Simulation of the Tunka Area Instrument for cosmic rays and Gamma ray Astronomy (TAIGA)

Maike Kunnas for the Tunka-HiSCORE Collaboration

M. Kunnas[1], M. Brückner[6], N. Budnev[5], O. Chvalaev[5], A. Dyachok[5], S. Epimakhov[1], T.V.Eremin[3], O. Gress[5],A. Grinyuk[9], D. Hampf[1], D. Horns[1], A. Ivanova[5], S.N.Kiryuhin[5], K.G. Kompaniets[8], E. Konstantinov[5], E. Korosteleva[3], L. Kuzmichev[3], B.K. Lubsandorzhiev[4], N.B. Lubsandorzhiev[4], R. Mirgazov[5], R. Mirzoyan[7], R. Monkhoev[5], R. Nachtigall[1], A. Pakhorukov[5], A.A. Petrukhin[8], V. Poleschuk[5], A. Porelli[2], E.B. Postnikov[3], V. Prosin[3], G.I. Rubtsov[4], M. Rüger[6], V.S. Samoglia[5], P.S. Satunin[4], Yu. Semeney[5], C. Spiering[2], L. Sveshnikova[3], A.Tkachenko[9], L. Tkachev[9], M. Tluczykont[1], R. Wischnewski[2], I.I. Yashin[8], A. Zagorodnikov[5], V.L. Zurbanov[5]

[1] Institute for Experimental physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany [2] DESY, Platanenallee 6, 15738 Zeuthen, Germany [3] Skobeltsyn institute for Nuclear Physics, Lomonosov Moscow State University, 1 Leninskie gory, 119991 Moscow, Russia, [4] Institute for Nuclear Research of the Russian Academy of Sciences 60th October Anniversary st., 7a, 117312, Moscow, Russia [5] Institute of Applied Physics ISU, Irkutsk, Russia [6] Institut für Informatik, Humboldt University, Rudower Chaussee 25, Berlin [7] Max Planck Institut für Physik, Föhringer Ring, München, Germany [8] National Research Nuclear University MEPhI, Kashirskoye shosse 31, Moscow,Russia [9]Joint Institute for Nuclear Research JINR, Joliot-Curie 6, 141980 Dubna, Russia,

Up to 100 TeV, Imaging Air Cherenkov Telescopes (IACTs) have proven to be the instruments of choice for GeV/TeV gamma-ray astronomy due to their good reconstrucion quality and gamma-hadron separation power. However, sensitive observations at and above 100 TeV require very large effective areas, which the current and planned telescopes do not achieve (10 km^2 and more).
The alternative to IACTs are shower front sampling arrays (non-imaging technique or timing-arrays) with a large area and a wide field of view. Such experiments provide good core position, energy and angular resolution, but only poor gamma-hadron separation. Combining both experimental approaches, using the strengths of both techniques, could optimize the sensitivity to the highest energies.
The TAIGA project plans to combine the non-imaging HiSCORE array with small (~10m^2) imaging telescopes. This presentation covers the simulation results of this hybrid approach.

A hybrid system:

IACT: 2 or more telescopes with mirrors and multi-channel cameras

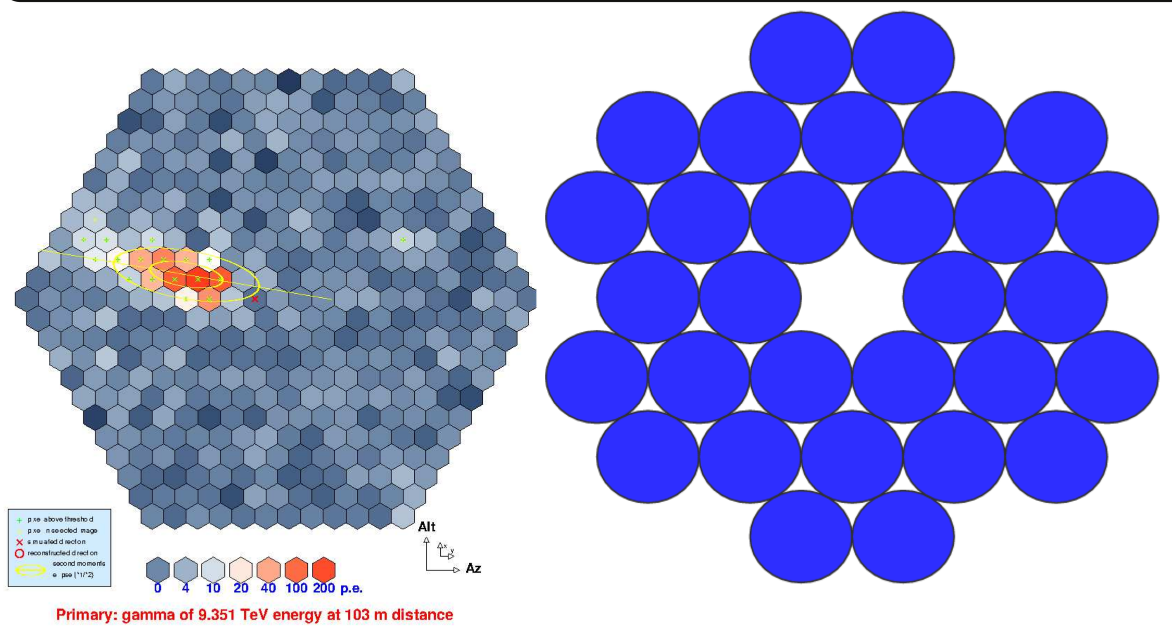
- Good gamma-hadron separation power
- Precise incident angle and core position reconstruction only in stereoscopic view
  - ➔ Spacing between telecopes must be small enough
- But: highest energies need huge effective areas
  - ➔ Too expensive with telescopes

Shower front sampling arrays: stations cheap

- Good reconstruction of core position and incident angle
- But: weak gamma-hadron-separation

Combination: core position and incident angle from array for reconstruction of telescope images (see figure top center)

- ➔ No need for stereoscopy
- ➔ Increase telescope spacing
- ➔ Get large effective areas as needed for highest energies with fewer telescopes, preserving gamma-hadron separation power



Left: sim_telarray generated camera image of a MC gamma shower with zenith angle 0°, 9.4 TeV energy and 103m distance from the telescope. Right: Schematic drawing of the TAIGA telescope mirror layout.

For evaluation of telescope design and gamma-hadron-separation: Monte-Carlo (MC) simulation

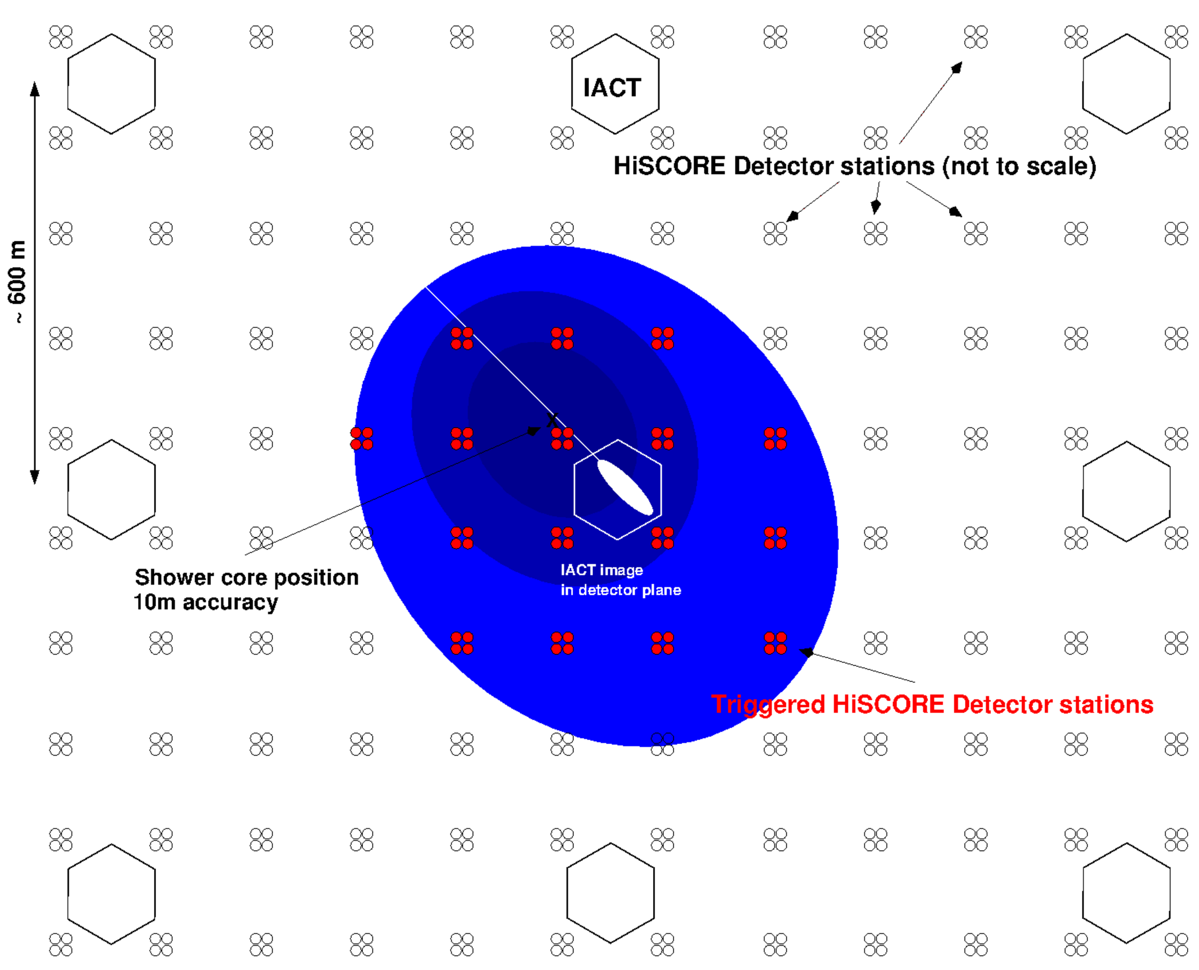
1. Air shower data generation with CORSIKA
   - Bernloehr package for generation of air shower Cherenkov light (IACT option)
   - Properties of primary (γ, p) : energy, zenith angle, number of showers
   - Detector layout: telescope/station position as input

2a. HiSCORE detector response simulation with sim_score [1]
   - Custom simulation software
   - Determine core resolution and angular resolution
   - Different array layouts and electronic systems implemented

2b. IACT response simulation with sim_telarray [2]
   - Details of telescope design:
     - Mirror dish configuration
     - Mirror details
     - Camera configuration
     - Camera details (PMT response, funnels etc.)
     - Electronic response
     - Mast and camera shadowing
   - Includes raytracing routine
   - With automatic reconstruction of MC images
   - Over 80 million events simulated, statistics rising

References:

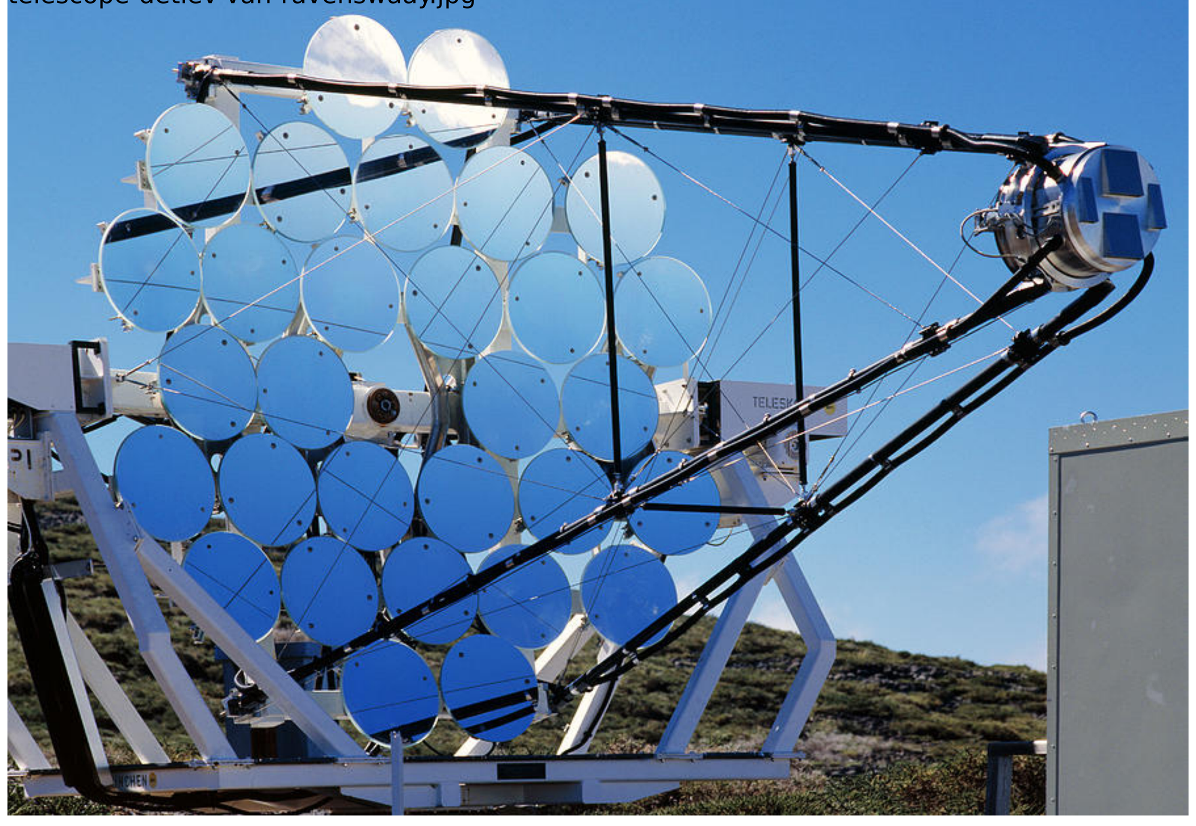
[1] Tjuczykont et al, 2014, *The HiSCORE concept for gamma-ray and cosmic-ray astrophysics beyond 10 TeV*, Astroparticle Physics, p.42-53, 10.1016/j.astropartphys.2014.03.004
[2] K. Bernlöhr, 2008, *Simulation of imaging atmospheric Cherenkov telescopes with CORSIKA and sim_telarray*, Astroparticle Physics, p. 149-158, 10.1016/j.astropartphys.2008.07.009
[3] Hampf, Tluczykont and Horns, 2012/13, *Event reconstruction techniques for the wide-angle air Cherenkov detector HiSCORE*, Nuclear Instruments and Methods in Physics Research A, p. 137-146, 10.1016/j.nima.2013.02.016
[4] Tluczykont et al., 2011, Advances in Space Research Vol. 48, 1935-1941S.
[5] Schliesser, A. and Mirzoyan, R., 2005, *Wide-field prime-focus imaging atmospheric Cherenkov telescopes: A systematic study*, X- and gamma-ray telescopes and instrumentation, Adaptive and segmented optics, p. 382-390,
[6] A. M. Hillas. 1985, *Cerenkov light images of EAS produced by primary gamma rays and by nuclei*. In F. C. Jones, editor, International Cosmic Ray Conference, volume 3 of International Cosmic Ray Conference, p. 445–448.



Principle behind the combined technique: A shower is seen by HiSCORE stations and IACTs simultaniously. The shower core position is reconstructed from the triggered HiSCORE stations and then used to scale the camera image, making stereoscopic view of the shower by IACT unneccessary.

TAIGA itself will be a combination of small IACT telescopes (in development) and the HiSCORE array (Hundred * i Square-km Cosmic Origin Explorer, currently in deployment at Tunka valley, Russia) [3][4]

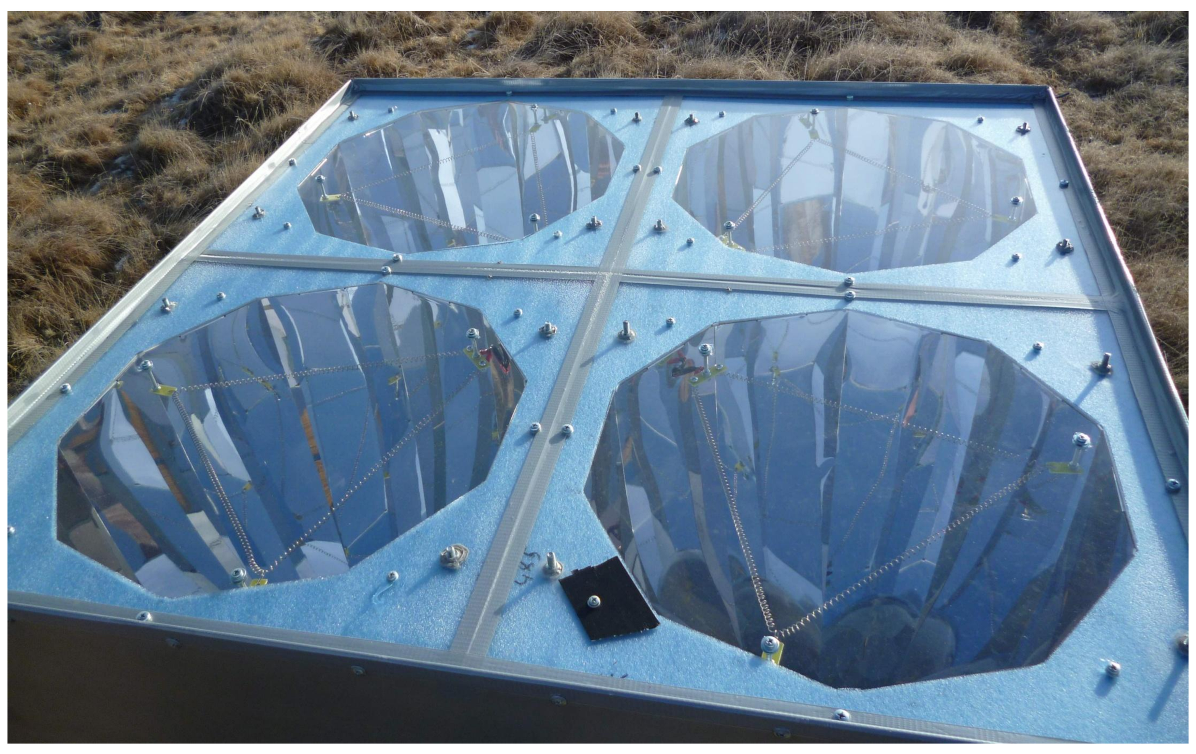
Image source: http://images.fineartamerica.com/images-medium-large/hegra-gamma-ray-telescope-detlev-van-ravenswaay.jpg



HEGRA reflector, similar to the intended TAIGA IACT design

IACT telescopes:

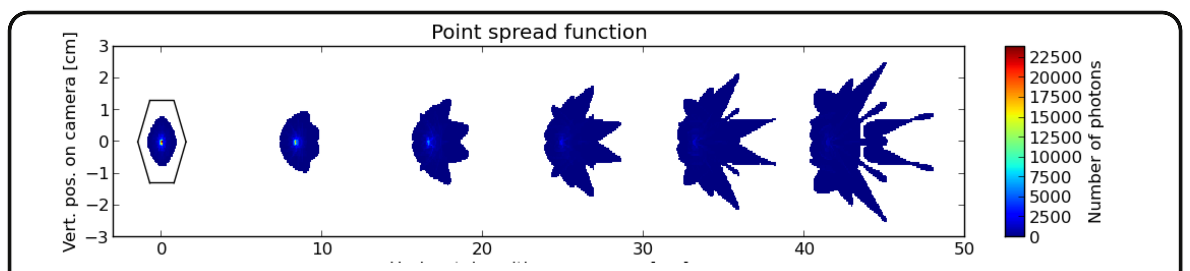
- Davies-Cotton configuration
- 4.3 m tesselated mirror dish
- Mirror segment diameter 60 cm
- 4.75 m focal length
- ~8° telescope Field of View (FoV)
- 397 camera pixels with ~0.38° FoV each
- 600 m spacing



A HiSCORE detector station (top view)

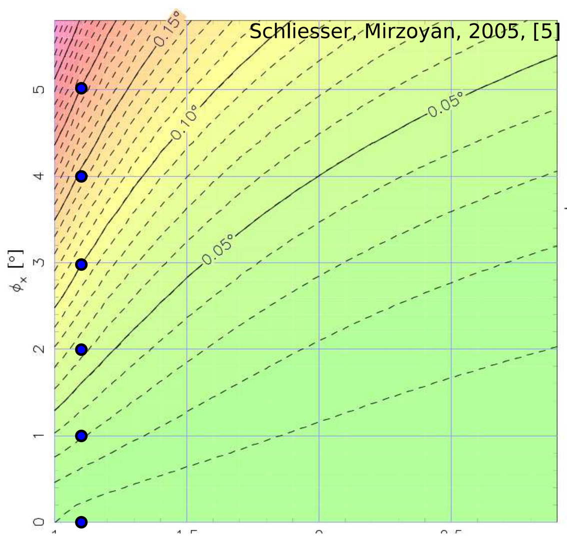
HiSCORE:

- Photomultiplier Tubes (PMTs) looking directly into the sky through Winston Cones
- One station: 4 PMTs
- ~120 m spacing
- Since 10/2013: 9 station array
- 25+9 station array planned for deployment 2014/2015
- Large array of the order of 10 km^2 envisaged



IACT Point Spread Function (PSF) for the zenith angles of 0 - 5°. Raw PSF without mirror misalignment options. The structures are an effect of the outermost mirror segments.

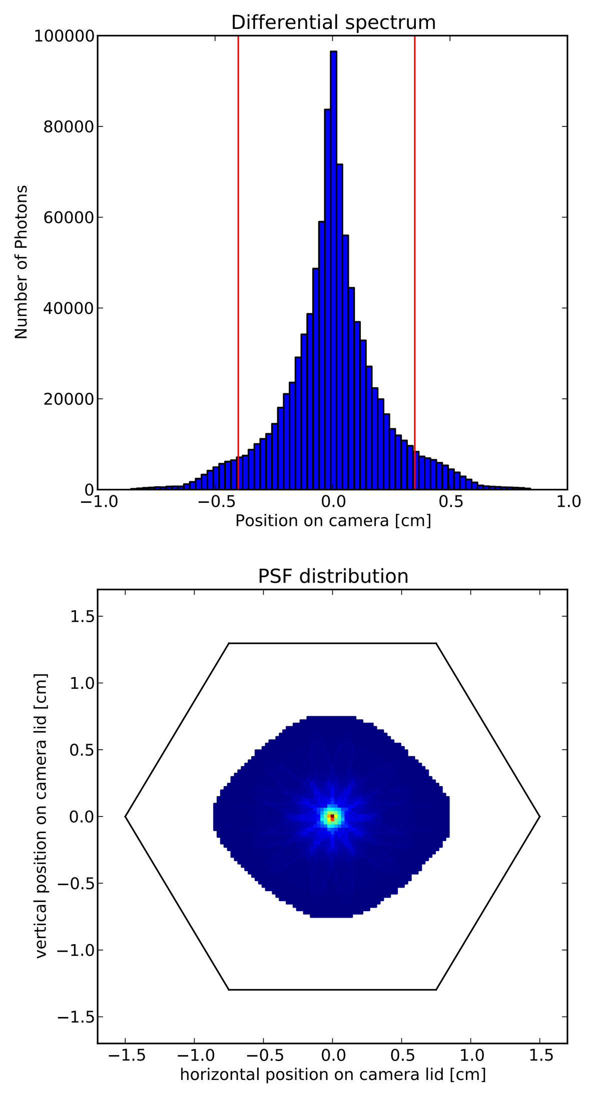
One MC simulation study is the **Point Spread Function (PSF)** of our telescope. A good PSF is essential for good image quality and thus for good reconstruction. With the high field of view (FoV) of about 8°, the abberation effects of the spherical mirror structure come into play, therefore its impact needs to be evaluated.

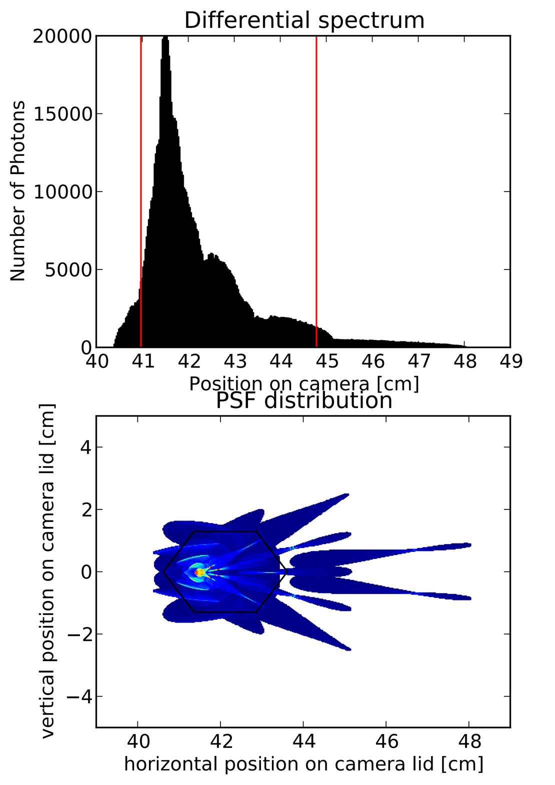


Comparison with expected values for the PSF for our F/D = ~1.1:

Offs.	Tangential PSF	Expected PSF
0°	0.027	0.01
1°	0.036	0.03
2°	0.056	0.07
3°	0.084	0.11
4°	0.116	0.15
5°	0.157	0.22

RMS value of the PSF in degrees





Left: IACT PSF for the zenith angle 0°. Right: PSF for camera offset of 5°. The black hexagon marks the edges of a camera pixel. The red lines show the radius in which 95% of all photons hit. The PSF is significantly smaller than a pixel.

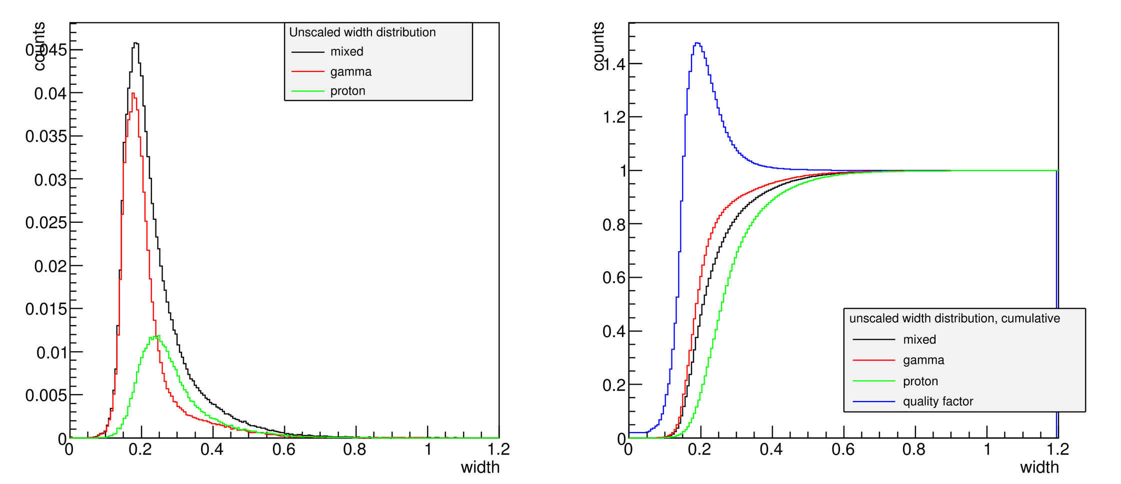
Gamma-hadron-separation via the mean scaled width (mscw):

Parameter used: width of camera image [6]

- Depending on: type of primary, incident angle, energy, core distance to telescope

Type of primary gives shape of distribution (see figure)

➔ Width cut possible for seperation



Left: Width distribution of simulated events with different primary particles for θ = 0°. Red: gammas, green: protons, black: total event distribution. Right: Cumulative width distribution. Red: gammas, green: protons, black: total distribution, Blue: quality factor Q.

Unscaled distribution's quality factor is not very good

➔ Rescaling to the expectancy value for gammas

For this, a lookup-table is generated:

- Mean width for gamma events calculated from MC
- Dimensions: core distance, zenith angle, image size

Then, each event's width is divided by the respective lookup-table entry

➔ Gamma and proton distribution peaks move apart

For first estimate on combined reconstruction quality:

- Randomize MC core position by HiSCORE core resolution
- Use randomized core position in width scaling (toy core)
- We expect an increase in quality from Q=~1.4 to Q=2-3

Conclusion and Outlook:

- Hybrid system combines timing arrays with IACT telescopes
- TAIGA is the first project to implement this design
- Telescope design concept gives an great imaging quality as seen on the PSF
- TAIGA will improve HiSCORE's gamma-hadron separation
- Next step: Toy core analysis
- Combinable with time development analysis, both for array and IACT

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Maike.Kunnas@gmail.com