QCD in the Nuclear Matter and Cherenkov gluons

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INTRODUCTION

- COLLECTIVE EFFECTS IN AA-COLLISIONS
- J/Ψ-suppression, v_2, jet quenching, Cherenkov gluons etc
- QGP — sQGP — liquid — pQCD — classical solutions of in-vacuum eqs — hydrodynamics
- collective excitations – external current – nuclear permittivity (QED analogy) – gluodynamics
- classical lowest order solutions – Cherenkov gluons as quasiparticles=quanta of medium excitations
- experimental data
- rest system – impact on experimental installations

Classical in-vacuum Yang-Mills equations

$$D_\mu F^{\mu\nu} = J^\nu,$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu - ig[A^\mu, A^\nu],$$

$$D_\mu = \partial_\mu - ig[A_\mu, \cdot], \quad J^\nu(\rho, \mathbf{j}).$$

In the covariant gauge $\partial_\mu A^\mu = 0$ they are

$$\Box A^\mu = J^\mu + ig[A_\nu, \partial^\nu A^\mu + F^{\mu\nu}],$$

where $\Box$ is the d'Alembertian operator.

Classical gluon field=solution of Abelian problem; no real gluons produced, i.e. no radiation in forward light-cone in lowest order

Chromoelectric and chromomagnetic fields

$$E^{\mu} = F^{\mu 0},$$
$$B^{\mu} = -\frac{1}{2}\epsilon^{\mu ij} F^{ij}.$$

For gauge potentials in vector notations

$$\mathbf{E}_a = -\mathrm{grad}\Phi_a - \frac{\partial \mathbf{A}_a}{\partial t} + g f_{abc} \mathbf{A}_b \Phi_c,$$
$$\mathbf{B}_a = \mathrm{curl}\mathbf{A}_a - \frac{1}{2} g f_{abc} [\mathbf{A}_b \mathbf{A}_c].$$

Equations of motion in vector form

$$\mathrm{div}\mathbf{E}_a - g f_{abc} \mathbf{A}_b \mathbf{E}_c = \rho_a,$$
$$\mathrm{curl}\mathbf{B}_a - \frac{\partial \mathbf{E}_a}{\partial t} - g f_{abc} (\Phi_b \mathbf{E}_c + [\mathbf{A}_b \mathbf{B}_c]) = \mathbf{j}_a.$$

IN-MEDIUM ELECTRODYNAMICS

$$\triangle \mathbf{A} - \epsilon \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mathbf{j},$$

$$\epsilon(\triangle \Phi - \epsilon \frac{\partial^2 \Phi}{\partial t^2}) = -\rho.$$

The permittivity = the matter response to the induced fields due to internal current sources in the medium.

$(\rho, \mathbf{j})$ - external current sources.

Lorentz gauge condition is

$$\mathrm{div}\mathbf{A} + \epsilon \frac{\partial \Phi}{\partial t} = 0.$$

N.B.! - RADIATION for $\epsilon \neq 1$.

IN-MEDIUM GLUODYNAMICS

I.D., Eur. Phys. J. C **56** (2008) 81; arXiv:0802.4022

1. Introduce the nuclear permittivity, denote it also by ϵ.
2. Replace $\mathbf{E}_a$ by $\epsilon\mathbf{E}_a$.
For fields

$$\epsilon(\mathrm{div}\mathbf{E}_a - gf_{abc}\mathbf{A}_b\mathbf{E}_c) = \rho_a,$$

$$\mathrm{curl}\mathbf{B}_a - \epsilon\frac{\partial\mathbf{E}_a}{\partial t} - gf_{abc}(\epsilon\Phi_b\mathbf{E}_c + [\mathbf{A}_b\mathbf{B}_c]) = \mathbf{j}_a.$$

For potentials

$$\triangle \mathbf{A}_a - \epsilon \frac{\partial^2 \mathbf{A}_a}{\partial t^2} = -\mathbf{j}_a - g f_{abc}(\frac{1}{2}\mathrm{curl}[\mathbf{A}_b, \mathbf{A}_c] + \frac{\partial}{\partial t}(\mathbf{A}_b \Phi_c) + \frac{1}{2}[\mathbf{A}_b \mathrm{curl} \mathbf{A}_c] - \epsilon \Phi_b \frac{\partial \mathbf{A}_c}{\partial t} - \epsilon \Phi_b \mathrm{grad} \Phi_c - \frac{1}{2} g f_{cmn}[\mathbf{A}_b[\mathbf{A}_m \mathbf{A}_n]] + g \epsilon f_{cmn} \Phi_b \mathbf{A}_m \Phi_n),$$

$$\triangle \Phi_a - \epsilon \frac{\partial^2 \Phi_a}{\partial t^2} = -\frac{\rho_a}{\epsilon} + g f_{abc}(2\mathbf{A}_b \mathrm{grad} \Phi_c + \mathbf{A}_b \frac{\partial \mathbf{A}_c}{\partial t} - \epsilon \frac{\partial \Phi_b}{\partial t} \Phi_c) + g^2 f_{amn} f_{nlb} \mathbf{A}_m \mathbf{A}_l \Phi_b.$$

$A \propto J \propto g$, **higher order corrections** $\propto g^3$

Cherenkov gluons as a classical solution

Phase and coherence length

$$\Delta\phi = \omega\Delta t - k\Delta z\cos\theta = k\Delta z\left(\frac{1}{v\sqrt{\epsilon}} - \cos\theta\right).$$

For Cherenkov effects

$$\cos\theta = \frac{1}{v\sqrt{\epsilon}}.$$

Coherence $\Delta\phi = 0$ independent of Δz.

Specific for Cherenkov radiation only.

The external current

$$\mathbf{j}(\mathbf{r},t) = \mathbf{v}\rho(\mathbf{r},t) = 4\pi g\mathbf{v}\delta(\mathbf{r}-\mathbf{v}t).$$

$$\mathbf{A}^{(1)}(\mathbf{r},t) = \epsilon\mathbf{v}\Phi^{(1)}(\mathbf{r},t).$$

$$\Phi^{(1)}(\mathbf{r},t) = \frac{g}{2\pi^2\epsilon}\int d^3k \frac{\exp[i\mathbf{k}(\mathbf{r}-\mathbf{v}t)]}{k^2-\epsilon(\mathbf{kv})^2}.$$

Cylindrical coordinates:

$d\phi \rightarrow J_0(k_\perp r_\perp),\ dk_z \rightarrow$**poles,**

$\int dk_\perp J_0 \sin(k_\perp ...) \rightarrow \theta$.

$$\Phi^{(1)}(\mathbf{r},t) = \frac{2g}{\epsilon}\frac{\theta(vt-z-r_\perp\sqrt{\epsilon v^2-1})}{\sqrt{(vt-z)^2-r_\perp^2(\epsilon v^2-1)}}.$$

Cone

$$z = vt - r_\perp\sqrt{\epsilon v^2-1}.$$

Poynting vector

$$S_x = -S_z \frac{(z - vt)x}{r_\perp^2},\ S_y = -S_z \frac{(z - vt)y}{r_\perp^2}.$$

Cherenkov angle

$$\tan^2 \theta = \frac{S_x^2 + S_y^2}{S_z^2} = \epsilon v^2 - 1.$$

The intensity

$$\frac{dW}{dl} = 4\pi\alpha_S \int \omega d\omega (1 - \frac{1}{v^2 \epsilon}).$$

The dispersion and imaginary part of $\epsilon(\omega, \mathbf{q}) = \epsilon_1(\omega, \mathbf{q}) + i\epsilon_2(\omega, \mathbf{q})$.

Energy loss

$$\frac{dW}{dl} = -gE_z,$$

First order:

$$\Phi_a^{(1)}(k) = 2\pi g Q_a \frac{\delta(\omega - kv\zeta)v^2\zeta^2}{\omega^2\epsilon(\epsilon v^2\zeta^2 - 1)},$$

$$A_{z,a}^{(1)}(k) = \epsilon v \Phi_a^{(1)}(k),$$

$$E_z^{(1)} = i\int \frac{d^4k}{(2\pi)^4}[\omega A_z^{(1)}(\mathbf{k},\omega) - k_z\Phi^{(1)}(\mathbf{k},\omega)]e^{i(\mathbf{kv}-\omega)t},$$

$$\frac{dW_a^{(1)}}{dld\zeta d\omega} = \frac{g^2\omega}{2\pi^2 v^2\zeta}\mathrm{Im}\left(\frac{v^2(1-\zeta^2)}{1-\epsilon v^2\zeta^2} - \frac{1}{\epsilon}\right),$$

$$\zeta = \cos\theta, \quad x = \zeta^2, \quad \nu = \epsilon_2/\epsilon_1, \quad x_0 = \epsilon_1/|\epsilon|^2 v^2,$$

$$\frac{dN^{(1)}}{dldxd\omega} = \frac{dW_a^{(1)}}{\omega dldxd\omega} = \frac{\alpha_S C}{\pi}\left[\frac{(1-x)\nu x_0}{(x-x_0)^2 + (\nu x_0)^2}\right],$$

The nuclear permittivity

$$\epsilon = n^2.$$

The refractive index of water (see Fig.).

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

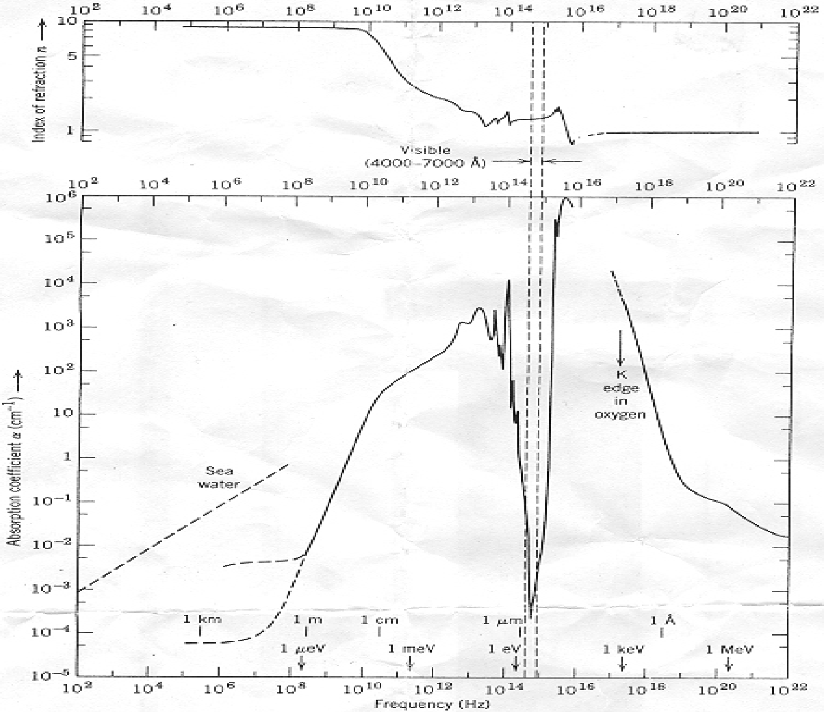
N_s - the density of scattering centers.

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

Hadronic amplitudes: Low energies - resonances; high energies - experimental data+dispersion relations; threshold.

The definition of the rest system for trigger and non-trigger experiments.

ϵ can be calculated if Vlasov QCD-equation is known.


Index of refraction n
Visible
(4000–7000 Å)
Absorption coefficient α (cm⁻¹)
Sea
water
K
edge
in
oxygen
1 km
1 m
1 cm
1 μm
1 Å
1 μeV
1 meV
1 eV
1 keV
1 MeV
Frequency (Hz)

Predicted experimental effects.

- **Rings around the high-energy partons - non-trigger experiments:**
  I.D., JETP Lett. **30** (1979) 140; Sov. J. Nucl. Phys. **33** (1981) 726.
- **Rings around the low-energy partons - trigger experiments:**
  I.D., Nucl. Phys. A**767** (2006) 233; A**785** (2007) 369.
  A. Majumder, X.N. Wang, Phys. Rev. C**73** (2006) 172302.
  V. Koch et al, Phys. Rev. Lett. **96** (2006) 172302.
  I.D., M.R. Kirakosyan, A.V. Leonidov, A.V. Vinogradov, Nucl. Phys. A **825** (2009); arXiv:0809.2472.
- **The low-mass dilepton excess:**
  I.D., V.A. Nechitailo, Int. J. Mod. Phys. A **24** (2009) 1221; hep-ph/0704.1081

Reviews:

I.D., Int. J. Mod. Phys. A**22** (2007) 1;
I.D., Phys. Atom. Nucl. (July 2009 issue).

THE NUCLEAR MEDIUM PROPERTIES

1. The refractive index; $|n| \approx 2 - 3$
2. The density of partons; $N_s \approx 20$ per nucleon
3. The energy loss of Cherenkov gluons; about 0.1 – 1 GeV/fm
4. The free path length of gluons; several fm.

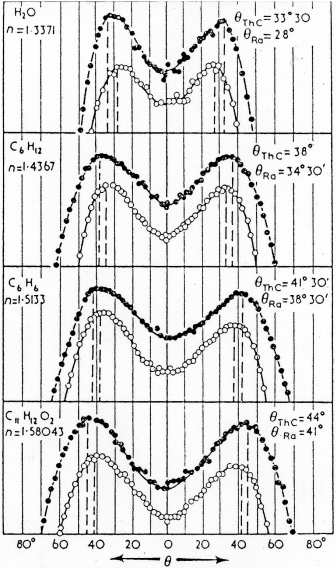
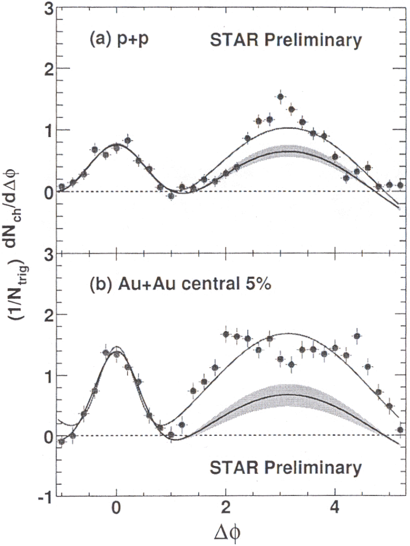
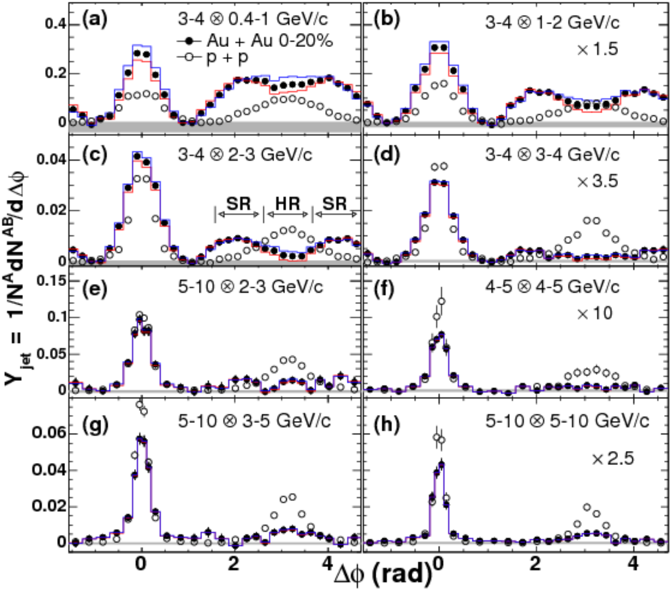


FIG. 1.8. The variation of θ with n, for two different sources of γ-rays. (Čerenkov, 1937d and 1938c.)

The Figure is from the book of J. Jelley "Cherenkov radiation and its applications 1958

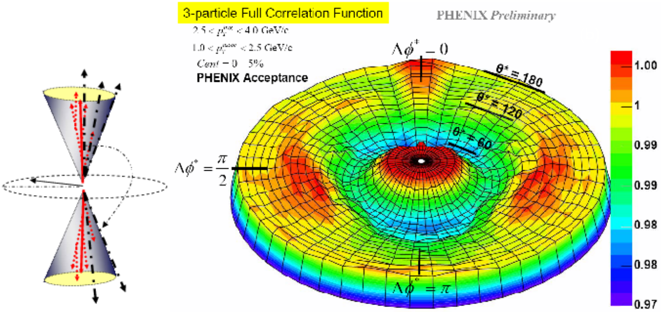


The $\Delta\phi$-distribution of particles produced by trigger and companion jets at RHIC shows two peaks in *pp* and three peaks in AuAu-collisions.



(A. Adare et al for PHENIX collaboration, arXiv0705.3238)
Per-trigger yield versus $\Delta\phi$ in *pp* and Au-Au collisions.

The 3-particle correlations reveal clearly the ring-like structure around the away-side jet.



(N.N. Ajitanand for PHENIX Collaboration, nucl-ex/0609038)

Coordinate system (left) and full 3-particle correlation surface for charged hadrons in central Au+Au collisions at RHIC.

COMPLEX $\epsilon = \epsilon_1 + i\epsilon_2$

The angular δ-function $\rightarrow$ a'la BW-shape.
Using the relation of θ with the lab angles $\cos\theta = |\sin\theta_L \cos\phi_L|$ and integrating over θ_L , one gets (quite lengthy) analytical expression for the measured (ϕ_L)-distribution (two-hump structure!).

I.D., M.R. Kirakosyan, A.V. Leonidov, A.V. Vinogradov, Nucl. Phys. A **825** (2009); arXiv:0809.2472

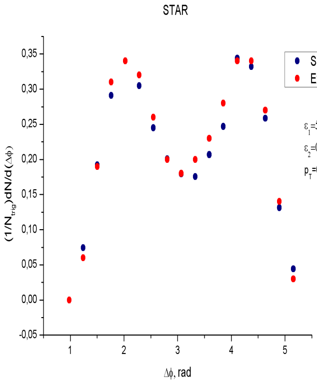
1. PYTHIA for initial partons
2. Cherenkov angular distribution of gluons
3. the gluon fragmentation function to pions (LEP) with gaussian suppression of transverse momenta $\propto \exp(-p_t^2/2\Delta_\perp^2)$

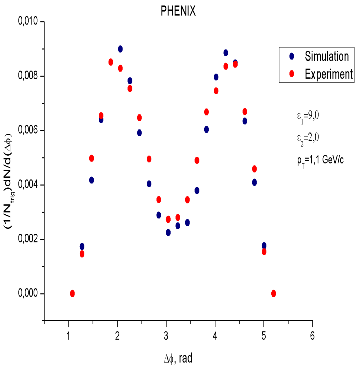
we get the reasonable fits of experimental data with three parameters $(\epsilon_1, \epsilon_2, \Delta_\perp)$

Table 1

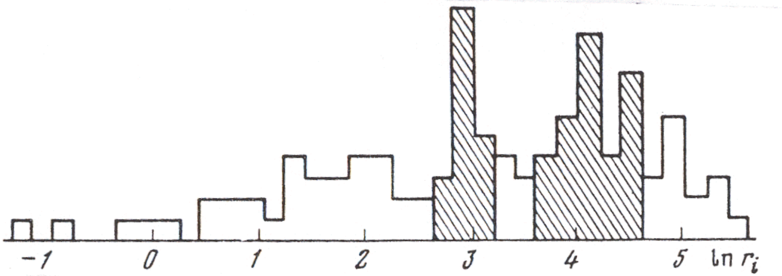
Experiment	$\theta_{\max}$	ε_1	ε_2	$\Delta_\perp$, GeV/c
STAR	1.04 rad	5.4	0.7	0.7
PHENIX	1.27 rad	9.0	2.0	1.1

NOTE: $(\epsilon_2/\epsilon_1)^2 \leq 0.05 \ll 1$





COSMIC RAY EVENTS and SPS DATA



The distribution of produced particles in the stratospheric event (1979) at 10^{16} eV as a function of the distance from the collision axis (pseudorapidity) has two pronounced peaks.

SPS DATA

$\Delta n \ll 1$

Prediction of forward rings at LHC.

Shape-asymmetry of in-medium resonances

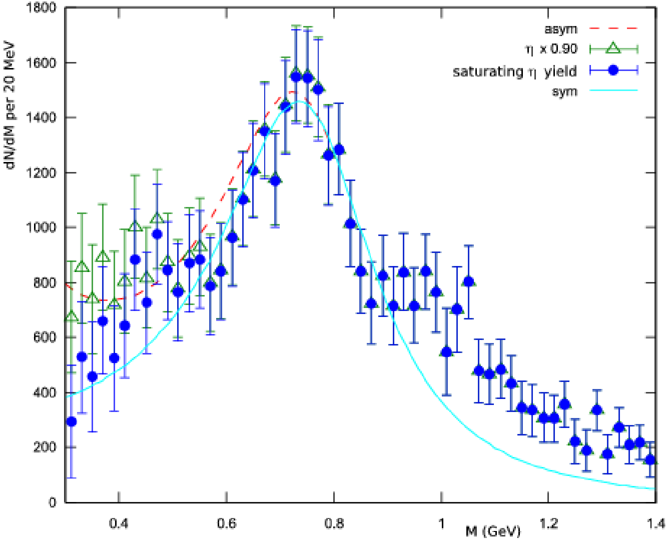
I.D., V.A. Nechitailo, Int. J. Mod. Phys. A **24** (2009) 1221; arXiv: hep-ph/ 0704.1081

$$\Delta n = \mathrm{Re}\, n - 1 = 2\pi N \mathrm{Re} F(E, 0^o)/E^2 \propto \frac{m_\rho^2 - M^2}{M\Gamma}\theta(m_\rho^2 - M^2).$$

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

M is the total c.m.s. energy of two colliding objects (the dilepton mass), m_ρ=775 MeV is the in-vacuum ρ-meson mass. The second term is proportional to $\mathrm{Re} F(E, 0^o)$.

Universal prediction for ALL in-medium resonances!



Excess dilepton mass spectrum in semi-central In-In collisions at 158 AGeV (dots - NA60 data) compared to the in-medium ρ-meson peak with additional Cherenkov effect (dashed line).