Quenching of high-\(p_T\) hadrons: Alternative scenario

Boris Kopeliovich
UTFSM, Valparaiso
U. Heidelberg
JINR, Dubna

In collaboration with Jan Nemchik, Hans-Jürgen Pirner, Irina Potashnikova and Ivan Schmidt
Hadron quenching in heavy ion and electron-nucleus collisions

The geometry and kinematics are uncertain: the model must be tested somewhere else.

**RHIC – LHC**

$E_\pi = p_T < 20$ GeV/c

The density, geometry, kinematics are known. $Q^2$ and $\nu$ are uncorrelated. The best way to test models.

**HERMES – JLAB**

$E_\pi < 20$ GeV/c

$\gamma^*$
Perturbative hadronization

Perturbative color neutralization

Quenching of high-$p_T$ hadrons: Alternative scenario – p. 3/14
Two sources of hadron quenching:

(i) energy loss of the parton prior production of a pre-hadron;
Two sources of hadron quenching:

(i) energy loss of the parton prior production of a pre-hadron;

(ii) attenuation of the pre-hadron in the medium (absorption).
Perturbative hadronization

In the energy loss scenario one assumes (ad hoc) that color neutralization always happens outside of the medium, \( l_p \gg R_A \).
Perturbative hadronization

In the energy loss scenario one assumes (ad hoc) that color neutralization always happens outside of the medium, $l_p \gg R_A$

However, even in the string model this distance is not long, e.g. at $E_h = p_T = 10$ GeV and $z = 0.7$,

$$l_p = \frac{E_h}{\kappa} (1 - z_h) = 3 \text{ fm}$$

B.K. & F.Niedermayer (1983)
A.Bialas & M.Gyulassy (1987)

Dissipation of energy by a highly virtual quark is more intense, therefore $l_p$ should be even shorter.
$p_T$ broadening in DIS

The mean pathlength of a hadronizing quark in nuclear medium can be directly measured via $p_T$-broadening:

$$\langle l \rangle = \frac{\Delta \langle p_T^2 \rangle}{z^2 \hat{q}}$$
\( p_T \) broadening in DIS

The mean pathlength of a hadronizing quark in nuclear medium can be directly measured via \( p_T \)-broadening:

\[
\langle l \rangle = \frac{\Delta \langle p_T^2 \rangle}{z^2 \hat{q}}
\]

---

**HERMES preliminary**

- Ne
- Kr
- Xe

π⁺, π⁻, K⁺
There is a consensus between different sources of information about the transport coefficient $\hat{q}$ in nuclei.

<table>
<thead>
<tr>
<th></th>
<th>Dipole 10 - 20 GeV</th>
<th>BDMS -</th>
<th>Drell-Yan 200 - 800 GeV</th>
<th>Cronin 200 - 800 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{q}$ (GeV$^2$/fm)</td>
<td>0.042</td>
<td>0.045</td>
<td>0.026 - 0.056</td>
<td>0.033 - 0.037</td>
</tr>
</tbody>
</table>

Thus, the mean pathlength of the quark in $Kr$ and $Xe$ at $z = 0.7$ and $\langle \nu \rangle = 13.4$ GeV is very short:

$$\langle l \rangle \approx 0.6 \pm 0.4 \text{ fm}$$

Absorption of the produced prehadron plays key role in quenching of pions produced in DIS off nuclei.
Time evolution of a high-$p_T$ jet

Born approximation for the fragmentation function

$$\frac{\partial D_{q/\pi}(z, k)}{\partial k^2} \propto \frac{1}{k^4} z^2 (1 - z)^2$$

Changing the variable to

$$l_c = \frac{2z(1 - z)E}{k^2}$$

one gets a constant distribution over pion production length,

$$\frac{\partial D_{q/\pi}(z, l_c)}{\partial l_c} \propto z(1 - z)$$
Time evolution of a high-$p_T$ jet

The produced high-$p_T$ "bare" quark has no field with transverse frequencies $k < p_T$. It can be expanded over Fock states containing different number of gluons, which are radiated in accordance with their coherence times. The quark has lower energy in higher Fock components, correspondingly, the fractional pion momentum should be redefined:

$$z \Rightarrow \tilde{z}(l) = \frac{z}{1 - \Delta E(l)/E},$$

where $\Delta E(l)$ is vacuum energy loss.

To respect energy conservation only gluons with $\omega < E(1 - z)$ contribute to $\Delta E(l)$. 

![Graph showing quenching of high-$p_T$ hadrons](image)
Time evolution of a high-$p_T$ jet

The rest nonradiated gluons produce Sudakov suppression,

$$S(z, l) = e^{-\langle n_g(z, l) \rangle}$$

The $l_c$ distribution of pions is modified by gluon radiation,

$$\frac{\partial D_q/\pi(z, l_c)}{\partial l_c} \propto \tilde{z}(l_c)[1 - \tilde{z}(l_c)] S(z, l_c)$$

Weak energy dependence, $\langle l_c \rangle$ slowly decreases with energy.
Quenching of high-$p_T$ hadrons

For central collision of nuclei with constant density,

$$R_{AA} = \frac{\langle l_c^2 \rangle}{R_A^2} \left[ 1 - A \frac{L}{\langle l_c \rangle} + B \frac{L^2}{\langle l_c^2 \rangle} \right],$$

where the effective absorption length is,

$$L^3(E) = \frac{3E}{8R_A\rho_A^2X}$$

The prehadron dipole is produced with a rather large starting separation,

$$\langle r_T^2 \rangle \approx \frac{2\langle l_c \rangle}{zE} + \frac{1}{E^2}$$

e.g. at $E_\pi = 10$ GeV the initial dipole size is $r_T \sim 0.3$ fm.
Quenching of high-$p_T$ hadrons

For such a large dipoles the survival probability in a dense medium is vanishingly small. Assuming that $L \ll \langle l_c \rangle$ we arrive at a simple result,

$$R_{AA} = \frac{\langle l_c^2(p_T) \rangle}{R_A^2}$$

No unknowns!

Suppression is independent of the medium density. The suppression is not to be fitted, but can be predicted.
Discussion

If the density of the created medium is high, the production length of a prehadron colorless dipole controls the suppression $R_{AA}$ which decouples from the medium density.
If the density of the created medium is high, the production length of a prehadron colorless dipole controls the suppression $R_{AA}$ which decouples from the medium density.

The $A$-dependence is predicted to be $R_{AA} \propto A^{-2/3}$. If $R_{AA} = 0.2$ for $Au - Au$ central collision, it has to be $R_{AA} = 0.42$ for $Cu - Cu$ in excellent agreement with data.
Discussion

• If the density of the created medium is high, the production length of a prehadron colorless dipole controls the suppression $R_{AA}$ which decouples from the medium density.

• The $A$-dependence is predicted to be $R_{AA} \propto A^{-2/3}$. If $R_{AA} = 0.2$ for $Au - Au$ central collision, it has to be $R_{AA} = 0.42$ for $Cu - Cu$ in excellent agreement with data.

• Vacuum energy is the same for heavy and light quarks. Therefore, heavy flavors must be suppressed same way as pions, even somewhat more, since their fragmentation function is shifted to larger $z$, so $l_c$ is shorter.
Discussion

- Although two hadrons are absorbed stronger than one, in the regime of high density $L \ll \langle l_c \rangle$ this does not affect $R_{AA}$. 
Discussion

- Although two hadrons are absorbed stronger than one, in the regime of high density $L \ll \langle l_c \rangle$ this does not affect $R_{AA}$.

- Since $L \propto p_T^{1/3}$, the neglected absorption terms rise with $p_T$ and eventually will take over. Then $R_{AA}(p_T)$ will start rising. At LHC this will happen at larger $p_T$, than at RHIC.
Backup slides

Quark jet

$E = 10$ GeV

$\Lambda = 0.6$ GeV

$z = 0.9$

$z = 0.8$

$z = 0.7$

$z = 0.6$

$\langle n(L) \rangle$ - Sudakov

$S(l,z)$ - Sudakov

Quenching of high-$p_T$ hadrons: Alternative scenario – p. 14/1