# Event reconstruction using pattern spectra and convolutional neural networks for the Cherenkov Telescope Array

Jann Aschersleben[1], Manuela Vecchi[1], Michael H. F. Wilkinson[2], Reynier Peletier[1] for the CTA Consortium[3]

[1]*Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands*
[2]*Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, University of Groningen, PO Box 407, NL-9700 AK Groningen, the Netherlands*
[3]*See www.cta-observatory.org*

j.j.m.aschersleben@rug.nl

cherenkov telescope array

university of groningen

## ABSTRACT

The Cherenkov Telescope Array (CTA) is the future observatory for ground-based imaging atmospheric Cherenkov telescopes. Each telescope will provide a snapshot of gamma-ray induced particle showers by capturing the induced Cherenkov emission at ground level. The simulation of such events provides camera images that can be used as training data for convolutional neural networks (CNNs) to differentiate signals from background events and to determine the energy of the initial gamma-ray events. Pattern spectra are commonly used tools for image classification and provide the distributions of the sizes and shapes of features comprising an image. The application of pattern spectra on a CNN allows the selection of relevant combinations of features within an image.

In this work, we generate pattern spectra from simulated gamma-ray images to train a CNN for signal-background separation and energy reconstruction for CTA. We compare our results to a CNN trained with CTA images and find that the pattern spectra-based analysis is computationally less expensive but not competitive with the purely CTA images-based analysis. Thus, we conclude that the CNN must rely on additional features in the CTA images not captured by the pattern spectra.

## 1 - Introduction

**The interaction of a gamma ray with the Earth atmosphere induces a particle shower, which produces a flash of Cherenkov light. The Cherenkov Telescope Array (CTA) will be able to capture the Cherenkov emission at ground level, which provides information about the energy of the initial gamma ray. Pattern spectra [1] are commonly used tools for image classification, which provide the distributions of the shapes and sizes of various objects comprising an image (Fig. 1). Requiring significantly less computational power compared to other algorithms, they can be used for signal-background separation and to reconstruct the energy of the initial gamma ray [2].**

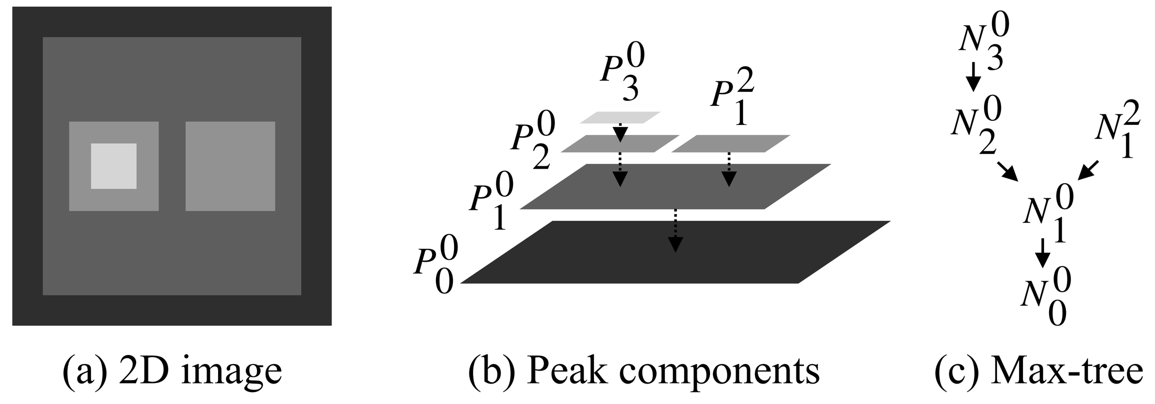


Fig 1: Visual representation of the pattern spectra algorithm (adapted from [1, 3] ).

## 2 - Analysis

**The pattern spectra are generated from the CTA images by calculating the size (area *A* ) and shape (*I/A²* with the moment of inertia *I* ) of each feature (Fig. 2). Separately, the CTA images or the pattern spectra are used as an input for a convolutional neural network (CNN), which is trained and tested for signal-background separation and energy reconstruction. The CNN is trained ten times for energy reconstruction to obtain a mean energy resolution and its uncertainty.**

## 3 - Results

**The CTA images-based analysis outperforms the pattern spectra-based analysis in both the signal-background separation (Fig. 3) and the energy reconstruction (Fig. 4).**

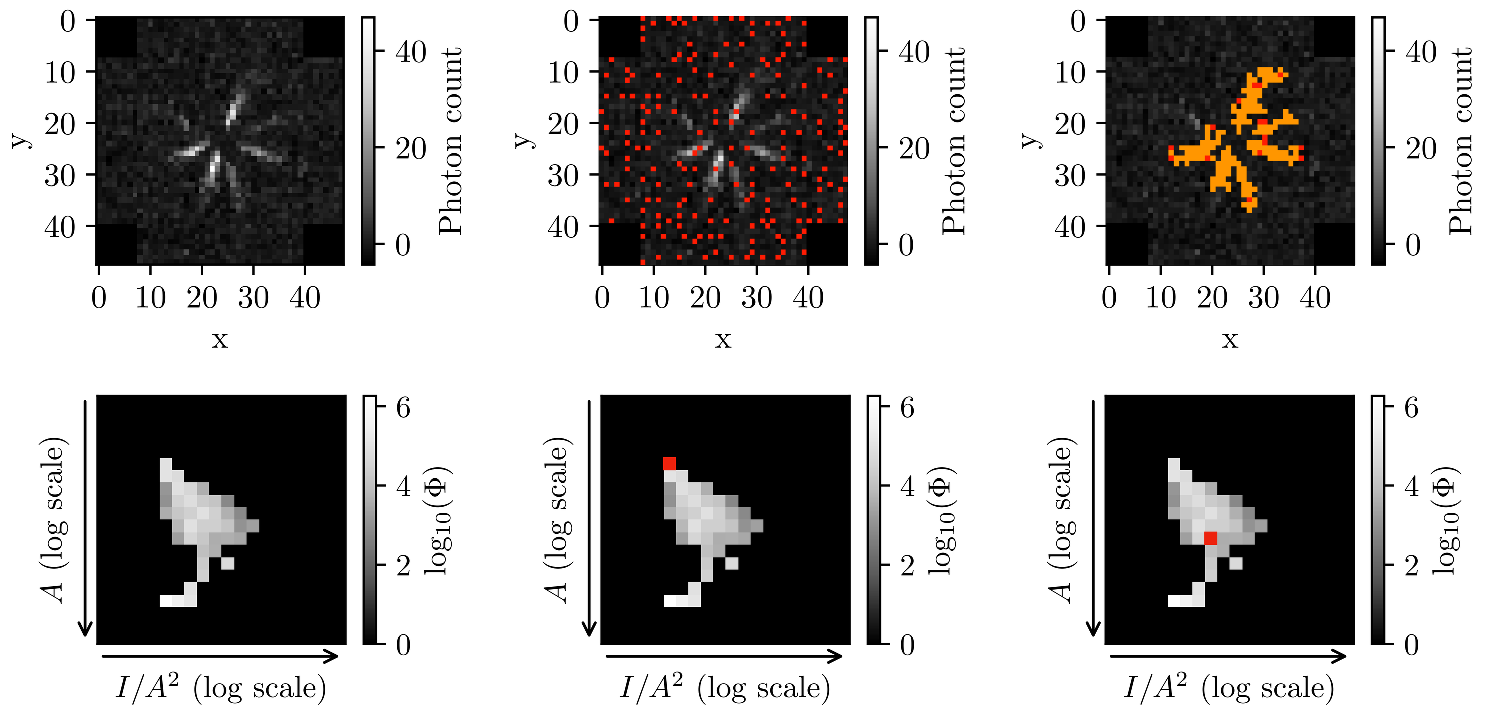


Fig 2.: Top: CTA image with detected features (in red/orange).
Bottom: pattern spectrum with the pixel (in red) corresponding to the detected features.

**During training, the CNN based on pattern spectra needs a factor 3.1 less random access memory (RAM) and is a factor 2.6 faster compered to the CNN based on the CTA images (Tab. 1).**

## 4 – Discussion

**The pattern spectra-based analysis is computationally less expensive but not competitive with the CTA images-based analysis. Thus, we conclude that the CNN must rely on additional features in the CTA images not captured by the pattern spectra.**

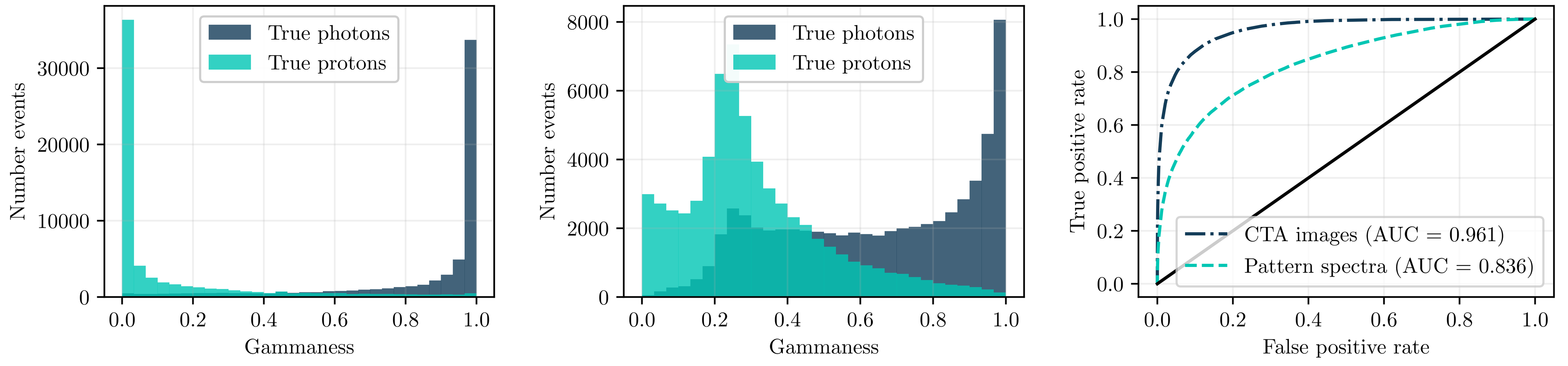


Fig. 3: Gammaness distribution of the events obtained with the CTA images (left) and pattern spectra (middle). Receiver operating characteristic (ROC) curve and area under curve (AUC) comparison (right).

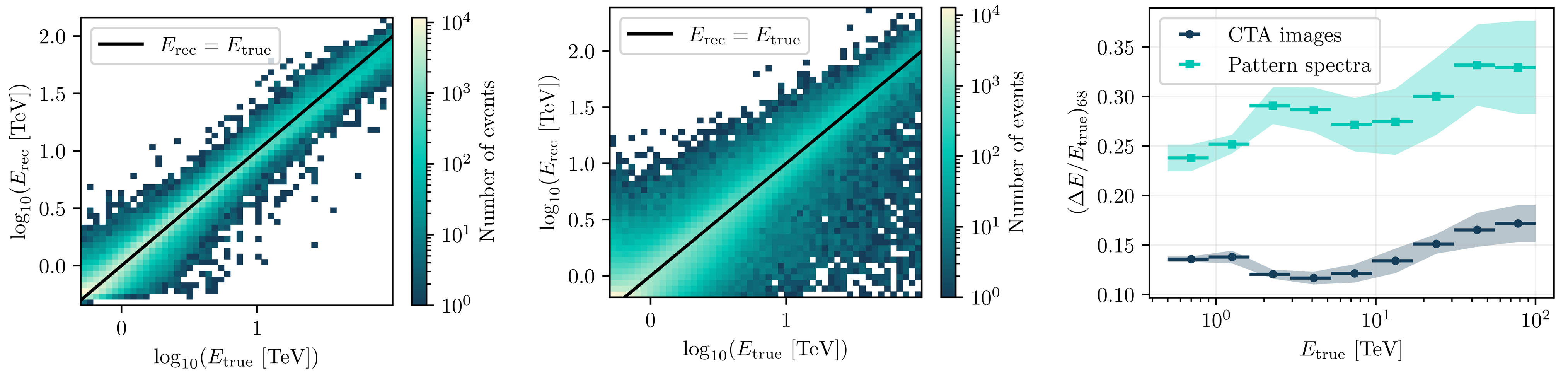


Fig. 4: Reconstructed energy $E_{rec}$ as a function of true energy $E_{true}$ obtained with CTA images (left) and pattern spectra (middle). Energy resolution comparison (right). The data points represent the mean value and the shadowed regions one standard deviation.

Tab. 1: Computational performance of the CNNs based on (a) CTA images and (b) pattern spectra during training as energy reconstruction

| | CTA images | Pattern spectra | ratio |
|---|---|---|---|
| Max. RAM | ~100 GB | ~32 GB | 3.1 |
| Time | ~29 ks | ~11 ks | 2.6 |

## BIBLIOGRAPHY

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