Cherenkov gluons
(predictions and proposals)\textsuperscript{1}

I.M. Dremin\textsuperscript{2}

Lebedev Physical Institute, Moscow, Russia

Abstract

The coherent hadron production analogous to Cherenkov radiation of photons gives rise to the ring-like events. Being projected on the ring diameter they produce the two-bump structure recently observed for the away-side jets at RHIC. The position of the peaks and their height determine such properties of the hadronic medium as its nuclear refractive index, the parton density, the free path length and the energy loss of Cherenkov gluons. Cherenkov gluons may be responsible for the asymmetry of dilepton mass spectra near $\rho$-meson observed in experiment. Beside comparatively low energy gluons observed at RHIC, there could be high energy gluons at LHC, related to the high energy region of positive real part of the forward scattering amplitude and possessing different characteristics. This would allow to scan $(x, Q^2)$-plane determining the parton densities in its various regions.

1 Introduction.

Analogous to Cherenkov photons \cite{1, 2, 3}, the Cherenkov gluons \cite{4, 5, 6, 7, 8} can be emitted in hadronic collisions. Considered first for processes at very high energies \cite{4, 5}, the idea about Cherenkov gluons was extended to resonance production \cite{6, 9, 10}.

For Cherenkov effects to be pronounced in ordinary or nuclear matter, the (either electromagnetic or nuclear) refractive index of the medium $n$ should be larger than 1. There exists the general relation (see, e.g., \cite{11}) between the refractive index and the forward scattering amplitude $F(E, 0^o)$:

$$\Delta n = \text{Ren} - 1 = \frac{8\pi N_c \text{Re} F(E, 0^o)}{E^2}. \quad (1)$$

\textsuperscript{1}The talk at the seminar during the CERN TH-workshop ”Heavy Ion Collisions at the LHC. Last Call for Predictions.” May 14th - June 8th 2007.
\textsuperscript{2}email: dremin@lpi.ru
Here $E$ is the photon (gluon) energy, $N_s$ is the density of the scattering centers in the medium. We shall use this relation as a starting point for all results on Cherenkov gluons. The necessary condition for Cherenkov radiation is

$$\Delta n > 0 \quad \text{or} \quad \text{Re} F(E, 0^o) > 0.$$  \hspace{1cm} (2)

If these inequalities are satisfied, Cherenkov photons (gluons) are emitted along the cone with half-angle $\theta_c$ in the rest system of the infinite medium determined by $n$:

$$\cos \theta_c = \frac{1}{\beta n},$$  \hspace{1cm} (3)

where $\beta (\approx 1$ for relativistic partons) is the ratio of the velocities of the parton and (in-vacuum) light.

Let us stress that the notion of the angle is not relativistically invariant. Therefore one should be careful in choosing the coordinate system where to apply Eq. (3) in nucleus-nucleus collisions. This problem is discussed in more detail at the end of the paper.

In classical electrodynamics, it is the dipole excitation and polarization of atoms by the electromagnetic field of charged beams moving in the medium which results in the Breit-Wigner shape of the amplitude $F(E, 0^o)$. The relation (1) demonstrates that the forward scattering amplitudes account in some way for properties of excited states as well. Atoms behaving as oscillators provide the refractive indices larger than 1 within their low-energy wings (see, e.g., Fig. 31-5 in vol. 1 of Feynman lectures [12]). The target rest system is precisely defined. In distinction to Bremsstrahlung where transverse fields are important, the Cherenkov radiation is induced by the longitudinal component of the polarization vector.

The forward scattering amplitude for gluons is infinite. To define the refractive index in the absence of the theory of nuclear media (for a simplified approach see [8]) I prefer to rely on our knowledge about hadronic reactions translated in partonic language to develop phenomenological models.

There are two common features for all hadron-hadron collisions. First, the prominent resonances are formed at rather low energies. They are described by the Breit-Wigner amplitudes which have the positive real part in their low-mass wings. In hadronic medium, there should be some modes (quarks, gluons or their preconfined bound states, condensates, blobs of hot matter...?) which can get excited by the gluon field of the impinging parton and radiate coherently if $n > 1$. The necessary condition (2) for the Cherenkov effect is satisfied for those gluons colliding with these internal modes.
whose energies are suitable for production of the states within these wings. Thus, the resonance amplitude is chosen for $F(E, 0^\circ)$ at comparatively low energies.

Second, it follows both from experiment and from dispersion relations that the real parts of hadronic amplitudes (and, consequently, $\Delta n$) become positive at very high energies as well. They are usually negative at intermediate energies. Their common feature is the rather high energy threshold above which the real parts of amplitudes become positive for all processes studied.

One can expect that these general features also hold for gluons as carriers of strong interaction forces. Then the gluonic Cherenkov effects can be observable in the two (low and high energy) regions.

Summarizing, the scenario, we have in mind, is as follows. Any parton, either belonging to a colliding nucleus or already scattered in the medium, can emit a gluon which traverses the nuclear medium. On its way, the gluon collides with some internal modes. Therefore it affects the medium as an ”effective” wave which accounts also for the waves emitted by other scattering centers. Beside incoherent scattering, there are processes which can be described as the refraction of the initial wave along the path of the coherent wave (see, e.g., [11]). The Cherenkov effect is the induced coherent radiation by a set of scattering centers placed on the way of propagation of the gluon. The longitudinal components of their polarization vector are important. That is why the forward scattering amplitude plays such a crucial role in formation of the refractive index. At low energies its excess over 1 is related to the resonance peaks as dictated by the Breit-Wigner shapes of the amplitudes. In experiment, usual resonances are formed during the color neutralization process. The resonant structure can reveal itself in the virtual states as well. However, only those gluons whose energies are within the left-wing resonance region of $n > 1$ give rise also to the collective Cherenkov effect proportional to $\Delta n$. At high energies these excitations should lead to Cherenkov jets. In both energy regions the coherent Cherenkov emission proceeds at angles determined by Eq. (3) where $n$ can depend on energy.

2 Resonance rings.

Prediction 1. According to Eq. (3) the ring-like two-dimensional distribution of hadrons similar to Cherenkov rings of photons can be observed in
the plane perpendicular to the cone (jet) axis if \( n > 1 \).

**Proposal 1.** Plot the one-dimensional pseudorapidity \( \eta = -\ln \tan \theta/2 \) distribution with trigger momentum as z-axis neglecting the mismatch of trigger and away-side jets directions\(^3\). It should have maximum at (3).

This is the best possible one-dimensional projection of the ring.

This plot is still unavailable at RHIC. RHIC experiments \([13, 14, 15, 16]\) have shown the two-bump structure of the azimuthal angle (\( \Delta \phi \)) distribution (now with z-axis chosen along the collision axis) of particles with rather low transverse momenta near the away-side jets in central heavy-ion collisions. There is no such structure in pp-collisions. The difference has been attributed to ”in-medium” effects. These features are clearly seen in Fig. 1 (the upper part for pp, lower one for Au-Au).

One easily notices the remarkable difference between particle distributions in the direction opposite to the trigger jet maximum positioned at \( \Delta \phi = 0 \). Both trigger and companion high-\( p_T \) jets have been created in central Au-Au collisions at \( \sqrt{s} = 200 \text{ GeV} \) at the periphery of a nucleus. They move in opposite directions if produced in head-on collisions of partons with equal energies. The trigger parton immediately escapes the nucleus and, therefore, is detected as the ”in-vacuum” jet. The companion (away-side) jet traverses the whole nucleus before it comes out. It is modified by ”in-medium” effects.

These features can be interpreted in the following way. Beside normal jet fragmentation, the parton impact on the medium initiates emission of Cherenkov gluons which produce a ring of hadrons in the plane perpendicular to the away-side jet axis. Ring’s plane is perpendicular both to the trigger momentum and to the collision plane in which momenta of the colliding particles and the trigger are placed. The two-bump structure results due to the one-dimensional projection of the ring on the azimuthal plane. The analogous two-bump structure was shown by Cherenkov in his earlier papers \([1]\) (see also Fig. 1.8 in \([17]\)). It is clear that projection of a ring on its diameter in the azimuthal plane is not the best one to reveal its properties. The Proposal 1 uses better (circular) projection of the ring. The shapes of two- and three-particle correlations studied at RHIC \([18]\) are its less direct indications although they have the ring-like structure themselves.

Thus we can ascribe two contributions to the away-side hadrons associ-
ated with the companion jet: one from jet fragmentation and the other from Cherenkov gluons. The hadrons from jet fragmentation are smoothly distributed within the phase space volume. In distinction, the one-dimensional distribution along the ring diameter of the away-side hadrons created by Cherenkov gluons must possess two peaks.

Let us note that the azimuthal angles $\Delta \phi$ in Fig. 1 are considered as the polar angles $\theta$ in our treatment because the role of $z$-axis is now played by the jet axis in place of the axis of collisions. The ring is placed in the plane perpendicular to the jet axis. The two maxima in the right-hand side of Fig. 1 appear due to its projection on the diameter. The distance between them is exactly equal to the diameter of the ring.

From the distance between the peaks defined in angular ($\theta = D$ in PHENIX notation) variables in Fig. 1 one gets according to Eq. (3) the nuclear refractive index. Its value is found to be quite large $n = 3$ compared to usual electromagnetic values for gases close to 1. If interpreted in terms of the Breit-Wigner resonances, as explained below, it results in the large density of partons in the created quark-gluon system with about 20 partons within the volume of a single nucleon [9]. It agrees with its estimates from $v_2$ and hydrodynamics. This value is also related to the energy loss of gluons estimated in [9] as $dE/dx \approx 1$ GeV/fm. The height of the peaks determines the width of the ring which in its turn defines the free path length of Cherenkov gluons [9] which happens to be long enough $R_f \sim 7$ fm. Thus they hadronize, probably, close to the surface of the initial volume.

These estimates are obtained [9] as follows. If the hadronization of gluons is a soft process then the gluon energy closely corresponds to the energy of the produced resonance. It implies that in this particular experiment Cherenkov gluons can be emitted only with energies within the lower wings of hadronic resonances. Their amplitude is of the Breit-Wigner shape. For a single resonance at energy $E_R$ and with width $\Gamma_R$ one gets

$$\text{Ren}(E) = 1 + \frac{2J + 1}{(2s_1 + 1)(2s_2 + 1)} \cdot \frac{6\mu^3 \Gamma_R \nu}{E_R^2} \cdot \frac{E_R - E}{E[(E - E_R)^2 + \Gamma_R^2/4]}.$$  \hspace{1cm} (4)

Here $J$ is the spin of the resonance, $s_i$ are the spins of ”incident particles”. We have used the number of partonic scatterers $\nu$ within a single nucleon volume $4\pi/3\mu^3$ with $\mu$ the pion mass. For $n = 3$, its estimated value $\nu \approx 20$ given above follows from Eq. (4). Let us note that the similar expressions are widely used in optics, in particular, for defining the variety and abundance of chemical elements in the sun atmosphere (e.g., see [12]).
Another information can be obtained from the height of the peaks in Fig. 1. It determines the width of the Cherenkov ring $\delta$. This is the ring in the plane perpendicular to the cone axis filled by evenly distributed within it particles over the smooth background due to jet fragmentation. Its projection on the diameter corresponds to the particle distribution which has a minimum at the center, increases, reaches the maximum at the internal radius of the ring $r_i$ and then decreases to zero at its external radius $r_e$. For narrow rings ($\delta \ll r_i$) the height of the maximum over the minimum is easily determined as

$$h_{\text{max}} = \sqrt{2r_i \delta - \delta}. \quad (5)$$

With $h_{\text{max}} \approx 1.6 - 1.2 = 0.4$ and $r_i = 1.2$ in Fig. 1 one gets

$$\delta \approx 0.1. \quad (6)$$

The ring of Cherenkov gluons is really quite narrow. Following Proposal 1, its width can be directly measured by plotting the pseudorapidity distribution of particles with the away-side jet direction chosen as $z$-axis.

Actually, Eq. (3) implies that the ring is squeezed to a circle. There are three physical reasons which can lead to the finite width of the ring. First, it is the dispersion, i.e. the energy dependence of the refractive index. Its contribution to the width is well known

$$\delta_d = \int_0^{\delta_d} d\theta = \cot \theta_c \int_0^{\infty} \frac{1}{n} \frac{dn}{dE} dE. \quad (7)$$

If the Breit-Wigner expression (4) for $n(E)$ is used, the result is

$$\delta_d = 0. \quad (8)$$

It is amazing that there is no widening of the Cherenkov cone due to the dispersion of $n(E)$ described by the formula (4) with Breit-Wigner resonances.

Second, the width of the Cherenkov ring can be due to the finite free path length for partons. Qualitatively, it can be estimated as the ratio of the parton wavelength $\lambda$ to the free path length $R_f$

$$\delta_f \sim \frac{\lambda}{R_f}. \quad (9)$$

For $\lambda \sim 2/E_R$ and $\delta_f < 0.1$ one gets the estimate for the free path length

$$R_f > 20/E_R \sim 4.5/\mu \sim 7 \cdot 10^{-13}\text{cm}. \quad (10)$$
This appears to be quite a reasonable estimate. The inequality sign shows that the partial width due to this particular effect is smaller than the total width.

Finally, the width of the ring can become larger due to the processes of resonance formation (hadronization of the gluon collective mode) and decays. However, this can be quantified only if the Monte Carlo program for jets with Cherenkov gluons is elaborated.

The energy loss can be calculated using the standard formula

\[
\frac{dE}{dx} = 4\pi\alpha_S \int_{E_R - \Gamma_R}^{E_R} E \left(1 - \frac{1}{2n^2(E)}\right) dE. \tag{11}
\]

The integration limits define the most important region discussed above. With expression (11) for \( \rho \)-meson one gets from (11)

\[
\frac{dE}{dx} \approx 1 \text{ GeV/fm}. \tag{12}
\]

This estimate is an order of magnitude higher than the value of 0.1 GeV/fm obtained in the model of [8] which is somewhat underestimated, in our opinion. It is determined by energies required to excite resonances. However, it is still smaller than the radiative loss.

Thus, using the RHIC data, we have estimated such parameters of the nuclear matter in heavy-ion collisions as its nuclear refractive index, the density of partons, their free path length and energy loss.

### 3 Asymmetry of in-medium resonances.

Another specific feature of low-energy Cherenkov effect is that it leads to the somewhat unusual particle content within the ring.

**Prediction 2.** Masses of Cherenkov states are less than in-vacuum meson masses. This leads to the asymmetry of decay spectra of resonances with increased role of low masses.

**Proposal 2.** Plot the mass distribution of \( \pi^+\pi^- \), \( \mu^+\mu^- \), \( e^+e^- \)-pairs near resonance peaks.

Apart from the ordinary Breit-Wigner shape of the cross section for resonance production, the dilepton mass spectrum would acquire the additional
term proportional to $\Delta n$ (that is typical for Cherenkov effects) at masses below the resonance peak [19]. Therefore its excess (e.g., near the $\rho$-meson) can be described by the following formula

$$
\frac{dN_{ll}}{dM} = \frac{A}{(m_{\rho}^2 - M^2)^2 + M^2 \Gamma^2} \left( 1 + w \frac{m_{\rho}^2 - M^2}{M^2} \theta(m_{\rho} - M) \right). \quad (13)
$$

Here $M$ is the total c.m.s. energy of two colliding objects (the dilepton mass), $m_{\rho}=775$ MeV is the in-vacuum $\rho$-meson mass. The first term corresponds to the Breit-Wigner cross section. According to the optical theorem it is proportional to the imaginary part of the forward scattering amplitude. The second term is proportional to $\Delta n$ where the ratio of real to imaginary parts of Breit-Wigner amplitudes is taken into account

$$
\frac{\text{Re} F(M, 0^o)}{\text{Im} F(M, 0^o)} = \frac{m_{\rho}^2 - M^2}{M \Gamma}. \quad (14)
$$

so that

$$
\Delta n = \frac{N_s}{\Gamma} \sigma_{BW} \frac{m_{\rho}^2 - M^2}{M^2}, \quad (15)
$$

where $\sigma_{BW}$ is the Breit-Wigner cross section.

This term vanishes for $M > m_{\rho}$ in Eq. (13) because only positive $\Delta n$ lead to the Cherenkov effect. Namely it describes the distribution of masses of Cherenkov states. In these formulas, one should take into account the in-medium modification of the height of the peak and its width. In principle, one could consider $m_{\rho}$ as a free in-medium parameter as well. Let us rely on experimental findings that its shift in the medium is small. Theoretical estimates would ask for some dynamics to be known. In our approach, it is not determined. Therefore, first of all, one may just fit the parameters $A$ and $\Gamma$ by describing the shape of the mass spectrum at $0.75 < M < 0.9$ GeV measured in [20] and shown in Fig. 2. In this way any strong influence of the $\phi$-meson is avoided. Let us note that $w$ is not used in this procedure. The values $A=104$ GeV$^3$ and $\Gamma = 0.354$ GeV were obtained. The width of the in-medium peak is larger than the in-vacuum $\rho$-meson width equal to 150 MeV.

---

4Only $\rho$-mesons are considered here because the most precise experimental data are available [20] about them. To include other mesons, one should evaluate the corresponding sum of similar expressions. Other experimental data can be found in [21, 22, 23, 24, 25, 26, 27, 28, 29].
Thus the low mass spectrum at $M < m_\rho$ depends only on a single parameter $w$ which is determined by the relative role of Cherenkov effects and ordinary mechanism of resonance production. It is clearly seen from Eq. (13) that the role of the second term in the brackets increases for smaller masses $M$. The excess spectrum in the mass region from 0.4 GeV to 0.75 GeV has been fitted by $w = 0.19$. The slight downward shift about 40 MeV of the peak of the distribution compared with $m_\rho$ may be estimated from Eq. (13) at these values of the parameters. This agrees with the above statement about small shift compared to $m_\rho$. The total mass spectrum (the dashed line) and its widened Breit-Wigner component (the solid line) according to Eq. (13) with the chosen parameters are shown in Fig. 2. The overall description of experimental points seems quite satisfactory. The contribution of Cherenkov gluons (the excess of the dashed line over the solid one) constitutes the noticeable part at low masses. The formula (13) must be valid in the vicinity of the resonance peak. Thus we use it for masses larger than 0.4 GeV only.

The excess of masses larger than 0.9 GeV is ascribed to $\phi$-meson not considered here. The estimated value $w = 0.19$ corresponds to the lowest possible contribution of Cherenkov gluons because the fit in the region 0.75 - 0.9 GeV is most unfavorable for it. This is clearly seen in Fig. 2 where the solid line is systematically below experimental points at 0.75 - 0.8 GeV and above them at 0.8 - 0.9 GeV.

One would expect slightly lower $p_T$ for low-mass dilepton pairs from coherent Cherenkov processes than for incoherent scattering at higher masses. Qualitatively, this conclusion is supported by experiment [20]. The Cherenkov dominance region of masses from 400 MeV to 600 MeV below the $\rho$-resonance has softer $p_T$-distribution compared to the resonance region from 600 MeV to 900 MeV filled in by usual incoherent scattering. More accurate statements can be obtained after the microscopic theory of Cherenkov gluons developed.

Whether the in-medium Cherenkov gluonic effect is as strong as shown in Fig. 2 can be verified by measuring the angular distribution of the lepton pairs with different masses. The trigger-jet experiments similar to that at RHIC are necessary to check this prediction. One should measure the angles between the companion jet axis and the total momentum of the lepton pair. The Cherenkov pairs with masses between 0.4 GeV and 0.7 GeV should tend to fill in the rings around the jet axis. The angular radius $\theta$ of the ring is determined by the usual condition (3).

Another way to demonstrate it is to measure the average mass of lepton
pairs as a function of their polar emission angle (pseudorapidity) with the companion jet direction chosen as $z$-axis. Some excess of low-mass pairs may be observed at the angle $\theta$.

In practice, these procedures can be quite complicated at comparatively low energies if the momenta of decay products are comparable to the transverse momentum of the resonance. It can be a hard task to pair leptons in reliable combinations. The Monte Carlo models could be of some help.

In non-trigger experiments like that of NA60 there is another obstacle. Everything is averaged over directions of initial partons. Different partons are moving in different directions. The angle $\theta$, measured from the direction of their initial momenta, is the same but the total angles are different, correspondingly. The averaging procedure would shift the maxima and give rise to more smooth distribution. Nevertheless, some indications on the substructure with maxima at definite angles have been found at the same energies by CERES collaboration [30]. It is not clear yet if it can be ascribed to Cherenkov gluons. To recover a definite maximum, it would be better to detect a single parton jet, i.e. to have a trigger.

The prediction of asymmetrical in-medium widening of any resonance at its low-mass side due to Cherenkov gluons is universal. This universality is definitely supported by experiment. Very clear signals of the excess on the low-mass sides of $\rho$, $\omega$ and $\phi$ mesons have been seen in KEK [25, 26]. This effect for $\omega$-meson is also studied by CBELSA/TAPS-collaboration [28]. Slight asymmetry of $\phi$-meson near 0.9 - 1 GeV is noticeable in the Fig. 2 shown above but the error bars are large there. We did not try to fit it just to deal with as small number of parameters as possible. There are some indications from PHENIX at RHIC (see Fig. 6 in [27]) on this effect for $J/\psi$-meson. It is astonishing that this effect has been observed in a wide interval of initial energies. The relative share of Cherenkov effects, described by the parameter $w$ above, can depend on energy.

To conclude, the universal asymmetry of in-medium mesons with an excess over the usual Breit-Wigner form at low masses is predicted as a signature of Cherenkov gluons produced with energies which fit the left wings of resonances.

Let us stress that we do not require $\rho$-mesons or other resonances pre-exist in the medium but imply that they are the modes of its excitation formed during the hadronization process of partons. The Cherenkov gluon emission is a collective response of the quark-gluon medium to impinging partons related to its preconfinement and hadronization properties. It is
defined by energy behaviour of the second term in Eq. (1).

For the sake of simplicity, Eqs. (1) and (4) valid at small $\Delta n_R$ typical for gases are used here. The value $n = 3$ corresponds to a dense liquid. Therefore, one must use [12]

$$\frac{n^2 - 1}{n^2 + 2} = \frac{m_\alpha^3 \nu \alpha}{4\pi} = \sum_R \frac{2J_R + 1}{(2s_1^R + 1)(2s_2^R + 1)} \cdot \frac{4m_\alpha^3 \Gamma_R \nu}{EE_R^2} \cdot \frac{E_R - E}{(E - E_R)^2 + \Gamma_R^2/4},$$

where $\alpha$ denotes the colour polarizability of the colour-neutral medium. The value $\nu$ obtained from this expression is almost twice lower than given above. It does not change the qualitative conclusions about the dense medium (for more details see [9, 10]).

\section{High-energy rings.}

At much higher energies one can expect better alignment of the momenta of initial partons. This would favour the direct observation of emitted by them rings in non-trigger experiments. The first cosmic ray event [31] with ring structure gives some hope that at LHC energies the initial partons are really more aligned and this effect can be found. The possible additional signature would be the enlarged transverse momenta of particles within the ring.

\textbf{Prediction 3.} The very high energy forward moving partons can emit high energy Cherenkov gluons producing jets.

\textbf{Proposal 3.} Plot the pseudorapidity distribution of dense groups of particles in individual events (now again with collision axis chosen as $z$-axis) and look for maxima at angles determined by Eq. (3).

Gluons with such energy are not abundant at RHIC but they will become available at LHC. Namely such gluons were discussed in [4, 5] in connection with the cosmic ray event at energy $10^{16}$ eV (in the target rest system $E_t$) with the ring-like structure first observed [31]. This energy just corresponds to LHC energies. The partons emitting such gluons move with high energy in the forward direction. With Re$F(E_t)$ fitted to experimental data and dispersion relation predictions at high energies one can expect (see [4, 5]) that the excess of $n$ over 1 behaves as

$$\Delta n_R(E_t) \approx \frac{a\nu h}{E_t} \theta(E_t - E_{th}).$$

(17)
Here, $a \approx 2 \cdot 10^{-3}$ GeV is a parameter of $\text{Re} F(E_t)$ obtained from experiment (with dispersion relations used) and $\nu_h$ is the parton density for high energy region. It can differ from $\nu$ used at low energies. $\Delta n_R(E_t)$ is small and decreases with energy for constant $\nu_h$. It would imply that the medium reminds a gas but not a liquid for very high energy gluons, i.e. it becomes more transparent.

The angles of the cone emission in c.m.s. of LHC experiments must be very large nevertheless (first estimates in [5] are $60^\circ$ - $70^\circ$), i.e. the peaks can be seen in the pionization region at central pseudorapidities. In more detail it is discussed in [4, 5, 11]. In this region the background is large, and some methods to separate the particles in the cone from the background were proposed in [32, 33].

The main difference between the trigger experiments at RHIC and this nontrigger experiment is in the treatment of the rest system of the medium. The influence of the medium motion on cone angles was considered in [34]. It is important because all the above formulas are valid for emission in the rest system of the medium.

At RHIC, the $90^\circ$ trigger jet defines the direction of the away-side jet. Because of position of the trigger perpendicular to the collision axis of initial ions, the accompanying partons (particles) feel the medium at rest on the average in the c.m.s. The similar trigger experiments are possible at LHC. It is important to measure the cone angles for different angular positions of the trigger to have an access to different coordinate systems where the target is at rest on the average and to register the medium motion.

In nontrigger experiments, dealing with forward moving high energy partons inside of one of the colliding ions, the rest system of the medium is the rest system of another colliding ion. Therefore the cone angle should be calculated in that system and then transformed to the c.m.s. That is why these angles are so large even at small values of the refractivity index for high energy gluons. The low energy Cherenkov gluons emitted at rather large angles in the rest system of this nucleus are hard to observe because at LHC they fly backward inside the accelerator pipe (with $|y| \approx 8$, i.e. close to $180^\circ$ in c.m.s.).

The idea about Cherenkov gluons was first used to interpret the cosmic ray event at energy $10^{16}$ eV [4, 31] where two rings more densely populated by particles than their surroundings were noticed. It is demonstrated in Fig. 3 where the number of produced particles is plotted as a function of the distance from the collision point. It clearly shows two maxima. They
correspond to two maxima on the pseudorapidity scale which would arise due to two rings produced. Again, the medium rest system coincides with the target rest system.

This event has been registered in the detector with nuclear and X-ray emulsions during the balloon flight at the altitude about 30 km. The most indefinite characteristics of the event is the height $H$ over the detector at which the interaction took place. However, it can be estimated if one assumes that the two rings observed with radii $r_1 = 1.75$ cm and $r_2 = 5$ cm are produced, correspondingly, by forward and backward moving (in c.m.s.) partons. Using the transformation of angles from target ($t$) to c.m.s. ($c$)

$$\tan \frac{\theta_c}{2} \approx \gamma \theta_t$$

and assuming the symmetry of rings $\theta_{2c} = \pi - \theta_{1c}$, one gets $\theta_{1c} \approx 61^\circ$ and $\gamma \approx 2.3 \cdot 10^3$. The angle in the target rest system is $\theta_{1t} \approx 2.6 \cdot 10^{-4}$ and the height $H = r_1/\theta_{1t} \approx 68$ m. It corresponds rather well to the experimental estimates obtained by three different methods \[35\]. The most reliable of them give values ranging from 50 m to 100 m. Even though the observed angles were quite small in the target rest system, at LHC they would correspond to large c.m.s. angles about 60° - 70°. The peaks in the angular distribution of jets over the background at these angles would be observable \[32, 33\].

The substructure similar to that in Fig. 3 was also found in PbPb-interactions at 158 GeV. The content of peaks of both cosmic ray and PbPb-events was revealed by the wavelet analysis \[36, 37\] of the particle distribution in the plane perpendicular to the axis of collision. Fig. 4 shows the dark regions with large wavelet coefficients corresponding to dense groups of particles in a PbPb-event. There is a tendency for these groups to fill in the two rings. We ascribe them to Cherenkov gluonic rings.

The multiplicities at LHC will be much higher. Therefore the wavelet analysis of very high multiplicity events can be more effective and should be used for search of different patterns like jets, rings, fractality, elliptic flow, higher Fourier coefficients, i.e., in general, for event-by-event studies of the three-dimensional phase space structure. Fig. 4. The two-dimensional ($\eta - \phi$) distribution of particles in a PbPb-event at 158 GeV as revealed by the wavelet analysis.

The problem of the finiteness of the nuclear target was discussed in \[5\].

13
The criterium for the target size $L$ to be considered as infinite is

$$E_t L \Delta n \gg 1 \quad \text{or} \quad L \gg \frac{1}{E_t \Delta n}. \quad (19)$$

It is well fulfilled in the RHIC trigger experiment. Here $\Delta n \approx 2$ and $E_t$ is approximately given by the energy of emitted Cherenkov states. It asks for some care at small $\Delta n$, however.

5 Discussion and conclusions.

One of the most intriguing problems is that the RHIC and cosmic ray data were fitted with very different values of the refractive index equal to 3 and close to 1, correspondingly. This could be interpreted as due to the difference in values of $x$ (the parton share of energy) and $Q^2$ (the transverse momenta). It is well known that the region of large $x$ and $Q^2$ corresponds to the dilute partonic system. At low $x$ and $Q^2$ the density of partons is much higher.

As clearly stated in the PDG report [38], ”the kinematical ranges of fixed-target and collider experiments are complementery, which enables the determination of PDF’s over a wide range in $x$ and $Q^2$“.

At RHIC one deals with rather low $x$ and $Q^2$. One would expect the large density of partons in this region and, therefore, high $n$. It is interesting to note that the two-bump structure disappears in RHIC data at higher $p_t$ where the parton density must get lower. It corresponds to smaller $n$ and $\theta$, i.e. bumps merge in the main away-side peak.

In the cosmic ray event one observes effect due to leading partons with large $x$. Also, the experimentalists pointed out that the transverse momenta in this event are somewhat enlarged [35]. In this region one would expect for low parton density and small $n$.

Thus the same medium can be seen as a liquid or a gas depending on the parton energy and transferred momenta. This statement can be experimentally verified by using triggers positioned at different angles to the collision axis and considering different transverse momenta. In that way, the hadronic Cherenkov effect can be used as a tool to scan $(1/x, Q^2)$-plane and plot on it the parton densities corresponding to its different regions.

The experimental separation of ”mismatched” events with direction of the away-side jet not opposite to the trigger jet can also help in scanning this plane.
The interesting theoretical domain not yet explored is the longitudinal nature of the polarization field responsible for the Cherenkov effect. One can speculate that the non-perturbative string forces become more important than pQCD parton interactions.

To conclude, the predictions about Cherenkov gluons and proposals for their verification are presented. The ring-like structure of events is discussed. The properties of the nuclear medium are determined from the data about the rings. The universal asymmetry of in-medium resonances is described as a signature of Cherenkov gluons. The low- and high-energy effects for different trigger positions and events with away-side jets unaligned to the trigger jet can be used to scan regions with various parton densities.

Acknowledgments
I am grateful to A.V. Leonidov for comments and to V.A. Nechitailo for collaboration. This work has been supported in part by the RFBR grants 06-02-16864, 06-02-17051.

6 Appendix.

The mismatch of jets in trigger experiments.

Let us first consider the experiment where the jet trigger is positioned at $\pi/2$ to the collision axis and registers jets with energy $p_{tr}$. These jets are initiated by scattering of two partons with energies $x_1p$ and $x_2p$. If $x_1 = x_2 = x$, this is the scattering at $\pi/2$ with two jets of equal ($p_{tr} = xp$) and opposite momenta created. There is no mismatch in their emission angles. If $x_1$ differs from $x_2$, such a mismatch appears. For a fixed value of the trigger jet momentum $p_{tr}$, only collisions with a definite relation between the momenta of colliding partons $x_i p$ can initiate such a process.

The energy-momentum conservation requires that

$$x_2 = \frac{x_1 p_{tr}}{2x_1 p - p_{tr}},$$

i.e. a special asymmetry of initial parton momenta is required for this process to proceed. No mismatch case corresponds to $x_1 = x_2 = p_{tr}/p$. As an example of a mismatch, considering $x_1 = 2p_{tr}/p$ one gets $x_2 = 2p_{tr}/3p$. The
momentum of the away-side jet $p_a$ is
\[ p_a = x_1 p - \frac{(x_1 p - p_{tr})p_{tr}}{2x_1 p - p_{tr}}. \] (21)

The angle of its emission determines the angular mismatch
\[ \sin \theta_a = \frac{p_{tr}}{p_a}. \] (22)

For a general case of the trigger positioned at the angle $\theta$ to the collision axis one gets
\[ x_2 = \frac{x_1 p_{tr}(1 - \cos \theta)}{2x_1 p - p_{tr}(1 + \cos \theta)}, \] \[ p_a = x_1 p - \frac{(x_1 p - p_{tr})p_{tr}(1 + \cos \theta)}{2x_1 p - p_{tr}(1 + \cos \theta)}, \] \[ \sin \theta_a = \frac{p_{tr}}{p_a} \sin \theta/p_a. \] (23) (24) (25)

The probability of mismatched jets is lower by a factor $f(x_1)f(x_2)$ where $f$ is pdf.

To conclude, the jet trigger at fixed energy and angle chooses a well defined set of events with mismatched energies of initial colliding partons. It can be used to measure the $x$-dependence of pdfs.

The impact of the mismatched jets on the azimuthal projection of Cherenkov rings can be estimated. In no mismatch case the maximum angle $\Delta \phi_0$ is equal to the cone angle $\theta_c = 1/n$. Using the ratio of the radius of the ring $r_0$ to the distance from the collision vertex $h_0$ one gets
\[ \tan \Delta \phi_0 = \frac{r_0}{h_0} = \tan \theta_c. \] (26)

The ring around the mismatched away-side jet projected on the azimuthal plane is spread up to
\[ \tan \Delta \phi_m = \frac{\tan \Delta \phi_0}{\sin \theta_a} = \frac{p_a \tan \Delta \phi_0}{p_{tr} \sin \theta_a}. \] (27)

The mismatch widens the $\Delta \phi$-distribution of ring projections. These formulas are valid for $\theta_a \geq \theta_c$, i.e. for comparatively small mismatch. For strongly different $x_1$ and $x_2$ the part of the cone can even enter the opposite hemisphere (if $\theta_c \geq \theta_a$). However the diminished probability of the mismatched
jets and the decreased intensity of the projection due to the turned by the angle $\theta_a$ ring should reduce the influence of this shift.

Let us consider two examples of mismatch for the $\pi/2$-trigger.

For $x_1 = 2p_{tr}/p$ one gets $x_2 = 2p_{tr}/3p$, $p_a = 5p_{tr}/3$, $\sin \theta_a = 0.6$, $f(x_1)f(x_2) = 0.75^{1.3} \approx 0.688$ for $f(x) \propto x^{-1.3}$. If $\Delta \phi_0 = \pi/4$, widened $\Delta \phi_m = 1.03$, i.e. $59^o$ instead $45^o$. If $\Delta \phi_0 = \pi/3$, widened $\Delta \phi_m = 1.237$, i.e. $71^o$ instead $60^o$.

For $x_1 = 3p_{tr}/p$ one gets $x_2 = 0.6p_{tr}/p$, $p_a = 2.6p_{tr}$, $\sin \theta_a = 5/13$, $f(x_1)f(x_2) = (5/9)^{1.3} \approx 0.466$ for $f(x) \propto x^{-1.3}$. If $\Delta \phi_0 = \pi/4$, widened $\Delta \phi_m = 1.2$, i.e. $69^o$ instead $45^o$. If $\Delta \phi_0 = \pi/3$, widened $\Delta \phi_m = 1.352$, i.e. $77.5^o$ instead $60^o$.

For RHIC trigger with $p_{tr} = 5$ GeV, the mismatched initial partons in the above examples have energies $p_1 = 10$ GeV, $p_2 = 3.33$ GeV and $p_1 = 15$ GeV, $p_2 = 3$ GeV, correspondingly.

If the angular shifts are boldly weighted by corresponding $f(x_1)f(x_2)$, one gets the shifts from $45^o$ to $54.7^o$ and from $60^o$ to $67.3^o$.

Thus, the account of mismatched jets can somewhat reduce the estimate of $n$ (and, therefore, the parton density) obtained without it but not very strongly according to the above values of angular shifts.

**Figure captions.**

Fig. 1. The $\Delta \phi$-distribution of particles produced by trigger and companion jets at RHIC [13] shows two peaks in $pp$ and three peaks in AuAu-collisions (two of them are on the away side).

Fig. 2. Excess dilepton mass spectrum in semi-central In-In collisions at 158 AGeV (NA60 data are shown by dots) compared to the in-medium $\rho$-meson peak with additional Cherenkov effect (the dashed line).

Fig. 3. The dependence of the number of produced hadrons on the distance from the collision point in the cosmic ray event.

Fig. 4. The two-dimensional ($\eta - \phi$) distribution of particles in a PbPb-event at 158 GeV as revealed by the wavelet analysis.
References

[1] P.A. Cherenkov, Doklady AN SSSR 2 (1934) 451; 3 (1936) 413.
[2] I.E. Tamm, I.M. Frank, Doklady AN SSSR 14 (1937) 109.
[3] I.E. Tamm, J. Phys. USSR 1 (1939) 439.
[4] I.M. Dremin, JETP Lett. 30 (1979) 140.
[5] I.M. Dremin, Sov. J. Nucl. Phys. 33 (1981) 726.
[6] I.M. Dremin, Nucl. Phys. A767 (2006) 233.
[7] A. Majumder, X.N. Wang, Phys. Rev. C73 (2006) 051901.
[8] V. Koch, A. Majumder, X.N. Wang, Phys. Rev. Lett. 96 (2006) 172302.
[9] I.M. Dremin, Nucl. Phys. A785 (2007) 369.
[10] I.M. Dremin, J. Phys. G34 (2007) N9.
[11] M. Goldberger, K. Watson, Collision Theory (John Wiley and Sons Inc., 1964) Ch. 11, sect. 3, sect. 4.
[12] R.P. Feynman, R.B. Leighton, M. Sands, The Feynman Lectures in Physics (Addison-Wesley PC Inc., 1963) vol. 1, ch. 31.
[13] J. Adams et al (STAR), Phys. Rev. Lett. 95 (2005) 152301.
[14] S.S. Adler et al (PHENIX), Phys. Rev. Lett. 97 (2006) 052301.
[15] A. Adare et al (PHENIX), LANL arXiv 0705.3238.
[16] J. Jia, LANL arXiv 0705.3060.
[17] J.V. Jelley, Cherenkov radiation and its applications (Pergamon Press, 1958), p. 13.
[18] J.G. Ulery (STAR), Nucl. Phys. A783, 511 (2007); C.A. Pruneau (STAR), nucl-ex/0703006 0703007.
[19] I.M. Dremin, V.A. Nechitailo, hep-ph/0704.1081.
[20] R. Arnaldi et al (NA60), Phys. Rev. Lett. 96 (2006) 162302;
    S. Damjanovic et al (NA60), Eur. Phys. J. C49 (2007) 235,
    nucl-ex/0609026 and Nucl. Phys. A783 (2007) 327, nucl-ex/0701015
[21] G. Agakichiev et al (CERES), Phys. Rev. Lett. 75 (1995) 1272;
    Phys. Lett. B422 (1998) 405; Eur. Phys. J. C41 (2005) 475.
[22] D. Adamova et al (CERES), Phys. Rev Lett. 91 (2003) 042301; 96 (2006)
    152301; nucl-ex/0611022.
[23] S. Damjanovic et al (NA60), Phys. Rev. Lett. 96 (2006) 162302.
[24] D. Trnka et al Phys. Rev. Lett. 94 (2005) 192303.
[25] M. Naruki et al (KEK), Phys. Rev. Lett. 96 (2006) 092301,
    nucl-ex/0504016.
[26] R. Muto et al (KEK), Phys. Rev. Lett. 98 (2007) 042501,
    nucl-ex/0511019.
[27] A. Kozlov (PHENIX), nucl-ex/0611025
[28] M. Kotulla (CBELSA/TAPS), nucl-ex/0609012.
[29] I. Tserruya, Nucl. Phys. A774 (2006) 415.
[30] S. Kniege, M. Ploskon, nucl-ex/0703008.
[31] A.V. Apanasenko et al, JETP Lett. 30 (1979) 145.
[32] N.M. Agababyan et al (NA22), Phys. Lett. B389 (1996) 397.
[33] I.M. Dremin, L.I. Sarycheva, K.Yu. Teplov, Eur. Phys. J. C46 (2006)
    429.
[34] L.M. Satarov, H. Stoecker, I.N. Mishustin, Phys. Lett. B627 (2005) 64.
[35] A.K. Managadze et al, Proc. XXIX RCRC, HE-02, Moscow, 2006; Phys.
    Atom. Nucl. (2006).
[36] N.M. Astafyeva, I.M. Dremin, K.A. Kotelnikov, Mod. Phys. Lett. A12
    (1997) 1185.
[37] I.M. Dremin et al, Phys. Lett. B499 (2001) 97.

[38] Particle Data Group, J. Phys. G33 (2006) 184.
This figure "fig1a.png" is available in "png" format from:

http://arXiv.org/ps/0706.0596v2
This figure "fig2a.png" is available in "png" format from:

http://arXiv.org/ps/0706.0596v2
This figure "fig3a.png" is available in "png" format from:

http://arXiv.org/ps/0706.0596v2
This figure "fig4a.JPG" is available in "JPG" format from:

http://arXiv.org/ps/0706.0596v2