MACROSCOPIC QCD AND QUARK-GLUON PLASMA

I.M. DREMIN

Lebedev Physical Institute

Quarks-2010, 7 June 2010

EXPERIMENT - AA $\neq$ sum of independent pp
THEORY - notion of QGP (asks for in-medium QCD)

Electrodynamics - in-vacuum (LL II); in-medium (LL VIII)

MICRO- and MACRO-APPROACHES

Main experimental tests - energy losses of charged probes (e^-, partons) in the medium (ED-plasma or QGP)
Micro - CGC, Glasma, QGP + medium impact on a probe
Macro - collective medium excitations induced by a probe

Micro - **v** changes - scattering, bremsstrahlung, synchrotron rad.
Macro - **v** $\approx$ const - dielectric (or chromo-) permittivity ϵ - Cherenkov photons (gluons), wake, transition radiation

Polarization - $(\epsilon \neq 1)$

$$\mathbf{P} = \frac{\epsilon - 1}{4\pi}\mathbf{E},$$

$$\frac{\Delta E}{E} = (\gamma^2 - 1)\frac{\Delta v}{v} \gg \frac{\Delta v}{v} \qquad (\gamma \gg 1)$$

IN-MEDIUM GLUODYNAMICS

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

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

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

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

The permittivity = the matter response to the induced fields due to internal current sources in the medium.
$(\rho, \mathbf{j})$ - external current sources.

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 $\propto g^3$ - can lead to color rainbow!

Cherenkov gluons as a classical solution

Phase and coherence length (role of ϵ!)

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

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

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

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

We consider the polarization losses (not bremsstrahlung!).

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

Cylindrical coordinates:

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

$\int dk_\perp J_0 \sin(k_\perp ...) \to \Theta$.

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

Cone (shock wave!)

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

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 same as from coherence condition $\Delta\phi = 0$)

The intensity (Tamm-Frank formula)

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

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

Energy loss

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

First order:

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

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

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

Cherenkov gluons (first term) + **wake** (second term)

$$\frac{dN^{(1)}}{dzdxd\omega} = \frac{dW^{(1)}}{\omega dzd\zeta^2 d\omega} = \frac{\alpha_S C_R}{2\pi}\left[\frac{(1-x)\Gamma_t}{(x-x_0)^2 + (\Gamma_t)^2/4} + \frac{\Gamma_l}{x}\right],$$

$x = \zeta^2 = \cos^2\theta,\ x_0 = \epsilon_{1t}/|\epsilon_t|^2 v^2,\ \Gamma_j = 2\epsilon_{2j}/|\epsilon_j|^2 v^2,\ \epsilon_j = \epsilon_{1j} + i\epsilon_{2j}.$

Predicted experimental effects (observed)

- **Rings around the high-energy partons - non-trigger experiments and cosmic rays:** I.D., JETP Lett. **30** (1979) 140; Sov. J. Nucl. Phys. **33** (1981) 726.
- **Rings around the low-energy partons - trigger:** 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
- **Wake:** - I.D., Mod. Phys. Lett. A**25** (2010) 591; arXiv:0911.3233

Reviews:

I.D., A.V. Leonidov, Uspekhi **180** (October 2010);
I.D., Phys. Atom. Nucl. **73** (2010) 684;
I.D., Int. J. Mod. Phys. A**22** (2007) 1

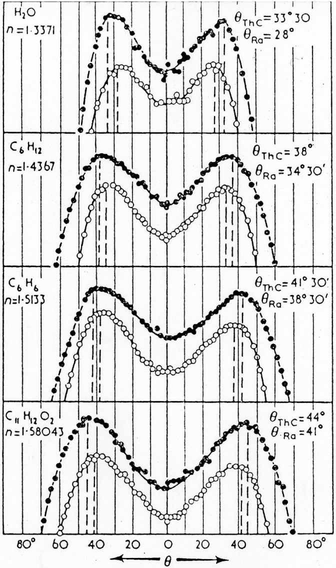
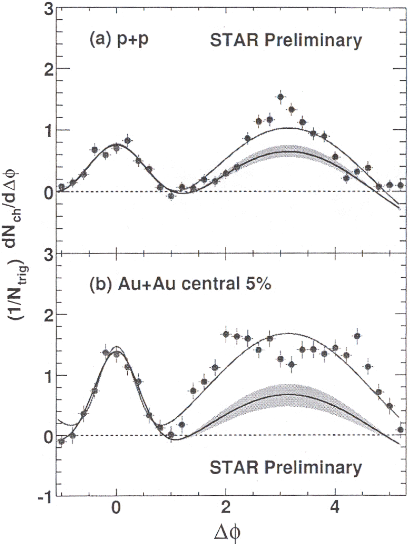
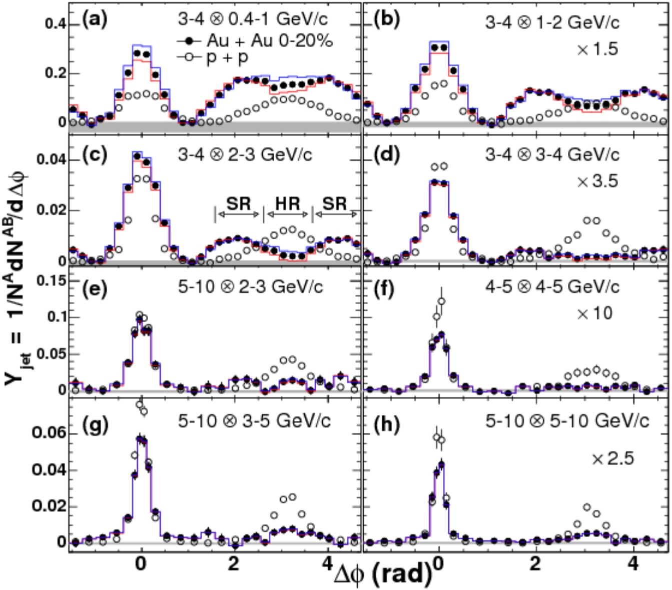


FIG. 1.8. The variation of θ with n, for two different sources of γ-rays. (Čerenkov, 1937d and 1938c.)

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

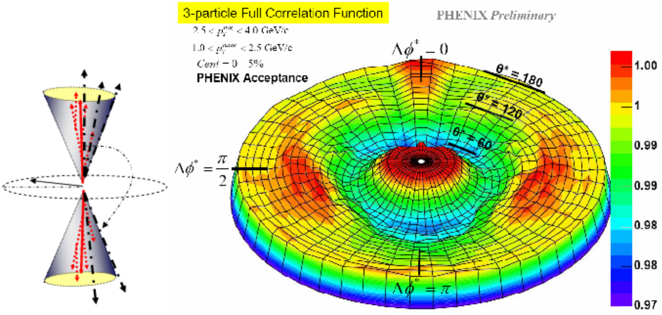


The $\Delta\phi$-distribution of particles produced by trigger and companion jets at RHIC shows two peaks in *pp* and three peaks in AuAu-collisions.



(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

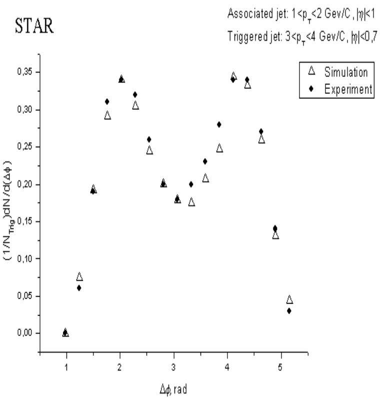
1. PYTHIA for initial partons (structure functions)
2. Cherenkov angular distribution of gluons
3. the gluon fragmentation function to pions (LEP) with gaussian suppression of transverse momenta $\propto \exp(-p_t^2/2\Delta_\perp^2)$

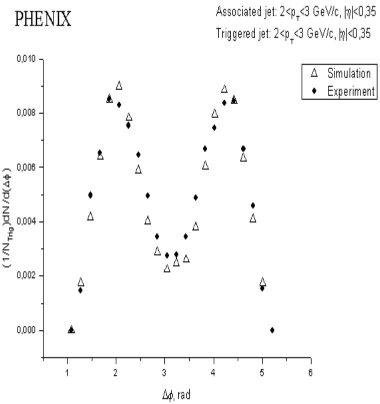
we get the reasonable fits of experimental data with three parameters $(\epsilon_1, \epsilon_2, \Delta_\perp)$

Table 1 Medium chromopermittivity

Experiment	$\theta_{\max}$	ϵ_1	ϵ_2	$\Delta_\perp, GeV/c$	new data
STAR	1.04 rad	5.4	0.7	0.7	$\theta_{\max} \approx$1.1 rad
PHENIX	1.27 rad	9.0	2.0	1.1	$\epsilon_1 \approx 6$; $\epsilon_2 \approx 0.8$

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





Shape-asymmetry of in-medium resonances

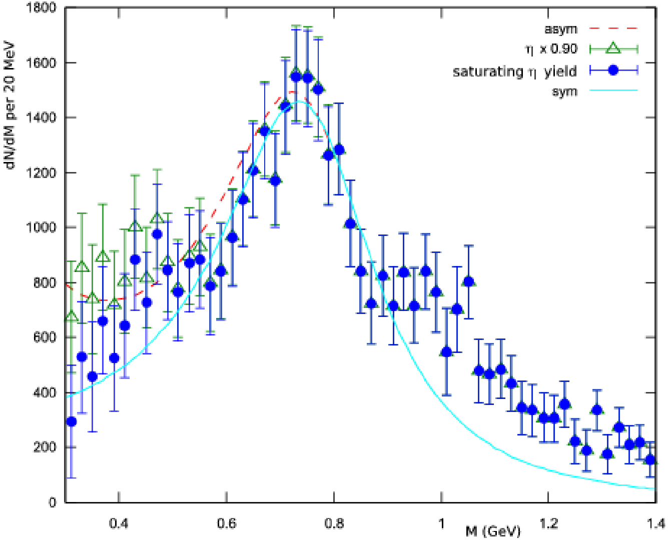
I.D., V.A. Nechitailo, Int. J. Mod. Phys. A**24** (2009) 1221; arXiv: hep-ph/ 0704.1081

$$\Delta\epsilon = \mathrm{Re}\epsilon - 1 = 4\pi N \mathrm{Re} F(E, 0^o)/E^2 \propto \frac{m_\rho^2 - M^2}{M\Gamma}\theta(m_\rho^2 - M^2).$$

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

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 at left (low-mass) wing of the resonance
(where $\mathrm{Re}F(E, 0^o) > 0$ for any Breit-Wigner resonance)



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

The wake effect arises from equation

$$\mathrm{div}\mathbf{E}(\mathbf{r},\omega) = \rho(\mathbf{r},\omega)/\epsilon(\omega)$$

or in space-time

$$\mathrm{div}\mathbf{E}(\mathbf{r},t) = \rho(\mathbf{r},t) + \int_0^\infty d\tau\rho(\mathbf{r},t-\tau)\int_{-\infty}^\infty \frac{d\omega}{2\pi}\frac{1-\epsilon(\omega)}{\epsilon(\omega)}\exp(i\omega\tau)$$

which for $\epsilon(\omega)\to 0$ gives

$$\Delta\rho(\mathbf{r},t) = g\delta(x)\delta(y)\theta(t-z)\omega\sin[\omega(z-t)]\exp[-\delta(t-z)].$$

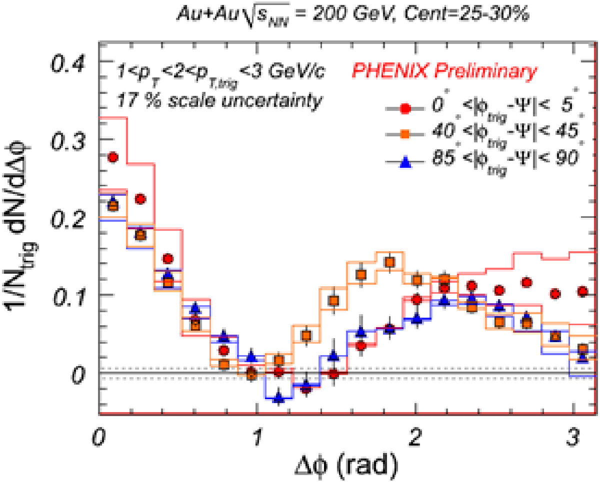
The ratio **[wake/Cherenkov]** at maximum of Cherenkov:

$$\frac{\Gamma_t\Gamma_l}{4x_0(1-x_0)} \approx \frac{\epsilon_{2t}\epsilon_{2l}}{\epsilon_{1t}(1-\epsilon_{1t}/|\epsilon|^2)} \approx 4\cdot 10^{-3} \ll 1.$$

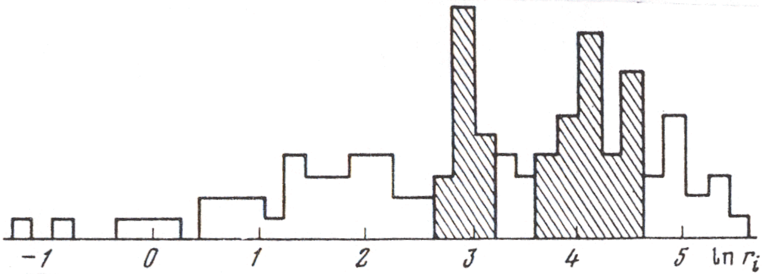
They become comparable (I.D. Mod. Phys. Lett. A**25** (2010) 591) at

$$x_e \approx \frac{x_0^2}{2x_0+1}$$

i.e. at $\pi - \Delta\phi_L \approx 1.43$ rad and maximum shifts (next Fig.)!


Au+Au $\sqrt{s_{NN}}$ = 200 GeV, Cent=25-30%
$1<p_T<2<p_{T,trig}<3$ GeV/c
17 % scale uncertainty
PHENIX Preliminary
$0^\circ<|\phi_{trig}-\Psi|<5^\circ$
$40^\circ<|\phi_{trig}-\Psi|<45^\circ$
$85^\circ<|\phi_{trig}-\Psi|<90^\circ$
$1/N_{trig}\, dN/d\Delta\phi$
$\Delta\phi$ (rad)
0.4
0.3
0.2
0.1
0
0
1
2
3

THE COSMIC RAY EVENT



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.

$\Delta\epsilon \ll 1$ (differs from RHIC)

New regime at high energies for "forward"non-trigger jets

CONCLUSIONS

CHERENKOV GLUONS AND WAKE EFFECT ARE OBSERVED IN EXPERIMENT AND THE NUCLEAR MEDIUM PROPERTIES ARE DETERMINED.

THE NUCLEAR MEDIUM PROPERTIES

1. The chromopermittivity
   $|\epsilon| \approx 6$ at comparatively low energies of jets;
   $\Delta\epsilon \ll 1$ at high energies
2. The density of partons; $N_s \approx 20$ per nucleon
3. The energy loss of Cherenkov gluons; about C_R GeV/fm
4. The free path length of gluons - fm.

New predictions (*under investigation*):

1. Forward rings at LHC.

2. Transition radiation at LHC.

3. Instabilities.

4. Color rainbow (quantum effect at higher orders)