Study of anomalous events in TUS detector and simulation of upward going EAS

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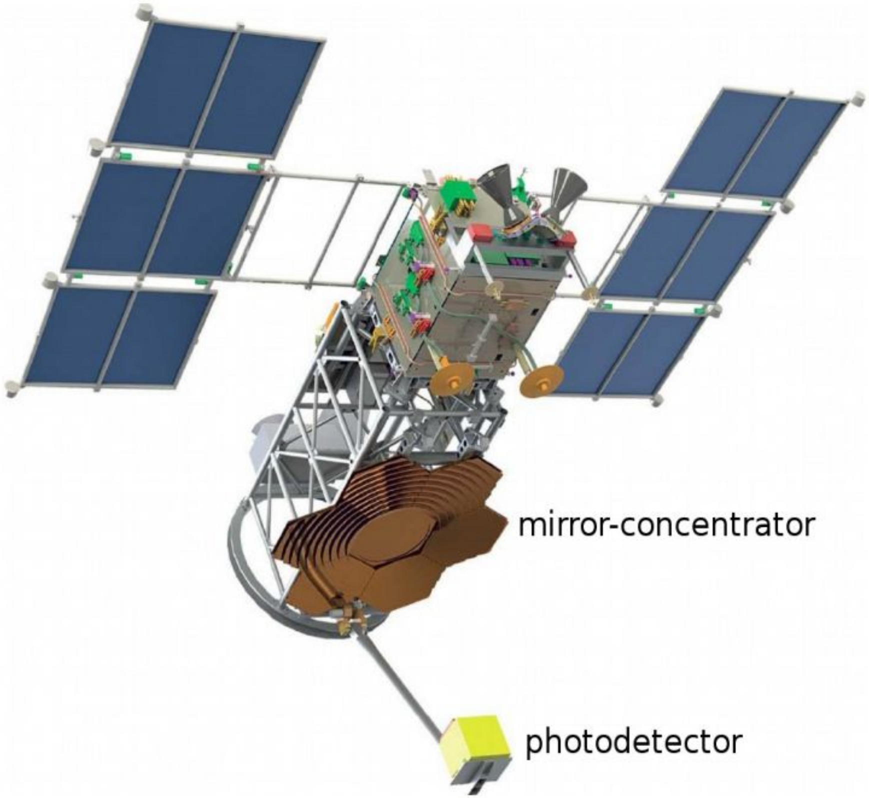
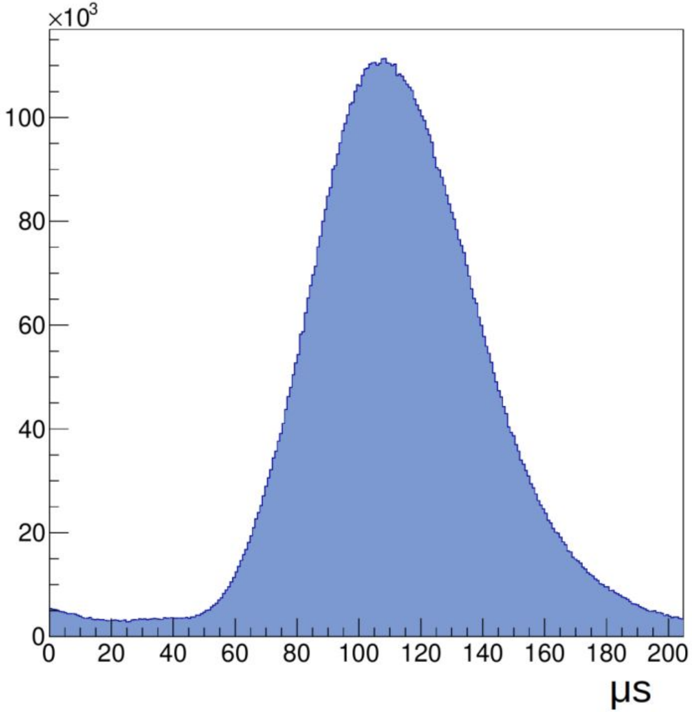
Schematic view of the tus detector

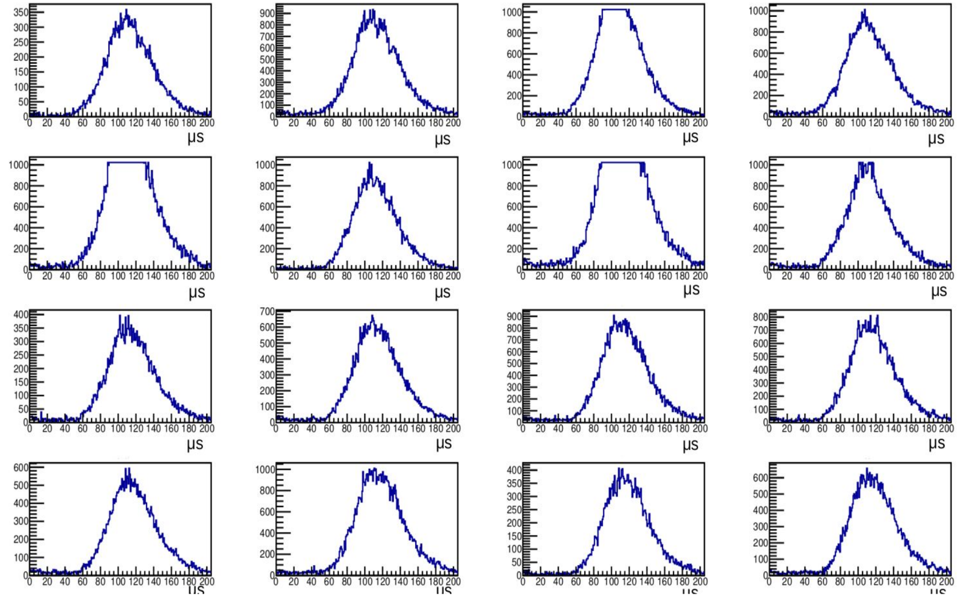


Mass	< 60 kg.
Power	65 W.
Data rate	200 Mbytes/day
Number of pixels	16x16 PMTs
FOV	±4,5 degree.
Duty cycle	30%
Altitude	500 km
Pixel:	10 mrad(5x5 km)
Mirror area	1,8 m^2.
Focal distance	1,5 m
Period	94 min

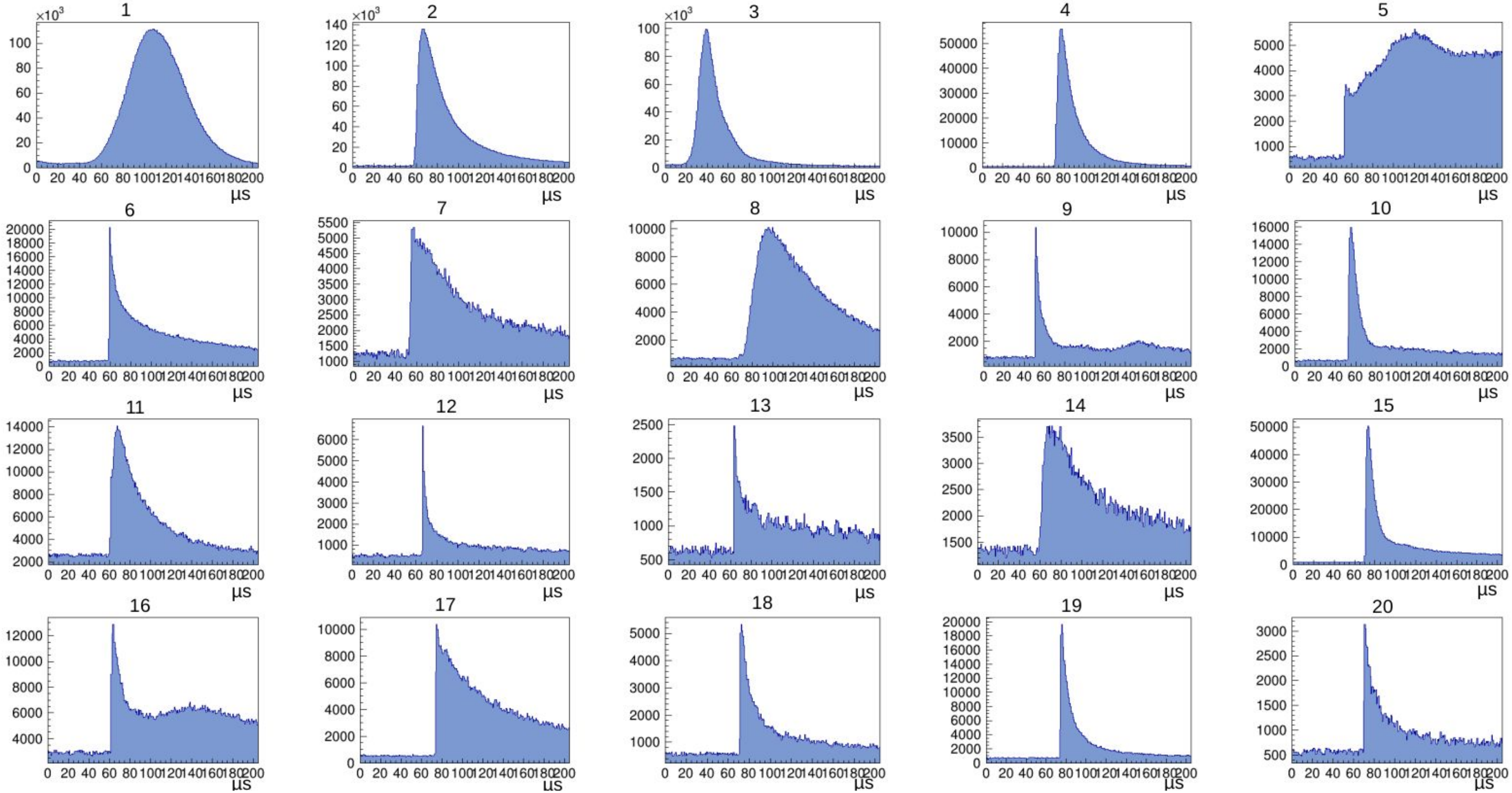
Anomalous events



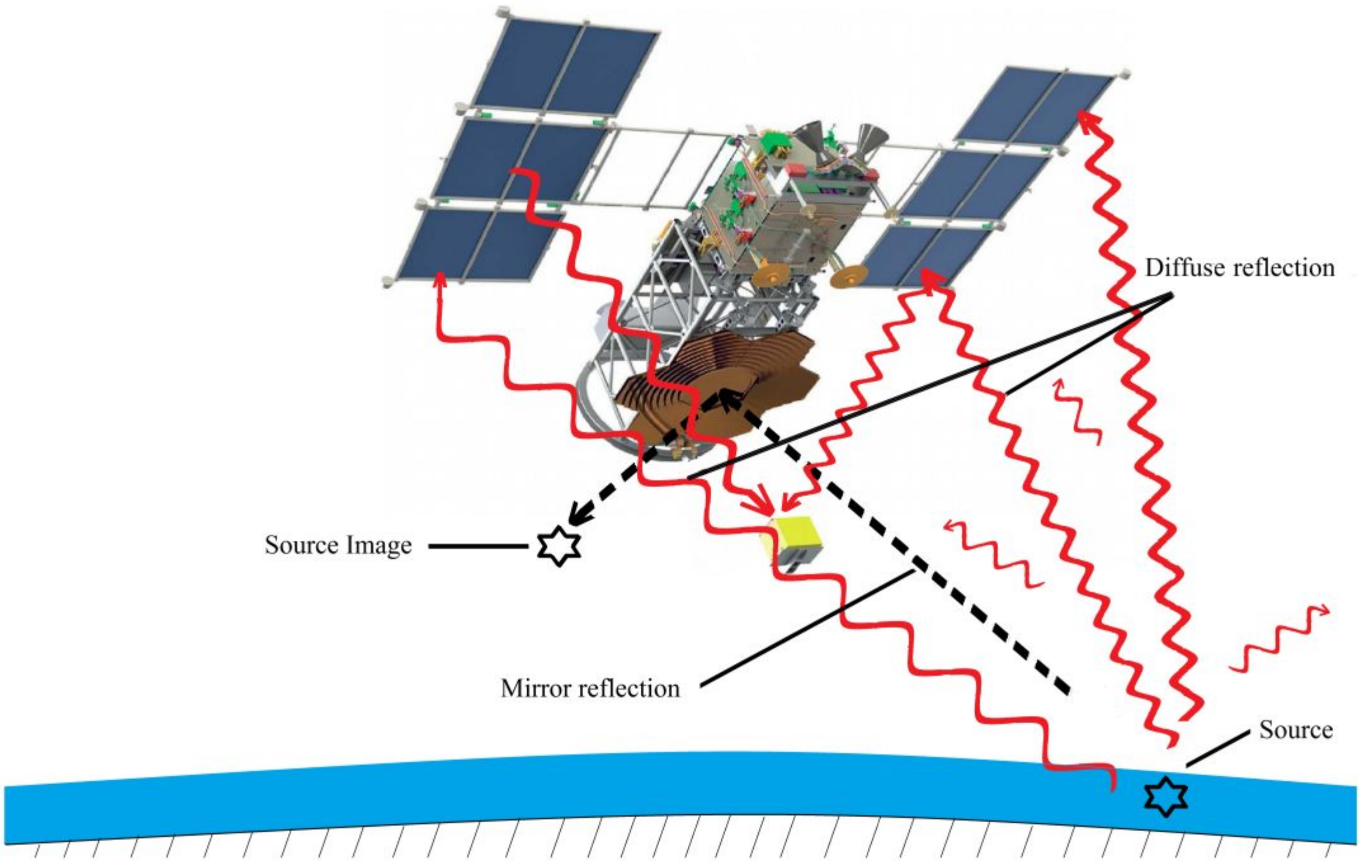
Integral histogram of the time dependence amplitude on time of event 170818-131536-072



Time dependencies of signal amplitudes in event 170818-131536-072 in separate PMTs of module 10.

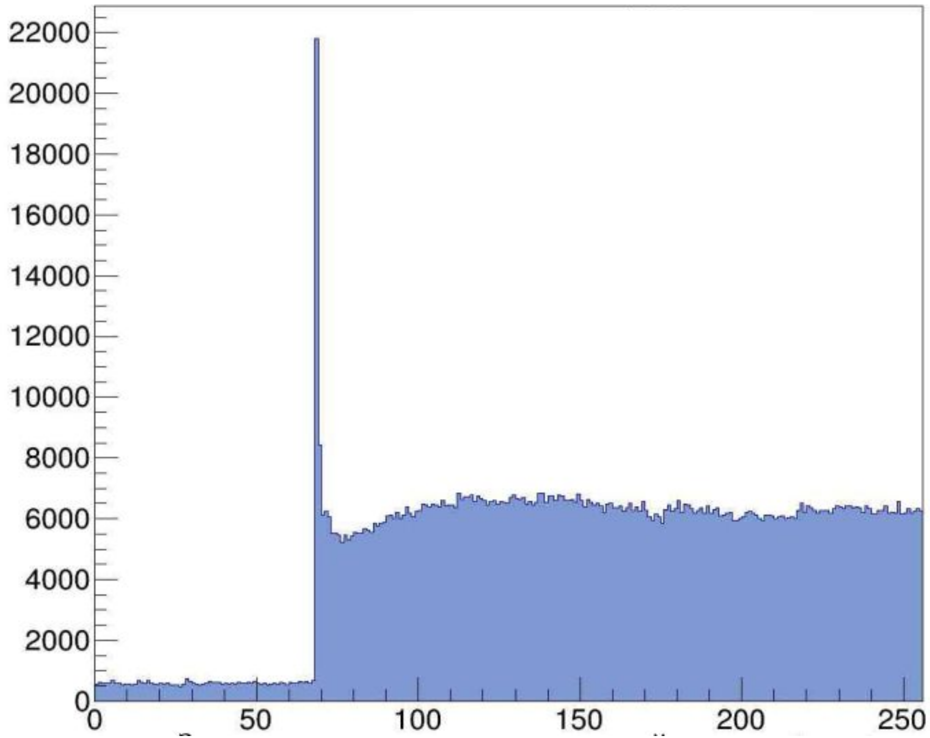


Examples of time dependencies of the integral amplitudes of anomalous events.

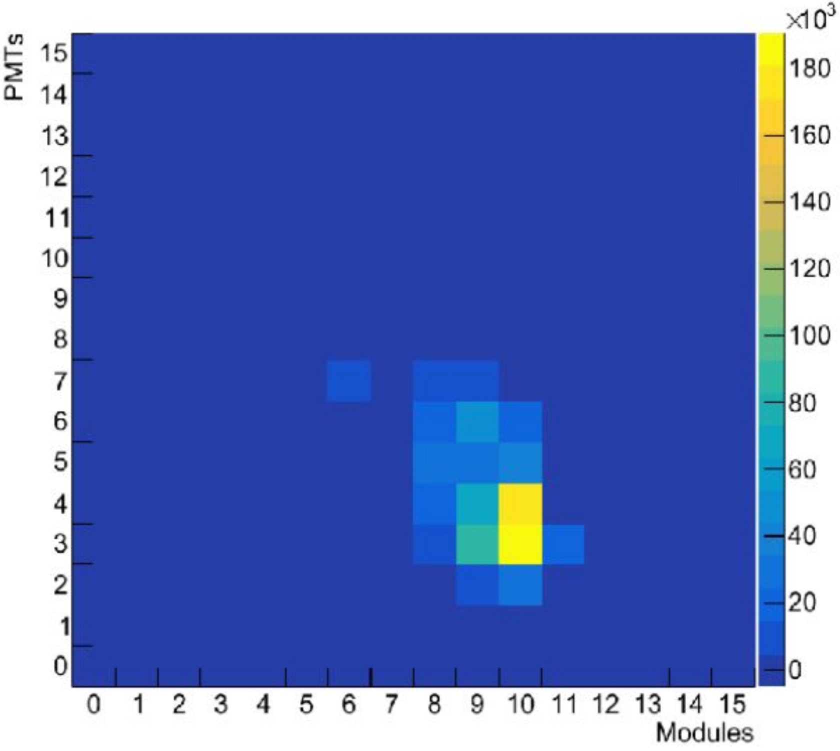


Schematic view of an anomalous
event in the TUS detector

Combined hybrid event 160905_230528-129



Time dependence of the integral signal amplitude

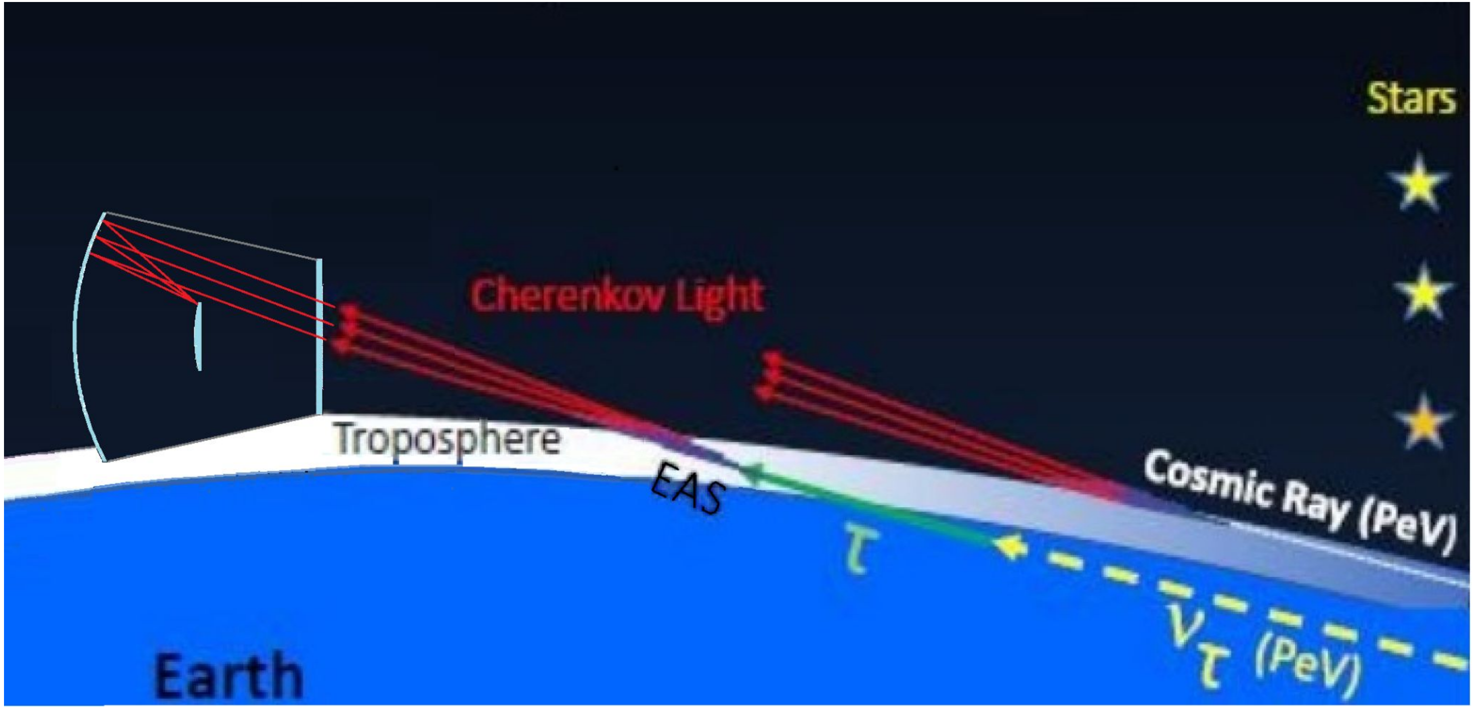


xy-projection of the integral amplitudes with a threshold of 3RMS

Possible interpretations

- Ultrashort gamma-ray bursts (GRB) ~100 μs
- Upward going EAS with diffuse reflection on solar panels. Correlation of EAS and lightning strike
- Terrestrial gamma ray flashes (TGFs)

Simulation of upward going EAS



Simulation of upward going EAS

Atmospheric depth [1] :

$$X(h) = \int_{h}^{\infty} p(l)dl = p_0 * H * exp\left(\frac{-h}{H}\right) \quad (2)$$

$$X(0) = 1030\ g/cm^2$$

Shower age [1]:

$$s(X) \simeq \frac{3}{\left(1 + 2 * \frac{X_{max}}{X}\right)} \qquad 0.0 < s < 2.0$$

$s < 1.0$ young shower

$s = 1.0$ shower at its maximum development

$s > 1.0$ old shower

Universality of electron distributions

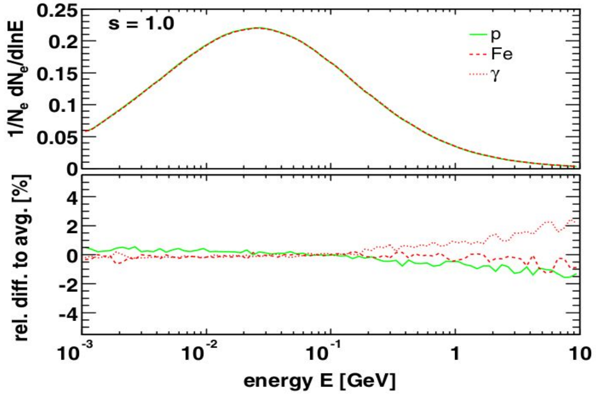
e’s energy distribution: $f_e(X,E) = \frac{1}{N_e(X)} \frac{dN_e}{dE}$

e’s energy spectra is independent of:
- primary particle type
- primary energy
- shower zenith angle (up to 60°)

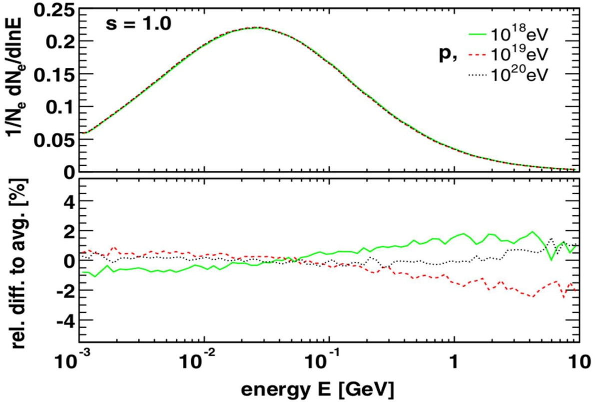
Parameterisation:

$$f_e(E,\ s) = a_0(s)\cdot\frac{1}{\left(E + a_1(s)\right)\left(E + a_2(s)\right)^s}$$

$$a_0(s),\ a_1(s),\ a_2(s)\ - \text{fitting parameters}$$



Universality of electron energy spectra — different primary particle type [2]



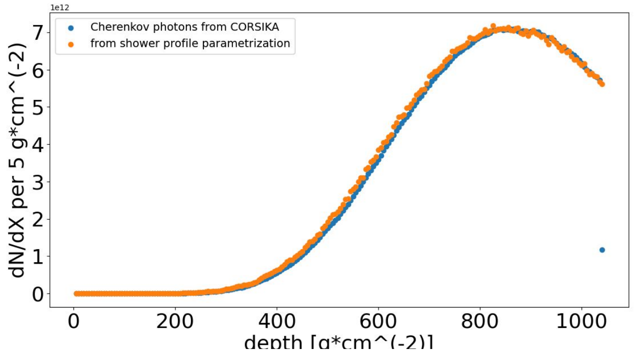
Universality of electron energy spectra — different primary energy [2]

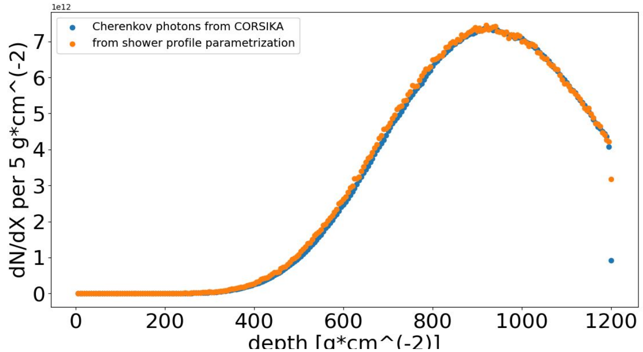
Calculation of Cherenkov light production

$$\frac{dN_\gamma}{dX}(X,h) = N(X) * \int_{E_{thr}(h)} y_\gamma(h,\ E) f_e(X,\ E) dE$$

$N(X)$ – **e**'s number at *X*

$y_\gamma(h,\ E)$ – number of Cherenkov photons produced by a **e** of total energy *E* at height *h*





Comparison of the total number of Cherenkov photons produced per slant depth within an individual shower (proton, 10^{19} eV, top figure 0°, bottom figure 30°) simulated with CORSIKA and analytically calculated by parameterisation

Angular spectrum of **e**'s and Cherenkov photons

e's angular spectrum is independent of:

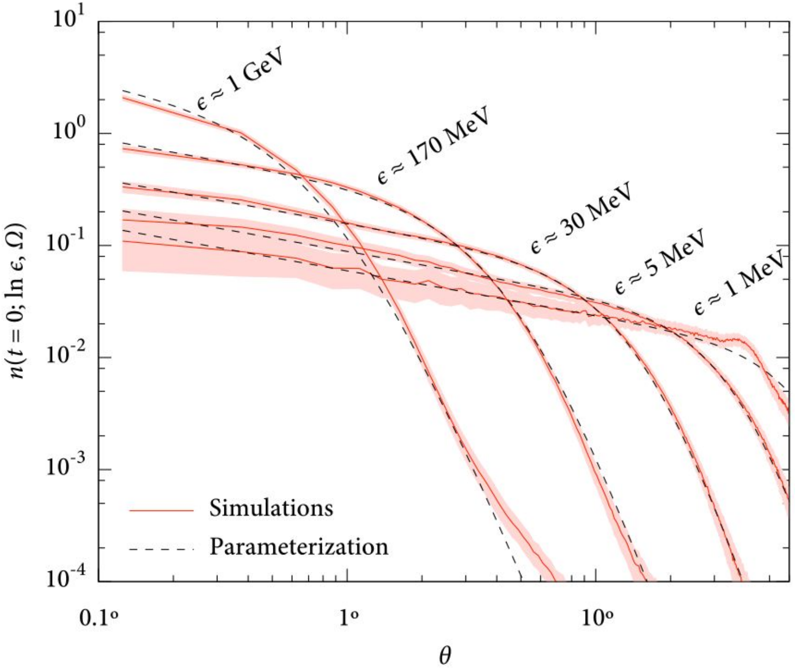
- Shower age
- primary energy
- shower zenith angle

The effect of primary particle type is small[3].

Parameterisation:

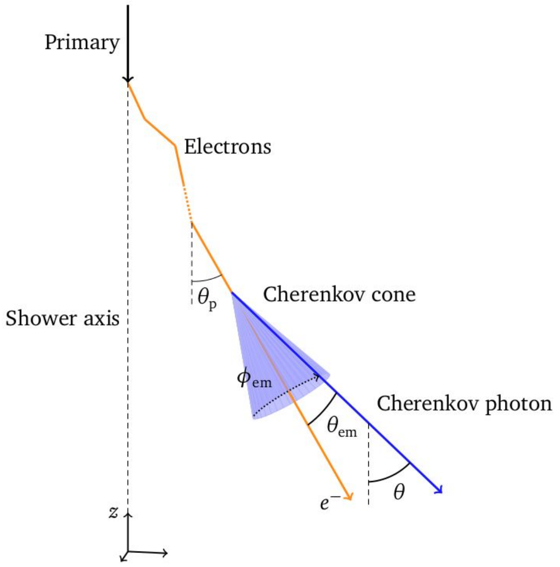
$$\frac{dN_e}{d\theta_p}(\theta_p, E) = C\left[\left(e^{b_1}\theta_p^{a_1}\right)^{-\frac{1}{\sigma}} + \left(e^{b_2}\theta_p^{a_2}\right)^{-\frac{1}{\sigma}}\right]^{-\sigma}$$

First term describes the flatter portion of the angular distribution parallel to the shower axis and the second represents the steep drop. The value of **σ** determines the smoothness of the transition from the flat region to the steep region.[3]

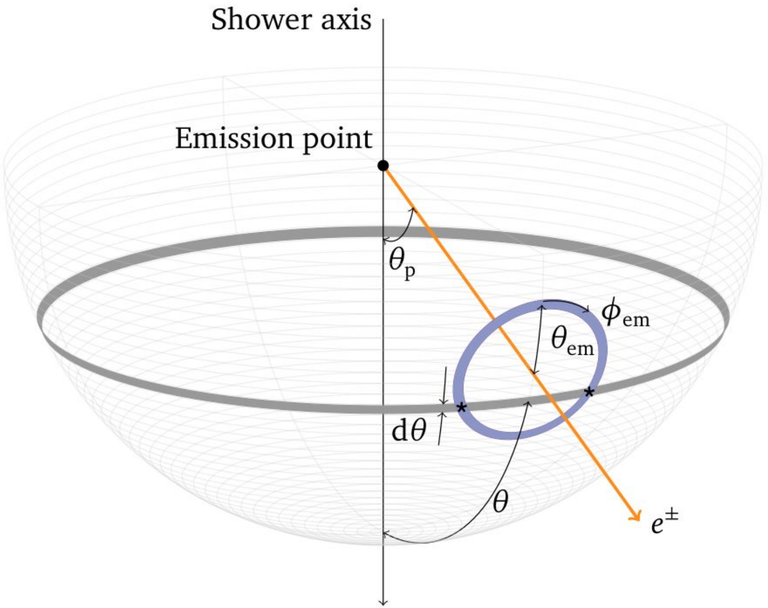


Normalised average electron angular distributions for 20 proton showers at 10^{18} eV with 3σ statistical error margins.

Angular spectrum of **e**’s and Cherenkov photons



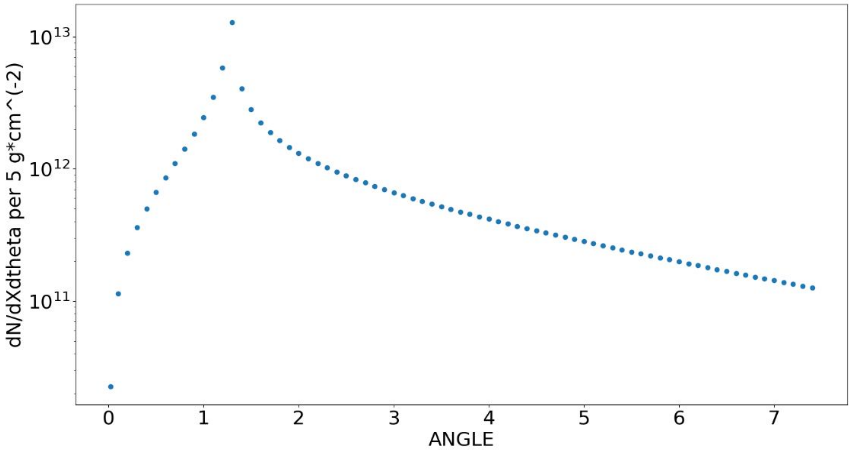
Relevant angles for Cherenkov light emission in air showers. The final angle between each Cherenkov photon (blue trajectory) and the shower axis is denoted by θ [4].

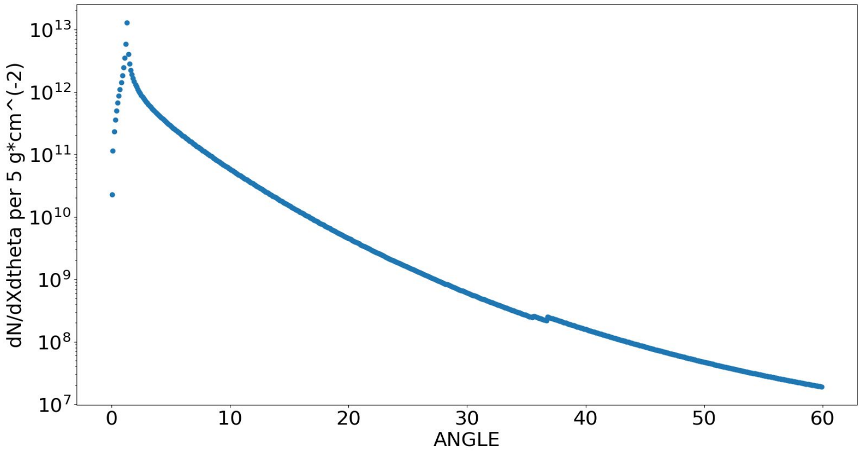


Depiction of the intersecting region between the Cherenkov cone (blue ring) and the ring of width dθ around the angle θ (grey ring) in the unit sphere. There are two intersection points whenever |θ − θp | < θem and none otherwise [4].

$$\frac{d^2N_\gamma}{d\theta dX}(\theta,\ X,\ h) = \frac{1}{\pi}N(X)sin(\theta)\int_{E_{thr}(h)}^{\infty} f_e(X,E)y_\gamma(h,E)dE\ \times \int_{|\theta-\theta_{em}|}^{\theta+\theta_{em}} \frac{dN_e}{d\theta_p}(\theta_p, E)\frac{d\theta_p}{cos\theta_p\sqrt{sin^2(\theta_p)sin^2(\theta_{em}) - (\mathrm{coscos}\,(\theta_p)\ \mathrm{coscos}\,(\theta_{em}) - \mathrm{coscos}\,(\theta))^2}}$$

Angular spectrum of **e**'s and Cherenkov photons

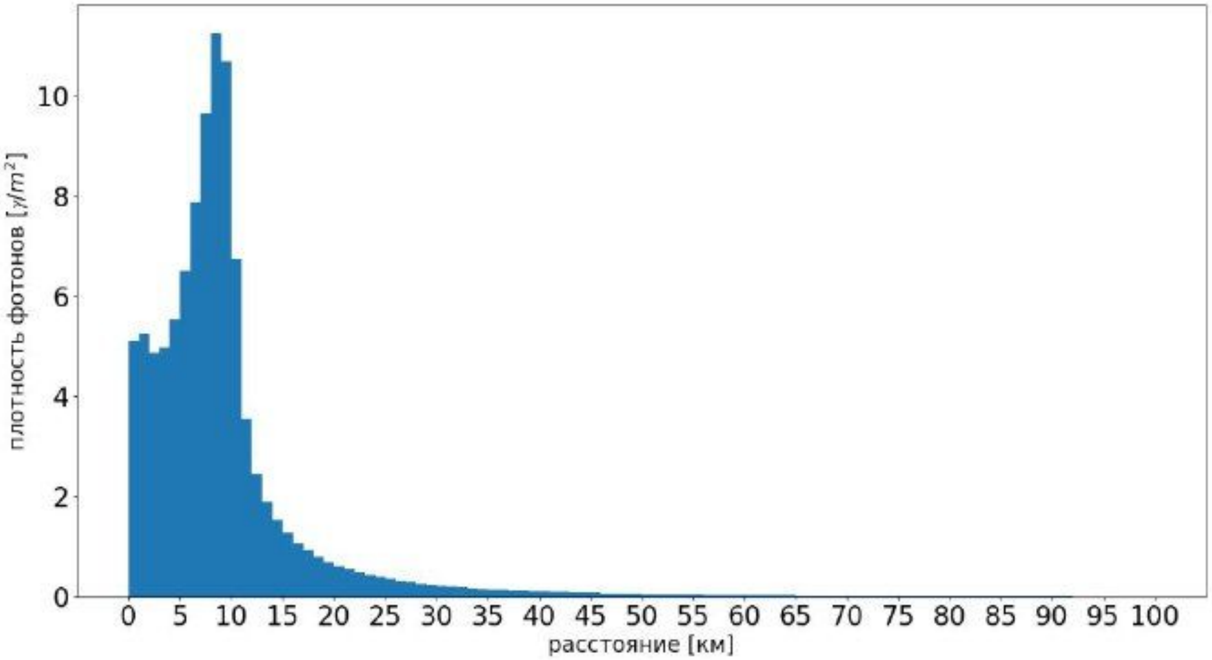




Cherenkov photons angular distribution at small angles for proton shower of 10^{19} eV at s = 1

Cherenkov photons angular distribution angles for proton shower of 10^{19} eV at s = 1

Result



The spatial profile of the Cherenkov signal (photons/m2) at 500 km altitude for a 100 TeV upward EAS

Conclusion

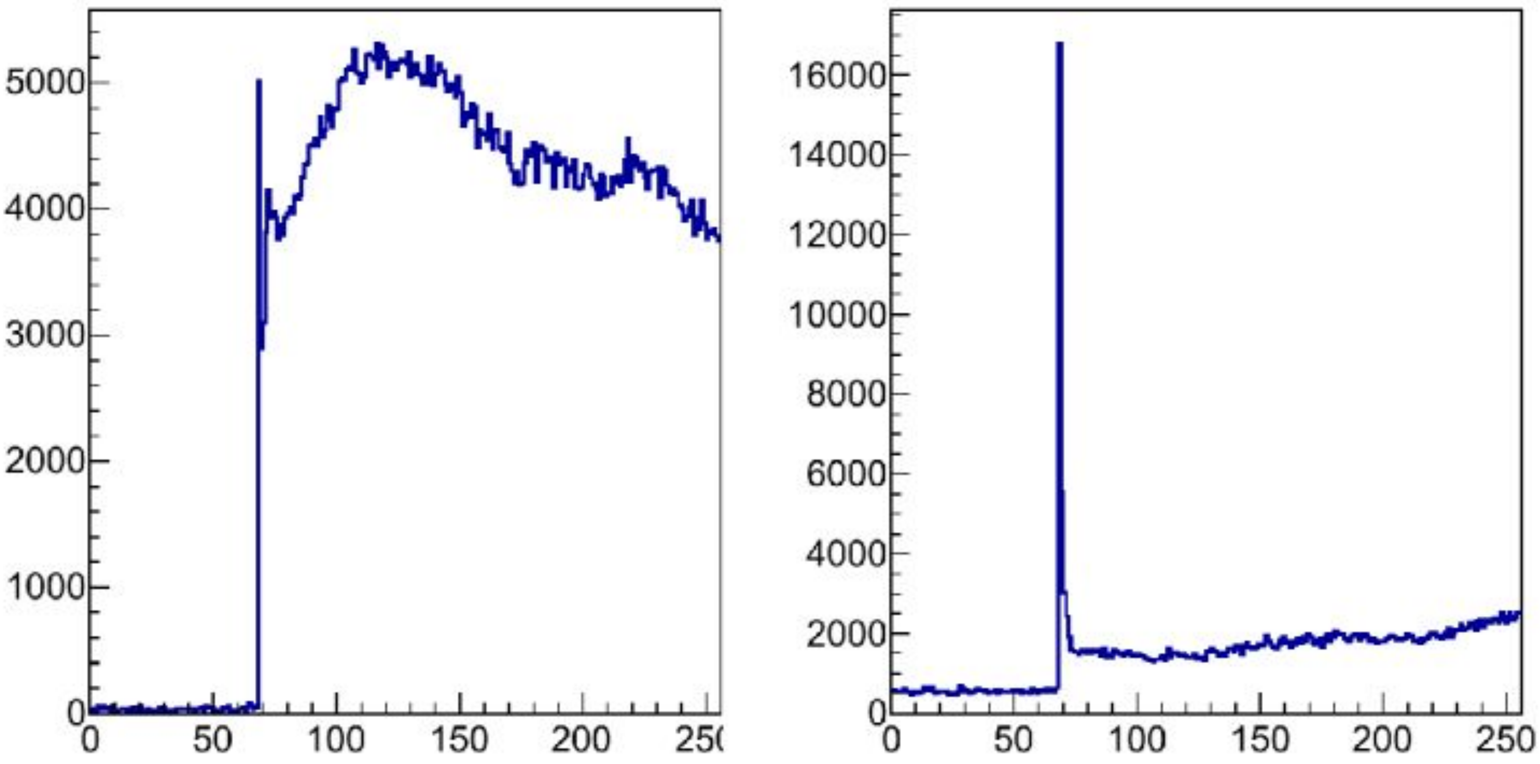
About 40 anomalous events were found by TUS detector. One of the possible interpretations was upward going EAS. In this work analytical method of simulating upward going EAS was studied. It was shown that signal from highest possible energy upward going EAS is not enough to be the cause of TUS anomalous events.

The method will be used for simulation of upward and horizontal EAS for the IVGSHAL experiment.

Thank you for your attention!

References

1. Peter K.F. Grieder, Extensive Air Showers Volume I
2. F. Nerling, Description of Cherenkov Light Production in Extensive Air Showers, Ph.D. thesis, Report FZKA 7105, Forschungszentrum Karlsruhe, Germany, 2005.
3. S. Lafebre, R. Engel, H. Falcke, J. Horandel, T. Huege, J. Kuijpers, R. Ulrich, Universality of electron-positron distributions in extensive air showers, Astropart. Phys. 31 (2009) 243–254, doi:10.1016/j.astropartphys.2009.02.002.
4. Arbeletche, L.B., de Souza, V. Parametrization of the angular distribution of Cherenkov light in air showers. Eur. Phys. J. C 81, 195 (2021). https://doi.org/10.1140/epjc/s10052-021-08971-7

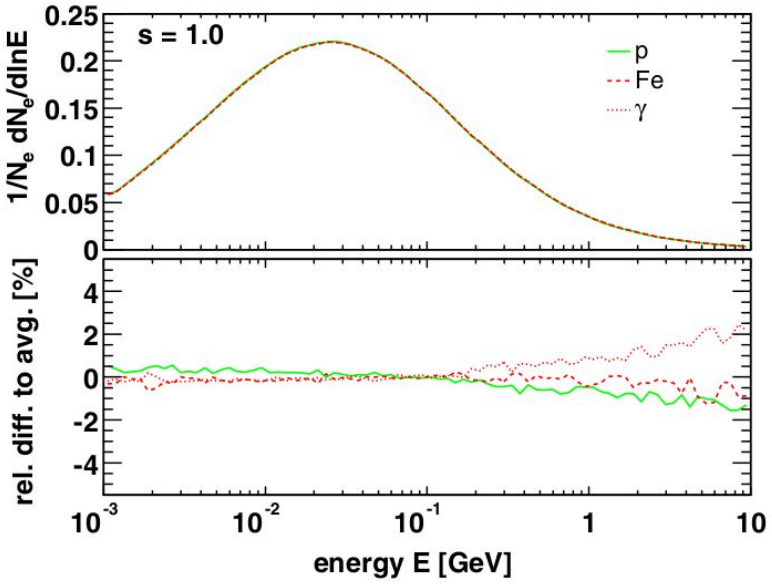


Time dependence of integral signal amplitudes in event 160905_230528-129.
On the left is an area of 18 pixels inside the border, on the right is an area of 190 pixels outside the border.

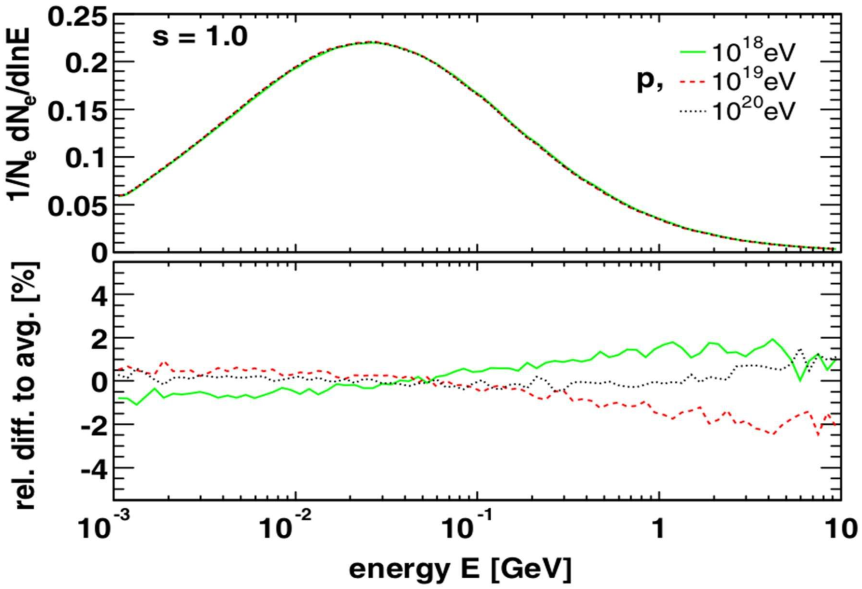
normalization:

$$\int_{E_{cut}} f_e(X,E)\,dE = 1$$

Universality of electron distributions



Universality of electron energy spectra — different primary particle type. Mean proton, iron and gamma-ray showers of energies > 10^{17} eV (each curve represents the mean distribution averaged over 10^{18}, 10^{19}, and 10^{20} eV) [2]

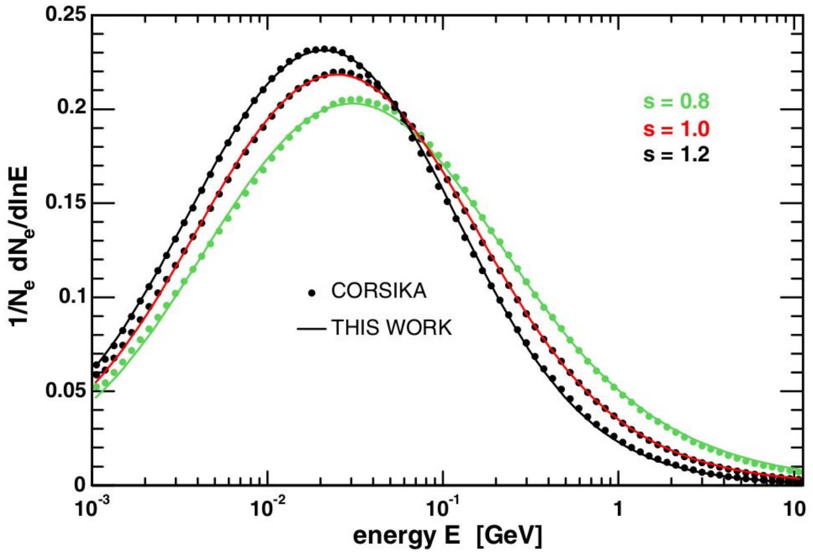


Universality of electron energy spectra — different primary energy. Mean showers of 10^{18}, 10^{19} and 10^{20} eV [2]

Parameterisation of e's energy spectrum

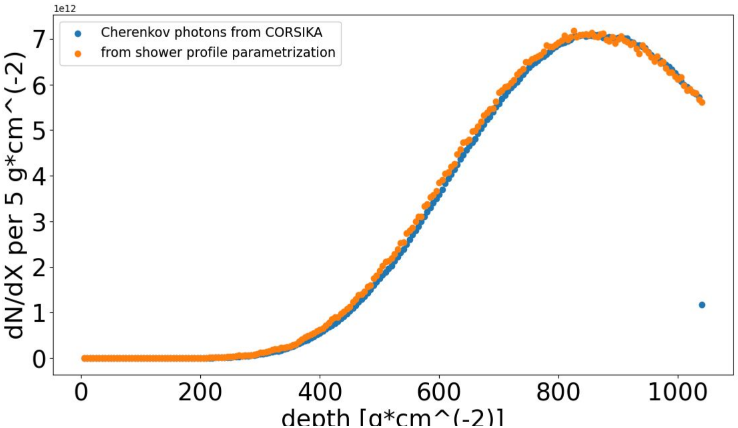
$$f_e(E,\ s) = a_0(s)\cdot\frac{1}{\left(E + a_1(s)\right)\left(E + a_2(s)\right)^s}$$

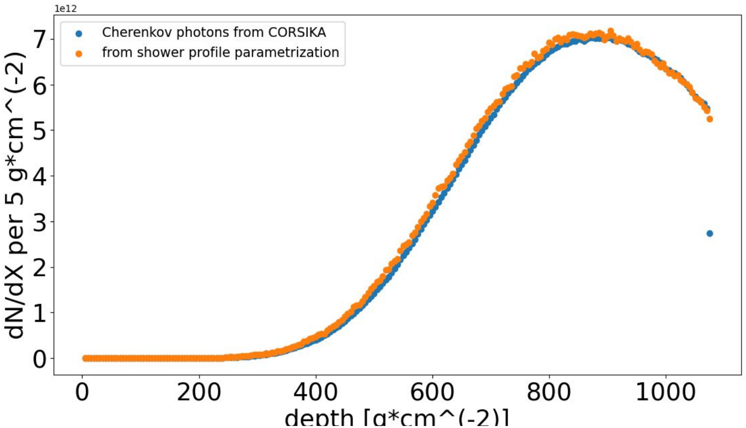
$a_0(s),\ a_1(s),\ a_2(s)$ − fitting parameters



Comparison of the parameterisation and the energy spectrum of an individual shower obtained with CORSIKA, proton, 10^{19} eV [2]

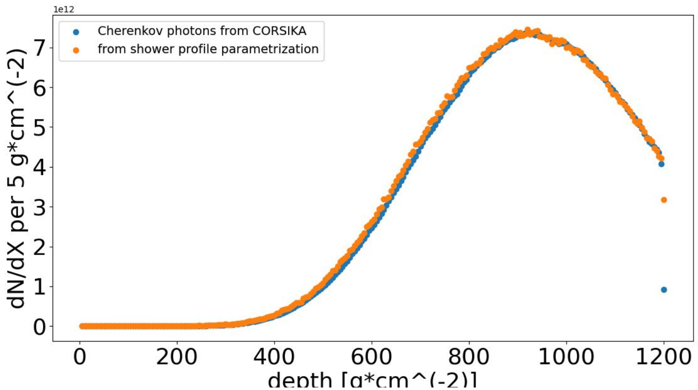
Calculation of Cherenkov light production

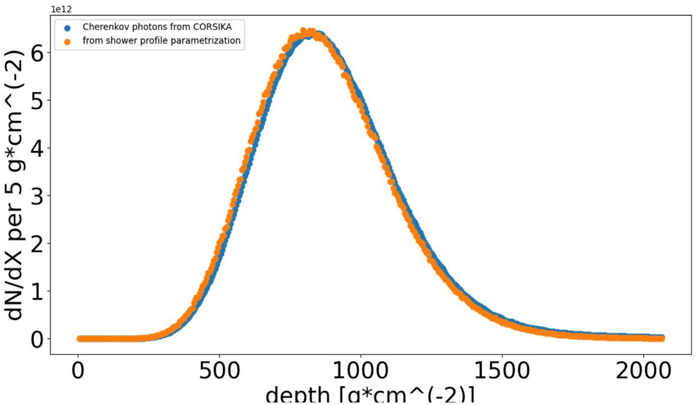




Comparison of the total number of Cherenkov photons produced per slant depth within an individual shower (proton, 10^{19} eV, left figure 0°, right figure 15°) simulated with CORSIKA and analytically calculated by parameterisation

Calculation of Cherenkov light production





Comparison of the total number of Cherenkov photons produced per slant depth within an individual shower (proton, 10^{19} eV, left figure 30°, right figure 60°) simulated with CORSIKA and analytically calculated by parameterisation

Angular spectrum of **e**'s and Cherenkov photons

Expressing θ in terms of θ_p, θ_{em} and ϕ_{em}:

$$cos(\theta) = cos(\theta_p)cos(\theta_{em}) - sin(\theta_p)sin(\theta_{em})cos(\phi_{em})$$

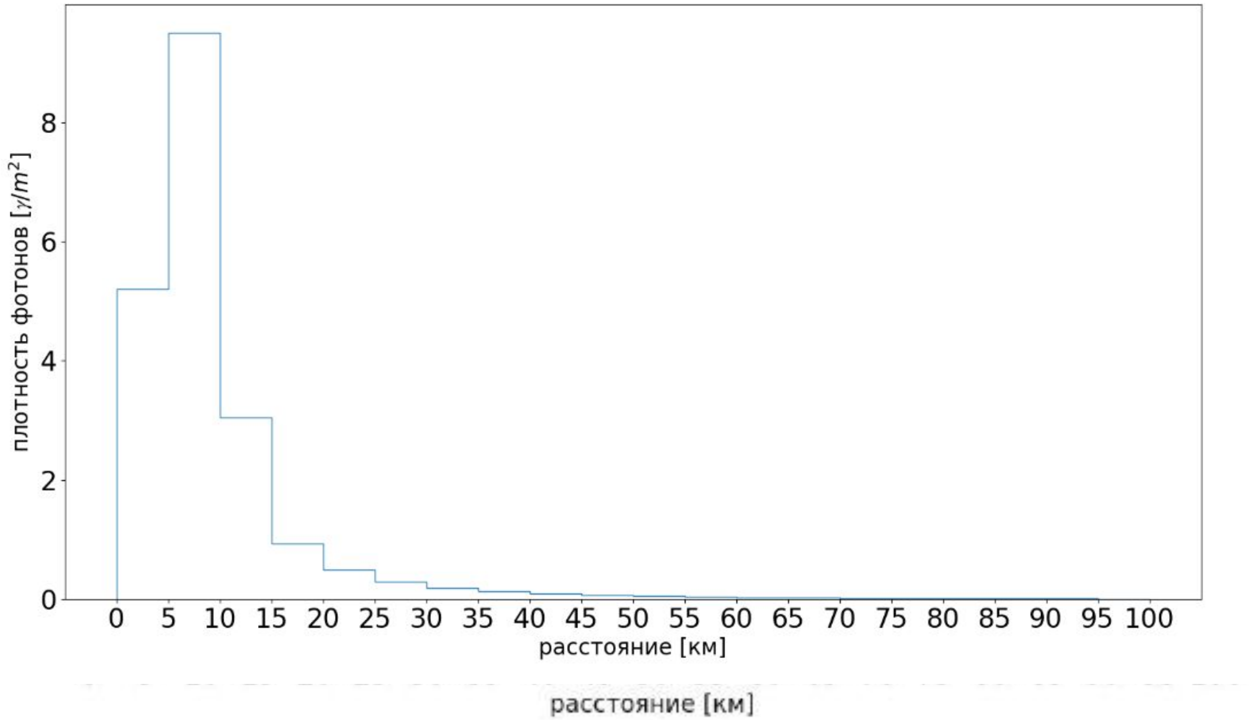
$$dN_\gamma = N(X)f_e(X, E)dE\frac{dN_e}{d\theta_p}(\theta_p, E)d\theta_p y_\gamma(h, E)sec(\theta_p)dX\frac{d\phi_{em}}{2\pi}$$

$$d\phi_{em} = 2\left|\frac{d\phi_{em}}{d\theta}\right|d\theta = \frac{2sin(\theta)d\theta}{\sqrt{sin^2(\theta_p)sin^2(\theta_{em}) - \left(cos(\theta_p)cos(\theta_{em}) - cos(\theta)\right)^2}}$$

Angular spectrum of **e**'s and Cherenkov photons

$$\frac{d^2N_\gamma}{d\theta dX}(\theta, X, h) = \frac{1}{\pi}N(X)sin(\theta)\int_{E_{thr}(h)}^{\infty} f_e(X,E)y_\gamma(h,E)dE$$

$$\times \int_{|\theta-\theta_{em}|}^{\theta+\theta_{em}} \frac{dN_e}{d\theta_p}\left(\theta_p, E\right)\frac{d\theta_p}{cos\theta_p\sqrt{sin^2\left(\theta_p\right)sin^2\left(\theta_{em}\right)-\left(cos\left(\theta_p\right)cos\left(\theta_{em}\right)-cos(\theta)\right)^2}}$$


плотность фотонов [γ/m²]
0
2
4
6
8
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
расстояние [км]
расстояние [км]