Eur. Phys. J. C 36, 375–379 (2004)
Digital Object Identifier (DOI) 10.1140/epjc/s2004-01880-7

THE EUROPEAN
PHYSICAL JOURNAL C

Calorimetric transverse energy–energy correlations as a probe of jet quenching

I.P. Lokhtin[a], L.I. Sarycheva[b], A.M. Snigirev[c]

M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, 119992, Vorobievy Gory, Moscow, Russia

Received: 10 February 2004 / Revised version: 29 March 2004 /
Published online: 16 July 2004 –

Abstract. The sensitivity of the calorimetric energy–energy correlation function to the medium-induced energy loss of fast partons in high multiplicity heavy ion interactions is demonstrated at the appropriate selection of events for the analysis, namely, the availability of one high-p_{T} jet in an event at least and using the procedure of "thermal" background subtraction. Without jet trigger this correlation function manifests the global structure of transverse energy flux: the correlator is isotropic for central collisions, and for non-central collisions it is sensitive to the azimuthal anisotropy of energy flow reproducing its Fourier harmonics but with the coefficients squared.

1 Introduction

The QGP creation and the properties of this new type of superdense matter are extensively discussed in the current literature [1] dedicated to high energy heavy ion physics. In the last several years many new phenomena have been observed at RHIC, such as strong elliptic flow [2] and suppression of the high transverse momentum two particle back-to-back correlations [3]. These observations together with other important evidence support the idea that a dense partonic matter (QGP) has been created in such high energy nuclear collisions.

The center of mass energy for heavy ion collisions at the LHC will exceed that at RHIC by a factor of about 30. This provides exciting opportunities for addressing unique physics issues in a new energy domain, where hard and semihard QCD multi-particle production can certainly dominate over underlying soft events [4]. The methodological advantage of azimuthal jet observables is that one needs to reconstruct only the azimuthal position of the jet in heavy ion event, which can be done with a fine enough resolution (slightly worse as compared with the pp case but still less than the typical azimuthal size of a calorimeter tower [4,5]). However, the observation of the jet azimuthal anisotropy due to medium-induced partonic energy loss [6,7] requires event-by-event determination of the nuclear event plane. Recently the ability to reconstruct the reaction plane using calorimetric measurements has been shown in [8] as well as the possibility to observe jet azimuthal anisotropy without direct determination of the event plane, considering the second [9] and higher [10] order correlators between the azimuthal position of the jet axis and the angles of the particles not incorporated in the jet. This calorimetric information allows us to study also the energy–energy correlations which are sensitive to partonic energy loss (as it has been pointed out in [11]) and this investigation does not demand also the reconstruction of the event plane which is still far from complete.

The observed suppression of the high transverse momentum two particle back-to-back correlations [3] at RHIC supports strongly the belief that the calorimetric measurements of energy–energy correlations at LHC will be able to provide new additional information about the medium-induced energy loss of fast partons. Namely these correlations are the subject of the present investigation.

2 Energy–energy correlation functions in e^+e^-, hadronic and nuclear collisions

The energy–energy correlation function Σ has been used by all for LEP experiments [12] at CERN and the SLD experiment [13] at SLAC to measure the strong coupling constant α_{s} in e^+e^--annihilation at the Z^0 resonance with a high accuracy. Σ is defined as a function of the angle χ between two particles i and j in the following form:

$$\frac{\mathrm{d}\sum(\chi)}{\mathrm{d}\cos(\chi)} = \frac{\sigma}{\Delta\cos(\chi)N_{\mathrm{event}}}\sum_{\mathrm{event}}\sum_{i\neq j}\frac{E_iE_j}{E^2}, \qquad (1)$$

where E is the total energy of the event, E_i and E_j are the energies of the particles i and j. The sum runs over all

[a] e-mail: igor@lav01.sinp.msu.ru
[b] e-mail: lis@alex.sinp.msu.ru
[c] e-mail: snigirev@lav01.sinp.msu.ru

pairs i, j with $\cos(\chi)$ in the bin width $\Delta\cos(\chi)$:

$$\cos(\chi) - \Delta\cos(\chi)/2 < \cos(\chi) < \cos(\chi) + \Delta\cos(\chi)/2.$$

σ is the total cross section for $e^+e^- \to$ hadrons. The limits $\Delta\cos(\chi) \to 0$ and $N_{\text{event}} \to \infty$ have to be taken in (1).

This function can be calculated in perturbative QCD as a series in α_s:

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\Sigma(\chi)}{\mathrm{d}\cos(\chi)} = \frac{\alpha_s(\mu)}{2\pi}A(\chi) + \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2\left(\beta_0 \ln\left(\frac{\mu}{E}\right)A(\chi) + B(\chi)\right) + O(\alpha_s^3), \quad (2)$$

where $\beta_0 = (33-2n_f)/3$; n_f is the number of active flavours at the energy E. The first order term $A(\chi)$ has been calculated by Basham et al. [14] from the well-known one gluon emission diagrams $\gamma^*, Z^0 \to q\bar{q}g$ with the result

$$A(\chi) = C_F(1+\omega)^3\frac{1+3\omega}{4\omega} \times \left((2-6\omega^2)\ln(1+1/\omega) + 6\omega - 3\right), \quad (3)$$

where $C_F = 4/3$, $\omega = \cot^2(\chi)/2$, and χ is the angle between any of the three partons. This allowed one to determine the strong coupling constant directly from a fit to the energy–energy correlations in e^+e^--annihilation, since Σ is proportional to α_s in the first order.

In hadronic and nuclear collisions jets are produced by hard scattering of partons. In this case it is convenient to introduce the transverse energy–energy correlations which depend very weakly on the structure functions [15] and manifest directly the topology of events. Thus, for instance, in high-p_T two-jet events the correlation function is peaked at the azimuthal angle $\varphi = 0°$ and $\varphi = 180°$, while for the isotropic background this function is independent of φ.

Utilization of hard jet characteristics to investigate QGP in heavy ion collisions is complicated because of a huge multiplicity of "thermal" secondary particles in an event. Various estimations give from 1500 to 6000 charged particles per rapidity unit in a central Pb–Pb collision at LHC energy, and jets can be really reconstructed against the background of energy flux beginning from some threshold jet transverse energy $E_T^{\text{jet}} \sim 50$–100 GeV [4,5,16]. The transverse energy–energy correlation function is just sensitive to the jet quenching as well as to the global structure of energy flux (i.e. its anisotropy for non-central collisions) if we select events by an appropriate way. The generalization of (1) for calorimetric measurements of the energy flow is straightforward:

$$\frac{\mathrm{d}\Sigma_T(\varphi)}{\mathrm{d}\varphi} = \frac{1}{\Delta\varphi\, N_{\text{event}}}\sum_{\text{event}}\sum_i \frac{E_{Ti}E_{T(i+n)}}{(E_T^{\text{vis}})^2}, \quad (4)$$

where

$$E_T^{\text{vis}} = \sum_i E_{Ti}$$

is the total transverse energy in N calorimetric sectors covering the full azimuth, E_{Ti} is the transverse energy deposition in the sector i ($i = 1, \ldots, N$) in the considered pseudo-rapidity region $|\eta|$, $n = [\varphi/\Delta\varphi]$ (the integer part of the number $\varphi/\Delta\varphi$), and $\Delta\varphi \sim 0.1$ is the typical azimuthal size of a calorimetric sector. In the continuous limit $\Delta\varphi \to 0$, $N = [2\pi/\Delta\varphi] \to \infty$, (4) reads

$$\frac{\mathrm{d}\Sigma_T(\varphi)}{\mathrm{d}\varphi} = \frac{1}{N_{\text{event}}}\sum_{\text{event}}\frac{1}{(E_T^{\text{vis}})^2}\int_0^{2\pi}\mathrm{d}\phi\,\frac{\mathrm{d}E_T}{\mathrm{d}\phi}(\phi)\,\frac{\mathrm{d}E_T}{\mathrm{d}\phi}(\phi+\varphi), \quad (5)$$

where $E_T^{\text{vis}} = \int_0^{2\pi}\mathrm{d}\phi\,\frac{\mathrm{d}E_T}{\mathrm{d}\phi}(\phi)$, and $\frac{\mathrm{d}E_T}{\mathrm{d}\phi}$ is the distribution of the transverse energy flow over the azimuthal angle ϕ.

The events with high-p_T jet production are rare events and their contribution to Σ_T is negligible without the special jet trigger. As a result, the transverse energy–energy correlator is expected to be independent of φ for central collisions due to the isotropy of the energy flow on the whole. For non-central collisions with a clearly visible elliptic flow of the transverse energy,

$$\frac{\mathrm{d}E_T(\phi)}{\mathrm{d}\phi} = \frac{E_T^{\text{vis}}}{2\pi}[1 + 2v_2\cos(2(\phi - \psi_R))], \quad (6)$$

this correlator $\mathrm{d}\Sigma_T/\mathrm{d}\varphi$ is independent of the reaction plane angle ψ_R and is calculated explicitly:

$$\frac{\mathrm{d}\Sigma_T(\varphi)}{\mathrm{d}\varphi} = \frac{1}{2\pi}\left[1 + 2v_2^2\cos(2\varphi)\right]. \quad (7)$$

The strength of the collective flow (6) being determined by the value of v_2, and the intensity of oscillations in (7) – by v_2^2! Moreover, one can prove that $\mathrm{d}\Sigma_T/\mathrm{d}\varphi$ reproduces all Fourier harmonics of the transverse energy flow decomposition but with the coefficients squared.

3 The model to simulate heavy ion events without and with jets at the LHC

In order to see the manifestation of the jet structure we must cut the background events, i.e. consider the sum in (4) over only the events containing at least one jet with $E_T^{\text{jet}} > E_T(\text{threshold}) \sim 100$ GeV and subtract the background from soft thermal particles using its isotropy on the whole. We demonstrate the productivity and effectiveness of such a strategy in the framework of our well worked-out model of jet passing through a medium applied early to the calculation of various observables sensitive to the partonic energy loss: the impact parameter dependence of the jet production [17], the mono/dijet rate enhancement [18,19], the dijet rate dependence on the angular jet cone [20], the elliptic coefficient of the jet azimuthal anisotropy [6–10], the anti-correlation between the softening jet fragmentation function and the suppression of the jet rate [21]. For details of the model one can refer to these mentioned papers (mainly [17,20,21]). Here we note only the main steps essential for the present investigation.

PYTHIA_6.2 [22] was used to generate the initial jet distributions in nucleon–nucleon sub-collisions at $\sqrt{s} = 5.5\,\text{TeV}$. After that, event-by-event Monte Carlo simulation of rescattering and energy loss of jet partons in QGP was performed. The approach relies on accumulative energy losses, when gluon radiation is associated with each scattering in the expanding medium together with including the interference effect by the modified radiation spectrum as a function of decreasing temperature. Such a numerical simulation of the free path of a hard jet in QGP allows any kinematical characteristic distributions of jets in the final state to be obtained. Besides, the different scenarios of medium evolution can be considered. In each ith scattering a fast parton loses energy collisionally and radiatively, $\Delta e_i = t_i/(2m_0)+\omega_i$, where the transfer momentum squared t_i is simulated according to the differential cross section for elastic scattering of a parton with energy E off the "thermal" partons with energy (or effective mass) $m_0 \sim 3T \ll E$ at temperature T, and ω_i is simulated according to the energy spectrum of coherent medium-induced gluon radiation in the BDMS formalism [23]. Finally we suppose that in every event the energy of an initial parton decreases by the value $\Delta E = \sum_i \Delta e_i$.

The medium was treated as a boost-invariant longitudinally expanding quark–gluon fluid, and partons as being produced on a hyper-surface of equal proper times τ [24]. For certainty we used the initial conditions for the gluon-dominated plasma formation expected for central Pb–Pb collisions at LHC [25]: $\tau_0 \simeq 0.1\,\text{fm/c}$, $T_0 \simeq 1\,\text{GeV}$. For non-central collisions we suggest proportionality of the initial energy density to the ratio of the nuclear overlap function and the effective transverse area of nuclear overlapping [17].

The energy–energy correlator depends on not only the absolute value of partonic energy loss, but also on the angular spectrum of in-medium radiated gluons. Since coherent Landau–Pomeranchuk–Migdal radiation induces a strong dependence of the radiative energy loss of a jet on the angular cone size [20, 23, 26–28], it will soften particle energy distributions inside the jet, increase the multiplicity of secondary particles, and to a lesser degree, affect the total jet energy. On the other hand, collisional energy loss turns out to be practically independent of the jet cone size and causes the loss of total jet energy, because the bulk of the "thermal" particles knocked out of the dense matter by elastic scatterings fly away in an almost transverse direction relative to the jet axis [20]. Thus although the radiative energy loss of an energetic parton dominates over the collisional loss by up to an order of magnitude, the relative contribution of the collisional loss of a jet grows with increasing jet cone size due to the essentially different angular structure of loss for two mechanisms [20]. Moreover, the total energy loss of a jet will be sensitive to the experimental capabilities to detect low-p_T particles – products of soft gluon fragmentation: thresholds for a giving signal in calorimeters, influence of the strong magnetic field, etc. [5].

Since the full treatment of the angular spectrum of emitted gluons is rather sophisticated and model-dependent [20, 23, 26–28], we considered two simple parameterizations of the distribution of in-medium radiated gluons over the emission angle θ. The "small-angular" radiation spectrum was parameterized in the form

$$\frac{\mathrm{d}N^g}{\mathrm{d}\theta} \propto \sin\theta \exp\left(-\frac{(\theta-\theta_0)^2}{2\theta_0^2}\right), \tag{8}$$

where $\theta_0 \sim 5^0$ is the typical angle of the coherent gluon radiation estimated in [20]. The "broad-angular" spectrum has the form

$$\frac{\mathrm{d}N^g}{\mathrm{d}\theta} \propto \frac{1}{\theta}. \tag{9}$$

We believe that such a simplified treatment here is enough to demonstrate the sensitivity of the energy–energy correlator to the medium-induced partonic energy loss.

The following kinematical cuts on the jet transverse energy and pseudo-rapidity were applied: $E_T^{\text{jet}} > 100\,\text{GeV}$ and $|\eta^{\text{jet}}| < 1.5$. After this, the dijet event is imposed upon the Pb–Pb event, which was generated using the fast Monte-Carlo simulation procedure [9, 16, 29] giving a hadron (charged and neutral pion, kaon and proton) spectrum as a superposition of the thermal distribution and collective flow. To be definite, we fixed the following "freeze-out" parameters: the temperature $T_f = 140\,\text{MeV}$, the collective longitudinal rapidity $Y_L^{\max} = 3$ and the collective transverse rapidity $Y_T^{\max} = 1$. We set the Poisson multiplicity distribution. For non-central collisions, the impact parameter dependence of the multiplicity was taken into account in a simple way, just suggesting that the mean multiplicity of the particles is proportional to the nuclear overlap function. We also suggested [9] that the spatial ellipticity of the "freeze-out" region is directly related to the initial spatial ellipticity of the nuclear overlap zone. Such a "scaling" allows one to avoid using additional parameters and, at the same time, results in an elliptic anisotropy of particle and energy flow due to the dependence of the effective transverse size of the "freeze-out" region on the azimuthal angle of a "hadronic liquid" element. The azimuthal distribution of the particles obtained in such a way is described well by the elliptic form (6) for the domain of reasonable impact parameter values.

4 Numerical results and discussion

At first, we became convinced that for non-central collisions with the elliptic anisotropy of particle and energy flow (generated in the framework of the simple Monte-Carlo procedure described above) the energy–energy correlation function $\mathrm{d}\Sigma_T/\mathrm{d}\varphi$ (5) closely followed the formula (7).

Further, only central collisions (in which the effect of jet quenching is maximum and "thermal" background is azimuthally isotropic) will be considered. In order to extract the jet-like energy–energy correlator from the "thermal" background in a high multiplicity environment, the energy deposition in each calorimeter sector i is recalculated event-by-event as follows:

$$E_{Ti}^{\text{new}}(\varphi) = E_{Ti}(\varphi) - \overline{E_{Ti}(\varphi)} - k \cdot D_T, \tag{10}$$

where $\overline{E_{\mathrm{T}i}(\varphi)} = \frac{1}{N}\sum_i \left(E_{\mathrm{T}i}^{\mathrm{thermal}}(\varphi) + E_{\mathrm{T}i}^{\mathrm{jet}}(\varphi)\right)$ is the average energy deposition in a calorimeter sector and $D_\mathrm{T} = \sqrt{\overline{(E_{\mathrm{T}i}(\varphi))^2} - \left(\overline{E_{\mathrm{T}i}(\varphi)}\right)^2}$ is the energy dispersion in the given event; N is the total number of calorimeter sectors. If $E_{\mathrm{T}i}^{\mathrm{new}}$ becomes negative, it is set to zero. Thus only the energy deposition higher than the confidential interval $k \cdot D_\mathrm{T}$ around the mean value is taken into account, decreasing the background influence in such a way. Let us emphasize that due to event-by-event background fluctuations, subtracting not only the average energy deposition but also its dispersion with some factor $k > 0$ is necessary (although this results also in some reduction of the signal itself). A similar procedure is applicable to increase the efficiency of jet reconstruction in heavy ion collisions at LHC [4, 5].

To be specific, we consider the geometry of the CMS detector [30] at LHC. The central ("barrel") part of the CMS calorimetric system covers the pseudo-rapidity region $|\eta| < 1.5$, the segmentation of electromagnetic and hadron calorimeters being $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$ and $\Delta\eta \times \Delta\phi = 0.0872 \times 0.0872$ respectively [30]. In order to reproduce roughly the experimental conditions (not including real detector effects, but just assuming calorimeter hermeticity), we applied (10) to the energy deposition of the generated particles, integrated over the rapidity in $N = 72$ sectors (according to the number of sectors in the hadron calorimeter) covering the full azimuth. Then the energy–energy correlation function (4) is calculated for the events containing at least one jet with $E_\mathrm{T}^{\mathrm{jet}} > E_\mathrm{T}(\mathrm{threshold}) = 100\,\mathrm{GeV}$ in the considered kinematical region. The final jet energy is defined here as the total transverse energy of the final particles collected around the direction of a leading particle inside the cone $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} = 0.5$, where η and φ are the pseudo-rapidity and the azimuthal angle, respectively. Note that the estimated event rate in the CMS acceptance, $\sim 10^7$ jets with $E_\mathrm{T} > 100\,\mathrm{GeV}$ in a one month LHC run with lead beams [4, 5], will be large enough to carefully study the energy–energy correlations over the whole azimuthal range.

Before discussing the numerical results, let us expand upon the role of background fluctuations for our analysis. A simple estimation on this can be obtained from the following considerations. The average (over events) energy deposition in a calorimeter sector for the mean total particle multiplicity $\langle N_p\rangle$ and mean particle transverse momentum $\langle p_\mathrm{T}\rangle$ is approximately $\left\langle E_{\mathrm{T}i}^{\mathrm{thermal}}\right\rangle \approx \langle p_\mathrm{T}\rangle \cdot \langle N_p\rangle / N$. Then the energy dispersion in a calorimeter sector can be roughly estimated to be $\sigma_\mathrm{T}^{\mathrm{thermal}} \sim \langle p_\mathrm{T}\rangle \cdot \sqrt{\langle N_p\rangle / N}$. For realistic values $N = 72$, $\langle p_\mathrm{T}\rangle = 0.55\,\mathrm{GeV}/c$ and $\langle N_p\rangle \sim 20\,000$ (this corresponds to the charged particle density per unit rapidity $\mathrm{d}N^{\pm}/\mathrm{d}y(y = 0) = 5000$ and $\Delta\eta = 3$), we get $\left\langle E_{\mathrm{T}i}^{\mathrm{thermal}}\right\rangle \sim 150\,\mathrm{GeV}$ and $\sigma_\mathrm{T}^{\mathrm{thermal}} \sim 10\,\mathrm{GeV}$. Namely, these background parameters were fixed for our calculations. Note that a really measurable energy flux (and correspondingly absolute value of its fluctuations) can be essentially less than above values, because of limited experimental capabilities to detect low-p_T particles which give a bulk of total multiplicity. In particular, in CMS most of the charged low-p_T particles may be cleared out of the central calorimeters by the strong magnetic field. Thus the analysis of the quality of extracting the jet-like energy–energy correlator from background fluctuations based on the detailed simulation of detector responses (together with the optimization of the jet detection threshold) should be performed for each specific experiment.

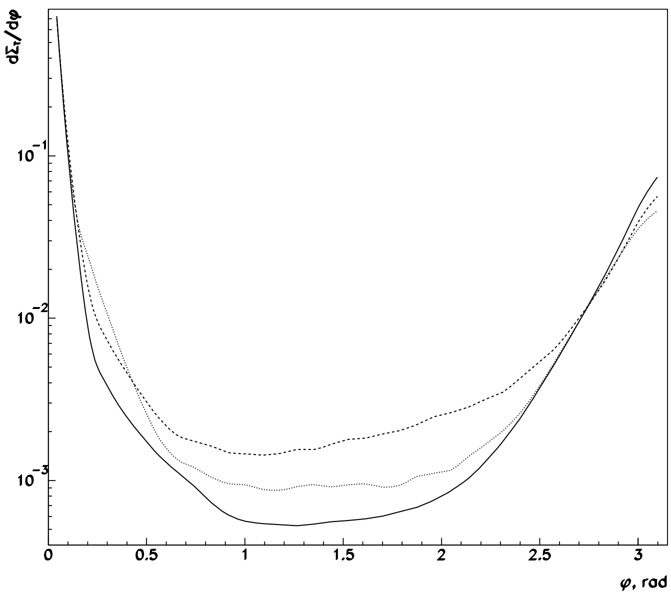

Fig. 1. The transverse energy–energy correlator $\mathrm{d}\Sigma_\mathrm{T}/\mathrm{d}\varphi$ as a function of azimuthal angle φ without (solid histogram) and with medium-induced partonic energy loss for the "small-angular" (8) (dotted histogram) and the "broad-angular" (9) (dashed histogram) parameterizations of emitted gluon spectrum in central Pb−Pb collisions. Applied kinematical cuts are described in the text

The results of the numerical simulations are presented on Fig. 1 for the cases without and with partonic energy loss, the two parameterizations of the distribution on the gluon emission angles (8) and (9) being used. The important issue is whether the procedure of event-by-event background subtraction (10) (with the factor $k = 2$ here) allows the extraction of the jet-like energy–energy correlation function to be done even in high multiplicity heavy ion events. The efficiency of such a strategy is closely related with the following.

Due to the background isotropy, the average (over events) "thermal" energy deposition in the given calorimeter sector, $\left\langle E_{\mathrm{T}i}^{\mathrm{thermal}}\right\rangle$, is approximately equal to the average "thermal" energy deposition in a sector in the given event, $\overline{E_{\mathrm{T}i}^{\mathrm{thermal}}(\varphi)}$, at the large enough N and numbers of particles in the sectors.

The correlation function is sensitive to the medium-induced partonic energy loss and angular spectrum of gluon radiation. Three features of the medium-modified energy–energy correlation function can be noted.
(1) Moderate broadening of the near-side jet region $\varphi \lesssim 0.5$ (more pronounced for the "small-angular" radiation), which is related with discussed in the recent literature jet shape modification [31].

(2) Significant strengthening in the wide region of azimuthal angles around $\varphi \simeq \pi/2$ (more pronounced for the "broad-angular" radiation) at the relatively small, but hopefully still statistically reliable signal values.
(3) Small additional suppression of back-to-back correlations for $\varphi \simeq \pi$ (the analog of acoplanarity [32]) as compared to the original (in *pp*) suppression due to the initial and final state gluon radiation.

The observation of the above modifications demands both the high enough statistics ($\gtrsim 10^6$ events) and the fine azimuthal resolution of the jet position ($\lesssim 0.1$ rad) which, however, are expected to be attainable in calorimetric measurements at LHC [4, 5].

Note that for events with the trigger on the pair of energetic jets ($E_T^{jet}(1,2) > E_T(\text{threshold}) = 100\,\text{GeV}$) the calculated correlator is practically insensitive to the partonic energy loss, mainly because such jets must lose a small amount of energy to be visible simultaneously.

5 Conclusions

In summary, at the special selection of events for the analysis (at least one high-p_T jet) and the procedure of event-by-event background subtraction in high multiplicity heavy ion collisions, the transverse energy–energy correlator is sensitive to the partonic energy loss and angular spectrum of radiated gluons. The medium-modified energy–energy correlation function manifests significant strengthening in a wide interval of azimuthal angles around $\pi/2$, moderate broadening of the near-side jet region $\varphi \lesssim 0.5$ and weak additional suppression of back-to-back correlations for $\varphi \sim \pi$. Without jet trigger this correlation function shows the global structure of the transverse energy flux: the correlator is isotropic for central collisions and for non-central collisions it is sensitive to the azimuthal anisotropy of the energy flow reproducing its Fourier harmonics but with the coefficients squared. We believe that such an energy–energy correlation analysis may be useful at LHC data processing.

Acknowledgements. Discussions with Yu.L. Dokshitzer, S.V. Petrushanko, I.N. Vardanyan, B.G. Zakharov and G.M. Zinovjev are gratefully acknowledged. This work is supported by grant N 04-02-16333 of Russian Foundation for Basic Research.

References

1. Proceedings of 16th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions Quark Matter'2002 (Nantes, France, 18–24 June, 2002), Nucl. Phys. A **715**, (2003); Proceedings of 17th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions Quark Matter'2004 (Oakland, California, 11–17 January, 2004), in press
2. A.K. Ackermann et al. (STAR Coll.), Phys. Rev. Lett. **83**, 402 (2001)
3. C. Adler et al. (STAR Coll.), Phys. Rev. Lett. **90**, 082301 (2003)
4. A. Accardi et al., writeup of the working group Jet Physics for the CERN Yellow Report on Hard Probes in Heavy Ion Collisions at the LHC, hep-ph/0310274
5. G. Baur et al., Heavy Ion Physics Programme in CMS, CERN CMS Note 2000/060
6. I.P. Lokhtin, S.V. Petrushanko, L.I. Sarycheva, A.M. Snigirev, Phys. At. Nucl. **65**, 943 (2002); Pramana **60**, 1045 (2003)
7. I.P. Lokhtin, A.M. Snigirev, I. Vitev, hep-ph/0212061
8. I.P. Lokhtin, S.V. Petrushanko, L.I. Sarycheva, A.M. Snigirev, CERN CMS Note 2003/019
9. I.P. Lokhtin, L.I. Sarycheva, A.M. Snigirev, Phys. Lett. B **537**, 261 (2002); Nucl. Phys. A **715**, 633c (2003)
10. I.P. Lokhtin, L.I. Sarycheva, A.M. Snigirev, Eur. Phys. J. C **30**, 103 (2003)
11. J. Pan, C. Gale, Phys. Rev. D **50**, 3235 (1994)
12. P. Abreu et al. (DELPHY Coll.), Phys. Lett. B **252**, 149 (1990); Z. Phys. C **59**, 21 (1993); M. Akrawy et al. (OPAL Coll.), Phys. Lett. B **252**, 159 (1990); Phys. Lett. B **276**, 547 (1992); B. Adeva et al. (L3 Coll.), Phys. Lett. B **257**, 469 (1991); O. Adriani et al. (L3 Coll.), Phys. Lett. B **284**, 471 (1992)
13. K. Abe et al. (SLD Coll.), Phys. Rev. D **50**, 5580 (1994); Phys. Rev. D **51**, 962 (1995)
14. C.L. Basham, L.S. Brown, S.D. Ellis, T.S. Love, Phys. Rev. Lett. **41**, 1585 (1978); Phys. Rev. D **17**, 2298 (1982)
15. A. Ali, E. Pietarinen, W.J. Stirling, Phys. Lett. B **141**, 447 (1984)
16. N.A. Kruglov, I.P. Lokhtin, L.I. Sarycheva, A.M. Snigirev, Z. Phys. C **76**, 99 (1997)
17. I.P. Lokhtin, A.M. Snigirev, Eur. Phys. J. C **16**, 527 (2000)
18. I.P. Lokhtin, L.I. Sarycheva, A.M. Snigirev, Phys. At. Nucl. **62**, 1258 (1999)
19. S.A. Bass et al., Nucl. Phys. A **661**, 205c (1999)
20. I.P. Lokhtin, A.M. Snigirev, Phys. Lett. B **440**, 163 (1998)
21. I.P. Lokhtin, A.M. Snigirev, Phys. Lett. B **567**, 39 (2003)
22. T. Sjostrand, Comp. Phys. Com. **135**, 238 (2001)
23. R. Baier, Yu.L. Dokshitzer, A.H. Mueller, D. Schiff, Phys. Rev. C **60**, 064902 (1999); Phys. Rev. C **64**, 057902 (2001)
24. J.D. Bjorken, Phys. Rev. D **27**, 140 (1983)
25. K.J. Eskola, K. Kajantie, K. Tuominen, Phys. Lett. B **497**, 39 (2001); K.J. Eskola, P.V. Ruuskanen, S.S. Rasanen, K. Tuominen, Nucl. Phys. A **696**, 715 (2001)
26. B.G. Zakharov, JETP Lett. **70**, 176 (1999)
27. U.A. Wiedemann, M. Gyulassy, Nucl. Phys. B **560**, 345 (1999); U.A. Wiedemann, Nucl. Phys. B **588**, 303 (2000); Nucl. Phys. A **690**, 731 (2001)
28. M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B **571**, 197 (2000); Phys. Rev. Lett. **85**, 5535 (2000); Nucl. Phys. B **594**, 371 (2001)
29. I.P. Lokhtin, A.M. Snigirev, hep-ph/0312204
30. CMS Collaboration, Technical Proposal, CERN/LHCC 94-38
31. C.A. Salgado, U.A. Wiedemann, hep-ph/0310079
32. D.A. Appel, Phys. Rev. D **33**, 717 (1986); J.P. Blaizot, L.D. McLerran, Phys. Rev. D **34**, 2739 (1986)