Exotic events in cosmic ray experiments at super high energies: a manifestation of New Physics?

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Abnormal events

observed in CR experiments at Tien Shan and Pamirs

The most intriguing unusual events and processes observed in the energy range and phase space which are inaccessible at collider experiments:

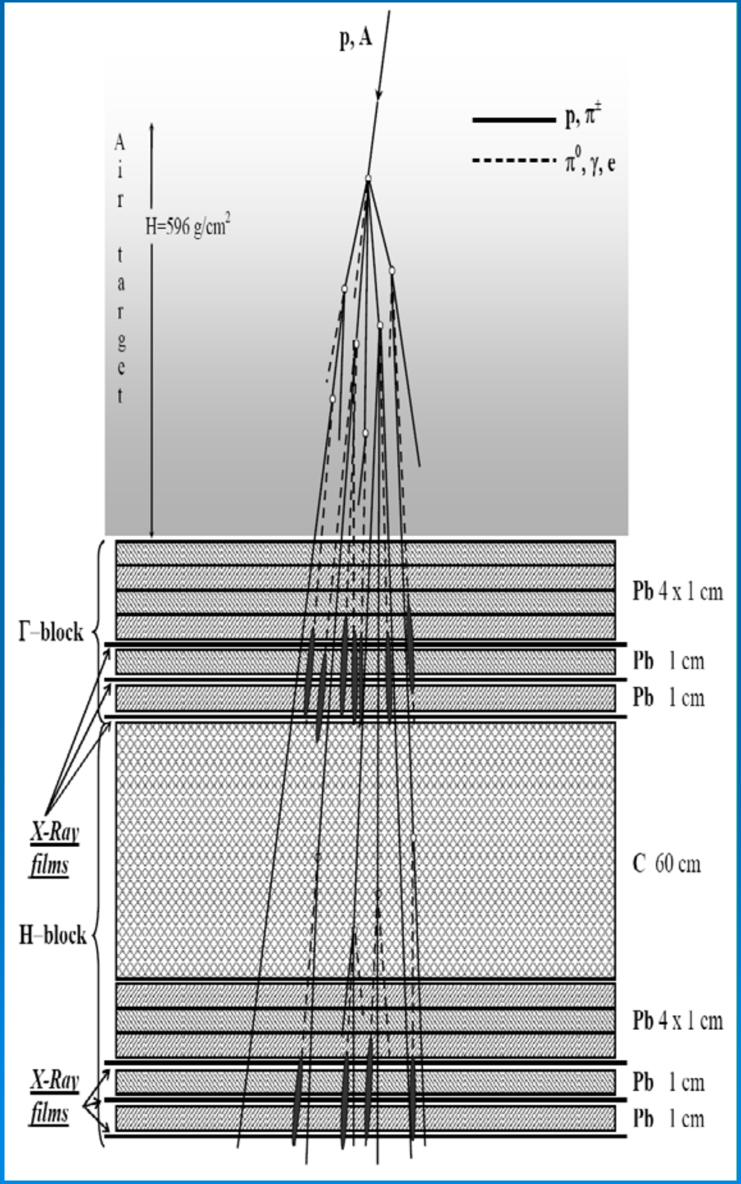
- **coplanar emission of the most energetic hadrons and γ-rays in multiparticle production processes (so-called 'alignment effect');**
- **Centauro- and Anti-Centauro-type events with abnormal ratio of charged to neutral particles (pions);**
- **abnormally weak hadron absorption in lead (so-called 'long-flying CR component');**
- **appearance of several fronts in horizontal EAS;**
- **. . .**

CR and HE studies with XREC exposed at mountain elevations

- XRECs are designed for study of individual highest energy e-m particles (γ, $e^{+/-}$) 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;
- 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:

$$\sigma E/E \sim 0.2\text{–}0.3$$

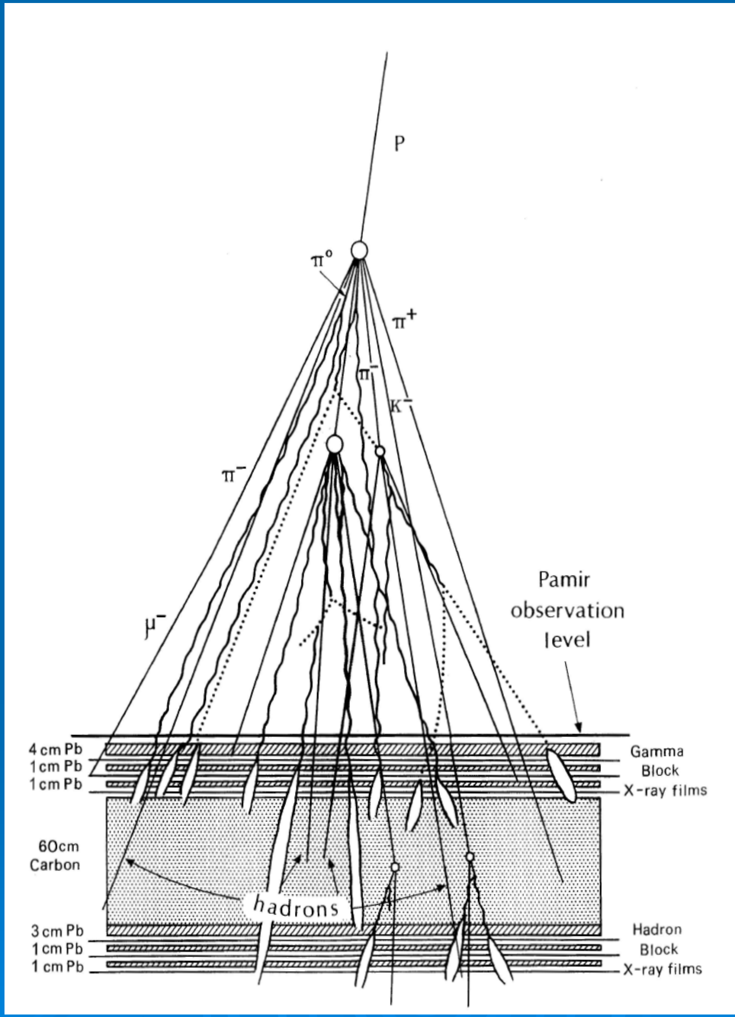
$$\Delta x, \Delta y \sim 10\ \mu m, \Delta\theta \sim 3°, \Delta\varphi \sim 15°$$



CR and HE studies with XREC exposed at mountain elevations

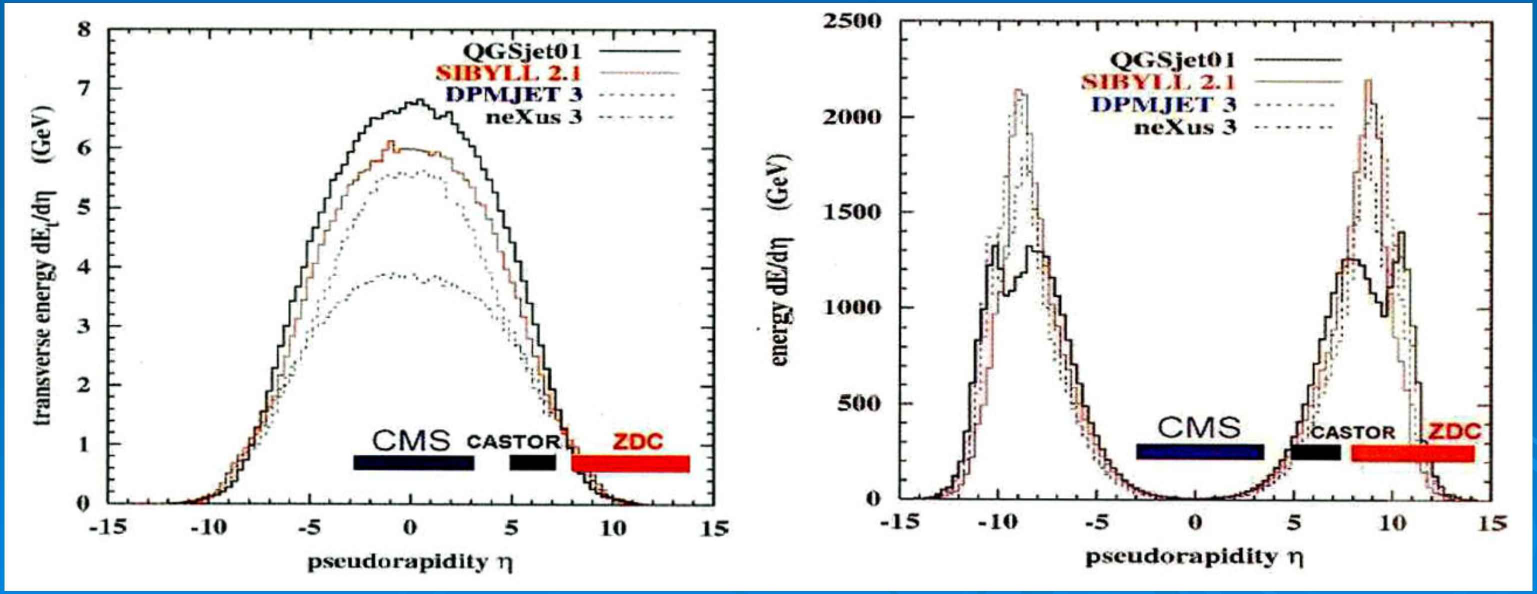
- **Due to high energy threshold ($E_{th} \geq 4$ TeV) and high spatial resolution, XRECs make it possible to study production of the most forward particles, i.e., to study the forward kinematic region of the phase space (so-called fragmentation region of a projectile particle) which is practically unattainable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

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



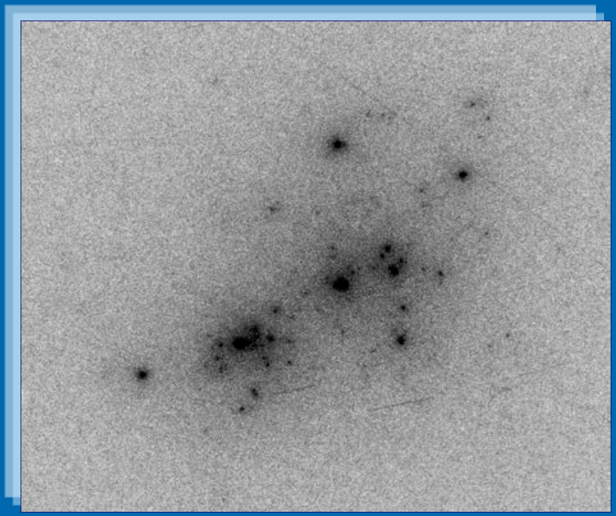
Specific features of collider experiments

- **Particles, which are produces in the forward cone of phase-space with high values of pseudo-rapidity *η* (i.e., in so-called fragmentation region of the projectile particle), are practically inaccessible for studies at colliders due to their constructive peculiarities;**
- **The significance of this kinematic region increases with interaction energy and it begins to play a crucial role in the investigated range of primary energies, since about 90 % of total released energy is deposited in this range ($\eta \geq 5$) already at the LHC energy ($E_0 \sim 10^{17}$ eV);**
- **Thus, it is not by chance that models of hadron-nuclear interactions that are based on** low energy accelerator data and which are currently used for data analysis of experiments with ultrahigh-energy cosmic rays, provide significantly different predictions for the LHC results.



Distributions of charge particle number (left) and energy flux (right) over pseudo-rapidities *η* at $\sqrt{s}$ = 14 TeV according to predictions of various models.

'Pamir' experiment



Observables:

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

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

A family definition and selection criteria:

a collimated ($\Delta\theta \leq 3°$, $\Delta\varphi \leq 15°$) 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 $ST \sim 4000$ m^2•yr

Available statistics: $N_f \approx 2000$

The Pamir-Chacaltaya experimental results

Since 1980, the members of the *Pamir* collaboration worked side by side with physicists engaged in the *Mt.Chacaltaya Experiment* in the framework of the *Pamir-Chacaltaya Joint EC Experiment* and carried out several joint expositions both at the Pamirs and Mt.Chacaltaya the results of which were analyzed in numerous joint papers:

- in the energy range $E_0=5\cdot10^{14} - 3\cdot10^{15}$ eV which corresponds to released energies $\Sigma E\gamma = 100 \div 400$ TeV, QGS model-inspired simulation codes (MC0, MQ, etc.) incorporating hard jet production and based on extrapolation of accelerator data produce a good fit to the main experimental results;
- estimation of the inelastic cross-section for $p^{14}N$ interactions gave a value of 360 ± 40 mb;
- increase of the inelasticity coefficient K for $p^{14}N$ reactions from $K=0.5$ at accelerator energies up to $K= 0.78$ at $E_0\approx10^{16}$ eV;

The Pamir-Chacaltaya experimental results

- scaling violation in the fragmentation region for pion production was established, i.e., the inclusive cross-section falls 2-3 times at $x=0.3$, when energy increases from values formerly attainable with accelerators to those under investigation, due to re-scattering of particles from nucleons inside a nucleus;
- estimation of transversal cross-section for quark-gluon string production $\sigma_{jet} = (24 \pm 7)$ *mb* at jet transverse momentum $p_t^{jet} \geq 3$ *GeV/c* and $X_j^F > 0.05$;
- existence of the Landau-Pomeranchuk-Migdal effect was confirmed.

However, even in the low energy range $E_0=5{\bullet}10^{14}– 3{\bullet}10^{15}$ *eV* experimental data exhibit larger fluctuations than simulated ones (Centauro events, penetrating particles, etc.) which can be account for by under estimation of chamber response only partially.

Unusual events

In the energy range $4 \cdot 10^{15} \div 10^{17}$ eV significant discrepancies between experimental and simulated data are observed more distinctly.

The most challenging phenomena are:

- the coplanar emission of the most energetic hadrons and γ-rays in the multiple particle production (so-called 'alignment effect');
- Centauro- and Anti-Centauro-type events events with abnormal ratio of charged to neutral particles (pions);
- abnormal behavior of a hadron absorption curve, which significantly deviates from exponential law at large depths in lead absorber (so-called 'long-flying CR component');
- appearance of several fronts in horizontal EAS

Abnormal events

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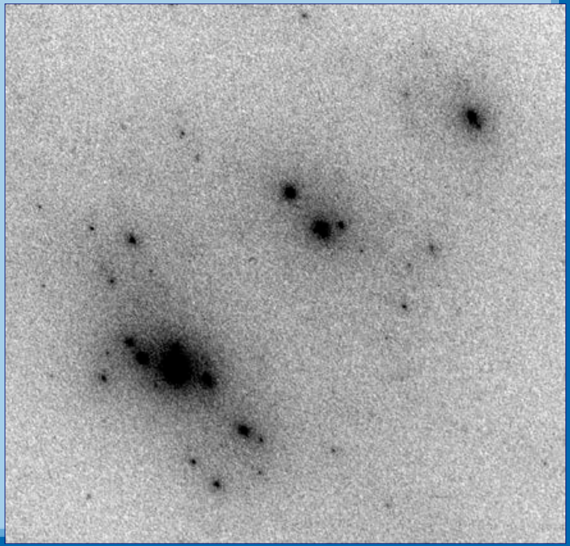
Phenomenon of coplanar emission of hadrons



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 a certain straight line in the target plane .

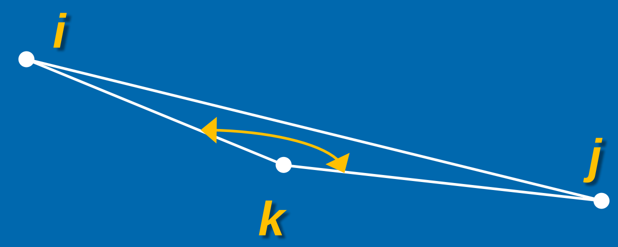
The highest energetic cores (HEC) in a family can be represented by:

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

The Alignment Criterion

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

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

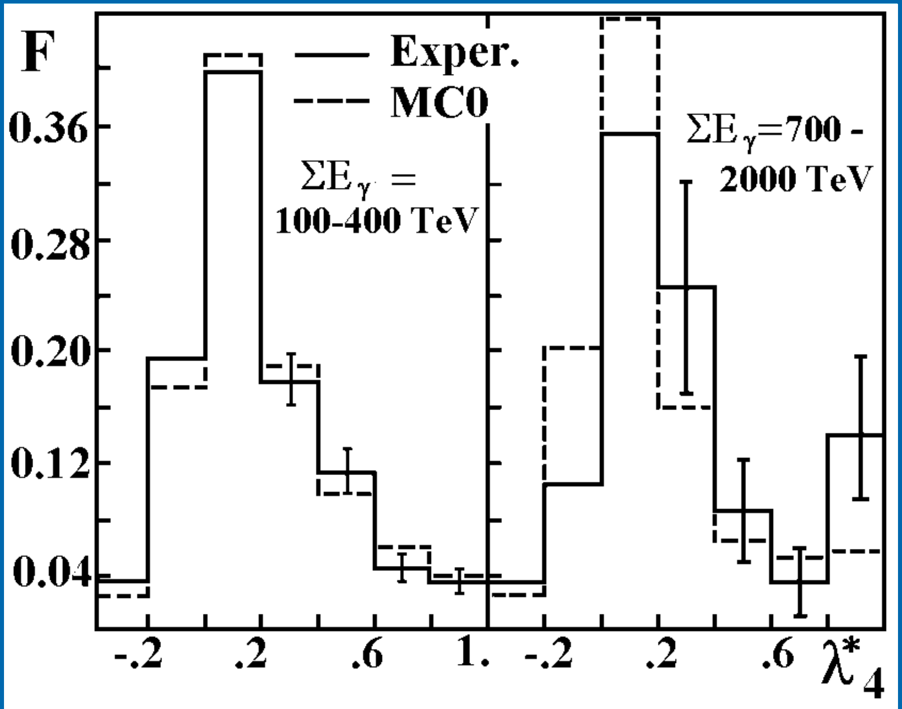


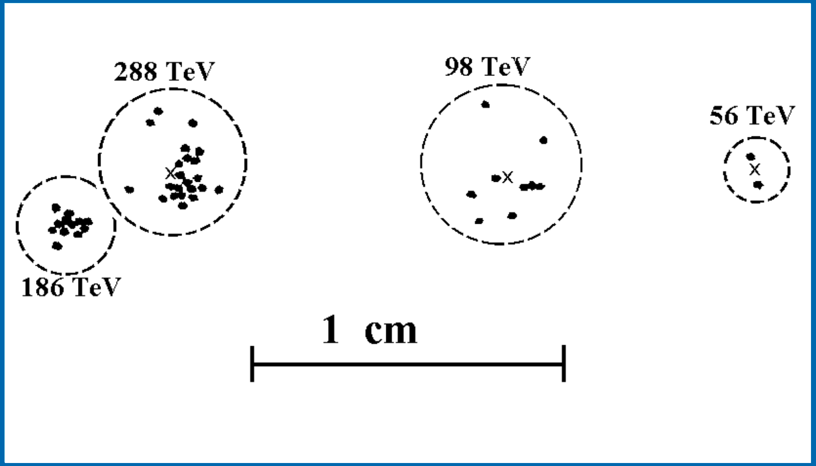
where φ_{ijk} is the angle between the straight lines connecting the *i*-th and *j*-th cores with the *k*-th core.

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.

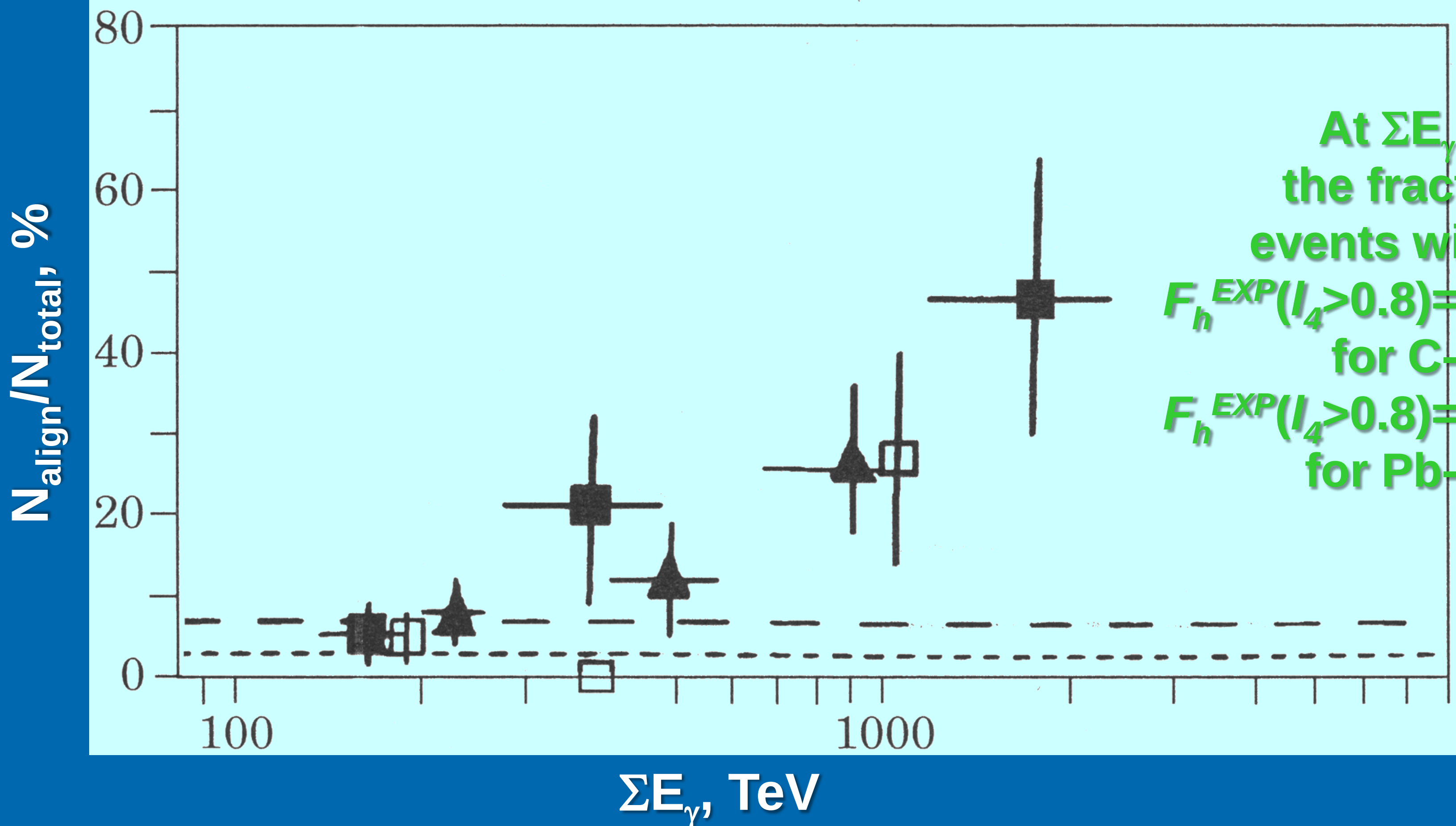
Aligned γ-families





Example of the target diagram of an aligned superfamily. Circles schematically show particles unified into clusters.

λ_4-distribution of experimental and simulated γ-families in two energy ranges after applying clusterization procedure $\chi_{ij} = R_{ij}\sqrt{E_i E_j} \le \chi_c = 48\,TeV \cdot cm$



At $\Sigma E_\gamma \geq 700$ TeV
the fraction of the
events with $\lambda_4 \geq 0.8$
$F_h^{EXP}(l_4>0.8) = 0.26 \pm 0.09$
for C-chambers
$F_h^{EXP}(l_4>0.8) = 0.43 \pm 0.17$
for Pb-chambers

Dependence of the fraction of families with alignment on ΣE_γ

Experiment: ■ Pb-chamber data, □ C-chamber of the Pamir Joint Experiment, ▲ Pamir C-chamber

Simulations:

— — — simulated families with MC0-model

- - - - - randomly incident objects

Main treats of coplanar production of hadrons in the most forward region:

- existence of an energy threshold for aligned event production ($\Sigma E\gamma \geq 700$ TeV $\leftrightarrow E_0 \geq (5\div8)\cdot10^{15}$ eV);
- related to most energetic particles;
- large transverse momentum (about several GeV/c);
- A ratio of longitudinal component $\langle p_t \rangle^{\parallel}$ of the average transverse momentum of secondaries to transverse component $\langle p_t \rangle^{\perp}$, determined in reference to the coplanarity plane, can be estimated as $\langle p_t \rangle^{\parallel}/\langle p_t \rangle^{\perp} \approx \langle R_c \rangle_4^{\parallel}/\langle R_c \rangle_4^{\perp} = 12\pm3$;
- considerable cross-section for the production ($\sigma^p_{copl} \sim \sigma^p_{inel}$) since nuclear cascade development and subsequent interactions should disrupt the coplanar pattern occurring in the first one.

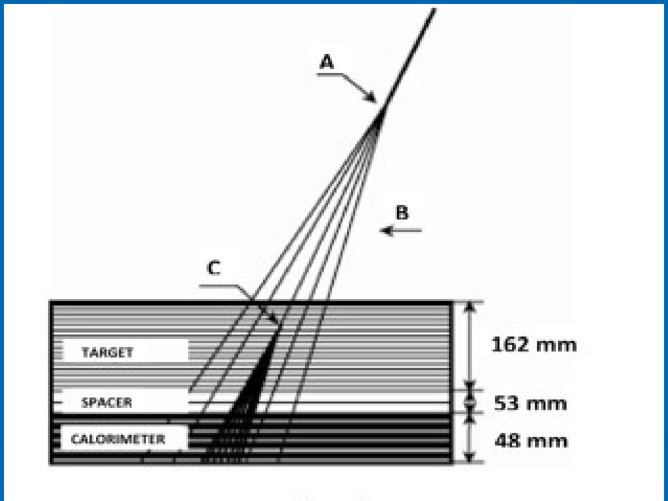
Aligned events in Stratosphere

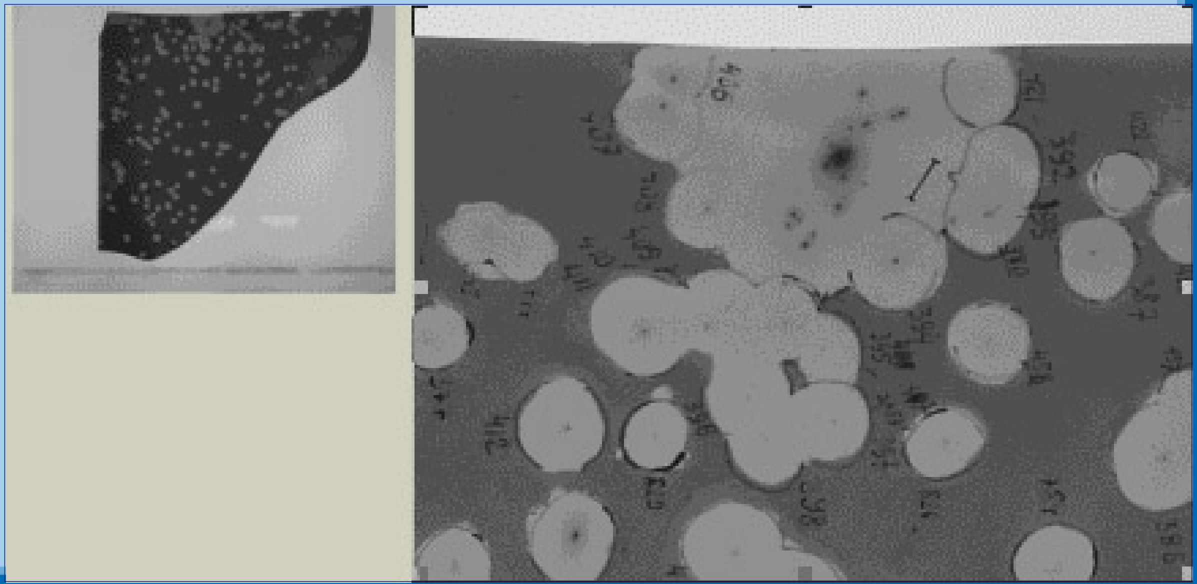
Two superfamilies induced by the PCR particles with $E_0 \geq 8 \bullet 10^{15}$ eV were once detected at the balloon and aircraft-borne EC experiments by chance and both of them appeared to be extremely aligned ($\lambda_4 > 0.99$):

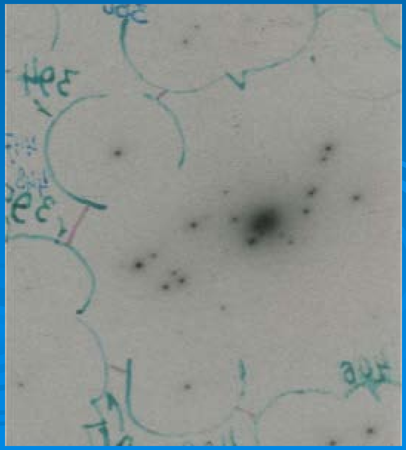
Event	H (g/cm^2)	E_{th} /Tev/	N_γ	N_h	ΣE_γ /Tev/	ΣE_h /Tev/	λ_4	λ_{38}
JF2af2 (Concorde)	100	0.2	211		1586		0,998	0,95
'Strana' (baloon)	10	2.0	76	30	1400	2500	0,99	0,99

Aligned event: 'Strana' superfamily

Baloon-borne experiment carried out by Prof. Dobrotin and his colleagues of Lebedev Physical Institute in 1975



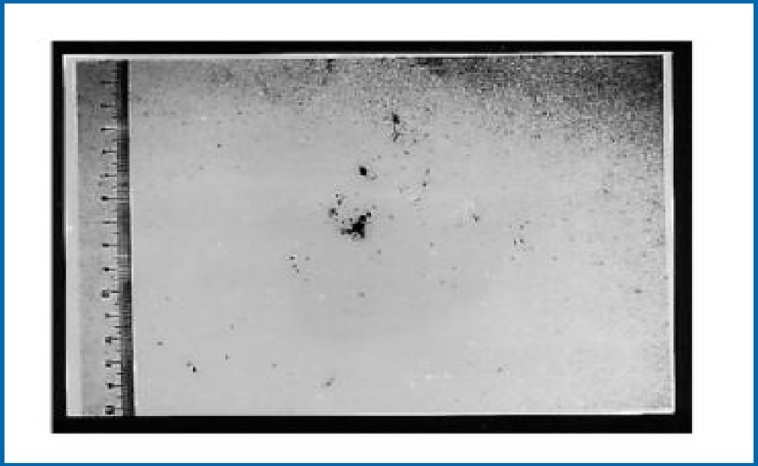


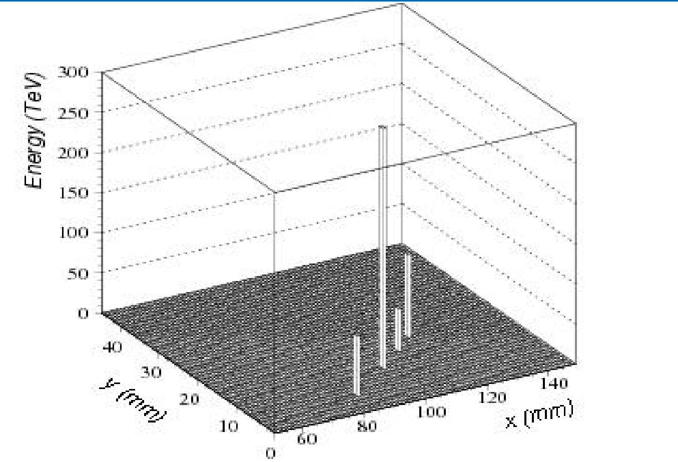


Estimated primary energy

$E_0 \approx 2*10$^16 eV

Aligned event: JF2af2 (Concorde)





- Xray film under 8 c.u.
- Lego plot with the 4 most energetic gamma's

34 g 's are aligned (about **50%** of the visible energy)
3 most energetic clusters (A,AP,B) each containing the highest energy gammas (about **33%** of the visible energy) are aligned :

	A	Ap	B
ΣE_γ /TeV/	331.0	455.4	610,6
N_γ	60	10	77
<R>	8.62	0.49	10.26

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 $\rightleftarrows$ 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*

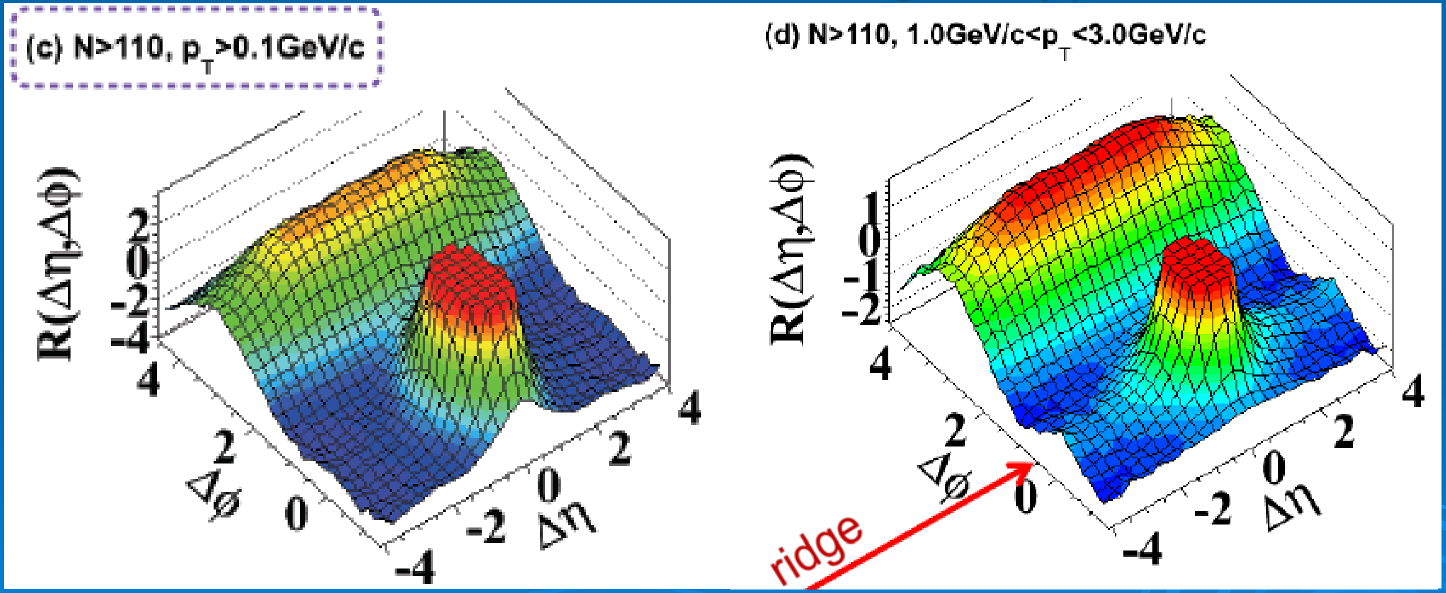
Conclusion: *the LHC experiments have the potential to discover correlations between jets in pp → 4 jet scattering processes if $\Lambda_3 \leq 1.25(1.6)$ TeV.* **/arXiv:1012.1870v2/**

Alignment phenomenon: possible explanations

- ***alignment of HEC is a projection of rupture of the quark-gluon string produced in the process of hard double inelastic diffraction dissociation**, the string being inclined between a semihard scattered fast quark and the incident hadron remnants* (I.Royzen).
- ***Accelerator experiment indications: ridge effect (***Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC with CMS)

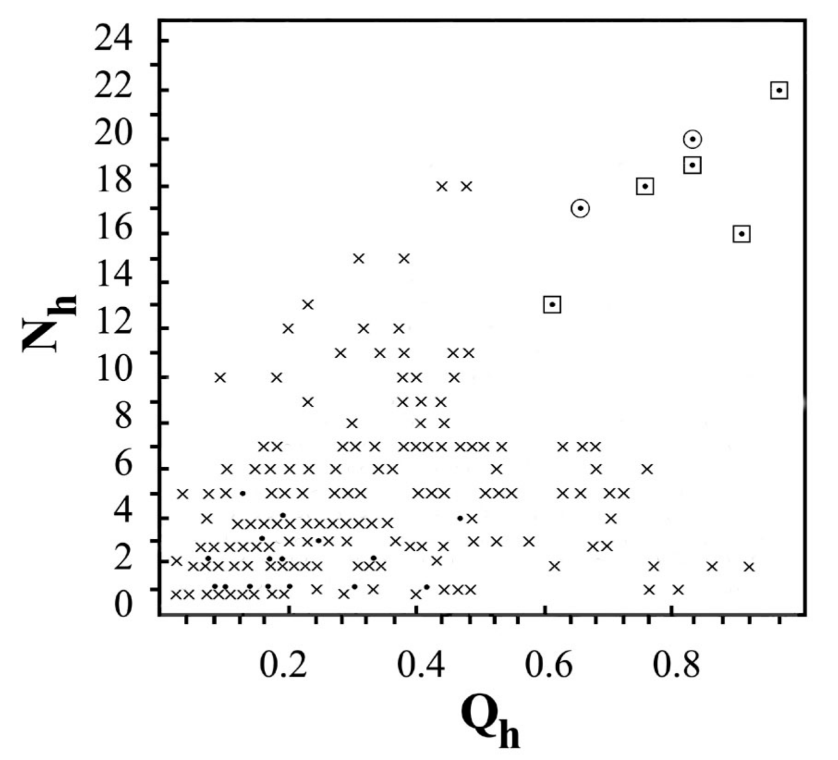
Alignment phenomenon: possible explanations

- ***Accelerator experiment indications: ridge effect*** (Observation of Long-Range, Near-Side Angular Correlations in Nucleus-Nucleus and Proton-Proton Collisions, recently found at RHIC and LHC, i.e., essential excess of events with $\Delta\varphi$ close to zero and large $\Delta\eta$.)



2-D two-particle correlation functions for 7 TeV pp: (c) high multiplicity (N ≥ 110) events with p_T > 0.1 GeV/c and (d) high multiplicity (N ≥110) events with 1 < p_T < 3 GeV/c.

Centauro-type events



N_h* vs. *$Q_h=\Sigma E_h^{(\gamma)}/(\Sigma E_\gamma+\Sigma E_h^{(\gamma)})$

(Dots stand for experimental events while crosses refer to simulated ones. Candidates for Centauro-type events in the *Pamir* and the *Chacal-taya* experiment data are marked by squares and circles, respectively).

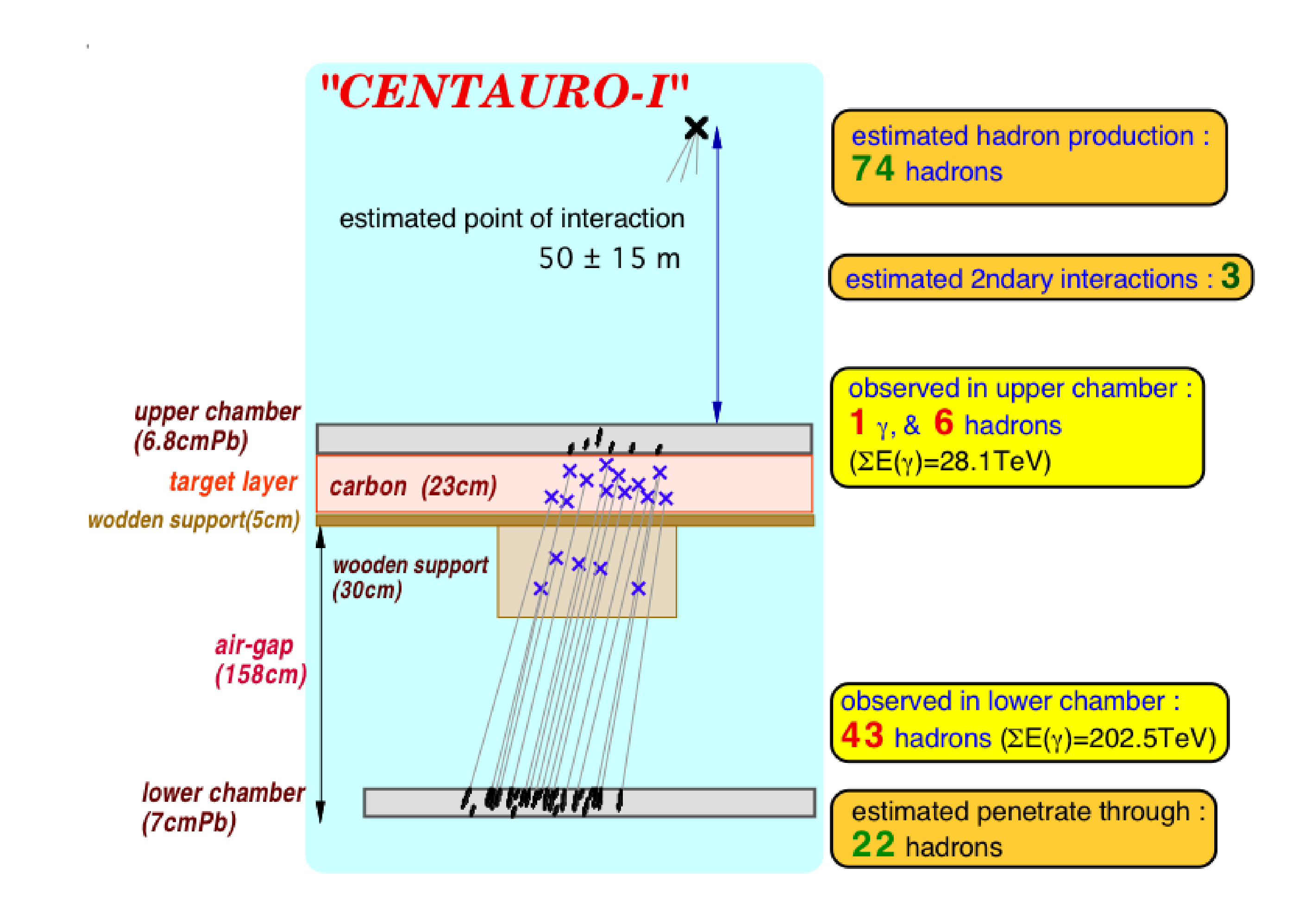
Centauro **events first observed by the Japan-Brazil Collaboration in a two-storey emulsion chamber exposed at the Mt.Chacaltaya are distinguished by abnormally high fraction of energy carried by charged hadrons as compared to that of gammas.**

Pamir experiment:

88 γ-h families were analysed with visible energy $\Sigma E_\gamma+\Sigma E_h^{(\gamma)} \geq 100$ TeV which were detected by deep uniform Pb-chambers of 60 cm thick with total exposition of 132 $m^2 \cdot$year.

CENTAURO : original data and interpretation

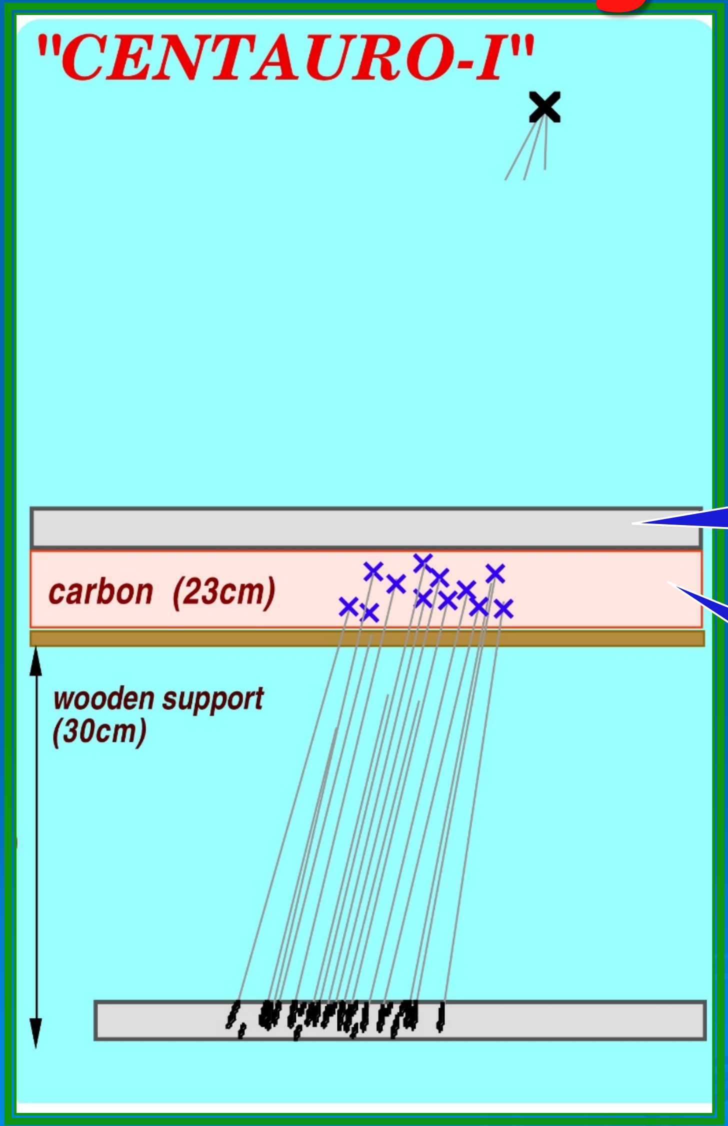
M.Tamada, 2008



N_h~100, $< p_t >$ ~1.5 GeV/c , non-π^0 production

Re-analysis of Centauro-I event: again very exotic !!

M.Tamada, 2008



a bundle of hadrons w/o accompanying γ-rays

no collisions in the upper chamber !!

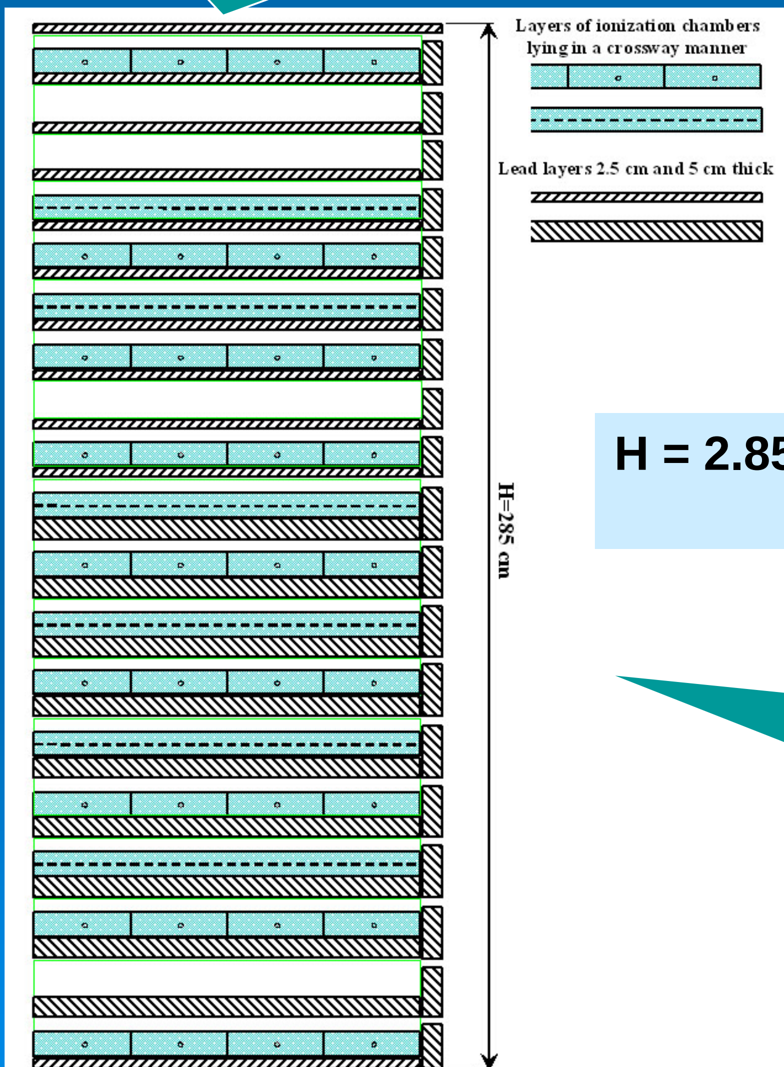
≥ 28 collisions In the target layer !!

Abnormally weak hadron absorption in lead

The Tien-Shan High Altitude Cosmic Ray Station

Big Ionization Calorimeter within EAS array at the Tien Shans in 1973 - 1974

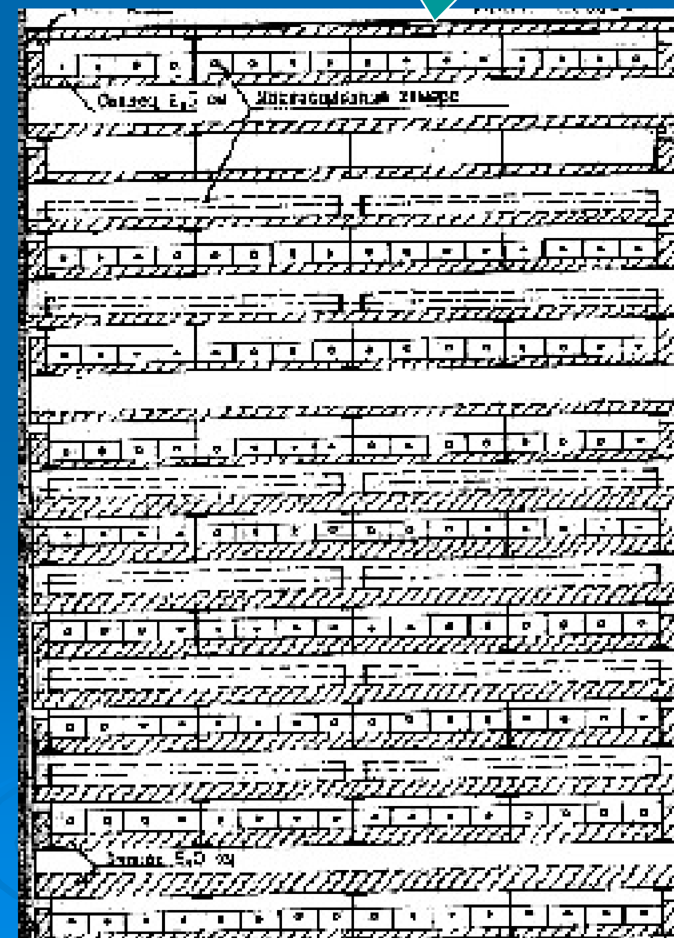
Profile of the BIC with lead absorber



H = 2.85 m (850 g/cm^2)
S = 36 m^2

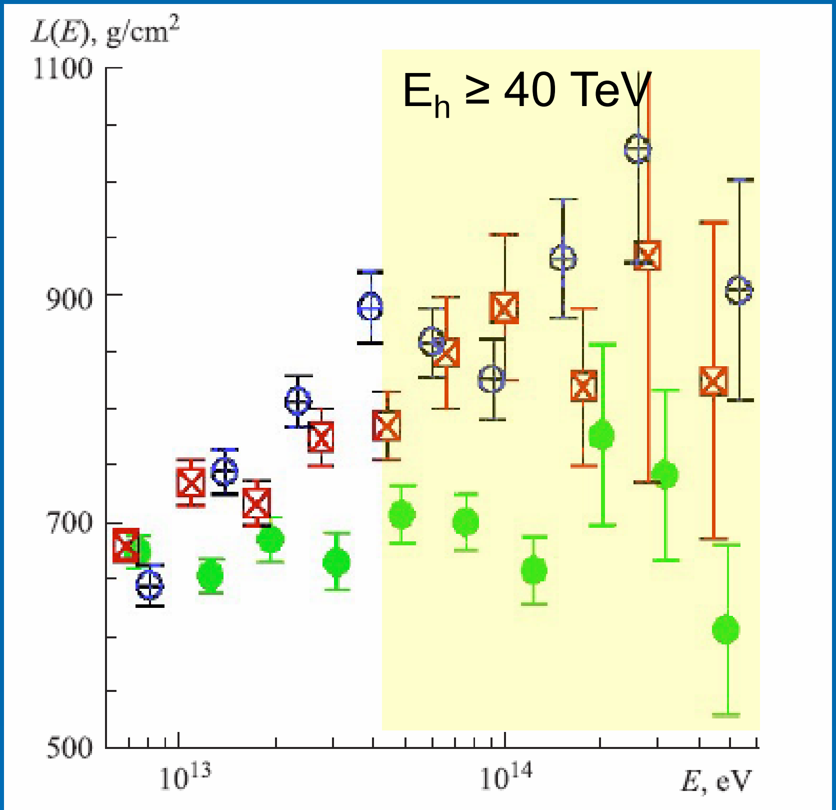
15 layers of ionization chambers in total

Historical layout

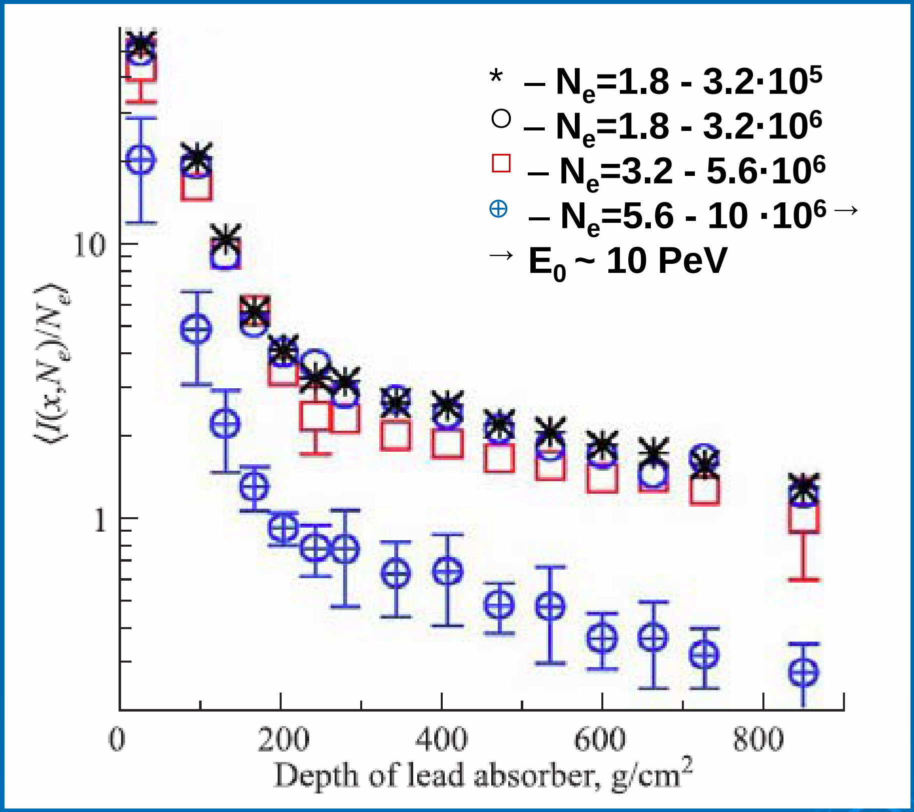


Tien Shan effect: 'Long-Flying' CR component

!!! Evidence of abnormally weakly absorbed EAS cores in lead !!!



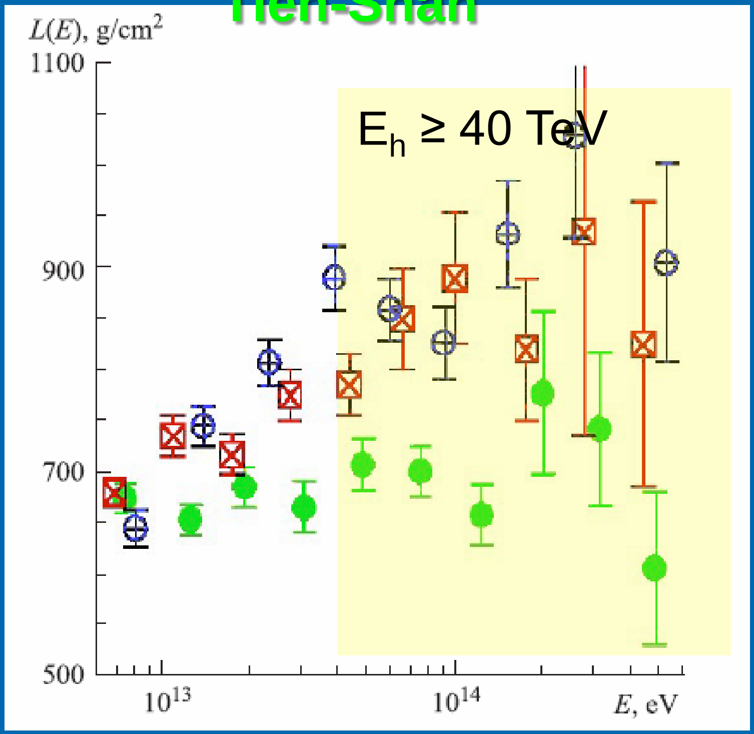
Attenuation length L(E) of hadronic component in EAS cores observed with ionization calorimeter: cross-circles – experiment, solid circles – Monte Carlo without charm, crossed squares – Monte Carlo simulation with charm.



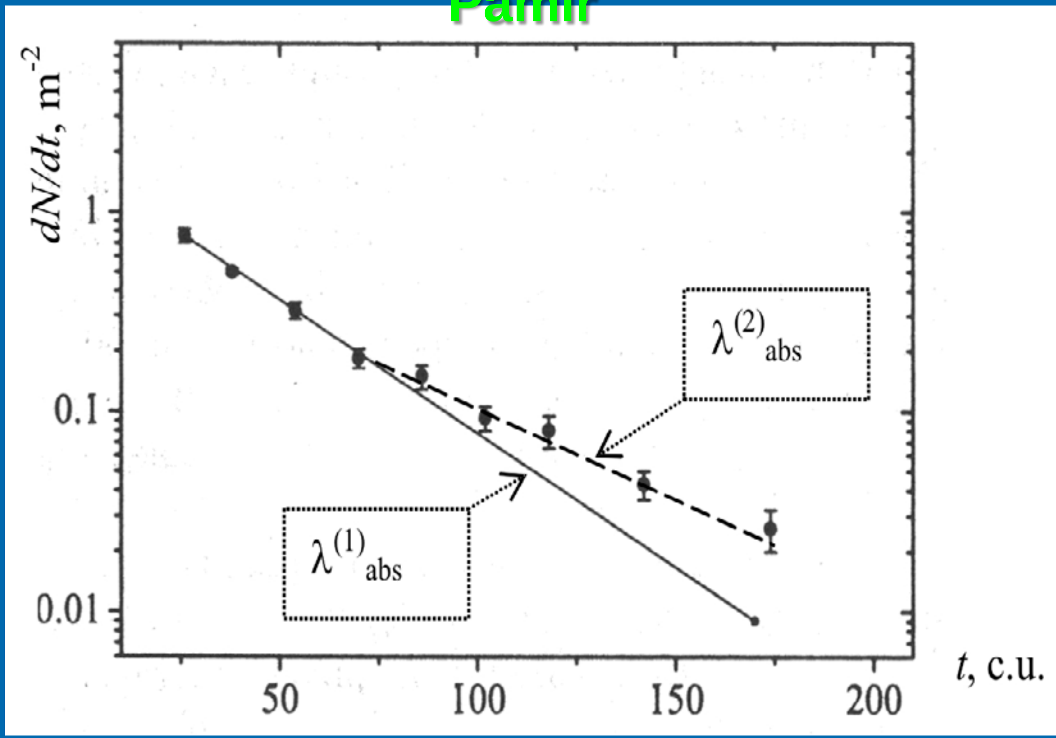
Absorption curves of e-h cascades in the calorimeter normalized to EAS size when the showers are grouped by energy release E_h.

Nature of 'Long-Flying' component

Tien-Shan



Pamir



Two hypotheses were introduced two explain the effect:

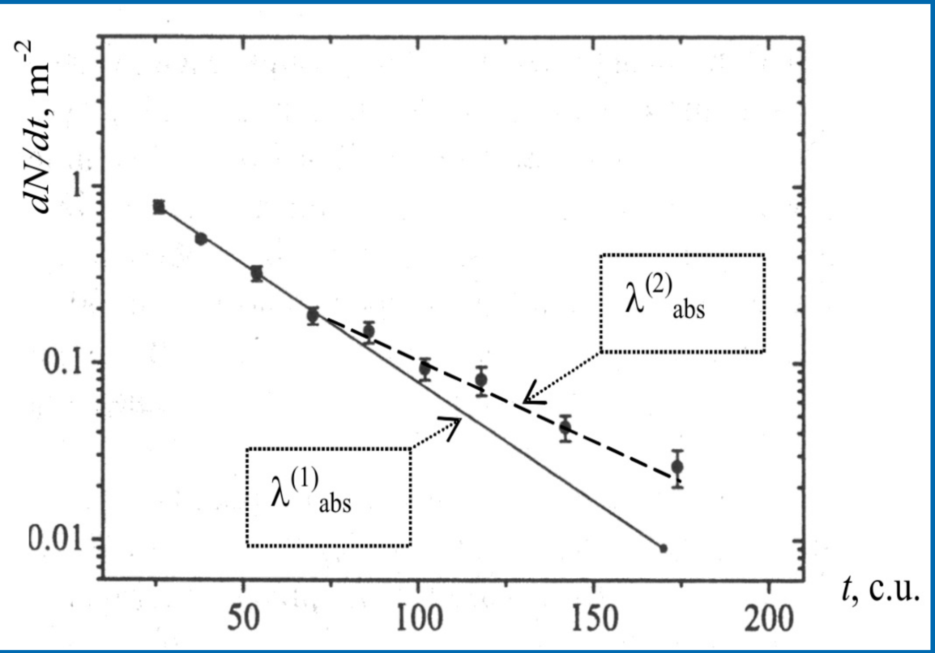
- **considerable contribution of charm particles (I.Dremin, V.Yakovlev);**

/Note that production cross sections at √s < 20 GeV were quite small, i.e., σ_c^{prod} ~10 μb/

- **manifestation of quark strange matter/existence of strangelets (Z.Vlodarchik, E.Gładysz-Dziaduś, S.B.Shaulov, etc.).**

Both candidates can carry effectively the energy deep through the lead absorber.

Penetrating hadrons with abnormal absorption



Distribution of the cascade origin points for hadrons with $E_h^{(\gamma)} \geq 6.3$ TeV obtained in the Pamir experiment by means of homogeneous Pb-chambers 110 cm thick.

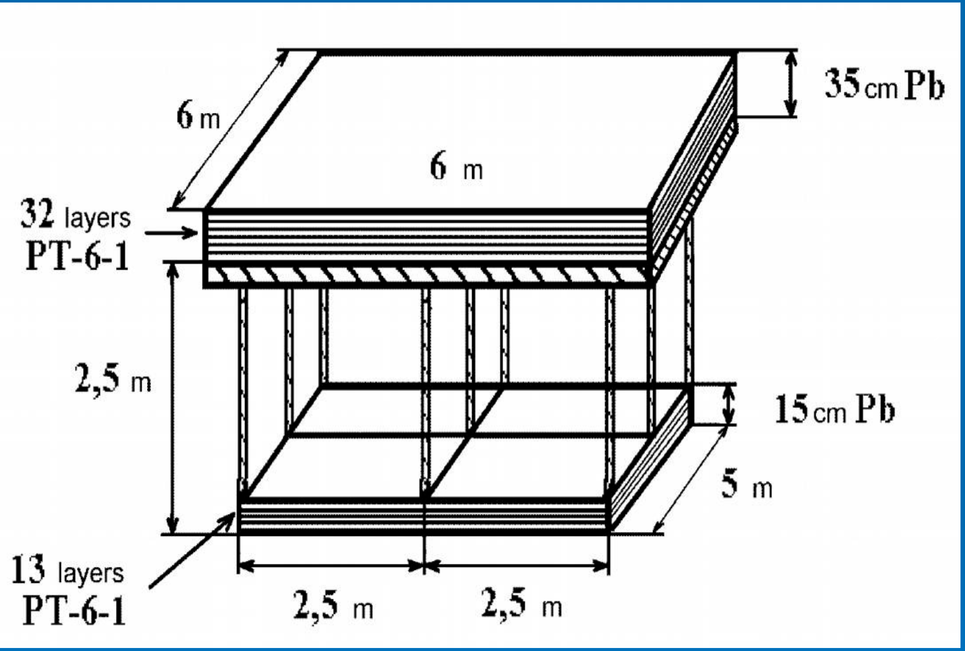
In the range of 0÷70 rad. lengths, the absorption curve obeys the standard exponential law with index $\lambda^{(1)}_{abs}$=(200±5) g/cm^2. However, at larger depths (>70 c.u.), the absorption length of hadrons in lead changes and becomes as high as $\lambda^{(2)}_{abs}$=(340±80) g/cm^2.

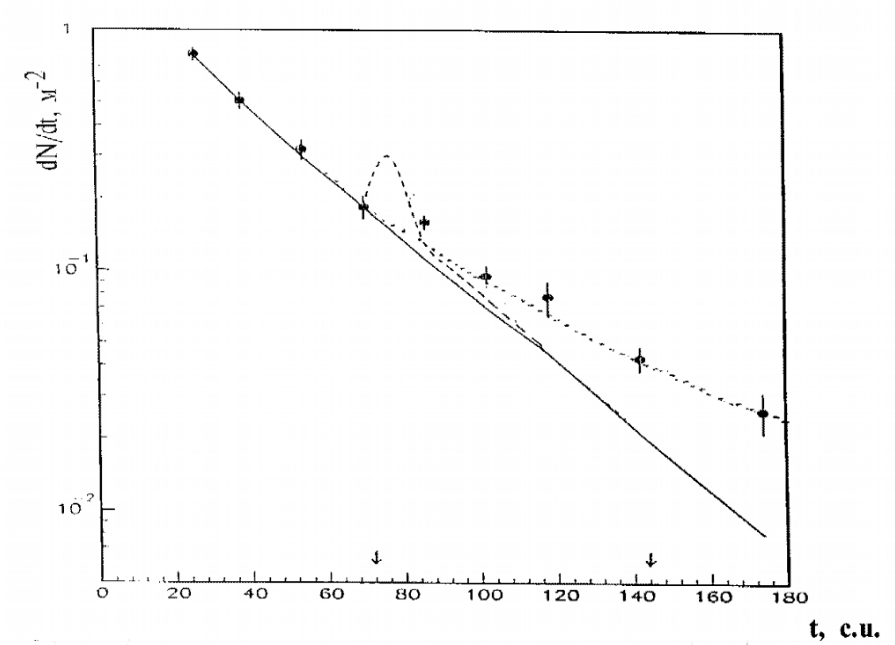
This unusual phenomenon seems to be similar to that discovered earlier at the Tien Shan Mountain Station when absorption of EAS hadron cores in an ionization calorimeter with lead absorber was studied (a hypothesis of *long-flying component* of cosmic rays introduced by V.I. Yakovlev).

Testing of the charmed origin of penetrating particles with 2-tier XREC

Hypothesis: Excessive cascades are initiated by charm particles

/Feinberg, Dremin, Yakovlev/ ($\sigma^{prod}_{\Lambda_c, D} \approx 3$ mb/nucl. at $E_L \geq 20$ TeV, $x_F > 0.1$)





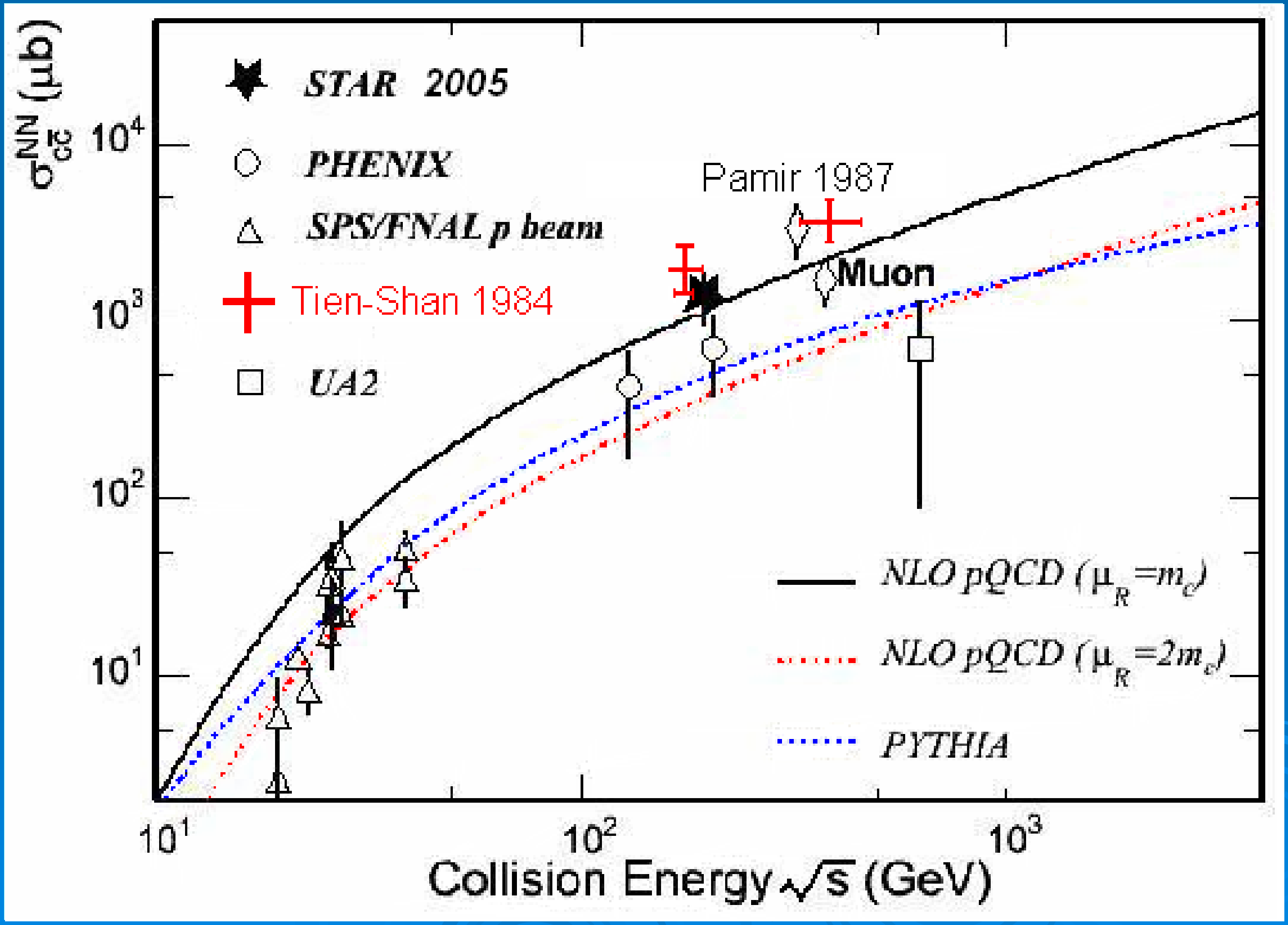
- A Lay-out of a 2-storey XREC with 2,5 m air-gap *(L.G.Sveshnikova et al.)*

$$H = c\tau\gamma = c\tau \frac{E}{m} \approx 2.5 \text{ m}$$

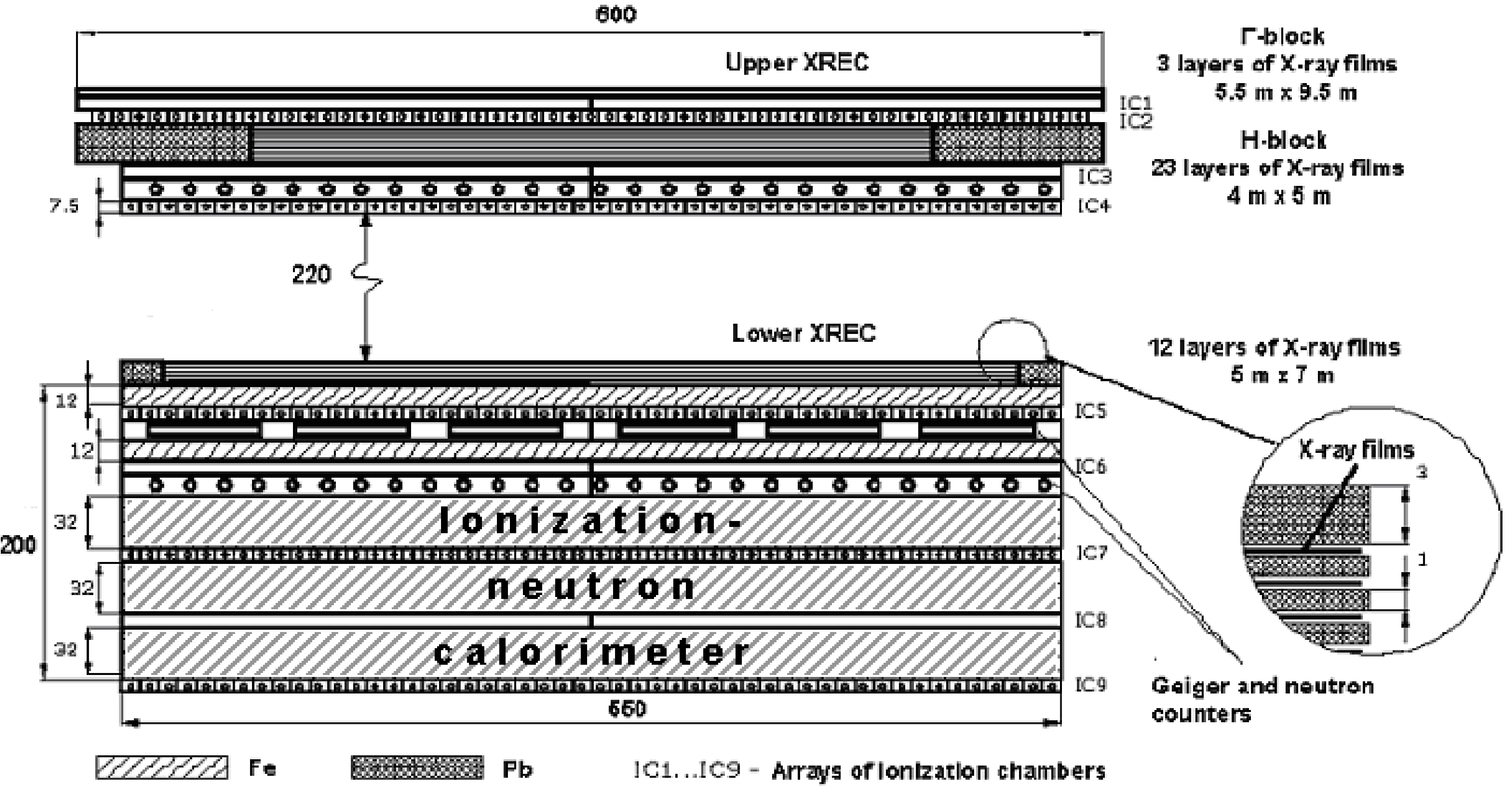
- Distribution of cascade origin points in deep uniform lead chamber and in 2-storied XREC with 2,5 m air-gap

RHIC experiments (STAR, PHENIX)

STAR: $\sigma_{c\bar{c}}^{NN} =$ **1,4±0,2±0,4 mb; PHENIX:** $\sigma_{c\bar{c}}^{NN} =$ **0,92±0,15±0,54 mb at $\sqrt{s}$ = 200 GeV in d-Au collisions**



Two-storey X-ray emulsion chamber with air gap at the Tien Shan Mountain Station (3340 m a.s.l.)

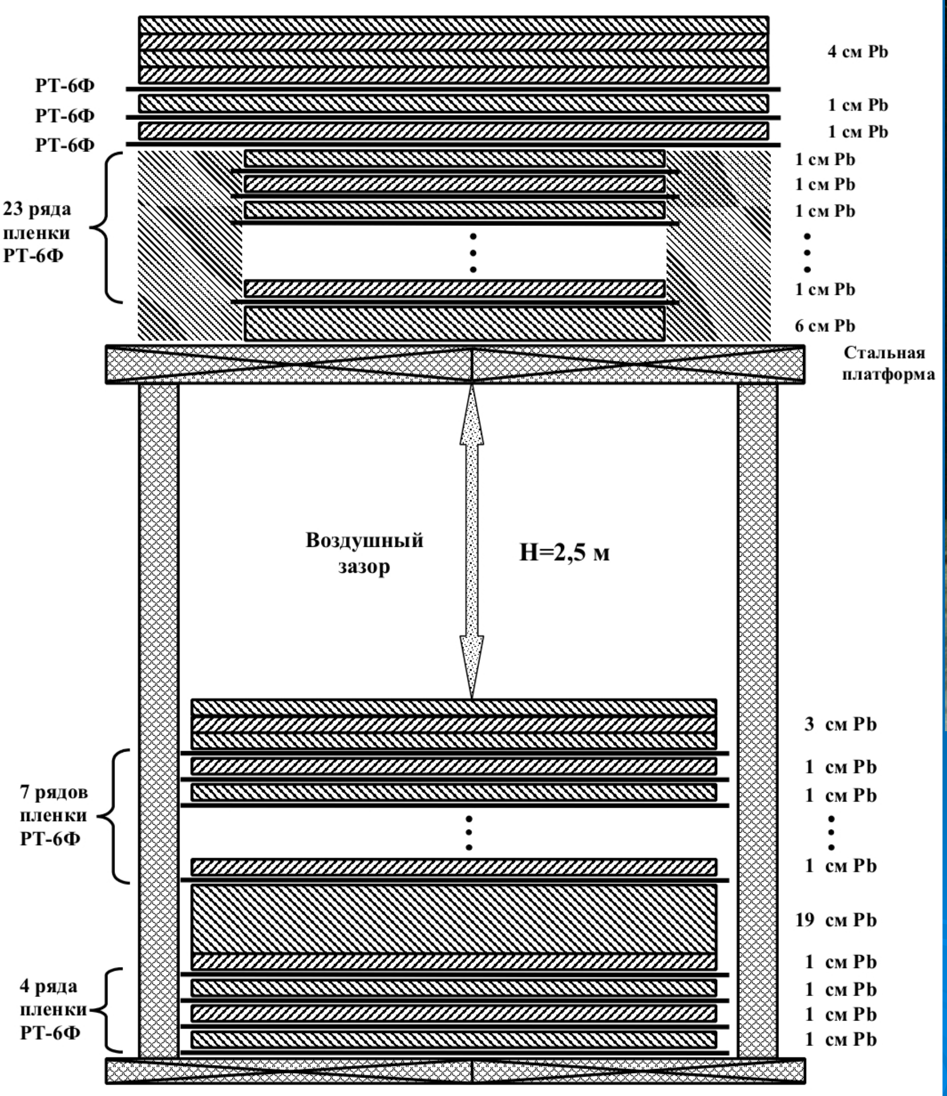


➤ A section view of ionization-neutron calorimeter with 2-storied X-ray emulsion chamber at the top of it (project).

Upper storey of XREC with 2.2 m air gap at TSMRS (assembled in 2004)

Lower storey of XREC with 2.16 m air gap at TSMRS

Exotic Phenomena study with 2-tier XREC at the Pamirs



The envisaged goals of the experiment:

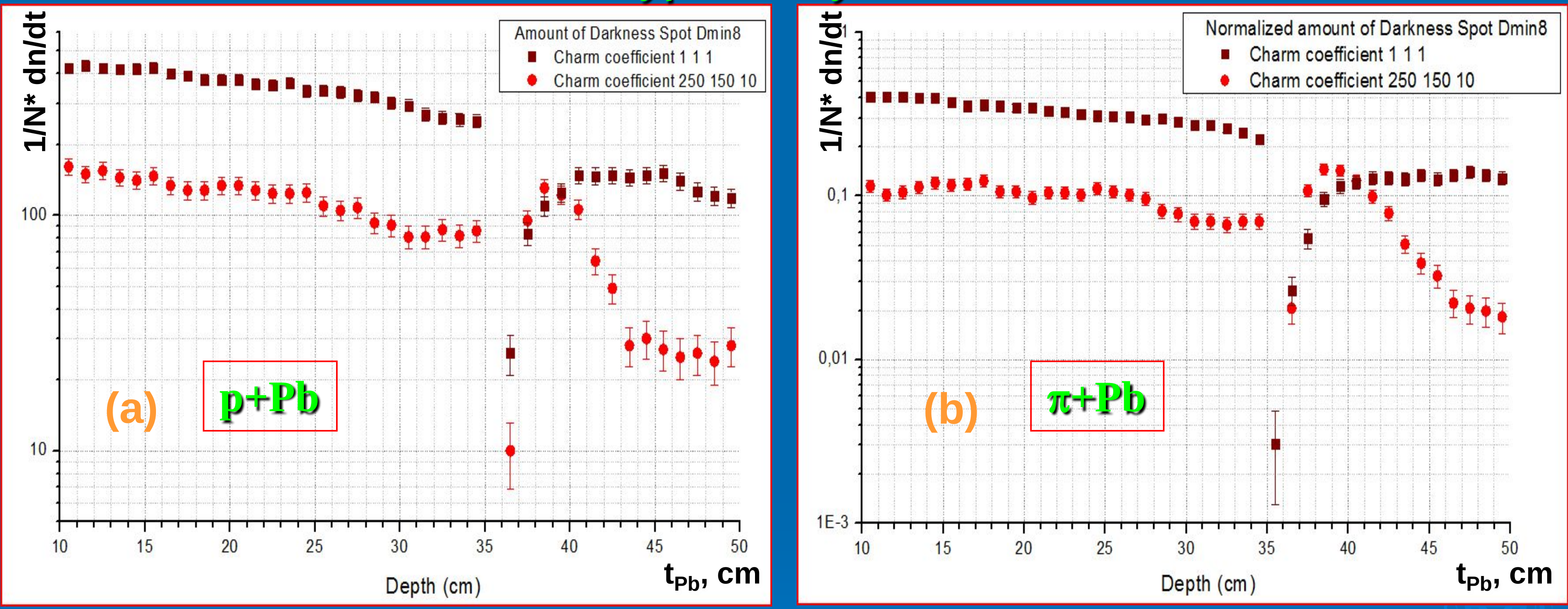
- origin of penetrating hadronic particles (strangelets or charm hadrons);
- search for Centauros;
- study of coplanarity phenomenon.

Simulation of 2-storey XREC response with ECSim 2.0+FANSY 1.0 code accounting for charm production

- **MC code FANSY 1.0 (developed by R.A. Mukhamedshin of INR RAS) represents a phenomenological hadronic interaction model implementing quark-gluon string theoretical approaches and assuming various charm production cross section parameters (in many features close to QGSGETII model except for the x-spectra of secondary particles including charmed ones: they appeared to be too soft as compared to the LHC data).**
- **MC code ECSim 2.0 is based on GEANT 3.21 and allows to calculate the detector response for XREC of a given design taking into account the exact experimental technique used in the 'Pamir' experiment.**

Simulation of 2-storey XREC response with ECSim 2.0+FANSY 1.0 code accounting for charm production

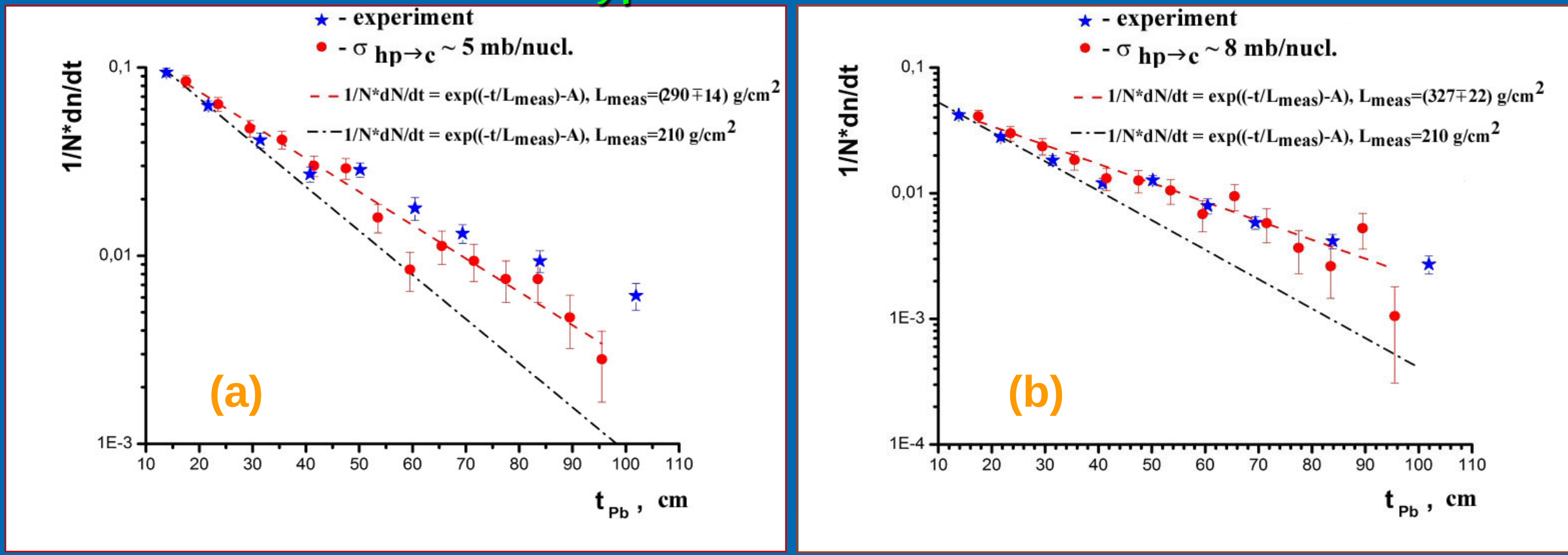
Pamir-type 2-storey XREC



Distribution of darkness spots produced by incident protons (a) and pions (b) in 2-storey XREC in the case of conventional charm production cross section and abnormally high one ($\delta_c = \sigma_c^{hPb} / \sigma_{in}^{hPb}$ = 0.2÷0.5 , $\sigma_{pp \to cc}$ ~ 5÷8 mb at $E_L \approx$ 75 TeV)

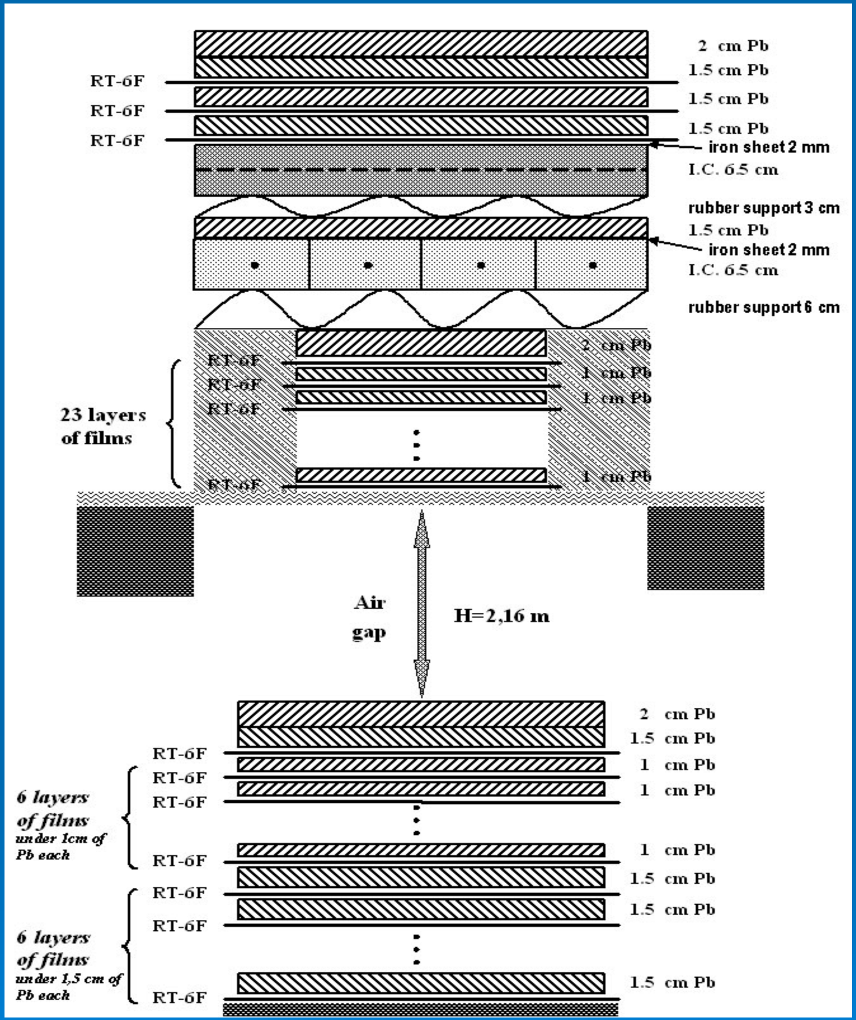
Analysis of data obtained with homogeneous lead XREC 110 cm depth

Pamir-type uniform lead XREC



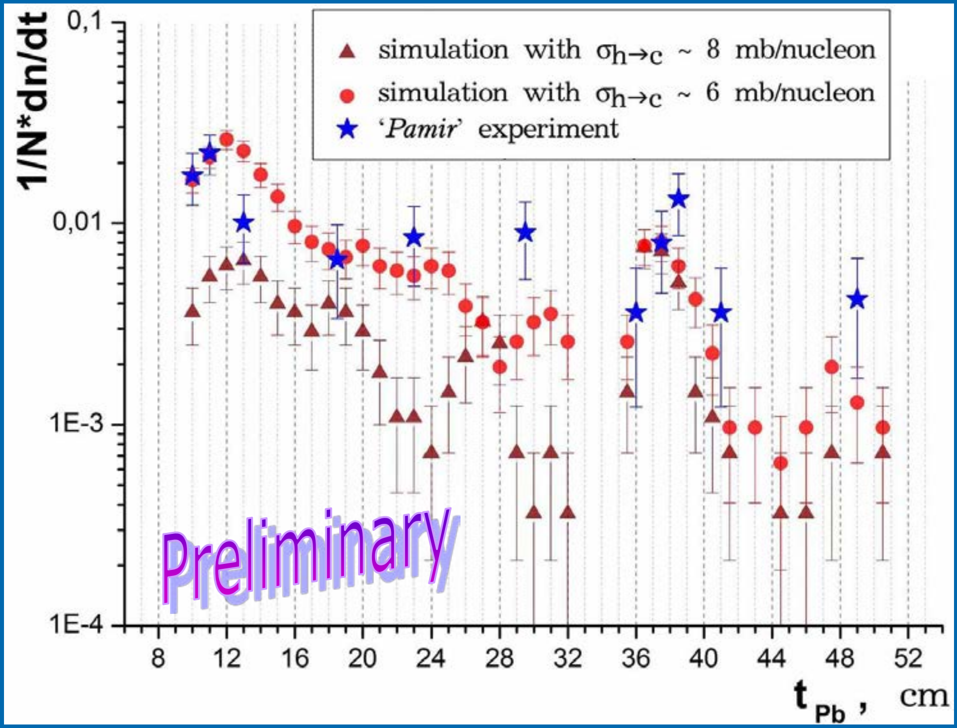
- **Distribution of darkness spots produced in homogeneous lead XREC if $\sigma_c^{prod} \approx$ 5 mb/nucl. (a) or if $\sigma_c^{prod} \approx$ 8 mb/nucl. (b) at $x_{lab} \geq 0.1$ on assumption that the fractions of nucleons and pions among incident particles are 70% and 30 %, respectively.**

Experimental data from 1-year exposition of 2-tier XREC at TSS



- A layout of 2-tier XREC at TSS

$S_{upper} = 48\ m^2$, $S_{lower} = 32\ m^2$, $E_\gamma^{th} \approx 5$ TeV



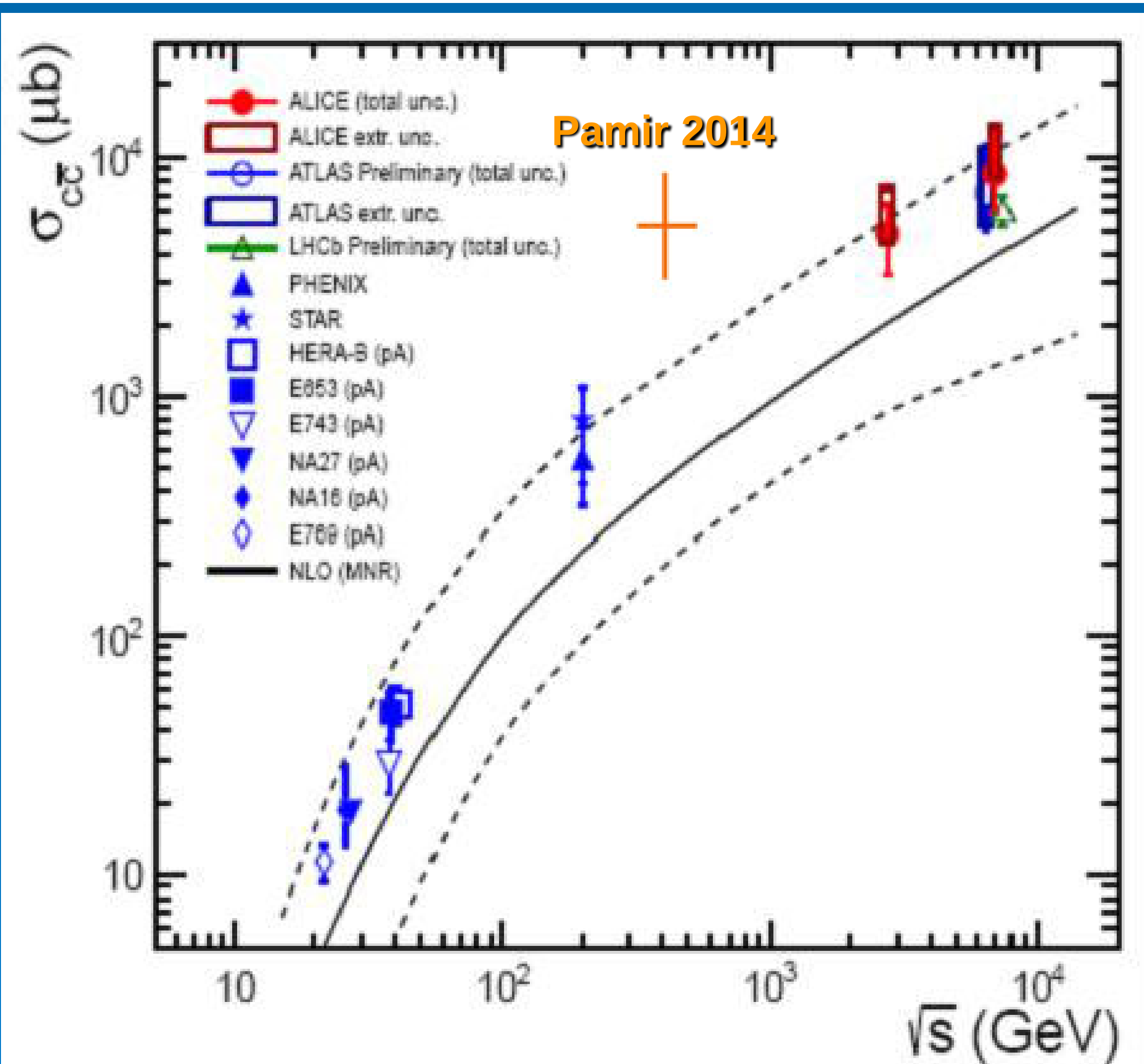
- Number of darkness spots produced by hadron cascades as a function of lead depth *t (experiment and simulation according to FANSY code with different options for σ_c^{prod} and accounting for chamber response with ECSim2.0 based on GEANT 3.21)*

$\sigma_{pp \to cc} \sim E^{0.8}$

Recent RHIC and LHC results

$$\sigma_{c\bar{c}}^{tot}(2.76\ \mathrm{TeV}) = 4.8 \pm 0.8\,(\mathrm{stat.})\,^{+1.0}_{-1.3}\,(\mathrm{syst.}) \pm 0.06\,(\mathrm{BR}) \pm 0.1\,(\mathrm{FF.}) \pm 0.1\,(\mathrm{lum.})\,^{+2.6}_{-0.4}\,(\mathrm{extr.})\ \mathrm{mb},$$

$$\sigma_{c\bar{c}}^{tot}(7\ \mathrm{TeV}) = 8.5 \pm 0.5\,(\mathrm{stat.})\,^{+1.0}_{-2.4}\,(\mathrm{syst.}) \pm 0.1\,(\mathrm{BR}) \pm 0.2\,(\mathrm{FF.}) \pm 0.3\,(\mathrm{lum.})\,^{+5.0}_{-0.4}\,(\mathrm{extr.})\ \mathrm{mb}.$$



LHC: The total charm production cross section at √S =2.76 TeV and at 7 TeV was evaluated by extrapolating from the central rapidity range to the full phase space.

Simulations: perturbative-QCD calculations accounting for Next-to-Leading Order corrections

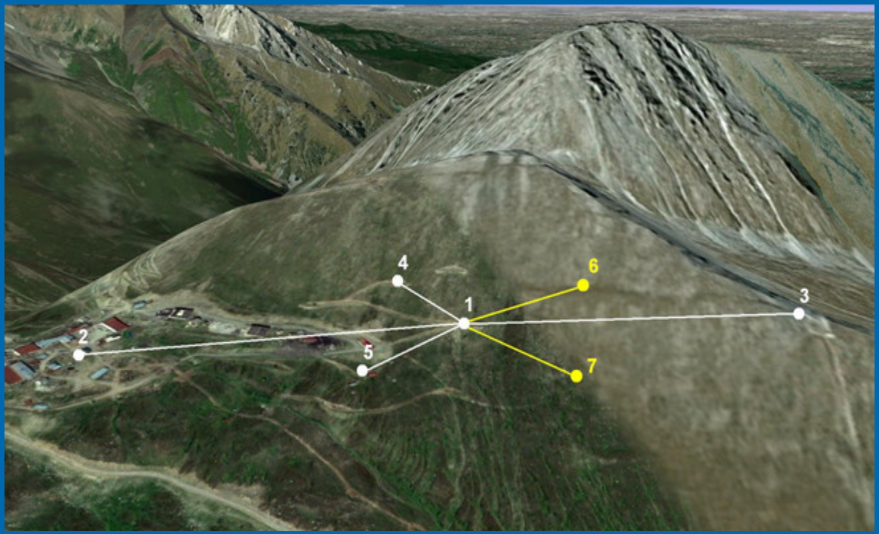
Important note.

Due to the high energy threshold ($E_{th} \geq 4$ TeV), XREC experiments observe production of the most forward particles, i.e., they can study the kinematic fragmentation region of a projectile particle:

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

Multimodal Horizontal Air Showers

The abnormal air showers with several successive fronts shifted by ~100 ns were first observed in the VEGA experiment while studying inclined showers ($\theta = 70 \div 85°$).



- The 'Horizon-T' experiment:

$A = S \cdot \Omega = 1\ km^2 \cdot sr$

$E_0 = 10^{16} \div 10^{18}\ eV$

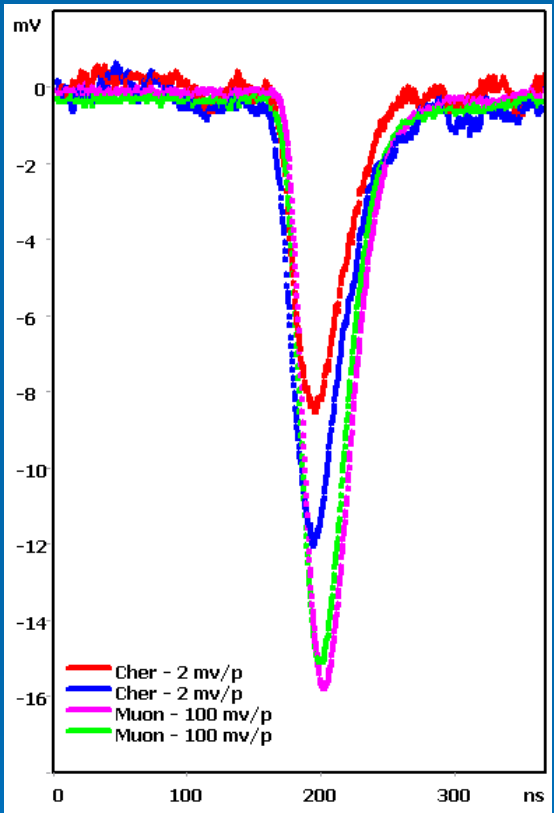
$\Delta\tau = 5\ ns.$

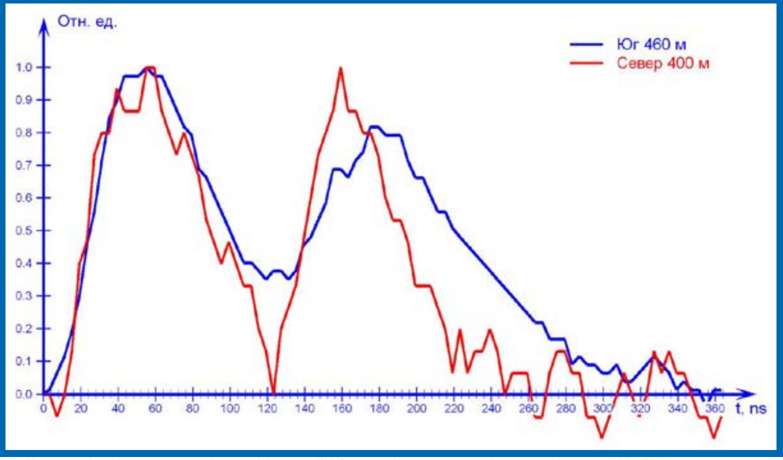
- CD are mounted on the rotating support allowing detection in zenith angle range of 0°-80° and in azimuthal angle range of 0° - 360°.

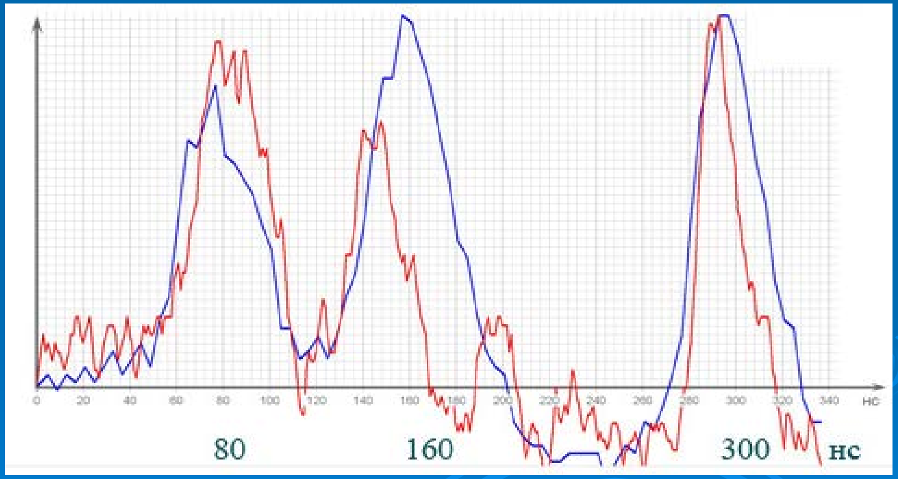
- The 'Horizon-T' experimental setup layout for inclined EAS lateral-temporal distribution study with ns accuracy making use both of Cherenkov light and muon component.

Now it consists of 7 stations with mutual distance as large as 900 m:
#1 contains 3 Cherenkov detectors made of a parabolic mirror of 1.5 m in diameter@focal length of 65 cm and a PMP ФЭУ-49 in the focal plane while other 6 stations have only few scintillation detectors of 1 m^2 in area which is stooped at 45° (26 in total).

Multimodal Horizontal Air Showers in the 'Horizon' experiment at TSS







An example of EAS with $E_0 = 10^{16}$ eV observed both with Cherenkov light and muons by two C-detectors and two scintillation detectors simultaneously (impulse duration is ~ 30 ns).

Examples of inclined (θ >70°) EAS with two and three shower fronts of very high energy: $E_0 > 10^{17}$ eV
(red and blue curves stand for different PMPs, i.e., ФЭУ-65 and ФЭУ-49, respectively).

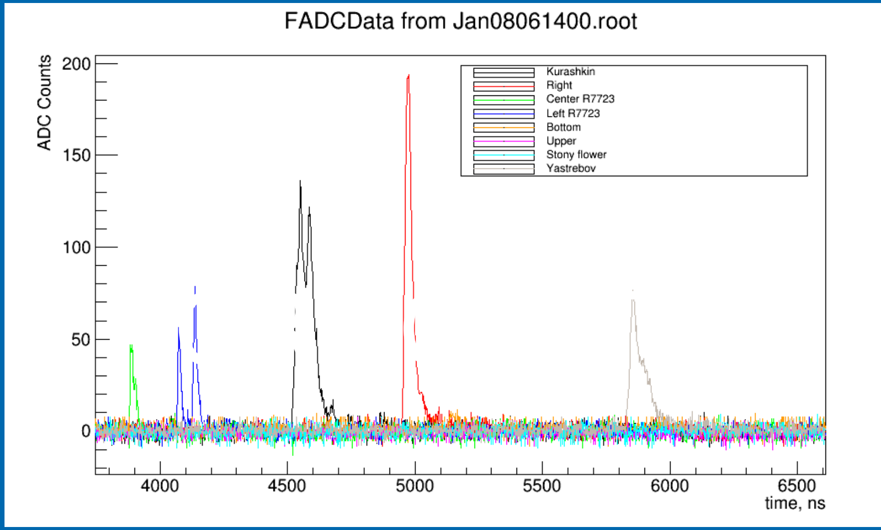
The 'Horizon-T' experiment: *preliminary results*

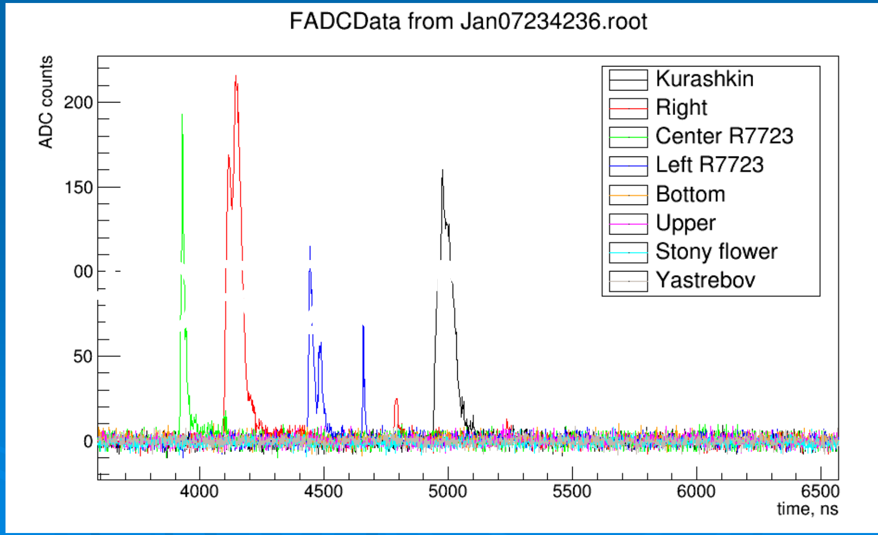
- **More than 300 multimodal inclined events with abnormal time structure have been detected by several stations simultaneously.**
- **The energy threshold of the phenomenon is $E_0^{th} = 10^{17}$eV.**
- **The majority of inclined events with $E_0^{th} = 5\cdot10^{17}$ eV are multimodal ones.**
- **Diurnal variation of multimodal events is absent (no preferential direction).**

Probable explanation: multimodal inclined EAS have several distant cores produced at the top or out of the atmosphere by separated groups of particles originated via decay of a massive particle (???).

EAS with Unusual Structure

- These are examples of 'unusual' EAS signals.
  - All hardware has been calibrated to ensure signal purity.
- First observed by J. Jelly and W. Whitehouse [12], attributed to delayed particle effect at the time.
  - J.V. Jelly and W.J. Whitehouse. Proc. Phys. Soc. (London) A66 454 (1953).
- Need delayed particle with mass ~10^{12} eV
  - Unknown particle
  - Particle creation probability ~$1/m^2$
- Called 'multimodal' at Horizon-T
- Very frequent at E>~10^{17} eV





CONCLUSIONS

- **Several new phenomena are observed in CRs with XREC at energies around and beyond the 'knee' energy which are hard to explain within conventional QCD processes (new physics beyond the SM ?).**
- **All unusual events and phenomena observed in EC experiments can be accounted for by an assumption of presence of highly penetrating particles in CRs which are able to penetrate deep in the atmosphere and then interact (or decay) nearby XREC producing halo events, coplanar events or Centauro-type events.**
- **Current CR experiments and scheduled ones at LHC (CASTOR, LHCf, ZDC, MoEDAL) will make it possible to study the observed phenomena in details.**