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Physics of non-Abelian matter in high energy hadronic and nuclear collisions

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A brief review of the recent studies of the properties of dense non-abelian matter is given. A particular emphasis is made on collective effects such as Cherenkov gluon radiation, ridge structure in proton-proton collisions and modification of QCD cascades in dense matter.

1. Introduction. The present mini-review is devoted to results obtained in the course of working in the framework of the RFBR grant 09-02-00741-a and published in [1–14]. Our research was focused on the physics of non-abelian matter created in high energy hadronic and nuclear collisions. Most of the results obtained are covered in the detailed review paper [1]. Below we shall touch upon several most important topics including the generic formulation of the equations of in-medium QCD [2, 3], physics of gluon Cherenkov radiation [4–7], ridge pattern in high multiplicity proton-proton collisions [10, 11] and role of multiple parton interactions in proton-proton interactions [12].

2. Dense non-Abelian matter in high energy collisions. *2.1. In-medium QCD.* To describe collective properties of quark-gluon medium such as Cherenkov gluon radiation [4–7] or the wake [13] it is convenient to introduce effective equations of motion for in-medium QCD [2, 3] (see also an appendix in [7])

$$\begin{gathered}\mathrm{div}\mathbf{D}_a - g f_{abc}\mathbf{A}_b\mathbf{D}_c = \rho_a,\\ \mathrm{curl}\mathbf{B}_a - \frac{\partial \mathbf{D}_a}{\partial t} - g f_{abc}(\Phi_b\mathbf{D}_c + [\mathbf{A}_b\mathbf{B}_c]) = \mathbf{j}_a,\end{gathered} \qquad (1)$$

where generically $D_a = \epsilon_{ab}E_b$ corresponding to a linear response of a medium to an applied external chromoelectric field E_a parametrized by the chromoelectric permittivity tensor ϵ_{ab}. In most applications considered below, with an exception of color rainbow phenomenon considered in the next paragraph, we shall make the simplest assumption of color-diagonal linear response $\epsilon_{ab} = \epsilon\delta_{ab}$.

Properties of quark-gluon medium were considered in the framework of equations of in-medium QCD. In the linear reponse approximation a notion of chromopermittivity was introduced. The properties of eigenmodes of the system were studied. It was shown that at large energies there apppears an instability. Properties of Cherenkov gluon radiation were discussed. The result has been published.

2.2. Cherenkov gluon radiation. A large body of research conducted in the framework of the project was devoted to the physics of Cherenkov gluon radiation.

In the simplest case of color-diagonal frequency-dependent chromopermittivity $\epsilon_{ab}(\omega) = \epsilon(\omega)\delta_{ab}$ the Cherenkov energy loss of colored probe moving with the velocity v calculated from the linearized equations (1) reads

$$\frac{dE}{dl} = 4\pi\alpha_S C_R \int \omega d\omega \left[1 - \frac{1}{v^2\epsilon(\omega)}\right]\Theta[v^2\epsilon(\omega) - 1], \qquad (2)$$

where C_R is a corresponding Casimir invariant.

The formula (2) can be generalized in several ways [1, 5, 7].

The first generalization considered in [1] takes into account the nontrivial tensor structure of the permittivity ϵ_{ab}. Generically ϵ_{ab} is a symmetric tensor, $\epsilon_{ab} = \epsilon_{ba}$, with the equal diagonal $\epsilon^{(\mathrm{d})}$ and off-diagonal $\epsilon^{(\mathrm{o})}$ components. Then it is easy to show that diagonalization of ϵ_{ab} leads to the following eigenvalues:

$$\begin{gathered}\epsilon^{(1)} \equiv \epsilon^* = \epsilon^{(\mathrm{d})} + 2\epsilon^{(\mathrm{o})},\\ \epsilon^{(2),\cdots,(N_c^2-1)} \equiv \epsilon^{**} = \epsilon^{(\mathrm{d})} - \epsilon^{(\mathrm{o})},\end{gathered} \qquad (3)$$

so that one gets, again for the linearized Yang–Mills equations (1), a Cherenkov color rainbow with radiation at two Cherenkov angles

$$\cos\theta^* = \frac{1}{v\sqrt{\epsilon^{(d)} + 2\epsilon^{(o)}}}, \quad \cos\theta^{**} = \frac{1}{v\sqrt{\epsilon^{(d)} - \epsilon^{(o)}}}. \tag{4}$$

Another important feature that has to be taken into account is the absorption in the medium leading to nonzero imaginary part of the chromopermittivity. The differential energy loss due to the Cherenkov radiation generalizing that corresponding to (2) to the case of complex permittivity $\epsilon(\omega) = \epsilon_1(\omega) + i\epsilon_2(\omega)$ reads [5]:

$$\frac{dW}{dl d\omega d\phi d\cos\theta} = \frac{4\alpha_S C_R}{\pi} \frac{\cos\theta(1-\cos^2\theta)\Gamma(\omega)}{[\cos^2\theta - \xi(\omega)]^2 + \Gamma^2(\omega)}, \tag{5}$$

where

$$\xi(\omega) = \frac{\epsilon_1(\omega)}{\epsilon_1^2(\omega) + \epsilon_2^2(\omega)}, \quad \Gamma(\omega) = \frac{\epsilon_2(\omega)}{\epsilon_1^2(\omega) + \epsilon_2^2(\omega)}. \tag{6}$$

In [5] it was shown that equation (5), together with taking into account rescattering of Cherenkov glue in the hot dense matter, allows to reproduce the pattern of away-side correlations observed at RHIC, see Fig. 1.

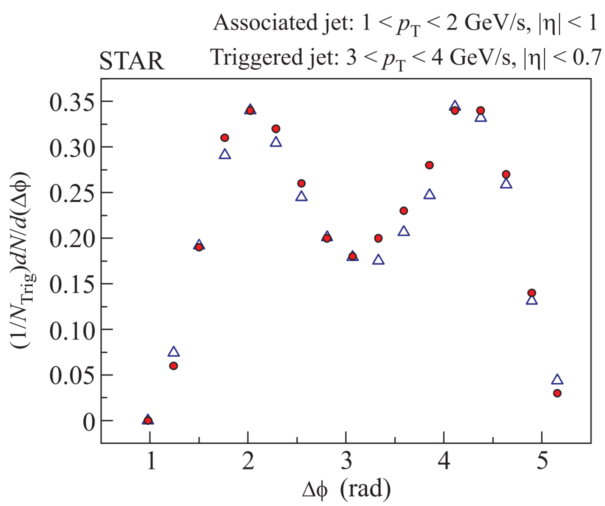

Fig. 1. Associated azimuthal correlations at STAR: circles – experiment, triangles – theory ($\varepsilon_1 = 5.4$; $\varepsilon_2 = 0.7$; $\Delta_\perp = 0.7$ GeV/s)

A full quantum picture of the in-medium QCD was considered in [7]. In particular, a quantum calculation of the rate of Cherenkov gluon radiation of gluon currents $\gamma_{g\to g\tilde{g}}(\omega|E)$ generalizing that corresponding to (1) leads to the following rate of Cherenkov gluon production by gluon current:

$$\gamma_{g\to g\tilde{g}} = \alpha_s N_c \left(1 - \frac{1}{\varepsilon}\right)\left(1 - \frac{\omega}{E} - \frac{\varepsilon - 1}{4}\frac{\omega^2}{E^2}\right) \times \tag{7}$$

$$\left[1 + \frac{1}{2}\left(\varepsilon + \frac{\varepsilon+1}{1-\frac{\omega}{E}} + \frac{\varepsilon}{\left(1-\frac{\omega}{E}\right)^2}\right)\frac{\omega^2}{E^2} + \frac{(\varepsilon+1)^2}{8\left(1-\frac{\omega}{E}\right)^2}\frac{\omega^4}{E^4}\right],$$

where g denotes a usual gluon and $\tilde{g}$ a Cherenkov one. Another inherently non-Abelian process related to Cherenkov gluons considered in [7] is of the gluon decay into two Cherenkov gluons $\gamma_{g\to\tilde{g}\tilde{g}}$. The corresponding rate reads:

$$\gamma_{g\to\tilde{g}\tilde{g}}(\omega|E) = \frac{\alpha_s N_c}{2}\left[1 - \left(\sqrt{\varepsilon} - \frac{\varepsilon-1}{2\sqrt{\varepsilon}}\frac{E}{\omega}\right)^2\right] \times$$
$$\times \left[1 + \varepsilon\frac{\omega^2}{E^2} + \frac{\frac{\omega^2}{E^2}}{(1-\frac{\omega}{E})^2} + \right.$$
$$\left. + \varepsilon\left(1 - \frac{\varepsilon-1}{2\varepsilon}\frac{1}{1-\frac{\omega}{E}} + \frac{\frac{\omega^2}{E^2}}{1-\frac{\omega}{E}}\right)^2\right]. \tag{8}$$

It was argued, in particular, that double Cherenkov decay provides another possibility of explaining the two-humped away-side structure observed at RHIC.

Another interesting manifestation of the physics of Cherenkov gluons is their possible role in generating the experimentally observed asymmetry of dilepton mass spectra in the vicinity of rho meson [4]. The corresponding formula for the dilepton spectrum reads:

$$\frac{dN_{ll}}{dM} = \frac{A}{(m_r^2 - M^2)^2 + M^2\Gamma^2} \times$$
$$\times \left[1 + w_r\frac{m_r^2 - M^2}{M^2}\Theta(m_r - M)\right], \tag{9}$$

where M is the dilepton mass and m_r is the resonance mass. The first term corresponds to the ordinary Breit–Wigner cross section, while the origin of the second one is in coherent Cherenkov response of the medium proportional to the real part of the scattering amplitude. The theoretical spectrum (9) provides a good description of the experimental data, see Fig. 2.

2.3. In-medium QCD cascades. One of the most important issues in the physics of multiparticle production in high energy nuclear collisions is understanding the modifications of QCD jets as compared to the well understood reference case of pp collisions or e^+e^--annihilation. The main idea of the mechanism of such modification suggested in [8, 9] is a disruption of angular ordering for that part of gluon cascade that evolves inside the dense and hot zone treated in ultrarelativistic heavy ion collisions, see Fig. 3. To analyze the physical consequences of such a picture a Monte-Carlo program explicitly tracking the times at which cascade branchings occur was developed. The corresponding space-time

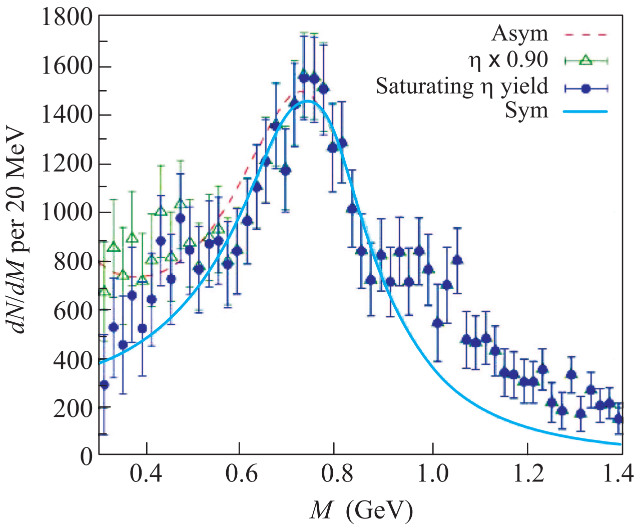

Fig. 2. Modified spectrum of dileptons in semi-central collisions In(158 A GeV)-In for NA60 (points) compared to the ρ-meson peak in the medium with additional Cherenkov contribution (dashed line)

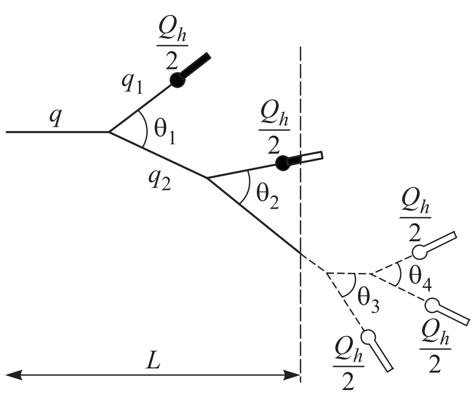

Fig. 3. In-medium QCD cascade

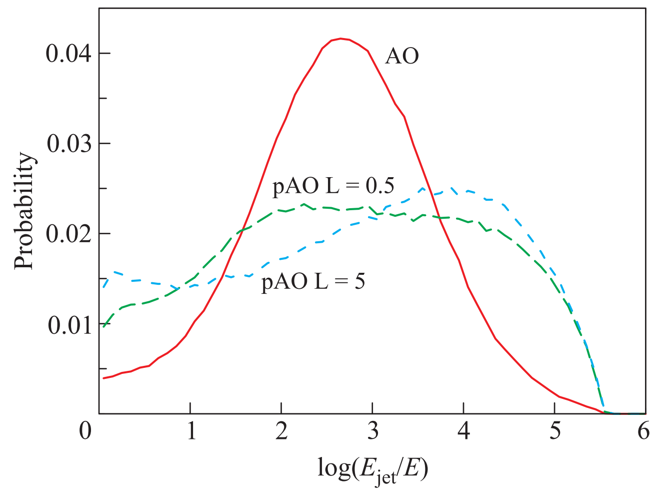

Fig. 4. (Color online) Distribution in rapidity $P(y)$ of final prehadrons: $L = 0\,\mathrm{fm}$, full angular ordering, red, full line (1); $L = 0.5\,\mathrm{fm}$, partial angular ordering, green, dashed line (2); $L = 5\,\mathrm{fm}$, partial angular ordering, blue, dotted line (3)

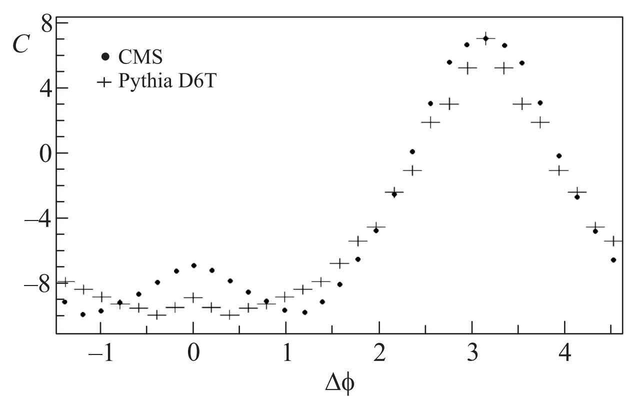

Fig. 5. Comparison of the correlation function for experimental data (dots) and MC simulation (crosses)

picture is based on taking into account the lifetimes of parent gluons

$$\tau = E\left(1/Q^2 - 1/Q^2_{\mathrm{par}}\right), \qquad (10)$$

where Q^2_{par} and Q^2 are virtualities of the parent and daughter partons respectively and E is an energy of the daughter parton. The effects of disruption of angular ordering and non-radiative energy losses in QCD jets in the dense non-abelian medium of finite size formed in ultrarelativistic heavy ion collisions at the LHC energy turned out to be quite substantial. It was shown, in particular, that the considered effects lead to significant modifications of the spectra of produced particles, see Fig. 4.

2.4. Ridge in proton-proton collisions. Two papers [10, 11] were devoted to the possible origins of the ridge effect in proton-proton collisions observed by the CMS collaboration at LHC. The ridge effect manifests itself in long-range two-particle rapidity correlations at zero relative azimuthal deistance $\Delta\phi$ as seen in the experimentally measured correlation function $C(\Delta\eta, \Delta\phi)$.

In the analysis of [10] the common origin of such nontrivial properties of the angular distributions and correlations of hadrons in the multiparticle production processes at high energies at the LHC as the azimuthal asymmetry, ridge and acoplanarity, was attributed to the general structure of the corresponding QCD matrix elements describing generic gluon radiation pattern.

The study of [11] was focused on the possible nonperturbative mechanisms leading to ridge-like angular correlations. In particular, it was shown that the soft mechanism of multiparticle production by Lund hadronic strings formed by constituent degrees of freedom of colliding hadrons generates a shape of angular correlations similar to the ridge structure observed in proton-proton collisions at the LHC albeit of somewhat lower intensity. The resulting pattern was found to be in qualitative agreement with the experimental data, see Fig. 5.

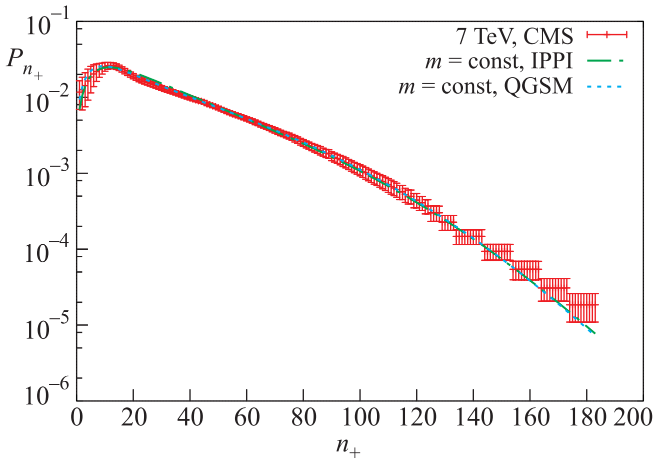

Fig. 6. IPPI (dash-dotted line) fit of the CMS data on multiplicity distribution in pp collisions at $\sqrt{s} = 7$ TeV

2.5. Multiple parton interactions. One of the most important aspects of the changes in the pattern of multiparticle production at high energies is the growing role of multiparton interactions. In the paper [12] multiplicity distributions of charged particles in proton-proton collisions at Tevatron and LHC energies were studied in the framework of the independent pair parton interaction model (IPPI). The main equation of the IPPI model reads

$$P(n; m, k) = \sum_{j=1}^{j_{\max}} w_j P_{\mathrm{NBD}}(n; jm, jk), \qquad (11)$$

so that the probability of the n-particle production channel is defined by the sum of NBDs with shifted maxima (jm) and larger widths (jk) for independent parton collisions weighted by their probabilities w_j. It was demonstrated that the model provides a very good description of multiplicity distribution at LHC energies, see Fig. 6. A very important outcome of the analysis of [12] was that the number of soft pair parton interactions is large and grows with energy.

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