On connection of the cosmic-ray coplanarity of most energetic particles with the collider long-range near-side "ridge" effect

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August 30, 2022

21st International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2022)
Online, 23-27 May 2022
doi:10.21468/SciPostPhysProc.?

Abstract

Coplanarity of most energetic subcores of γ-ray–hadron families observed in cosmic-ray experiments at $E_0 \gtrsim 10^{16}$ eV is explained only with a process of coplanar generation of most energetic hadrons. Long-range near-side "ridge" effect at $\sqrt{s} = 7$ TeV was found by the CMS Collaboration in two-particle $\Delta\eta - \Delta\varphi$ correlation functions. The FANSY 2.0 model reproduces both the hadron coplanarity and "ridge" effect.

Contents

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1 Introduction

A tendency to a coplanarity of most energetic subcores of γ-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 with X-ray emulsion chamber (XREC) experiments.

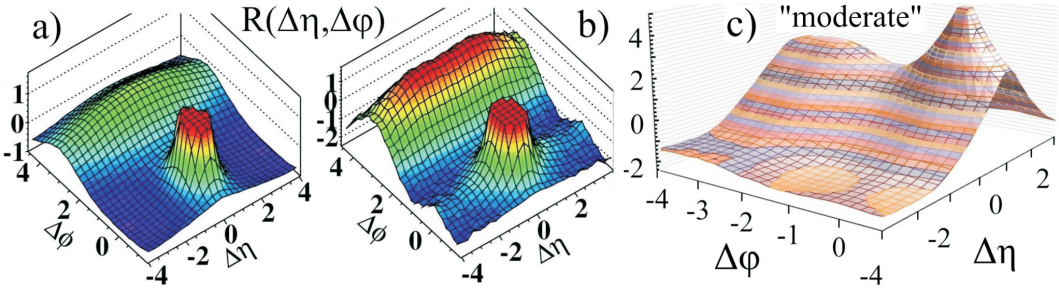

Figure 1: Charged-particle $R(\Delta\eta, \Delta\varphi)$ functions at $|\Delta\eta| \leq 4$ by the CMS Collaboration for a) minimum-bias and b) high-multiplicity events (Figs. 7b and 7d in Ref. [19]); c) $R(\Delta\eta, \Delta\varphi)$ function simulated with FANSY 2.0 CPG ("moderate") for minimum bias events.

Five experimental-data sets have been accumulated by the *Pamir* Collaboration on γ-ray families with energies $\sum E_\gamma \geq 700$ TeV with using so-called "carbon" and "lead" XRECs [1, 2] as well as by Mt.Canbala Collaboration with using Fe-XRECs ($\sum E_\gamma \geq 500$ TeV) [3]. Besides, two stratospheric events with a very high energy ($\sum E_\gamma > 1$ PeV) and extreme coplanarity of MEPs, namely, the *Strana* [4, 5] and *JF2af2* [6]), have been detected.

Detection of such events as a result of EAS fluctuations is unlikely ($\lesssim 10^{-10}$) [7–9]. So, this phenomenon was 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 characterized by MEPs' high transverse momenta ($p_t^{copl} \gtrsim 1$ GeV/c) forming a coplanarity plane.

Several theoretical ideas were proposed to describe this phenomenon as a result of (a) conservation of QGS's angular momentum [10]; (b) generation of specific leading systems [11–14]; (c) changing the dimension of space from three to two [15]. High-p_t^{copl} values, forming a coplanar plane, are almost necessarily included in the first two concepts [10–14], while p_t^{copl} components directed perpendicular to this plane have typical values of standard interaction models. The concept of 2D-dimension space [15] does not include this requirement.

An unexpected structure in a two-charged-particle $\Delta\eta - \Delta\varphi$ correlation function at $|\Delta\eta| \gtrsim 3.0$, $\Delta\varphi \approx 0$ (so-called long-range near-side "ridge" effect) [16] was observed by the CMS Collaboration. Here $\Delta\varphi$ and $\Delta\eta$ are differences in azimuthal angle φ and pseudorapidity η, respectively. Simulations using conventional models do not reproduce this effect [19].

The analysis made by the CMS Collaboration [16] and repeated in this paper is as follows. Events including charged particles with $|\eta| < 2.4$ and $p_t > 0.1$ GeV/c are divided into two data sets, namely, so-called minimum-bias (including all collisions) and high-multiplicity (including events with charged-particle multiplicity $N_{trk}^{offline} \geq 110$) ones (see details in Refs. [16, 17]).

The two-charged-particle $\Delta\eta - \Delta\varphi$ correlation function is defined [16] as
$R_N(\Delta\eta, \Delta\varphi) = \langle(\langle N\rangle - 1)(S_N(\Delta\eta, \Delta\varphi)/B_N(\Delta\eta, \Delta\varphi) - 1)\rangle$, where
$S_N(\Delta\eta, \Delta\varphi)$ and $B_N(\Delta\eta, \Delta\varphi)$ are the signal and background distributions (see Refs. [16, 17]).

In Figs. 1a and 1b (Figs. 7b and 7d in Ref. [19]), 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 [18], based on high-x_F data and describing the coplanarity phenomenon, can reproduce the "ridge" effect.

Table 1: Effective parameters of "weak", "moderate", "strong" FANSY 2.0 versions.

Parameter	"weak"	"moderate"	"strong"
$\langle\Delta_y^{\rm CPG}\rangle$	3.60	4.40	4.90
$\langle\sigma_{\varphi 0}^{\rm CPG}\rangle$	0.10	0.09	0.06
$\langle\beta\rangle$	1.00	0.85	0.40

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 [20] in all characteristics (except azimuth ones at $\sqrt{s} \gtrsim 2$ TeV), reproduce a lot of LHC and low-energy data on hadron generation [20], including data on jets and resonances, which affects two-particle correlations.

The initial concept of MEPs' high-$p_{\rm t}^{copl}$ coplanarity [8, 9] gives a qualitative description of the cosmic-ray phenomenon, but creates a stable peak in the $d\sigma/d\eta$ cross section at $2 \lesssim |\eta| \lesssim 4$, which contradicts LHC data [20]. 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 [20]. In this case, the experimental and simulated $\langle p_{\rm t}\rangle$ values in all η bins do not differ significantly.

Main coplanarity-generation concept is as follows.

1. The most notable coplanarity is associated with the most energetic hadrons.

2. There is no some coplanarity phenomenon in the central rapidity region.

The cross section for pp CPG interactions, $\sigma_{\rm inel}^{\rm CPG}(s)$, increases from ~ 0 to 42 mb as the energy, $\sqrt{s}$, increases from $\sim$ 1.25 to 7 TeV [20]. The "coplanarization" algorithm is implemented for hadrons with rapidities $|y|$ higher than $|y_{\rm thr}^{CPG}))| = |y_2| - \Delta_y^{\rm CPG}$ [17]. Here y_2 is the rapidity of the second-in-energy particle and only used to calculate the threshold value, $|y_{\rm thr}^{CPG}|$. Naturally, $|y_{\rm thr}^{\rm CPG}|$ fluctuates due to fluctuations in values of y_2 and other parameters. If the hadron rapidity is large ($|y| > |y_{\rm thr}^{\rm CPG}|$), the algorithm rotates its transverse momentum, $\overrightarrow{\mathbf{p}}_t$, towards the coplanarity plane along the shortest path. The azimuthal-angular distribution of MEPs' $\overrightarrow{\mathbf{p}}_t$ is sampled according to the Gaussian distribution with a standard deviation (relative to the coplanarity plane), which depends on rapidity as $\sigma_\varphi^{\rm CPG}(y) = \sigma_{\varphi 0}^{\rm CPG} \cdot (|y_2/y|)^\beta$.

The $\Delta_y^{\rm CPG}$, $\sigma_{\varphi 0}^{\rm CPG}$, and β parameters are most important. An increase in $\Delta_y^{\rm CPG}$ and/or decrease in $\sigma_{\varphi 0}^{\rm CPG}$ and β, enhance both the coplanarity and "ridge" effect. A decrease in $\Delta_y^{\rm CPG}$ and/or increase in $\sigma_{\varphi 0}^{\rm CPG}$ and β suppress both these effects.

Several FANSY 2.0 CPG versions with different $\Delta_y^{\rm CPG}$, $\sigma_{\varphi 0}^{\rm CPG}$, and β values were exploited. In Ref. [17] and this paper, the similar results were obtained using three combinations of these parameters, hereinafter referred to as "weak", "moderate" and "strong". The parameters used in these papers were defined slightly different (compare Table 1 in Ref. [17] and Table 1 in this paper) to test the robustness of the results to small variations in selection criteria. The results were in line with expectations, i.e. small changes in parameter values resulted in small changes in magnitude of the phenomena.

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 (Fig. 3 in Ref. [17]). The $R(\Delta\eta, \Delta\varphi)$ function simulated with the use of FANSY 2.0 CPG ("moderate") for minimum bias events is shown

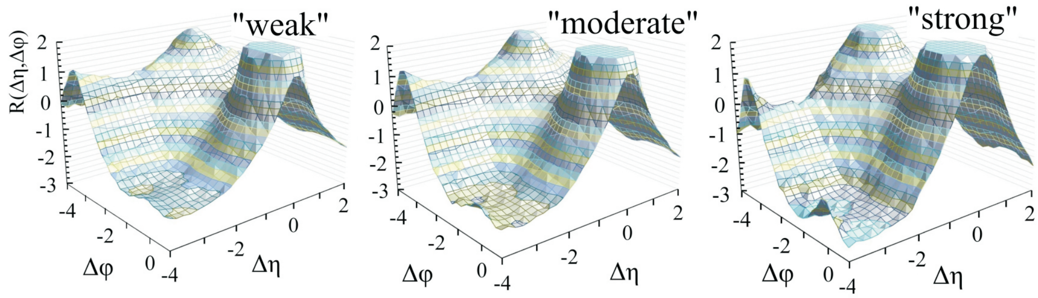

Figure 2: The $R(\Delta\eta, \Delta\varphi)$ functions simulated for high-multiplicity events with "weak", "moderate", and "strong" FANSY 2.0 CPG versions.

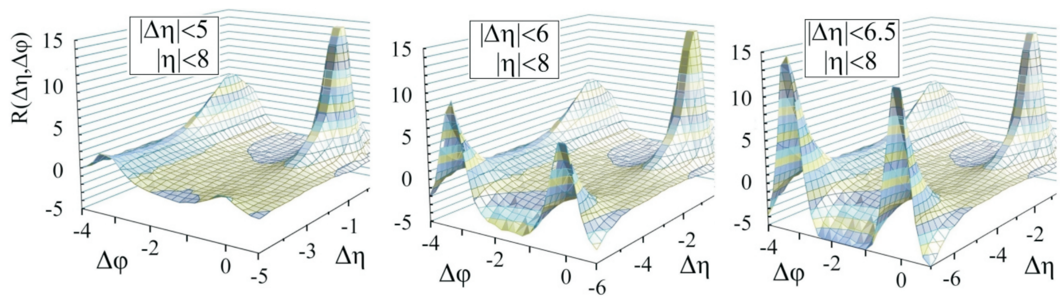

Figure 3: $R(\Delta\eta, \Delta\varphi)$ distributions simulated by FANSY 2.0 CPG ("moderate") for high-multiplicity events at $|\Delta\eta| \leq 5$, $|\Delta\eta| \leq 6$, $|\Delta\eta| \leq 6.5$ and $|\eta| \leq 8$.

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 Tabl. 1. The most strong "ridge" effect is obviously reproduced by the "strong" version.

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 η values of particles under consideration vary in a wide range, namely, $|\eta| \leq 8.0$. At $|\Delta\eta| > 4$, the FANSY 2.0 CPG predicts that the "ridge" effect will rapidly develop into a much stronger phenomenon with rising $|\Delta\eta|$. Namely, it is expressed in the appearance of two peaks at $|\Delta\varphi| \approx 0$ and $|\Delta\varphi| \approx \pi$, which are close in magnitude. This phenomenon could be called the "twin peaks" effect.

It can be seen that 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 $|\Delta\varphi| \approx \pi$. The simulated functions have local maxima at $|\Delta\eta| \approx 0$ and $\gtrsim 3$, while the experimental $R(\Delta\eta, \Delta\varphi)$ function is sufficiently monotonic. Just the CPG process 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 algorithm is a very primitive procedure. So, one cannot rule out, for example, different orientations of the coplanarity planes in the opposite hemispheres (or even more complex cases) that will entail

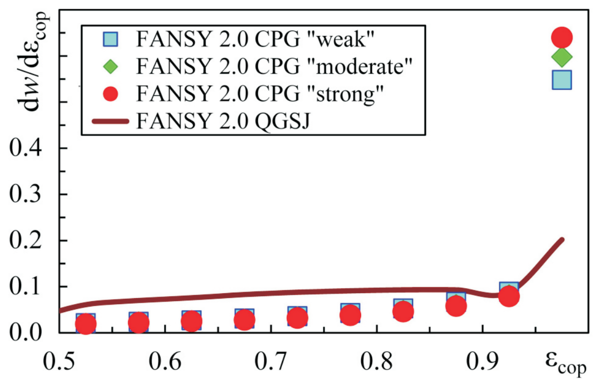

Figure 4: Probability $d\omega/d\varepsilon_{\text{copl}}$ distributions predicted by "weak", "moderate", and "strong" FANSY 2.0 CPG versions for the CASTOR detector.

corresponding changes in $R(\Delta\eta, \Delta\varphi)$ functions.

3 Search for coplanarity signatures at the LHC

Simulations show that CPG signatures can appear in the range $5.25 < |\eta| < 6.5$ [20], so the CASTOR experiment [21], focused on this pseudorapidity interval, seems promising.

For a simplified assessment of the capabilities of the CASTOR detector, we assume that it consists of 16 radially arranged segments and is divided in half by a vertical slit. If the pseudorapidities of particles are in the range $5.25 < \eta < 6.5$, and at the same time they do not fall into the slit, then the particles will be considered as registered, and their energies as "measured". Undoubtedly, a detailed study of the coplanarity phenomenon requires much more accurate and complex simulations.

Only interactions with a "measured" total energy $\sum E_i$ greater than 1 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 $E_i > E_{i\,min} = 100$ 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: $E_{\text{copl}} = E_1 + E_9$; $E_{tr} = E_5 + E_{13}$; $\varepsilon_{\text{copl}} = E_{\text{copl}}/(E_{\text{copl}} + E_{tr})$. Obviously, at $\varepsilon_{\text{copl}} = 1$, the degree of event coplanarity is maximum.

Figure 4 shows $d\omega/d\varepsilon_{\text{copl}}$ 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 $d\omega/d\varepsilon_{\text{copl}}$ at $\varepsilon_{\text{copl}} \to 1$.

4 Conclusion

Within the FANSY 2.0 CPG model,
• the long-range near-side "ridge" effect observed by the CMS Collaboration is a by-product of the coplanar generation of most energetic particles in hadronic interactions;
• a significant "twin peaks" effect is predicted, which appears in the correlation functions $R(\Delta\eta, \Delta\varphi)$ at $|\Delta\eta| > 4$ in high-multiplicity events;

• ccoplanarity signatures could be observed with the CASTOR detector.

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