Data augmentation problem for imaging atmospheric Cherenkov telescopes in stereo mode: the TAIGA-IACT Example

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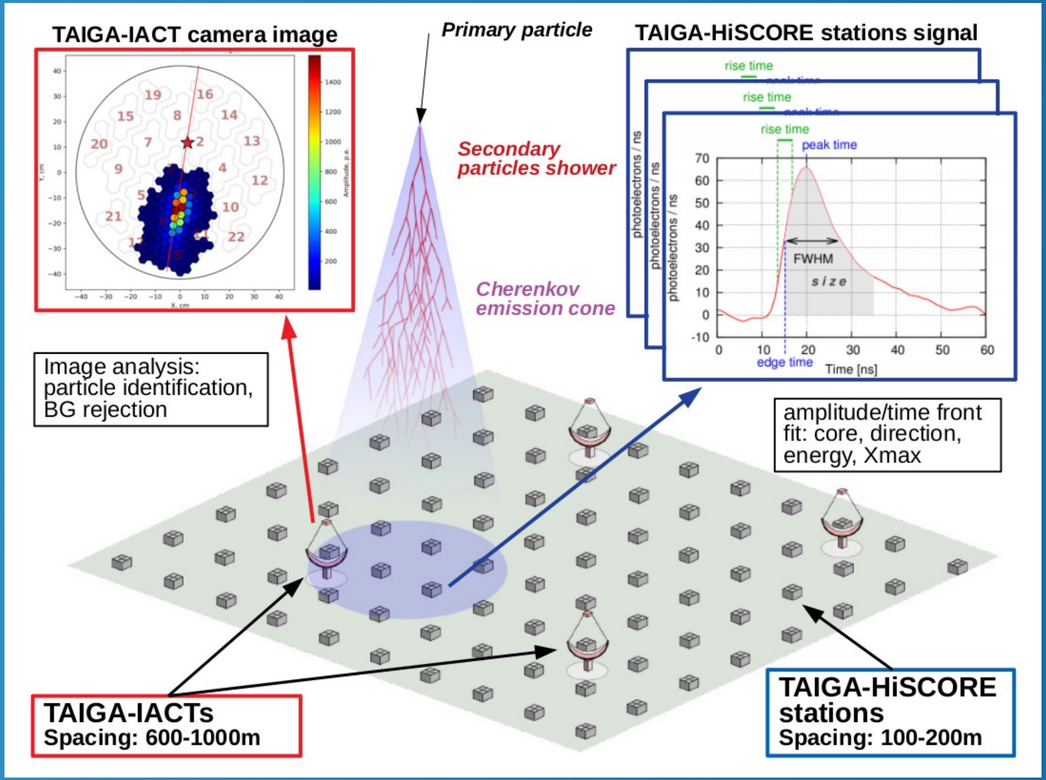
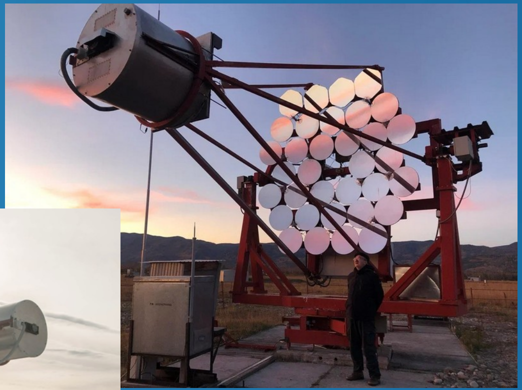
TAIGA experiment

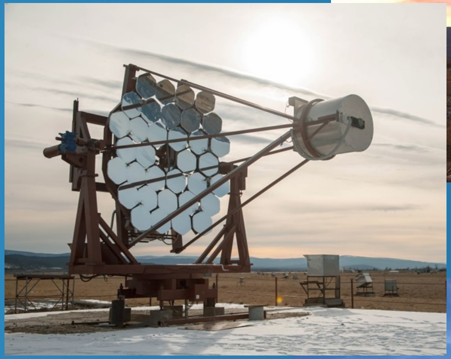
- TAIGA-1 installation (1 km²):
  - **TAIGA-HiSCORE** — array of wide-angle Cherenkov detectors
  - **TAIGA-IACT** — atmospheric Cherenkov telescopes
  - **Scintillation facilities:** Tunka-GRADE and TAIGA-Muon
- **Objectives:** Study of high-energy gamma radiation
- **Location:** 50 km from Lake Baikal in the Tunkinskaya Valley
- **Future development:** expansion of the project — TAIGA-100 installation (100 km²)



TAIGA-IACT installation

- TAIGA-IACT — Array of Imaging Atmospheric Cherenkov Telescopes (IACT)
  - Segmented reflector with a diameter of 4.3 meters; focal length (f) = 4.75 meters
  - Field of view of the telescope: 9.6°
  - PMT-based camera for registering extensive air shower (EAS) images; pixel size: 0.36°
  - Energy threshold: approximately 4 TeV
  - Current status: 4 telescopes are operational
- Operational Principle:
- The telescopes record the angular distribution of Cherenkov light from extensive air showers (EAS), forming images.The parameters of the shower are determined based on the images.



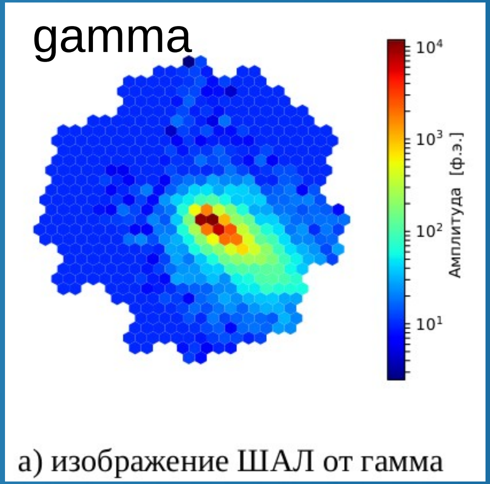


Event processing modes with TAIGA-IACT

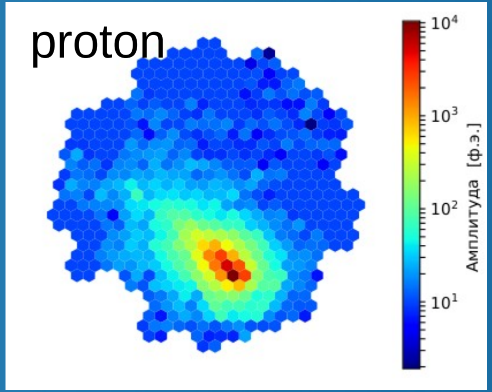
- Mono Mode:
  - Single-telescope detection of EAS (images from one IACT)
  - Energy threshold: approximately 4 TeV
- Stereo Mode:
  - Multi-telescope detection of EAS (images from several IACTs)
  - Energy threshold: 10 TeV
- Joint Detection:
  - Combined detection of the same EAS using both TAIGA-IACT telescopes and TAIGA-HiSCORE stations
  - Energy threshold: approximately 40 TeV
  - Multimodal data

TAIGA-IACT Data

- To extract gamma signal, it is necessary to significantly suppress the background of charged cosmic rays (~1 EAS from gamma rays per 10^4 EAS from charged cosmic rays).
- Since obtaining reliable labeling from real data is challenging, simulation data is used for neural network training.
- EAS simulation is time-consuming. It may take an hour of CPU time per high energy shower.
- Optical modeling and electronics response simulation require relatively little time.
- Millions of events are required for training, which is difficult to achieve using only simulation, therefore, data augmentation is necessary for training purposes.
- Currently, we have several hundred thousand events for mono mode, and several times fewer events for stereo mode. The events are simulated with a tilted energy spectrum, so they are predominantly in the energy range close to the threshold.

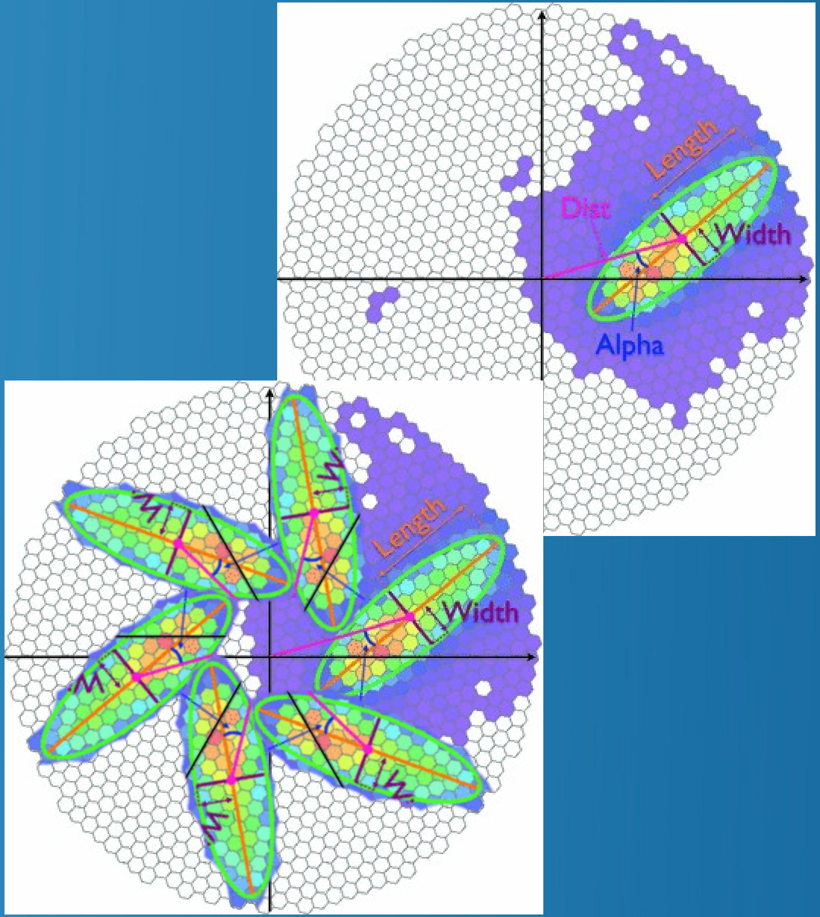


а) изображение ШАЛ от гамма



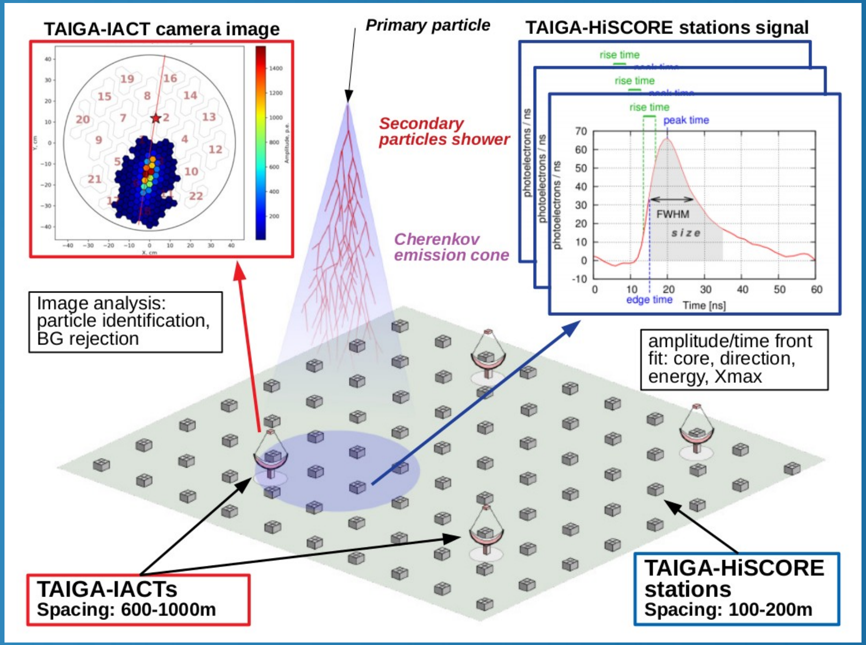
Data Augmentation for Mono Mode

- Augmentation Methods for EAS Images in TAIGA-IACT Mono Mode:
  - Different telescope positions relative to the shower during EAS simulation
  - image (for charged cosmic-ray EAS augmentation)
  - Image rotations around source direction
  - Various noise implementations
- The application of augmentation in classification and regression tasks for mono mode in our previous studies has significantly improved the performance of neural networks



Augmentation problem for stereo

- Compared to mono events, the stereo event sample is significantly smaller
  - This makes data augmentation critically important
- A single shower is observed by multiple telescopes simultaneously
  - Stereo helps reconstruct EAS axes and arrival directions more accurately, so it is crucial to keep this information and avoid producing impossible events during augmentation.



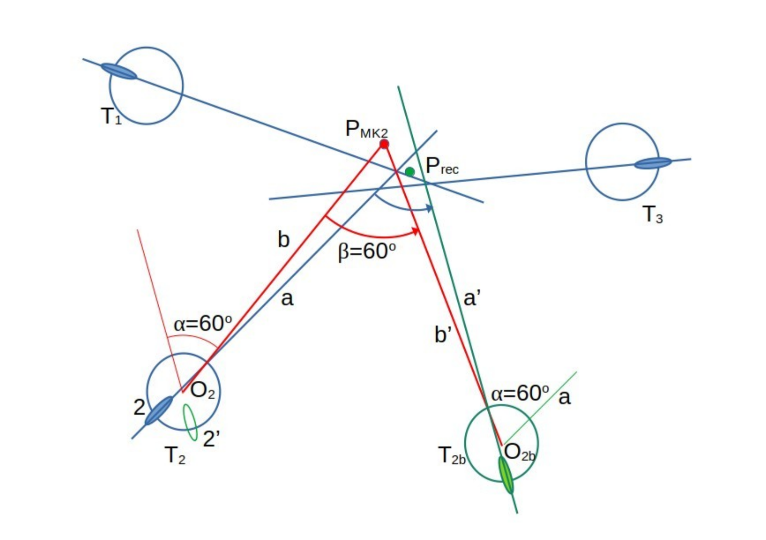
Possible augmentation techniques in stereo mode

Stereo data augmentation can be performed using:

- Various telescope positions relative to the shower during EAS simulation
- Telescope direction shifts (change source position on the camera)
- Different noise implementations
- Image rotation around the source direction
  - This rotation can in some cases be interpreted as observing the EAS from a different spatial position

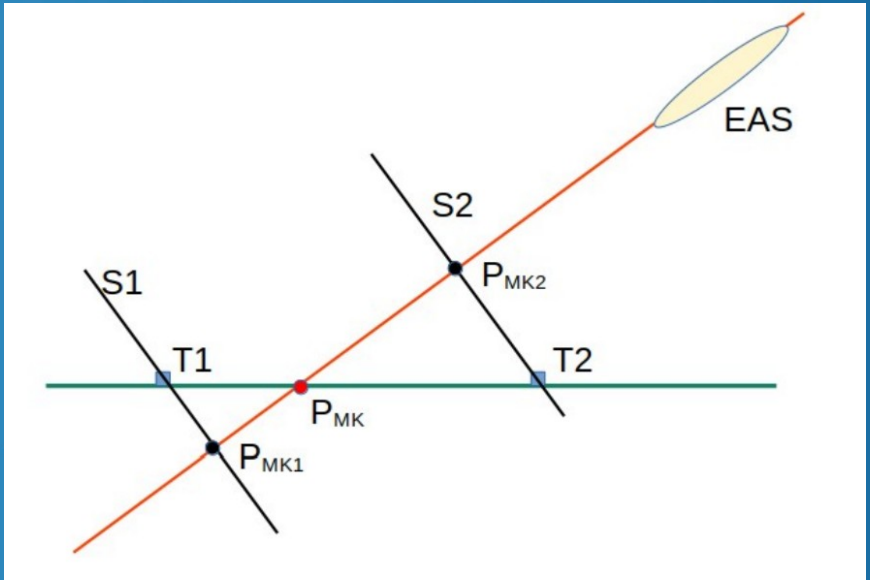
Interpretation of image rotation around EAS arrival direction

- We believe that the EAS has axial symmetry
- If the rotation angle is 60 degrees, then the image in the telescope is easily rotated.
- To rotate the telescope at an arbitrary angle, it is necessary to maintain the orientation of the telescope to the point of arrival of the EAS.



Interpretation of image rotation around EAS arrival direction

- Rotation of the image around the projection of the source direction corresponds to the rotation of the telescope position around the shower axis while maintaining its orientation
  - The telescope itself may end up outside the installation plane during this rotation
- The principal aspect of using this method requires inputting telescope spatial coordinates into the neural network, possibly making the task more challenging (the network has to solve the problem for arbitrary telescope positions).



Conclusion

- Training neural networks for classification and regression tasks on imaging atmospheric Cherenkov telescopes is only possible using simulation data
- Shower development simulation requires significant computational time, necessitating data augmentation for neural network training
- Rotation of the image around the projection of the source direction can be interpreted as rotation of the telescope position around the shower axis
  - It can be used for augmentation, but requires providing telescope positions as input to the neural network for stereo mode
- This method allows modeling multi-telescope events from events with a small number of telescopes and even from mono-events. This is often important for the procedure of training neural networks.
- We are currently studying the effectiveness of the proposed augmentation method for the case of 3 and 4 telescopes.