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Performance update of an event-type based analysis for the Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) will be the next-generation observatory in the field of very-high-energy (20 GeV to 300 TeV) gamma-ray astroparticle physics. The traditional approach to data analysis in this field is to apply quality cuts, optimized using Monte Carlo simulations, on the data acquired to maximize sensitivity. Subsequent steps of the analysis typically use the surviving events to calculate one set of instrument response functions (IRFs) to physically interpret the results. However, an alternative approach is the use of event types, as implemented in experiments such as the *Fermi*-LAT. This approach divides events into sub-samples based on their reconstruction quality, and a set of IRFs is calculated for each sub-sample. The sub-samples are then combined in a joint analysis, treating them as independent observations. In previous works we demonstrated that event types, classified using Machine Learning methods according to their expected angular reconstruction quality, have the potential to significantly improve the CTA angular and energy resolution of a point-like source analysis. Now, we validated the production of event-type wise full-enclosure IRFs, ready to be used with science tools (such as *Gammapy* and *ctools*). We will report on the impact of using such an event-type classification on CTA high-level performance, compared to the traditional procedure.

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1. Introduction

The Cherenkov Telescope Array (CTA)[1] represents the next-generation observatory in the field of very-high-energy gamma-ray astroparticle physics. It employs two arrays of imaging atmospheric Cherenkov telescopes (IACTs), one for each hemisphere, composed of telescopes of three different sizes. Its optimized configuration provides a major improvement in sensitivity and in angular and energy resolution with respect to the current generation of IACTs over a very broad energy range from 20 GeV up to more than 300 TeV.

The performance of this future observatory is estimated from detailed Monte Carlo (MC) simulations, described by a set of Instrument Response Functions (IRFs). The main IRF components describing the instrument performance to gamma-ray observations are the effective area, the energy dispersion and point-spread function (PSF). These IRFs are then used by science tools (such as gammapy [6] and ctools [10]) to simulate the instrument performance over specific science cases. The methodology to calculate the expected sensitivity and associated IRFs of CTA, as well as their detailed description, has been described in previous contributions (see [2, 4, 8]) and is briefly discussed in section 3.

The *Fermi* Large Area Telescope (LAT) Collaboration [3] proved that high-level analysis performance can be significantly improved by separating events for which the response of the detector is different into event types and producing specific IRFs for each event type [5]. By including this extra knowledge into the likelihood analysis, multiple benefits are achieved: reducing background contamination, increasing the effective area and sensitivity as well as significantly improving the angular and energy resolution for a subset of the events. Inspired by the success of event types in *Fermi*-LAT, we present in this work the status of an analog implementation for IACTs, specifically for the future CTA.

This work is a natural continuation of Ref. [9], where we demonstrated that event types are able to improve the angular and energy resolution by up to 25% for a point-like source located at the center of the field of view (FoV). This first step did not allow the generalized use of event-type-wise IRFs at the science tools level to properly evaluate their impact over specific science cases.

In this work, we have validated the production of event-type wise offset-dependent point-like and full-enclosure IRFs for CTA (i.e. valid for both point-like or extended sources located anywhere within the FoV). These IRFs, tailored to each event type, are now ready to be used by science tools. We also present the impact of this event-type classification on the high-level performance of CTA, comparing it to the standard procedure (not using event types), as well as evaluate the potential for further improvement with a better event-type classification.

2. Event type partitioning

Previous work successfully demonstrated the effectiveness of machine learning (ML) methods in separating event types based on their expected quality in angular reconstruction [9]. Our approach begins at the Data Level 2 (DL2), as the product of a classical IACT analysis, which classification score called *gammaness* and a list of lower-level parameters describing individual telescope images

[1]www.cta-observatory.org

and stereo parameters (such as Hillas parameterization, reconstructed altitude of shower maximum, etc...).

An event type is a unique tag for each event in a DL2 table that classifies of all them in terms of their quality in angular reconstruction. We use a ML regression model to predict the angular difference between true and reconstructed direction (from now on, predicted misdirection), so the division of event types reduces to establishing thresholds for the top X% reconstructed events (lowest predicted misdirection), the following Y%, etc. Where the number of event types and their proportions can be freely decided.

The event type partitioning methodology employed for this study is almost identical to the one described in the previous contribution [9] with the following differences:

- The MC simulated data used is diffuse (covering the full FoV of CTA telescopes) for gammas, protons and electrons.
- The regression model we use, a multilayer perceptron (MLP) neural network with a *tanh* as neuron activation function, has been further optimized.
- The thresholds in predicted misdirection to divide the event types are now dependent in both energy and offset angle, instead of only energy.

3. IRF production

The standard methodology to compute CTA IRFs [2, 4, 8] starts from DL2 table. A re-weight of the simulated events is needed so that they resemble the particle statistics expected from a CTA observation of a Crab-Nebula-like source (as a test case). To compute IRFs a cut optimization is needed, generally maximizing sensitivity as a function of the reconstructed energy. Events surviving these quality cuts are the ones that will be used to compute the final set of IRFs. The cut optimization is usually performed over the following parameters: multiplicity (number of telescopes used in the reconstruction of an event), *gammaness* and, in the case of a point-like source analysis, the angular size of the signal region (*ON region*). Once CTA data is produced, the list of events surviving the *gammaness* and multiplicity cuts together with their corresponding IRFs form the Data Level 3 (DL3) products.

With this procedure, the amount of data surviving quality cuts (and therefore actually used in the analysis) is small compared to the rejected data, while the latter could still be useful. Furthermore, as there is only one set of IRFs generated applied equally for all events, all the extra knowledge we have from the low-level analysis is lost.

In an event-type based analysis, the event type partitioning (as explained in Section 2) occurs before optimizing the cuts and computing the IRFs. This allows to create a number of independent lists (as many as event types), each one with their corresponding set of IRFs describing their average quality.

To compute the IRFs and store them in the proper format[2] we used the library *pyirf*[3]. This library first needed to be tested and validated to produce offset-dependent and full-enclosure IRFs.

[2]https://gamma-astro-data-formats.readthedocs.io/en/v0.3/irfs/index.html
[3]https://github.com/cta-observatory/pyirf

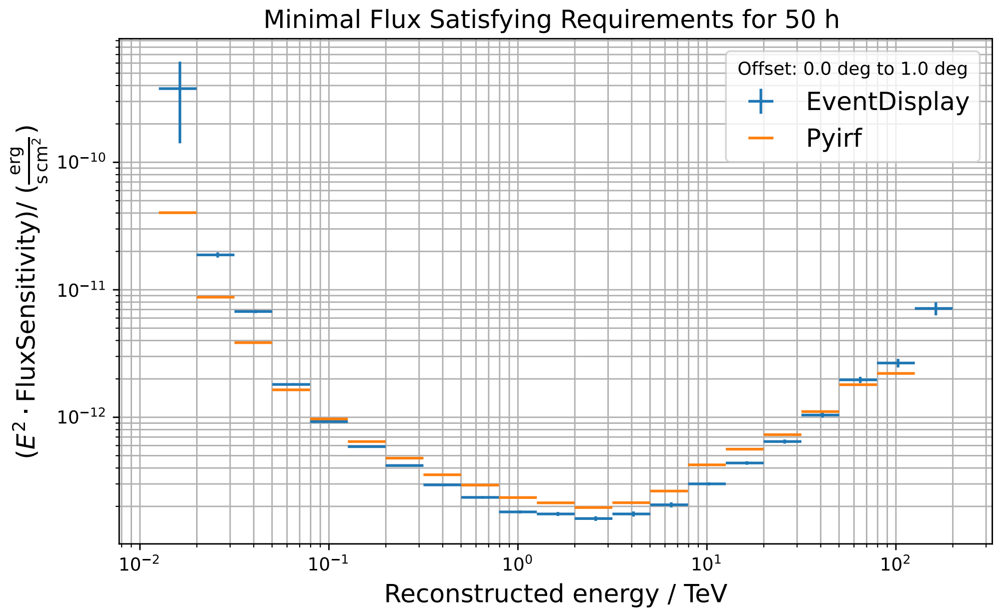

Figure 1: *EventDisplay* and *pyirf* comparison of the resulting sensitivity for a Crab-like observation of 50 hours in the central FoV offset bin.

To validate it, we compared the resulting sensitivity and IRFs to the ones computed by *EventDisplay* [11] with the same MC data. The tests consisted in two steps:

1. Validate pyirf IRF computation. By using identical DL2 tables, we compared the computed IRF components by using exactly the same quality cuts as *EventDisplay*. The results were identical, and therefore the computation of all IRF components was validated.

2. Validate pyirf cut optimization. We performed two independent cut optimizations (with *pyirf* and *EventDisplay*) by selecting the cuts that provide a better sensitivity in each energy bin, and compared resulting sensitivities. As shown in Fig. 1, they are not exactly the same but they agree to within 50% between 30 GeV and 100 TeV (also across different values of the FoV). The reason of the disagreement is not known, but is probably related to small differences in the cut selection methods (for example, *EventDisplay* uses smaller bins for the direction cuts).

After performing these tests, we conclude *pyirf* is suitable to our needs, as it allows us to compute both point-like and full-enclosure IRFs properly for all different camera offset angles up to 6 *deg*. Once the production of IRFs was validated, we produced various sets of event-type-wise IRFs, ready to be used with high-level science tools, in this case, *Gammapy*.

4. Results

We evaluate the expected angular reconstruction quality of all events, rank them and eventually classify them into different event-type partitionings to then produce event-type-wise offset-

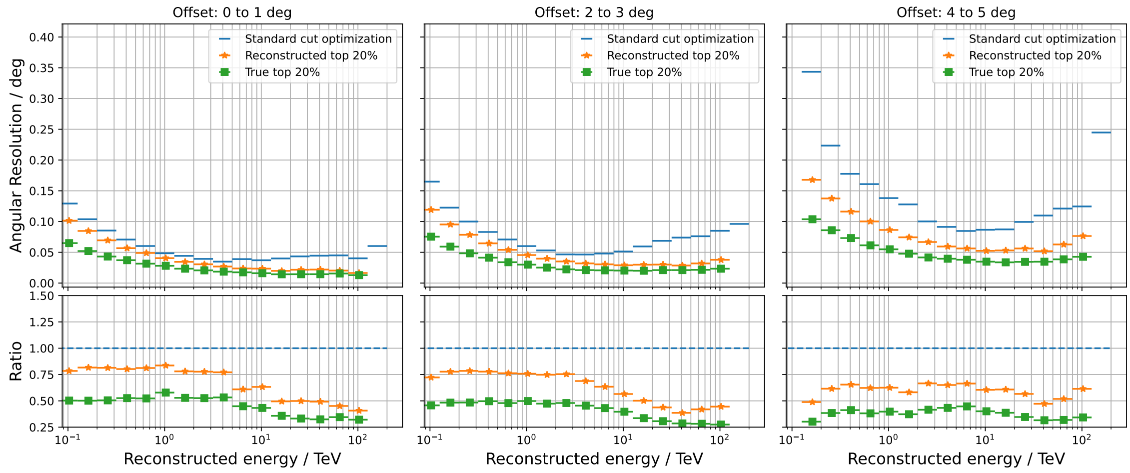

Figure 2: Angular resolution for a 50 hours observation, comparison between the standard cuts case, the reconstructed top 20% events and the true top 20%. Repeated for different offset ranges.

dependent IRFs for 50 hours of observing time for the "Alpha" layout of CTA-North (4 LSTs and 9 MSTs) [7].

By computing the angular resolution for the ranked top 20% events as reconstructed by our model, we show a 25 to 50 % improvement in angular resolution with respect to the standard cut optimization method (not using event types), as shown in Figure 2. We also computed the angular resolution for the true top 20% events, i.e.: ranking by the actual difference between the reconstructed and the true simulated position of each event, so we can see there is still room for improvement of our regression model.

We can use these IRFs to perform either 1D (spectral evaluations of point-like sources) or 3D (spectral and morphological studies) simulations with *Gammapy*. Datasets are simulated from a set of IRFs: we are able to perform simulations for a single IRFs set and for event-type-wise IRFs treating them as independent samples that may be combined in a joint-likelihood analysis. By doing this with a Crab-like source simulations over a wide range of fluxes, we can reconstruct the combined sensitivity from all event types as shown in Figure 3, by identifying over each bin in reconstructed energy the simulated flux that provides a 5σ detection. Note this method to compute sensitivity (for any set of observations or simulations at *Gammapy* level) does not have the usual requirements generally included in the calculation of sensitivity, such as the requirement of the excess being larger than a 5% of the background (to account for systematics in the background) or the minimum number of 10 excess events (heavily affecting the sensitivity at the highest energies), which is the main reason of the disagreements at the lowest and highest energies with the *pyirf*-estimated curve.

5. Conclusions

The conclusions of this work can be summarized by the following milestones:

1. Our ML regression model is able to predict the misdirection of each event and, therefore, can be used to separate event types. It should be noted there is still room for improvement.

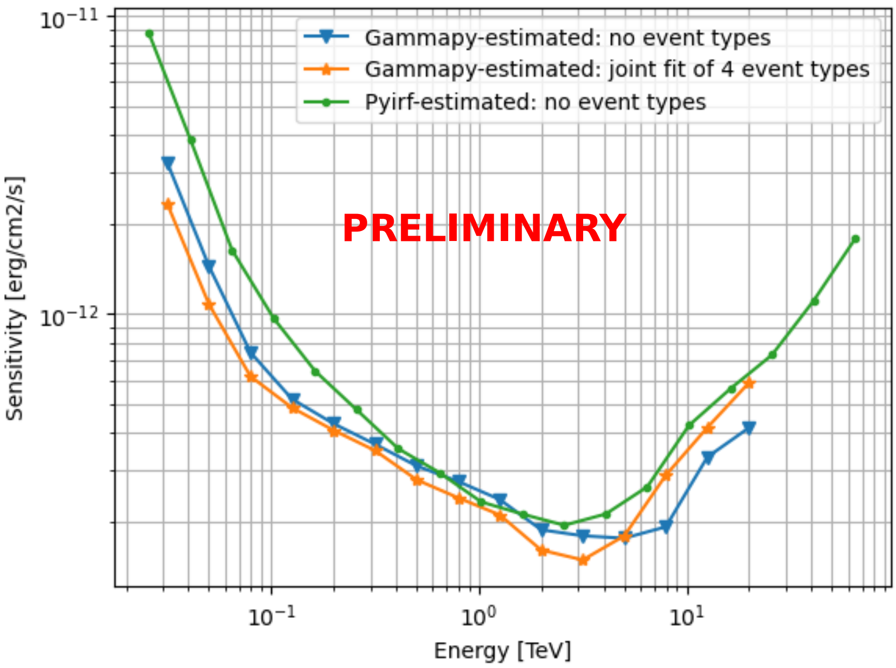

Figure 3: Preliminary sensitivity curve reconstructed with *Gammapy* by doing a likelihood analysis with combined event types (4 types with 25% of the events each) and with no event types, compared to the standard sensitivity computed with *pyirf*. Note that Gammapy-estimated sensitivity does not take into account any conditions on background systematics and minimum number of excess events, which affect the highest and the lowest energies.

2. Offset-dependence has been introduced and validated in the event-type partitioning process.

3. We are now able to produce consistently both point-like and full-enclosure event-type-wise IRFs over the full FoV, which allows high-level simulations with science tools such as *Gammapy*.

4. Event-type-wise IRFs show a significant improvement in angular resolution (25 to 50% over a subset of the events).

5. Preliminary *Gammapy* analysis already shows that is possible to combine observations from different event-type samples for a better performance.

This work shows the great potential that an event-type based analysis could have for improving CTA's performance. A specific science case for fundamental physics with gamma-ray propagation [1] that could be benefited by event types is measuring intergalactic magnetic fields, in which the size of the PSF is crucial. Another important example is the Galactic Plane Survey, where the improved angular resolution at large offset angles will allow to separate sources and determine extensions and morphologies better than ever in this energy range.

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