Space-time development of in-medium hadronization

Scenario for leading hadron

B. GUIOT

in collaboration with B. Z. Kopeliovich

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UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Outline

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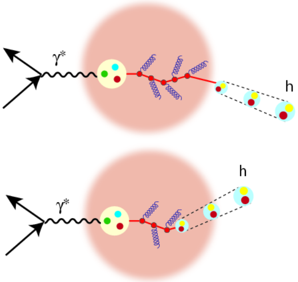
Scenario for leading quark

1. Quark kicked-out by the virtual photon
2. Propagates through the nuclear medium
3. Turns into a white object which eventually will give a hadron

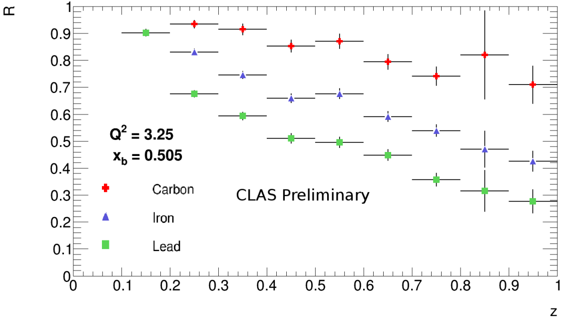


Depending of the kinematic, the colorless dipole (pre-hadron) can be produced inside or outside of the medium (semi-classical picture).

- Additional effect in comparison to DIS on nucleon : Fermi motion, induced energy loss, nuclear absorption.

Typical observable : multiplicity ratio

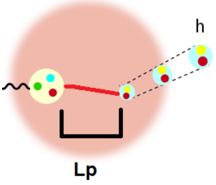
- $R_A(\nu, Q^2, z_h, p_t^2) = \frac{1}{N_A^e} \frac{dN_A^h(\nu, Q^2, z_h, p_t^2)}{d\ldots} / \frac{1}{N_D^e} \frac{dN_D^h(\nu, Q^2, z_h, p_t^2)}{d\ldots}$



Models with Induced energy loss or nuclear absorption explain (more or less) the data...

Models based on nuclear absorption

1. After production length, Lp, a white pre-hadron (dipole) is formed
2. Inelastic interaction with the medium gives $R_A < 1$

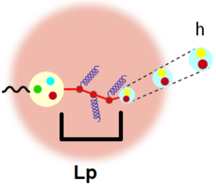


Remark : Due to energy loss and energy conservation $Lp = 0$ for $z = \frac{E_h}{\nu} = 1$

What can we learn : Lp , dependence of the dipole cross section on time, with Q^2 (color transparency)

Remark : at $z = 1$, $Lp = 0 \Rightarrow$ biggest path for nuclear absorption $\Rightarrow$ minimal value for R_A

Models based on induced energy loss (IEL)



1. IEL of the quark during the length Lp
2. Modification of the vacuum frag. function by a shift of $z = \frac{E_h}{\nu}$

Simple implementation :

- X.N. Wang et al. Phys. Rev. Lett. 77 (1996) 231
- F. Arleo hep/0306235v2

$$zD^A(z,Q^2) = \int_0^{\nu - E_h} d\varepsilon D(\varepsilon, \nu, Lp, \hat{q}) z^* D^N(z^*, Q^2) \; ; \; z^* = \frac{z}{1-\varepsilon/\nu}$$

- $R_A \simeq D^A/D^N$: suppression since $D^N(z)$ decreases with z

What can we learn : Lp , $\hat{q}$ which caracterises the interacting medium

Remark : at $z = 1$, $Lp = 0 \Rightarrow$ No IEL $\Rightarrow R_A = 1$

Induced energy loss v.s nuclear absorption

- Issue : Both effects have to be taken into account. But some models working with just nuclear absorption or IEL can reproduce the data

Goals :

1. Build a model for (in-medium) hadronization which includes both effects.
2. Quantify each contribution
    - We already know that at $z = 1$, all suppression should come from nuclear absorption
3. Learn more about Lp, $\hat{q}$, dipole cross section (evolution)
4. Build a code which will be given to the experimentalist group at UTFMS (working on CLAS data for SIDIS)

Outline

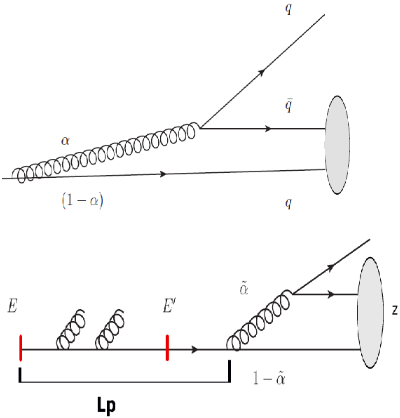
Hadronization based on Berger's model (for leading hadron)

Fragmentation function in the Born Approximation :

- $\frac{\partial D(z,k_t)}{\partial k_t} \propto \frac{(1-z)^2}{k_t^4}$

Including vacum energy loss :

- $\tilde{z} = \frac{z}{1-\Delta E/E}$
- $Lp = \frac{4E(1-\tilde{z})}{k_t^2}$



Improved fragmentation function : $\frac{\partial D}{\partial L_p} \propto 1 - \tilde{z}$

Vacuum energy loss

Perturbative energy loss :

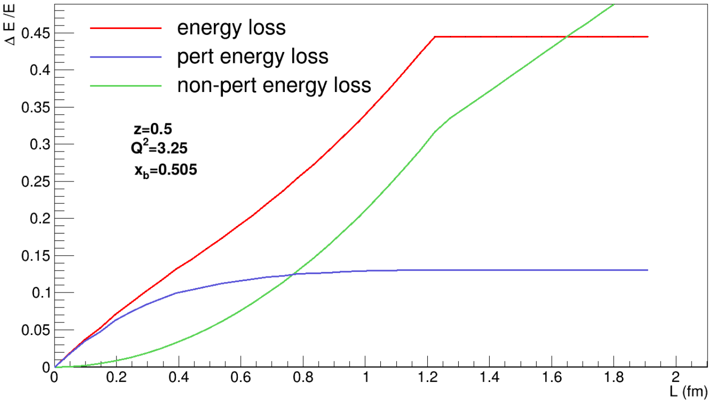
- Energy conservation $\Rightarrow \beta < 1 - z$, β energy fraction taken by the emitted gluon

$$\frac{\Delta E}{E}(Q^2, z, L) = \int_{\lambda/E}^{1-z} d\beta \int_{l_{min}}^{l_{max}} dl_g \beta \frac{dn_g}{dl_g d\beta}$$

- Gluon radiation length : $l_g = \frac{2E\beta}{q_t^2}$
- $l_{min} = \frac{2E\beta}{Q^2}$, $l_{max} = min\left[\frac{2E\beta}{\lambda^2}, L\right]$
- $\frac{dn_g}{dl_g d\beta}(\beta, l_g) = \frac{2\alpha_s}{3\pi} \frac{1+(1-\beta)^2}{\beta l_g}$: gluon number distribution

Non-perturbative energy loss based on lund strings

Result for vacuum energy loss

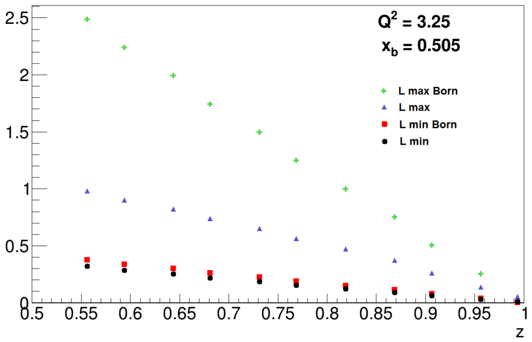


When $\frac{\Delta E}{E} = 1 - z$, energy loss is stoped

Vacuum fragmentation function and production length

$$D^N(z,Q^2,E) \propto \int_{Lp_{max}}^{Lp_{min}} dLp \frac{\partial D^N}{\partial Lp}(z,Q^2,E,Lp)$$

$$Lp_{min} = \frac{4E(1-\tilde{z}(Lp_{min}))}{Q^2} \; , \; Lp_{max} = \frac{4E(1-\tilde{z}(Lp_{max}))}{\lambda^2}$$



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In-medium fragmentation function and multiplicity ratio

$$D^A(z,Q^2,E) \propto \int db \int dz_l\, \rho(b,z_l) \int_{Lp_{max}}^{Lp_{min}} dLp \frac{\partial D^N}{\partial Lp}()\, Tr(\ldots, z_l + Lp, \infty)$$

- $\rho(b,z_l)$: nuclear density
- $Tr(z,Q^2,E,z_l+Lp,\infty)$: suppression factor due to nuclear absorption. Also called color transparency factor

- **Multiplicity ratio :** $R^A \simeq \frac{1}{A}\frac{D^A}{D^N}$

Color transparency factor

$$Tr = \left| \frac{\int d^2 r_1 d^2 r_2 \psi_h^*(r_2) G(z_2, r_2, z_1, r_1) \psi_{q\bar{q}}(r_1)}{\int d^2 r \psi_h^*(r) \psi_{q\bar{q}}(r)} \right|^2$$

- $G(z_2, r_2, z_1, r_1)$: Green function, solution of the 2 dim light cone Schrodinger equation [Phys. Rev. D62, 054022]
- $\mathrm{Re}\, V =$ harmonic oscillator , $\mathrm{Im}\, V(z_2, r) = -\frac{\sigma_{q\bar{q}}(r)}{2} \rho(z_2)$

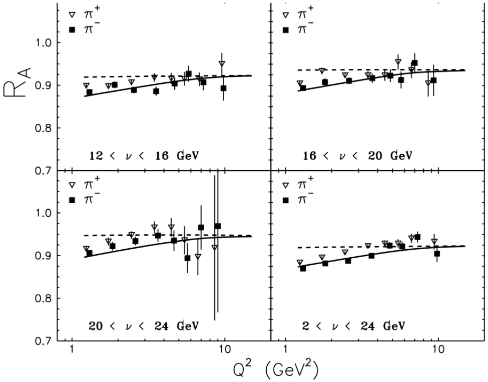
Imaginary part responsible for the suppression. $\sigma_{q\bar{q}}(r)$ is the dipole-nucleon cross section

- Small r approx. $\sigma_{q\bar{q}}(r) \propto r^2$ (pQCD)
- $\sigma_{q\bar{q}}(r) = C(s) r^2$ with $C(s) = \frac{\sigma_{tot}^{\pi}(s)}{\langle r_\pi^2 \rangle}$. **No free parameter!**

Dipole wave function

- $\psi_{q\bar{q}}(z, Q^2, E, Lp, r) \propto exp\left\{-\frac{1}{2}\frac{r^2}{\langle r^2_{q\bar{q}}\rangle}\right\}$
- $\langle r^2_{q\bar{q}}\rangle(z, Q^2, E, L = 0) \propto \frac{1}{Q^2}$

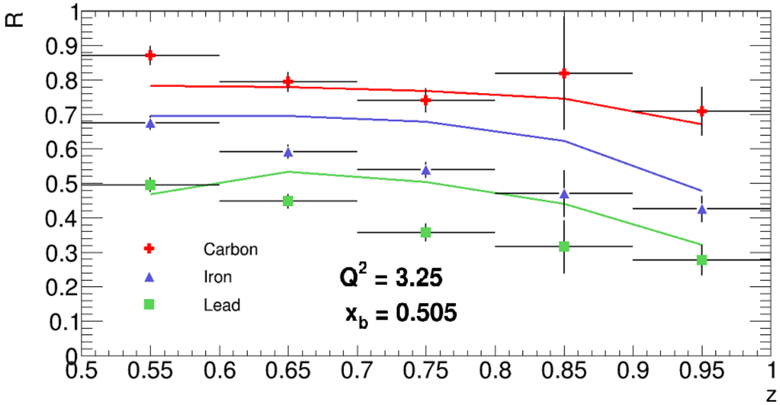
- Q^2 dependence responsible for color transparency. Higher Q^2, smaller dipole size, less suppression ($\sigma_{q\bar{q}} \propto r^2$)
- $\langle r^2_{q\bar{q}}\rangle = \langle r^2_{\pi}\rangle$ gives the pion wave function and the maximum nuclear absorption



Plot : B. Z. Kopeliovich et al., 0311220v3

Outline

Results for $\langle r_{q\bar{q}}^2 \rangle = \langle r_\pi^2 \rangle$



No free parameter

- With max suppression, our model based on nuclear absorption still **20%** above data for $z = 0.75$... Is something missing?

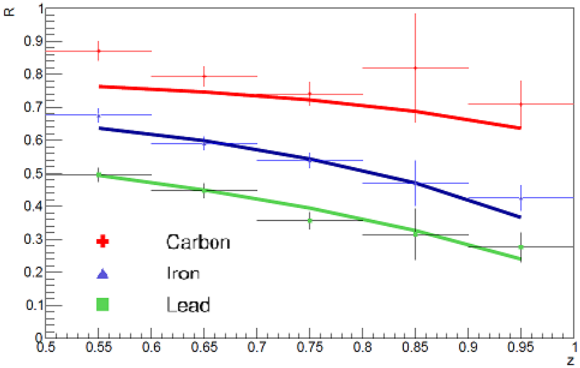
Missing ingredient

Should give :

1. small contribution at high z
2. non-negligeable contribution for medium z

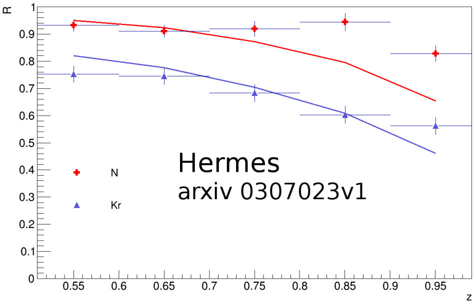
- **Induced energy loss could work**
- Still not implemented. But IEL z dependence not so different from vacuum energy loss. Could mimick it using bigger value for α_s

Results with "induced energy loss" : $\alpha_s \to 3\alpha_s$



- $\langle r_{q\bar{q}}^2 \rangle = \langle r_\pi^2 \rangle$ good approximation for sufficiently low energy and heavy nucleus

Results for Hermes



- Hermes energy at higher energy than CLAS. The approximation $\langle r^2_{q\bar{q}} \rangle = \langle r^2_\pi \rangle$ is less accurate and the suppression is more overestimated.

Summary and outlooks

- Interest of CLAS experiment : high statistics and low energy ($\langle r^2_{q\bar{q}} \rangle = \langle r^2_\pi \rangle$ is a good approx.)
- At CLAS energy, short production length $Lp < 1$fm for $z > 0.5$
- Implementation of our model without free parameters shows that both IEL and nuclear absorption give non negligeable contribution to R_A (not the usual conclusion)
- Implementation of IEL will allow to test models and give more constraints on $\hat{q}$

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Interest of SIDIS on nuclei

- Clear kinematics : z, Q^2 and ν are easily measurable independent variables :

  $\Rightarrow$ Best tool for testing models

Importance for LHC :

- Some results can be appplied to AA collisions at RHIC or LHC. For instance, high p_t jet suppression.

B. Z. Kopeliovich et al. : [arXiv:1208.4951]

- Will change the estimated value of $\hat{q}$ for QGP