Cherenkov gluons at RHIC and LHC

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The coherent hadron production analogous to Cherenkov radiation of photons gives rise to the ring-like events.

1. Being projected on the ring diameter they produce the two-bump structure 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 index of refraction, the parton density, the free path length and the energy loss of Cherenkov gluons.

2. 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.

Analogous to Cherenkov photons, the Cherenkov gluons can be emitted in hadronic collisions provided the nuclear index of refraction n exceeds 1. The partons moving in such nuclear medium would emit them. These gluons should be emitted at the cone surface with the cone angle θ in the **rest system** of the **infinite** medium defined by the relation

$$\cos\theta = \frac{1}{\beta n}, \tag{1}$$

The ring-like distribution of particles must be observed in the plane perpendicular to the momentum of the parton-emitter.

RHIC

RHIC experiments have shown the two-bump structure of the azimuthal angle distribution near the away-side jet axis. This angle is determined as the angle of the projection of the momentum of any particle to the trigger jet axis in the plane (let call it as the plane 1) formed by the momenta of the initial colliding nuclei and of the trigger jet axis. Particles emitted on the Cherenkov cone around the away-side jet form the ring in the plane 2 perpendicular to the away-side jet axis and to the plane 1. The ring projected on plane 1 results in two peaks observed at RHIC. Unfortunately, there is no direct observation of the two-dimensional distribution of particle positions in the plane 2 which should have pronounced ring-like structure over the more smooth background. The studied two- and three-particle correlations are its indirect indications.

LEG

The distance between the peaks defined in angular variables determines according to Eq. (1) the nuclear index of refraction. Its value is quite large $n = 3$ compared to usual electromagnetic values close to 1. If interpreted in terms of the Breit-Wigner resonances, it results in the large density of partons in the created quark-gluon system with about **30 partons** within the volume of a single nucleon. The energy loss of gluons is $dE/dx \approx 1$ GeV/Fm. The height of the peaks determines the width of the ring. In its turn it defines the free path length of Cherenkov gluons which is long enough $R_f \sim 7$ Fm.

These estimates are obtained using the relation of the index of refraction to the forward scattering amplitude

$$\mathrm{Re}n(E) = 1 + \Delta n_R = 1 + \frac{3m_\pi^3\nu}{8\pi E}\sigma(E)\rho(E). \tag{2}$$

Here E denotes the energy, ν is the number of scatterers within a single nucleon, m_π the pion mass, σ the cross section and ρ the ratio of real to imaginary parts of the forward scattering amplitude. Thus the emission of Cherenkov gluons is possible only for processes with positive ρ.

This requirement is fulfilled within one of the wings of any Breit-Wigner resonance. Gluons with wide energy spectrum are emitted during the collision. However only those which can form a resonance (e.g., ρ-meson) with the thermalized (or any other) gluons of the medium satisfy the requirement of being superluminal. That is why the two-bump structure disappears for away-side jet particles with somewhat higher momenta. Inserting the Breit-Wigner shapes in Eq. (2) one gets

$$\mathrm{Re}\,n(E) = 1 + \frac{2J+1}{(2s_1+1)(2s_2+1)}\frac{3m_\pi^3\Gamma_R\nu}{EE_R^2}\frac{E_R-E}{(E-E_R)^2+\Gamma_R^2/4}. \tag{3}$$

Here J, s_1, s_2 are spins of the resonance and its decay products, E_R, Γ_R are its position and width. The estimates of parton density ν follow from this expression for n.

Thus one obtains knowledge about such crucial properties of the hadronic medium as its index of nuclear refraction n, density of partons ν, free path length R_f and energy loss

dE/dx. The unusual particle content within the ring is predicted. According to Eq. (3), the resonances will have somewhat peculiar properties with masses and widths shifted to smaller values when reconstructed from their decay products. Let us stress that we do not require ρ-mesons or other resonances pre-exist in the medium but imply that they are formed during the hadronization process.

The Cherenkov emission is a collective response of the medium to the perturbations initiated by the incoming particle. Here, it would imply the collective reaction of the quark-gluon medium to the impinging partons. They are determined by the energy behavior of the second term in Eq. (3).

HEG and LHC

The Cherenkov gluons discussed above are rather low energy ones and coalesce to resonances. They originate from those regions of positive real part of the forward scattering amplitude which are bound within the resonances. However, from dispersion relation predictions and experiments with various colliding hadrons we know that there exists the high energy region of hadronic reactions where the real part of the forward scattering amplitude (or, equivalently, its ratio to the imaginary part $\rho(E)$) is positive for all colliding partners. In general, it happens at energy exceeding 70 - 100 GeV in the target rest system. Considering it as a common property of hadronic reactions, we hope that the same happens with high energy gluons.

There are no gluons with such energy at RHIC but they will become available at LHC. Namely such gluons were discussed in connection with the cosmic ray event at energy 10^{16} eV (in the target rest system) with the ring-like structure first observed. This energy just corresponds to LHC energies. The partons emitting such gluons move with high energy in the forward direction. The corresponding index of refraction can be fitted by the formula

$$\Delta n_R(E) \approx \frac{a\nu_h}{E}\theta(E-E_{th}) \qquad (4)$$

above some threshold energy E_{th} about 70 - 100 GeV at target rest system. Here, $a \approx 2 \cdot 10^{-3}$ GeV is a fitted parameter of Re$F(E)$ and ν_h is the parton density for high energy region. It can differ from ν used in the low energy region. The index of refraction is small and decreases with energy. Nevertheless the angles of the cone emission in c.m.s. of LHC experiments must be very large (about 60^o - 70^o), i.e. the peaks can be seen in the pionization region at central pseudorapidities. Some methods to separate the particles in the cone from the background were proposed.

The main difference between the trigger experiments at RHIC and this no-trigger experiment is in the treatment of the rest system of the medium. All the above formulas are valid for emission in the rest system of the medium. At RHIC, the 90^o 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. It is interesting to measure the cone angles for different angular positions of the trigger to reveal the medium motion. For 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 at that system and then transformed to the c.m.s. That is why these angles are so large even at smaller values of the refractivity index for high energy partons.