Unusual Event Alignment Topologies in Cosmic Rays and Expectation for the LHC

A. De Roeck[1], *I.P. Lokhtin*[2], *A.K. Managadze*[2], *L.I. Sarycheva*[2], *A.M. Snigirev* [2]

[1]CERN, 1211 Geneva 23, Switzerland

[2]M.V.Lomonosov Moscow State University, D.V.Skobeltsyn Institute of Nuclear Physics, 119991, Vorobievy Gory, Moscow, Russia

Based on the observation of the so called alignment phenomenon in cosmic ray emulsion experiments, namely a strong collinearity of shower cores related to coplanar scattering of secondary particles in the interaction, events with an unusual topology in the mid-forward rapidity region are expected to be produced at the LHC.

1 Introduction

The intricate phenomenon of coplanarity of the most energetic cores of γ-ray-hadron secondary particles (families) has been observed since a long time ago in mountain-based [1, 2] and stratospheric [3] x-ray-emulsion chamber experiments. So far no simple satisfactory explanation for these cosmic ray observations as been given, in spite of numerous attempts (see, e.g. [2, 4] and references therein). Among these explanations, a jet-like mechanism [5] looks very attractive and can give a natural explanation of the alignment of three spots, i.e. the particles resulting from the energy deposits of the secondaries in showering material, along a straight line, resulting from momentum conservation in a simple parton scattering picture. The relation between the observed alignment of spots in the x-ray film in cosmic ray emulsion experiments and the characteristics of events dominated by jets at very high energies, was tested in our earlier work [6, 7]. Based on these studies we now report on predictions from the alignment phenomenon for the CERN Large Hadron Collider (LHC).

2 Problem under Consideration

For clarity, let us recall that in the Pamir experiment [1, 2] families with a total energy of the γ-quanta above a given threshold, and with the requirement of at least one hadron (identified by the travel length in the material), were selected and analyzed. The alignment effect becomes clearly apparent for event with $\sum E_\gamma > 0.5$ PeV (which corresponds to interaction energies with a CMS energy $\sqrt{s} \gtrsim 4$ TeV). The families are produced dominantly by an incident proton with an energy $\gtrsim 10^4$ TeV interacting at a height h of several hundred meters to several kilometres in the atmosphere above the detector [1, 2]. The collision products are observed as spots within a radial distance $r_{\max}$ up to several centimetres in the emulsion, where the spot separation $r_{\min}$ is of the order of 1 mm.

Our analysis [6, 7] shows that a jet-like mechanism can, in principle, provide an explanation of the results of these emulsion experiments. For this explanation to work it is necessary that particles from both hard jets (with rapidities close to zero in the centre-of-mass system) hit the detection region as a result of the large Lorentz factor from the transformation from the centre-of-mass system to the laboratory one. This is possible when the combination of h, $\sqrt{s}$ and $r_{\max}$ meets the following condition:

$$2hm_p/\sqrt{s} \lesssim kr_{\max}, \tag{1}$$

where m_p is the proton mass. A value of $k \sim 1/2$ is needed in order to have particles with adjacent positive and negative rapidities in the centre-of-mass system to hit the detection region. At a height of $h = 1000\,\mathrm{m}$ (which is a standard height used in emulsion experiment estimations) and $r_{\max} = 15$ mm, the condition in (1) is fulfilled for an energy energy $\sqrt{s} \gtrsim 270$ TeV , i.e. much higher than the LHC high energy range for heavy ions and protons $\sqrt{s} \simeq 5.5 \div 14$ TeV and the threshold interaction energies after which the alignment appears $\sqrt{s_{\mathrm{eff}}} \simeq 4$ TeV [1, 4], corresponding to the alignment phenomenon. Eq. (1) can be fulfilled and at the LHC energy (14 TeV) also, but at the considerably less height $h \lesssim 50$ m which is different from the traditional emulsion experiment assumption of about 1 km.

On the other hand if particles from the central rapidity region and the jet-like mechanism are insufficient to describe the observed alignment, and there is another *still unknown* mechanism of its appearance at the energy $\sqrt{s} \sim 5.5 \div 14$ TeV and the accepted height $h \sim 1000\,\mathrm{m}$, then in any case some sort of alignment should arise at the LHC too in the mid-forward rapidity region (following from the laboratory acceptance criterion for, e.g., pp collisions) [6, 7]:

$$r_{\min} < r_i \Longrightarrow \eta_i < \eta_{\max} = \ln(r_0/r_{\min}) \simeq 4.95, \tag{2}$$

$$r_i < r_{\max} \Longrightarrow \eta_i > \eta_{\min} = \ln(r_0/r_{\max}) \simeq 2.25, \tag{3}$$

where

$$r_0 = 2h/e^{\eta_o} = 2hm_p/\sqrt{s}, \tag{4}$$

$\eta_0 = 9.55$ is the rapidity of centre-of-mass system in the laboratory reference frame, η_i is the particle rapidity in the centre-of-mass system, r_i is the radial particle spacing in the x-ray film. In that case at the LHC a *strong azimuthal anisotropy of energy flux will be observed, namely almost all of the energy will be deposited along a radial direction* for all events with the total energy deposition in the rapidity interval (2) and (3) above a threshold. Note that at present there are no models or theories which give such azimuthal anisotropy which can explain the experimentally observed alignment phenomenon at $\sqrt{s} \gtrsim \sqrt{s_{\mathrm{eff}}} \simeq 4\mathrm{TeV}$ and $h \sim 1000\,\mathrm{m}$ [1, 4].

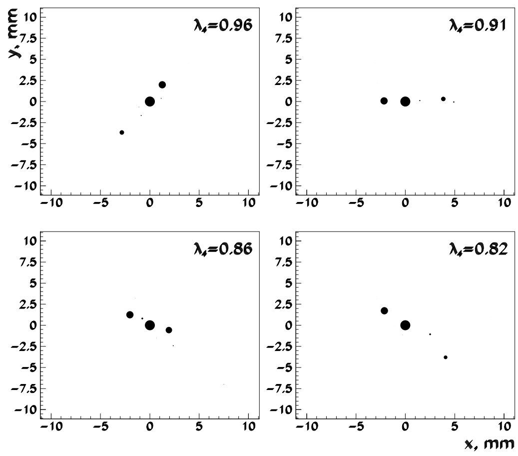

Figure 1: Samples of core distributions for simulated events with $E_{\Sigma}^{\mathrm{thr}} = 10$ PeV and $\lambda_4 > 0.8$. The size of spots is proportional to their energy (except for the central spot which is not to scale).

3 Topology of Alignment Events

Here we would like to draw the attention to the unusual topology of such alignment events in the centre-of-mass system, in order to design a selection at the LHC. As was mentioned above, hard enough i.e. high p_T jets ($p_T^{\rm jet} \gtrsim 3$ TeV), centrally produced in the centre-of-mass system, can imitate the appropriate topology of events with the large degree of alignment P_N in the laboratory system at a small enough height $h \sim 50$ of the primary interaction. The spatial distribution of the most energetic clusters in the transverse (xy)-plane for a few generated events along with the corresponding values of λ_N are presented in Figs. 1 and 2 (from the work [6]) to give the reader a feeling for the topology of alignment events in the laboratory reference frame close to experimentally observed ones [1, 2].

The alignment parameter λ_N, for N spots, is conventionally defined as [2]:

$$\lambda_N = \frac{\sum_{i\neq j\neq k}^{N} \cos(2\phi_{ijk})}{N(N-1)(N-2)}, \tag{5}$$

Here ϕ_{ijk} is the angle between two vectors $(\mathbf{r_k} - \mathbf{r_j})$ and $(\mathbf{r_k} - \mathbf{r_i})$ (for the central spot $\mathbf{r} = \mathbf{0}$). This parameter characterises the location of N points along a straight line and varies from $-1/(N-1)$ to 1. For instance, in the case of a symmetrical, close to the most probable random configuration of three points in a plane (the equilateral triangle) $\lambda_3 = -0.5$. The case of perfect alignment corresponds to $\lambda_N = 1$, when all points lie exactly along a straight line, while for an isotropic distribution $\lambda_N < 0$. The degree of alignment P_N is defined as a fraction of events with $\lambda_N > 0.8$ [2], for events with a number of points larger or equal to N.

The threshold on the total energy of all $(N-1)$ selected clusters $E_\Sigma^{\rm thr} \sim E_{\rm lab}/2$ (without taking into account the energy deposition in the central cluster around $r = 0$), $\sum_{l=1}^{N-1} E_l > E_\Sigma^{\rm thr}$, was introduced to select the events with hard jets. To be specific we consider a collision of two protons and fix a primary energy in the laboratory system $E_{\rm lab} \simeq 9.8 \times 10^4$ TeV, that is equivalent to $\sqrt{s} \simeq 14$ TeV — the maximum energy at LHC – (the rapidity shift from laboratory system to CMS is then $\eta_0 \simeq 9.55$ after a transformation from the centre-of-mass system to the laboratory one). To simulate pp collision a these energies we use the Monte Carlo generator PYTHIA [8], which is expected to give a fair description of –be it low multiplicity– jet events in hadron-hadron interactions and has been tuned using the available experimental data.

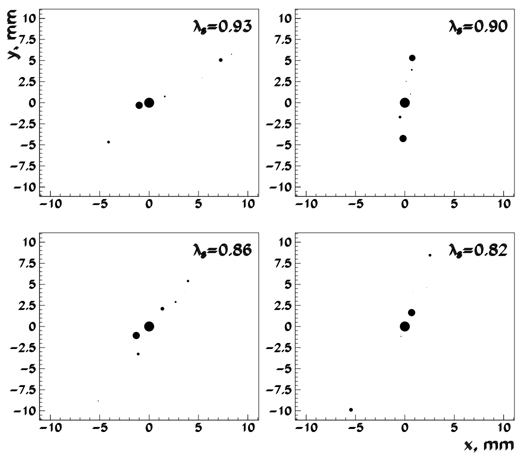

Figure 2: Samples of core distributions for PYTHIA simulated events with $E_\Sigma^{\rm thr} = 10$ PeV and $\lambda_8 > 0.8$. The size of spots is proportional to their energy (except for the central spot which is not to scale).

In the centre-of-mass system the alignment events with jets with sufficiently high p_T have two pronounced concentrations of energy deposition in $\eta \times \phi$-space (rapidity×azimuthal angle) with the azimuthal separation close to π. The typical structure (topology) of energy deposition for such events is presented in Fig. 3. As it was shown [6, 7], for $p_T^{\rm jet} \gtrsim 3$ TeV, particles from these hard jets together with particles flying close to the z-axis (within the transverse radius $\lesssim 1$ mm in the laboratory reference frame) result in a degree of alignment P_N comparable with the experimentally observed one (Fig. 4, from [6]).

We can introduce a quantitative measure of energy deposition allowing the alignment events to be selected in the centre-of-mass system, namely:

$$v_2^{p_T} = \frac{1}{N_{\rm event}} \sum_{\rm event} \frac{\sum\limits_i p_{Ti}^2 \cos 2(\phi_i - \phi_{\rm axis})}{\sum\limits_i p_{Ti}^2}, \qquad (6)$$

where ϕ_i is the azimuthal angle for the ith particle with the transverse momentum p_{Ti}. The sum runs over all particles under consideration. For two jet events

$$\phi_{\rm axis} = (\phi_{\rm jet1} + \phi_{\rm jet2} - \pi)/2, \qquad (7)$$

where $\phi_{\rm jet1}$ and $\phi_{\rm jet2}$ are the azimuthal angles for the first and second jets respectively. Experimentally they can be defined as the directions of leading particles. Without a weight factor p_{Ti} this definition (6)

$$v_2 = \frac{1}{N_{\rm event}} \sum_{\rm event} \frac{\sum\limits_i \cos 2(\phi_i - \phi_{\rm axis})}{\sum\limits_i} \qquad (8)$$

coincides with the definition of the elliptic flow coefficient relative to the azimuthal angle of the reaction plane (instead of $\phi_{\rm axis}$) used in a standard flow analysis [10, 11].

Figure 5 shows the elliptic anisotropy coefficients $v_2^{p_T}$ and v_2 as functions of jet hardness $p_{T\rm hard}^{\rm min}$ (the minimum transverse momentum of hard parton-parton subscattering, a parameter of PYTHIA) for jets from the central rapidity region. Thus events with a high degree of alignment, e.g. the upper dashed curve in Fig. 4, can be also characterised by a relatively large value of the topological parameters of the energy anisotropy in the centre-of-mass system:

$$v_2^{p_T} \gtrsim v_2^{p_T}(p_{T\rm hard}^{\rm min} = 3{\rm TeV}) = 0.98$$
$$\text{or} \quad v_2 \gtrsim v_2(p_{T\rm hard}^{\rm min} = 3{\rm TeV}) = 0.6 \qquad (9)$$

as it follows from Fig. 5 and from our previous study [6, 7]. One should note that the alignment parameter λ_N is defined in the $r \times \phi$-space (radial distance×azimuthal angle) of the laboratory reference frame while the elliptic anisotropy coefficients $v_2^{p_T}$ and v_2 are defined in the $p_T \times \phi$-space (transverse

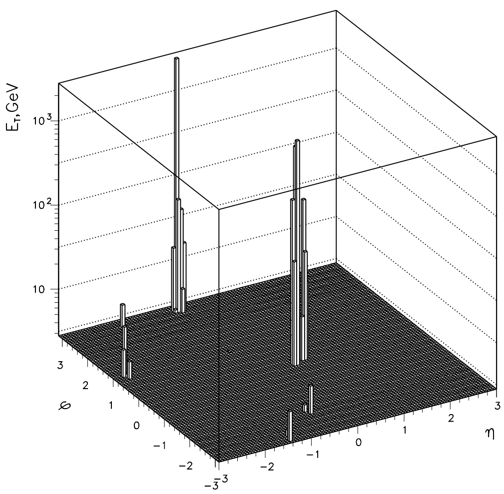

Figure 3: The typical energy deposition in the centre-of-mass system for alignment events in the laboratory frame.

momentum×azimuthal angle) of the centre-of-mass system. λ_N characterises the location of N points just along the straight line while $v_2^{p_T}$ and v_2 characterise the narrowness of energy thrust which is necessary because of the Lorentz invariance of the azimuthal angle (but not yet sufficient) to allow for the observation of a large degree of alignment P_N. Therefore we conclude that a relatively large value of the elliptic anisotropy coefficients $v_2^{p_T}$ and v_2 can result in a large value of the alignment parameter λ_N. We prefer also to consider $v_2^{p_T}$ and v_2 as a quantitative measure of alignment events in the centre-of-mass system instead of some analog of λ_N in the $p_T \times \phi$-space because the radial particle spacing r_i in the x-ray film is practically independent of the value of the transverse momentum for ultrarelativistic particles ($p_{Ti} \gg m_i$) and is mainly determined by the particle rapidity η_i [6, 7] (see also Eqs. (2) and (3)).

4 Discussion and Conclusions

Let us discuss what follows from the experimental observation of alignment phenomenon and our proposal to describe it with a jet-like mechanism. We found that only jets with high enough p_T can imitate the appropriate topological characteristics of alignment events. These hard jets can be selected in a "natural" physical way, namely, by the introduction of the threshold on the energy deposition in the detection region [6, 7]. We are not interested in the exact relation between the threshold energy and the jet hardness but note that the introduction of a threshold on the energy deposition in the detection region results in an appearance of the azimuthal anisotropy (preferred direction) of energy deposition. This azimuthal anisotropy (the elliptic anisotropy coefficients $v_2^{p_T}$ and v_2) becomes stronger with increasing threshold value. One should note that in the Pamir experiment the events with a threshold on the total energy deposition (and by taking into account the energy deposition in the central cluster around $r = 0$ unlike the procedure used in this paper) were selected and analyzed. The Pamir Collaboration consequently concludes the presence of threshold on *the energy of primary interaction* for the onset of the alignment phe-

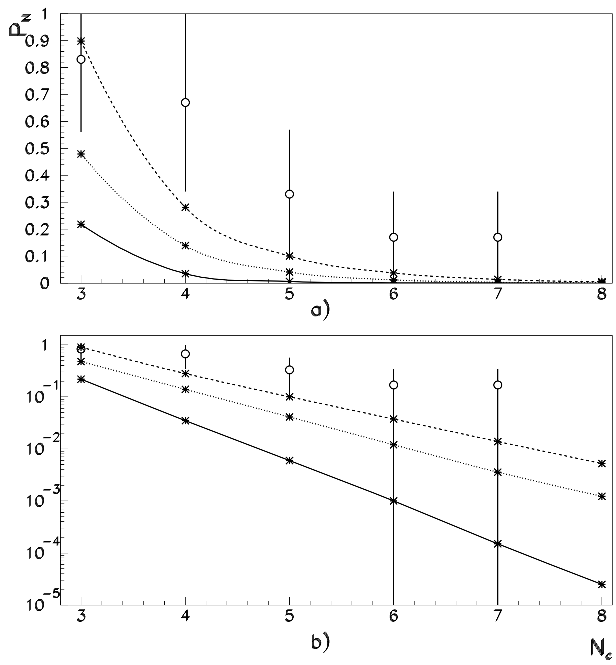

Figure 4: The alignment degree P_N as a function of cluster number $N = N_c$ at $h = 50$ m and $\sqrt{s} = 14$ TeV in linear (a) and logarithmic (b) scales. The solid curve is the result (coincident with one at $h = 1000$ m) without restriction on the minimum value of process hardness $p_{T\text{hard}}^{\text{min}}$, the dotted curve — at $p_{T\text{hard}}^{\text{min}} = 300$ GeV, the dashed curve — at $p_{T\text{hard}}^{\text{min}} = 3$ TeV. Points (∘) with errors are experimental data from [9].

nomenon, and estimates this threshold energy to be $\sqrt{s} \gtrsim \sqrt{s_{\rm eff}} \simeq 4\,$TeV. While we conclude that at the *fixed* energy of primary interaction the threshold on the total energy of all $(N-1)$ selected clusters (without taking into account the energy deposition in the central cluster around $r=0$) must exist *also* to allow for the observation of a large degree of alignment, since for alignment events the energy of all these $(N-1)$ selected clusters is comparable with the energy in the central cluster around $r=0$. Our studies with jets strongly supports this conclusion. The central cluster is a special one and should be treated separately to compare the colliding beams experiment results with those of fixed target ones more consistently. For instance, all ultrarelativistic particles ($p_{Ti} \gg m_i$) from the rapidity interval $4.95 \lesssim \eta_i \lesssim 9.55$ in the centre-of-mass system form one central cluster around $r=0$ with the size ~ 1 mm in the laboratory reference frame at the accepted height $h \sim 1000$ m and the LHC energy due to the strong Lorentz compression. Therefore the energy of central cluster is not taken into account in our threshold analysis.

At the accepted height $h \sim 1000$ m the particles from the restricted rapidity interval between (2) and (3) in the centre-of-mass system form all remaining $(N-1)$ energetic selected clusters in the laboratory reference frame. Note that the absolute rapidity interval can be shifted corresponding to the height: it is necessary only that the difference $(\eta_{\rm max} - \eta_{\rm min})$ is equal to $\simeq 2.7$ in accordance with the variation of the radial distance by a factor of ~ 15 ($r_{\rm max}/r_{\rm min} = 15$) due to the relationship $r_i \simeq r_0/e^{\eta_i}$ (independently of $r_0(h)$). A strong azimuthal anisotropy (the large elliptic anisotropy coefficients $v_2^{p_T}$ and v_2) must be experimentally observed in this restricted rapidity interval (2) and (3) in the centre-of-mass system for the energy deposition above threshold, if the alignment phenomenon exists.

In the mid-forward rapidity region discussed for this analysis, jets can also lead to events with the required values for the thrust of energy deposition in the $\eta \times \phi$-space but with the large dispersion of the azimuthal separation relative to π and not enough large values of $v_2^{p_T}$ and v_2. The reason is simple: jets are not hard enough to provide for the strong momentum correlations (memory) with the primary scattering plane due to the kinematic restriction [12]

$$e^{\eta^{\rm jet}} p_T^{\rm jet} \lesssim \sqrt{s}/2. \qquad (10)$$

For instance if $\eta^{\rm jet} = 4$ then $p_T^{\rm jet}(\max) \simeq 130\,$GeV, $v_2^{p_T}(\max) \simeq 0.83$ and $v_2(\max) \simeq 0.38$ as one can estimate from Fig. 5. Such a maximal azimuthal anisotropy is small in comparison with needed one (9) for the observation of a large degree of alignment.

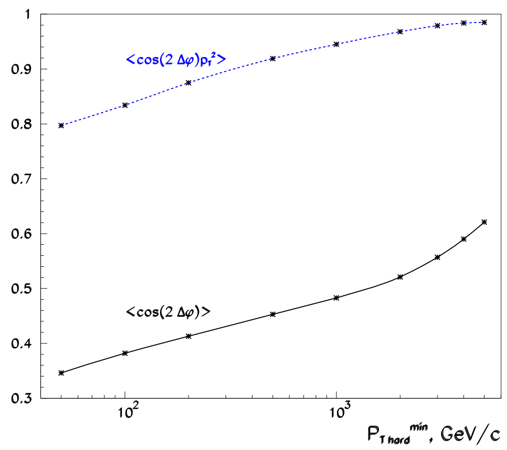

Figure 5: The elliptic anisotropy coefficients $v_2^{p_T}$ and v_2 as functions of jet hardness $p_{T\rm hard}^{\rm min}$ for jets from central rapidity region $|\eta| < 2$.

Thus basing on our dealing with jets and the existence of the alignment phenomenon we predict anomalously large values (on the level of our estimation (9)) of the elliptic anisotropy coefficients $v_2^{p_T}$ and v_2 in comparison with its "background" values from jets in the mid-forward rapidity interval (2) and (3) beginning from some threshold on the energy deposition in this rapidity region. The order of value of this transverse threshold energy can be estimated again from the jet background: ~ 100 GeV and higher since we do not know any mechanism of a large degree of alignment in this case.

The suggested investigation of the azimuthal anisotropy of the energy deposition in dependence on the threshold energy 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, give the new restrictions on the values of height and energy, and possibly discover new still unknown physics.

Acknowledgements

It is pleasure to thank A.I. Demianov, S.V. Molodtsov, R.A. Mukhamedshin, L.G. Sveshnikova and G.T. Zatsepin for discussions. A.M.S is specially thankful to the organisers of EDS'09 for the warm welcome and hospitality. This work is supported by Russian Foundation for Basic Research (grants No 08-02-91001 and No 08-02-92496), Grants of President of Russian Federation (No 107.2008.2 and No 1456.2008.2) and Dynasty Foundation.

References

[1] Pamir Collaboration, A. Borisov *et. al.*, in Proceedings of 4th International Symposium on Very High Energy Cosmic Ray Interactions, Beijing, edited by D. Linkai, 4 (1986);
Pamir Collaboration, in Proceedings of the 21st International Cosmic Ray Conference, Adelaide, Australia (1989), edited by R.J.Protheroe (University of Adelaide, Australia), 227 (1990);
S.A. Slavatinsky, in Proceedings of the 5th International Symposium on Very High Energy Cosmic Ray Interactions, Lodz, Poland (1988), edited by M. Giler (University of Lodz, Lodz, Poland), 90 (1989).

[2] V.V. Kopenkin, A.K. Managadze, I.V. Rakobolskaya and T.M. Roganova, Phys. Rev. D **52**, 2766 (1995).

[3] A.V. Apanasenko *et. al.*, in Proceedings of 15th International Cosmic Ray Conference, Plovdiv, **7** 220 (1977);
A.K. Managadze *et. al.*, in Proceedings of 27th International Cosmic Ray Conference, Hamburg, **1** 1426 (2001).

[4] R.A. Mukhamedshin, J. High Energy Phys. IHEP**05**, 049 (2005).

[5] F. Halzen and D.A. Morris, Phys. Rev. D **42**, 1435 (1990).

[6] I.P. Lokhtin, A.K. Managadze, L.I. Sarycheva and A.M. Snigirev, Eur. Phys. J **C 44**, 51 (2005).

[7] I.P. Lokhtin, A.K. Managadze, L.I. Sarycheva and A.M. Snigirev, Phys. Atom. Nucl. **69**, 113 (2006).

[8] T. Sjostrand, Comp. Phys. Com. **135**, 238 (2001).

[9] V.V. Kopenkin, A.K. Managadze, I.V. Rakobolskaya and T.M. Roganova, Izv. Rus. Akad. Nauk. Ser. Fiz. **58**, 13 (1994).

[10] S. Voloshin and Y. Zang, Z. Phys. C **70**, 665 (1996).

[11] A.M. Poskanzer and S.A. Voloshin, Phys. Rev. C **58**, 1671 (1998).

[12] Yu.L. Dokshitzer, D.I. Dyakonov and S.I. Troyan, Phys. Rep. **58**, 269 (1980).