1 Introduction

A tendency to some coplanarity of most energetic subcores of $\gamma$-ray–hadron families (groups of most energetic particles (MEP) in EAS cores) initiated mainly by primary protons with energies $E_0 \gtrsim 10^{16}$ eV has been observed in X-ray emulsion chamber (XREC) experiments characterized by very high lateral resolution ($\lesssim 1$ mm).

Five experimental data sets on $\gamma$-ray families with energies $\sum E_\gamma \gtrsim 700$ TeV and $\sum E_\gamma \gtrsim 500$ TeV have been accumulated by the Pamir [1, 2] and Mt.Canbala [3] Collaborations, respectively. Besides, two stratospheric events with extreme energies ($\sum E_\gamma > 1$ PeV) and coplanarity of MEPs, namely, the Strana [4, 5] and JF2af2 [6]), have been detected.
The coplanarity phenomenon was also studied using the so-called Big Ionization Calorimeter (BIC) [7] (which was a part of a complex facility for studying EAS at the Tien Shan high-mountain (3340 m a.s.l.) station), with an area of 36 m² and thickness of five mean free paths for proton interaction. Since the lateral resolution of the BIC was worse than 0.25 m, main interactions in the selected showers took place at a noticeably higher altitude as compared with the XREC experiments. Preliminary results showed significant azimuthal effects in large-scale hadronic subcores in EAS cores at a level of six standard deviations above the background at $E_0 = 0.1 - 10$ PeV [8]. Relevant studies are planned to be continued using a large new ionization calorimeter at the same altitude [9].

Since the detection of these effects as a result of EAS fluctuations is unlikely ($\lesssim 10^{-10}$) [10–12], they were originally interpreted as a result of coplanar generation of fragmentation-region MEPs ($x_{Lab} = E/E_0 \gtrsim 0.01$) in first interactions of primary protons.

Several theoretical ideas were proposed to explain this phenomenon as a result of (a) conservation of the quark-gluon-string (QGS) angular momentum [13]; (b) generation of specific leading systems [14–17]; (c) evolution of the dimension of space from three to two dimensions [18]. High-$p_t^{\text{copl}}$ values, forming a coplanar plane, are almost necessarily included in the first two concepts [13–17], while $p_t$ components directed perpendicular to this plane are traditional. The concept of two-dimensional space [18] does not require high-$p_t^{\text{copl}}$ values.

A long-range near-side "ridge" effect in a two-charged-particle $\Delta \eta - \Delta \varphi$ correlation function, $R_N(\Delta \eta, \Delta \varphi)$, was observed by the CMS Collaboration [19] at $|\Delta \eta| \gtrsim 3.0$, $\Delta \varphi \approx 0$. Here $\Delta \varphi$ and $\Delta \eta$ are differences in azimuthal angle $\varphi$ and pseudorapidity $\eta$, respectively.

The analysis performed by the CMS Collaboration (and used in this paper) is as follows [19]. First, all events including charged particles with $|\eta| < 2.4$ and $p_t > 0.1$ GeV/c are used to form so-called minimum-bias data set (including all the events) and high-multiplicity one (including collisions with charged-particle track multiplicity $N_{\text{trk}}^{\text{off}line} \geq 110$ at $p_t > 0.4$ GeV/c). The correlation function is defined as $R_N(\Delta \eta, \Delta \varphi) = \langle (N) \rangle^{-1} (S_N(\Delta \eta, \Delta \varphi)/B_N(\Delta \eta, \Delta \varphi) - 1)$. The signal function $S_N(\Delta \eta, \Delta \varphi) = \langle 1/N_{\text{pair}}^{\text{sign}} \rangle d^2N_{\text{sign}}^{\text{pair}}/d(\Delta \eta)d(\Delta \varphi)$ and background function $B_N(\Delta \eta, \Delta \varphi) = \langle 1/N_{\text{pair}}^{\text{mix}} \rangle d^2N_{\text{mix}}^{\text{pair}}/d(\Delta \eta)d(\Delta \varphi)$ are determined, respectively, by counting the number of charged-particle pairs within each event, $N_{\text{pair}}^{\text{sign}}$, and the number of particle pairs constructed by randomly selecting two different events (with multiplicities $N_1$ and $N_2$) and pairing every charged particle within one event with each particle from another event. Here $N_{\text{pair}}^{\text{mix}} = N_1N_2$, $\langle N \rangle$ is the average number of charged particles per event, $\Delta \eta$ and $\Delta \varphi$ are always taken to be positive to fill one quadrant of the $\Delta \eta - \Delta \varphi$ histograms (other quadrants are filled by reflection).

In Figs. 1a and 1b (Figs. 7b and 7d in Ref. [22]), experimental $R(\Delta \eta, \Delta \varphi)$ functions for minimum-bias and high-multiplicity events are shown. The "ridge" effect is seen in Fig. 1b.

Experiments in cosmic rays and at colliders are carried out under fundamentally different selection criteria. Therefore, it is not possible to directly compare their results. However, we can test whether the FANSY 2.0 model [21], based on high-$x_F$ data and designed to describe the coplanar generation of secondary MEPs, can reproduce any of effects observed in the central kinematic region, in particular, the "ridge" effect.

## 2 Coplanarity simulation and results

The FANSY 2.0 includes conventional (QGSJ) and coplanar-particle generation (CPG) processes. The QGSJ and CPG versions are similar [23] in all characteristics (except azimuth ones at $\sqrt{s} \gtrsim 2$ TeV), reproduce a lot of LHC and low-energy data on hadron generation [23], including data on jets and resonances. It should be emphasized that the model was designed...
2 COPLANARITY SIMULATION AND RESULTS

Figure 1: Charged-particle \( R(\Delta \eta, \Delta \varphi) \) functions at \( |\Delta \eta| \leq 4 \) by the CMS Collaboration for a) minimum-bias and b) high-multiplicity events (Figs. 7b and 7d in Ref. [22]); c) \( R(\Delta \eta, \Delta \varphi) \) function simulated with FANSY 2.0 CPG ("moderate") for minimum bias events.

specifically for the phenomenological description of the phenomenon of coplanarity of the most energetic EAS subcores, discovered in cosmic-ray experiments, and all important model parameters were introduced irrespective of the "ridge" effect.

To obtain more detailed conclusions within the FANSY 2.0 model, a large amount of simulations will be carried out, and the results will require separate publications. Until now, the main goal of this series of works was to show that the predictions of the developed model do not contradict the main results of experiments carried out at the LHC.

The initial concept of MEPs’ high-\( p_t \) copl coplanarity \([11,12]\) gives a qualitative description of the cosmic-ray phenomenon, but contradicts LHC data \([23]\). Only a new concept of coplanarity, assuming a reduction in MEPs’ transverse-momentum components, directed normal to the coplanarity plane, makes it possible to reconcile the LHC data and the MEPs’ coplanarity \([23]\).

In this case, the experimental and simulated \( \langle p_t \rangle \) values in all \( \eta \) bins do not differ significantly.

The cross section for pp CPG interactions, \( \sigma_{\text{CPG}}^\text{inel}(s) \), increases from \( \sim 0 \) to 42 mb as \( \sqrt{s} \) increases from \( \sim 1.25 \) to 7 TeV \([23]\). At \( |y| > |y_{\text{thr}}^{\text{CPG}}| = |y_2| - \Delta_y^{\text{CPG}} \) \([20]\) (where \( y_2 \) is the rapidity of the second-in-energy particle and only used to calculate a fluctuating threshold value, \( |y_{\text{thr}}^{\text{CPG}}| \)), the "coplanarization" algorithm rotates hadron transverse momentum, \( \vec{p}_t \), towards the coplanarity plane along the shortest path. The azimuthal-angular distribution of MEPs’ \( \vec{p}_t \) is sampled according to the Gaussian distribution (relative to the coplanarity plane) with a standard deviation depending on rapidity as \( \sigma_{\varphi}^{\text{CPG}}(y) = \sigma_{\varphi_0}^{\text{CPG}} \cdot (|y_2/y|)^{\beta} \).

Obviously, the most important parameters are those that determine the coplanarity degree, namely, (a) the dispersion of the deviation of the hadron’s azimuth angle from the coplanarity plane, \( \sigma_{\varphi_0}^{\text{CPG}} \); (b) the rate of its increase with decreasing rapidity determined by the parameter \( \beta \) of the particles, and (c) the minimum value of MEPs’ rapidities, \( |y_{\text{thr}}^{\text{CPG}}| \) depending on \( \Delta_y^{\text{CPG}} \).

The effective value of \( |y_{\text{thr}}^{\text{CPG}}| \) can only be chosen phenomenologically.

In Ref. [20] and this paper, similar results were obtained using three slightly different combinations of the \( \Delta_y^{\text{CPG}} \), \( \sigma_{\varphi_0}^{\text{CPG}} \) and \( \beta \) parameters (compare Table 1 in both papers), hereinafter referred to as "weak", "moderate" and "strong" versions. The aim was to test the robustness of the results. The conclusion is in line with expectations, i.e. small changes in parameter values resulted in small changes in the phenomenon magnitude.

The \( R(\Delta \eta, \Delta \varphi) \) function simulated with the FANSY 2.0 QGSJ version for high-multiplicity events does not show any "ridge"-like effect as expected (see Fig. 3 in Ref. [20]). The \( R(\Delta \eta, \Delta \varphi) \) function simulated with the use of FANSY 2.0 CPG ("moderate") for minimum bias events is shown in Fig. 1c, and no significant "ridge"-like effect is also observed in this case.

Figure 2 presents \( R(\Delta \eta, \Delta \varphi) \) functions for high-multiplicity events obtained with the use of "weak", "moderate" and "strong" versions using parameters given in Table 1. The most strong "ridge" effect is obviously reproduced by the "strong" version, i.e., an increase in the degree of
Table 1: Effective parameters of "weak", "moderate", "strong" FANSY 2.0 versions.

| Parameter | "weak" | "moderate" | "strong" |
|-----------|--------|------------|----------|
| $\langle \Delta_{\text{CPG}} \rangle$ | 3.60   | 4.40       | 4.90     |
| $\langle \sigma_{\text{CPG}} \phi \rangle$ | 0.10   | 0.09       | 0.06     |
| $\langle \beta \rangle$ | 1.00   | 0.85       | 0.40     |

Figure 2: The $R(\Delta \eta, \Delta \varphi)$ functions simulated for high-multiplicity events with "weak", "moderate", and "strong" FANSY 2.0 CPG versions.

coplanarity of MEPs causes a corresponding increase in the effect in the correlation function.

All the above-considered results were obtained with $|\Delta \eta| \leq 4$ and $|\eta| \leq 2.4$. If the $|\Delta \eta|$ interval could be expanded, then interesting effects would be observed for high-multiplicity events. Figure 3 shows the $R(\Delta \eta, \Delta \varphi)$ function simulated by FANSY 2.0 CPG ("moderate") at $|\Delta \eta| \leq 5$, $|\Delta \eta| \leq 6$, $|\Delta \eta| \leq 6.5$, while $|\eta|$ values of particles under consideration vary in a wider range, namely, $|\eta| \leq 8.0$. At $|\Delta \eta| > 4$, the "ridge" effect will rapidly develops into a brighter phenomenon expressed in the appearance of two peaks close in size ("twin peaks") at $|\Delta \varphi| \approx 0$ and $|\Delta \varphi| \approx \pi$. So, Fig. 3 shows that an expansion of the $|\Delta \eta|$ range can inform us on features of the MEP coplanarity region. If the peak growth is found to stop at $|\Delta \eta| \sim 5$, and amplitude of peaks begin to decrease with a further increase in $|\Delta \eta|$, this means that the "ridge" effect is not associated with the process of coplanar generation of MEPs.

Thus, there is a qualitative agreement between the experimental and simulated $R(\Delta \eta, \Delta \varphi)$ functions in the region of the "ridge" effect, while there are differences between the functions at $|\Delta \varphi| \approx \pi$. It is the CPG process that creates some growth of the simulated $R(\Delta \eta, \Delta \varphi)$ functions at $|\Delta \varphi| \approx \pi$ and $|\Delta \eta| \gtrsim 3$.

Within the FANSY 2.0 CPG model, the coplanarity planes have the same azimuthal orientation in the opposite hemispheres. The "twin peaks" effect at $|\Delta \eta| \gtrsim 4$ is determined mainly by hadrons from different hemispheres, both at $|\Delta \varphi| \sim 0$ and $|\Delta \varphi| \sim \pi$. The coplanarization

Figure 3: $R(\Delta \eta, \Delta \varphi)$ distributions simulated by FANSY 2.0 CPG ("moderate") for high-multiplicity events at $|\Delta \eta| \leq 5$, $|\Delta \eta| \leq 6$, $|\Delta \eta| \leq 6.5$ and $|\eta| \leq 8$. 
3 Search for coplanarity signatures at the LHC

Simulations show that CPG signatures can appear in the range 5.25 < \eta < 6.5 [23], so the CMS-CASTOR very-forward calorimeter experiment [24], focused on this \( |\eta| \) interval, seems promising. For a simplified assessment of CASTOR capabilities, let us assume that it consists of 16 radially arranged segments divided in half by a vertical slit. If the pseudorapidities of particles (which do not fall into the slit) are in the range 5.25 < \eta < 6.5, particles are considered to be registered, and their energies are considered to be "measured". Only interactions with the total "measured" energy \( \sum E_i > 1 \text{ TeV} \) are considered. Here \( E_i \) is the energy value "measured" in the \( i \)-th segment (1 \( \leq i \leq 16 \)). In addition, the number of segments \( N_s \), in each of which the "measured" energy \( E_i > E_{i_{\min}} = 100 \text{ GeV} \), must be equal to or greater than two. The segment with the maximum energy release, \( E_{\max} \), gets the first number, i.e. \( E_1 = E_{\max} \). The remaining segments are numbered clockwise in ascending order. Finally, let us define variables as follows: \( E_{copl} = E_1 + E_9; \ E_{tr} = E_5 + E_{13}; \ e_{copl} = E_{copl}/(E_{copl} + E_{tr}) \). Obviously, at \( e_{copl} = 1 \), the degree of event coplanarity is maximum.

Figure 4 shows \( d\omega/d\epsilon_{copl} \) probability distributions obtained using the QGSJ version (line), as well as the "weak", "moderate" and "strong" CPG versions. As expected, the "strong" CPG version predicts the highest value of \( d\omega/d\epsilon_{copl} \) at \( \epsilon_{copl} \to 1 \). Undoubtedly, a detailed study of the coplanarity phenomenon requires much more accurate simulations.

4 Conclusion

The long-range near-side "ridge" effect observed by the CMS Collaboration can be a by-product of the coplanar generation of most energetic particles in hadronic interactions. A significant "twin peaks" effect is predicted, which appears in \( R(\Delta \eta, \Delta \phi) \) correlation functions at \( |\Delta \eta| > 4 \) in high-multiplicity events. Coplanarity signatures could be observed with the CMS-CASTOR very-forward calorimeter.
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