Studies for the optimization of the working point of the SAND calorimeter read-out electronics in DUNE

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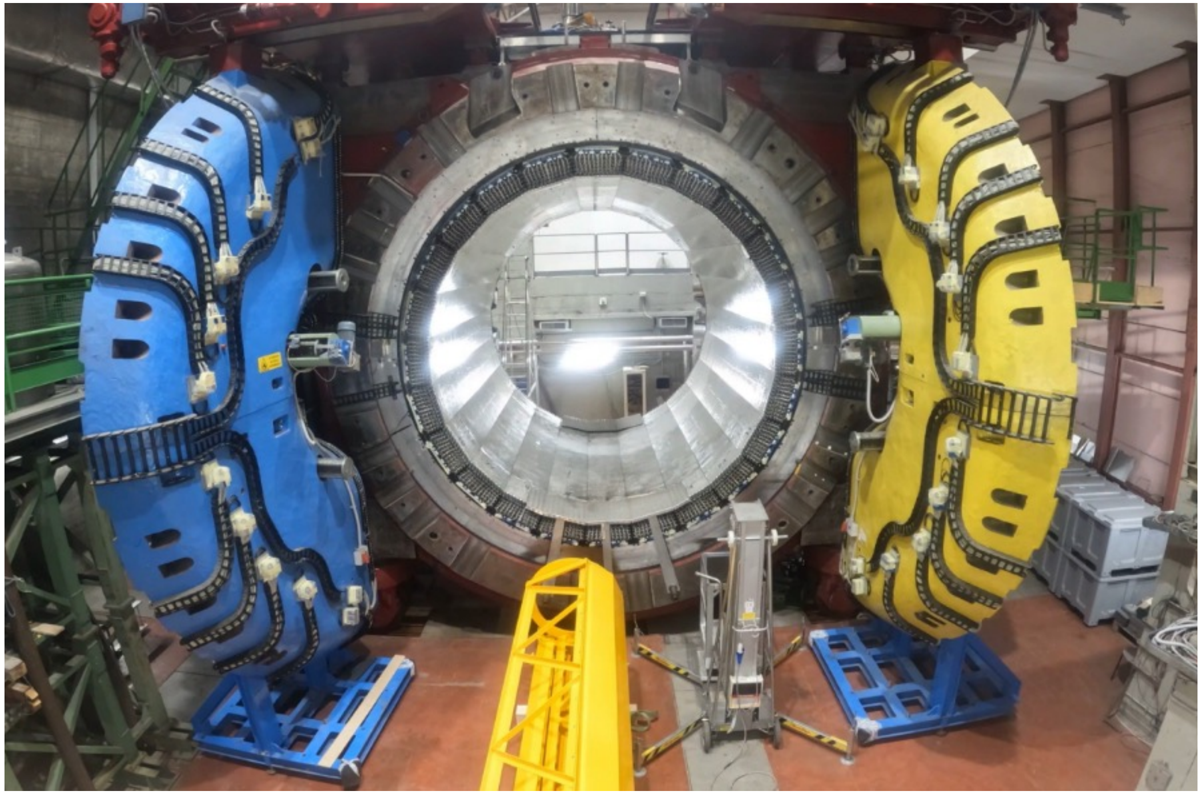


ECAL WG Meeting – 12 June 2023

Neutrino energy spectrum in DUNE

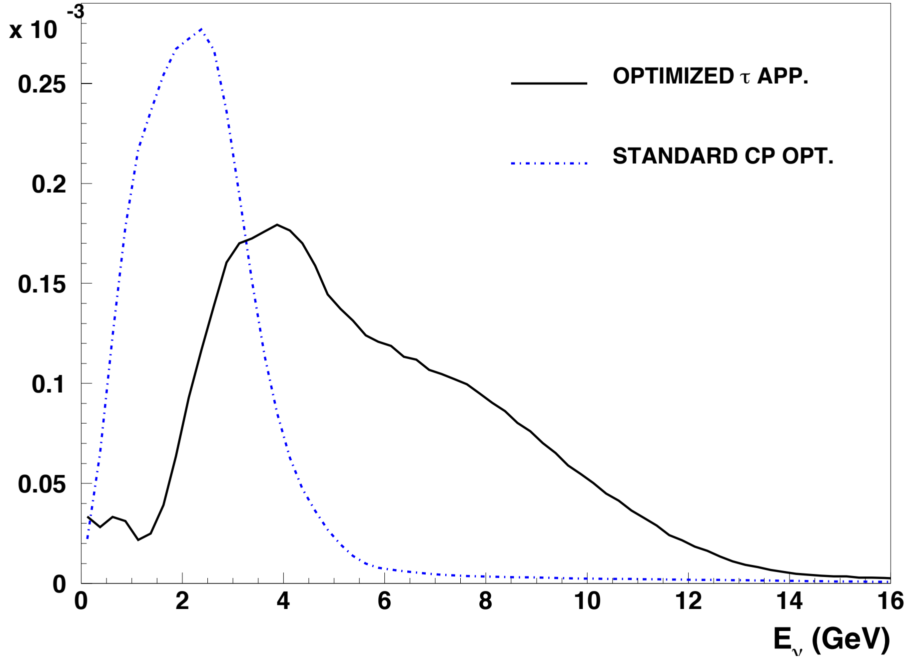


Figure 87: Comparison of LBNF ν_μ fluxes: (a) default 3 horn beam optimized for CP violation (dash-dotted); (b) ν_τ appearance optimized beam (solid).

From DUNE docDB note 13262
A proposal to enhance the DUNE near detector complex

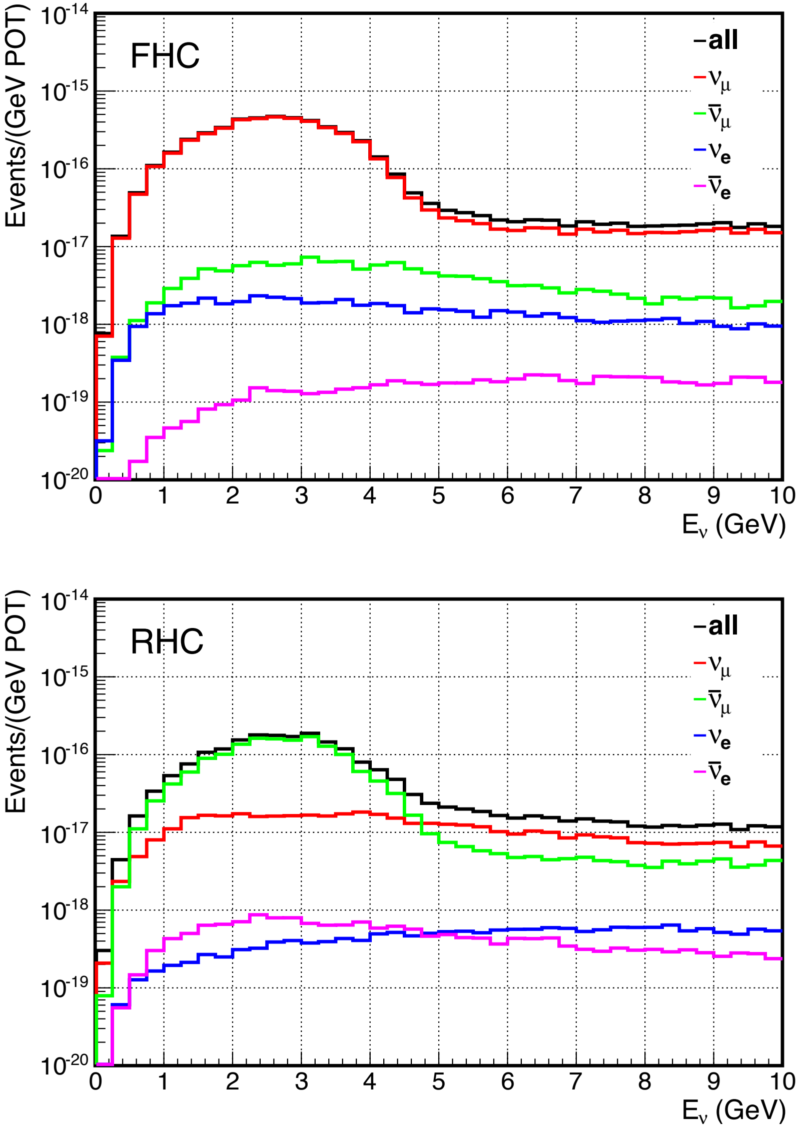
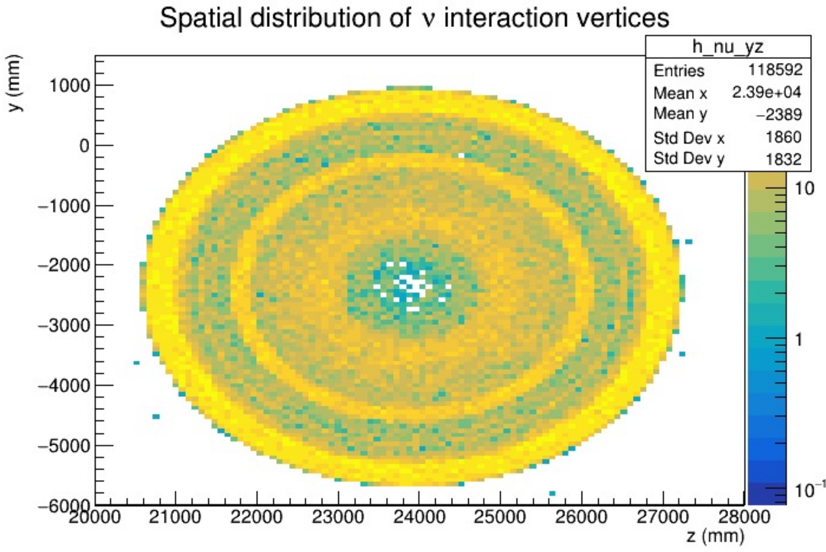


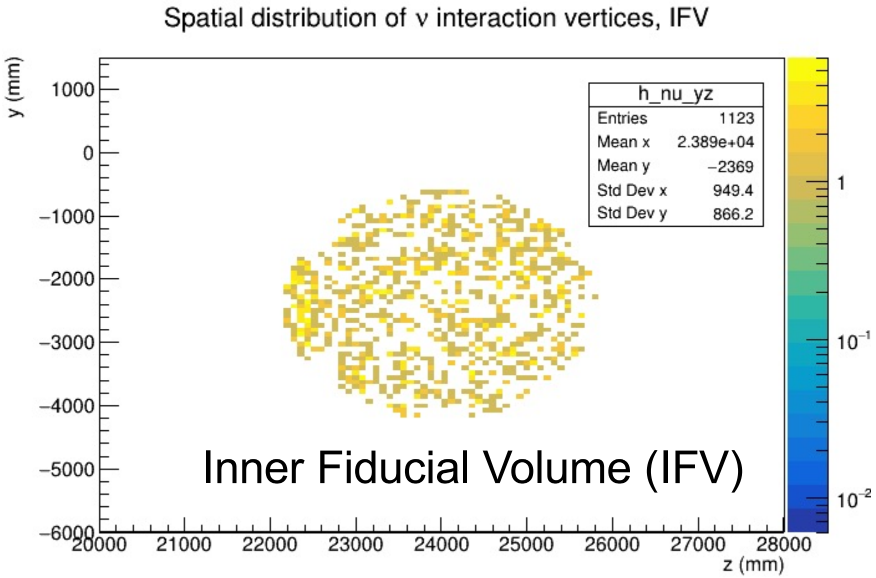
Figure 89: Energy spectra of CC interacting neutrinos in the internal LAr target, having a mass of 1.01 ton, and considering a 120 GeV proton beam in both FHC and RHC modes.

SAND MC simulation

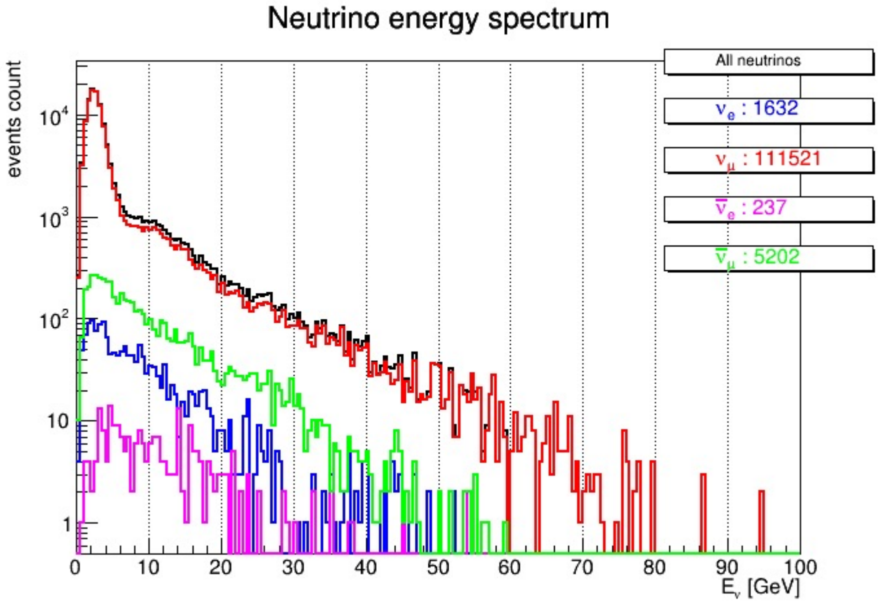
- Analyzed sample: sand-events.*.digi.root and sand-events.*.edep.root **(thanks to Matteo Tenti)**

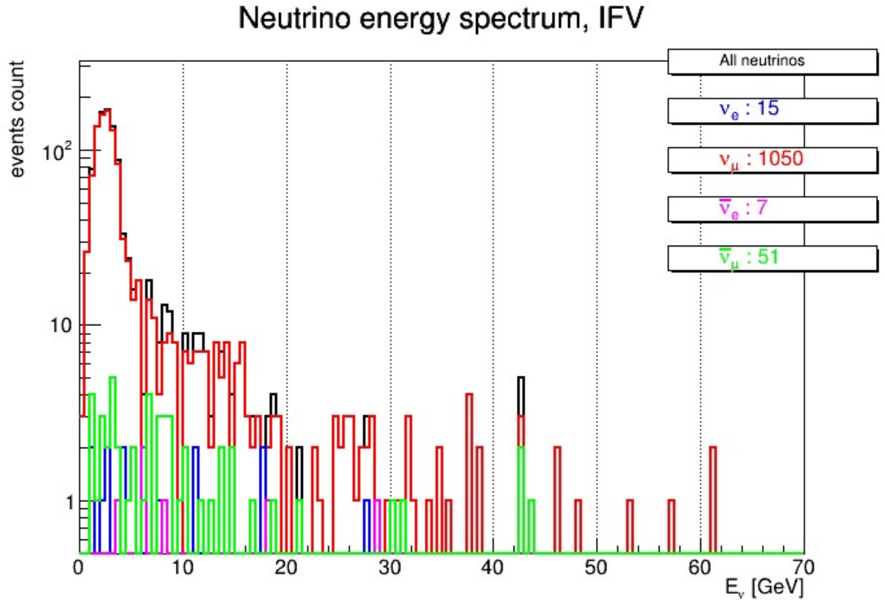
- 100 files
- Total evts = 118592
- Total p.o.t = 1.011×10^{17}
- p.o.t./spill = 7.5×10^{13} at 1.2 MW beam power
- corresponding to ~ 30 minutes of data taking in FHC mode
- Inner Fiducial Volume (IFV) defined at a distance of 20 cm from ECAL internal surface


Spatial distribution of ν interaction vertices

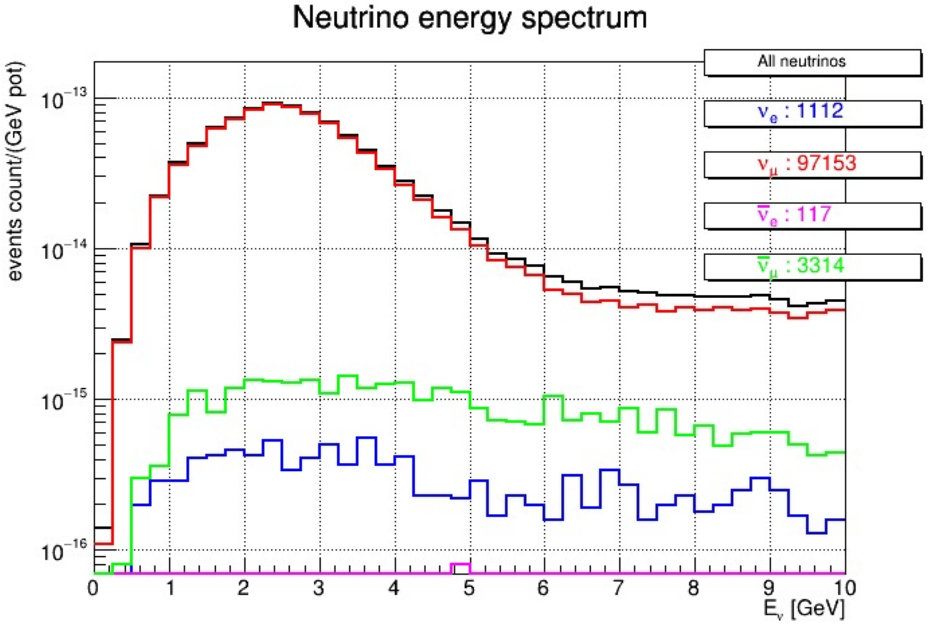

Spatial distribution of ν interaction vertices, IFV

Neutrino energy spectrum in SAND MC



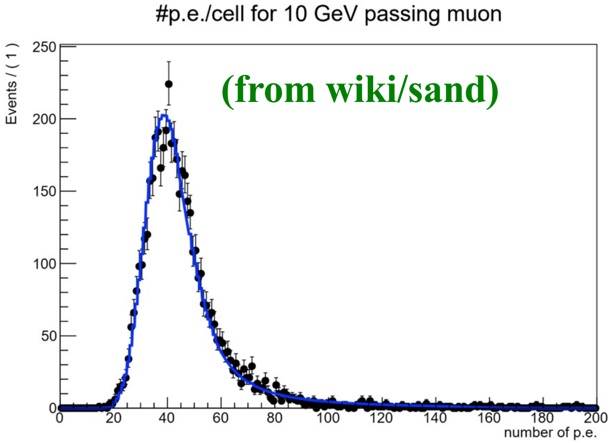


as a cross-check



ECAL digitization

Digitization of ECAL similar to KLOE MC:


#p.e./cell for 10 GeV passing muon

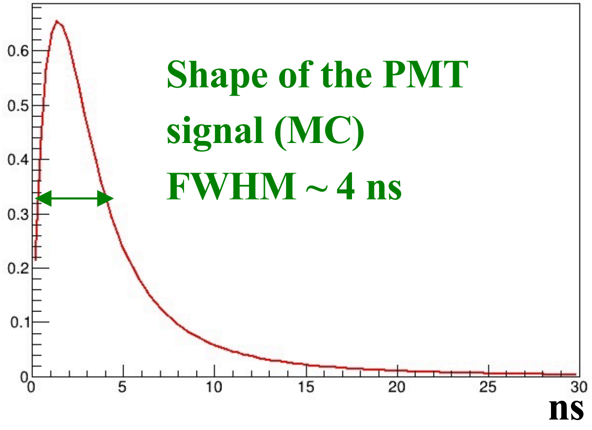
(from wiki/sand)

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

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

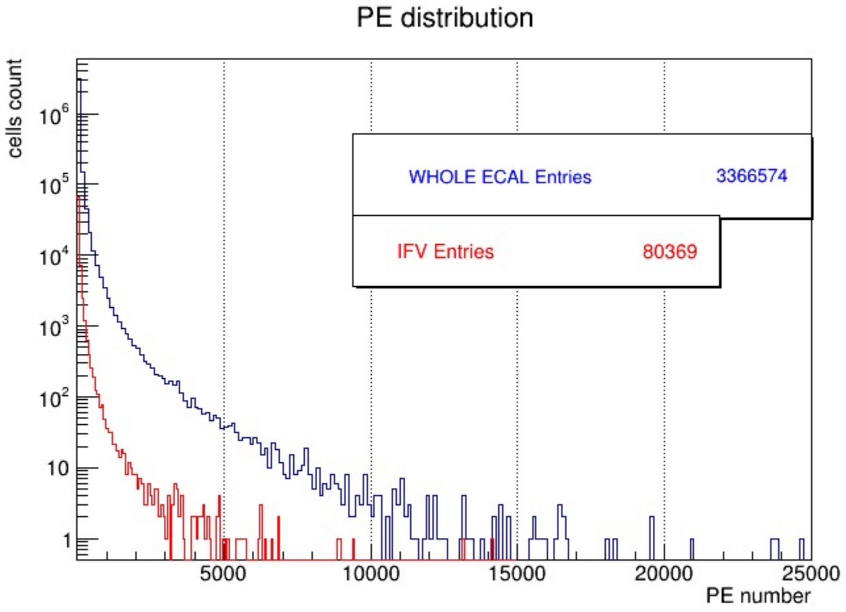
- Converted into p.e. number ⇒ 18.5 p.e./MeV of deposited energy (MIP at the module center ~ 40 p.e.)
- Light yield ~ 1 p.e./MeV of total energy of the particle
- Threshold = 2.5 p.e.

- 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

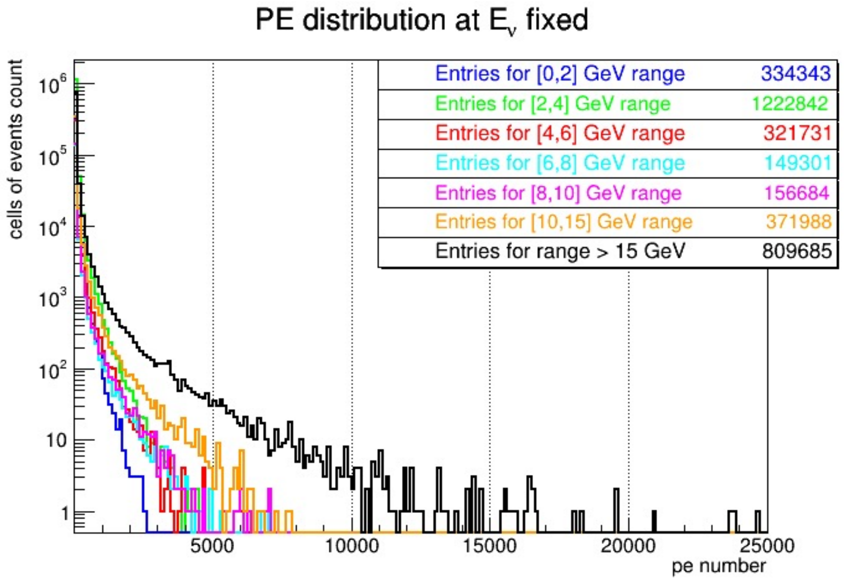
Np.e. distributions

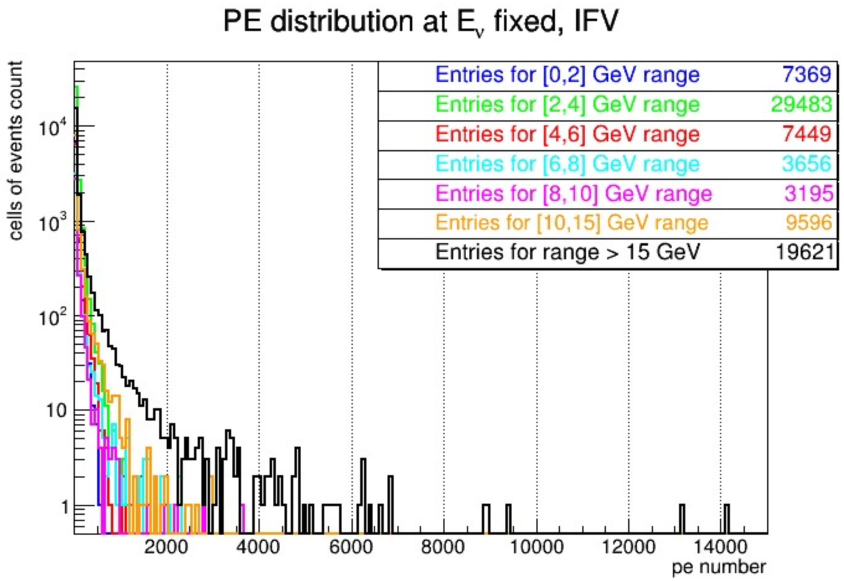


E_ν range = [0,10] GeV
Events number 101,696
Events cells number 2,184,901

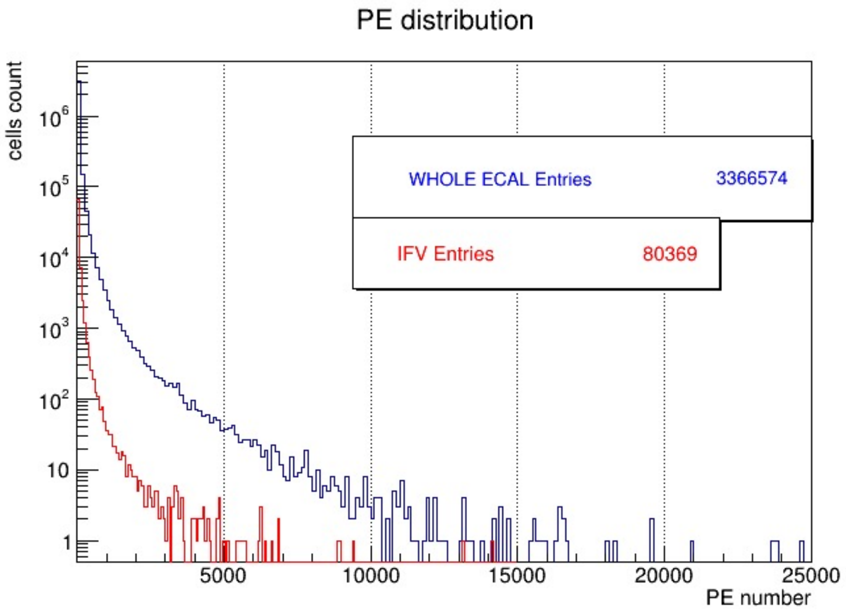
Fraction of events with at least one cell above PE threshold	[%]
1000 PE threshold	2.58
2000 PE threshold	0.49
3000 PE threshold	0.13
4000 PE threshold	$3.64 \cdot 10^{-2}$

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



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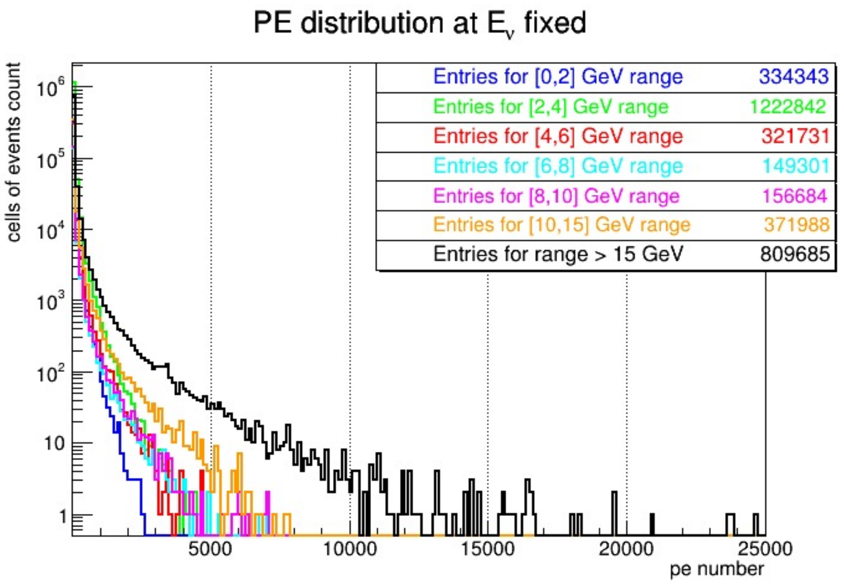
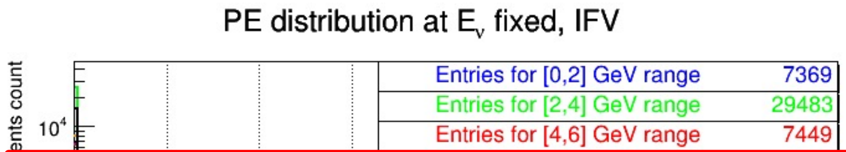
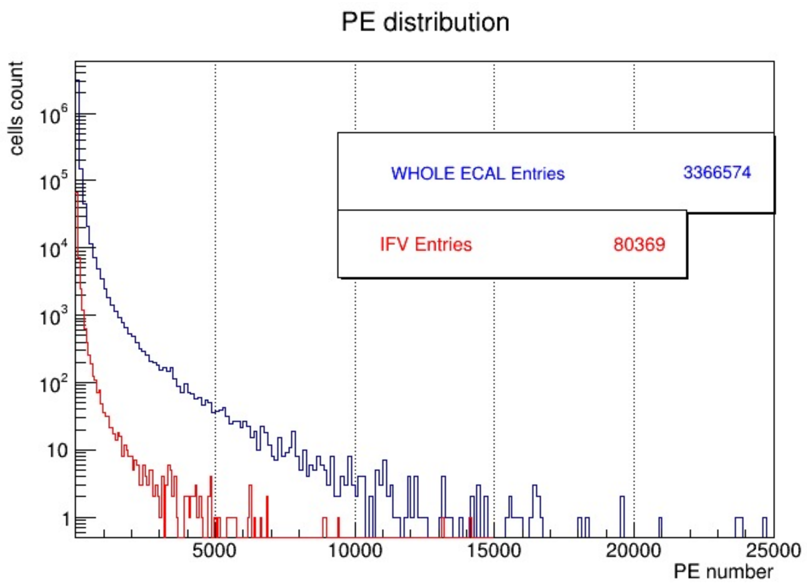
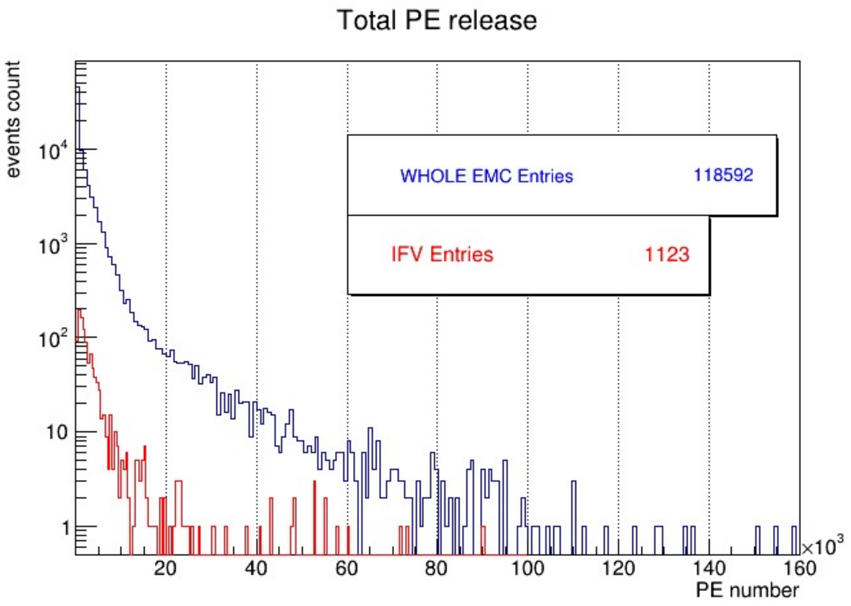


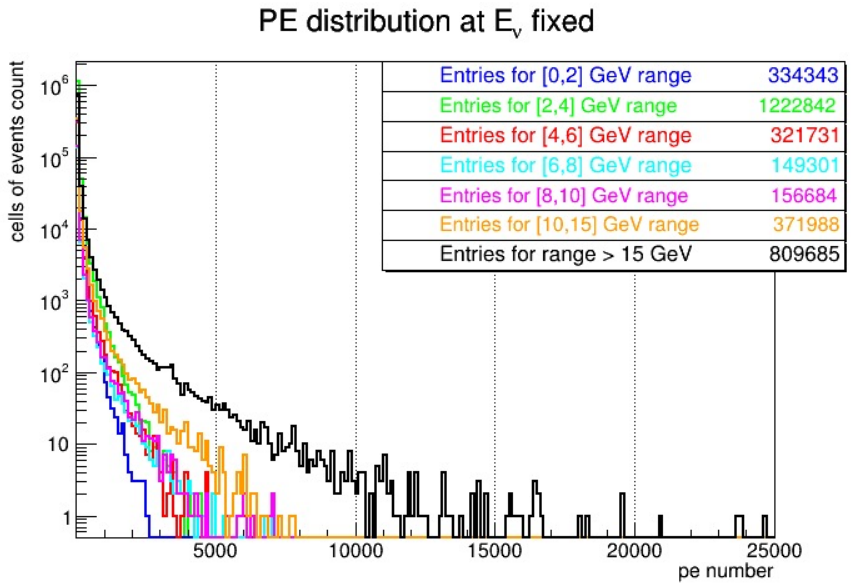


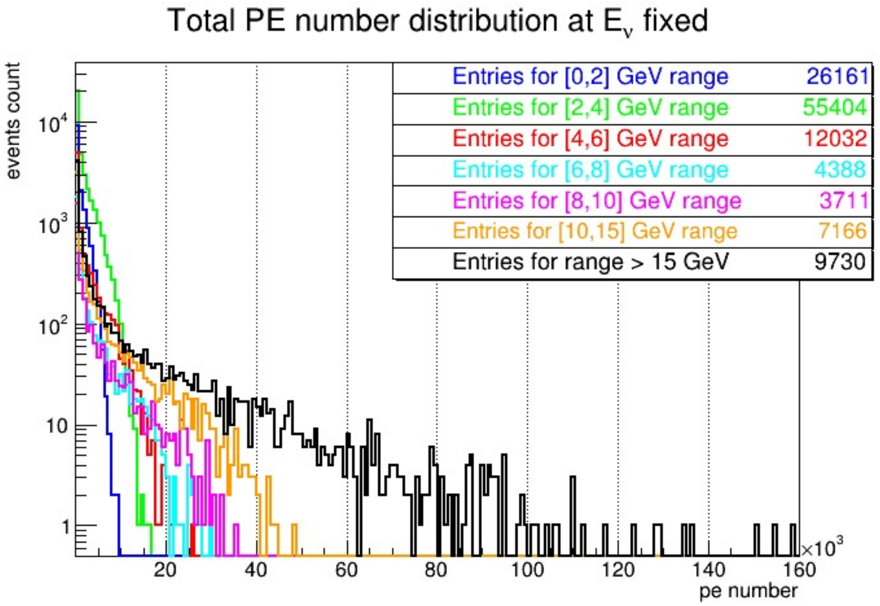
- Neutrino energy range of interest for oscillation analyses is [0,10] GeV
- In this range the MAXIMUM Np.e. that has to be treated by FEE can be safely set between 1000 and 2000
  => see next slides for the choice of the FEE dynamic range

Np.e. distributions

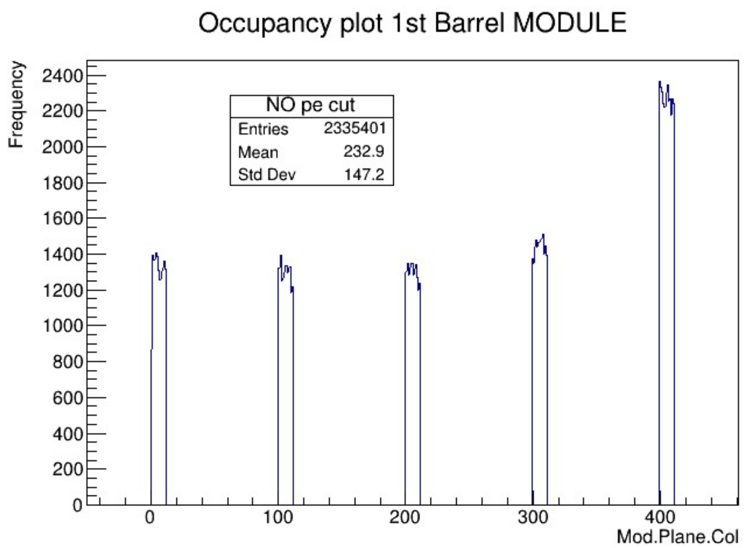




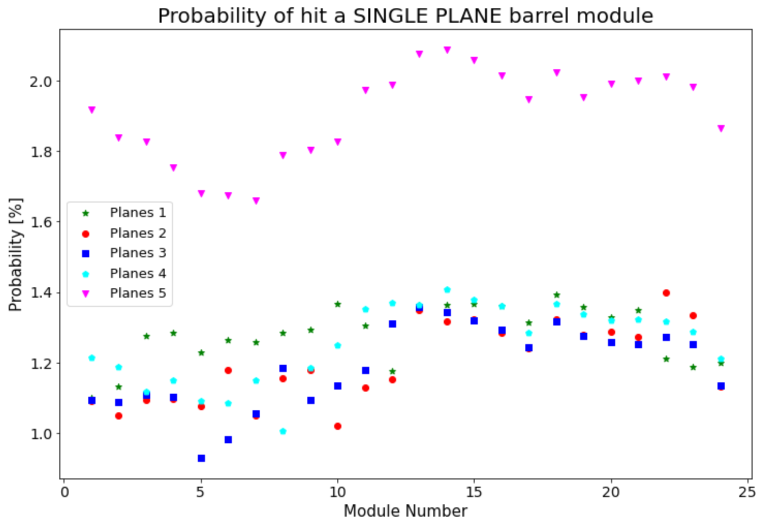




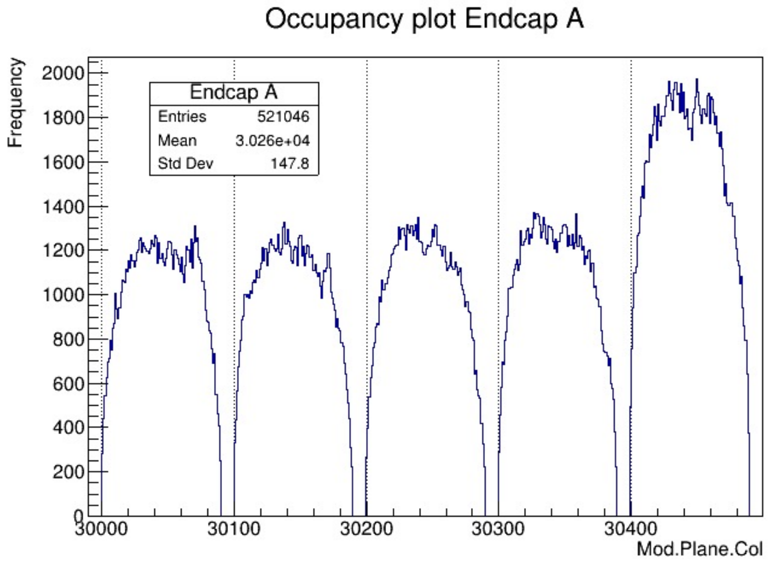
Cell occupancy plots and hit probability


Occupancy plot 1st Barrel MODULE

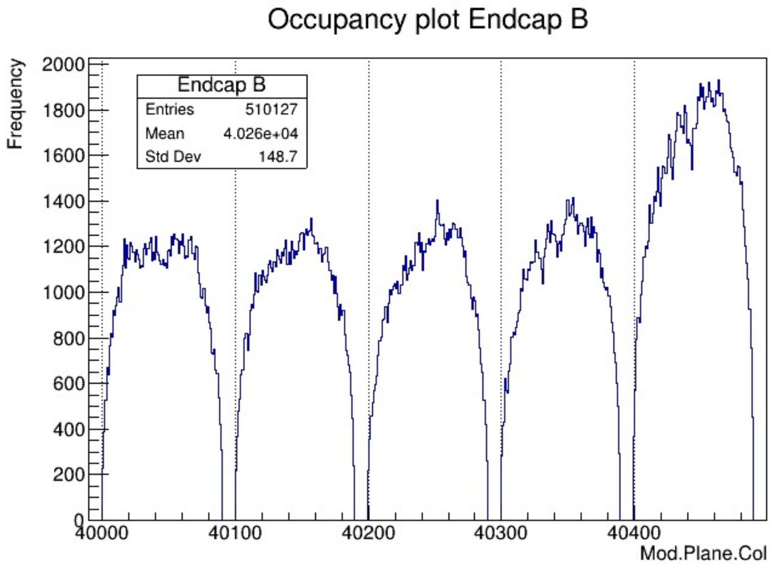
Barrel


Probability of hit a SINGLE PLANE barrel module

Ecap A


Occupancy plot Endcap A

Ecap B


Occupancy plot Endcap 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%

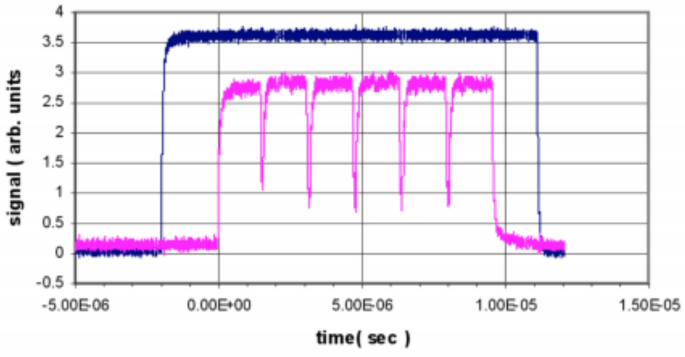
P_{cell} = 1.16%

Beam, spill structure, and event rates in SAND

Beam power 1.2 MW
7.5×10^{13} protons extracted every 1.2 s at 120 GeV
1.1×10^{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

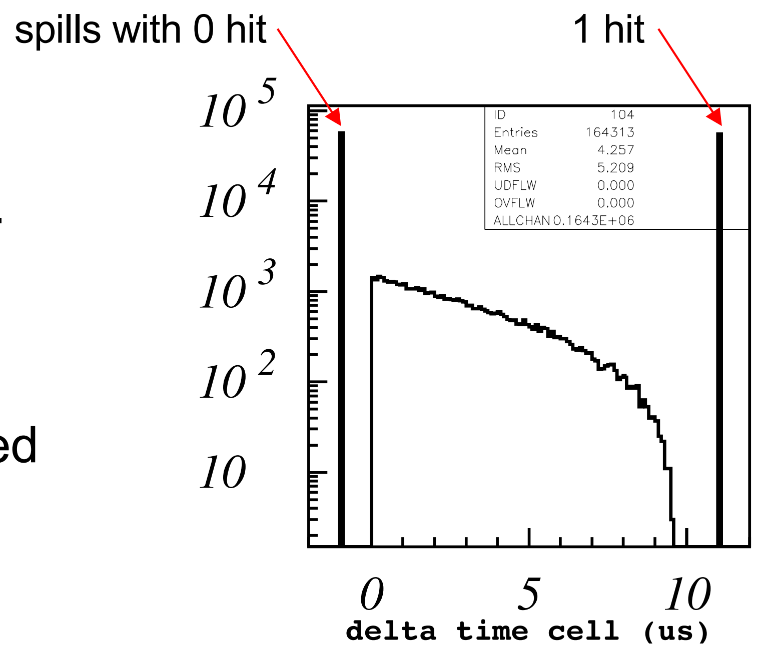
~ 84 interactions/spill
$\lesssim$1 interaction/spill in the SAND fiducial volume

Pile-up probability

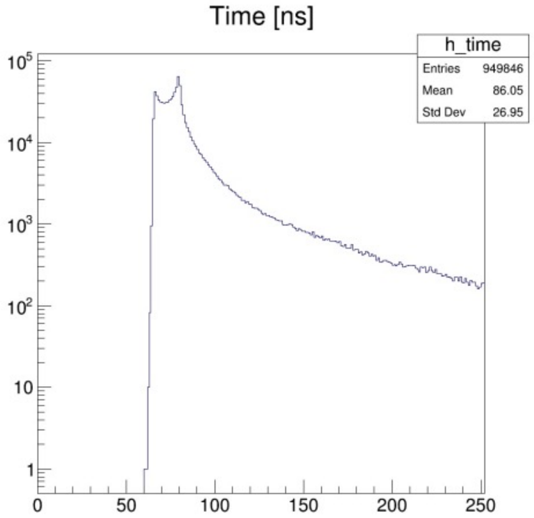
The beam time structure is reconstructed to simulate the time of the neutrino interaction event and calculate the pile-up probability that, given a PMT signal, a second signal arrives within a fixed time window (TW) after the first signal.

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.

Pile-up probability

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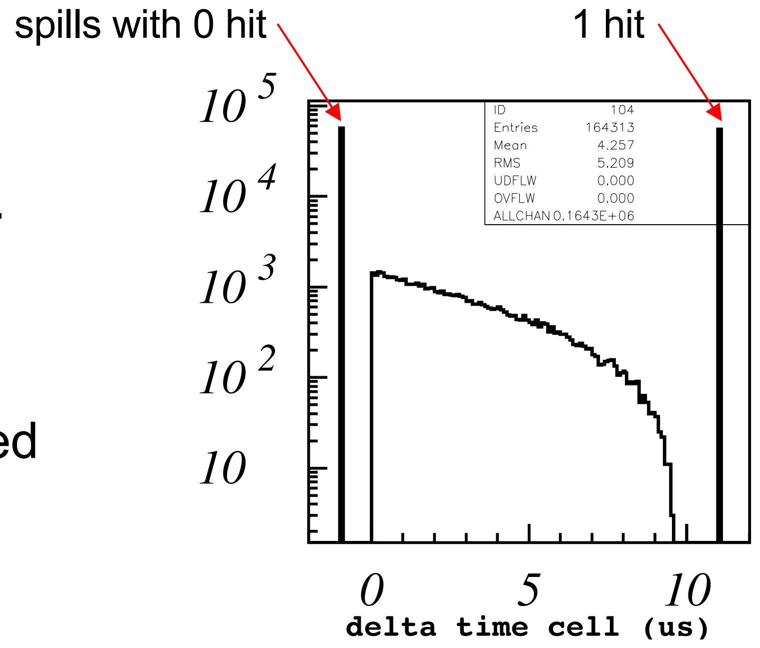

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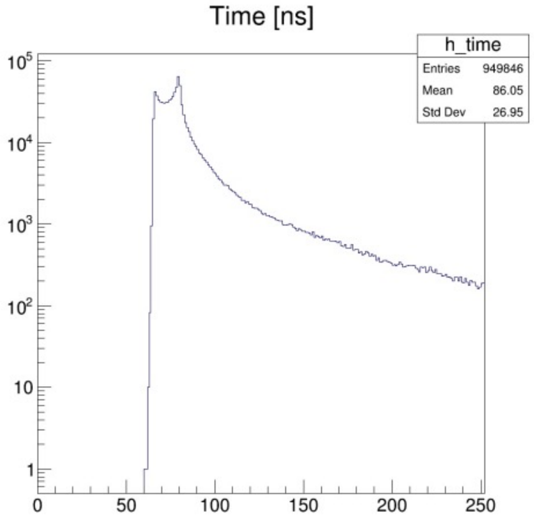


Time propagation/smearing of hits in a single neutrino interaction event.

PMT signal and discriminator threshold in KLOE

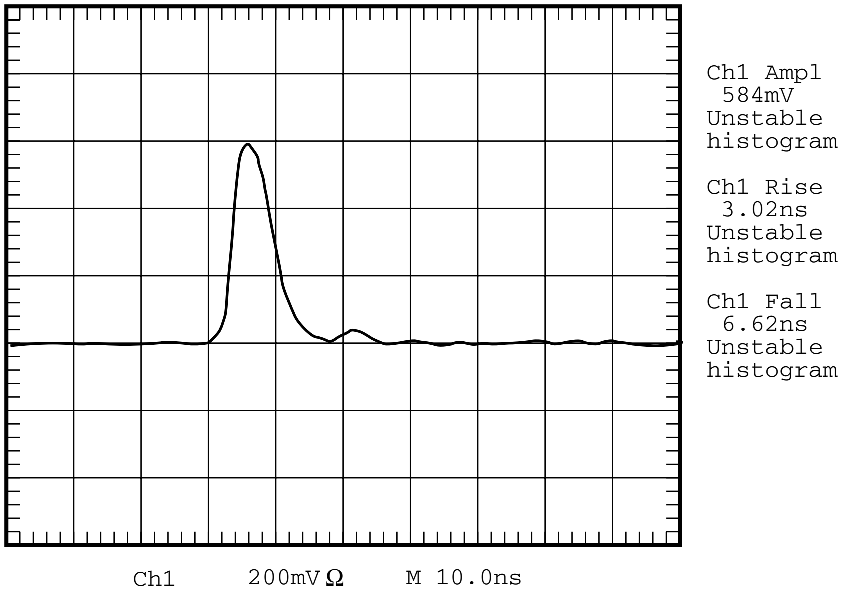
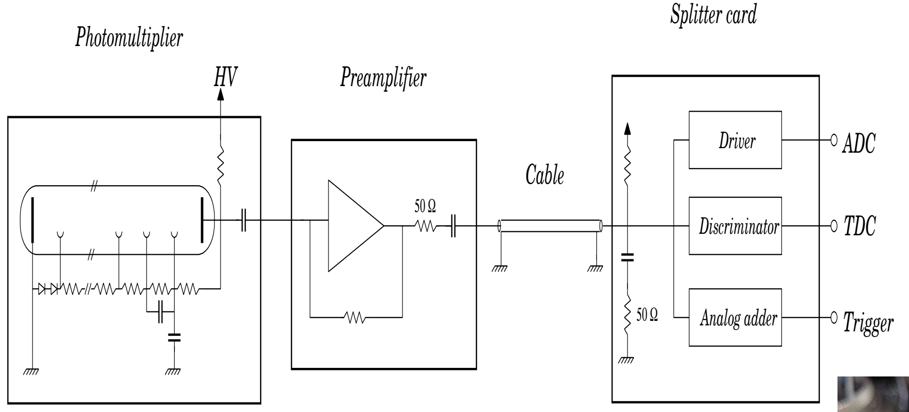
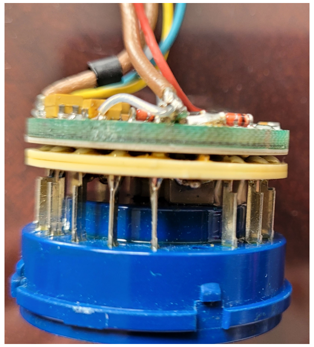


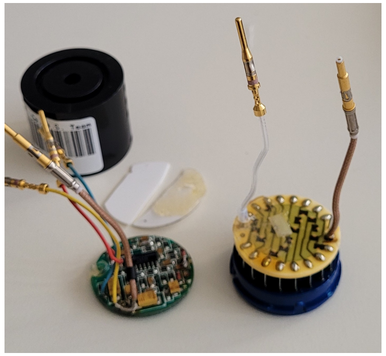
Figure 4: Typical signal from the PM base.

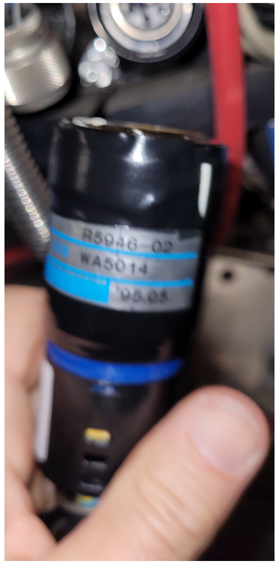
Constant fraction discriminators.
Effective thresholds are in the range 4–5 mV:
They correspond to signals originated by 3–4 photoelectrons or a 3–4 MeV photon at 2 m from PMT



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

Choice of the dynamic range

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 => 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:
  V_{dis}(max) = V_{preamp}(max) • 0.5 • C_{ATT}= 1.74 V
- signal ampl = V_{dis}(max)/N_{pe}(max)
- N_{pe}(min)=V_{TH}/(signal ampl) => N_{pe}(max)/N_{pe}(min) = V_{dis}(max)/V_{TH}

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	~ 2000	0.87	~ 6	6.0
5.5	1.38	~ 1500	1.16	~ 4	4.0
8.3	2.1	~ 1000	1.74	~ 3	3.0
10	2.5	~ 800	2.18	~ 2	2.0

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- 12m long cable attenuation: C_{ATT} = 0.74
- MAX single pulse amplitude at the discriminator/digitizer input is: $V_{dis}(max) = V_{preamp}(max) \cdot 0.5 \cdot C_{ATT}$= 1.74 V
- signal ampl = $V_{dis}(max)/N_{pe}(max)$
- $N_{pe}(min)=V_{TH}$/(signal ampl) => $N_{pe}(max)/N_{pe}(min) = V_{dis}(max)/V_{TH}$

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
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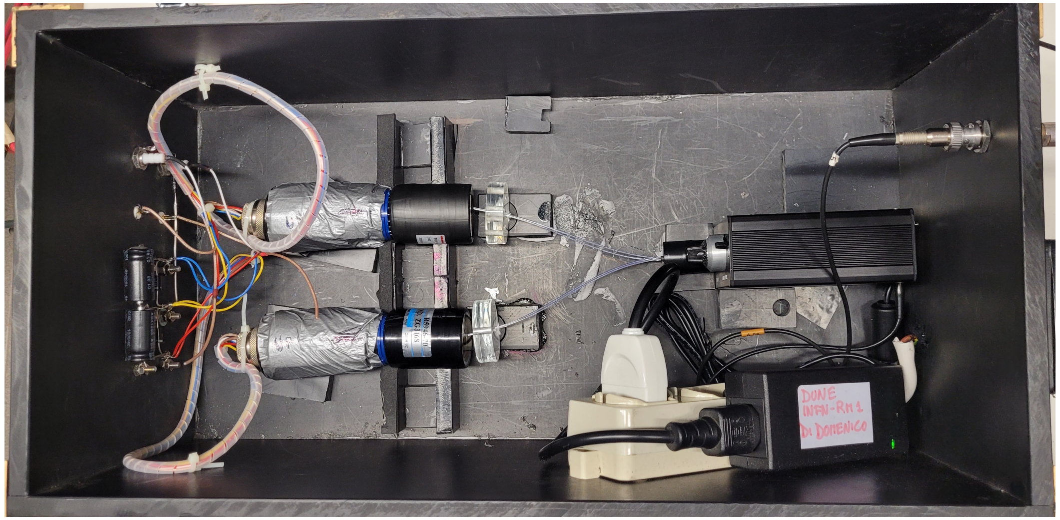
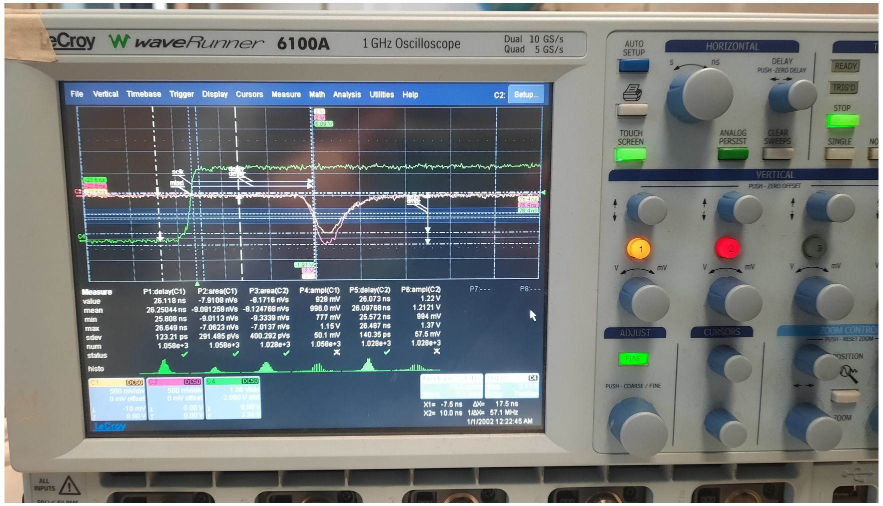
PMT system test at LNF

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

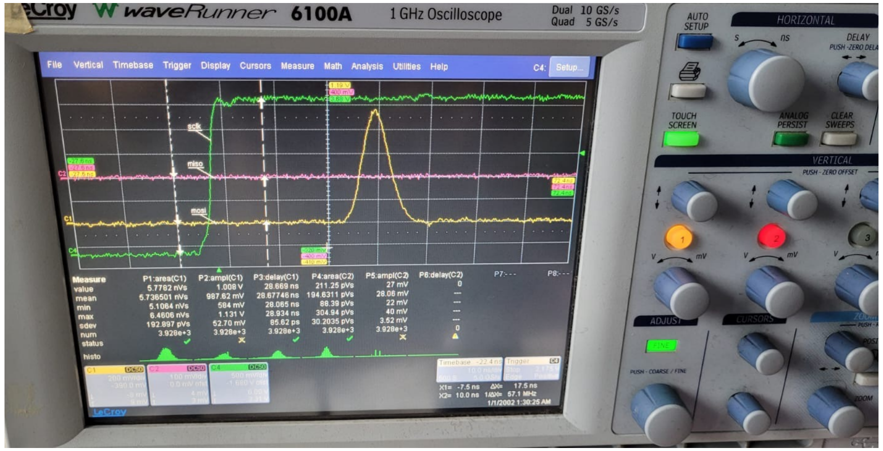
two PMTs, one for reference



no preamplifier



with preamplifier



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

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	✓	✓	✓	✓	✗	⚠		

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:
$V_{dis}(max) = V_{preamp}(max) \bullet 0.5 = 2.35$ 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
$V_{dis}(max) = V_{preamp}(max) \bullet 0.5 = 2.7$ V

“Stretching” the choice of the dynamic range

Assuming:

- to increase V_{preamp}(max) by 15% => V_{preamp}(max) = 5.4 V
- (N_{pe} G_{PM})(max) = $95 \cdot 10^7$
- V_{dis}(max) = V_{preamp}(max) • 0.5 • C_{ATT}= 2.0 V
- 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

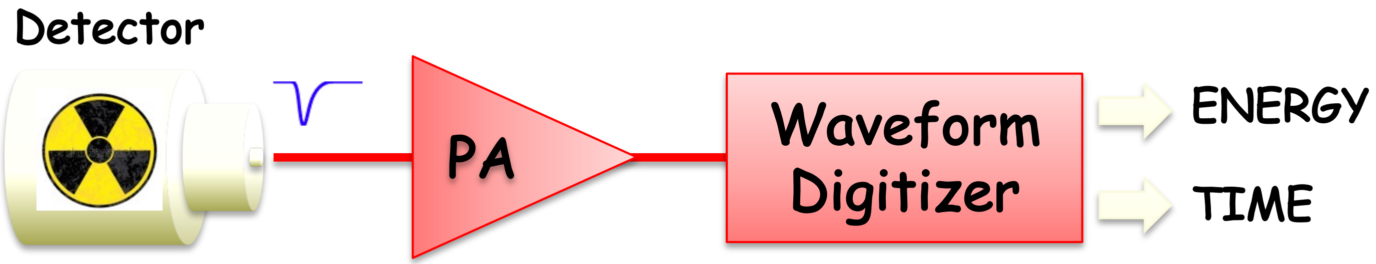
- Different dynamic ranges can be implemented changing G_{PM} => the final choice should be a compromise between an affordable level of events with energy saturated cells, depending on N_{pe}(max), and an acceptable neutron detection efficiency, depending on N_{pe}(min).

Choice of FEE for SAND/ECAL

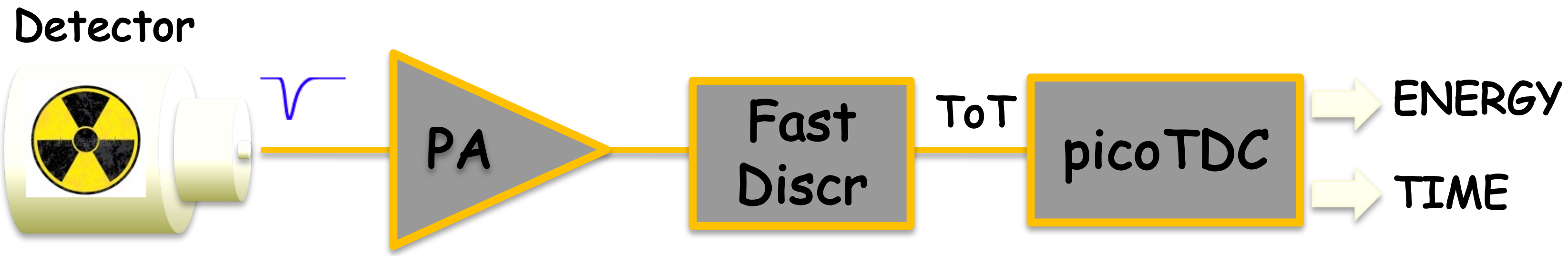
Constraints on signal dynamic range

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 $V_{dis}(max)$

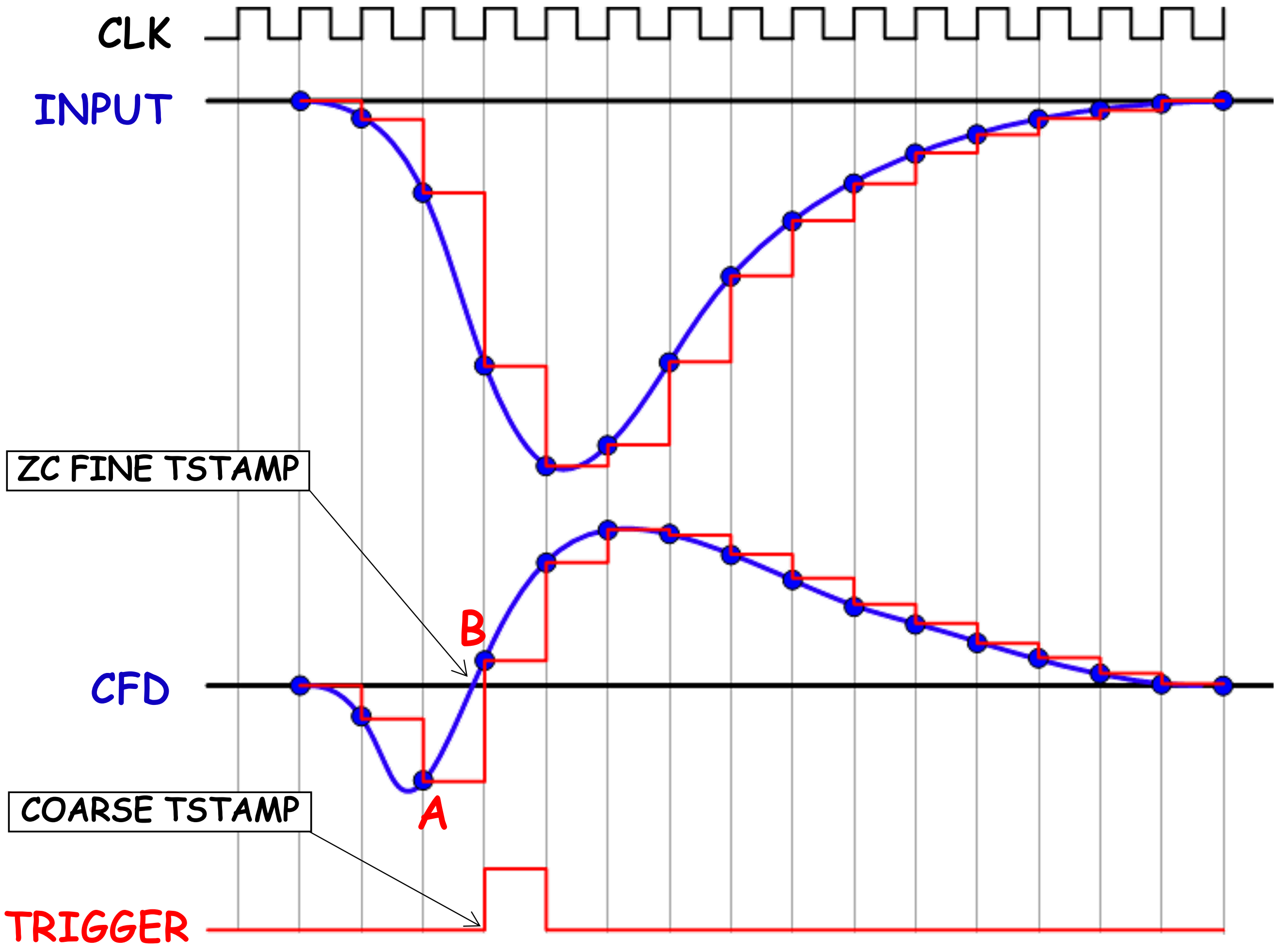
Best choice, high cost:
1 GS/s digitizer
=> 1 ns: 4-5 time measurements on the rising edge of the 14 ns base signal to preserve time resolution

Lower cost choice:
A shaper is needed to stretch the signal to use a lower cost digitizer, 125 or 250 MS/s => 8 or 4 ns

Optimal choice:
250 MS/s digitizer
=> 4 ns
stretch x4 the signal from 14 to 56 ns to keep the pile-up at the minimum (1%).

Digital CFD with interpolation

CAEN Tools for Discovery



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.

The preamplifiers of PMT bases are well compatible with the proposed FEE solutions, given that the maximum amplitude of signals accepted before digitalization 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.
It has to be tested how much the preamp linearity is worsened when extending $V_{preamp}(max)$ from 4.7 to 5.4 V (most likely it will remain within 1%).
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.

A possible solution for the FEE that could constitute a good compromise between cost and performance is the use of a 250 MS/s digitizer with a x4 signal stretcher in front.
This solution could be provided by CAEN ready-to-use. A meeting with CAEN will be organized soon to discuss more technical issues and costs of the possible solutions.

Spare

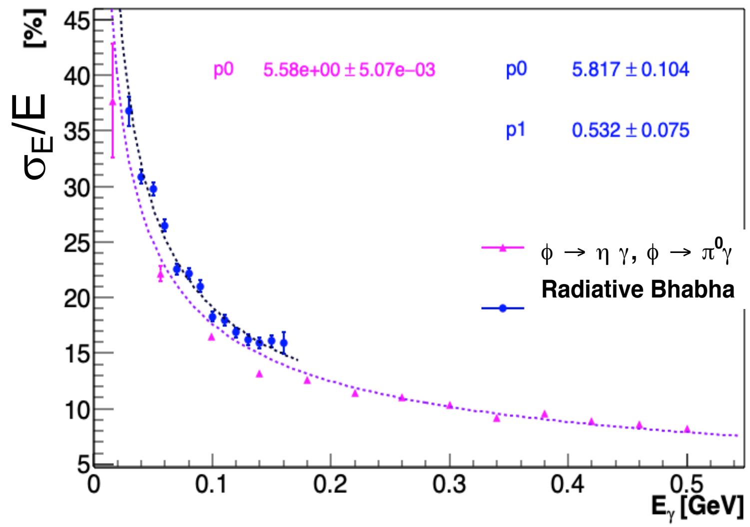
KLOE ECAL performance in KLOE-2 and with neutrons

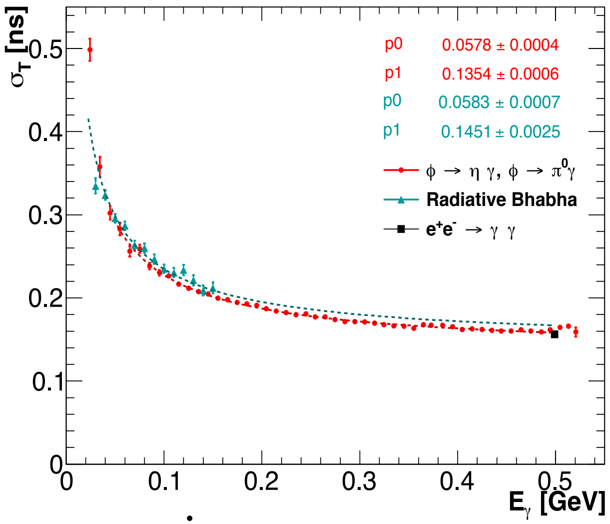
Check e.m. calorimeter performance

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

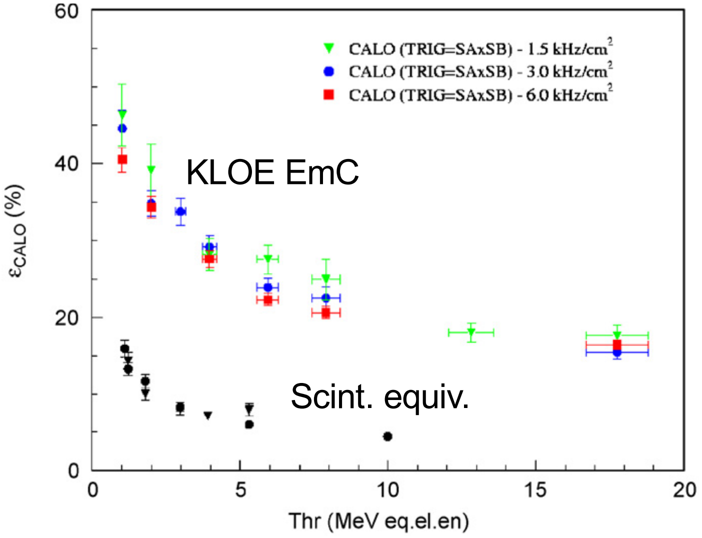
$\sigma_E/E \cong 5.6\% /\sqrt{E(\mathrm{GeV})}$

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





Thanks to E. Diociauti - LNF

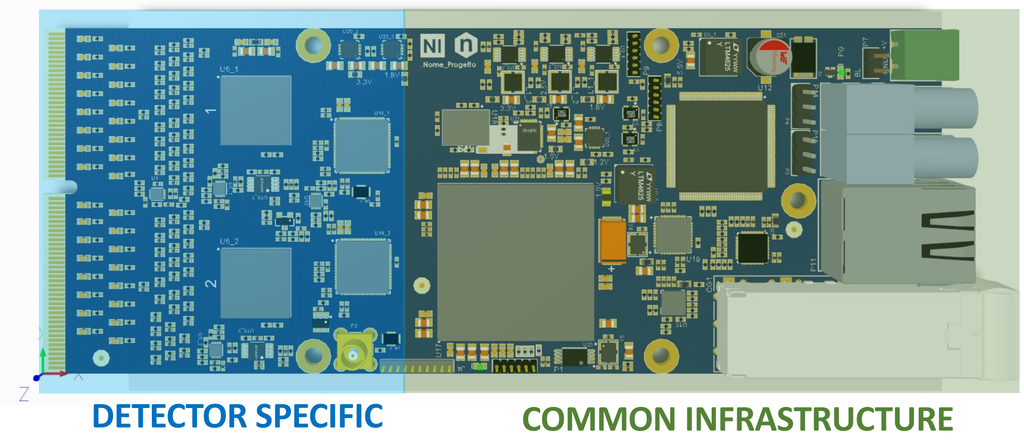


Measurement of the neutron response of the KLOE EmC

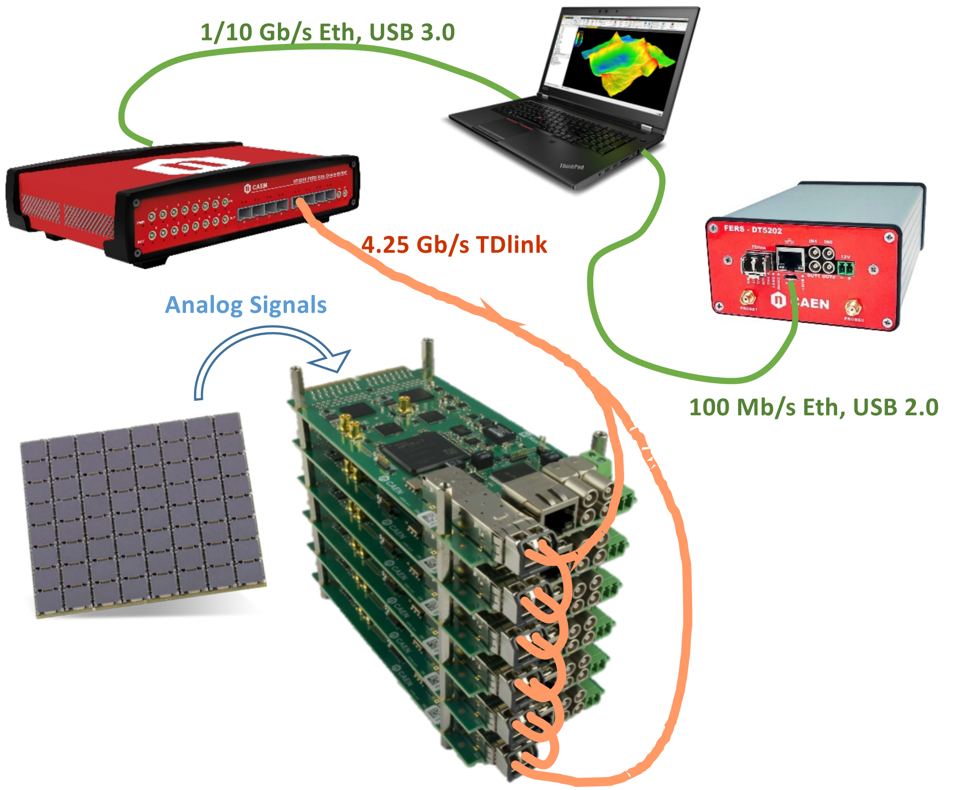
- M. Anelli et al., *"Measurement and simulation of the neutron response and detection efficiency of a Pb-scintillating fiber calorimeter "*, NIM **A581** (2007) 368
-
- M. Anelli et al., *“Measurement of the neutron detection efficiency of a 80% absorber–20% scintillating fibers calorimeter ”*, NIM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

Choice of FEE for SAND/ECAL

FERS: a scalable readout system



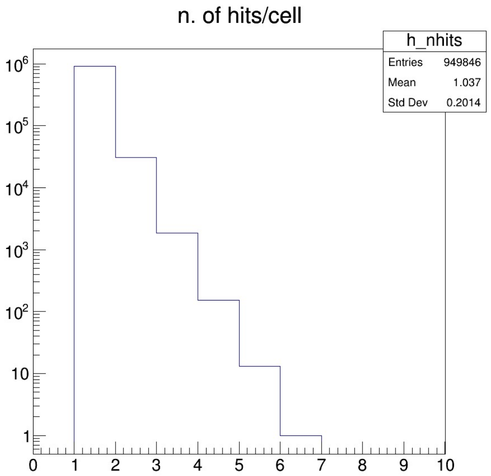
- **FERS:** Front End ASIC + ADC/TDC + Scalable Readout Infrastructure
- Easy **integration** of new ASICs
- **Scalability:** from single stand alone version for evaluation, to 10k/100k channels with same electronics
- **TDL:** daisy chainable optical link protocol with **data+sync**
- **Readout Tree:**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

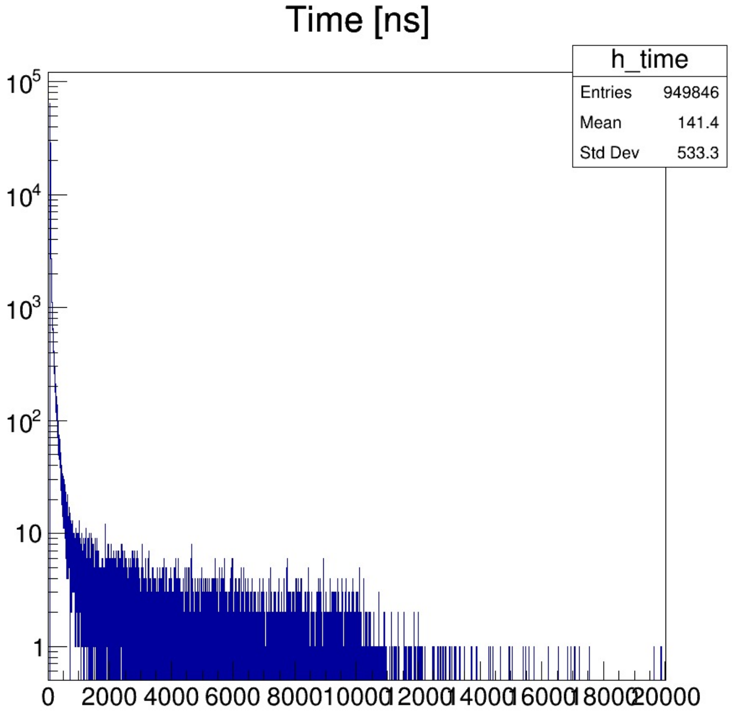


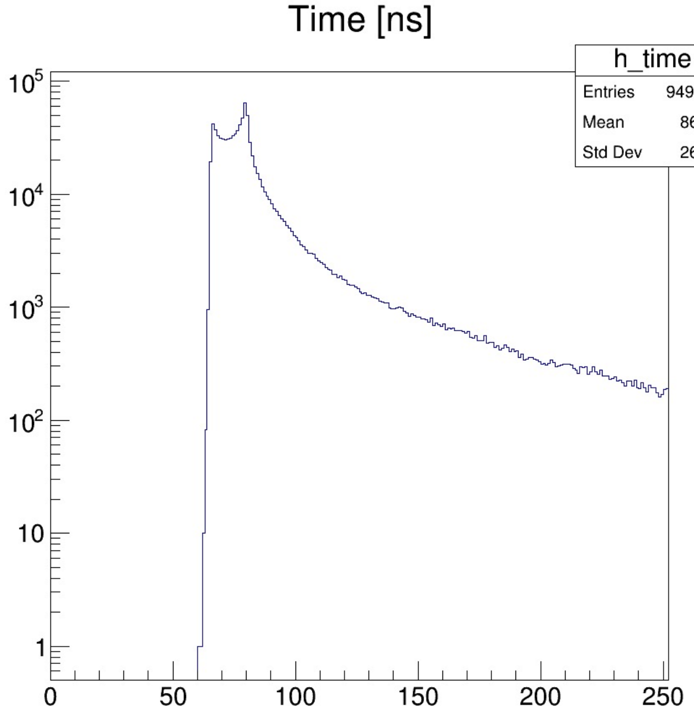
picoTDC (FERS A5203) + ToT solution

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



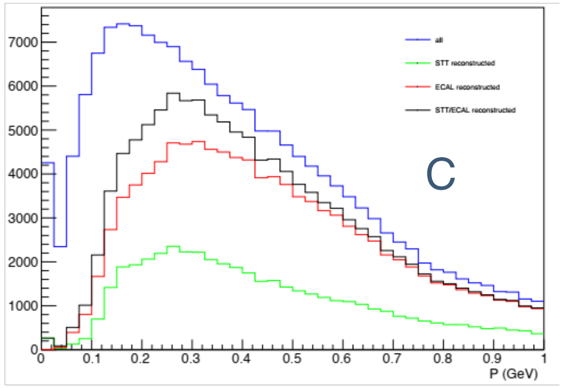


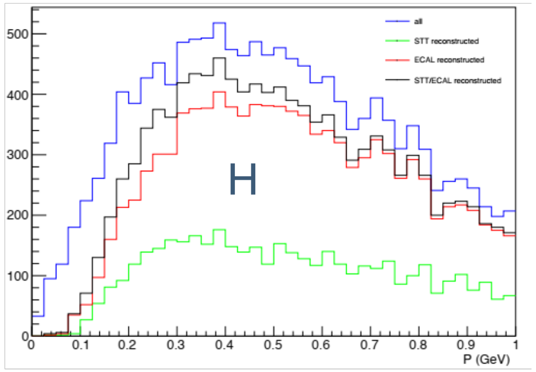


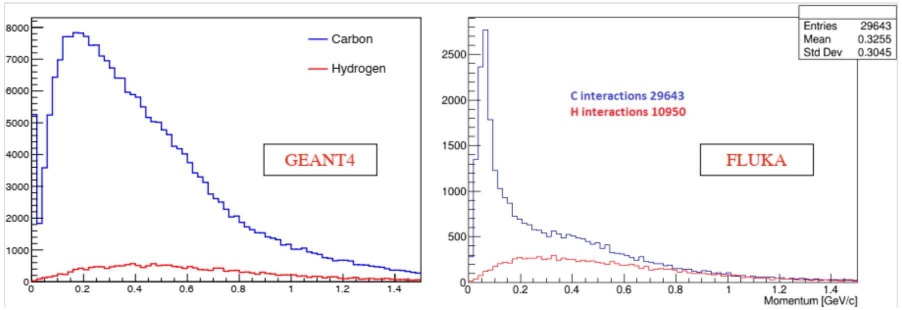
Neutrons in SAND

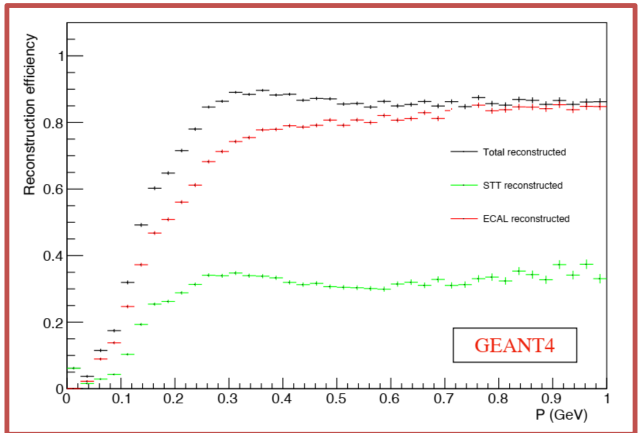
Neutron detection efficiency

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 %