Search for disoriented chiral condensate in cosmic γ-hadron families

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We present a systematic study of the large asymmetries in neutral pion fraction distribution in high energy cosmic ray families (100 TeV $< E_{vis} <$ 700 TeV) detected at high mountain altitudes at Pamir (4300 m, 595 g/cm^2). With this in mind we have constructed robust observables, ratios of factorial moments, in experimental and simulated families in a similar way. We have found that our experimental data do not exclude the possibility of a DCC formation mechanism in high energy interactions. [S0556-2821(99)06901-5]

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I. INTRODUCTION

The study of hadron interactions through the observation of γ-hadron families produced by cosmic rays in the atmosphere and detected in emulsion chambers at mountain altitudes provides information on new phenomena in the far-forward region at superhigh energies still not very much explored by current experiments with colliders.

When a particle of primary cosmic radiation, for example, a proton, enters the atmosphere, it dissipates its energy in several successive interactions with atmospheric nuclei. Secondary particles originate in these successive interactions, forming an extensive air shower. The high energy particles (hadrons, electrons, and photons) are concentrated very close to the shower core and arrive at the observational level as a group of showers, called the γ-hadron family.

Emulsion chambers are electron shower detectors which are widely used in the mountain experiments of large exposure at Chacaltaya, the Pamirs, Mt Fuji, and Kambala [1]. The emulsion chamber is particularly suitable for observation of high energy electromagnetic components, called for simplicity gamma rays hereafter. The details of the experimental setup of the Pamir experiment are very well described in Refs. [2,3].

The characteristics of secondary particles (mostly pions and gamma rays) in a family are strongly dependent on the mechanism of nuclear interaction in the fragmentation region. Because of the high energy detection threshold in experiments with emulsion chambers, the investigation of high energy interactions is essentially limited to the projectile particle fragmentation region. This situation is opposite to collider experiments where secondary particles emitted with small angles in the far-forward region of collision cannot be detected because they have gone inside the collider pipe. Also the triggers used in most of the cases are sensitive essentially to inelastic nondiffractive parts of events observed in the central region.

Recently there has been growing interest in the possibility of producting a disoriented chiral condensate (DCC) in high energy collisions [4]. This hypothesis gives one explanation for the peculiar events with large isospin fluctuations known as Centauro and anti-Centauro-type events in cosmic ray experiments [5].

In most of the cases the successive nuclear interactions and the stochastic electromagnetic processes in a family development in the atmosphere smear out the original characteristics of pions and the differences between experimental and simulated generic families cannot be seen easily.

In spite of complicated stochastic processes and fluctuations in family development in the atmosphere, it is possible to observe some family characteristics through special systematic analysis.

On the other hand, to analyze data from the MiniMax experiment, for which the main goal is the search for DCCs at the Fermilab Tevatron collider [6], there have been proposed special parameters, so-called robust observables. Analytical and Monte Carlo simulation calculations have shown that these quantities are sensitive to the DCC admixture in the pion multiple production mechanism.

In order to see a possible DCC signature in γ-hadron families the algorithm of MiniMax is applied to both experimental and artificial generic families only after reduction of degradation effects by electromagnetic cascade processes by using the decascading procedure and after the jet-clustering procedure that relates to the nuclear interaction processes.

We use experimental data from thick lead chambers of homogeneous structure exposed at the Pamirs in 1977–1991 [2,3]. These data give us a chance for a broad study with high accuracy of the γ-hadron families, especially their hadron component. The chamber thickness (40–110 cm Pb) is large enough to make the detection probability close to 1. Also the chamber design enables us to see the full development of electron showers generated through the nuclear cascade of incoming hadron from the top of the chamber till the large depths at the bottom. However, in order to increase the experimental statistics we use also families detected in Pamir experiment carbon chambers [7].

The present analysis is based on 139 families with visible energy $\Sigma E_{vis} = \Sigma E_\gamma + \Sigma E_h(\gamma)$ above 100 TeV and until 700 TeV, found in $\sim$780 m^2 yr of exposure.

We have shown that to find the peculiarities in the fine structure of the families it is necessary to perform a careful systematic analysis with full use of such appropriate parameters as the robust observables.

II. SEMICLASSIC INTERPRETATION OF DCC FORMATION

Basically, the formation of a DCC in one hadronic collision can be explained within the semiclassic frame and σ model [4,8] using a fireball shell production mechanism. In a hadron collision fireball with mass M_X can be formed in the leading particle region. The fireball is initially small in size and it can expand to a big macroscopic volume ($R \leqslant 5$ fm). The interior of the fireball cools quickly before the hadronization starts. Under these circumstances the fireball interior region can be characterized by a state of a different vacuum. The chiral orientation of the vacuum leans from the original direction, to the new one (DCC formation). This vacuum relaxes to the original direction again emitting pions, governed by the following distribution

$$\frac{dN}{df} = \frac{1}{2\sqrt{f}}, \tag{1}$$

where $f = N_{\pi^0}/(N_{\pi^0} + N_{\pi^\pm})$, not by a binomial one.

At the tevatron energy ($\sqrt{s} = 1800$ GeV) overlapping with the energy of cosmic ray families the spontaneous production rate of a DCC is estimated as 24% on average for the leading particle region [8]. For the whole inelastic channel this value is less than 5%.

The production rate of DCCs can be linked to the formation of exotic families, for example clean families of the Centauro type. As was mentioned above, the small spontaneous production rate of DCCs does not allow a direct correlation with the observed large fraction of about 20% of the hadron-rich families [9]. In other words, exotic families cannot be interpreted as a simple extrapolation of the well-known collision characteristics from accelerator experiments.

So we expect that the production rate of DCCs can have a significant increase. For example, there is the possibility of DCCs to be induced by a strong electromagnetic field, under certain circumstances described in [10].

III. ROBUST OBSERVABLES AND DCC FORMATION

It has been shown in [6] that there are robust observables with sensitivity to DCC admixture in particle multiple production. The robust observables are constructed through the ratio of factorial momenta sensitive to the distribution $p(f)$, where f is the fraction of produced neutral pions. The robust observables can be expressed as

$$r_{i,1} = \frac{F_{i,1}}{F_{i+1,0}}, \tag{2}$$

with

$$F_{i,j} = \frac{\langle n_{ch}(n_{ch}-1)\cdots(n_{ch}-i+1)n_\gamma(n_\gamma-1)\cdots(n_\gamma-j+1)\rangle}{\langle n_{ch}\rangle^i \langle n_\gamma\rangle^j}. \tag{3}$$

If the $p(f)$ distribution is governed by a binomial distribution and peaked at $f \sim 1/3$, then standard pion multiple production is observed, which is also called generic pion production. In this case for all indexes $i \geqslant 1$ and $j = 1$ we have the following relation:

$$r_{i,1}(\text{generic}) = 1. \tag{4}$$

If the f distribution has the form of $p(f) = 1/(2\sqrt{f})$, then it is connected to DCC formation in the semiclassical limit and the robust observables are expressed as

$$r_{i,1}(\text{DCC}) = \frac{1}{i+1}. \tag{5}$$

Increasing the order of the moments becomes more sensitive to DCC formation. If there are peculiar clusters of pions with large asymmetries in the neutral pion fraction distribution, then it can be reflected in values of the robust observables. Thus, statistically significant values of $r_{i,1}$ below 1 can be an indication of events with DCC formation overlaying generic events.

However, to estimate the efficiency of these algorithms to the sensitivity of DCC admixture taking into account the experimental bias, a Monte Carlo calculation is inevitable. The effect of an admixture of DCC on $r_{i,1}$ values in generic PYHTIA events in the MiniMax calorimeter is summarized in Fig. 1.

IV. MONTE CARLO GENERIC FAMILIES

For the generation of generic Monte Carlo families ($\sim$1000) we used a hybrid Monte Carlo code that consists of the following parts. The first part is a superposition model. It describes the number of wounded nucleons in a nucleus-air collision and takes into account the fragmentation processes. This method has been presented in [11]. The second part is the hadron-hadron, nucleon-nucleon, and pion-nucleon collision. They are described on the basis of the algorithms GENCL and DIFFR for nondiffractive and single diffractive mechanisms, respectively, and reported by the UA5 Group [12]. The other necessary assumptions for the generation of a family in air are very well described in [13,14]. An experi-

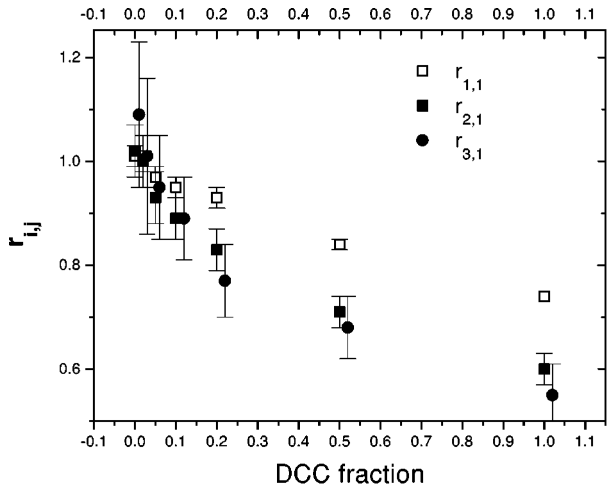

FIG. 1. Effect on the robust observables $r_{i,1}$, of an admixture of DCC in generic Phytia events as is expected in the MiniMax calorimeter.

mental bias in both the thick lead chamber and carbon chamber has been taken into account in simulation calculations [15].

V. ROBUST OBSERVABLES IN GAMMA-HADRON FAMILIES

A. Main characteristics of gamma-hadron families

First of all let us see two important characteristics of experimental γ-hadron families detected at a large atmospheric depth. They can be easily examined in artificial families, where all interactions of particles can be traced and located from their initial point until the observational level.

The first characteristic is the height of the family main interaction, that is, the one contributing most for the observed family energy. To detect the family the main interaction should happen not far above the chamber level.

The second characteristic is the type of primary particle that initiates family. Since the atmospheric depth in the Pamir experiment is very large (595 g/cm^2), only light nuclei and especially protons are expected to induce families that can be detected at the Pamirs level. Protons are the ones to have a high probability of penetration deep into the atmosphere.

Figure 2 shows the distribution of the chemical composition of the nuclei in the primary cosmic radiation used as input and the distribution of the composition of the nuclei inducing the families with energy $\Sigma E_{vis} > 100$ TeV observed as output. We can see in this illustration that fraction of families originated by heavy nuclei are strongly suppressed at the observational level.

Figure 3 shows the height distribution for the family main interaction at the Pamir level. We can see that $\sim$40% of families have a main interaction height under 1.0 km. Besides, $\sim$70% of families have H_{main} under 2.0 km. Here only protons were considered as primary particles.

From this analysis some general characteristics of the families can be derived.

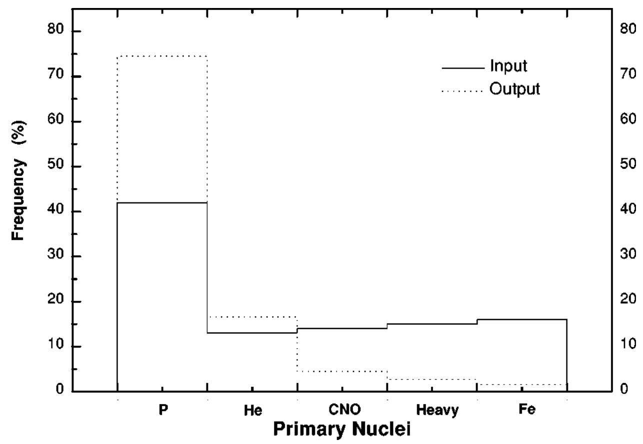

FIG. 2. Distribution of the chemical primary cosmic ray composition in the simulation at Pamir level: solid line, input; and dashed line, output.

(a) Most of the families observed by emulsion chambers at mountain altitudes such as the Pamirs are induced by protons. It means that the atmosphere plays the role of filter for heavy components. So most of the particles detected in the form of family come from proton primaries at the top of the atmosphere, almost irrespectively to the primary particles abundance.

(b) In spite of the fact that the degradation and fluctuations in family development in the atmosphere are large, the majority of families have a low height of their main interaction. This characteristic is a consequence of (a).

B. Procedure of jet construction

We are going to examine the pattern of energy flow in individual families through the picture of jets. The stream of energy in the air cascade is represented by jets produced in the nuclear interactions. The purpose of this analysis is to get back to the main interaction and to the primary particle, to reveal the structure of the cascade complex that gives rise to the family.

We have constructed jets in experiment and simulated families in a similar way, from the level of individual show-

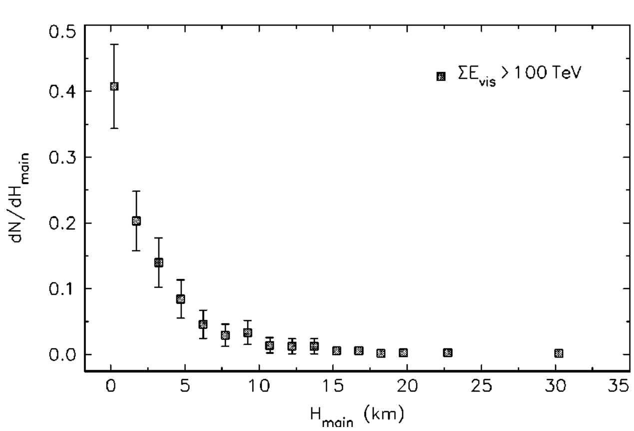

FIG. 3. Main interaction-height distribution at the Pamir level, for families with visible energies above 100 TeV.

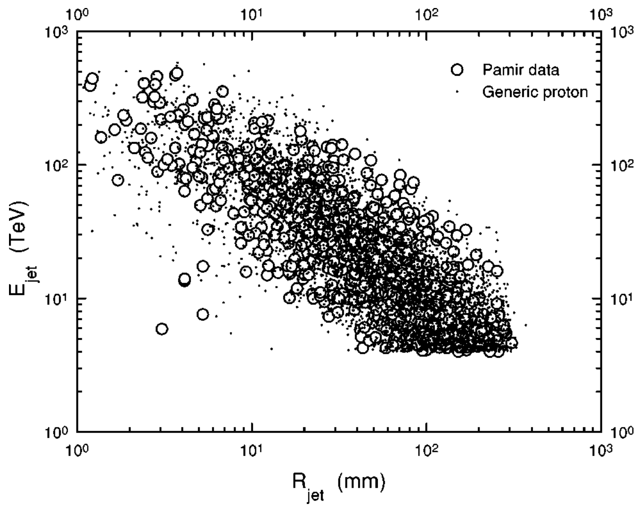

FIG. 4. Correlation diagram of the energy of jet E_{jet} and distance of jet R_{jet} from the family center: open circles, experiment; dots, simulation.

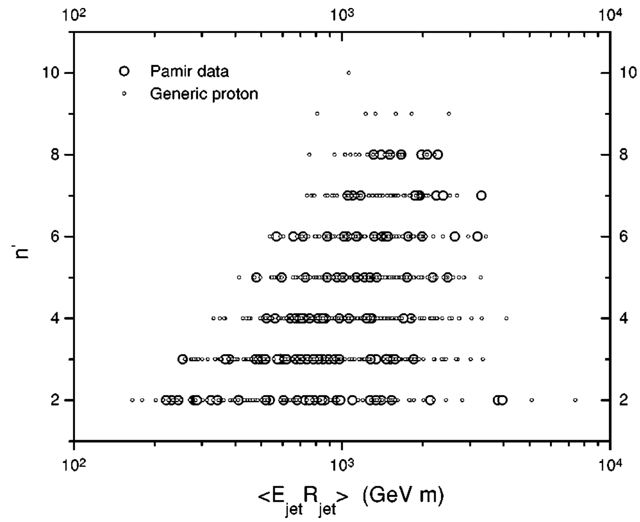

FIG. 5. Correlation diagram of the number of rejuvenated jet clusters $n'(f'>0.04)$ and average value $\langle E_{jet}R_{jet}\rangle$ in a family: open circles, experiment; dots, simulation.

ers observed in the x-ray film as gamma and hadron showers, to gamma clusters and then jet clusters. To construct the energy flow pattern representing the main stream of energy in a family we make the following steps [16].

(1) Decascading of gamma showers to clusters with parameter $Z_{dec}=11.0$ TeV mm [1]. With this procedure it is possible to trace back the atmospheric electromagnetic cascade processes for reconstruction of the original gamma quanta at the point of their production.

(2) Jet clustering of all showers, clusters, hadrons, and gammas with parameter $Z_{jet}=200$ TeV mm; this procedure is related to the nuclear interaction processes [1].

(3) Normalizing jet energy by setting the threshold $f_{min}=0.04$ for their fractional energy $f=E_j/E_{tot}$.

The parameters Z_{dec} and Z_{jet} reflect the average transverse momentum in electromagnetic and strong interactions with the assumption of an efficient height of family production as 1 km; so the unit TeV mm is equivalent to MeV km. A certain presumed value of $f_{min}=0.04$ was chosen to omit low energy showers. In these terms the interval E_{tot} is defined as $E_{min}=f_{min}E_{tot}$. In this way the number of jets $n'(>f_{min})$ will have some of the original features of the parent nuclear interaction.

In our definition a jet does not always mean production in the parent atmospheric interaction, but includes successive interactions in the atmosphere by hadrons from parent interactions. As can be seen, jet analysis eliminates the problem of the identification of showers as of gamma or hadron origin in their consideration since they include both groups equally.

C. Jet picture

To review the average picture of jets in cosmic ray families we show their basic characteristics on jet energy E_{jet}, transverse momentum $E_{jet}R_{jet}$ and multiplicity n'. Figure 4 presents the scatter plot on E_{jet}-R_{jet} correlation of all experimental and simulated jets. R_j is the distance from the family energy weighted center and E_{jet} stands for the jet energy. The average spread of the jet cluster $\langle E_{jet}R_{jet}\rangle$ is about 1000 TeV mm. This will correspond to minijets in events of the collider experiment. We can see agreement between simulation and experiment represented by dots, and open circles respectively. Figure 5 gives the correlation on multiplicity n' of jets with $f'>0.04$ and average value of $\langle E_{jet}R_{jet}\rangle$ in a family. We recognize families of a large spread for small n' and for large n' as well. They can be produced either by successive interaction or due to high transverse momentum.

D. Leading jet

Now we are going to examine the picture of the leading jet that in the pattern of atmospheric nuclear electromagnetic cascade represents the main stream of energy flow. In our analysis to trace the family back the leading jet is close to the initial stage of family development, its main interaction. Fig-

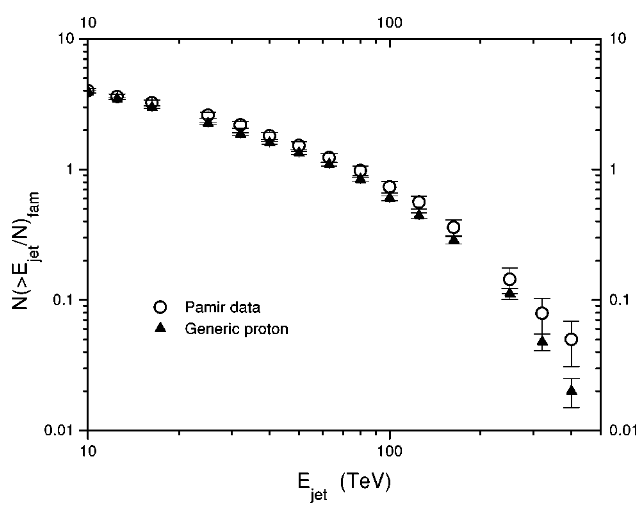

FIG. 6. Integral energy spectrum of all jets after jet clustering procedure: open circles, experiment; triangles, simulation.

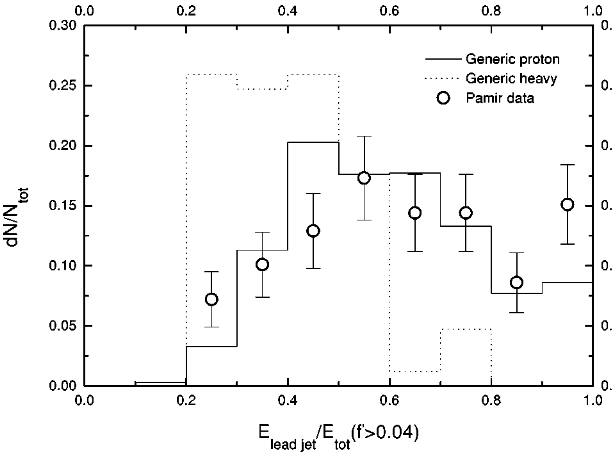

FIG. 7. Distribution of the leading jet energy fraction $f = E_{jet}/E_{tot}$: open circles, experiment; solid line, proton simulation; dashed line, heavy simulation.

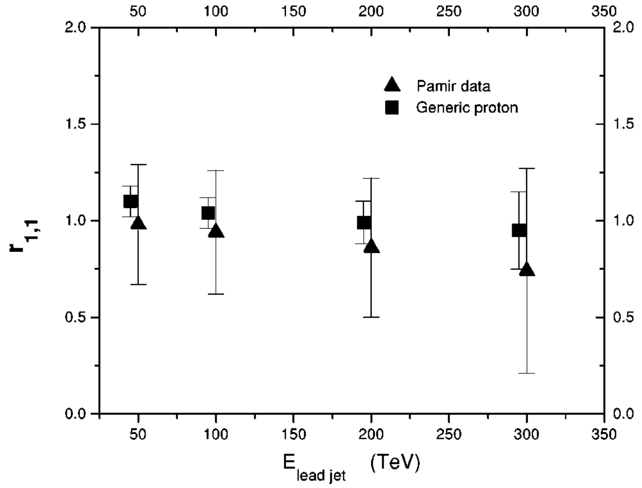

FIG. 8. The robust observable $r_{1,1}$ as a function of the visible leading jet energy: triangles, experiment; squares, simulation.

ure 6 gives the normalized energy spectrum of all jets in integral form. The spectrum of experimental jets (open circles) and simulated jets (solid triangles) is well reproduced by a power law. High energy jets reflect the primary energy spectrum of cosmic ray hadrons. Families from experiment and simulation agree well and show that the jets we have constructed are close to the origin of the family. The energy fraction carried by the leading jet will show a signature of primary particle origin and surviving nucleon in interaction. Figure 7 gives the distribution of leading jet fractional energy $f' = E_{lead}/E_{tot}$ in experiment (open circles) and simulation (proton simulation, solid line; heavy simulation, dashed line). The value $f' > 0.5$ corresponds to the families with a clear energy center. The rest of the distribution shows families with several energy centers. There is clear agreement between experiment and simulation based on the primary proton dominant composition hypothesis.

Proton primary families show a substantially large number of families with a clear energy center. If 100% of families were of heavy origin, then the distribution would have an absence of collimated energy concentration as we can see in Fig. 7 as the dashed line.

E. Robust observables

Let us use the robust observables $r_{i,j}$ in the analysis of the particle distribution inside leading jets in experiment and simulation. We take into account gamma and hadron showers inside of each leading jet. This heuristic systematic study through the extraction of the robust observables in γ-hadron families allows us to see the possible formation of clusters with large asymmetries in the pion neutral fraction as is expected under the assumption of DCC formation in the main interaction of the family.

Figures 8, 9, and 10 summarize the situation where the robust observables $r_{1,1}$, $r_{2,1}$, and $r_{3,1}$ are shown, respectively, as a function of the leading jet energy. The absolute values of $r_{i,1}$ are decreasing with increasing energy of the jets and the order of moments *i*. With increasing order of the robust observables the difference between experiment and simulation becomes clearer. Experimental values of $r_{i,1}$ far below 1 can be an indication of events with DCC formation overlaying generic events.

From the last three figures we can see that the robust observables $r_{i,1}$ in artificial families are close to 1, which corresponds to the absence of the neutral pion fraction asymmetry. Fluctuations are due to statistics in our simulation.

The experimental average values of $r_{3,1}$ that are most sensitive to DCC formation are below 1, but by less than a standard deviation. However, the 95% confidence interval of the average experimental value of $r_{3,1}$ does not exceed 1, as one can see in Table. I.

A further increase of experimental statistics will give a better clarification of the possible evidence of DCC formation in high energy interactions.

VI. SUMMARY AND CONCLUSIONS

In this analysis the ratio of factorial moments (robust observables, $r_{i,1}$) is studied in γ-hadron families generated by

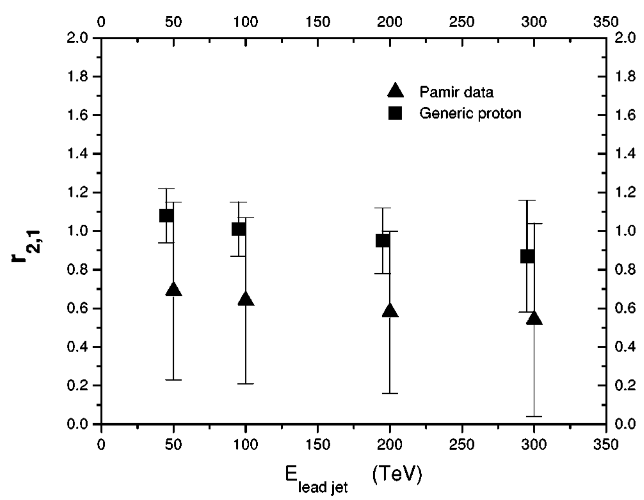

FIG. 9. The robust observable $r_{2,1}$ as a function of the visible leading jet energy: triangles, experiment; squares, simulation.

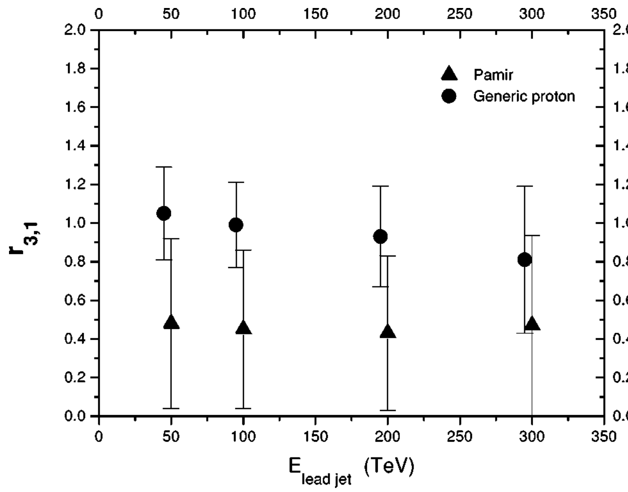

FIG. 10. The robust observable $r_{3,1}$ as a function of the visible leading jet energy: triangles, experiment; circles, simulation.

cosmic ray interactions in the atmosphere and observed in 780 m^2 yr of exposure of x-ray emulsion chambers at the Pamirs. In our consideration of families we studied the main pattern of energy flow represented by jets. The object jet is derived from the parent interaction of primary particles that initiates family development after interaction with air nucleus. We can conclude that the general characteristics of cosmic ray families are compatible with predictions based on the UA5 simulation.

The results of a systematic analysis of generic families detected at large atmospheric depth show that most of the families originate by protons. In spite of the fact that the family is the result of repeated complex processes, it is possible to obtain information on the main interaction and to study the peculiarities in the fine structure of families.

It is found that experimental families do not exclude the possibility of the existence of peculiar clusters with large asymmetries in the neutral pion fraction distribution.

The results shown above can be examined under the hypothesis that there can be a transformation of far-forward reaction products, formed in the beam fragmentation region, into a very high mass system and its subsequent evolution to a disoriented chiral condensate.

It could be the main reason to explain the absence of DCC generation in collider experiments at the energy of the collision compatible with the one of cosmic ray families.

We would like to note that this result is in agreement with a previous analysis [9] carried out on the basis of Chacaltaya and Pamir experimental carbon chamber data. It has been shown that there is large fraction of experimental families ($\sim$20%) with exotic characteristics exceeding the one expected from simulation with an ordinary pion multiple production mechanism.

TABLE I. Experimental statistics and 95% confidence interval of the average $r_{3,1}$.

Jet energy (TeV)	$r_{3,1}$	Number	95% confidence interval
50	0.48 ± 44	78	(0.38,0.58)
100	0.45 ± 41	61	(0.38,0.55)
200	0.43 ± 40	30	(0.28,0.58)
300	0.47 ± 49	10	(0.12,0.82)

We are expecting that the existence of these peculiar processes in the far-forward angular region of cosmic ray hadron interactions can be confirmed in the next generation of accelerator experiments such as the Large Hadron Collider (LHC) at CERN and Relativistic Heavy Ion Collider (RHIC) at BNL, as well as D0 and Collider Detector at Fermilab (CDF) at Fermilab after upgrade of their detectors. After that we can hope to find out a definite answer to the following questions:

(a) Can the DCC domain be produced in hadron collisions? (b) If so, are we capable of detecting them? (c) Are Centauro species the result of a consequent DCC domain formation process?

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[1] S. G. Bayburina *et al.*, Nucl. Phys. **B191**, 1 (1981).
[2] T. Arisawa *et al.*, Nucl. Phys. **B424**, 241 (1994).
[3] V. Kopenkin *et al.* Nuovo Cimento C **19**, 1017 (1997).
[4] J. Bjorken, Acta Phys. Pol. A **7**, 4189 (1992).
[5] C. M. G. Lattes *et al.*, Phys. Rep. **61**, 151 (1980).
[6] T. C. Brooks *et al.*, Phys. Rev. D **55**, 5667 (1997).
[7] L. T. Baradzei *et al.*, Nucl. Phys. **B370**, 365 (1992).
[8] C. E. Navia *et al.*, Phys. Rev. D **55**, 5834 (1997).
[9] S. Hasegawa *et al.*, Nucl. Phys. **B474**, 141 (1996).
[10] H. Minakata *et al.*, Phys. Lett. B **377**, 135 (1996).
[11] Y. Niihori *et al.*, Phys. Rev. D **36**, 783 (1987).
[12] UA5 Collaboration, Nucl. Phys. **B291**, 445 (1987).
[13] M. Tamada, J. Phys. G **20**, 487 (1994).
[14] C. R. A. Augusto *et al.*, Phys. Rev. D **52**, 4976 (1995).
[15] M. Tamada, J. Phys. G. **21**, 1387 (1995).
[16] M. Moriya, Master thesis, Waseda University, 1997.