IACT image reconstruction using a spatio-temporal likelihood for the LST

cherenkov telescope array

C. Alispach[1,*], G. Emery[1,*], A. Carosi[1], M. Dalchenko[1], D. Della Volpe[1], L. Foffano[1], M. Heller[1], D. Medina[1], T. Montaruli[1] and A. Nagai[1]

[1] Université de Genève - DPNC
[*] Corresponding author

ABSTRACT

Imaging Atmospheric Cherenkov Telescopes (IACTs) collect the Cherenkov light emitted in Extensive Air Showers from highly energetic particles in the atmosphere. One of the main challenges of IACT based astronomy is to discriminate between images from very high energy gamma-rays and other particles, mainly protons, and to identify the energy and direction of the primary gamma-rays. Here, an innovative method using the maximization of a likelihood function describing the spatial and temporal distributions of the signal in the camera is presented. It allows propagation of the calibration parameters during the extraction of the image parameters. These parameters are used to discriminate gamma-rays over cosmic-rays and to estimate the energy, and the arrival direction of the gamma-ray.

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Image properties

The projection of an extensive air shower in the camera resembles an ellipse (Fig. 1-left). The time development of the image along the longitudinal axis is linear (Fig. 1-right). From these observations, a set of 8 independent image parameters (including the Hillas parameters [1]) can be used to reconstruct the primary particle energy, direction, and type.

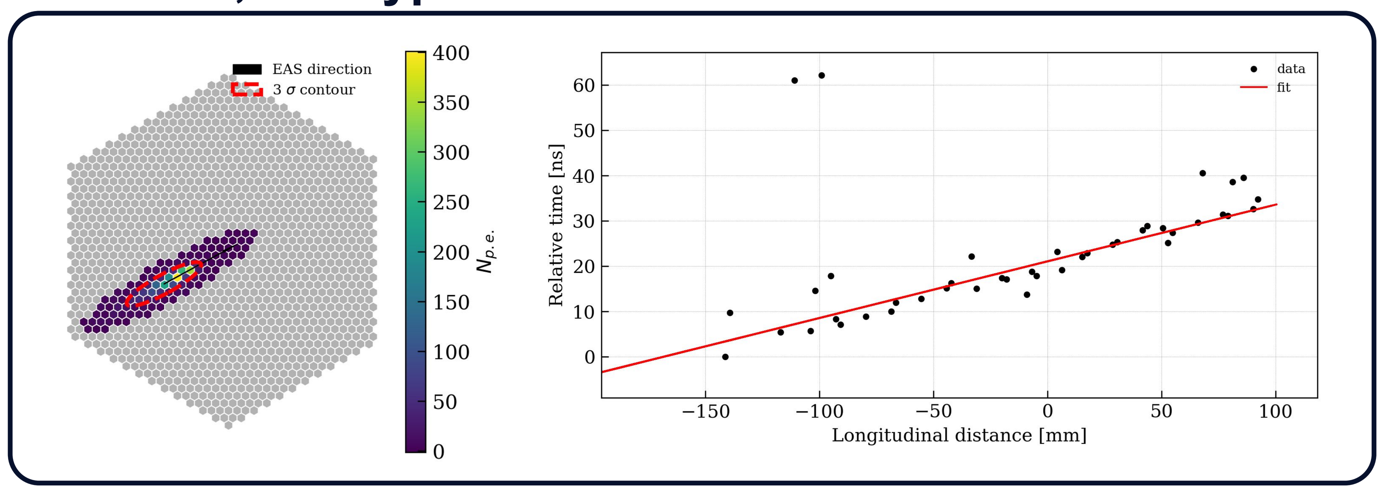

Fig. 1: ***left*** **: Distribution of the charge in the camera in number of photo-electron.**
right **: Time of maximum signal in the pixels as a function of the position on the EAS direction axis.**

Pixel signal

Photo-multiplier tubes (PMTs) convert a photon reaching the photo-cathode into a measurable charge at their anodes. The anode signal fluctuates because of several effects which include: Poisson fluctuations, gain smearing, dark noise, electronic noise, after-pulsing and predominantly night-sky background (NSB). The reconstructed charge can be described statistically by a pixel photo-electron likelihood (Fig. 2).

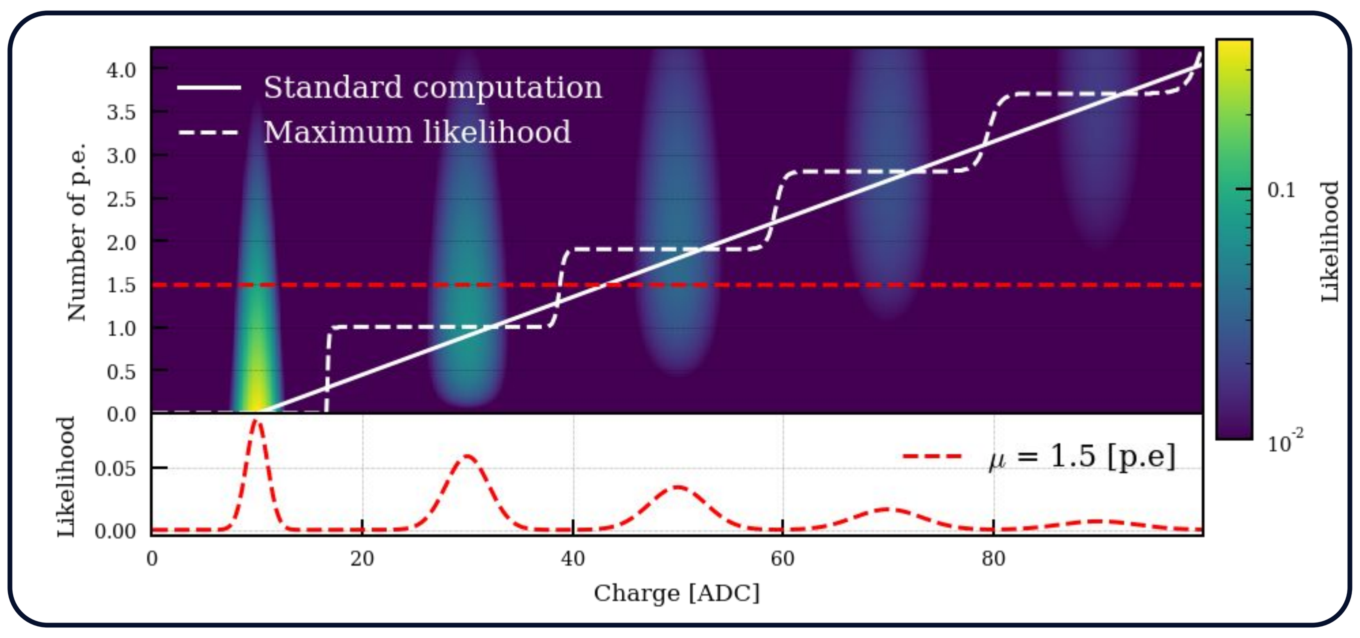

Fig. 2: Pixel likelihood as a function of the reconstructed charge and the mean number of photo-electron.

Likelihood reconstruction

The shower image parameters are obtained by maximizing the log-likelihood built from the individual pixel likelihood (Fig. 2) and summed over the time samples and the pixels. The spatial and temporal constraints (Fig. 1) are used to establish a relation between the pixels and the time samples, thus reducing the degrees of freedom. The log-likelihood is similar to the one in [2] but here the time development is added. To include the temporal part, a time-dependent signal of gain G_{ij} is compared to the baseline subtracted waveforms W_{ij}-B_i. The time-dependent gain G_{ij} arises from the PMT photo-electron pulse template. The pulse templates for each pixel are shifted with respect to the expected photo-electron arrival times obtained using a linear model along the shower longitudinal axis (Fig. 1-right). The model assumes that the expected number of photo-electron in each pixel μ_i follows a 2D Gaussian from which 6 independent parameters are obtained. Charge fluctuations σ_{kij}, mainly from NSB fluctuations, are included. The model also accounts for optical cross-talk μ_{XTi} which is accounted for silicon photo-multiplier pixels. Here this value is set to zero.

$$\ln \mathcal{L}(\vec{\theta};\, W_{ij},\, \vec{\theta}_c) = \sum_{i=1}^{N_{pixels}} \sum_{j=1}^{N_{samples}} \ln \sum_{k=0}^{\infty} \frac{\mu_i(\mu_i + k\mu_{XT_i})^{k-1}}{k!} e^{-\mu_i - k\mu_{XT_i}} \frac{1}{\sqrt{2\pi}\sigma_{k_{ij}}} e^{-\frac{(W_{ij} - kG_{ij} - \bar{B}_i)^2}{2\sigma^2_{k_{ij}}}}$$

Sensitivity

Once the image parameters are extracted, either using the presented method or a more classical approach, they are used to infer the event properties from supervised machine learning models. These models allow us to identify if the event is a gamma-ray and to reconstruct the arrival direction and the primary gamma-ray energy.

The performance of the method in terms of: flux sensitivity, energy resolution, angular resolution, and background rejection efficiency as a function of the reconstructed energy are shown in Fig. 3.

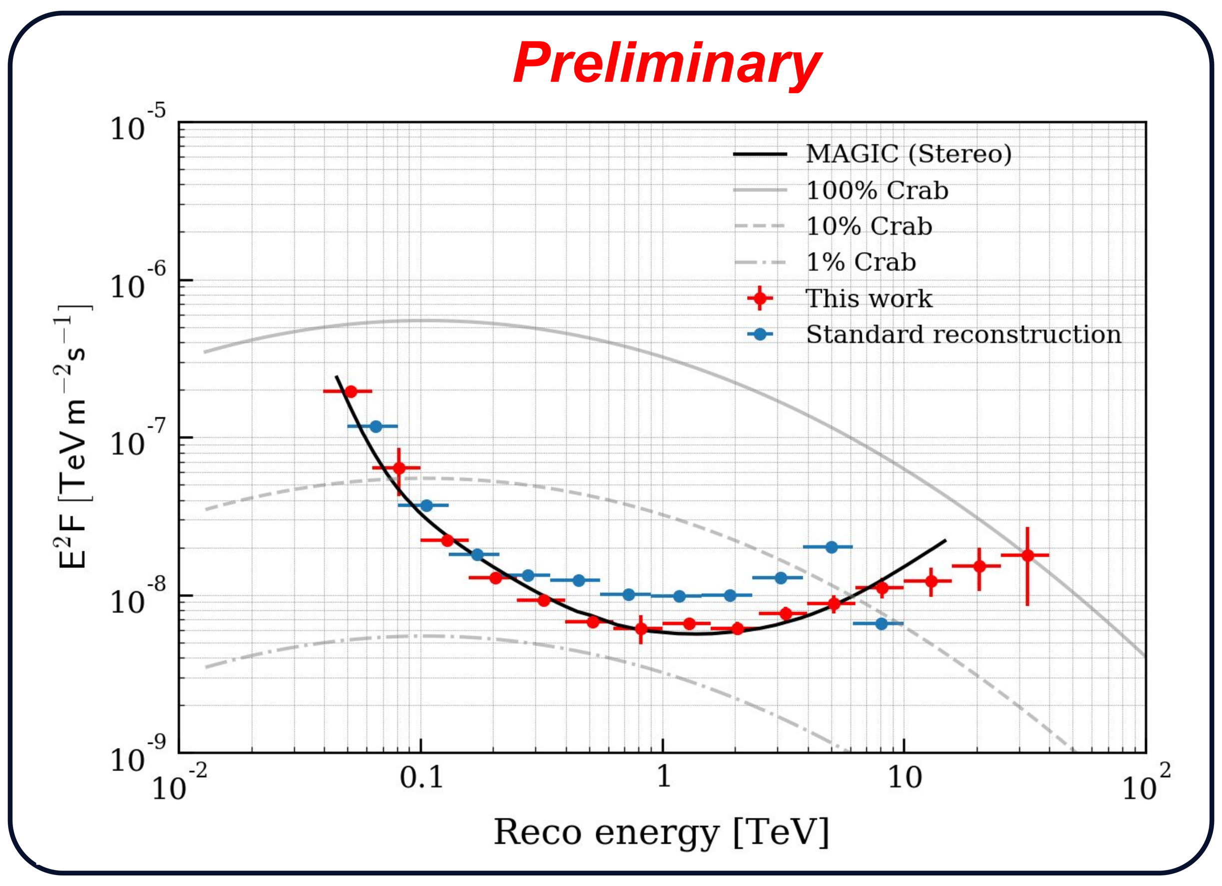

Fig. 3-a: Sensitivity as a function of reconstructed energy. It corresponds to the flux needed to detect the source at a 5σ confidence level when observing for 50 hours.

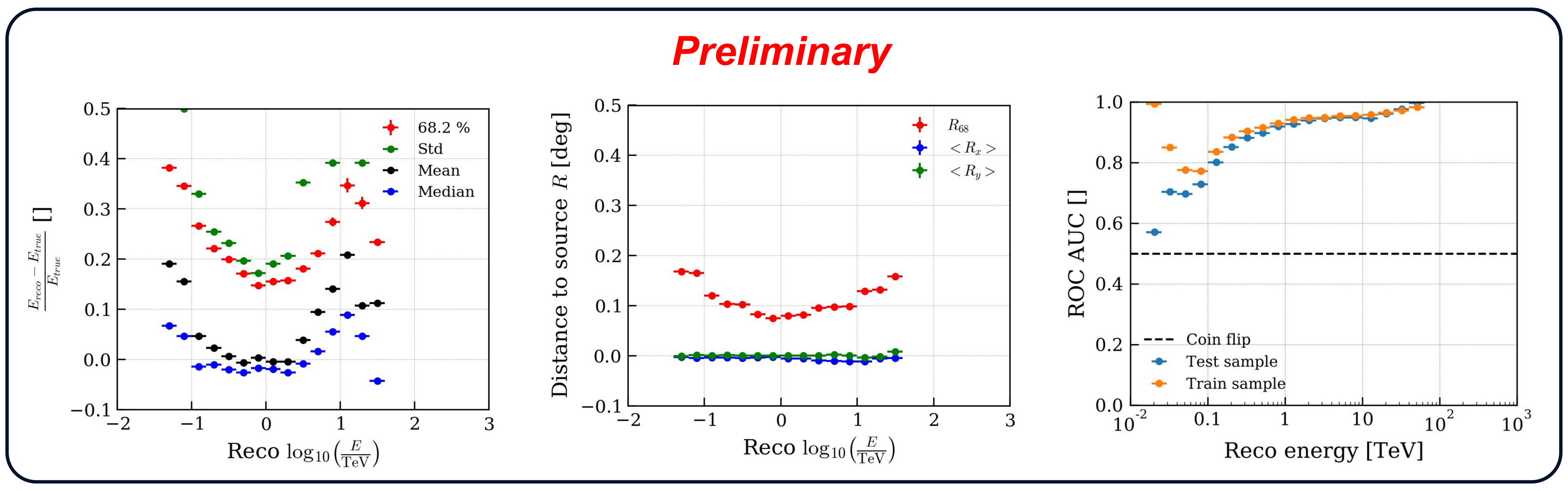

Fig. 3-b: ***left*** **: Energy resolution and bias.** ***middle*** **: Angular resolution and bias.** ***right*** **: ROC AUC.**

References

[1] A.M. Hillas, Proc. 19th International Cosmic Ray Conf. (La Jolla) 3, 445-448 (1985).

[2] De Naurois, M. and L. Rolland. "A high performance likelihood reconstruction of γ-rays for imaging atmospheric Cherenkov telescopes." *Astroparticle Physics* 32 (2009): 231-252

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