Correlation method for analyzing gamma families with energies $\Sigma E_\gamma = 40$–500 TeV

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(Submitted 26 December 1980; resubmitted 2 March 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, 389–391 (5 April 1981)

Analysis of γ families with large values of $\overline{ER}$ reveals azimuthal correlations of dynamic origin.

PACS numbers: 94.40.Lx

In this letter we will see how azimuthal effects are influenced by the spatial characteristics of γ families, and we will compare these effects with calculations from various models for the strong interaction.

To study the azimuthal correlations, we use the sensitive statistical criterion proposed in Ref. 1 and used in Refs. 2–4 to analyze γ families:

$$\alpha = \frac{\beta_2}{\sqrt{n_\gamma (n_\gamma - 1)}}, \text{ where } \beta_2 = \frac{\sum\limits_{i \neq j}^{n_\gamma} \cos 2\epsilon_{ij}}{\sqrt{n_\gamma (n_\gamma - 1)}}$$

where the ϵ_{ij} are the angles between the transverse momenta of particles i and j, defined as the difference between their azimuthal angles ϕ ($\epsilon_{ij} = \phi_i - \phi_j$, $i = 1, 2, \ldots, n_\gamma$; $j = 1, 2, \ldots, n_\gamma$; $i \neq j$; $0 \leqslant \phi < 2\pi$; $0 \leqslant \epsilon_{ij} \leqslant \pi$) in the plane perpendicular to the direction of the primary particle. Any function of the relative angles ϵ_{ij} is independent of the origin selected for ϕ. The criterion α does not depend on the multiplicity n_γ, and the value $\alpha = 1$ corresponds to the completely coplanar case, i.e., the case in which all

0021-3640/81/07371-04$00.60

n_γ momenta of the particles lie in a plane perpendicular to the azimuthal plane. The value of α is at its minimum, ~ 0 (if $n_\gamma \gg 1$), in the case of an isotropic, uniform azimuthal distribution of particles.

Let us compare the data from the Pamir experiment with the theoretical families calculated at Łódź University from three models for the strong interaction (the *S*, *WS*, and *HS* models[5]).

In the first model (the scaling *S* model), the fireball mass is set equal to $M = 2.6$ GeV, and the decay temperature of the cluster is set equal to $P_0 = 0.169$ GeV/*c*, which corresponds to an average transverse momentum $\overline{P}_\perp = 0.4$ GeV/*c* for the particles.

The second model (*WS*) is also a scaling model, but with a fireball mass $M = 5.2$ GeV and with $P_0 = 0.388$ GeV/*c*. In this model the transverse momenta of the secondary particles are twice as high as in the *S* model ($\overline{P}_\perp = 0.8$ GeV/*c*).

The third model (*HS*) has a scaling violation. The secondary particles are produced through a heavy cluster with a mass $M = 20.8$ GeV; in other words, there is a rapid division of energy among the secondary particles.

For a study of azimuthal effects, 328 γ families were selected, with energies $\Sigma E_\gamma = 40$–500 TeV and with $n_\gamma \geqslant 4$ particles detected within a radius $R \leqslant 30$ cm of the energy-weighted center of the family. The minimum threshold energy of the γ rays in the families was set at $E_{\text{th}} \geqslant 4$ TeV.

The experimental data were grouped in several ΣE_γ intervals, for each of which the average value of $\bar{\alpha}$ was determined. Figure 1a is a plot of the data for the azimuthal correlations against the family energy (the crosses correspond to the *S* model, the squares to the *WS* model, the triangles to the *HS* model, and the circles to the experimental data for $E_{\text{th}} \geqslant 4$ TeV).

Figure 1a reveals a general tendency for the azimuthal effects to fall off increasing ΣE_γ. The average value $\bar{\alpha}$ in the *HS* model is several times smaller than the experimental value and the values from the other scaling models. The values of $\bar{\alpha}$ found from the *S* and *WS* models are in approximate agreement with the experimental results.

We know that the γ families detected at mountain altitudes are formed by an intense cascade multiplication of the initial γ rays as they pass through the atmosphere. There is thus the problem of distinguishing the nontrivial azimuthal correlations,

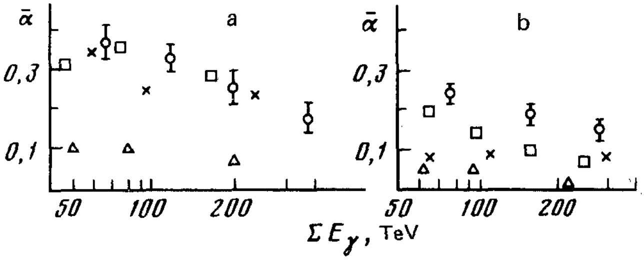

FIG. 1.

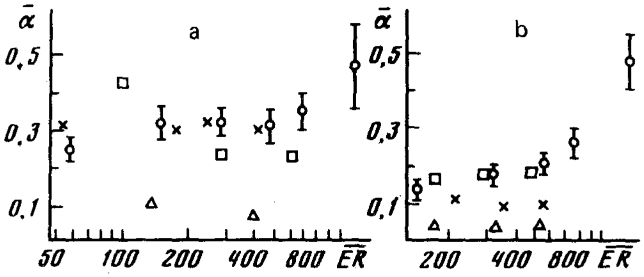

FIG. 2.

which arise from the dynamics of the strong interaction, from the background of electromagnetic multiplication of the initial γ rays in the atmosphere.

An effort was accordingly made to approximately "recombine" the observed γ rays into the original γ rays at a single average formation height in the atmosphere (the decascading procedure of Ref. 6 was used). The decascading parameter was set equal to $Z_0 = 10$ TeV • mm.

Figure 1b shows how the decascading procedure changes the relationship between the azimuthal effects and the energy ΣE_γ. The suppression of the electromagnetic cascading multiplication of the original γ rays reduces the azimuthal parameter $\bar{\alpha}$. The values of $\bar{\alpha}$ found from the *S* and *WS* models turn out to be much lower than the experimental value, implying that nontrivial azimuthal correlations of dynamic origin occur experimentally over the entire energy range, $\Sigma E_\gamma = 40$-500 TeV.

Figure 2a is a plot of the azimuthal correlations against the quantity $\langle \overline{ER} \rangle$, which has been averaged over various intervals of the average product $\overline{ER}$; these values are proportional to the average transverse momentum of the particles (*E* is the energy of the γ ray, and *R* is its separation from the axis of the family).

It can be seen from Fig. 2a that in the range $\overline{ER} = 0$-600 TeV • mm the values of $\bar{\alpha}$ from the *S* and *WS* models are consistent with the experimental values, while the value of $\bar{\alpha}$ from the *HS* model is much lower than the experimental values. At $\overline{ER} > 600$ TeV • mm, $\bar{\alpha}$ increases substantially.

The sharp increase in the azimuthal correlations at large values of $\overline{ER}$ can be seen particularly clearly after the decascading procedure (Fig. 2b).

In the range $\overline{ER} < 600$ TeV • mm only the *WS* model agrees with the experimental data; the *S* and *HS* models predict far smaller values of $\bar{\alpha}$. At the large values $\overline{ER} > 800$ TeV • mm, $\bar{\alpha}$ is ~ 3.5 times the average value, possibly indicating that a string mechanism is predominant in the formation of families with $\overline{ER} > 600$ TeV • mm.

If the excess of families with azimuthal parameters $\bar{\alpha}$ higher than in the *WS* model is a consequence of events of the string type, then the relative number of such events among all γ families with energies $\Sigma E_\gamma \geqslant 90$ TeV would be 24 ± 5%.

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Translated by Dave Parsons
Edited by S. J. Amoretty