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On alignment of most energetic substructures of γ-ray-hadron families and hadron interactions at $E_0 \gtrsim 10^{16}$ eV

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It is shown that the phenomenon of alignment of the most energetic substructures of $\gamma - h$ families cannot be originated by cascade fluctuations without assuming the manifestation of a large transverse-momentum process in hadron interactions at $E_0 \gtrsim 10^{16}$ eV ($\sqrt{s} \gtrsim 4$ TeV).

1. Introduction

Studies of superhigh-energy cosmic rays using techniques of extensive air showers (EAS) and X-ray–emulsion chambers (XREC) have formed an opinion that hadron interactions at $E_0 \gtrsim 10^{16}$ eV are well-described with quark-gluon string models (QGSM). However, sudden effects were observed. One of the most robust phenomena is the alignment of so-called energetic distinguished cores (EDC) along a straight line on target planes in gamma-ray–hadron ($\gamma - h$) families with energies $\sum E_\gamma \gtrsim 700$ TeV (i.e., at interaction energies $\sqrt{s} \gtrsim 4$ TeV). This phenomenon found by the *Pamir* Collaboration with XRECs [1, 2, 3] and confirmed in mountain [4] and stratospheric [5, 6] experiments was related to a coplanar particle generation. However, we must, first of all, understand whether this phenomenon can be originated by cascade fluctuations.

2. Experimental data and simulation models

Definitions. To analyze the alignment, the λ_n parameter [1] decreasing from 1 (for n points disposed along a straight line) to $-1/(n-1)$ (in isotropic cases) is applied. Events are referred to as aligned, if the inequality $\lambda_n \geq \lambda_{fix}$ is valid for their n most energetic objects. Most often, $\lambda_{fix} = 0.8$ and $n = 3$ or 4. The term "EDC" is used in reference to the most energetic isolated substructures in $\gamma - h$ families. A "decascading" procedure is used to select EDCs by integrating particles inside subcascades initiated by "initial" particles generated in the first interaction. If for the most energetic (ith) particle and a kth one placed R_{ik} apart with energies E_i and E_k, the condition $z_{ik} = R_{ik}(1/E_i + 1/E_k)^{-1/2} < Z_c$ is fulfilled, particles are integrated. Usually, $Z_c \simeq 1, 4, 20$ TeV·cm. At the Pamirs level, this permits to select, on average, subcascades initiated by "initial" γ-rays, π^0-mesons, and hadrons, respectively. Decascading is not used in the stratosphere.

Experimental data. When exploiting so-called (a) "lead" (Pb) and (b) "carbon" (C) XRECs, the *Pamir* Collaboration has accumulated two data sets, wherein the total numbers of families with energies $\sum E_\gamma \geq 700$ TeV, $N^{\rm exp}_{\rm tot}$, are (a) 14 and (b) 35 with numbers of aligned families $N^{\rm exp}_{\rm cop\,4}(\lambda_4 \geq 0.8) = 6$ and 9; and fractions of aligned families $F^{\rm exp}_{\rm cop\,4}(\lambda_4 \geq 0.8) = 0.43 \pm 0.17$ [2] and 0.26 ± 0.10 [3], respectively.

For γ-families with energies $\sum E_\gamma \geq 500$ TeV registered in Fe-XRECs at Mt.*Kanbala* (China), the fraction of aligned events is $F^{\rm exp}_{\rm cop\,3}(\lambda_3 \geq 0.8) = 0.5 \pm 0.2$ [4] ($N^{\rm exp}_{\rm tot} = 6$, $N^{\rm exp}_{\rm cop\,3} = 3$).

Two $\gamma - h$ families with $\sum E_\gamma > 1000$ TeV have been observed in the stratosphere, and both events are highly aligned, namely, *Strana* ($\lambda_4 = 0.99$) [5]) and *JF2af2* ($\lambda_4 = 0.998$) [6].

Simulation models. The QGSM-based MC0 code used for simulations describes the totality of the *Pamir* Collaboration's data at energies $\sqrt{s} \lesssim 3$ TeV (see Refs. [30-37] in [7]). To estimate the influence of large

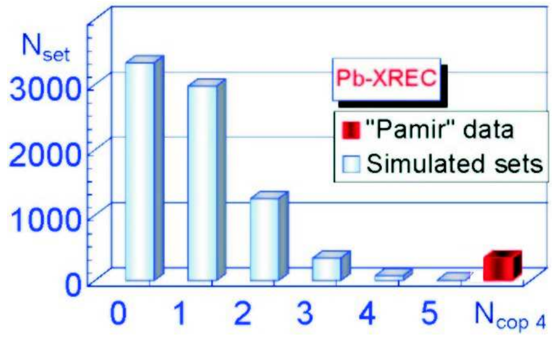

Figure 1. Distribution of number of sets 14 events each vs. $N^{\rm MC0}_{\rm cop\,4}$ in each of sets. Dark cube denotes the *Pamir*'s set.

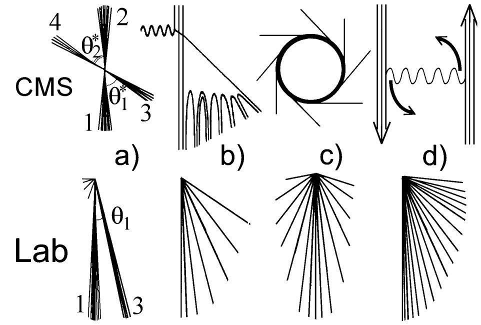

Figure 2. Types of interactions with a violation of azimuthal symmetry in CMS and Lab frames.

Experimental data	Selection criterion	Experiment		Simulation			
		$N^{\rm exp}_{\rm tot}$	$N^{\rm exp}_{\rm cop}$	$\langle N^{\rm MC0}_{\rm cop}\rangle$	$\sigma^{\rm MC0}_{\rm fluct}$	$\Delta\sigma^{\rm MC0}_{\rm fluct}$	$w^{\rm MC0}_{\rm fluct}$
1	2	3	4	5	6	7	8
Pamir (Pb-XREC)	$\lambda_4 \geq 0.8$	14	6	1.0	1.0	5.0	$9.0\cdot 10^{-5}$
Pamir (C-XREC)	$\lambda_4 \geq 0.8$	35	9	2.1	1.5	4.6	$1.5\cdot 10^{-4}$
Mt.*Kanbala*	$\lambda_3 \geq 0.8$	6	3	1.2	1.2	1.5	$9.0\cdot 10^{-2}$
the *Strana* event	$\lambda_4 \geq 0.99$	1	1	–	0.05	–	$2.9\cdot 10^{-3}$
the *JF2af2* event	$\lambda_4 \geq 0.998$	1	1	–	0.015	–	$6.0\cdot 10^{-4}$

Table 1. Summary of data. Columns: 1. Experimental data used for the analysis; 2. Criterion for the selection of aligned events; 3. Experimental total number of events, $N^{\rm exp}_{\rm tot}$; 4. Experimental number of aligned events, $N^{\rm exp}_{\rm cop}$; 5. Expected number of aligned events, $\langle N^{\rm MC0}_{\rm cop}\rangle$; 6. Calculated standard deviation $\sigma^{\rm MC0}_{\rm fluct}$; 7. Deviation $\Delta\sigma^{\rm MC0}_{\rm fluct}$ of $N^{\rm exp}_{\rm cop}$ from $\langle N^{\rm MC0}_{\rm cop}\rangle$ (in $\sigma^{\rm MC0}_{\rm fluct}$); 8. Probability $w^{\rm MC0}_{\rm fluct}$ that the experimental number $N^{\rm exp}_{\rm cop}$ is caused by fluctuations.

transverse-momentum processes, a coplanar particle generation model (CPGM) has been designed as a rough heuristic tool, reflecting only basic CPG features with the following parameters: (a) the multiplicity is $\langle n\rangle \simeq 10$; (b) mean transverse momenta of five most energetic particles are $\langle p_T^{cop}\rangle = 2.34$ GeV/c in and $\langle p_t\rangle = 0.4$ GeV/c transversely to the coplanarity plane; (c) CPG interactions occur in all proton-initiated cascades at $E_0 \geq 8$ PeV (the contribution of nuclei is neglected, as about 80% of γ-families are produced by protons).

3. Fluctuations and alignment

To estimate the probability w_{fluct} that *Pamir*'s data accumulated by (a) Pb-XRECs and (b) C-XRECs are caused by fluctuations, (a) 8000 and (b) 3000 sets of families, respectively, have been simulated. The event number in each of these sets corresponds to experimental data. Fig. 1 shows the derived distributions as functions of number of aligned families, $N_{\rm cop\,4}$ ($\lambda_4 \geq 0.8$), in each of the sets for Pb-XREC. In both the cases none of simulated sets of families coincides with the corresponding experimental set. So, the probability that these two statistically independent experimental results are caused by fluctuations can be roughly estimated at $\lesssim 10^{-7}$. A more formal approach says that if the probability to satisfy some criterion is p, the probability to find k events, satisfying this criterion, among a set of n events is $P(k) = n!p^k(1-p)^{n-k}/\,[k!(n-k)!]$. In our case, $n = N^{\rm exp}_{\rm tot}$; $p = F^{\rm MC0}_{\rm cop\,n}(\lambda_n \geq \lambda_{fix})$; and $P(k) = w_{fluct}$. In part, $F^{\rm MC0}_{\rm cop\,4} = 0.059 \pm 0.003$ and $F^{\rm MC0}_{\rm cop\,3} = 0.209 \pm 0.005$. Table 1 presents a summary of experimental data and calculated values. As is seen,

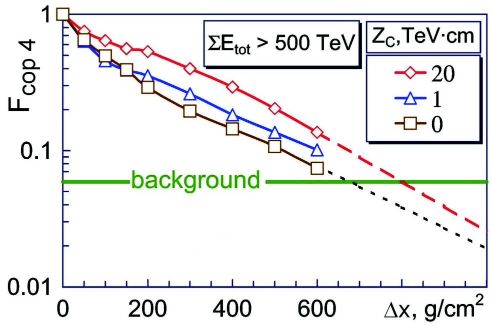

Figure 3. Dependence of $F^{\rm CPGM}_{\rm cop\ 4}$ on distance Δx (g·cm^{-2}) from the CPG point to observation level.

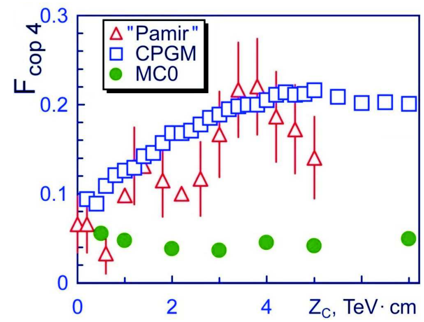

Figure 4. Dependence of $F_{\rm cop\ 4}$ on Z_c. $\triangle-$ experiment [13], ● – MC0, □ – CPGM.

the total probability W_{fluct} for all the experimental results to be produced by fluctuations is $\sim 9\cdot 10^{-5}\times 2\cdot 10^{-4}\times 9\cdot 10^{-2}\times 3\cdot 10^{-3}\times 6\cdot 10^{-4}\simeq 3\cdot 10^{-15}<10^{-14}$. If the alignment of 38 γ-rays in *JF2af2* is taken into account, W_{fluct} decreases by more than five orders of magnitude down to $W_{fluct}\lesssim 10^{-20}$! [7]. Thus, the alignment phenomenon, as a whole, cannot be caused by fluctuations.

4. Hadron interactions and alignment

Theoretical models. The **first** group of models exploits processes with a transverse-momentum transfer (gluon jet generation [8], e.g.). QCD cannot help due to the XREC's high threshold, correlation between longitudinal and transverse momenta of jet particles ($p_{t\,i}\propto p_{L\,i}$) (Fig.2*a*). As a result, a significant fraction of aligned events could be generated only at unrealistic energies and jet transverse momenta ($P_{t\,jet}\gtrsim 3$ TeV/c at $\sqrt{s}\sim 14$ TeV [9]). In the model of semihard double diffraction inelastic dissociation (SHDID) [10], the coplanarity is a result of a rupture of a quark-gluon string stretched inside the diffraction cluster between a scattered quark and spectator quarks (Fig.2*b*). This model provide an appropriate momentum anticorrelation: the larger is $p_{t\,i}$, the lower is $p_{L\,i}$. The **second** group considers the appearance and coplanar decay of high-spin systems: (a) the generation of heavy leading resonances [7, 11] (Fig.2*c*); (b) the angular momentum conservation in the creation of a relativistic fast-rotating quark-gluon string stretched between colliding hadrons [12] (Fig.2*d*).

Analysis. An analysis of *Pamir*'s data and families simulated with MC0 and CPGM has been carried out. Fig. 3 shows (at $Z_c=0,\ 1$, and 20 TeV·cm) the dependence of the fraction of aligned families, $F^{\rm CPGM}_{\rm cop\ 4}(\lambda_4\geq 0.8)$, rapidly decreasing with distance from the CPG point to observation level. This leads to a crucial conclusion: the CPG cross section has to be comparable with the inelastic one, $\sigma^{p-air}_{copl}\simeq\sigma^{p-air}_{inel}$, if $F^{\rm exp}_{\rm cop\,4}\gtrsim 0.2$ at mountain levels. Besides, CPG processes can be only studied in high-altitude experiments, not at the sea level. Finally, $F^{\rm CPGM}_{\rm cop\ 4}$ depends on Z_c (correlating with transverse momentum). Figures 4 and 5 show that the $F^{\rm exp}_{\rm cop\,4}$ depends on both Z_c [13] and $\sum E_\gamma$ [14] that is described by CPGM and sharply differs from MC0 results. Fig. 6 shows the $\sum E_\gamma$-dependence of ratios of $\langle\overline{ER}\rangle_4$ values for aligned γ-families to those of unaligned ones, i.e., $\varepsilon=\langle\overline{ER}\rangle_4(\lambda_4\geq 0.8)/\langle\overline{ER}\rangle_4(\lambda_4<0.8)$ by data [14], MC0 and CPGM results. Here E and R are the EDC energy and distance from the event center. The behaviour of ε in the presence ($\varepsilon>1$) and absence ($\varepsilon<1$) of CPG is different. The energy and model dependence of $\rho=\langle\overline{R}\rangle_4(\lambda_4\geq 0.8)/\langle\overline{R}\rangle_4(\lambda_4<0.8)$ is very weak. However, just its experimental value ($\sim$ 2.6 [14]) exceeds strongly even the CPGM values ($\sim$ 1.4).

Information on high-energy interactions could be derived from high-energy muon group and EAS experiments. However, simulations [7] show that azimuthal characteristics of muon groups are CPG-insensitive due to low probability of high-energy meson decay. EAS characteristics are mainly changed by the CPG process in

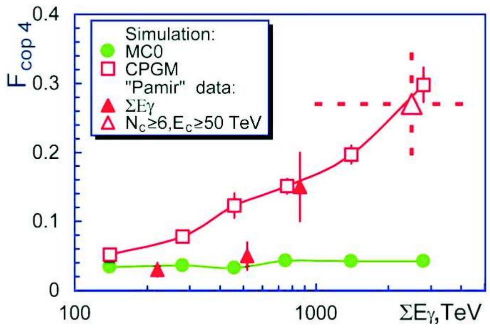

Figure 5. Energy dependence of $F_{\text{cop }4}$. Experiment [14]: selection by $\sum E_\gamma$ (▲) and $N_c \geq 6$, $E_c \geq 50$ TeV (△).

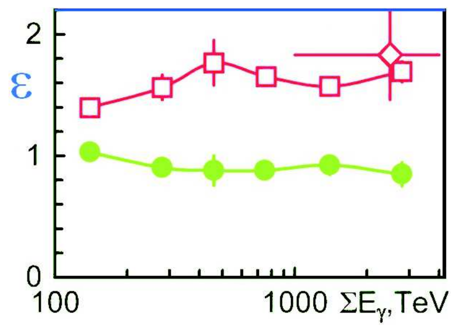

Figure 6. Dependence of ε on $\sum E_\gamma$. ◇ – experiment [14], ● – MC0, □ – CPGM.

a narrow central range ($R \lesssim 10$ cm) [7]. Although this result is model-dependent, it is really impossible to observe such effects in EAS experiments. Furthermore, CPG-caused effects are negligible deep in the atmosphere, comparable with those caused by light nuclei, and weaker than those caused by heavy nuclei.

5. Conclusion

1. The alignment phenomenon cannot be explained with present-day QGS models without assuming a CPG process with large transverse momenta manifestating itself at $E_0 \gtrsim 10^{16}$ eV ($\sqrt{s} \gtrsim 4$ TeV).
2. If this process occurs through proton interactions, its cross section should be comparable with the total inelastic section at $E_0 \gtrsim 10^{16}$ eV; it should be similar to QGS models in energy characteristics.
3. This process is to be only studied in stratospheric and high-altitude mountain experiments.

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