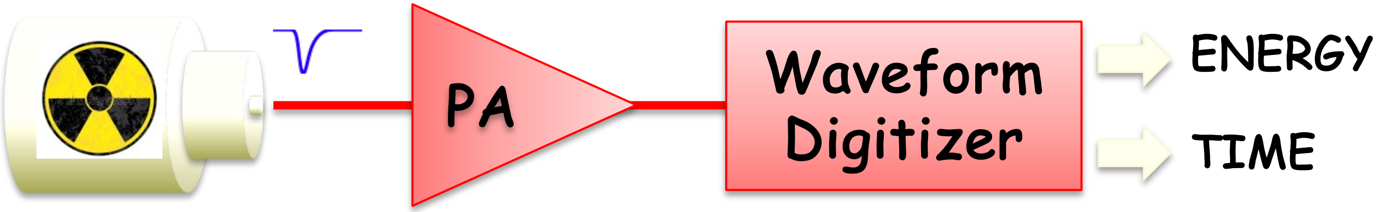
Studies and tests for FEE choice

What choice of FEE for SAND/ECAL?

Choice of FEE for SAND/ECAL

Three possible read-out schemes:

Detector

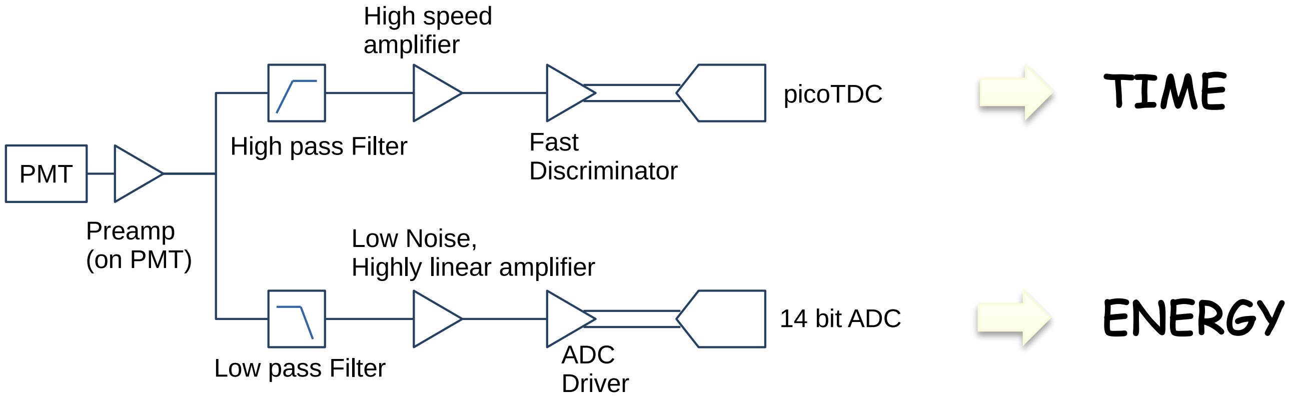


Highest Flexibility
=>
Fsampl ~ 1 GS/s =>High Cost or
Fsampl ~ 125-250 MS/s
+ signal shaper

Detector

Less Flexibility
=> energy by ToT
with 2 or more thresholds
not to worsen energy resol.
Time walk correction
needed

a more conventional approach

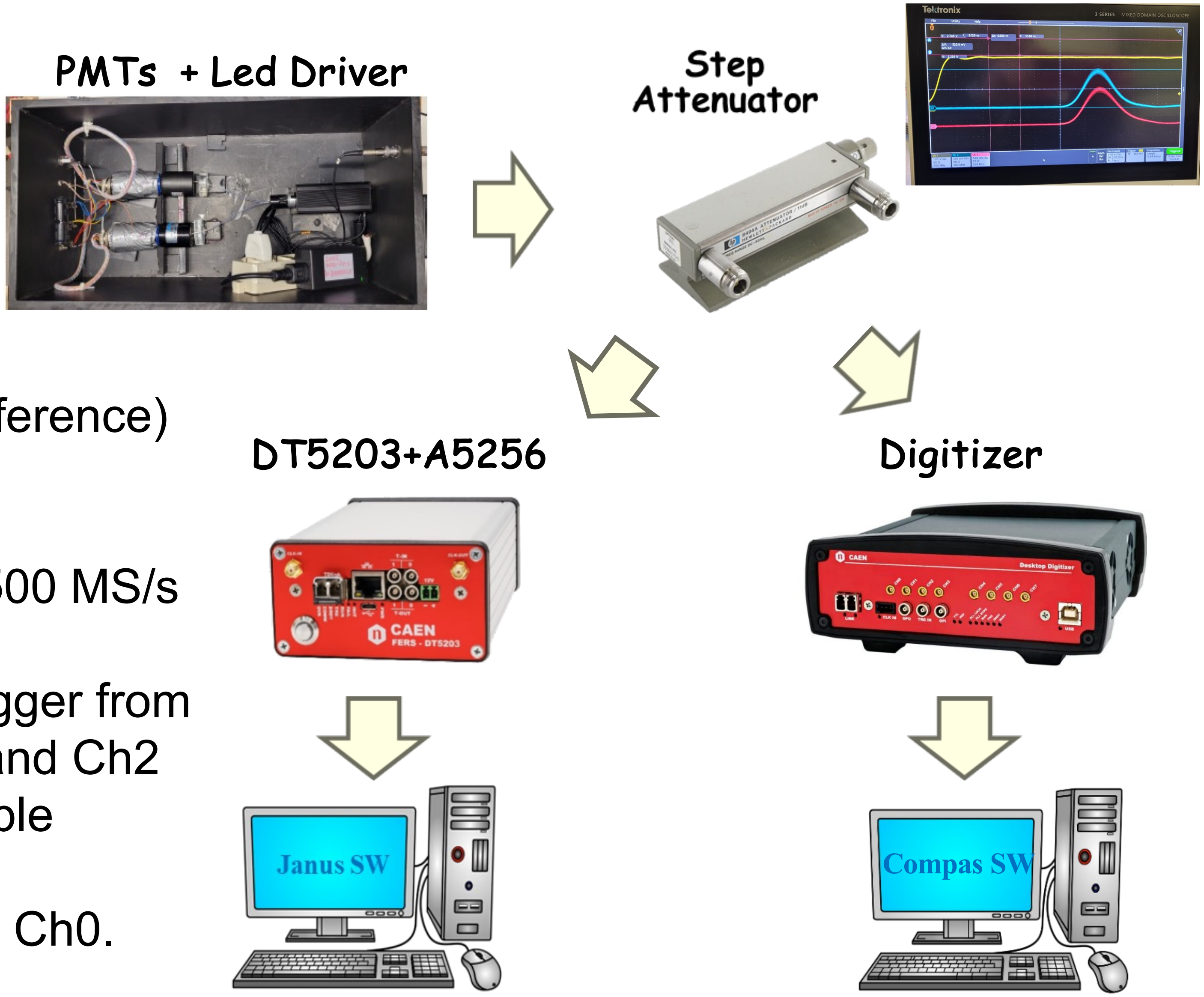


CAEN:

collaboration for a commercial (partly customized) solution keeping KLOE energy and time performance

Pico TDC test (CAEN+INFN)

Test setup:



- Led Driver CAEN SP5601 (λ~400 nm) + fiber splitter
- two KLOE PMTs (test + reference)
- test PMT signal splitted:

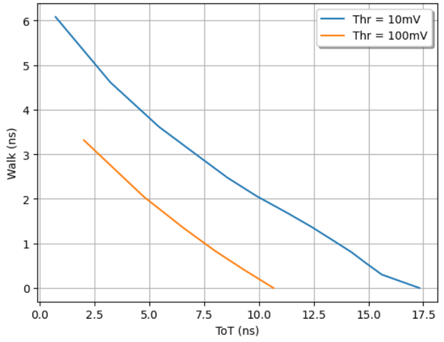
i. Pico TDC

ii. Digitizer 730S 14 bit @ 500 MS/s

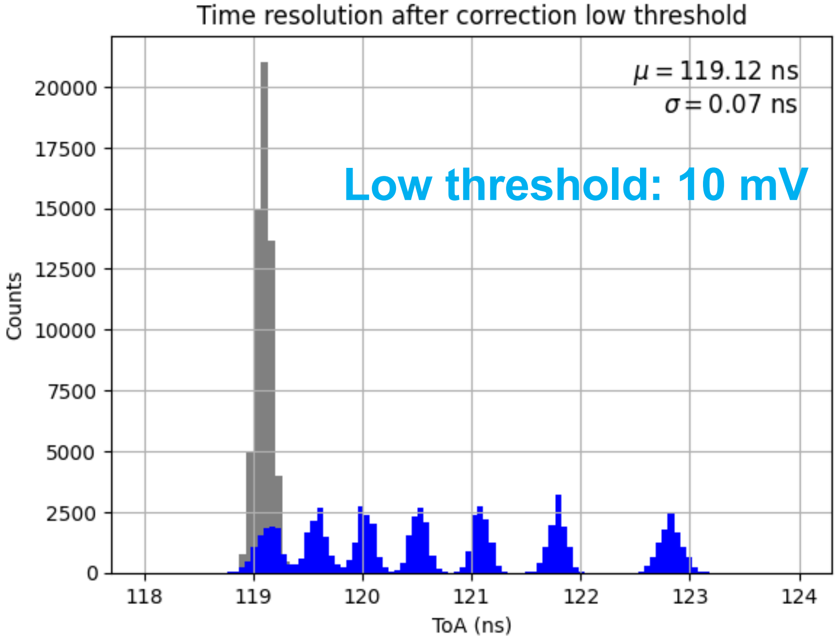
- Resolution comparison
- TDC: Start on Ch0 with trigger from LED Driver. Stop on Ch1 and Ch2 (dual threshold) with variable amplitude.
- Digitizer: autotriggering on Ch0.

Pico TDC test (CAEN+INFN)

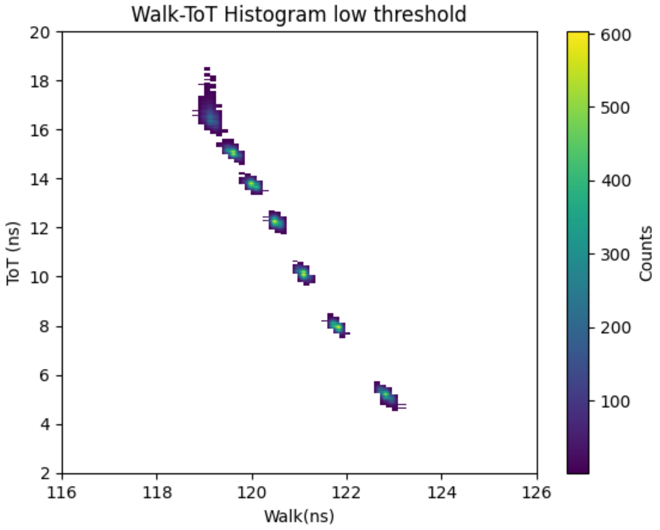
Time Reconstruction (using ToT-Walk correction)



- Acquired pulses at 7 different amplitudes over a 40 dB dynamic range, the walk causes ~3-4 ns spread on ΔT: 7 separate peaks appear on the histogram. (sample independent from calibration sample)
- ΔT corrected by ToT using calibration data with a 5th order polynomial fit of the **ToT-Walk** points taken at the lower threshold (10 mV)
- Corrected ΔT histogram presents one single peak:
- **Time Resolution ~ 70 ps**



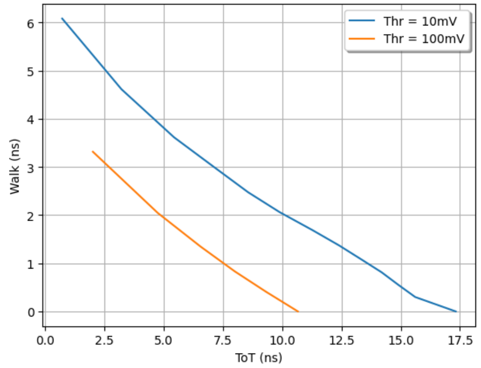
(peak at 119.1 ns at limit)

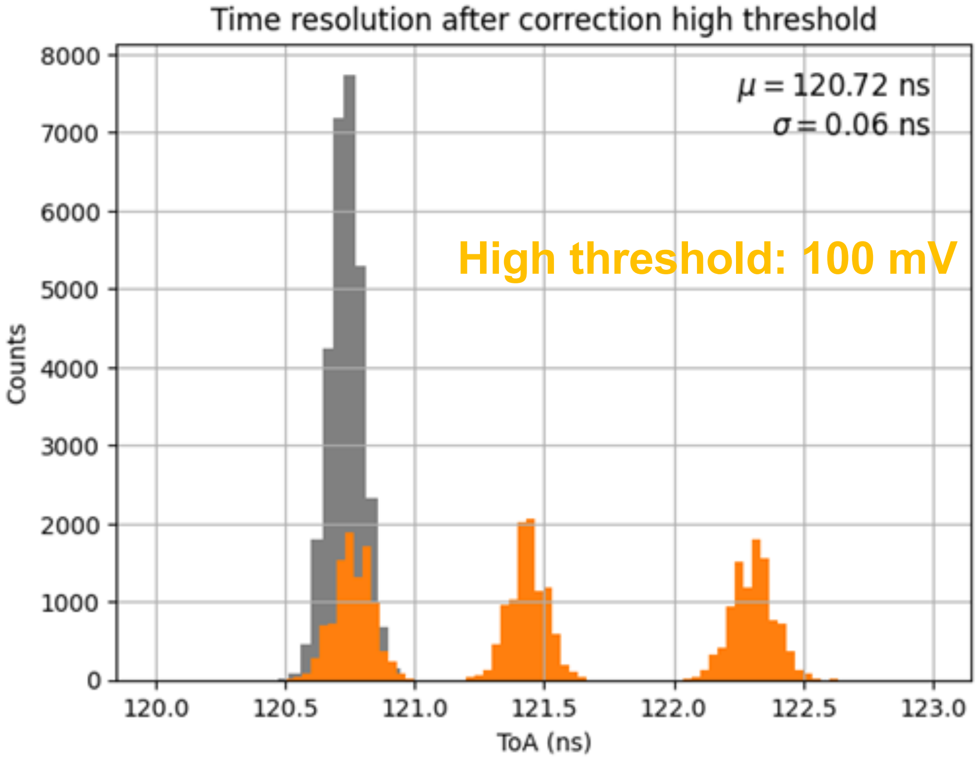


Walk (ns)	Sigma before (ps)	Sigma after (ps)
119.1	-	-
119.6	89	72
120.0	81	71
120.5	75	70
121.1	74	65
121.8	77	63
122.8	100	71

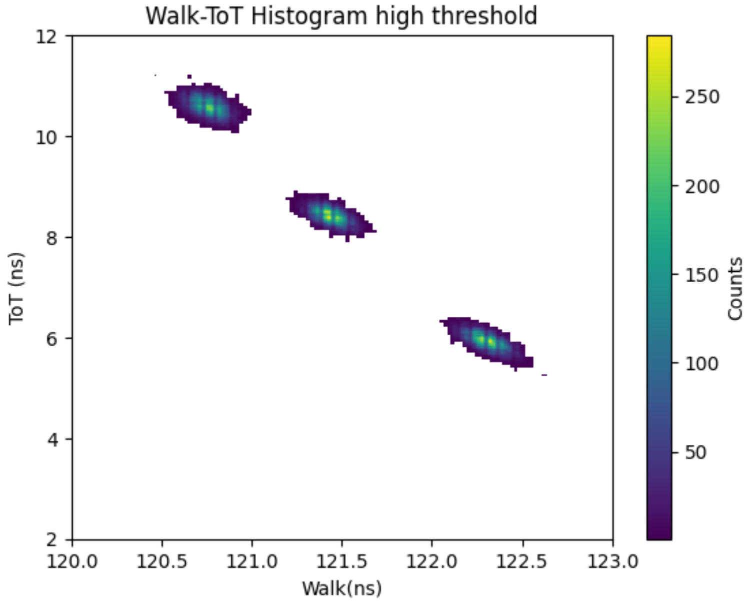
Pico TDC test (CAEN+INFN)

Time Reconstruction (using ToT-Walk correction)





High threshold: 100 mV



Walk (ns)	Sigma before (ps)	Sigma after (ps)
120.8	74	69
121.4	72	61
122.3	82	62

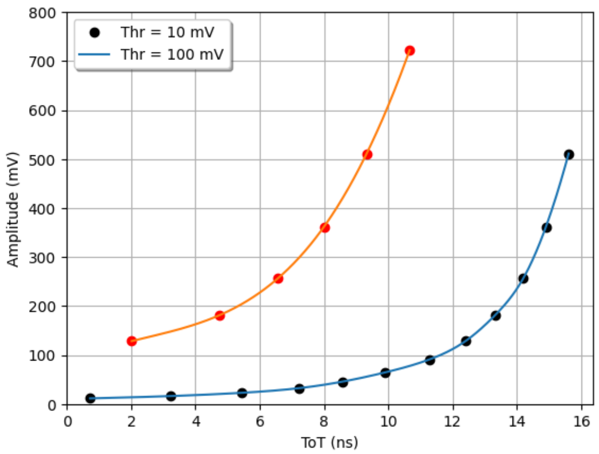
Time Resolution ~ 60 ps

(ECAL resol. ~ 54ps/√E + 100 ps)

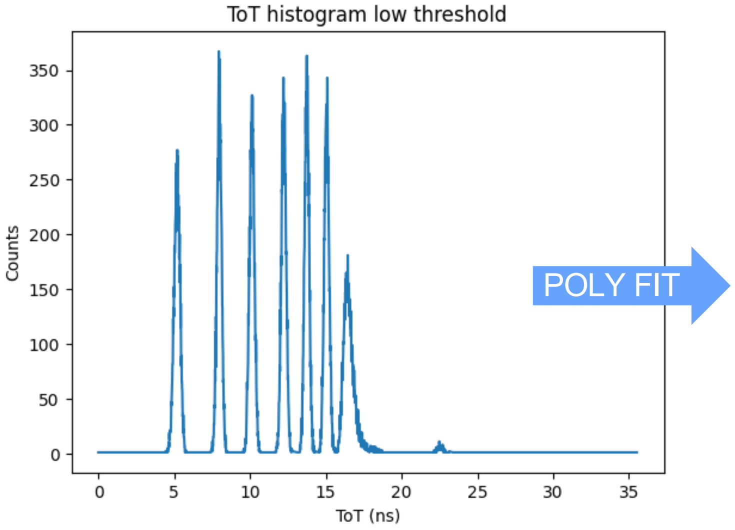
Pico TDC test (CAEN+INFN)

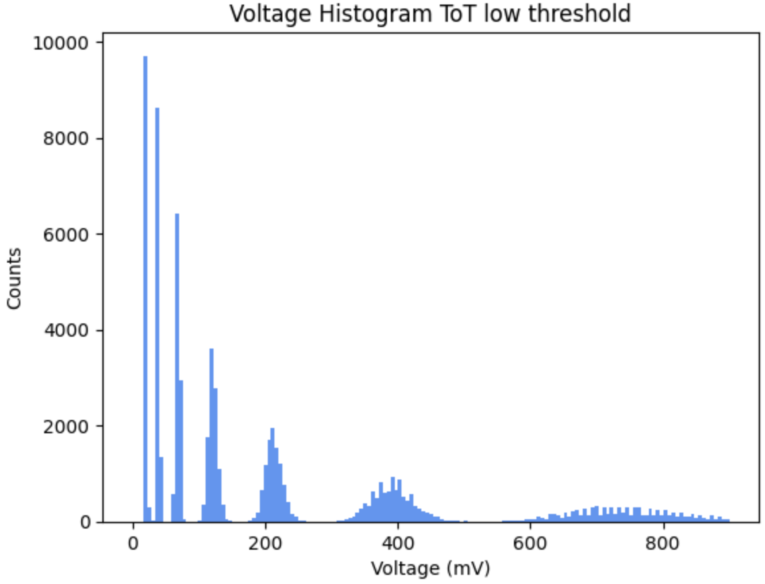
Amplitude Reconstruction

(using ToT-Amp correction)



Low threshold: 10 mV





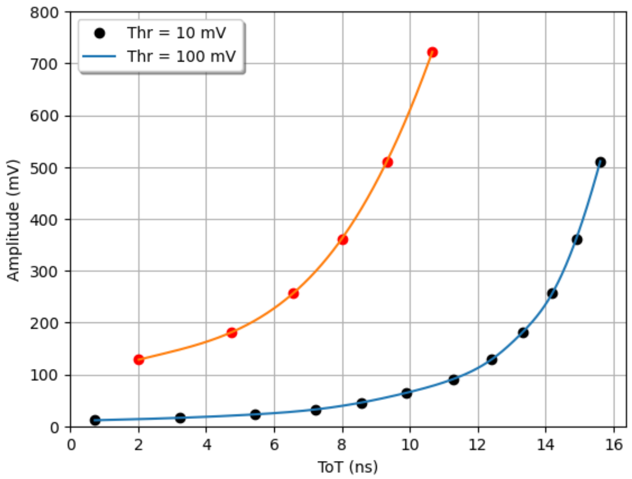
Amplitude (mV)	Sigma (%)
722.0	-
406.0	8.0
228.3	5.9
128.4	5.4
72.2	4.0
40.6	4.0
22.8	3.2

Amplitude resolution from 3 to 6 % in the low/medium range
(well below ECAL resol. ~ 5.7%/√E in this range – see next slides)

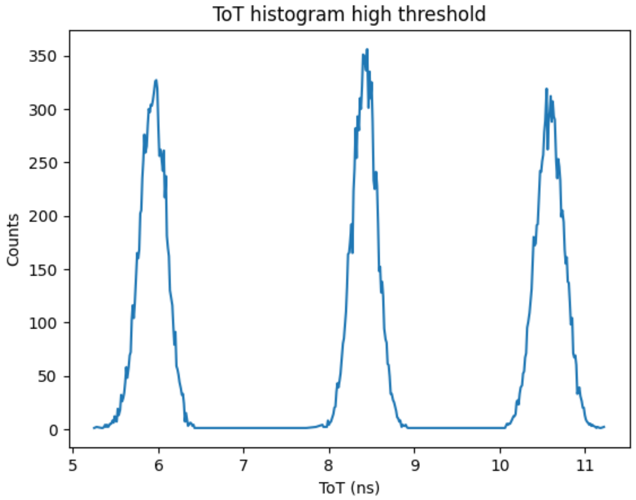
Pico TDC test (CAEN+INFN)

Amplitude Reconstruction

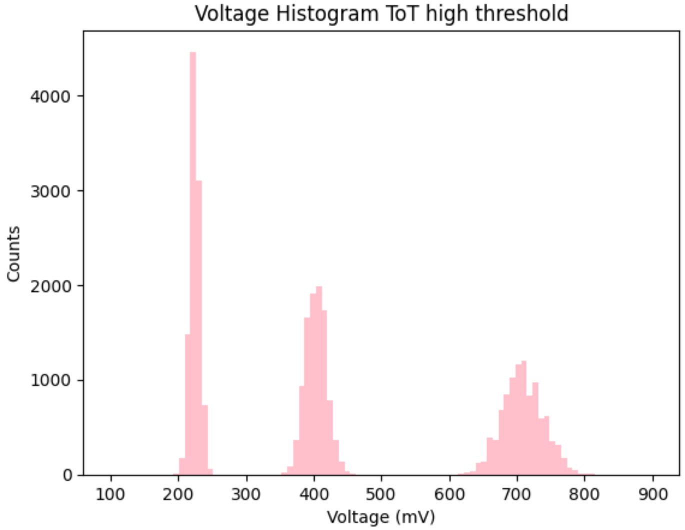
(using ToT-Amp correction)



High threshold: 100 mV



POLY FIT



Amplitude (mV)	sigma (%)
722.0	4.2
406.0	3.8
228.3	3.2

Amplitude resolution ~ 3-4 % in the higher range
(below ECAL resol. ~ 5.7%/√E – see next slides)

Pico TDC test (CAEN+INFN)

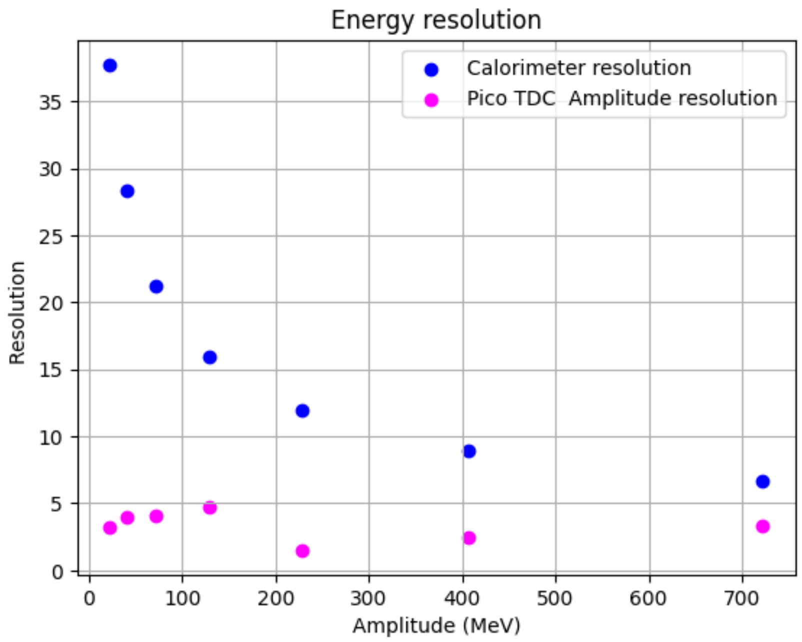
comparison with Ecal resolution

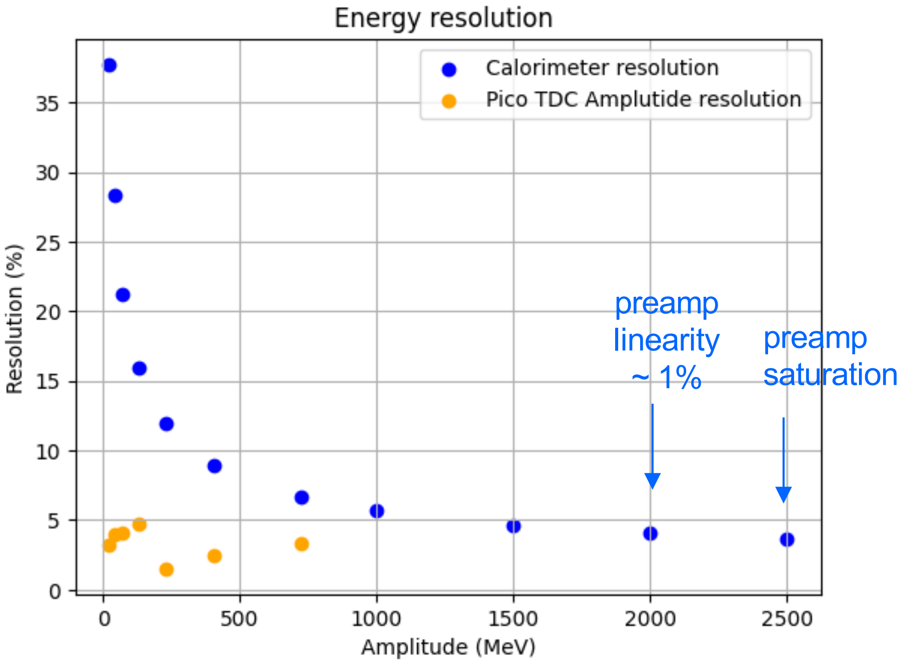
From previous studies on dynamic range:

- V_{dis}(max) = V_{preamp}(max) • 0.5 • C_{ATT}= 2.0 V
- minimum discriminator threshold possible V_{TH}= 2.5 mV

G_{PM} $(\times 10^5)$	G_{tot} $(\times 10^6)$	$N_{pe}(\max)$	signal amplitude (mV/pe)	$N_{pe}(\min)$ $V_{TH} = 2.5$ mV	MeV (min) at module center
4.8	1.2	~ 2000	1.0	~ 3	3.0
6.4	1.6	~ 1500	1.3	~ 2	2.0
9.5	2.4	~ 1000	2.0	~ 1	1.0

Amplitude resolution obtained from ToT is compared with the intrinsic calorimeter resolution (assuming 1 mV = 1 p.e. = 1 MeV => 1 V = 1 GeV)





preamp linearity ~ 1%

preamp saturation

Conclusions

- ECAL testing is about to start at LNF in a dedicated area

- Studies for the optimization of the working point of the SAND calorimeter read-out electronics have been performed.
- The dynamic range and pile-up of the signals have been studied with MC.
- PMT preamplifiers have been tested for linearity and are well compatible with needed dynamic range and proposed FEE solutions, with the additional advantage of lowering the PMT gain (and HV), that is beneficial for PMT lifetime.
- The features of preamp saturation could be exploited to partially recover input signal information during saturation regime and measure amplitude even for saturated signals.

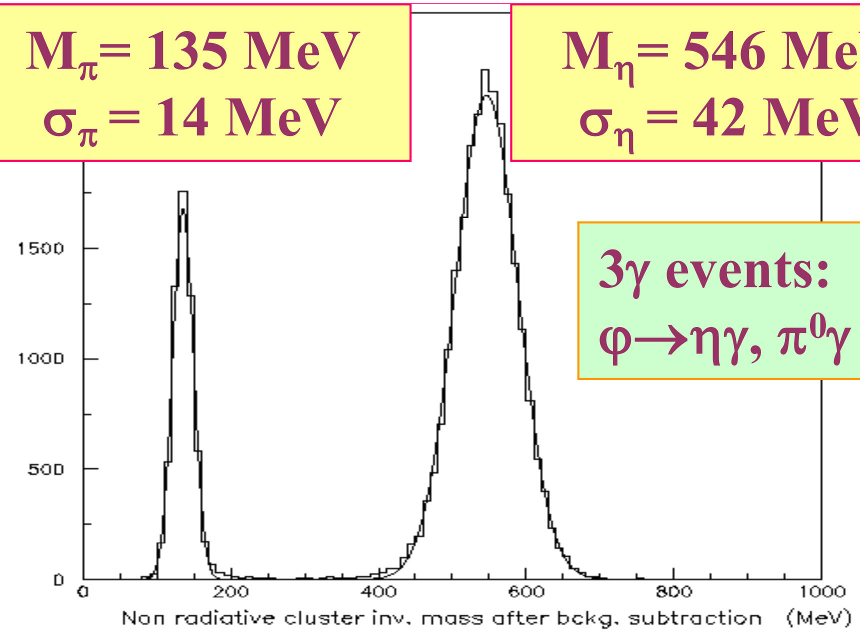
- Possible solutions for the FEE that could constitute a good compromise between cost and performance are being investigated in collaboration with CAEN.
- The picoTDC with double threshold discriminator constitutes a good option.
- To further improve amplitude resolution at higher energies, optimization of the thresholds for the best perfomance in the whole expected dynamic range (2.5-2000 mV) is being studied.
- Other solutions based on PicoTDC + amplitude meas. (RADIOROC chip) are being investigated in collaboration with CAEN and appear also promising.

Spare Slides

Examples of mass reconstruction in KLOE

M_π = 135 MeV
σ_π = 14 MeV

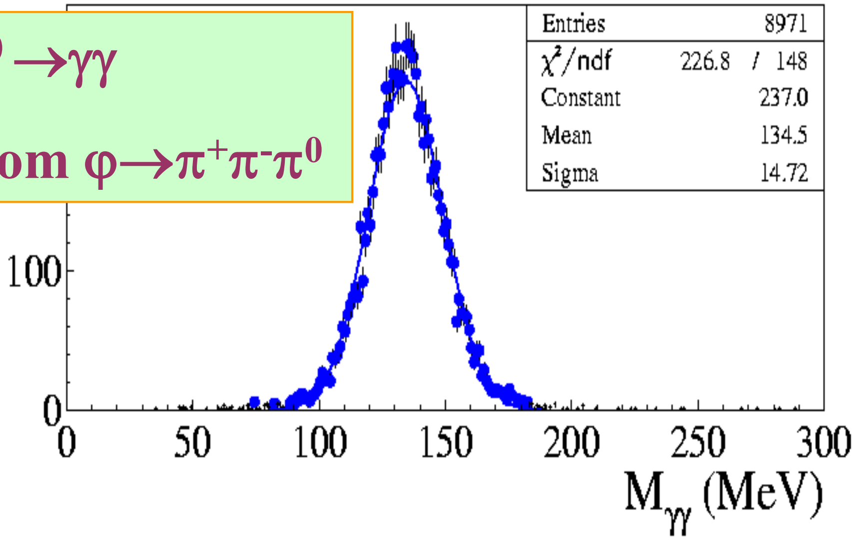
M_η = 546 MeV
σ_η = 42 MeV



3γ events:
$\phi \to \eta\gamma$, $\pi^0\gamma$

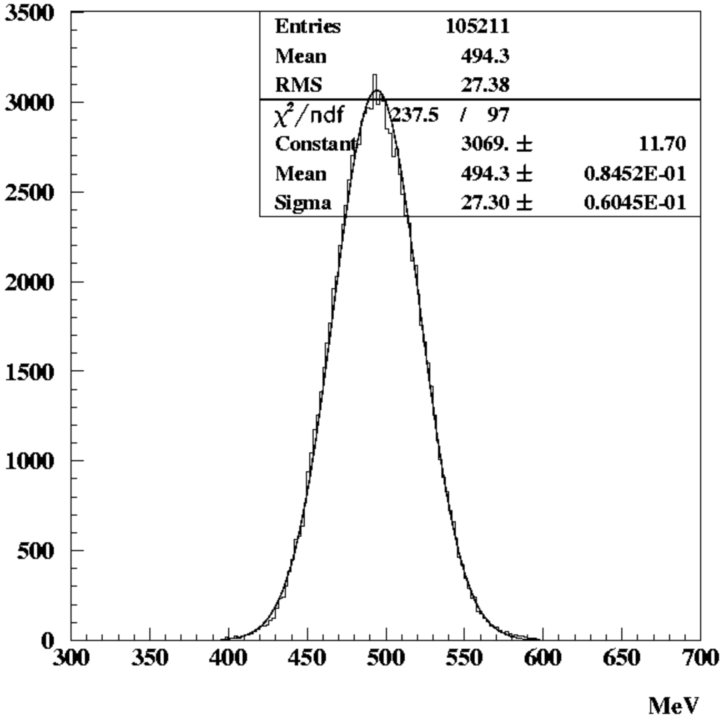
$\pi^0 \to \gamma\gamma$

from $\phi \to \pi^+\pi^-\pi^0$



$K_s \to \pi^0\pi^0$

M_K = 494 MeV
σ_K = 27 MeV



Mass reconstruction within 1%with PDG. Resolutions are in good agreement with MC expectation.