Reconstruction of muon LDF using ADC and binary channels of UMD

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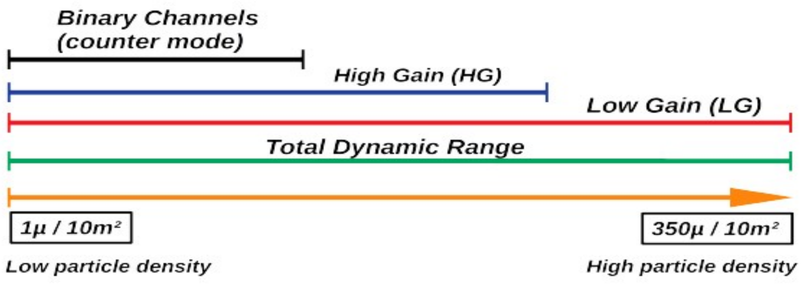
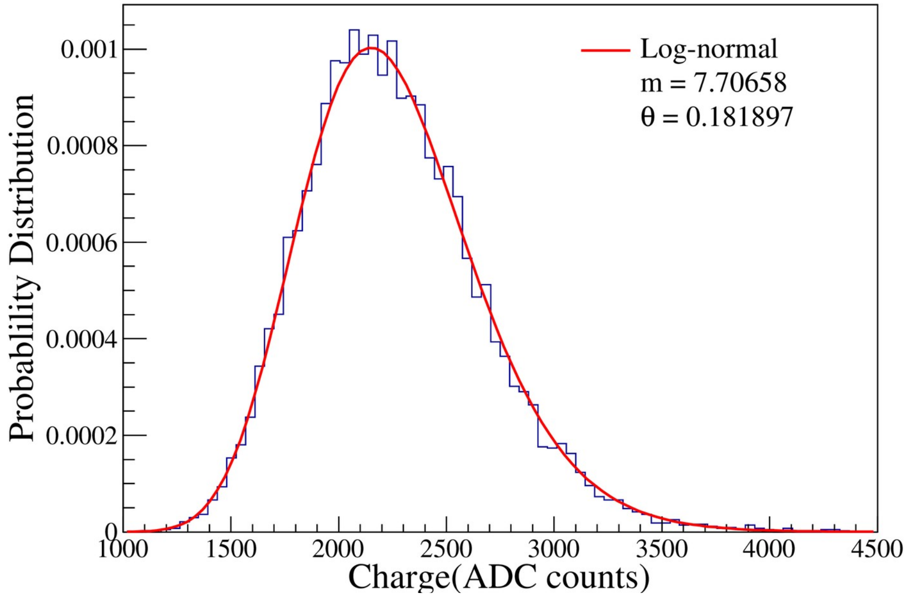
ITeDA

UMD ADC channel

- ADC channel estimates the number of muons in the detector by dividing the total signal charge by the mean charge of a single muon.
- The charge distribution of one muon is assumed to follow a lognormal distribution



[2]

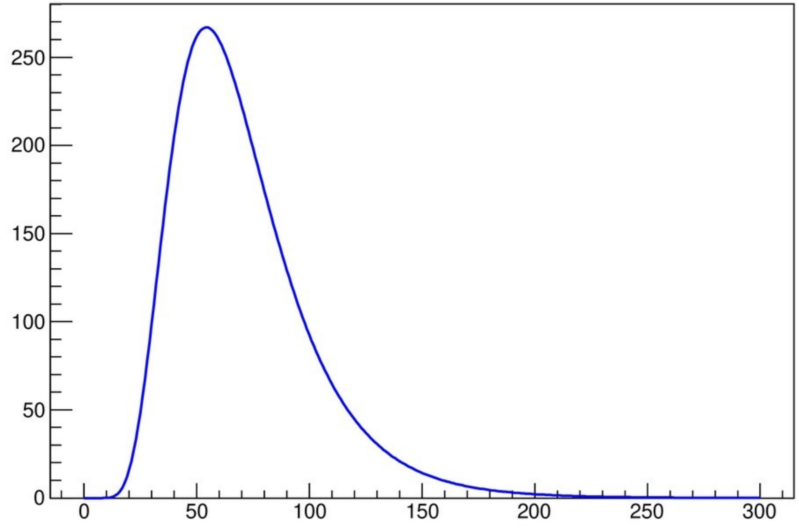


ADC Simulation

ADC signals can be described by, [3]

$$f(t;\mu,\sigma) = \frac{Q_J}{\sum_{i=1}^{N} \frac{e^{-\frac{(\ln(t_i - t_0) - \mu)^2}{2\sigma^2}}\Delta t}{t_i - t_0}} \cdot \frac{e^{-\frac{(\ln(t_i - t_0) - \mu)^2}{2\sigma^2}}\Delta t}{t_i - t_0}$$

Single signal

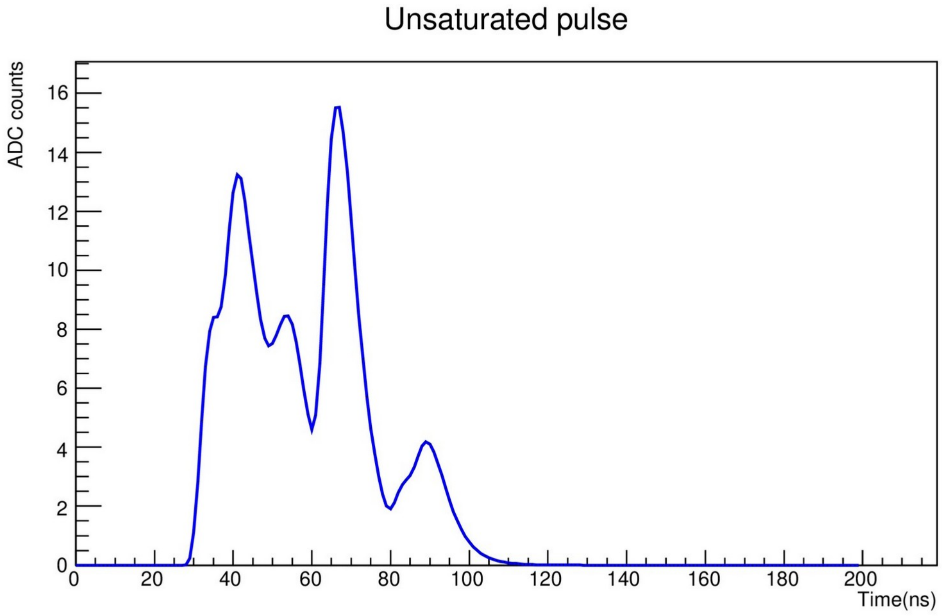


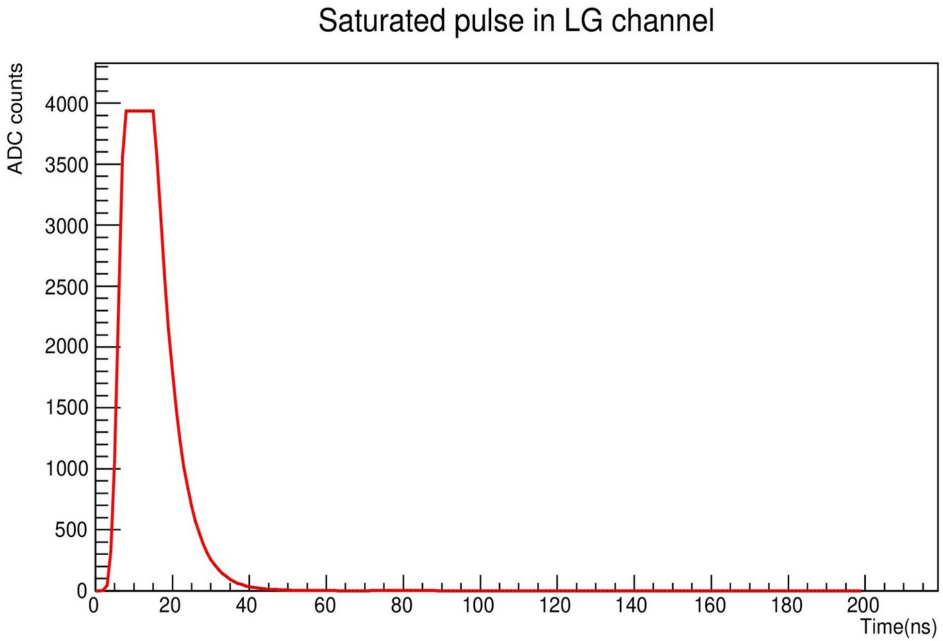
The saturation level of the signal is calculated as,

$$S_L = N_\mu \cdot \frac{Q_J e^{-\mu + \sigma^2/2}}{\sum_{i=1}^{N} \frac{e^{-\frac{(\ln(t_i - t_0) - \mu)^2}{2\sigma^2}}\Delta t}{t_i - t_0}}$$

$N_\mu = 3 \times 362$ for the LG channel [2]

ADC pulse shape

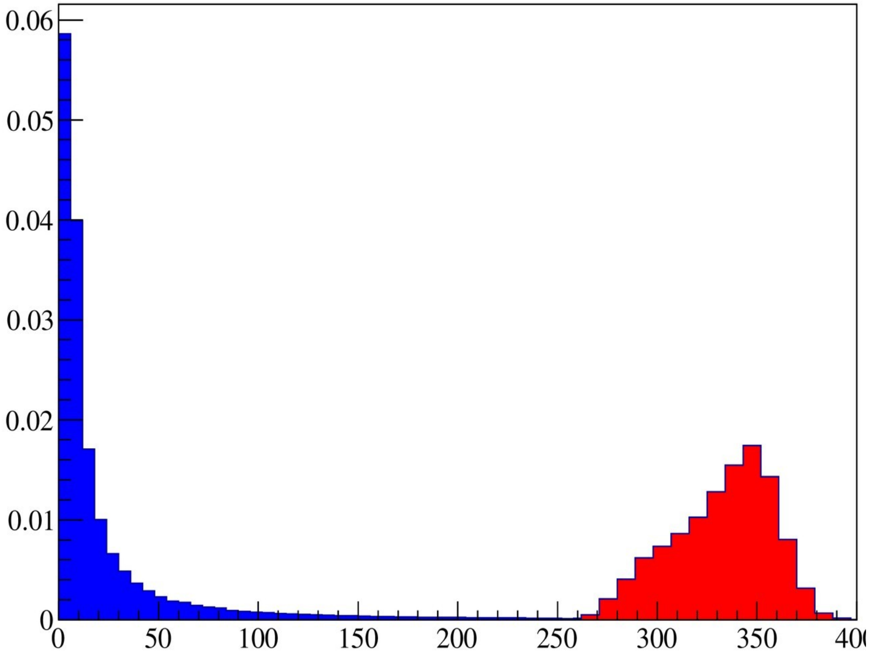




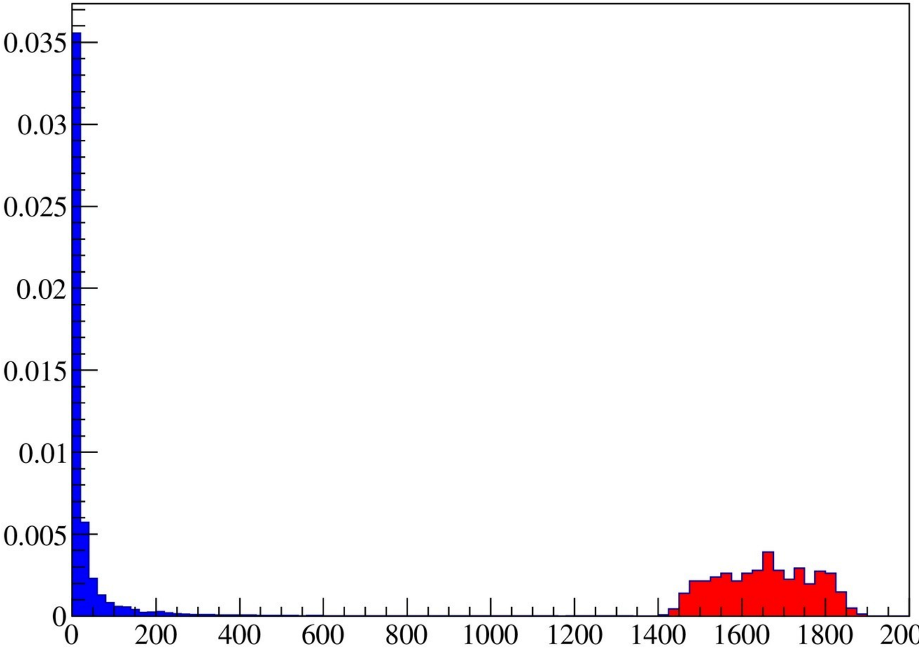
Multiple signals arriving at different times added to get a single pulse

Injected number of muons at the each channel

Binary



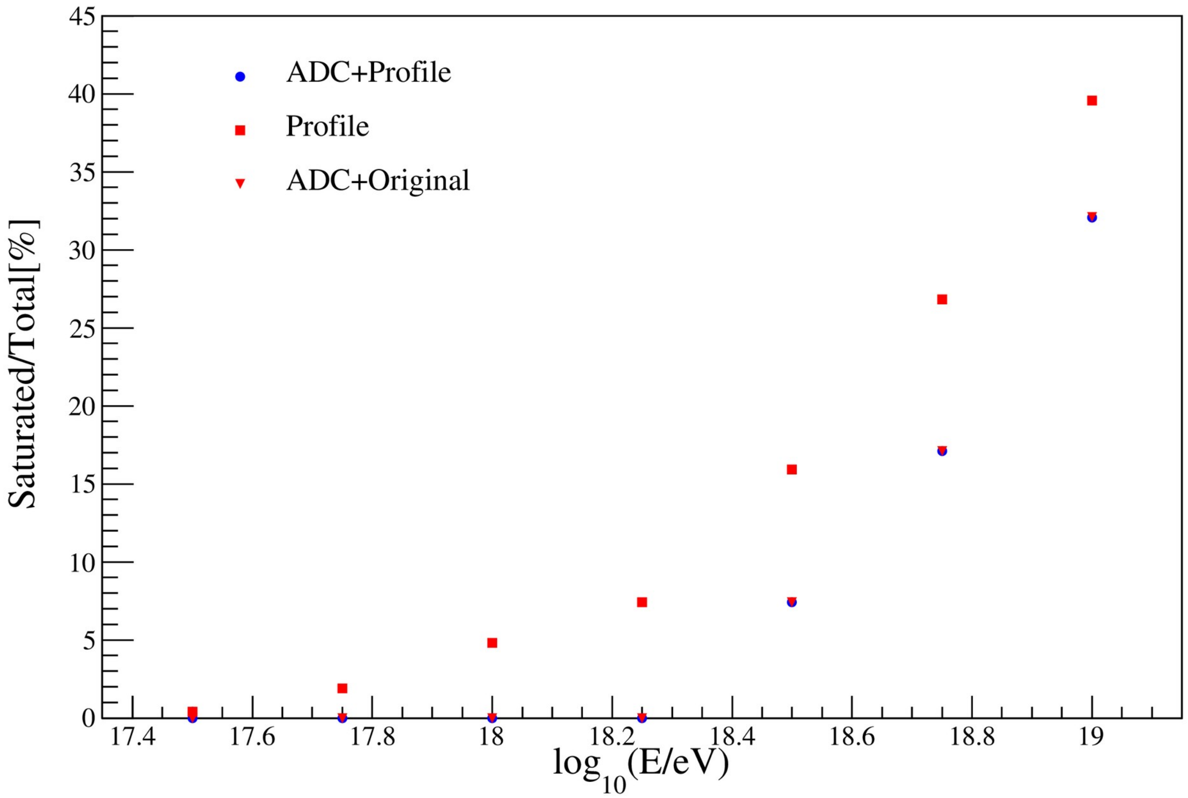
ADC



ADC increases the detection range

Saturated fraction of events

- Fraction of saturated events increases with energy.
- Detectors saturate less when ADC is included.



Current reconstruction method

- Profile/integrated likelihood method with the detector timing in the counter mode
- Original likelihood reconstruction method

Likelihoods used for the hybrid reconstruction method

- The MLDF $\mu(r_i, \vec{p})$ depends on the distance between the detector and the shower axis (r_i) and the free parameters in $\vec{p}$, obtained by maximising the likelihood function.

When binary channel is saturated and the estimated number of muons in the ADC channel is less than 200

$$\theta_n = \sqrt{\ln\left(1 + \frac{e^{\theta^2} - 1}{n}\right)}$$

$$m_n = m + \frac{\theta^2}{2} + \ln\left(\frac{n}{\sqrt{1 + \frac{e^{\theta^2}-1}{n}}}\right)$$

$$L = \sum_{n=1}^{n_{LG}} \frac{1}{\sqrt{2\pi}\theta_n n_{LG}} \cdot \exp\left(\frac{-(\ln(n_{LG}\left\langle q \right\rangle) - m_n)^2}{2\theta_n^2}\right) \cdot \frac{e^{-\mu(r_i;\vec{p})}\mu(r_i;\vec{p})^n}{(1 - e^{-\mu(r_i;\vec{p})})n!}$$

When binary channel is saturated and the estimated number of muons in the ADC channel is between 200 and the LG saturation limit (around 3×362),

$$\langle n \rangle = \frac{\mu(r_i;\vec{p})}{1 - e^{-\mu(r_i;\vec{p})}}$$

$$\sigma^2 = \langle n \rangle \left((\varepsilon^2 + 1) - \langle n \rangle e^{-\mu(r_i;\vec{p})} \right)$$

$$L = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(n_{LG} - \langle n \rangle)^2}{2\sigma^2} \right)$$

When the estimated number of muons in the ADC channel is greater than LG saturation limit (around 3×362)

$$L = 0.5 \times \left(1 - erf\left(\frac{n_{LG} - \langle n \rangle}{\sqrt{2\sigma^2}} \right) \right)$$

Simulations

CORSIKA simulated showers → average MLDF
+
muon time distribution

input for the detector simulations

- For each sampled event, the distance of the detector to the shower axis and arival time of each muon are obtained.
- The average LDF → expected number of muons (μ) → actual number of muons
- The LDF is fitted to the detector data by either minimizing the χ^2 or by maximizing a likelihood function. In this work, the method of maximizing a likelihood is used.

For each event μ(r) was adjusted using a second Kascade Grande like muon LDF.

$$\mu = \mu_0 \frac{g(r)}{g(r_0)}$$

$$g(r) = \left(\frac{r}{r_1}\right)^{-\alpha} \left(1 + \frac{r}{r_1}\right)^{-\beta} \left(1 + \left(\frac{r}{10 r_1}\right)^2\right)^{-\gamma}$$

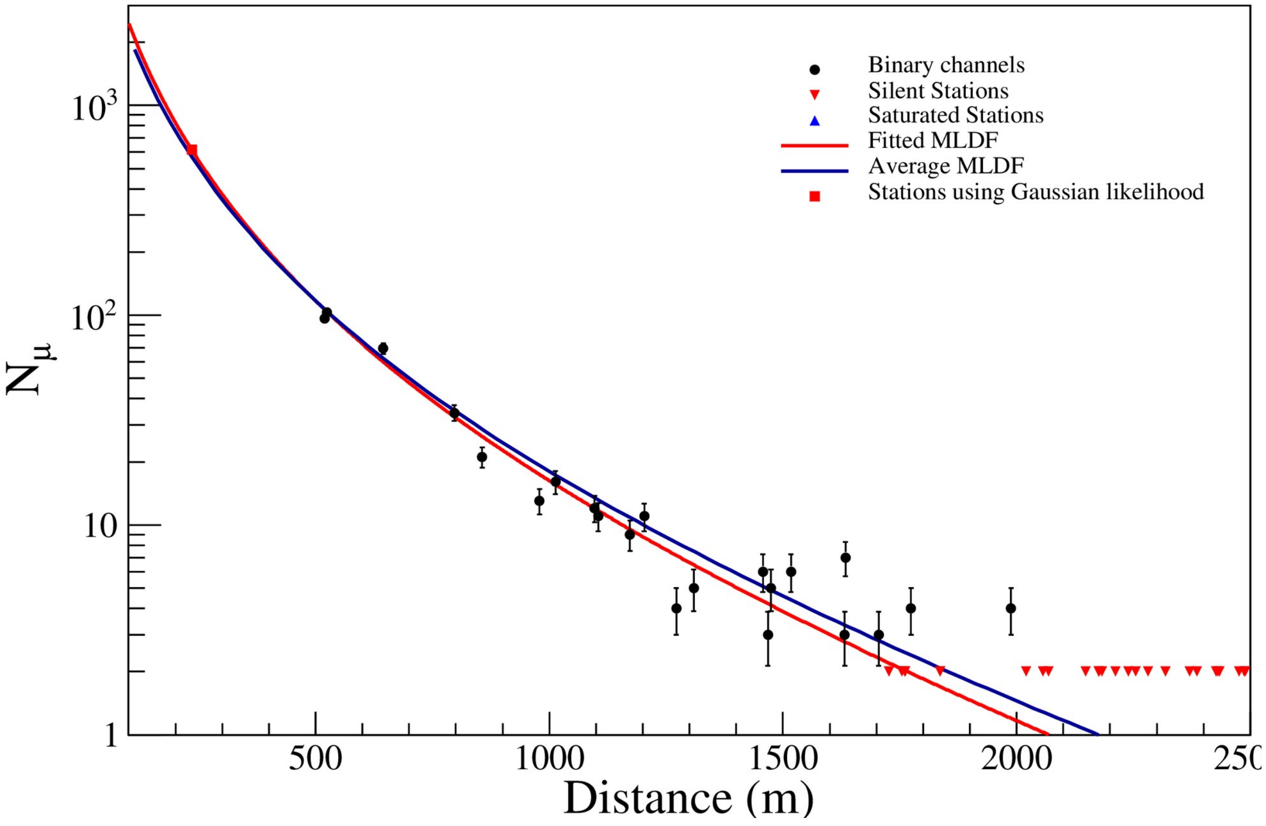
$\alpha = 0.75$
$r_1 = 320$m
$\gamma = 2.55$

r → distance to the shower axis measured in the shower plane

μ_0 and β are adjusted by minimizing the function

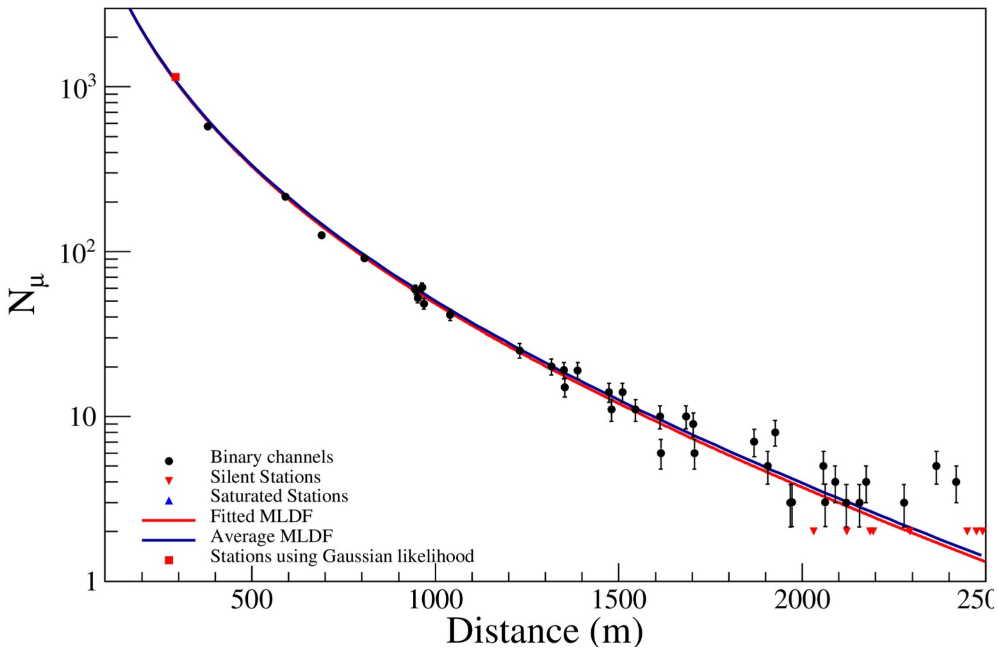
$$-2\ln(L_{fit}(\mu_0, \beta)) = -2 \sum_i \ln L_i(\mu(r_i, \mu_0, \beta))$$

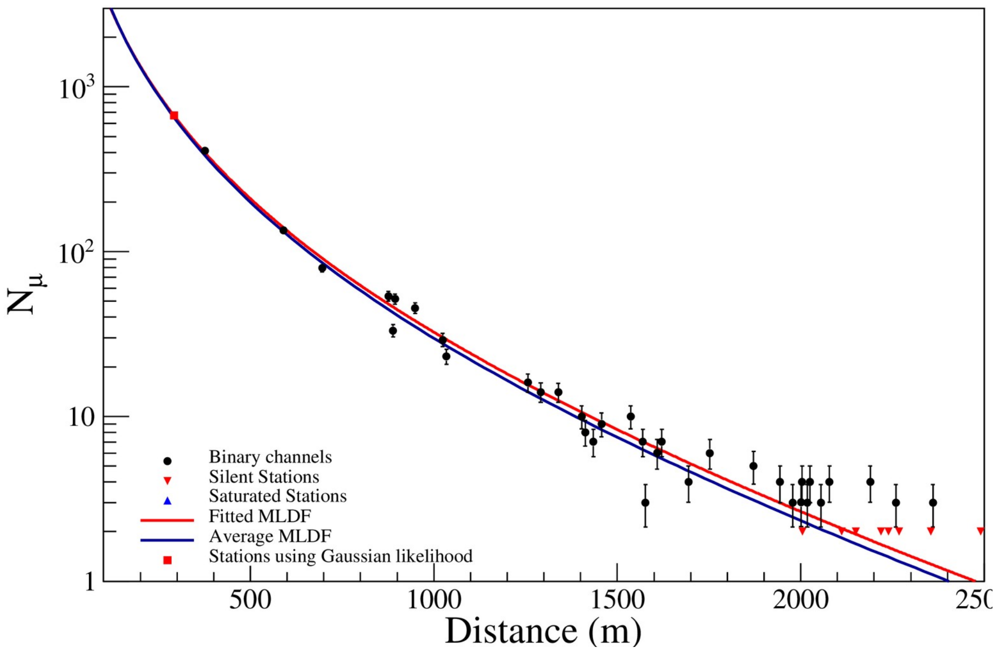
MLDF fitted to simulated detector data



Iron primaries
Time bin 40 ns
$\log_{10}(E/eV) = 18.5$
$\theta = 30°$

Examples of events

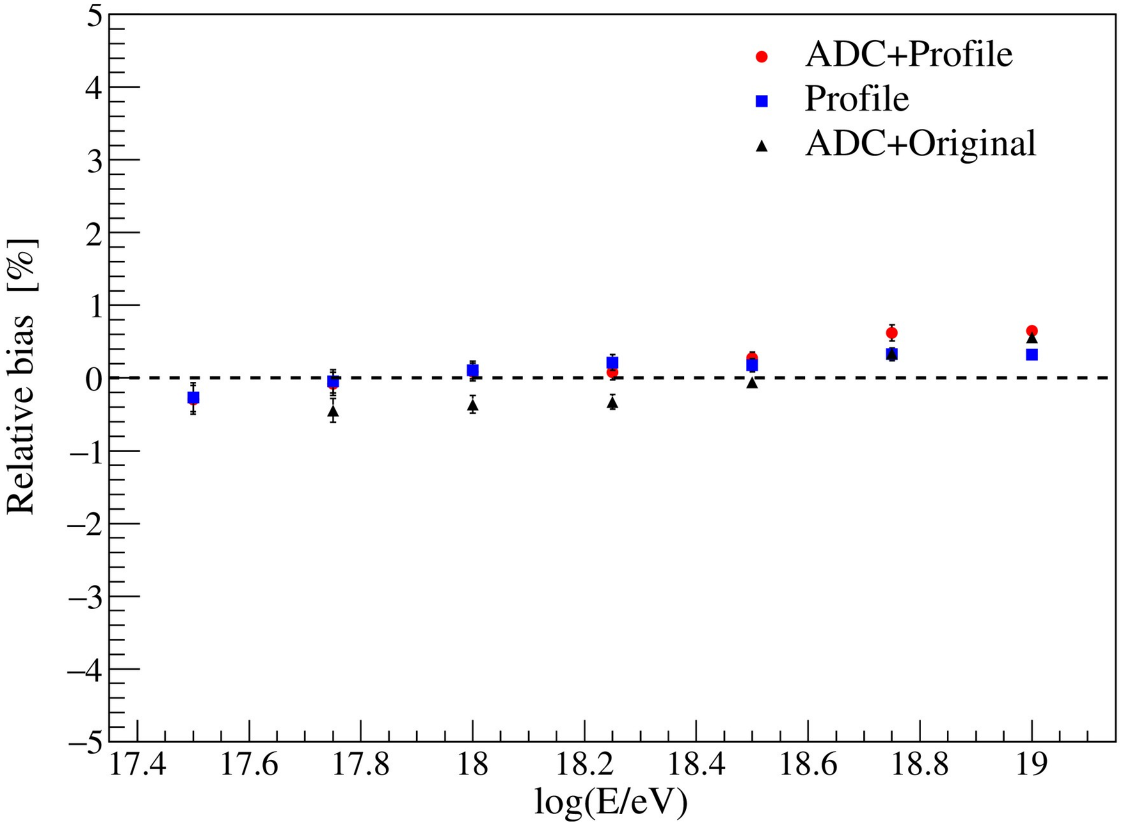




$\log_{10}(E/eV) = 19$

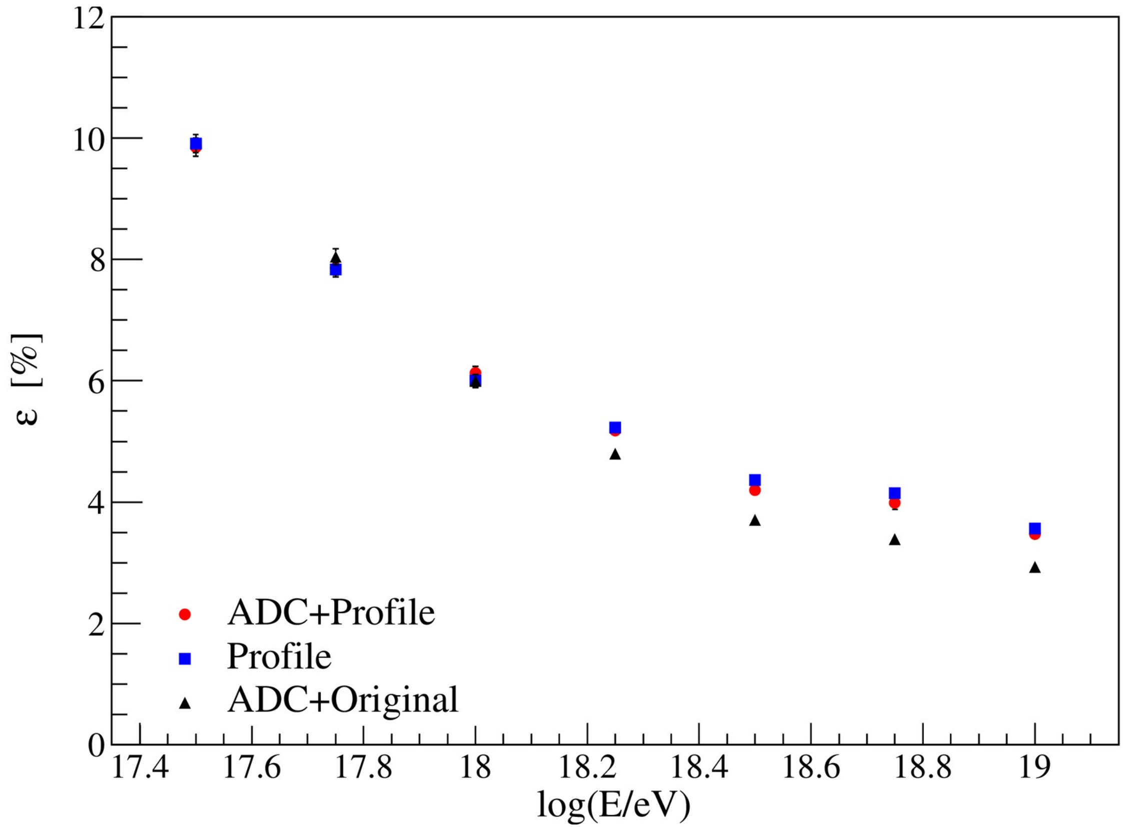
$\log_{10}(E/eV) = 18.75$

Reconstruction performance
Bias

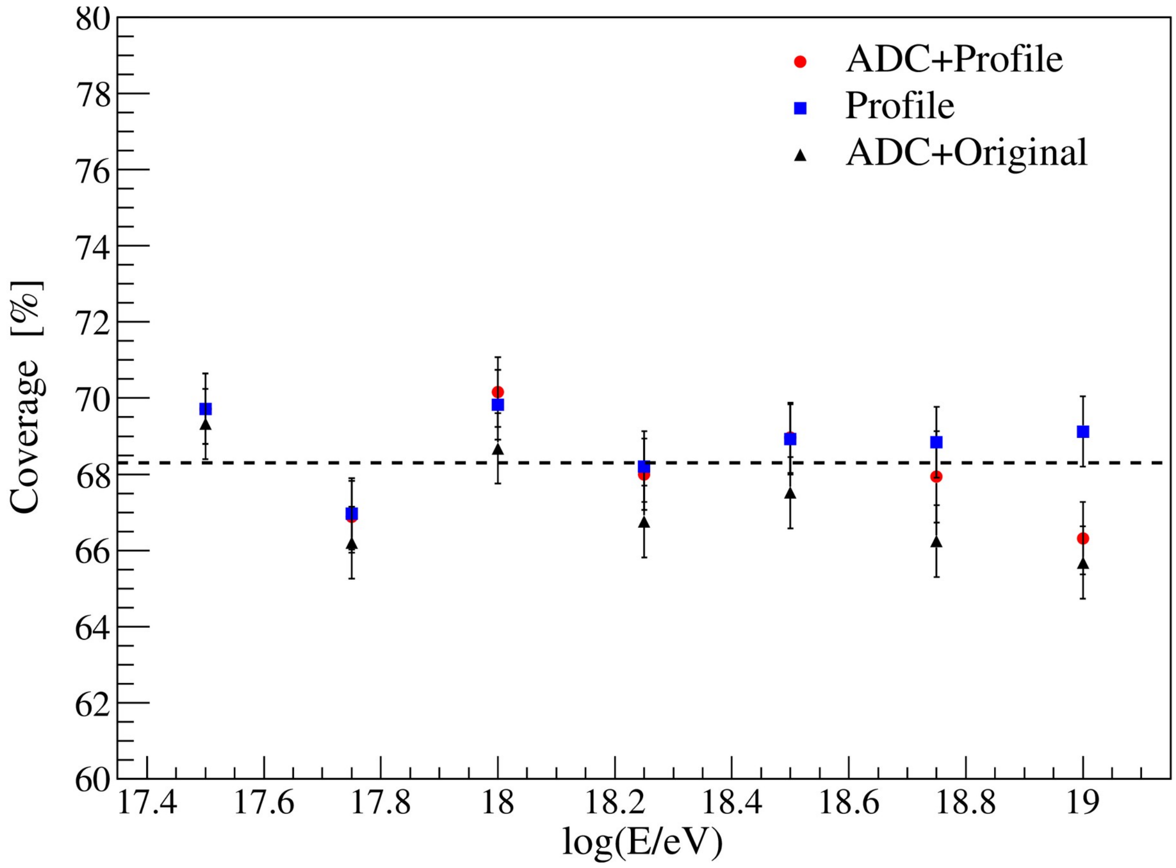


Low bias

Standard deviation



Coverage



ADC+Profile
Profile
ADC+Original
Coverage [%]
log(E/eV)
80
78
76
74
72
70
68
66
64
62
60
17.4
17.6
17.8
18
18.2
18.4
18.6
18.8
19

Conclusions

- ADC channel → investigate closer to the shower core.
- Increases the precision of the UMD.
- Saturation in ADC happens for a very large number of injected muons.
- Using the new reconstruction method, more events can be reconstructed.
- The small bias and the low standard deviation achieved allows for a good estimation of μ(450).

Future work

- Study the profile+ADC method in detail.
- The correlation between X_{max} and the total number of muons of the showers can be used to differentiate between a mixed composition scenario from a pure one, in a given energy bin.

$$r = \frac{cov(X_{max}, N_{\mu})}{\sigma(X_{max})\sigma(N_{\mu})}$$

- N_{μ} will be calculated from the hybrid reconstruction method explained in the previous slides.

References

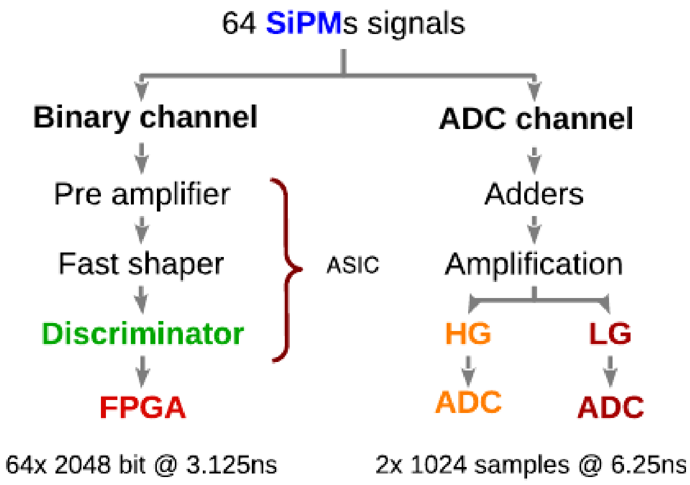
[1] Calibration of the underground muon detector of the Pierre Auger Observatory, The Pierre Auger collaboration (2021)

[2] Design, upgrade and characterization of the silicon photomultiplier front-end for the AMIGA detector at the Pierre Auger Observatory, The Pierre Auger collaboration (2021)

[3] A.M.Botti, GAP2020_003

Backup slides

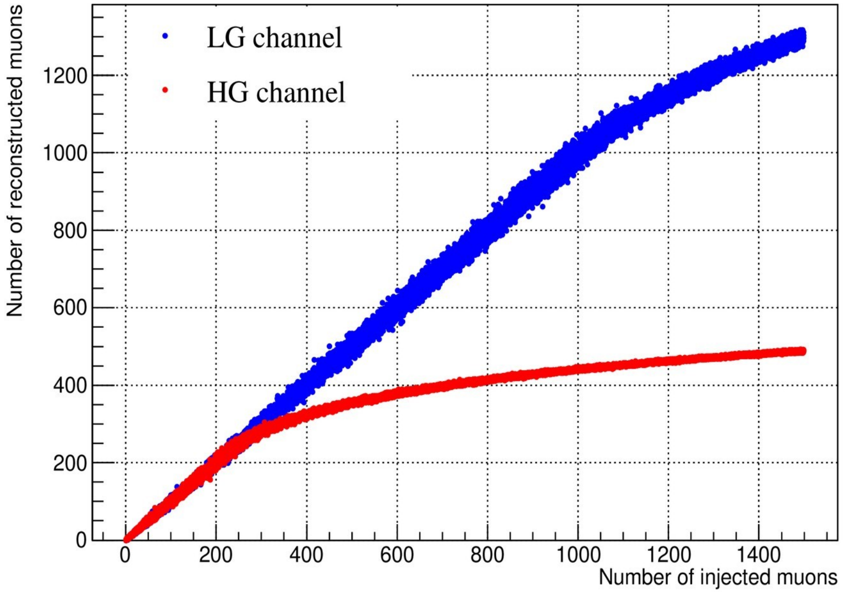
AMIGA UMD

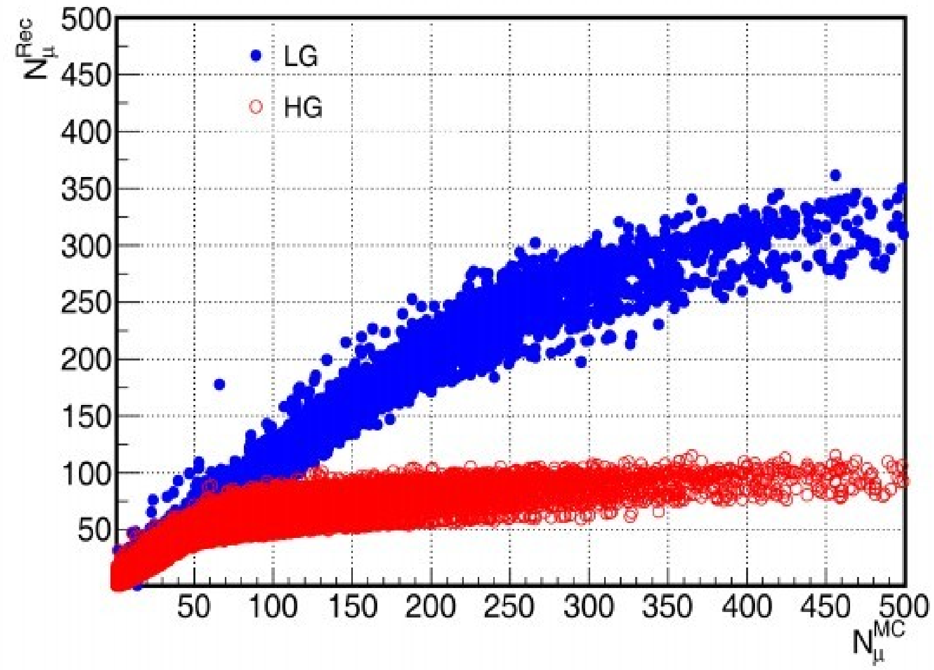


[1]

- UMD measures the fall of muon density with the distance to the shower axis → the lateral distribution function (LDF).
- Measures showers between $10^{16.5}$ eV to 10^{19} eV and events up to 45° zenith angle.
- The detectors are buried 2.3 m underground
- Counter mode measures low densities and number of muons is determined by counting signals above a threshold.
- The integrator mode measures high muon densities.

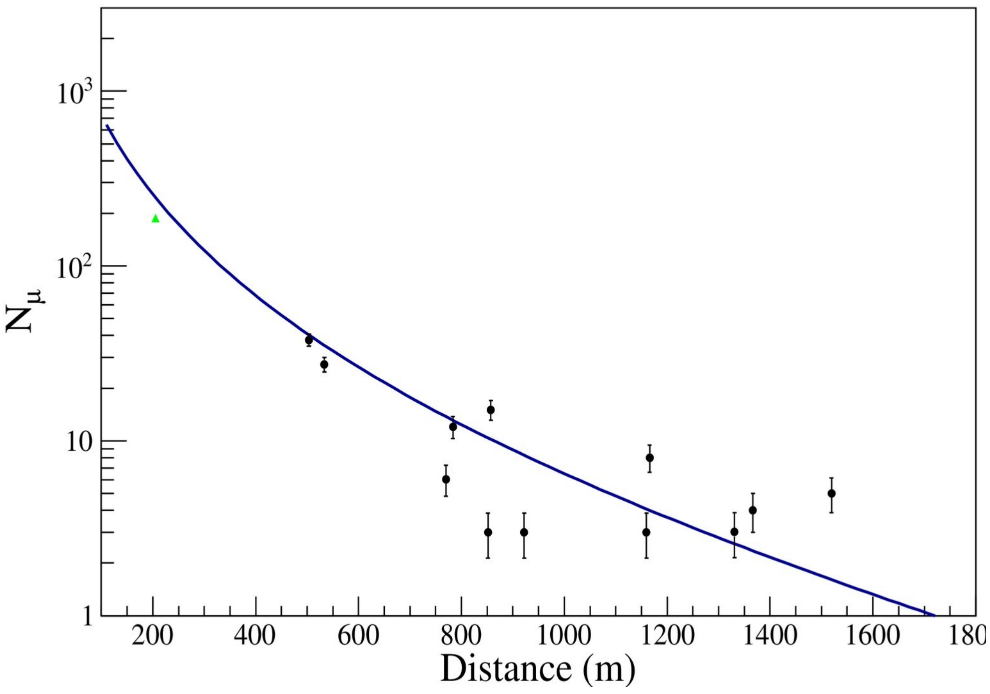
Detector simulation

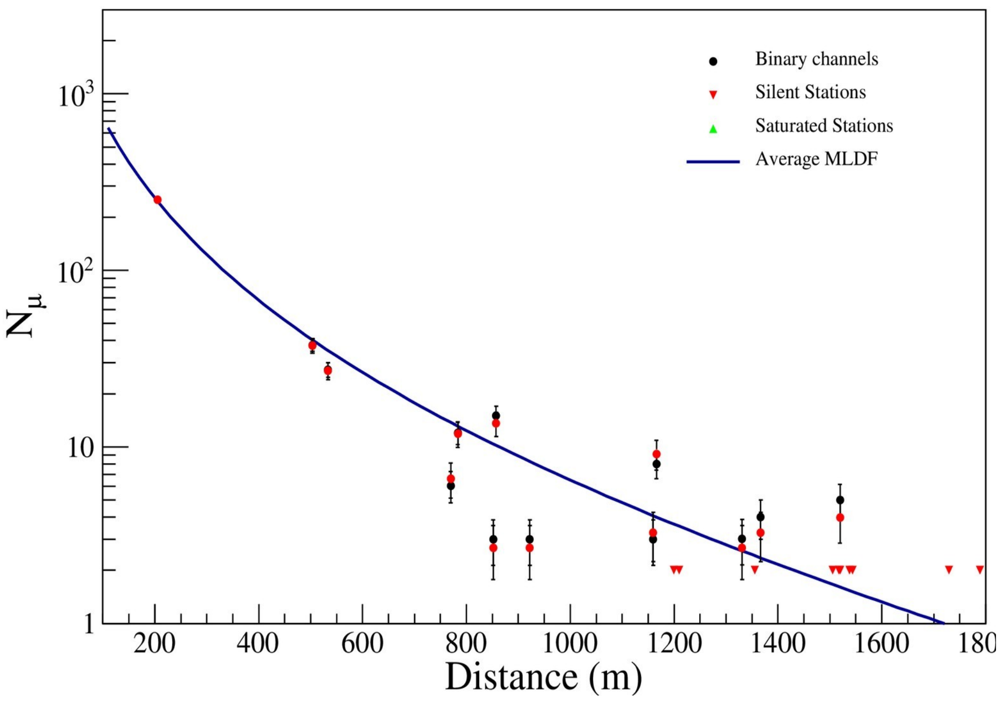




[3]

Simulation of the detectors

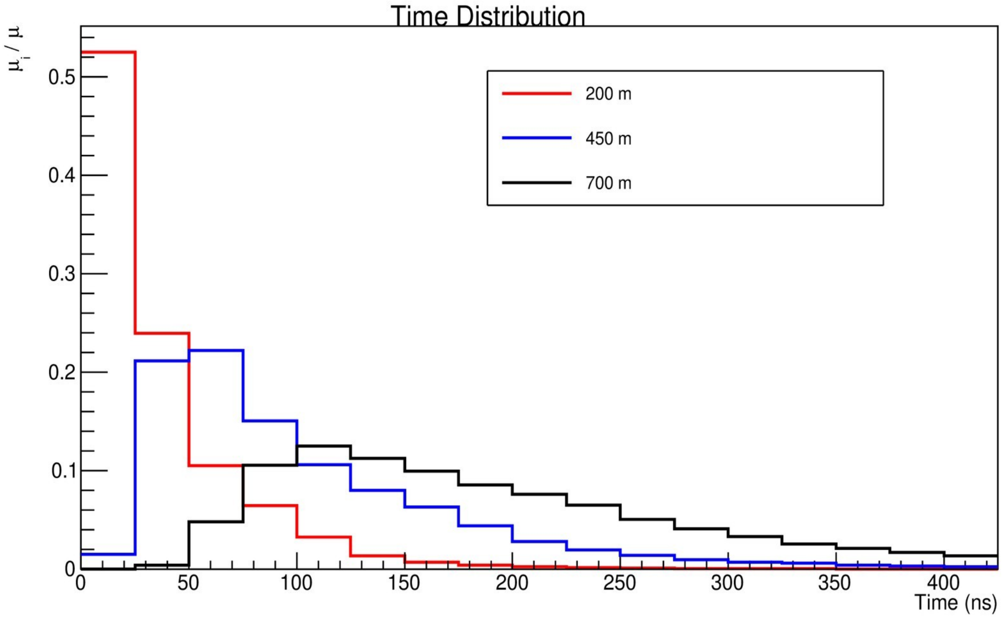




Using only
binary channels

Using binary and
ADC channels

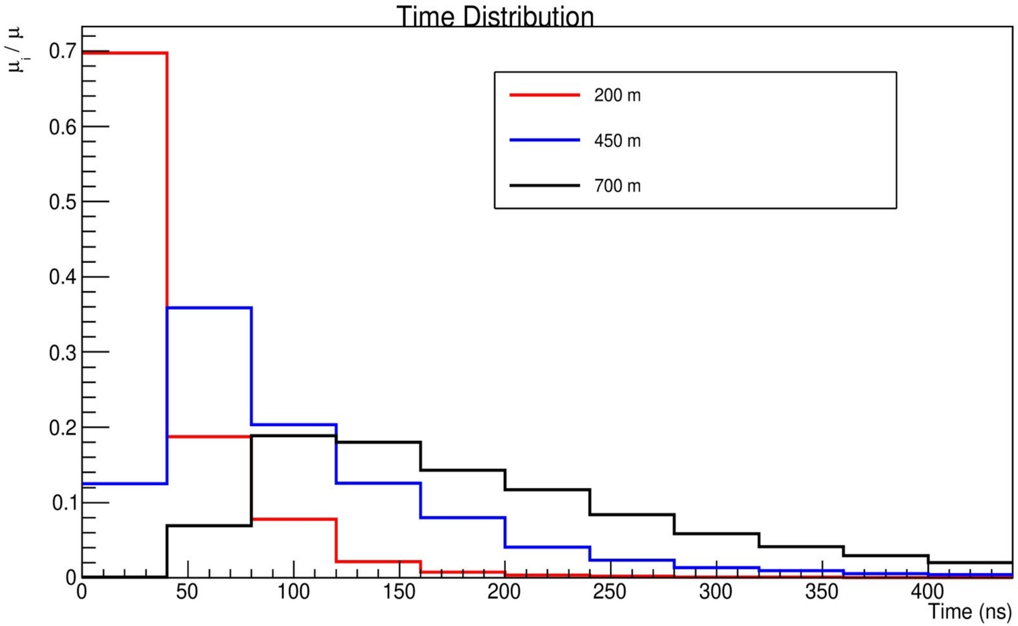
Muon time distribution at different shower axis distances



25 ns time window

For larger r → time distribution becomes wider

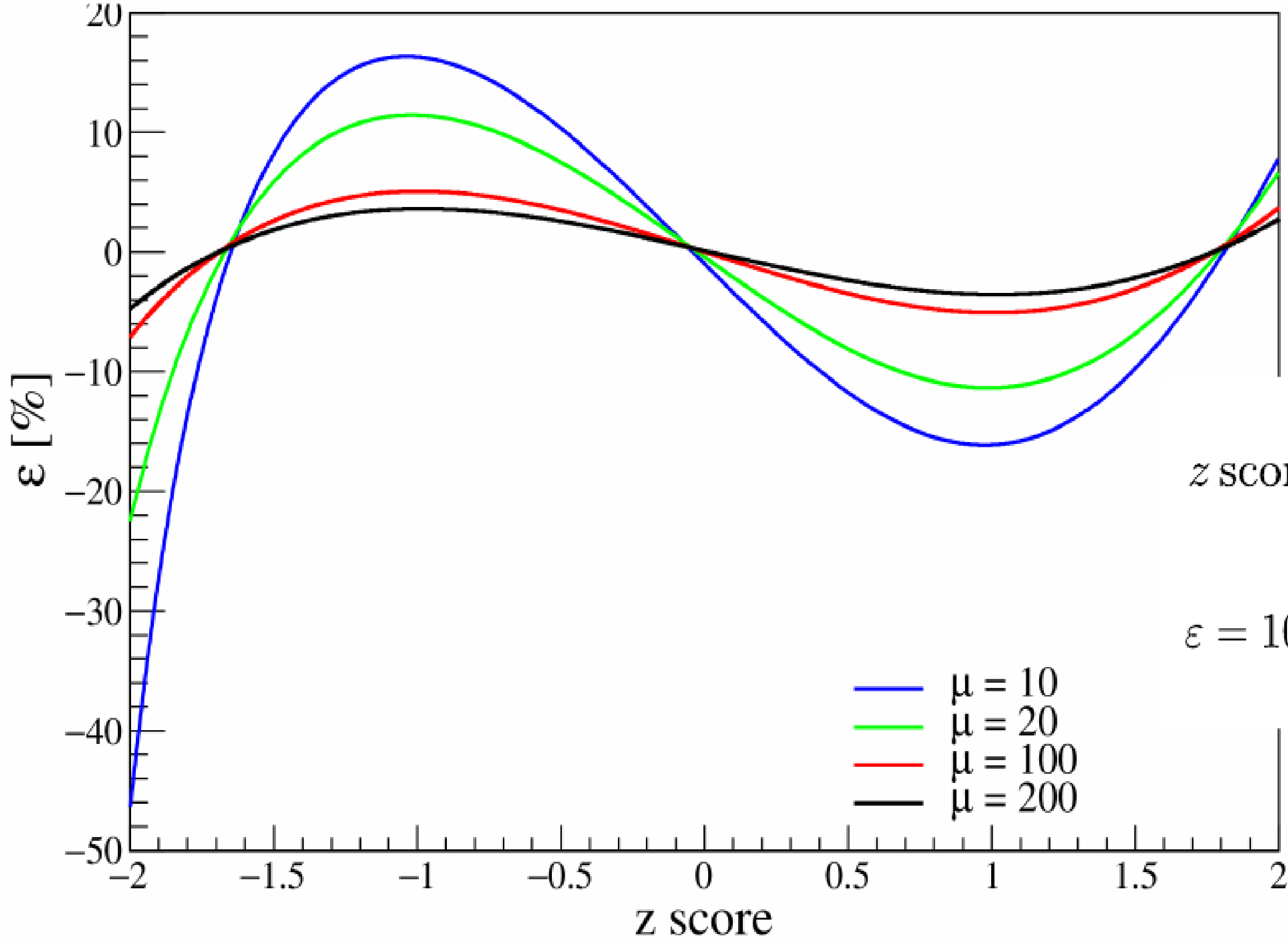
40 ns time window



We use 40 ns time window for the analysis

12 inhibition windows × 3.125 ns time = 37.5 ns

Comparison of log-normal and Gaussian distributions in 2σ region



$$z\,\mathrm{score} = \frac{\hat{n} - \langle \hat{n} \rangle}{\sigma[\hat{n}]}$$

$$\varepsilon = 100\% \left(1 - \frac{P_G}{P}\right)$$