CHERENKOV GLUONS
(predictions and proposals)

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Heavy ion collisions at the LHC
Last call for predictions
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PREHISTORY (1904 - 10 - 26).

HISTORY:

a) photons (34 - 37 - 39).

Transverse Bremsstrahlung vs longitudinal Cherenkov.
Incoherent vs coherent.

b) mesons (49 ...).

c) gluons (79 ...).
THE GENERAL RELATION

$$\Delta n = \text{Re} n - 1 = 8\pi N_s \text{Re} F(E, 0^\circ) / E^2.$$  

$N_s$ - the density of scattering centers; $E^2 = s$.

Necessary condition $\Delta n > 0$ or $\text{Re} F(E, 0^\circ) > 0$.

Hadronic amplitudes:
Low energies - resonances;
High energies - experiment + dispersion relations; threshold.
SCENARIO:

Emitted gluon affects the medium as an "effective" wave which accounts also for the waves emitted by other scattering centers. Beside incoherent scattering, there are collective processes which can be described as the refraction of the initial wave along the path of the coherent wave. The Cherenkov effect is the induced coherent radiation by a set of scattering centers positioned on the way of propagation of the gluon.
• **Rings around the ”low”-energy partons - trigger experiments;**

• **The low-mass dilepton excess;**
  ID, V.A. Nechitailo, hep-ph/0704.1081

• **Rings around the high-energy partons - non-trigger experiments.**
Coherent Cherenkov emission is along the conical surface with the cone angle $\theta_c$ to the momentum of the parton-emitter in the rest system of the infinite medium:

$$\cos \theta_c = \frac{1}{\beta n}. \quad (1)$$

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

Cherenkov rings in the plane perpendicular to the parton momentum with radius equal to $\theta_c$. 
Prediction 1. According to Eq. (1) the ring-like two-dimensional distribution of particles must be observed in the plane perpendicular to the momentum of the parton.

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. It should have maximum at (1).
This plot is still unavailable at RHIC.

RHIC experiments have shown the two-bump structure of the azimuthal angle distribution (now with z-axis chosen along the collision axis) near the away-side jets in central heavy-ion collisions.

This is the projection of the ring on its diameter.

Also - the 3-particle correlations indicate on the ring-like structure.
The $\phi$-distribution of particles produced by trigger and companion jets at RHIC shows two peaks in $pp$ and three peaks in AuAu-collisions.
THE NUCLEAR MEDIUM PROPERTIES

1. The refractive index;
2. The density of partons;
3. The energy loss of Cherenkov gluons;
4. The free path length of gluons.
$n \approx 3$ from the distance between the peaks using (1),

$\nu \approx 20$ from averaged (2), LIQUID (!?)

$$\text{Re}n(E) = 1 + \frac{2J + 1}{(2s_1 + 1)(2s_2 + 1)} \cdot \frac{6m_\pi^3 \Gamma_R \nu}{E_R^2} \cdot \frac{E_R - E}{E[(E - E_R)^2 + \Gamma_R^2/4]}$$ (2)

$$\frac{dE}{dx} = 4\pi \alpha_S \int_{E_R - \Gamma_R}^{E_R} E \left(1 - \frac{1}{n^2(E)}\right) dE \approx 1\text{GeV/fm}.$$

$R_f > 20/E_R \sim 4.5/m_\pi \sim 7 \cdot 10^{-13}\text{cm.}$

from the width of the ring.
THE LOW-MASS DILEPTON EXCESS

Prediction 2. According to Eq. (2) the Cherenkov states formed within the ring have masses less than $m_R$ that leads to the asymmetry of decay spectra of resonances with substantial contribution of low masses.

Proposal 2. Plot the distribution of masses of $\pi^+\pi^-$, $\mu^+\mu^-$ or $e^+e^-$-pairs near resonance peaks.
The excess of $n$ over 1 in the left wing of any Breit-Wigner resonance leads to Cherenkov gluons and excess of low-mass lepton pairs.

$$
\frac{dN}{dM} = \frac{A}{(m_\rho^2 - M^2)^2 + M^2 \Gamma^2} \left( 1 + w \frac{m_\rho^2 - M^2}{M^2} \theta(m_\rho - M) \right)
$$

where

$$
\Delta n = \frac{N_s}{\Gamma} \sigma_{BW} \frac{m_R^2 - M^2}{M^2}.
$$

(3)
Excess dilepton mass spectrum in semi-central In-In collisions at 158 AGeV (dots - NA60 data) compared to the in-medium $\rho$-meson peak with additional Cherenkov effect (dashed line).
MEASURE:
1. the angular distribution of the lepton pairs with different masses.
2. the average mass of lepton pairs as a function of their polar emission angle (pseudorapidity).

The transverse momenta distribution - lower $p_T$ for coherent processes at low masses than for incoherent scattering at larger masses.

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 (NA60).
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.

KEK - $\rho$, $\omega$ and $\phi$.

CBELSA/TAPS - $\omega$.

RHIC - indications for $J/\psi$-meson.
For the sake of simplicity, Eqs. valid at small $\Delta n$ typical for gases are used. The value $n = 3$ corresponds to a dense liquid. Therefore, one must use the Lorenz-Lorentz formula

$$\frac{n^2 - 1}{n^2 + 2} = \frac{m^3 \nu \alpha}{4\pi} =$$

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

where $\alpha$ denotes the color polarizability of the color-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.
THE HIGH-ENERGY PARTONS

Prediction 3. Very high energy forward moving partons can emit high energy Cherenkov gluons producing jets.

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. (1).
Processes with gluons of such energy at RHIC would ask for the event-by-event analysis. They are rare and rings are concentrated at the central rapidities where the background is high. They will become more abundant at the LHC.

\[
\Delta n_R(E_t) \approx \frac{a_{\nu h}}{E_t} \theta(E_t - E_{th}).
\]

\[E_{th} \sim 100 \text{ GeV} \text{ in the target rest system.}\]

GAS (!?)

Maximum \( \Delta n \) at \( E_{t,p} \approx 1 \text{ TeV} \). \( x_p \sim 10^{-4} - 10^{-5} \).
The distribution of produced particles in the stratospheric event at $10^{16}$ eV as a function of the distance from the collision axis (pseudorapidity) has two pronounced peaks.
The two rings with radii $r_1 = 1.75$ cm and $r_2 = 5$ cm are produced by forward and backward moving (in c.m.s.) partons. The transformation of angles from target ($t$) to c.m.s. ($c$)

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

The ratio

$$\frac{\theta_{1t}}{\theta_{2t}} = \frac{r_1}{r_2} = \frac{\tan \theta_{1c}/2}{\tan \theta_{2c}/2} = 0.35.$$

The symmetry of rings $\theta_{2c} = \pi - \theta_{1c}$ gives $\theta_{1c} \approx 61^\circ$ and $\gamma \approx 2.3 \cdot 10^3$, i.e. $E_t \approx 10^{16}$ eV (LHC!).
The target rest system angle 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 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 $60^\circ - 70^\circ$.
Proposal 4. Use triggers at different angular positions.

Different rest systems and transverse momenta $(x, Q^2)$ - different $\cos \theta_c$ - different $n$ - different $N_s$.

Scan $(1/x, Q^2)$-plane by plotting the observed density of scatterers $N_s$.  

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The two-dimensional $(\eta - \phi)$ plot of the wavelet coefficients at scale $j = 5$ obtained from analysis of PbPb event at 158 GeV. Dark regions denote large values of wavelet coefficients, i.e. strongly correlated groups of particles. The ring regions $1.8 < \eta < 2.3$ and $2.7 < \eta < 3.0$ correspond to peaks of the pseudorapidity distribution. $\eta = 2.5$ is equivalent to c.m.s. angle $\pi/2$. The dots indicate particle positions.
Proposal 5. Do the event-by-event wavelet analysis - the "tomography" of the phase space.

Rings; $v_2$, $v_4$ etc as "cucumbers", "flowers" ...; others (?)