Propagation of partons in the medium

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Energy loss

One should discriminate between vacuum and induced loss of energy. Hadronization does't happen instantaneously, but takes time, and the parton initiating the jet keeps losing energy for production of new hadrons. This is the **vacuum** energy loss.

A parton propagating through a medium experiences multiple interactions which increase the hadron multiplicity. Therefore, the energy loss increases. The excess is called **induced** energy loss.

String model

- In this case the rate of energy loss is just the string tension

$$\frac{dE}{dt} = -\varkappa \approx 1\,\frac{GeV}{fm}$$

Correspondingly, the energy loss linearly rises with length of the path

$$\Delta E_{vac} = \varkappa L \qquad \text{vacuum E-loss}$$

- a quark carries a cloud of Weizsäcker-Williams gluons and sea $q\bar{q}$s

$$|q\rangle = \alpha|q\rangle_0 + \beta|qq\bar{q}\rangle + \cdots$$

The higher Fock component also can interact in the medium creating new strings.

According to the AGK cutting rules (Abramovsky-Gribov-Kancheli) the number of strings rises as the number of multiple interactions. Correspondingly rises the rate of energy loss

$$-\frac{dE}{dt} = \varkappa\left(\underset{\text{vacuum}}{1} + \underset{\text{induced}}{\sigma^{qN}\rho_A L}\right)$$

Thus, the induced E-loss is proportional to the square of the pathlength

$$\Delta E_{ind} \propto L^2$$

Perturbative QCD

amazingly, pQCD leads to similar results

- The rate of <u>vacuum</u> energy loss is also constant

$$\Delta E(t) = E_q \int d^2k_T \int dx \, \frac{x \, dn_g}{dx \, d^2k} \, \theta(t_c - t)$$

$$t_c = \frac{2E_q \, x(1-x)}{k_T^2}$$ is the coherence time of gluon radiation.

J. Gunion & G. Bertsch 1982

Using $\frac{dn_g}{dx \, d^2k_T} = \frac{3\alpha_s}{\pi x k_T^2}$

$$\frac{dE}{dt} = -\underbrace{\frac{3\alpha_s}{\pi}\langle k_T^2 \rangle}_{\text{constant}} \propto Q^2$$

F. Niedermayer 1986

Like in the string model

S. Brodsky & P. Hoyer 1990

More energetic gluons are radiated less frequently, but take away more energy.

- In terms of Color Glass Condensate a nucleus has a higher resolution than a nucleon, the saturation scale Q_s. Therefore, it is able to resolve higher Fock states in a quark i.e. to induce more gluon radiation.

The rate of E-loss is proportional to $\langle p_T^2(t)\rangle$ - the accumulated kick. Due to Brownian motion in transverse mom. plane $\langle p_T^2(t)\rangle \propto t$, therefore

$$\frac{dE_{ind}}{dt} = -\frac{3\alpha_s}{4}\langle p_T^2(t)\rangle \propto L$$

$$\Delta E \propto \alpha_s L^2$$

R. Baier et al. BDMPS, 1997

Independent of energy

- Dimensional analysis

$\frac{dE}{dt}$ is <u>invariant</u> relatie longitudinal Lorentz boosts.

The only relative invariant in vacuum is $\langle k_T^2 \rangle$. Therefore $\frac{dE_{vac}}{dt}$ is independent of time, and

$$\Delta E_{vac} \propto Q^2 L$$

In a medium $\frac{dE_{ind}}{dt}$ should depend on the density ρ. The only longitudinal boost-invariant combination is $\frac{dE_{ind}}{dt} \propto \rho L$,

$$\Delta E_{ind} \propto \rho L^2$$

p_T broadening of partons

$$\frac{d\sigma}{d p_T^2} = \int d^2 r\, d^2 r'\, e^{i \vec{p}_T(\vec{r}-\vec{r}\,')}\, \Omega(\vec{r}, \vec{r}\,')$$

$$\times \exp\left[-\frac{1}{2}\, \sigma_{q\bar{q}}(\vec{r}-\vec{r}\,')\, T_A(b)\right]$$

the universal dipol Xsection fitted to $F_2(x, Q^2)$

M. Johnson, A. Tarasov
B. K.
2000

$$\Delta \langle p_T^2 \rangle = C\, T_A$$

$$C = \left.\frac{d^2 \sigma_{q\bar{q}}(r)}{d r^2}\right|_{r=0}$$

J. Hüfner B. K.
1993

$$C = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \times G(x)$$

L. Frankfurt
M. Strikman
1993

BDMPS 1997

The first calculation of the Cronin effect not fitted to the data to be explained

B.K., J. Nemchik, A. Schäfer, A. Tarasov PRL 88 (2002) 232303

Cronin effect

$pA \to \pi X$

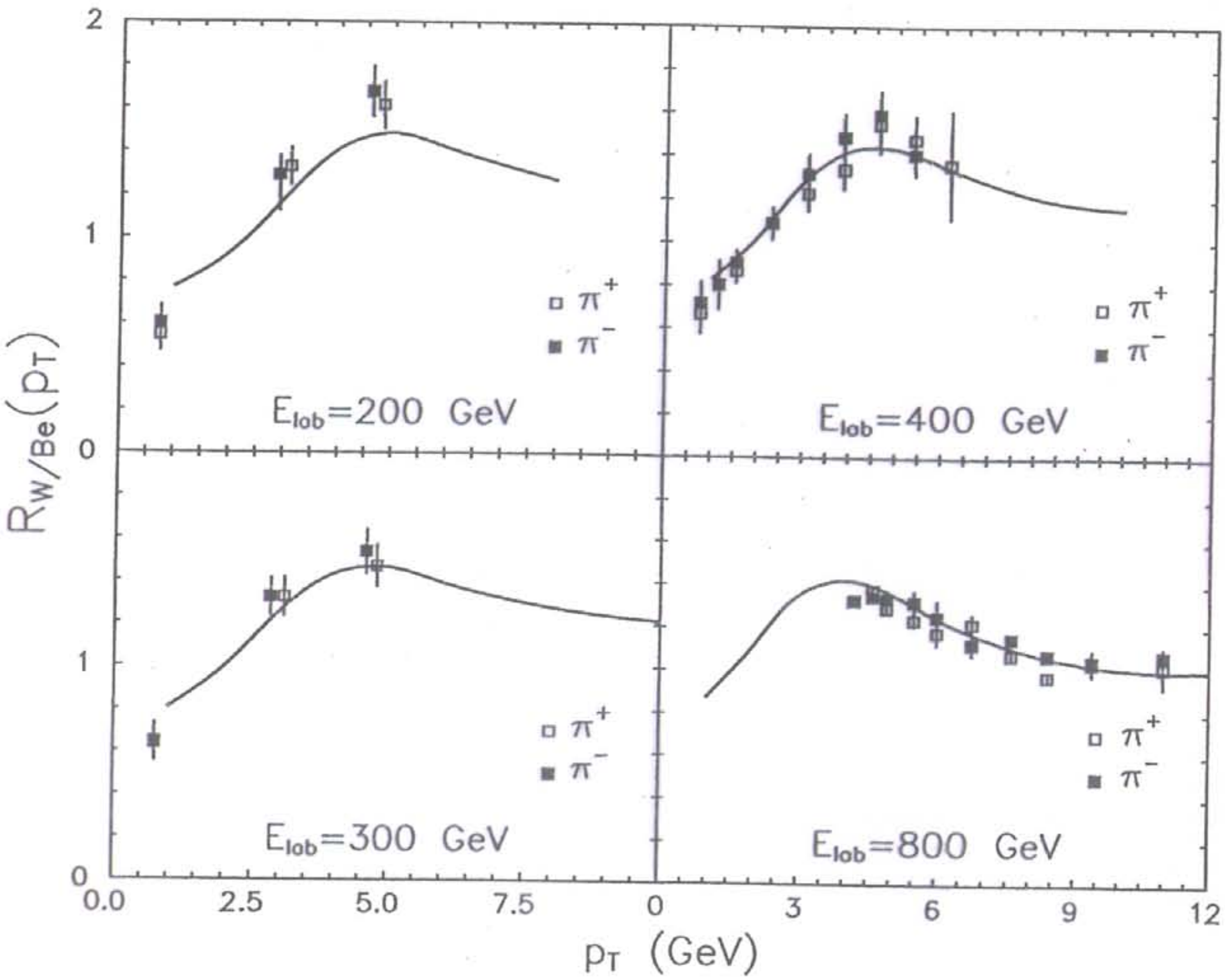


FIG. 1: Ratio of the charged pion production cross sections for tungsten and beryllium function of the transverse momentum of the produced pions. The curves correspond to the parameter-free calculation Eq. (5), the data are from fixed target experiments [22, 23]

The energy-shift recipe

a quark with energy E_q propagates through a nucleus and produces a hadron (outside the nucleus) with fraction

$$z_h = E_h / E_q$$

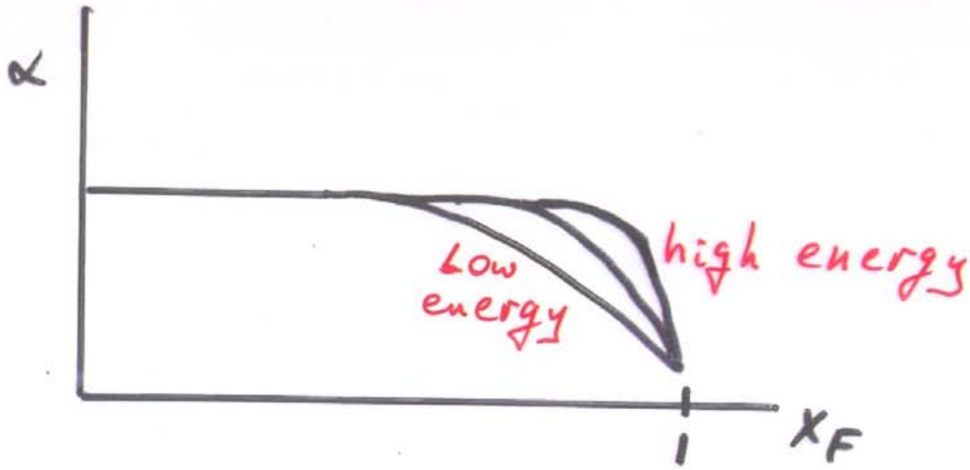
The modified fragmentation function

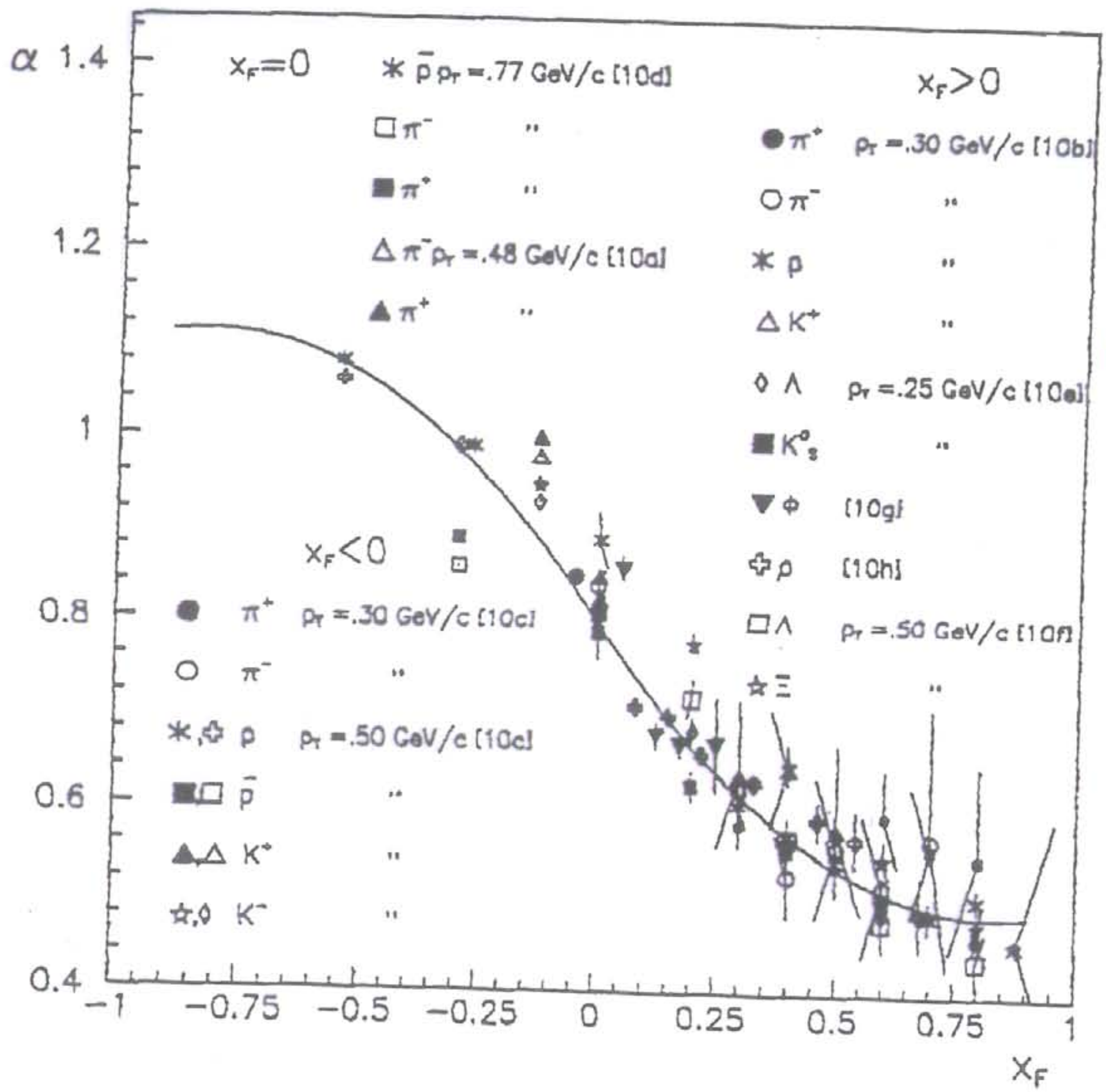
$$\tilde{D}(z_h) = D(z + \Delta z)$$

$$\Delta z = \frac{\Delta E_{ind}}{E_q}$$

$$\frac{\tilde{D}(z_h)}{D(z_h)} < 1$$ nuclear attenuation

$\Delta z \propto 1/E_q$, i.e. the effect is expected to vanish at high energies.





W. Geist
1991

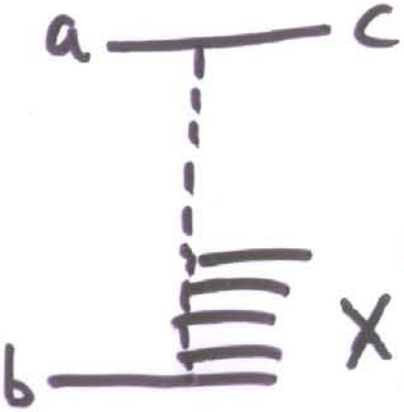
Fig. 5 : α as function of x_F for various hadron species produced in pA collisions.

Energy conservation constrains

The mean loss of energy is not relevant, since it is dominated by rarely radiated energetic gluons. Those are forbidden by E-conservation at large $z_h \to 1$, or $x_F \to 1$.

- This is a large rapidity gap (LRG) event which has a small survival probability in nuclei.

Any reaction, $a+b \to c+X$, ($c = h, e\bar{e}, J/\psi, \ldots$) is a large rapidity gap (LRG) process at $x_F \to 1$



Rapidity intervals

$$\ln \frac{s}{M^2} = \ln \frac{1}{1-x_F}$$

$$\ln \frac{M^2}{s_0}$$

The probability to radiate no gluons in the rapidity interval $\Delta y = \ln \frac{1}{1-x_1}$, is suppressed by the Sudakov's formfactor $S(\Delta y)$ which violates QCD factorization

$$S(\Delta y) = e^{-\langle n_G(\Delta y)\rangle}$$

The mean number of gluons radiated in the interval Δy is

$$\langle n_G(\Delta y)\rangle = \Delta y \, \frac{dn_G}{dy}$$

where dn_G/dy is constant

Correspondingly,

$$S(\Delta y) = (1-x_1)^{\frac{dn_G}{dy}}$$

$$\frac{dn_G}{dy} \approx \frac{3\alpha_s}{\pi} \ln \frac{m_p^2}{\Lambda_{QCD}^2} \approx 1$$

Gunion
Bertsch
1982

Thus, $S(x_1) = 1 - x_1$

Amazing! The same as is given by Regge theory (Kaidalov)

- Glauber model: survival probability of LRG in multiple nuclear interactions

$$\sigma^{A}_{LRG}(b) = \sum_{n=1} \frac{(\sigma_{in} T_A(b))^n}{n!} e^{-\sigma_{in} T_A(b)} S^n_{(x_1)}$$

The basis is the AGK cutting rules. Same σ^A_{LRG} is employed in the dual parton model.

at $x_1 \to 1$ only the first term survives, thus

$$\sigma^A_{LRG} = \int d^2b\, \sigma^A_{LRG}(b) \underset{x_1 \to 1}{\propto} A^{1/3}$$

like data suggest

Another example of LRG reaction on nuclei, diffractive excitation of the nuclear target

$$\sigma^{pA}_{diff} = \int_{x_0}^{1} dx_F \frac{d\sigma(pA \to pX)}{dx_F} = \sigma_0 A^{0.35 \pm .02}$$

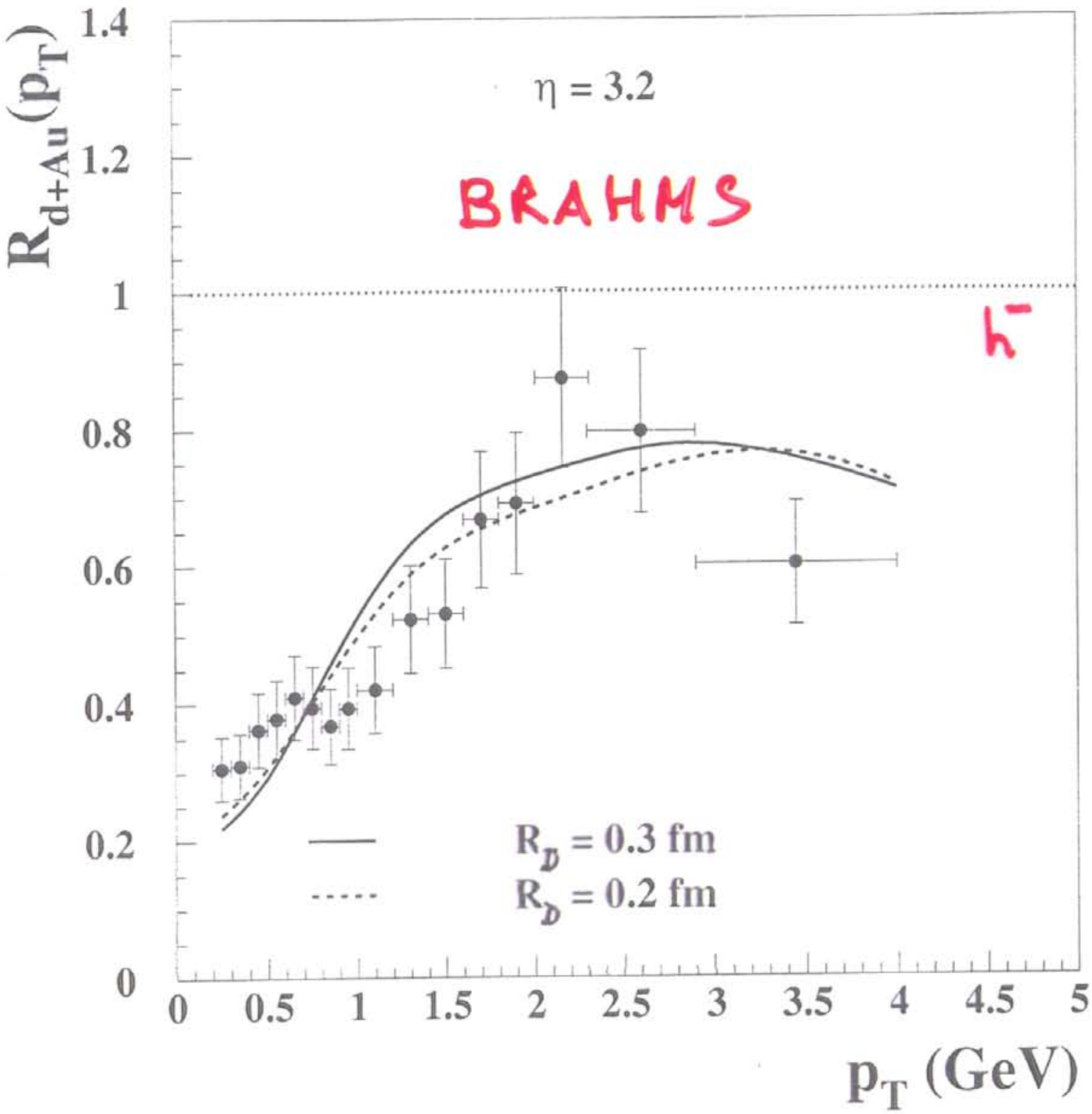
$1 - x_0 = 0.075$

$\sigma_0 = 3.84 \pm 0.94$ mb

HELIOS experiment 450 GeV

Only the nuclear periphery contributes

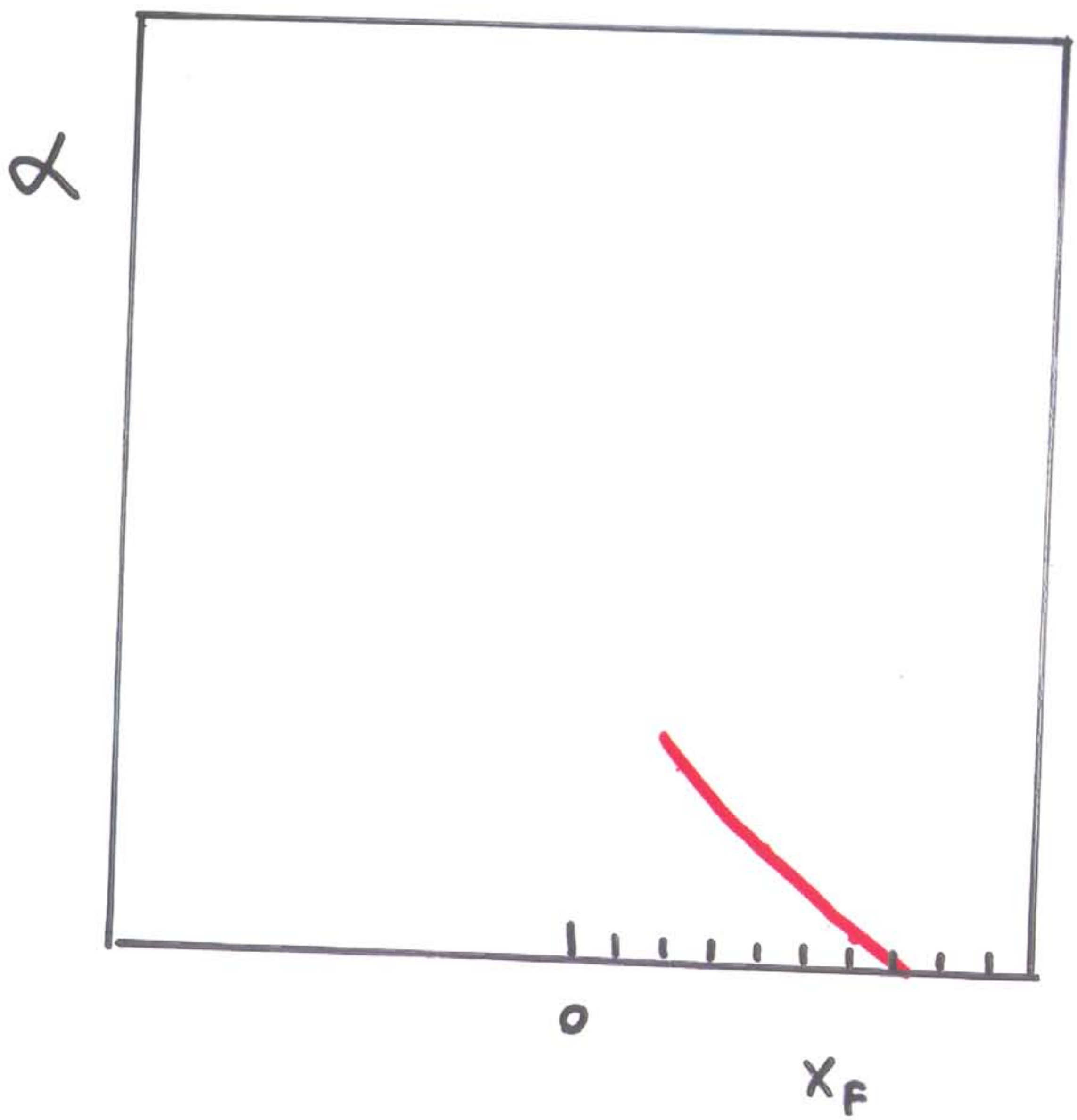
M. Johnson
J. Nemchik
I. Potashnikova
B.K.



Fragmentation functions $u \to \pi^-$ and $d \to \pi^-$ were used

$$R_A(x_F) = \frac{1}{6A}\int d^2b \sum_{n=1}^{A} \frac{(6T_A)^n}{n!}(1-x_F)^{n-1} e^{-6T_A}$$

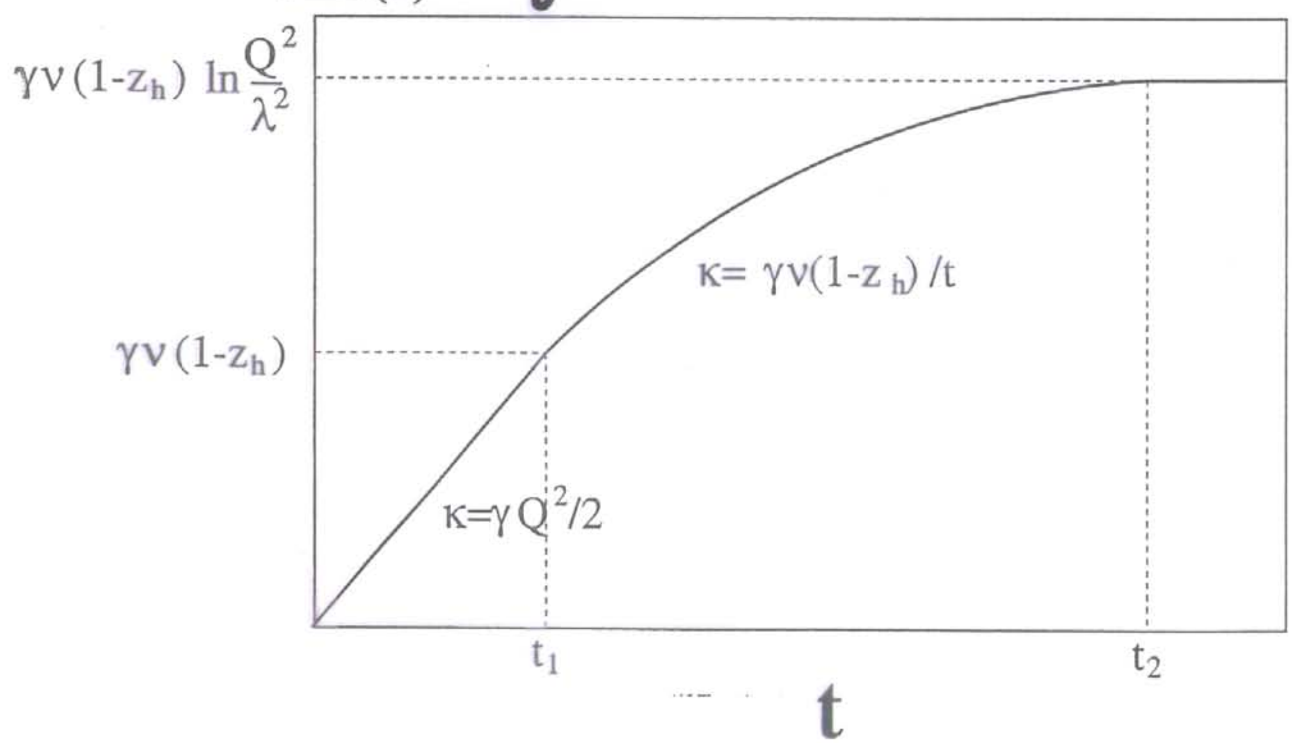
$$= \frac{1}{6A}\int d^2b \frac{e^{-6T_A}}{1-x_F}\left(e^{(1-x_F)6T_A} - 1\right)$$



B.K.
J. Nemchik
E. Predazzi
1995

At large z_h energy conservation constrain the energies of radiated gluons, $\omega < E_q(1-z_h)$. This makes the rate of energy loss in vacuum dependent on time

$$\Delta E(t) = \int_0^t dt' \, \varkappa(t')$$



Steepness of the p_T dependence of hadron production (HI collisions), or kinematic constrans (in DIS) leads to a bias in the energy loss distribution.

! The mean $\langle \Delta E \rangle$ is <u>not</u> relevant

R. Baier et al, BDMS 2001

The effective shift

$$\Delta z_h = \frac{2\alpha_s C_F}{\pi E_q} \sqrt{2\pi \omega_c \omega_1} \;\; \propto L \sqrt{E_q} / E_q$$

$$\omega_c = \rho_A \frac{2\pi^2 \alpha_s C_R}{N_c^2 - 1} \, xG(x) \, L^2$$

$$\omega_1 = -E_q \left[\frac{\partial}{\partial z_h} \ln D(z_h)\right] = \frac{E_q \, z_h (1 - z_h)}{\beta z_h - \alpha (1 - z_h)}$$

For high energies $E_h \gg \omega_1$

Δz_h is energy independent

Conclusions

- Both the string model and pQCD lead to vacuum energy loss which rises $\propto L$ and is independent of energy

- In both cases induced energy loss in a medium is $\propto L^2$ and is energy independent.

- These results follow from Lorentz invariance

- Nuclear broadening of $\langle p_T^2 \rangle$ is well predicted

- The mean energy loss is irrelevant for nuclear attenuation of hadrons.