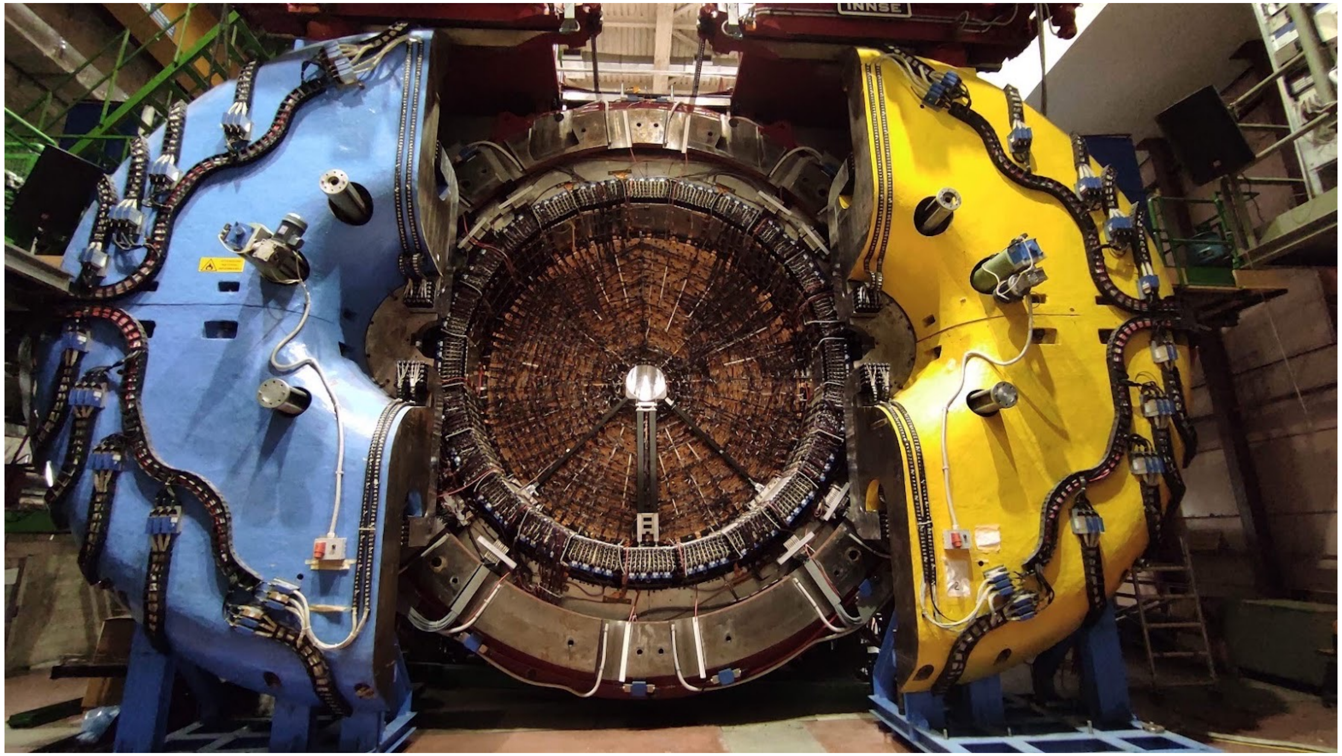
ECAL: electronics

Antonio Di Domenico
Dipartimento di Fisica, Sapienza Università di Roma
and INFN-Roma, Italy



Meeting DUNE-Italia – Ferrara, 28-30 Ottobre 2024

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

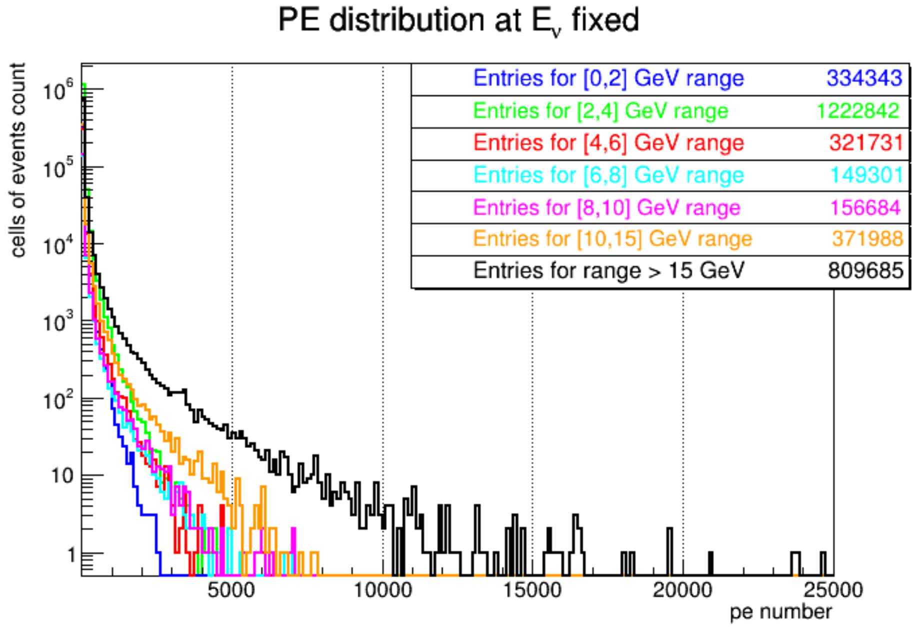
- MC simulation of neutrino interactions in SAND
- sample of 118k evts corresponding ~ 30 minutes at 1.2 MW in FHC mode (or ~15 min at 2.4 MW)
- Digitization of ECAL (as in KLOE MC): deposited energy in the cells propagated to PMTs and converted into p.e. number; constant fraction discriminator simulated

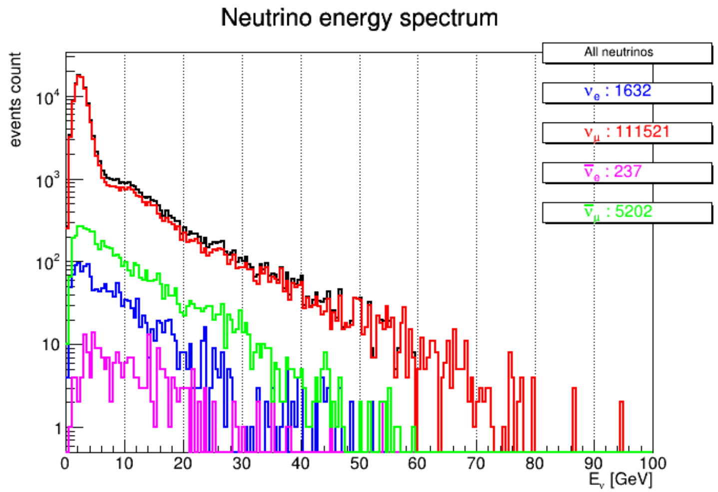
E_ν range = [0,10] GeV

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	$3.64 \cdot 10^{-2}$

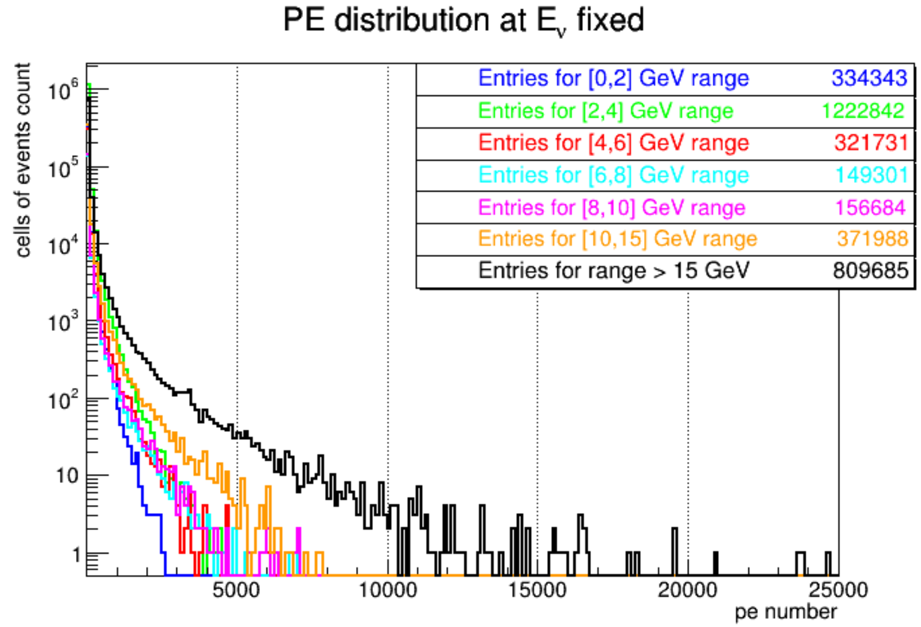
Fraction of hit cells above PE threshold	[%]
1000 PE threshold	0.19
2000 PE threshold	$3.03 \cdot 10^{-2}$
3000 PE threshold	$7.19 \cdot 10^{-3}$
4000 PE threshold	$2.11 \cdot 10^{-3}$





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

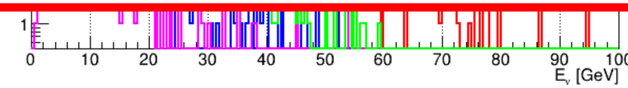


E_ν range = [0,10] GeV	
Events number	101,696
Events cells number	2,184,901

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	$3.64 \cdot 10^{-2}$

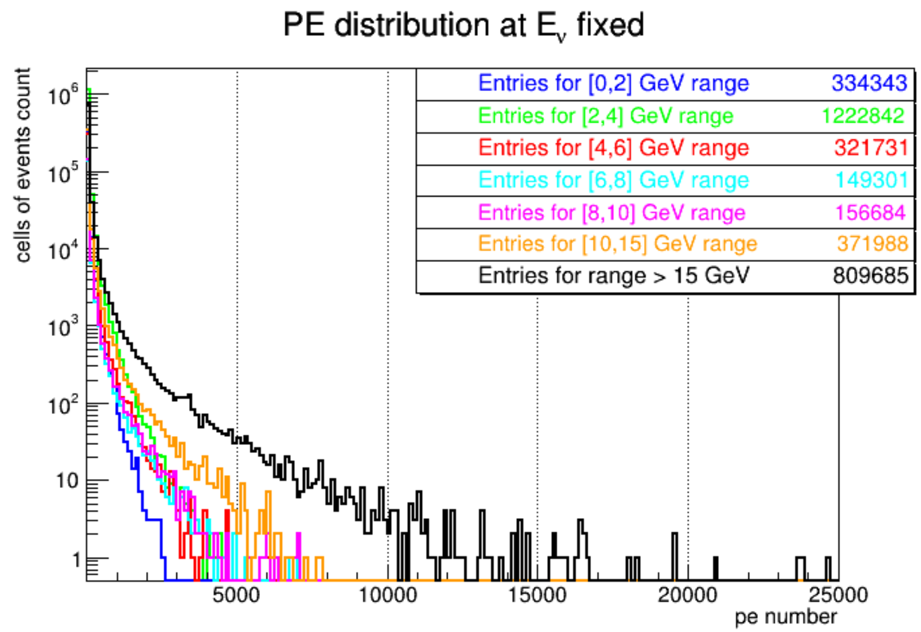
Fraction of hit cells above PE threshold	[%]
1000 PE threshold	0.19
2000 PE threshold	$3.03 \cdot 10^{-2}$
3000 PE threshold	$7.19 \cdot 10^{-3}$
4000 PE threshold	$2.11 \cdot 10^{-3}$

- 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



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



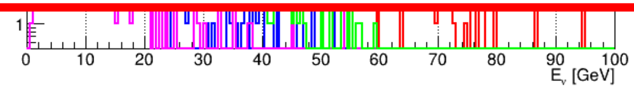
E_ν range = [0,10] GeV

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
2000 PE threshold	$3.03 \cdot 10^{-2}$
3000 PE threshold	$7.19 \cdot 10^{-3}$
4000 PE threshold	$2.11 \cdot 10^{-3}$

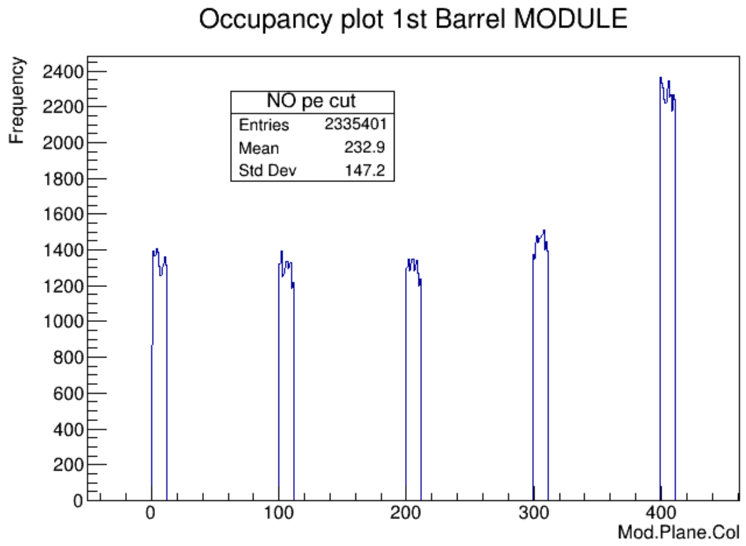
- Neutrino energy range of interest for oscillation analyses is [0,10] GeV
- In this range the MAXIMUM Np.e. that has to be treated by FEE can be safely set between 1000 and 2000
  => see next slides for the choice of the FEE dynamic range



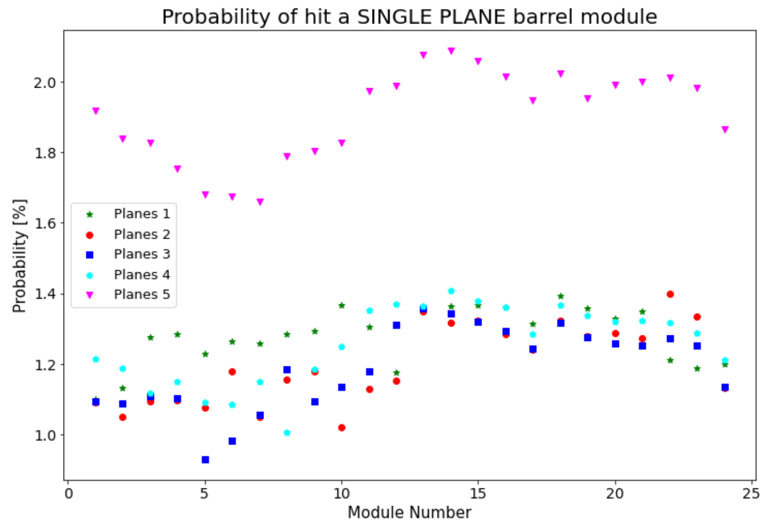
- to maximize the neutron detection efficiency by ECAL the MINIMUM Np.e. that has to be treated by FEE is the lowest possible, ideally 1-3 Np.e.

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

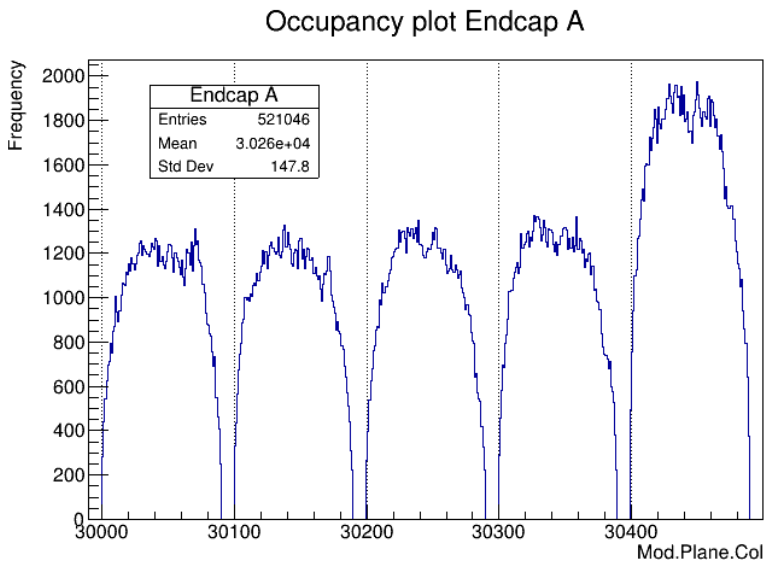
Cell occupancy plots and hit probability



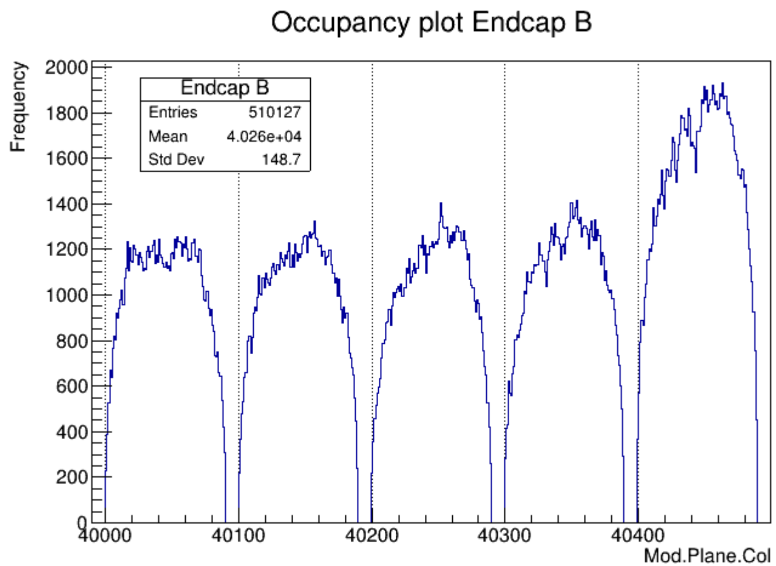
Barrel



Ecap A



Ecap B



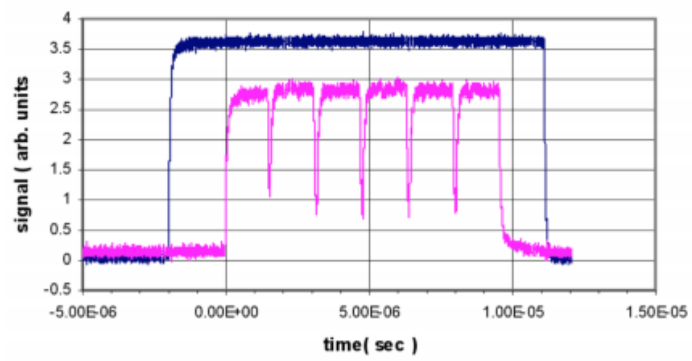
Average probability that a cell is fired/hit in a neutrino interaction event:

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

P_{cell} = 1.16%

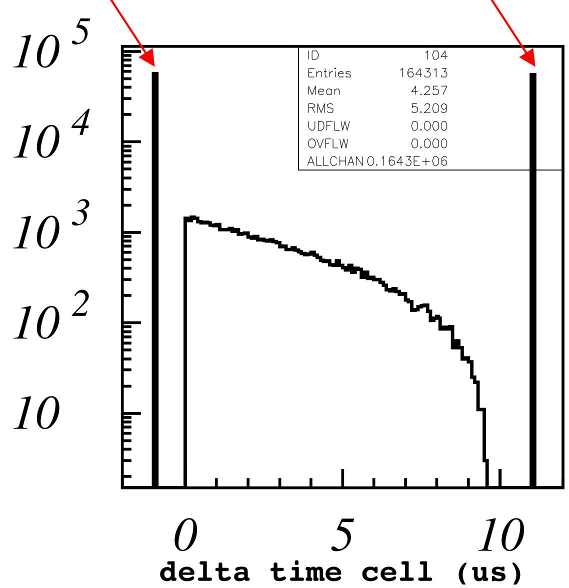
Pile-up probability

- 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

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

PMT signal in KLOE and preamp linearity test

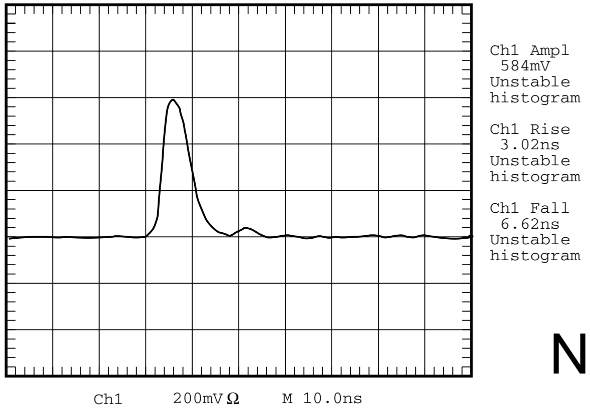
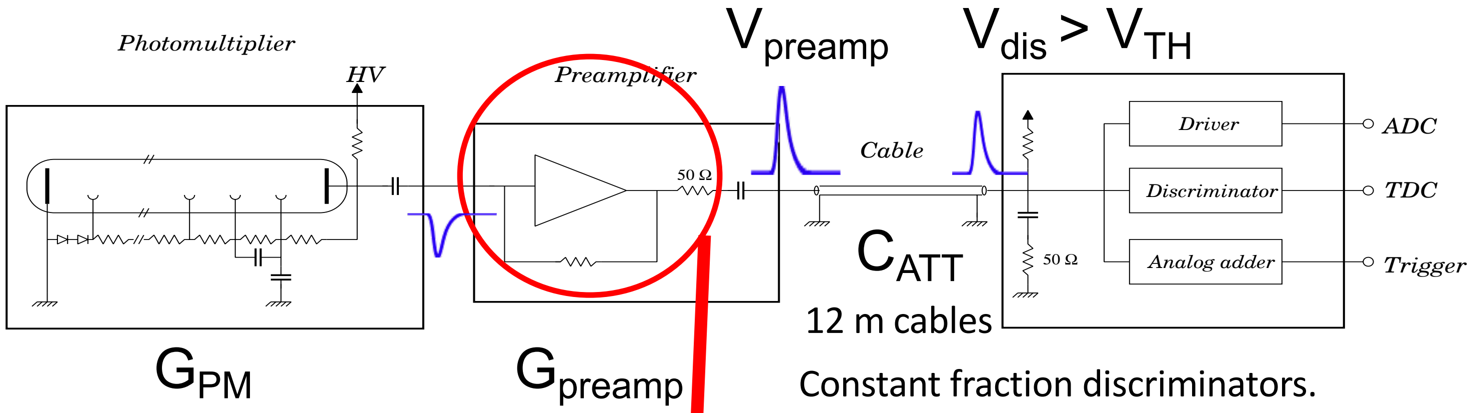
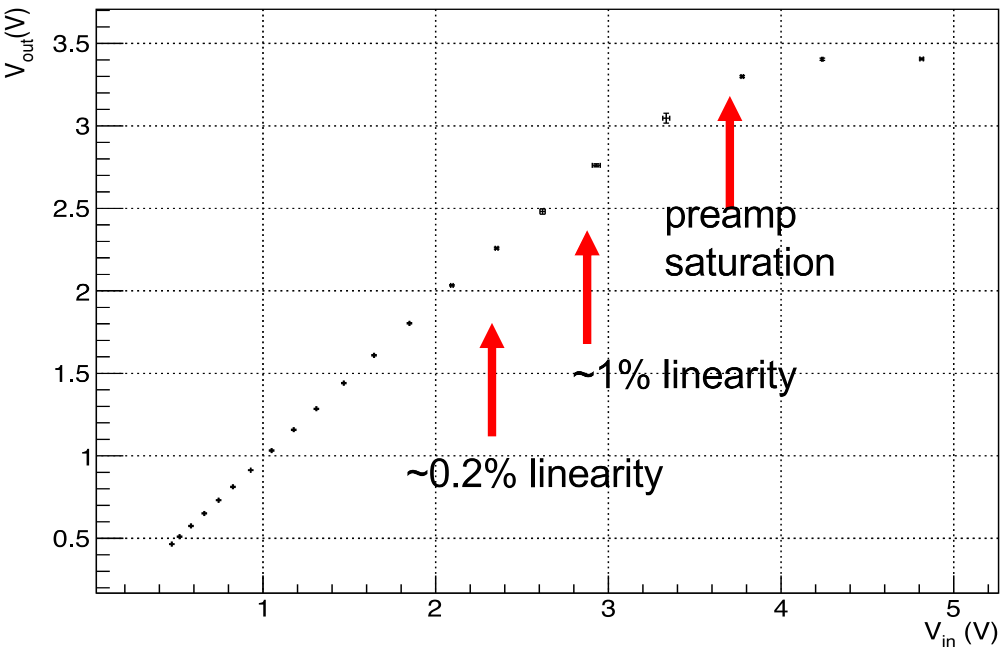


Figure 4: Typical signal from the PM base.



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:

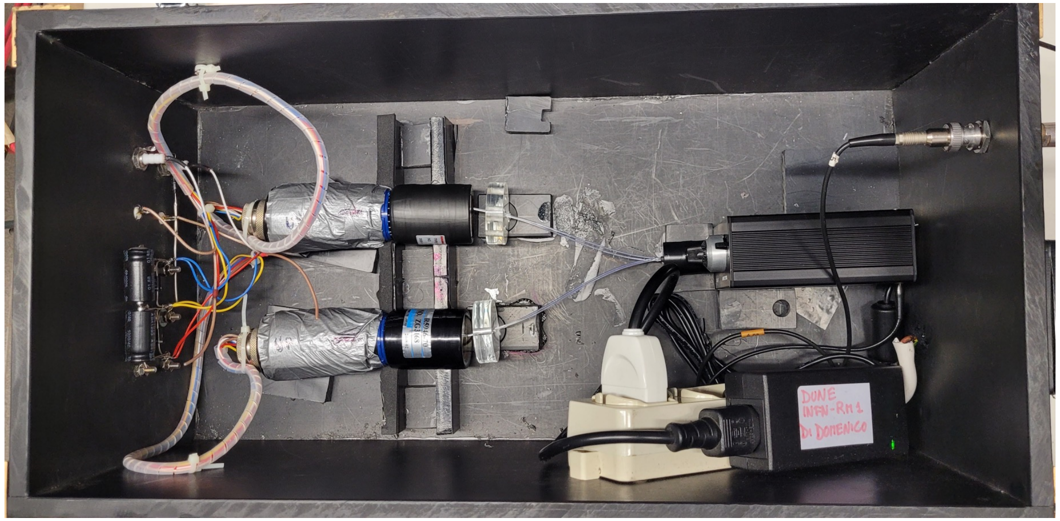
- V_{preamp}(max)=4.7 V increase by 15% => V_{preamp}(max) = 5.4 V (G_{preamp}=2.5)
  (linearity from 0.2% to 1%)
- V_{dis}(max) = V_{preamp}(max) • 0.5 • C_{ATT}= 2.0 V (12m long cable attenuation: C_{ATT} = 0.74)
- to have a very low noise environment as in KLOE => lowering (halving) the minimum discriminator/digitizer threshold to V_{TH}= 2.5 mV

G_{PM} $(\times 10^5)$	G_{tot} $(\times 10^6)$	N_{pe}(max)	signal amplitude (mV/pe)	N_{pe}(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

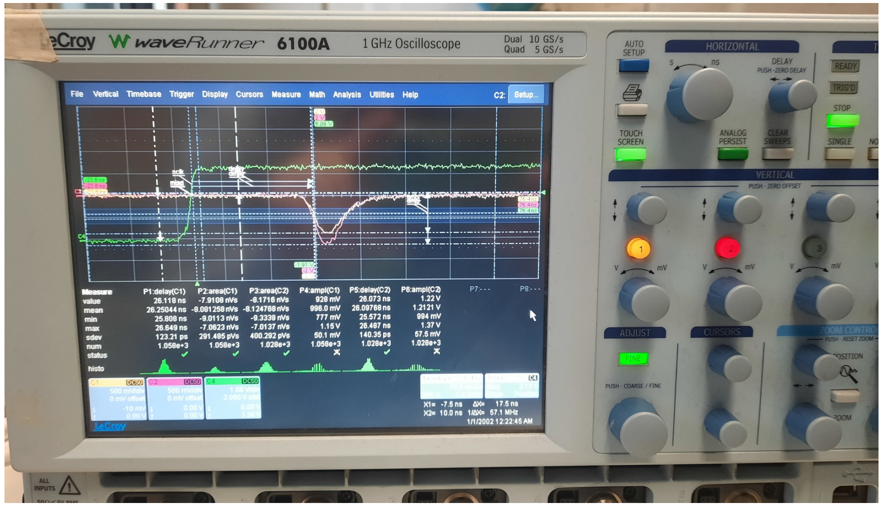
- => N_{pe}(max)\ N_{pe}(min) ~ 300 (in KLOE) increases up to 600 – 1000.
- Different dynamic ranges can be implemented changing G_{PM} =>
  the final choice should be a compromise between an affordable level of events with energy saturated cells, depending on N_{pe}(max), and an acceptable neutron detection efficiency, depending on N_{pe}(min).

Preamp linearity test with PMT signals

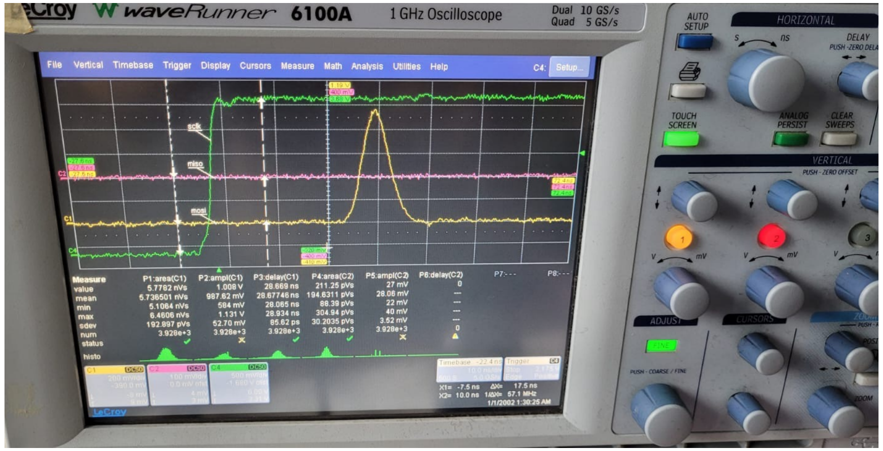
PMT system test at LNF with
- CAEN LED driver SP5601 (wavelength ~ 400 nm) with fine tunable LED intensity
- scint. fiber splitter
- two PMTs (for relative QE meas.)



no preamplifier



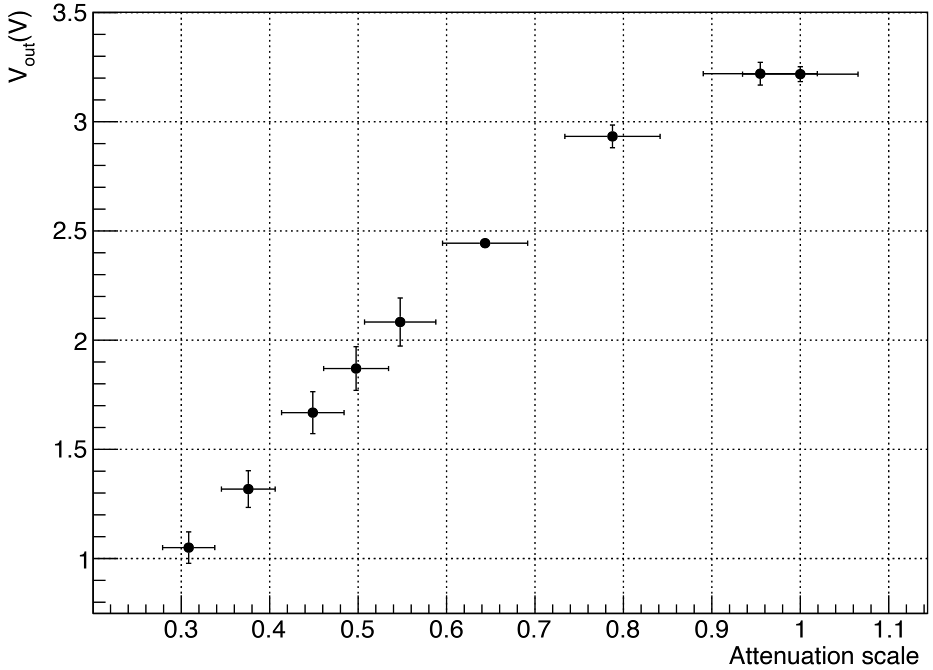
with preamplifier



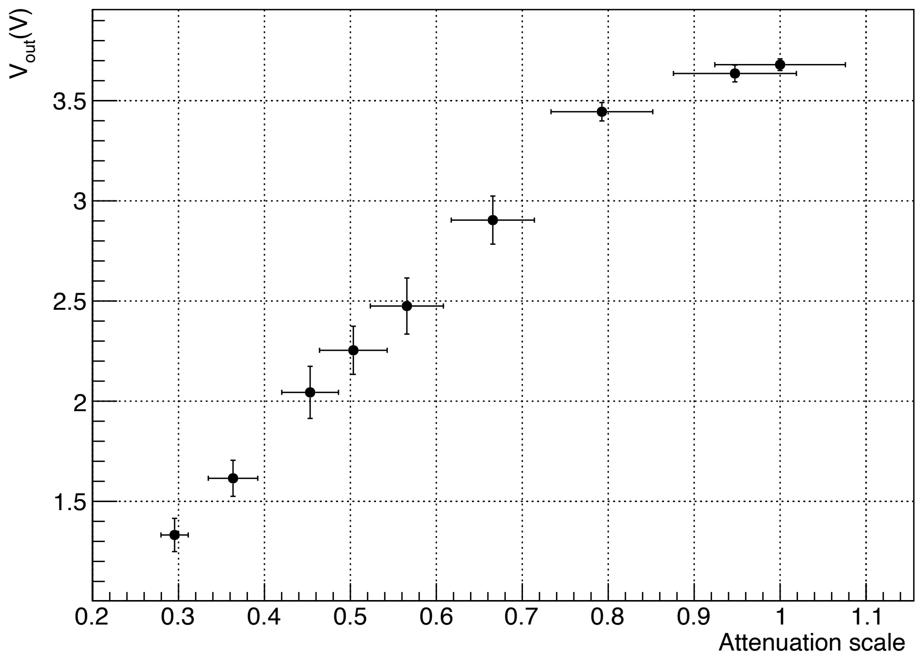
Preamp linearity test with PMT signals: results

LED driver attenuation scale checked and calibrated with PMT response in linear region

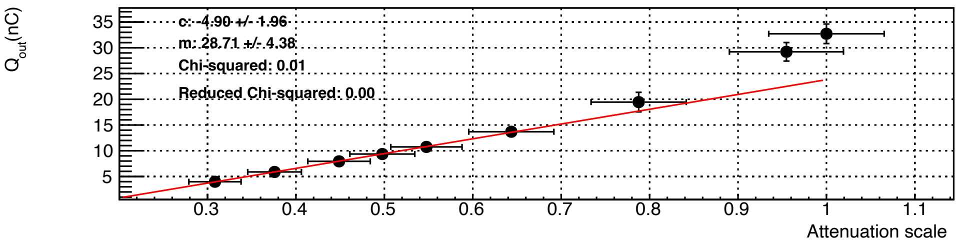
Saturation curve PMT1



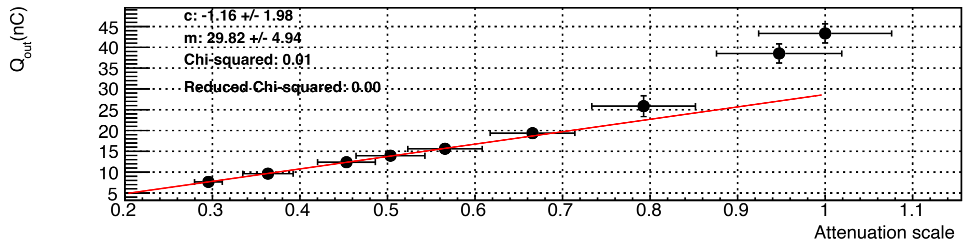
Saturation curve PMT2



Linear fit PMT1



Linear fit PMT2



Preamp linearity test with PMT signals => saturation

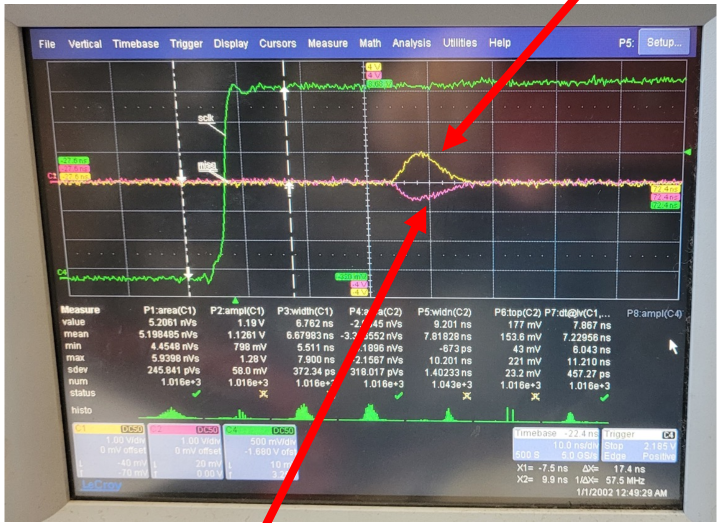
PMT2 HV=1700 V

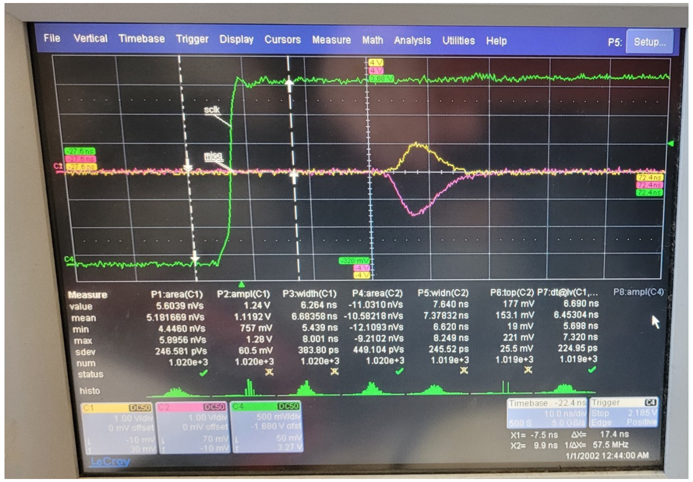
REF PMT1

HV=1900 V

fixed LED intensity (full)

HV=2100 V





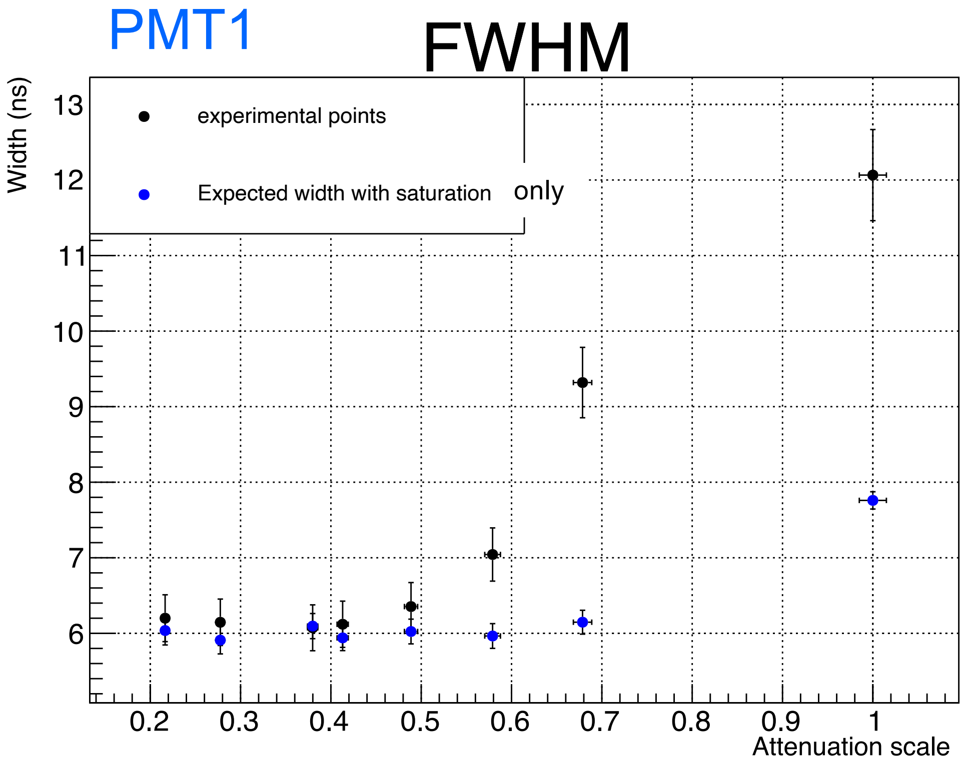
no preamp PMT2

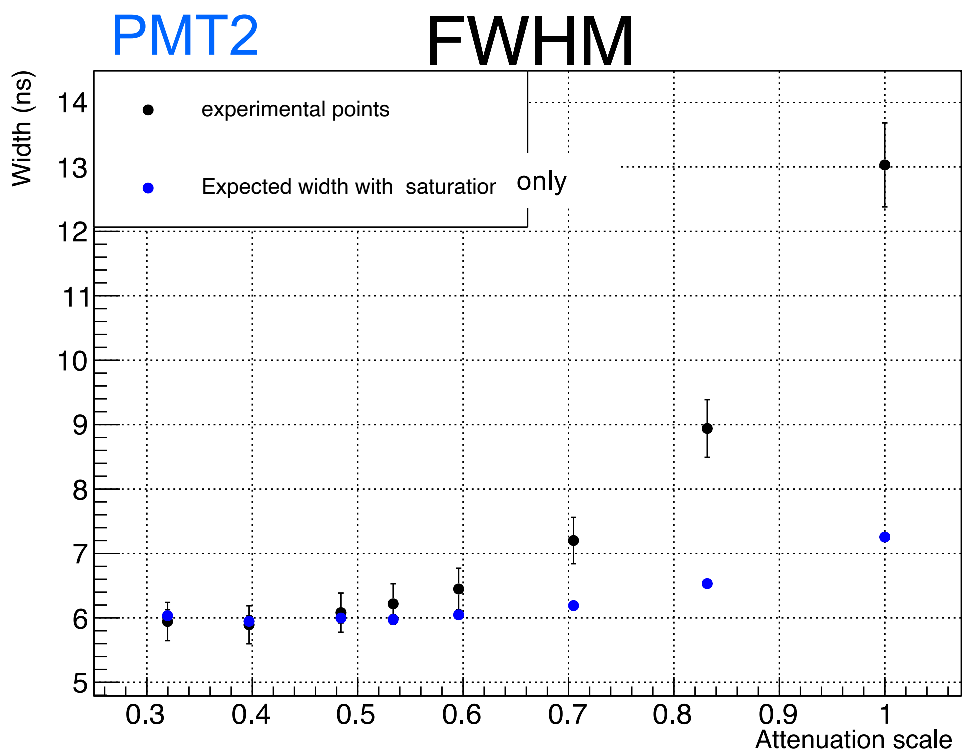
with preamp PMT2

preamp recovery time from saturation depends on input amplitude signal

Preamp linearity test with PMT signals => saturation

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





- 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

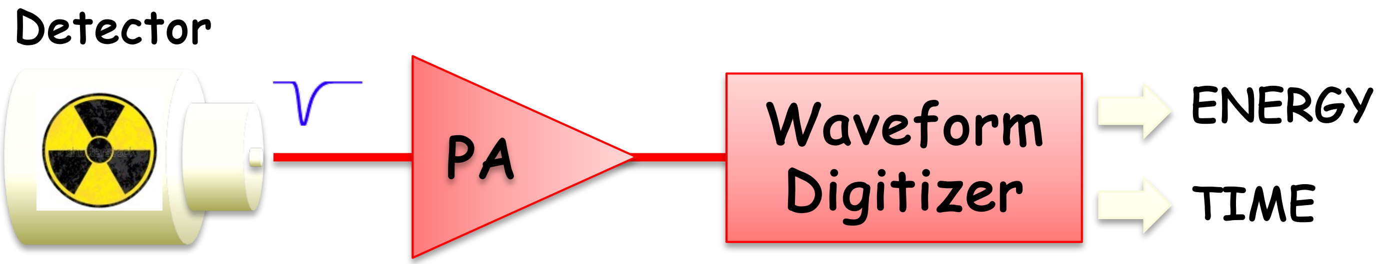
What choice of FEE for SAND/ECAL?

Studies in collaboration with CAEN

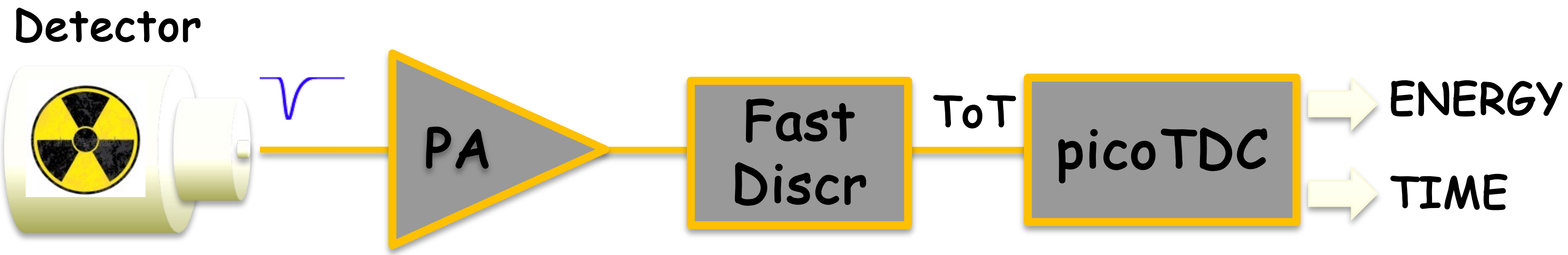
A. Di Domenico, V. Di Silvestre, P. Gauzzi - INFN-RM1
C. Tintori, C. Maggio, L. Colombini – CAEN, Viareggio

Choice of FEE for SAND/ECAL

Three possible read-out schemes:

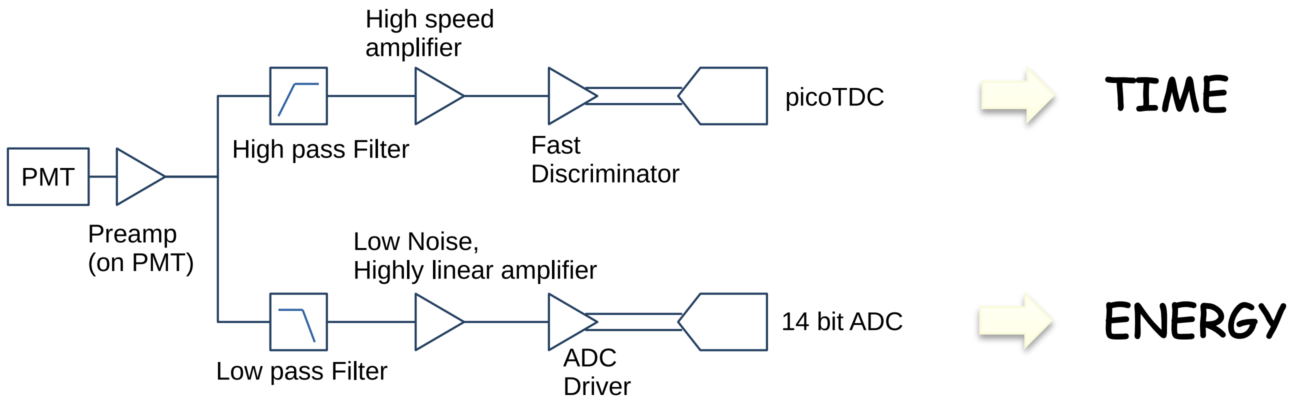


Highest Flexibility
=>
Fsampl ~ 1 GS/s =>High Cost or
Fsampl ~ 125-250 MS/s
+ signal shaper



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

a more conventional approach

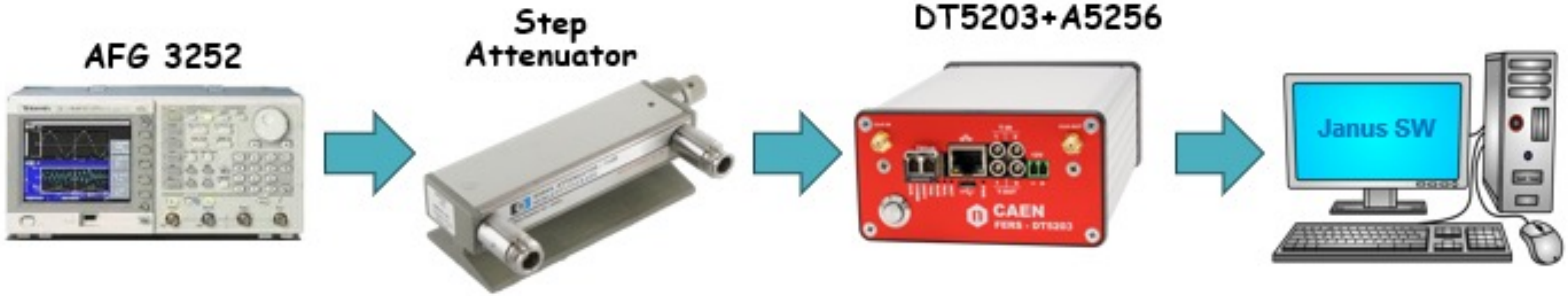


CAEN:

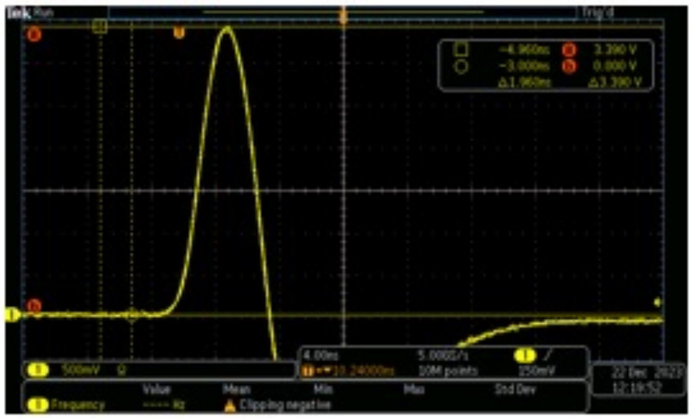
collaboration for a commercial (partly customized) solution keeping KLOE energy and time performance

Pico TDC test (CAEN)

Test setup:



Pulse: Amp = 3.85 V, Rise = ~2.5 ns



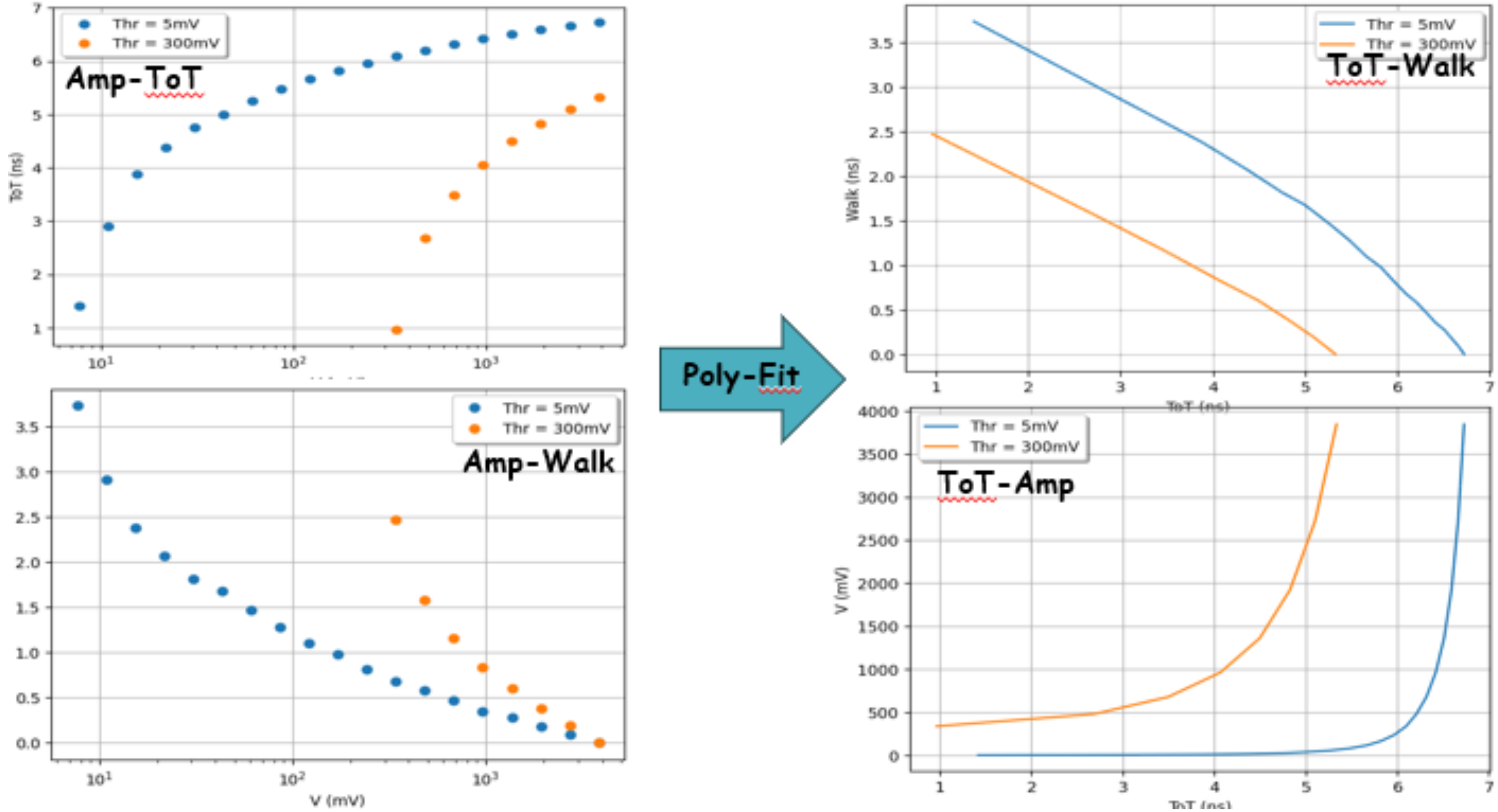
- Start on Ch0 with fixed amplitude. Stop on Ch1 and Ch2 (dual threshold) with variable amplitude (max = 3.85 V). Delay = 13 ns.
- Acquire **ToT** (ToT= Time Over Threshold) and **ΔT** (**ΔT** = walk) at different amplitudes (from 0 to 52 dB, 3 dB step)
- Fit points and build **ToT-Walk** and **ToT-Ampl** curves
- Use curves to correct Walk from ToT (replace CFD)
- Use curves to get Amplitude from ToT (make ADC from TDC)

Pico TDC test (CAEN)

Calibration Curves:

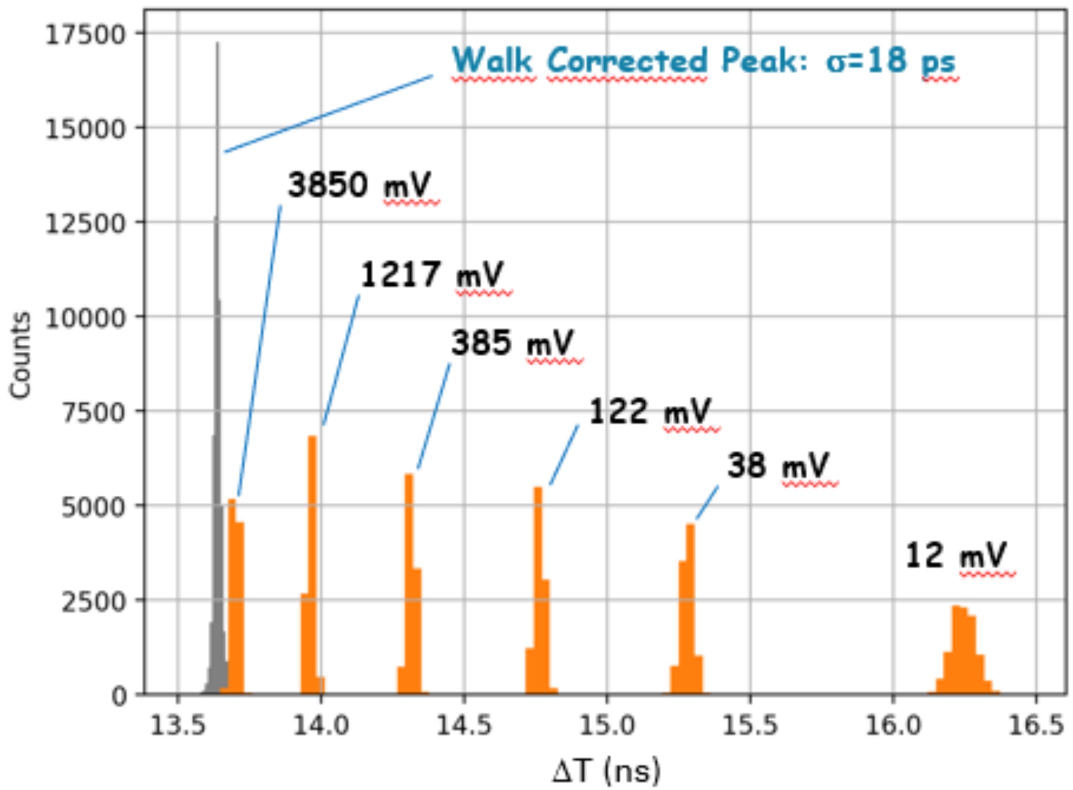
Low threshold: 5mV

High threshold: 300mV



Pico TDC test (CAEN)

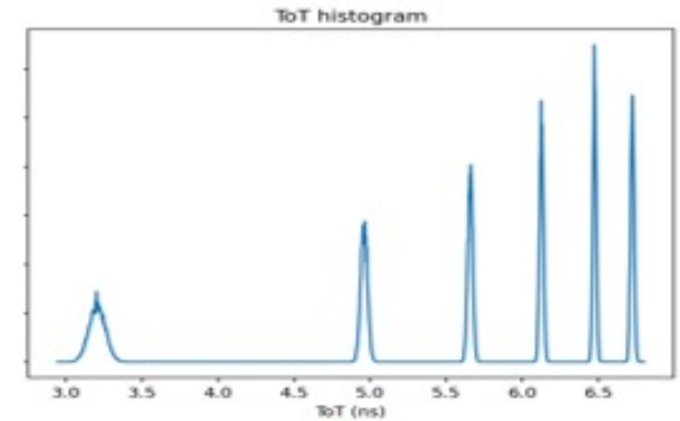
Time Reconstruction (using ToT-Walk correction)

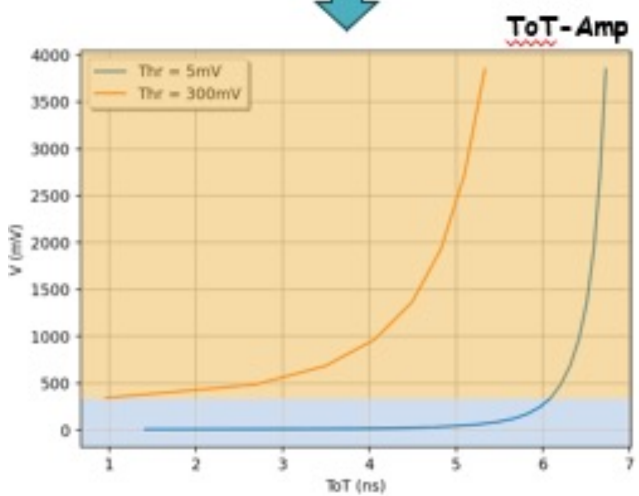


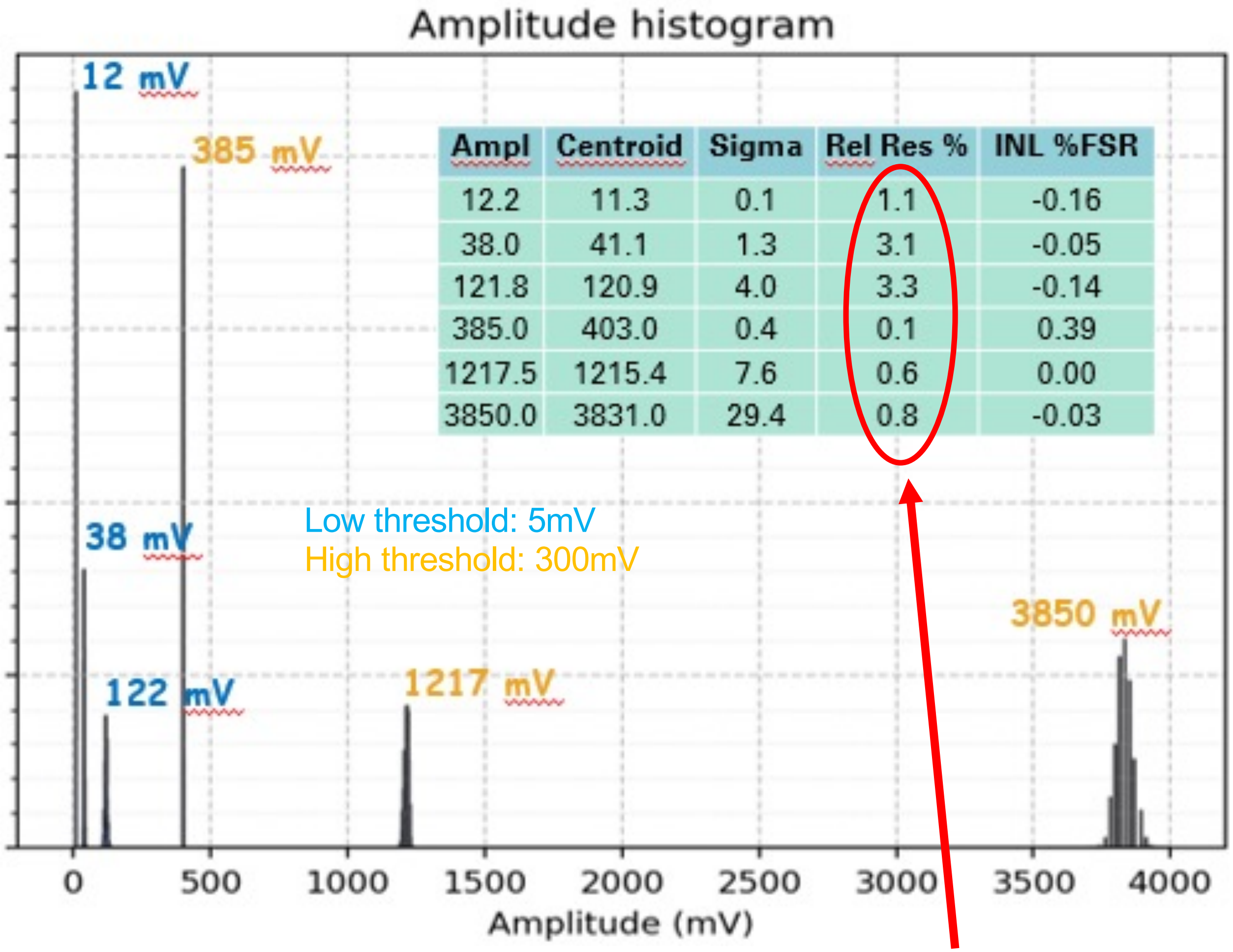
- Acquired pulses at 6 different amplitudes over a 50 dB dynamic range, the walk causes ~2 ns spread on ΔT: 6 separate peaks appear on the histogram
  (sample independent from calibration sample)
- ΔT corrected by ToT using calibration data with a 5th order polynomial fit of the **ToT-Walk** points taken at lower threshold (5 mV)
- Corrected ΔT histogram presents one single peak:
- **Time resolution ~18 ps**
  over 50 dB dynamic range

Pico TDC test (CAEN)

Amplitude Reconstruction (using ToT-Amp correction)







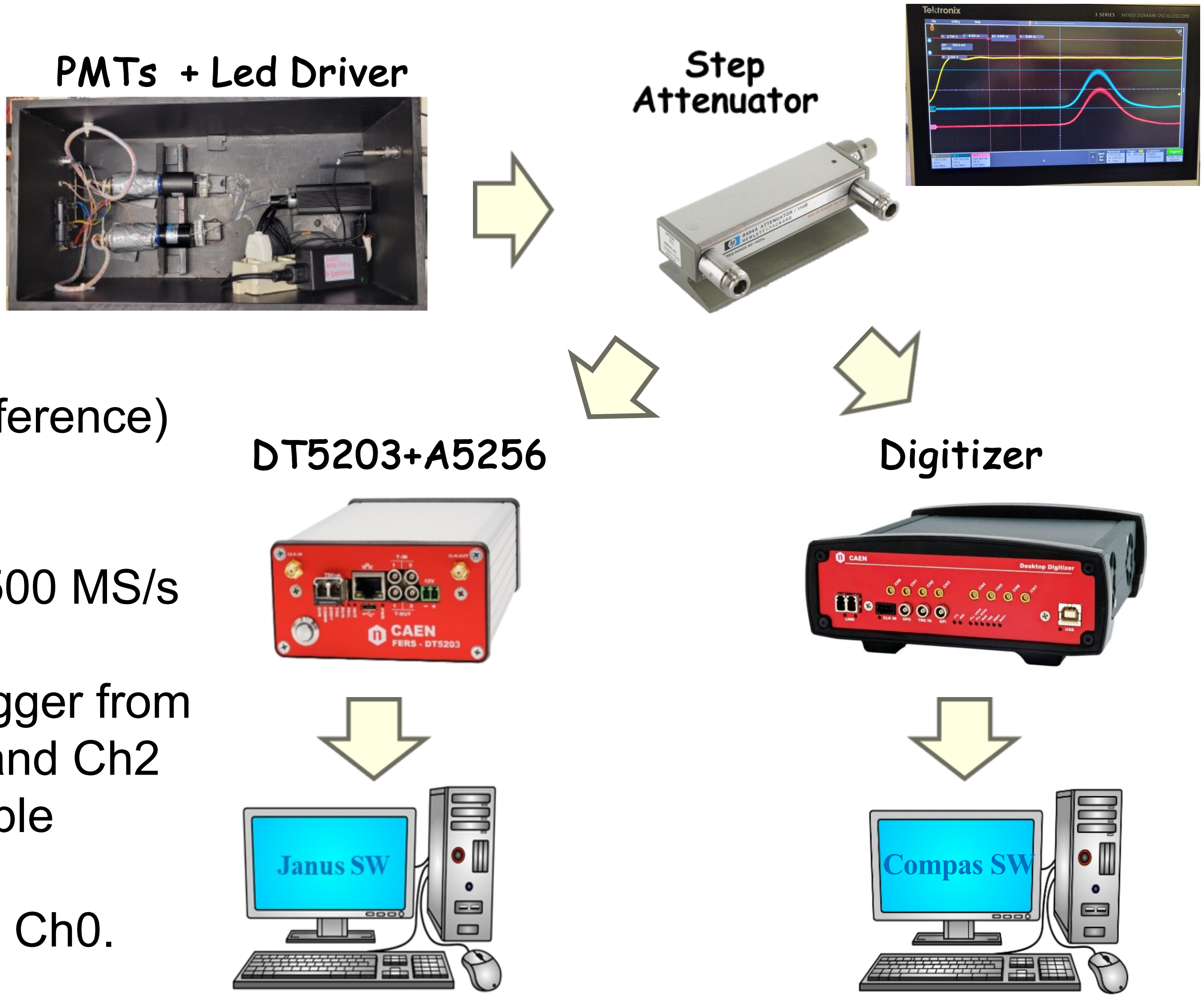
Ampl	Centroid	Sigma	Rel Res %	INL %FSR
12.2	11.3	0.1	1.1	-0.16
38.0	41.1	1.3	3.1	-0.05
121.8	120.9	4.0	3.3	-0.14
385.0	403.0	0.4	0.1	0.39
1217.5	1215.4	7.6	0.6	0.00
3850.0	3831.0	29.4	0.8	-0.03

Amplitude resolution <1% at large values

(well below ECAL resol. ~ 5.7%/√E in the whole range)

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:

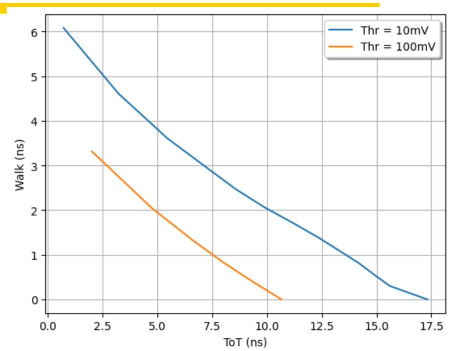
i. Pico TDC

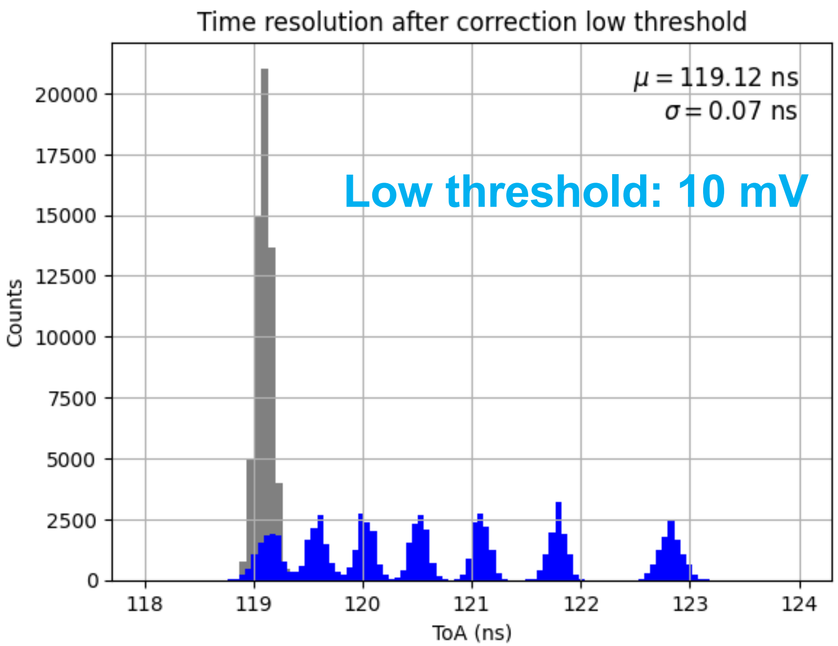
ii. Digitizer 730S 14 bit @ 500 MS/s

- 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)

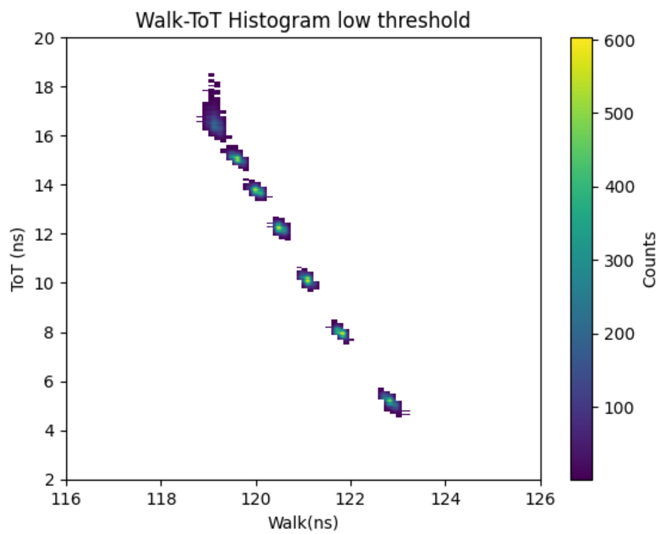
Time Reconstruction (using ToT-Walk correction)





(peak at 119.1 ns at limit)

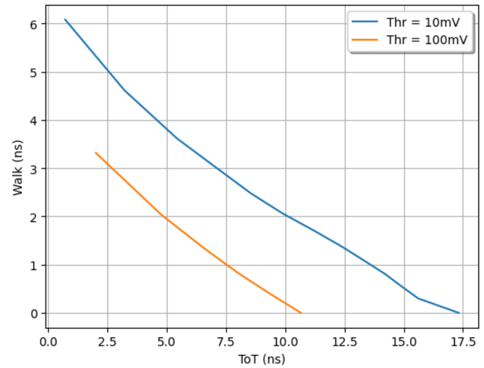
- Acquired pulses at 7 different amplitudes over a 40 dB dynamic range, the walk causes ~3-4 ns spread on ΔT: 7 separate peaks appear on the histogram. (sample independent from calibration sample)
- ΔT corrected by ToT using calibration data with a 5th order polynomial fit of the **ToT-Walk** points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

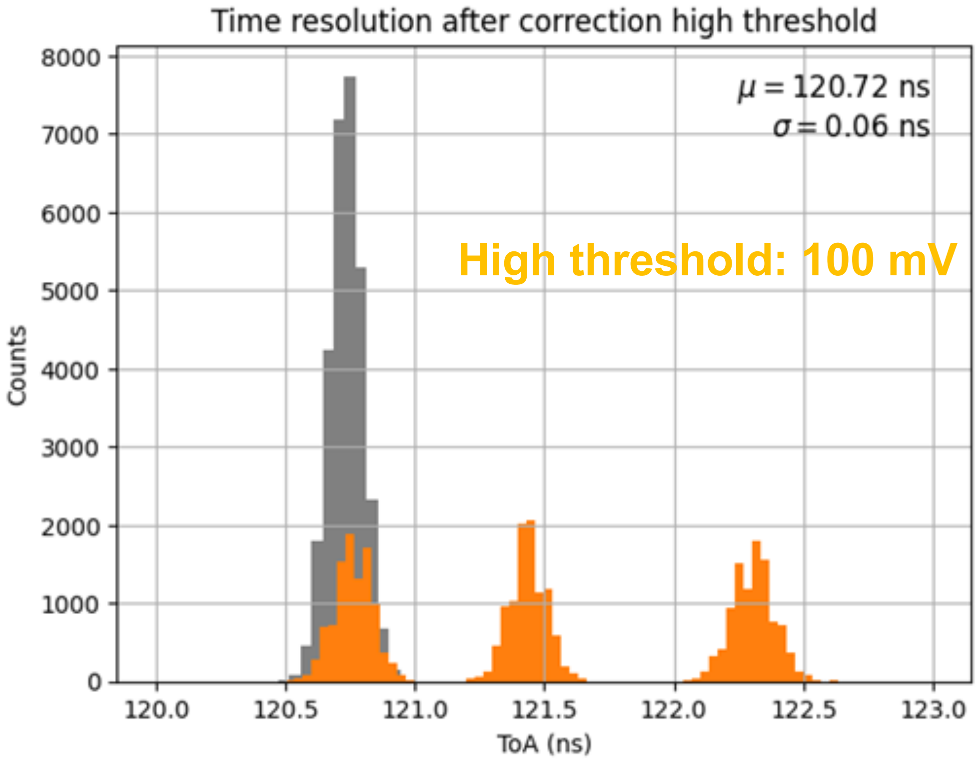


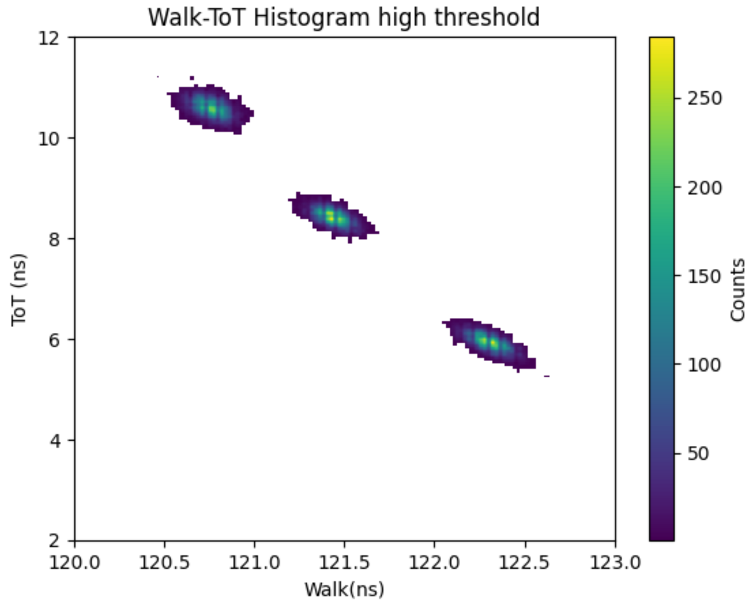
Walk (ns)	Sigma before (ps)	Sigma after (ps)
119.1	-	-
119.6	89	72
120.0	81	71
120.5	75	70
121.1	74	65
121.8	77	63
122.8	100	71

Pico TDC test (CAEN+INFN)

Time Reconstruction (using ToT-Walk correction)







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

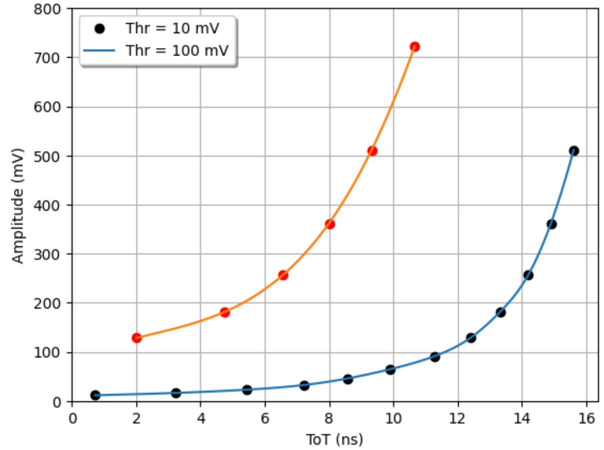
Time Resolution ~ 60 ps

(ECAL resol. ~ 54ps/√E + 100 ps)

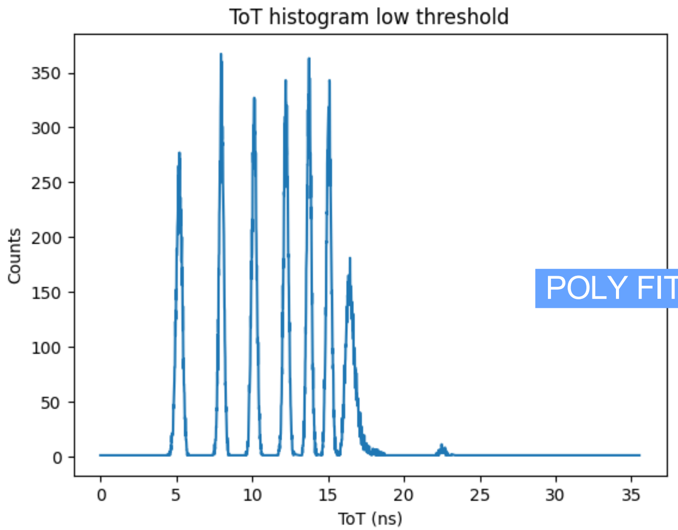
Pico TDC test (CAEN+INFN)

Amplitude Reconstruction

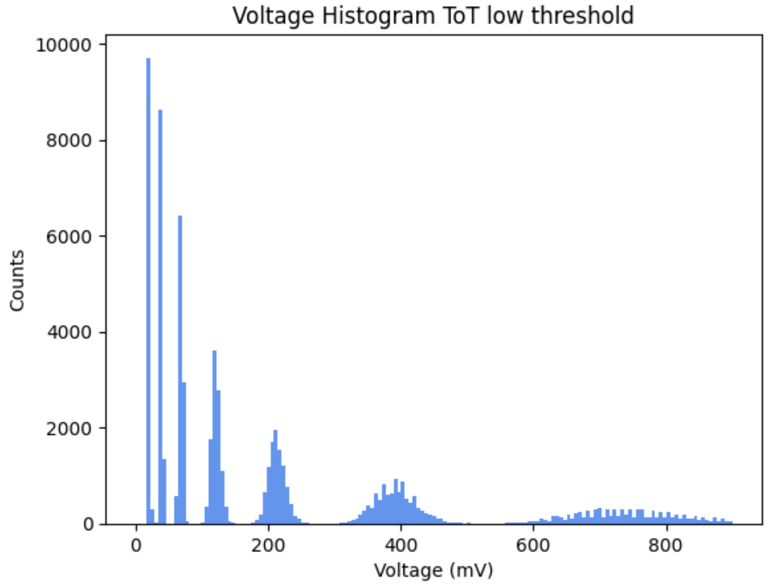
(using ToT-Amp correction)



Low threshold: 10 mV



POLY FIT



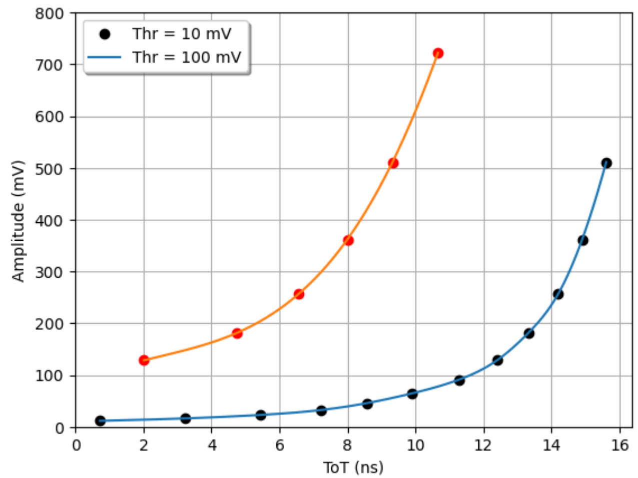
Amplitude (mV)	Sigma (%)
722.0	-
406.0	8.0
228.3	5.9
128.4	5.4
72.2	4.0
40.6	4.0
22.8	3.2

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

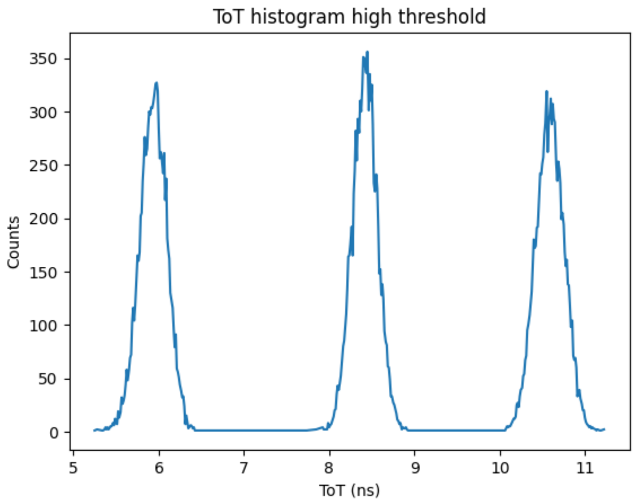
Pico TDC test (CAEN+INFN)

Amplitude Reconstruction

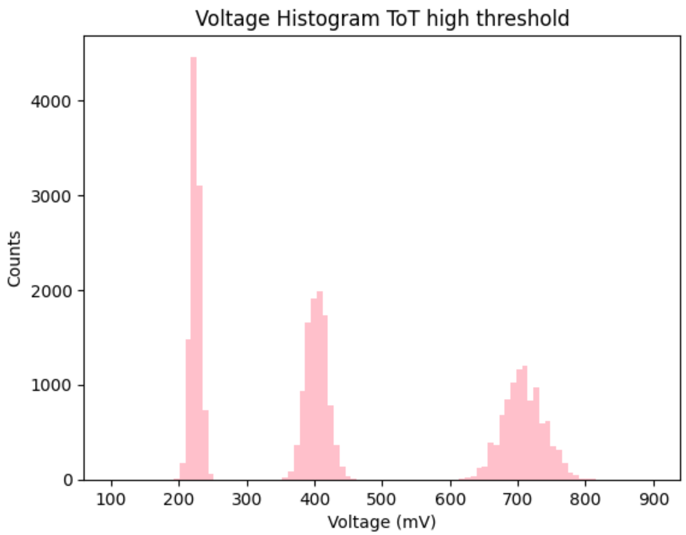
(using ToT-Amp correction)



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)

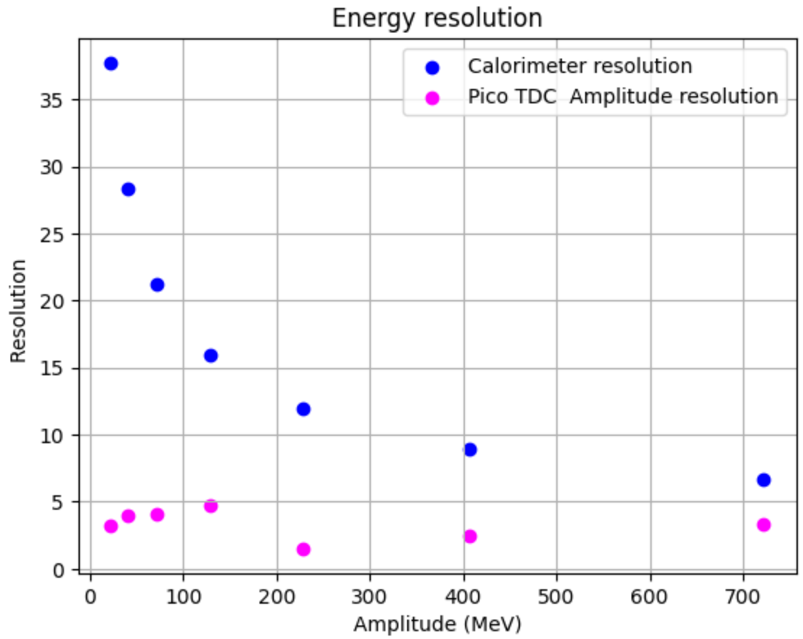
comparison with Ecal resolution

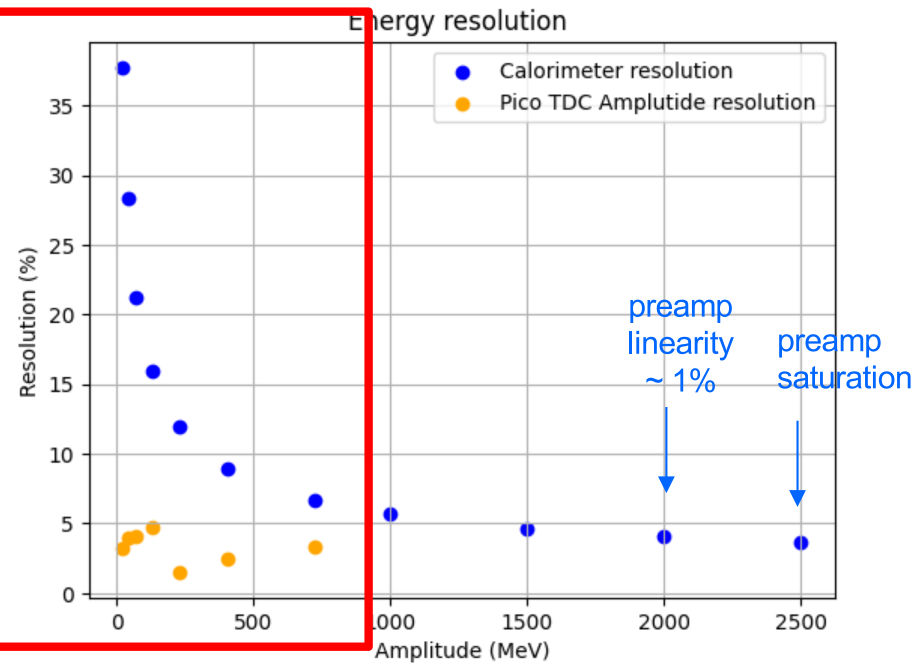
From previous studies on dynamic range:

- $V_{dis}(max) = V_{preamp}(max) \cdot 0.5 \cdot C_{ATT}$= 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

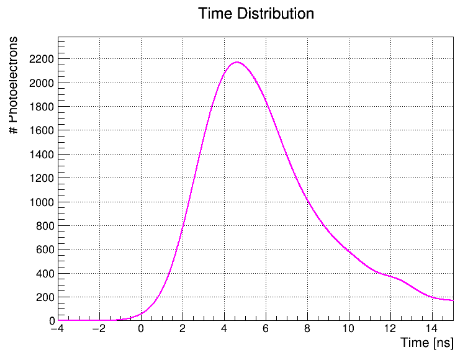
Amplitude resolution obtained from ToT is compared with the intrinsic calorimeter resolution (assuming 1 mV = 1 p.e. = 1 MeV => 1 V = 1 GeV)

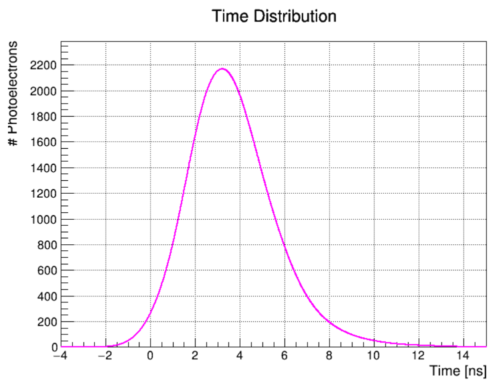




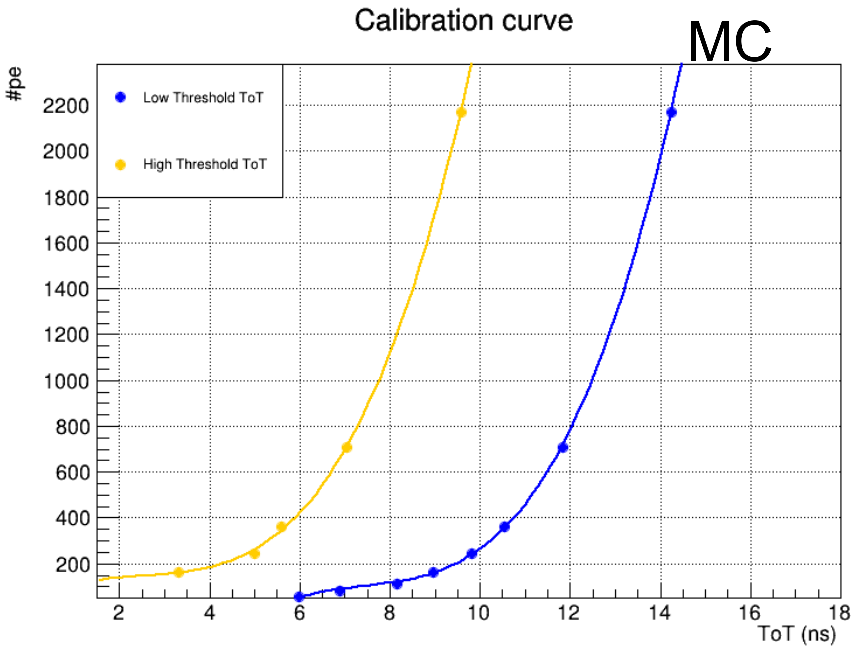
Implementation of ToT in SAND simulation

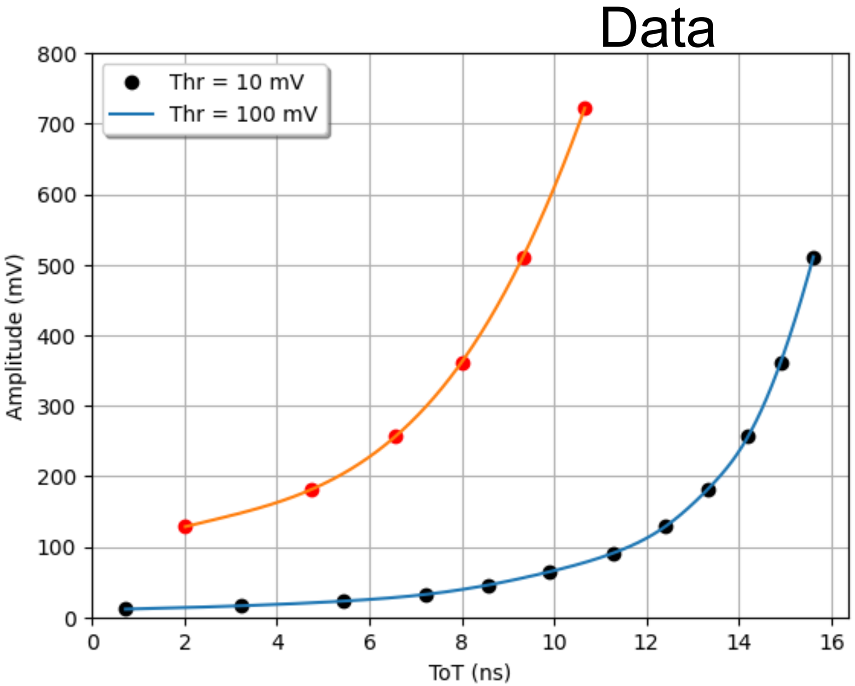
- PMT signal simulation:
  - a gaussian distribution in time is associated at the arrival time of each generated photoelectron
  - each gaussian is convolved with an exponential
  - all distributions are then summed





- Two thresholds, low: 10mV, High: 100mV
- Comparison with the experimental calibration curve





Choice of FEE for SAND/ECAL

Four possible solutions investigated with CAEN

Digitizer VX2730

Fsampl ~ 500 MS/s => **~ 3.5 Meuro**

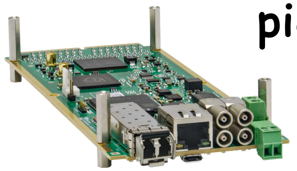
Digitizer VX2745B

Fsampl ~ 125 MS/s
+ shaper 64 ch. => **~ 1.6 Meuro**

DT5203+A5256

PicoTDC + discr. double threshold with ToT => **~ 790 keuro**

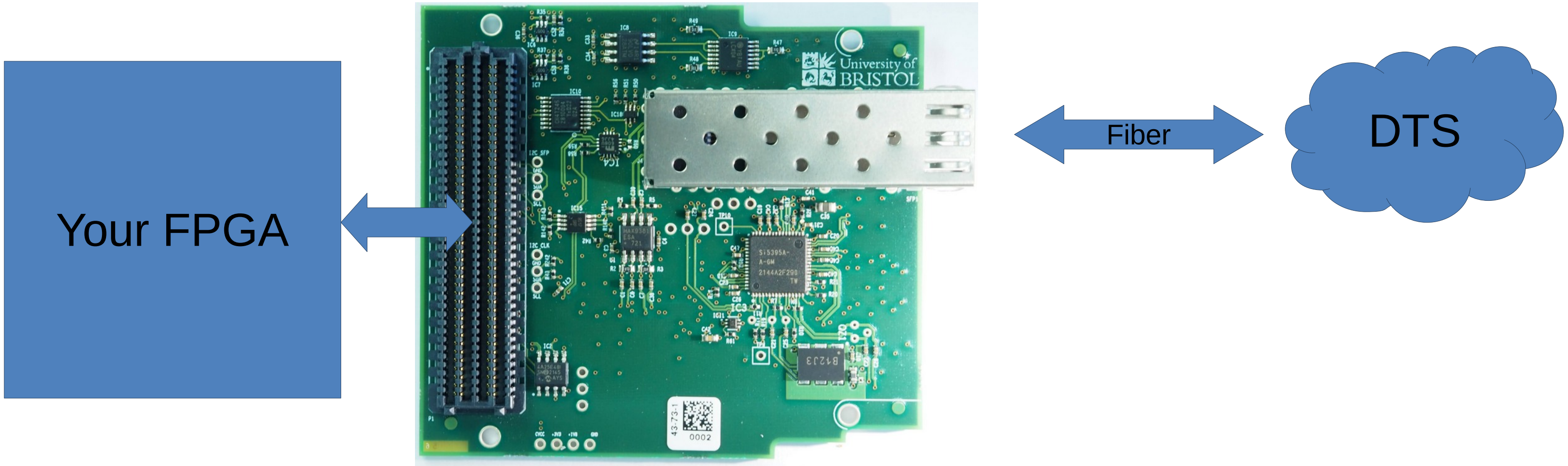
A5204
RADIOROC with
picoTDC



PicoTDC + discr. single threshold with ToT (for all signals)
+ peak sensing ADC with slow shaper – dead time 20μs
and good resolution (for rarer signals of large amplitude);
feasibility study in progress => **~ 520 keuro**

Integration with DAQ SAND

- Reference endpoint hardware: an optical transceiver and a PLL



- DTS also provides reference firmware and a software library
- Built in delay compensation and control/monitoring functions

Conclusions

- 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.

- Next steps:
  1. Optimization of the thresholds for the best perfomance in the whole expected dynamic range (2.5-2000 mV) and in the preamp saturation regime.
  2. Improve simulation of the PMT signal and FEE electronics in the official SAND MC simulation; implementation of Walk-ToT correction, ToT amplitude reconstruction, preamp saturation etc.. (in progress)
  3. Test of PicoTDC and ToT with KLOE modules at test stand in Frascati.
  4. Other solutions based on PicoTDC + amplitude meas. (RADIOROC chip) are being investigated in collaboration with CAEN and appear very promising.
  5. DAQ integration after the choice of FEE