THE VATLY CHERENKOV DETECTOR AND ITS RESPONSE TO ELECTRONS AND MUONS

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Content

1. Motivation and method
2. Response to feed-through muons: VEM calibration
3. Muon decays: simulation
4. Data collection and analysis
5. Simulation and interpretation of the results
6. Summary

1. Motivation

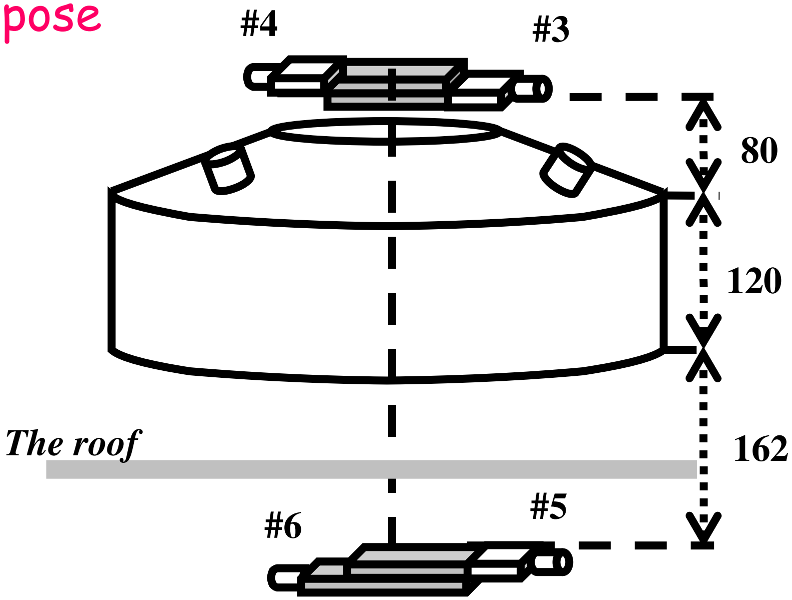
- To study the response of the Cherenkov detector to low charges.
- To measure the contribution of multimuons from the same shower and compare it with the lateral distribution function evaluated using the satellite tanks.

Method

Detect stopping muon decays and pairs of correlated muons by measuring auto-correlation spectra for several detection delays and thresholds.

2. Response to feed-through muons: VEM calibration

A Cherenkov detector has been assembled on the roof of our Hanoi laboratory. A scintillator hodoscope bracketing the Cherenkov detector from above and below provides a trigger on such muons for calibration purpose



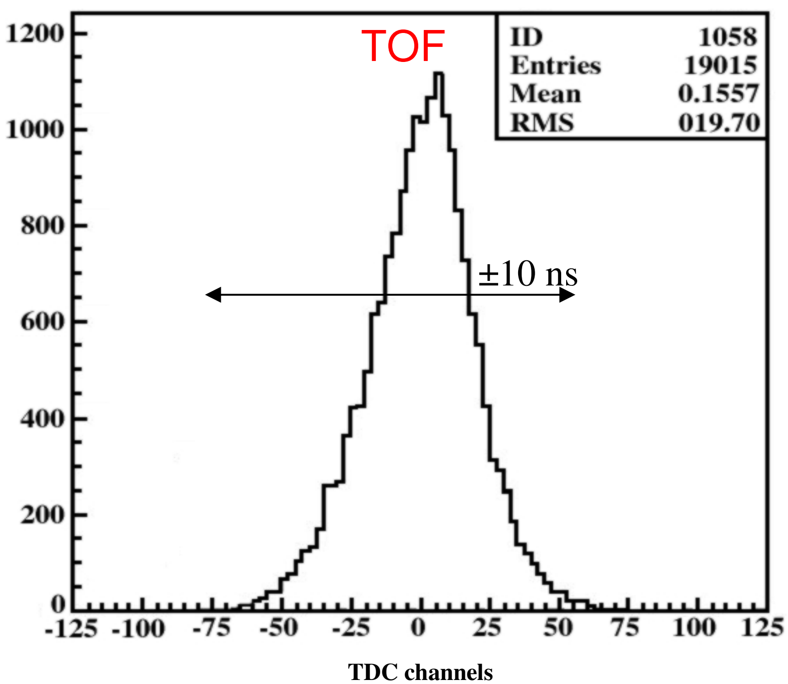
The signal produced by vertical central relativistic muons (so-called VEM, Vertical Equivalent Muon) is used as reference unit in the charge measurement. Adjustment of the high voltages and delays of the four signals; pedestal subtraction.

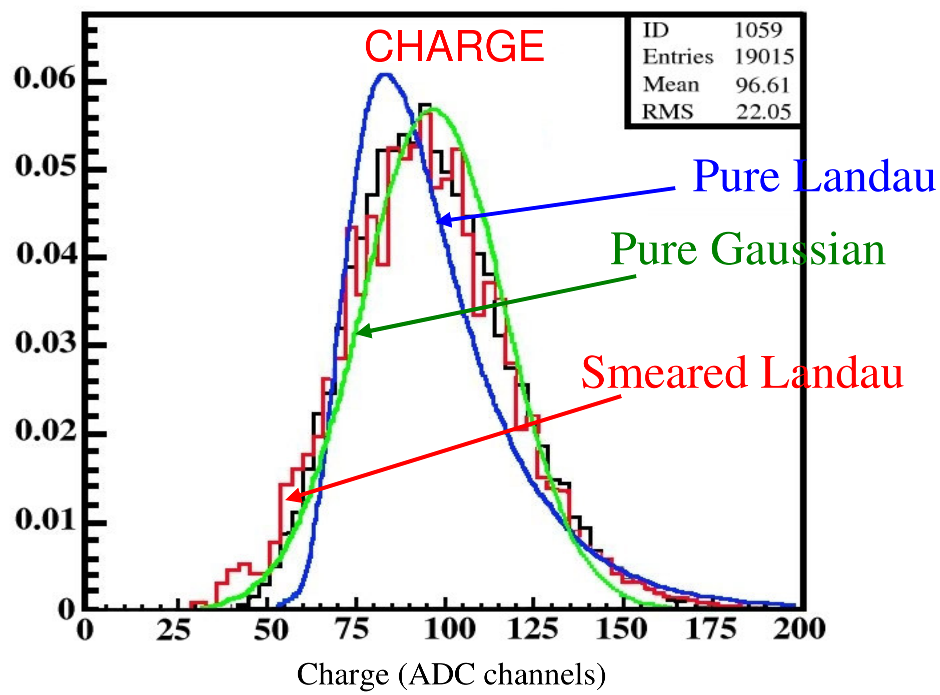
✓ Good stability is observed from run to run.

✓ Time slewing and light absorption effects compensate when averaging over a pair.

✓ A 4-fold coincidence rate of 0.48 ± 0.03 Hz.

Retaining only events where each of the four charge measurements and each of the four time measurements are confined to reasonable windows removes ~46% of the triggers. For this selected sample of clean relativistic muons, the TOF distribution has an rms of 2.8 ns. The mean charge distribution has an rms to width ratio of 23%. A good fit is obtained by smearing the Landau distribution with a Gaussian, meaning a relative 18% contribution to the width of instrumental origin.

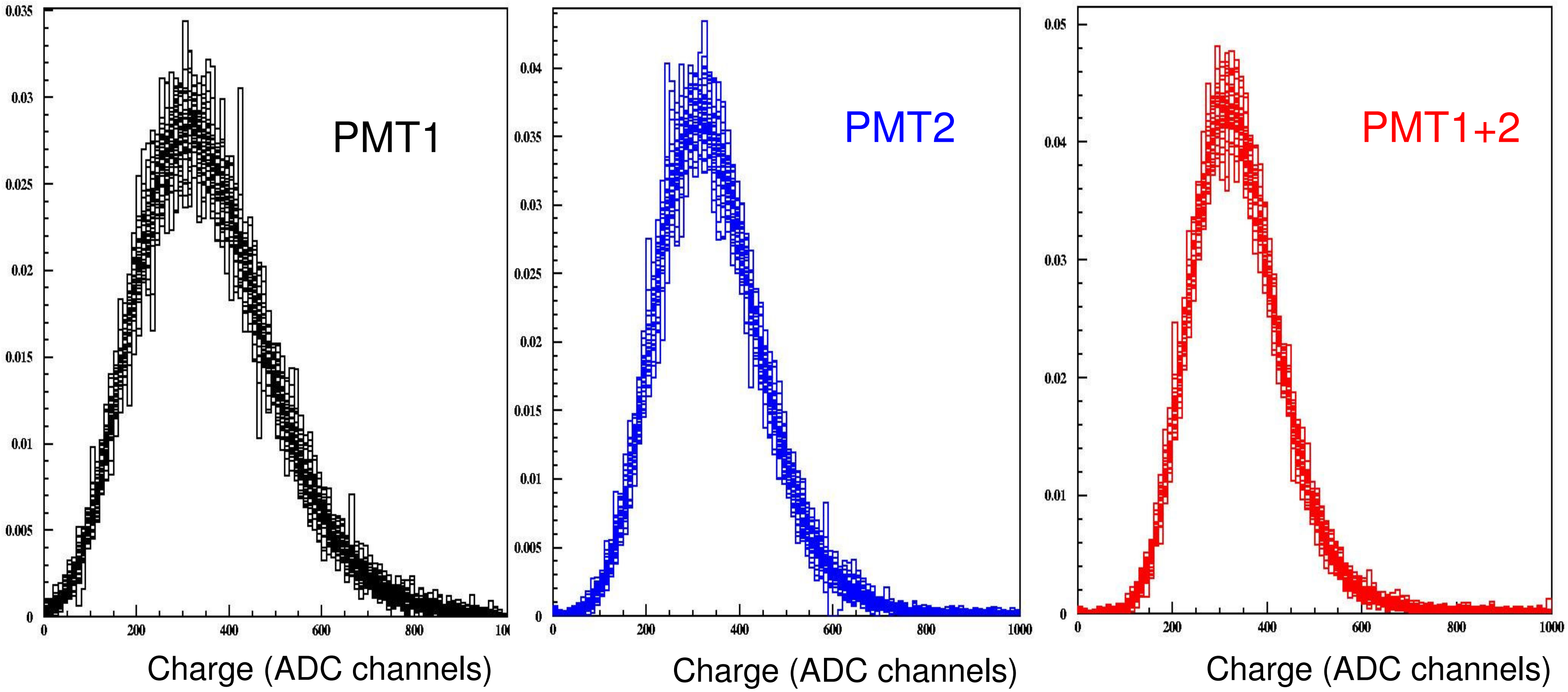




VEM calibration uses events with the sample of clean relativistic muons

14±1 photoelectrons/VEM

The VEM to ADC channel calibration is measured with a precision of 2.4%



3. Muon decays: simulation

Basic processes are the slowing down of muons due to:

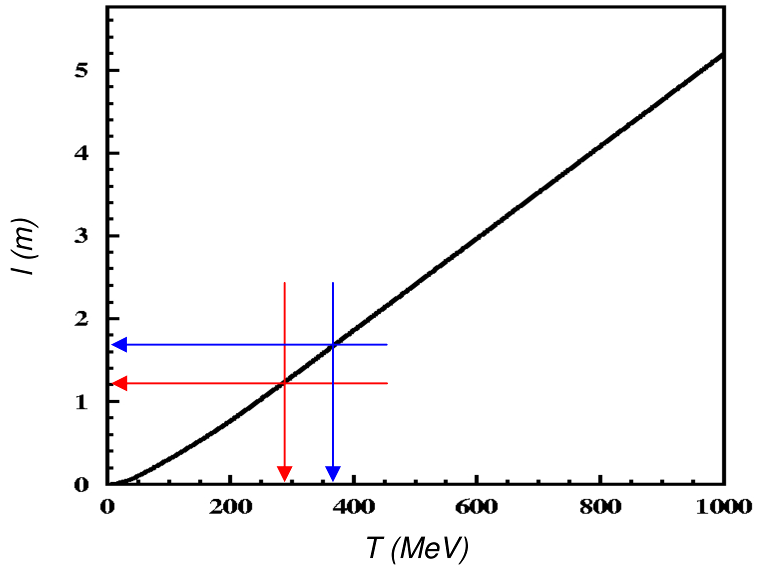
1. Ionization losses

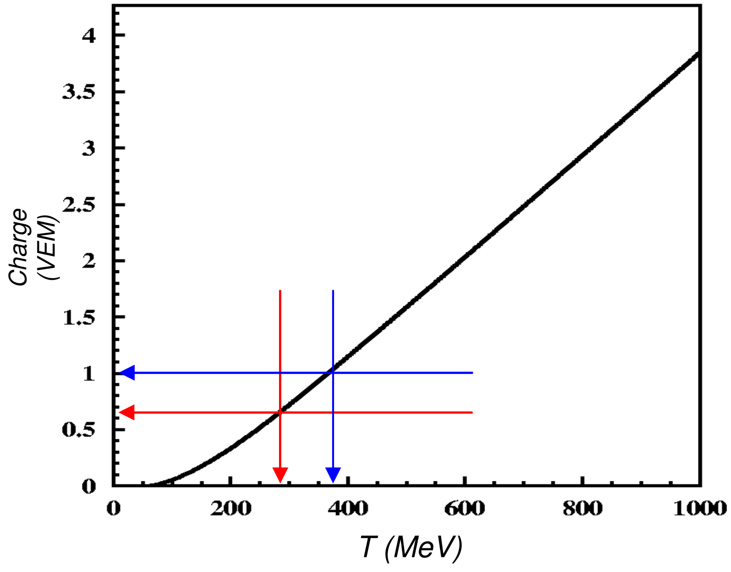
Largest track length, ~3.8 m, corresponds to kinetic energy T ~0.8 GeV. Differential energy loss is either at minimum (1.8 MeVcm^2/g from 331 MeV on) or in $1/T$ below it. Vertical muons feed through for T >280 MeV.

2. The emission of Cherenkov photons.

Cherenkov threshold is $\beta_0=1/n=0.75$ ($T_0=54$ MeV for muons and 0.26 MeV for electrons) with n = 1.34, refractive index of water. Half-aperture of light cone is $\theta = \cos^{-1}(1/\beta n)$ (θ ~41^o at $\beta=1$).

The photon density is $dN/dx=1.9\ 10^{-2}\{1-1/(\beta n)^2\}$ VEMcm^{-1}





Goal

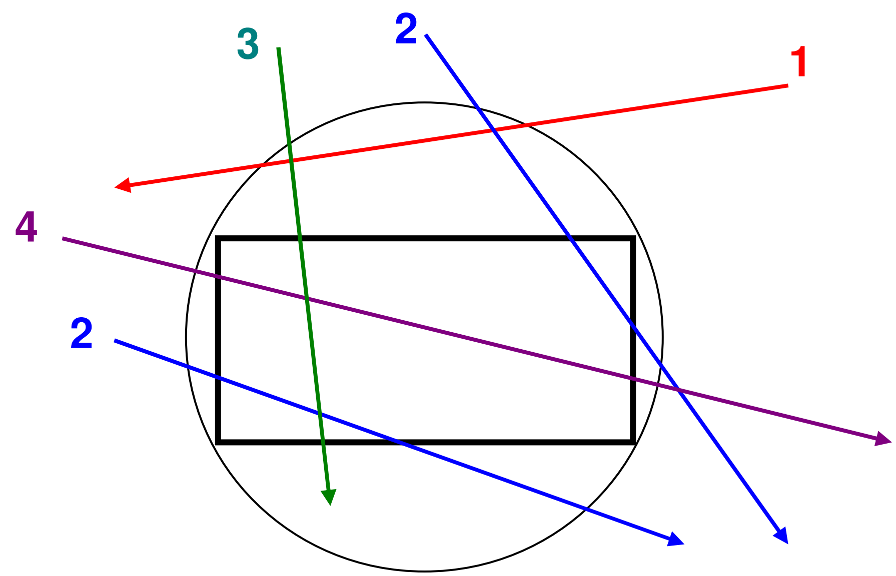
Predict stopping muon and decay electron signals in terms of rates and charges.

Simulation

✓ Muon trajectories are generated with an isotropic angular distribution.

✓ Their distance to the centre of water volume not exceeding $\frac{1}{2}\times3.8$ m.

✓ Each muon is given a weight $(1-0.108\ \sin^2\theta)\cos^2\theta$.



✓ A muon must stop in the tank to produce any detectable decay electron.

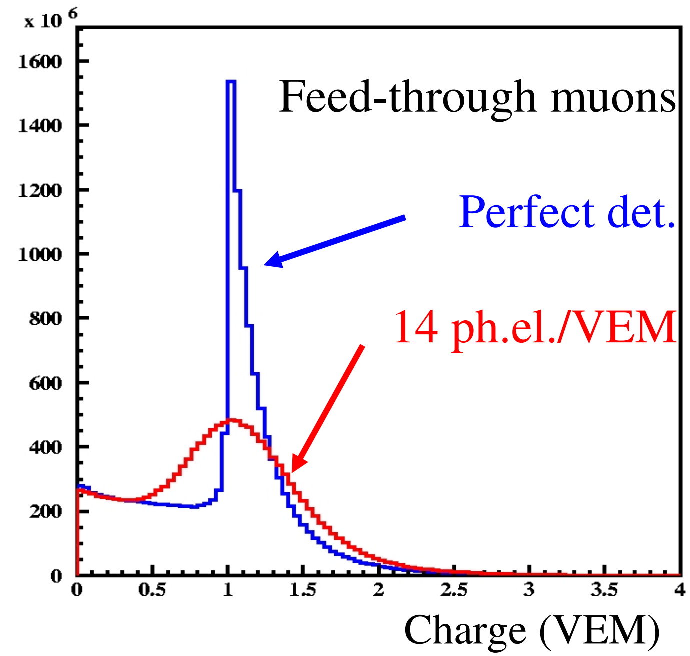
✓ A muon may produce no detectable photon either because it misses the tank or because its kinetic energy is lower than the Cherenkov threshold.

What to expect? Three different families of tracks

Family	1 Missing	2 Wall-plate	3 Plate-Plate	4 Wall-wall
Abundance	9.7%	42.2%	47%	1.1%
% stopping	-	5.3%	7.8%	9.2%
<VEM> fd-thr	-	0.73	1.19	1.47
<VEM> stop	-	0.22	0.28	0.55
$< f >$	-	0.74	0.81	0.84

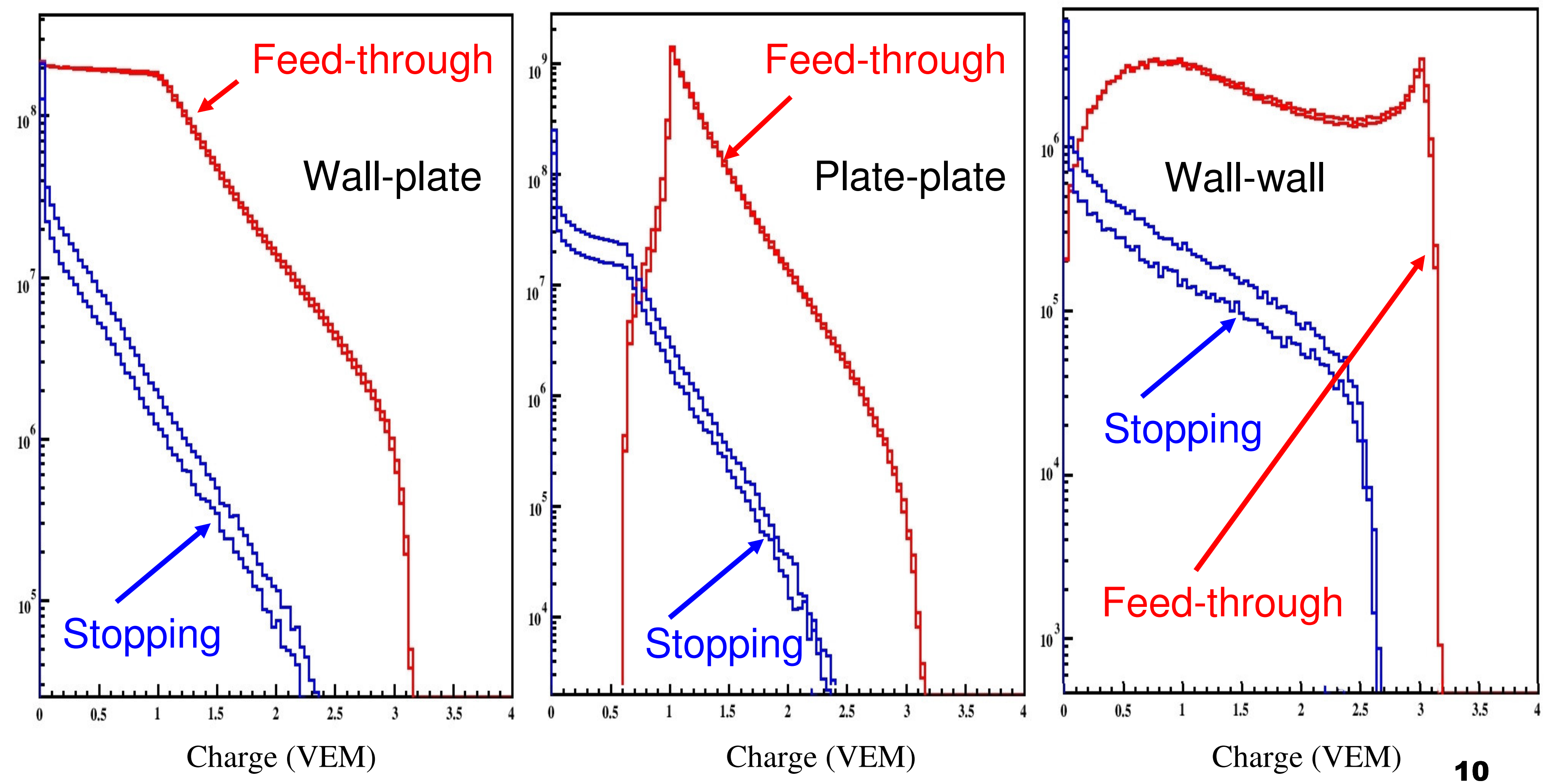
E_{mean}= *4* Gev

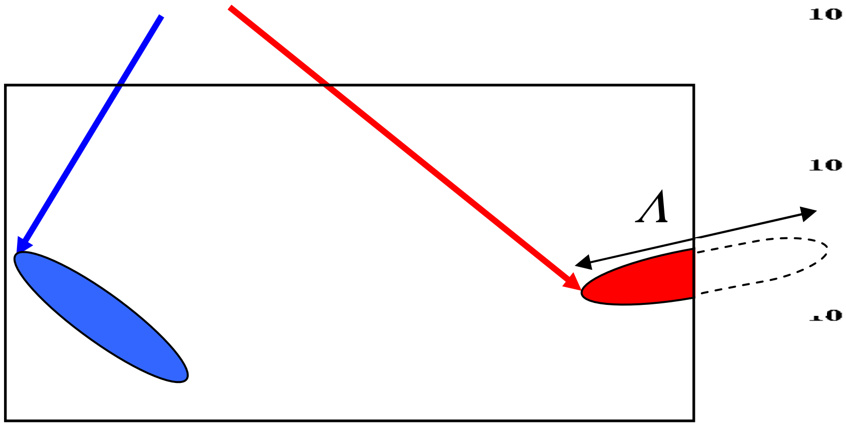
~7% of muons crossing the detector will be stopped

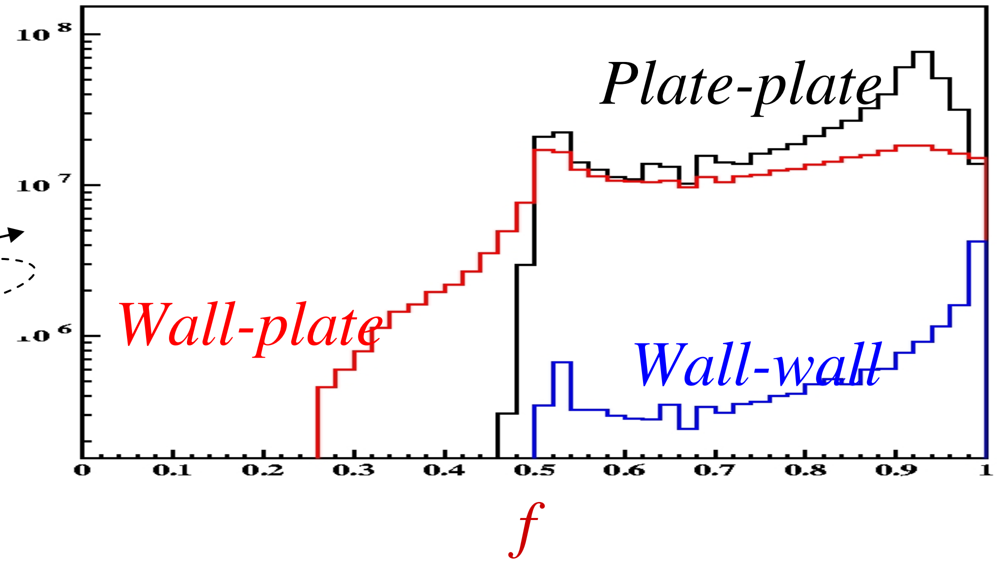


The expected rate is ~1.4 kHz for feed-through muons and ~20 Hz for coincidences of two feed-through muons in a window of 10 μs. The total stopping muon rate is at the 100 Hz scale. Of these, only a fraction will be detected and an even smaller fraction will produce a detectable decay electron.

Charge distributions for both feed-through muons and stopping muons do not depend much on the energy spectrum (E_{mean}=3 and 5 GeV).





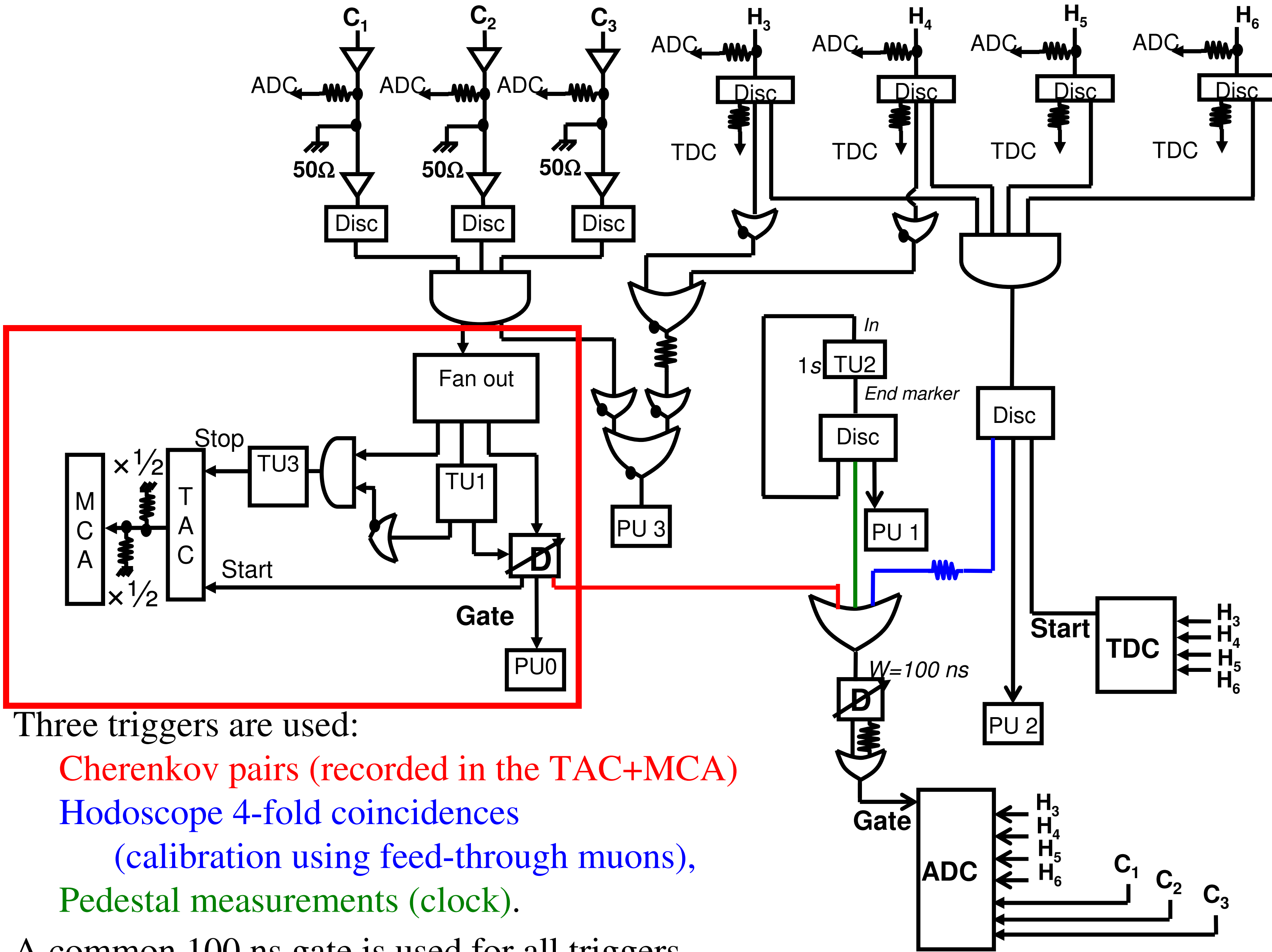


$$S_{sh} \propto f \times E$$

Shower size parameter Λ is the maximum longitudinal development of the electron shower. The factor f is the fraction of the electron shower energy contained inside the tank, [0, 1].

The energy E of the decay electron has a distribution of the form $d\Gamma/dx=2(3x^2-2x^3)$ with $x=2E/M_\mu c^2$ between 0 and 1. $\langle x \rangle \sim 0.7$, meaning $\langle E \rangle \sim 37$ MeV, a very low energy: in practice only the high energy tail will be detected.

3. Data collection and analysis



Three triggers are used:

Cherenkov pairs (recorded in the TAC+MCA)

Hodoscope 4-fold coincidences

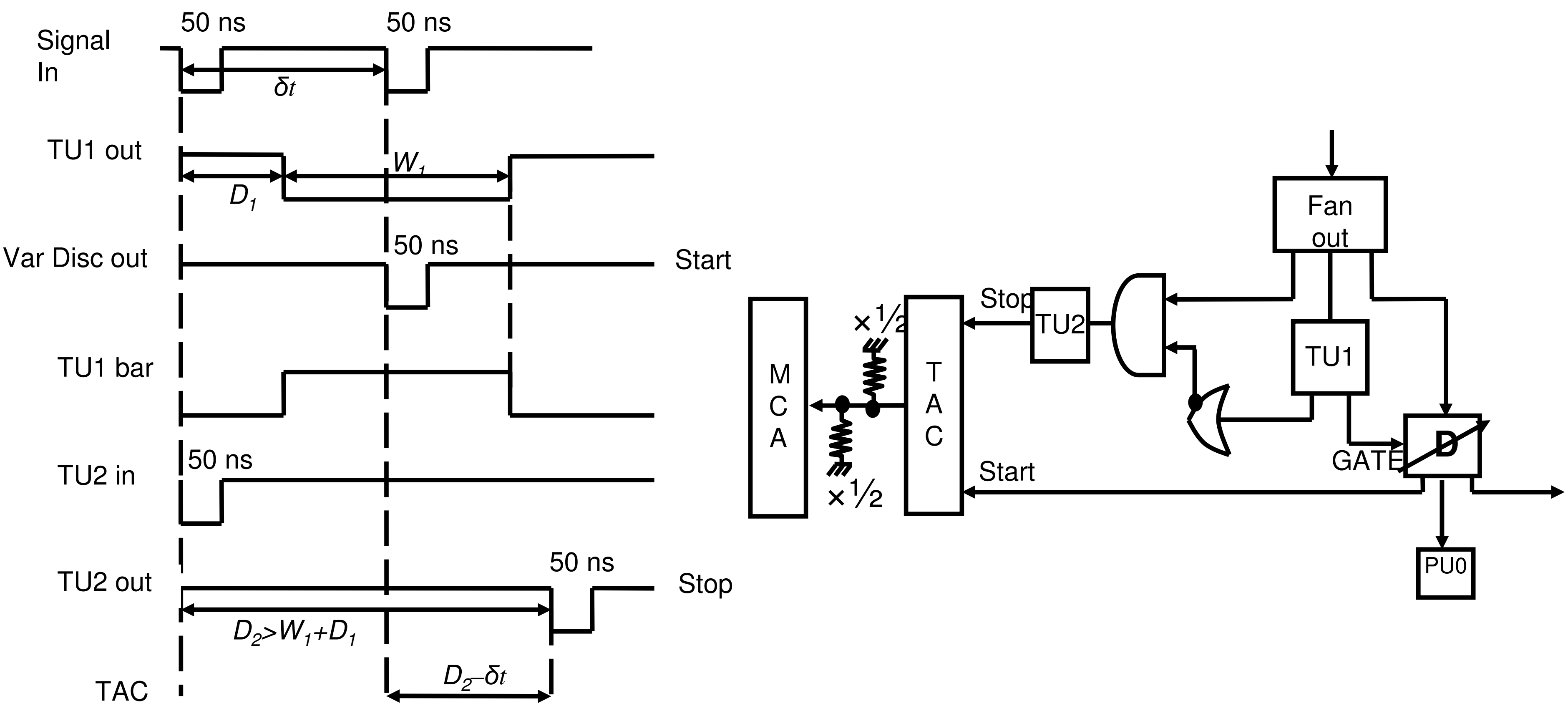
(calibration using feed-through muons),

Pedestal measurements (clock).

A common 100 ns gate is used for all triggers.

Data collection and analysis: time auto-correlations

To deal with low rates, we select pairs of consecutive signals within a ~10 μs window. This implies waiting for 10 μs before deciding and imposes to start the TAC by the second signal and stop it by the first delayed by ~10+D_1 μs (D_2).



We measure time auto-correlations using a TAC and a MCA. Single rates are ~2 kHz. δt is the time interval between two consecutive signals.

Time spectra are fitted to a form

$$R\exp(-R\delta t)+g_0 R_{sh}\exp(-R_{sh}\delta t)+\varphi\rho_+ R_+\exp(-R_+\delta t)+\varphi\rho_- R_+\exp(-R_-\delta t)$$

another muon from another shower, rate R

another muon from the same shower (g_0, R_{sh})

a positron from a μ^+ decay (no capture)

an electron from a μ^- decay (includes capture)

The known values

ρ_+ =0.56 ; ρ_- =0.44; R =2 kHz; R_+ =1/2.2 $(\mu s)^{-1}$; R_- =0.55 $(\mu s)^{-1}$

The fitted parameters

g_0 and R_{sh} for the multimuon contribution.

φ for the electron contributions at seven different threshold values.

The number of parameters to be adjusted is 9

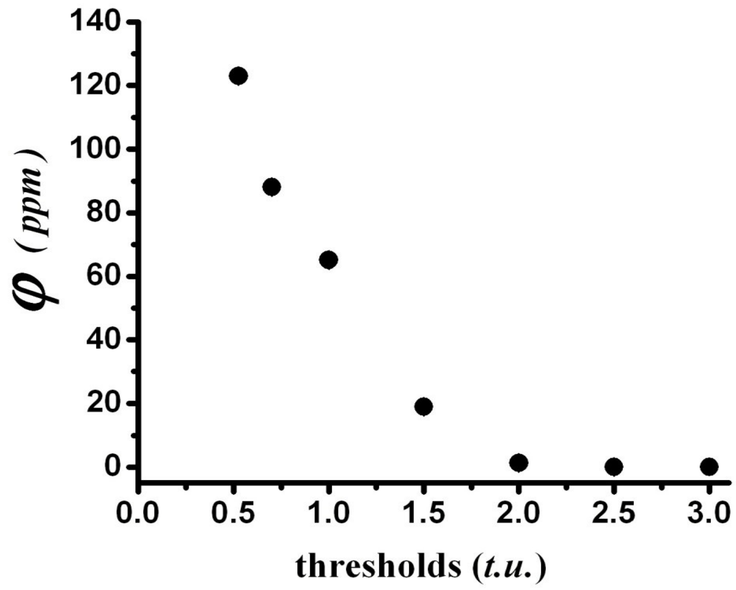
χ^2 = 1.020/degree of freedom

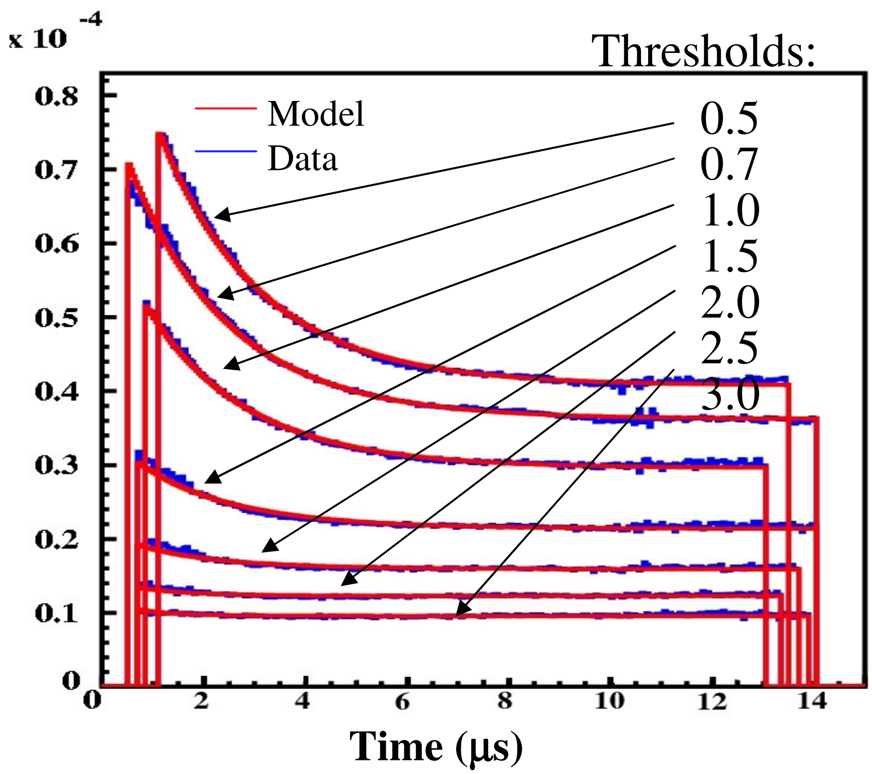
(of which there are 118'185)

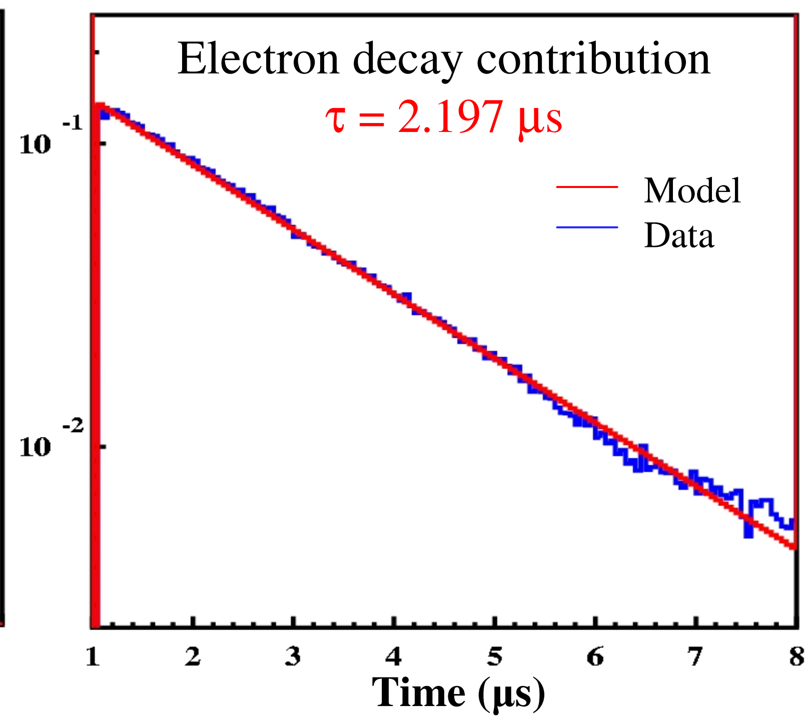
$g_0 = 0.79 \pm 0.05 \times 10^{-5}$

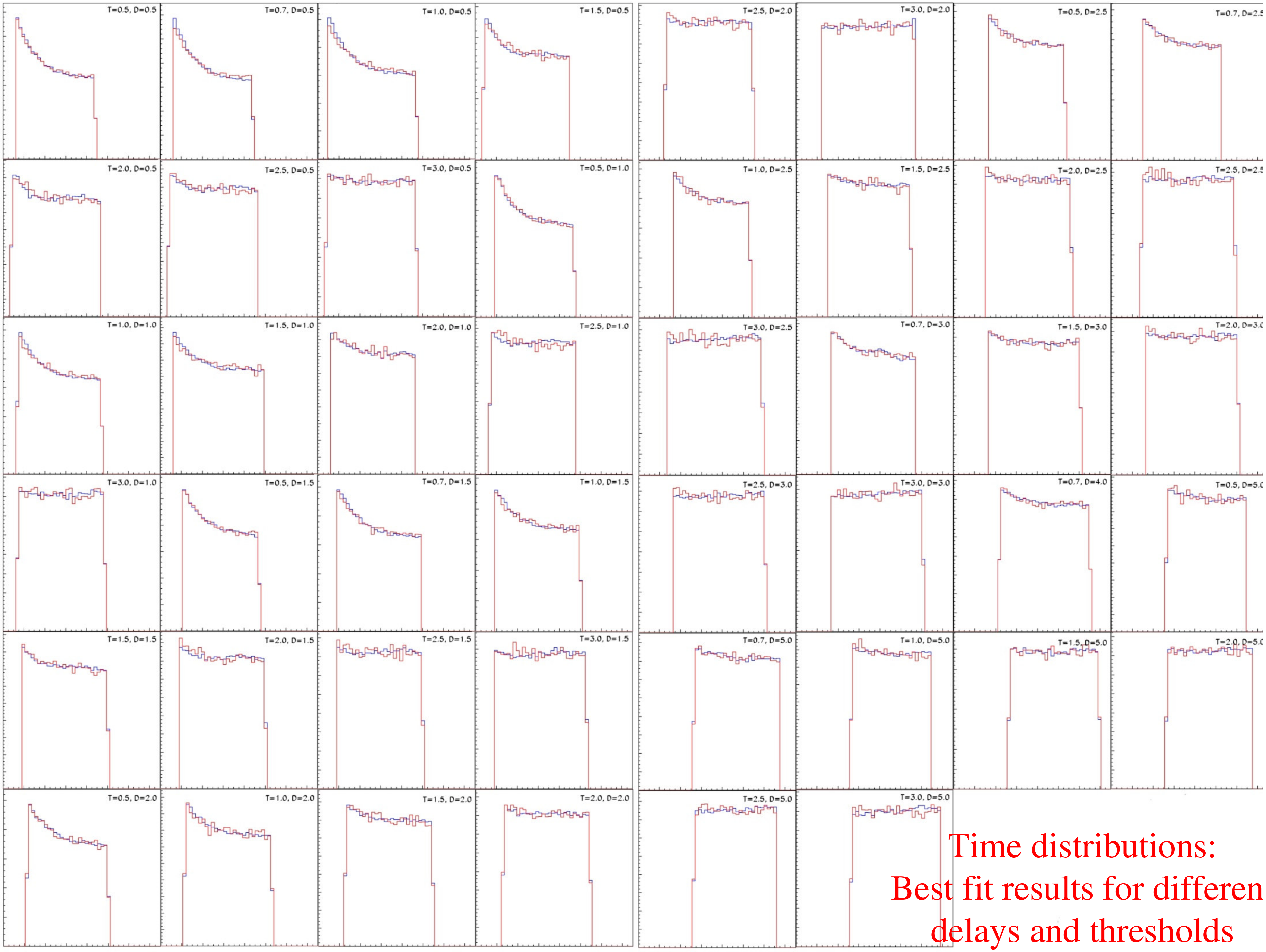
$R_{sh} = 0.89 \pm 0.03\ \mu s^{-1}$

$\rightarrow$ 7.0±0.5 Hz for the rate of multimuon in the same shower.





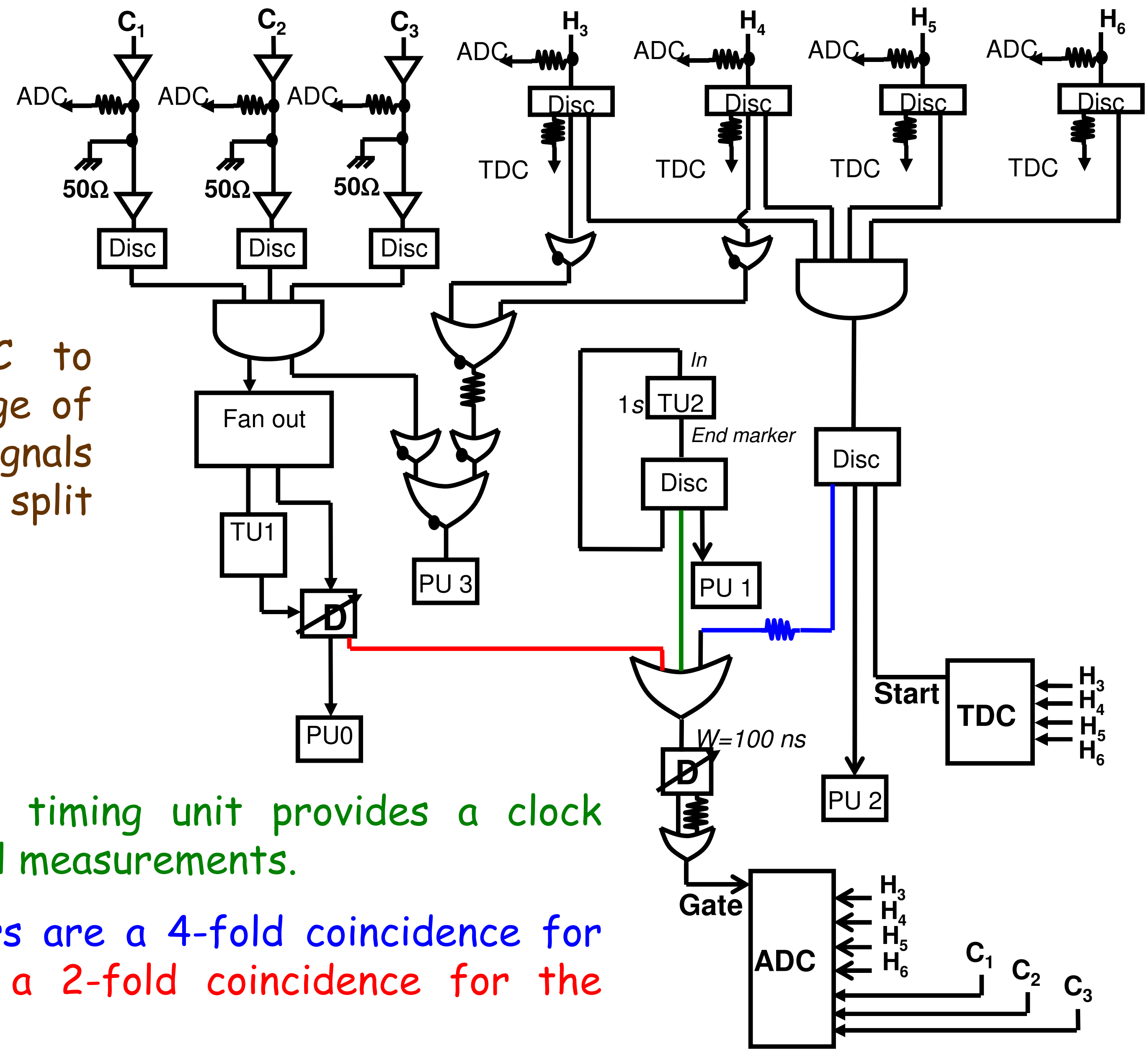




Time distributions:
Best fit results for differen
delays and thresholds

Data collection and analysis: charge distributions

We use an ADC to measure the charge of the Cherenkov signals that are passively split in two beforehand.



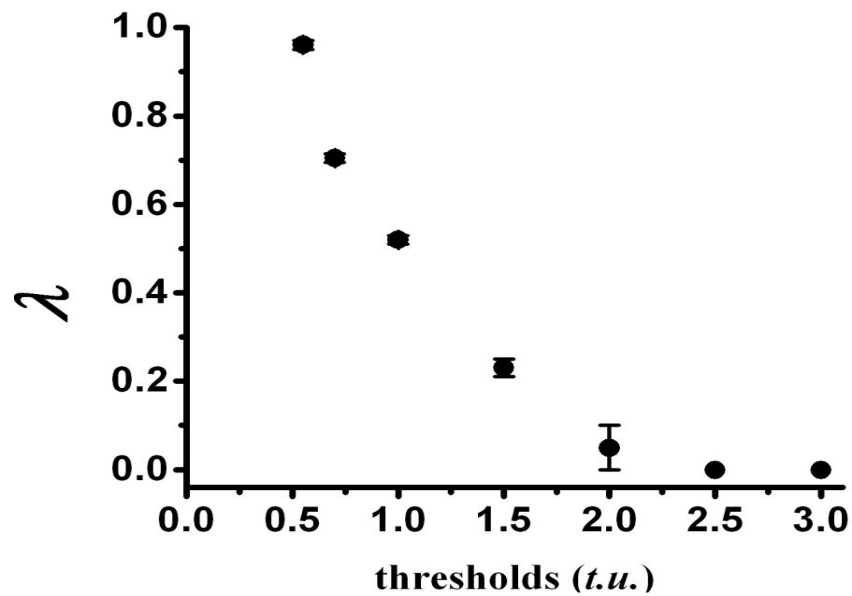
✓ A self-triggered timing unit provides a clock trigger for pedestal measurements.

✓ Standard triggers are a 4-fold coincidence for the hodoscope or a 2-fold coincidence for the Cherenkov.

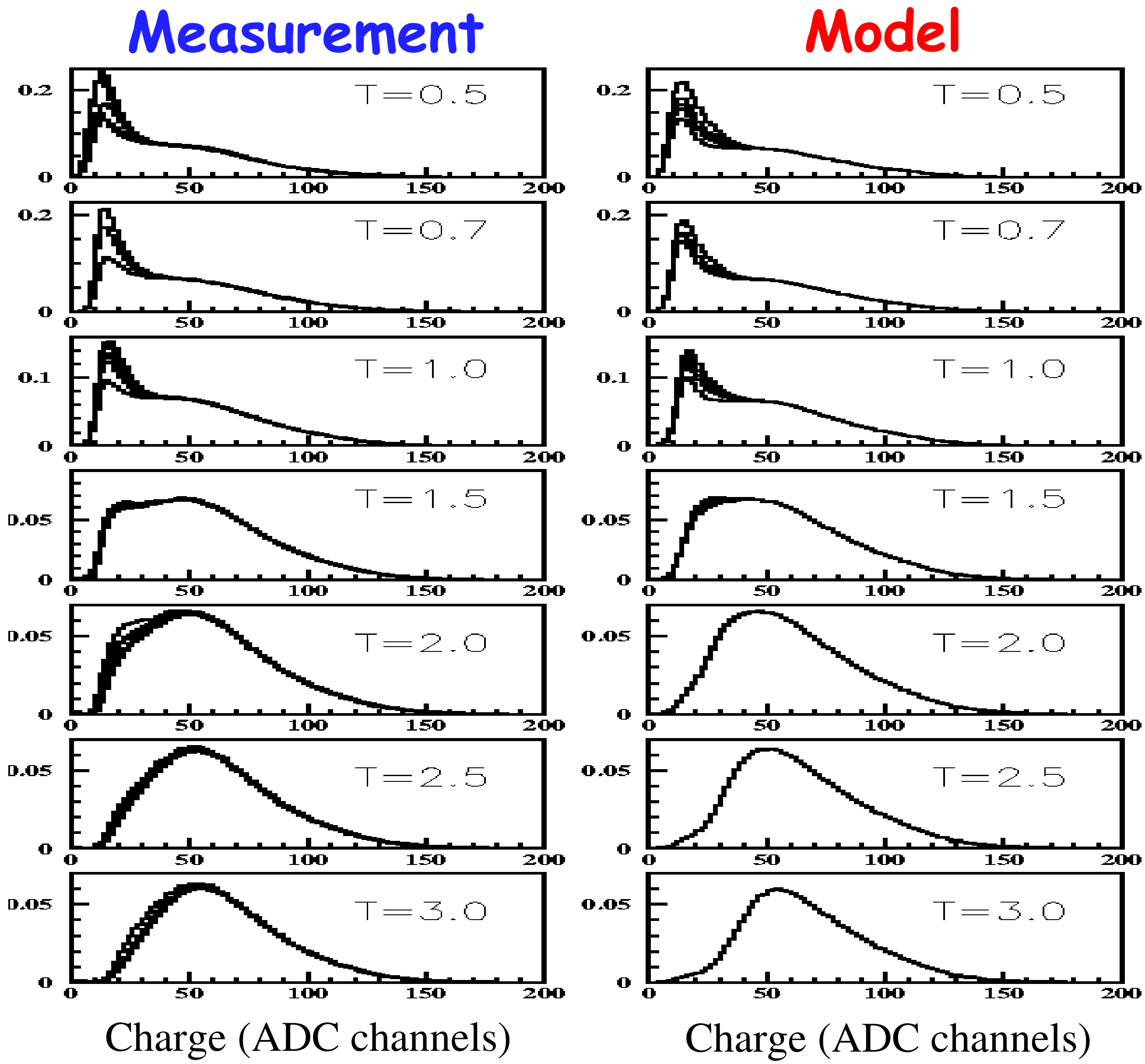
Charge spectra are fitted to the sum of a muon and an electron contributions:

$$S_{i,j,k}=N_{i,j}C_i\{F_\mu{}^k+\lambda_i exp(-(D_j/\tau)F_e{}^k\}$$

where i labels the threshold, j the delay and k the charge bin.



The sharp decrease of λ with threshold means that the evaluation of the electron contribution rests on low thresholds; higher thresholds are only good at fixing the muon contribution.

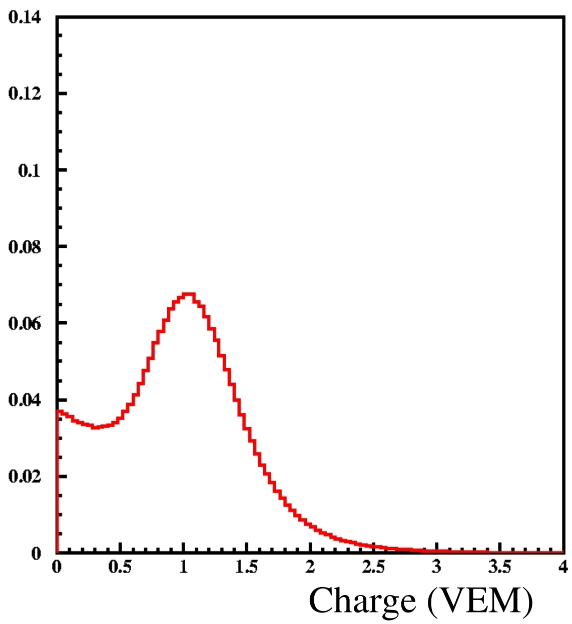


The quality of the fits is not very good, in particular at low charges

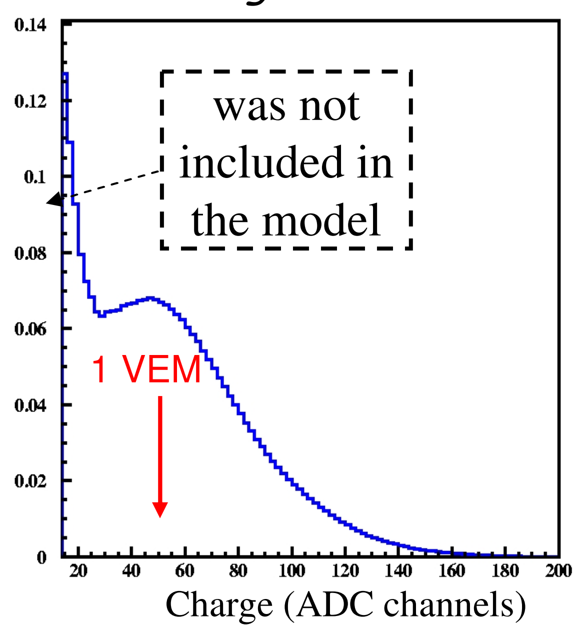
✓ The presence of a soft component adding to the muon component.

✓ The effect of discriminator thresholds on each of the two PMT pulses separately.

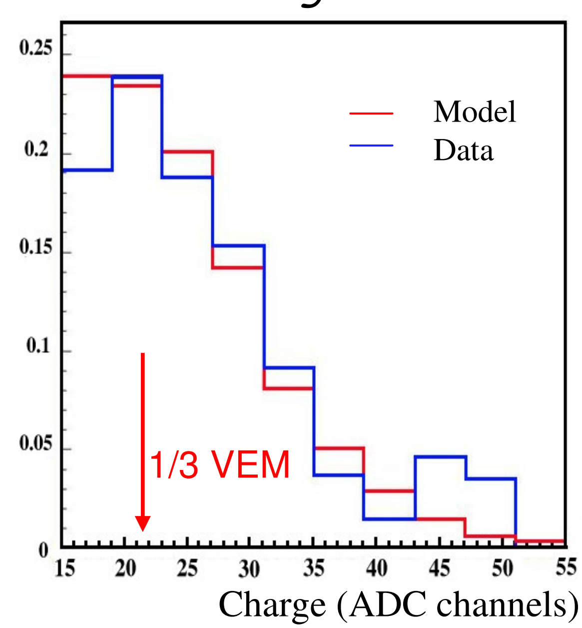
Muon charge prediction



"Muon" charge distribution



Electron charge distribution



4. Simulation and interpretation of the results

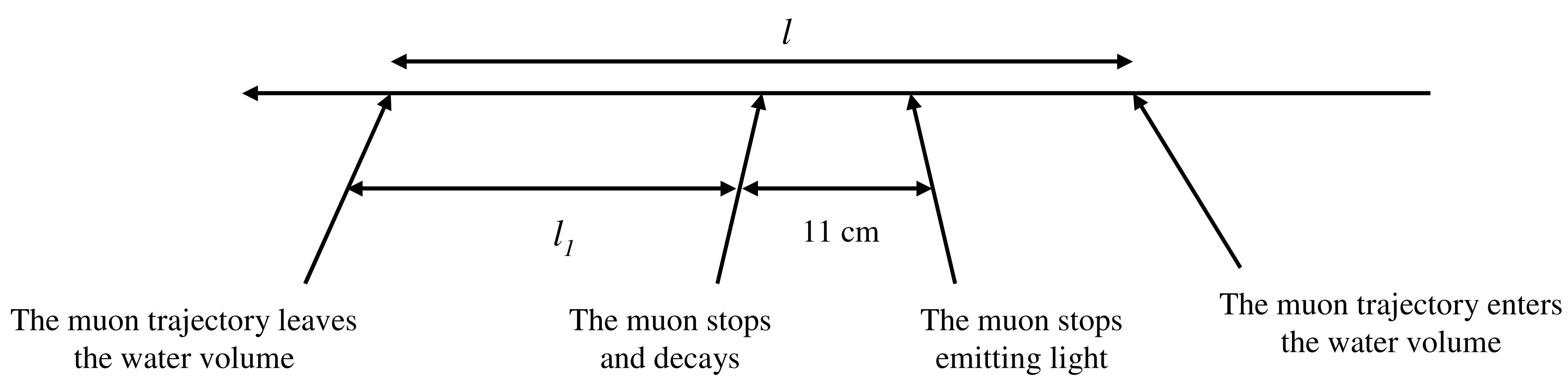
Having learned from the simple analysis above and from that of time autocorrelations. We use a simulation including a number of modifications.

✓ Contributions of muon decays into electrons/positrons, of cosmic muons and of a soft electron/positron/photon component.

✓ A cut-off function applied to each PMT separately.

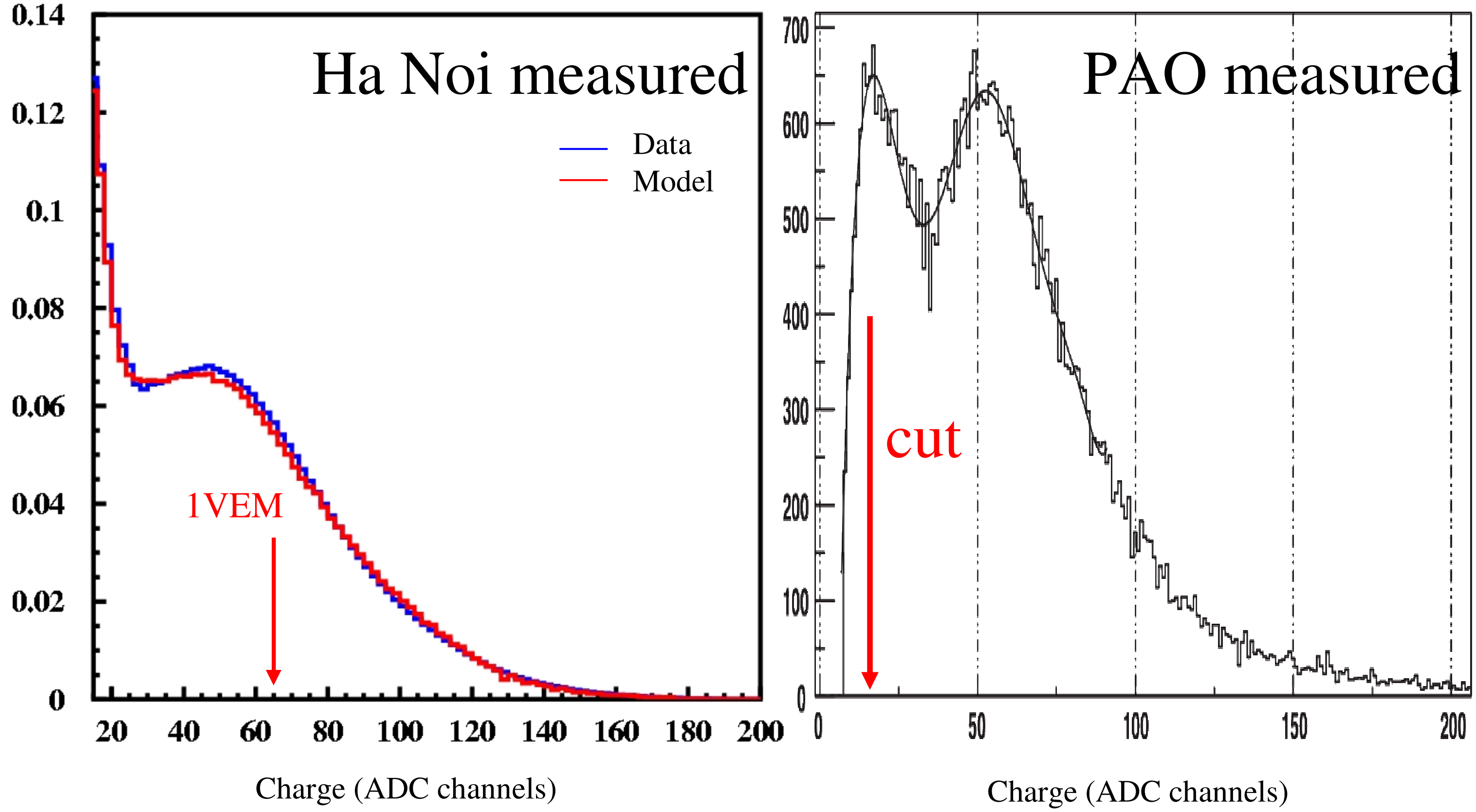
✓ A dependence on zenith angle of the light collection efficiency.

We now analyze simultaneously the time auto-correlation and charge distribution data, and compare them with the predictions of a detailed model of the physics at play and of the detection process.



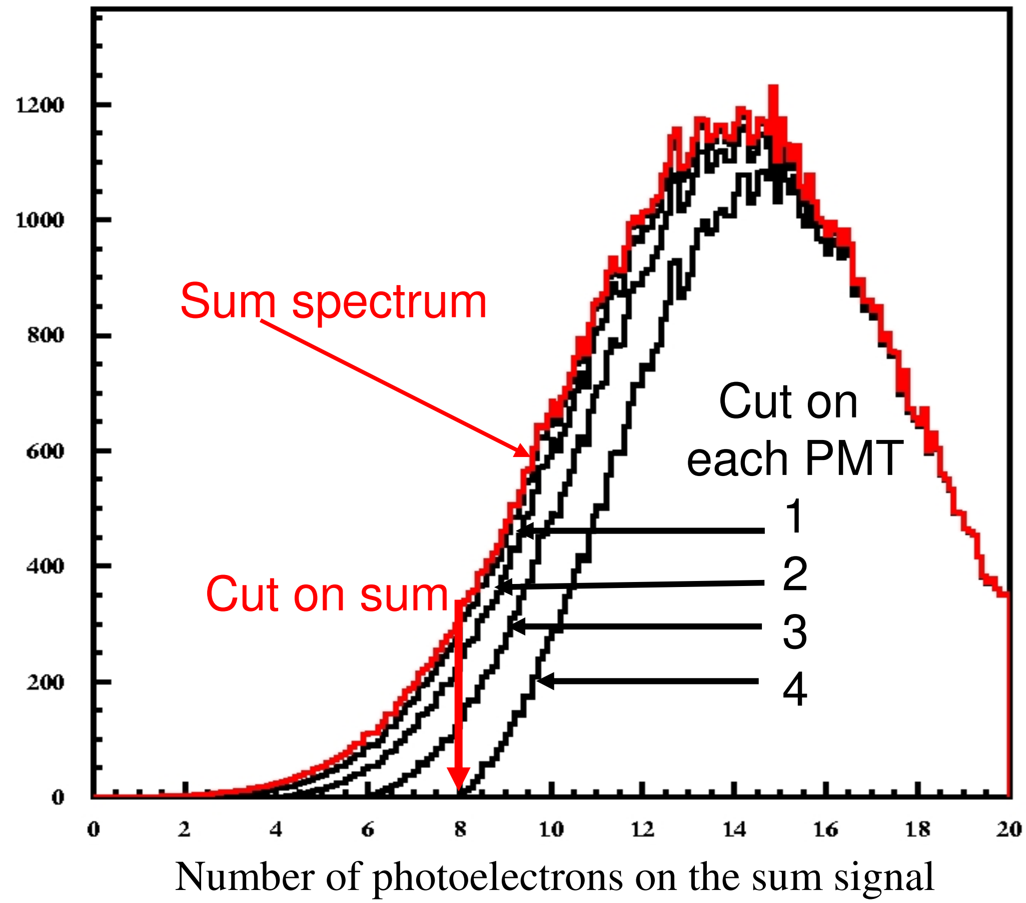
In both Hanoi and PAO data the inclusive charge distribution requires a soft component that we now include in the model as

$$dN/dq = q_{soft}^{-1} \exp(-q/q_{soft})$$

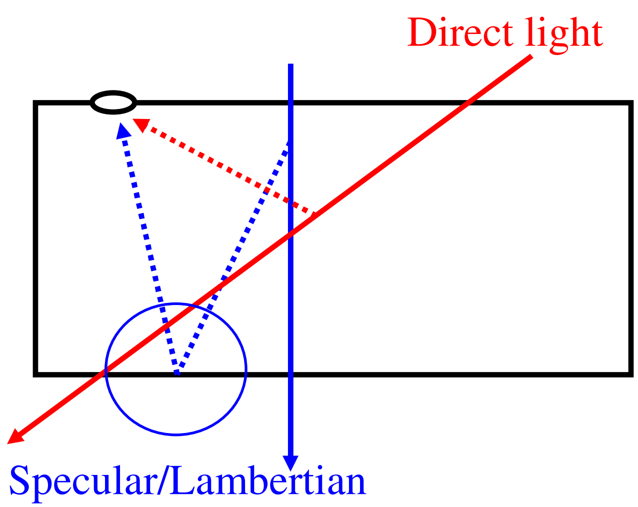


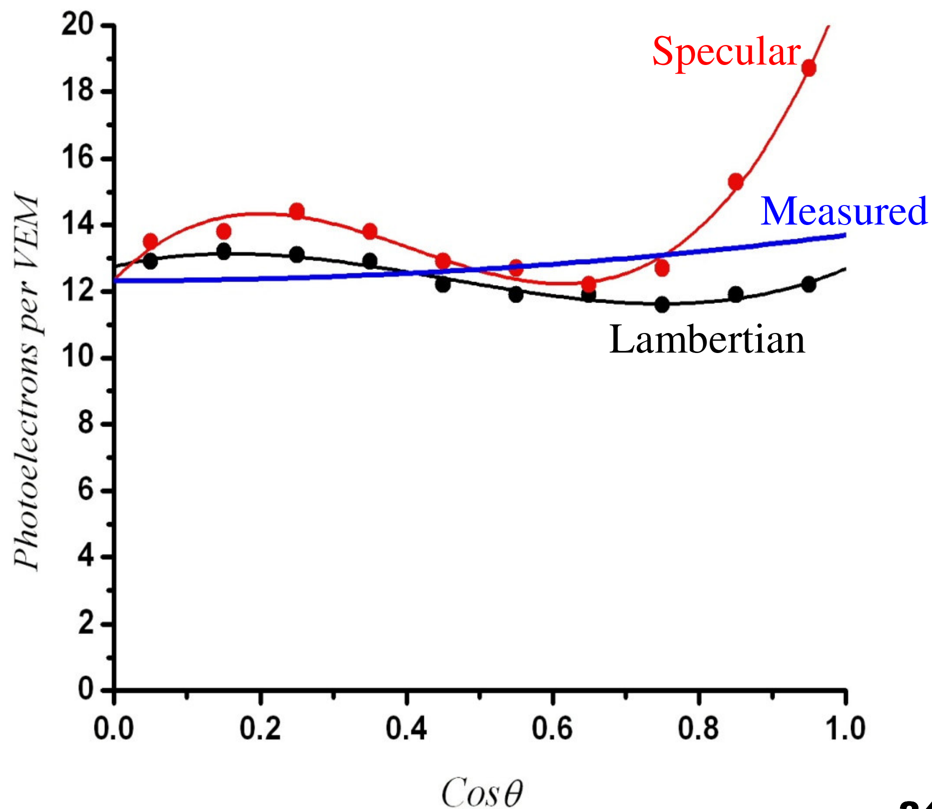
Threshold cut-offs: example of PMT signals Gaussian distributed around 7 photoelectrons with a σ of $\sqrt{7}$.

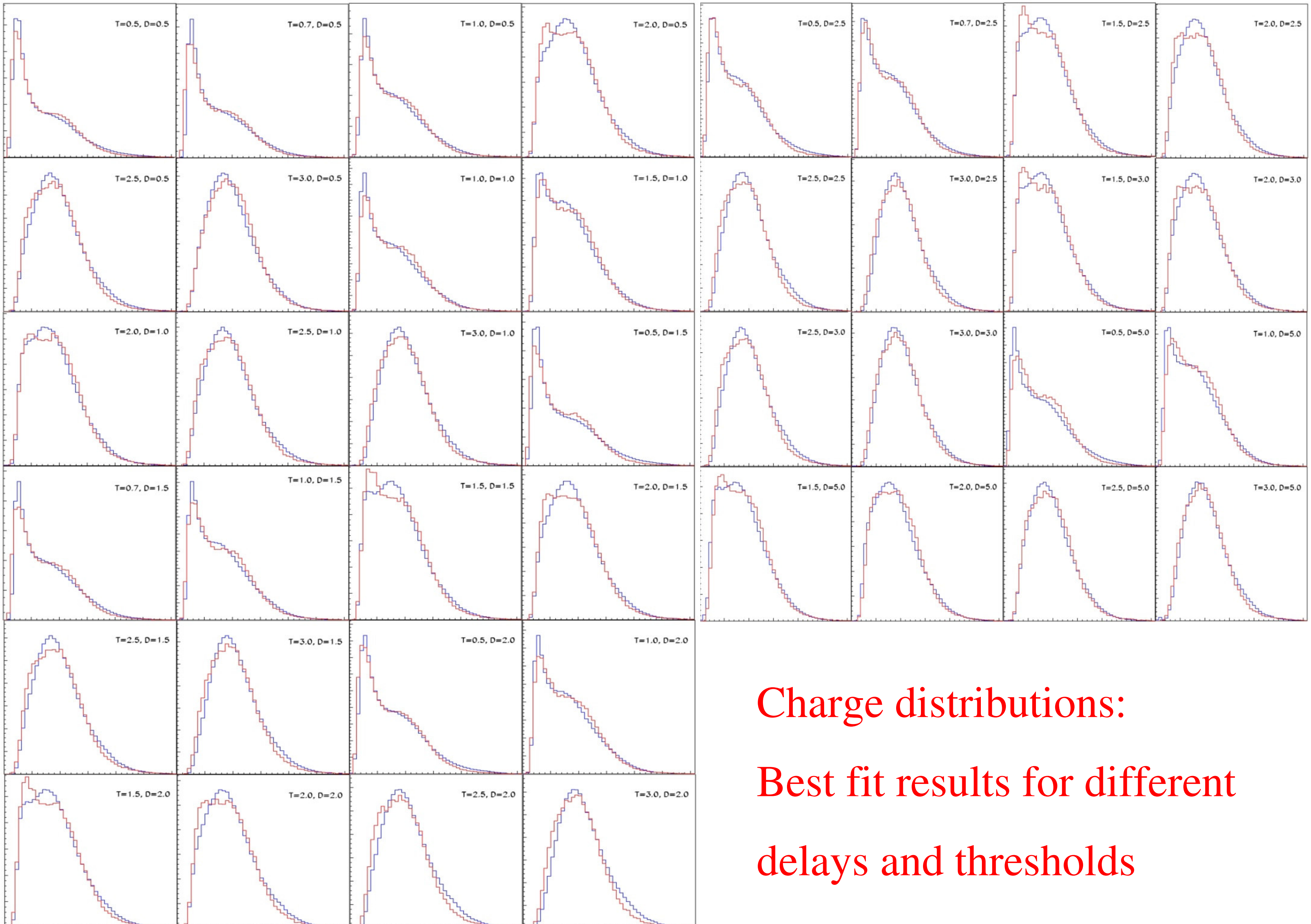
A cut on the sum **can not** reproduce cuts on individual PMTs.



We have also allowed for a possible dependence of the light collection efficiency on zenith angle, such as could be expected from direct light. Simulations assuming either specular reflection or Lambertian diffusion on the tank walls with efficiency η and an attenuation length Λ_{att} in water suggest Λ_{att}~20 m and η ~0.85.





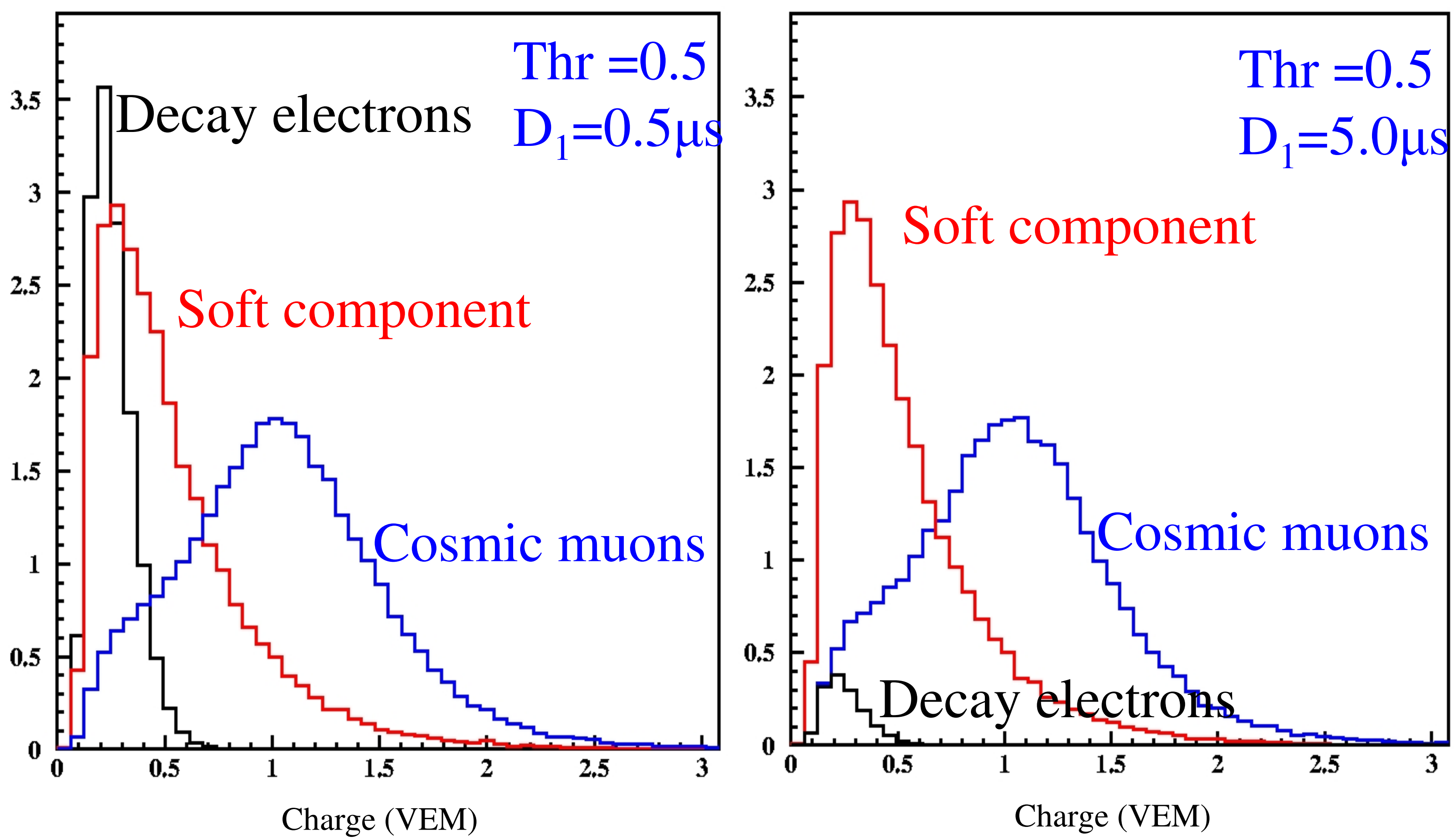


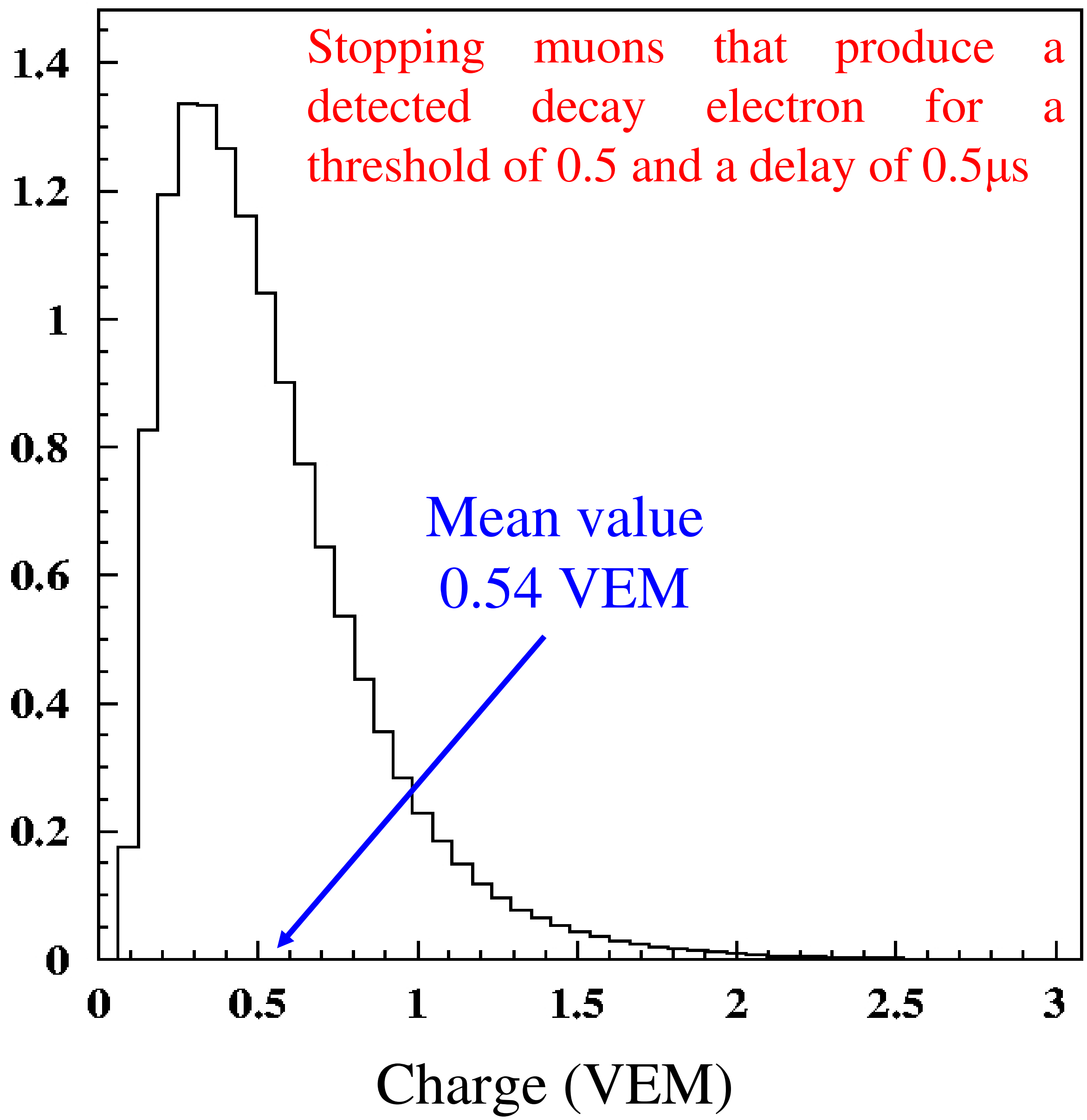
Charge distributions:

Best fit results for different

delays and thresholds

Respective contributions of the soft component, decay electrons and cosmic muons to the charge distribution

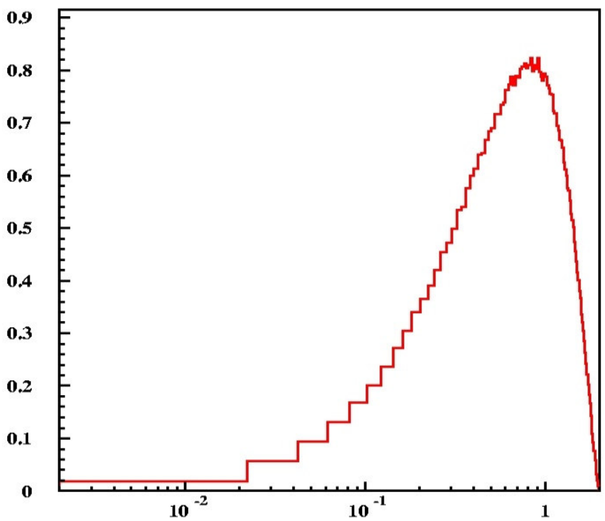



Stopping muons that produce a detected decay electron for a threshold of 0.5 and a delay of 0.5μs
Mean value
0.54 VEM
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
Charge (VEM)

The rate of multimuon in the same shower 7.0±0.5 Hz compared with an inclusive muon rate of ~2 kHz meaning a probability of 3.5‰ *(P)* to detect a second muon from the same shower when one has already been detected.

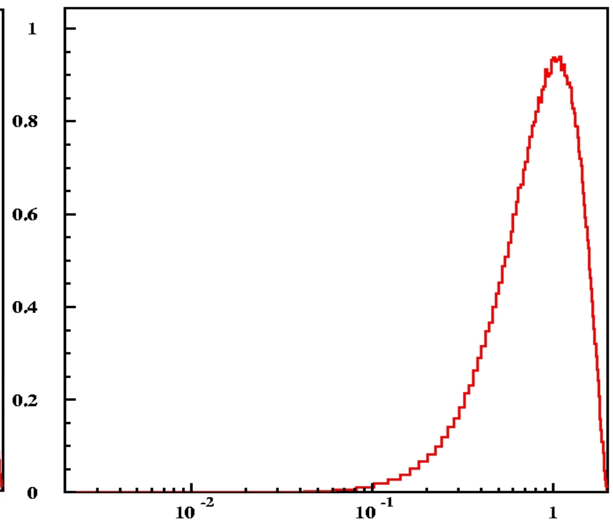
$$P=(m-1)(r_0/r_{sh})^2$$

For m=2, it means a shower radius of ~30 m.



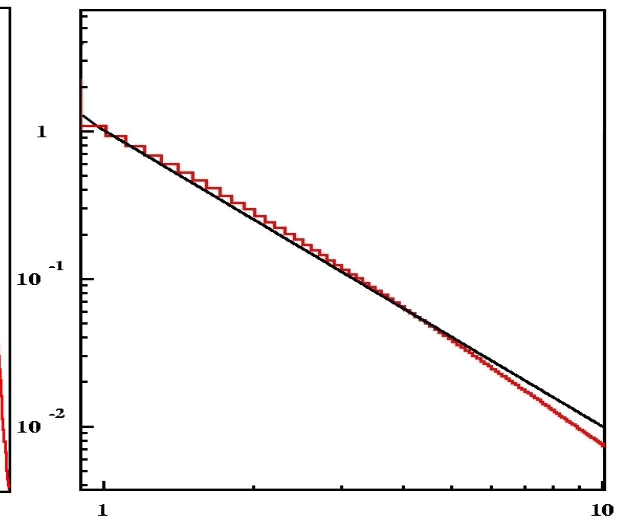
distance (m)

Distribution of the separation between two points on ground for a shower density distribution of the form $exp\,(-r)$



distance (m)

Distribution of the separation between two points in the Cherenkov tank for a uniform density distribution



r_{sh}/r_0

The probability to detect a second muon from the same shower, $r_{sh} > r_0$

5. Summary

- The number of photoelectrons per VEM is ν=13.0±0.9 in good agreement with our earlier estimate of 14 obtained from the width of the calibration curves.

- The value of the end point of the charge distribution of decay electrons is E_{end}= 0.275±0.018 VEM, consistent with PAO data (<E>=0.12 VEM).

- The soft component is described by f_{soft}= 0.795±0.012 and q_{soft}= 0.32±0.02 VEM but charges smaller than ~0.1 VEM are cut by the threshold.

- The value taken by the shower size parameter is Λ=36±6 cm, equal to the value of the radiation length in water as expected.

- The parameters describing the dependence of the cut-off function on threshold are measured with typical precisions of 10^{-3} VEM per threshold unit. It is essential to cut PMT 1 and PMT 2 charges separately

- We have simulated light attenuation in water (attenuation length Λ) and diffusion on the walls (efficiency η) and find the data to be consistent with Λ_{att} =20 m and η =0.85

- The mean muon kinetic energy is E_{mean}= $4.0^{+0.4}_{-0.3}$ GeV, in agreement with the expected value.

- For a muon multiplicity of 2, the shower radial size is ~30 m.

The availability of a replica of a PAO Cherenkov detector in our laboratory has proven to be useful not only for training purposes but also for contributing a better understanding of the response of such a detector, in particular to low amplitude signals at the level of a fraction of a VEM. It will continue to be used as a training tool for students, not only at the scale of the VATLY team but at a broader scale.

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THANK YOU FOR
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