EFFECTS OF MACROSCOPIC QCD OBSERVED IN HEAVY-ION COLLISIONS

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FIRST SURPRISES FROM LHC pp-RUN!

$\sqrt{s} = 0.9; \ 2.36; \ 7 \text{ TeV}$

1. High particle densities $dN/d\eta|_{\eta = 0}$ comparable to heavy-ion results at RHIC (ALICE, CMS, ATLAS)
2. Large size of the emission region at high multiplicities (CMS)
3. Ridge-like structure at high multiplicities ($N_{ch} \geq 110$) (CMS-talk, 22.09)

FIRST HEAVY-ION RUN IN NOVEMBER

Pb+Pb at $\sqrt{s} = 2.76A$ TeV
RHIC EXPERIMENT - AA ≠ 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 ≈ const - dielectric (or chromo-) permittivity ε -

Cherenkov photons (gluons), wake, transition radiation.

Purely coherent collective response of the matter!

Polarization - (ε ≠ 1)

\[ P = \frac{\epsilon - 1}{4\pi} E, \]

\[ \frac{\Delta E}{E} = (\gamma^2 - 1) \frac{\Delta \nu}{\nu} \gg \frac{\Delta \nu}{\nu} \quad (\gamma \gg 1) \]
HOW TO FORMULATE
MACROSCOPIC CHROMODYNAMICS
1. Introduce the chromopermittivity, denote it also by $\epsilon$.
2. Replace $E_a$ by $\epsilon E_a$.

For fields

$$\epsilon (\text{div} E_a - g f_{abc} A_b E_c) = \rho_a,$$

$$\text{curl} B_a - \epsilon \frac{\partial E_a}{\partial t} - g f_{abc} (\epsilon \Phi_b E_c + [A_b B_c]) = j_a.$$

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

$(\rho, j)$ - external current sources.
For potentials

\[ \Delta A_a - \epsilon \frac{\partial^2 A_a}{\partial t^2} = -j_a - gf_{abc} \left( \frac{1}{2} \text{curl}[A_b, A_c] + \frac{\partial}{\partial t}(A_b \Phi_c) + \frac{1}{2}[A_b \text{curl}A_c] - \epsilon \Phi_b \frac{\partial A_c}{\partial t} - \epsilon \Phi_b \text{grad}\Phi_c - \frac{1}{2} gf_{cmn}[A_b[A_mA_n]] + g \epsilon f_{cmn} \Phi_b A_m \Phi_n \right), \]

\[ \Delta \Phi_a - \epsilon \frac{\partial^2 \Phi_a}{\partial t^2} = -\frac{\rho_a}{\epsilon} + gf_{abc} \left( 2A_b \text{grad}\Phi_c + A_b \frac{\partial A_c}{\partial t} - \epsilon \frac{\partial \Phi_b}{\partial t} \Phi_c \right) + g^2 f_{amn} f_{nlb} A_m A_l \Phi_b. \]

A \propto J \propto g, classical equations are as in ED, higher order corrections \( \propto g^3 \) can lead to color rainbow!
Cherenkov gluons as a classical solution

Phase and coherence length (role of $\epsilon$!)

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

For Cherenkov effects

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

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

Specific for Cherenkov radiation only.

The external current

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

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

We consider the polarization losses (not bremsstrahlung!).
\[
\Phi^{(1)}(r, t) = \frac{g}{2\pi^2\epsilon} \int d^3k \frac{\exp[ik(r - vt)]}{k^2 - \epsilon(kv)^2}.
\]

Cylindrical coordinates:

d\phi \rightarrow J_0(k_\perp r_\perp), \; dk_z \rightarrow \text{poles},
\int dk_\perp J_0 \sin(k_\perp \ldots) \rightarrow \theta.

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

Cherenkov cone (shock wave!) and wake (1/\epsilon-term)

\[
z = vt - r_\perp \sqrt{\epsilon v^2 - 1}.
\]
Poynting vector

\[ S_x = -S_z \frac{(z - vt)x}{r^2}, \quad S_y = -S_z \frac{(z - vt)y}{r^2}. \]

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:

\[ \Phi_a^{(1)}(k) = 2\pi gQ_a \frac{\delta(\omega - kv\zeta)v^2\zeta^2}{\omega^2\epsilon(\epsilon v^2\zeta^2 - 1)}, \quad A_z^{(1)}(k) = \epsilon v\Phi_a^{(1)}(k), \]

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

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

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

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

\[ x = \zeta^2 = \cos^2 \theta, \quad x_0 = \epsilon_1 t/|\epsilon_t|^2 v^2, \quad \Gamma_j = 2\epsilon_2 j/|\epsilon_j|^2 v^2, \quad \epsilon_j = \epsilon_{1j} + i\epsilon_{2j}. \]

**ANALITICAL RESULTS!**
Experimental effects


- **Rings around the low-energy partons - trigger:**


Reviews:

I.D., A.V. Leonidov, Uspekhi 180 Nov. 2010; Ginzburg memo arXiv:1006.4607

I.D., Int. J. Mod. Phys. A22 (2007) 1
CERENKOV GLUONS AND AWAY-SIDE REGION STRUCTURE (TWO HUMPS)
Fig. 1.8. The variation of $\theta$ with $n$, for two different sources of $\gamma$-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.
Per-trigger yield versus $\Delta \phi$ in $pp$ and Au-Au collisions.

(A. Adare et al for PHENIX collaboration, arXiv0705.3238)
COMPLEX $\epsilon = \epsilon_1 + i\epsilon_2$

The angular $\delta$-function $\rightarrow$ a’la BW-shape.

Using the relation of $\theta$ with the lab angles $\cos \theta = | \sin \theta_L \cos \phi_L |$ and integrating over $\theta_L$, one gets (quite lengthy) analytical expression for the measured ($\phi_L$)-distribution (two-hump structure!).


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 $\propto \exp(-p_t^2/2\Delta^2_\perp)$

we get the reasonable fits of experimental data with three parameters ($\epsilon_1, \epsilon_2, \Delta_\perp$)
Table 1  Medium chromopermittivity

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\theta_{\text{max}}$</th>
<th>$\epsilon_1$</th>
<th>$\epsilon_2$</th>
<th>$\Delta_{\perp}$, GeV/$c$</th>
<th>new data</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR</td>
<td>1.04 rad</td>
<td>5.4</td>
<td>0.7</td>
<td>0.7</td>
<td>$\theta_{\text{max}} \approx 1.1$ rad</td>
</tr>
<tr>
<td>PHENIX</td>
<td>1.27 rad</td>
<td>9.0</td>
<td>2.0</td>
<td>1.1</td>
<td>$\epsilon_1 \approx 6$; $\epsilon_2 \approx 0.8$</td>
</tr>
</tbody>
</table>

NOTE: $(\epsilon_2/\epsilon_1)^2 \leq 0.05 \ll 1$
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. The trigger is located at $\pi/2$ to the collision axis. The away-side parton goes in the opposite direction to the trigger parton. Cherenkov gluons form the ring of hadrons just around this direction.
CHERENKOV EFFECT AND
ASYMMETRY OF SHAPES OF
ALL IN-MEDIUM RESONANCES
\( \epsilon > 1 \) is the necessary condition for Cherenkov effect.

\[
\Delta \epsilon = \text{Re} \epsilon - 1 = 4\pi N \text{Re} F(E, 0^\circ)/E^2 \propto \frac{m^2_\rho - M^2}{M \Gamma} \theta(m^2_\rho - M^2).
\]

**NOTE:** \( \Delta \epsilon \) is proportional to the density \( N \) of scatterers! \( \text{Re} F(E, 0^\circ) > 0 \) - necessary condition.

\[
\frac{dN_{ll}}{dM} = \frac{A}{(m^2_\rho - M^2)^2 + M^2 \Gamma^2} \left( 1 + w \frac{m^2_\rho - M^2}{M \Gamma} \theta(m^2_\rho - M^2) \right)
\]

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

**Universal prediction for ALL in-medium resonances!**

Excess at left (low-mass) wing of the resonance (where \( \text{Re} F(E, 0^\circ) > 0 \) 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 (TRAIL) EFFECT
The wake effect: \( \text{div} \mathbf{E}(r, \omega) = \frac{\rho(r, \omega)}{\epsilon(\omega)} \)

or in space-time

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

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

\[
\Delta \rho(r, t) = g \delta(x) \delta(y) \Theta(t - z) \omega \sin[\omega(z - t)] \exp[-\delta(t - z)].
\]

Note the damped oscillations along the trail \( t > z! \)

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

\[
\frac{\Gamma_t \Gamma_l}{4x_0(1 - x_0)} \approx \frac{\epsilon_2 t \epsilon_2 l}{\epsilon_{1t} (1 - \epsilon_{1t} / |\epsilon|^2)} \approx 4 \cdot 10^{-3} \ll 1.
\]

They become comparable at

\[
x_e \approx \frac{x_0^2}{2x_0 + 1}
\]

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

The trail behind the parton radiates as a dipole.
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)
THE COSMIC RAY DATA:
RINGS AND FANS
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 - the ringlike INDIVIDUAL event.

$\epsilon - 1 = \Delta \epsilon \ll 1$ (it differs from RHIC!)

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

**FAN-shaped events or alignment in CR data**

remind RIDGE! (see RHIC and CMS data)

Why coplanar emission? Who ordered it? Energy threshold?
CONFIDENT IS OFTEN WRONG

It ai’nt what you do not know that gets you into trouble.

It is what you know for sure that just ai’nt so.

Mark Twain
CONCLUSIONS

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

THE NUCLEAR MEDIUM PROPERTIES

1. The chromopermittivity $|\epsilon| \approx 6$ at rather low energies of jets (with $\epsilon_2 \ll \epsilon_1$) while $\Delta \epsilon \ll 1$ at high energies.
2. The density of partons; $N_s \approx 20$ per nucleon.
3. The energy loss of Cherenkov gluons is LARGE: $\approx C_R$ 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. Instability.
4. Color rainbow (quantum effect at higher orders)