Advanced Image Cleaning

CTA Consortium Meeting

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October 25, 2016

Introduction

Subject

Try to improve image cleaning before reconstruction (*Hillas*)

Improve methods to remove:

- Instrumental noise
- Background noise

Motivations:

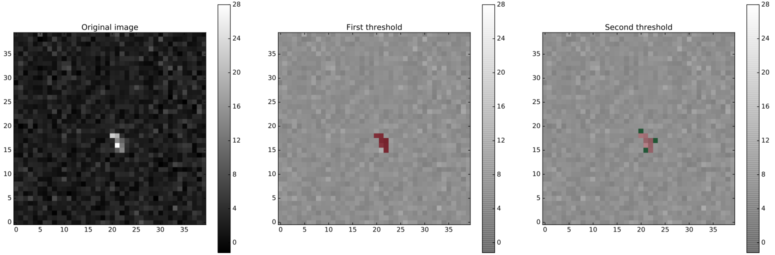
- Keep more signal (deeper into the noise)
- Reduce threshold
- Maybe eventually do cleaning and time-integration all at once

Image cleaning algorithms

The "Tailcut clean" algorithm

A very simple cleaning procedure:

- Keep pixels above a given threshold (e.g. 50% max)
- Keep some neighbors of these selected pixels: those above a second (lower) threshold (e.g. 25% max)



Remarks

- Fast and simple
- Sufficient for bright showers
- But surely we can do better for faint showers

Basic idea to go beyond

- Tailcut method: threshold in the main space
- Better idea: threshold in a different space where signal and noise can be easily separated
  - Wavelet transform
  - Cosmostat tools (iSAP/Sparse2D) (`http://www.cosmostat.org/software/isap/`)

We are considering *Wavelet Transform* method

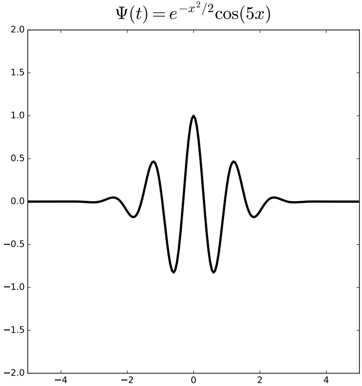
Roughly the same idea than doing filtering with Fourier Transform

- Apply the transform on the signal
- Apply a threshold in the transformed space
- Invert the transform to go back to the original signal space

Differences with Fourier Transform

- Use functions named *wavelets* instead sin and cos functions as new bases in the transformed space
- The transformed space contains spatial information

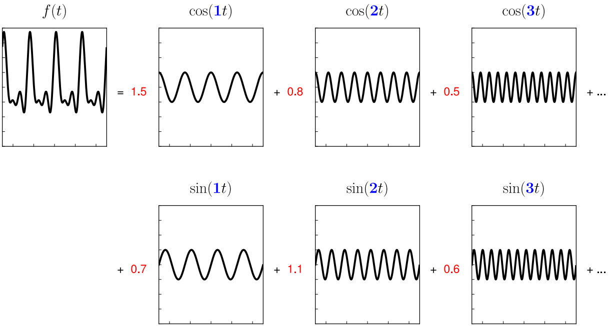
Example of wavelet function (*Morlet wavelet*)



"A short wave-like oscillation with a beginning and an end"

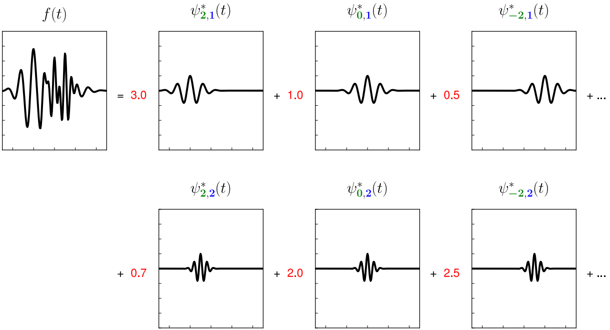
Cleaning procedure: general idea with Fourier Transform

- Input signal is converted to a weighted sum of sin and cos at different frequencies
- Threshold is applied on these weights to remove some frequencies in the input signal (e.g. high pass filter, low pass filter, ...)



Cleaning procedure: general idea with Wavelet Transform

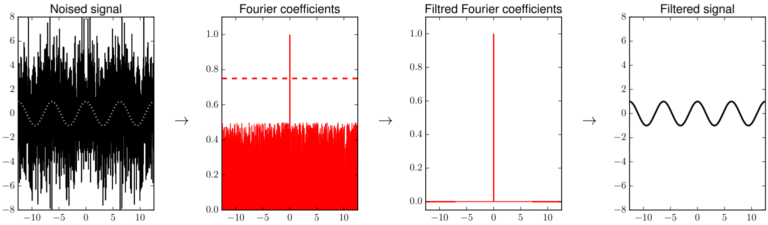
- Input signal is converted to a weighted sum of these wavelet functions at different scales (dilate factor) and positions (translate factor)
- Threshold is applied on these weights to remove locally (in space or time) some frequencies (or scales) in the input signal



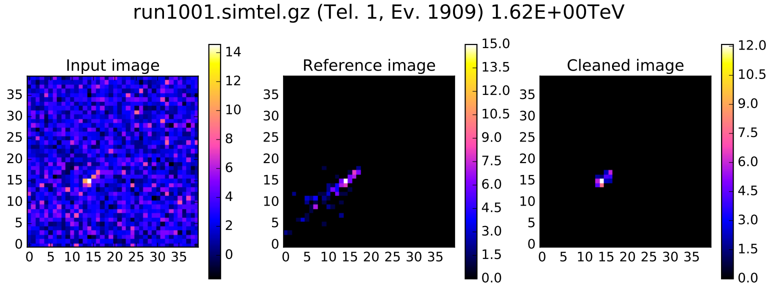
Find a base where signal and noise can be easily separated

In this example:

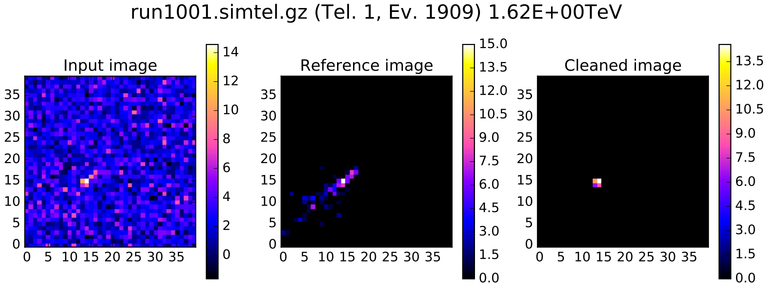
- Remove noise in direct space is difficult
- Remove noise in the transformed space is easy:
  - noise is uniformly distributed on small coefficients
  - signal is defined by few big coefficients



Example


run1001.simtel.gz (Tel. 1, Ev. 1909) 1.62E+00TeV
Input image
Reference image
Cleaned image
0 5 10 15 20 25 30 35
14 12 10 8 6 4 2 0
15.0 13.5 12.0 10.5 9.0 7.5 6.0 4.5 3.0 1.5 0.0
12.0 10.5 9.0 7.5 6.0 4.5 3.0 1.5 0.0

The same example with Tailcut

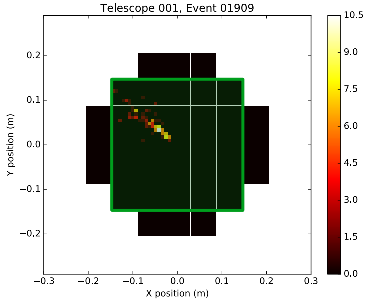


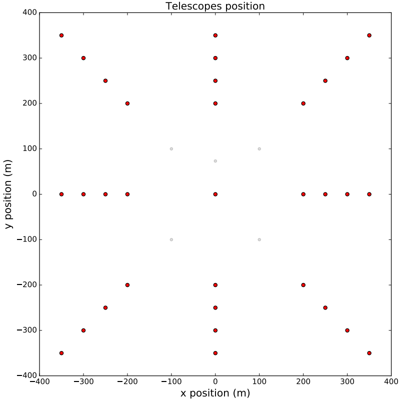
Experimental setting

Dataset used to assess cleaning algorithms

"ASTRI mini-array" test set

- Kindly provided by the Astri team
- 33 ASTRI telescopes
- Cropped to get squared pixel arrays





Benchmark function

The error on the shape:

$$\mathcal{E}_{\text{shape}}(\hat{\mathbf{s}}, \mathbf{s}^*) = \text{mean}\left(\text{abs}\left(\frac{\hat{\mathbf{s}}}{\sum_i \hat{\mathbf{s}}_i} - \frac{\mathbf{s}^*}{\sum_i {\mathbf{s}^*}_i}\right)\right)$$

The error on the energy:

$$\mathcal{E}_{\text{intensity}}(\hat{\mathbf{s}}, \mathbf{s}^*) = \frac{\text{abs}\left(\sum_i \hat{\mathbf{s}}_i - \sum_i {\mathbf{s}^*}_i\right)}{\sum_i {\mathbf{s}^*}_i}$$

Where:

- $\hat{\mathbf{s}}$ the image "cleaned" by algorithms
- $\mathbf{s}^*$ the actual "clean" image
- i is the index of a PMT (i.e. of a pixel) within an image

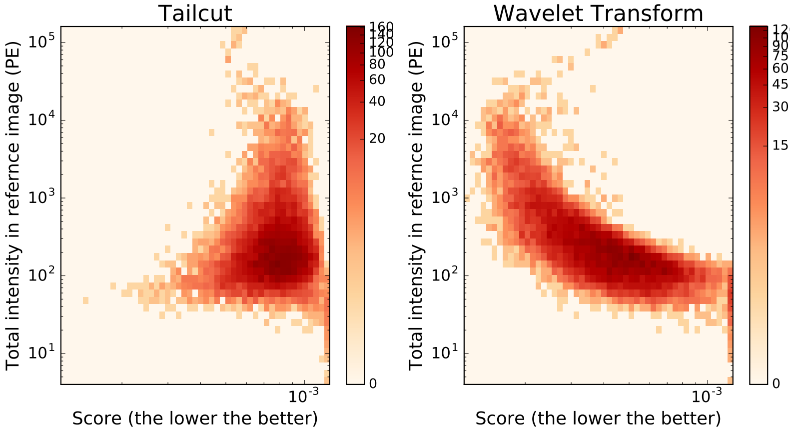
Preliminary results

Dataset used to assess cleaning algorithms

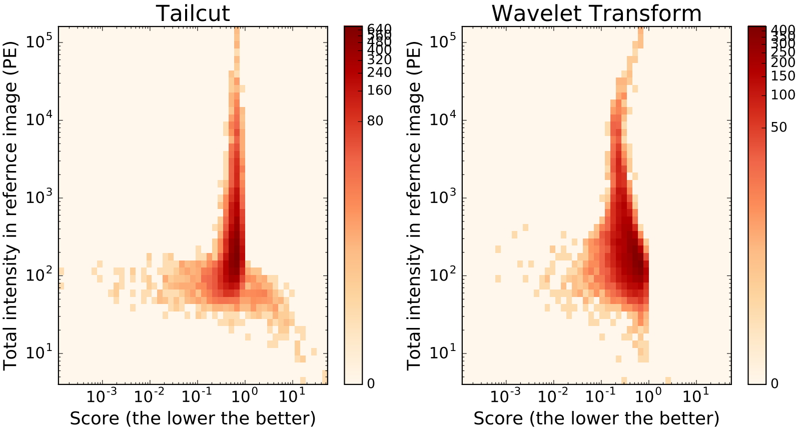
Realistic event set:

- Gamma photons: 4461 events, 14899 images
- Protons: 747 events, 2203 images

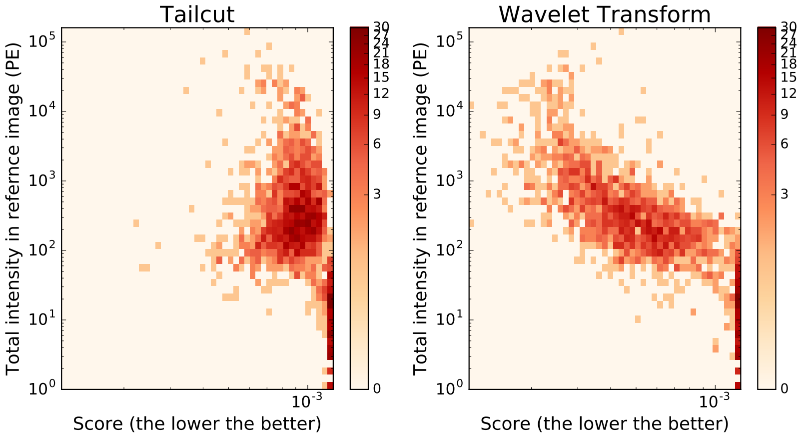
$\mathcal{E}_{shape}$ (gamma photons)



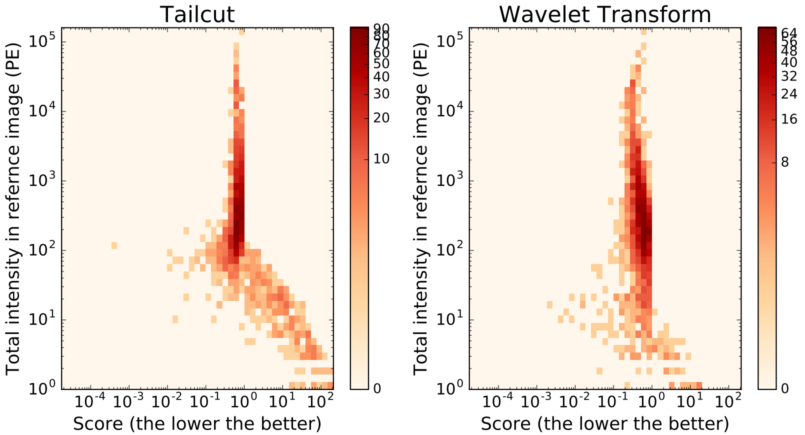
$\mathcal{E}_{intensity}$ (gamma photons)



$\mathcal{E}_{shape}$ (protons)



$\mathcal{E}_{intensity}$ (protons)



Conclusion

Conclusion

This is a work is in progress...

- Optimize algorithms setting:
  - wavelet function
  - wavelet filtering methods
  - filtering thresholds
  - pre processing
  - post processing
  - ...
- Compare to optimized Tailcut
- Adapt the cleaning method to real cameras (full pixel array, hexagonal shapes, ...)
- Check ability to do real time analysis

References I

- CK Bhat, *Search for diffuse galactic/extra-galactic tev gamma rays*.
- ______, *Search for diffuse cosmic gamma-ray flux using fractal and wavelet analysis from galactic region using single imaging cerenkov telescopes*, Astroparticle Physics **34** (2010), no. 4, 230–235.
- Stefan Funk, *Hadron suppression using wavelet transformations for the hess telescope system*, Master's thesis, 2002.
- A Haungs, J Knapp, I Bond, and R Pallassini, *Application of fractal and wavelet analysis to cherenkov images of the whipple telescope*, Proceedings of ICRC, vol. 2001, 2001.

References II

- A Haungs, AK Razdan, CL Bhat, RC Rannot, and H Rebel, *First results on characterization of cherenkov images through combined use of hillas, fractal and wavelet parameters*, Astroparticle Physics **12** (1999), no. 3, 145–156.
- RW Lessard, L Cayón, GH Sembroski, and JA Gaidos, *Wavelet imaging cleaning method for atmospheric cherenkov telescopes*, Astroparticle Physics **17** (2002), no. 4, 427–440.
- S. Mallat, *A wavelet tour of signal processing: The sparse way*, Elsevier Science, 2008.

References III

- A Razdan, A Haungs, H Rebel, and CL Bhat, *Image and non-image parameters of atmospheric cherenkov events: a comparative study of their γ-ray/hadron classification potential in ultrahigh energy regime*, Astroparticle Physics **17** (2002), no. 4, 497–508.
- ______, *Novel image and non-image parameters for efficient characterisation of atmospheric cerenkov images.*

References IV

BM Schaefer, W Hofmann, H Lampeitl, M Hemberger, HEGRA Collaboration, et al., *Particle identification by multifractal parameters in γ-astronomy with the hegra-cherenkov-telescopes*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **465** (2001), no. 2, 394–403.

Appendix

Wavelets: why is it promising ?

- Should handle more complex signal (faint signal, ...)
- May use coefficients for photon/hadron discrimination
- Data compression on site
- Require few calibration

Wavelets: mother wavelet Ψ

Family $\psi_{a,b}$ (where $(a, b) \in \mathbb{R}^{+*} \times \mathbb{R}$) is defined from the "mother wavelet" Ψ:

$$\forall t \in \mathbb{R}, \psi_{a,b}(t) = \frac{1}{\sqrt{a}} \Psi \left(\frac{t - b}{a} \right)$$

where a is the scale factor, b is the translation factor.

Wavelets: general case (1D continuous case)

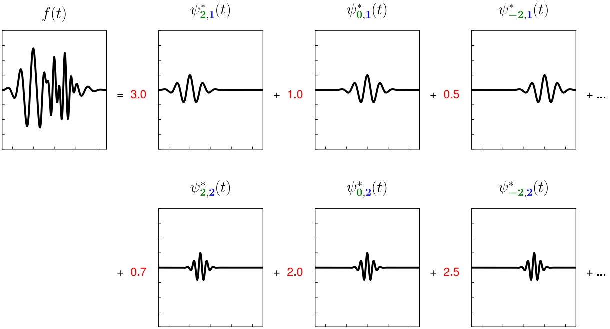
The original signal f defined as:

$$f(t) = \frac{1}{C_\Psi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{g(a,b)}{|a|^2} \psi_{a,b}(t) da\, db$$

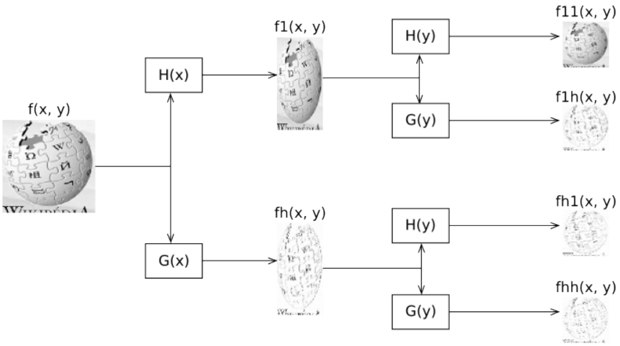
where C_Ψ is a constant which depends on the chosen wavelet mother Ψ.
Weights are given by:

$$g(a,b) = \int_{-\infty}^{\infty} f(t) \psi^*_{a,b}(t)\, dt$$

Wavelets: general case (1D continuous case)



Wavelets: general case (2D hints)



Fourier transform: general case (1D continuous case)

The original signal f defined as:

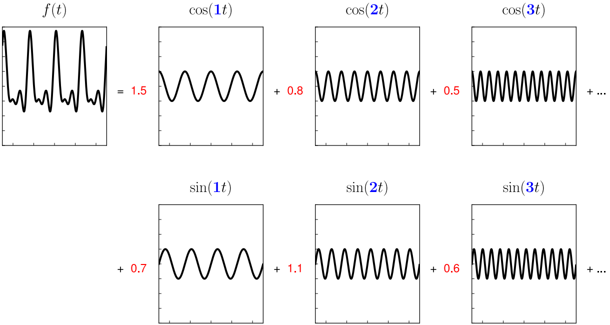
$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n \cos(nt) + b_n \sin(nt))$$

Weights are given by:

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(t)\cos(nt)dt$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(t)\sin(nt)dt$$

Fourier transform: general case (1D continuous case)



Fourier transform: remarks

FFT can be applied to any T-periodic function f verifying the *Dirichlet conditions*:

- f must be continuous
- *and* monotonic
- on a finite number of sub-intervals (of T)

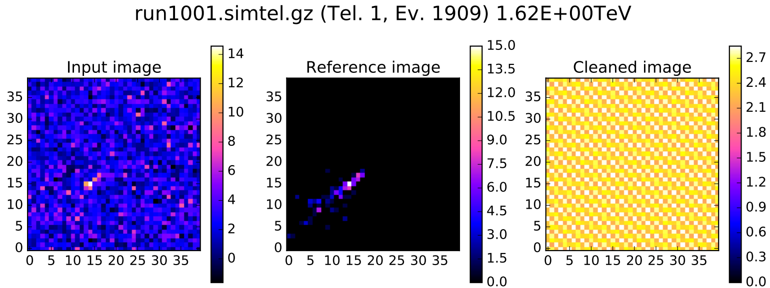
Signals defined on bounded intervals (e.g. images) can be considered as periodic functions (applying infinite repetitions)

Fourier transform: analyse

Works well:

- when the Fourier coefficients for the signal and the noise can easily be separated in the Fourier space (obviously...)
- e.g. when either the signal *or* the noise can be defined with few big Fourier coefficients (i.e. signal or noise have a few number of significant harmonics)

Fourier transform: a bad example



Different kind of “noise” in telescope images

1. Instrumental noise (Photomultiplier Tubes, ...)
   - Thermionic emission
   - Radiations
   - Electric noise
2. Background noise (*Night Sky Background* or NSB)
   - Parasite light (moon, stars, planes, light pollution, ...)

MC simulations

"ASTRI mini-array" configuration

Number of events per simtel files:

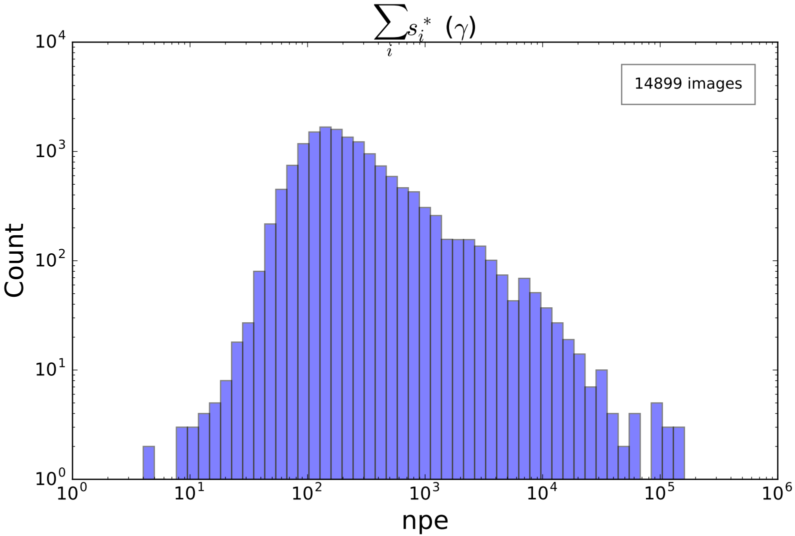
File	Num. events
gamma/run_1001.simtel.gz	4461
gamma/run_1002.simtel.gz	4567
gamma/run_1003.simtel.gz	4425
gamma/run_1004.simtel.gz	4401
gamma/run_1005.simtel.gz	4451
gamma/run_1006.simtel.gz	4451
gamma/run_1007.simtel.gz	4614
gamma/run_1008.simtel.gz	4423
gamma/run_1009.simtel.gz	4411

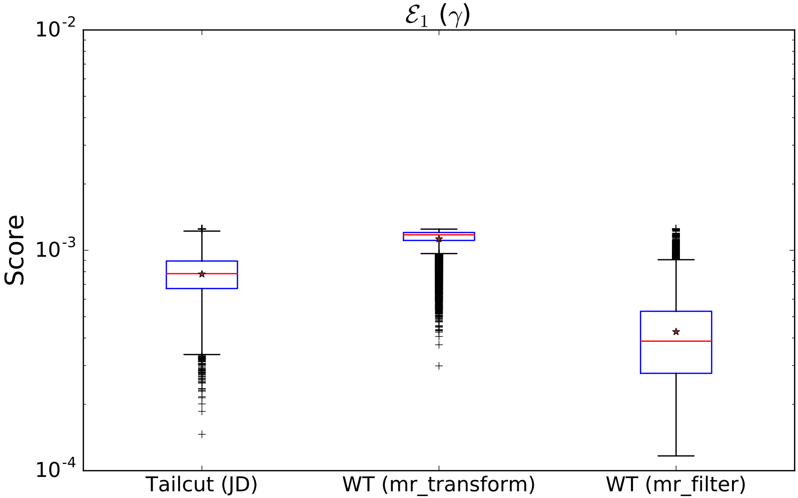
MC simulations

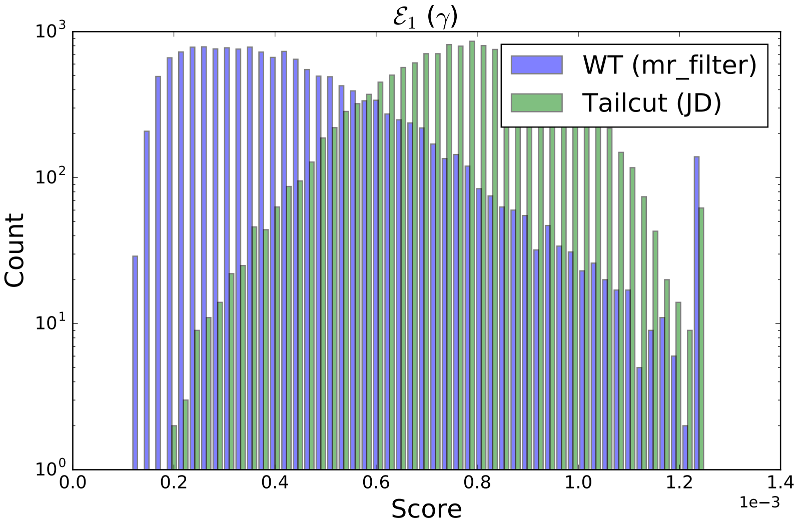
"ASTRI mini-array" configuration

Number of events per simtel files:

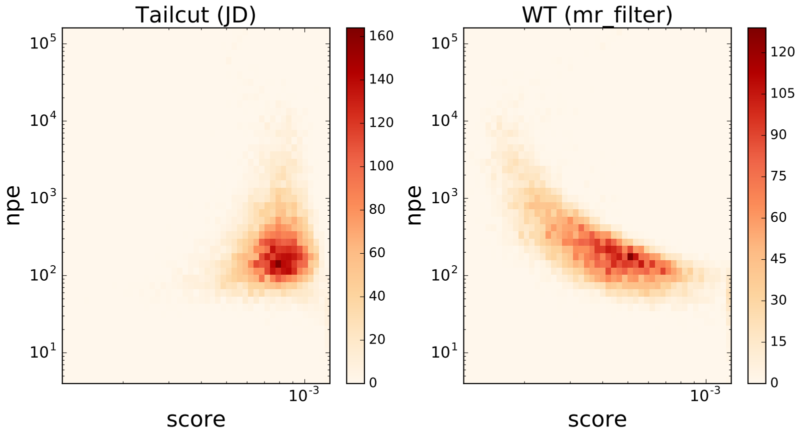
File	Num. events
proton/run_10000.simtel.gz	747
proton/run_10001.simtel.gz	680
proton/run_10002.simtel.gz	763
proton/run_10003.simtel.gz	792
proton/run_10004.simtel.gz	763
proton/run_10005.simtel.gz	776
proton/run_10006.simtel.gz	738
proton/run_10007.simtel.gz	749
proton/run_10008.simtel.gz	760
proton/run_10009.simtel.gz	812

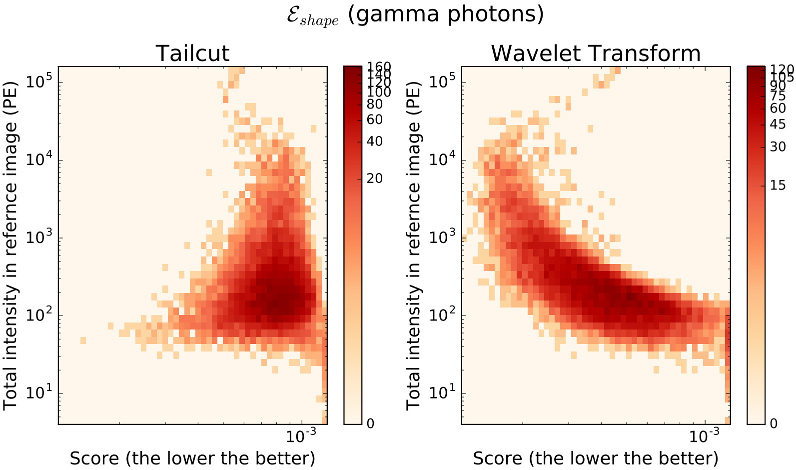

$\sum_i s_i^*$ (γ)
14899 images
Count
npe
10^0
10^1
10^2
10^3
10^4
10^5
10^6

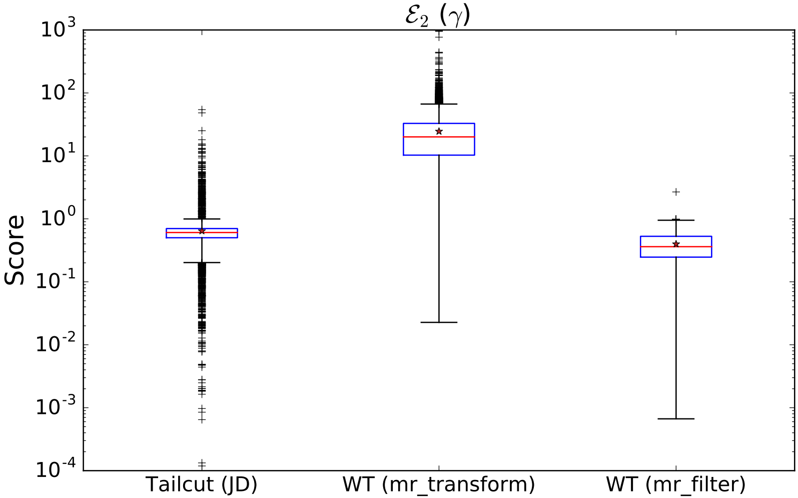

$\mathcal{E}_1$ (γ)
Score
10^{-2}
10^{-3}
10^{-4}
Tailcut (JD)
WT (mr_transform)
WT (mr_filter)

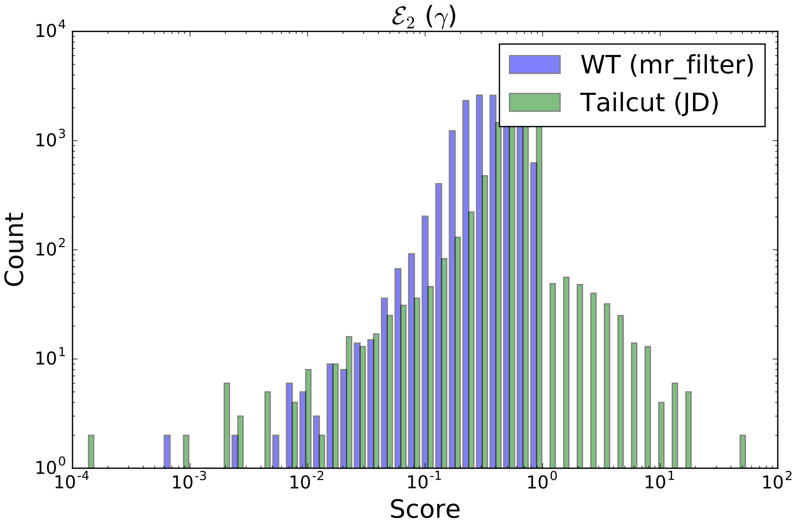

$\mathcal{E}_1$ (γ)
Count
Score
1e−3
WT (mr_filter)
Tailcut (JD)
10^0
10^1
10^2
10^3
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

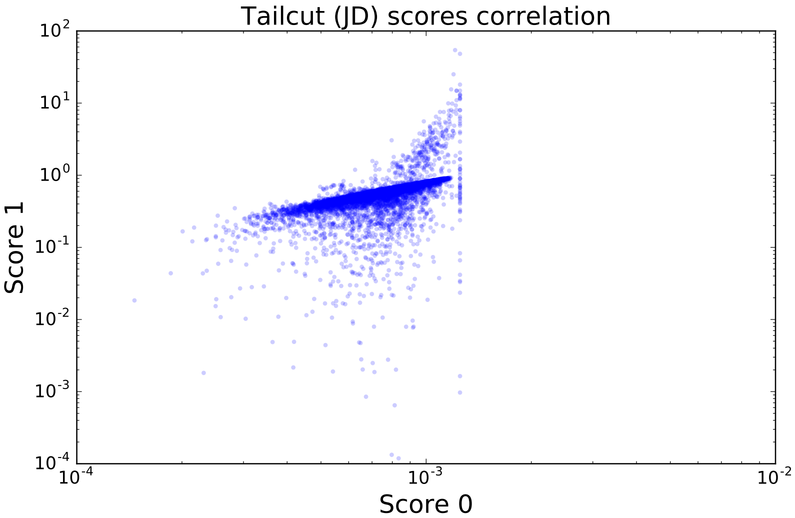
$\mathcal{E}_1$ (γ)

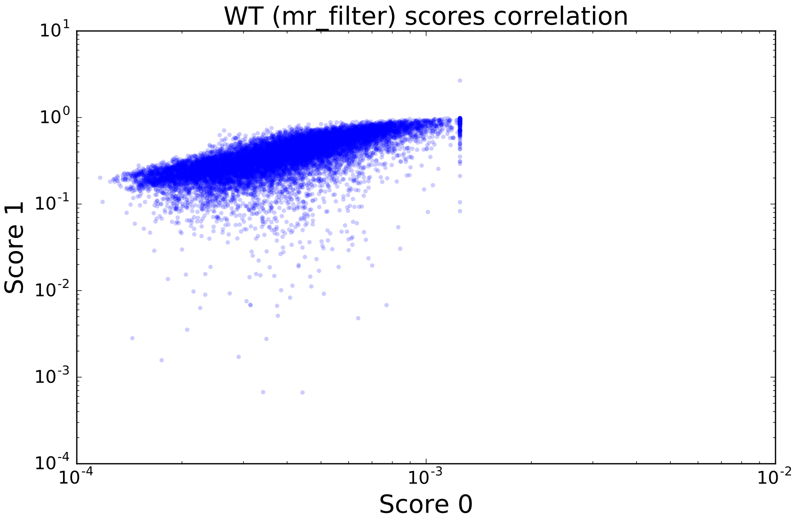



$\mathcal{E}_{shape}$ (gamma photons)
Tailcut
Wavelet Transform
Total intensity in refernce image (PE)
10^5
10^4
10^3
10^2
10^1
10^{-3}
Score (the lower the better)
160
140
120
100
80
60
40
20
0
120
105
90
75
60
45
30
15
0

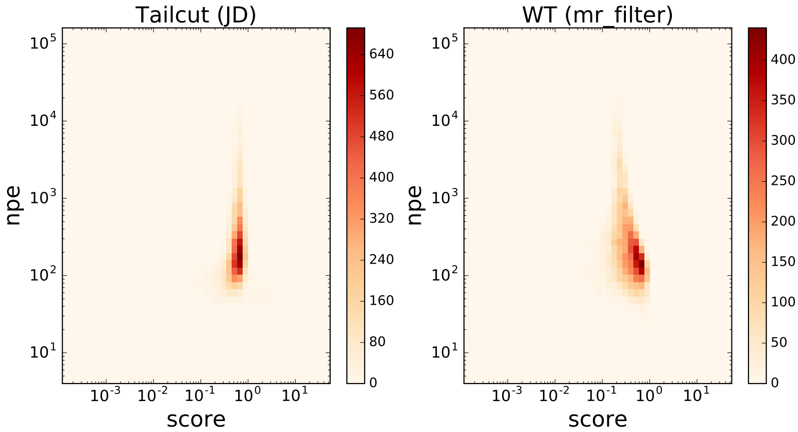

$\mathcal{E}_2$ (γ)
Score
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Tailcut (JD)
WT (mr_transform)
WT (mr_filter)


$\mathcal{E}_2$ (γ)
WT (mr_filter)
Tailcut (JD)
Count
Score
10^0
10^1
10^2
10^3
10^4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2

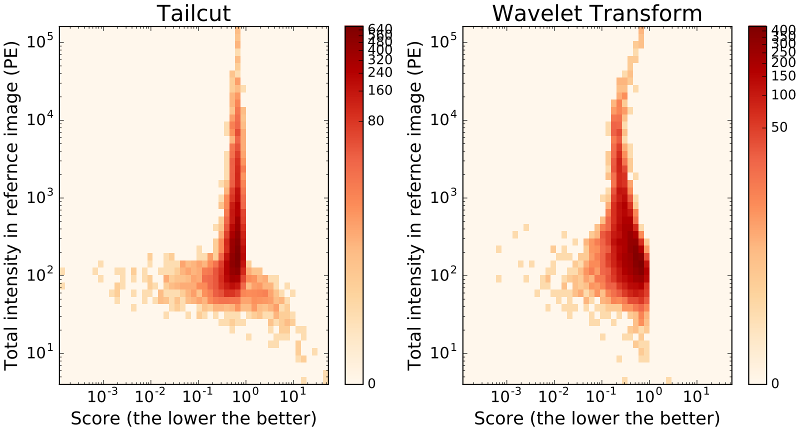

Tailcut (JD) scores correlation
Score 1
Score 0
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}

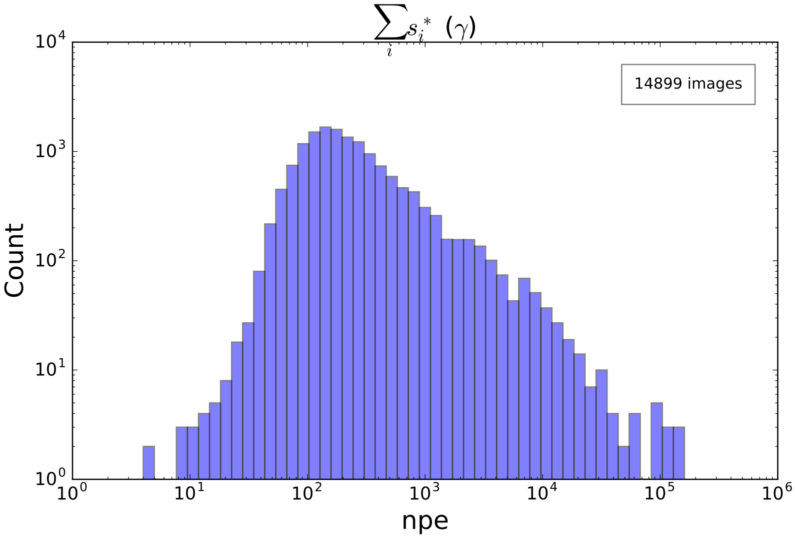

WT (mr_filter) scores correlation
Score 1
Score 0
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}

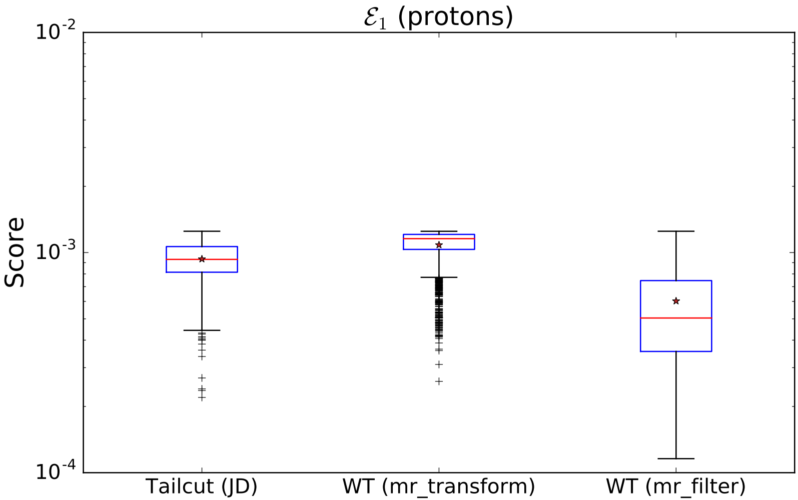
$\mathcal{E}_2$ (γ)

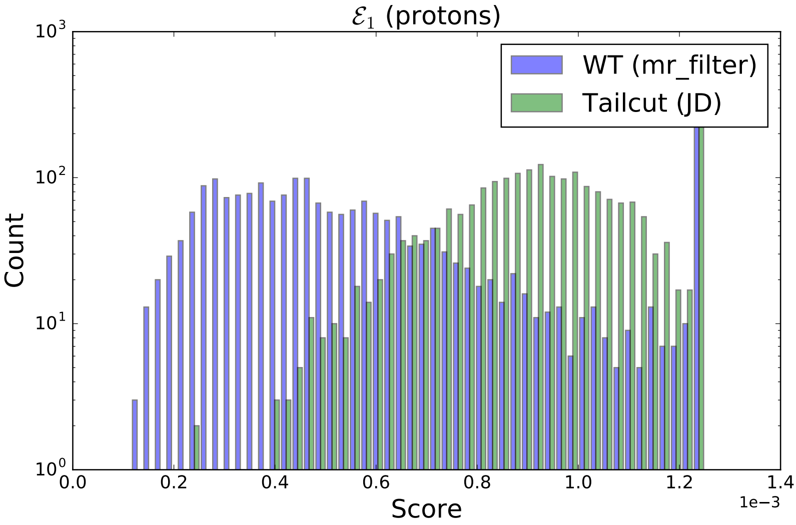


$\mathcal{E}_{intensity}$ (gamma photons)

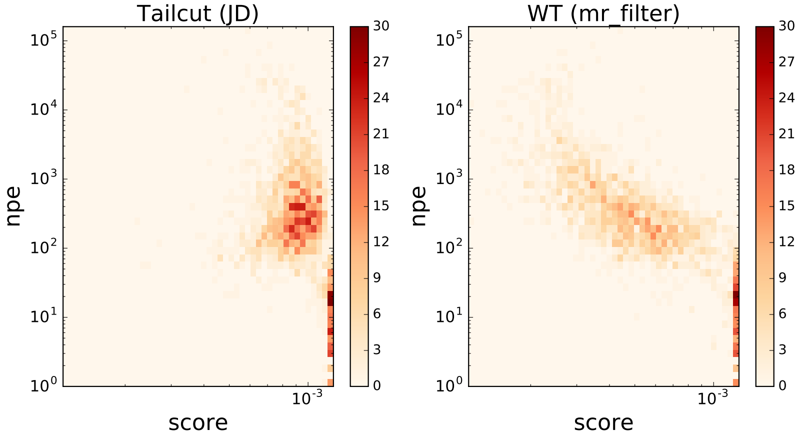



$\sum_i s_i^*\ (\gamma)$
14899 images
Count
npe
10^0
10^1
10^2
10^3
10^4
10^5
10^6

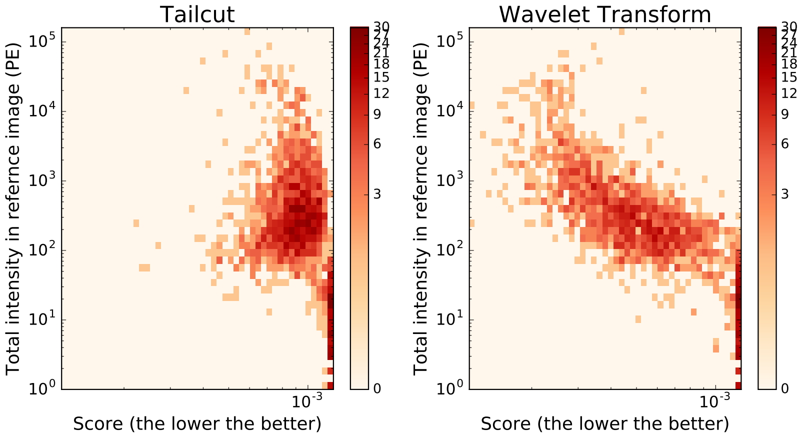

$\mathcal{E}_1$ (protons)
Score
10^{-2}
10^{-3}
10^{-4}
Tailcut (JD)
WT (mr_transform)
WT (mr_filter)

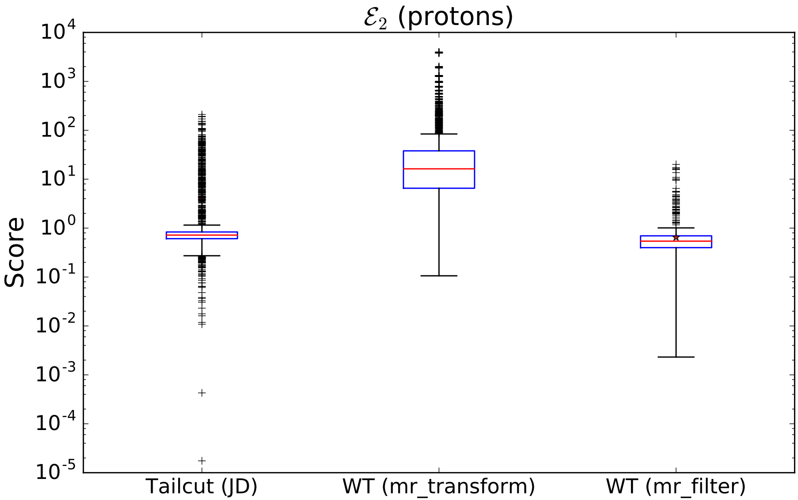

$\mathcal{E}_1$ (protons)
WT (mr_filter)
Tailcut (JD)
Count
Score
1e−3
10^3
10^2
10^1
10^0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

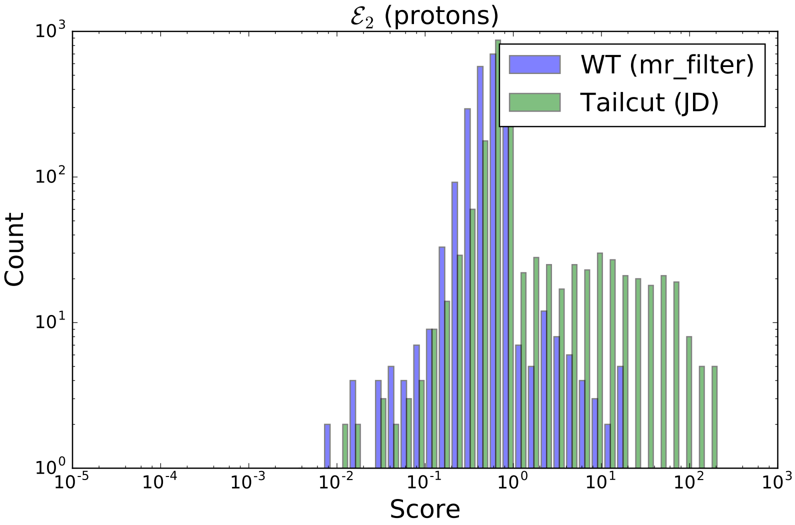
$\mathcal{E}_1$ (protons)

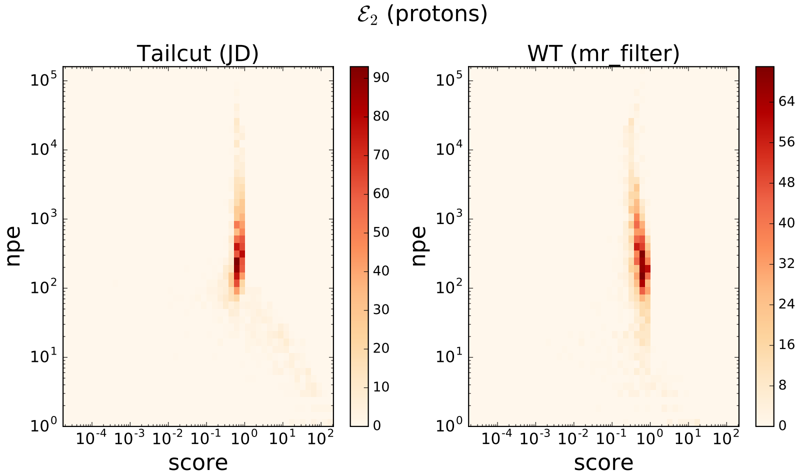


$\mathcal{E}_{shape}$ (protons)

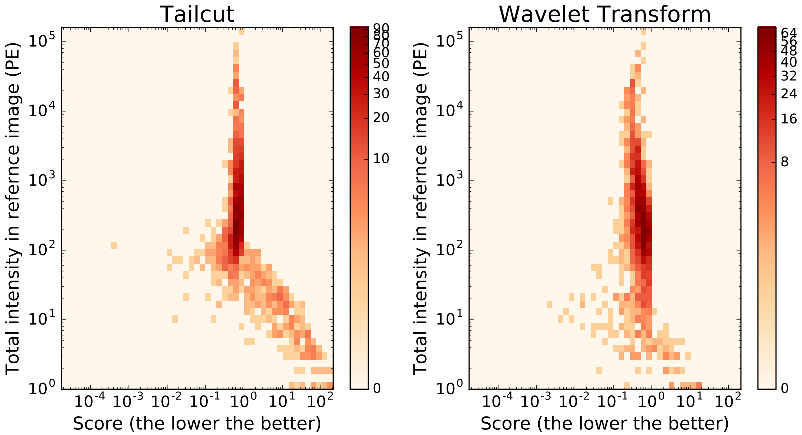


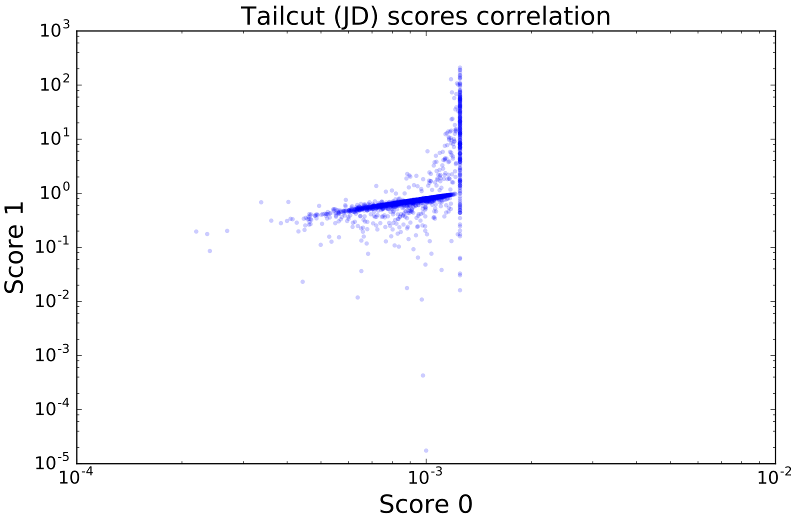

$\mathcal{E}_2$ (protons)
Score
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Tailcut (JD)
WT (mr_transform)
WT (mr_filter)

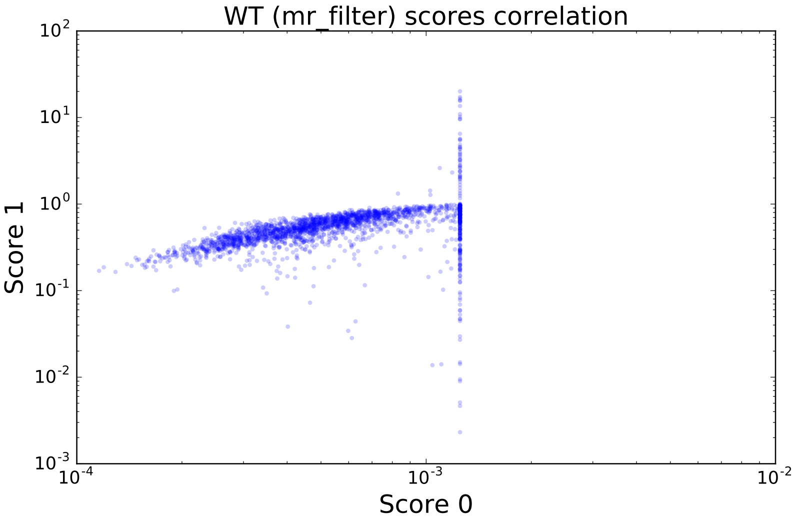

$\mathcal{E}_2$ (protons)
WT (mr_filter)
Tailcut (JD)
Count
Score
10^0
10^1
10^2
10^3
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3


$\mathcal{E}_2$ (protons)
Tailcut (JD)
WT (mr_filter)
npe
score
10^0
10^1
10^2
10^3
10^4
10^5
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2
0 10 20 30 40 50 60 70 80 90
0 8 16 24 32 40 48 56 64

$\mathcal{E}_{intensity}$ (protons)




Tailcut (JD) scores correlation
Score 1
Score 0
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}


WT (mr_filter) scores correlation
Score 1
Score 0
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}

Papers

"Hadron suppression using Wavelet Transformations for the H.E.S.S. Telescope system" (2002, Stefan Funk)

Stefan's Paper

Subject

- Uses Wavelets for γ-ray/hadron separation
- Mention a little bit image cleaning but no experiments (e.g. section 3.3 and conclusion)

Stefan's Paper

Methodology

1. Add margins on the input image
2. Map the orthogonal camera coordinates into a hexagonal coordinate system
3. Apply the hexagonal wavelets to the hexagonal grid ; get wavelets coefficients for each scale
4. Compute the standard deviation of wavelet coefficients for each plane
5. Give these moments to the neural network used to discriminate γ-rays to hadrons (in addition to Hillas parameters)