Muon efficiency with the HESS telescope

Raphaël Chalmé-Calvet

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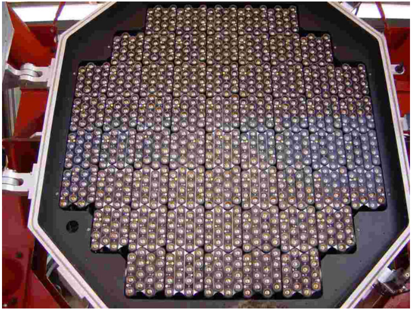
Outline

Introduction

HESS Telescope

- 4 (+1) Telescopes :
  - Mount : Davis-Cotton (Parabolic)
  - Radius : $\sim$ 6.5 m ($\sim$ 15.5 m)
  - Focal length : 15 m (30 m)
  - Total mirrors area : 107 m^2 (600 m^2)
- 4 (+1) Cameras :
  - Field of view : 5° (3.1°)
  - 960 photomultipliers (2048 PM)
  - Fast electronic :
    - Sampling : 1 ns
    - Reading window : 16 ns



- Gain calibration

  Need to know the accurate conversion between ADC counts and photoelectrons (p.e.)

- Optical calibration :

  Need to know the number of Cherenkov photons lost in the telescope :

  - Mirror reflectivity
  - Translation from mirrors to the camera
  - Losses between Winston Cone
  - Quantum efficiency of the PMs

Outline

Camera calibration parameters

Amplitude in photo-electrons (p.e.) for low and high gains (LG and HG) :

$$A^{HG} = \frac{ADC^{HG} - P^{HG}}{\gamma_e^{ADC}} \times FF$$

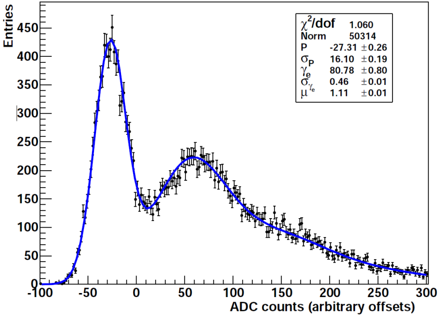
$$A^{LG} = \frac{ADC^{LG} - P^{LG}}{\gamma_e^{ADC}} \times \frac{HG}{LG} \times FF$$

with :

- γ_e^{ADC} : gain of the high gain channel (in ADC/p.e.)
- P^{HG} and P^{LG} : ADC position of the base-line for both channels (pedestal)
- $\frac{HG}{LG}$: amplification ratio of high gain to low gain
- FF : flat-field coefficient

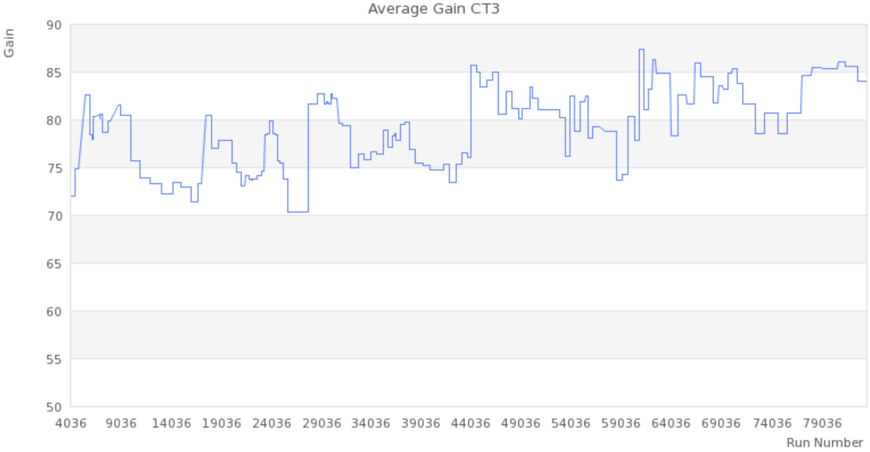
- Single p.e. illumination of the camera in nominal configuration
- High gain γ_e^{ADC} are extracted from a fit to the ADC count distribution of each pixel
- The signal distribution can be simply described by a sum of gaussians :

Single p.e. signal



$$\mathcal{G}(x) = N \times \left(\frac{e^{-\mu}}{\sqrt{2\pi}\sigma_P} exp\left[-\frac{1}{2}\left(\frac{x-P}{\sigma_P}\right)^2 \right] + \kappa \sum_{n=1}^{m \gg 1} \frac{e^{-\mu}}{\sqrt{2\pi}\sigma_{\gamma_e}} \frac{\mu^n}{n!} exp\left[-\frac{1}{2}\left(\frac{x-(P+n\gamma_e^{ADC})}{\sigma_{\gamma_e}}\right)^2 \right] \right)$$

Mean high gain history for CT3



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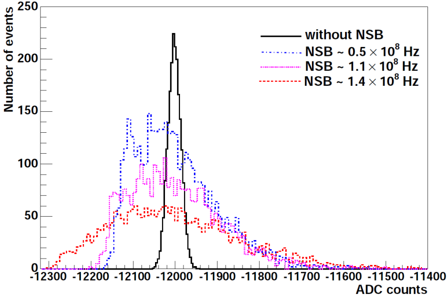
Low gain determination

- High and low gain channels are linear in the 30 to 150 p.e. range
- In this range :
  Ratio of the signals = Amplification ratio between the two channels
- Multiplying this ratio by the high gain directly gives the low gain

Pedestal

- The pedestal position is defined as the mean ADC value recorded in absence of Cherenkov light
- Pedestal are estimated on each pixel that doesn't contain Cherenkov light
- Pedestals are determined during observation runs as often as possible (approximately every minute)

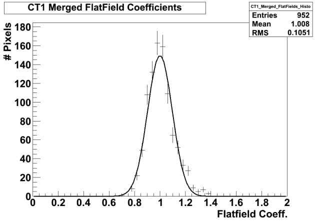
  $\Rightarrow$ Consideration of camera temperature variations



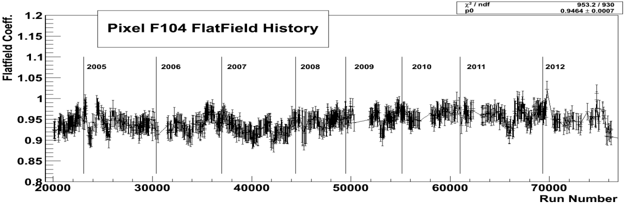
Pedestal mean doesn't vary with usual Night Sky Background (NSB) rate in Namibia (RC circuit)

Flat-Field coefficient

- Flat-field coefficients corrects the inhomogeneity between pixels
  - Quantum efficiency
  - Winston cone light collection efficiencies



- FF are determined during special flat-filed runs using LED flashers mounted on the telescope dish providing an uniform illumination



Flat-field coefficients are quite constant over time

Outline

1. Calibration of HESS cameras
2. Muon efficiency : Theory
   - Theoretical muon efficiency
   - Muon behavior and parameters in a IACT
   - Muon ring model for a circular mirror
3. Muon efficency : Application

Why studying muons ?

- Studying muon efficiency is the only way to understand the losses of Cherenkov photons in the detector
- HESS mirrors can only see the muon trajectory on the 400 last meters above HESS

  $\Rightarrow$ They only lose a few energy over this distance
- From muon parameters we can know the number of Cherenkov photons it emitted

  $\Rightarrow$ We can compare this number to the one we have in the camera

$\Rightarrow$ **Global telescope efficiency**

Goal of the study

- From muons study, we want to reconstruct the gloabal efficiency of the HESS telescope for γ photons, ie :

$$\epsilon_{\text{global}} = \frac{\#\text{ of photon-electrons}}{\#\text{ of photons hitting HESS mirrors}}$$

Definition of global efficiency

- Calculation method of theoretical efficiency from telescope simulation

Global Efficiency

$$\epsilon_{\text{global}} = \epsilon_{\text{PM}} \times \epsilon_{\text{shadow}} \times \epsilon_{\text{reflectivity}} \times \epsilon_{\text{collection}}$$ [1]

$$\epsilon_{\text{PM}} = \frac{\#\text{ of photons with PM}}{\#\text{ of input photons without PM}}$$

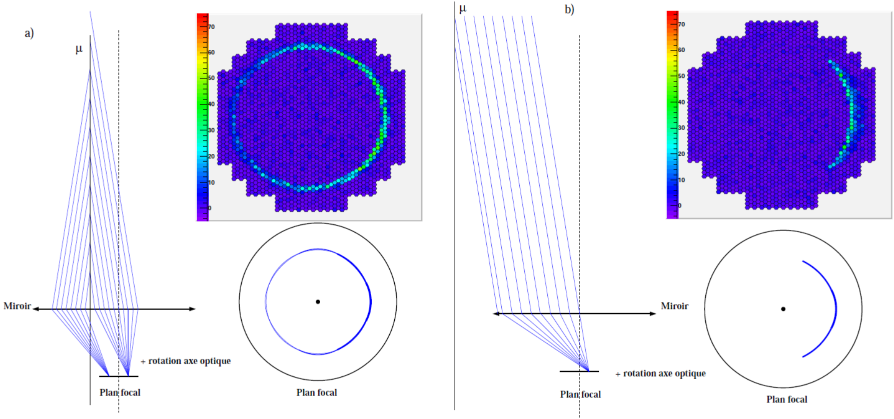
$$\epsilon_{\text{shadow}} = 1 - \frac{\#\text{ of input photons in shadow}}{\#\text{ of input photons}}$$

$$\epsilon_{\text{reflectivity}} = 1 - \frac{\#\text{ of photons absorbed}}{\#\text{ of input photons - }\#\text{ in shadow}}$$

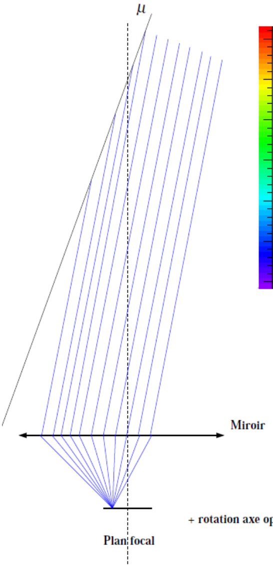
$$\epsilon_{\text{collection}} = \frac{\#\text{ of photons in pixels}}{\#\text{ of photons leaving mirrors}}$$

1. $\epsilon_{\text{collection}}$ = losses between Winston cones and for high angles

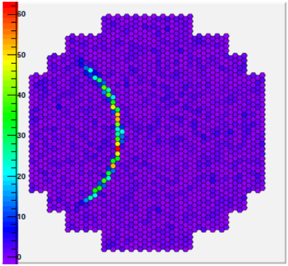
Muon ring pictures in the camera

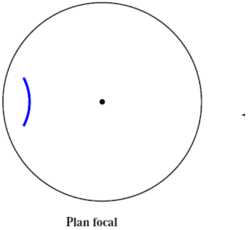


Muon ring pictures in the camera



+ rotation axe optique





Reconstruction parameters of muon rings

- Muon ring reconstruction parameters :
  - Cherenkov angle θ_c = ring radius
  - Impact parameter ρ
  - Incidence angle ξ between muon trajectory and the optical axis = center position of the ring (x,y)
  - Gaussian ring width σ
  - Azimuthal angle of maximum intensity of the ring ϕ
  - Global efficiency of the telescope Ψ

Muon ring model for circular mirror

Vacanti et al. (1993)

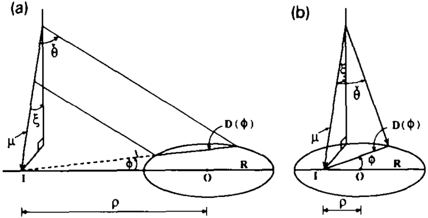


Fig. 2. Geometry of emission for a muon falling outside (a) or inside (b) the mirror. ρ = impact parameter of the muon; R = radius of the mirror; ξ = angle of incidence; $\check{\theta}$ = Čerenkov angle of emission.

where :

- $\Psi(\lambda)$ is the global efficiency
- $a(r, \lambda)$ is the absorption coefficient
- σ_T is the gaussian width of the ring

Rovero et al. (1996)

Number of photons in the camera :

$$\frac{d^3N}{dl\, d\phi\, d\lambda} = \frac{\alpha}{2} \sin(2\theta_c) \frac{\psi(\lambda)}{\lambda^2} D(\phi) a(l, \lambda)$$

Number of photons per pixel :

$$\frac{d^4N_i}{dr\, d\phi\, d\lambda\, d\theta} = \frac{\alpha}{2} \sin(2\theta_c) \frac{\psi(\lambda)}{\lambda^2} \frac{D(\phi) a(r, \lambda)}{\sqrt{2\pi}\, \sigma_T(r, \theta_c)} \times \exp\left(- \frac{(\theta - \theta_c)^2}{2\sigma_T^2(r, \theta_c)} \right) \qquad (2)$$

- $D(\phi)$ is a chord defined by the intersection with the mirror and the plane of the photons trajectory

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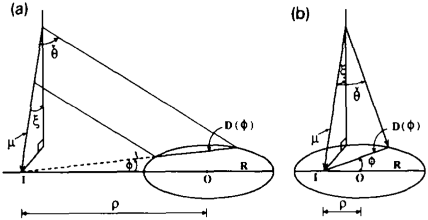
Vacanti et al. (1993)



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Number of photons in the camera :

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Number of photons per pixel :

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"It can be shown that" (Vacanti et al.)

$$D(\phi) = 2R\sqrt{1 - (\rho/R)^2 \sin^2 \phi} \qquad \text{if } \rho > R$$

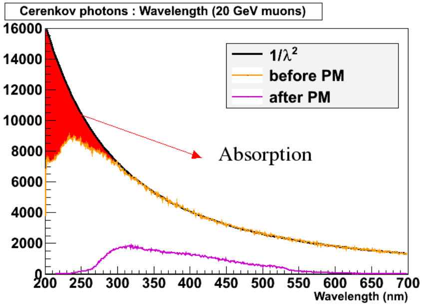
$$D(\phi) = R\left(\sqrt{1 - (\rho/R)^2 \sin \phi^2} + (\rho/R) \cos \phi\right) \qquad \text{if } \rho \leq R$$

Outline

1. Calibration of HESS cameras
2. Muon efficiency : Theory
3. Muon efficency : Application
   - Calibration curve from atmosphere and detector simulation
   - From muon efficiency to gamma efficiency
   - Application to real data

Photons distribution at the ground from muon emission

Simulations



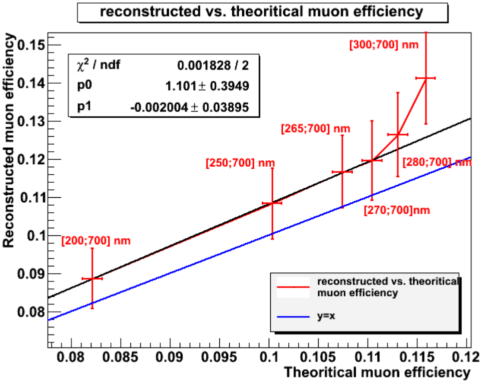
20 GeV muons launched 1000 m above HESS

$$\frac{d^4 N_i}{dr\, d\phi\, d\lambda\, d\theta} = \frac{\alpha}{2} \sin(2\theta_c) \frac{\psi(\lambda)}{\lambda^2} \frac{D(\phi) a(r, \lambda)}{\sqrt{2\pi}\, \sigma_T(r, \theta_c)} \times \exp\left(-\frac{(\theta - \theta_c)^2}{2\sigma_T^2(r, \theta_c)} \right) \qquad (2)$$

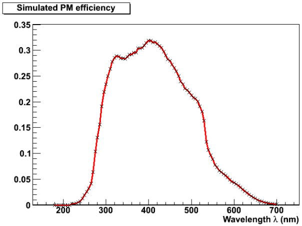
- The first difficulty is to take into consideration the absorption of the atmosphere in the muon ring model
- It depends of the emission depth of the considered particule

- We have to replace $\int_{\lambda_1}^{\lambda_2} \frac{a(r,\lambda)}{\lambda^2}\, d\lambda$ in the model by the integral over a simulated photons distribution at the ground from muon emission (in yellow)

Calibration curve from MC muons



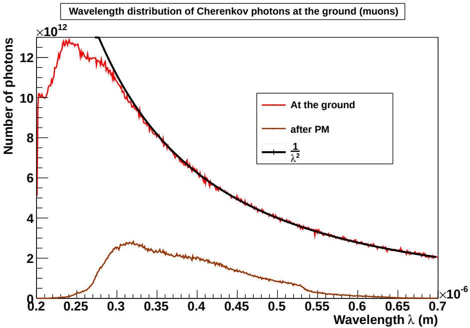
- Calibration curve is linear with wavelength
- Excepted starting from 270 nm where the quantum efficiency begins to be too high



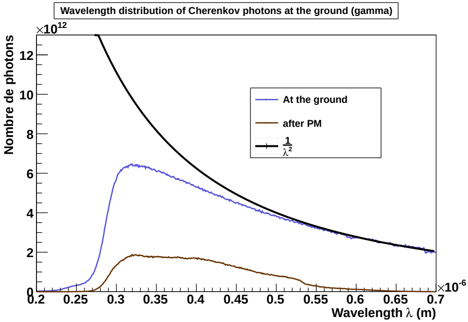
- As the calibration is linear, we can choose any wavelength lower limit in the integral
- We choose to integrate from 270 to 700 nm to not be annoyed by abosption

From muon efficiency to gamma efficiency

Cerenkov photons distributions for muons and gammas



20 GeV muons, 1000 m above HESS



500 GeV gammas, 50 km above HESS

- For gammas, the UV photons are largely absorbed by the 10 km atmosphere
- Due to this effect, gamma efficiency is different from muon one

From muon efficiency to gamma efficiency

- So, to reconstruct the gamma efficiency, we have to :
  1. calculate the theoritical gamma efficiency
  2. calculate the conversion factor between theoritical gamma efficiency and reconstructed muon efficiency
  3. apply this factor to the reconstructed muon efficiency

From muon efficiency to gamma efficiency

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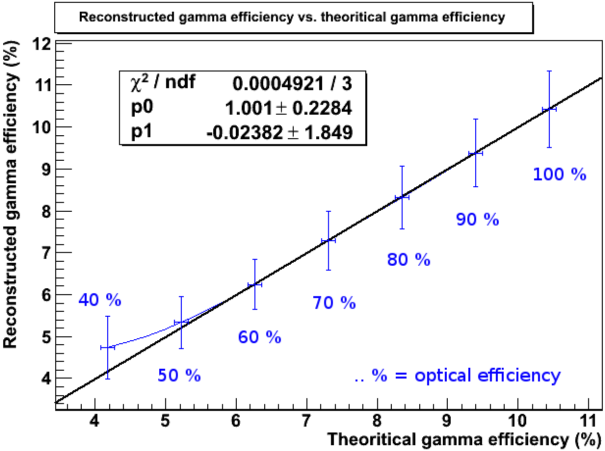
We found 10.4% as theoritical gamma efficiency
and 11.9% $\pm$ 0.1% as reconstructed muon efficiency

$\Rightarrow$ Conversion factor : 0.87 $\pm$ 0.01

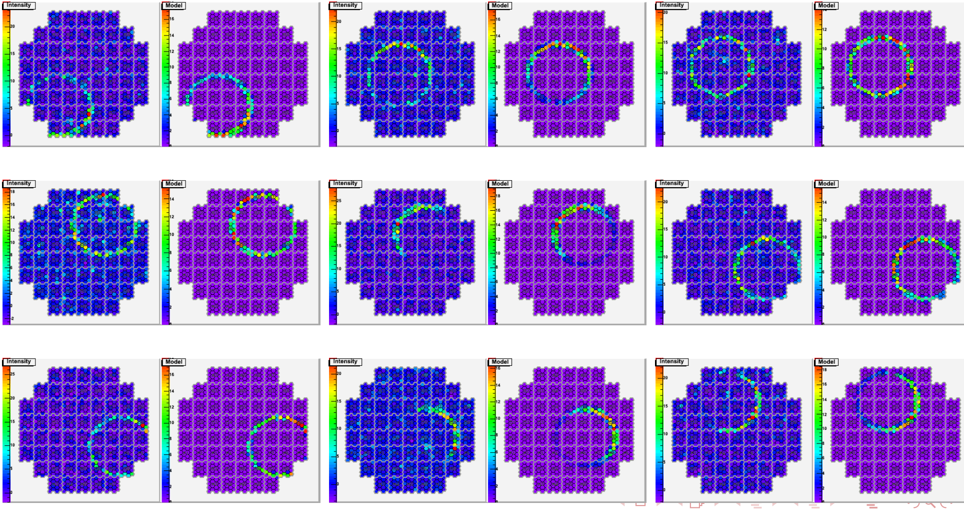
Variation with optical efficiency (from MC)



Except at low optical effiency ($\leq$ 50%), the reconstruction is linear with opt. eff. and the slope is nearly 1 as expected

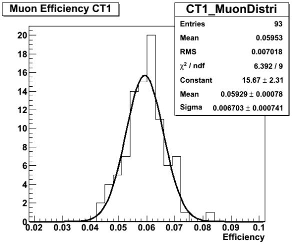
Application to real data

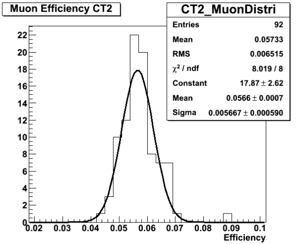
Some fitted muons in a real run

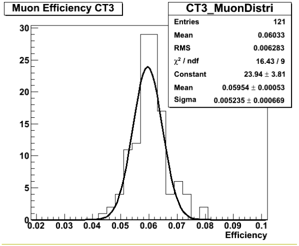


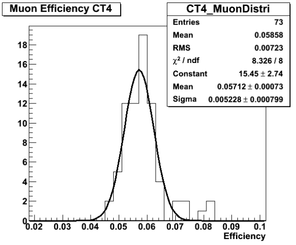
Application to real data

Efficiency distribution for one real run (200 000 events)

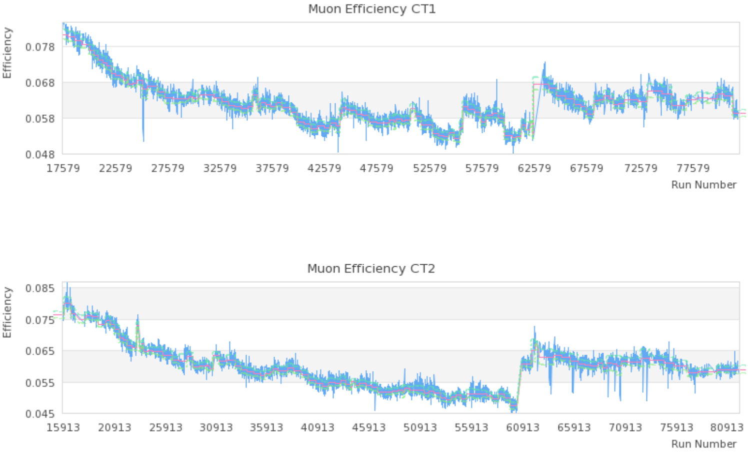






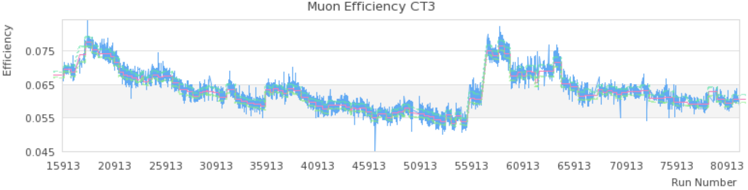


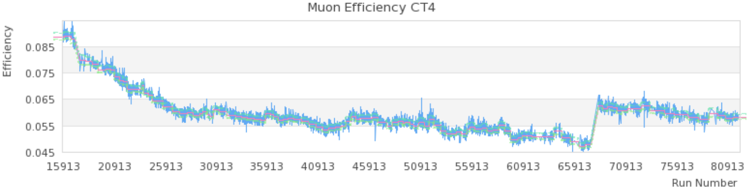
Efficiency over time : CT1 and CT2



Application to real data

Efficiency over time : CT3 and CT4





Conclusion

- Calibration parameters of the HESS cameras are well reconstructed and monitered over years
- Muon efficiency study needs a calibration from MC study
- It needs a good knowledge in :
  - atmospheric model for cherekenov light absorption
  - developpement of electromagnetic showers from gamma photons in the atmosphere
  - muon propagation in the atmosphere
  - detector simulation