Do LHC data contradict superhigh-energy cosmic-ray coplanarity of most energetic particles?

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Abstract. To research for a coplanarity of most energetic subcores of γ-ray–hadron families observed in cosmic-ray experiments at $E_0 \gtrsim 10^{16}$ eV ($\sqrt{s} \gtrsim 5$ TeV), a new phenomenological FANSY 2.0 model is designed. The model makes it possible to simulate interactions for both traditional and coplanar hadron generation options, reproduces LHC data, including high-$x_F$ data on γ-rays and neutrons. An experiment at the LHC is proposed to test the model.

1. Introduction

The paper considers one of phenomena observed in mountain-based and stratospheric X-ray–emulsion chamber (XREC) experiments, namely, a strong azimuthal effect that manifests itself as a tendency to a coplanarity of most energetic subcores of γ-ray–hadron ($\gamma - h$) families, i.e., groups of high-energy ($\gtrsim 1$ TeV) particles in EAS cores initiated mainly by protons and light nuclei of the primary cosmic radiation (PCR) with energies $E_0 \geq 10^{16}$ eV.

The effect has been found by the Pamir Collaboration [1, 2, 3, 4, 5] and observed in other experiments [6, 7, 8, 9] with different XREC types, i.e., so-called “carbon”, “lead”, “iron” (C, Pb, Fe) XRECs. Five sets of experimental data were accumulated. This is, first of all, data of mountain-based Pamir Collaboration’s C- and Pb-XRECs on $\gamma - h$ families with observed energies of γ-rays and $e^\pm$, $\sum E_\gamma \geq 700$ TeV. Close results at $\sum E_\gamma \geq 500$ TeV were obtained by Mt.Canbala Collaboration using Fe-XRECs [6]. Besides, only two stratospheric events with $\sum E_\gamma > 1$ PeV (the Strana [7, 8] and JF2af2 [9]) have been observed at very high altitudes, and both these events demonstrate a very high coplanarity of most energetic particles (MEP).

A new parameter $\lambda_N$ was proposed [1] to calculate the degree of a so-called alignment of $N$ point-like tracks on a target plane, namely, $\lambda_N = 1$ for $N$ points aligned along a straight line and $\lambda_N \approx -1/(N-1)$ in the isotropic cases.

Table 1 presents experimental data sets and types of used XRECs; criteria used to select experimental coplanar events ($\lambda_N$ and $\sum E_\gamma$); number of coplanar families, $N_{\text{exp}}^{\text{copl}}$, and total family number $N_{\text{tot}}$; fraction of coplanar families, $F_{\text{exp}}^{\text{copl}}$; references (Columns 1–6, respectively).

Simulated background fractions of coplanar γ-ray families, $F_{\text{sim}}^{\text{copl}}$, obtained with the use of the QGSM-based FANSY 1.0 model [12] are given in Column 7. Although the statistical security of experimental data is not too high, each of these data sets shows an phenomenon excess over the simulated value. Both stratospheric events are unique in energy and coplanarity.

This phenomenon cannot be studied in EAS experiments because of their poor coordinate and energy resolution. Fortunately, it could be investigated in LHC experiments (Sect. 4).
The probability for the total set of these experimental results to be produced by cascade fluctuations is much lower than $\sim 10^{-10}$ [10, 11, 12].

The phenomenon was initially interpreted as a manifestation of coplanar generation of MEPs ($x_{Lab} = E/E_0 \gtrsim 0.01 - 0.05$) characterized by relatively large transverse momenta, $p_t^{\text{copl}} \gtrsim 1$ GeV/c. However, as regards $\gamma$-ray–hadron families, an accurate measurement of $p_t^{\text{copl}}$ values was not made. The average ratio of $p_t$ components lying in the coplanarity plane, $p_t^{\text{copl}}$, to $p_t$ components directed normally to the coplanarity plane, $p_t^{\text{norm}}$, was only estimated, namely, $\langle p_t^{\text{copl}}/p_t^{\text{norm}} \rangle \sim 10$ [3]. It is also very important that the coplanar particle generation (CPG) is characterized by a relatively large cross section (comparable with $\sigma_{\text{prod}}^{p-air}$) [10].

A few theoretical ideas were proposed to explain this phenomenon [14, 15, 16], which include large $p_t$ as an almost mandatory element. Besides, the most extraordinary and speculative idea was proposed which assumes a connection between the coplanarity phenomenon and the hypothesis of so-called "crystal world" [17, 18] which implies a gradual reduction of space dimensionality from three to two dimensions at sufficiently high energies and entails $p_t$ localization in some plane and a reduction of transverse momenta directed perpendicularly to this plane. Unfortunately, all of these ideas are not quantitatively developed. In any case, this experimental result shows that strong "forward-physics" interactions at superhigh energies are not well-described with the concept used by QGS models.

The coplanar generation of MEPs can be phenomenologically realized in the framework of two modes, i.e., initial generation of (a) quark-gluon strings with the following hadron production; (b) an energetic leading system (diffraction cluster, e.g.) with a lower multiplicity and higher energies of hadrons. The first approach is considered in this work.

The phenomenological model FANSY 1.0 [11, 12] was developed a dozen of years ago. It described main characteristics of $\gamma$-ray families and helped to understand general features of the experimental coplanar events. However, FANSY 1.0 cannot properly describe some features of $\gamma$-ray families [19] and LHC data. Therefore, a new phenomenological model FANSY 2.0 [21] is designed. The model makes it possible to simulate both QGSM-based traditional interactions and coplanar particle generation (QGSJ and QGSCPG versions, respectively). All interaction characteristics (excluding azimuthal ones) simulated with QGSJ and QGSCPG versions, are similar. Both QGSJ and QGSCPG versions become identical at $\sqrt{s} = 2$ TeV. They reproduce high-$x_F$ and high-$\eta$ data on $\gamma$-rays and neutron-like hadrons accumulated by the LHCf experiment (Sect. 3) as well as low-rapidity data. FANSY 2.0 reproduces a lot of low-energy data as well.

A detailed comparison of experimental data with results of FANSY 2.0 QGSJ simulation at energies $\sqrt{s} = 17$ GeV – 13 TeV are given in Ref. [21].

Sect. 2 presents a short discussion on simulation problems related to the initial concept of coplanarity features and describes shortly the FANSY 2.0 QGSCPG’s algorithm of hadron coplanarization. Sect. 3 compares high-$x_F$ and high-$\eta$ experimental and simulated results. Sect. 4 considers proposed experiment at the LHC.

2. Coplanarity simulation

2.1. Coplanarity concepts

Simulations using tentative FANSY 2.0 QGSCPG versions show the following problem. The initial concept exploited earlier [11, 12] qualitatively explains the observed coplanarity with assuming high $p_t^{\text{copl}}$ of MEPs in a coplanarity plane. However, a significant $p_t^{\text{copl}}$ growth suppresses $d\sigma/dy$ and $d\sigma/d\eta$ cross sections of hadron generation at highest $|y|$ and $|\eta|$ values and creates robust peaks at $2 \lesssim |y, \eta| \lesssim 4$ which are contrary to LHC data. This is an unsolvable problem for all considered high-$p_t^{\text{copl}}$ QGSCPG versions.
Table 1. Summary of experimental data. Columns: 1. Data set and type of used XRECs; 2–3. Criteria for selection of coplanar events; 4. Number of coplanar families, \( N_{\text{copl}}^{\text{exp}} \), and total family number \( N_{\text{tot}} \); 5. Fraction of coplanar families, \( F_{\text{copl}}^{\text{exp}} \). 6. References. 7. Simulated background fraction of coplanar \( \gamma \)-ray families, \( F_{\text{sim}}^{\text{copl}} \) [12].

| Experimental data set | Selection criteria | \( N_{\text{copl}}^{\text{exp}} / N_{\text{tot}} \) | Ref. | \( F_{\text{sim}}^{\text{copl}} \) |
|-----------------------|-------------------|---------------------|-----|---------------------|
| Pamir (Pb)            | \( \lambda_{4} \geq 0.8 \) \( \sum E_{x} \), TeV \( \geq 700 \) | 6 / 14 | \( 0.43 \pm 0.13 \) | [3] | 0.041 \( \pm 0.004 \) |
| Pamir (C)             | \( \lambda_{4} \geq 0.8 \) \( \sum E_{x} \), TeV \( \geq 700 \) | 5 / 35 | \( 0.15 \pm 0.05 \) | [5] | 0.049 \( \pm 0.004 \) |
| Mt. Kanbala (Fe)      | \( \lambda_{3} \geq 0.8 \) \( \sum E_{x} \), TeV \( \geq 500 \) | 6 / 12 | \( 0.50 \pm 0.13 \) | [6] | 0.180 \( \pm 0.010 \) |
| the Strana            | \( \lambda_{4} = 0.99 \) \( \sum E_{x} \), TeV \( \approx 1500 \) | 1 / 1 | 1 | [13] | \( (26 \pm 3) \cdot 10^{-4} \) |
| the JF2of2            | \( \lambda_{4} = 0.998 \) \( \sum E_{x} \), TeV \( \approx 1500 \) | 1 / 1 | 1 | [9] | \( (9 \pm 3) \cdot 10^{-4} \) |

Figure 1. Particle tracks on a target plane in cases of traditional particle generation (left), initial large-\( p_{t} \) CPG model (mid) and new traditional-\( p_{t} \) CPG concept (right).

Figure 2. Qualitative scheme of traditional and coplanarity ranges of \( \frac{d\mathcal{N}}{dy} \) distribution.

However, the coplanarity is actually observed in cosmic-ray experiments. Is it possible to reconcile this result with the LHC data?

Simulation shows that an agreement of LHC data and idea of coplanar generation becomes real only using a new concept assuming some decrease of \( p_{t} \) components directed normally to the coplanarity plane, while \( p_{t} \) becomes (almost) invariant simultaneously with the appearance of azimuth effects. It could be provided with some turning of MEPs’ \( \vec{p}_{t} \) vectors with no change of its absolute value.

Figure 1 shows three versions of observed tracks of particles, generated in the same imaginary interaction and arriving on a target plane placed at some distance from the interaction point: (1) traditional QGSM-like interaction (left); (2) initial-concept coplanar interaction with high-\( p_{t}^{\text{copl}} \) (mid); (3) new-concept coplanar interaction with traditional \( p_{t}^{\text{copl}} \) values (right). MEPs are shown with large black symbols. The geometric scale is given in arbitrary units.
2.2. Coplanarity simulation

All characteristics of the main bulk of secondary particles are primarily simulated with the traditional QGSJ option through the QGS fragmentation. After this, c.m.s. longitudinal momenta of hadrons are listed in decreasing order of magnitude, i.e., \( p_{\text{max}} > p_1 > p_2 > p_3 \ldots > -p_{\text{max}} \), where \( p_{\text{max}} = \sqrt{s/4 - m^2} \). Rapidities of these hadrons are denoted as \( y_1, y_2, y_3 \ldots \).

Figure 2 shows a schematic drawing of traditional and coplanarity ranges of \( dn/dy \) distributions. A "coplanarization" algorithm rotates the \( \vec{p}_t \) vector of each of MEPs with \( |y| > y_{\text{copl}}^{\text{thr}} \) towards the coplanarity plane along the shortest path, if the total energy of secondary particles in their c.m.s., \( \sqrt{s_{\text{eff}}} \), is higher than a fixed value, \( \sqrt{s_{\text{eff}}^{\text{thr}}} \). Here \( y_{\text{copl}}^{\text{thr}} = y_2 - \Delta y_{\text{copl}}^{\text{thr}} \), where a free parameter \( \Delta y_{\text{copl}}^{\text{thr}} \approx 3 - 5 \), \( y_{\text{copl}}^{\text{thr}} \) varies from \( 3 - 5 \) for hadrons with \( p_z > 0 \) due to fluctuations of hadron rapidity values. Similar procedure is carried out for hadrons with \( p_z < 0 \).

Fluctuations are mainly determined by variations of \( \sqrt{s_{\text{eff}}} \) and \( y_2 \) values. The coplanarity-plane orientation is determined by the total \( \vec{p}_t \) of two leading hadrons. The azimuthal-angle distribution of \( \vec{p}_t^{\text{copl}} \) of MEPs with respect to the coplanarity plane is described by a Gaussian distribution with a standard deviation \( \sigma_{\text{copl}} \). Results are obtained at \( \sqrt{s_{\text{eff}}^{\text{thr}}} = 250 \) GeV/c, \( \Delta y_{\text{copl}}^{\text{thr}} = 4, \sigma_{\text{copl}} = 0.05 \) rad, \( \langle y_2 \rangle = 7.15, \langle y_{\text{copl}}^{\text{thr}} \rangle = 3.15 \).

The described coplanarization algorithm is highly arbitrary and can be used as a zero-order approximation tool only to estimate the influence of CPG processes on interaction characteristics.

Figure 3. CMS+TOTEM and FANSY 2.0 QGSCPG \( dn_{\text{ch}}/d\eta \) data at \( \sqrt{s} = 8 \) TeV. (a) "NSD-enhanced" events: \( n_{\text{ch}} \geq 1 \) at \(-6.5 < \eta < -5.3 \) and \( 5.3 < \eta < 6.5 \); (b) "more-forward" events: \( n_{\text{ch}} \geq 1 \) at \(-6.5 < \eta < -5.3 \) or \( 5.3 < \eta < 6.5 \); (c) "SD-enhanced" events (lower symbols): \( n_{\text{ch}} \geq 1 \) only in the ranges \(-6.5 < \eta < -5.3 \) or only \( 5.3 < \eta < 6.5 \) (c); "more-forward" data (upper symbols): \( n_{\text{ch}} \geq 1 \) at \(-7.0 < \eta < -6.0 \) or \( 3.7 < \eta < 4.8 \).

3. LHC data and FANSY 2.0 QGSCPG results

As the coplanarity is associated with MEPs, only high \( \eta \) and \( x_F \) data of the CMS+TOTEM [22] on charged particles at \( \sqrt{s} = 8 \) TeV and LHCf experiments [20] at \( \sqrt{s} = 7 \) TeV are considered below.

Figure 3 shows CMS+TOTEM [22] and FANSY 2.0 QGSCPG \( dn_{\text{ch}}/d\eta \) data at \( \sqrt{s} = 8 \) TeV.

Figure 4 shows FANSY 2.0 QGSCPG and LHCf "neutron" \( (n, \bar{n}, \Lambda^0, \bar{\Lambda}^0, K^0_L) \) \( d\sigma/dE \) cross sections.

Figure 5 shows FANSY 2.0 and LHCf \( \gamma \)-ray \( n_{\gamma}/N_{\text{inel}}/\text{GeV} \) energy spectra [20] at \( \sqrt{s} = 7 \) TeV. The upper spectrum is multiplied by 10.
Figure 4. LHCf and FANSY 2.0 "neutron" \(d\sigma/dE\) cross sections at \(\eta > 10.76\) (top) and \(8.81 < \eta < 8.99\) (bottom), \(\Delta\phi = 360^\circ\).

Figure 5. LHCf and FANSY 2.0 \(\gamma\)-ray \(n_\gamma/N_{inel}/\text{GeV}\) energy spectra at \(\eta > 10.94\), \(\Delta\phi = 360^\circ\) (upper symbols) and \(8.81 < \eta < 8.99\), \(\Delta\phi = 20^\circ\) (lower symbols).

4. Search for coplanarity at the LHC

The LHCf detector aimed at the study of high \(x_F\) and \(\eta\) values is capable of detecting only one neutral particle for several dozens of interactions. This makes it impossible to study azimuthal correlations of particles. Let us estimate potentialities of the CASTOR detector, which seems to be more promising, taking into account that much more detailed simulation is undoubtedly required. CPG effects could manifest themselves in its operation pseudorapidity range, i.e. \(5.25 < \eta < 6.5\). The detector consists of 16 segments. Particles are assumed to be detected if their \(\eta\) values are in the range \(5.3 < \eta < 6.5\) and they do not fall into the vertical gap.

Figure 6 shows a simplified cross section scheme of CASTOR and an example of detection of one coplanar interaction. Black circles show tracks of particles. The larger the circle size, the higher the energy of the particle. High-energy particles show a tendency to some coplanarity. Low-energy particles form a more or less azimuthally isotropic background.

To analyze observed interactions, energy values "measured" in each of the segments, \(E_i\), are used. Events with total energy \(\sum E_i \geq 1\) TeV are only analyzed, in which the number of segments with measured energy \(E_i > 100\) GeV is \(N_s \geq 2\). The first number is assigned to a segment with the maximum release of energy, \(E_{max}\). Other segments are numbered clockwise. Here and below, \(E_1 = E_{max}, E_{copl} = E_1 + E_9; E_{tr} = E_5 + E_{13}\), i.e., \(E_{tr}\) is the energy measured in the 9th and 13th segments, perpendicular to the first segment. A simple parameter is applied, namely, \(\varepsilon_{copl} = E_{copl}/(E_{copl} + E_{tr})\). The degree of event coplanarity is maximum at \(\varepsilon_{copl} = 1\).

Figure 7 shows \(d\omega/d\varepsilon_{copl}\) probability distributions (normalized to unity) reproduced with FANSY 2.0 QGSJ and QGSCPG versions, which obviously, predict different probability magnitudes to observe coplanar interactions at \(\varepsilon_{copl} \rightarrow 1\).

5. Conclusion

The FANSY 2.0 model is developed to study superhigh-energy cosmic-ray "forward physics" interactions in general and the coplanar particle generation (CPG) phenomenon in particular.

FANSY 2.0 includes the traditional QGSJ-based QGSJ version and unconventional QGSCPG one with a CPG mode. Results of the QGSCPG version do not contradict to LHC data if to move from the primary concept of growth of \(p_t\) of MEPs in the coplanarity plane to a new concept of reduction of transverse momentum component directed normally to the coplanarity plane so that the average \(p_t\) values remain traditional.
Figure 6. CASTOR’s simplified cross section with an example of a coplanar interaction.

Figure 7. Probability $d\omega/d\varepsilon_{\text{copl}}$ distributions predicted by FANSY 2.0 QGSJ and QGSCPG versions.

It is proposed to test the FANSY 2.0 QGSCPG model with using the CASTOR detector.

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