

# Jet activity versus alignment

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**Abstract.** The hypothesis of the relation between the observed alignment of spots in x-ray films in cosmic ray emulsion experiments and the features of events in which jets prevail at super-high energies is tested. Due to the strong dynamical correlation between jet axis directions and that between the momenta of jet particles (almost collinearity), the evaluated degree of alignment is considerably larger than that for randomly selected chaotically located spots in the x-ray film. It appears to be comparable with the experimental data provided that the height of the primary interaction, the collision energy and the total energy of the selected clusters meet certain conditions. The Monte Carlo generator PYTHIA, which basically well describes jet events in hadron–hadron interactions, was used for the analysis.

## 1 Introduction

The intriguing phenomenon of the strong collinearity of cores in emulsion experiments [1], closely related to coplanar scattering of secondary particles in the interaction, has been observed a long time ago. So far there is no simple satisfactory explanation of these cosmic ray observations in spite of numerous attempts to find it (see, for instance, [2] and references therein). Among them, the jet-like mechanism [3] looks very attractive and gives a natural explanation of alignment of three spots along a straight line which results from momentum conservation in a simple parton picture of scattering. Besides, the strong momentum correlation of particles inside a jet and correlation between jet axes due to singularity of QCD matrix elements allow us to suggest a high degree of alignment for more than three spots. This has already been demonstrated for four cores in [3] but using a simplified picture of hadronization.

With increasing energy of the colliding hadrons (nuclei), hard and semi-hard jets begin to play an important role due to the growth of their production cross sections. Thus the jet activity is likely to be a feature of all events above a certain threshold collision energy. One of the manifestations of this activity and the strict momentum ordering inside a hard enough jet may be observed as a strong collinearity of spots in emulsion experiments. The main purpose of the present paper is just to trace this relation in detail. In Sect. 2 we formulate the problem on the whole. Section 3 describes the results of a numerical simulation

made under conditions close to the emulsion experiments in the framework of PYTHIA [4], and some discussion. A summary can be found in Sect. 4.

## 2 Problem under consideration

In the Pamir experiment the observed events ( $\gamma$ -hadron families with the alignment) are produced, mostly, by a proton with energy  $\gtrsim 10^4$  TeV interacting at a height of several hundred meters to several kilometers in the atmosphere above the chamber [2, 5]. The collision products are observed within a radial distance up to several centimeters in the emulsion where the spot separation is of the order of 1 mm. One can estimate the typical transverse momentum in the events under consideration using the ratio (see also (4))

$$p_T h = r E, \quad (1)$$

where  $E$  is the energy deposition in the spot,  $r$  is its spacing in the x-ray film,  $h$  is the height of the interaction. So  $p_T$  is of the order of 10 GeV for  $r = 15$  mm,  $h = 1$  km,  $E = 700$  TeV. The particles with such transverse momenta can be typically initiated by a jet with  $p_T^{\text{jet}} \sim 50$  GeV or larger, since the most probable value of a fraction of jet energy carried by leading particles is  $\sim 0.2$  [4]. Such energetic jets are already enough collimated: their effective angular cone size  $\theta_{\text{eff}} \lesssim 15^\circ$  due to the strict ordering of transverse and longitudinal particle momenta in the leading logarithm approximation of perturbative QCD [6]. QCD “teaches” us also that this effective size decreases with the growth of the “jet hardness” (transverse momentum) as follows:

$$\theta_{\text{eff}} \sim (\ln(p_T^{\text{jet}}/\Lambda_{\text{QCD}}))^{-1}, \quad (2)$$

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where  $\Lambda_{\text{QCD}}$  is the dimensional QCD parameter.

The main conjecture is that the particle distribution from the hard enough jets in the x-ray film plane can lead to the alignment of the emulsion spots due to the strong collimation of such particles and the dynamical correlation between the jet axis directions. Let us consider the kinematics in detail. For our analysis it is convenient to parametrize the 4-momentum of each produced particle  $i$  under consideration with its transverse momentum  $p_{\text{T}i}$  (relative to the collision axis  $z$ ), azimuthal angle  $\phi_i$  and rapidity  $\eta_i$  in the center-of-mass system:

$$\left[ \begin{array}{l} \sqrt{p_{\text{T}i}^2 + m_i^2} \cosh \eta_i, \quad p_{\text{T}i} \cos \phi_i, \quad p_{\text{T}i} \sin \phi_i, \\ \sqrt{p_{\text{T}i}^2 + m_i^2} \sinh \eta_i \end{array} \right]. \quad (3)$$

In this case the transformation from the center-of-mass system to the laboratory one reduces to a simple rapidity shift:  $\zeta_i = \eta_0 + \eta_i$ , where  $\zeta_i, \eta_0$  are the rapidities of particle  $i$  and the center-of-mass system respectively in the laboratory reference frame. If we neglect the further interactions of the particles propagating through the atmosphere (this gives the maximum estimation of the alignment effect), then their positions in the transverse ( $xy$ )-plane are easily calculated:

$$\mathbf{r}_i = \frac{\mathbf{v}_{ri}}{v_{zi}} h = \frac{\mathbf{p}_{\text{T}i}}{\sqrt{p_{\text{T}i}^2 + m_i^2} \sinh(\eta_0 + \eta_i)} h, \quad (4)$$

where  $\mathbf{v}_{ri}$  and  $v_{zi}$  are the radial and longitudinal components of particle velocity respectively ( $E_i = \sqrt{p_{\text{T}i}^2 + m_i^2} \cosh(\eta_0 + \eta_i)$  is the particle energy in the laboratory frame).

Since the size of the observation region is of the order of several centimeters, these radial distances must obey the following restriction:

$$r_{\min} < r_i, \quad (5)$$

$$r_i < r_{\max}. \quad (6)$$

We set  $r_{\min} = r_{\text{res}} \simeq 1$  mm,  $r_{\max} \simeq 15$  mm. The restriction (5) simply means that spots are not mixed with the central one formed by the particles which fly close to the collision axis (mainly from the fragmentation region of an incident proton). The separation of spots in the x-ray film gives another restriction on the distance between the particles:

$$d_{ij} = \sqrt{r_i^2 + r_j^2 - 2r_i r_j \cos(\phi_i - \phi_j)}. \quad (7)$$

It must be larger than 1 mm:

$$d_{ij} > r_{\text{res}}; \quad (8)$$

in the opposite case the particles must be combined in one particle cluster until there remain only particles and/or particle clusters with mutual distances larger than  $r_{\text{res}}$ , each such particle cluster being considered as a single particle with coordinates defined in the same way as center-of-mass coordinates of two bodies:

$$\mathbf{r}_{ij} = (\mathbf{r}_i E_i + \mathbf{r}_j E_j) / (E_i + E_j). \quad (9)$$

Then we select the 2, ..., 7 clusters/particles which are most energetic and obey the restrictions (5), (6) and (8) and calculate the alignment  $\lambda_{N_c}$  using the conventional definition [2, 5]

$$\lambda_{N_c} = \frac{\sum_{i \neq j \neq k}^{N_c} \cos(2\phi_{ijk})}{N_c(N_c - 1)(N_c - 2)}, \quad (10)$$

and taking into account the central cluster, i.e.  $N_c - 1 = 2, \dots, 7$ . Here  $\phi_{ijk}$  is the angle between the two vectors  $(\mathbf{r}_k - \mathbf{r}_j)$  and  $(\mathbf{r}_k - \mathbf{r}_i)$  (for the central spot  $\mathbf{r} = 0$ ). This parameter characterizes the location of  $N_c$  points just along the straight line and varies from  $-1/(N_c - 1)$  to 1. For instance, in the case of the symmetrical and close to the most probable random configuration of three points in a plane (the equilateral triangle)  $\lambda_3 = -0.5$ . The ultimate case of perfect alignment is  $\lambda_{N_c} = 1$  when all points lie exactly along the straight line, while for an isotropic distribution  $\lambda_{N_c} < 0$ . The degree of alignment  $P_{N_c}$  is defined as the fraction of events with  $\lambda_{N_c} > 0.8$  [2] with the number of cores not less than  $N_c$ .

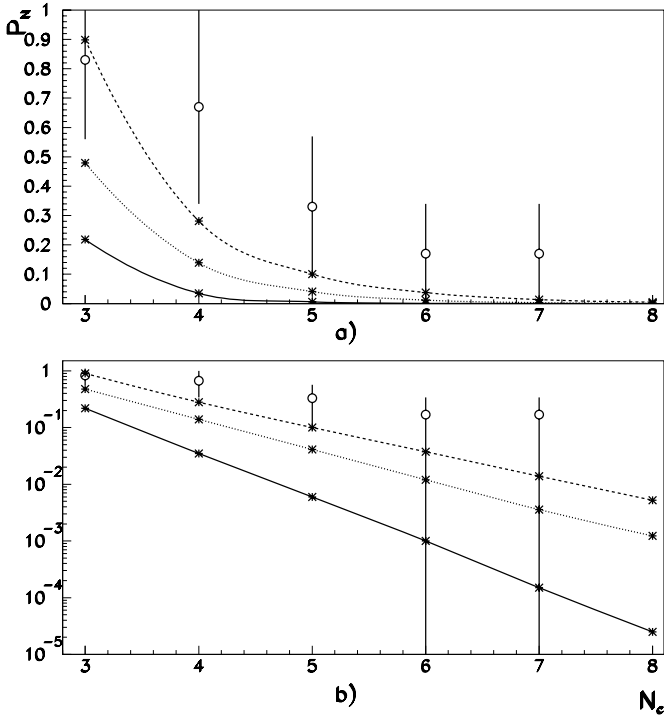
### 3 Numerical results and discussion

If the hypothesis of the relation of the alignment to the prevailing jet character of events at super-high energies is valid, then this must manifest itself first of all in nucleon-nucleon collisions. Therefore, to be specific we consider a collision of two protons and fix a primary energy in the laboratory system  $E_{\text{lab}} \simeq 9.8 \times 10^4$  TeV, which is equivalent to  $\sqrt{s} \simeq 14$  TeV – just the energy attainable at LHC (the rapidity shift being  $\eta_0 \simeq 9.55$  after a transformation from the center-of-mass system to the laboratory one). To simulate the collision of two protons with such energies we use the Monte Carlo generator PYTHIA [4], which basically well describes jet events in hadron-hadron interactions and is tuned using the available experimental accelerator data.

The results of a numerical simulation which follows the consideration in the previous section are presented in Fig. 1 (solid curve) with the parameters  $r_{\min} = r_{\text{res}} = 1$  mm,  $r_{\max} = 15$  mm,  $h = 1000$  m, which are close to the conditions of emulsion experiments, with the additional restriction on the energy threshold of particle registration in the emulsion  $E_i > E^{\text{thr}} = 4$  TeV<sup>1</sup>. The estimated degree of alignment  $P_{N_c}$  for  $N_c$  cores is considerably larger than that for randomly selected chaotically located spots in the x-ray film, but is still too small (by a factor of 3–4) to describe the experimental data [7] even taking into account their large errors. This can mean that the jet activity is not sufficient at such energies or the jet mechanism can not, in principle, give the large experimentally observable alignment.

In order to try to answer this question let us consider the influence of the applied restrictions (5) and (6) (the laboratory acceptance criterion) on the spectrum of

<sup>1</sup> Our calculations are practically insensitive to this threshold in the wide interval of its variation.



**Fig. 1.** The degree of alignment  $P_{N_c}$  as a function of cluster number  $N_c$  at  $h = 50$  m and  $\sqrt{s} = 14$  TeV in linear **a** and logarithmic **b** scales. The solid curve is the result (coincident with the one at  $h = 1000$  m) without restriction on the minimum value of process hardness  $p_T^{\text{hard}}$ , the dotted curve at  $p_T^{\text{hard}} = 300$  GeV, the dashed curve at  $p_T^{\text{hard}} = 3$  TeV. Points (o) with errors are experimental data from [7]

particles selected to calculate the alignment. For particles with high enough transverse momenta  $p_{T_i}$  relative to their masses  $m_i$  these conditions (5) and (6) reduce, mainly, to the restriction on the available particle rapidities in the center-of-mass system:

$$r_{\min} < r_i \implies \eta_i < \eta_{\max} = \ln(r_0/r_{\min}) \simeq 4.95, \quad (11)$$

$$r_i < r_{\max} \implies \eta_i > \eta_{\min} = \ln(r_0/r_{\max}) \simeq 2.25, \quad (12)$$

since in this case  $r_i \simeq r_0/e^{\eta_i}$  for  $\eta_0 + \eta_i \gtrsim 1$ , where

$$r_0 = 2h/e^{\eta_0}. \quad (13)$$

Due to the kinematical restriction [6],

$$e^{\eta^{\text{jet}}} p_T^{\text{jet}} \lesssim \sqrt{s}, \quad (14)$$

the production of harder jets with larger rapidities becomes possible with the growth of  $\sqrt{s}$ . The rapidity region (11) and (12) just corresponds to the transition from soft to hard QCD physics, where the jet activity *could* manifest itself.

Here one should note that ultrarelativistic particles ( $p_{T_i} \gg m_i$ ) are detected in the x-ray film from the restricted rapidity region (11) and (12) which excludes such configurations as back-to-back hard jets with rapidities close to zero in the center-of-mass system. But just such

configurations with scattering of hard partons at angles close to  $90^\circ$  in the considered hadronic center-of-mass system (which in this case practically coincides with the partonic center-of-mass system) can be expected to be responsible for the alignment phenomenon. The point is that leading particles from both these hard jets have quantitatively comparable energies in the laboratory frame together with the “strong memory” of the scattering plane. Meanwhile leading particles from any other back-to-back hard jets with relatively large modulo rapidities  $|\pm\eta_{\text{PCMS}}^{\text{jet}}|$  in the partonic center-of-mass system have essentially different laboratory energies due to the Lorentz boost, and the energy distinction is mainly determined by the value of  $\exp(2|\pm\eta_{\text{PCMS}}^{\text{jet}}|)$ . In the latter case particles from a forward hard jet produce as a rule the most energetic clusters (apart from the central one) in the laboratory frame, even if the particles from a backward (in the partonic center-of-mass system) jet hit the detection region. However most such energetic clusters from one jet are less correlated with the primary scattering plane and therefore will not be much aligned as clusters from both hard jets. This argumentation is confirmed by our simulation.

In this connection it is necessary to comment on the work [3] in which the jet hypothesis has been suggested for the first time for the explanation of the alignment phenomenon. There the high degree of alignment has been demonstrated for the four cores only, using a simplified picture of the fragmentation process. In fact, an axis distribution has been calculated in the partonic center-of-mass system in the first order of perturbative QCD theory at the partonic level, considering three partons in the final state only. Then a Lorentz transformation has been done in order to find their directions and localizations with respect to the central spot in the laboratory frame, considering each parton jet as one long-living system (the fragmentation time is of the order of the flight time) with some effective mass and aggregate group velocity. The velocity has been fixed ( $\beta^* \simeq 0.7$  in [3]) so as to be able to include the events giving a high degree of alignment and corresponding to the two final-state parton jets in the backward hemisphere and one in the forward hemisphere in the partonic center-of-mass system. In our variables this means that a mass factor  $p_T/\sqrt{p_T^2 + M^2}$  must be very small for such a massive system ( $M \gg p_T$ ) so that it hits the detection region even with negative rapidities (i.e. corresponds to the backward hemisphere in the partonic center-of-mass system), if one uses the same boost parameters as for the hadronic center-of-mass system without taking into account the possible additional boost due to the distinction between these partonic and hadronic frames. Note that for real particles, e.g.  $\pi$ -mesons which mainly contribute to the multiplicity, this mass factor becomes significant for very small transverse momenta,  $p_{T\pi} \ll m_\pi = 0.14$  GeV, only. However, as our investigation shows, the falling of appropriately correlated particles in the observation region is still not sufficient to obtain the high degree of alignment because of the energy selection procedure, if the total number of particles is large and they generate many distinctly separated spots.

For completeness one should also mention that high transverse momentum jet production has a connection to the double-core configuration of cosmic ray events as it has been pointed out in [8]. Under certain conditions a hard forward (in the partonic center-of-mass system) jet together with a central bunch gives two relatively far separated clusters with large energies. The detailed studies of double-core (or binocular) phenomena with estimations of event rates and average lateral spread of the  $\gamma$ -family using a PQCD based Monte Carlo can be found, for instance, in [9, 10].

Ultrarelativistic particles from the central rapidity region in the hadronic center-of-mass system (as possible sources of appropriately correlated spots) can hit the observation region owing to the decrease of  $r_0$  *only*, i.e. the decrease of the height  $h$  of primary interaction or the increase of the rapidity  $\eta_0$  of the center-of-mass system due to the growth of energy  $\sqrt{s}$ , as it follows from (13). The energy growth seems preferable, if we intend to be closer to the emulsion experiments and increase the jet activity. However this demands the extrapolation of PYTHIA parameters and their special tuning to the experimentally untested energy domain. Updating can be done appropriately after the LHC operation starts. Moreover at present this generator already uses the extrapolation of experimentally tested cross sections and structure functions to the LHC energy region  $\sqrt{s} \simeq 14$  TeV in order to estimate the effects expected at such energies.

For illustration we utilize the first “less dangerous” alternative – decrease the interaction height by a factor of 20 rather than increase the energy  $\sqrt{s}$  by the same factor of 20 at the initial height so that particles from both hard jets (with back-to-back structure), hitting the registration region, come from some rapidity range near  $\eta_i \simeq 0$  including adjoint positive and negative values. In this case the degree of alignment becomes strongly dependent on the minimum transverse momentum of hard process,  $p_T^{\text{hard}}$ , which is a parameter of PYTHIA. At the height  $h = 1$  km such a dependence was not visible, although we might catch some marginal tendency of the degree of alignment to grow with the increase of  $p_T^{\text{hard}}$  at that height. However without the restriction on  $p_T^{\text{hard}}$  from below (minimum bias) the result coincides practically with the one obtained earlier (solid curve in Fig. 1) that shows some general characteristics of the jet structure of the events. If  $p_T^{\text{jet}} \geq 3$  TeV, particles from these hard jets together with particles flying close to the  $z$ -axis (within the transverse radius  $< 1$  mm) result in a degree of alignment (dashed curve) comparable with the experimentally observed one [7].

Thus the jet-like mechanism can, in principle, attempt to explain the results of the emulsion experiments. For such an explanation it is necessary (but not sufficient) that particles from both hard jets (with rapidities near  $\eta_i \simeq 0$  in the center-of-mass system) hit the observation region. This is possible at the relatively small height  $h = 50$  m and  $\sqrt{s} \simeq 14$  TeV; or at the height  $h = 1000$  m, but the considerably higher energy  $\sqrt{s} \simeq 14 \times 20 = 280$  TeV, or at some reasonable and acceptable intermediate combination

of  $h$ ,  $\sqrt{s}$  and  $r_{\text{max}}$  which meets the following condition:

$$r_0 = 2h/e^{\eta_0} = 2hm_p/\sqrt{s} \lesssim kr_{\text{max}}, \quad (15)$$

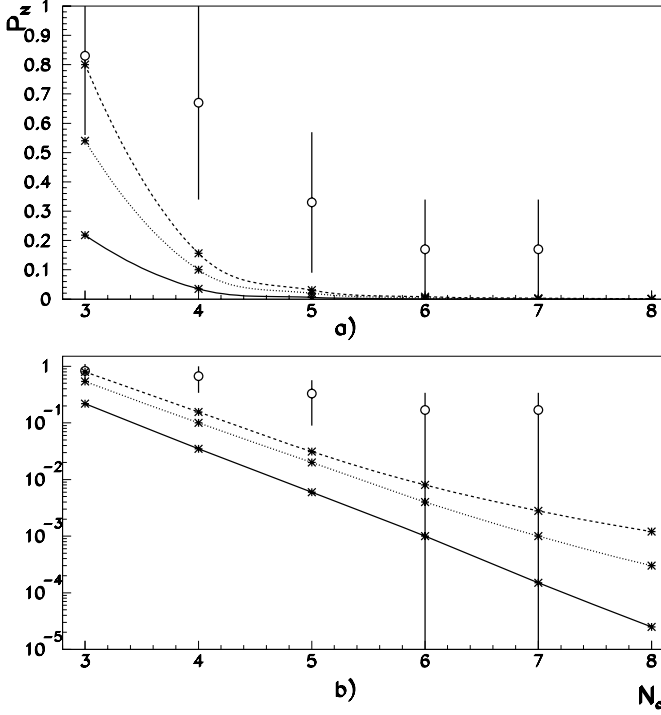
where  $m_p$  is the proton mass.  $k \simeq 1/2 < 1$  is needed in order to have particles with  $\eta_i < 0$  that hit the detection region (see (12)). We verified the decisive significance of condition (15) to allow for the observation of a large degree of alignment and its dependence on the process hardness for the smaller energy of  $\sqrt{s} \simeq 1.4$  TeV (where the prediction of PYTHIA is quite adequate) and a height  $h = 5$  m (in accordance with (15)) thereby confirming this peculiar kinematic “scaling”.

At  $p_T^{\text{hard}} = 3$  TeV the jets carry away about half of the energy of colliding protons in the center-of-mass system due to the relationship in a parton picture  $\xi \simeq 2p_T^{\text{jet}}/\sqrt{s}$ , where  $\xi$  is the fraction of proton energy carried by each interacting parton (quark or gluon). The striking feature of such configurations in the x-ray film is the approximate equality of the energy deposition in the central and the rest of the most energetic clusters, that can be one of the physical guidelines to select the events with very hard jets not only at the generator level (simulation). If we simply apply the additional threshold to the minimum energy of the detected clusters needed in the alignment analysis, then we still obtain neither the desirable selection of the jet hardness nor an increase of the degree of alignment. The small variation of the resolution parameter  $r_{\text{res}}$  does not provide the desirable effect also. However, the introduction of another threshold on the total energy of all  $(N_c - 1)$  selected clusters  $E_{\Sigma}^{\text{thr}} \sim E_{\text{lab}}/2$  (without taking into account the energy deposition in the central cluster around  $r = 0$ ),

$$\sum_{l=1}^{N_c-1} E_l > E_{\Sigma}^{\text{thr}}, \quad (16)$$

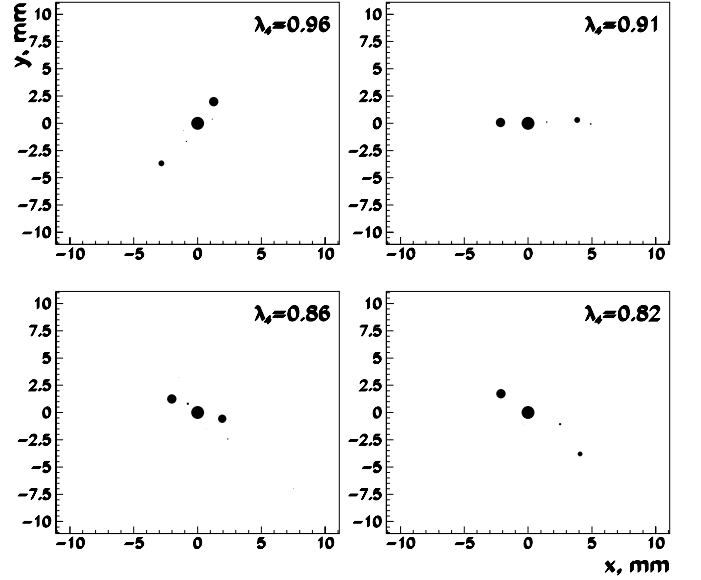
allows us to select the events with hard jets only in a “natural” physical way and to reduce the hypothesis to the really active mechanism. Figure 2 shows that the degree of alignment increases with the growth of  $E_{\Sigma}^{\text{thr}}$  (the restriction on  $p_T^{\text{hard}}$  is absent at all!), and it becomes large enough (dashed curve) and comparable with the experimentally observed one [7] above the threshold  $E_{\Sigma}^{\text{thr}} \simeq 0.1E_{\text{lab}} \simeq 10$  PeV. Though one should note that our estimations still give a too steep dependence on  $N_c$  as one can see in Figs. 1b, 2b from a comparison of the slopes of the straight lines with the experimental behavior.

To give the reader a feeling for the various measures of alignment we present in Figs. 3 and 4 the spatial distributions of the most energetic clusters in the  $(xy)$ -plane for a few generated events along with the corresponding values of  $\lambda_{N_c}$ . Some spots are hardly visible because of their small sizes which are proportional to the cluster energies (especially in the case  $\lambda_4 > 0.8$ ) or because they are outside the square  $10 \times 10$  mm<sup>2</sup> (but inside the circle with  $r = 15$  mm) as it sometimes happens in the case  $\lambda_8 > 0.8$ . Besides for  $\lambda_4 > 0.8$  we can distinctly see three relatively large spots resulting from two hard jets and a central bunch.

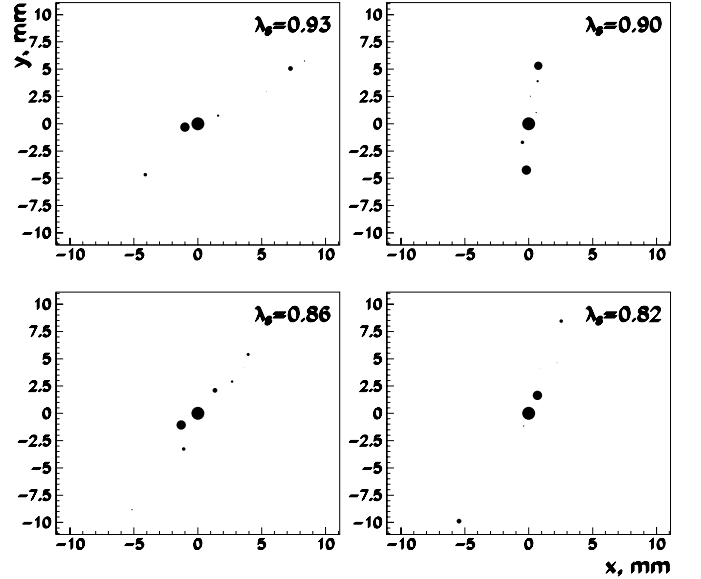


**Fig. 2.** The degree of alignment  $P_{N_c}$  as a function of cluster number  $N_c$  at  $h = 50$  m and  $\sqrt{s} = 14$  TeV in linear **a** and logarithmic **b** scales. The solid curve is the result (coincident with the one at  $h = 1000$  m) without restriction on the total cluster energy  $E_{\Sigma}^{\text{thr}}$ , the dotted curve at  $E_{\Sigma}^{\text{thr}} = 2$  PeV, the dashed curve at  $E_{\Sigma}^{\text{thr}} = 10$  PeV. Points (o) with errors are experimental data from [7]

Here one should note that there was a slightly different criterion for the selection of families for the analysis in the work of the Pamir Collaboration: the families with the total energy of the  $\gamma$ -quanta larger than a certain threshold and at least one hadron present were selected and analyzed. The alignment becomes apparent considerably at  $\sum E_{\gamma} > 0.5$  PeV (the families being produced, mostly, by a proton with energy  $\gtrsim 10$  PeV). Since an adequate comparison of our estimations with the experimental data is impossible without a full simulation of particle propagation through the atmosphere, taking into account the energy distribution of primary cosmic particles, etc., in order to demonstrate the possibility of the appearance of a high degree of alignment due to the jet mechanism, we restrict ourselves to the simpler (but as concerns the physics essentially close to experiment) criterion of selection over the total energy of all particles. These particles are mostly  $\pi$ -mesons, the neutrals among them being the main source of the detected  $\gamma$ -quanta. It is natural that the threshold on the total energy of all particles must be larger than the similar threshold on the total energy of  $\gamma$ -quanta at the same collision energy. For comparison we estimate also the degree of alignment selecting only the most energetic  $\gamma$ -quanta with their total energy larger than a certain thresh-



**Fig. 3.** Samples of core distributions for simulated events with  $E_{\Sigma}^{\text{thr}} = 10$  PeV and  $\lambda_4 > 0.8$ . The size of spots is proportional to their energy (except for the central spot which is not to scale)

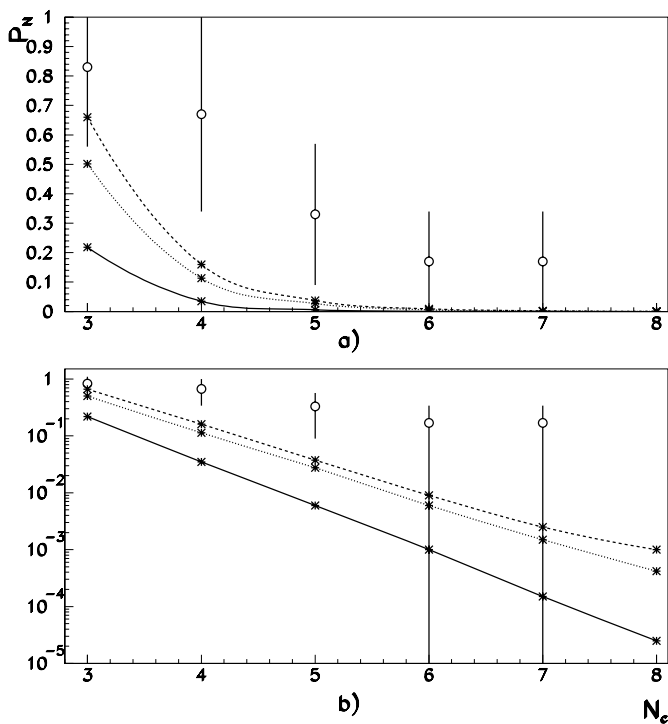


**Fig. 4.** Samples of core distributions for simulated events with  $E_{\Sigma}^{\text{thr}} = 10$  PeV and  $\lambda_8 > 0.8$ . The size of spots is proportional to their energy (except for the central spot which is not to scale)

old  $E_{\gamma}^{\text{thr}}$  (Fig. 5):

$$\sum_{l=1}^{N_c-1} E_{l\gamma} > E_{\gamma}^{\text{thr}}. \quad (17)$$

The result is close to that obtained previously with the threshold imposed on the total energy of all particles.



**Fig. 5.** The degree of alignment  $P_{N_c}$  as a function of cluster number  $N_c$  at  $h = 50$  m and  $\sqrt{s} = 14$  TeV in linear **a** and logarithmic **b** scales. The solid curve is the result (coincident with the one at  $h = 1000$  m) without restriction on the total energy of  $\gamma$ -quanta  $E_\gamma^{\text{thr}}$ , the dotted curve at  $E_\gamma^{\text{thr}} = 1$  PeV, the dashed curve at  $E_\gamma^{\text{thr}} = 5$  PeV. Points ( $\circ$ ) with errors are experimental data from [7]

Besides for jet events

$$\frac{P_{N_c}}{P_{N_c+1}} = \text{const} \quad (18)$$

with a high accuracy (see Figs. 1b, 2b and 5b, which present the dependence of the degree of alignment on the number of considered cores at different values of the hardness parameter (Fig. 1b) and the threshold total energy (Figs. 2b and 5b) in the logarithmic scale). This constant depends on  $p_T^{\text{hard}}$ ,  $E_\Sigma^{\text{thr}}$ ,  $E_\gamma^{\text{thr}}$ , decreasing with their growth, and it could in principle be determined by the kernels of the Gribov–Lipatov–Altarelli–Parisi–Dokshitzer equations [6, 11–14] which describe the process of radiation of quarks and gluons in the initial and final states. And, in fact, this process is implemented in the PYTHIA generator together with the subsequent hadronization of the quarks and gluons.

If nevertheless particles from the central rapidity region  $\eta_i \simeq 0$  and the jet-like mechanism are insufficient to describe the observed alignment and there is another mechanism of its appearance at the energy  $\sqrt{s} \sim 14$  TeV and the height  $h \sim 1000$  m (mostly used in emulsion experiment estimations), then in any case some sort of alignment should arise at LHC too in the rapidity region (11) and (12). This region must be investigated

more carefully with the purpose to study the azimuthal anisotropy of the energy flux in accordance with the procedure applied in the emulsion and other experiments, i.e. one should analyze the energy deposition in the cells of the  $\eta \times \phi$ -space in the rapidity interval (11) and (12) (the equivalent threshold minimum particle energy being  $E_{\text{CMS}}^{\text{thr}} = E^{\text{thr}}/\cosh \eta_0 \simeq 2E^{\text{thr}}/e^{\eta_0} \simeq 0.6$  GeV in the center-of-mass system). Note that the absolute rapidity interval can be shifted: it is necessary only that the difference  $(\eta_{\text{max}} - \eta_{\text{min}})$  is equal to  $\simeq 2.7$  in accordance with the variation of the radial distance by a factor of 15 ( $r_{\text{max}}/r_{\text{min}} = 15$ ) due to the relationship  $r_i \simeq r_0/e^{\eta_i}$  (independently of  $r_0$ ). In other words, since we use particle momenta in the center-of-mass system, future data should be treated in accordance with the algorithm described earlier in Sects. 2 and 3 introducing the corresponding laboratory observables.

## 4 Conclusions

Our analysis shows that for a  $pp$ -collision at a fixed height of primary interaction above the energy  $\sqrt{s}$ , when the condition (15) is fulfilled – that is, ultrarelativistic particles from the rapidity interval near  $\eta_i \simeq 0$  in the center-of-mass system fall into the observation region inside the radius  $r_{\text{max}}$  in the laboratory frame due to the large Lorentz factor – an alignment of spots arises (this, in principle, explains the existence of the experimental energy threshold of this effect) and the degree of alignment becomes strongly dependent on the process hardness. If the process hardness is close to maximum for the given energy  $\sqrt{s}$ , the estimated degree of alignment is already comparable with the experimentally observed one. Introducing another additional threshold (the scale of which is determined by the energy of the incident proton) on the total energy of all  $(N_c - 1)$  selected most energetic clusters (without taking into account the energy deposition in the central cluster) allows us to select the events with a high hardness in a “natural” physical way and thereby support the jet-like hypothesis, which later on may be accepted (or refuted) in further investigations of, for instance, the energy cluster distribution and their particle composition with regard to interactions in the atmosphere, etc.

Meanwhile we suggest the more careful investigation of the rapidity region (11) and (12) at LHC in order to reveal new still unknown mechanisms of alignment if they exist. For this purpose one should perform the analysis of energy deposition in calorimeters of CMS and ATLAS experiments in accordance with the procedure described in Sects. 2 and 3 (i.e. calculating the appropriate observables in the laboratory frame). Such an investigation can clarify the origin of the alignment, test the alternative hypotheses and give the new restrictions on the values of height and energy.

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