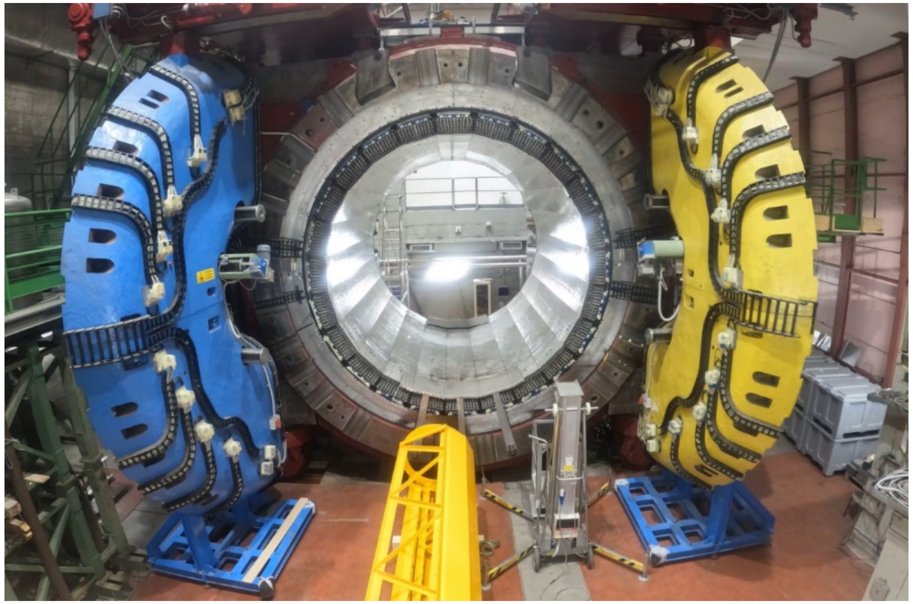
Studies for the optimization of the ECAL working point and FEE

Antonio Di Domenico, Viola Di Silvestre,
Paolo Gauzzi, Daniele Truncali
Dipartimento di Fisica, Sapienza Università di Roma
and INFN-Roma, Italy

Alessandro Balla
INFN-LNF



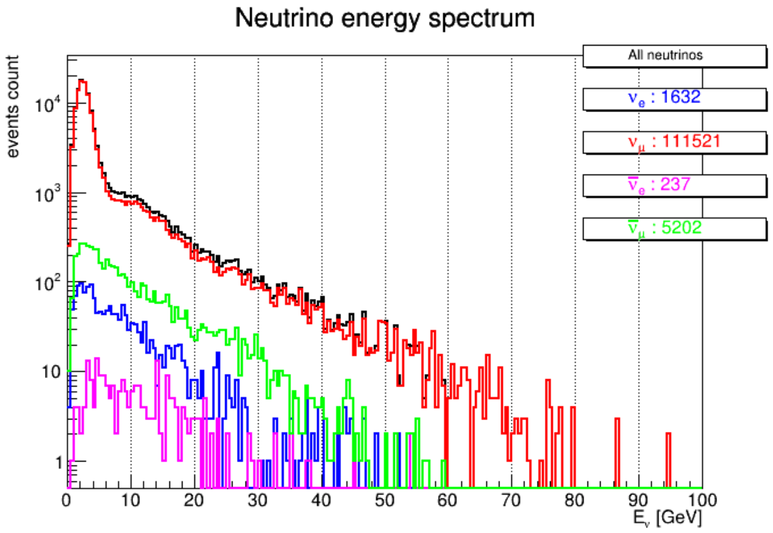
DUNE-ITALIA Meeting – Lecce 6 Novembre 2023

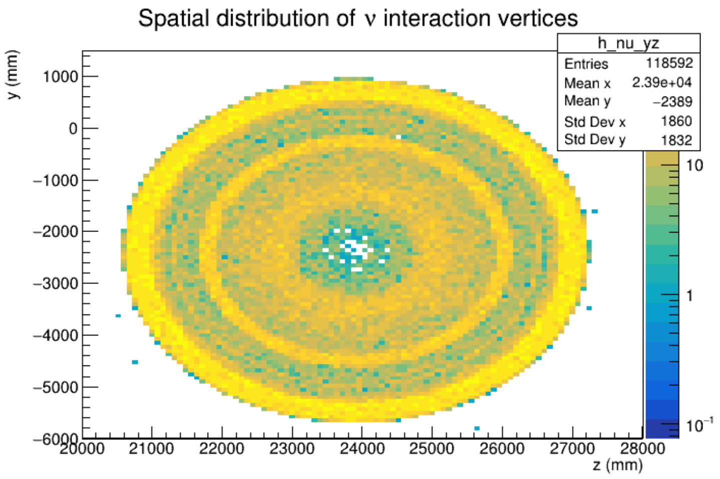
SAND MC simulation

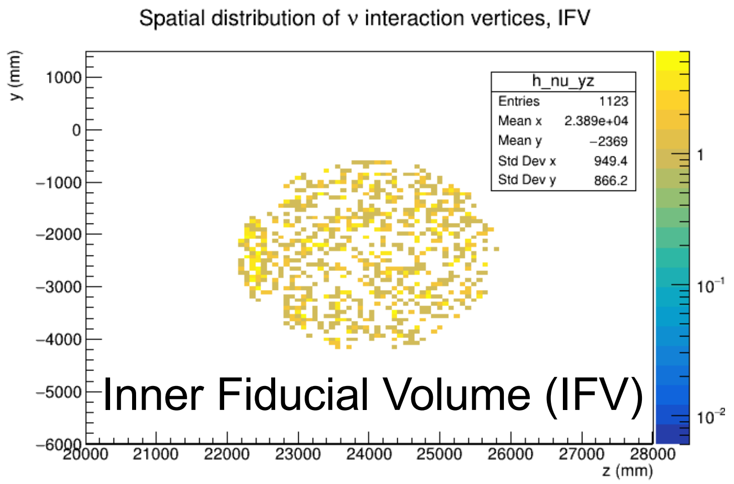
- Analyzed sample: sand-events.*.digi.root and sand-events.*.edep.root **(thanks to Matteo Tenti)**

(as for SAND docDB note 13262)

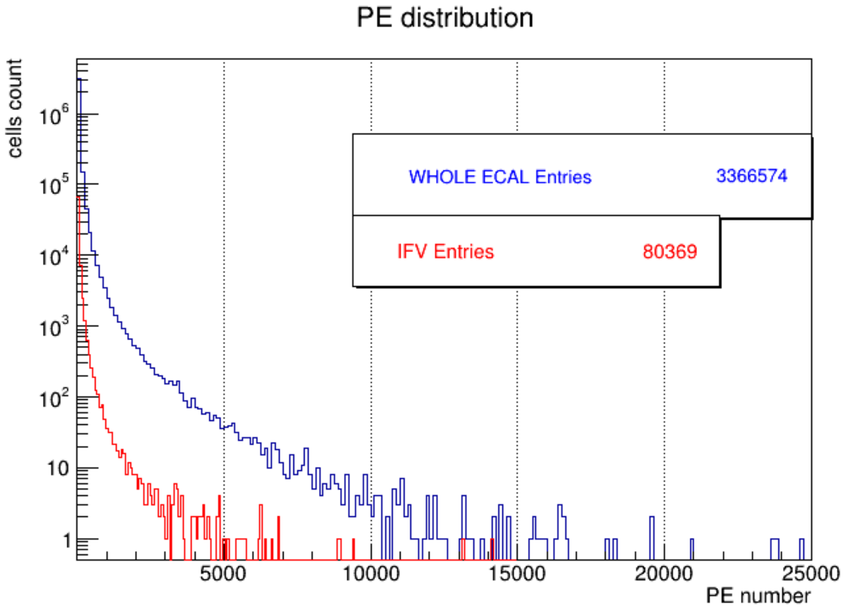
- 100 files
- Total evts = 118592
- Total p.o.t = 1.011×10^{17}
- p.o.t./spill = 7.5×10^{13} at 1.2 MW beam power
- corresponding to ~ 30 minutes of data taking in FHC mode
- Inner Fiducial Volume (IFV) defined at a distance of 20 cm from ECALinternal surface







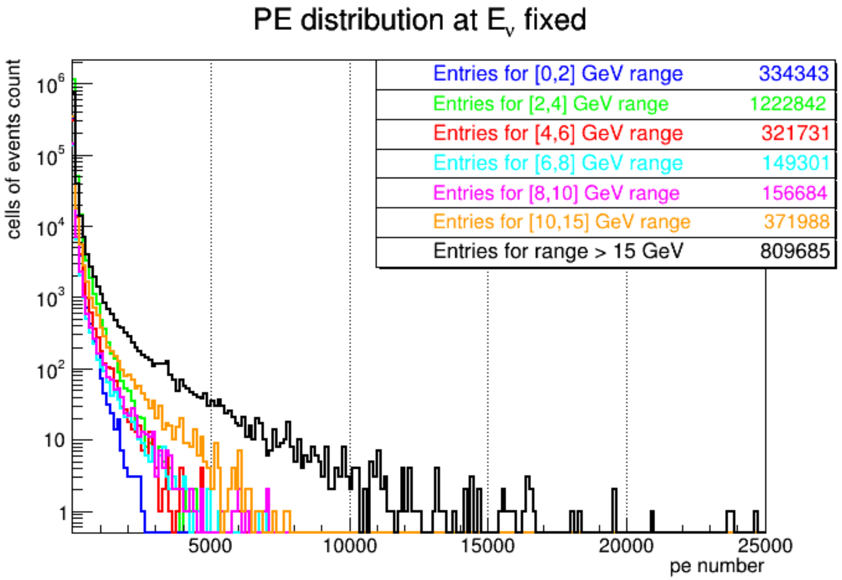
Np.e. distributions

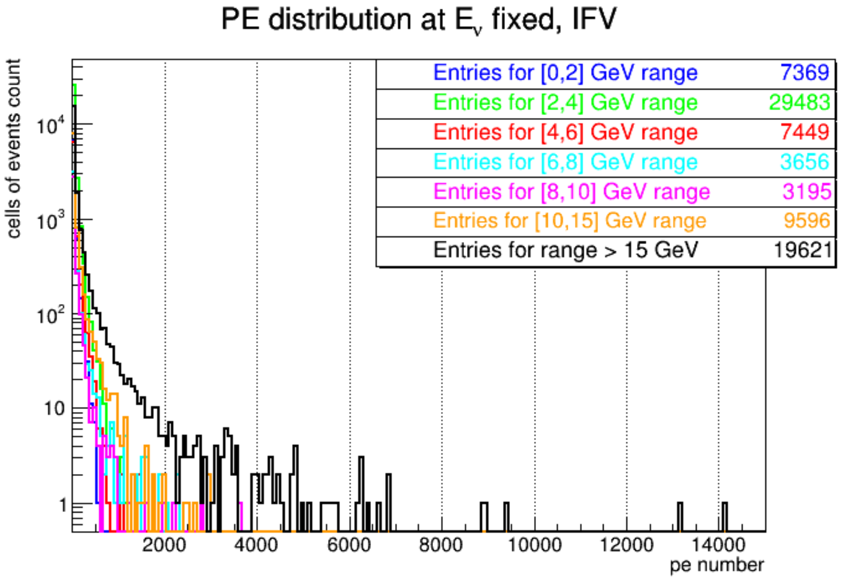

PE distribution

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

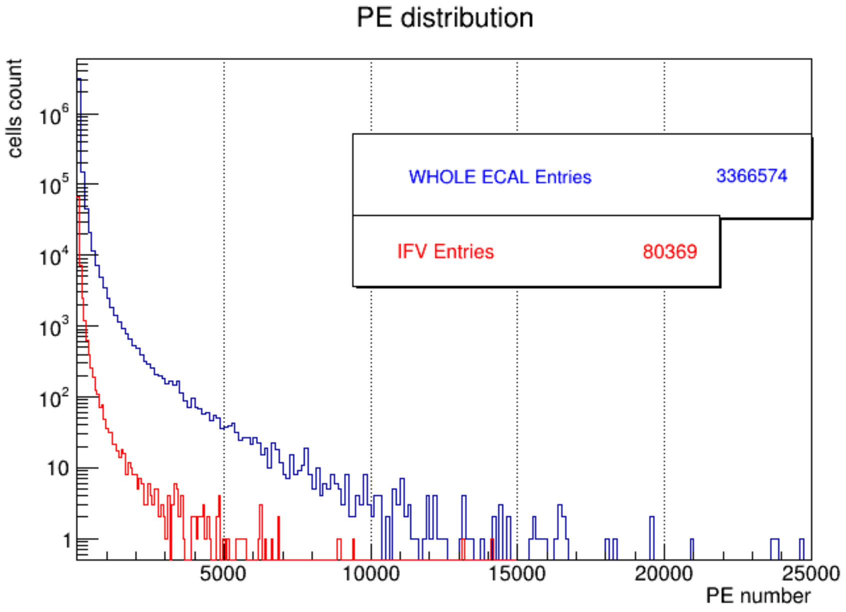
Fraction of events with at least one cell above PE threshold	[%]
1000 PE threshold	2.58
2000 PE threshold	0.49
3000 PE threshold	0.13
4000 PE threshold	$3.64 \cdot 10^{-2}$

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	$2.11 \cdot 10^{-3}$


PE distribution at E_ν fixed


PE distribution at E_ν fixed, IFV

Np.e. distributions



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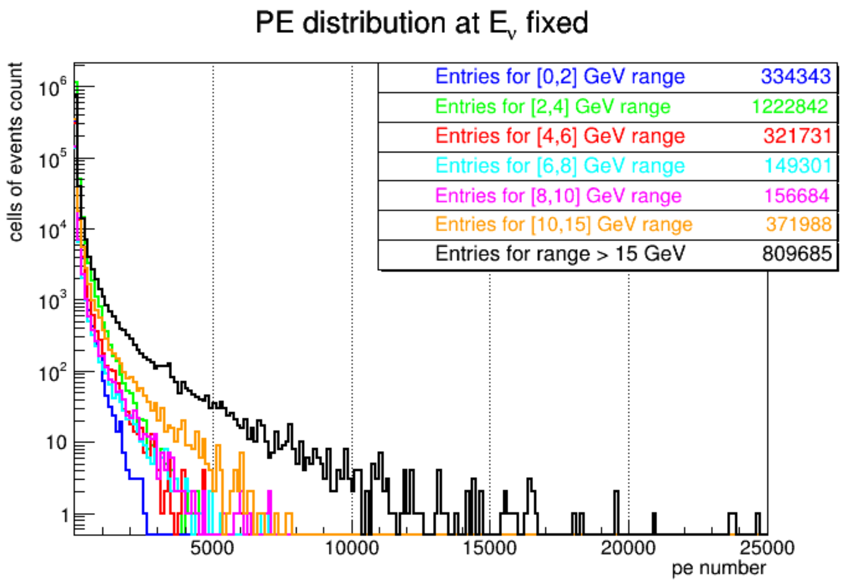
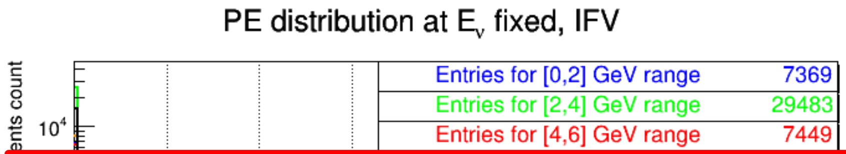
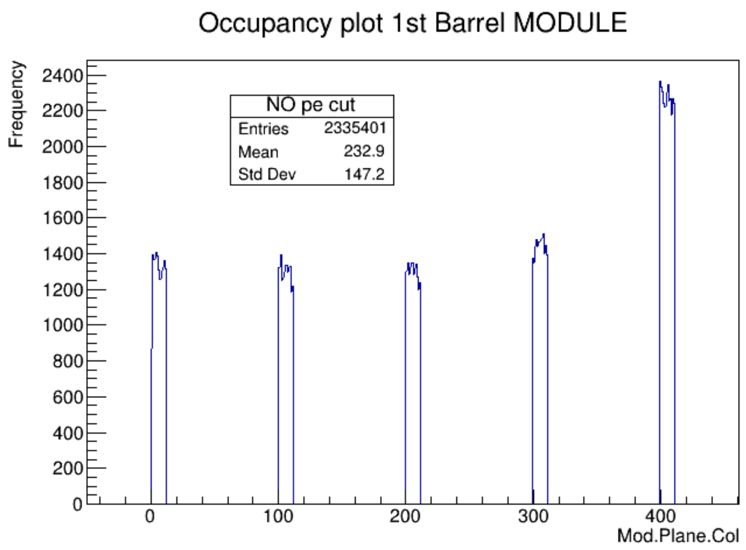


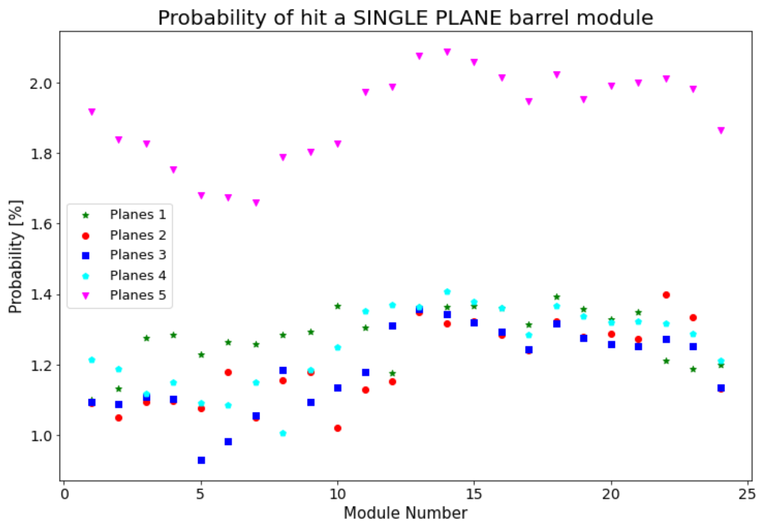


- Neutrino energy range of interest for oscillation analyses is [0,10] GeV
- In this range the MAXIMUM Np.e. that has to be treated by FEE can be safely set between 1000 and 2000
  => see next slides for the choice of the FEE dynamic range

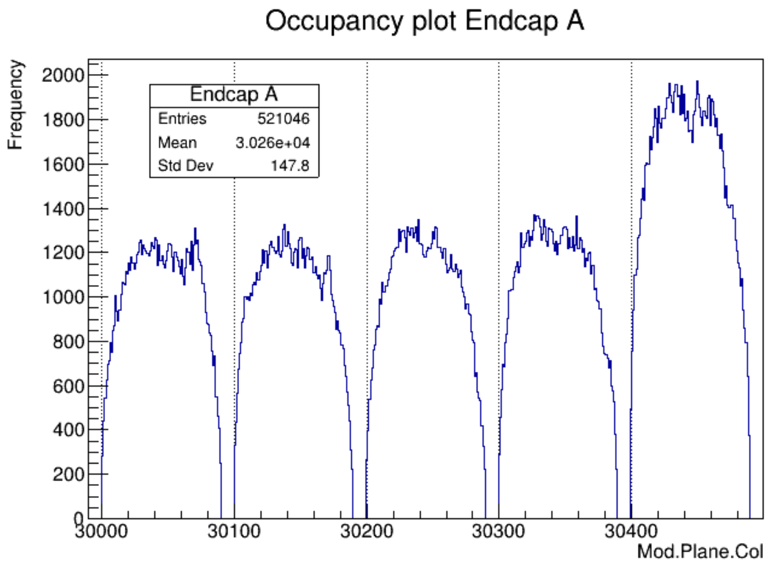
Cell occupancy plots and hit probability



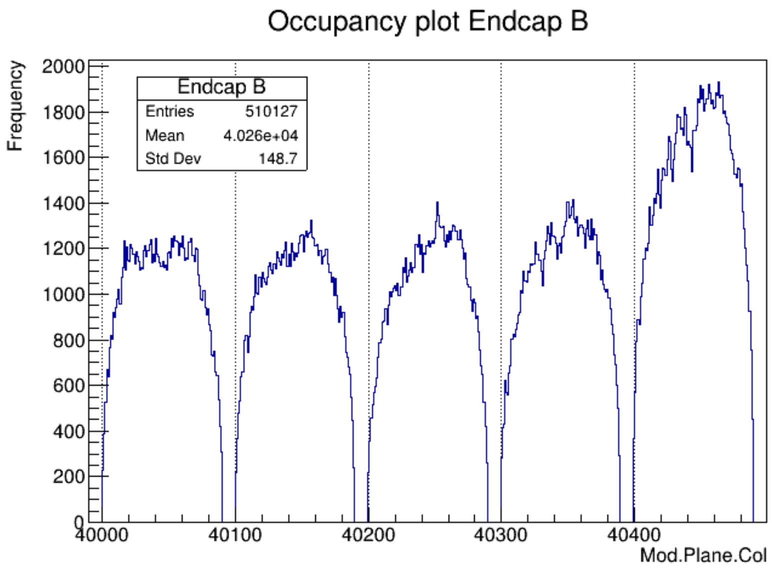
Barrel



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%

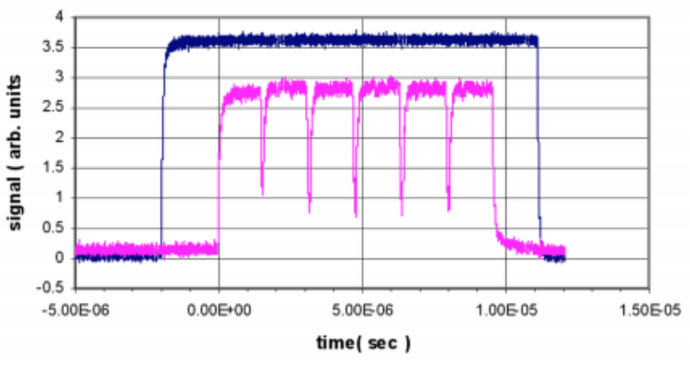
P_{cell} = 1.16%

Beam, spill structure, and event rates in SAND

Beam power 1.2 MW
7.5 x 10^{13} protons extracted every 1.2 s at 120 GeV
1.1 x 10^{21} pot/year

Spill time structure

- 9.6 μs per spill
- 6 batches, 84 bunches/batch
- 2 empty bunches
- 1 bunch: Gaus(σ = 1.5 ns)
- Δt bunches = 19 ns



Event rates expected in SAND

~ 84 interactions/spill
$\lesssim$1 interaction/spill in the SAND fiducial volume

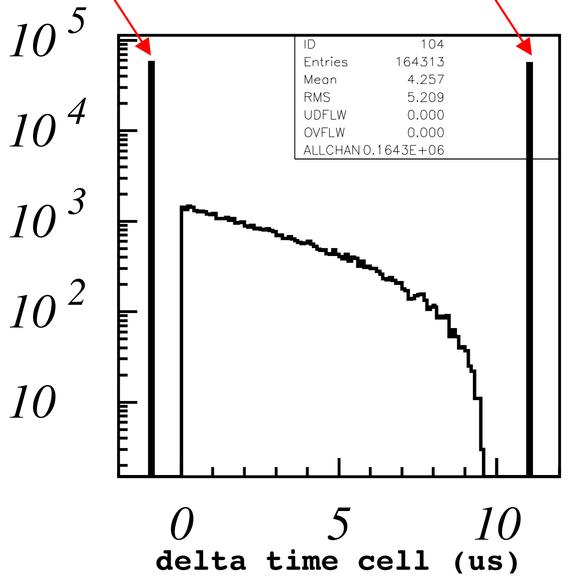
(negligible rock muons and cavern background assumed)

Pile-up probability

The beam time structure 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.

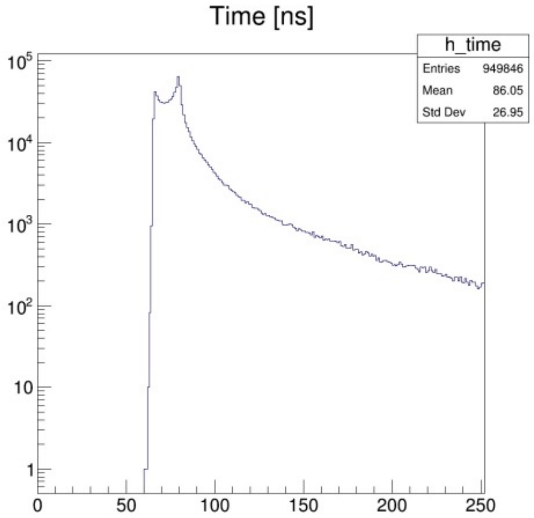
The times of N interactions per spill (in average **N=84**) are extracted uniformly between 0 and 9.6 μs. The time difference between two consecutive interactions is calculated for all spills, following an exponential distribution with $\tau_{spill} \simeq$ 114 ns. From this, the distribution of time differences for a single cell with a probability to be hit of P_{cell} = 1.16% is evaluated, and then the pile-up probabilities for different time windows are also evaluated, TW = 50, 100, 150, 200 ns.

	before smearing			after smearing		
P_{CELL} [%]	**1.16**	**1.5**	**2.0**	**1.16**	**1.5**	**2.0**
Time window [ns]						
50	0.67	0.90	1.28	0.64	0.86	1.36
100	1.33	1.81	2.52	1.32	1.71	2.56
150	1.95	2.71	3.72	1.91	2.60	3.78
200	2.59	3.58	4.87	2.52	3.48	4.93



spills with 0 hit

1 hit



Time propagation/smearing of hits in a single neutrino interaction event.

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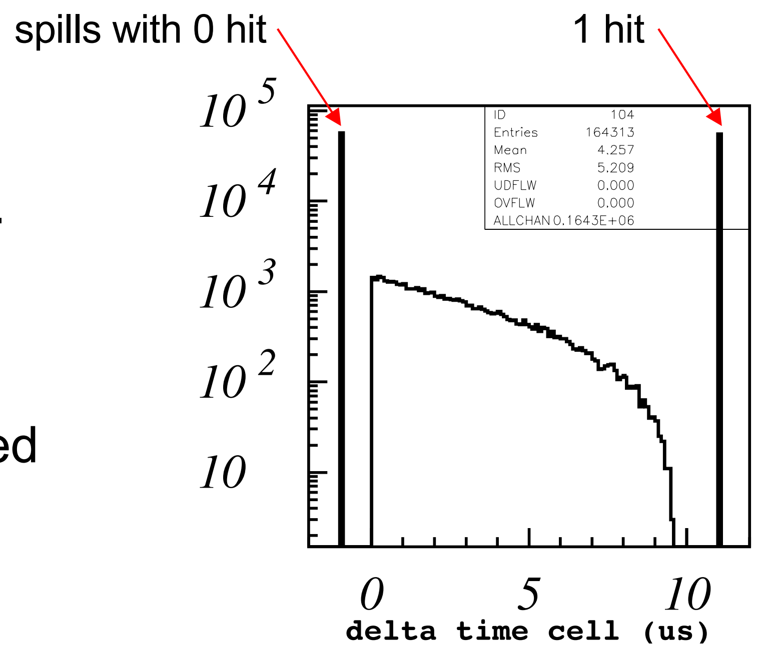

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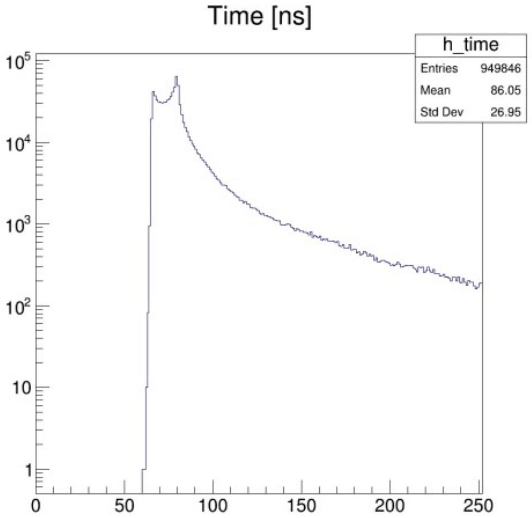


Time propagation/smearing of hits in a single neutrino interaction event.

PMT signal and discriminator threshold in KLOE

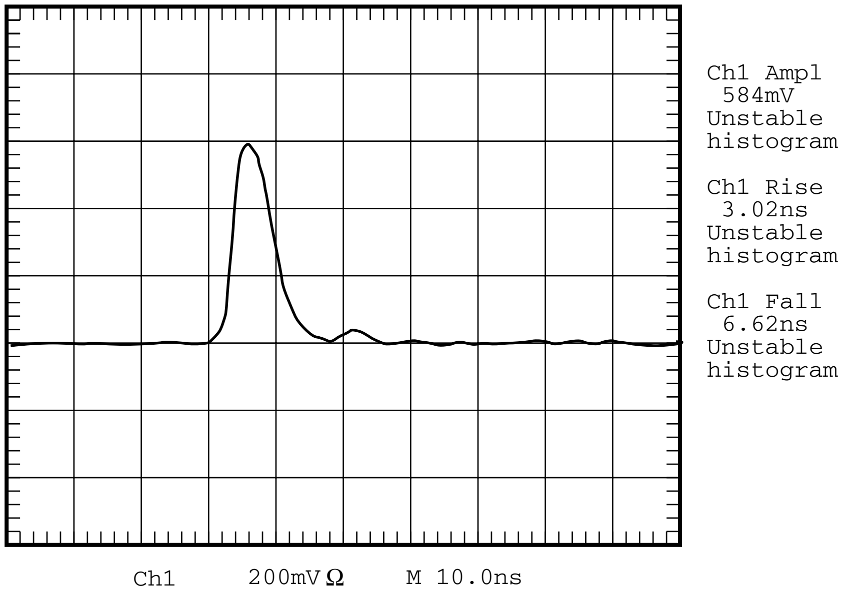
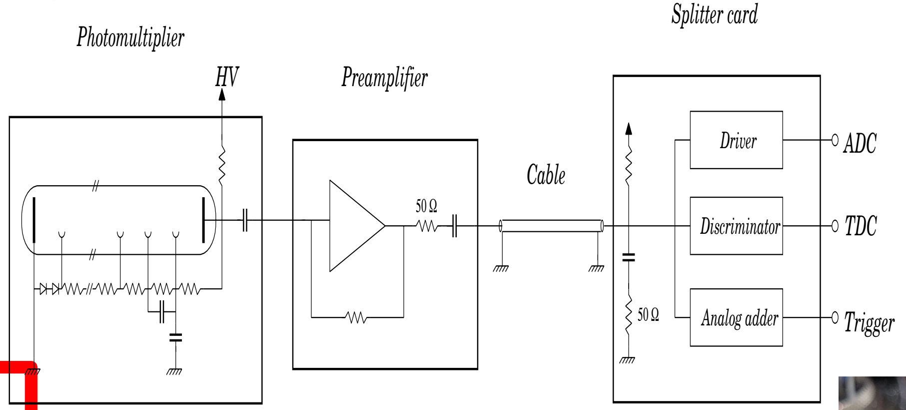
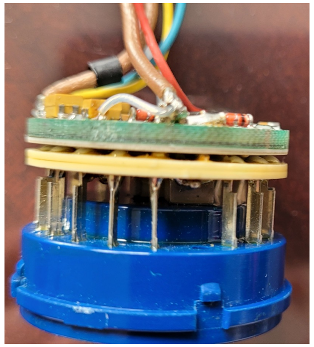


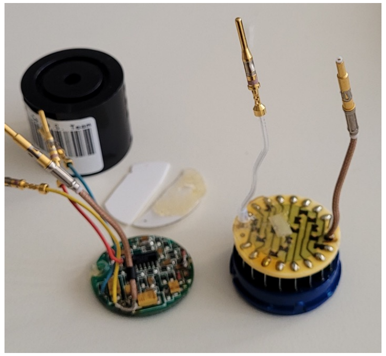
Figure 4: Typical signal from the PM base.

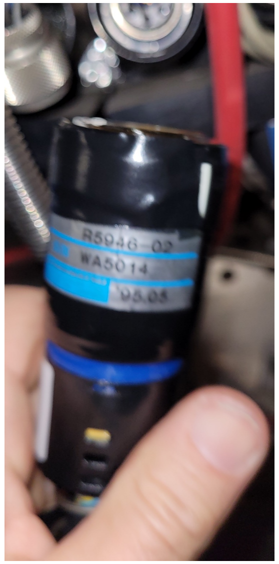
Constant fraction discriminators.
Effective thresholds are in the range 4–5 mV:
They correspond to signals originated by 3–4 photoelectrons or a 3–4 MeV photon at 2 m from PMT



Constraints:
- minimum discriminator threshold 4-5 mV
- maximum HV for PMs divider is 2300 V
  typical HV 1700-1800 => G~1-3 x 10^6
- preamplifier linear (within 0.2%) for signals
  up to 4.7 V (gain preamp ~ 2.5)
  => 1.74 V at discriminator level after
  12-15 m long cables and termination







thanks to A. Balla and P. Ciambrone

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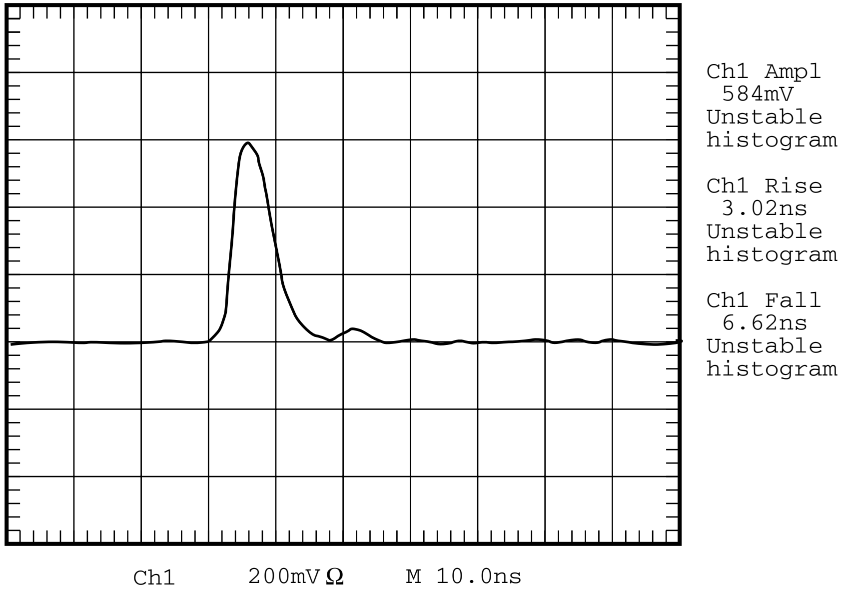

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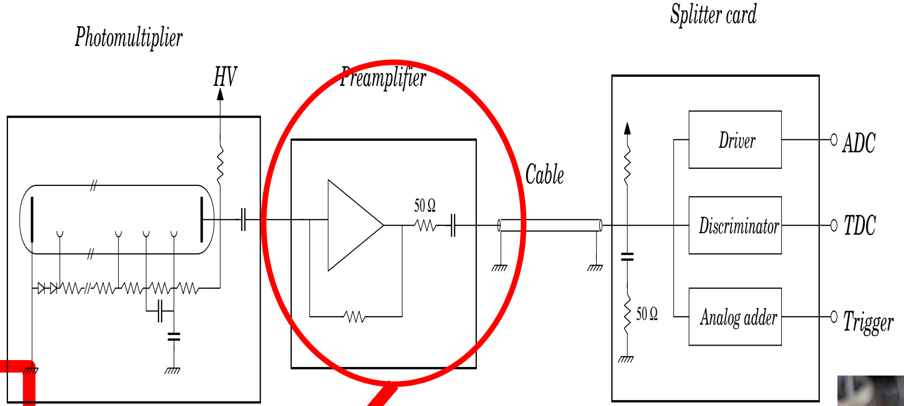

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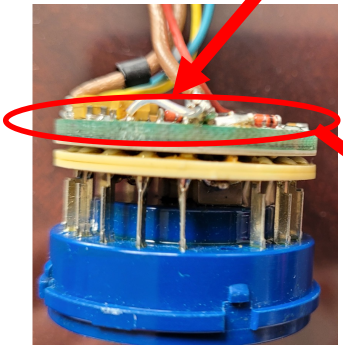

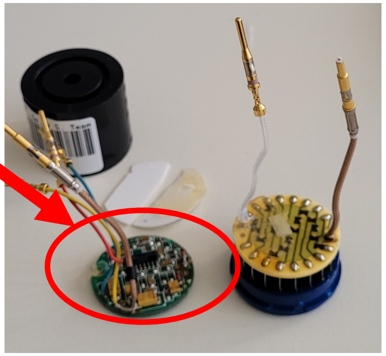

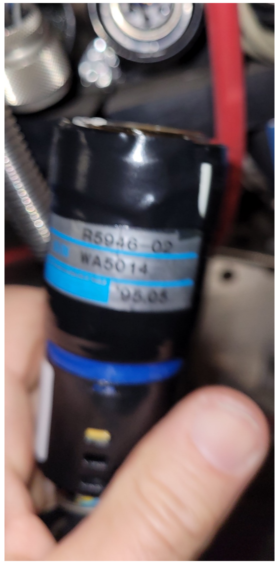

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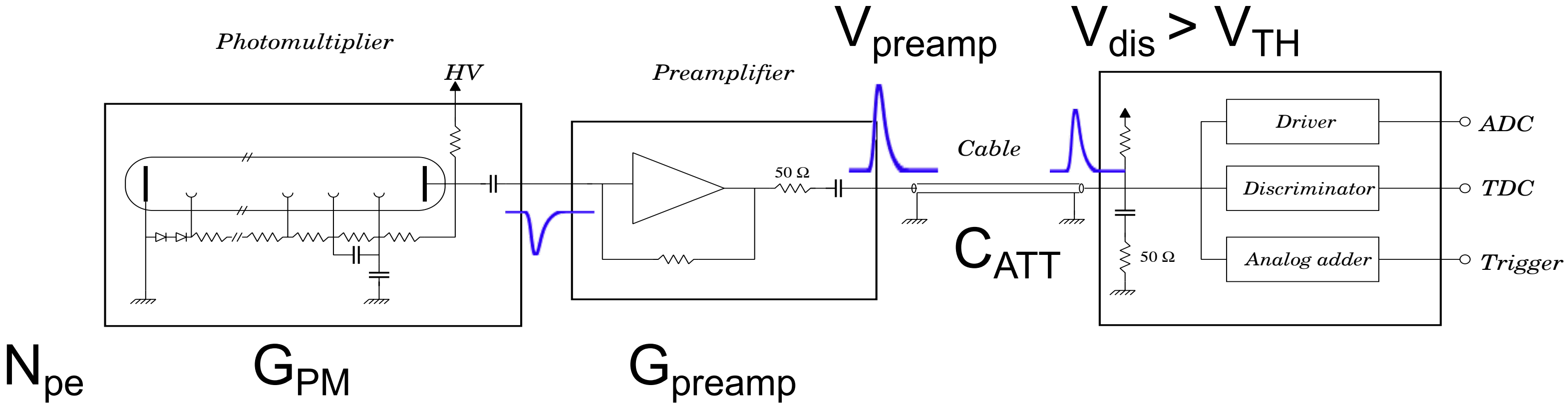
Choice of the dynamic range - I

The dynamic range in terms of N_{pe} can be evaluated using the following constraints for the FEE after the PMT:

- Minimum discriminator/digitizer threshold V_{TH}= 5 mV
- Preamplifier linearity (within 0.2%) range = [0, 4.7] V => $\mathbf{V_{preamp}(max) = 4.7\ V}$
- preamp transimpedance gain G= 250 V/A => I_{peak}(max)=19 mA => max signal charge Q(max)=133 pC; from $Q = e\, N_{pe}\, G_{PM}$ => $(N_{pe}\, G_{PM})(max) = 83 \cdot 10^7$
- $G_{TOT} = G_{PM}\, G_{preamp}$ with $G_{preamp} \simeq 2.5$
- 12m long cable attenuation: $C_{ATT} = 0.74$
- MAX single pulse amplitude at the discriminator/digitizer input is: $\mathbf{V_{dis}(max) = V_{preamp}(max) \cdot 0.5 \cdot C_{ATT} = 1.74\ V}$
- signal ampl = $V_{dis}(max)/N_{pe}(max)$
- $N_{pe}(min)=V_{TH}$/(signal ampl) => $\mathbf{N_{pe}(max)/N_{pe}(min) = V_{dis}(max)/V_{TH}}$



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G_{PM} $(\times 10^5)$	G_{tot} $(\times 10^6)$	N_{pe}(max)	signal amplitude (mV/pe)	N_{pe}(min) V_{TH} = 5 mV	MeV at module center
4.2	1.04	$\sim$ 2000	0.87	$\sim$ 6	6.0
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Test of preamp saturation

with preamplifier

saturation over 3.2 V

```
Measure  P1:area(C1)     P2:ampl(C1)  P3:delay(C1)   P4:area(C2)      P5:ampl(C2)  P6:delay(C2)  P7:---  P8:---
value    46.9877 nVs     3.538 V      27.602 ns      193.57 pVs       31 mV        0
mean     18.62874 nVs    2.5356 V     28.22170 ns    179.0622 pVs     28.19 mV     —
min      4.6581 nVs      935 mV       27.472 ns      87.51 pVs        22 mV        —
max      48.4638 nVs     3.59 V       28.967 ns      259.86 pVs       40 mV        —
sdev     12.42187 nVs    817.5 mV     264.18 ps      30.4737 pVs      3.58 mV      —
num      518             518          518            519              519          0
status   ✓               ✓            ✓              ✓                ✗            ⚠
histo

X1=  -7.5 ns    ΔX=    17.5 ns
X2=  10.0 ns    1/ΔX=  57.1 MHz
                1/1/2002 1:11:55 AM
```

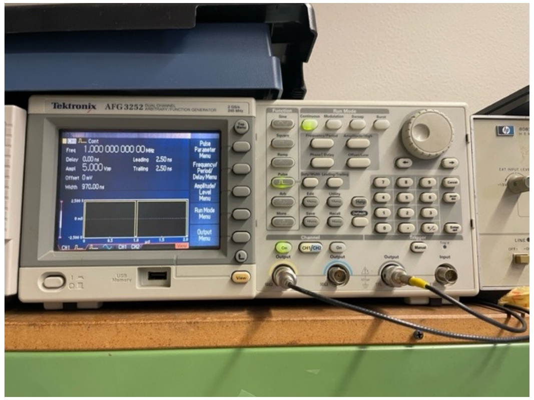
In this specific case (negligible cable length) we expect:
$V_{dis}(max) = V_{preamp}(max) \cdot\ 0.5\ = 2.35$ V

Assuming to increase $V_{preamp}(max)$ by 15% while keeping linearity at an acceptable level, e.g. 1% (to be tested), we get:

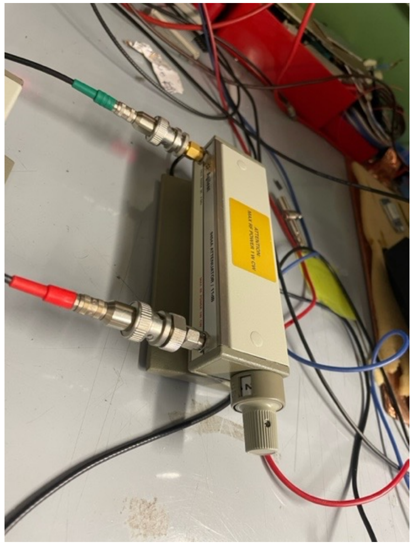
$V_{preamp}(max\ ) = 5.4$ V
$V_{dis}(max) = V_{preamp}(max) \cdot\ 0.5\ = 2.7$ V

Preamp linearity test and saturation threshold

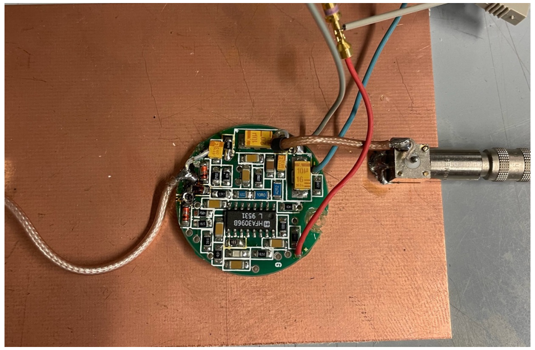
Test set-up



Signal amplitude varied with calibrated attenuators



Signal at a modified test input: preamp gain ~1



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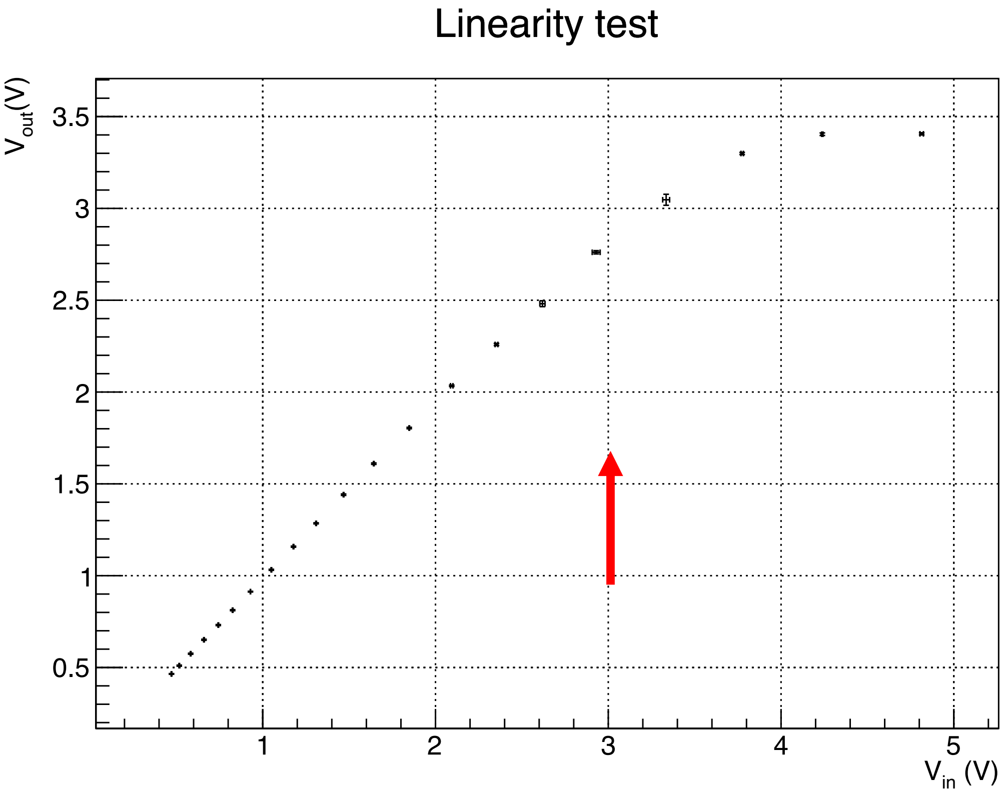
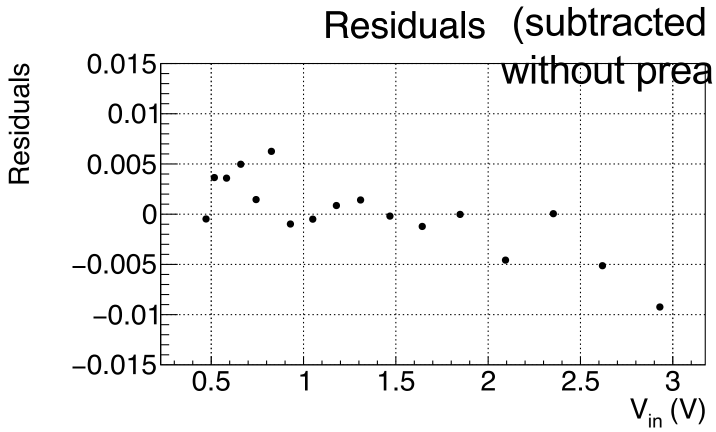
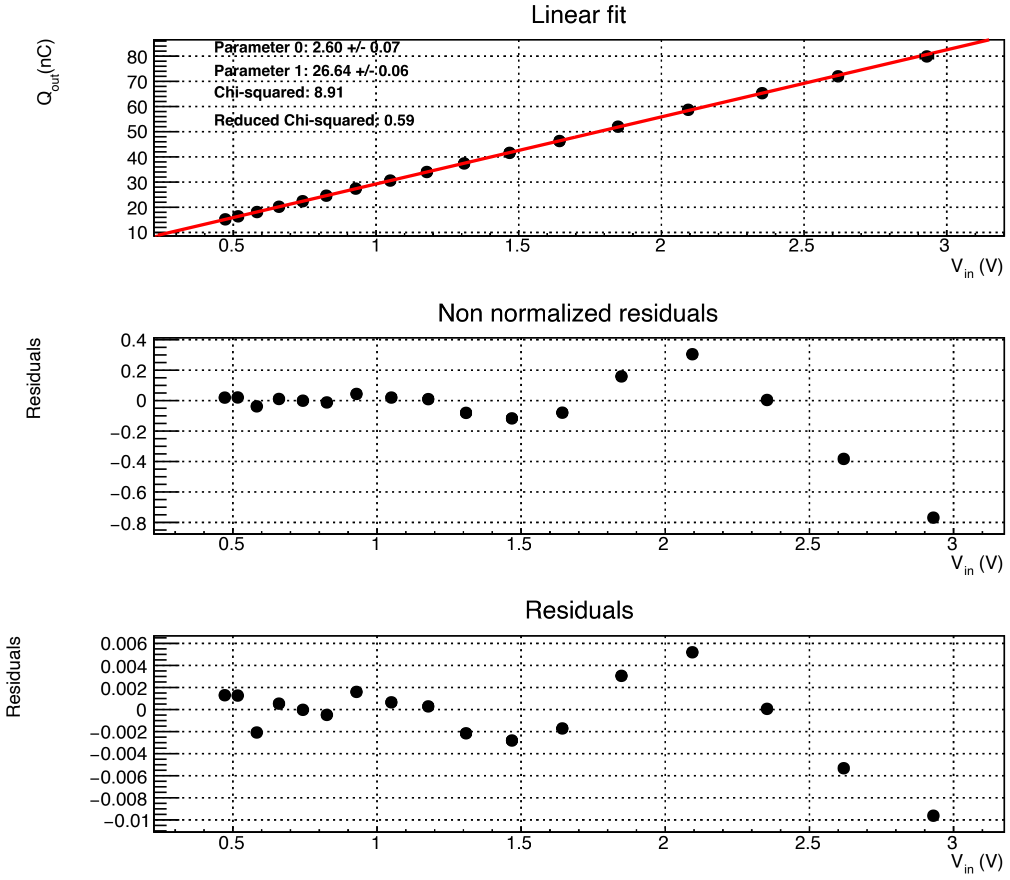

Linearity test


Residuals

(subtracted system response without preamp)


Linear fit

Parameter 0: 2.60 +/- 0.07
Parameter 1: 26.64 +/- 0.06
Chi-squared: 8.91
Reduced Chi-squared: 0.59

Non normalized residuals

Residuals

Choice of the dynamic range - II

Assuming:

- to increase V_{preamp}(max) by 15% => V_{preamp}(max) = 5.4 V
- $(N_{pe}\ G_{PM})(\text{max}) = 95 \cdot 10^7$
- $V_{dis}(\text{max}) = V_{preamp}(\text{max}) \cdot\ 0.5\ \cdot C_{ATT} = 2.0\ \text{V}$
- to have a very low noise environment as in KLOE => lowering (halving) the minimum discriminator/digitizer threshold to $V_{TH} = 2.5\ \text{mV}$

G_{PM} $(\times 10^5)$	G_{tot} $(\times 10^6)$	$N_{pe}(\text{max})$	signal amplitude (mV/pe)	$N_{pe}(\text{min})$ $V_{TH} = 2.5$ 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

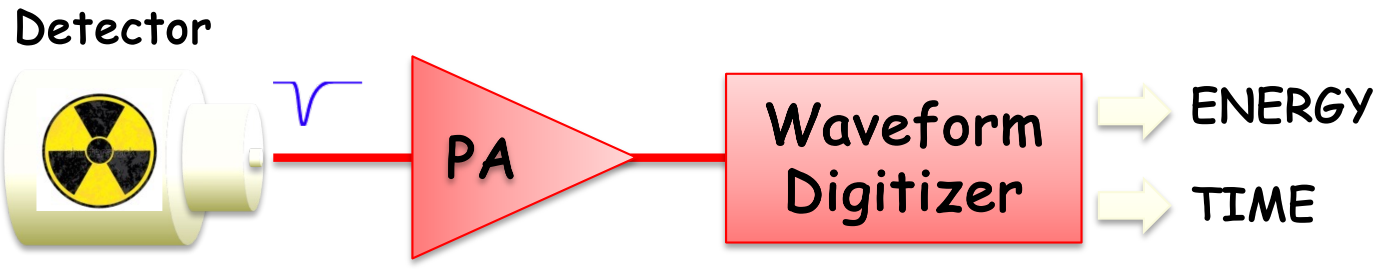
- Different dynamic ranges can be implemented changing G_{PM} => the final choice should be a compromise between an affordable level of events with energy saturated cells, depending on N_{pe}(max), and an acceptable neutron detection efficiency, depending on N_{pe}(min).

Choice of FEE for SAND/ECAL

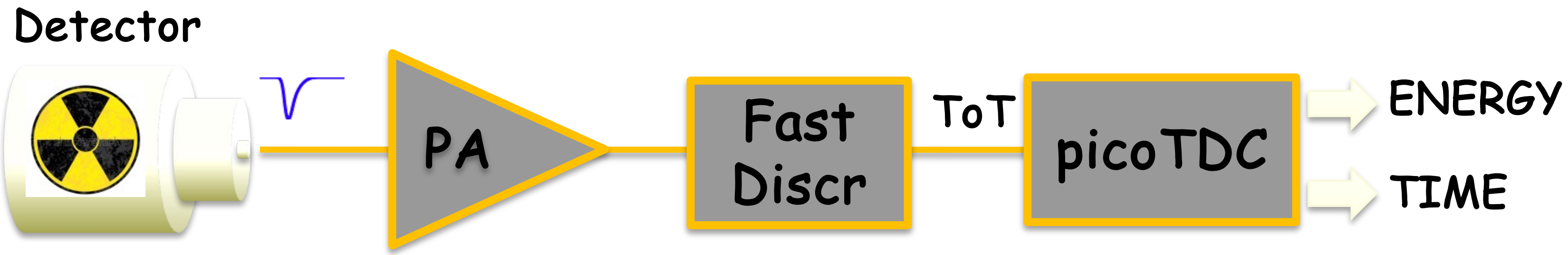
Constraints on signal dynamic range

see previous slides

Two possible read-out schemes:



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



No Flexibility
=>medium cost
energy by ToT
with 2 or more
thresholds not to
worsen energy resol.

CAEN:

possible ready-to-use solution maintaining KLOE energy and time performance

Choice of FEE for SAND/ECAL

Digitizer solution:
$V_{signal}(max) = 2$ V
$V_{signal}(min) = O(0.1)$ mV
=> no problems to set V_{TH} and $V_{signal}(max)$ to match $V_{dis}(max)$

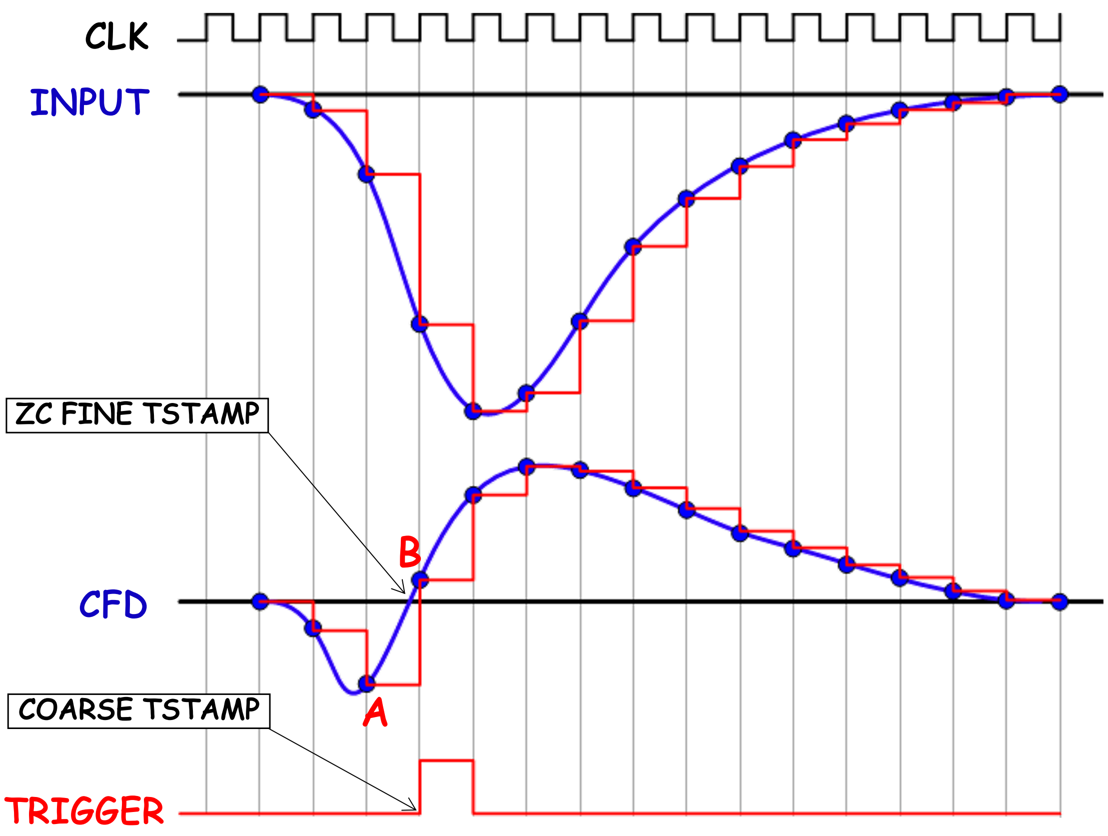
Best choice, high cost:
1 GS/s digitizer => 1 ns: 4-5 time measurements on the rising edge of the 14 ns base signal to preserve time resolution

Alternative lower cost choice:
Using a lower cost digitizer, 125 or 250 MS/s => 8 or 4 ns, requires a shaper to stretch the signal.
In principle this solution does not worsen the time resolution, but requires to keep the pile-up under control, as confirmed by MC (or to detect it from the signal shape).

A 500 MS/s digitizer (14 bit) => 2 ns might not need to stretch the signal (use of ad-hoc correction algorithms and calibration for measuring the time) => under test at CAEN.

Digital CFD with interpolation

CAEN Tools for Discovery



Preliminary tests with FERS by CAEN

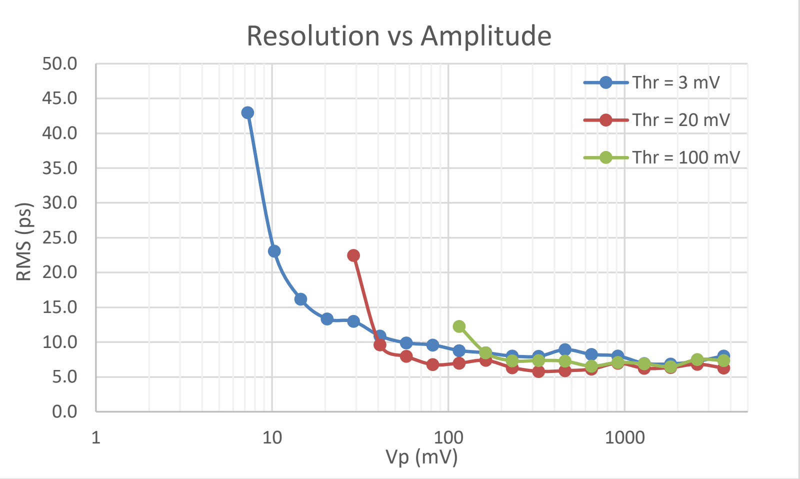


Fig. 2.2: Timing Resolution vs Pulse Amplitude

FERS A5203 (pico TDC)

fast input signal:
FWHM = 1.6 ns,
Rise = 1.1 ns,
Fall = 1 ns

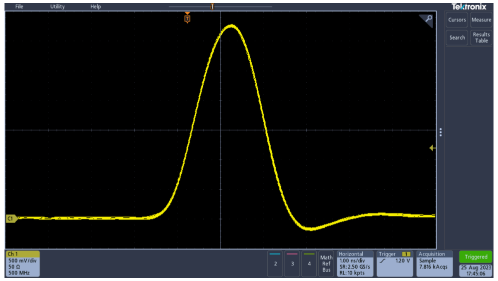


Fig. 2.1: Fast pulse from Agilent 81110A (width=1.5 ns; rise=fall=0.8 ns)

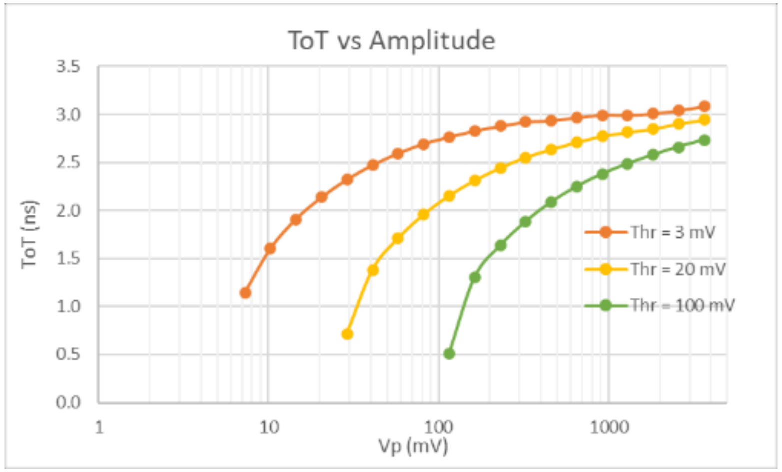


Fig. 2.3: ToT vs Amplitude

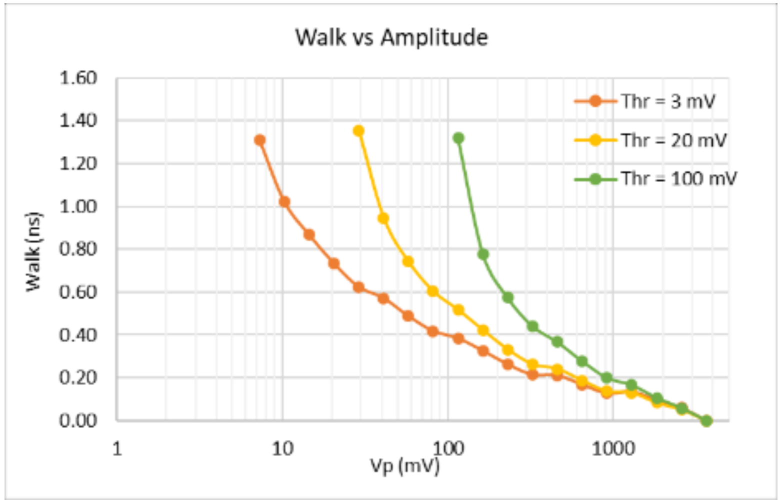


Fig. 2.4: Walk vs Amplitude

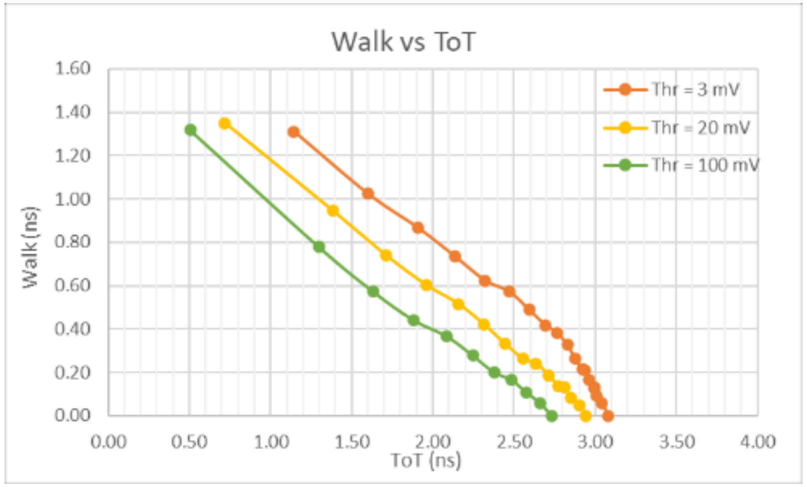


Fig. 2.5: Walk vs ToT

Conclusions

Studies for the optimization of the working point of the SAND calorimeter read-out electronics have been performed.
The MC simulation of the ECAL digitized response has been used to study the dynamic range and pile-up of the signals.
A test of the linearity of the PMT preamplifier has been performed; V_{preamp}(max) can be extended, e.g. from 4.7 to 5.4 V, still keeping the deviation from linearity < 1%.
The preamplifiers of PMT bases are well compatible with the proposed FEE solutions, given that the maximum amplitude of signals accepted before digitization is around 2 V, i.e. V_{signal}(max) = 2 V.

Keeping the preamplifiers has the advantage (i) to simplify the ECAL dismounting and test phases, and (ii) to keep the PMTs working point at a lower gain and HV level, beneficial for their lifetime.

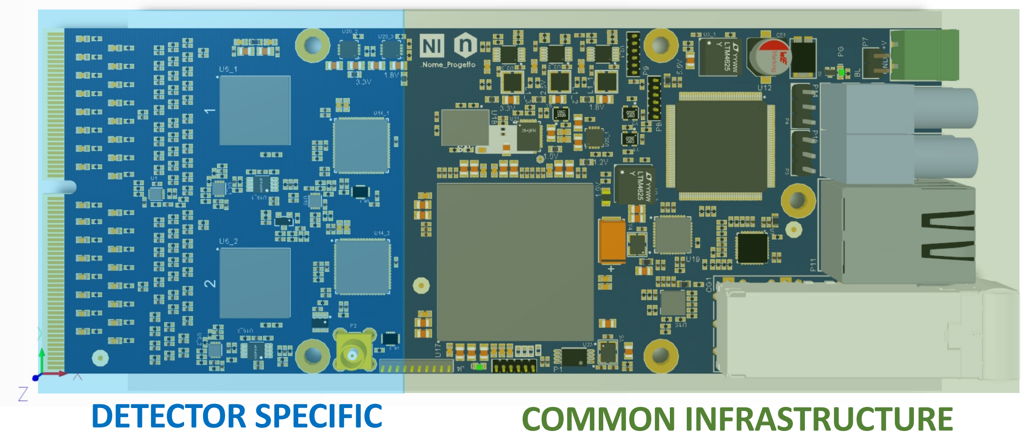
In the long term, it would be necessary to design and build anew spare bases (with new components), to cope with possible long-term degradation of electronic components.

Possible solutions for the FEE that could constitute a good compromise between cost and performance are being investigated in collaboration with CAEN. These solutions have the advantage to be ready-to-use, preliminary results are encouraging, more detailed tests tailored on our case are needed and are in progress.

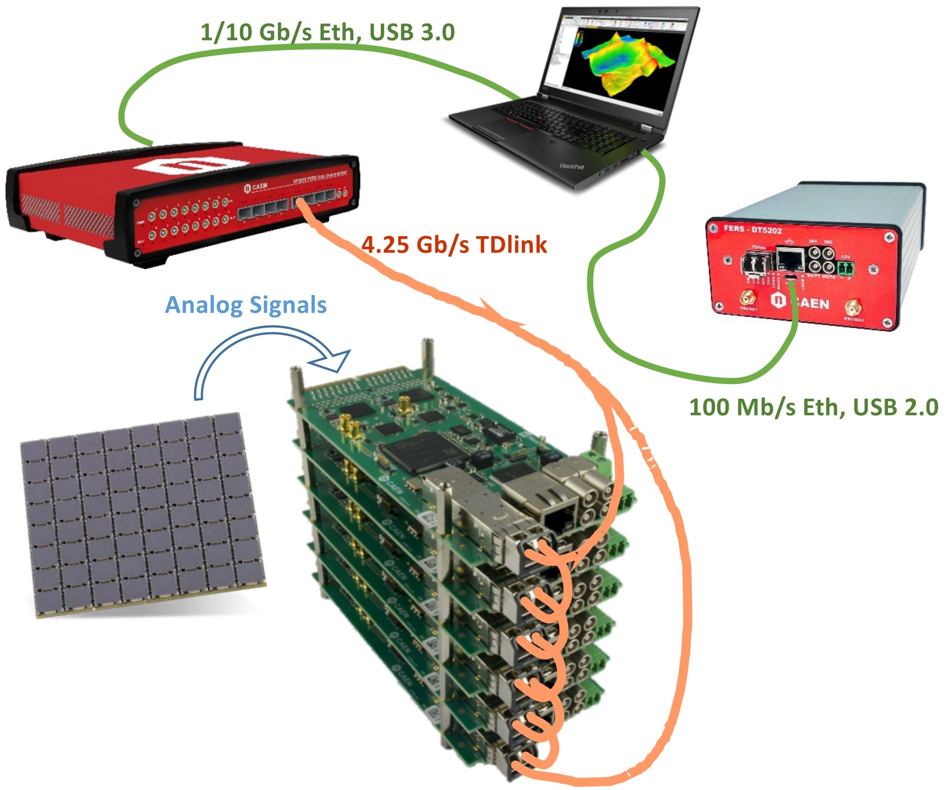
Spare

Choice of FEE for SAND/ECAL

FERS: a scalable readout system



- **FERS:** Front End ASIC + ADC/TDC + Scalable Readout Infrastructure
- Easy **integration** of new ASICs
- **Scalability:** from single stand alone version for evaluation, to 10k/100k channels with same electronics
- **TDL:** daisy chainable optical link protocol with **data+sync**
- **Readout Tree:**
  1 link = 16 FERS units
  1 Concentrator = 8 links = 128 FERS = 8k/16k channels
  Multiple Concentrators for unlimited readout…



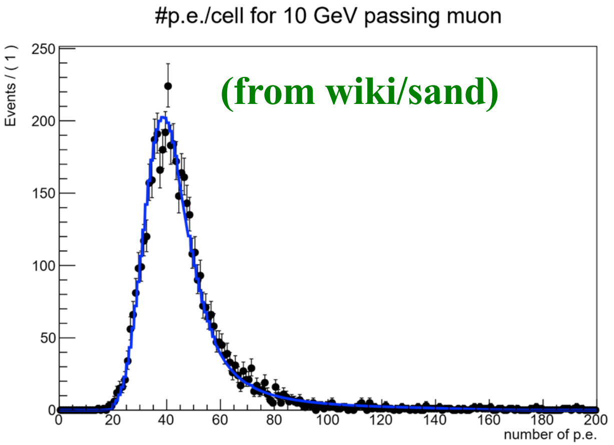
picoTDC (FERS A5203) + ToT solution

ECAL digitization

Digitization of ECAL similar to KLOE MC:

- Deposited energy in the cells propagated to PMTs with double exp. attenuation curve

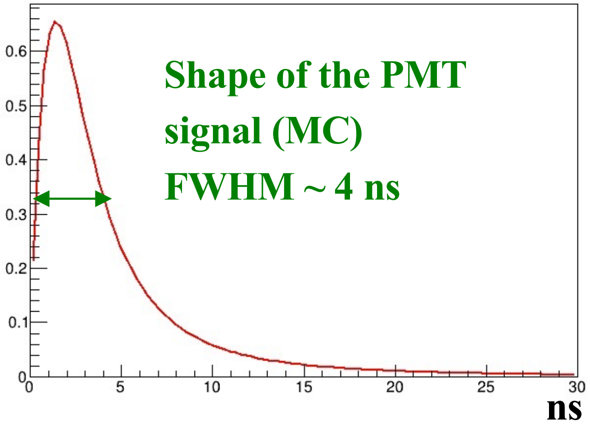
$$f(x) = Ae^{-\frac{x}{\lambda_1}} + (1 - A)e^{-\frac{x}{\lambda_2}}$$



(from wiki/sand)

- Converted into p.e. number ⇒ 18.5 p.e./MeV of <u>deposited energy</u> (MIP at the module center ~ 40 p.e.)
- Light yield ~ 1 p.e./MeV of <u>total energy</u> of the particle
- Threshold = 2.5 p.e.

- Constant fraction discriminator at 15% ot fhe signal
- Multihit TDC simulation (30 ns integration time + 50 ns dead time)



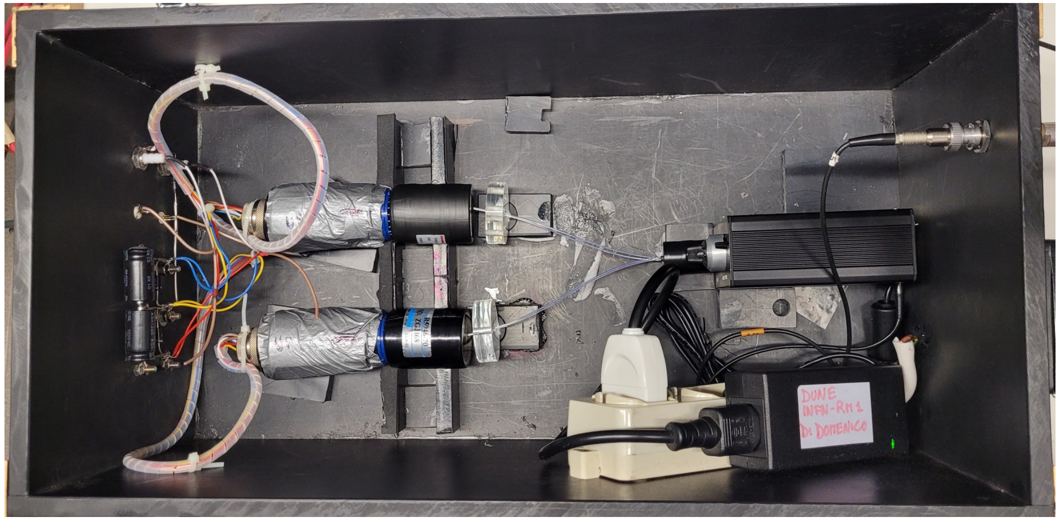
Shape of the PMT signal (MC)

FWHM ~ 4 ns

PMT system test at LNF

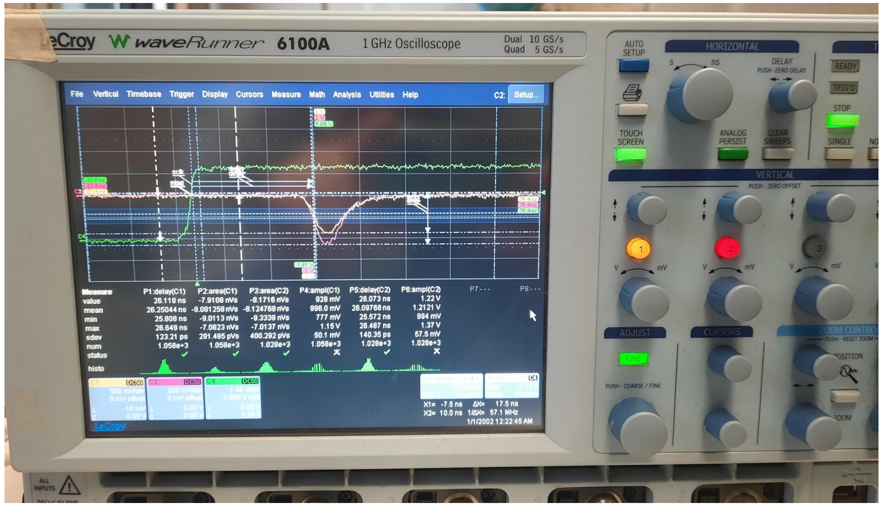
PMT system test with CAEN LED driver (wavelength ~ 400 nm) and scint. fiber splitter

two PMTs, one for reference

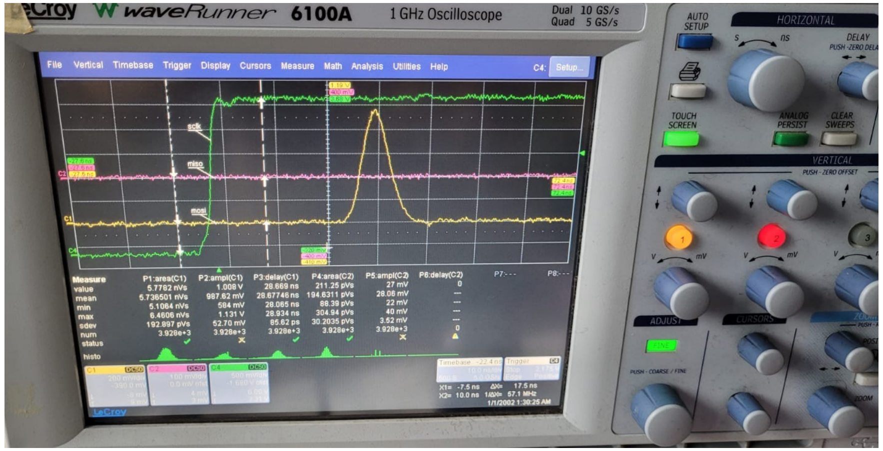


with preamplifiers a lower gain is needed, which is beneficial for PMT lifetime

no preamplifier

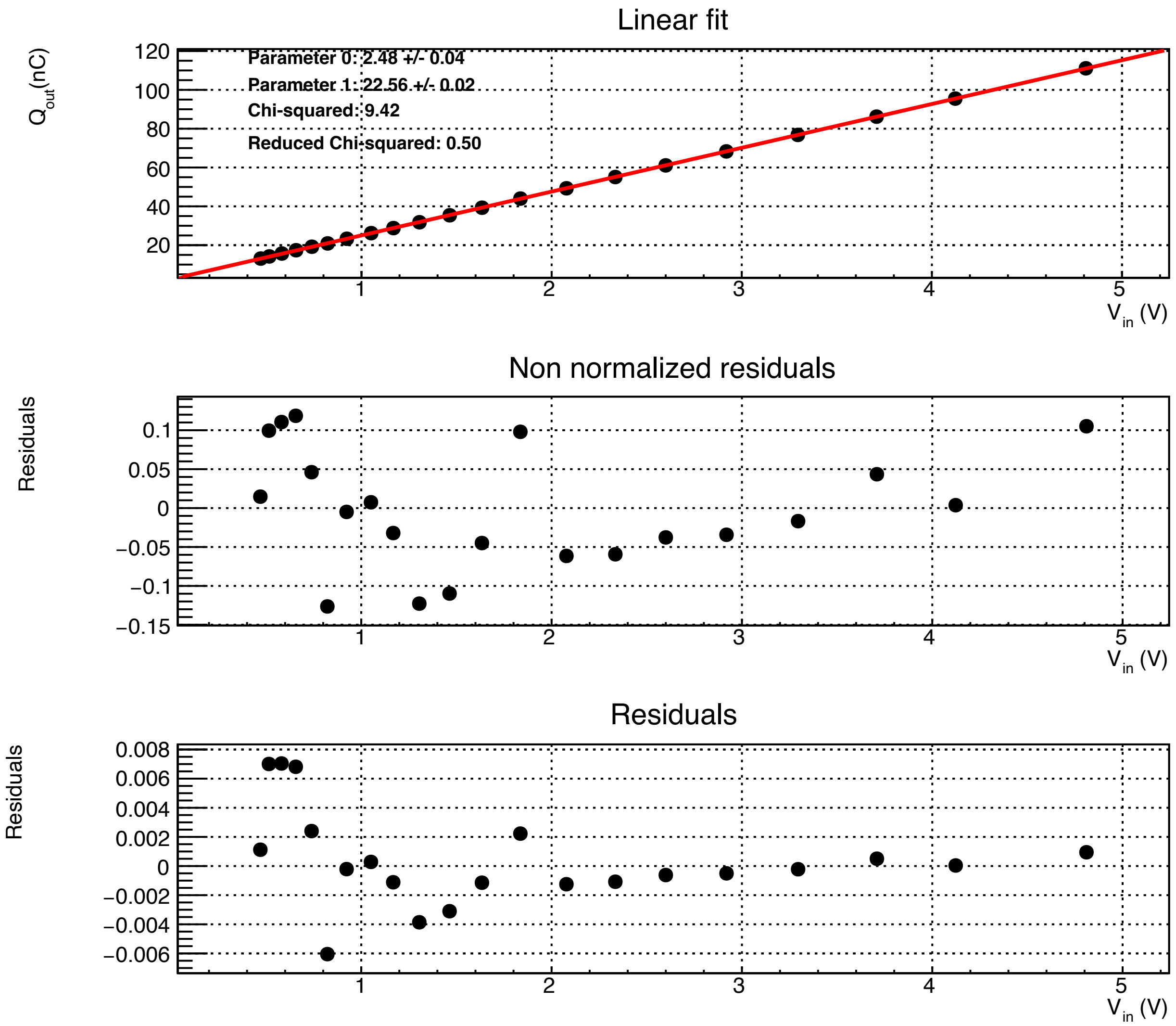


with preamplifier



Preamp linearity test and saturation threshold

Linearity of the test system without preamp


Linear fit

Parameter 0: 2.48 +/- 0.04

Parameter 1: 22.56 +/- 0.02

Chi-squared: 9.42

Reduced Chi-squared: 0.50

Non normalized residuals

Residuals

Neutrino energy spectrum in DUNE

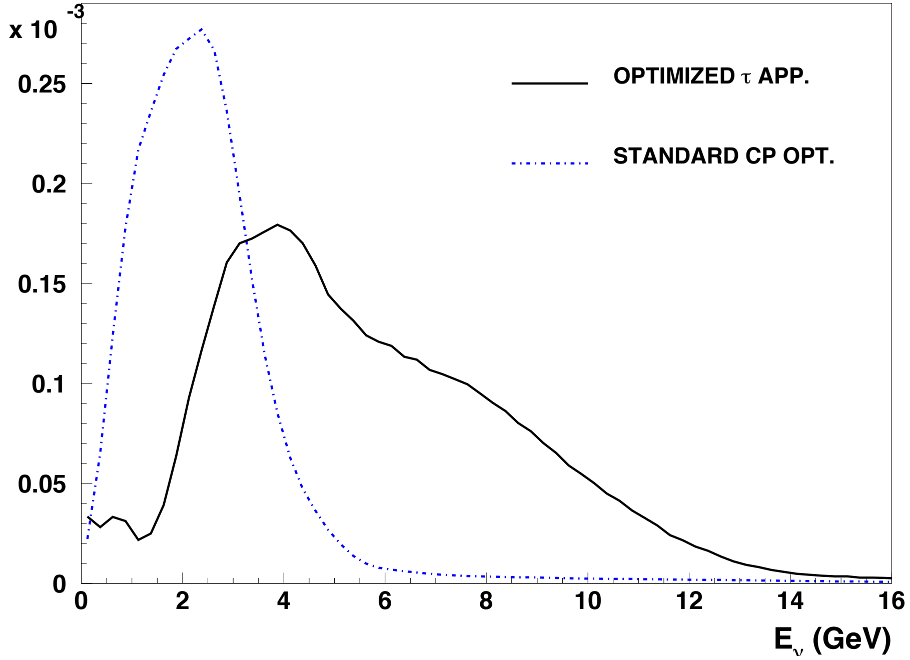


Figure 87: Comparison of LBNF ν_μ fluxes: (a) default 3 horn beam optimized for CP violation (dash-dotted); (b) ν_τ appearance optimized beam (solid).

From DUNE docDB note 13262

A proposal to enhance the DUNE near detector complex

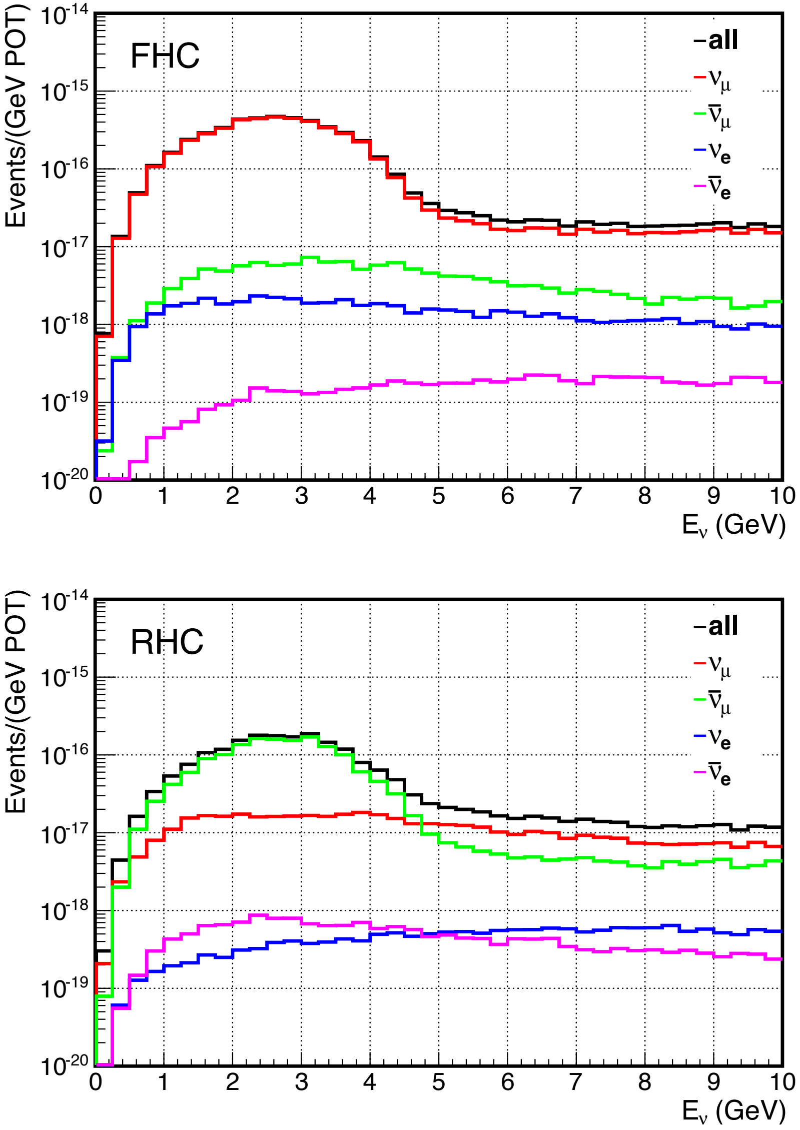
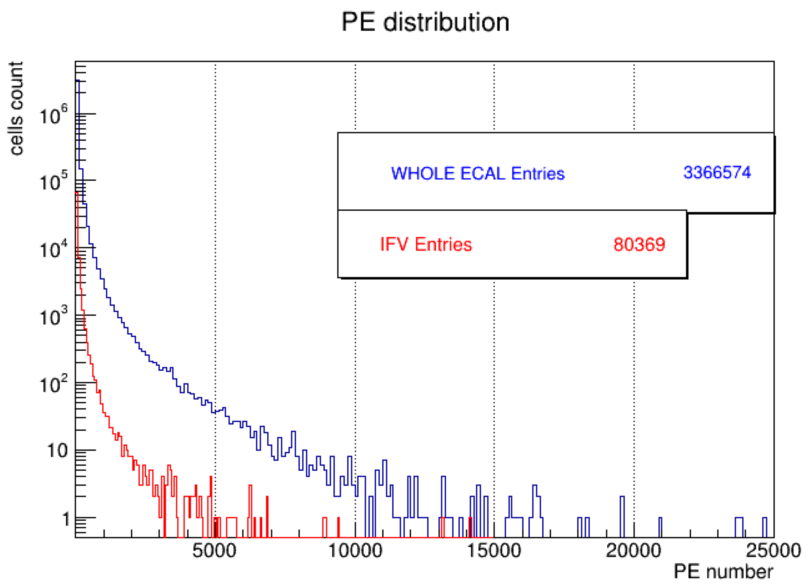
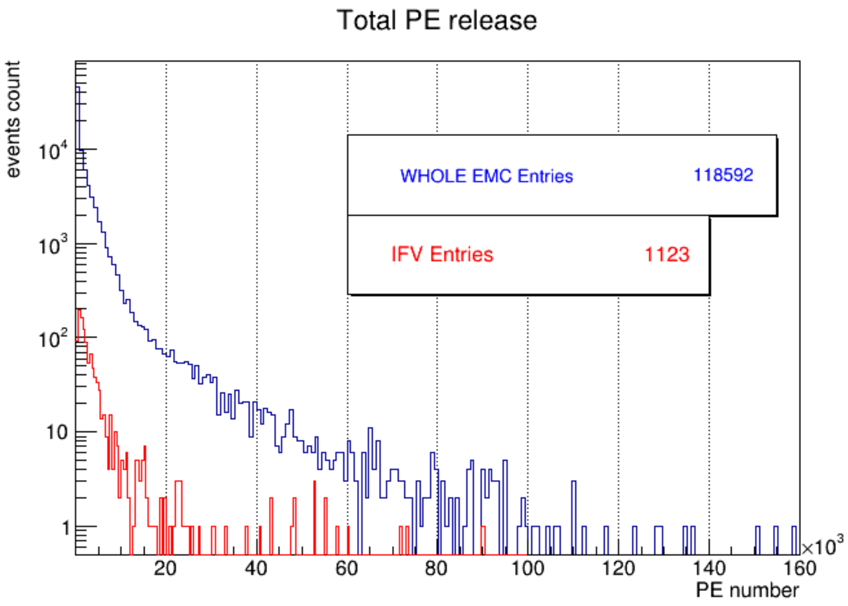
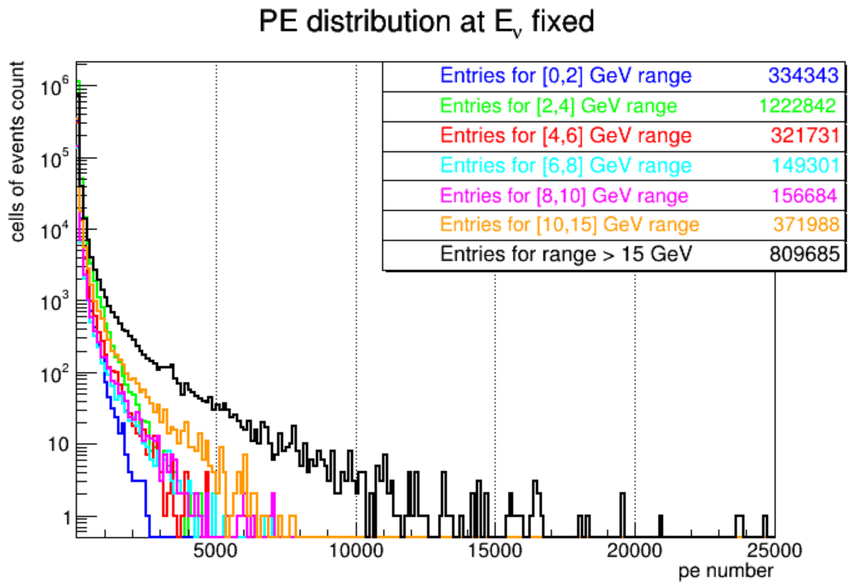


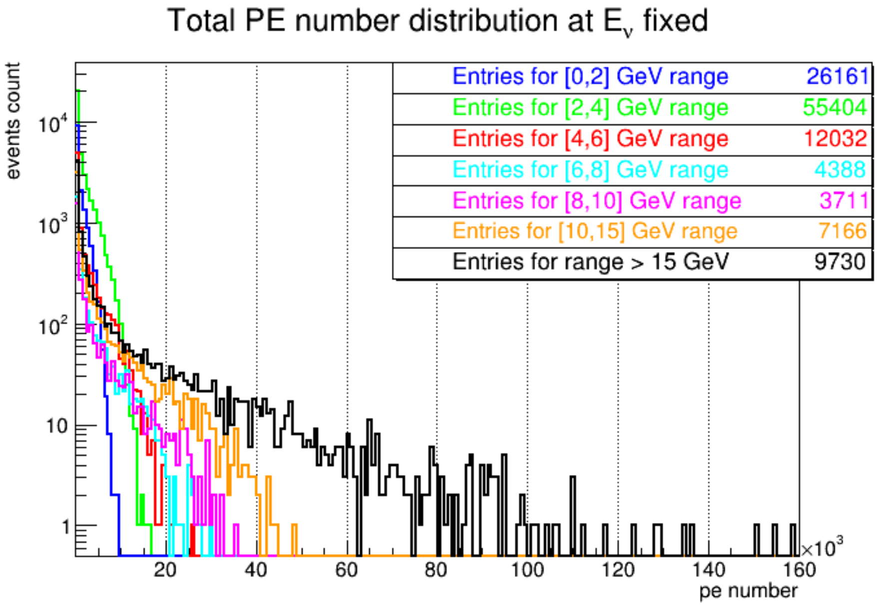
Figure 89: Energy spectra of CC interacting neutrinos in the internal LAr target, having a mass of 1.01 ton, and considering a 120 GeV proton beam in both FHC and RHC modes.

Np.e. distributions


PE distribution


Total PE release


PE distribution at E_ν fixed


Total PE number distribution at E_ν fixed

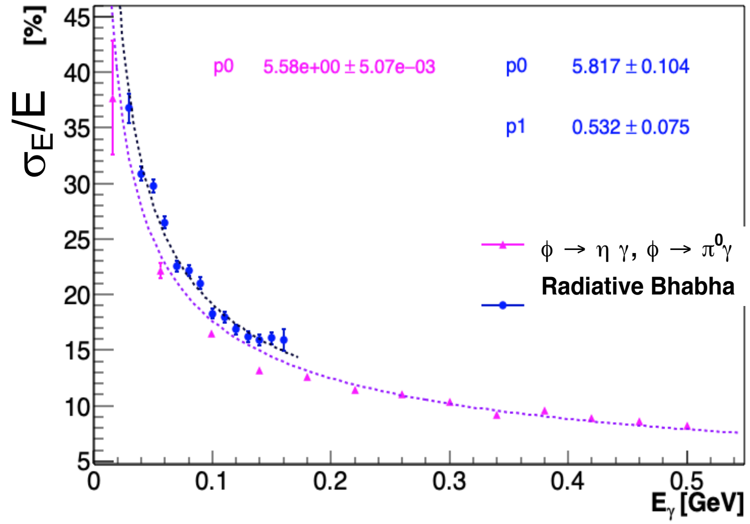
KLOE ECAL performance in KLOE-2 and with neutrons

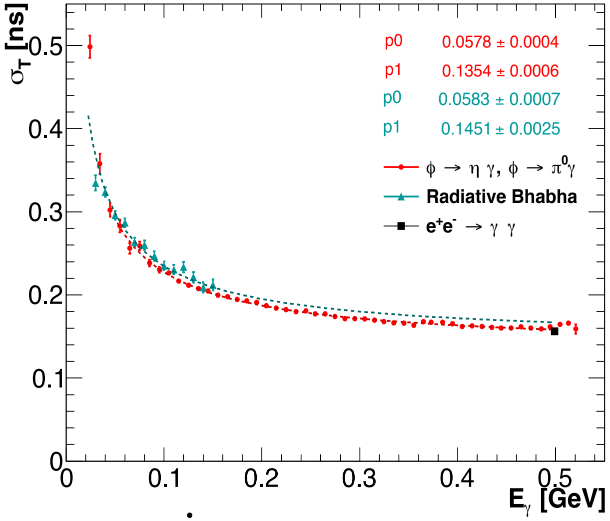
Check e.m. calorimeter performance

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

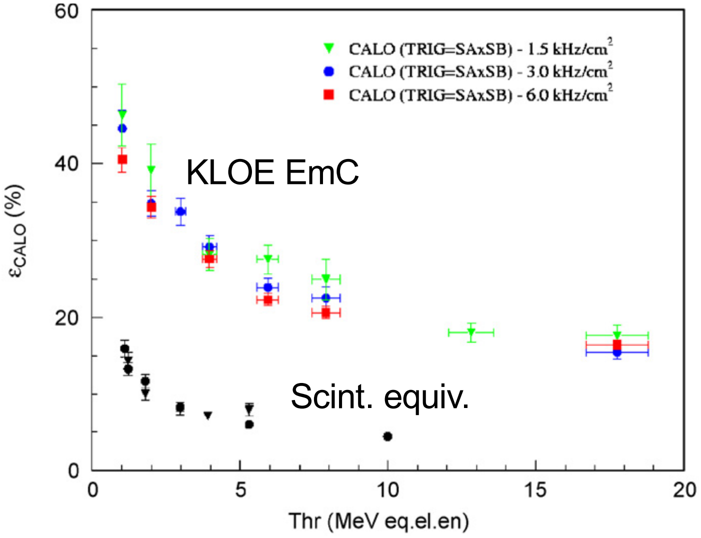
$\sigma_E/E \cong 5.6\% / \sqrt{E(GeV)}$

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





Thanks to E. Diociauti - LNF

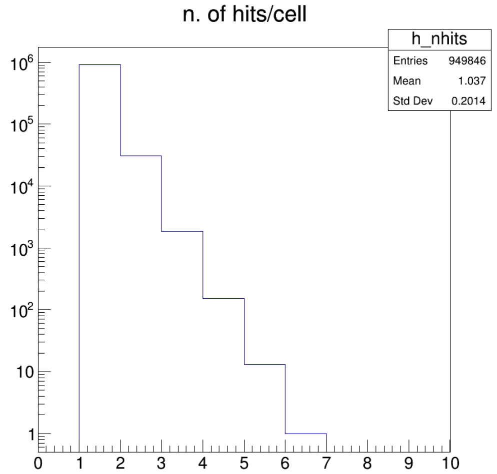


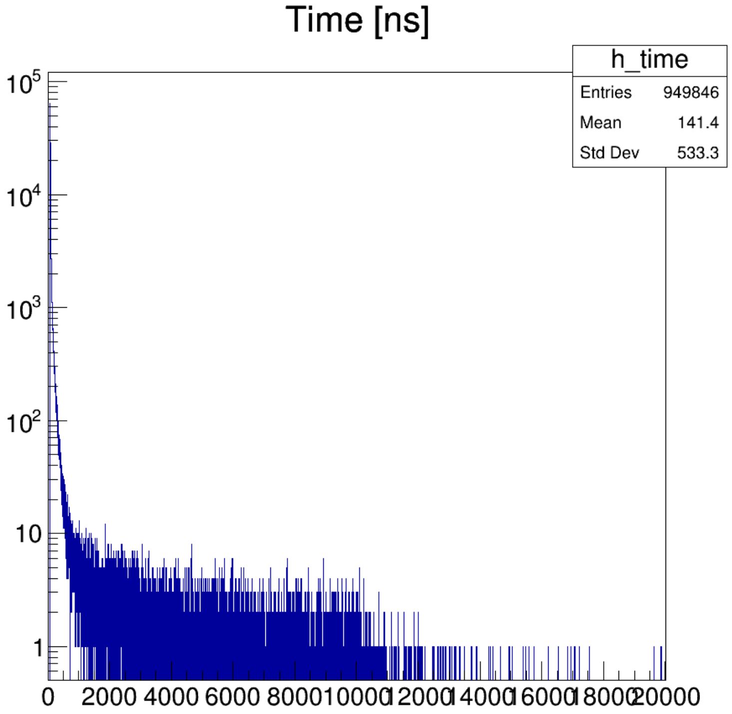
Measurement of the neutron response of the KLOE EmC

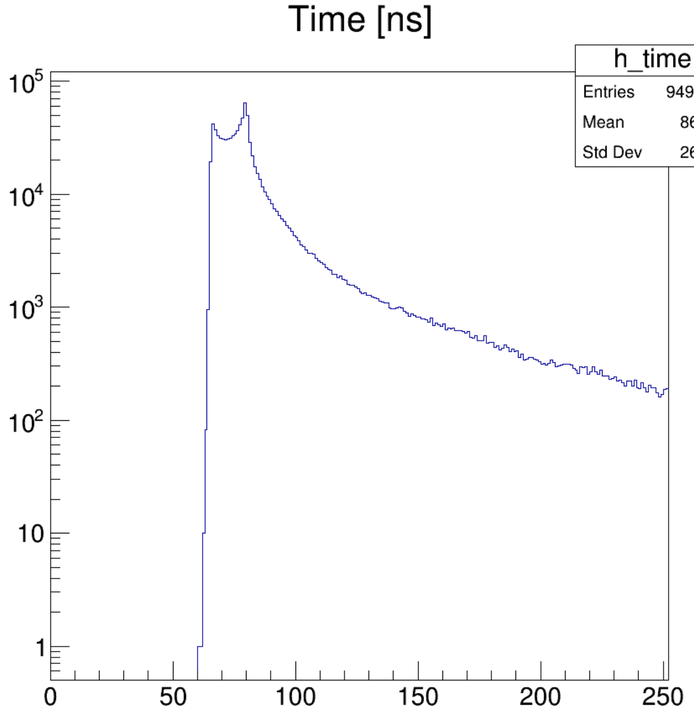
- M. Anelli et al., *"Measurement and simulation of the neutron response and detection efficiency of a Pb-scintillating fiber calorimeter "*, NIM **A581** (2007) 368
-
- M. Anelli et al., *"Measurement of the neutron detection efficiency of a 80% absorber–20% scintillating fibers calorimeter "*, NIM **A626** (2011) 67 (Gauzzi corresponding author)

Time simulation

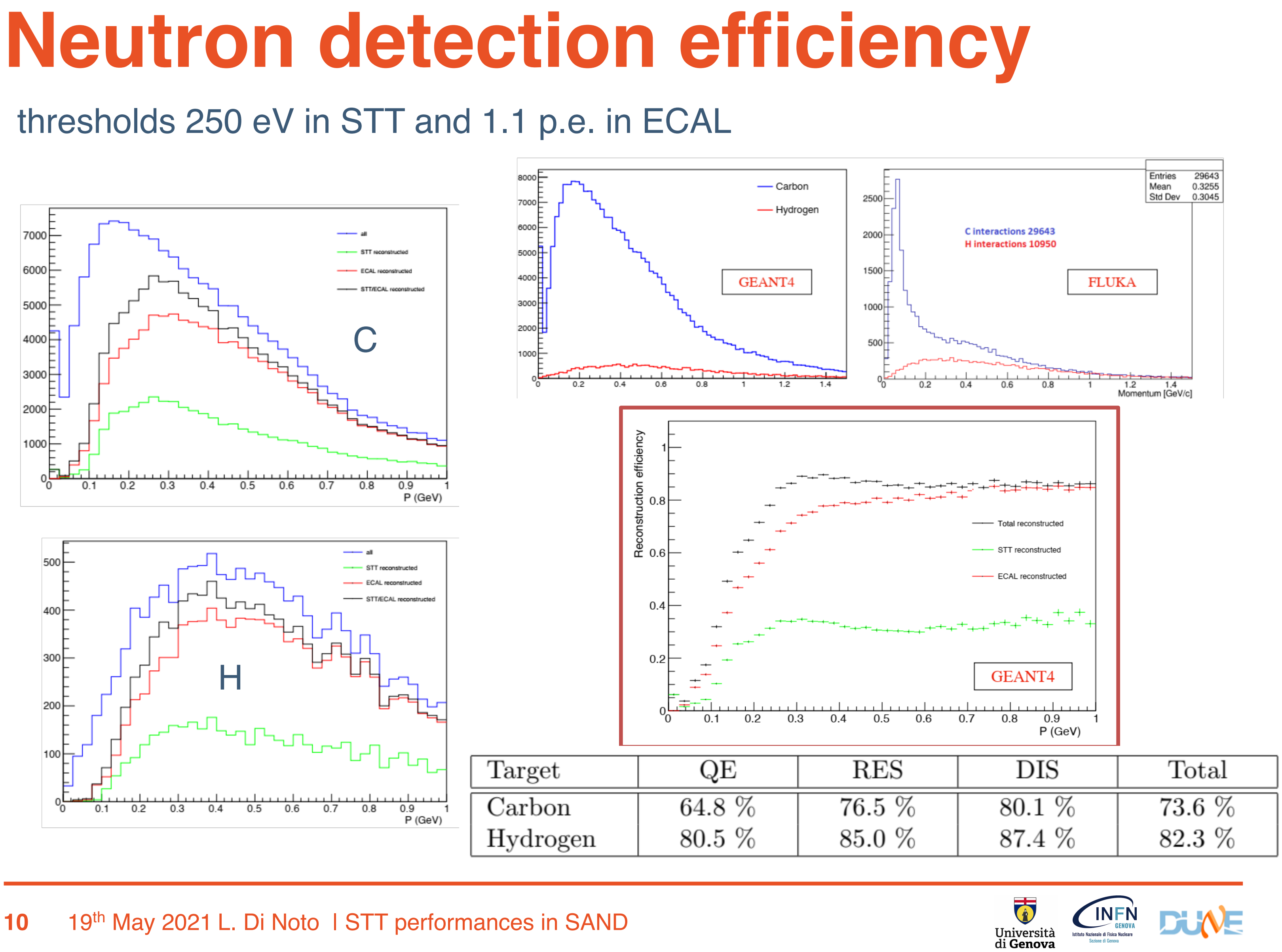
- **TDC Multihit simulation: integration time 30 ns (starting from first p.e. time) 50 ns dead time**
- **Constant fraction simulation: 15% of the total p.e. number**







Neutrons in SAND



Neutron detection efficiency

thresholds 250 eV in STT and 1.1 p.e. in ECAL

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

10 19th May 2021 L. Di Noto I STT performances in SAND

Università di Genova