On connection between the collider long-range near-side “ridge” effect at $|\eta| < 2.4$ and cosmic-ray coplanarity of most energetic particles

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Abstract Some coplanarity of most energetic subcores of γ -ray-hadron families is observed in cosmic-ray experiments at $E_0 \gtrsim 10^{16}$ eV ($\sqrt{s} \gtrsim 5$ TeV). This effect requires appearance of some coplanar generation of most energetic particles in hadron-nucleus interactions. On the other hand, a long-range near-side “ridge” effect was observed in pp collisions at $\sqrt{s} = 7$ TeV by the CMS Collaboration in two-particle $\Delta\eta - \Delta\phi$ correlation functions at $|\Delta\eta| \gtrsim 3$ and $|\Delta\phi| \approx 0$. To improve a research for possible relationship of these phenomena, a phenomenological FANSY 2.0 model is designed to simulate hadron interactions using both traditional and coplanar modes for the hadron generation, QGSJ and CPG, respectively. The FANSY 2.0 reproduces LHC data on generation of unflavoured, strange and charmed hadrons. Model parameters of coplanar hadron generation are given. It is shown that the FANSY 2.0 CPG reproduces the near-side “ridge” effect at $\sqrt{s} = 7$ TeV.

1 Introduction

One of phenomena obtained in mountain-based and stratospheric X-ray-emulsion chamber (XREC) experiments is a strong azimuthal effect that manifests itself in the form of a tendency to a coplanarity of most energetic subcores of so-called γ -ray-hadron families, i.e. groups of most energetic ($E \gtrsim 10$ TeV) particles in the central cores of relatively “young” extensive air showers (EAS). This means that these showers do not reach their maximum development at the observation level, and numbers of most energetic particles (MEP) in these showers are higher than the average one. These showers are mainly initiated by protons and helium nuclei of the primary cosmic radiation (PCR) with energies $E_0 \gtrsim 10^{16}$ eV ($\sqrt{s} \gtrsim 5$ TeV).

Five independent sets of experimental data [1–12] have been accumulated. First of all, it is high-mountain data obtained by the *Pamir* Collaboration with so-called “carbon” (C) and “lead” (Pb) XRECs on γ -ray families with measured energies $\sum E_\gamma \geq 700$ TeV [1–5] and Mt.Canbala Collaboration’s Fe-XRECs ($\sum E_\gamma \geq 500$ TeV) [6].

Besides, only two events (the *Strana* [7–10] and *JF2af2* [11,12]) with $\sum E_\gamma > 1$ PeV have been detected in stratospheric balloon experiments at very high altitudes using the emulsion technique, and both these events demonstrate a very high coplanarity of most energetic particles. It should be noted that features of high-energy events observed in the stratosphere are much more sensitive to parameters of first interactions of PCR particles in the atmosphere (due to a much smaller thickness of the atmospheric layer above the detectors in these experiments). Properties of events observed at the mountain level are heavily contaminated by secondary interactions of cascade hadrons.

The probability that the entire set of these experimental results is produced by EAS development fluctuations is very low ($\lesssim 10^{-10}$) [13–15].

One can summarize the key findings [13] as follows.

- The phenomenon is associated with the most energetic particles generated at the initial stage of the EAS;
- this process is not described by the QCD approach and traditional QGSM-based models used in high-energy physics;
- this process is characterized by a relatively large cross-section, comparable to σ_{prod}^{p-air} .

The phenomenon was initially interpreted as a manifestation of coplanar generation of most energetic particles in the fragmentation region ($x_{Lab} = E/E_0 \gtrsim 0.01 - 0.05$) characterized by relatively large MEP transverse momenta (lying in the coplanarity plane), namely, $p_t^{copl} \gtrsim 1$ GeV/c.

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As regards γ -ray families observed in ground-based experiments, a more accurate measurement or, at least, an estimation of the MEPs' average p_t^{copl} in coplanar events was not carried out in reality at the time of realization of the above-mentioned experiments due to difficulties in simulation of the XREC response.

A few theoretical ideas were proposed to explain this phenomenon in the framework of relatively traditional concepts of hadron interactions as a result of

- conservation of the angular momentum of a relativistic fast-rotating quark-gluon string (QGS) stretched between colliding hadrons [16];
- semihard double inelastic diffraction (SHDID) [17], which assumes the coplanarity to be a result of some QGS tension in the diffraction cluster between a semihardly scattered constituent quark and other spectator quarks of the projectile hadron;
- projectile's diquark breaking [18];
- appearance of very-high-spin leading systems [19, 20];
- connection between this phenomenon and a highly exotic "crystal world" hypothesis [21].

Finally, let us mention the assumption that this phenomenon is a signature of some coherent Cherenkov-like hadron radiation at ultrahigh energies [22].

The first four concepts [16–20] imply large transverse momenta as an almost mandatory element forming the coplanar plane, while transverse momenta directed perpendicular to this plane still have typical values of standard hadronic models. The "crystal world" concept [21] implies a gradual decrease in the dimension of space from three to two dimensions at sufficiently high energies, as well as some localization of $\mathbf{p}_t$ in a certain plane with a decrease in the $\mathbf{p}_t$ components directed perpendicular to this plane.

As for the collider experiments, the CMS Collaboration have found a so-called near-side "ridge" effect [23], which presents a two-particle long-range ($|\Delta\eta| > 2.0$), near-side ($\Delta\varphi \approx 0$) $\Delta\eta - \Delta\varphi$ correlation, where $\Delta\eta (= \eta_1 - \eta_2)$ and $\Delta\varphi (= \varphi_1 - \varphi_2)$ are the differences in pseudorapidity ($\eta (= \ln(\tan(\theta/2)))$ and azimuthal angle φ , respectively, between two charged particles. Here θ is the polar angle relative to the beam axis.

The energy range studied at the LHC corresponds to the energies responsible for the coplanar generation of MEPs. This makes it possible to search for a possible connection between these phenomena.

This paper is devoted to a comparison of the CMS Collaboration data and FANSY 2.0 [24, 25] results on the near-side "ridge" effect and organized as follows.

Section 2 describes algorithms for processing experimental data on the collider long-range near-side "ridge" effect and cosmic-ray coplanarity of most energetic particles.

Section 3 presents a short discussion on the concept of coplanarity origin and describes shortly the FANSY 2.0 CPG model.

Section 4 compares some experimental data and simulated results on interactions features.

In Sect. 5, some discussion on experimental and simulated results is carried out.

In conclusion, most important results are given.

2 On processing of experimental data

The analysis made by the CMS Collaboration is as follows [23]. At the preliminarily stage, all events including charged particles with transverse momenta $p_t > 0.1$ GeV/c are divided into two data sets, namely, so-called minimum-bias and high-multiplicity ones. The minimum-bias data set includes all collisions with charged particles with $|\eta| < 2.4$. The high-multiplicity event data set includes collisions with charged-particle track multiplicity $N_{trk}^{offline} \geq 110$ at $p_t > 0.4$ GeV/c and $|\eta| < 2.4$.

For both minimum-bias and high-multiplicity event data sets, the next step is to split each of the data sets into a several bins with different multiplicity of tracks.

The p_t -inclusive charged two-particle correlation is defined as a function of $\Delta\eta$ and $\Delta\varphi$ [23] as follows:

$$R_N(\Delta\eta, \Delta\varphi) = \left(\langle N \rangle - 1 \right) \left(\frac{S_N(\Delta\eta, \Delta\varphi)}{B_N(\Delta\eta, \Delta\varphi)} - 1 \right) \quad (1)$$

In Eq. (1), $\langle N \rangle$ is the number of charged particles with $|\eta| \leq 2.4$ per event averaged over a multiplicity bin.

For each multiplicity bin, the signal distribution

$$S_N(\Delta\eta, \Delta\varphi) = \frac{1}{N_{pair}^{sign}} \frac{d^2 N^{sign}}{d(\Delta\eta) d(\Delta\varphi)} \quad (2)$$

was determined by counting the number of charged-particle pairs within each event, N_{pair}^{sign} . Thus, Eq. (2) represents the two-charged-particle pair density function normalized to the unit integral.

The background distribution

$$B_N(\Delta\eta, \Delta\varphi) = \frac{1}{N_{pair}^{mix}} \frac{d^2 N^{mix}}{d(\Delta\eta) d(\Delta\varphi)} \quad (3)$$

denotes the distribution of uncorrelated particle pairs representing a product of two single particle distributions, also normalized to the unit integral. This distribution was constructed by randomly selecting two different events within the same multiplicity bin and pairing every charged particle with $|\eta| \leq 2.4$ in one event (with multiplicity N_1) with every charged particle with $|\eta| \leq 2.4$ in the other interaction (with multiplicity N_2). In this case, the normalization factor is $1/N_{pair}^{mix} = 1/N_1 N_2$.

Fig. 1 The $R(\Delta\eta, \Delta\varphi)$ functions measured by the CMS Collaboration for inclusive minimum bias events (a) and high-multiplicity events, ($N_{trk}^{offline} \geq 110$) (b), for charged particles (Fig. 7b and d, respectively, in Ref. [26])

The variables $\Delta\eta$ and $\Delta\varphi$ are always taken to be positive and used to fill one quadrant of the $\Delta\eta - \Delta\varphi$ histograms, while the other three quadrants are filled by reflection. Therefore, the resulting distributions are symmetric about $(\Delta\eta, \Delta\varphi) = (0, 0)$ by construction. To simplify the corresponding figures, it is possible to cut off a part of the distribution, for example, at $\Delta\varphi \lesssim -2$ without losing the information content of figures.

Figures 1a and 1b (Fig. 7b and d, respectively, in Ref. [26]) present p_t -integrated two-charged-particle correlation signal-to-background-ratio functions, $R(\Delta\eta, \Delta\varphi)$, for minimum bias events (Fig. 1a) and high-multiplicity events (Fig. 1b). In Fig. 1b, an unexpected distinct “ridge”-like structure appears at $\Delta\varphi \approx 0$, extending to $|\Delta\eta| = 4$ (near-side “ridge” effect). Simulations using all the traditional Monte Carlo models (see details in Ref. [26]) do not reproduce such an effect. The so-called away-side effect at $\Delta\varphi \approx \pi$ is not unexpected and can be explained by traditional processes, such as, for example, two-particle decays of resonances (first of all, ρ^0 mesons) or the generation of pairs of correlated jets initiated by mutual scattering of two quarks (gluons).

The parameter

$$\lambda_N = \sum_{i \neq j \neq k}^N \cos 2\varphi_{ij}^k / (N(N-1)(N-2)) \quad (4)$$

has been proposed by the *Pamir* Collaboration [1] to calculate the degree of a so-called *alignment* of N point-like tracks on the target plane that appear as a result of EAS’s most energetic particles hitting the XREC. Here φ_{ij}^k is the angle between two vectors, connecting the k -th point with the i -th and j -th points. The summation is performed over all possible combinations. The parameter λ_N is equal to unity for N points aligned along a straight line and $\lambda_N \approx -1/(N-1)$ in the isotropic cases.

The search for a possible connection between the coplanarity phenomenon and the near-side “ridge” effect is of great interest. The idea of the existence of some kind of connection between these phenomena was expressed in some works (see Ref. [27], e.g.). On the other hand, collider and cosmic-ray

experiments are carried out with completely different event-selection criteria: very high particle multiplicity in the central pseudorapidity range in the case of the near-side “ridge” effect and several high- x_F MEPs in the case of coplanar γ -ray families. As a result, approaches to studying the effects are completely different, as can be seen from the comparison of the parameter λ_N and correlation function $R(\Delta\eta, \Delta\varphi)$ (Eqs. (4) and (1), respectively).

However, we can test whether a model FANSY 2.0 [24, 25], which is based on data on high- x_F particles and describes the coplanarity phenomenon, reproduces the near-side effect observed in a range of relatively small pseudorapidities.

3 Coplanarity simulation

The model FANSY 2.0 makes it possible to simulate both traditional and coplanar particle generation processes (QGSJ and CPG versions, respectively). Both the FANSY 2.0 versions are similar [28] (excluding azimuthal characteristics at $\sqrt{s} \gtrsim 2$ TeV) and reproduce high- x_F and high- η data on γ -rays and neutron-like hadrons accumulated by the LHCf experiment, as well as ALICE, ATLAS, CMS, TOTEM data on generation of stable particles and resonances, mesons and baryons, unflavoured, strange and charmed hadrons [28]. In addition, FANSY 2.0 reproduces low-energy data on generation of stable particles and resonances, strange and charmed particles.

In brief, the FANSY 2.0 model simulates

- generation of fragmentation-range hadrons ($x_F \gtrsim 0.01$), whose relative contribution gradually decreases with increasing energy of interaction;
- soft generation of hadrons via quark-gluon string (QGS) generation; the effective QGS number gradually increases with energy;
- single and double diffraction processes (SD and DD, respectively);
- generation of QCD jets including both parton shower development at $Q^2 > 10$ (GeV/c)² and soft fragmentation at lower Q^2 values at sufficiently high energies;
- generation of light-quark, strange and charmed mesons and baryons, stable and resonance hadrons.

It should be noted that the generation of jets and resonances is of great importance in the study of two-particle correlation. The generation of jets makes a significant contribution in the central region ($\Delta\eta \sim 0$, $\Delta\varphi \sim 0$) and away-side “ridge” range ($\Delta\varphi \sim \pi$). The two-particle decay of resonances (especially, ρ^0 mesons) makes an appreciable contribution to the two-particle correlation at $\Delta\varphi \sim \pi$ in a wide $\Delta\eta$ range. Therefore, the model pays much attention to the generation of resonances. For example, the generation

of $\pi^{\pm,0}$, $\rho^{\pm,0}$, and ω , strange K and K^* , charmed D , and D^* , strange/charmed $D_s^{\pm}$ and $D_s^{\pm*}$ mesons and more heavy resonances as well as $N^{*+,0}$ nucleons, $\Delta^{++,+,0,-}$, $\Xi^{0,-}$, charmed Λ_c^+ (and more heavy) baryons and corresponding antibaryons is actually simulated by FANSY 2.0.

The LHC energy range is appropriate to study the coplanar particle generation (CPG) process. However, there is a number of difficulties caused by collider's specific kinematics of experiments and a high beam luminosity. Nevertheless, it was shown in a simplified way [28] that the CASTOR experiment [29] looks promising for the study of some coplanarity signatures.

Simulations using tentative CPG versions of the FANSY model show the following fundamental problem. The original concept of the MEP coplanarity used by FANSY 1.0 [14, 15] prior to the LHC operation provides a qualitative explanation of the phenomenon, assuming high transverse momenta of MEPs, p_t^{copl} , in the coplanarity plane. However, in this case, a significant p_t growth suppresses $d\sigma/dy$ and $d\sigma/d\eta$ cross sections for hadron generation at highest $|y|$ and $|\eta|$ values and creates robust peaks at $2 \lesssim |\eta| \lesssim 4$ which are contrary to LHC data [28]. This problem seems to be insoluble in the framework of the original high- p_t^{copl} coplanarity concept.

Some agreement of LHC data and idea of coplanar generation becomes real only in the framework of a new concept of coplanarity origin, which assumes some decrease of particles' transverse momentum components directed normally to the coplanarity plane [28]. This decrease takes place so that the average absolute p_t values in any η bin do not vary significantly and corresponding p_t distributions remain unchanged. This conceptual point is very important.

Other main ideas of the model, which do not contradict to the available experimental data, are as follows.

1. The most powerful coplanarity is associated with the most energetic hadrons. The lower the hadron energy, the weaker the coplanarity effect.
2. The coplanarity phenomenon is absent in the central kinematic region.

While beginning from the most energetic particle, transversal momenta of high-rapidity particles with $|y| > |y_{thr}^{CPG}|$ are coplanarized with a probability $w^{CPG}(s) = \sigma_{inel}^{CPG}(s)/\sigma_{inel}(s)$ if the summed energy of secondary particles, $\sqrt{s_{eff}}$, is higher than 250 GeV. Here, $\sigma_{inel}^{CPG}(s)$ is the cross section for inelastic CPG processes in pp interactions. $\sigma_{inel}^{CPG}(s)$ grows from 0 at $\sqrt{s} \approx 1.25$ TeV to ≈ 42 mb at 7 TeV [28].

The coplanarization algorithm is as follows. The azimuthal orientation of the coplanarity plane is determined by the sum of the p_x and p_y components of the transverse momenta of

Fig. 2 A qualitative scheme of traditional and coplanarity ranges of dn_{ch}/dy distribution

the two most energetic (in each of the hemispheres) hadrons and is assumed to be the same in both hemispheres.

All characteristics of n secondary hadrons are primarily simulated with the traditional way, i.e., applying the QGSJ version. In the case of CPG simulation, hadrons are ordered in decreasing order of their longitudinal momenta, i.e., $p_{max} \geq p_1 \geq p_2 \geq p_3 \dots p_n \geq -p_{max}$, where $p_{max} = \sqrt{s/4 - m_p^2}$. The corresponding rapidity values are $y_1, y_2, y_3, \dots y_n$. Here p_{max} is equal to the momentum of the colliding protons in their c.m.s. and shows the kinematic limit for momenta of secondary particles.

After this, the so-called “coplanarization” procedure is implemented for MEPs in the coplanarity range, i.e., at $|y| > |y_{thr}^{CPG}| = |y_2| - \Delta_y^{CPG}$. Here, the y_2 value is used only, firstly, to calculate the threshold value, $|y_{thr}^{CPG}|$, and secondly, to calculate the standard deviation of the azimuth-angle distribution of transverse momenta relative to the coplanarity plane with using Eq. (5) (see below). Besides, Δ_y^{CPG} is a free parameter depending on interaction energy so that the average value $\langle |y_{thr}^{CPG}| \rangle$ does not depend on energy. Figure 2 shows a schematic drawing of the traditional and coplanarity ranges of dn/dy distributions.

An algorithm rotates the p_t vectors of hadrons with $|y| > |y_{thr}^{CPG}|$ towards the coplanarity plane along the shortest path and stops this procedure at $|y| < |y_{thr}^{CPG}|$. The azimuth-angle distribution of transversal momenta of MEPs obeys a Gaussian distribution with a rapidity-dependent standard deviation of $\sigma_\varphi^{CPG}(y)$ relative to the coplanarity plane. Here

$$\sigma_\varphi^{CPG}(y) = \sigma_{\varphi 0}^{CPG} \cdot (|y_2/y|)^\beta \quad (5)$$

The $\sigma_\varphi^{CPG}(y)$ value is minimal for large-rapidity hadrons and increases with decreasing rapidity. Its maximum value cannot be larger than $\pi/2$.

The value of $|y_{thr}^{CPG}|$ can vary from interaction to interaction even with a constant Δ_y^{CPG} due to fluctuations of $\sqrt{s_{eff}}$ and y_2 values.

It should be noted that the most important parameters are Δ_y^{CPG} , $\sigma_{\varphi 0}^{CPG}$, and β . An increase in Δ_y^{CPG} , as well as a decrease in $\sigma_{\varphi 0}^{CPG}$ and β , enhances both the coplanarity and

Table 1 Effective parameters of “weak”, “moderate” and “strong” coplanarity versions

Parameter	“Weak”	“Moderate”	“Strong”
$\langle \Delta_y^{\text{CPG}} \rangle$	3.70	4.50	5.00
$\langle \sigma_{\varphi 0}^{\text{CPG}} \rangle$	0.10	0.09	0.05
$\langle \beta \rangle$	1.00	0.82	0.25
$\langle y_{\text{thr}}^{\text{CPG}} \rangle$	3.66	2.92	2.48

near-side “ridge” effect. A decrease in Δ_y^{CPG} , as well as an increase in $\sigma_{\varphi 0}^{\text{CPG}}$ and β , suppresses both the coplanarity and near-side “ridge” effect.

Several versions of the FANSY 2.0 CPG model were used with different values of parameters Δ_y^{CPG} , $\sigma_{\varphi 0}^{\text{CPG}}$, and β . The results presented in the paper have been obtained with using three combinations of these versions. These combinations are hereinafter referred to as “weak”, “moderate” and “strong” ones. Their effective parameters are given in Table 1.

In all three cases, $\langle y_2 \rangle = 7.33$ at $\sqrt{s} = 7$ TeV.

The only result of applying this procedure is a change in the direction of the transverse momenta of most energetic particles, but not their absolute values and, accordingly, the values of rapidity and pseudorapidity as well as the x_F values. Accordingly, both models reproduce with the same degree of accuracy the data on high-energy gamma-rays and neutron-like hadrons studied, for instance, by the LHCf experiment.

Very preliminary results obtained using other selection criteria with poorer statistical accuracy have been first reported in a short talk at Russian Cosmic-Ray Conference [30]. This paper presents much more accurate results based on an improved processing program and better statistical accuracy. However, it should be noted that the qualitative conclusions are the same in the both articles.

While it is obvious that the above-considered coplanarization algorithm is highly arbitrary, it contains some reasonable ansatz, which, on the one hand, does not contradict the LHC data, but, on the other hand, is introduced carefully enough to explain the coplanarity of the most energetic particles observed in cosmic rays. In general, this is some kind of phenomenological parameterization that does not provide an idea of the underlying physical mechanisms and their relationship with QCD dynamics.

4 LHC data and FANSY 2.0 CPG results

This paper uses an event selection procedure that matches the CMS Collaboration algorithm (although some similar selection criteria in experiment and simulation may differ slightly).

At the first stage, events are divided into two groups, namely, the minimum-bias and high-multiplicity data sets. The minimum-bias data set includes all events containing charged particles with $p_t > 0.1$ GeV/c at $|\eta| < 2.4$. The high multiplicity data set includes collisions satisfying the following requirement: multiplicity of charged-particle tracks $N_{ch} \geq 110$ at $p_t > 0.4$ GeV/c and $|\eta| < 2.4$.

Each of the two data sets is divided into a few bins in track multiplicity. Final distributions for these data sets are obtained by averaging over corresponding bins.

The two-particle correlation functions, $R(\Delta\eta, \Delta\varphi)$, signal distribution $S_N(\Delta\eta, \Delta\varphi)$ and background distribution $B_N(\Delta\eta, \Delta\varphi)$, are defined by Eqs. (1), (2) and (3), respectively.

The variables $\Delta\eta$ and $\Delta\varphi$ are always taken to be positive and used to fill one quadrant of the $\Delta\eta - \Delta\varphi$ histograms, while the other three quadrants are filled by reflection. Since, the resulting distributions are symmetric about $(\Delta\eta, \Delta\varphi) = (0, 0)$ by construction. Thus a part of the distribution, for instance, at $\Delta\varphi > 1$ and $\Delta\eta > 2$ can be cut off without losing the information content of the following figures.

Figure 3 shows the $R(\Delta\eta, \Delta\varphi)$ distribution simulated with the FANSY 2.0 QGSJ version at $|\Delta\eta| \leq 4$ for high-multiplicity events. Obviously, no significant structure similar to the experimental near-side “ridge” effect is observed.

Figure 4 shows the $R(\Delta\eta, \Delta\varphi)$ distribution simulated with FANSY 2.0 CPG (“moderate”) at $|\Delta\eta| \leq 4$ for minimum bias events. Obviously, no noticeable structure like the near-side “ridge” effect is also observed in this case.

Fig. 3 The $R(\Delta\eta, \Delta\varphi)$ distribution simulated with FANSY 2.0 QGSJ at $|\Delta\eta| \leq 4$ for high-multiplicity events **Fig. 4** The $R(\Delta\eta, \Delta\varphi)$ distribution simulated with FANSY 2.0 CPG (“moderate”) at $|\Delta\eta| \leq 4$ for minimum bias events

Fig. 5 The $R(\Delta\eta, \Delta\phi)$ distribution simulated with FANSY 2.0 CPG (“weak”) at $|\Delta\eta| \leq 4$ for high-multiplicity events

Fig. 6 The $R(\Delta\eta, \Delta\phi)$ distribution simulated with FANSY 2.0 CPG (“moderate”) at $|\Delta\eta| \leq 4$ for high-multiplicity events

Fig. 7 The $R(\Delta\eta, \Delta\phi)$ distribution simulated with FANSY 2.0 CPG (“strong”) at $|\Delta\eta| \leq 4$ for high-multiplicity events

Figures 5, 6 and 7 show $R(\Delta\eta, \Delta\phi)$ distributions for high-multiplicity events simulated with three (“weak”, “moderate” and “strong”) FANSY 2.0 CPG versions, respectively. Values of the effective parameters of these versions are shown in Table 1.

One can see that all three figures demonstrate near-side “ridge”-like structures, however their magnitudes are different. The weakest effect is seen in Fig. 5, while the most prominent near-side “ridge”-like structure is shown in Fig. 7.

An interesting effect could be observed for the high-multiplicity events if the range $|\Delta\eta|$ could be expanded. Figure 8 shows the $R(\Delta\eta, \Delta\phi)$ distribution simulated by FANSY 2.0 CPG (“moderate”) at $|\Delta\eta| \leq 4$ (a), $|\Delta\eta| \leq 5$ (b), $|\Delta\eta| \leq 6$ (c), $|\Delta\eta| \leq 7$ (d), while pseudorapidity values of particles under consideration can vary in ranges $|\eta| \leq 2.4$

(a), $|\eta| \leq 3.0$ (b), $|\eta| \leq 3.5$ (c), $|\eta| \leq 4.0$ (d), respectively. Recall that Figs. 6 and 8a are the same and differ only in the scale of their vertical axis.

In the range of large $|\Delta\eta|$ values ($|\Delta\eta| > 4$), one can see a rapid development of the near-side “ridge” effect and its development into a much stronger phenomenon, expressed in the form of two peaks at $|\Delta\phi| \approx 0$ and $|\Delta\phi| \approx \pi$, which are close in magnitude. This phenomenon could be called the “twin peaks” effect.

5 Discussion

When comparing the CMS Collaboration data (Fig. 1a, b) with simulations performed using the FANSY 2.0 model for events with minimum-bias and high-multiplicity events (Figs. 4, 5, 6, 7, respectively), one can see a qualitative agreement between the experimental data and simulation results in the region of the near-side “ridge” effect, i.e. at $|\Delta\phi| \approx 0$ and $|\Delta\eta| \gtrsim 3$.

However, one can see differences between experimental and simulated correlation functions at $|\Delta\phi| \approx \pi$ for high-multiplicity events. Obviously, in both experimental and simulated results, a noticeable positive correlation is observed over the entire range, $|\Delta\eta| < 4$. This correlation is determined, on the one hand, by the jet generation and, on the other hand, by the generation of energetic ρ^0 mesons decaying along the $\rho^0 \rightarrow \pi^+ + \pi^-$ mode. The experimental correlation function is sufficiently monotonic, while one can see a relatively small local maximum in the center at $|\Delta\eta| \approx 0$ and a moderate growth of simulated correlation functions at $|\Delta\eta| \gtrsim 3$.

Some contribution to the local maximum at $|\Delta\eta| \approx 0$ and $|\Delta\phi| \approx \pi$ is given by the generation of oppositely directed jets at $|\eta| \approx 0$.

The central maximum at $|\Delta\eta| \approx 0$ and $|\Delta\phi| \approx 0$ is formed by hadron pairs from the same jets.

Some growth of the correlation functions at $|\Delta\phi| \approx \pi$ and $|\Delta\eta| \gtrsim 3$ is determined by the CPG process, since the FANSY 2.0 QGSJ does not give such effect (Fig. 3).

In the FANSY 2.0 CPG model, the coplanarity planes of high-energy particles in the opposite hemispheres have the same azimuthal orientation. Therefore, in the region $|\Delta\eta| \gtrsim 4$, the correlation maxima of the function $R(\Delta\eta, \Delta\phi)$ (the “twin peaks” effect) are determined mainly by particles from different hemispheres, both at $|\Delta\phi| \sim 0$ and at $|\Delta\phi| \sim \pi$ (Fig. 8).

If it will be possible to study the correlations for $|\Delta\eta| \gtrsim 4$ in the future, we might get unexpected results. Let us suppose, for example, that at the largest values of $|\Delta\eta|$ there is only a near-side peak, or only an “away-side” peak, or both of these peaks disappear. In each of these cases, new ideas may be required.

Fig. 8 $R(\Delta\eta, \Delta\phi)$ distributions simulated by FANSY 2.0 CPG (“moderate”) for high-multiplicity events at $|\Delta\eta| \leq 4$ (a), $|\Delta\eta| \leq 5$ (b), $|\Delta\eta| \leq 6$ (c), $|\Delta\eta| \leq 7$ (d)

It should be emphasized that the coplanarity simulation in the FANSY 2.0 model is a very simplified procedure. The orientation of the coplanarity plane is assumed to be the same in both hemispheres. At present, more complex variants cannot be ruled out, for example, different orientations of the coplanarity planes in the opposite hemispheres can be assumed. Moreover, we can even talk not about planes, but, for example, consider curved surfaces.

Finally, it can be noted that the double diffraction is not able to give a noticeable number of high-multiplicity events that meet the above selection criteria within the framework of the FANSY 2.0 model. Therefore, it is highly unlikely that the explanation of coplanarity in the framework of the semi-hard double diffraction model [17] can reproduce the near-side “ridge” effect as well. The same conclusion can be drawn with respect to the models explaining the coplanarity of energetic particles by the projectile’s diquark breaking [18] or appearance of very-high-spin leading systems [19,20].

Undoubtedly, for a correct comparison of experimental and calculated results, it is necessary, first of all, to simulate all experimental processes and selection algorithms. Since the efficiency of detecting secondary particles and measuring their characteristics cannot always be as high as 100%, this inevitably leads to some blurring of local features of the $R(\Delta\eta, \Delta\phi)$ function.

Thus the FANSY 2.0 model can only be exploited as a zero-order phenomenological tool used to assess the impact of CPG processes on the observed characteristics of interactions. To improve our understanding of the physical processes responsible for generation of high x_F hadrons and to refine the model, a more detailed study of two-particle near- and away-side correlations in a wider range of changes in the parameter $|\Delta\eta|$ is needed using new LHC experiments.

Conclusion

The FANSY 2.0 model is developed to study superhigh-energy cosmic-ray “forward physics” interactions and includes two versions, namely, the traditional (QGSJ) and coplanar particle generation of most energetic particles (CPG) versions.

The FANSY 2.0 concept of the CPG process does not contradict LHC data. This concept assumes some decrease of particles’ transverse momentum components directed perpendicular to the coplanarity plane, so that the values of the transverse momenta do not change significantly.

In the FANSY 2.0 CPG framework, the near-side “ridge” effect observed by the CMS Collaboration at the LHC is a consequence of the coplanar generation of the most energetic particles. As a result, a strong “twin peaks” effect appears in the two-particle $\Delta\eta - \Delta\phi$ correlation functions at $|\Delta\eta| > 4$.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Author’s comment: All data generated or analysed during this study are included in this published article.]

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