Possibilities of unbiased estimation of EAS primary particle characteristics with *PAMIR-XXI* complex setup

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'Pamir-XXI'
Complex Setup Project

for Multi-Component Study of Superhigh Energy EAS and Parental PCRs in a wide energy range around and above the "knee"

within *'Pamir-Chacaltaya'* ISRC

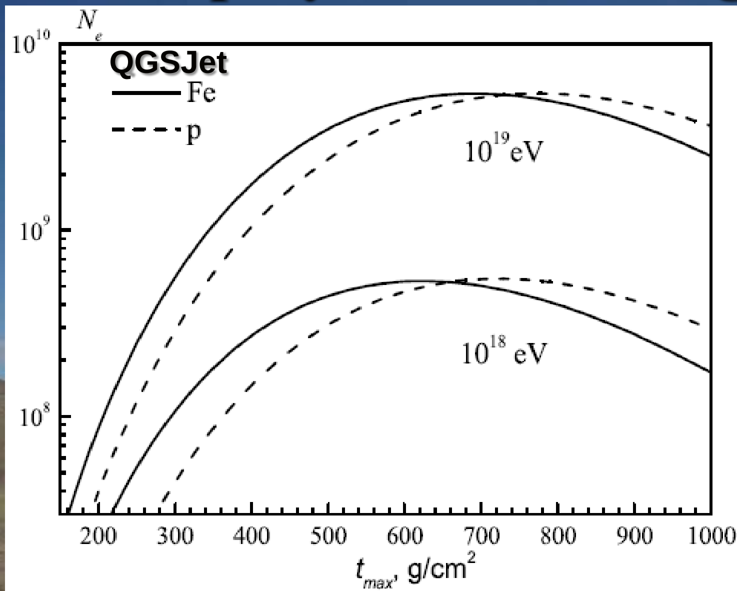
$E_0 = 30 \div 10^6$ TeV

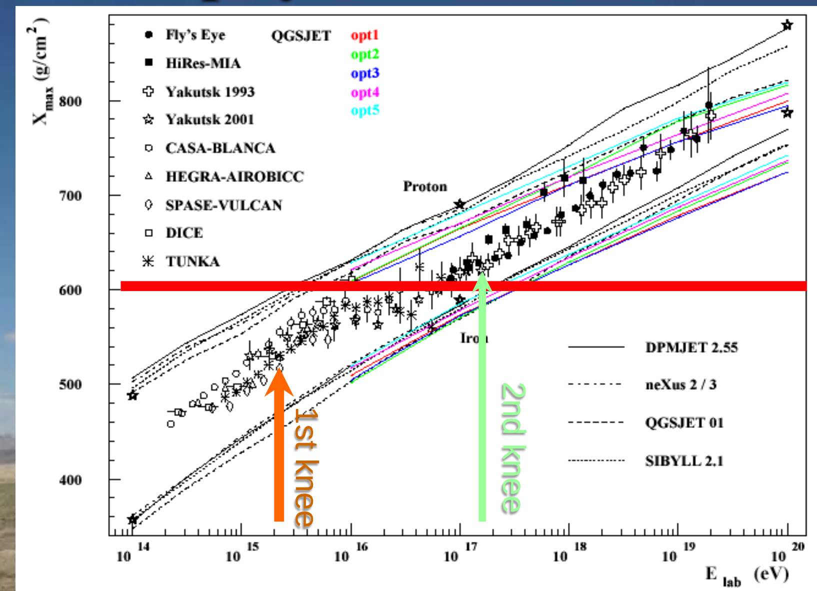
Observational altitude – 4260 m a.s.l. (606 g/cm^2)

Location – Eastern Pamirs

Potential of the Eastern Pamirs

for deployment of a large-scale astrophysical installation





- accessibility of vast high-altitude valleys suitable for deployment of a new large-scale setup of S≥1 кm^2 in area at altitude of H~600 g/cm^2 corresponding to the maximum of EAS development at the 'knee' energy, where EAS size fluctuations are minimal and hence the PCR energy estimations are the most accurate;

  due to high observation altitude, the showers are detected at earlier stages of their development that results in higher densities of charged particles and higher energies of hadrons in the shower cores,

  and besides the optical detectors are closer to the ĈL source that enables experimentalists to distinguish finer details of the event;

Potential of the Eastern Pamirs

for deployment of a large-scale astrophysical installation

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- unique astroclimate of the Eastern Pamirs, characterized by a large number (~300) of clear (cloudless) nights a year, fairly evenly distributed over the seasons, a low content of aerosols and water vapor in the atmosphere, a weak turbulence of surface air, and besides, almost complete absence of light pollution, i.e. illumination of the night sky by artificial light sources;

Main goals and physics problems of *'Pamir-XXI'* experiment

Pamir-XXI project mainly aims at:

- detailed and elementwise study of the PCR energy spectra and composition in a wide range of primary energies ***E_0=30÷10^6 TeV*** partially overlapping that of direct observations and also containing the 'knee' at E_0 ~ 3÷4 PeV and other spectrum peculiarities beyond it;
- EAS multi-component study (including e-m, Čerenkov, low&high energy muon and hadronic components) at the depth of ***H=600 g/cm^2*** in the atmosphere (which corresponds to the maximum of EAS development at the 'knee' energy where accuracy of energy E_0 determination with N_e is the highest) in order to fix the hadronic interaction model;
- simultaneous study of lateral and longitudinal EAS development, which is especially sensitive to the PCR mass composition, by means of a Čerenkov detector array, a system of Čerenkov image telescopes and a muon tracker;

Main goals and physics problems of *'Pamir-XXI'* experiment

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- a detailed study of EAS cores and their fine structure in order to clarify characteristics of hadronic interactions in a kinematic fragmentaion region of an incident particle and in processes with small transverse momenta transferred ('forward physics');
- detection of γ-rays with energies above 30 TeV from point-like & extended sources as well as diffuse ones; localization of Galactic γ-sources within the entire northern hemisphere of the sky with a sensitivity of ~3-4% I_{CRAB} in a year for their further detailed study at setups such as CTA or AGIS.

To achieve the goals, a complex detector array requires the inclusion of multiple detectors of different types.

Major components and parameters of the *Pamir-XXI* setup

- a deep (~3,5 λ_{int}) lead-carbon calorimeter with total area of 192 m^2 combined with the XREC and burst detector made in the form of solid crosswise lying series of plastic scintillation counters with fiber optic readout (center part);
- two concentric shower arrays around the calorimeter: a dense one with 5 m step of 80 x 80 m^2 in area and with a high detection threshold, and another more rare array with 85 m spacing of 1 x 1 km^2 in area and with low detection threshold;
- array of wide angle Čerenkov detectors spaced throughout the area of ~1 $км^2$ to determine the EAS ČL lateral distribution dQ/dR as well as characteristics of the EAS ČL pulse shape, i.e., time distribution dQ/dT and d2Q/dRdT; a step in the central part of the array is 25 m, at the periphery - 85 m (a fast ČD will be either similar to EMI 9350 photomultipliers with a hemispherical photocathode of 20cm in diameter or will be consist of a 19 PMT matrix placed in the focal plane of a mirror of 1-1.2 m in diameter);
- a fast timing system ('chronotron') of 8 scintillation points to determine the EAS arrival angles by front arrival delay at different points of the air shower array;
- four wide-angle (with field of view at least 30° and pixel size of PMT mosaic 0,6-0,8°) Image Čerenkov Telescopes (IACT) to determine the ČL spatial-angular distribution $d^3Q/dRd\theta_x d\theta_y$ for individual EAS;
- a muon tracker of 400 m^2 in area with angular resolution of 0.1-0.2° for determination of ČL angular distribution;
- lidar for monitoring the quality of a night atmosphere.

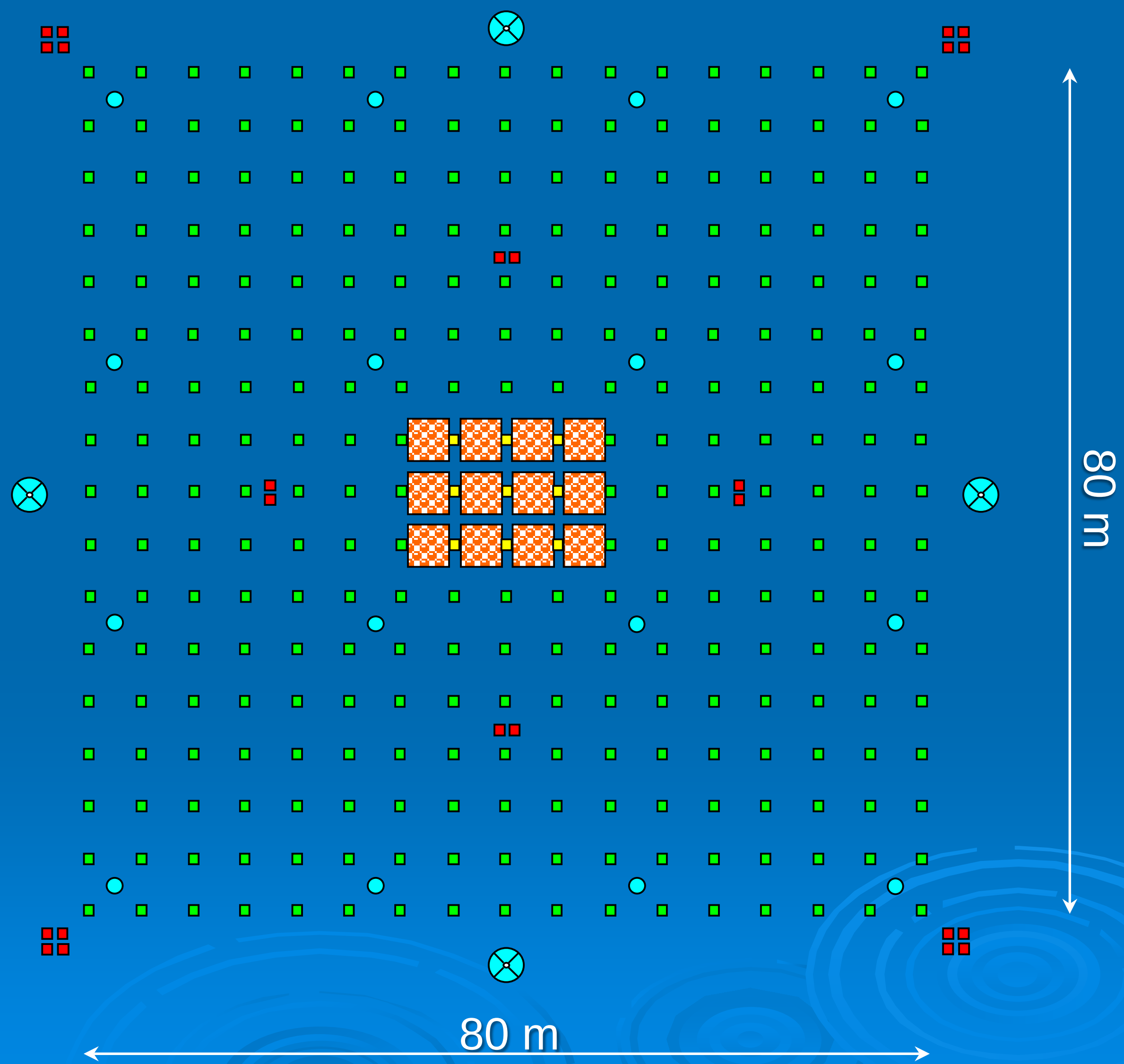
Layout of detectors in *PAMIR-XXI* complex setup

Central part of the shower array.

- combined detector ($e/\gamma + \mu$) with 0.5 cm Pb at the top, $S = 1\ m^2$, $N_{c.d.} = 280$
- sc-counter (e/γ), $S = 1\ m^2$, $N = 9$
- calorimeter section $S = 16\ m^2$, $N = 12$
- fast-timing detector ('chronotron' system)
- Čerenkov light detector
- Image Čerenkov telescope (IACT)

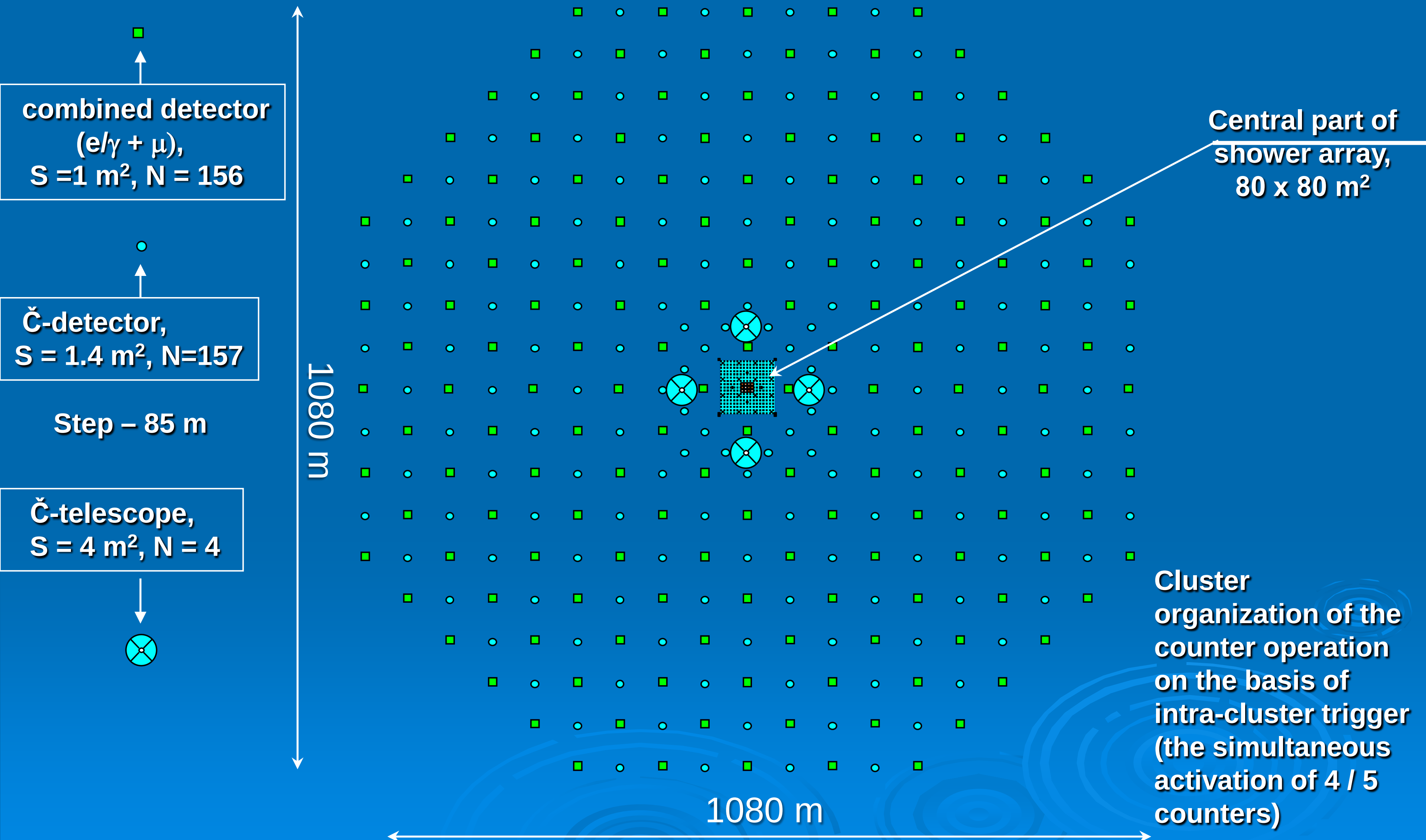
Spacing – 5 m

Initial stage: step – 10 m, $N_{c.d.} = 80$



Layout of detectors in *PAMIR-XXI* complex setup

Peripheral part of the shower array.



The problem of the PCR mass composition

- **To succeed in the studies of the PCR characteristics and ultrahigh-energy γ -radiation (that implies measuring of energy *E_0* and arrival direction *θ* of the primary particle, determination of its type (mass *A*), and estimation of the position *x_{core}* of the EAS axis at the observation level), it is necessary that the applied detector array and data processing methods should be optimized with respect to the most informatively demanding problems which are namely the primary mass determination and the γ-event selection.**
- **One must consider the most informatively-rich component to be the reference component for all other measured parameters. Among the EAS components the Cherenkov light (ĈL) is definitely the most informative and makes it possible to solve all the problems within the energy range *$E_0=30\div10^6$ TeV* even with a small duty cycle (≤10%).**

The Cherenkov part of the *PAMIR-XXI* setup

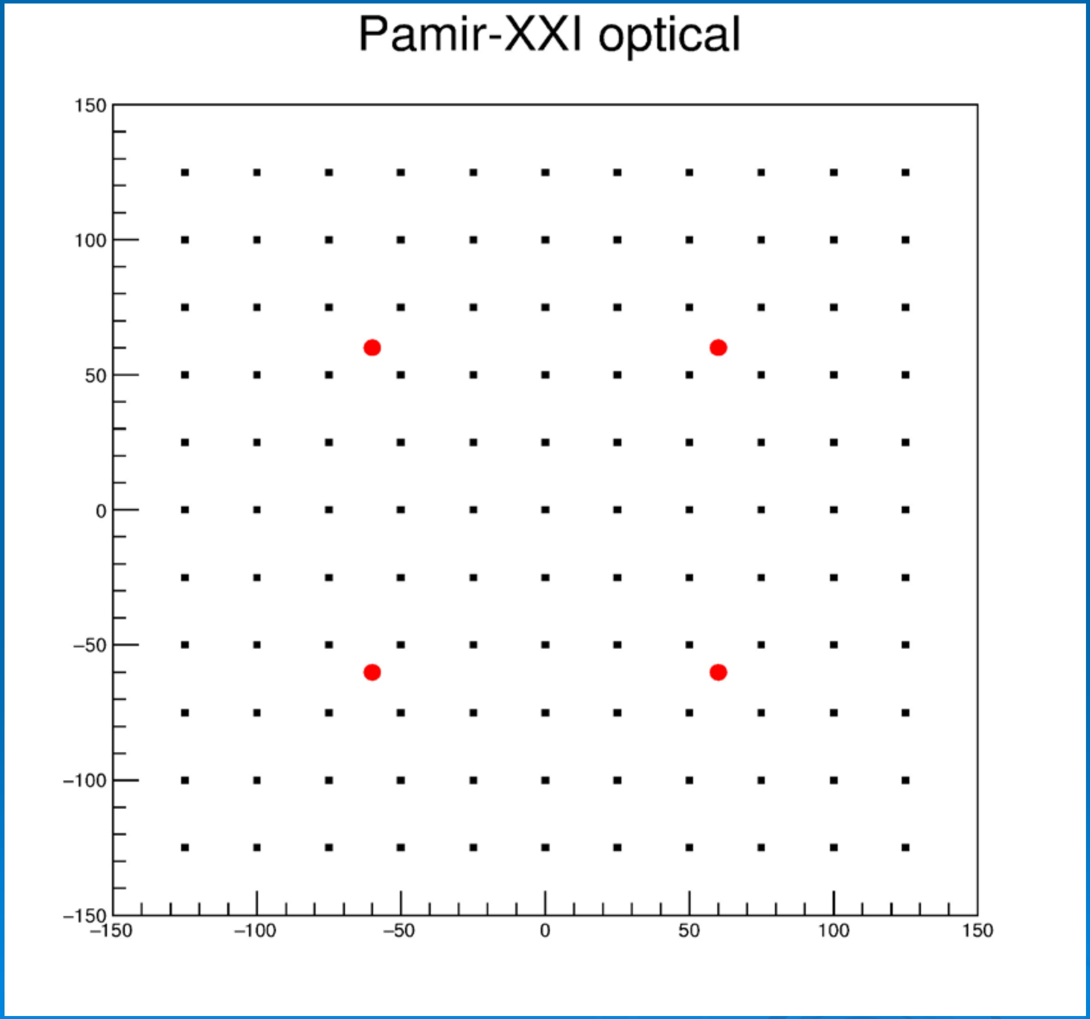
The optical part of the setup consists of two sets of detectors:

- a rectangular grid of 11 x 11 wide-angle fast detectors with an area of S ~ 1.0 m^2 and an aperture of Ω ~ 1 srad, located at a step of 25 m, allowing to determine
  - the direction of arrival of showers with an accuracy of ≤ 0.1º,
  - the axis position with an accuracy of ~1 m,
  - energy with an accuracy of about 15%

  and to analyze the shape of the Cherenkov pulse;
- optical telescopes with mirrors with an area of ~4 m^2, a field of view of ~30º and a pixel diameter of ~0.8º, spaced ~100 m apart, allowing to analyze the spatial-angular distribution of ĈL near the axis, which is sensitive to the mass of the primary particle.

Mind that the proposed method of nucleus separation by mass is essentially based on the exact determination of the direction of the primary particle arrival.

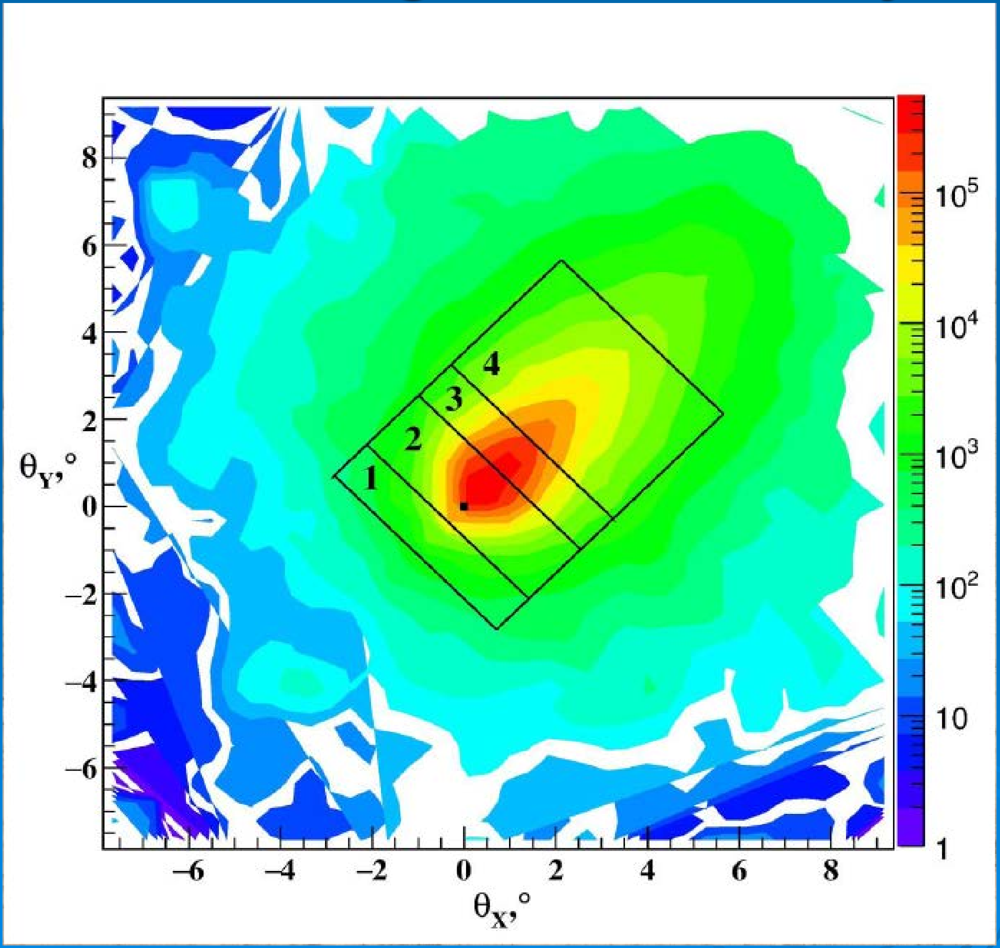
General features of a setup for the study of the PCR mass composition with EAS ĈL



- The simultaneous use of both the spatial-angular and spatial-temporal distributions of EAS ĈL allows us to count on the maximum separability of events from different primary nuclei.
- Telescopes (●) with mirrors S~4m^2 measure angular distribution of light, while fast detectors (■) determine the arrival direction, the point of event axis incidence and shower energy as well as allow to analyze ĈL spatial distributions.

Angular distribution of ĈL as a tool for mass composition *A* estimation

EAS Cherenkov angular images from different primary nuclei differ in size and shape. These differences reflect the shape of the cascading curves, and they can be used to estimate *A*.



The image is integrated over a certain area, and the integrals in its parts represent the longitudinal profile of the image. As features are the ratios $r_{ij} = S_i/S_j$ of ĈL integrals over shares S_i, i=1,...,4.

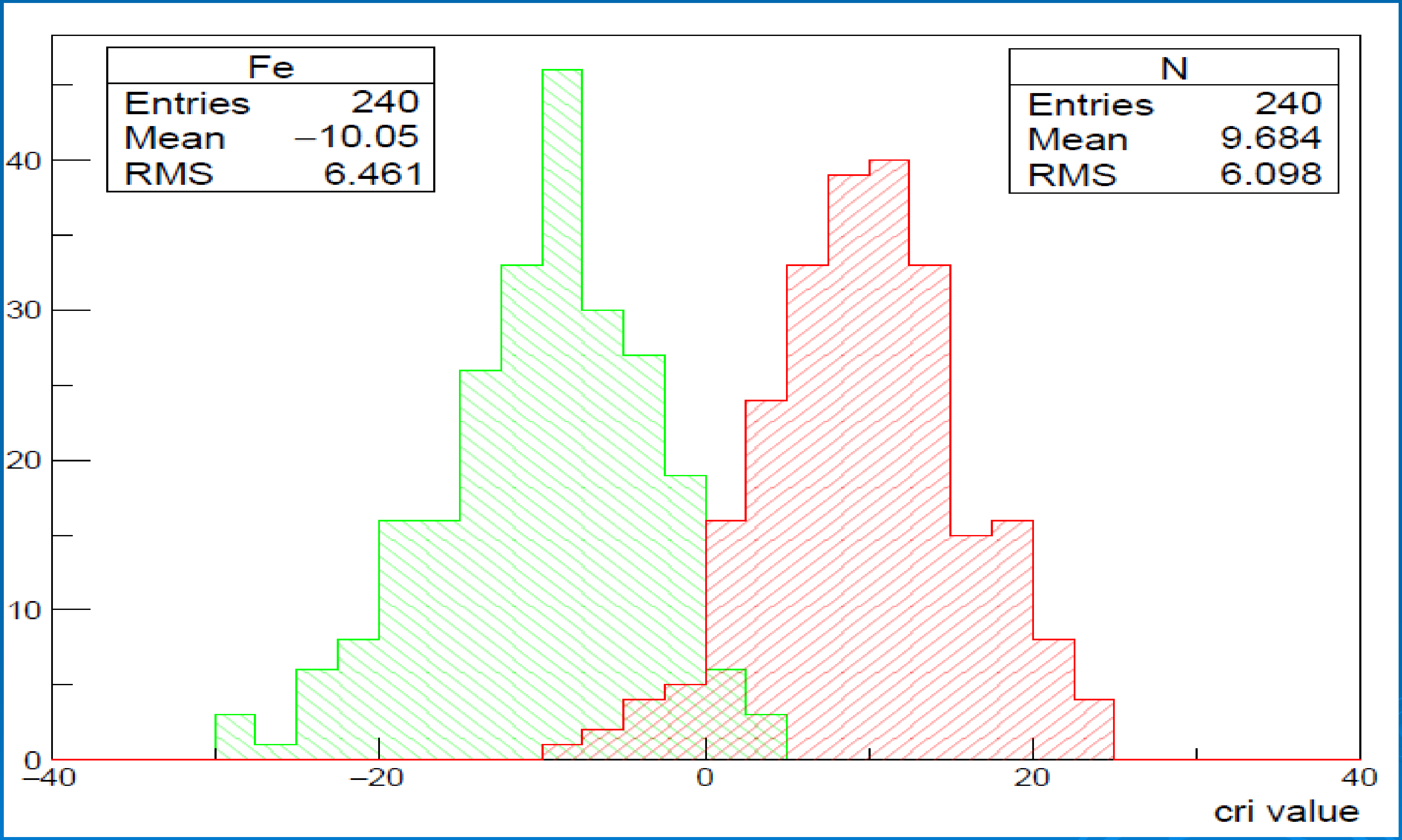
The widths of the fractions vary until the maximum separation of the nuclei is achieved.

EAS separation by masses *A* of the primary particles according to ĈL AD for *Pamir-XXI*

	1 ПэВ					10 ПэВ					100 ПэВ				
	21 м	50 м	100 м	150 м	200 м	21 м	50 м	100 м	150 м	200 м	21 м	50 м	100 м	150 м	200 м
	With background														
p_N	0,03	0,05	0,11	0,15	0,17	0,08	0,09	0,13	0,17	0,20	0,08	0,11	0,13	0,17	0,23
N_Fe	0,05	0,05	0,10	0,15	0,16	0,008	0,01	0,04	0,09	0,13	0,03	0,02	0,05	0,08	0,11
	With background and single criterion														
p_N	0,03	0,05	0,11	0,15	0,17	0,09	0,09	0,13	0,17	0,20	0,08	0,16	0,16	0,23	0,28
N_Fe	0,05	0,05	0,11	0,17	0,16	0,02	0,01	0,05	0,10	0,13	0,07	0,03	0,07	0,12	0,15

The classification errors (probability P{N→p} / P{p→N} and P{Fe→N} / P{N→Fe}) for pairs p-N and N-Fe are presented at the best criteria. Simulated events were calculated using the QGSJET01 model .

EAS separation by the primary particle masses

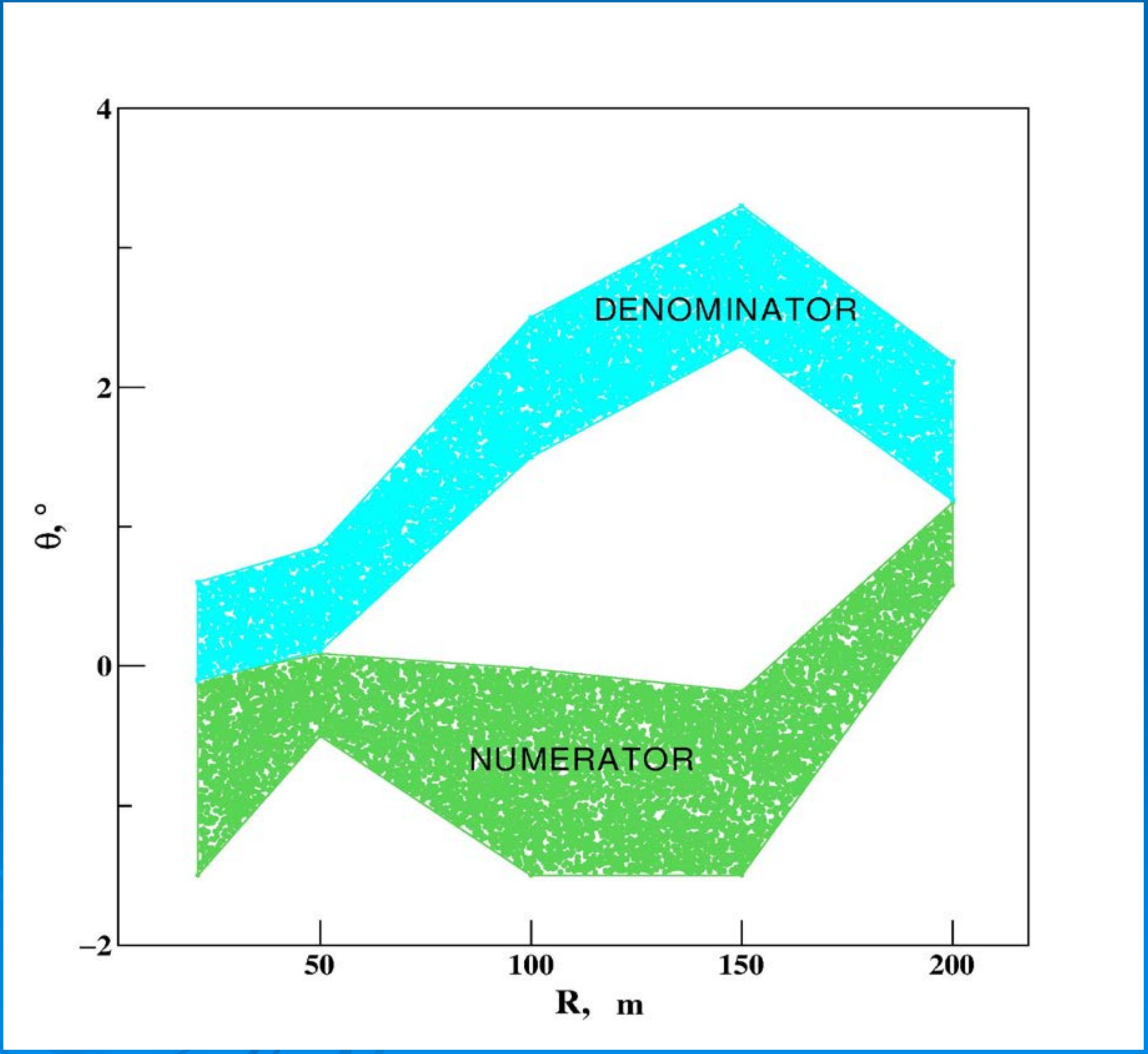


Distribution of values of the best criterion for a pair of N-Fe (E_0=10 PeV, R=100 m) accounting for background. Classification errors are 0.04

EAS separation by the primary particle masses

A single criterion was found, the same for all primary energies and pairs, depending only on R and working almost as well as the best.

The limits of integration for the single criterion ▸▸▸

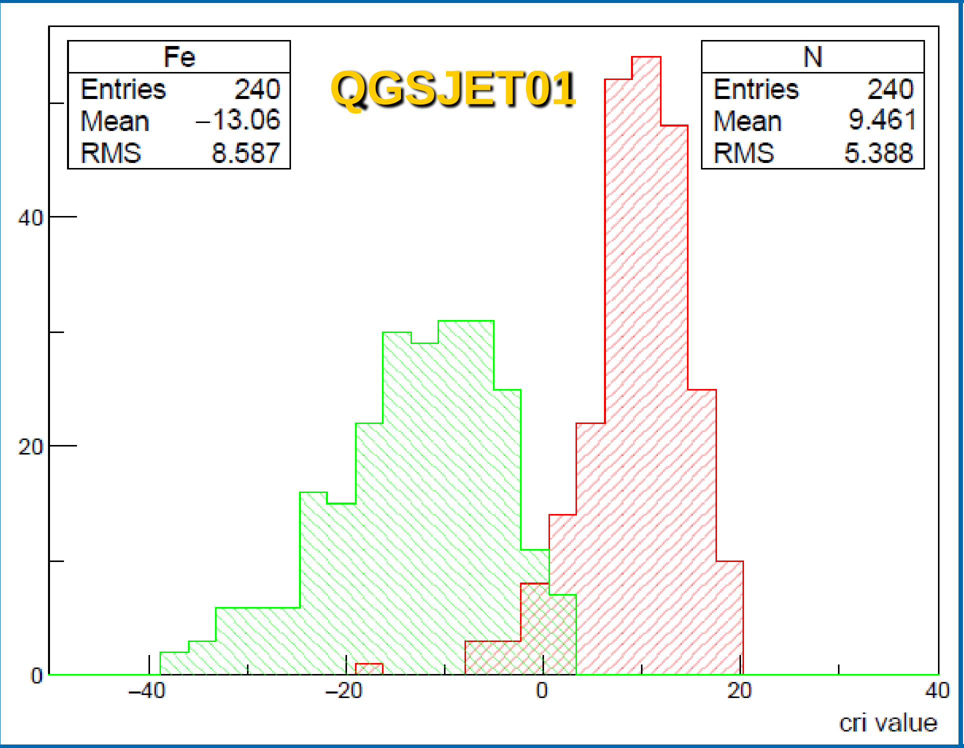


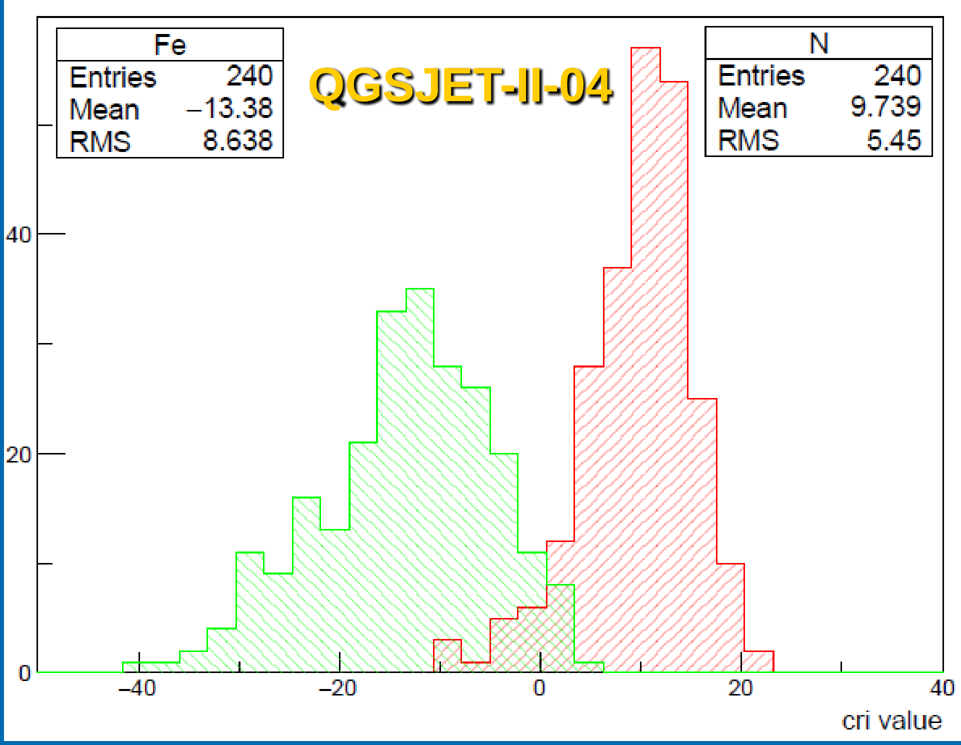
EAS separation by the primary particle masses

	1 ПэВ				
	21 м	50 м	100 м	150 м	200 м
	With background and single criterion (QGSJET01)				
p_N	0,03	0,05	0,11	0,15	0,17
N_Fe	0,05	0,05	0,11	0,17	0,16
	With background and single criterion (QGSJET II)				
p_N	0,05	0,05	0,12	0,19	0,19
N_Fe	0,06	0,05	0,16	0,18	0,20

The single criterion obtained for the QGSJET01 hadron interaction model was applied to the events with the energy of 1 PEV calculated with the QGSJET-II-04 model

EAS separation by the primary particle masses

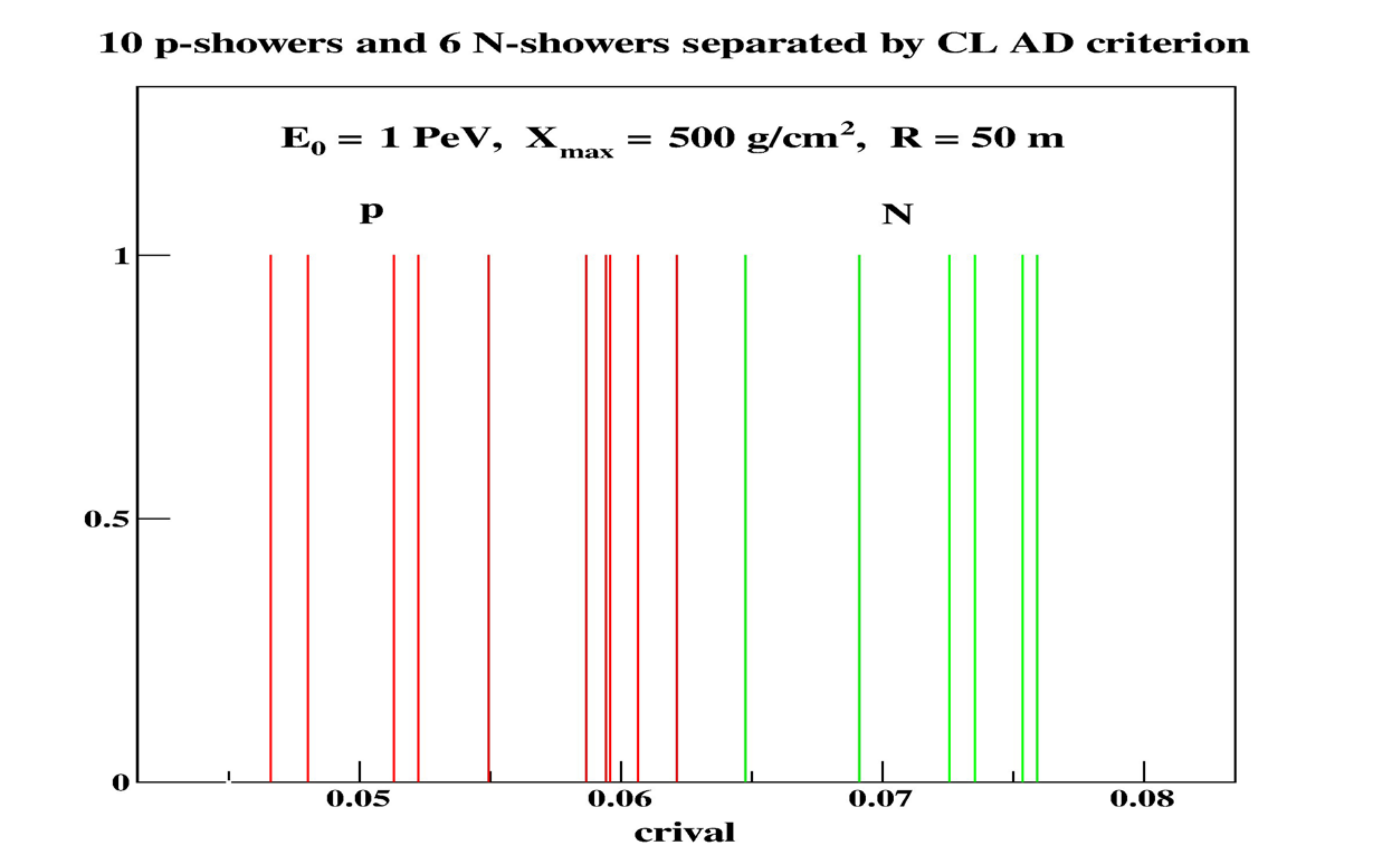




Separation without background for 1 PEV N_Fe nuclei at R=50 m (QGSJET01 hadronic model)

Separation without background for 1 PEV N_Fe nuclei at R=50 m (QGSJET-II-04 hadronic model)

EAS separation by the primary particle masses

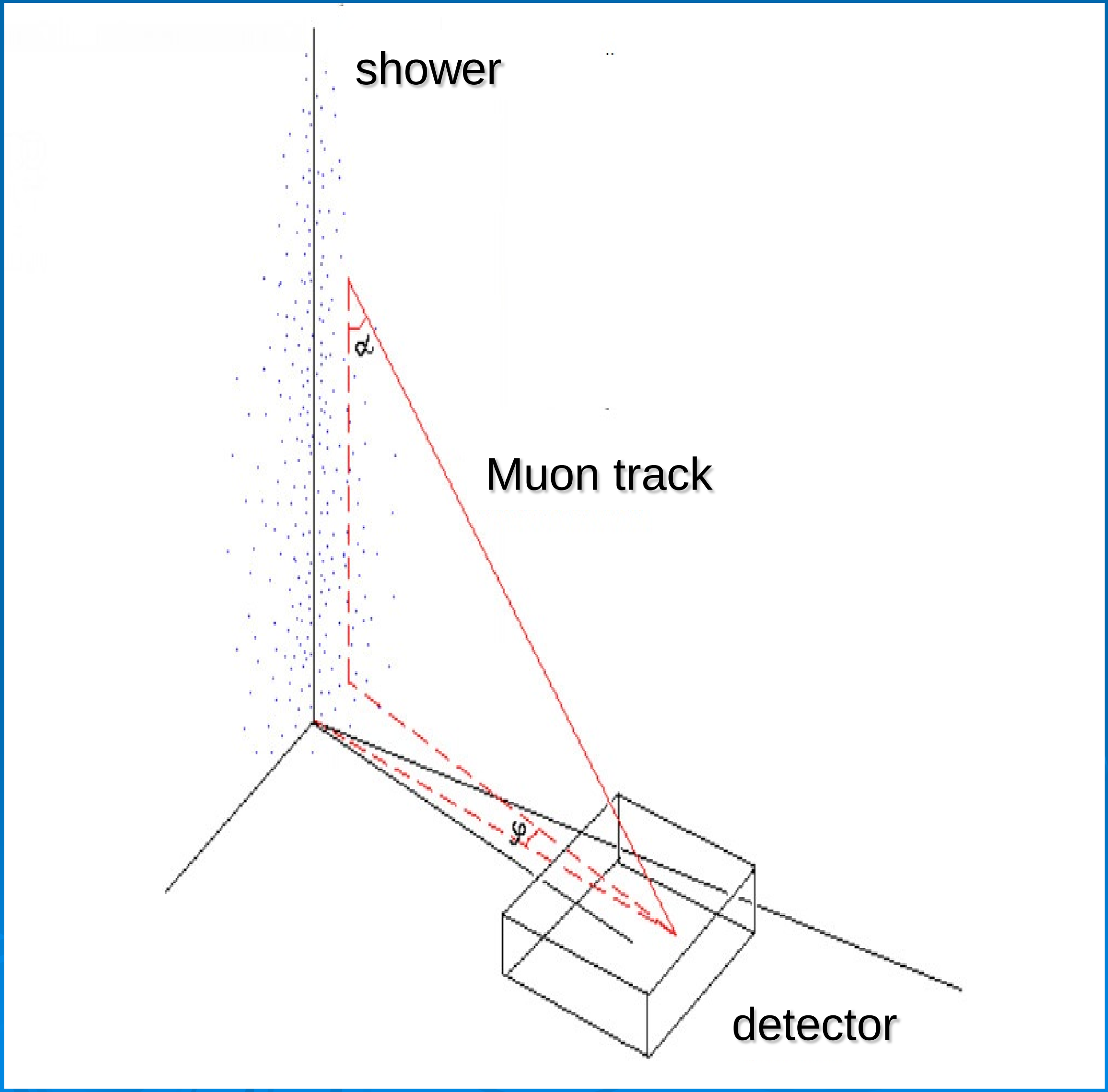


The found single criterion demonstrates noticeably better sensitivity to the primary mass than X_{max} !!!

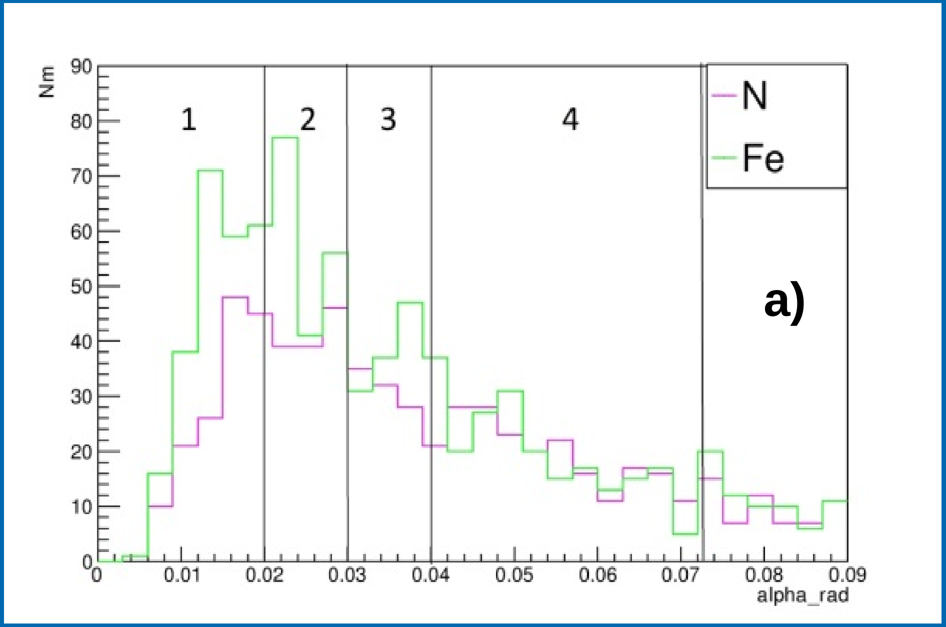
Estimation of the primary nucleus mass by angular distribution of EAS muons

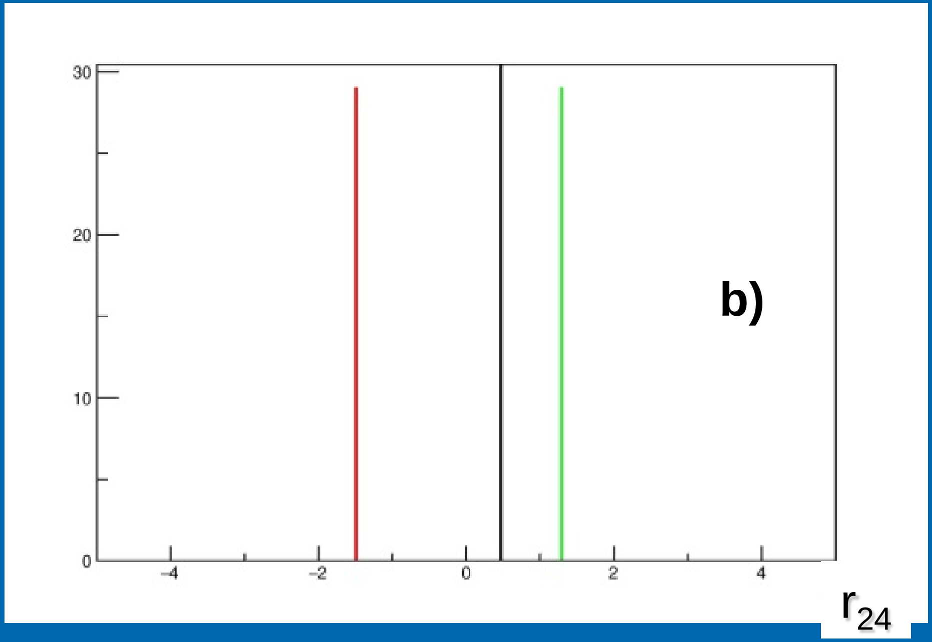
We used the positive experience of works with angular distribution of EAS ĈL in our analysis of the muon component.

Muons with energy not lower than 1 GeV coming from the vicinity (φ <0.1 rad) of the shower axis were considered.



Estimation of the primary nucleus mass by angular distribution of EAS muons





The procedure for processing the angular distribution of muons:

a) the angular distribution of individual showers from N and Fe at the distance of 100 m from the shower axis with an energy of 100 PEV (width of bins 0.020; 0.010; 0.010; 0.033 radians);

b) r_{24} criterion values characterizing these events.

Estimation of the primary nucleus mass by angular distribution of EAS muons

E_0	100 PeV			1 EeV					
R, м	100	120	150	100	150	200	250	300	400
p-N	0.34	0.33	0.31	0.35	0.35	0.32	0.35	0.33	0.35
N-Fe	0.34	0.31	0.31	0.32	0.30	0.33	0.31	0.32	0.32

The probability of incorrect classification for pairs of p-N and N-Fe, E_0=100 PEV – 1 EeV, with the optimum criteria.

The volume of all samples is 200 events.
Model QGSJET01.
Probability errors ±0.02 (everywhere).

Estimation of the primary nucleus mass by angular distribution of EAS muons

The optimal separation criteria, found for the pairs p-N and N-Fe for the QGSJET01 hadronic interaction model at high energies, were verified on the model QGSJET-II-04

The probability of incorrect classification for pairs of p-N and N-Fe, E_0=100 PEV – 1 EeV, with the optimum criteria ►►►

	Universal criteria. Bin widths are 0.015; 0.020; 0.010; 0.027 radians. k_{24}					
	QGSJET01			QGSJET-II		
R, м	100	120	150	100	120	150
p-N	0.40	0.35	0.34	0.39	0.37	0.32
N-Fe	0.34	0.30	0.34	0.34	0.36	0.37

A universal criterion (i.e., bin widths do not depend on distance) was also found for pairs of p-N and N-Fe with primary energies of 100 PeV for both models.

Estimation of the primary nucleus mass by angular distribution of EAS muons

! ! !

The separation of nucleus pairs by muons is much worse than by Cherenkov light, but we managed to find the parameter of the angular distribution of muons which is sensitive to the primary mass and insensitive to the interaction model.

! ! !

Conclusions

1. **The problem of estimation of the PCR mass composition with EAS technique requires substantially more dense and optimized installation.**
2. **The proposed optical part of Pamir-XXI is capable of achieving the required accuracies of the axis location (~1 m), the arrival direction (better than 0.1°) and the primary energy (≤15%) within the primary energy range 30 TeV – 100 PeV. Using this detector array, it is also possible to divide all primary nuclei into three groups (1 – 100 PeV) and reject not less than 99% of nuclear background events while selecting gamma-events (30 – 100 TeV).**
3. **The Cherenkov criterion of separation EAS by the masses of primary particles is practically independent of the interaction model in the range of 1 – 100 PEV.**
4. **Charged particle array ensables to estimate the core location within ~1 m accuracy, arrival direction with uncertainty ~ 0.2° and primary energy with uncertainty better than 15%. Preferable grid step is 15 m.**
5. **For the classification of EAS according to primary mass it is possible to use the angular distribution of energetic muons.**

We have found a universal criterion for the range of 100 PeV-1 EeV, independent of the interaction model and strongly correlating with the mass of the primary nucleus.

The details are in: *ISSN 0027-1349, Moscow University Physics Bulletin, 2018, Vol. 73, No. 2, pp. 179–186. © Allerton Press, Inc., 2018.*


Thank you for attention !