Study on the fitting functions of air shower profiles

Andres Delgado, Manuela Vecchi

May 4, 2022

Abstract

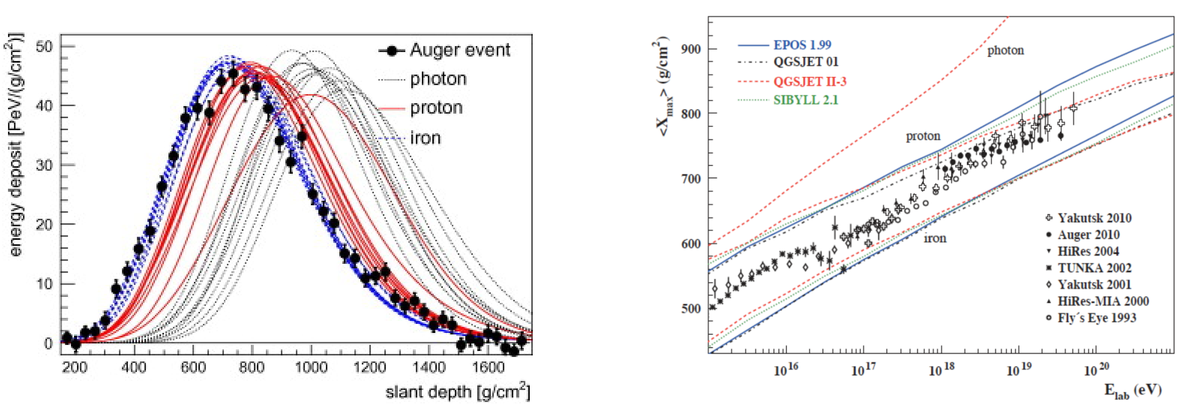
Research Description: The Cherenkov Telescope Array (CTA) is the next generation ground-based observatory for gamma-ray astronomy at very-high energies. With more than 100 telescopes located in the northern and southern hemispheres, CTA will be the world's largest and most sensitive high-energy gamma-ray observatory. One of the scientific motivations is to develop an analysis chain to allow CTA to be also a cosmic-ray (CR) experiment in the TeV energy range.

The longitudinal development of air showers generated by gamma-rays and CR will be reconstructed by CTA using a fit of a trial function. By this fit, it is possible to get an important parameter like the X_{max} of the shower, which is commonly used for the mass composition of CR.

In this project, we propose the study of two kinds of trial function, Gaisser-Hillas and Gaussian in age, to be tested on a set of simulated showers generated by CONEX. The goal is to investigate which function describes better the different kind of shower profiles and the fitting stability under the cutting of the shower profiles.

1 Introduction

Cosmic-rays (CR) are mostly protons (90%) followed by a smaller fraction of Helium nuclei (9%) and heavier nuclei (1%). They are continuously hitting the earth's atmosphere. When CR or gamma-ray interact with the components of the atmosphere, a cascade of secondary particles is generated. The number of particles at first increase, reach a maximum and then attenuate (see figure 1a taken from [1]). The atmospheric depth of this maximum, called shower maximum or X_{max}, is the most common way of inferring the primary composition of CR. Xmax depends on primary mass for an specific energy (see figure 1b). The motivation of this project is to study which function fits better to each kind of air shower in the TeV energy range. The idea of this project is based on [2].



(a) (b)

Figure 1: (a) Example of a longitudinal air shower development as measured with fluorescence telescopes, compared to simulated air showers for three different primary particle types. (b) Average of Xmax vs energy, as measured by different experiments. simulations of air showers are also shown. Image taken from https://www.ung.si/~sstanic/teaching/APP/P_Ghia_CosmicRayDetection_I.pdf

2 Trials functions to fit longitudinal profile

Gaisser-Hillas (GH) function and Gaussian in age (GIA) have been traditionally used to fit he longitudinal profile. The GH function defines the number of particles N at the atmospheric depth X measure in g/cm^2 as:

$$N(X)_{GH} = N_{max} \left(\frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max}-X_0}{\lambda}} e^{-\frac{X-X_{max}}{\lambda}}, \tag{1}$$

where Nmax and Xmax are physically meaningful, being the maximum number of particles in the shower, and the longitudinal depth which the shower reaches the maximum number of particles respectively. X_0 and λ has no direct physical meaning. In contrast the GIA function is defines as:

$$N(s)_{GIA} = N_{max}\ e^{-\frac{1}{2}\left(\frac{s-1}{\sigma}\right)^2}, \tag{2}$$

where the shower age s is defined as:

$$s = \frac{3X}{X + 2X_{max}}. \tag{3}$$

At shower maximum $s = 1$. For more details see [3].

3 Simulations

The simulations used in this project were done using CONEX [4]. The set of primary particles and energy is defined as follows:

- Primary particle: It will be considered three different kind of primary particles: gamma, proton and iron.
- Primary energy: the showers will be 10 TeV, 50 TeV, 100 TeV and 300 TeV.

For each primary particle and primary energy a set of 1000 shower were simulated using the QGSJETII-04 [reference] as hadronic interaction model (see table 1).

particle	Energy [TeV]	Number of showers
γ	10	1000
p	10	1000
Fe	10	1000
γ	50	1000
p	50	1000
...	...	...

Table 1: Number of simulated showers.

As result of the simulations, the number of particles along the atmosphere is obtained. The output is written in the form of ROOT files using the ROOT data analysis framework `https://root.cern/`.

4 Test of the functions

The fitting procedure starts by fitting a quadratic polynomial function in order to get the first guess of Nmax and Xmax parameters. The first procedure is done just by fitting the two functions and comparing Xmax obtained by each one.

The second procedure involves to cut the profiles as follows: a range of $\Delta X = 300\text{g/cm}^2$ is selected randomly, so that Xmax remains inside the field of view. The fitting is done in these cut-profiles obtaining a X^*_{max} for each function. The difference between the Xmax obtained before and after the cut is called ΔX^{cut}_{max}.

4.1 Results to be obtained:

4.1.1 1st part:

1. For simulated gamma-ray events, fit the full shower profile (take depth roughly from 0 to 1000 g/m^2) and obtain the X_{max} for all the simulated events.
2. Plot the 1D distribution (TH1D) of the X_{max} obtained from the fit to the polynomial function (one entry per shower). Start with a simulated events at 10 TeV.
3. Plot the 1D distribution (TH1D) of the X_{max} obtained from the fit to the GH function (one entry per shower). Start with a simulated events at 10 TeV.
4. Plot the 1D distribution (TH1D) of the X_{max} obtained from the fit to the GIA function (one entry per shower). Start with a simulated events at 10 TeV.
5. Repeat the previous procedure for 50, 100 , 300 TeV (TH1D).
6. Plot the 1D distribution of the difference between Xmax ($\mathrm{X}_{\mathrm{max}}^{\mathrm{GH}} - \mathrm{X}_{\mathrm{max}}^{\mathrm{GIA}}$) obtained with the two methods.
7. Make a plot (TGraph) of the average value of the difference (see previous points) as a function of energy (10, 50, 100 , 300 TeV).

4.1.2 2nd part:

- Fit the shower profile on a restricted range around the X_{max} and obtain the X^*_{max} for all the simulated events.
- Plot the histogram of $\Delta X^{cut}_{max} = X_{max} - X^*_{max}$ for GH and GIA functions for each primary and energy.
- Make a plot with the average and the RMS of the ΔX^{cut}_{max} distribution, obtained in the previous result, as function of the energy.
- Which function describes better the different longitudinal profiles in the scenario of cutting the shower profile?
- Repeat for all the particles (gamma, p , Fe).

5 Timeline

Week	Topic/Assignment	status
18 - 22 Ap	ROOT tutorial	done
25 - 29 Ap	Check results/questions	...
2 - 6 May	Write code GH & GIA / fit	...
9 - 13 May	Get 1st results	...
16 - 20 May	Check 1st results	...
23 - 27 May	Get 2nd results	...
30 May - 03 Jun	Check 2nd results	...

Table 2: timeline.

References

[1] Karl-Heinz Kampert and Michael Unger. Measurements of the cosmic ray composition with air shower experiments. *Astroparticle Physics*, 35(10):660–678, 2012.

[2] Raul Ribeiro Prado and Vitor de Souza. A study on the fitting functions of energy deposit profile of cosmic rays showers. In *33rd International Cosmic Ray Conference*, page 0640, 2013.

[3] J. A. J. Matthews, R. Mesler, B. R. Becker, M. S. Gold, and J. D. Hague. A Parametrization of Cosmic Ray Shower Profiles Based on Shower Width. *J. Phys. G*, 37:025202, 2010.

[4] Till Bergmann, R. Engel, D. Heck, N. N. Kalmykov, Sergey Ostapchenko, T. Pierog, T. Thouw, and K. Werner. One-dimensional Hybrid Approach to Extensive Air Shower Simulation. *Astropart. Phys.*, 26:420–432, 2007.