Heavy Ion Collisions at the LHC
Last Call for Predictions
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Alignment as a result from QCD jet production or new still unknown physics at the LHC?

I.P. Lokhtin, A.K. Managadze, L.I. Sarycheva, A.M. Snigirev

Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119992, Moscow, Russia

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The intriguing phenomenon of the strong collinearity of cores in emulsion experiments, 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.

Among them, the jet-like mechanism 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.

In the Pamir Collaboration:

the families with the total energy of γ-quanta larger than a certain threshold and at least one hadron present were selected and analyzed. The alignment becomes apparent considerably at

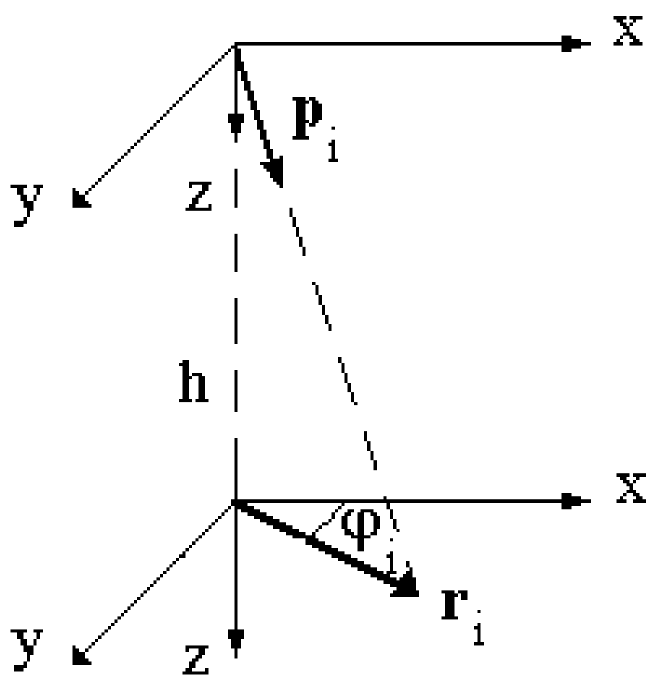
$$\Sigma E_\gamma > \mathbf{0.5\ PeV}\ (\sqrt{s} \geq \mathbf{4\ TeV}).$$

The families are produced, mostly, by a proton with energy

$$\gtrsim \mathbf{10\ PeV}$$

interacting at a height h of several hundred metres to several kilometres in the atmosphere above the chamber.
The collision products are observed within a radial distance up to several centimetres in the emulsion where the spot separation is of the order of 1 mm.

We start from kinematics



It is convenient to parametrize 4-momentum of each produced particle i under consideration with its transverse momentum p_{Ti} (relative to the collision axis z), azimuthal angle ϕ_i and rapidity η_i in the center-of-mass system:

$$[\sqrt{p_{Ti}^2 + m_i^2}\ \cosh\eta_i, \quad p_{Ti}\cos\phi_i, \quad p_{Ti}\sin\phi_i, \quad \sqrt{p_{Ti}^2 + m_i^2}\ \sinh\eta_i].$$

If we neglect the further interactions of particles propagating through the atmosphere (this gives the maximum estimation of the alignment effect), then their position in the transverse (xy)-plane is easily calculated

$$\bar{r}_i = \frac{\bar{v}_{ri}}{v_{zi}} h = \frac{\bar{p}_{Ti}}{\sqrt{p_{Ti}^2 + m_i^2}\ \sinh(\eta_0 + \eta_i)} h ,$$

where $\bar{v}_{ri}$ and v_{zi} are the radial and longitudinal components of particle velocity respectively ($E_i = \sqrt{p_{Ti}^2 + m_i^2}\ \cosh(\eta_0 + \eta_i)$ is the particle energy in the laboratory frame and η_0 are the rapidity of the center-of-mass system in the laboratory frame).

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

$$r_{\min} < r_i \qquad (1)$$

$$r_i < r_{\max} \qquad (2)$$

We set $r_{\min} = r_{\mathrm{res}} \simeq 1$ mm, $r_{\max} \simeq 15$ mm. The restriction (1) simply means that spots are not mixed with the central one formed by the particles which fly close to the collision axis.

The separation of spots in the x-ray film gives another restriction on the distance between particles

$$d_{ij} = \sqrt{r_i^2 + r_j^2 - 2 r_i r_j \cos(\phi_i - \phi_j)}. \tag{3}$$

It must be larger than 1 mm:

$$d_{ij} > r_{\mathrm{res}} , \tag{4}$$

in the opposite case the particles must be combined in one particle-cluster until there remain only particles and/or particle-clusters with the mutual distances larger than r_{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:

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

Then we select 2,...,7 clusters/particles which are most energetic and obey the restrictions (1, 2, 4) and calculate the alignment λ_{N_c} using the conventional definition:

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

and taking into account the central cluster, i.e. $N_c - 1 =$2,...,7.

Here ϕ_{ijk} is the angle between two vectors $(\bar{r}_k - \bar{r}_j)$ and $(\bar{r}_k - \bar{r}_i)$ (for the central spot $\bar{r} = 0$).

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 most probable random configuration of three points in a plane (the equilateral triangle) $\bullet$

$$\lambda_3 = -\,\mathbf{0.5}.$$

$\bullet \qquad \bullet$

The ultimate case of perfect alignment is $\lambda_{N_c} = 1$ when all points lie exactly along the straight line ($\bullet \quad \bullet \quad . \;\; . \;\; . \quad \bullet \quad \bullet \quad \bullet$),

while for an isotropic distribution $\lambda_{N_c} < 0$.

The alignment degree P_{N_c} is defined as a fraction of events with

$$\boldsymbol{\lambda_{N_c} > 0.8}$$

with the number of cores not less than N_c.

If the hypothesis about the relation of 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 $E_{\rm lab} \simeq 9.8\times$ **10 PeV**, that is equivalent to $\sqrt{s} \simeq$ **14 TeV** — **just the energy attainable at LHC** (the rapidity shift being $\eta_0 \simeq$ **9.55** after the transformation from the center-of-mass system to the laboratory one).

To simulate a collision of two protons with such energies we use the Monte Carlo generator PYTHIA, which basically well describes jet events in hadron-hadron interactions and is tuned using the available experimental accelerator data.

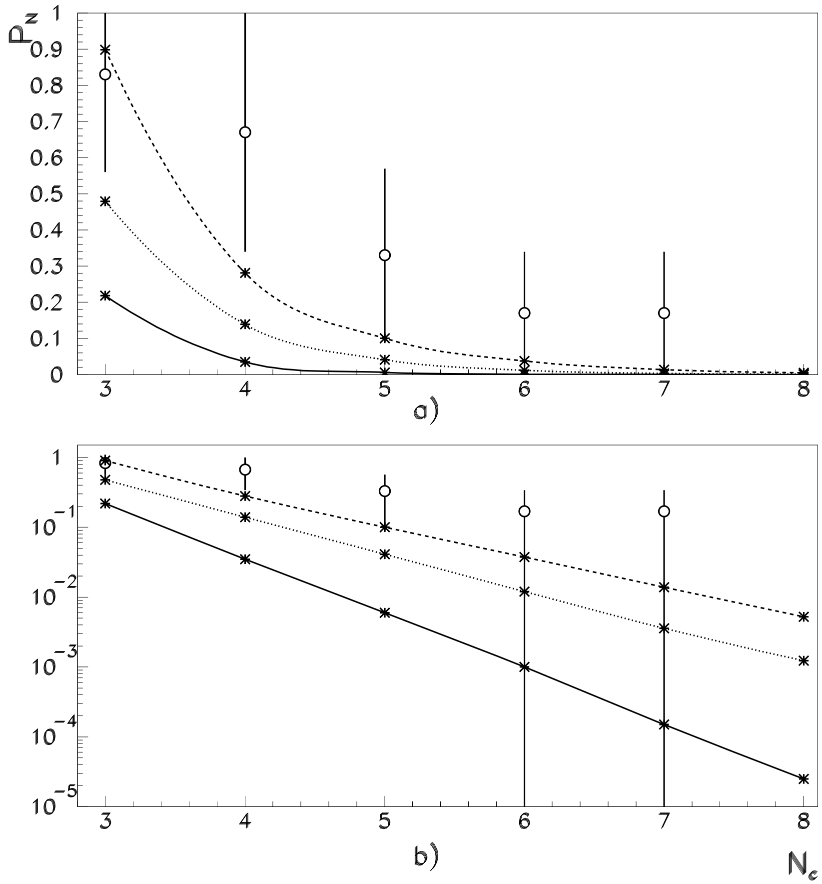
We set the following parameters:

$$r_{\rm min} = r_{\rm res} = \mathbf{1\ mm},\ r_{\rm max} = \mathbf{15\ mm},\ h = \mathbf{1000\ m},$$

with the additional restriction on the energy threshold of particle registration in the emulsion:

$$E_i > E^{\rm thr} = 4\ \mathbf{TeV},$$

which are close to the conditions of emulsion experiments



The alignment degree 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 one at h =1000 m)without restriction on the minimum value of process hardness p_T^{hard}, the dotted curve — at p_T^{hard} =300 GeV, the dashed curve — at p_T^{hard} =3 TeV. Points ($\circ$) with errors are experimental data.

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 even taking into account their large errors.

WHY???

Let us consider the influence of the applied restrictions (1, 2) (the laboratory acceptance criterion) on the spectrum of particles selected to calculate the alignment. For particles with high enough transverse momenta p_{Ti} relative to their masses m_i these conditions (1, 2) reduce, mainly, to the restriction on the available particle rapidities in the center-of-mass system:

$$r_{\min} < r_i \Longrightarrow \eta_i < \eta_{\max} = \ln(r_0/r_{\min}) \simeq 4.95, \qquad (5)$$

$$r_i < r_{\max} \Longrightarrow \eta_i > \eta_{\min} = \ln(r_0/r_{\max}) \simeq 2.25, \qquad (6)$$

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

$$r_0 = 2h/e^{\eta_o}. \qquad (7)$$

Thus ultrarelativistic particles ($p_{Ti} \gg m_i$) are detected in the x-ray film from the restricted rapidity region (5, 6) 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° 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.

Ultrarelativistic particles from the central rapidity region in the hadron 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 η_0 of the center-of-mass system due to the growth of energy $\sqrt{s}$, as it follows from (7).

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 alignment degree becomes strongly dependent on the minimum transverse momentum of hard process, $p_T^{\rm hard}$, which is a parameter of PYTHIA. At the height $h = 1$ km such dependence was not visible, although we might catch some marginal tendency of the alignment degree to grow with the increase of $p_T^{\rm hard}$ at that height. However without the restriction on $p_T^{\rm hard}$ from below (minimum bias) the result coincides practically with one obtained earlier (solid curve in previous Fig.)

If $p_T^{\rm jet} \geq 3$ TeV, particles from these hard jets together with particles flying close to z-axis (within the transverse radius < 1 mm) result in the alignment degree (dashed curve) COMPARABLE with the experimentally observed one.

Thus the jet-like mechanism can, in principle, attempt to explain the results of 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 $h =$1000 m, but the considerably higher $\sqrt{s} \simeq 14\times$ 20 = 280 TeV;

or at some reasonable and acceptable intermediate combination of h, $\sqrt{s}$, $r_{\max}$ which meets the following condition:

$$\boldsymbol{r_0 = 2h/e^{\eta_o} = 2hm_p/\sqrt{s} \lesssim kr_{\max},} \qquad (8)$$

**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.
We verified the decisive significance of condition (8) to allow the observation of large degree of alignment and its dependence on the process hardness for the smaller energy $\sqrt{s} \simeq$ 1.4 TeV (where the prediction of PYTHIA is quite adequate) and the height $h =$5 m (in accordance with (8)) thereby confirming this peculiar kinematic "scaling".**

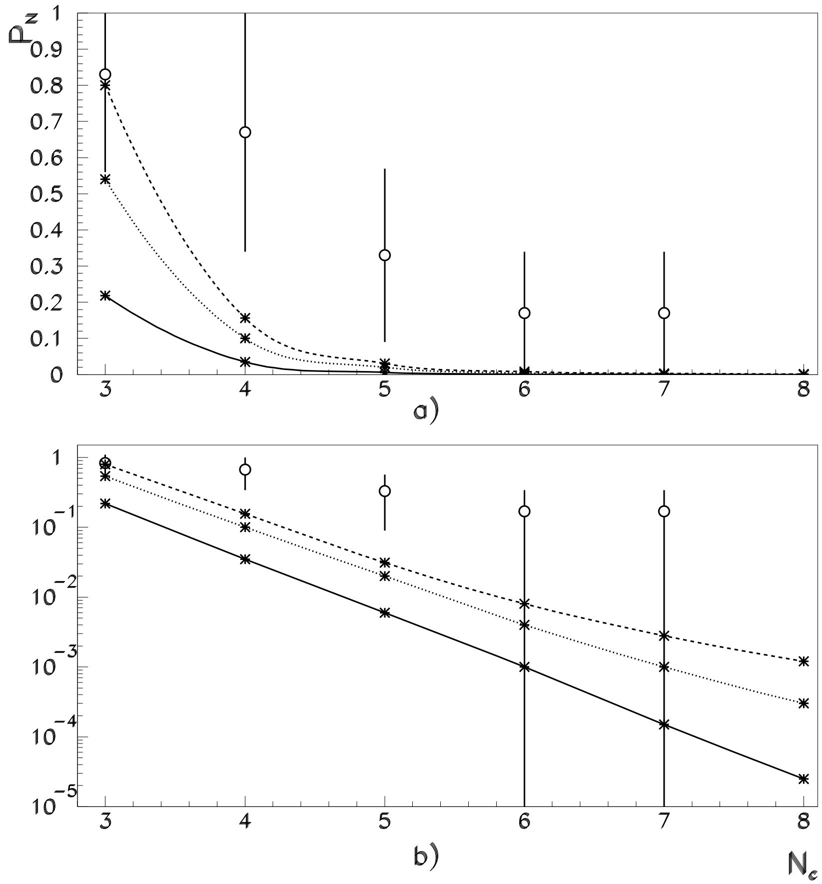
At $p_T^{\rm hard} = \mathbf{3\ TeV}$ jets carry away about half of the energy of colliding protons in the center-of-mass system due to the relationship in a parton picture $\xi \simeq 2p_T^{\rm jet}/\sqrt{s}$, where ξ is a fraction of proton energy carried by each interacting parton (quark or gluon).

The striking feature of such configurations in the x-ray film is approximate equality of energy deposition in the central and the rest most energetic clusters, that can be one of the physical guideline to select the events with very hard jets not only at the generator level (simulation).

Introduction of another threshold on the total energy of all $(N_c - 1)$ selected clusters $E_\Sigma^{\rm thr} \sim E_{\rm lab}/2$ (without taking into account the energy deposition in the central cluster around $r = 0$),

$$\sum_{l=1}^{N_c-1} E_l > E_\Sigma^{\rm thr},$$

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.



The alignment degree 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 one at h =1000 m)without restriction on the total cluster energy $E_{\Sigma}^{\rm thr}$, the dotted curve — at $E_{\Sigma}^{\rm thr}$ =2 PeV the dashed curve — at $E_{\Sigma}^{\rm thr}$ = 10 PeV. Points (○) with errors are experimental data.

We see that the alignment degree increases with the growth of $E_\Sigma^{\rm thr}$ (the restriction on $p_T^{\rm hard}$ is absent at all!), and it becomes large enough (dashed curve) and COMPARABLE with the experimentally observed one above the threshold $E_\Sigma^{\rm thr} \simeq 0.1 E_{\rm lab} \simeq$ 10 PeV.

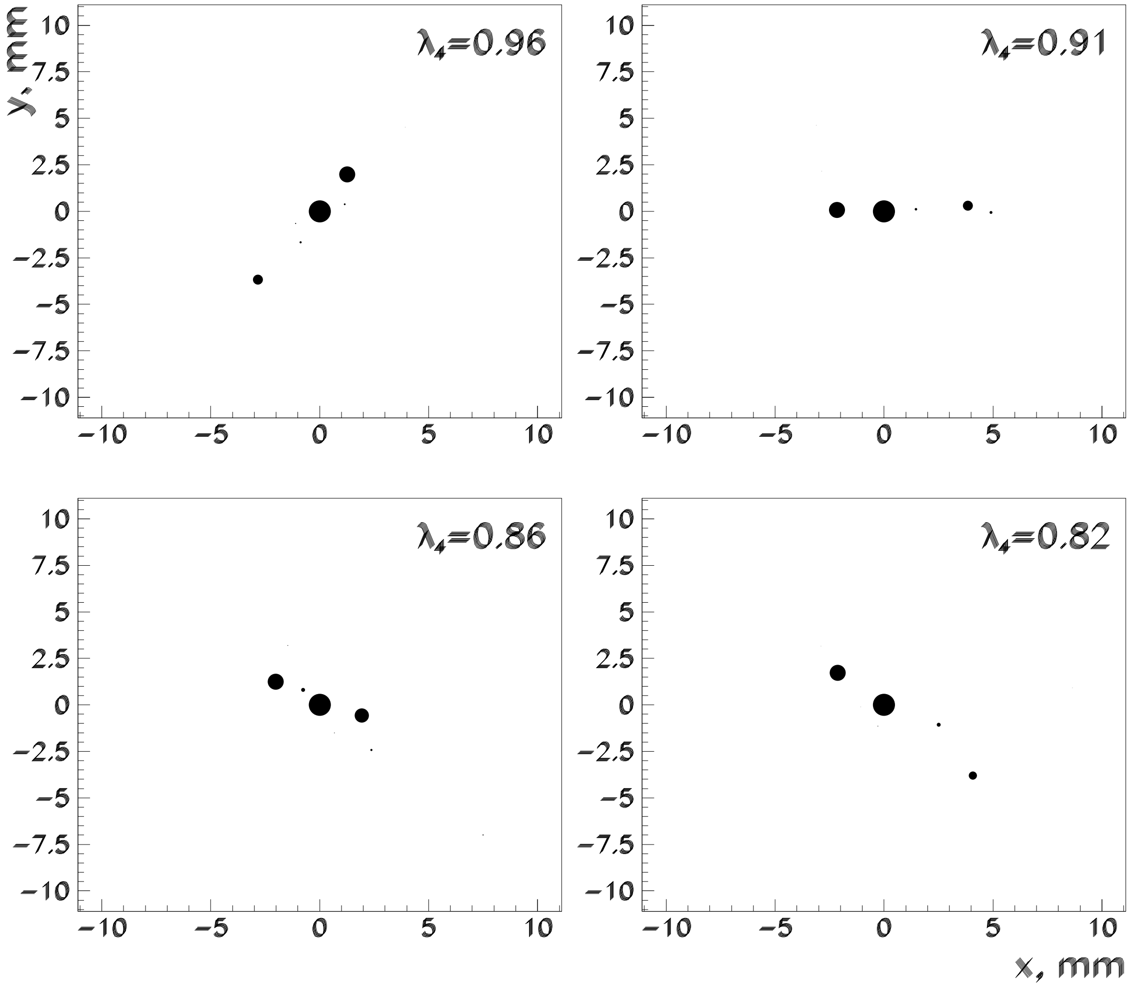
Though one should note that our estimations give still too steep dependence on N_c as one can see in Figs. 1b, 2b from a comparison of the slopes of the straight lines with the experimental behaviour.

Besides for jet events

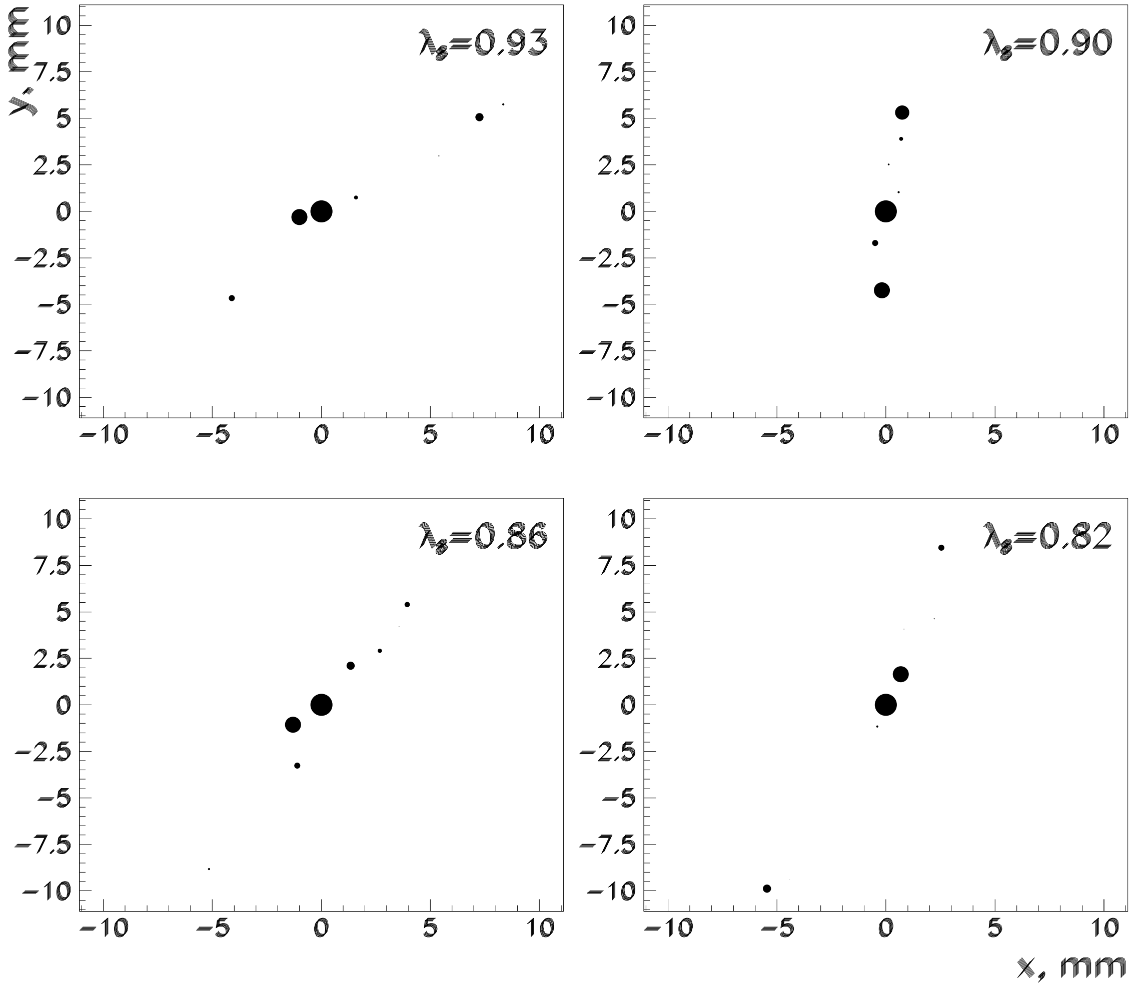
$$\frac{P_{N_c}}{P_{N_c+1}} = \text{const}$$

with a high accuracy

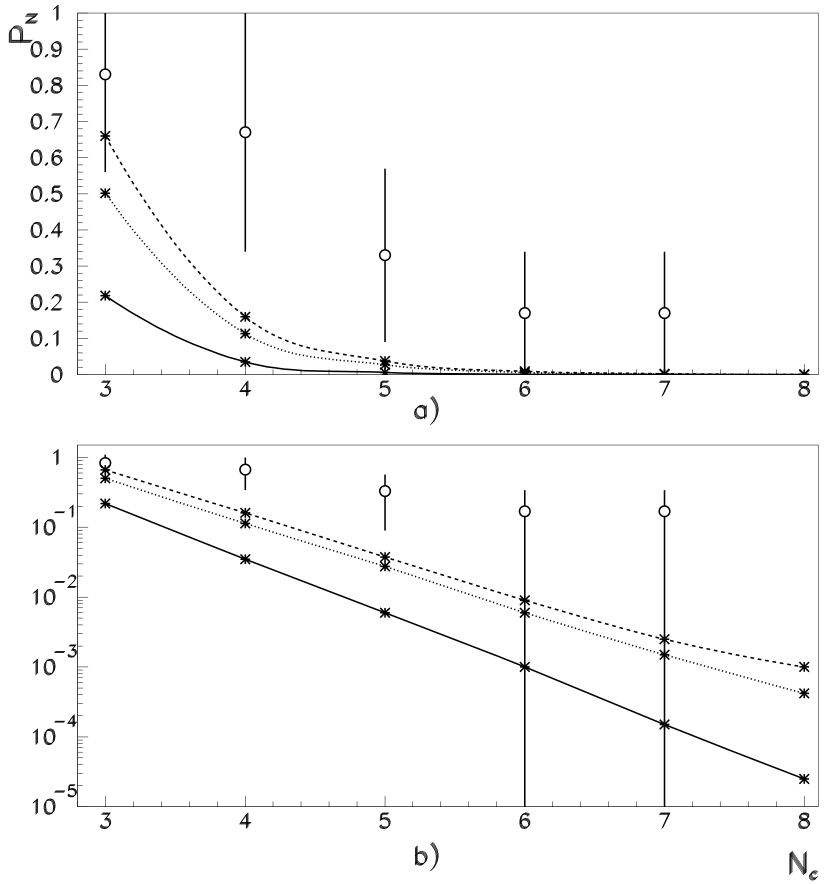
To give one a feeling for the various measures of alignment we present in Figs. 3 and 4 the spatial distributions of the most energetic clusters in the (xy)-plane for a few generated events along with the corresponding values of λ_{N_c}.



Samples of core distributions for simulated events with $E_{\Sigma}^{\mathrm{thr}}$ =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).



Samples of core distributions for simulated events with $E_{\Sigma}^{\rm thr}$ =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).



The alignment degree 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 one at h =1000 m)without restriction on the total energy of γ-quanta $E_\gamma^{\rm thr}$, the dotted curve — at $E_\gamma^{\rm thr}$ =1 PeV the dashed curve — at $E_\gamma^{\rm thr}$ = 5 PeV. Points ($\circ$) with errors are experimental data.

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 mid-forward rapidity region (5,6) (following from the laboratory acceptance criterion for, e.g., pp collisions).

Namely, at the LHC the *strong azimuthal anisotropy of energy flux (almost all main energy deposition along a radial direction) will be observed* **for all events with the total energy deposition in the rapidity interval (5,6) larger than some threshold ~ 1 TeV. Stress once more that at present there are no models or theories giving such azimuthal anisotropy following from the experimentally observed alignment phenomenon at $\sqrt{s} \geq \sqrt{s_{\rm eff}} \simeq 4$TeV and $h \sim 1000$ m**

This mid-forward region must be investigated more carefully on the purpose to study the azimuthal anisotropy of 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 $\eta \times \phi$-space in the rapidity interval (5, 6).

Note that the absolute rapidity interval can be shifted in correspondence with the variation of the height: it is necessary only that the difference $(\eta_{\max} - \eta_{\min})$ is equal to $\simeq \mathbf{2.7}$ in accordance with the variation of radial distance by a factor of ~ 15 $(r_{\max}/r_{\min} = \mathbf{15}$ independently of $r_0(h)$) due to the relationship $r_i \simeq r_0/e^{\eta_i}$.

Such an investigation both in pp and in heavy ion collisions (to differentiate between hadronic and nuclear interaction effects) at the LHC can clarify the origin of the alignment phenomenon, give the new restrictions on the values of height and energy, and possibly discover new still unknown physics.

Conclusions

- **Our analysis shows that for pp-collision at a fixed height of primary interaction above the energy $\sqrt{s}$, when the condition (8) 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 $r_{\max}$ 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 alignment degree becomes strongly dependent on the process hardness.**

- **Introducing another additional threshold (the scale of which is determined by the energy of an 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 high hardness in a "natural" physical way and thereby support the jet-like hypothesis.**

- **Meanwhile we suggest the more careful investigation of the mid-forward rapidity region at LHC in order to reveal the NEW still UNKNOWN mechanisms of alignment if they exist.**