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The selection of gamma events from IACT images with deep learning methods

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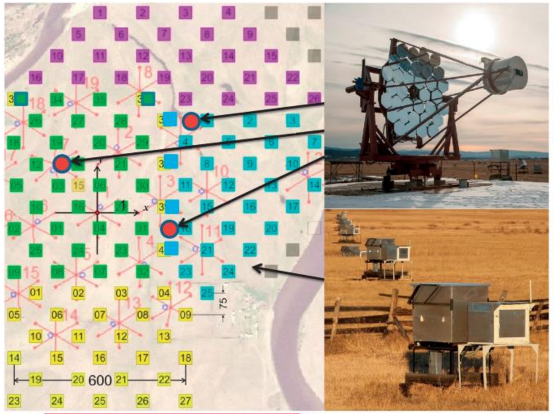
TAIGA-IACT

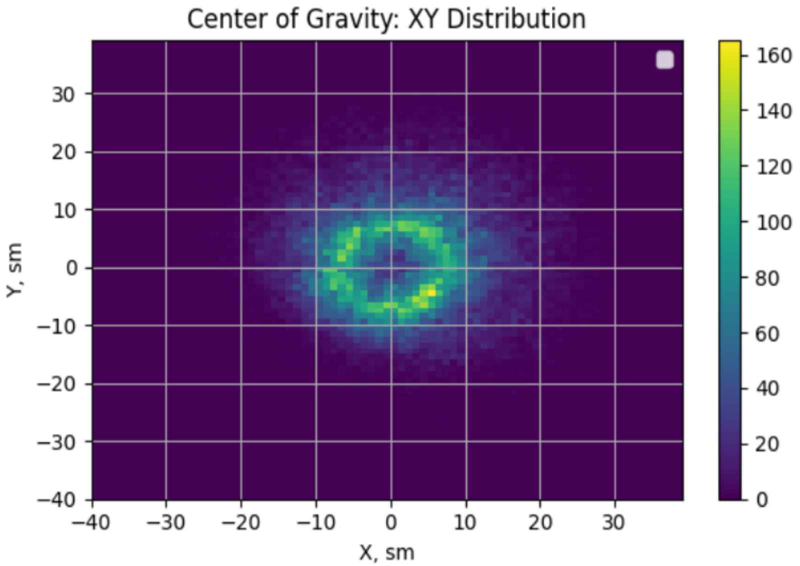
- Imaging Air Cherenkov Telescopes (IACT) are located in Tunka Valley (50 km from Lake Baikal), Republic of Buryatia, at the astrophysical gamma observatory TAIGA of the API ISU.
- They are telescopes-reflectors with a 4-meter segmented spherical mirror. In its focus there is a camera, representing as matrix of ~600 PMTs.
- They detect Cherenkov light from Extensive Air Showers (EASs), originating from the interaction of cosmic or gamma radiation with the atmosphere
- This type of detectors helps to select gamma-ray events from the hadron background based on obtained EAS images.



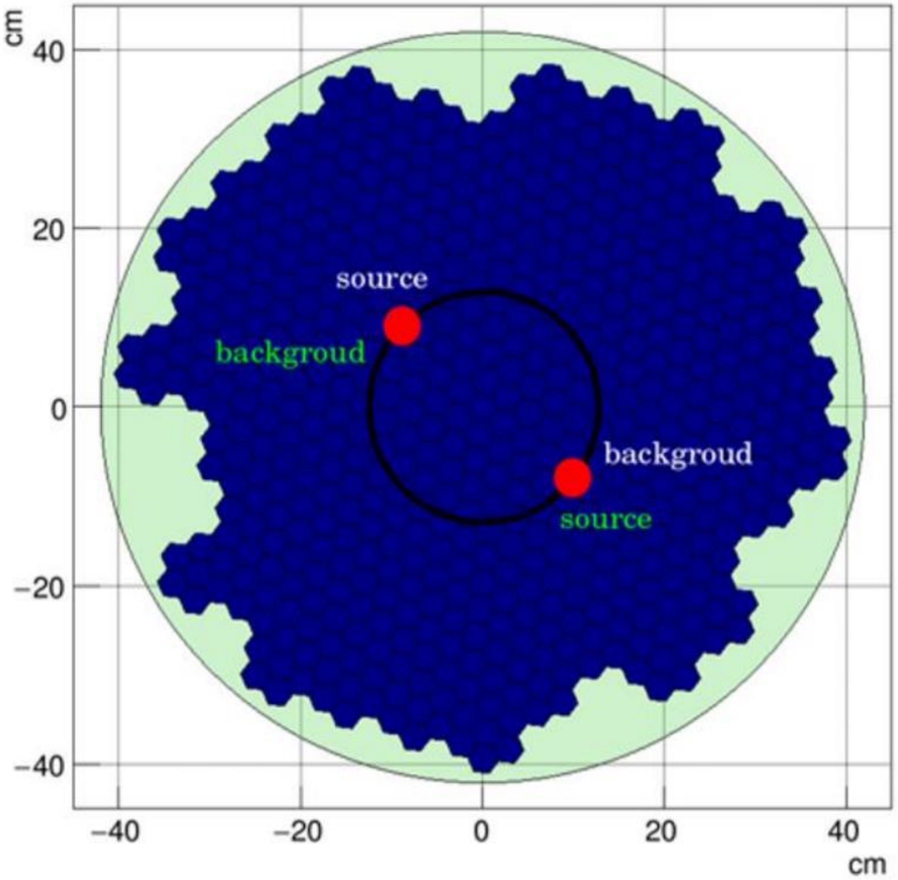
51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

Wobbling

- It's the telescope operating mode, in which the gamma radiation source is located *not in the center of the camera*, but *at a fixed distance from it*. In this mode the source periodically shifts from its position to another (opposite) offset position.
- *The idea*: simultaneous observation of a gamma radiation source and an isotropic hadron background to evaluate and select the signal from the source.



Gamma events location distribution from MC simulation.



True source (ON-source) – the true position of the gamma source on the telescope camera;

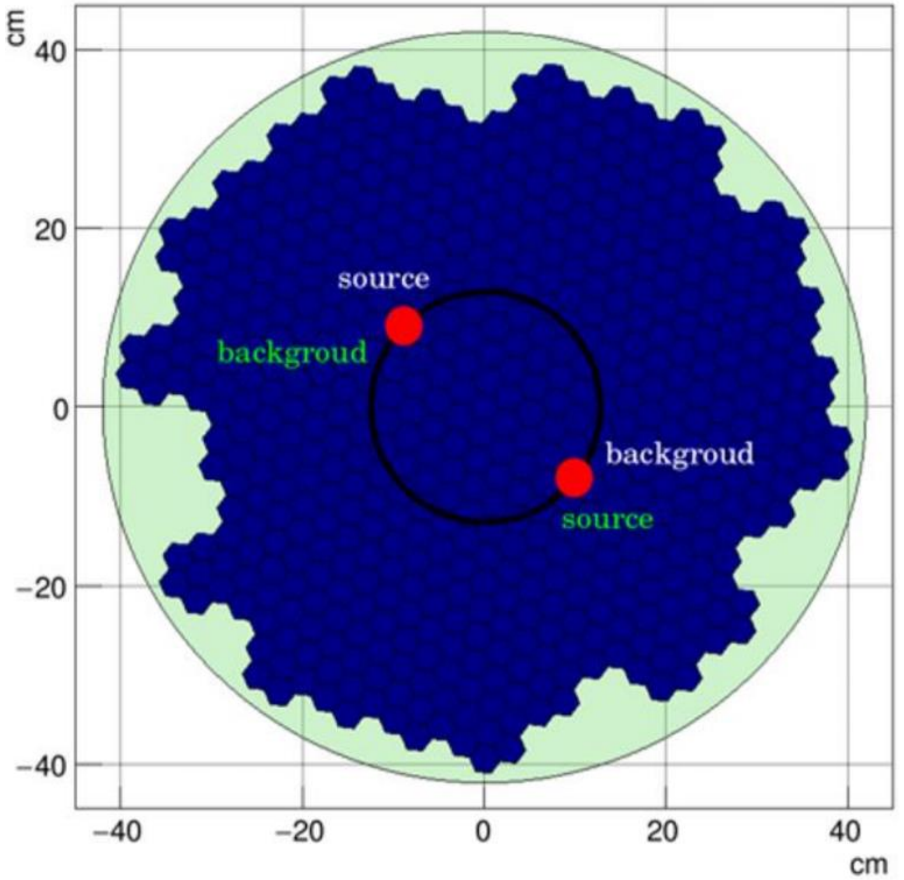
False source (OFF-source) – the position opposite to the ON-source; in data processing, several OFF-points can be selected for a more accurate assessment of the background;

Wobbling

- *TAIGA-IACT's wobbling mode* occurs by shifting the source by ***10.1 cm*** from the center of the camera; observation ~ 20 minutes, then there is a change in position.

- MC events do not have the offset mentioned while in the experiment the offset is present. Also MC are important for correct neural network training to solve tasks set. In this work classification task are considered.

- **Problem**: difference between the MC and experimental data may lead to reduction in the quality of the classification.



True source (ON-source) – the true position of the gamma source on the telescope camera;

False source (OFF-source) – the position opposite to the ON-source; in data processing, several OFF-points can be selected for a more accurate assessment of the background;

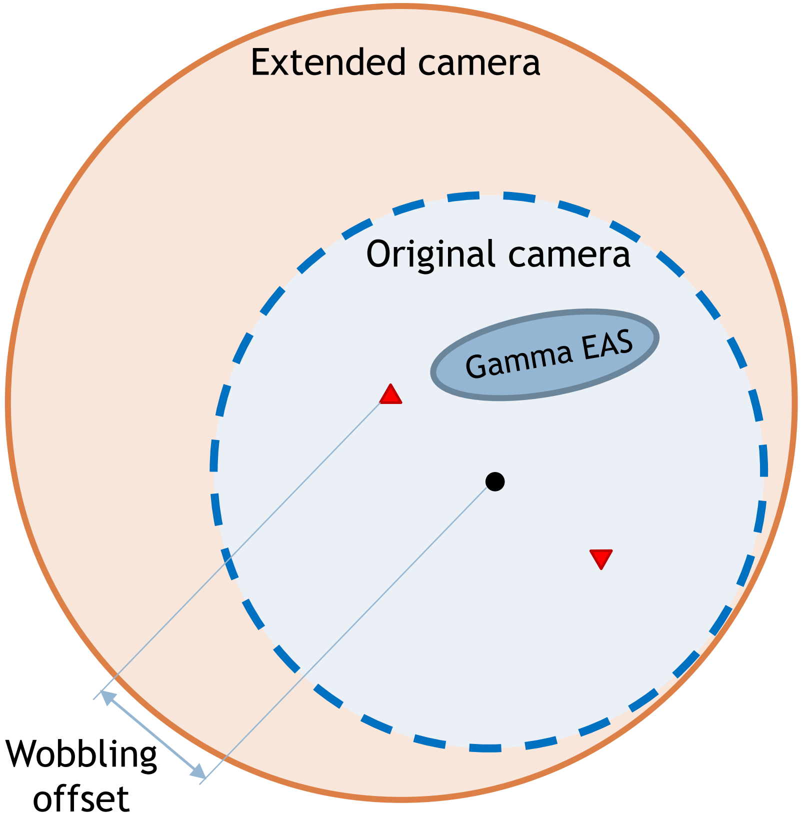
The aim and tasks of this work

- ***The aim***: development of neural network methods for processing and analyzing data from the Cherenkov telescopes TAIGA.

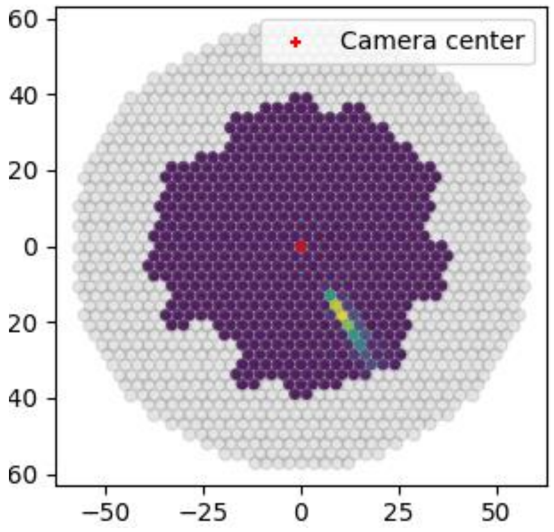
- ***Tasks*** considered in this work:
  - To develop software solution that would allow to take into account Wobbling mode and provide an opportunity to train neural networks on MC events with the possibility of their application to experimental data.
  - To evaluate the quality of gamma-event selection using this data modification method for Wobbling mode
  - To consider the classification task where a strong imbalance of cosmic and gamma radiation fluxes occurs.

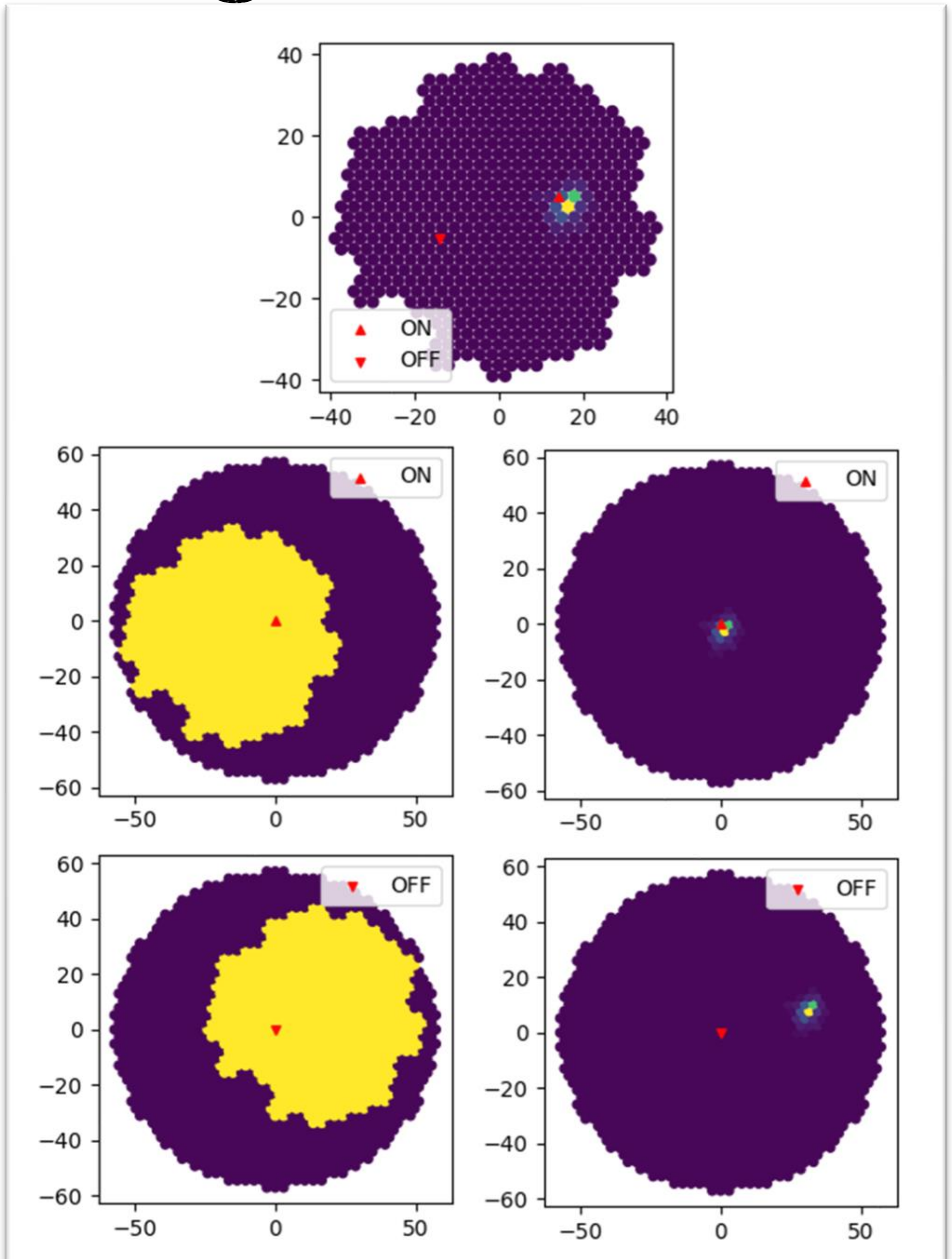
Image modification for Wobbling method

- Reflection of the original telescope camera matrix onto an expanded matrix. The center of expanded matrix corresponds to the location of true or false source.



Left: scheme of IACT image modifiction
Right: presentation of image modification for shifted images
Bottom: MC-event modification

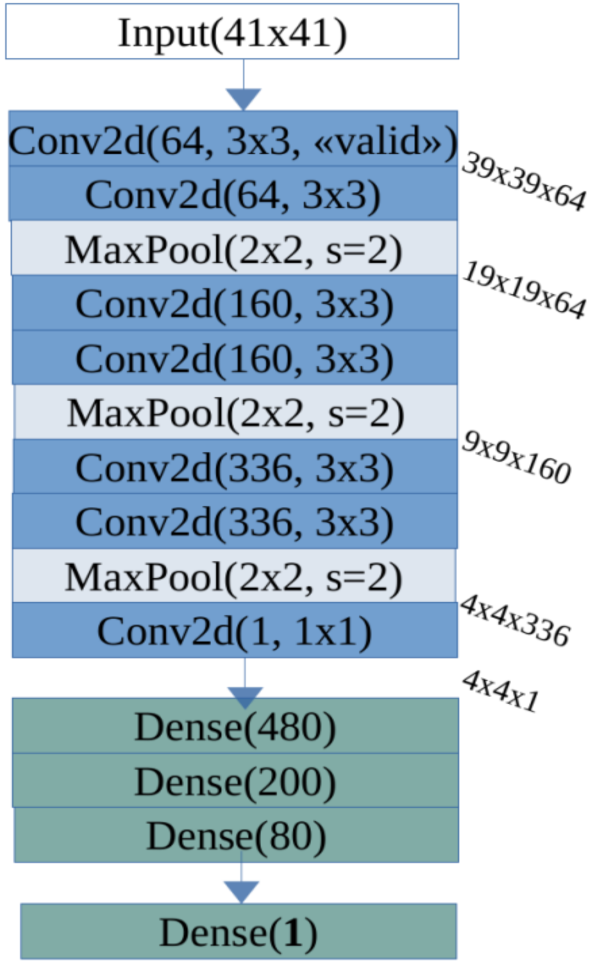




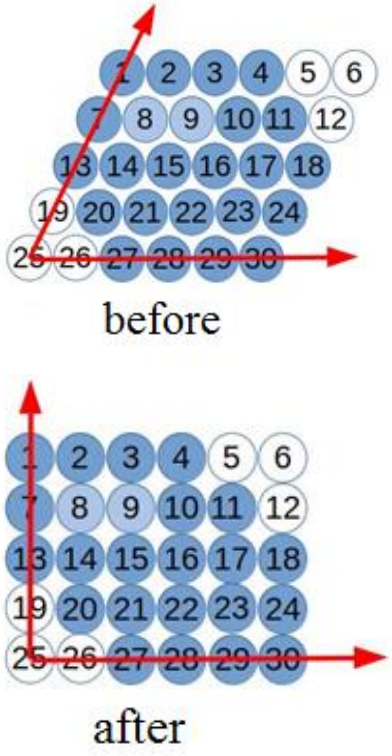
CNN architecture

- *Number of weights*: 1 981 882
- Loss function: binary crossentropy.

- *Training*: 50 519 MC events
  - Generated used by CORSIKA and TAIGA detector modeling software.
  - 25 242 gammas (1-50 TeV) & 25 277 protons (2-100 TeV)
- *Preprocessing*:
  - Cleaning with threshold 7 phe и N_pix>5;
  - Wobbling modification;
  - Transformation to a square image with the axial method;
  - Amplitude normalization: log(x+1) / max(log(x+1)), x - pixel amplitude;



CNN used in this work

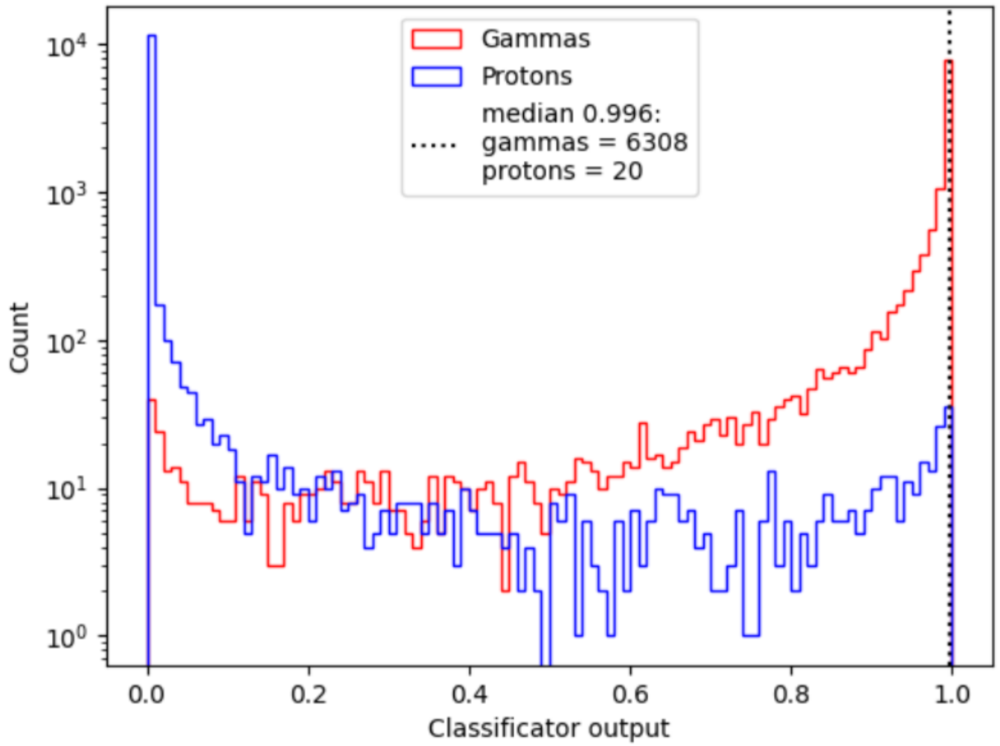


Axial transformation method

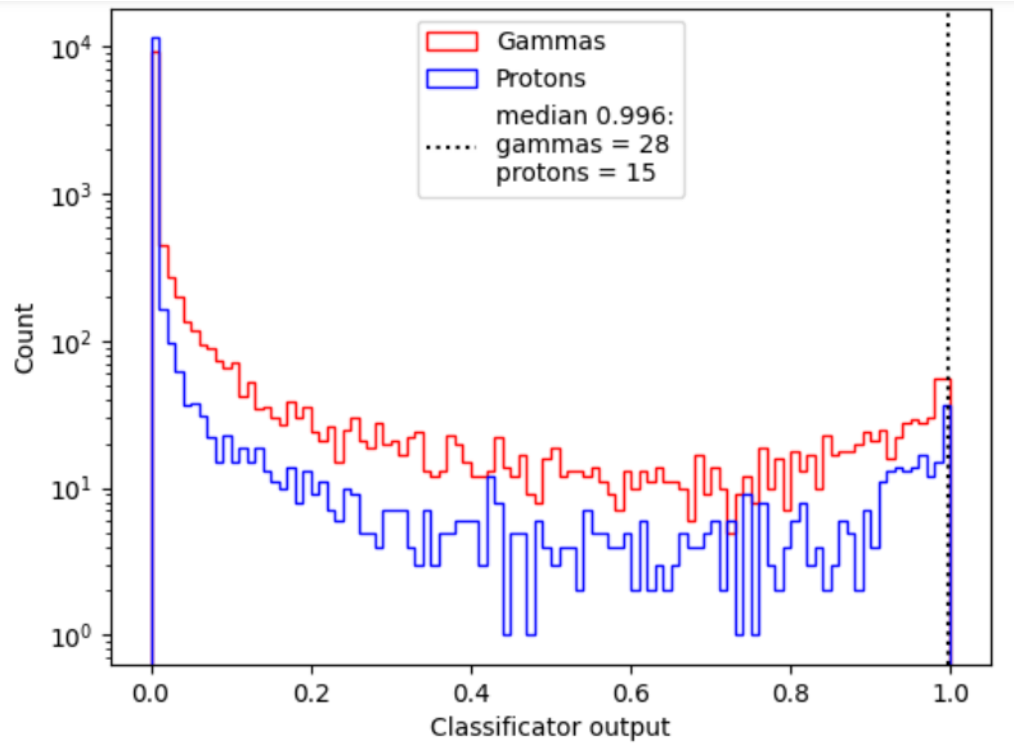
Validation results (model IACT data)

- Validation: 25 264 MC events (12 623 gammas & 12 641 protons)
- As expected, the wobbling offset significantly affects the quality of event recognition.
- The class selection threshold for ON point source is the value when half of the gamma events from the training set are lost.
  The class selection threshold for OFF point source is equal to the ON point threshold.

ON



OFF



Validation results (model IACT data)

- Q-factor is the coefficient of the quality of the signal selection over background fluctuations.

$$\boxed{Q = \frac{S_{after}}{S_{before}}}$$

$$S_{after} = \sqrt{2\left(\left(N_{g\_g} + N_{h\_g}\right) ln\left(1 + \frac{N_{g\_g}}{N_{h\_g}}\right) - N_{g\_g}\right)}$$

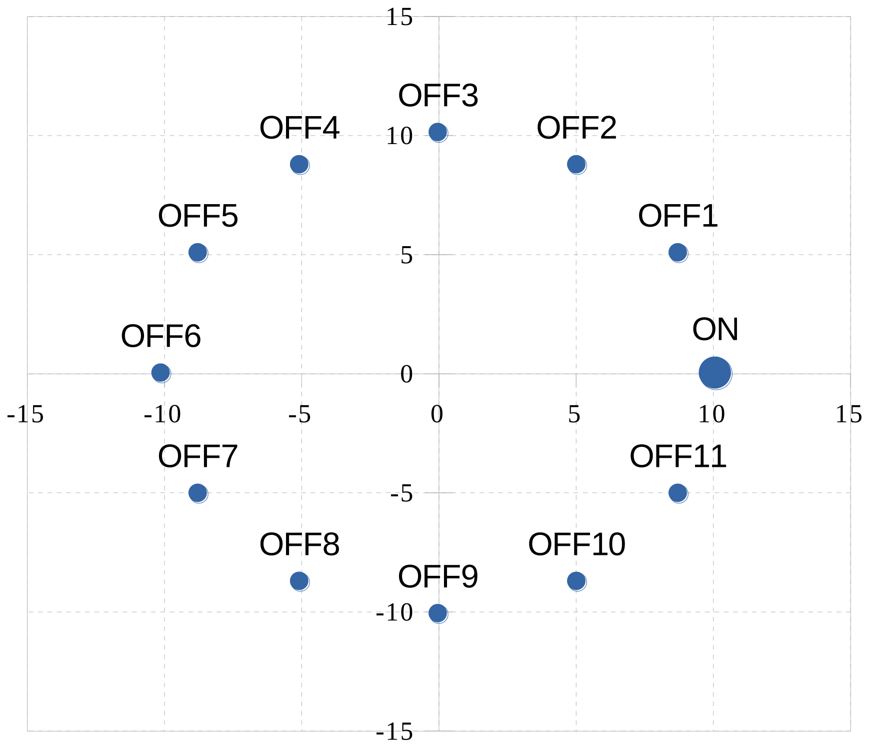
$$S_{before} = \sqrt{2\left(\left(N_{g} + N_{h}\right) ln\left(1 + \frac{N_{g}}{N_{h}}\right) - N_{g}\right)}$$

Source point	N_{total}	N_g	N_h	N_{g_g}	N_{h_g}	S_1	S_2	Q
ON	25264	12623	12641	6308	20	98,70	245,45	2,49
OFF	25264	12623	12641	28	15	98,70	5,88	0,06

- The hadron background suppression is equal to 600 with the loss of half of the gamma events. In the case of an equal flow of cosmic and gamma ray radiation, the gamma radiation signal stands out well.

Test results in case of significant class disbalance

- In the TAIGA-IACT experiment there is a strong difference in gamma and cosmic radiation fluxes (1:10 000 for Crab Nebula signal and hadron background).
- To estimate the classification quality, the classification was carried out on a samples consisting of experimental hadrons and MC gamma events. *The events ratio is considered as 10 : 100 000*.
- To evaluate the background 11 OFF-sources were selected, together with one ON-source.



Test results in case of significant class disbalance

- Test dataset:
  - 10 MC gamma events и 100 040 experimental hadron events;
- Preprocessing is similar to preprocessing the training set
- The class selection threshold: 0.996

- The calculated hadron background suppression coefficient (580) is approximately equal to the validation one.
- The signal *under the considered in this work conditions* (like CNN training conditions; architecture, etc) still does not stand out against the background fluctuations.

Point	True gamma	Fake gamma (Hadrons)	Total events
OFF1	2	182	184
OFF2	0	151	151
OFF3	0	166	166
OFF4	0	176	176
OFF5	0	166	166
OFF6	0	164	164
OFF7	0	180	180
OFF8	0	171	171
OFF9	1	169	170
OFF10	0	183	183
OFF11	2	164	166
ON	4	163	167

Mean (11 OFF-points)	170,6
Variance	94,3
σ	9,7

Comparison with previous results

- In the previous work* the estimations were carried out without wobbling modification and with simpler CNN architecture and softer cleaning threshold (5 phe).
- Also up to “1:1 000” class disbalance was considered.

“Gamma-proton” ratio	N_{total}	N_g	N_h	N_{g_g}	N_{h_g}	Q	Hadron background suppression
1:1	40000	20000	20000	11677	180	2,22	111
1:100	4182	58	4124	25	21	5,22	196
1:1000	36783	35	36748	19	262	6,35	140

- Wobbling modification has not effects on the obtained results.
- Classification had improved with changed training conditions , yet it’s not enough for “1:10 000” disbalance.

[*] E. Gres, A. Kryukov. The Preliminary Results on Analysis of TAIGA-IACT Images Using Convolutional Neural Networks - https://doi.org/10.22323/1.410.0015

Conclusion

- The method of image modification of the Cherenkov telescopes TAIGA-IACT was developed and implemented programmatically.

- The results showed that Wobbling is critical for TAIGA-IACT image recognition: without it, the quality of gamma events selection is much worse. It is necessary to take this effect into account while working with neural networks further.

- It is still problematic to separate the signal from the gamma source with a significant disbalance of gamma and cosmic radiation fluxes, further improvements of the deep learning method is required.

Thank you for your attention!

Test results in case of significant class disbalance

N_g	N_h	N_{g_g}	N_{h_g}	S_after	S_before	Q
10	100040	4	163	0,312036	0,031616	9,869573

- Experimental count rate for IACT - ~10 Hz
- Calculated* fluxes from Crab Nebula for 72 hours

Log(Size)	Size, phe	Gamma quantum, TeV	Integral flux, 10^{-14} 1/(sm^2 * s)	Expected number of Gamma events
1,9	79	7,9	68,41	347
2,0	100	10,0	44,06	224
2,1	126	12,6	28,39	144
2,2	158	15,8	18,28	93
2,3	200	20,0	11,78	60

[*] Using energy spectrum from: M. Amenomori et al. First Detection of Photons with Energy Beyond 100 TeV from an Astrophysical Source. - https://arxiv.org/pdf/1906.05521.pdf