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Delgado Giler, Andrés G.; Vecchi, M.; de Souza, V.

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PROCEEDINGS OF SCIENCE

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Cosmic-ray measurements by reconstructing longitudinal profiles for the Cherenkov Telescope Array

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Andrés G. Delgado Giler,[a,b,*] **M. Vecchi**[a] **and V. de Souza**[b]

[a] *Kapteyn Astronomical Institute,*
University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands
[b] *São Carlos Institute of Physics,*
University of São Paulo, Campus USP São Carlos, 13566-590, Av. Trab. São Carlense, 400 - Parque Arnold Schimidt, São Carlos, São Paulo, Brazil

E-mail: `a.g.delgado.giler@rug.n`, `m.vecchi@rug.nl`, `vitor@ifsc.usp.br`

The Cherenkov Telescope Array (CTA) will be the next generation gamma-ray observatory in the energy range from 20 GeV to 300 TeV, offering 5-10 times better flux sensitivity than the current generation of imaging atmospheric Cherenkov telescopes. Each telescope will capture an image of the Cherenkov light produced when air showers created by gamma rays or cosmic rays pass through the atmosphere. The longitudinal development of the shower in the atmosphere can be studied by measuring the number of charged particles produced as a function of depth. The reconstruction of the longitudinal shower profile provides the depth of the shower maximum X_{max} which is a mass-sensitive parameter useful for cosmic ray composition. In this work, we reconstruct the longitudinal profile and the X_{max} of air showers initiated by two kinds of cosmic ray species, proton, and iron, with energies between 10 TeV and 300 TeV. This reconstruction is different from other methods that have been used in the past as template-based fit techniques that require a detailed and computing-intensive simulation chain. In contrast, we use for the first time a parameterized function for the angular distribution of Cherenkov light around the shower axis.

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[*] Speaker

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1. Introduction

Cosmic ray (CR) and gamma ray particles interact in the atmosphere producing a cascade of secondary particles known as an air shower. Along the air shower, the number of charged particles reaches a maximum, referred to as X_{max}. The depth of the X_{max}, expressed in g/cm^2 of traversed matter, is a key observable to estimate the mass of primary cosmic particles (see [1] for a review). In this work, we applied a new method proposed in [2, 3] to reconstruct the longitudinal shower profile and the X_{max} from images recorded by imaging atmospheric Cherenkov telescopes (IACTs). The Cherenkov Telescope Array (CTA) [4] will be the next generation of IACTs in the energy range from 20 GeV to 300 TeV. In order to cover all sky, it will be distributed over two arrays, each with tens of telescopes: La Palma (CTA North) and Atacama desert (CTA South). CTA will have telescopes of three different sizes: Small-Sized Telescopes (SSTs), Medium-Sized Telescopes (MSTs), and Large-Sized Telescopes (LST) to cover the large energy range. Since the cosmic-ray flux dominates the incoming gamma-ray flux, CTA could also provide cosmic composition through indirect measurements in the energy regime where the transition from Galactic to extragalactic CRs occurs [5]. These indirect measurements would allow synergy and complementarity with data from space instruments such as CALET [6] and DAMPE [7]. Nevertheless, indirect measurements have difficulties in identifying individual CR because the primary mass can only be inferred from comparisons of experimental mass-sensitive observables with air shower simulations, and consequently, the composition has a lower resolution than direct measurements. Therefore, methods to measure mass-sensitive parameters as X_{max} are required. For instance, the Pierre Auger Observatory, which uses fluorescence telescopes to measure the development of CR air showers, have shown a total X_{max} resolution of about 15 g/cm^2 at energies above $10^{19.3}$ eV [8]. On the other hand, Monte Carlo template-based analysis [9] for IACTs are commonly used tools to find the best-fit shower parameters, which provide a spread of 30 g/cm^2 in the X_{max} reconstructed values of gamma shower simulations. The template-based analysis techniques require detailed and computing-intensive simulations of image templates for each array configuration and particle type while our method does not. Instead, our method uses a parameterized function that describes the development of the Cherenkov light along the air shower for gamma and cosmic rays separately [10]. For other techniques and resolution values (see [11, 12]).

This proceeding is organized as follows: in section 2, we describe the shower simulations for this analysis. In section 3, we describe the method used to reconstruct the longitudinal profiles and the quality cuts applied in the reconstruction. Section 4 presents the results of the X_{max} resolution. Finally, we conclude the work in section 5.

2. Data

The data set consists of simulated air showers generated by protons and iron particles detected by CTA-Southern array, which will be composed of SSTs, MSTs and LSTs. However, to provide a proof of concept of the method, in this work we have only used events detected by 25 simulated MSTs with FlashCam using Prod5. The camera is hexagonal with a radius of 1.2 m. The array dimension extends within a circle of ~ 500 m radius. The events come from random directions within a view-cone of 10 degrees pointing at 20 degrees zenith angle in the North direction. A set of ∼ 10^4 air showers from 10 TeV to 300 TeV was used for each particle type. The images are calibrated and parameterized using the ctapipe v11.0 [13]. This process consists of an initial step where pixels are required to be above a given threshold value and a neighbor above a second threshold. Afterward, the Hillas parametrization [14] allows the extraction of image parameters from these cleaned images. The parameters used in this work are image intensity, pixel coordinates, ellipsoid position in the camera, number of pixel clusters, position and direction of the telescopes, and the true values of the shower core, shower direction and shower energy. The true value of the X_{max} is also used only for comparison.

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3. Methodology

The longitudinal profile reconstruction is performed using the method described in [2, 3]. As a first step, we reconstruct a shower plane containing the shower axis. This shower plane is perpendicular to the plane spanned by the axis of the incoming shower and the telescope position with respect to the shower core. Within this shower plane, a geometrical projection of the camera pixels is achieved by using the pixel coordinates and the telescope axis. An example of one image produced by a proton shower is shown in Fig. 1a, where triggered pixels are highlighted in green. The corresponding reconstructed shower plane with the geometrical pixel projection is shown in Fig. 1b. Only triggered pixels are projected in the shower plane.

With the help of the reconstructed shower plane, the content of every projected pixel of an image is binned along the vertical axis corresponding to the altitude. Then, the altitude is transformed in depth using an atmospheric model for CTA South. This process generates one photon profile per telescope. In the final step of the reconstruction, the electron profiles are obtained from the photons profiles using a parametrization for the angular distribution of Cherenkov light f_C around the shower axis given by [10]:

$$\frac{d^2N_\gamma}{d\theta\, dX}(\theta, s, h) = \frac{1}{\pi} N_e(X) \times f_C(\theta, s, h, E), \tag{1}$$

where θ is the angle between the shower axis and the photon emission, E is the energy of the primary particle, $s = 3X/(X+2X_{max})$ is the shower age, and N_γ and N_e is the number of Cherenkov photons and electrons, respectively, at atmospheric depth X or altitude h. The attenuation and absorption of the photons in the atmosphere are also taken into account in the reconstruction by transmission factors due to Rayleigh (T_R) and Mie (T_M) scattering given in [15].

Since equation (1) depends on the shower maximum through the shower age, $s = 1$ is set at the beginning of the reconstruction. Once the electron profiles are calculated by using equation (1), the longitudinal profile is obtained as the average of the electron profiles. A Gaisser-Hillas (GH) function [16] is adjusted around the peak of the average profile to obtain the depth of the shower maximum reconstructed, which is referred to $\mathrm{X}_{\mathrm{max}}^{\mathrm{rec}}$ in the following. We recalculate and update the value of the $\mathrm{X}_{\mathrm{max}}^{\mathrm{rec}}$ in the next iterations. Fig. 1c shows the electron profiles at the 5th iteration considering all the triggered telescopes for the same event where each camera image produces a profile. As can be seen in Fig. 1c, including profiles from all telescopes results in a noisy measurement of the longitudinal profile. In order to identify the telescopes that provide the best description in the reconstruction, we applied the following quality cuts to select images: the position

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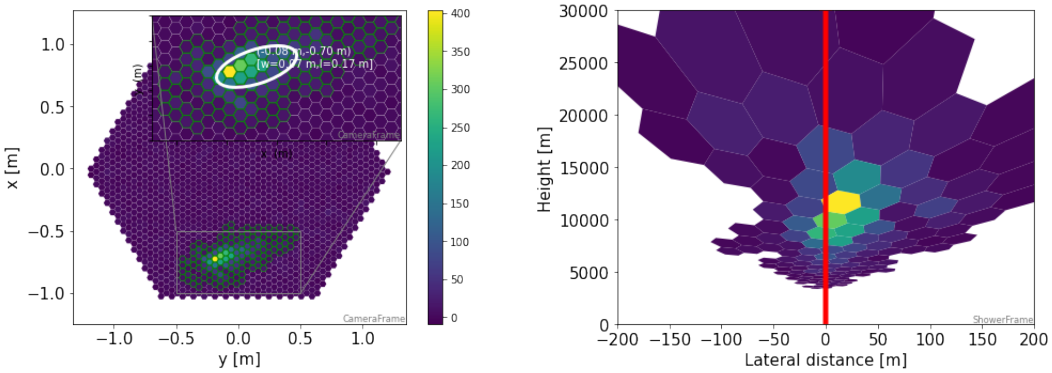
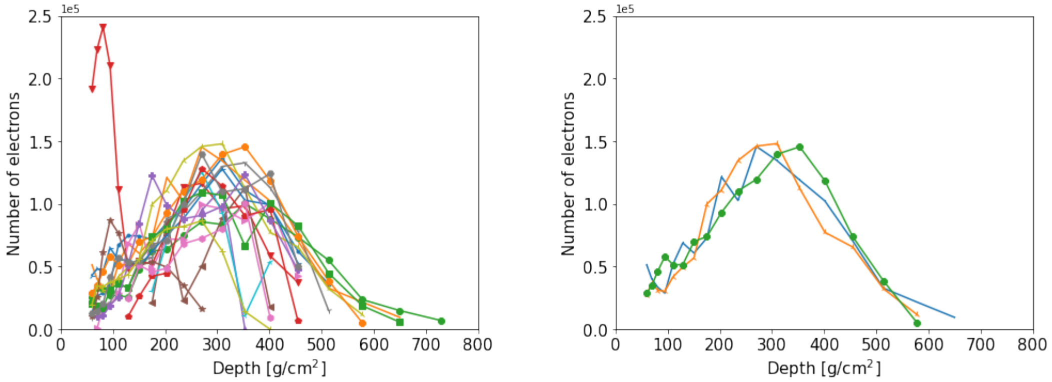
of the ellipse with respect to the center of the camera must be less than or equal to 0.8 m, the number of pixels clusters per image must be less than 3, the telescope position with respect to the shower core must be within a radius of at least 300 m in order to see the region of the shower maximum, and each event must trigger at least 5 telescopes. Fig. 1d shows the electron reconstructed profiles using these cuts. It is remarkable to note that profiles that do not provide a good reconstruction are rejected.



(a) Camera view. The number of photons in the pixels is denoted by the palette color. Triggered pixels are highlighted in green. The zoom box shows the ellipsoid obtained from Hillas parametrization.

(b) Shower plane. Pixels are projected along the height and lateral distance, and the intensity is the same of the camera view. The Red line denotes the direction of the shower axis.



(c) Electron profiles before applying quality cuts. Each curve belongs to one image of a triggered telescope. In this case, 19 telescopes were triggered.

(d) Electron profiles after applying quality cuts. Each curve belongs to one image of a triggered telescope.

Figure 1: Reconstruction of 11.2 TeV proton event.

4. Results

The Fig. 2 shows a reconstructed longitudinal shower profile for a proton event with the true depth of the shower maximum $\mathrm{X}_{\mathrm{max}}^{\mathrm{true}} = 298.46$ g/cm^2. The blue curve corresponds to the average from the three profiles of Fig. 1d. The red curve is the GH fitting around the maximum, which gives $\mathrm{X}_{\mathrm{max}}^{\mathrm{rec}} = 297.39 \pm 26.68$ g/cm^2 and is close to the true value. To validate the method, the resolution in the X_{max} reconstruction was estimated from the distribution of the difference between

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the reconstructed and the true shower maximum for proton and iron events separately. A Gaussian function is fitted on each distribution where the standard deviation σ and the mean of the distribution is considered as the resolution and bias of the method, respectively. The resolution for proton and iron events taking the full energy range is shown in Figure 3. In this case the resolution is 30.58 ± 1.09 g/cm^2 for proton showers and 36.55 ± 1.74 g/cm^2 for iron showers. In both cases, the bias is marginally compatible with zero, which means that the reconstructed maximum is slightly shifted. Since we are using one type of telescope, it is essential to mention that the resolution stated in this analysis does not represent the actual X_{max} resolution that is expected by the entire CTA South array at the end of the construction phase.

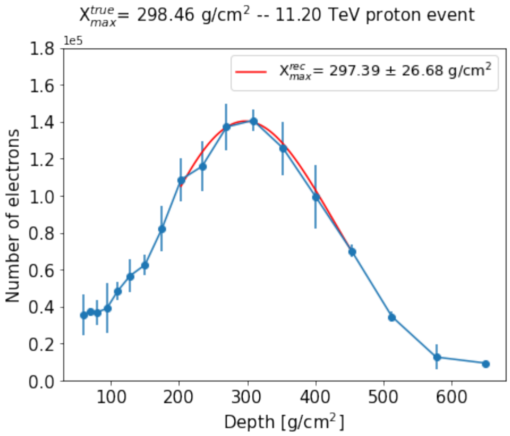

Figure 2: Reconstructed longitudinal profile of 11.2 TeV proton event. The profile is obtained as the average from three profiles of Fig 1d. The red curve is the Gaisser-Hillas fitting around the maximum.

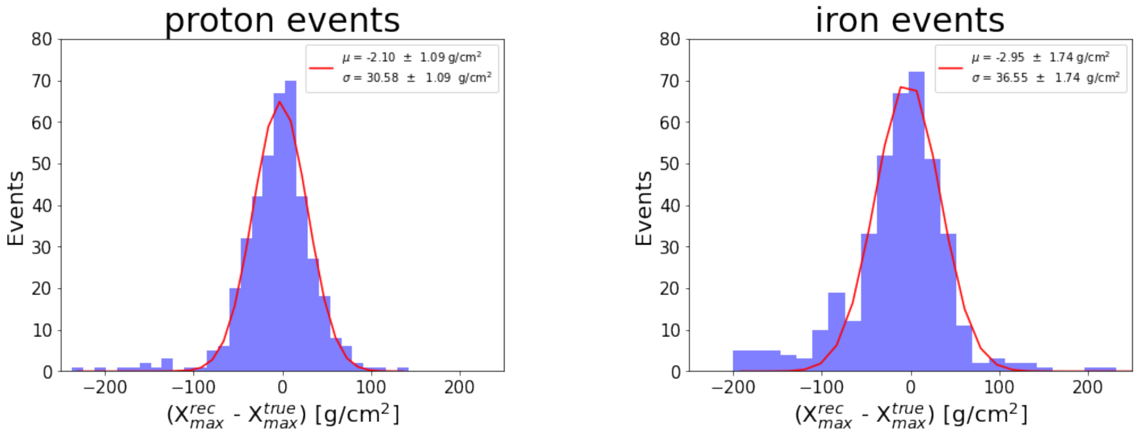

Figure 3: Distribution of the difference between the reconstructed and the true shower maximum for proton and iron events. Gaussian fitting is shown as a red curve.

5. Conclusions

For the first time, longitudinal profiles of the Cherenkov emission of simulated cosmic-ray air showers using the CTA telescopes were reconstructed. In this study, we used simulated images recorded by the MSTs of CTA South. The applied method yielded a measurement of the shower maximum on an event-by-event basis and the resolution was obtained for two kinds of cosmic-ray showers. For iron-induced showers the resolution was 36.55 g/cm^2 and the bias was -2.95 g/cm^2 in the energy range from 10 TeV to 300 TeV. For proton-induced showers the resolution was below compared to the iron case, 30.58 g/cm^2, and the bias was -2.10 g/cm^2. The bias in both cases showed a slight shift in the reconstructed shower maximum. Additionally, the reconstruction of the longitudinal profile and X_{max} opens the possibility for complementary indirect measurements of cosmic rays, especially in the energy regime where direct observations lack statistics. For instance, using the analysis described in [1] that is beyond this work, the reconstructed X_{max} distribution is suitable for distinguishing between light and heavy nuclei.

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