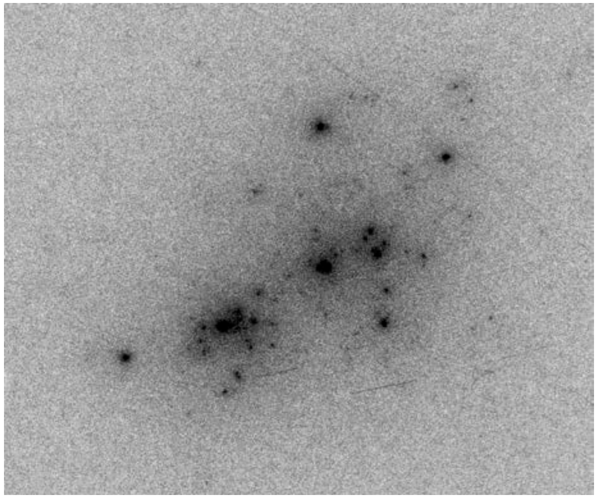
Evidence of the nontrivial nature of the alignment phenomenon at superhigh energies

A.S. Borisov[1], E.A. Ilyushina[2], A.V. Kurushin[2]

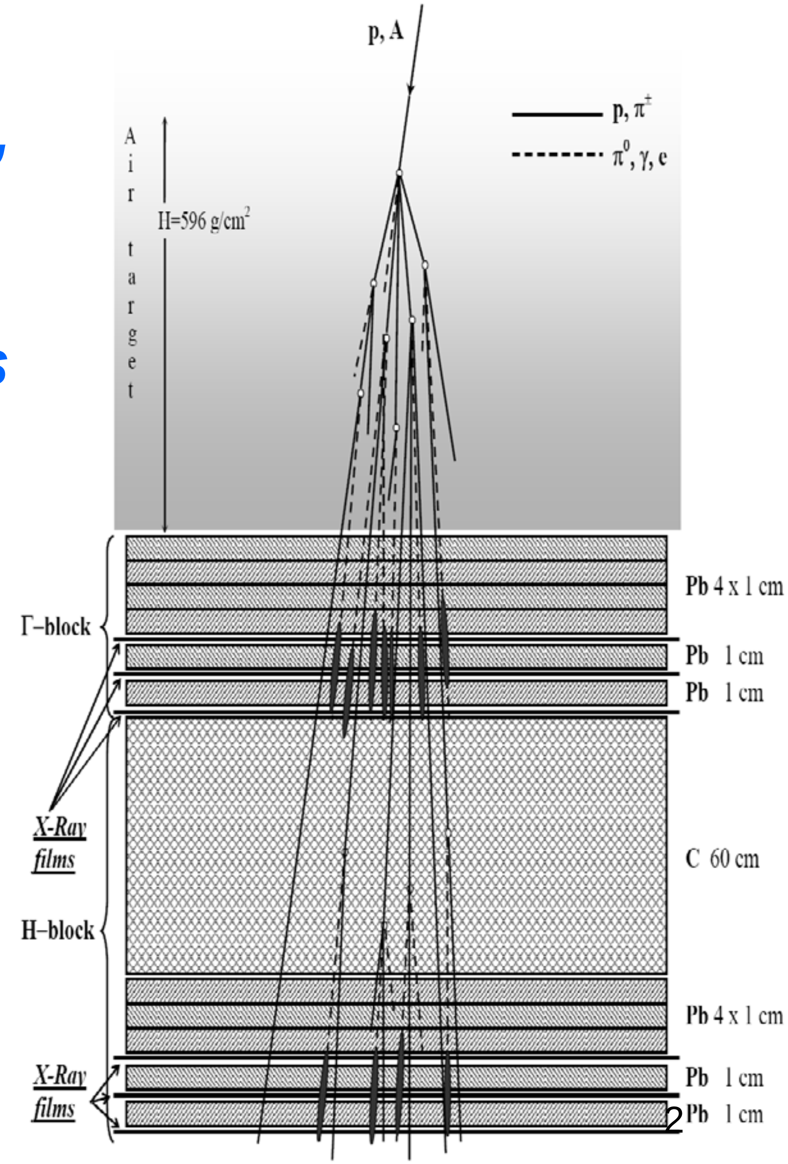
[1] **P.N.Lebedev Physical Institute of RAS, Moscow, Russia**
[2] **Department of Mechanics and Mathematics, Moscow State University**

Pamir experiment



Observables:

$n_{\gamma,h}$, $E_{\gamma,h}$, $\Sigma E_{\gamma,h}$, x, y, $R_{\gamma,h}$ and various combinations



A family definition and selection criteria:

a collimated ***($\Delta\theta \leq 3°, \varphi \leq \Delta 15°$)*** bundle of particles originated from one PCR particle

$\Sigma E\gamma \geq 100$ TeV, $n\gamma \geq 3$, $E\gamma \geq E_{th} = 4$ TeV, $E_h^{(\gamma)} \geq E_{th}$, $R_{\gamma,h} \leq 15$ cm

Total exposition ***ST ~ 3000 m²•yr***

Available statistics ***$N_f \approx 1000$***

CR and HE studies with XREC exposed at mountain elevations

- XRECs are designed for study of indivi-dual highest energy e-m particles (γ,$e^{+/-}$ or gammas) and charged hadrons within EAS cores generated by the PCR particles in the thick air target above the chamber;
- XREC is a sandwich of various dense material plates, e.g., lead or iron, interleaved with X-Ray films and is often supplemented by carbon blocks as particle converters;
- So, they represent a passive detector which combines advantages of calorimeters and high resolution tracking coordinate detectors enabling experimentalists to measure the energy and track geometry parameters of individual high energy particles with high precision:

$\sigma E/E \sim 0.2–0.3$

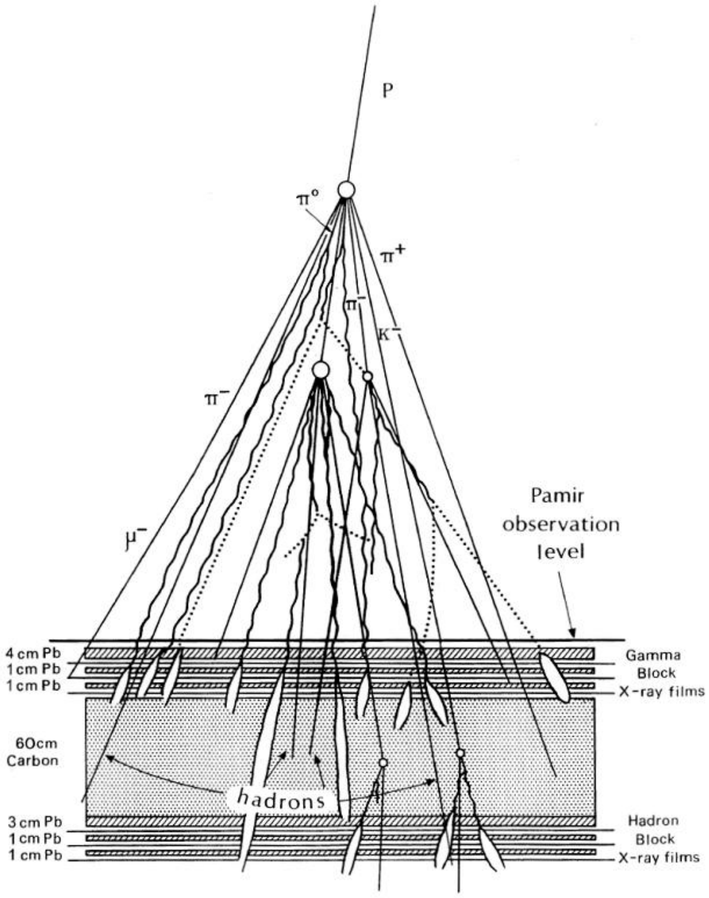
Δx, $\Delta y \sim 10\ \mu m$, $\Delta\theta \sim 3°$, $\Delta\varphi \sim 15°$

Ak-Arkhar experimental site: 4360 m a.s.l. at the Eastern Pamirs

CR and HE studies with XREC exposed at mountain elevations

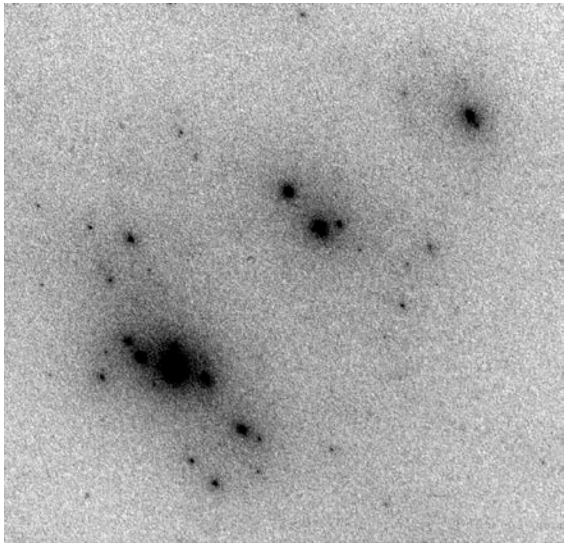
- **Due to high energy threshold (E$_{th}$ ≥ 4 TeV) and high spatial resolution (Δ x,y =10 μm), XRECs make it possible to study production of the most forward particles, i.e., to study the forward kinematic region of the phase space (so-called fragmentation region of a projectile particle) which is practically unattainable in the collider experiments:**

!!! XREC experiments should be considered as complementary ones to coliider experiments !!!



A scheme of the Pamir experiment with carbon (rubber) XREC exposed at the altitude of 4370 m a.s.l

Phenomenon of coplanar emission of hadrons



An example of aligned 3-core halo event

The effect, first observed in the *Pamir* experiment, manifested itself as a strong tendency for tracks of the most energetic particles in γ-h families as well for their narrow bundles (family cores) to be aligned along some straight line in the target plane .

The highest energetic cores (HEC) in a family can be represented by:

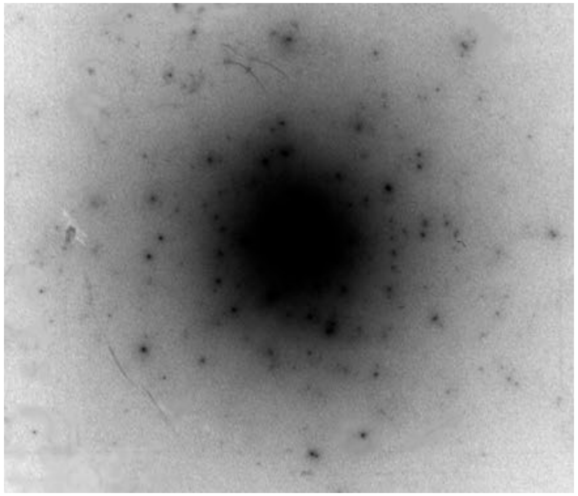
- halo cores;
- γ-clusters or reconstructed π^0;
- single gamma-ray or hadron.

Halo events

If $E_0 \geq 10^{16}$ eV, a sufficiently high number of overlapping under-the-threshold *EPhC* may overlap creating an optical "halo", i.e., a large diffuse optical spot inside the corresponding γ-family with a visible energy $\Sigma E\gamma \geq 500$ TeV.

Sometimes area of a halo $S \sim cm^2$.

The fraction of halo events increases with family energy and, at $\Sigma E\gamma \geq 1000$ TeV, amounts up to 70 %.



Scanner image of 'FIANIT' halo event
$S_{D=0.5} = 1'017\ mm^2$
Visible energy $E = (2÷3)\cdot 10^{16}$ eV
(Isodence D=0.5 corresponds to particle density 0.04 mm^{-2})

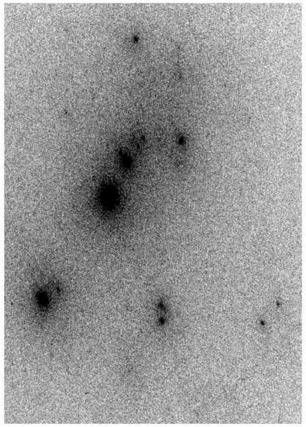
Halo event selection criteria: $\Sigma E_\gamma \geq 500$ TeV $n_\gamma \geq 3$, $E_\gamma \geq 4$ TeV

$S_{D=0.5} \geq 4\ mm^2$ or $\Sigma S^i_{D=0.5} \geq 4\ mm^2$, $S^i_{D=0.5} \geq 1\ mm^2$ $R_\gamma \leq 15$ cm

Statistics: $N_H = 61$, $ST = 3000\ m^2\cdot year$

$N_f^{tot}(\Sigma E\gamma \geq 500\ TeV) = 143$

Superfamilies with aligned 3-core halos



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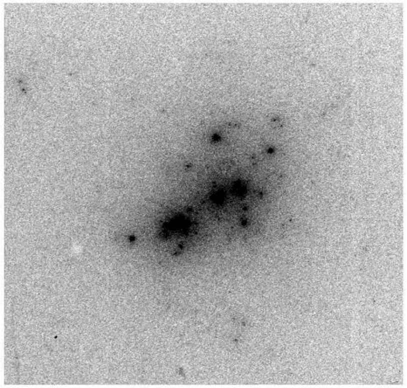

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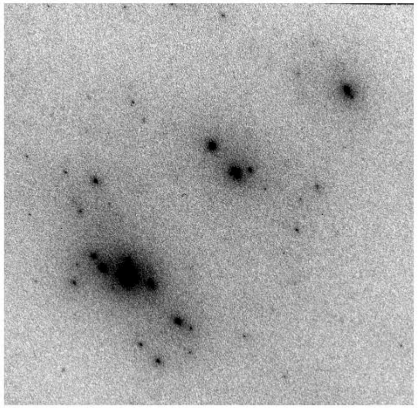

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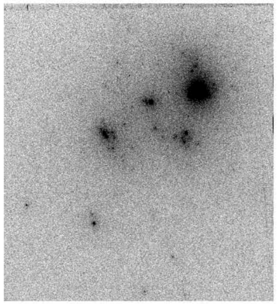

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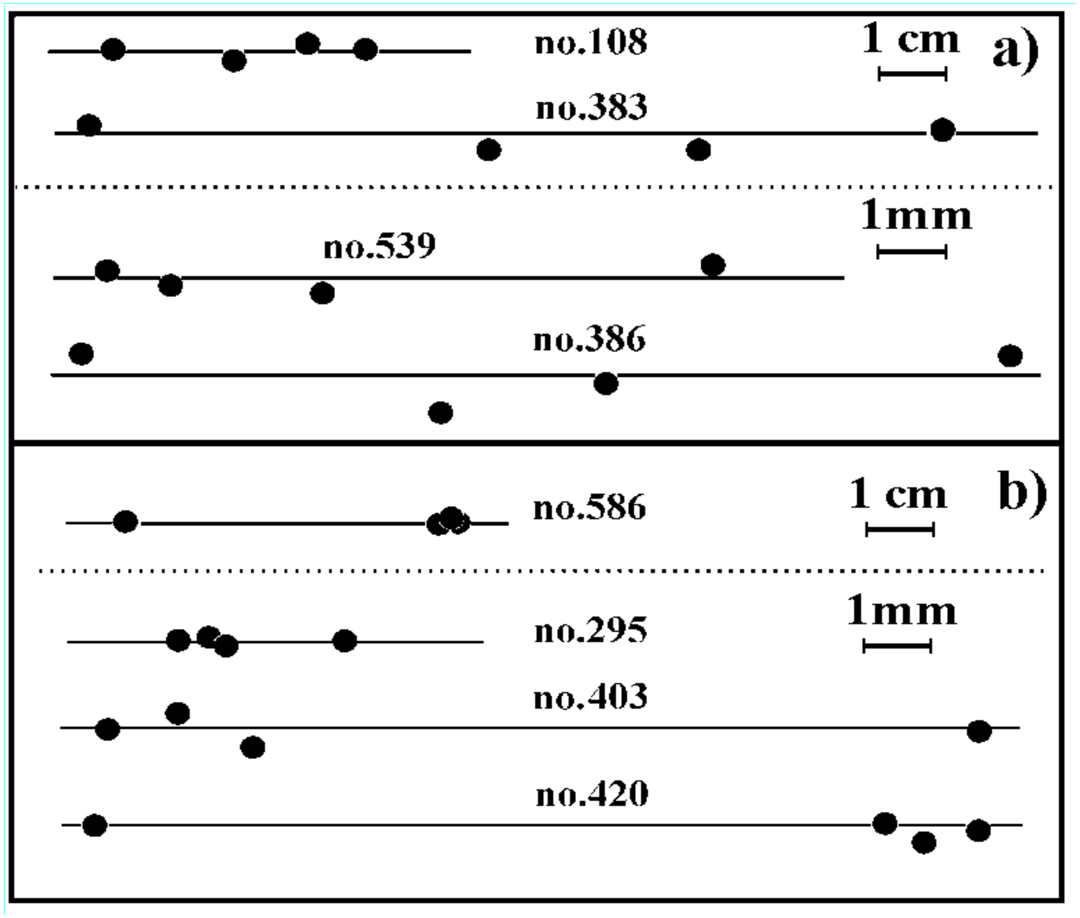
Scan images of super families with aligned halo cores

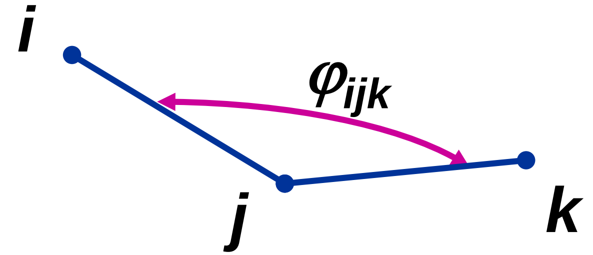
Target diagrams of experimental 4-core aligned structures composed of highest energy gammas



The Alignment Criterion

For quantitative definition of events with *N* cores aligned along one straight line, the following criterion was introduced:

$$\lambda_N = \frac{\sum_{i \neq j \neq k}^{N} \cos 2\varphi_{ij}^{k}}{N(N-1)(N-2)}$$



where φ_{ijk} is the angle between the straight lines connecting the i-th and j-th cores with the k-th core.

The parameter $\lambda_N = 1$ in the case of complete alignment of N cores along one straight line and tends to -1/(N-1) in an isotropic distribution case.

Families containing N-core structures, composed of the HEC and characterized by $\lambda_N \geq \lambda_C = 0.8$, are referred to as aligned events.

Application of cluster analysis technique for search of aligned structures

We used two close metrics to group gammas into clusters:

(1) $$z_{ik} = \frac{E_i E_k}{E_i + E_k} R_{ik} \leq z_c =$$

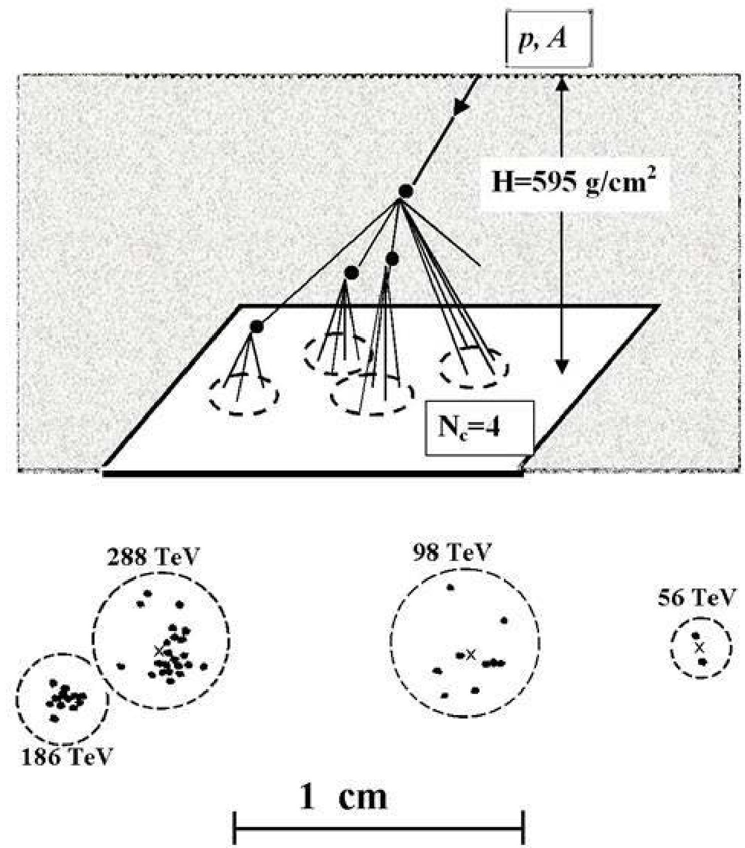
=1.2 TeV·cm – for γ –reconstruction

=3.4 TeV·cm – for π^0- reconstruction

(2) $$\chi_{ij} = \sqrt{E_i E_j} R_{ij} \leq \chi_c =$$

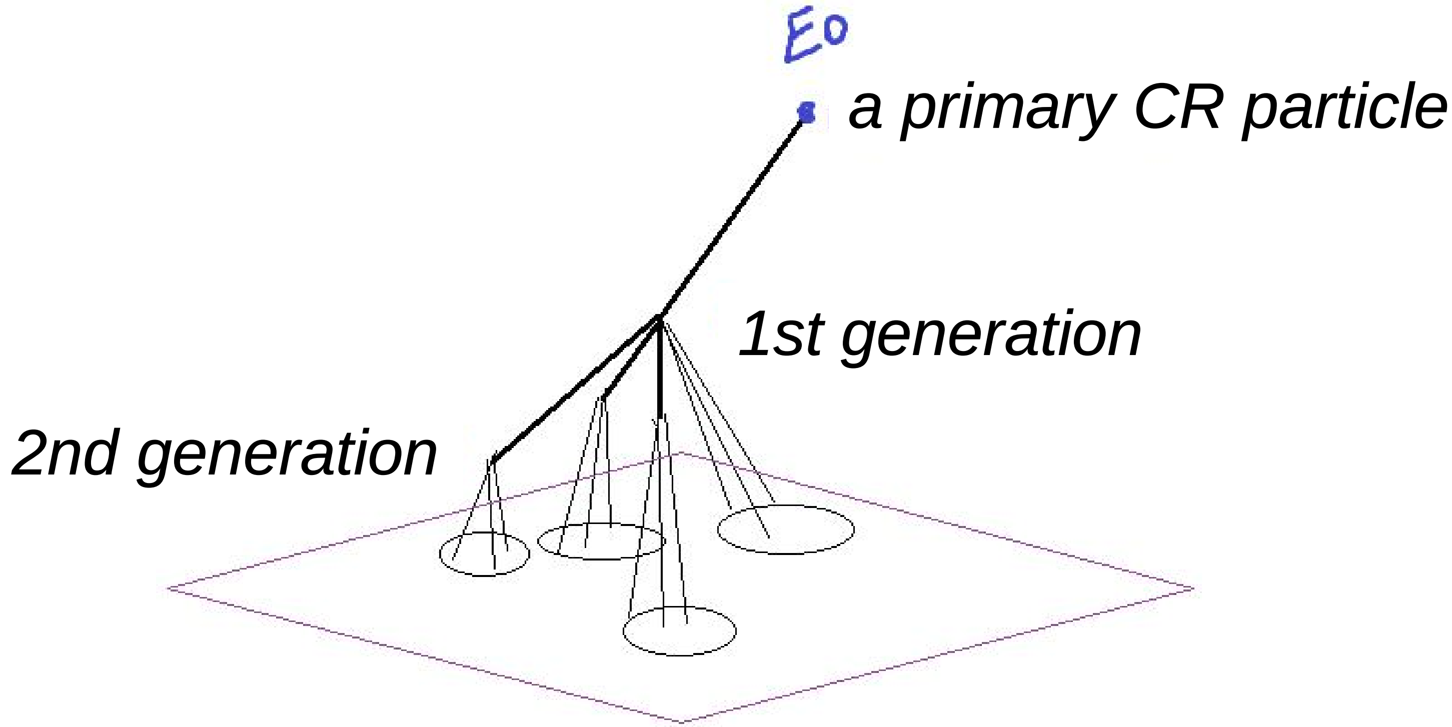
= 48 TeV·cm – for reconstruction of hadrons produced in the last interaction in the atmosphere

Note: in algorithm (1) the combining of particles always starts from the highest energy one, while in (2) – from pairs with the smallest current value of χ_{ij}



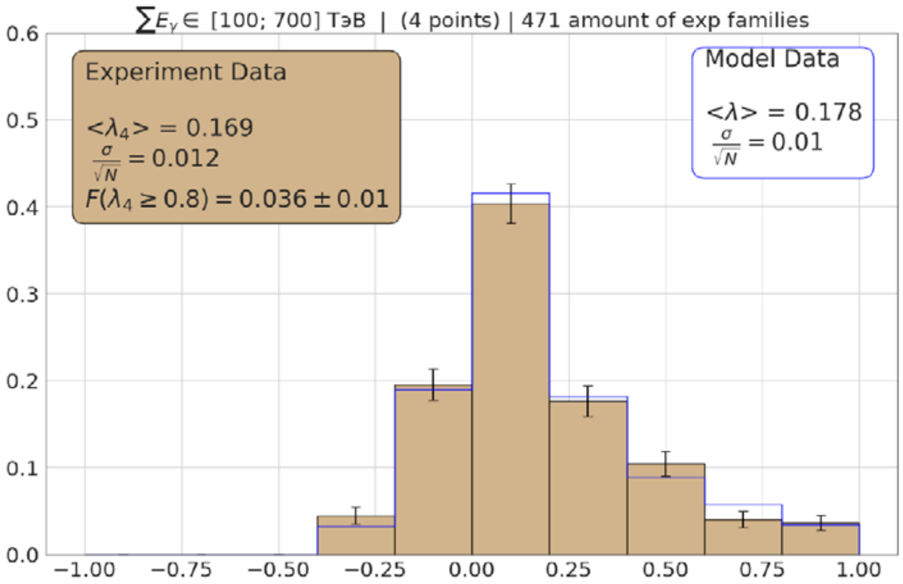
An ideal clusterization of γ-family and its interpretation

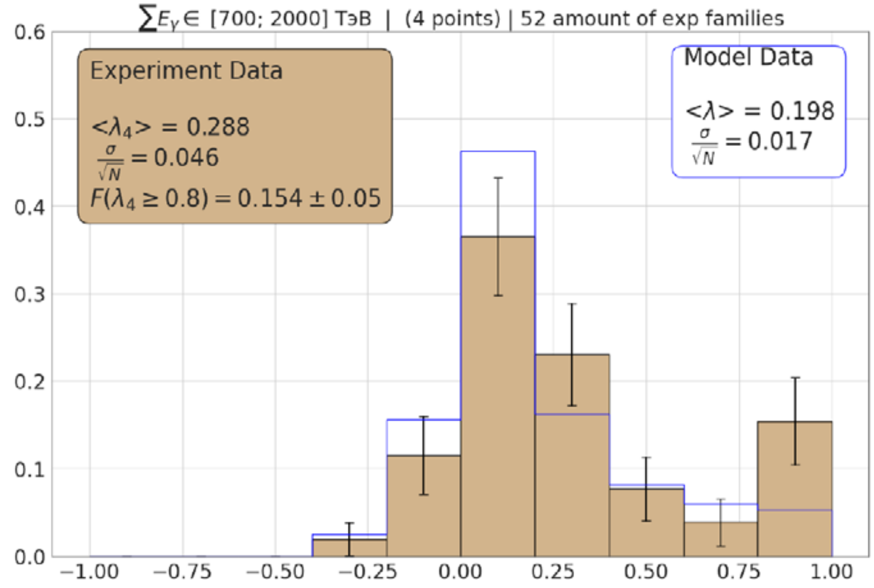
Rejuvenation of γ-families by means of clustering procedures



The energy threshold behavior of the alignment phenomenon

$$\chi_{ij} = R_{ij}\sqrt{E_i E_j} \le \chi_c = 48\,TeV \cdot cm$$





λ_4-distribution of experimental and simulated γ-families in two energy ranges after applying clusterization procedure

Efficiency of clustering of γ-families

Unfortunately, we can evaluate the efficiency of γ–family clustering by means of the above mentioned algorithms only employing the results of γ-family simulation where can trace the NEC development. For this purpose, we use the data-base calculated with MC0-code based on QGS-model of hadron interaction and supplemented with mechanism of hard QCD-jet production. This model rather well reproduce main experimental distributions of γ-families.

Clustering quality coefficients of γ-families

*The **purity** of the clusterized family is the mean value of purities p_i of all extracted clusters in the family:*

$$P = \frac{1}{N_c}\sum_{i=1}^{N_c} p_i \quad \text{, where} \quad p_i = \frac{n_d}{n_c}$$

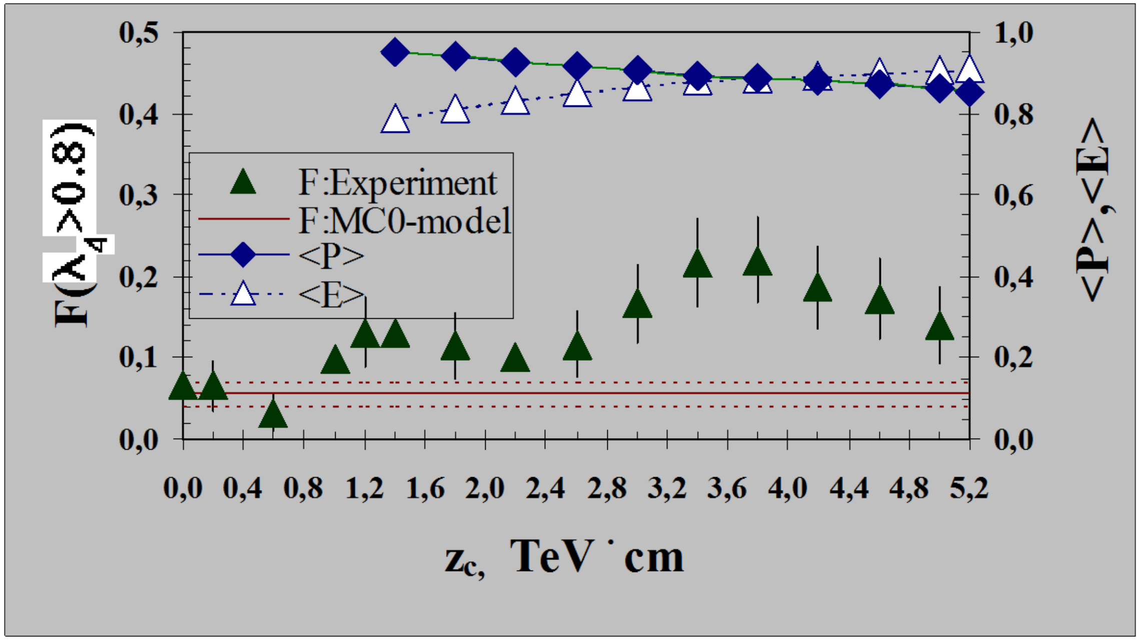
, n_d is the number of particles in each individual cluster produced in the interaction dominating in this cluster; n_c is total number of particles in the cluster.

*The **effectiveness** of the family clustering is the mean effectiveness of all clusters:*

$$E = \frac{1}{N_c}\sum_{i=1}^{N_c} e_i \quad \text{, where} \quad e_i = \frac{n_d}{n_I}$$

, n_I is the number of particles in the whole family produced in the dominating interaction.

$0 \le P,E \le 1$



Electromagnetic clustering procedure for γ's and π^0 reconstruction:

$$z_{ik} = \frac{E_i E_k}{E_i + E_k} R_{ik} \le z_c = $$

= *1.2 TeV·cm – for gammas*
3.4 TeV·cm – neutral pions

Dependence of aligned event fraction ***$F(\lambda_4^c > 0.8)$*** *and efficiency for π^0 reconstruction on decascading parameter* ***z_c***.

Simulated family dissection:

efficiency of π^0 reconstruction is the highest at z_c=3.6 TeV cm, i.e.

<P>=<E>=0.886±0.03 – almost 90 %

where ***$P = n_c^\pi / n_c$*** - *purity of extracted electromagnetic clusters*

$E = n_c^\pi / n^\pi$ - *efficiency of gathering of all e-m particles* ***n^π*** *related to a given π^0 into a single cluster*

n_c *– total number of particles in a cluster*

n_c^π *– number of particles in a cluster originated from π^0 dominating in the extracted cluster*

5- core aligned families

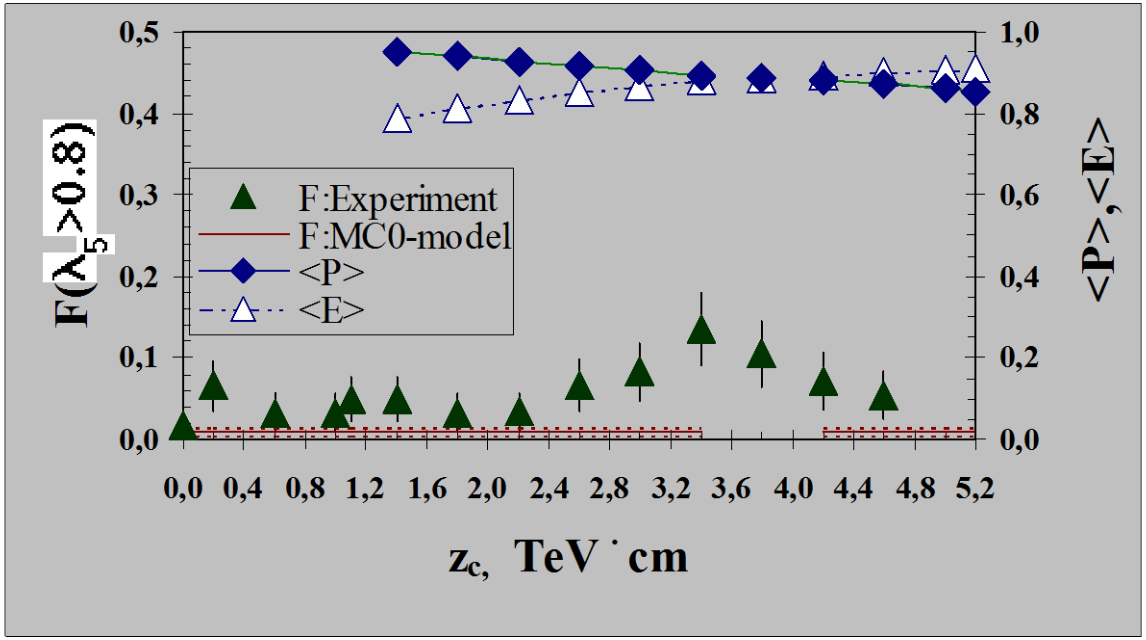


Fig. 2. *Dependence of aligned event fraction* $\boldsymbol{F(\lambda_5^c > 0.8)}$ *and efficiency for* π^0 *reconstruction on decascading parameter* $\boldsymbol{z_c}$.

4-core structures (4 highest energy π^0***):***

EXP: $F^{EXP}(\lambda_4^c > 0.8) = 22 \pm 5\ \%$ ***MC0:*** $F^{MC0}(\lambda_4^c > 0.8) = 6 \pm 1\ \%$

5-core structures (5 highest energy π^0***):***

EXP: $F^{EXP}(\lambda_5^c > 0.8) = 14 \pm 4\ \%$ ***MC0:*** $F^{MC0}(\lambda_5^c > 0.8) = 1 \pm 0.4\ \%$

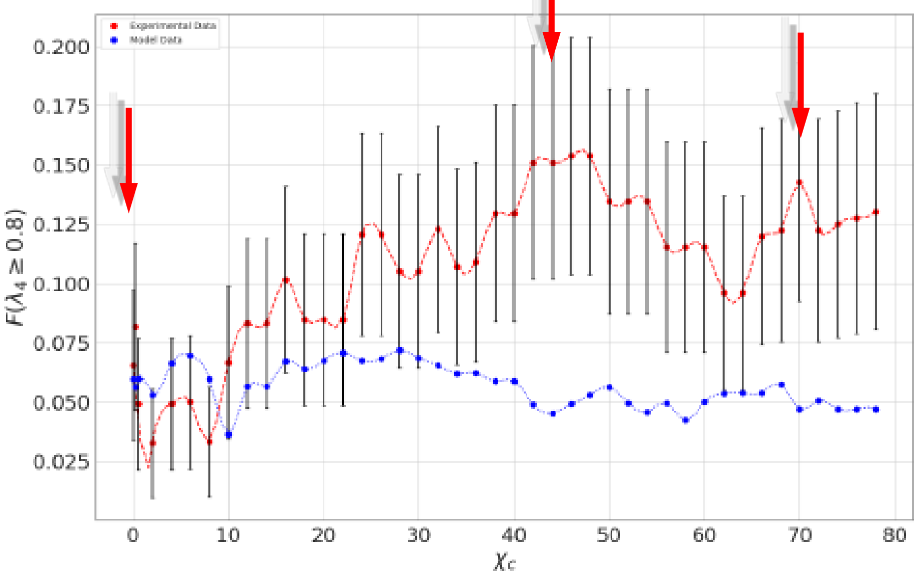
Summary on the fraction of aligned events

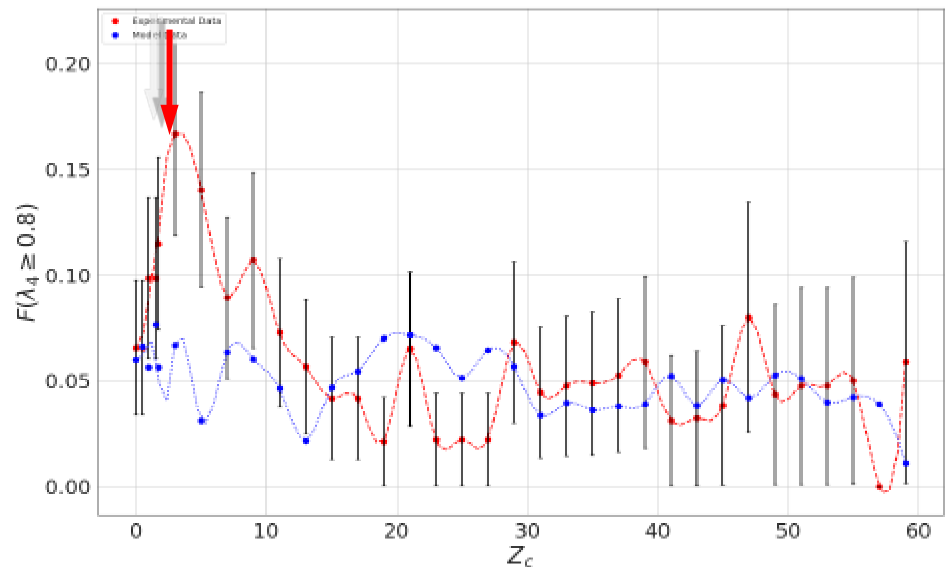
Type of reconstructed particles		π^{0*} (z_c=3.4 Tev·cm)	h^* (χ_c=48. Tev·cm)
EXP	**$F(\lambda_4^c > 0.8)$**	0.22 ± 0.05	0.16 ± 0.05
N_c=4	$\langle R_c \rangle_4$	1.3 ± 0.3	1.8 ± 0.5
MC0	**$F(\lambda_4^c > 0.8)$**	0.06 ± 0.01	0.05 ± 0.01
N_c=4	$\langle R_c \rangle_4$	0.6 ± 0.2	0.6 ± 0.1
EXP	**$F(\lambda_5^c > 0.8)$**	0.14 ± 0.04	0.06 ± 0.04
N_c=5	$\langle R_c \rangle_5$	1.5 ± 0.3	2.1 ± 0.6
MC0	**$F(\lambda_5^c > 0.8)$**	0.010 ± 0.004	0.
N_c=5	$\langle R_c \rangle_5$	0.7 ± 0.2	-

Table 1. Fraction of aligned 4- and 5-core structures composed of reconstructed particles (E_c^{th}=10 TeV).

Distributions of the fraction of aligned 4-core families $F(\lambda_4>0.8)$ over χ_c and z_c critical values

ΣE = 700 TeV ÷ 2000 TeV

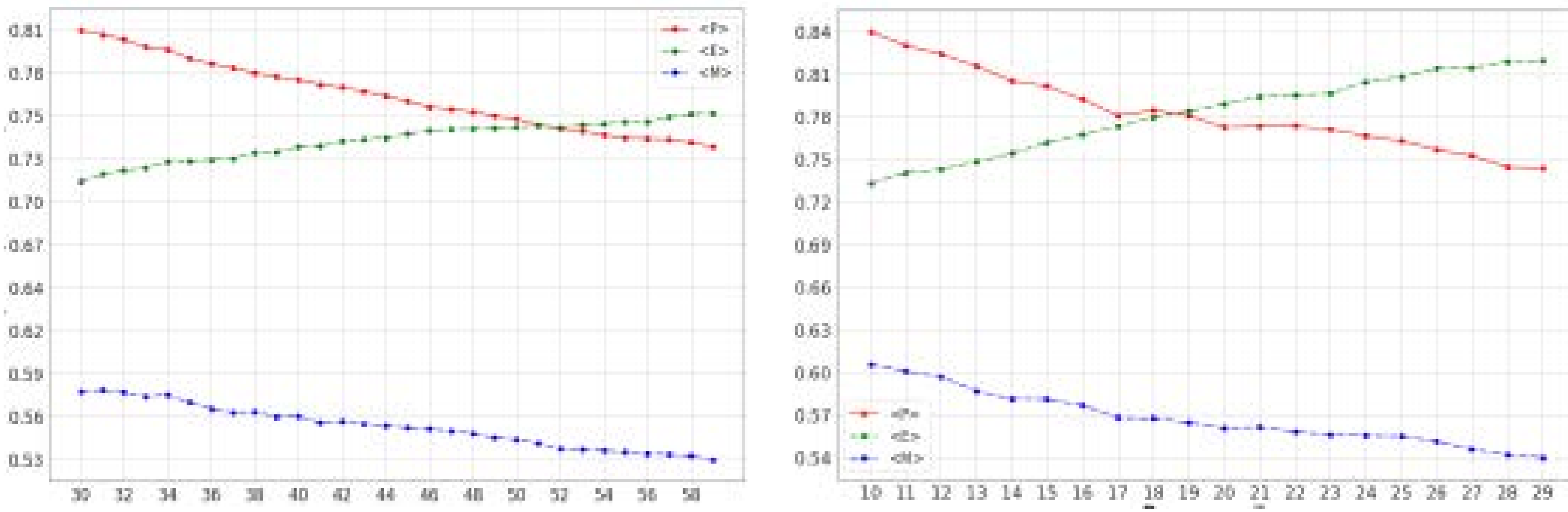




Having plotted the distribution of the fractions of aligned events depending on the value of the critical parameter χ_c and z_c, we discovered a number of features on this curve, which are easy to interpret accounting for kinematics and dynamics of the involved processes (decay of π^0, hadron production, etc) :

χ_c =1.2 TeV·cm – permits to merge effectively gammas;
χ_c = 40÷48 TeV·cm – effective merger of hadrons from the last generation;
χ_c = 70 TeV·cm – effective combining of hadrons from the last but one generation;
z_c = 3.4÷3.6 TeV·cm – effective merger of π^0 produced in the last interaction.

Dependence of the clustering quality coefficients on the χ_c and Z_c critical values



Dependence of <P> and <E> on the critical parameter χ_c

Alignment phenomenon: possible explanations

- **‘Searching for the Layered Structure of Space at the LHC’**

by Luis A. Anchordoqui, De Chang Dai, Haim Goldberg, Greg Landsberg, Gabe Shaughnessy, Dejan Stojkovic, Thomas J. Weiler

“…This phenomenon can be described within the recently proposed "crystal world," with latticized and anisotropic spatial dimensions. Planar events are expected to dominate particle collisions at a hard-scattering energy exceeding the scale Λ_3 at which space transitions from 3D 2D. Therefore, four jet events at the LHC will exhibit striking planar alignment (if the parton-parton momentum transfer Q exceeds the energy scale Λ_3 of the lattice)”

Underlying Hypothesis: *spacetime may be an ordered lattice structure that becomes anisotropic at very small distances*

/arXiv:1012.1870v2/

Accelerator experiment indications: ridge effect

Conclusions:

- **Alignment of γ-families detected by XEC cannot be explained by either large fluctuations in the NEC development or by emulsion chamber technique peculiarities but results from some new physical mechanism of coplanar emission of pions in multiple production of hadrons in fragmentation region at superhigh energies.**
- **The observed coplanar production of hadrons follows a clear energy threshold behavior, i.e., $E_c \geq 8$ PeV**
- **Comparatively wide sizes of aligned experimental structures indicates to a large transverse momentum $p_T \sim 2 \div 5$ Gev/c of the new process.**
- **It is shown that cluster analysis can be used to 'rejuvenate' gamma-families in order to increase the sensitivity of the experiment to the search and determination of the physical characteristics of the aligned events.**

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