Multi-time-over-threshold technique for photomultiplier signal processing
Characterisation of the SCOTT ASIC

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[3] Supported by the European Commission through FP6 and FP7

KM3NeT

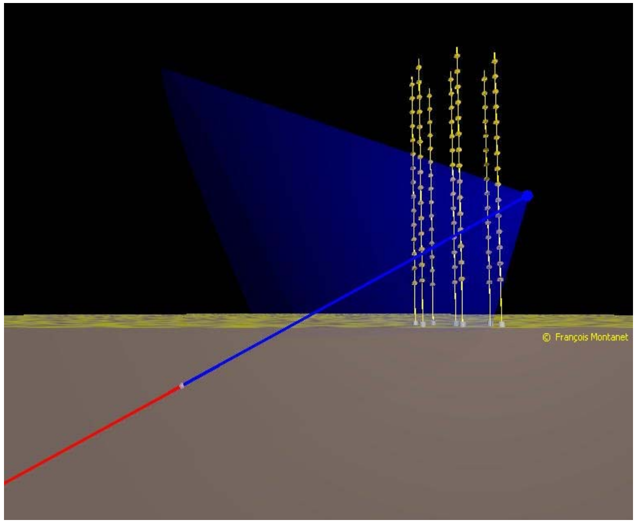
- Now in preparatory phase (FP7)

- A European deep-sea research infrastructure for a neutrino telescope
  - Mediterranean Sea
  - Instrumented volume ~ 5 km^3
  - 300 detection units
  - 12000 photo-detectors

- Cherenkov light detection
  - Upward $\nu \rightarrow \mu$
  - Downward cosmic μ
  - Optical background (100 Hz / cm^{-2})
    - ^{40}K decay in water
    - Bioluminescence

  $\Rightarrow$ Mainly single photon signals

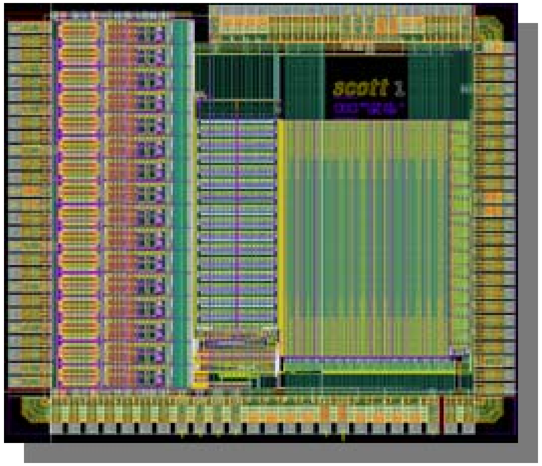
- All data to shore
  - On shore computer farm



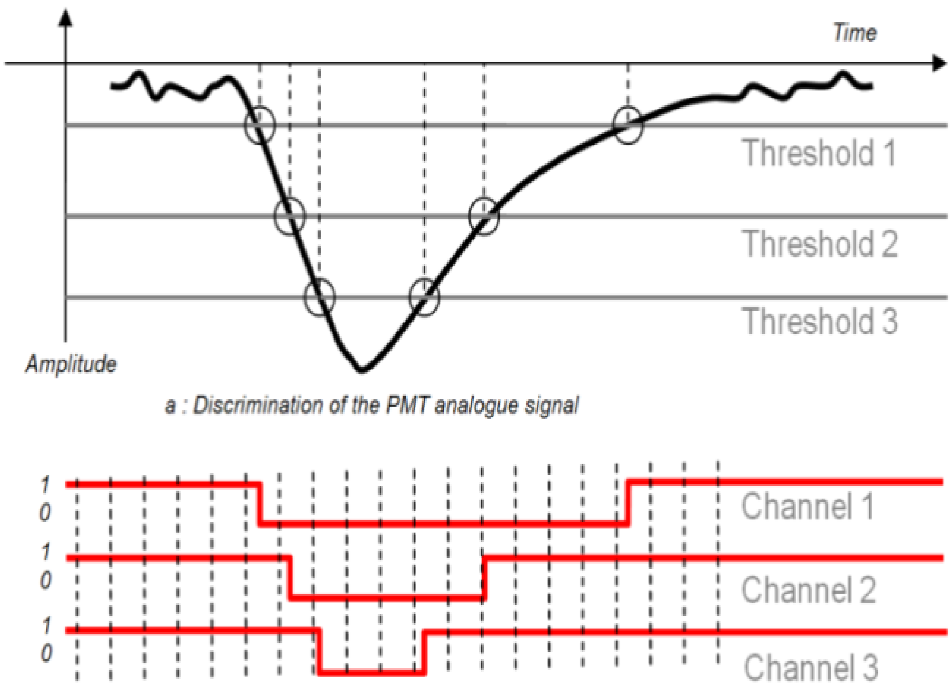
Front end requirements (from CDR)

- Time resolution (PMT+FE) < 2 ns at 1 pe (RMS)
- Charge dynamic range : 100 pe / 25 ns
  - Charge estimation
- Two-hit time separation < 25ns

⇒ SCOTT ASIC



SCOTT concept



a : Discrimination of the PMT analogue signal

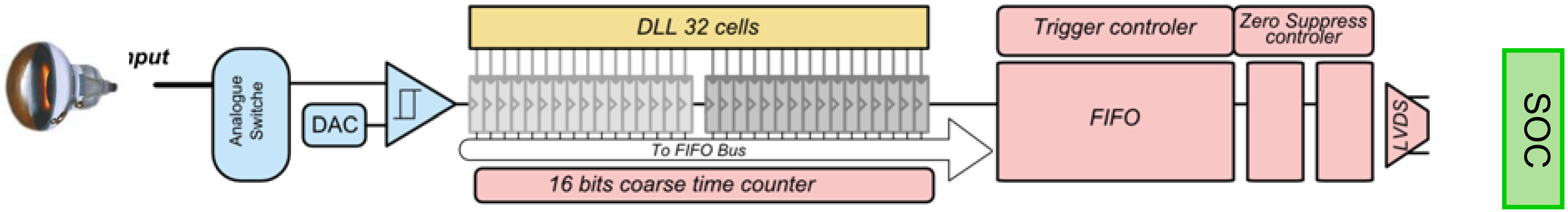
b : Discriminator output signals sampling

0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0
0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0

c : Digital data in the internal memory

- Time and Amplitude Sampling
  - “wave-form”-like image of the pulse
- Master Clock 50 MHz
  - 16 bit Time stamp
- 1.25 ns sampling
- 16 independent channels
  - Dynamic range : 0- 3V
  - 10 bit adjustable thresholds
- Auto-triggered
  - Each threshold can be a trigger
  - Handling several PMTs e.g.:
    - 2 PMTs x 8 thresholds
    - 16 PMTs x 1 threshold

SCOTT architecture

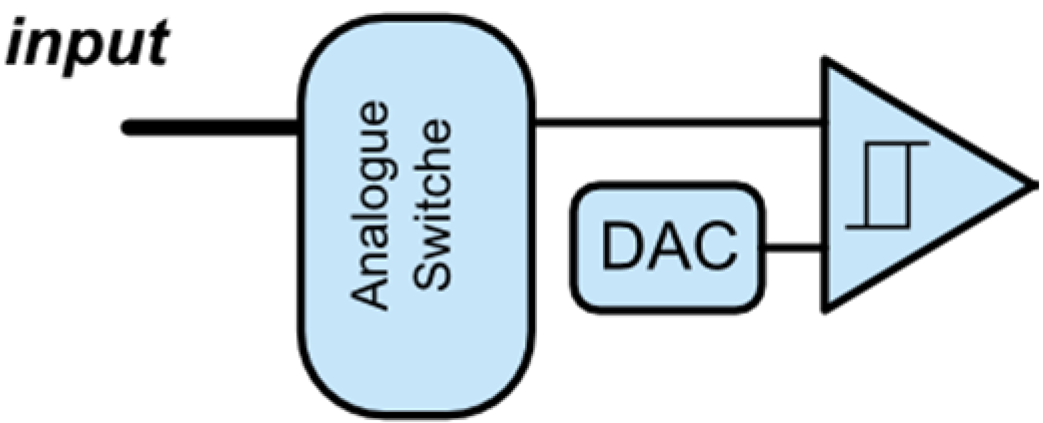


Analogue input

Analogue switches
Internal sharing of signals

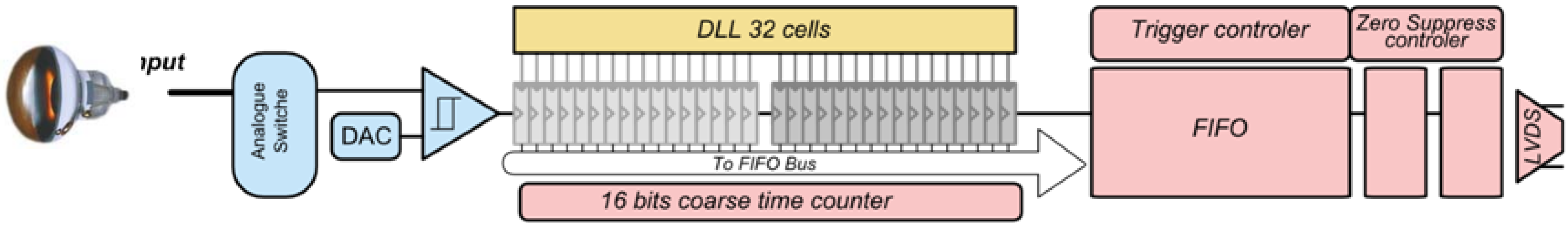
10 bit DAC
AMS BiCMos
0.35µm
Programmable thresholds
LSB<3mV

Discriminator
Analogue to digital convertor

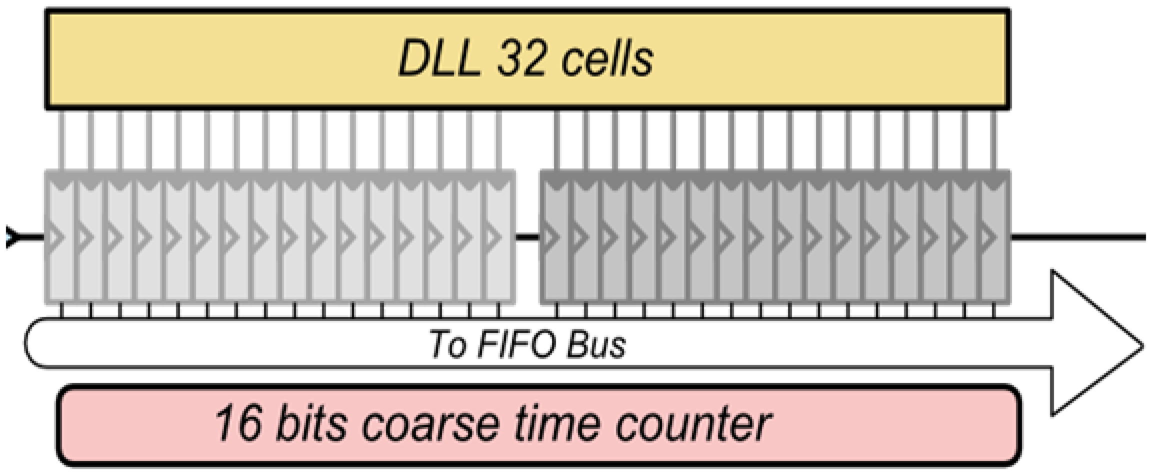


x16 channels

SCOTT architecture



Circular sampling memory



Delay locked loop (DLL)

All channels are synchronous

Circular digital memory

2 memory banks (MB)

1MB = 1 time slice =20 ns

No dead time

16 bit coarse time counter

LSB = 20 ns

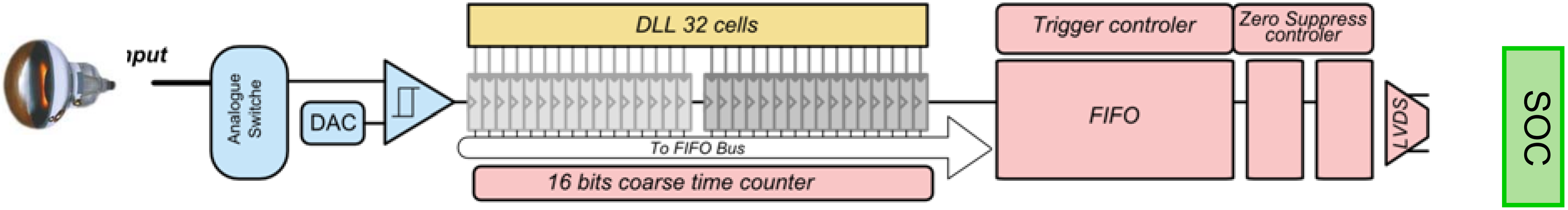
Time step

$T_{CK}/16$

T_s = 1.25ns (~ 800MHz)

x16 channels

SCOTT architecture



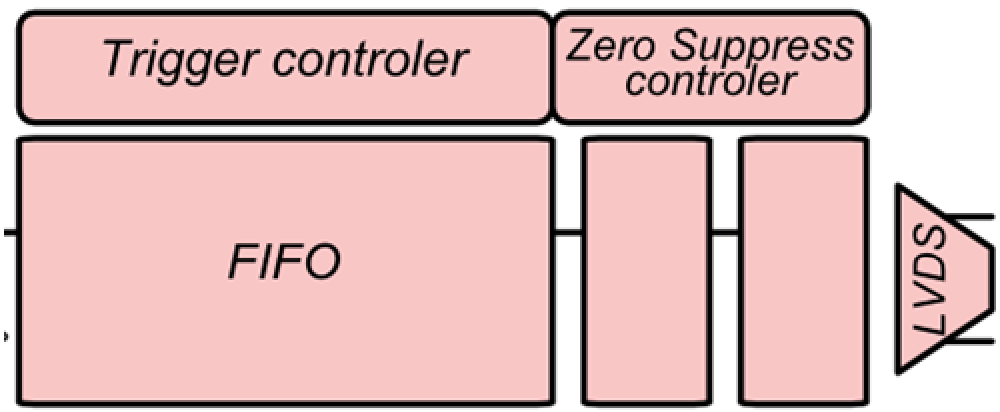
FIFO

Auto-triggered
Logical or channel triggered

Size
32 time slices
640 ns continuous wave-form
Data loss <1‰ for 200 kHits/s

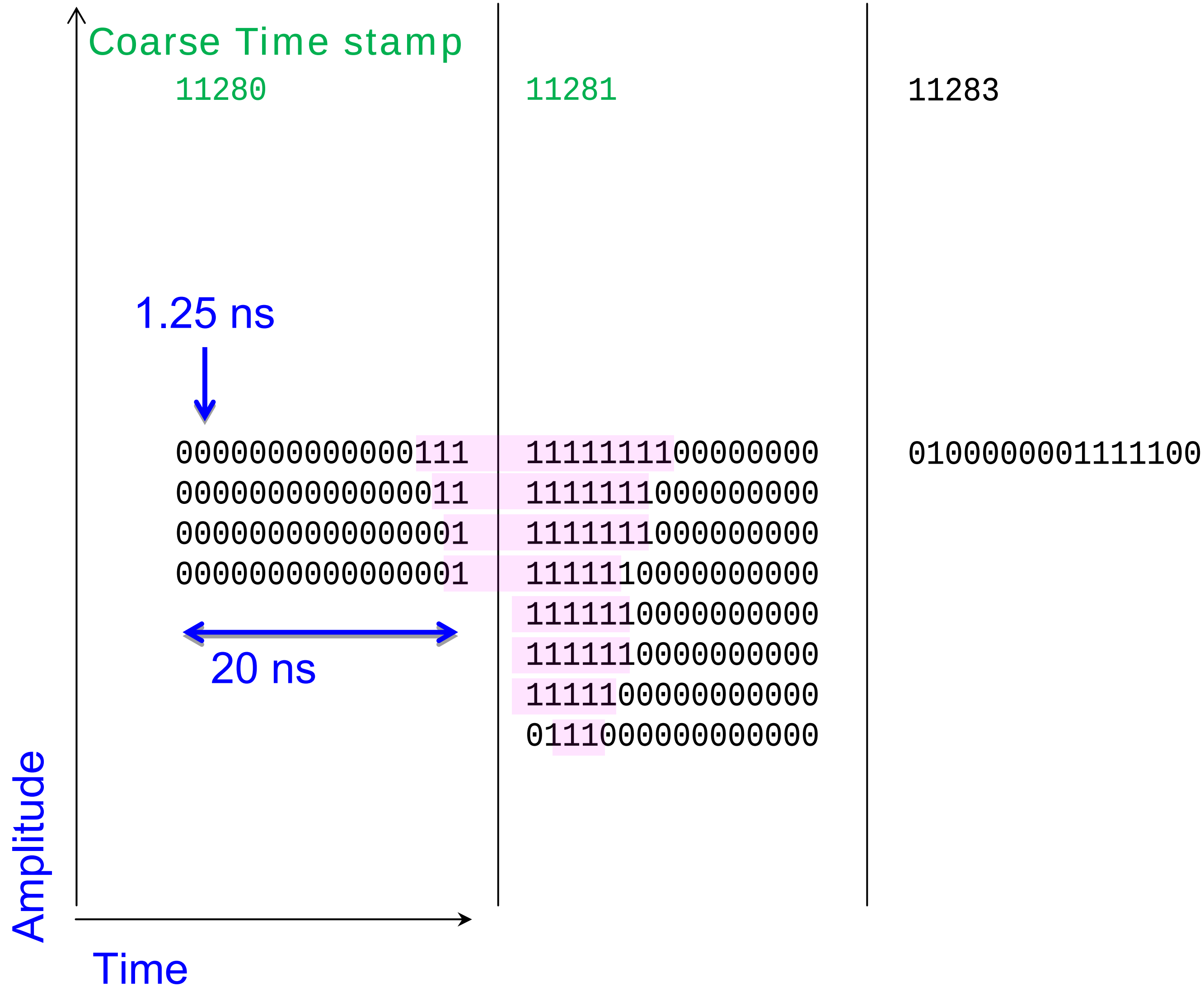
Double port
F_{ck} sample ≠ F_{ck} readout
Readout driven by System-on-Chip

Selective readout
Data reduction



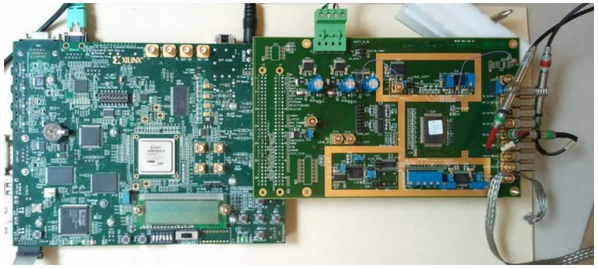
x16 channels

Scott output example



The SCOTT Opera

- *Act I* : Determination of thresholds
  - Which values for how many thresholds ?
- *Act II* : Charge
- *Act III*: Timing
  - Correction of the walk effect
  - SCOTT Intrinsic timing accuracy



ACT I
THRESHOLD DETERMINATION

Actors

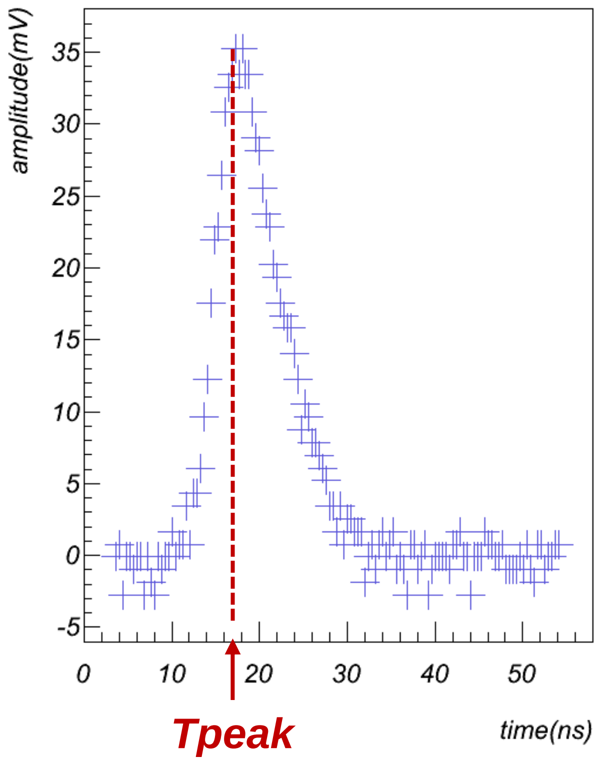
PMT : Antares 10'' Gain=$3 \cdot 10^7$ $\Rightarrow$ 1 pe $\approx$ 50mV 5pC

LED : flashes at 1pe up to 70pe

Oscilloscope : F=2.5GHz Bandwidth=500MHz

Determination of the best thresholds

- Data
  - Set 1 *(true)*
    - 10^4 digitised pulses @ 2,5GHz
    - 1pe to 70pe
  - Set 2 *(rec)*
    - Same pulses with "*SCOTTing*" :
    Keep points at thresholds' crossing



- Optimise positions of thresholds
  - Minimise δQ and δΔT with FRED :
    (Fast Rise Exp. Decay)

$$A(t) = a\, t^{\alpha} \exp\left(-\frac{t}{\tau}\right)$$

⇒ Tpeak and Charge(integral)

- Best solution 1pe – 70pe : 5 thresholds

pe: 1/3 2/3 1 3 8

With :

- δQ = 7% (1pe) 15 % (up to 25pe)
- δΔT = 0.4ns (1pe) 0.7ns (up to 25pe)

Performances verified with SCOTT

ACT II
CHARGE RESOLUTION

Actors

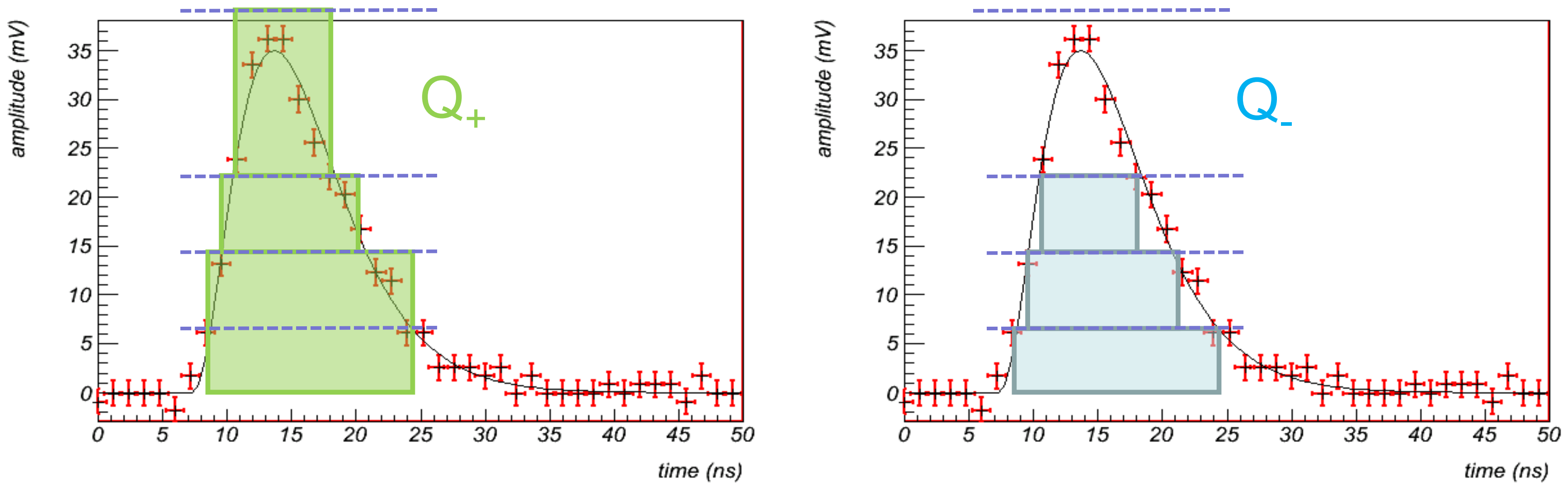
PMT : Antares 10'' gain=3.10^7 $\Rightarrow$ 1pe $\approx$ 50mV 5pC

LED : flashes at 1pe and 11pe

<u>SCOTT</u> : 5 thresholds

Charge estimation with Time over Threshold

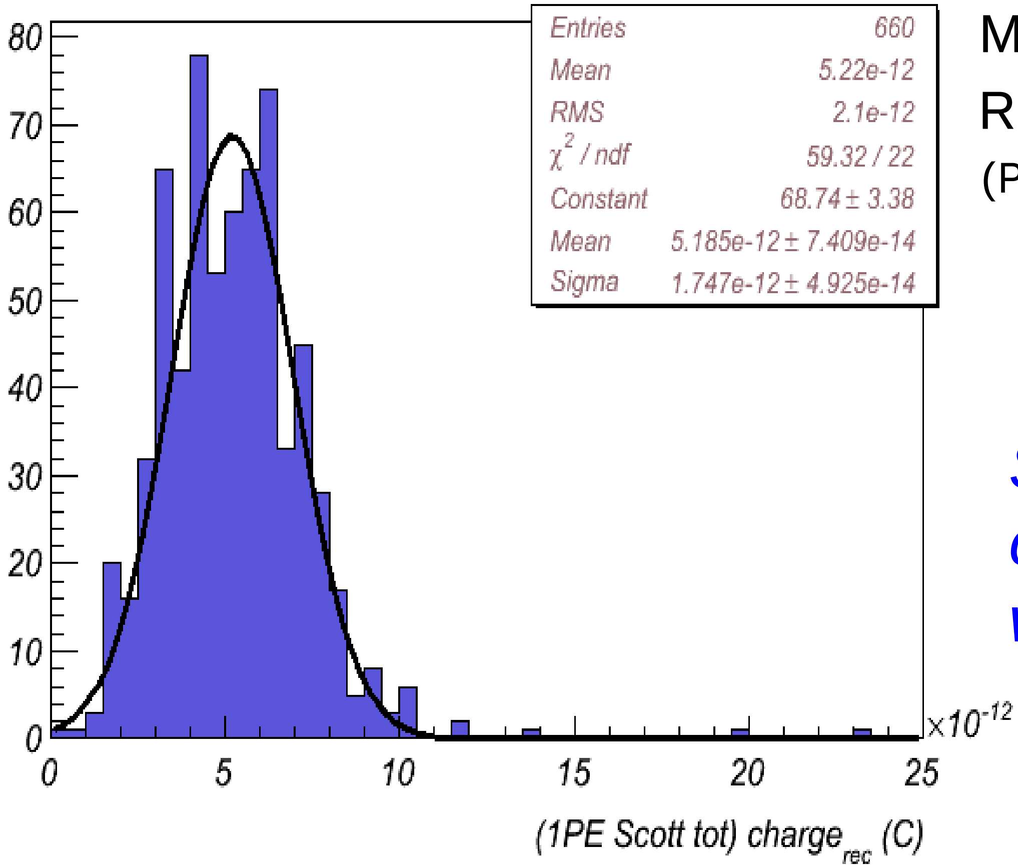
- Integration of FRED : needs CPU time
- Alternative based on Time-Over-Thresholds (TOT)
  - Upper (Q_+) and lower(Q_-) area under the thresholds



- $Q \approx (Q_+ + Q_-) / F_Q$
  - F_Q depends on
    - the last threshold reached
    - the threshold values
      $\rightarrow$ requires calibration

Charge resolution from TOTs

Charge 1pe



Mean=5pC

RMS =2pC = 40%

(PMT charge resolution ~ 35%)

SCOTT + TOT enable charge reconstruction with good accuracy

ACT III

TIMING RESOLUTION

Scene 1 : Pulse time resolution

Actors

PMT : Antares 10'' gain=3.10^7 $\Rightarrow$ 1pe $\approx$ 50mV 5pC

LED : flashes at 1pe and 11pe

SCOTT : PMT 5 thresholds

LED trigger 1 threshold

Pulse time reconstruction

Walk effect

- Threshold crossing time depends on the charge
- Peak time T_{peak} unchanged

Tpeak from TOT

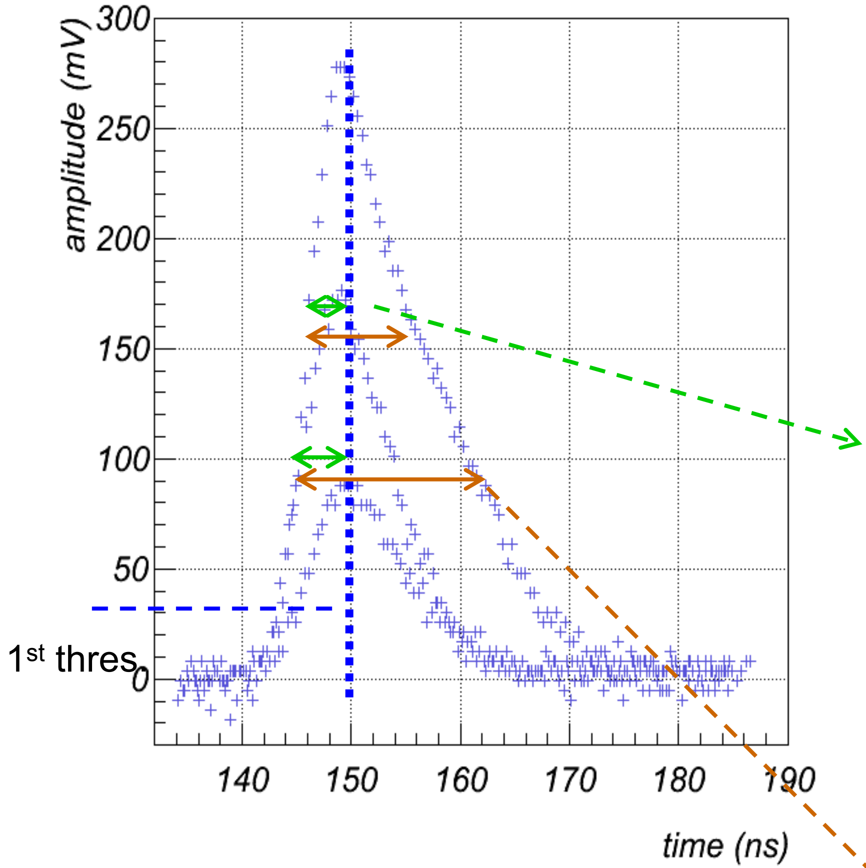
- Analytical solution with FRED

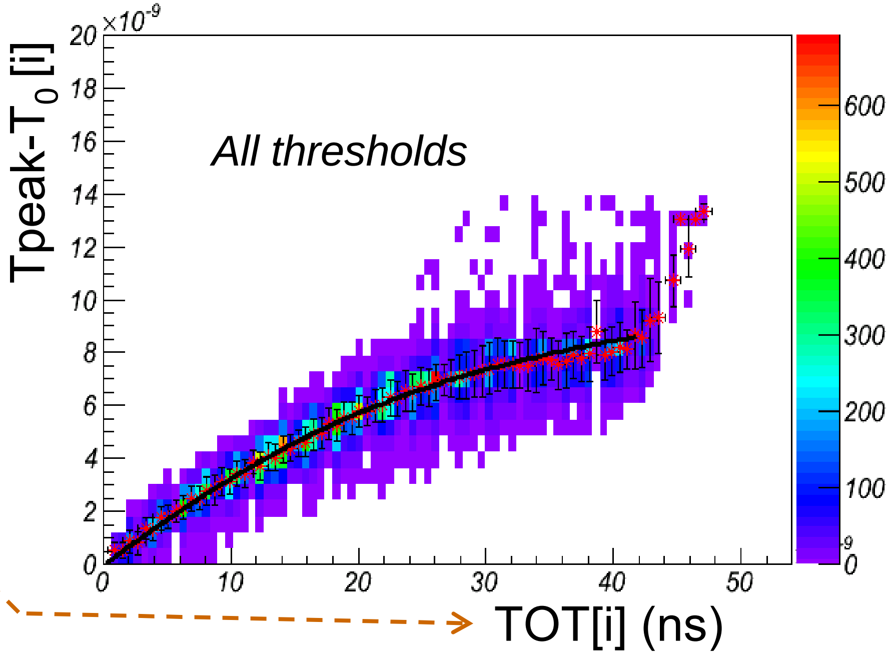
$$T_{peak} - T_0[i] = F(\,TOT[i]\,)$$

$$F = \frac{b}{X}\left(1-(1+X)e^{-X}\right)$$

$$X = \frac{1}{\propto\tau}\Delta t$$

- True for every thresholds

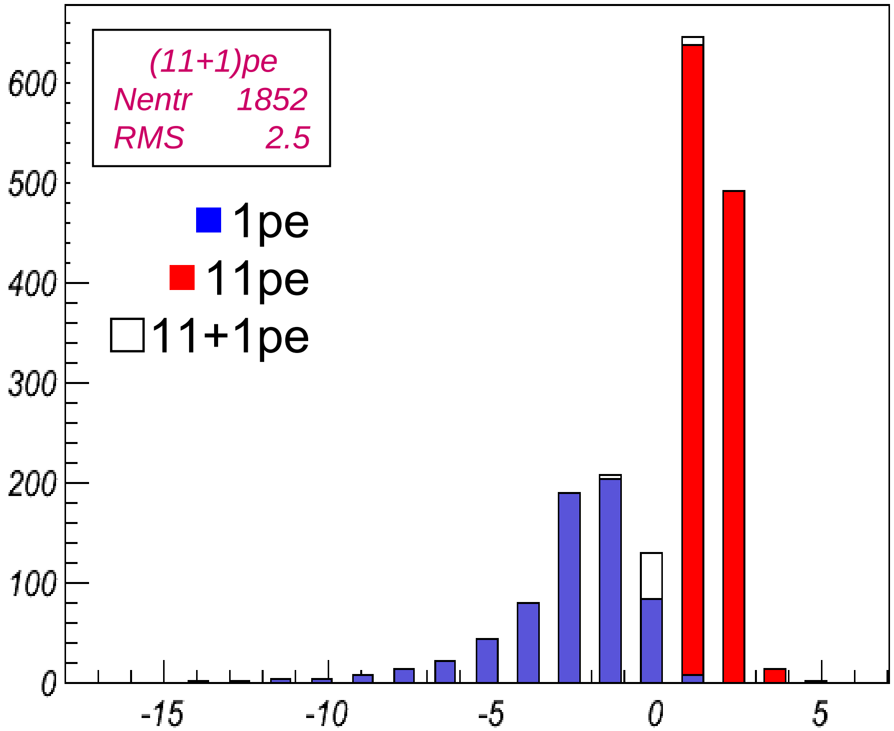




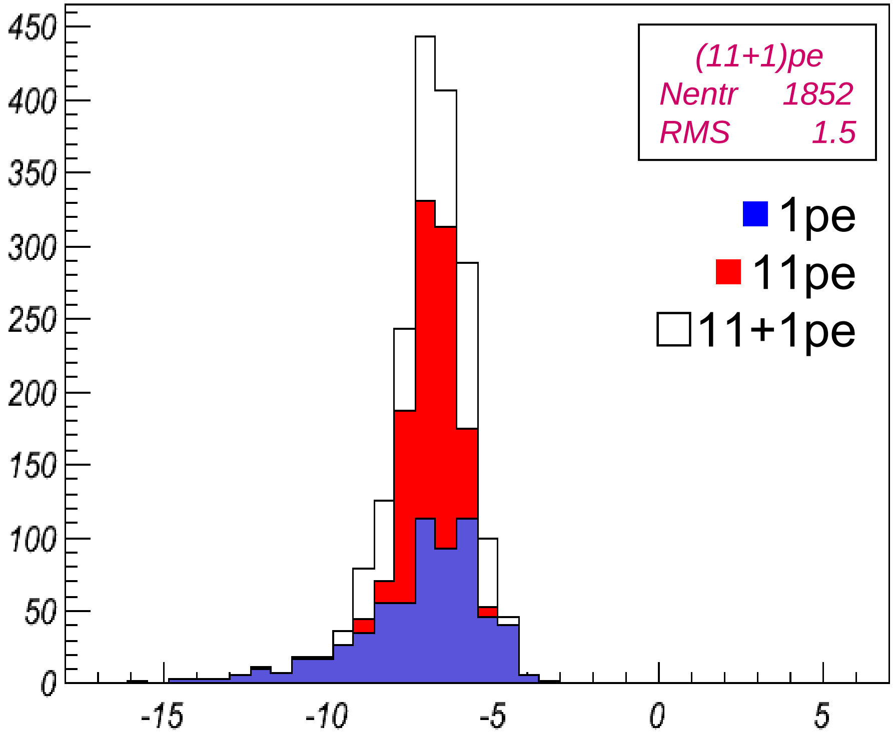
Tpeak and Walk correction with SCOTT

- $T_{1/3}$-T_{LED}

$T_{1/3}$ =crossing time of the 1st threshold



- T_{peak}- T_{LED}



$TTS_{PMT} \approx 1.3$ ns

Time resolution = 1.5 ns

No charge estimate needed

ACT III

TIMING RESOLUTION

Scene 2 : SCOTT Intrinsic timing accuracy

Actors

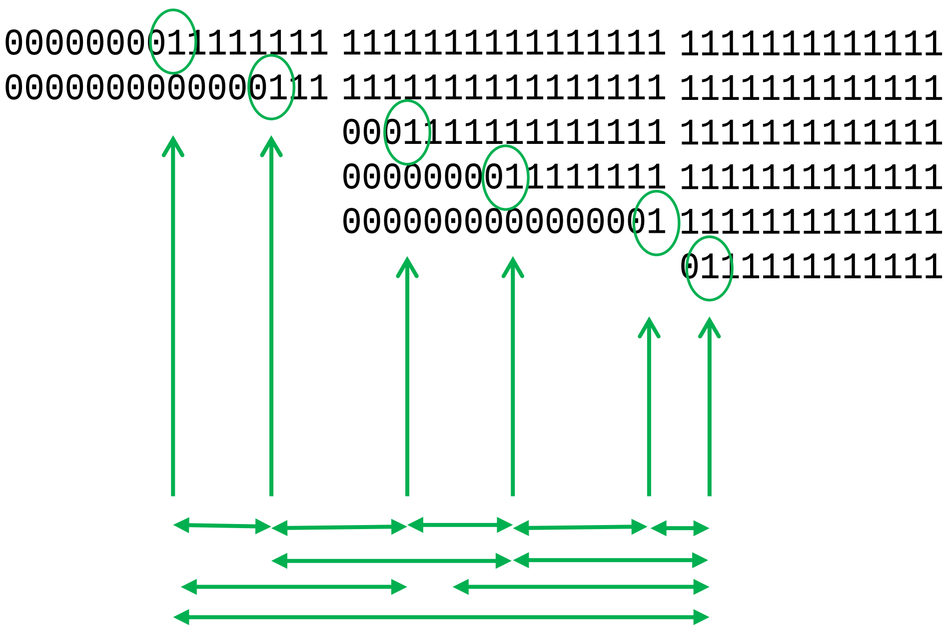
Generator: HP 81110A   330MHz

SCOTT

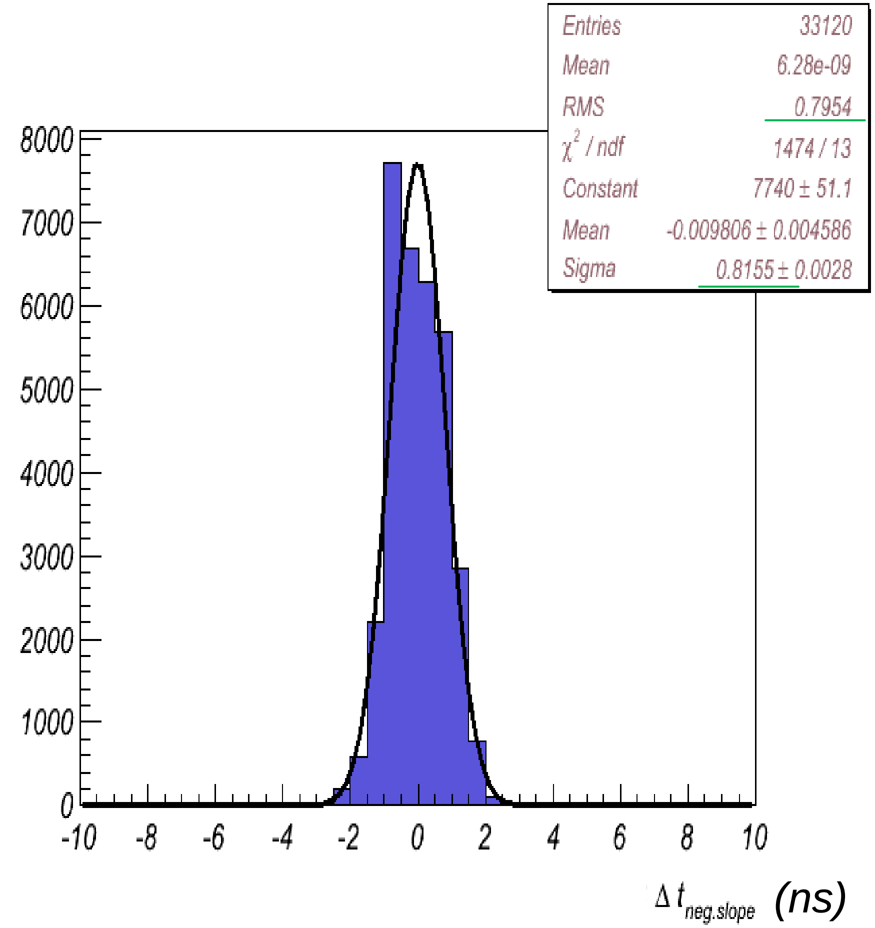
SCOTT intrinsic timing

- Generated Pulse
  - 120mV height
  - 1kHz
- SCOTT: 6 thresholds

15% 35% 50% 70% 85% 90%



- Consider all possible Δtime between crossing times for every couple of thresholds



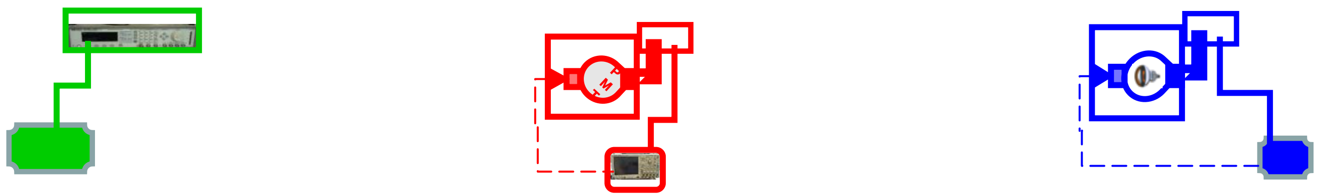
SCOTT intrinsic time resolution 0.8ns

Conclusion

- An ASIC for the KM3NeT neutrino telescope
  - Characterisation with an Antares 10'' PMT
- Optimal thresholds using pulse analytical function
  - 5 thresholds @ 1/3 2/3 1 3 8 pe
    - -> Charge resolution 15% up to 25pe
    - -> Timing 0.7ns up to 70pe

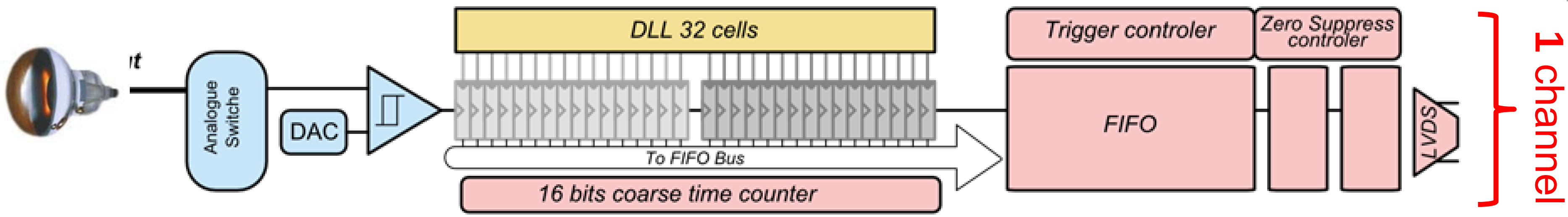
  ->Up to 3PMTs/SCOTT
- Charge
  - Explored up to 11pe
  - Estimation from thresholds value (TOT)
- Timing
  - Walk effect correction, pulse time δt = 1.5ns
  - Intrinsic Timing accuracy 0.8ns

  $\Rightarrow$ CDR requirement achieved
- Adapted to multi-PMT reading in KM3NeT
  - 30 x3''PMT = 2ASIC with 1threshold/PMT



The End

SCOTT architecture



- **Analogue input**

Analogue switches
Internal sharing of signals

10 bit DAC
AMS BiCMos 0.35µm
Programmable thresholds
LSB<3mV

Discriminator
Analogue to digital convertor

- **Fast memory sampling**

Delay locked loop (DLL)
All channels are synchronous

Circular digital memory
2 memory banks (MB)
1MB = 1 time slice =20 ns
No dead time

16 bit coarse time counter
LSB = 20 ns

Time step
$T_{CK}/16$
T_s = 1.25ns (~ 800MHz)

- **FIFO and zero suppress**

Auto-triggered
Logical or channel triggered

Size
32 time slices
640 ns continuous wave-form
Data loss <1 ‰ for 200 kHits/s

Double port
F_{ck} sample $\neq F_{ck}$ readout
Readout driven by System-on-Chip

Selective readout
Data reduction

FRED

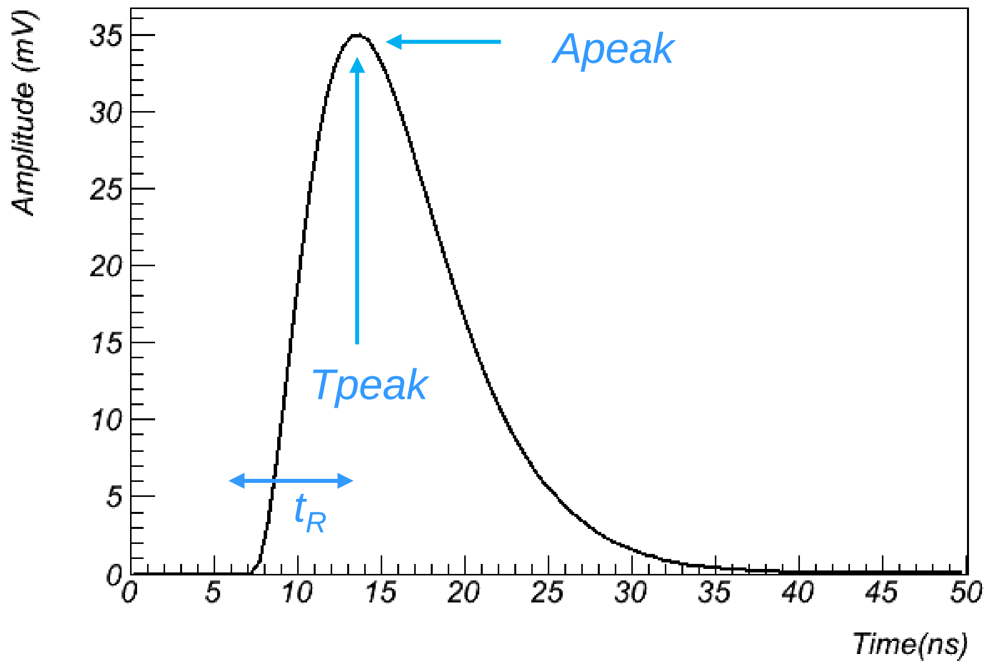
- Function to fit
  - Fast Rise Exp. Decay

$$A\,(t - t_0)^{\alpha}\exp\left(-\frac{t - t_0}{\tau}\right) \times H(t_0)$$

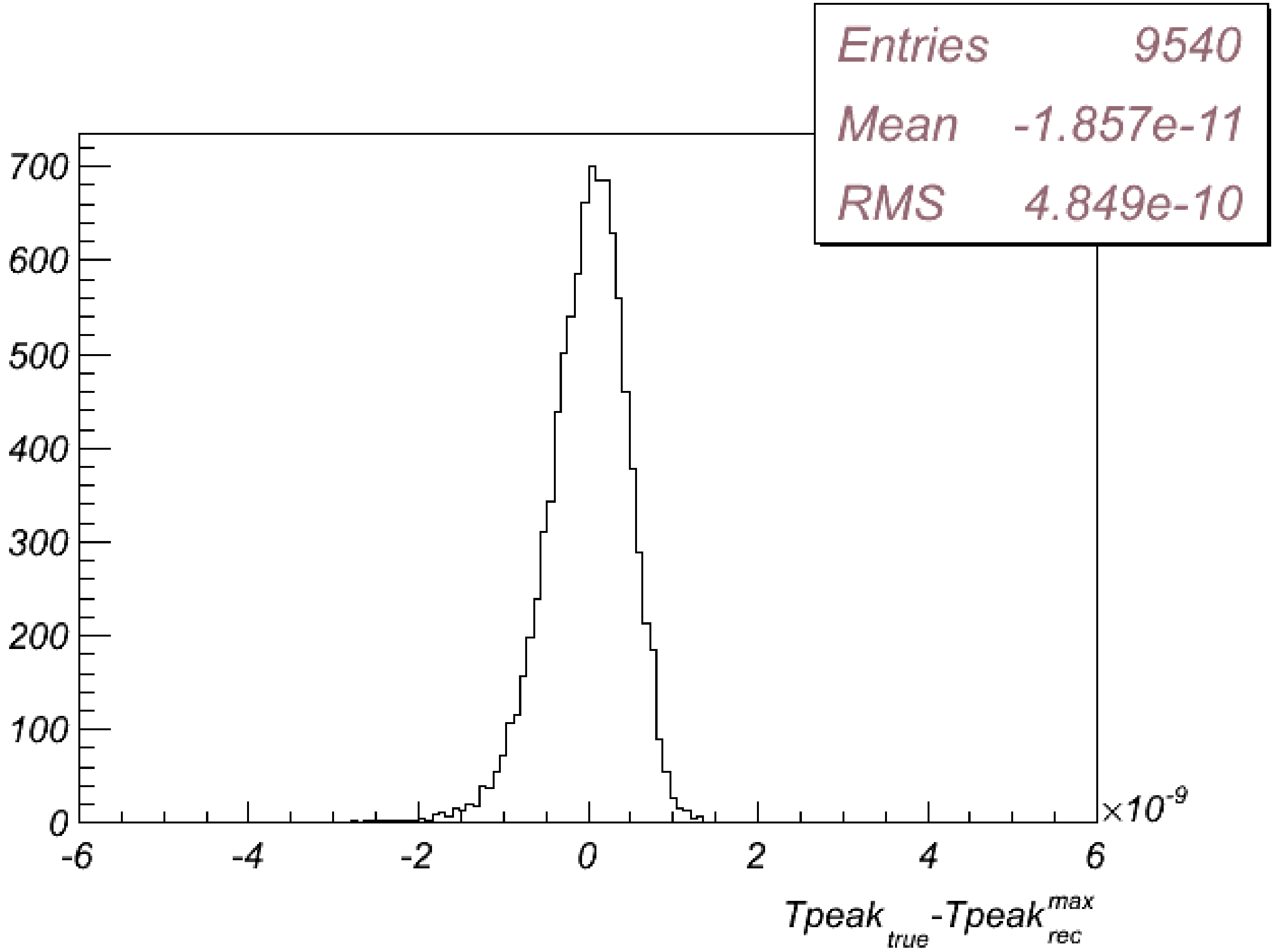
  - Variable change

$$\hat{A}\left(\frac{t - \hat{t}}{t_R} + 1\right)^{\alpha}\exp\left(-\frac{t - \hat{t}}{t_R}\propto\right) \times H(\hat{t} - t_R)$$

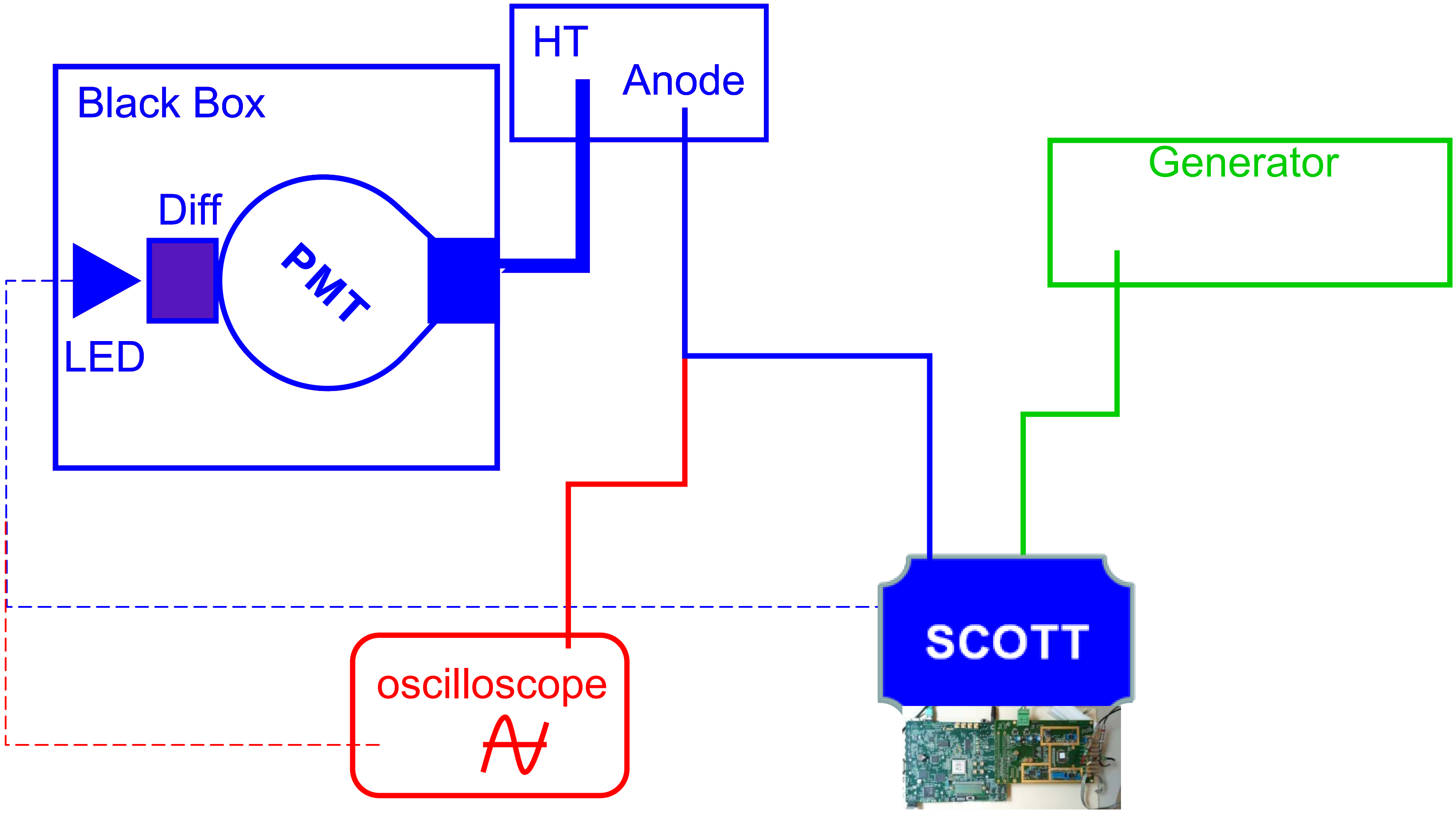
    - H Heaviside
    - $\hat{t}$ Tpeak
    - $\hat{A}$ Apeak
    - t_R Trise
    - α



Tpeak residuals

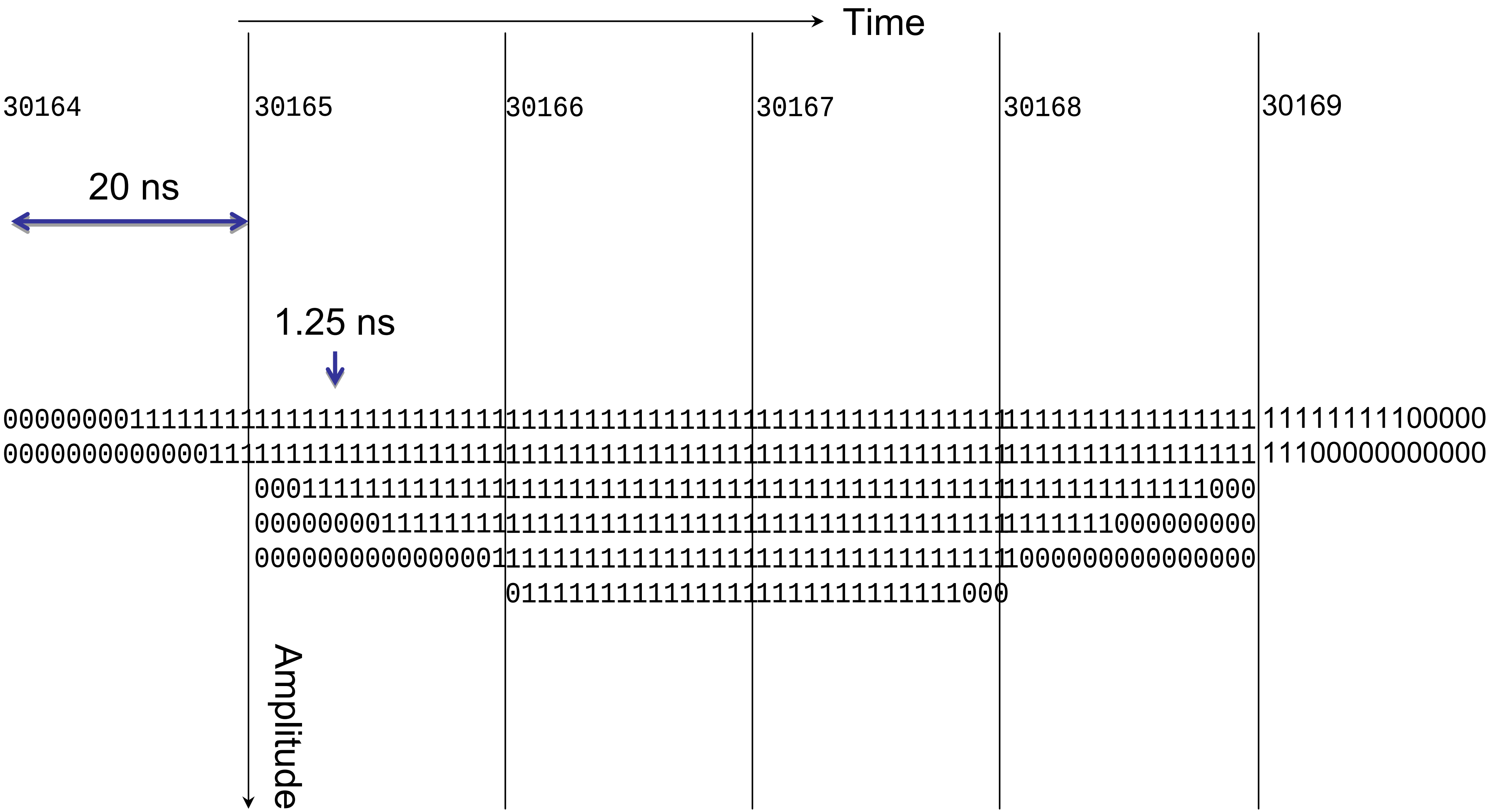


Test bench



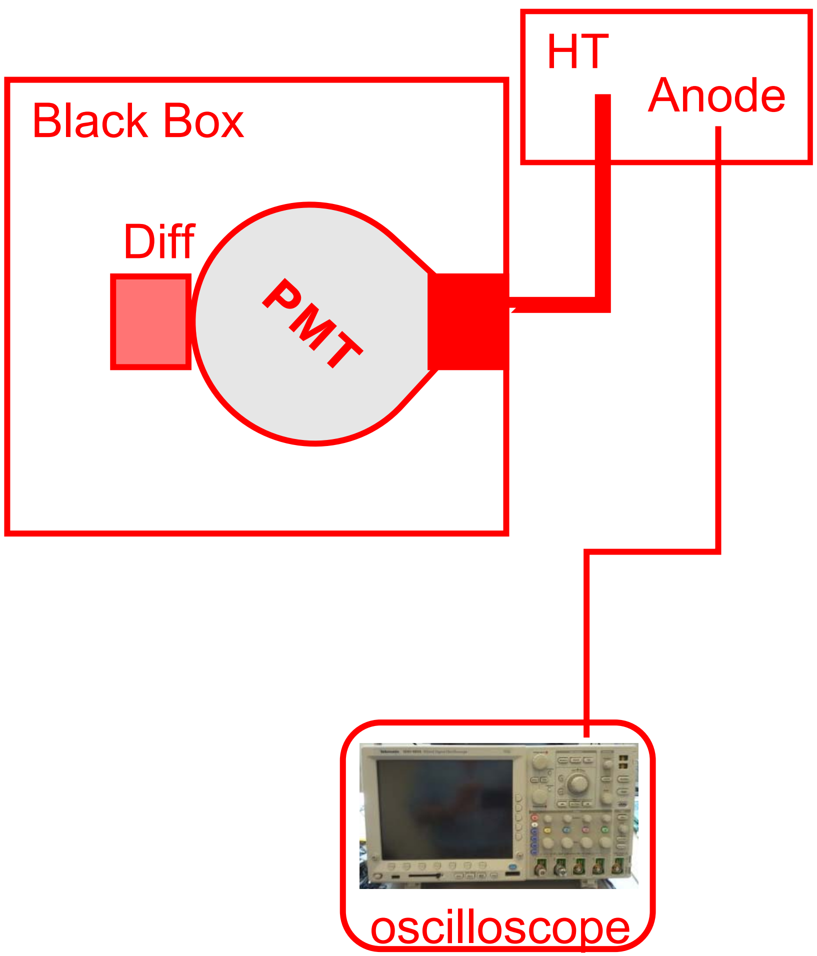
HT
Anode
Black Box
Generator
Diff
PMT
LED
SCOTT
oscilloscope

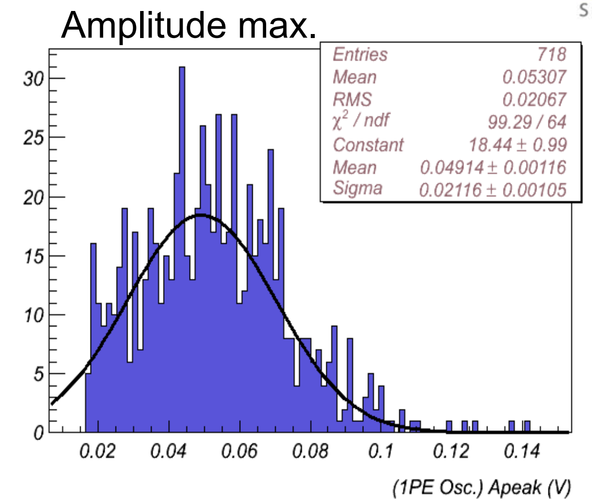
Generated pulse viewed with SCOTT

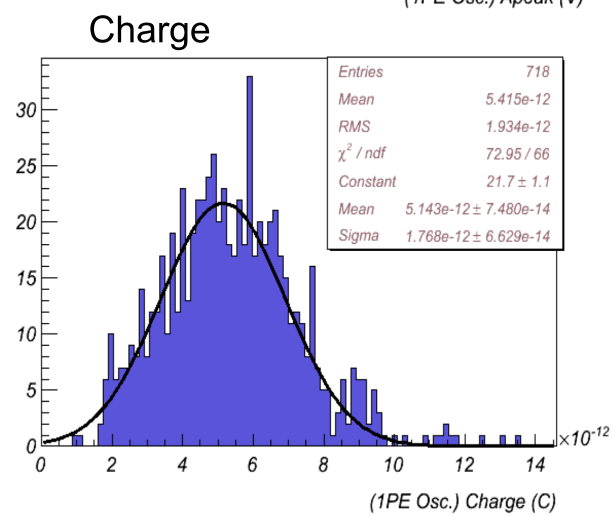


PMT characterisation

- PMT + Oscilloscope

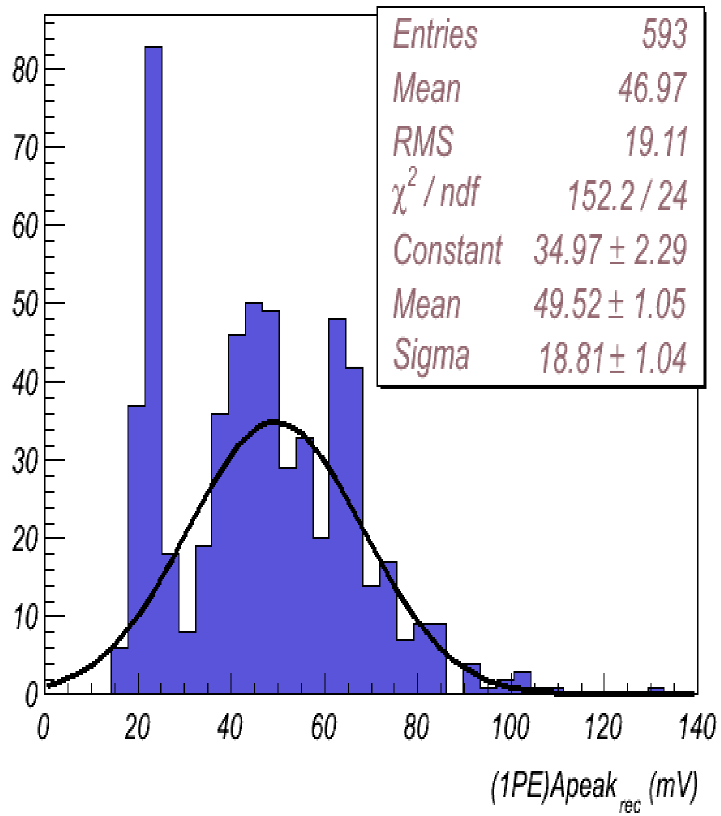


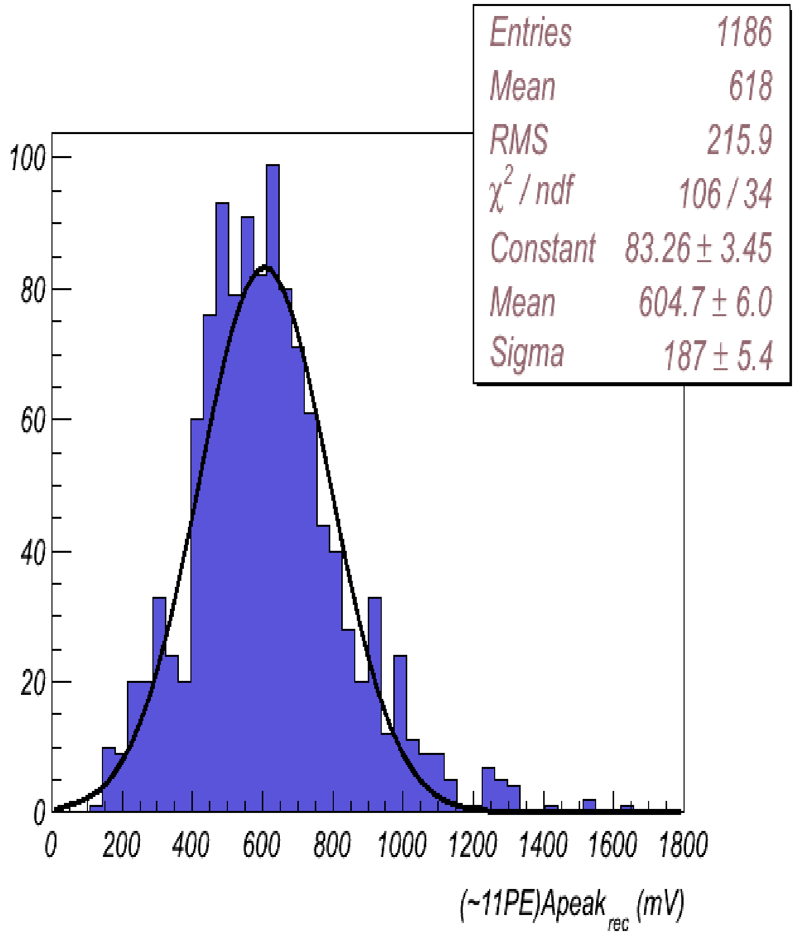




Define the 1PE
≈ 50 mV
≈ 5.4 pC

Amplitude with FRED & SCOTT

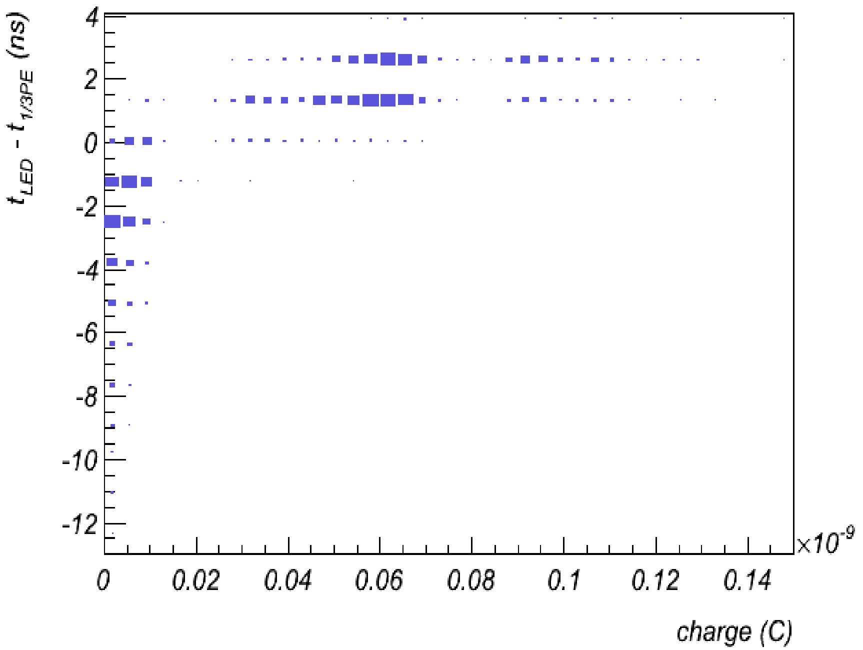




T1/3 versus charge

1PE and 11PE

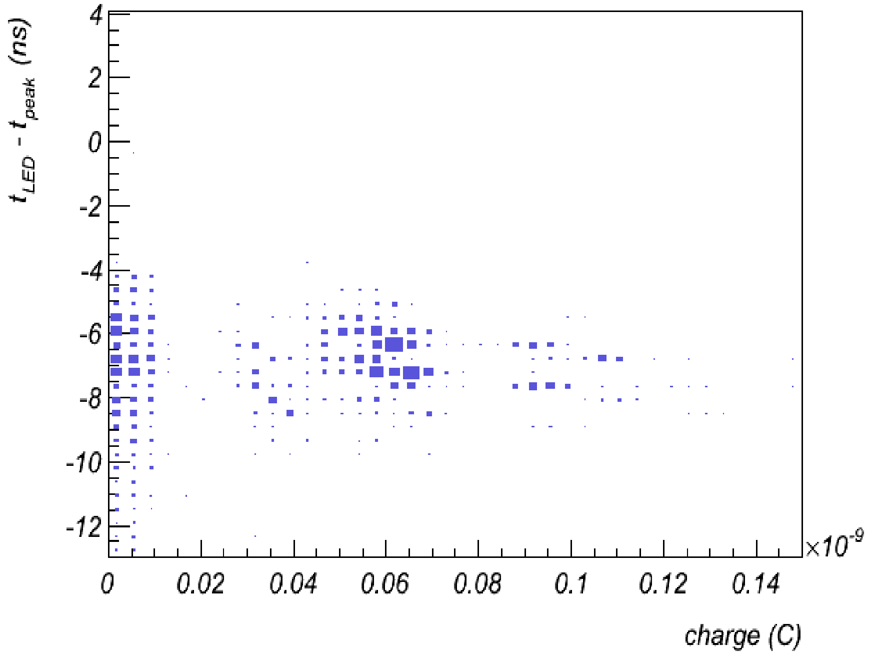
- $T_{1/3PE}$ versus charge



Tpeak versus charge

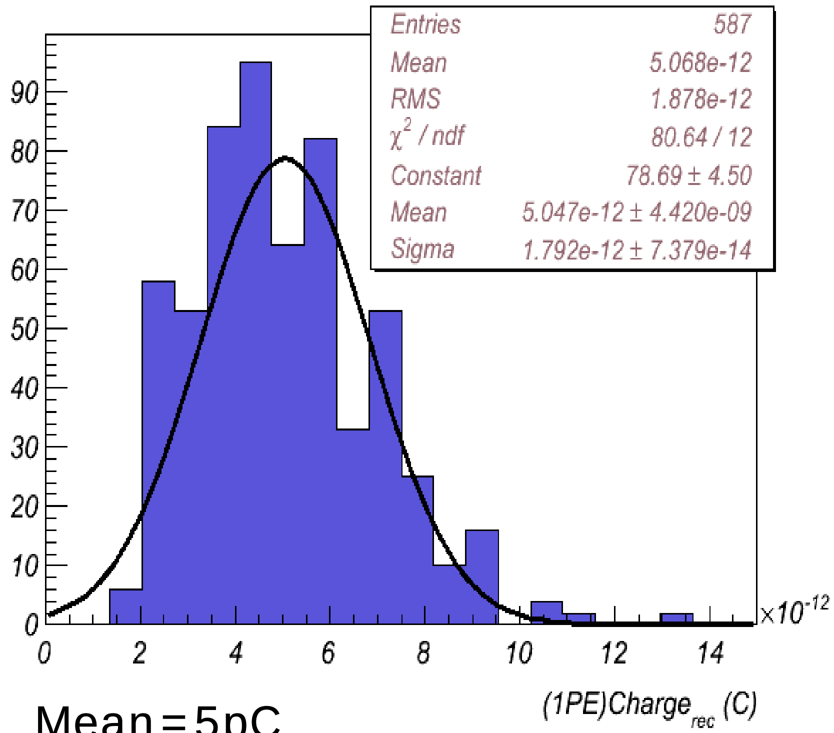
1PE and 11PE

- Tpeak versus charge



Charge resolution with FRED + SCOTT

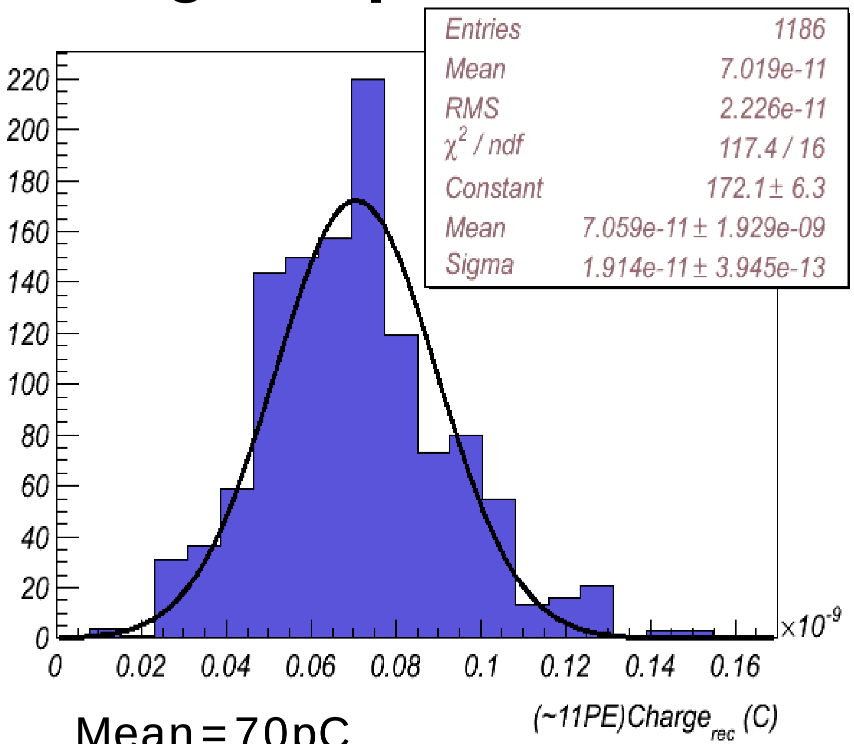
Charge 1pe



Mean=5pC

RMS=2pC: 37%

Charge 11pe



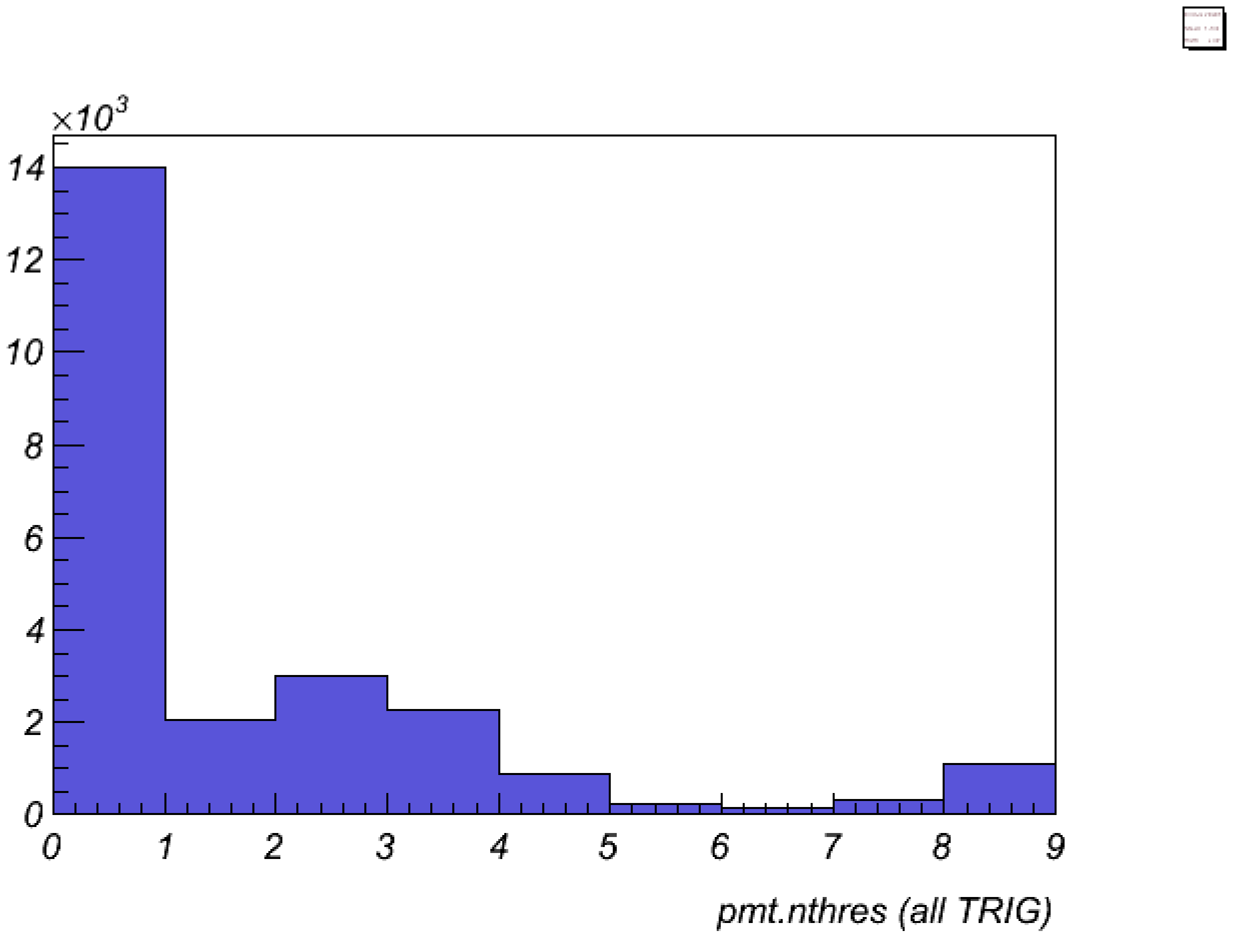
Mean=70pC

RMS=22pC: 32%

SCOTT + Pulse fit enable charge reconstruction without introducing further error

SCOTT data set

- 1 + 11 pe data sets



- 0 1/3 2/3 1 4/3 5/3 2 3 8 pe

Analogue to digital@ SCOTT