First detection of gamma-ray sources at TeV energies with the first imaging air Cherenkov telescope of the TAIGA installation

E. Postnikov for the TAIGA Collaboration

evgeny.post@gmail.com

Installation

For γ-ray astronomy, TAIGA uses a unique approach, combining

- **the timing (TAIGA-HiSCORE) technique**

with

- **imaging air Cherenkov telescopes (IACTs). First two IACTs were installed and commissioned (2nd one – 20/01/2020)**

evgeny.post@gmail.com

Concept

Hybrid concept:

- **TAIGA-HiSCORE (Timing array): direction, core location, energy**

- **Standalone mode IACTs at large distances, TAIGA-IACT (Imaging array): gamma-ray / cosmic ray separation**

evgeny.post@gmail.com

Perspective ways of γ-ray detection in TAIGA

- Standalone IACT analysis, E<10-15 TeV
- Stereoscopic analysis of two and more IACTs, E≥10 TeV
- Hybrid approach, joint analysis of TAIGA-HiSCORE and IACTs, E≥30 TэB
- Joint analysis of TAIGA-HiSCORE and muon detectors, E≥300-500 TэB

evgeny.post@gmail.com

Perspective ways of γ-ray detection in TAIGA

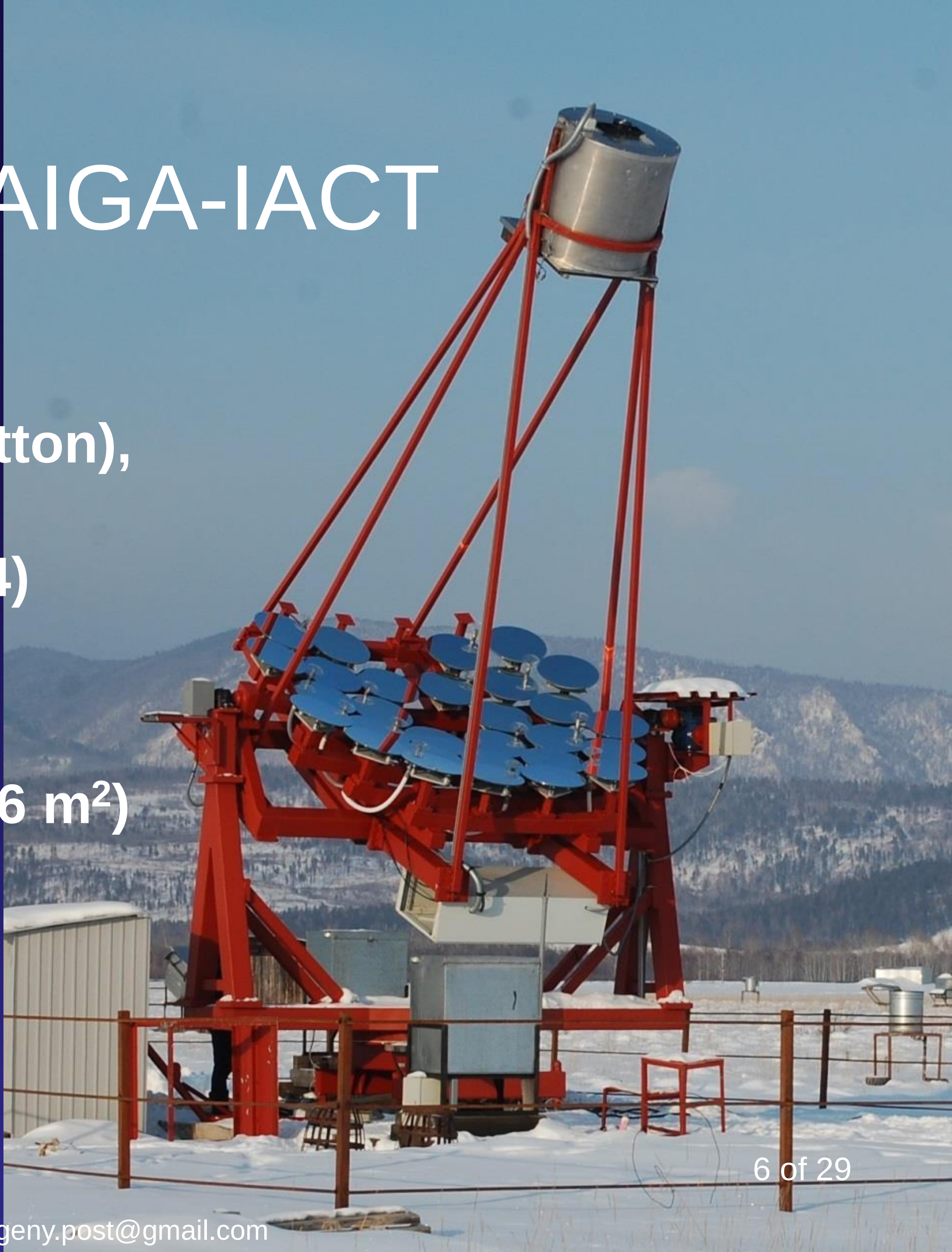
That is the subject of the report

- Standalone IACT analysis, E<10-15 TeV
- Stereoscopic analysis of two and more IACTs, E≥10 TeV
- Hybrid approach, joint analysis of TAIGA-HiSCORE and IACTs, E≥30 TэB
- Joint analysis of TAIGA-HiSCORE and muon detectors, E≥300-500 TэB

evgeny.post@gmail.com

1^{st} TAIGA-IACT

- **Reflector (Davies-Cotton), 29 segments (to be upgraded to 34)**
- **Alt-azimuth mount**
- **Area 8.2 m^2 (to be upgraded to 9.6 m^2)**
- **Focal length 4.75 m**



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IACT camera

- **560 pixels (modular structure 28 pix./module)**
- **0.36° one pixel size**
- **9.6° total field of view**
- **35 ns charge integration**

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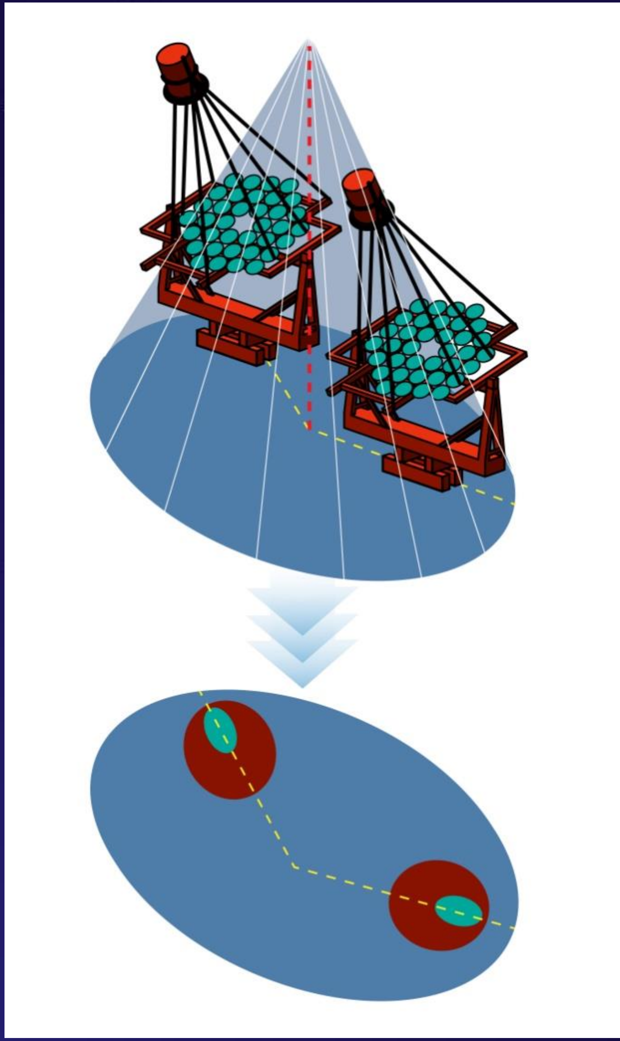
Image formation in the camera



Cherenkov radiation from an extensive air shower:

- falls on the mirrors
- reflects from them
- illuminates some of the camera PMTs

The image of the Cherenkov light from a shower:

- generally an elliptical light spot with a central peak

evgeny.post@gmail.com

Principles of data analysis

Main difficulty:

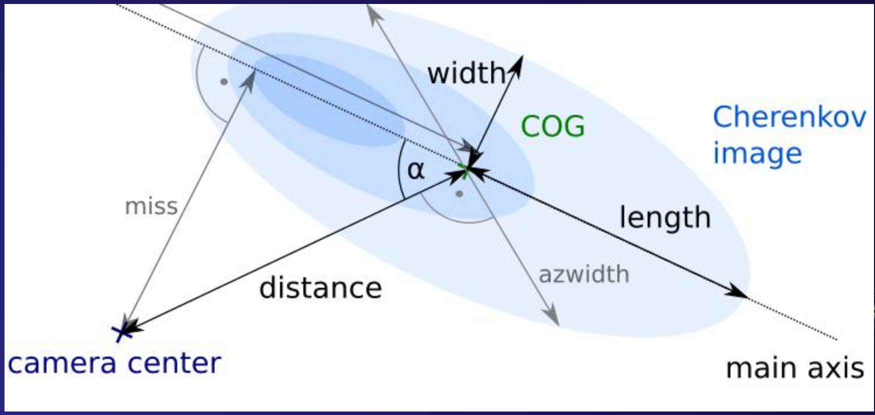
- presence of a significant (a factor of 1000 or larger) background of cosmic rays that are hard to distinguish from gamma rays

Basic task:

- determination of the criteria for selecting gamma-ray showers from background cosmic-ray showers

Solution:

- image dimension and orientation (the so-called Hillas parameters: Length, Width, Distance etc.) reflect the angular and lateral distributions of the Cherenkov light and therefore can suppress cosmic ray background



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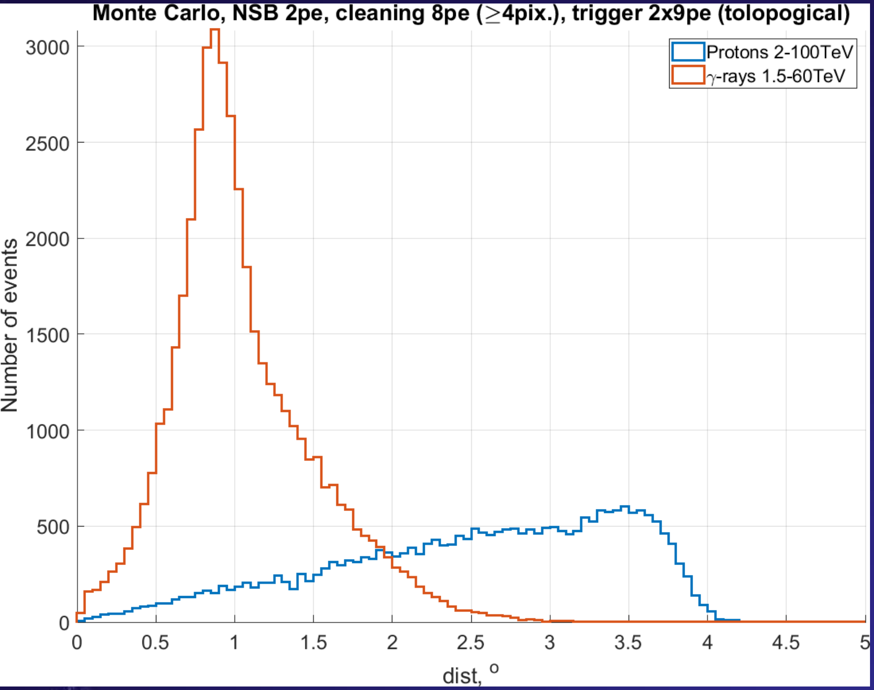
Selection efficiency (by Monte Carlo data)

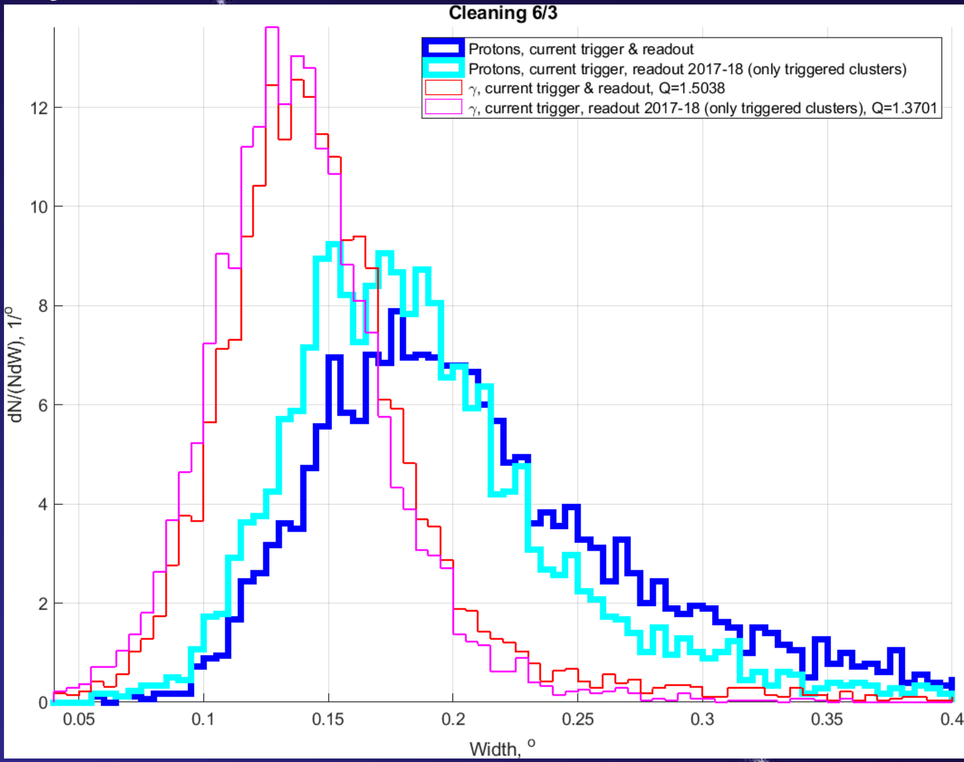
Monte Carlo of the Crab Nebula observation conditions:

- Cosmic ray background suppression by a factor of ~300
- Gamma-ray losses 48%

Monte Carlo of Markarian 421 observation conditions:

- Cosmic ray background suppression by a factor of ~1800
- Gamma-ray losses 85%





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1st gamma-ray sources

The Crab Nebula

- supernova remnant in our Galaxy;
- standard candle for TeV gamma-ray astronomy;
- available as steady source to test and calibrate the telescope;
- seen from both hemispheres;
- observed by the number of independent groups using different detection techniques

Markarian 421

- first extragalactic source detected at TeV energies;
- active galactic nucleus (blazar);
- strong flux variability (~0.1 Crab / ~10 Crab)

evgeny.post@gmail.com

Observations

The Crab Nebula

- ~45 hours in Oct-Dec 2019 (zenith angle ~30-40°)
- 1287 images after selection on the source (Non)
- 1007 images after selection off the source (Noff)
- 280 events above the background (Non-Noff) / Monte Carlo estimate is ~250
- Statistical significance ~6σ

Markarian 421

- ~60 hours in Nov 2019-Feb 2020 (zenith angle ~15-25°)
- 48 images after selection on the source (Non)
- 11 images after selection off the source (Noff)
- 37 events above the background (Non-Noff) / Monte Carlo estimate is 35
- Statistical significance ~5σ

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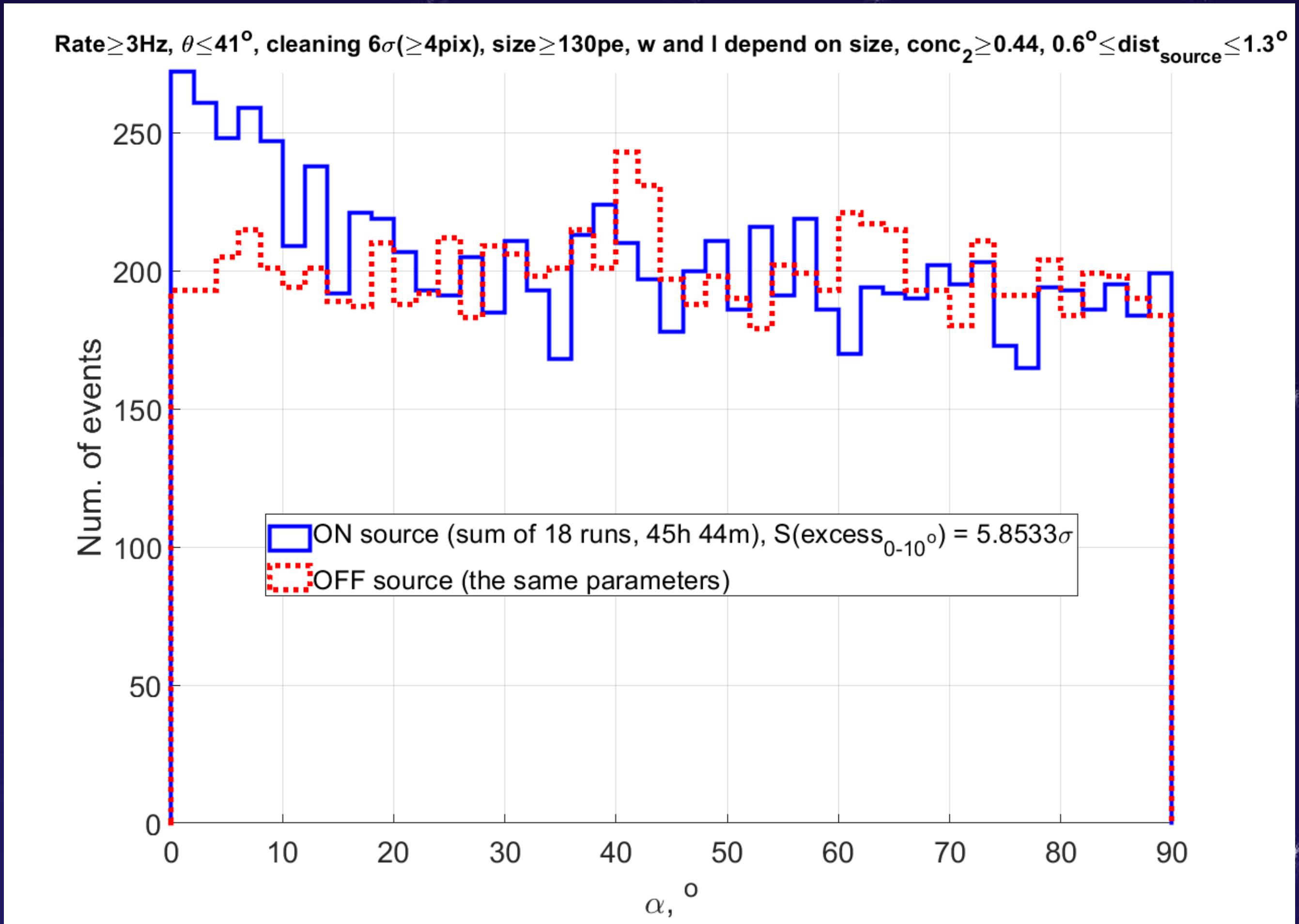
The Crab Nebula gamma-ray excess in a histogram



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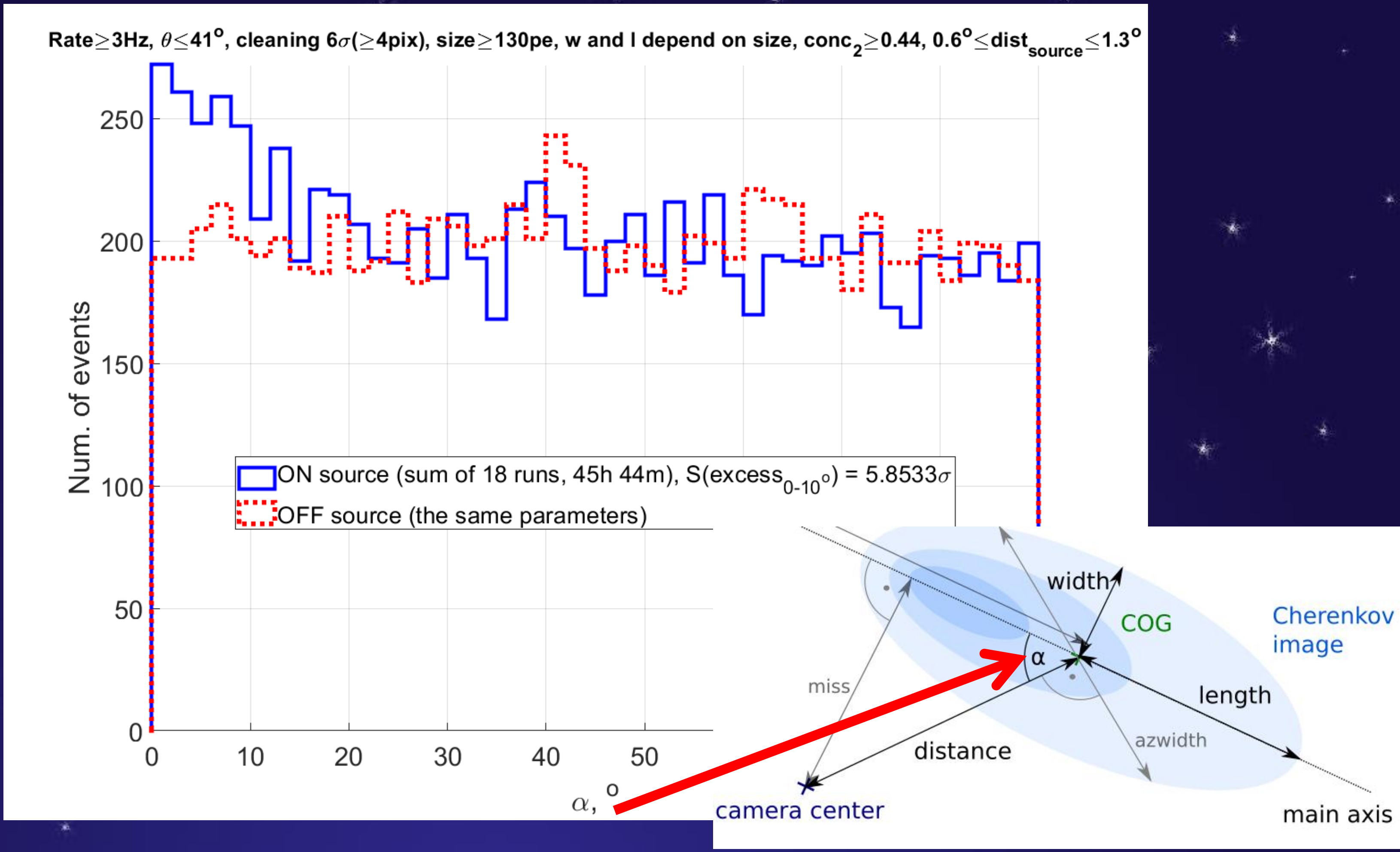

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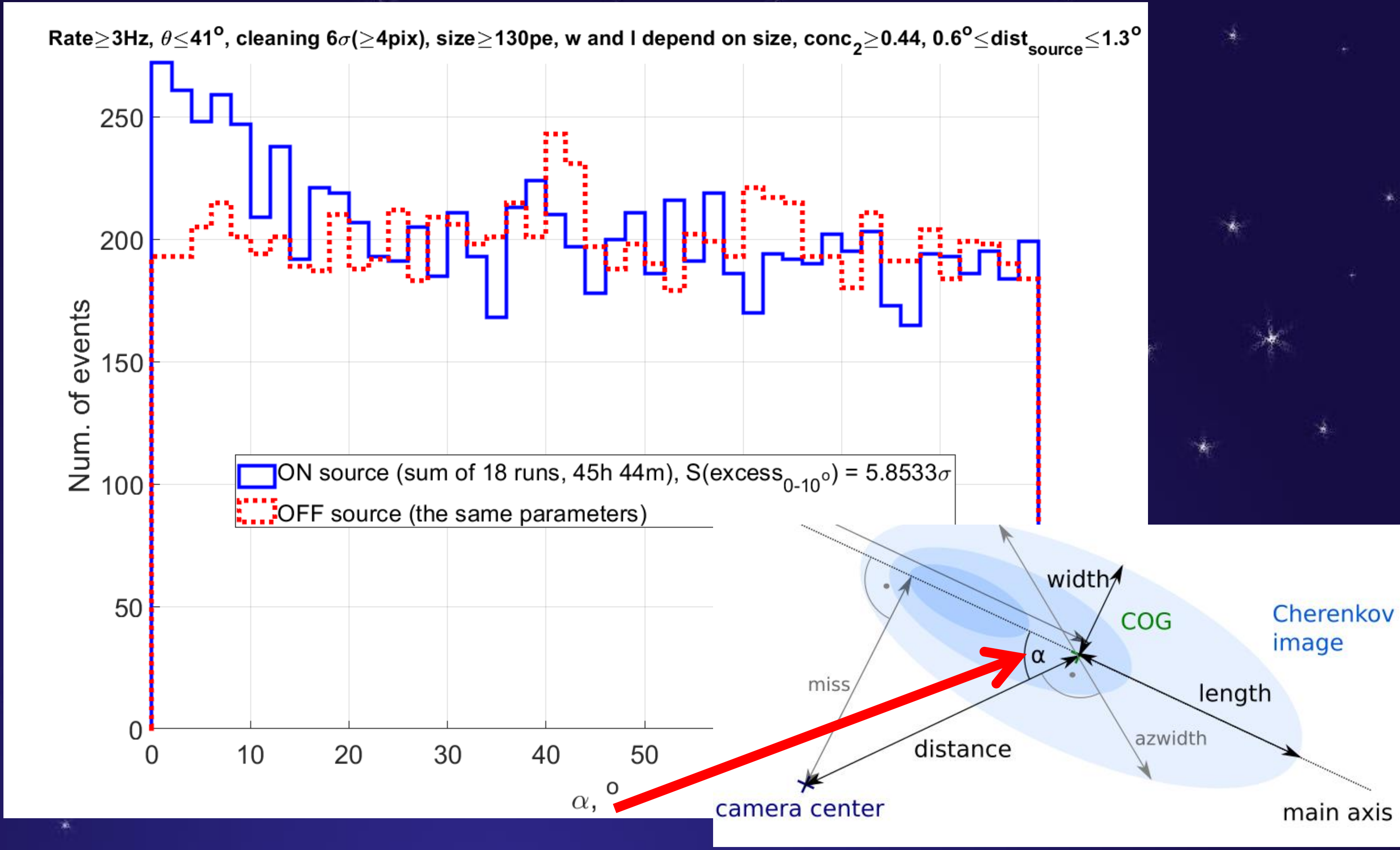

Angle between the image axis and the direction to γ-ray source: ~0 for γ rays

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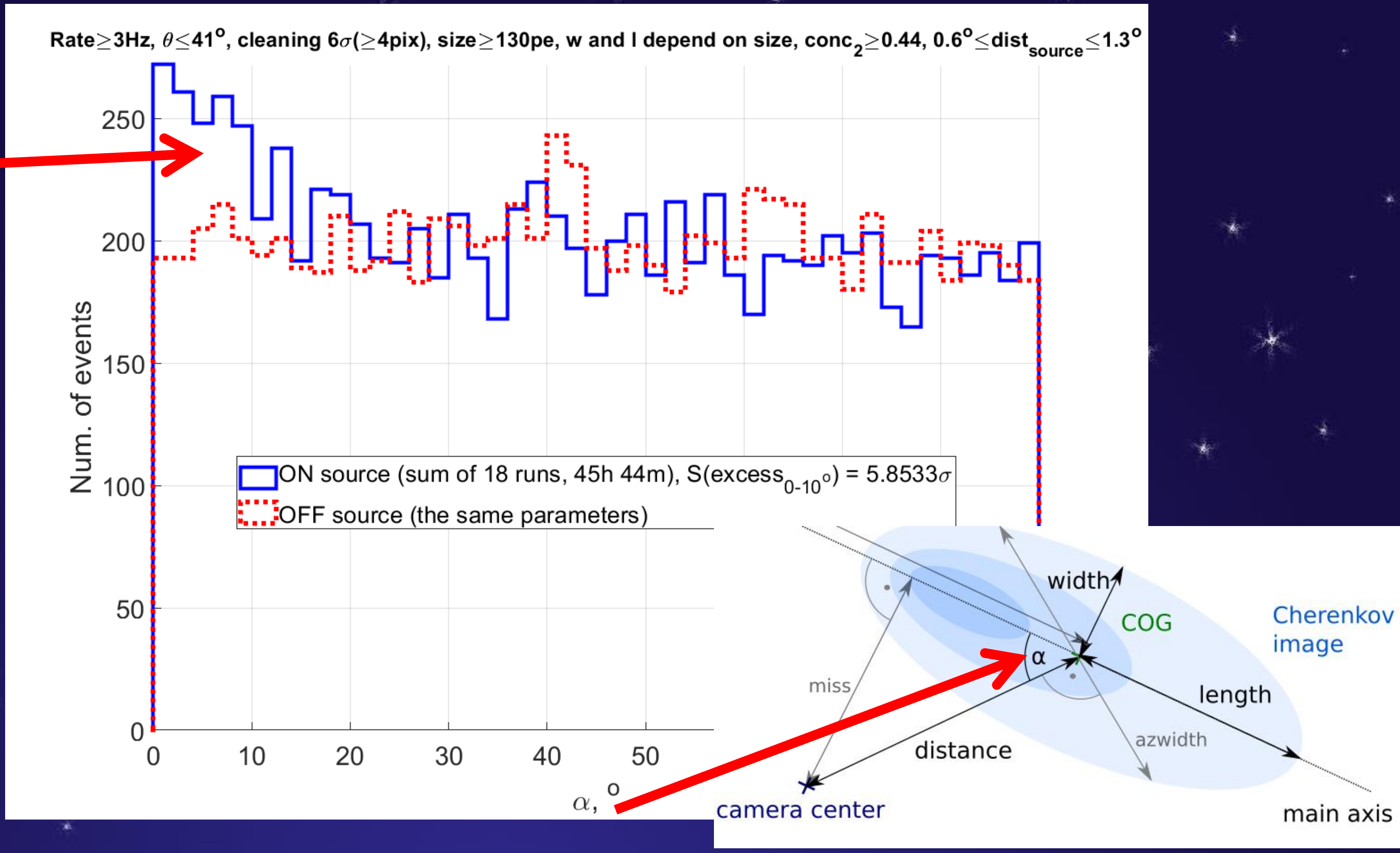
The Crab Nebula gamma-ray excess in a histogram

γ-ray excess



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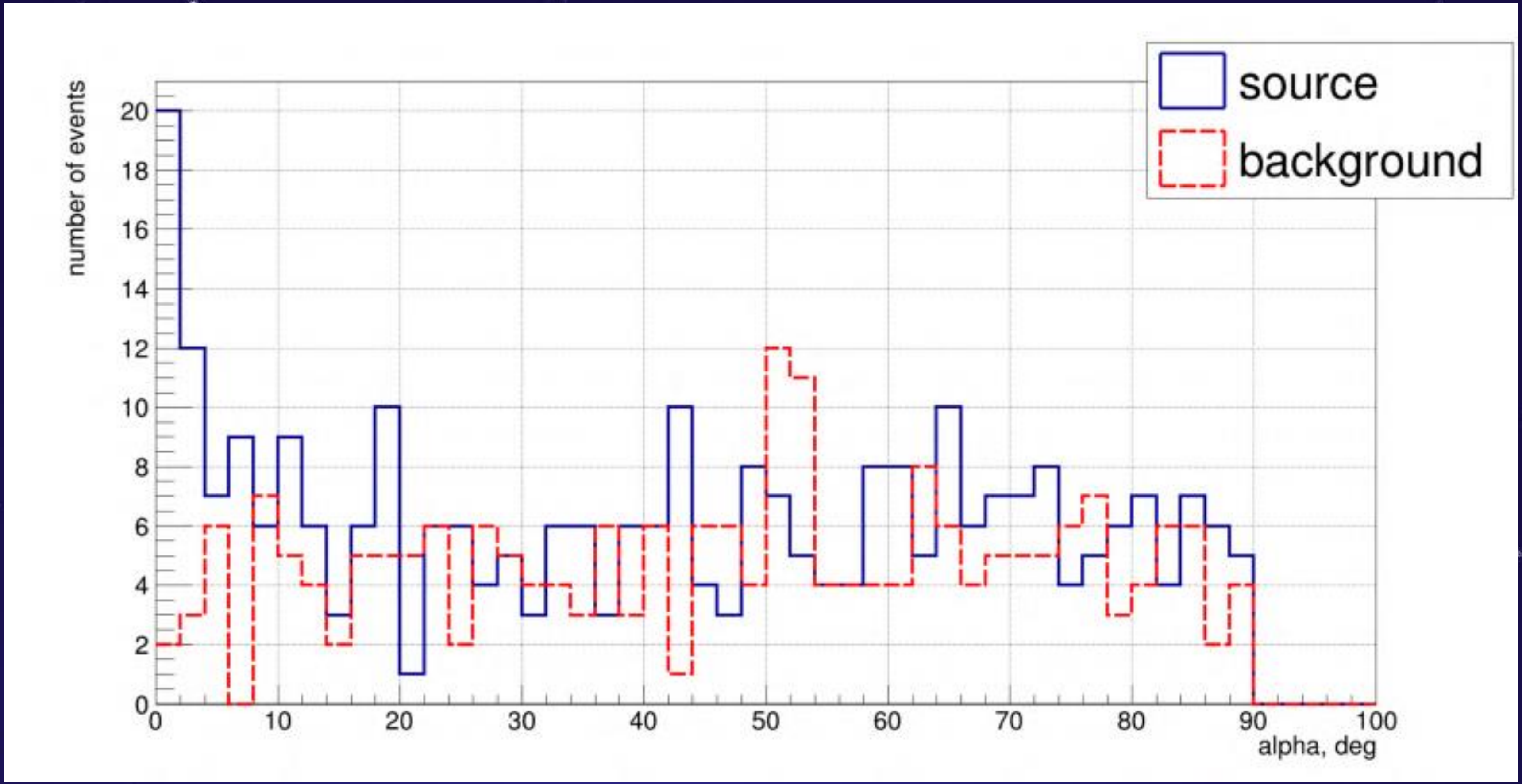
Markarian 421
gamma-ray excess in a histogram



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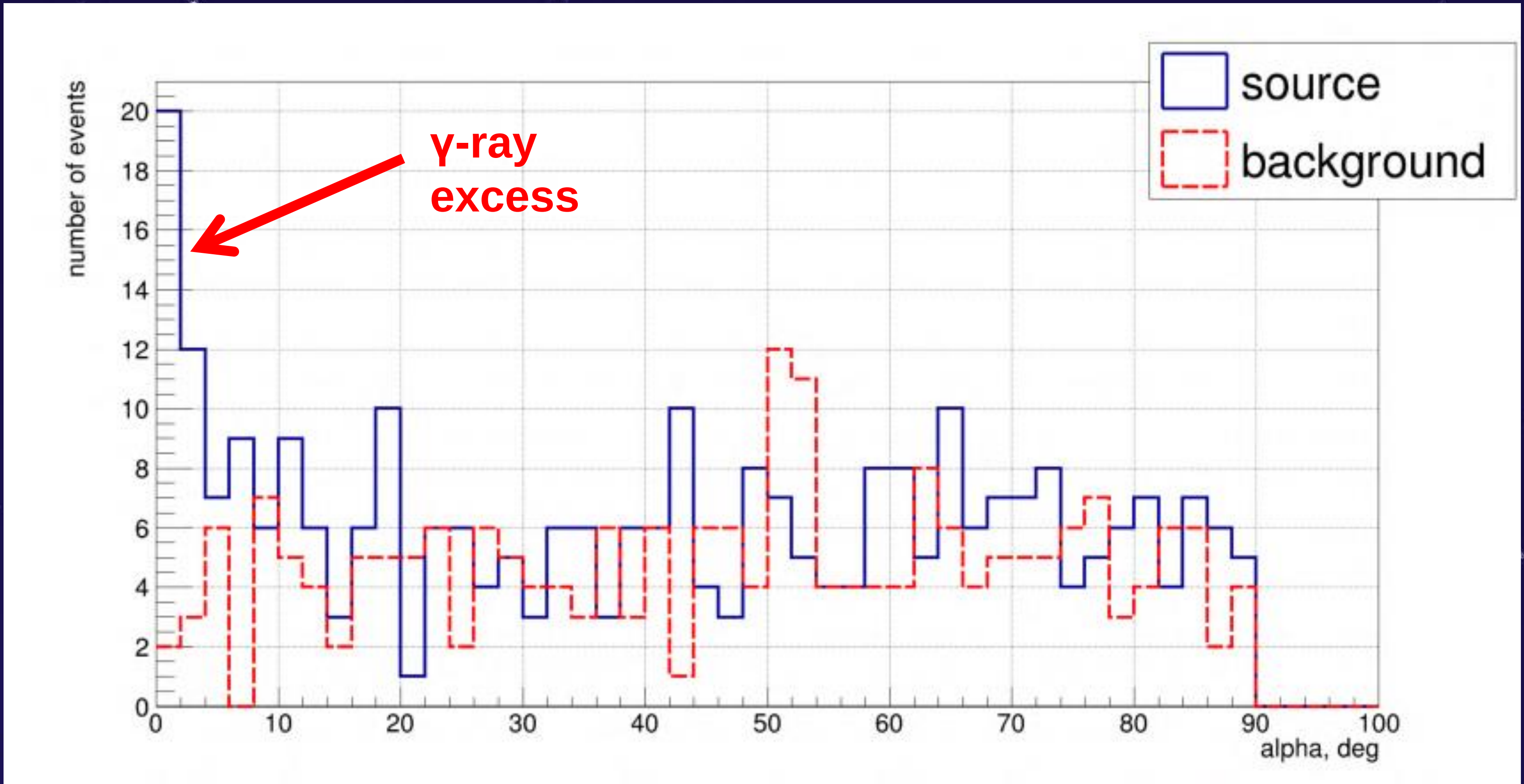
Markarian 421 gamma-ray excess in a histogram



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Conclusions

- First gamma-ray sources detected in the TAIGA experiment: the Crab Nebula (6σ), Markarian 421 (5σ)
- For the 1st detection only the 1st TAIGA telescope is used in standalone mode
- Data analysis technique is straightforward: set of consecutive cuts on an image parameters introduced by Michael Hillas in 1985

evgeny.post@gmail.com

Next steps

- Joint analysis of data from a few telescopes and the TAIGA-HiSCORE timing array
- Improving the accuracy of data analysis using machine learning / deep learning techniques, e.g. convolutional neural networks

evgeny.post@gmail.com

Backup slides

evgeny.post@gmail.com

IACT camera

The main difficulty in detecting and investigating very high energy gamma-ray sources is the presence of a significant (a factor of 1000 larger) background of cosmic

rays producing the Cherenkov flashes in the Earths atmosphere that are hard to distinguish from the flashes produced by gamma rays. Therefore, the determination of the criteria for selecting gamma-ray showers from background cosmic-ray showers is an important stage

of gamma-ray astronomical experiments.

evgeny.post@gmail.com

Observations

The Crab Nebula

- ~45 hours in Oct-Dec 2019 (zenith angle ~30-40°)
- ~3.8×10^5 shower images total
- 1287 images after selection on the source (Non)
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- 11 images after selection off the source (Noff)
- 37 events above the background (Non-Noff) / Monte Carlo estimate is 35

evgeny.post@gmail.com

gamma-ray sources at TeV energies

PHOTONS of TeV energy have been observed from a few sources in our Galaxy, notably the Crab Nebula[1]. We report here the detection of such photons from an extragalactic source, the giant elliptical galaxy Markarian 421. Mk 421 has a nucleus of the BL Lacertae type[2,3], and emission from it has been observed at radio[4–6], optical[3,6] and X-ray[6–8] frequencies, and most recently in the MeV-GeV bands, by the EGRET detector aboard the Compton observatory[9]. In March–June 1992, we observed Mk 421 with the Whipple Observatory γ-ray telescope

evgeny.post@gmail.com

Concept

Hybrid concept:

- **TAIGA-HiSCORE (Timing array): direction, core location, energy**
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- **29-segment reflectors (Davis-Cotton)**
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- **Focal length 4.75 m**
- **Field of view ~9.6°**

evgeny.post@gmail.com

Principles of data analysis

Main difficulty:

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of gamma-ray astronomical experiments.

- Analyzing the angular and lateral distributions of the shower Cherenkov light is of great interest for the selection of showers of primary gamma-rays.
- Image dimension and orientation (the so-called Hillas parameters: Length, Width, Distance are used for these purposes optimized for each experiment individually

evgeny.post@gmail.com

IACT camera

- The Cherenkov radiation from an extensive air shower
- falls on the mirrors and, being reflected from
- them, illuminates some of the photomultiplier tubes in
- the detector array. The image of the Cherenkov light from a shower in the detector plane is generally an elliptical light spot with a central peak. Analyzing the angular and lateral distributions of the shower Cherenkov light is of great interest for the selection of showers of primary gamma-rays.
- The so-called Hillas parameters: Length, Width, and Distance are used for these purposes in gamma-ray astronomy and optimized for each experiment individually.

evgeny.post@gmail.com

Gamma rays / protons

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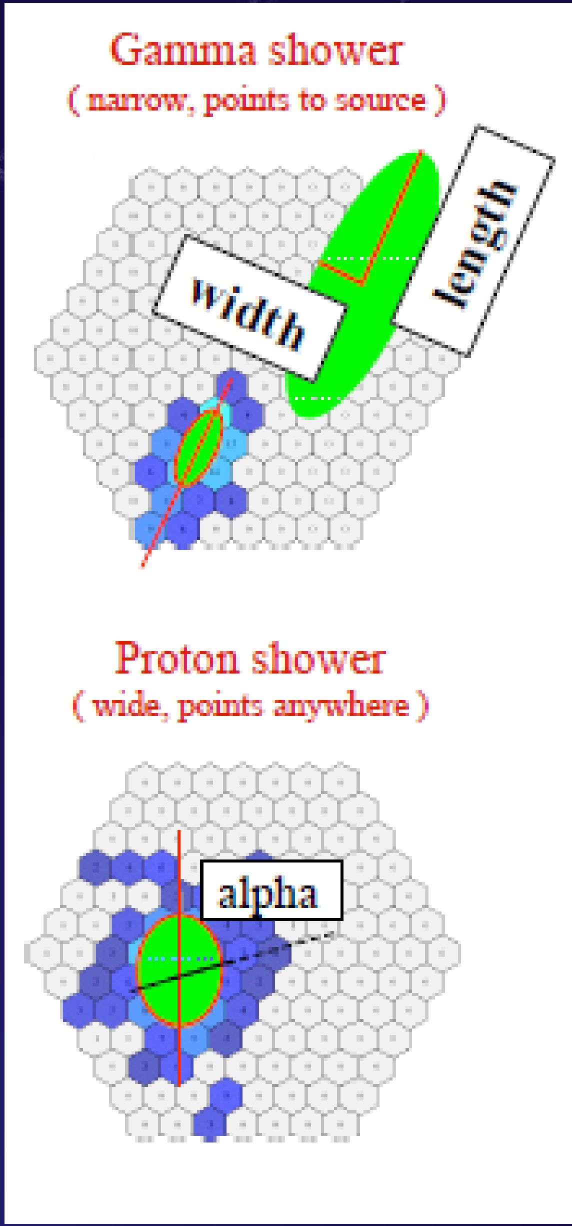
Proton rejection: Hillas technique



- Gamma /Proton discrimination

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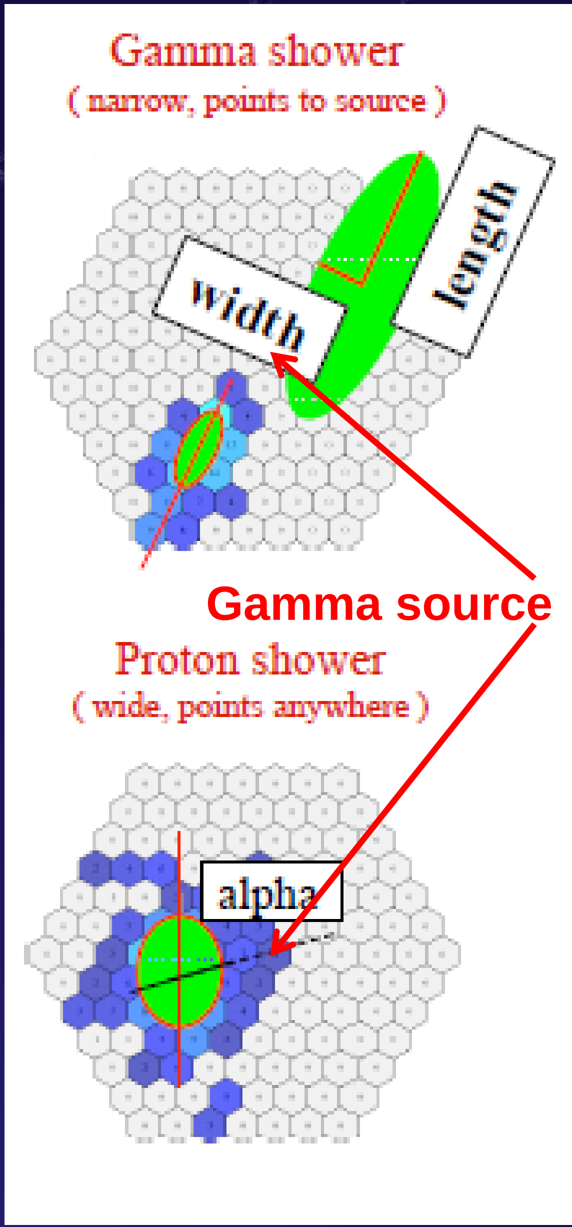
Proton rejection: Hillas technique

- Gamma /Proton discrimination



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Proton rejection: Hillas technique

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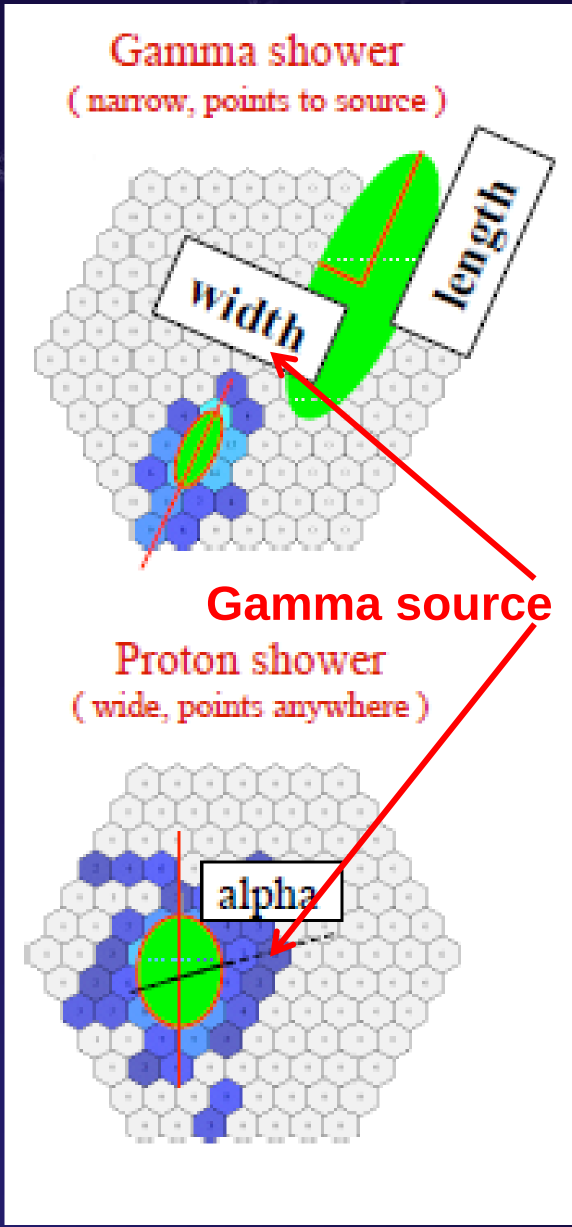

Alpha is to select the events NOT from the source direction

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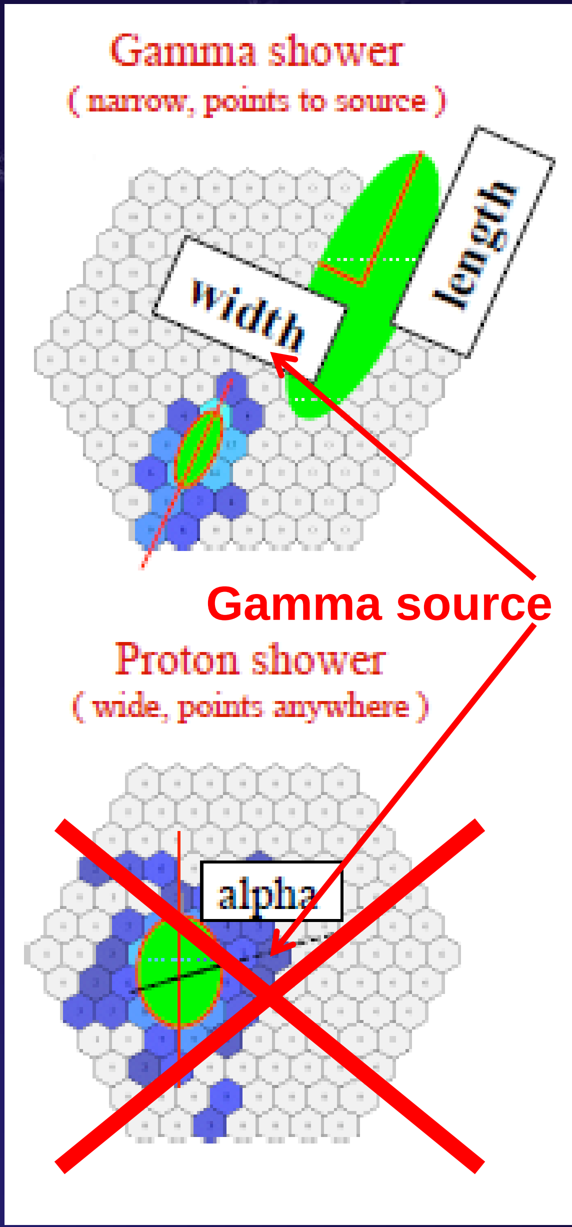
Proton rejection: Hillas technique

- Gamma /Proton discrimination

Alpha is to select the events NOT from the source direction
=> Alpha is not to be used in TAIGA: arrival direction from TAIGA-HiSCORE is 0.1^{o} -0.4^{o}



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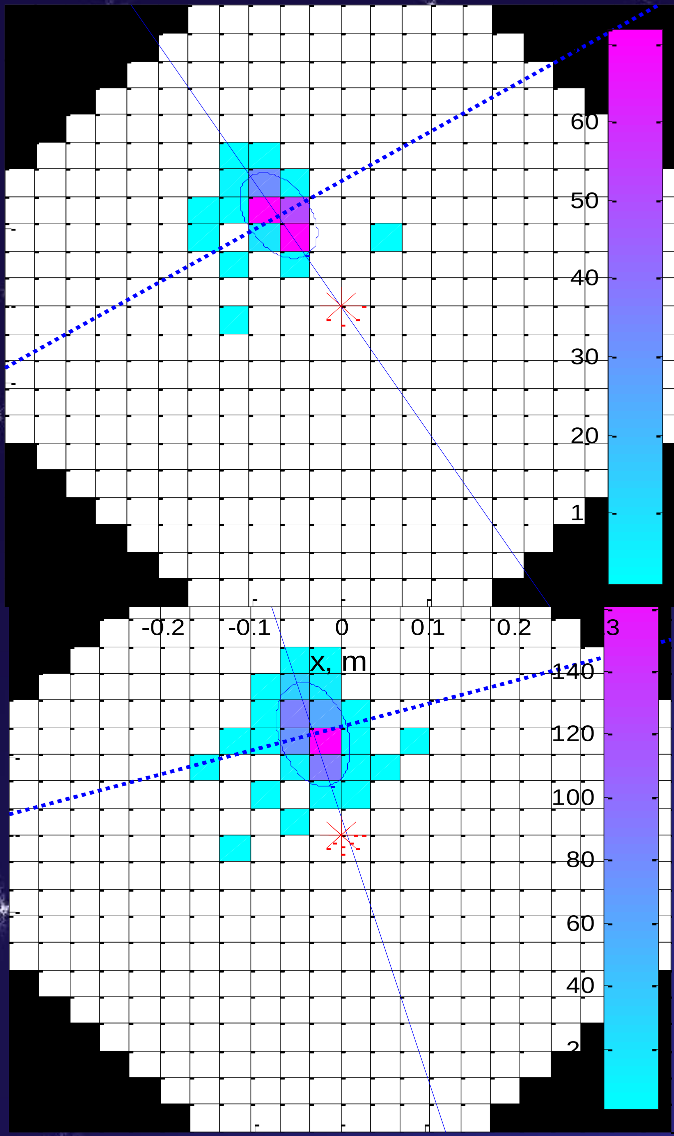
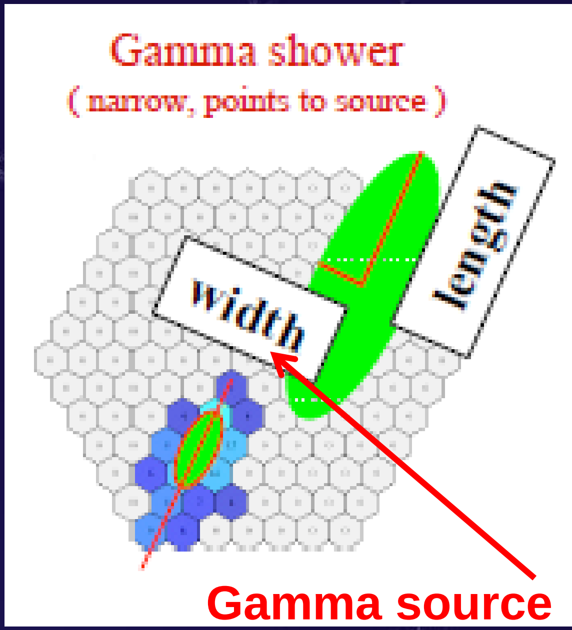
Proton rejection: Hillas technique





- Gamma /Proton discrimination

How to find width and length?

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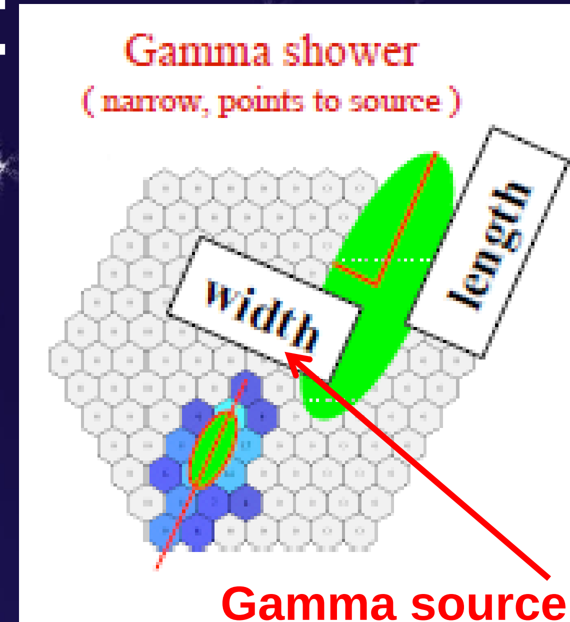
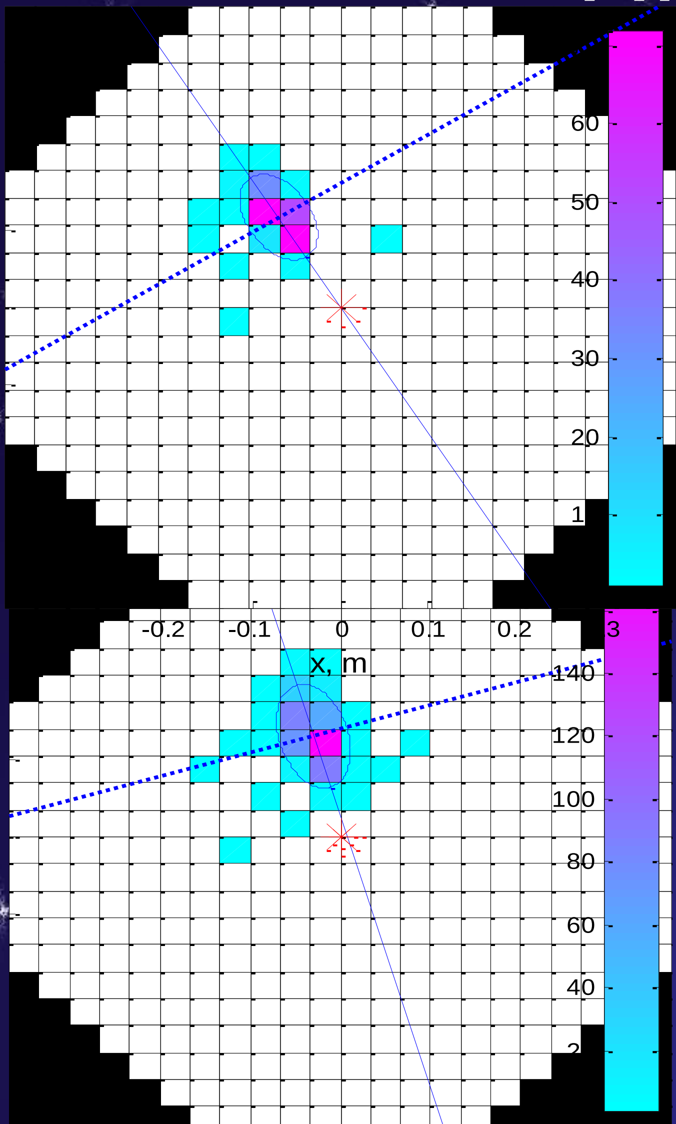
Proton rejection: Hillas technique





- Gamma /Proton discrimination

How to find width and length?

1. **Minimizing the signal-weighted spread of all pixels in various directions. "Orthogonal regression", the solution *width* is the minimal eigenvalue of the covariance matrix of x and y:**
   $[\sigma_{xx}\ \sigma_{xy}\ ;\ \sigma_{xy}\ \sigma_{yy}]*[v_1\ v_2]^T = w[v_1\ v_2]^T$

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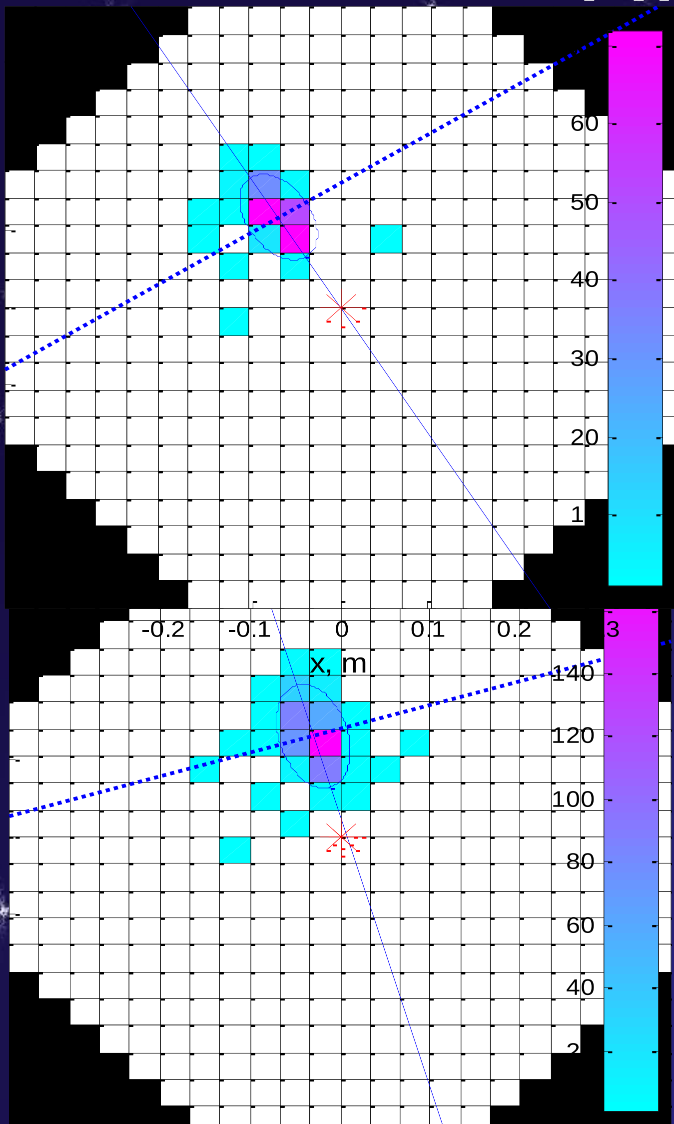
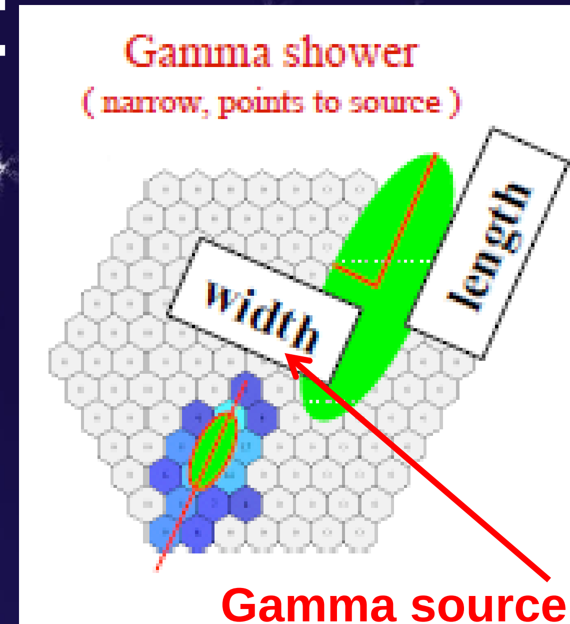
Proton rejection: Hillas technique





- Gamma /Proton discrimination

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   $[\sigma_{xx}\ \sigma_{xy}\ ;\ \sigma_{xy}\ \sigma_{yy}]*[v_1\ v_2]^T = w[v_1\ v_2]^T$
2. **Length is the data spread in the perpendicular direction (also equal to the maximal eigenvalue of the covariance matrix)**

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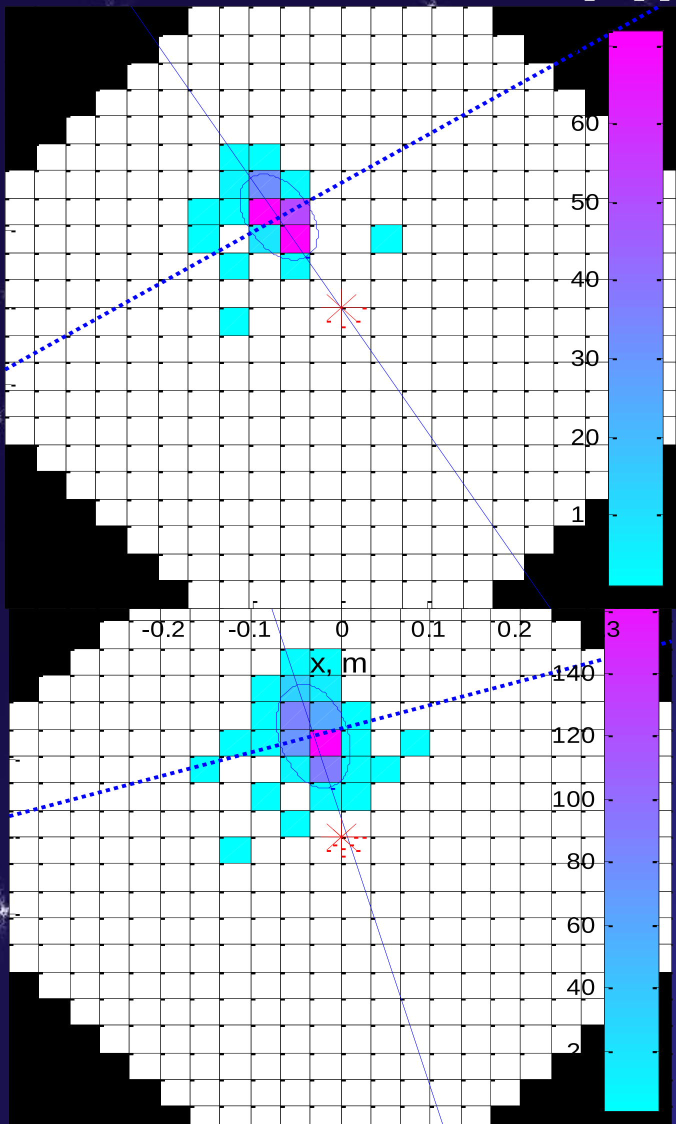
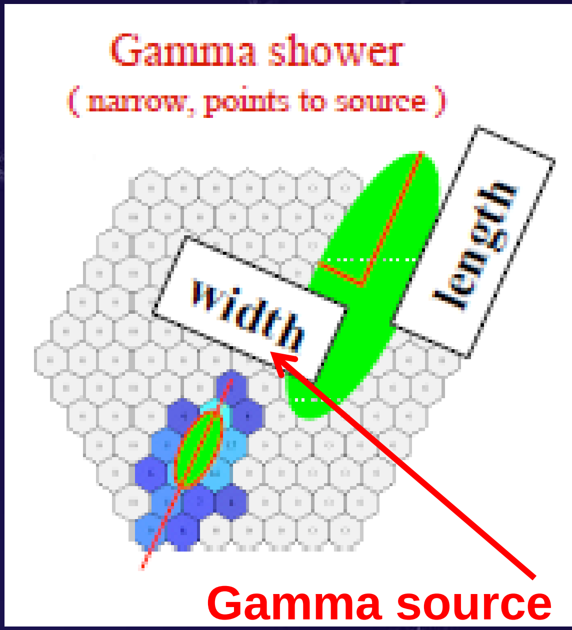
Proton rejection: Hillas technique





- Gamma /Proton discrimination

In TAIGA-IACT the best single parameter to separate gamma rays from protons is actually not width, but a modified width called 'azimuthal width'. It's a data spread not in 'the minimal direction', but in the exact direction between the center of gravity of the image and the center of the camera. This modified width was introduced also by Hillas

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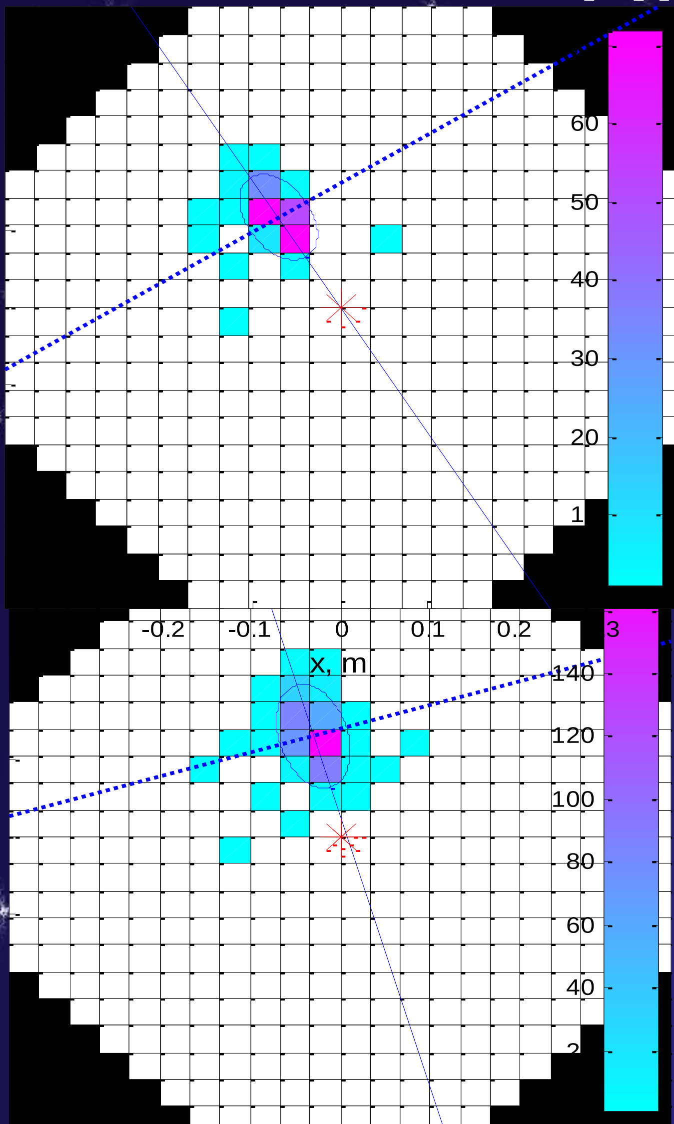

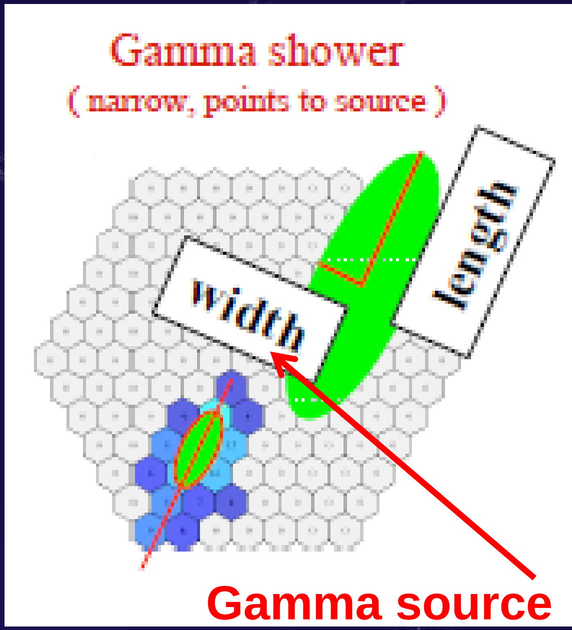

- Gamma /Proton discrimination

Any image parameter calculation is performed only after the image cleaning

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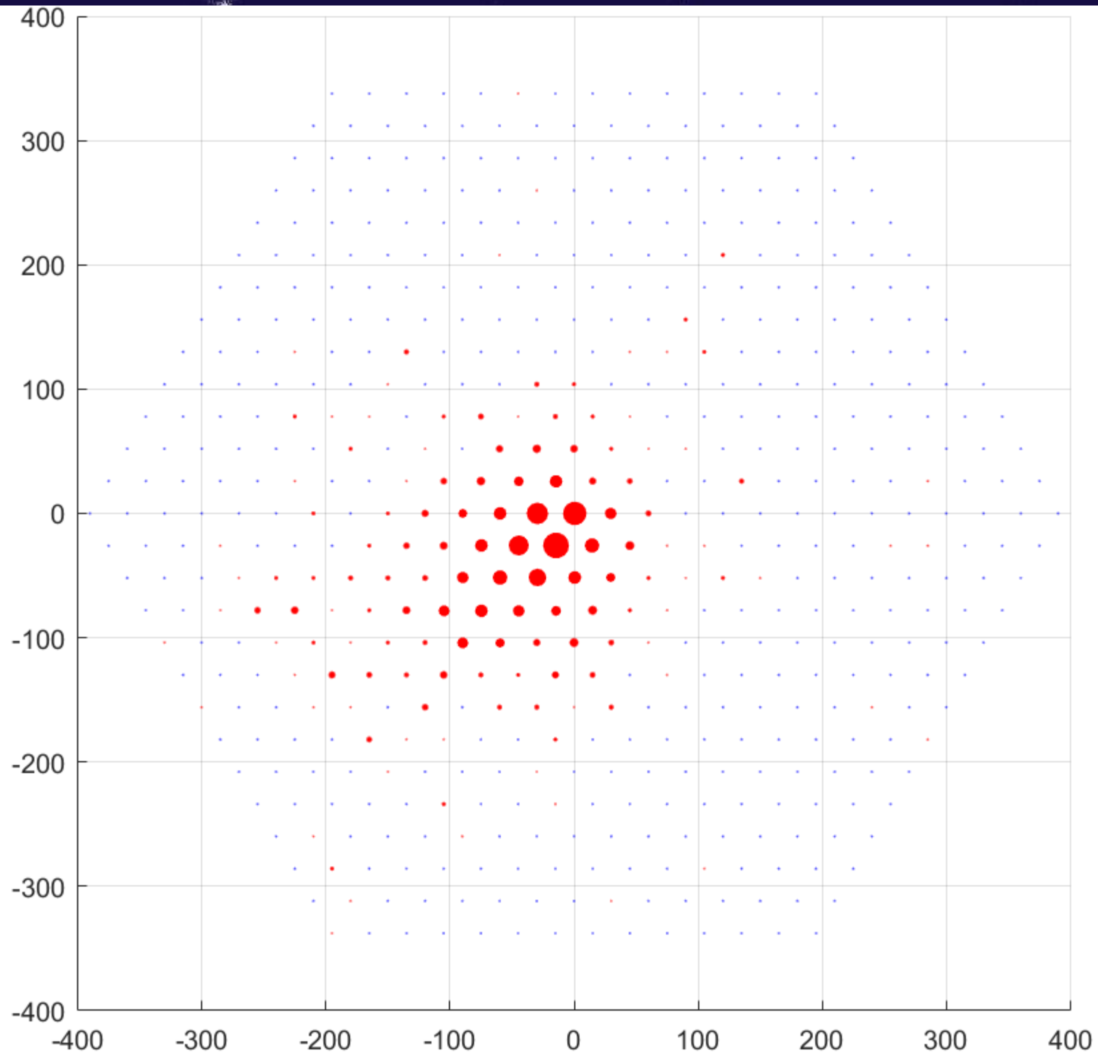
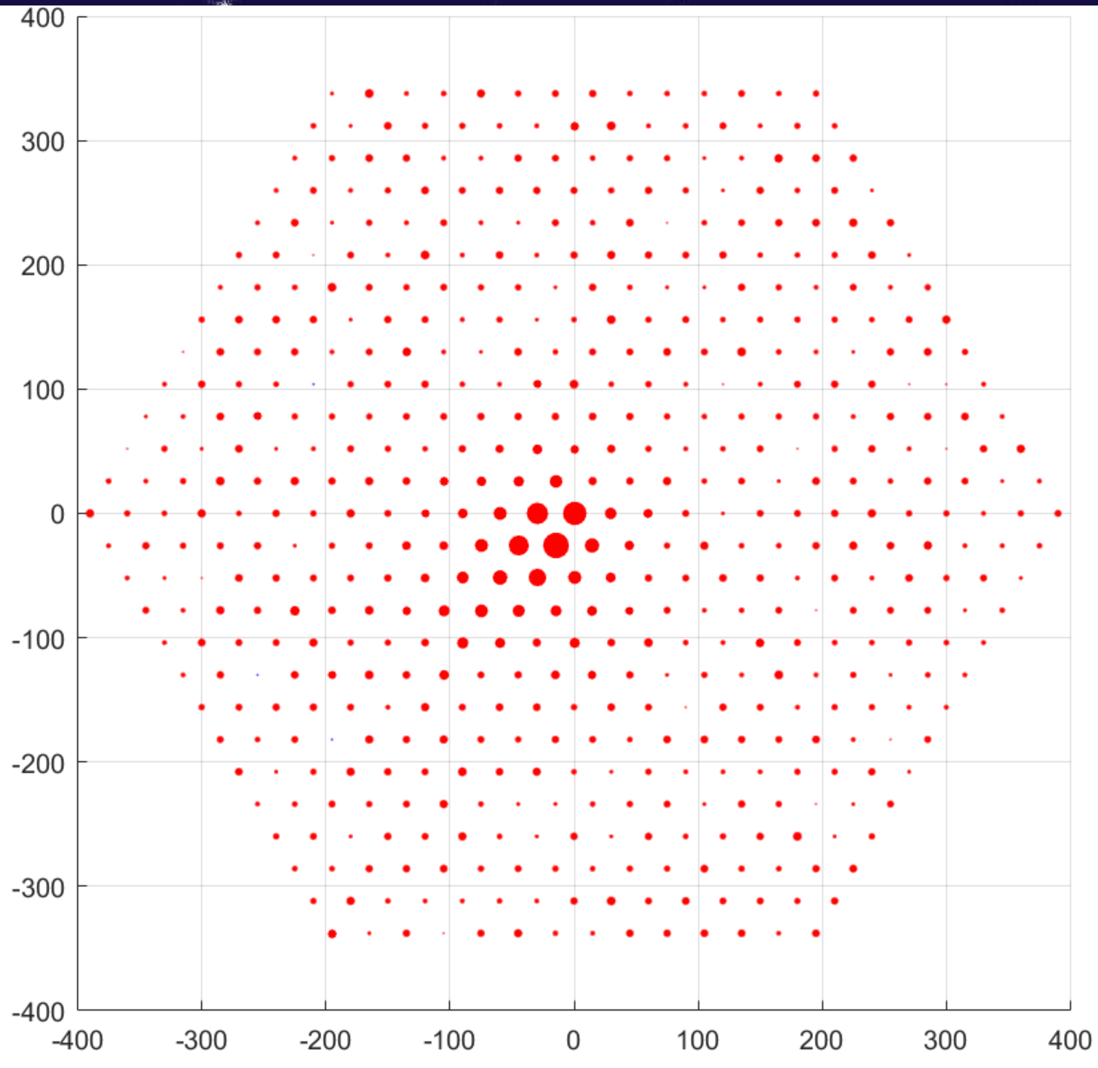
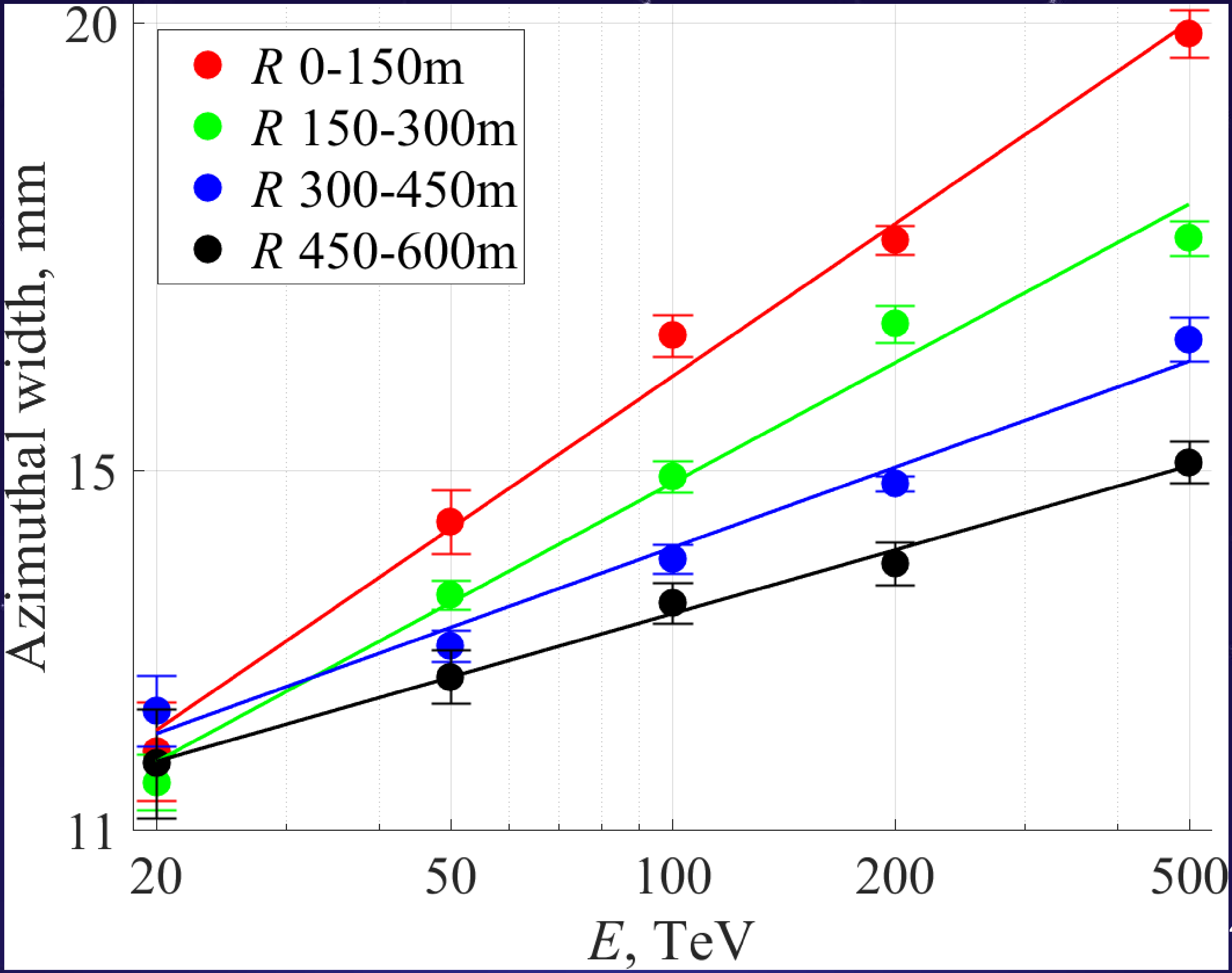
Night sky background (off)



Night sky background (on)



Azwidth cut depending on energy



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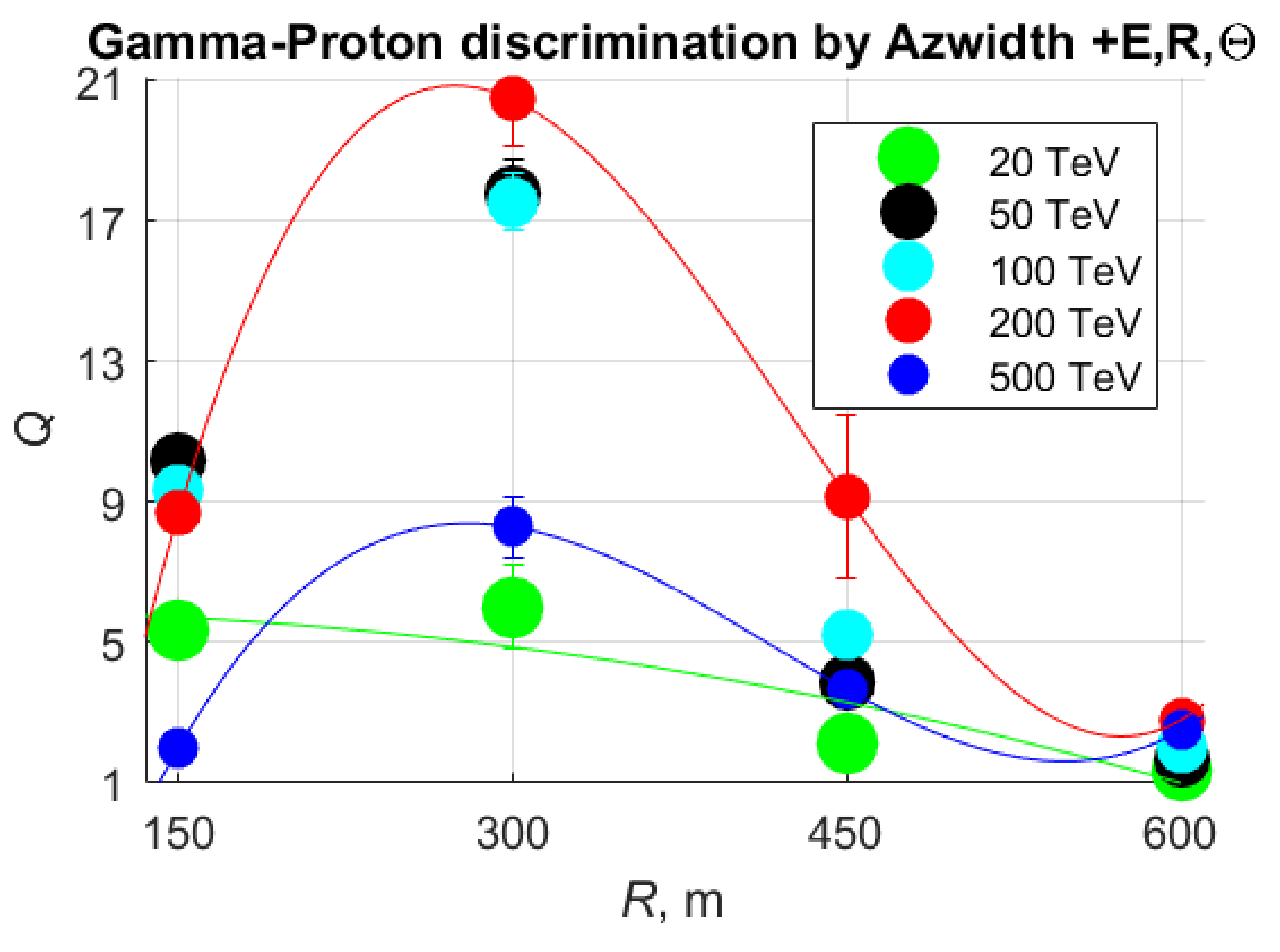
Q factor depending on R



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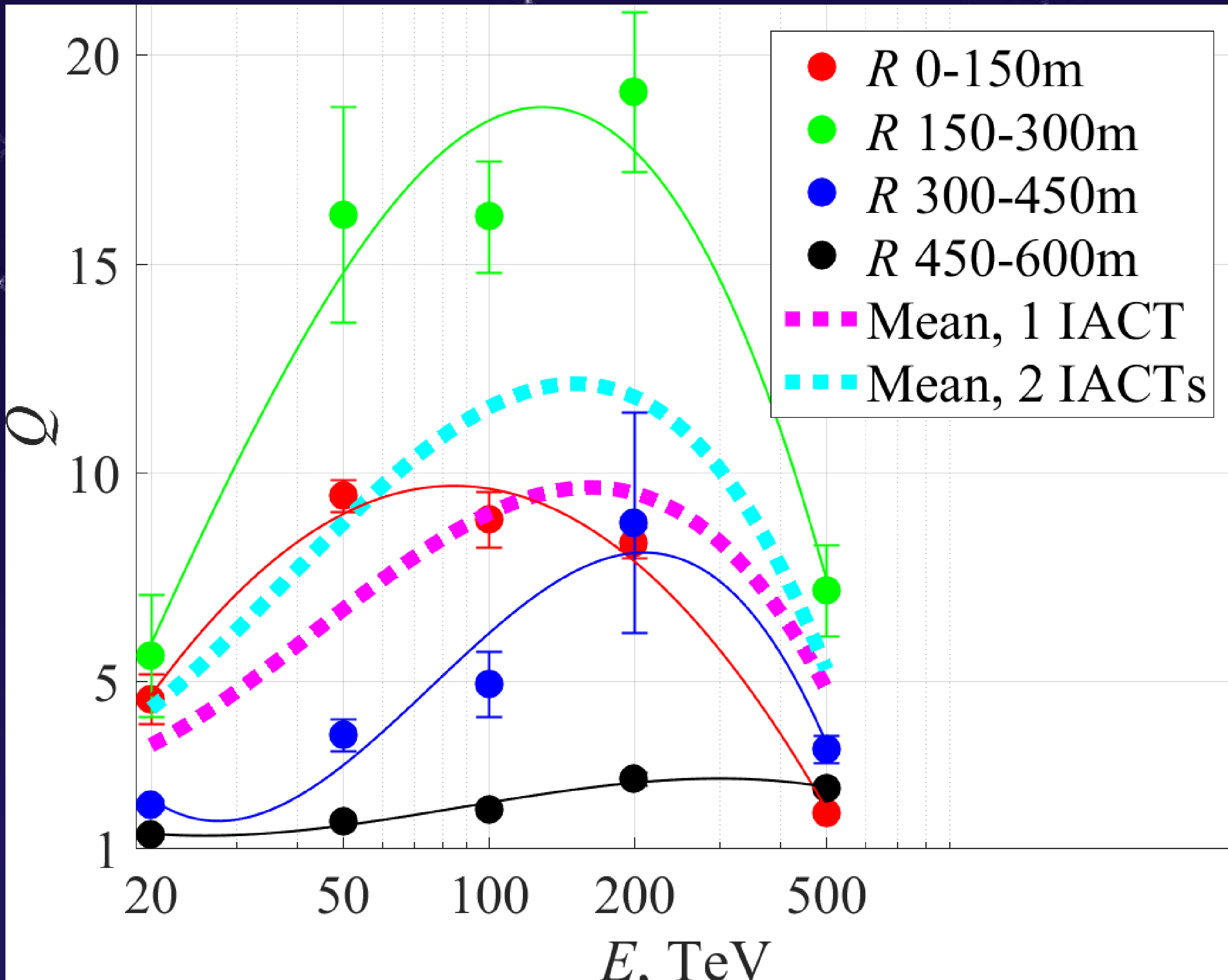
Q factor of the TAIGA installation (with 1 IACT or with 2 IACTs)



320 m between 2 IACTs

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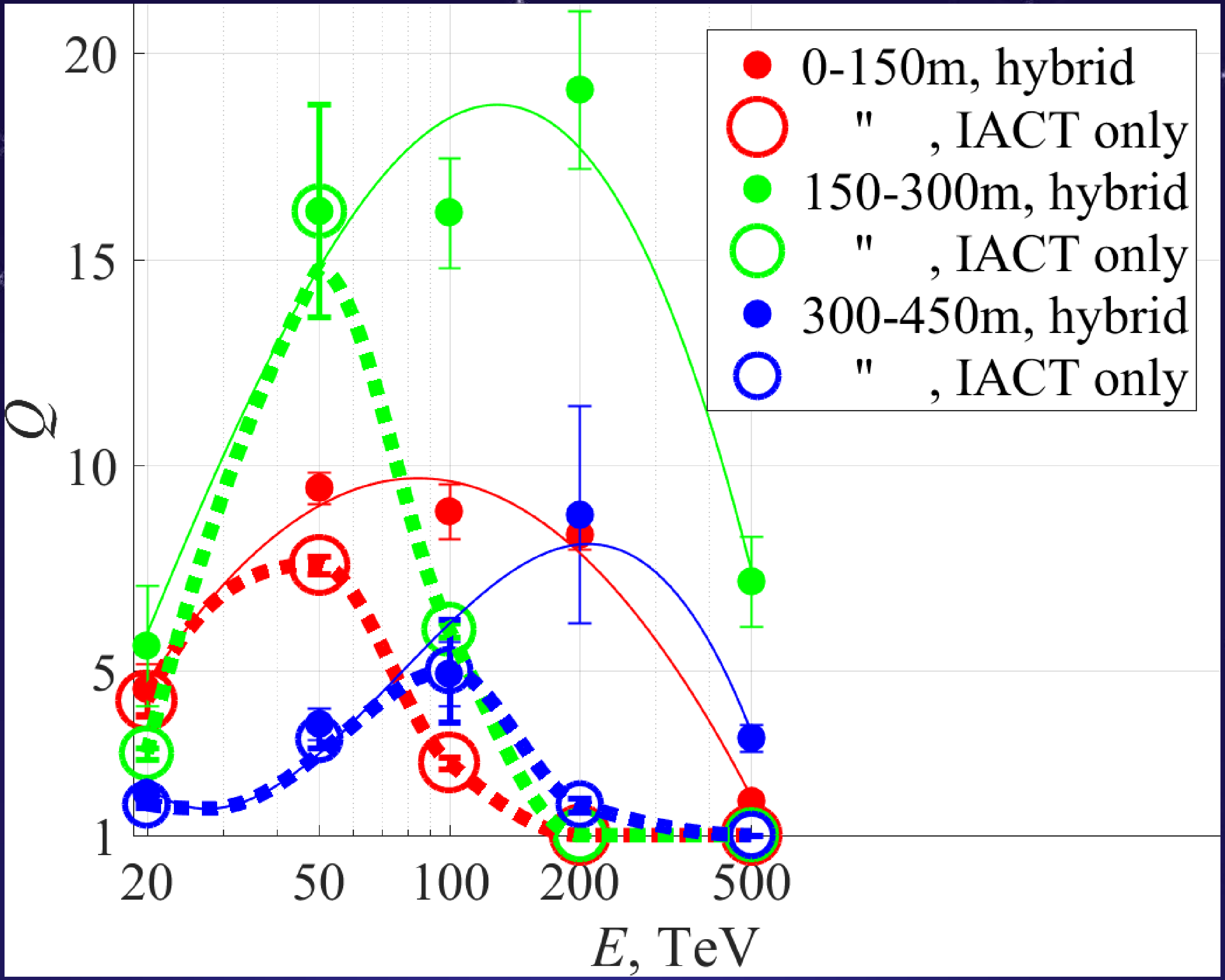
Q factor of the TAIGA installation ("without" HiSCORE)



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Nuclei / protons

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Discrimination of primary nuclei

- CR mass composition (hundreds of TeV) – can we distinguish between nuclei and protons?
  TAIGA is Tunka Advanced Instrument for cosmic ray physics and Gamma-ray Astronomy, so cosmic ray is also an option. What is about a hybrid technique in this case?

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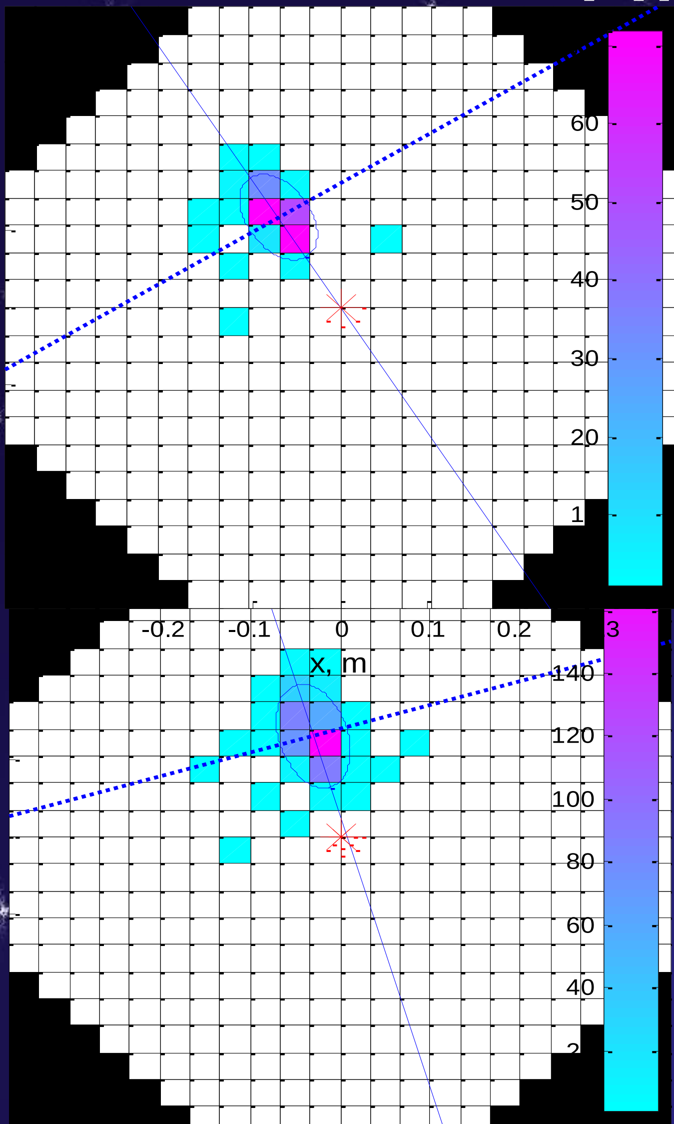
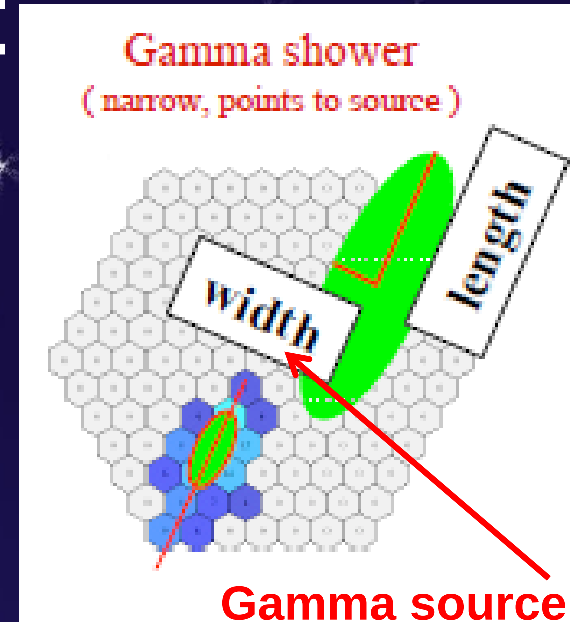
Proton rejection: Hillas technique





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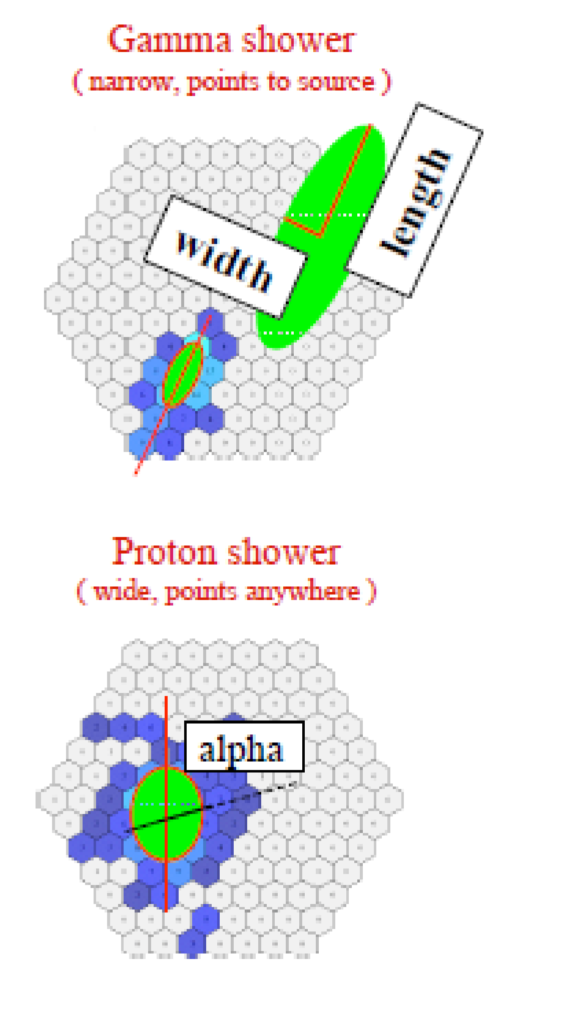

Both protons and nuclei arrive from isotropic directions → ~~alpha parameter~~

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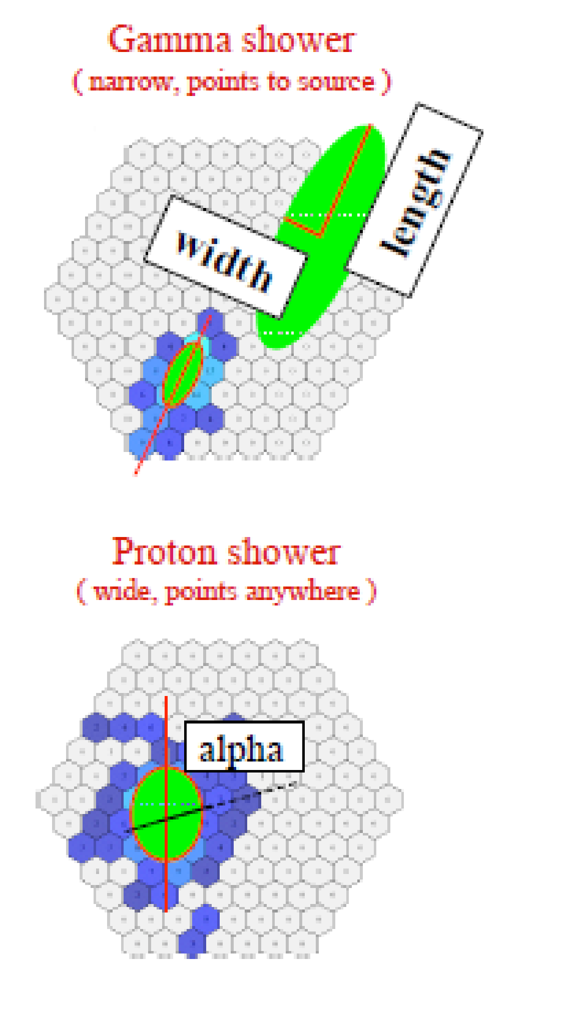
Proton rejection: Hillas technique

So again:
- Core position
- Energy
- Hillas parameters (this time no azwidth)

Both protons and nuclei arrive from isotropic directions → ~~alpha parameter~~ ~~azimuthal width~~



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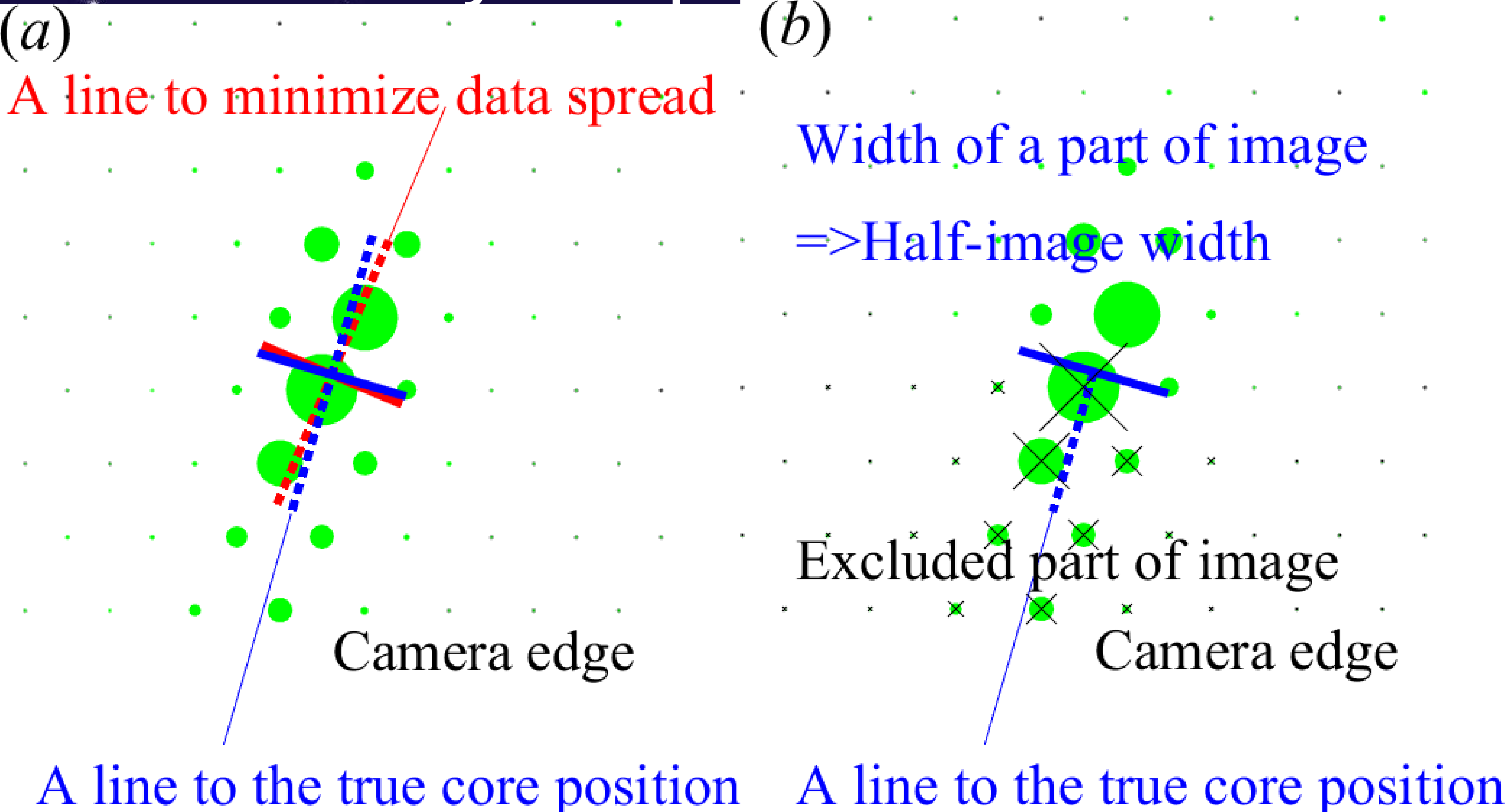
Proton rejection: hybrid parameters



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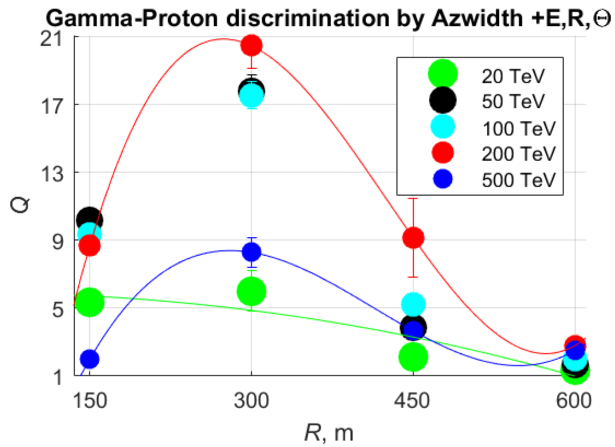
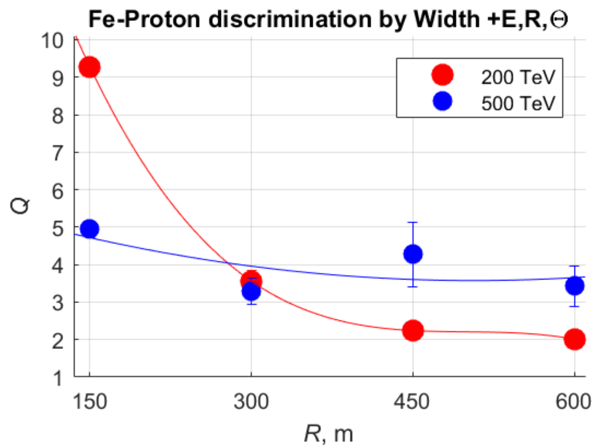
MC simulation

- Simulation was performed for the primary protons and nuclei with fixed energy 200 and 500 TeV, incident on the array of 1 km2 area with the grid of 16 IACTs tilting to the south by 30 degrees. This configuration is close to the HiSCORE ptototype design. In the present work we simulated in details only the images produced by showers in CCD camera of every IACT. The arrival direction, energy and core position of the every shower were known with the accuracy 0.1°, 10% and 10 m correspondingly.
- At the first step, the shower development in the atmosphere was simulated with CORSIKA, the response of IACT system was simulated at the second step with the specially developed program. The segmented mirror of every IACT has an area of about 10 m^2 and a focal length of 4.75 m. The camera consists of 547 PMT with the total FOV ~9.72°, and the one pixel FOV is 0.36°. Cherenkov photons of the shower were traced through the IACT optical system, then were converted to photoelectrons in each pixel of the camera, forming the image. The arrival directions of the showers was distributed within FOV of every telescope within ±5°.

evgeny.post@gmail.com

Optimal parameter combination and discrimination quality





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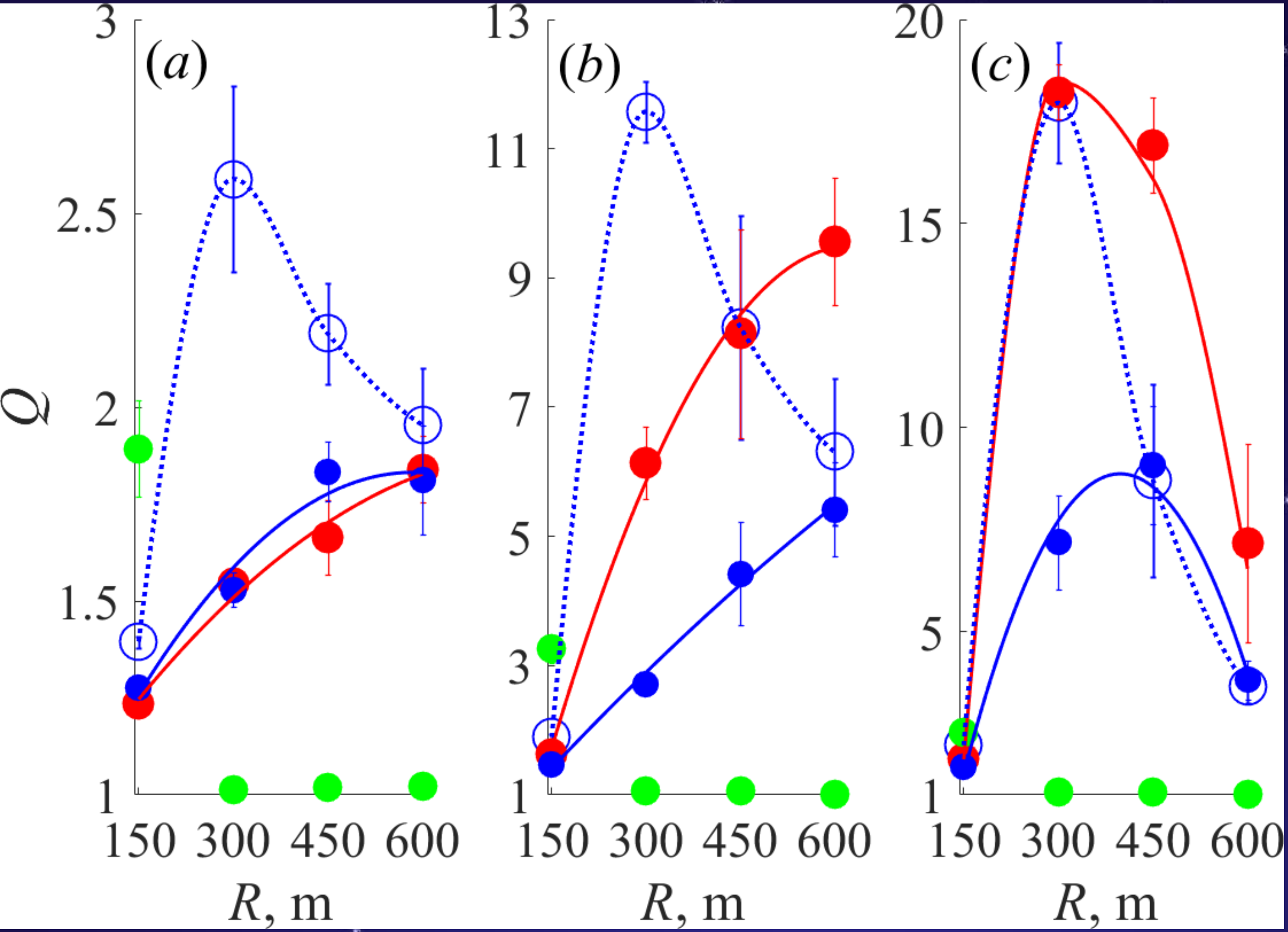
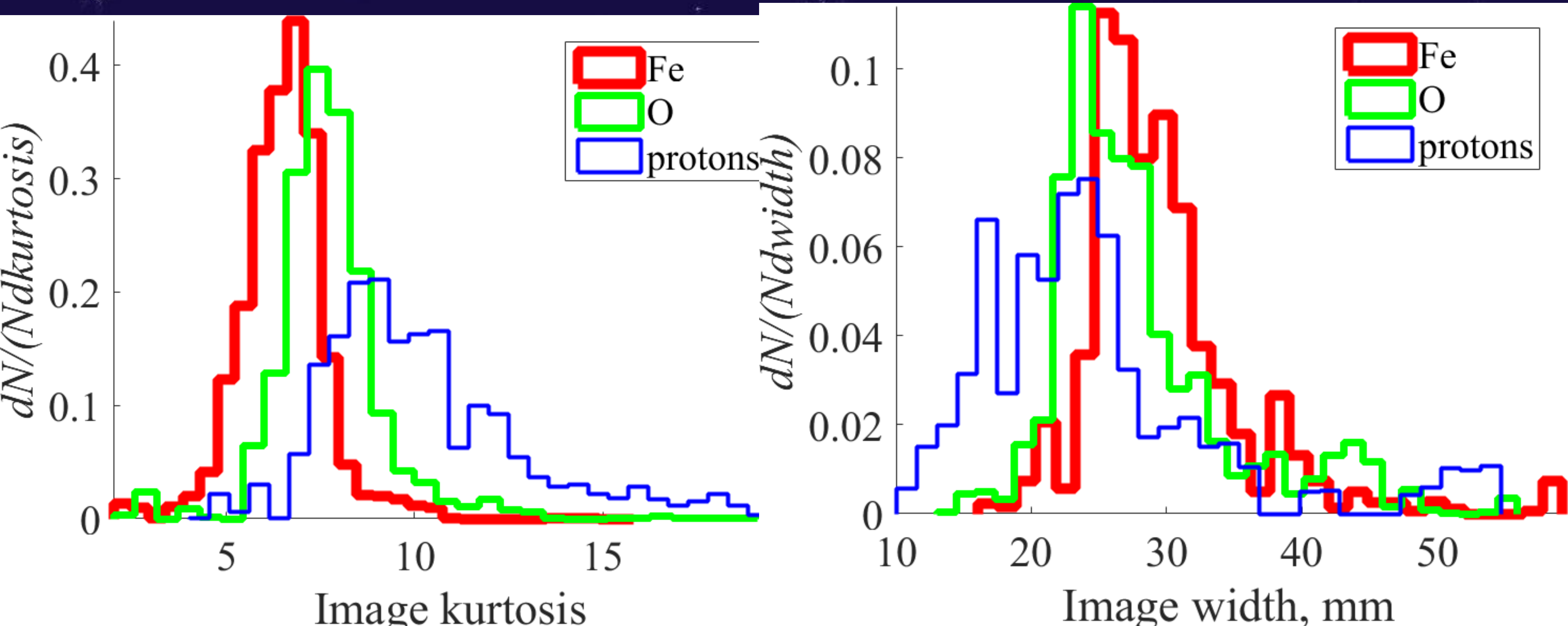


Selection quality factor
vs shower core distance.
(a) O 500 TeV,
(b) (b) Fe 500 TeV,
(c) Fe 200 TeV.
Green - image kurtosis, red - Hillas width, blue - half-image width, blue open circles – core azimuthal half-image width.

evgeny.post@gmail.com

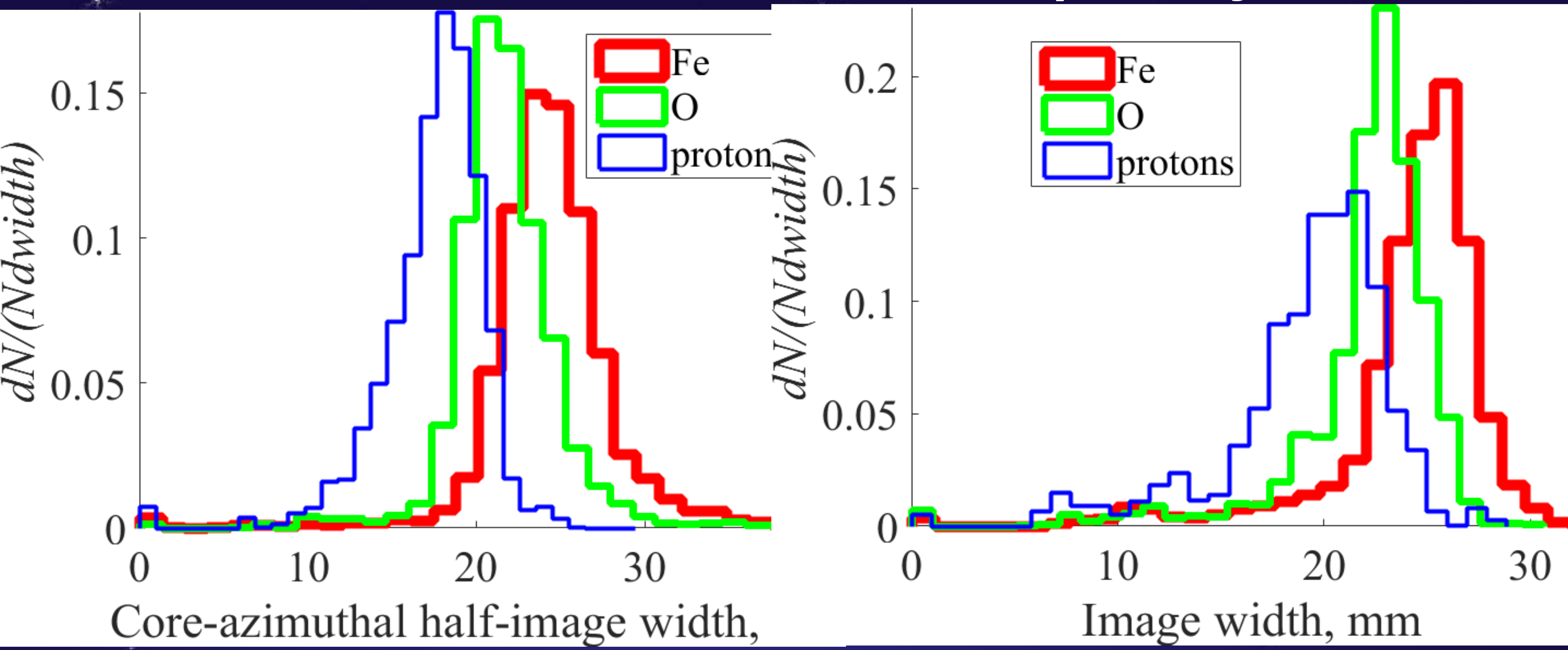
Optimal parameter combination and discrimination quality



R 0-150 m

evgeny.post@gmail.com

Optimal parameter combination and discrimination quality



R 150-300 m

evgeny.post@gmail.com

Conclusion

- Gamma-proton: Q>5 (*E>50 TeV, R<450 m*)

x100 in ~0.4º

- Fe-proton: Q>2 (*E>200 TeV, R<600 m*)

x16 in ~5º

- Selection of both gamma and nuclei is quite possible
- Joint operation of two kinds of installations is significant

evgeny.post@gmail.com

Backup slides

evgeny.post@gmail.com

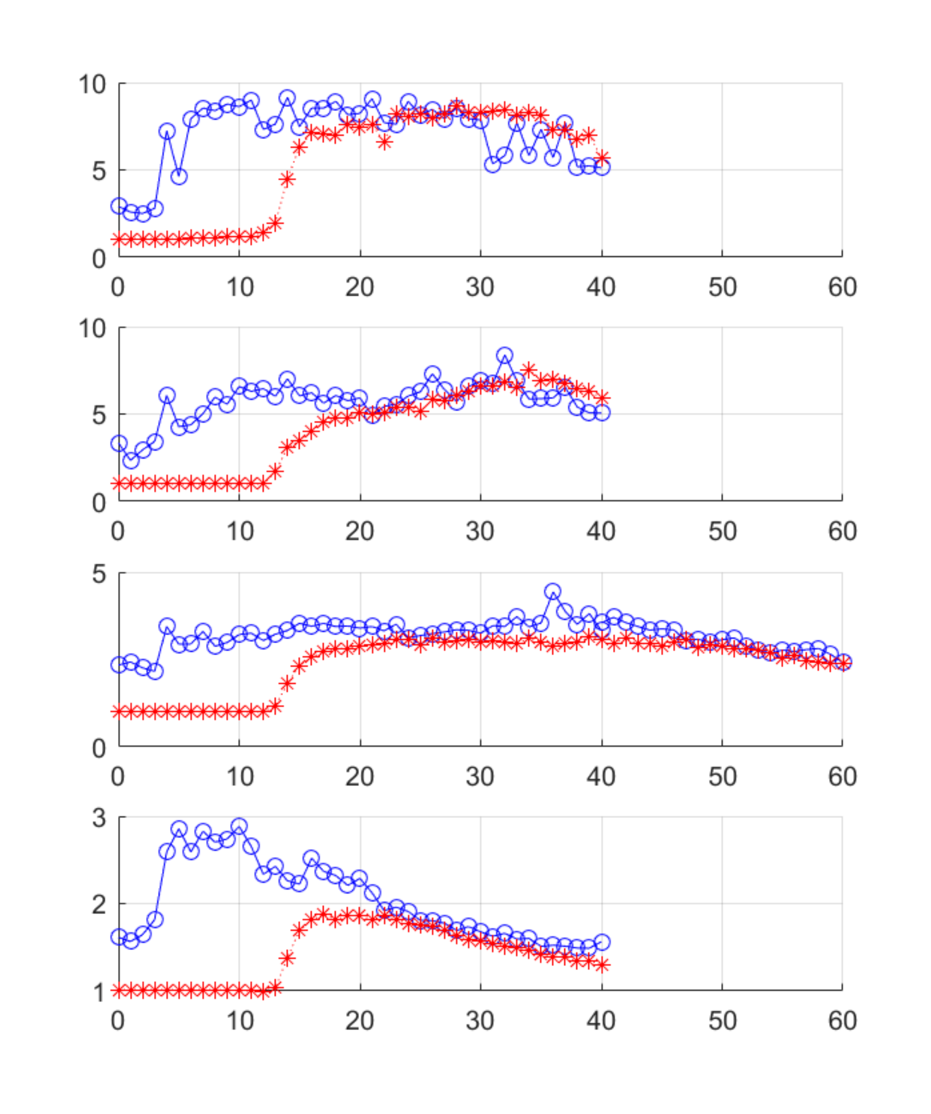
New set of parameters for hybrid analysis

- Timing arrays shower reconstruction data:
  - Source direction (±0.1−0.4º)
  - Core position (±10−15 m)
  - Energy (~15%, up to ~5%)

- IACT Image

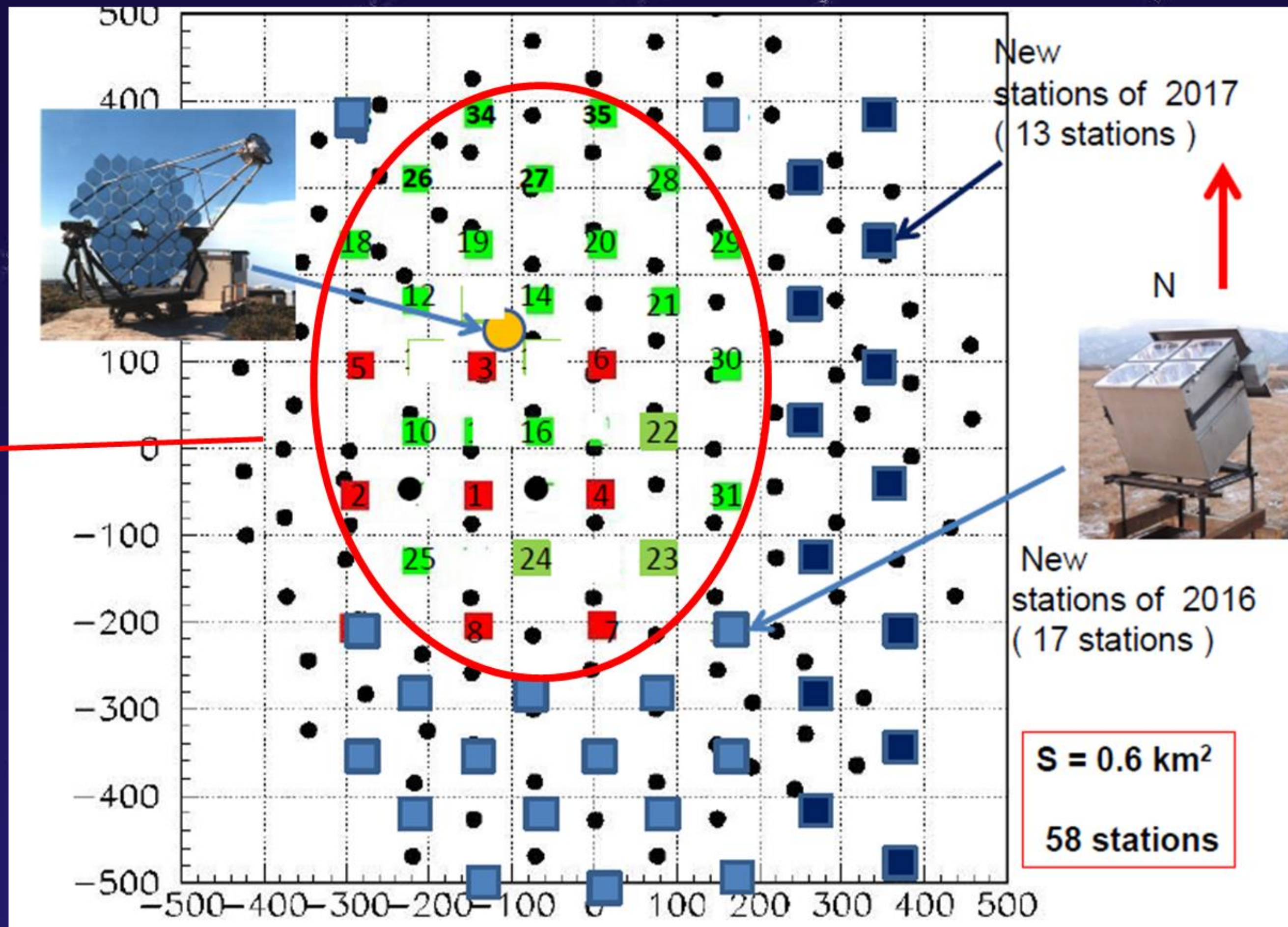
evgeny.post@gmail.com

Q factor vs signal cut



evgeny.post@gmail.com

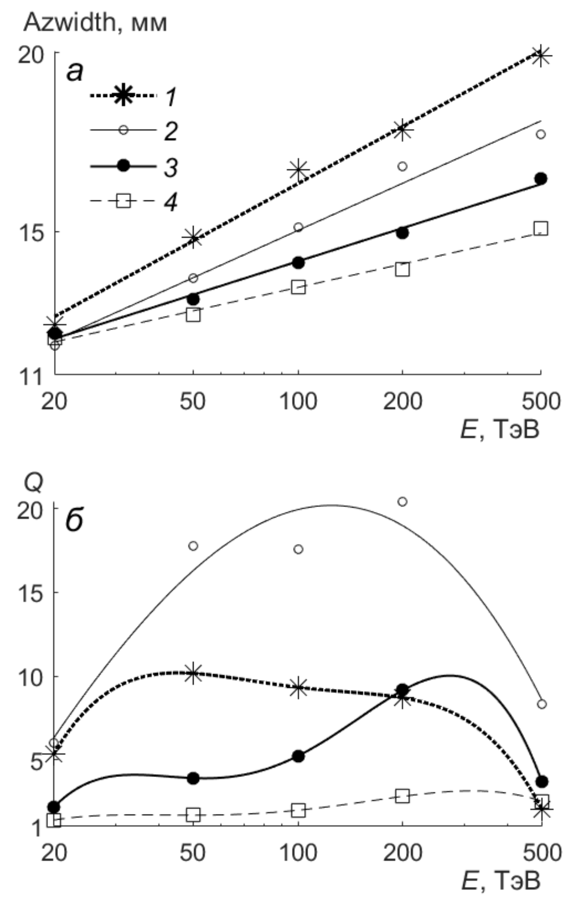
Wide angle timing array



28 detectors
106 m distance
0.25 km²

All stations are tilting to the South (25°)

Рис. 2. Зависимость оптимального порогового значения ширины имиджа (а) и достигающегося при этом пороге Q-фактора (б) от первичной энергии ШАЛ. Тип маркера соответствует расстоянию до оси ШАЛ: 0–150 м (1), 150–300 м (2), 300–450 м (3), 450–600 м (4)

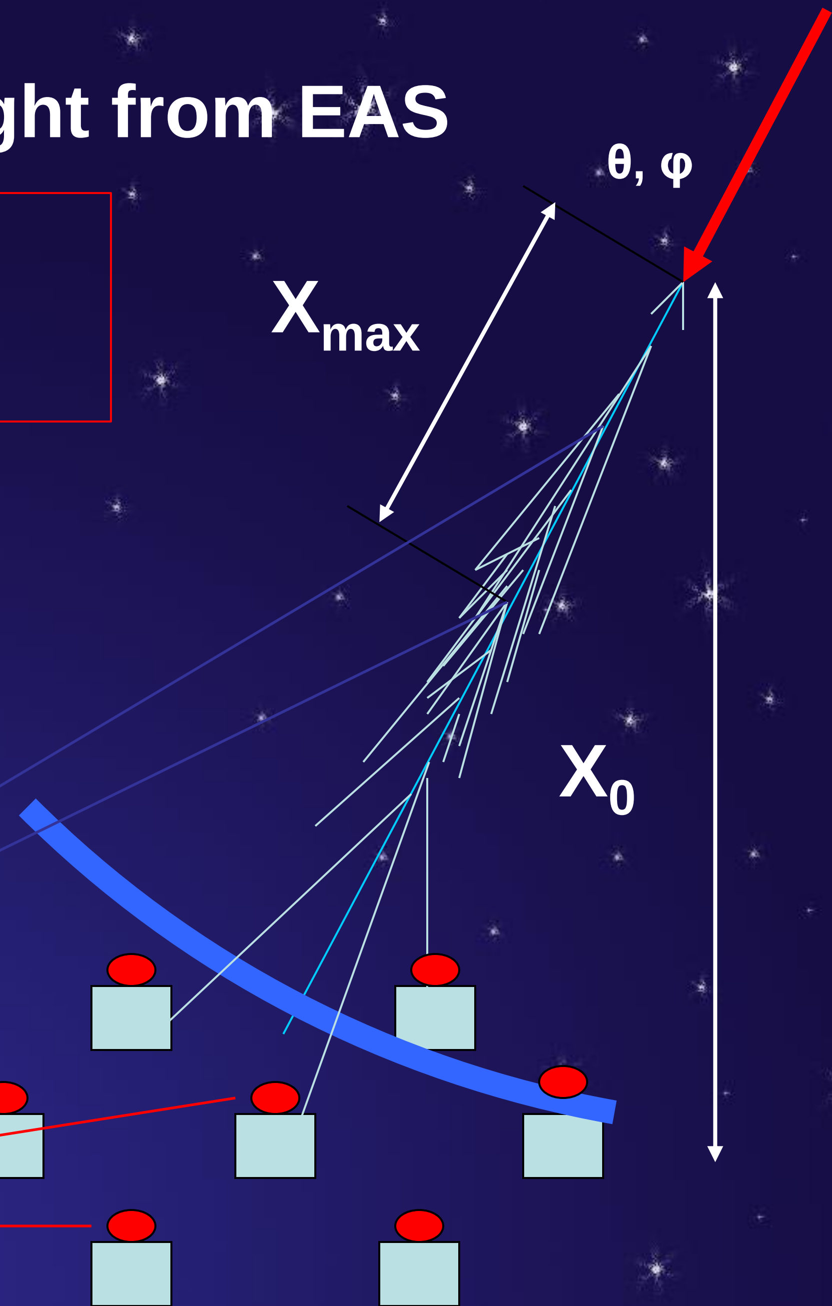


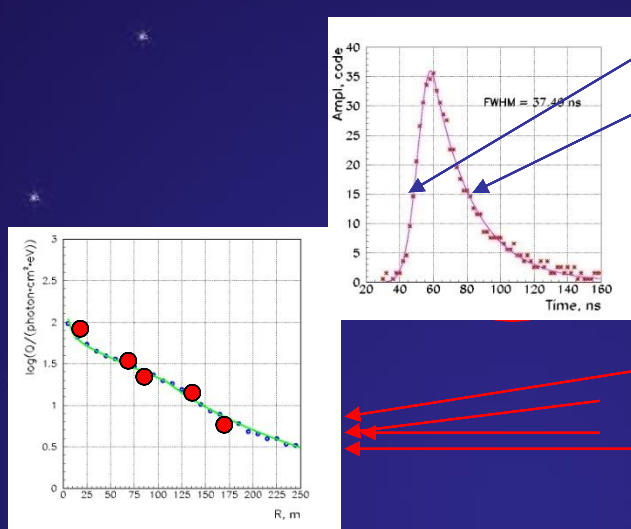
evgeny.post@gmail.com

Registration of Cherenkov light from EAS

Accuracy: core location ~ 10 m

Energy resolution ~ 15%





HiSCORE optical station

20 cm

40 cm

$S = 0.5\ m^2$

FOV = 0.6 ster
(±30°)