SCOTT: A time and amplitude digitizer ASIC for PMT signal processing using multi time over threshold technique.

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

KM3NeT

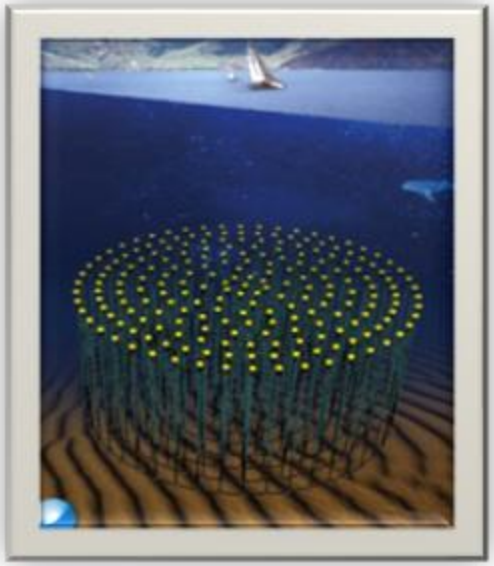
- A European deep-sea research infrastructure for a neutrino telescope
  - Mediterranean Sea
  - Instrumented volume ~ 5 km^3
  - 300 detection units
  - 12000 photo-detectors

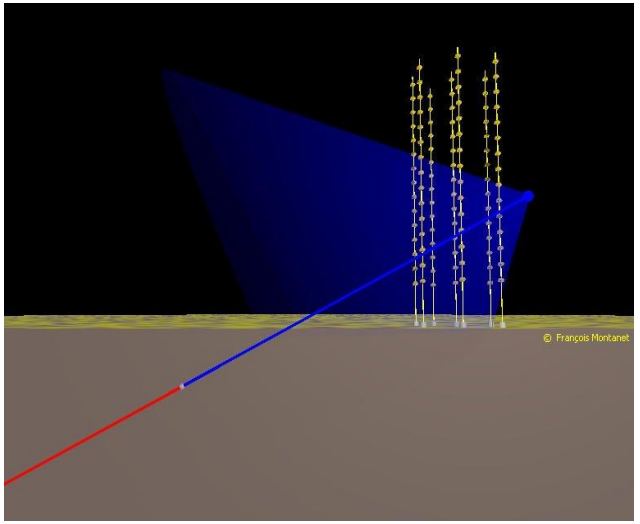
- Cherenkov light detection
  - Upward $\nu \rightarrow \mu$
  - Downward atmospheric μ
  - Optical background (100 Hz / cm^{-2})
    - ^{40}K decay in water
    - Bioluminescence

  $\Rightarrow$ Mainly single photon signals

- All data to shore
  - On shore computer farm

  $\Rightarrow$ Auto-triggered

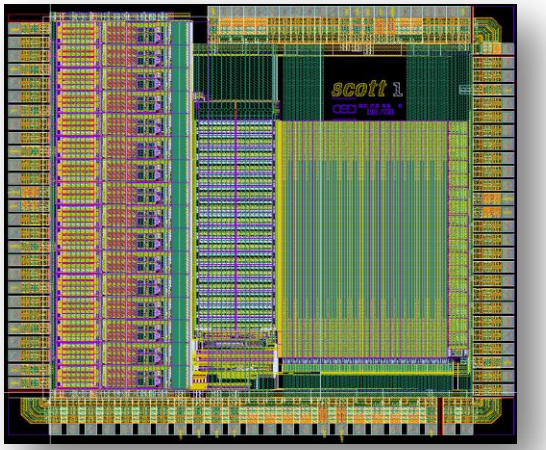


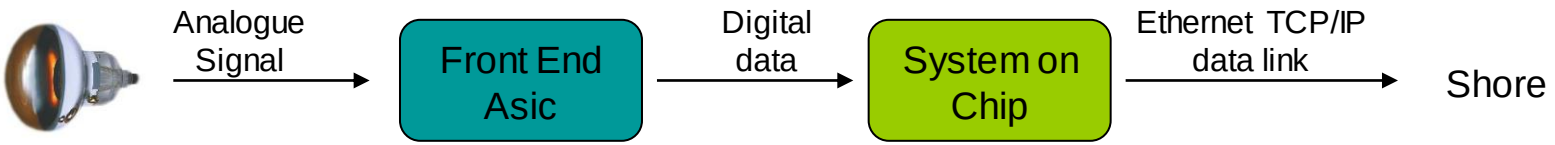


Front end requirements (from CDR)

- 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



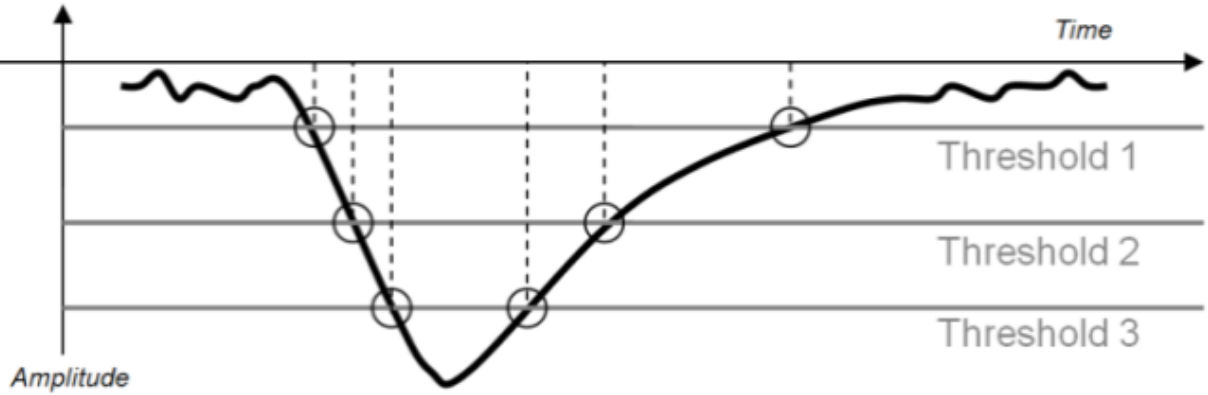


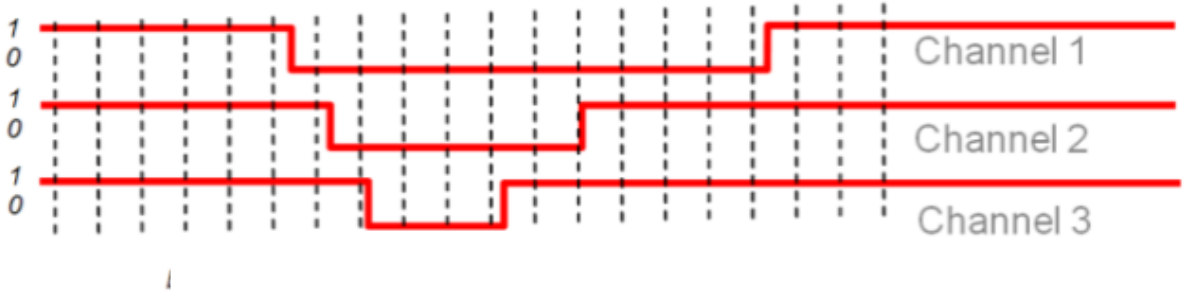
SCOTT concept

Amplitude sampling
Discrimination of the PMT analogue signal

Time sampling
1.25ns

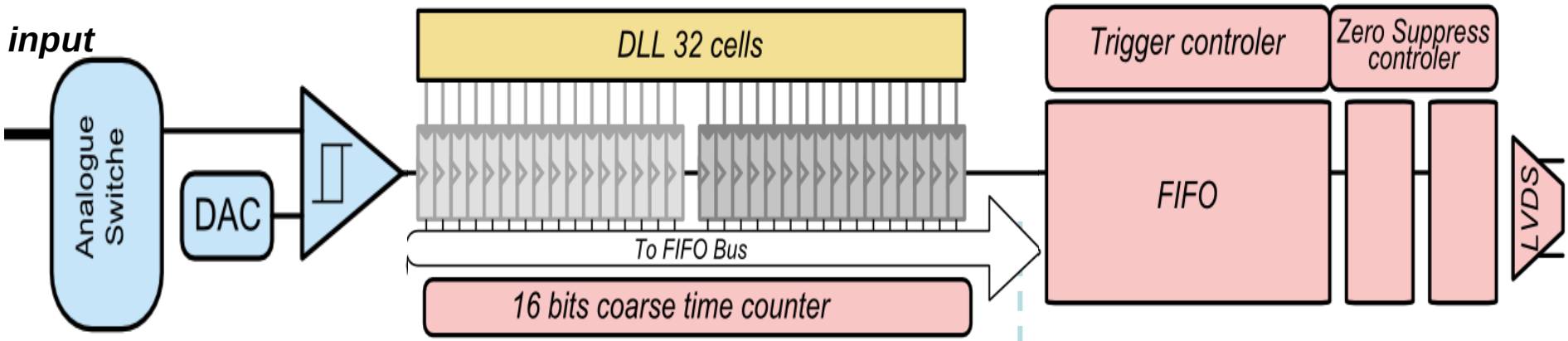
Digital data in the Internal Memory





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

ASIC Channel architecture



- **Analogue input**

AMS BiCMos 0.35µm

-Analogue switches

Internal sharing of signals

-10 bit DAC

Programmable thresholds

LSB<3mV

-Discriminator

Analogue to digital convertor

- **Fast sampling memory**

-Delay locked loop (DLL)

All channels are synchronous

Circular digital memory

-2 memory banks

No dead time

-16 bit coarse time counter

LSB = 20 ns

Time step $T_{CK}/16$

Ts = 1.25ns (~ 800MHz)

- **FIFO**

-Auto-triggered

640 ns continuous wave-form

-Double port

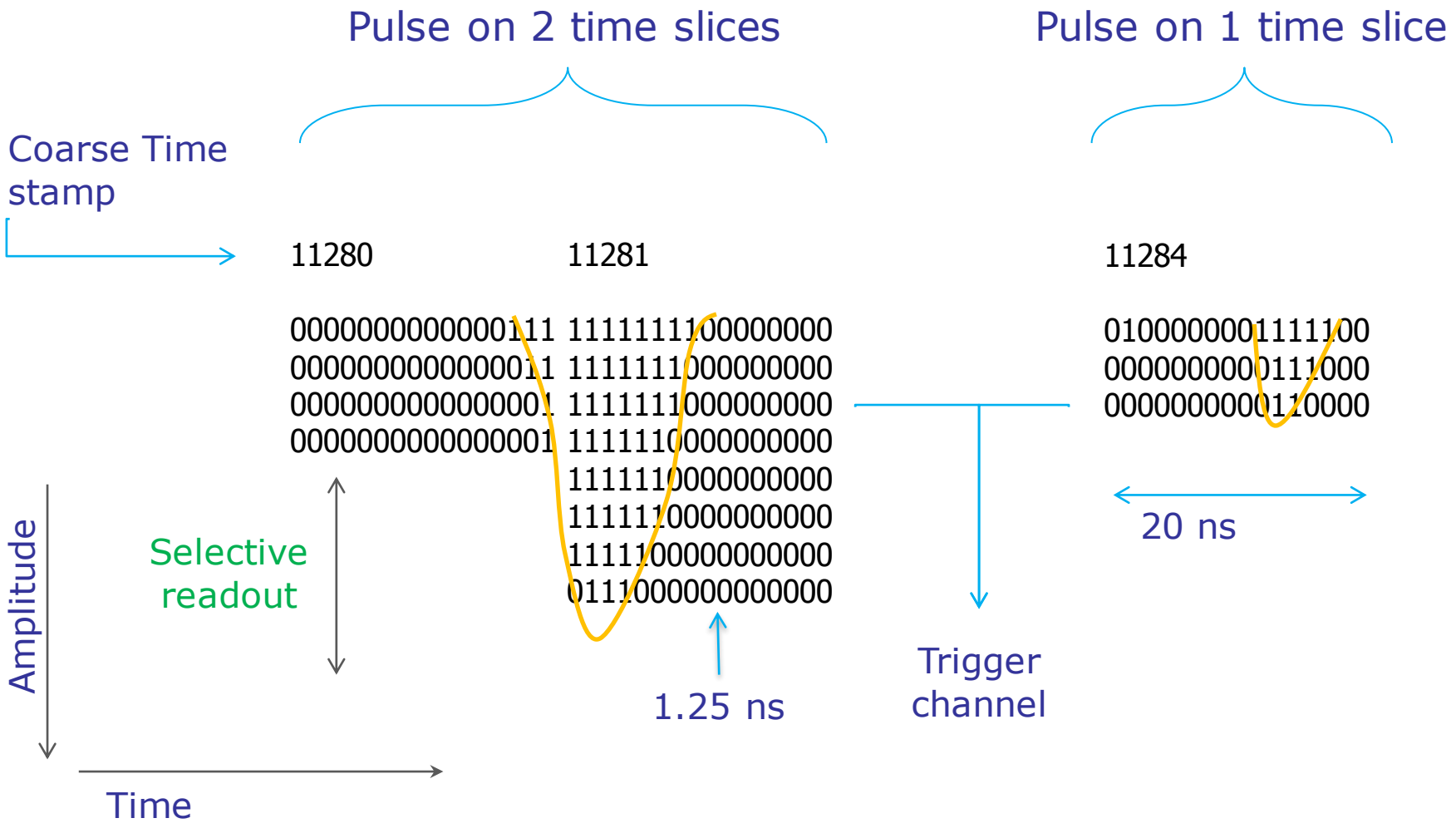
Fclk sample ≠Fclk readout

Readout driven by System-on-Chip

-Selective readout

Data reduction: zero suppress

Scott output example



The SCOTT Opera

Characterization of SCOTT ASIC reading a 10" PMT

- 𝔄*ct I* : Determination of thresholds
  - Which values for how many thresholds ?
- 𝔄*ct II* : Charge
- 𝔄*ct III*: Timing

Act I
Threshold determination

Actors

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

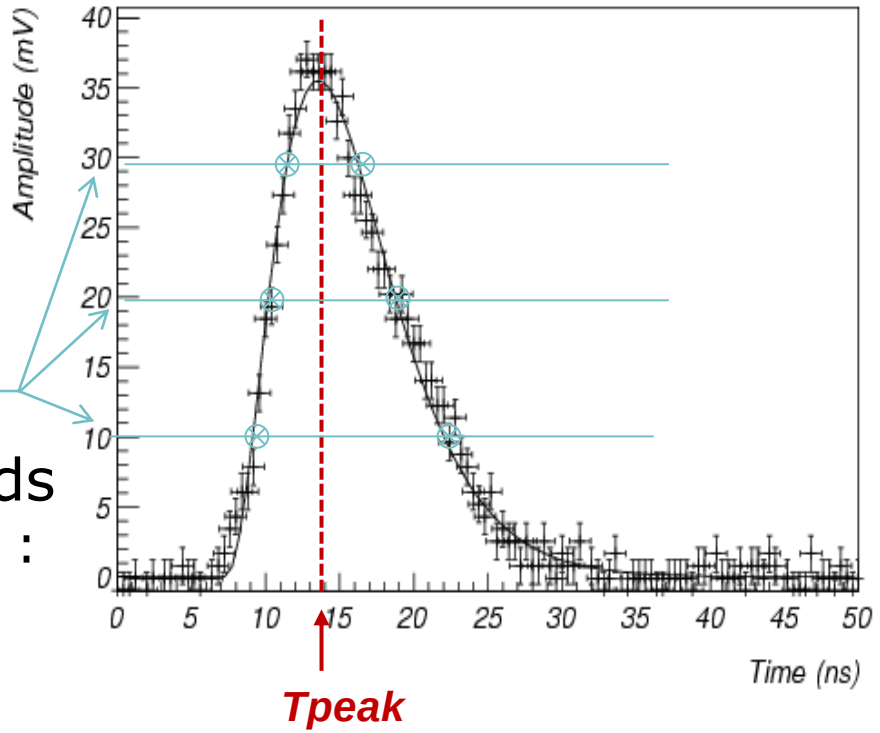
LED : flashes at 1pe up to 70pe

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 $\delta \Delta T$ with FRED : (Fast Rise Exp. Decay)

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

$\Rightarrow$ Tpeak and Charge(integral)

- Best solution 1pe – 70pe : 5 thresholds

  pe: 1/3 2/3 1 3 8

  With :
  - δQ = 9% (1pe) 12 % (up to 25pe)
  - $\delta \Delta T$ = 0.5ns (1pe) 0.7ns (up to 25pe)

Act II
Charge resolution

Actors

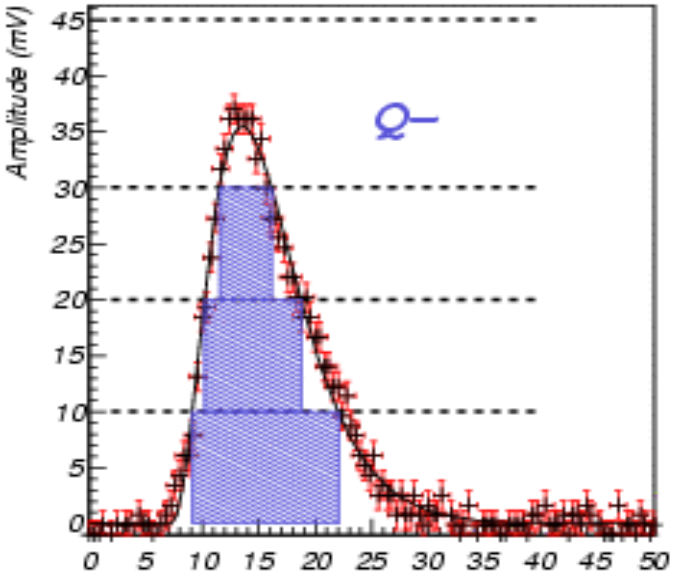
PMT : Antares 10” gain=3.10^7 $\Rightarrow$ 1pe $\approx$ 50mV 5pC

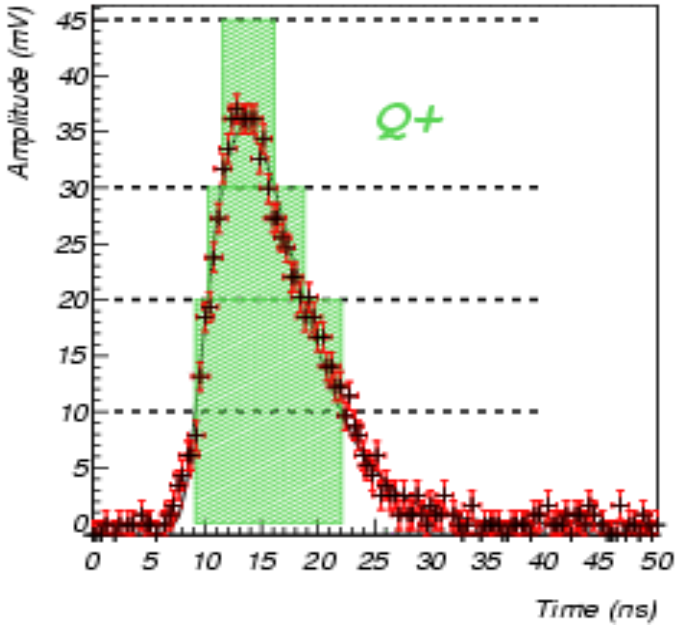
LED : flashes at 1pe and 11pe

SCOTT : 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

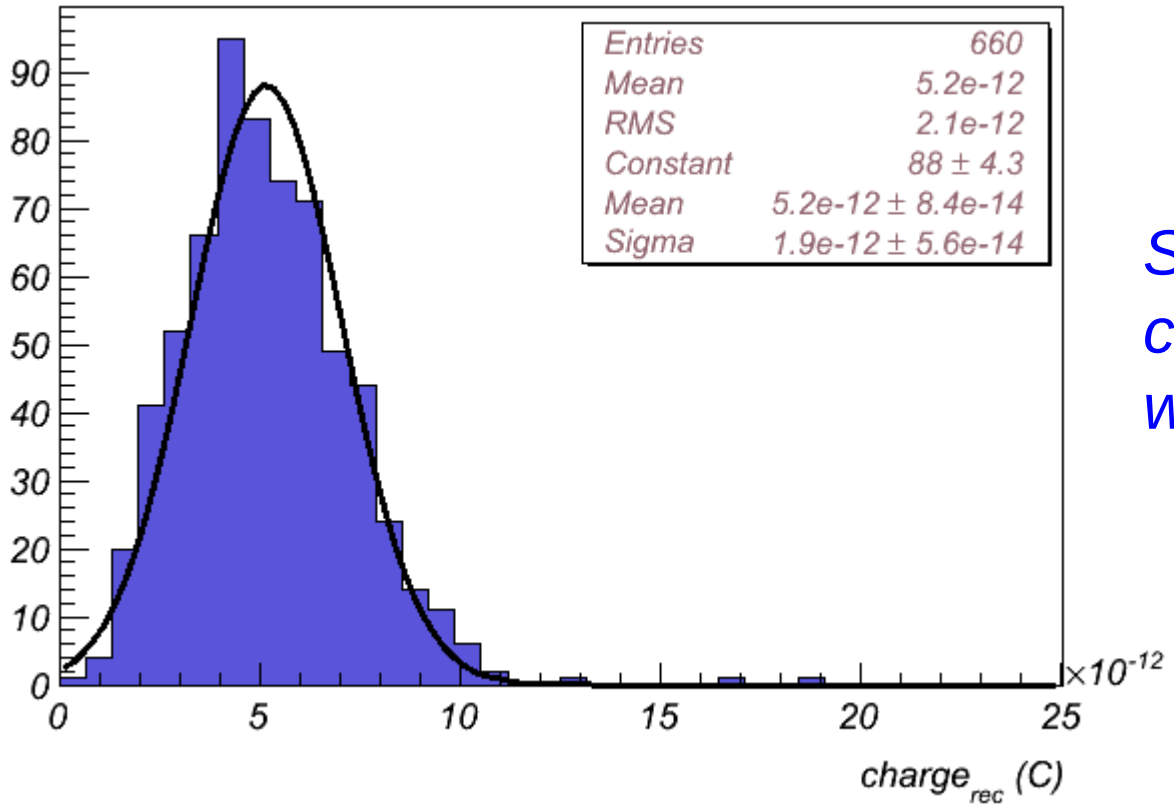
Can be estimated with *FRED* on a "calibration sample"

Charge resolution from TOTs

Charge 1pe

Mean=5pC
RMS =2pC

= PMT charge measured with an oscilloscope @2.5GHz



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

- Tpeak from TOT
  - Analytical solution with FRED
  - Tpeak- T0[i] = F(TOT[i])

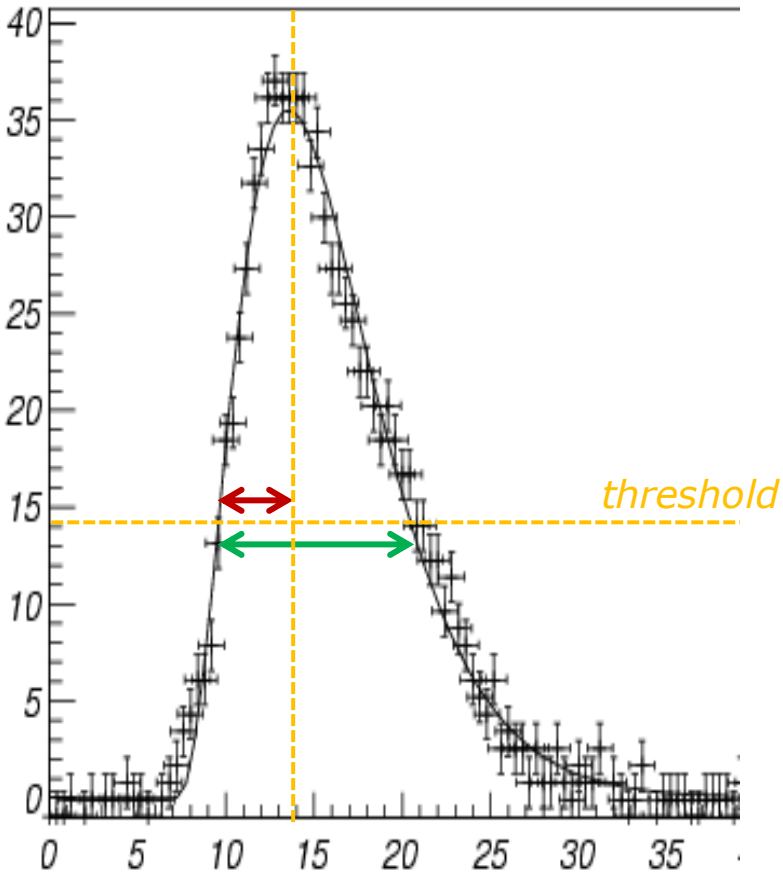
$$F = \frac{b}{X}(1-(1+X)e^{-X})$$

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

  - True for every thresholds
  - Best resolution when using the highest threshold crossed

- Insensitive to the walk effect
  - Walk effect:

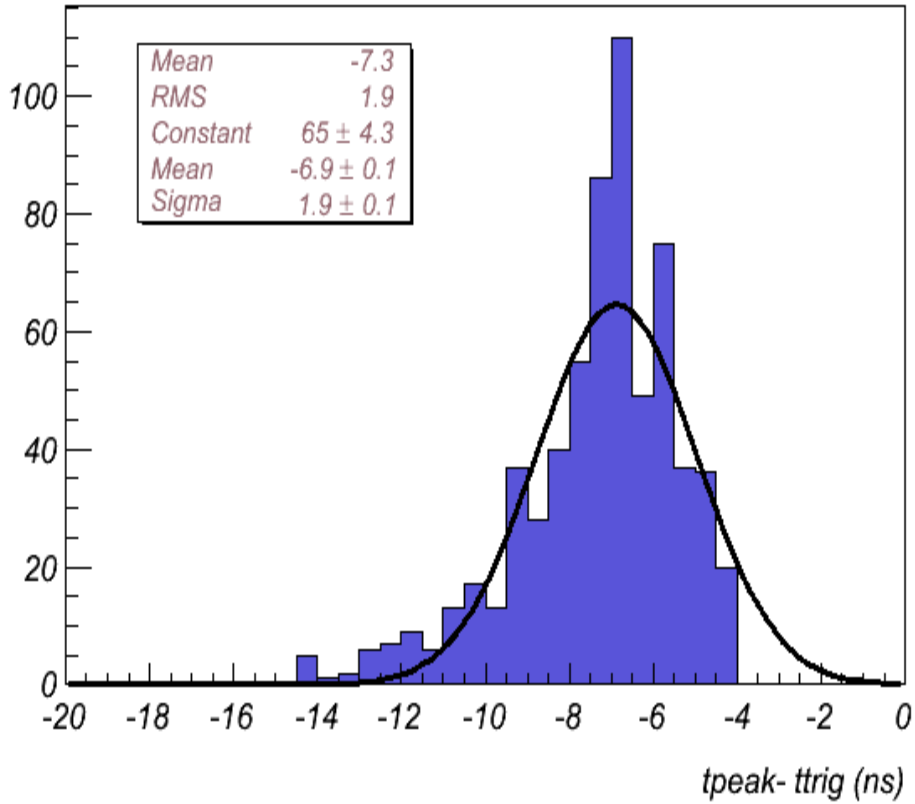
Consequence of the charge variation compared to the time measured directly at the crossing threshold



Pulse time resolution from TOTs

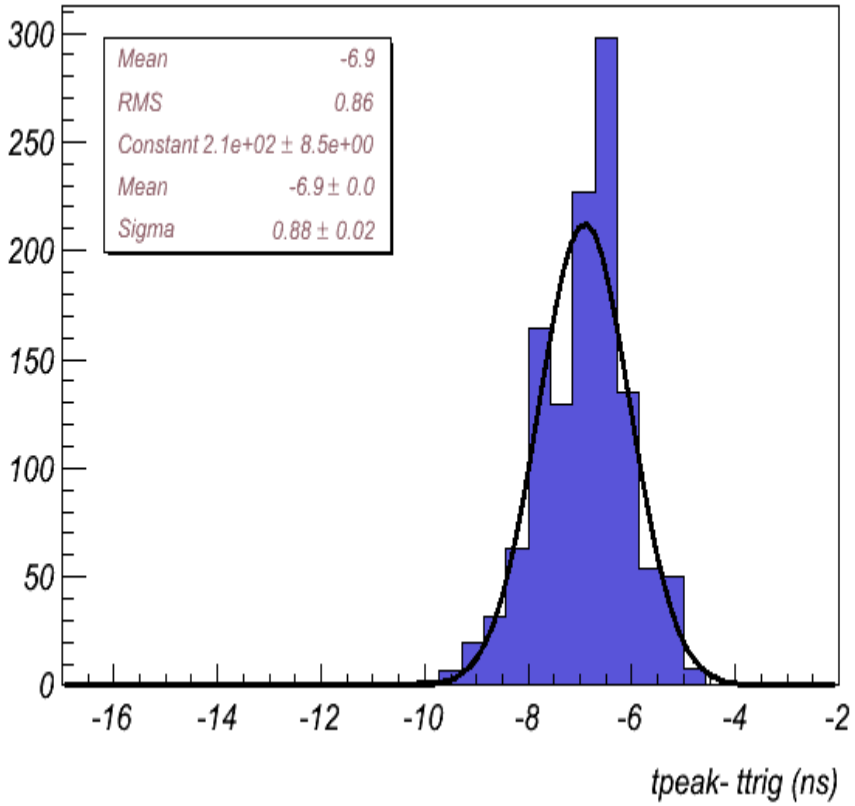
Charge 1pe

- RMS 1.9ns



Charge 11pe

- RMS 0.9 ns



$TTS_{PMT} \approx 1.3$ ns

Time resolution <2 ns

No charge estimate needed

Act III
Timing resolution

Scene 2 : SCOTT Intrinsic timing accuracy

Actors

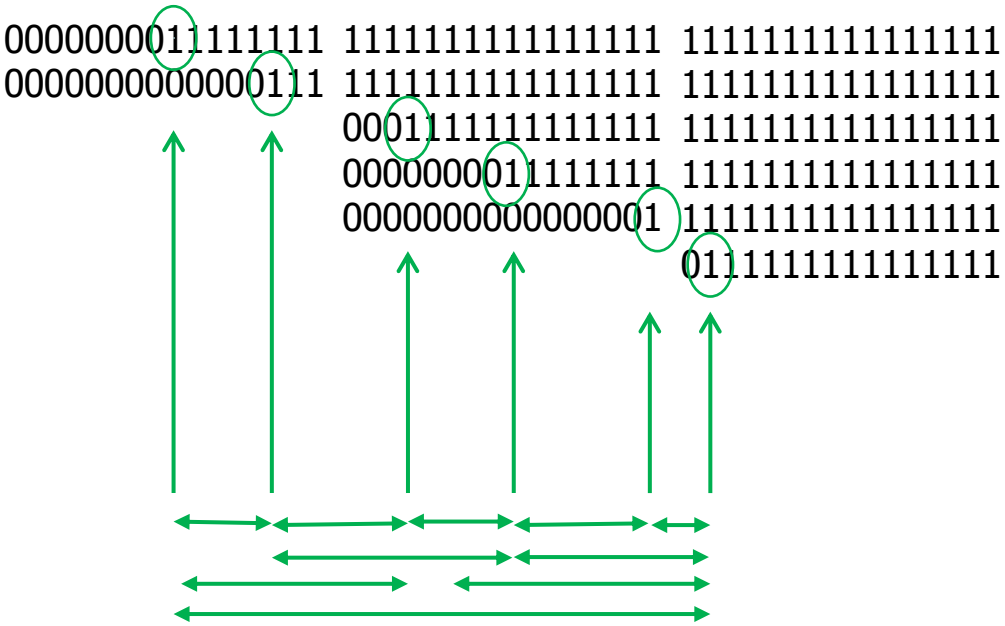
Generator: HP 81110A 330MHz

SCOTT

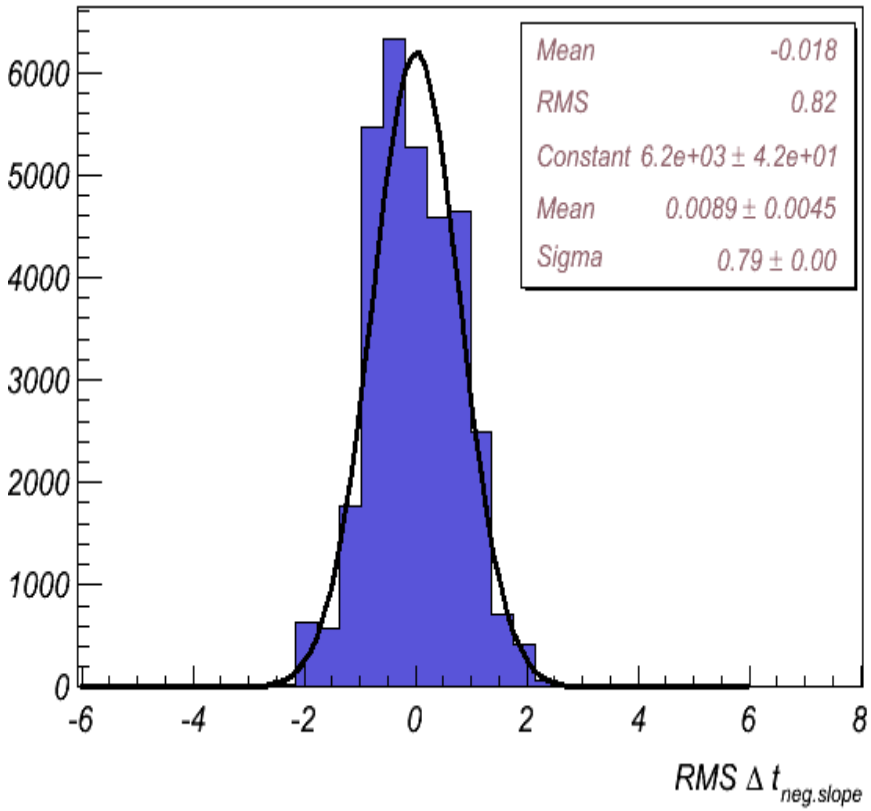
SCOTT intrinsic timing

- 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 0.8 ns

Corresponds to 0.7 mV threshold noise

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 12% up to 25 pe
    - -> Timing 0.5 ns at 1pe
  - TOT estimate
    - -> Timing 0.7 ns up to 60 pe
    - -> Charge 20% up to 60 pe

  -> Up to 3PMTs/SCOTT
- SCOTT reading a 10'' PMT
  - Explored up to 11pe
  - FRED fit -> TOT parameters
  - Charge & Timing
    - Walk effect correction, pulse time δt <2ns
    - Intrinsic timing accuracy 0.8ns

  $\Rightarrow$ CDR requirement achieved
- Adapted to multi-PMT reading in KM3NeT 31x3''PMT = 2ASIC with 1threshold/PMT

the SCOTT ASIC: versatile data processing relevant for any application which requires time precision, non-linear amplitude discrimination.

Irfu
cea
saclay

KM3NeT

Backup

FRED

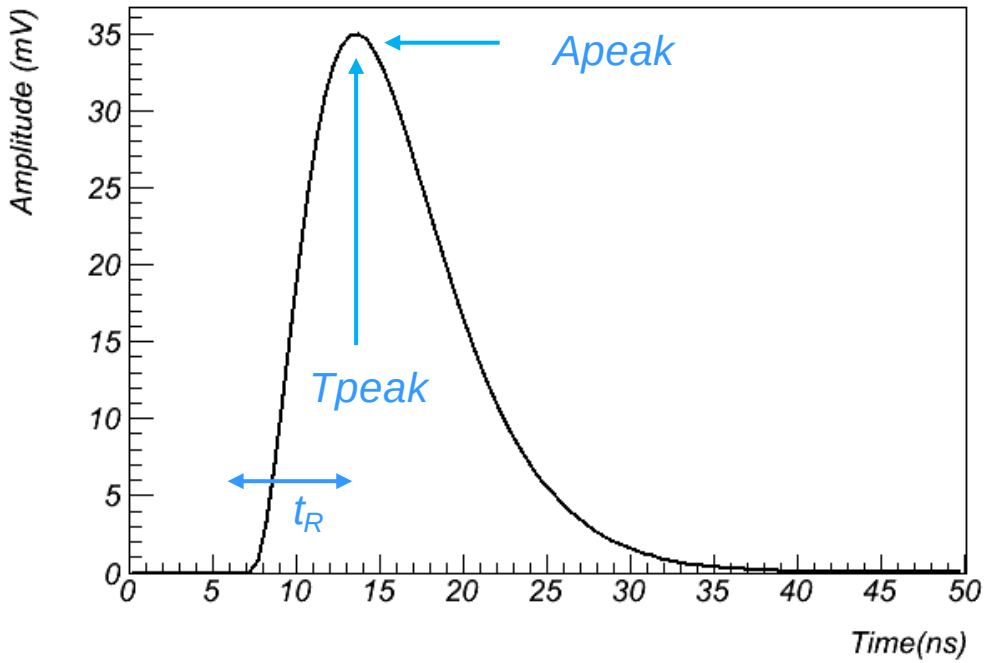
- Function to fit
  - Fast Rise Exponential Decay

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

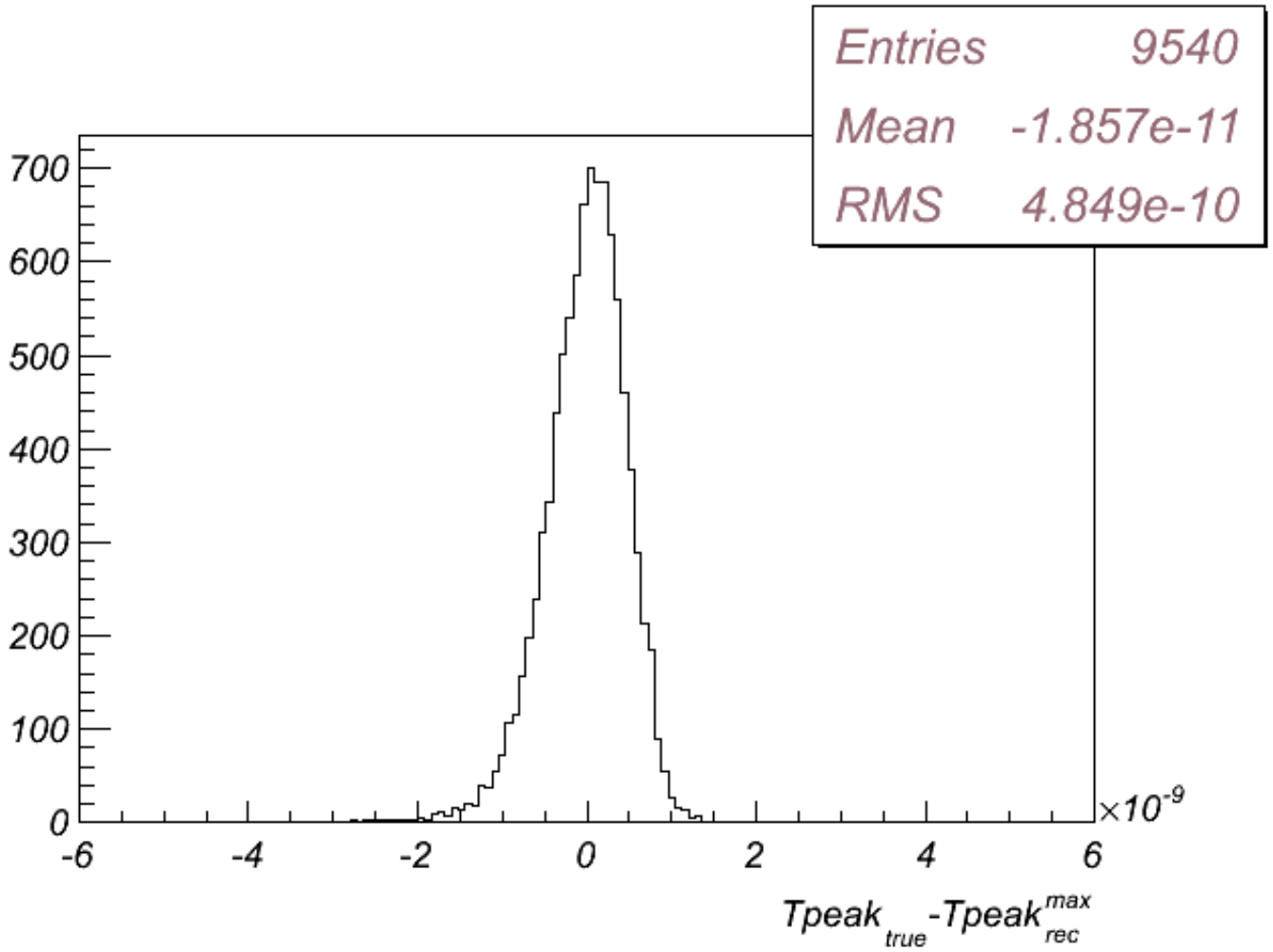
  - Variable change

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

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

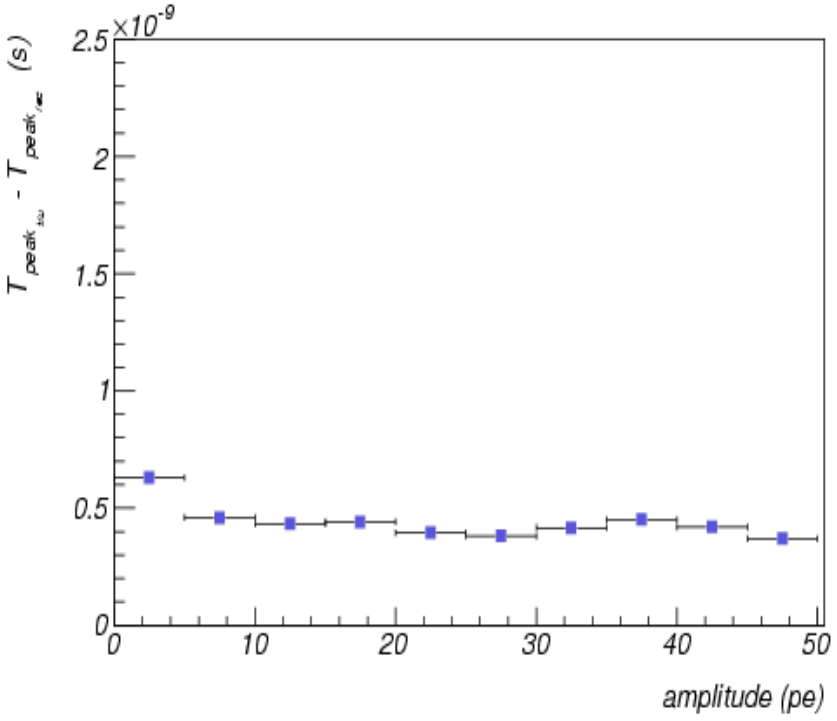


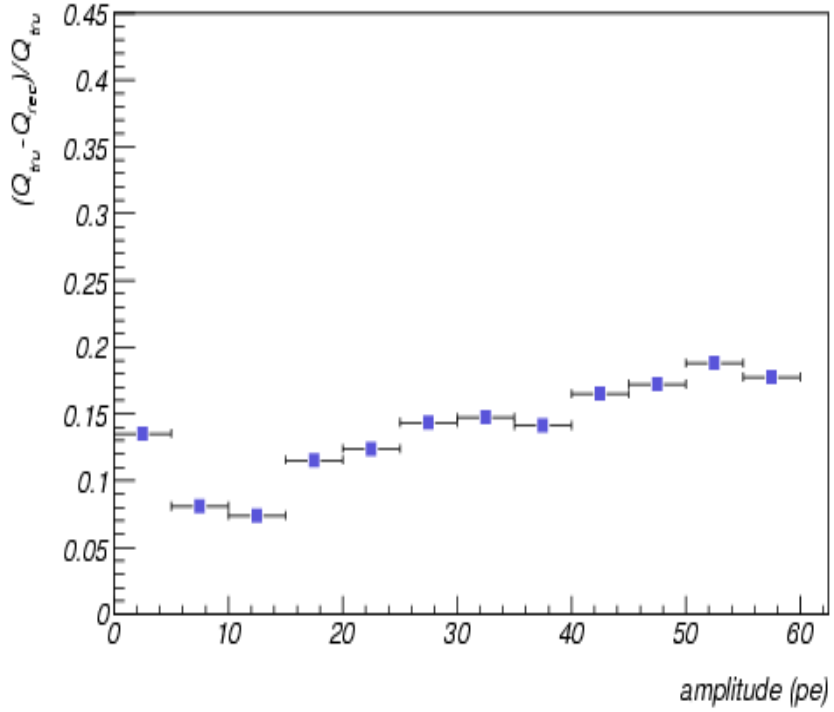
Tpeak residuals



TOT estimate performance

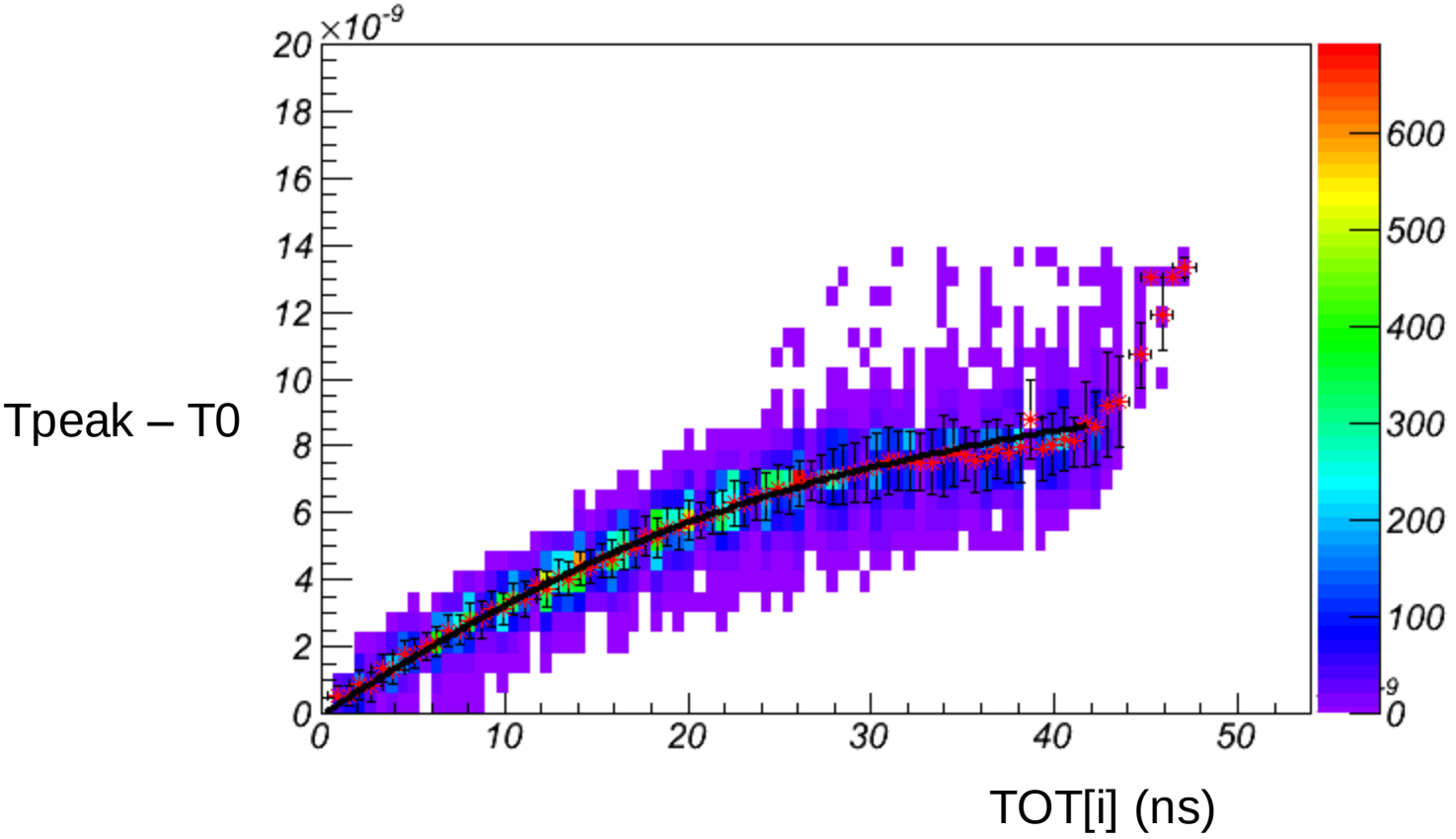
- Time
  <0.7ns @ [0-50]pe range
- Charge
  <20% @ [0-60]pe range





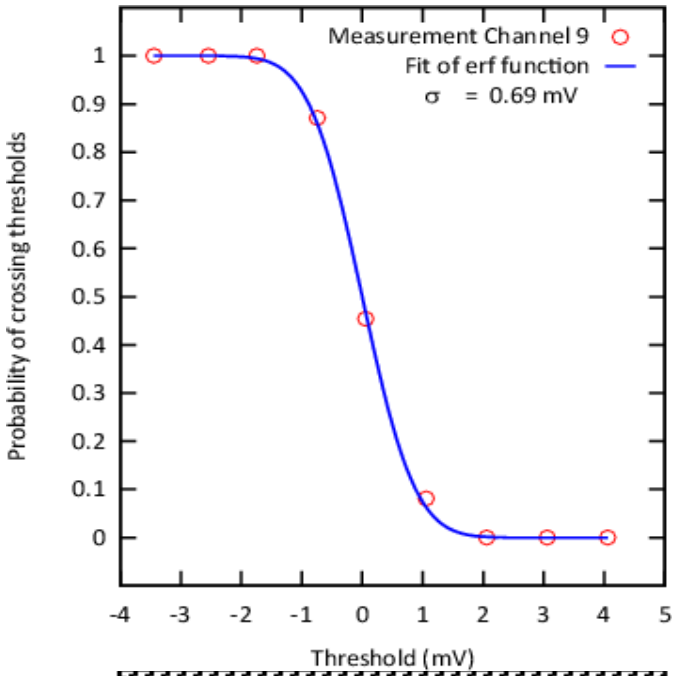
TOT to Tpeak correlation

All thresholds

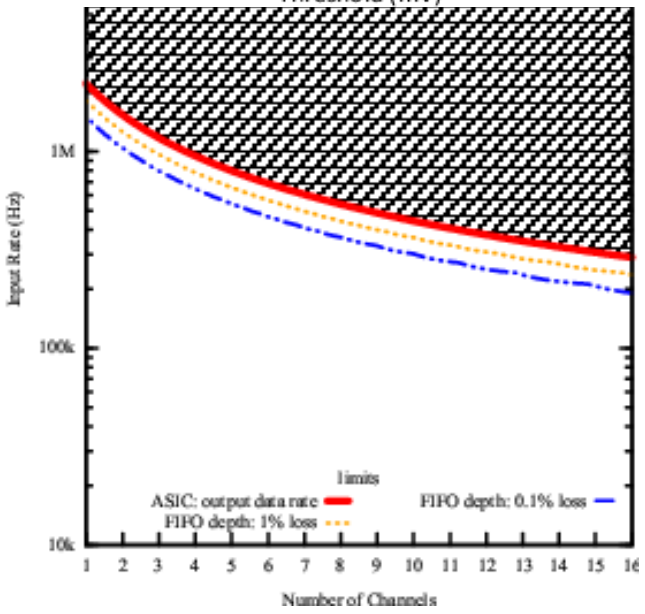


SCOTT Performances

- Minimal signal width 2ns
- S-curve
  - Probability of crossing the thresholds <0.7 mV



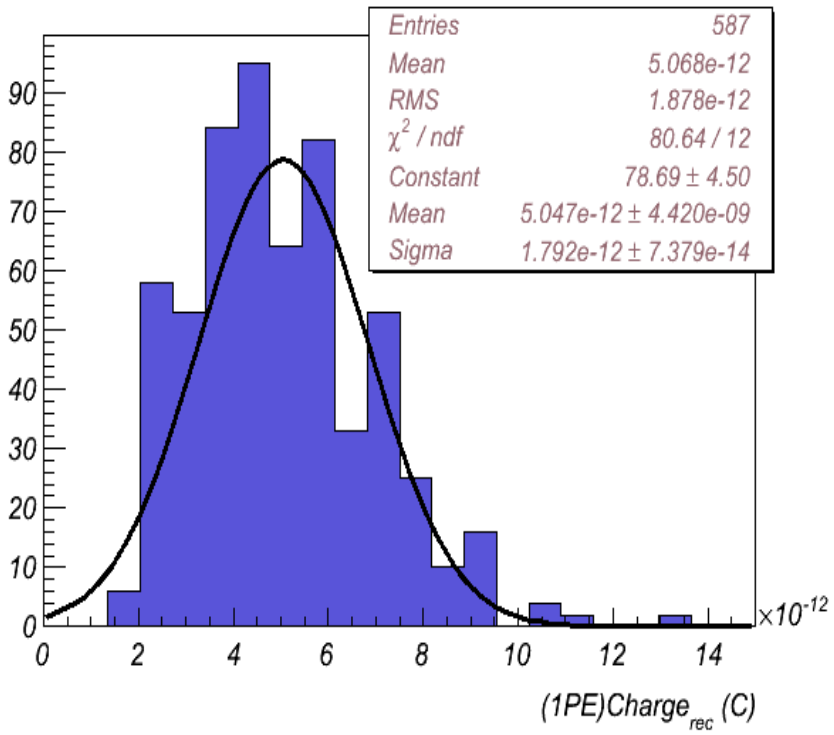
- Data rate limit
  - Simulation worse case data rate limit
  - Nominal operation 3thresholds->1MHz



Charge resolution with FRED + SCOTT

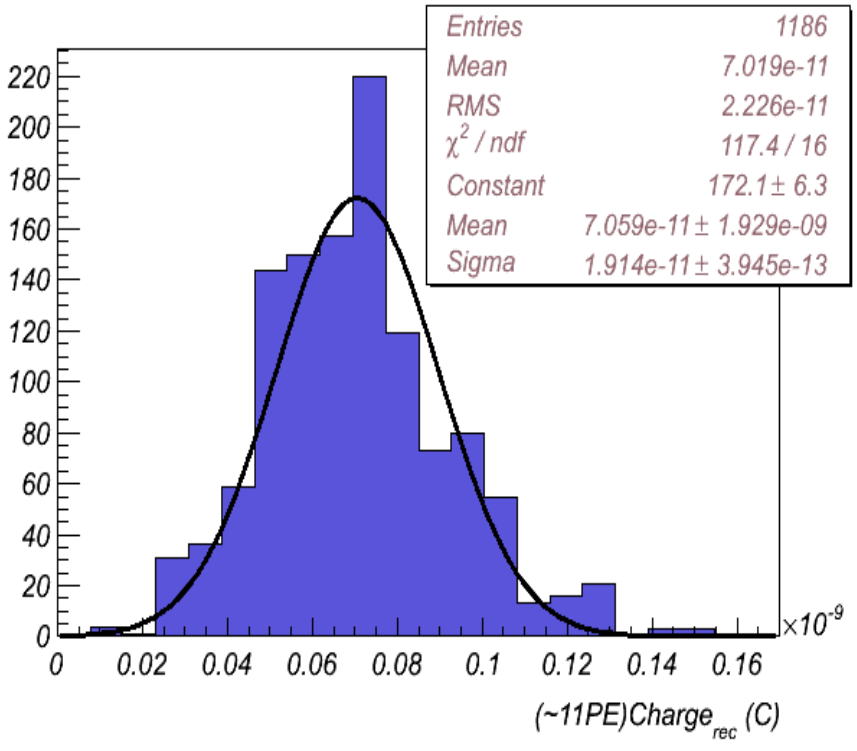
Charge 1pe

Mean=5pC
RMS=2pC



Charge 11pe

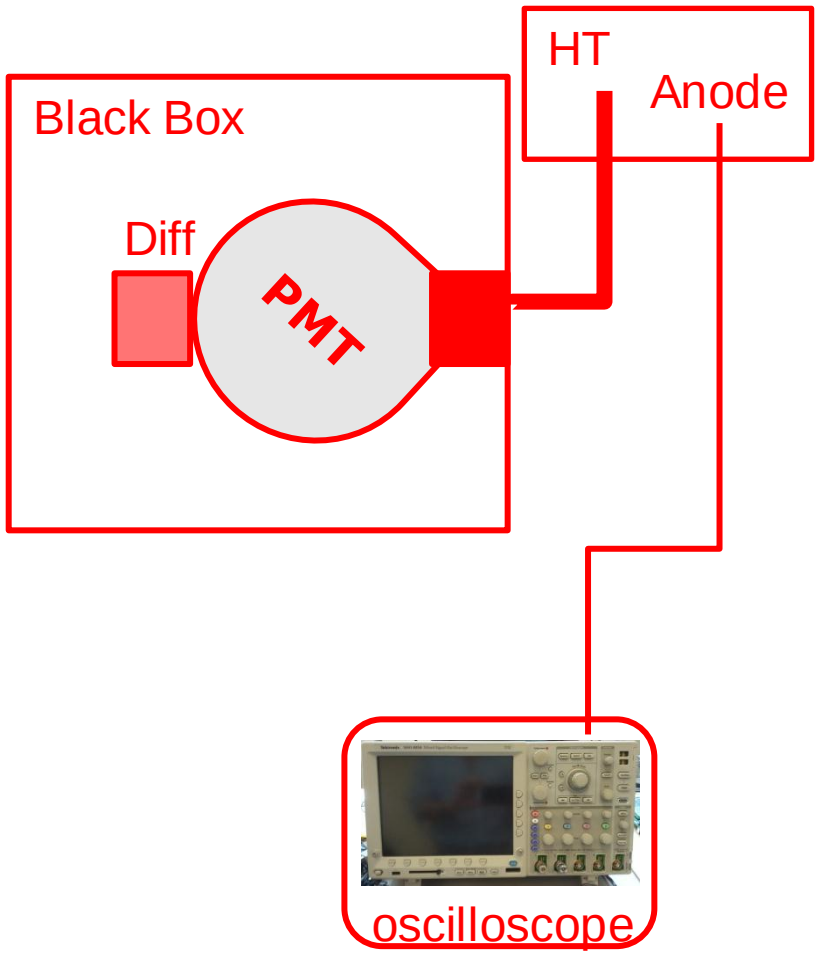
Mean=70pC
RMS=22pC

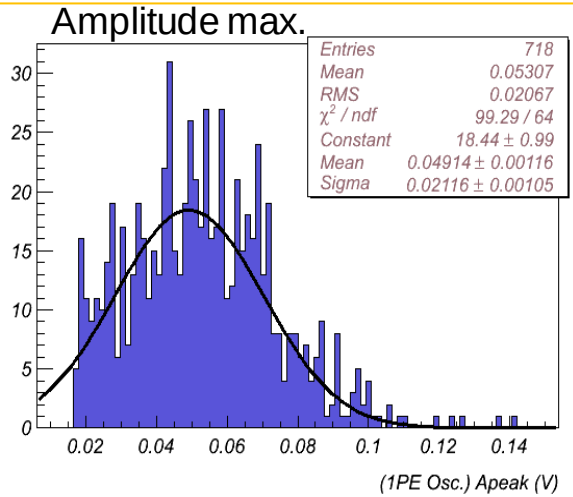


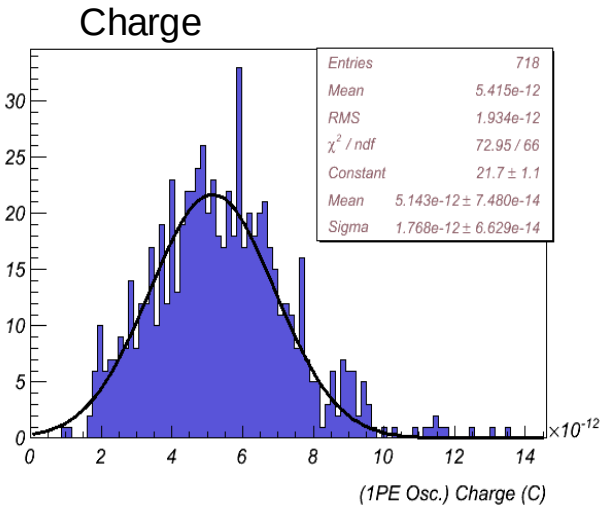
SCOTT + Pulse fit enable charge reconstruction without introducing further error

PMT characterisation

- PMT + Oscilloscope

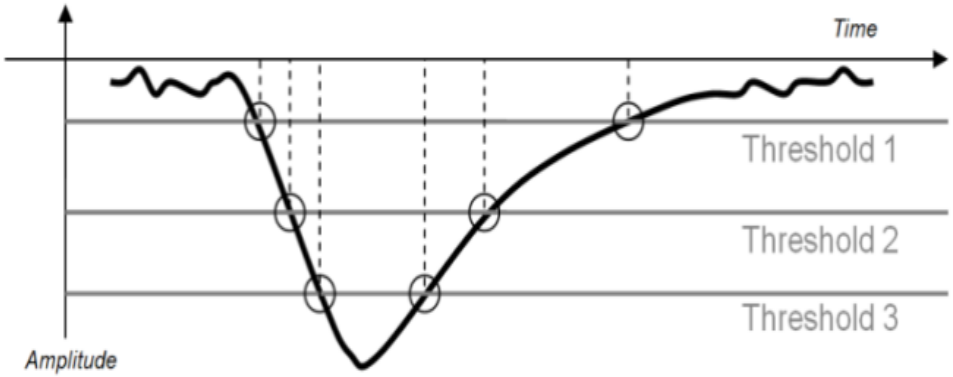




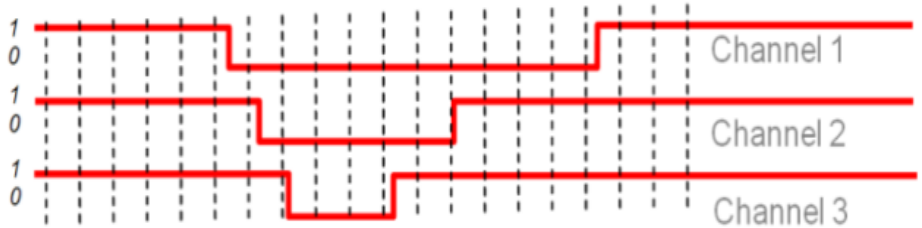


Defines the 1PE
≈ 50 mV
≈ 5.4 pC

SCOTT concept



a : Discrimination of the PMT analogue signal



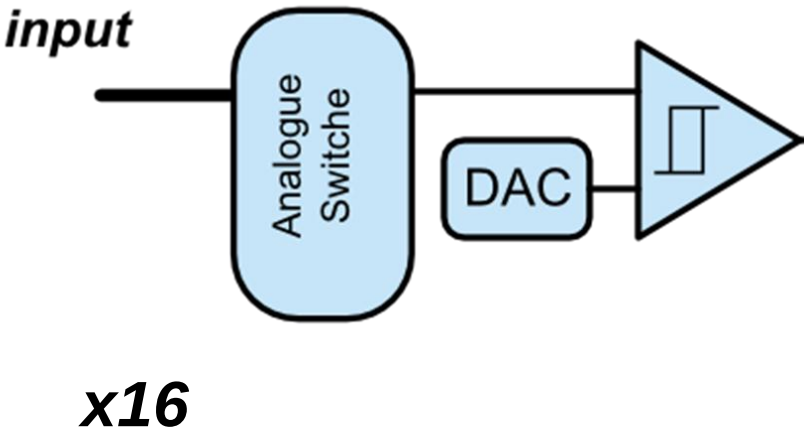
b : Discriminator output signals sampling

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

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

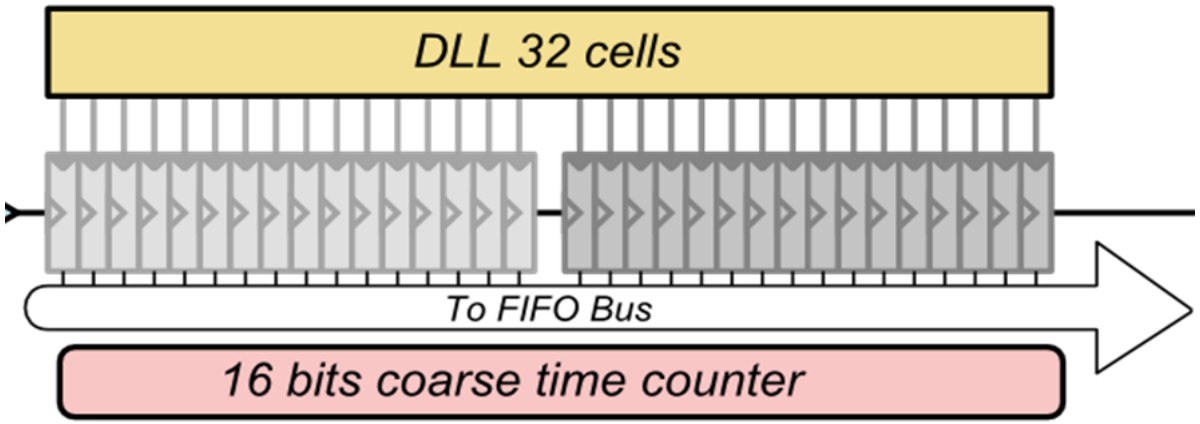
Analogue input



Amplitude sampling

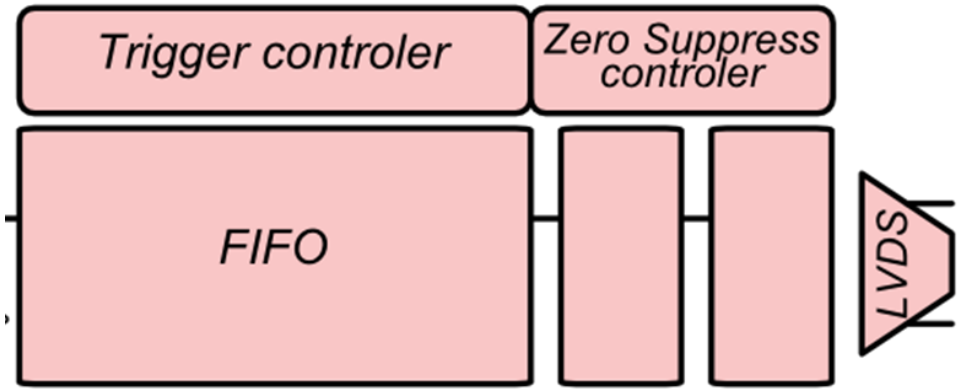
- AMS BiCMos 0.35mm
- Analogue switches
  - Internal sharing of signals
- 10 bit DAC
  - Programmable thresholds
  - LSB<3mV
- Discriminator
  - Analogue to digital convertor

Circular sampling memory



- Delay locked loop (DLL)
  - All channels are synchronous
- Circular digital memory
  - 2 memory banks (MB)
  - 1MB = 20 ns
  - No dead time
- 16 bit coarse time counter
  - LSB = 20 ns
- Time step $T_{CK}/16$
  - Ts = 1.25ns (~ 800MHz)

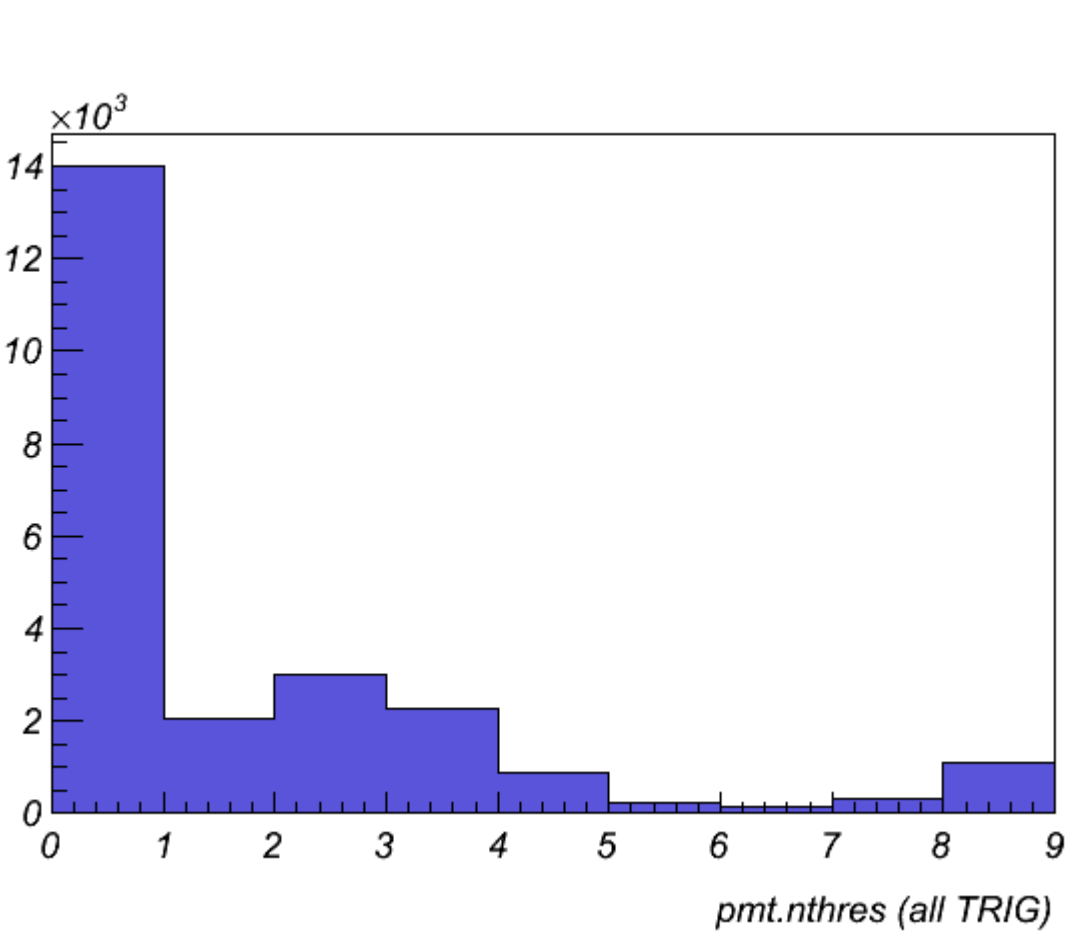
FIFO



- Auto-triggered
  - Logical or channel triggered
- Size 9kBits
  - 640 ns continuous wave-form
  - Data loss <1‰ for 200 kHits/s
- Double port
  - Fck sample ≠Fck readout
  - Readout driven by System-on-Chip
- Selective readout
  - Data reduction: zero suppress

SCOTT data set

- 1 + 11 pe data sets



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