Controversial Issues in the Energy Loss Scenario

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OUTLINE

- **Hadronization in vacuum:**
  how long does it take to produce a jet?
- **How lond does it take to produce a leading (pre)hadron?**
- **Upper bound for nuclear modification of the fragmentation function**
- **Where does the suppression come from?**
  Two regimes for hadron attenuation
- **Induced energy loss proportional to energy**

Vacuum energy loss

After a quark gets a strong kick in a hard reaction it shakes off a part of its field in the form of gluon/photon radiation.

This does not happen instantaneously, but takes time called coherence time or length,

$$l_c = \frac{2Ex(1-x)}{k_T^2 + x^2 m_q^2}$$

x is the fraction of the quark energy carried by the gluon. the quark keeps radiating and losing energy in vacuum long time, $t \propto E$, after the kick.

$$x\,\frac{dn_g}{dx\,dk^2} = \frac{C_R \alpha_s}{\pi\,k^2}\left(1 - x + \frac{x^2}{2}\right)$$

GLV energy loss: vacuum versus induced

$$-\frac{dE_{vac}}{dx} = \frac{2C_R\alpha_s}{\pi} E \left(1 - x + \frac{x^2}{2}\right) \ln\left(\frac{2Ex}{\mu}\right)$$

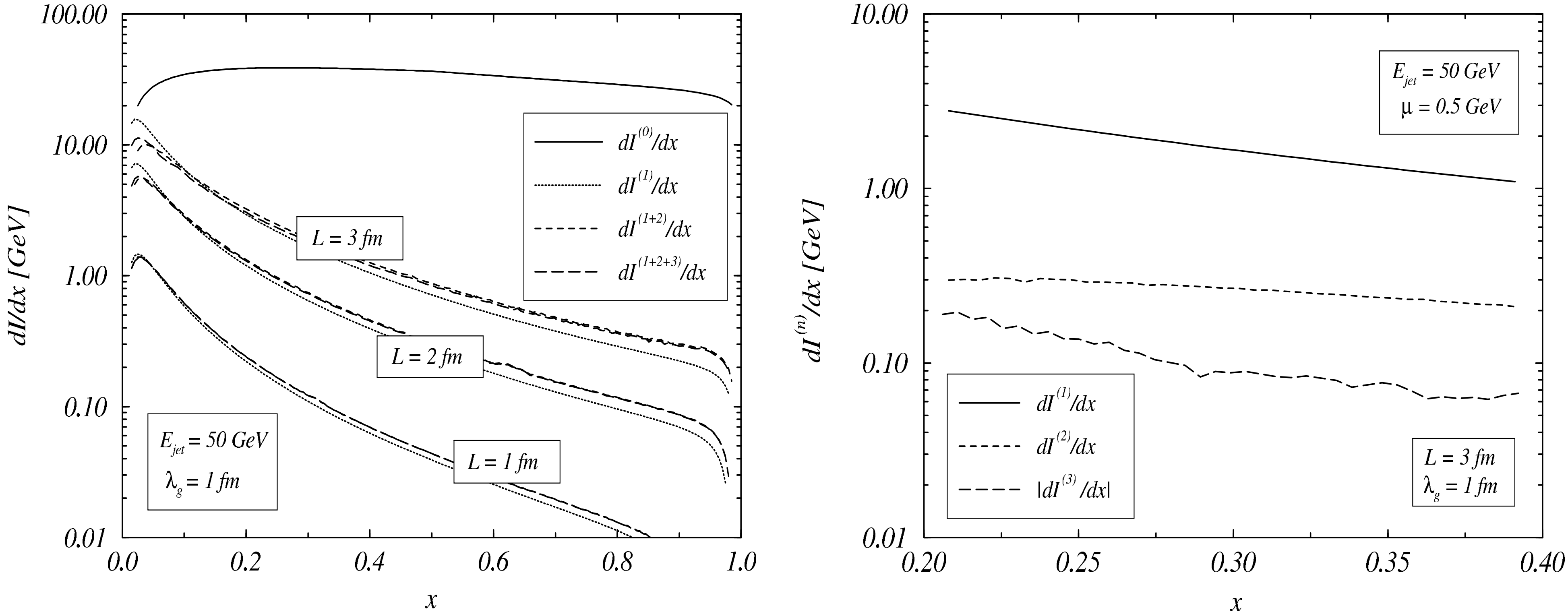


FIG 5. (a) The radiation intensity distribution is plotted vs. the light-cone momentum fraction x of the gluon. We consider a 50 GeV quark jet in a plasma with screening scale $\mu = 0.5$ GeV and $\lambda_g = 1$ fm. The solid curve shows the dominant medium-independent radiation intensity. The medium-induced gluon spectrum is plotted for up to third order in opacity ($dI^{(1)}, dI^{(1+2)}$ and $dI^{(1+2+3)}$) for opacities $L/\lambda_g = 1, 2, 3$. (b) The absolute value of the orders in opacity $dI^{(1)}, dI^{(2)}$ and $dI^{(3)}$ that contribute in part (a) are plotted for the same energy and opacity $L/\lambda_g = 3$.

$$\Delta E_{vac} = \frac{4 C_R \alpha_s}{3\pi} E \ln\left(\frac{E}{\mu}\right) \qquad \text{(GLV, 2000)}$$

Looks similar to the string model (the basis of our intuition) which leads to $\Delta E \sim E$, *since hadronization lasts over a long distance,* $\Delta z \sim E/\kappa$, *with energy loss rate* $-dE/dz = \kappa \approx 1\,\mathrm{GeV/\,fm}$.

How long does it take to radiate so much energy in pQCD?

$$\Delta E_{vac}(z) \;=\; E \int dk_T^2\, dx\, \frac{dE_{vac}}{dx\, d^2k_T}\, \Theta\left[z - \frac{Ex(1-x)}{k_T^2}\right]$$

$$-\frac{dE_{vac}}{dz} = \frac{C_R \alpha_s}{2\pi} E^2 \left[1 - \frac{Ez}{8} + \frac{(Ez)^2}{48}\right]$$

$$\Delta z \approx \frac{\Delta E_{vac}}{|dE_{vac}/dz|} \sim \frac{\ln(E/\mu)}{E}$$

Why does the rate of energy loss rise quadratically with energy?

DIS: The rate of energy loss in vacuum is constant and proportional to the hard scale,

$$\left(\frac{dE}{dz}\right)_{vac} = -\frac{3\alpha_s}{2\pi}\,Q^2 \qquad \text{(J.Nemchik, E.Predazzi\&B.K.1995)}$$

The stronger the hard kick is, the more intensive is gluon bremsstrahlung (JQ: radiates like a crazy).

For high-p_T parton production at the mid rapidity $Q^2 = p_T^2$, and $p_T = E$ is the jet energy.

- **Thus, the perturbative stage of high-p_T jet production is very short: gluons are radiated like a burst, almost instantaneously.**

Perturbative versus nonperturbative hadronization

How long does the gluon bremsstrahlung last, if it ends up by production of a leading hadron with $z_h \to 1$?

Energy conservation, like in the case of the string model, leads to a shrinkage of the production length towards $z_h = 1$,

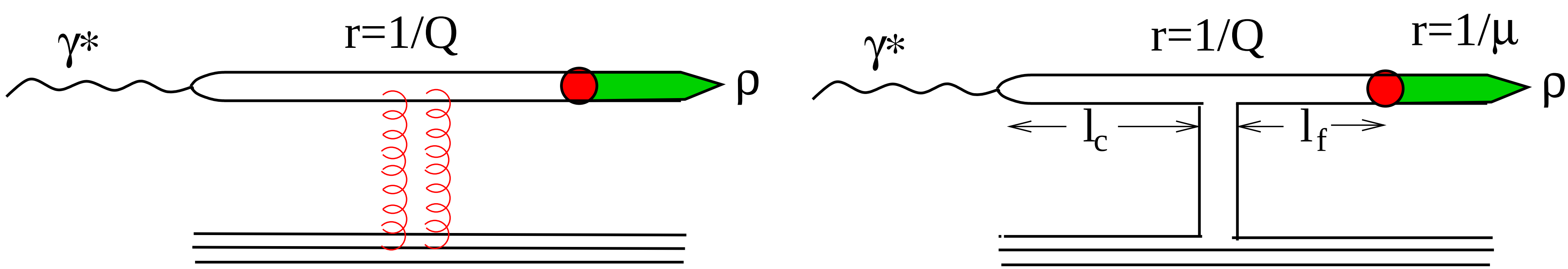
$$l_p = \frac{E}{|dE/dz|}(1 - z_h)$$

Here dE/dz includes both vacuum and induced energy losses. At high Q^2 the former is much larger than the latter, so $l_p \propto E/Q^2(1 - z_h)$.

At this distance energy loss stops, since a colorless and small, $r_T^2 \sim 1/Q^2$, dipole is produced which develops the hadronic wave function on much longer distance $l_f = 2Ez_h/\mu^2$.

Have we ever seen in data any evidence for such a perturbative hadronization?

Yes, this is the heart of the phenomenon called Color Transparency, which has been observed in a number of experiments, including HERMES.



Nuclear transparency rises with Q^2 indicating that a small perturbative pre-hadron was produced inside the nucleus.

This is the limiting case, $z_h \to 1$, of inclusive production.

The time scale of the leading pre-hadron production in high-p_T jet is even shorter than the radiation of the gluon burst,

$$t_p \sim \frac{\ln(E/\mu)}{E}\,(1 - z_h)$$

Medium induced radiation

Let's assume that whatever was said above is incorrect, and indeed it takes long time to neutralize the color, stop radiating and produce a colorless pre-hadron (this might be even true in DIS at small x).

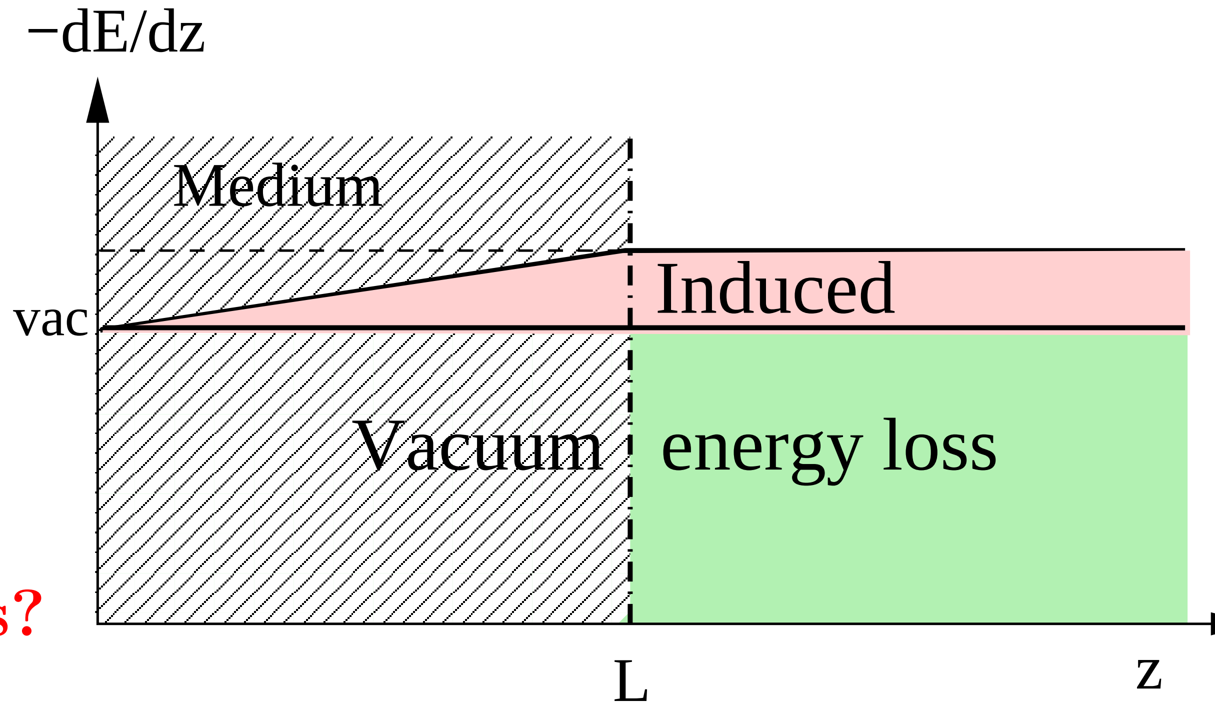
How would the fragmentation function modify in this case?

A quark propagating through a medium radiates more than in vacuum due to multiple interactions. Same as in vacuum, the rate of energy loss follows the accumulated kick from the medium, i.e. broadening of the transverse momentum (BDMPS),

$$-\frac{dE}{dz} = \frac{3\alpha_s}{4}\,\Delta p_T^2$$

Broadening of the transverse momentum of a jet linearly rises with number of collisions which is proportional to the path length and the medium density.

Thus, the rate of induced energy loss linearly rises with path length up to the medium surface.



What happens afterwards?

According to the Landau-Pomeranchuk principle, radiation at longer times does not resolve the structure of the interaction at the initial state. Important is the accumulated kick, and it dies not matter whether it was a single or multiple kicks. Therefore, the vacuum energy loss is continuing with a constant rate increased due to final state interaction.

As far as the parton created inside a medium loses more energy, than one produced in vacuum, the leading hadrons, $z_h \longrightarrow 1$ should be suppressed.

The modified fragmentation function

In order to incorporate the induced gluon radiation into the fragmentation function one needs a detailed knowledge of the hadronization dynamics. Lacking this one may rely on the unjustified, but popular procedure for the modification of the fragmentation function

$$\widetilde{D}_i^h(z_h, Q^2) = \int_0^1 \frac{d\epsilon}{1-\epsilon} W(\epsilon)\, D_i^h\left(\frac{z_h}{1-\epsilon}, Q^2\right) \;,$$

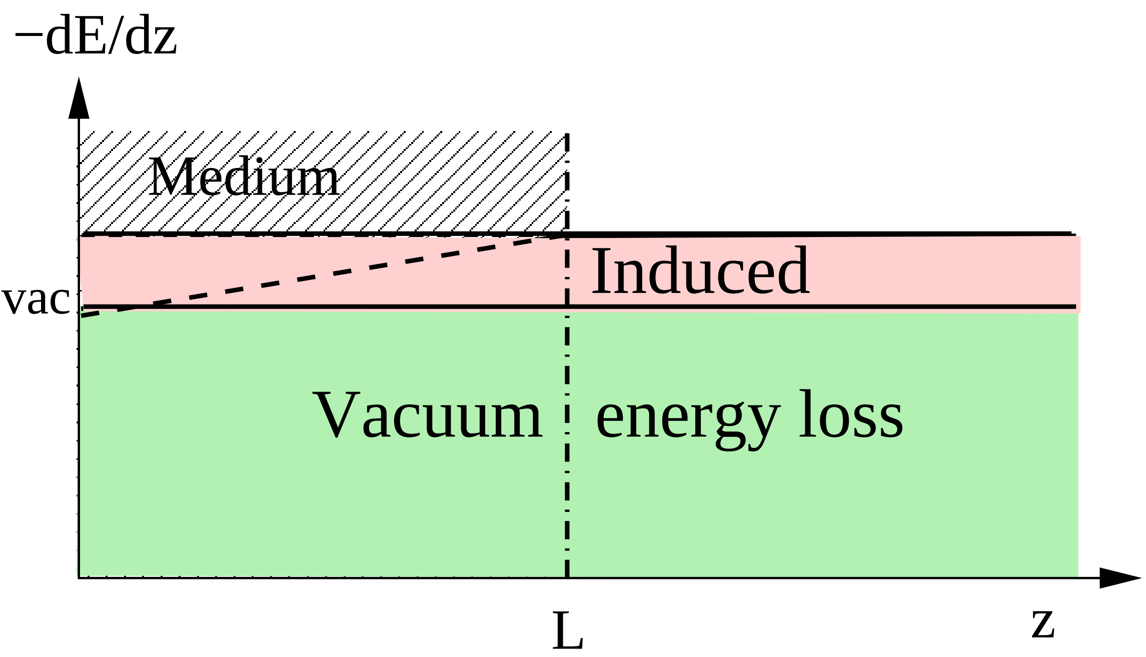
$W(\epsilon)$ is the induced energy loss distribution function.

This prescription assumes a two-stage hadronization: first induced energy loss in the medium, then hadronization which starts from the very beginning at the medium surface and continues in vacuum, but with a reduced starting energy.

Medium generated DGLAP evolution

In spite of lacking a good knowledge of the hadronization dynamics, one can impose an upper bound for the medium-induced suppression. This bound can be calculated precisely with no ad hoc procedures.

Let us increase the amount of induced energy loss assuming that its rate does not rise up to the maximal value near the medium surface, but starts with this maximal rate from the very beginning.



Since the induced energy loss is increased, the resulting suppression of leading hadrons can only be enhanced.

Thus, we arrived at a constant rate of energy loss which corresponds to hadronization in vacuum, but with increased scale $Q^2 \Rightarrow Q^2 + \Delta p_T^2$. The scale dependence of the fragmentation function can be calculated perturbatively by means of DGLAP equations

$$\widetilde{D}_i^h(z_h, Q^2) = D_i^h(z_h, Q^2) + \frac{\Delta p_T^2}{Q^2} \sum_j \int_{z_h}^{1} \frac{dx}{x} P_{ji}[x, \alpha_s(Q^2)] \, D_j^h(z_h/x, Q^2) \ ,$$

the splitting functions $P_{ji}[x, \alpha_s(Q^2)]$ are calculated perturbatively.

Although the DGLAP relation does not contain the induced energy loss explicitly, it is included. Indeed, the medium induces a harder scale which makes the energy loss more intensive. The difference is the induced energy loss which is $\propto \Delta p_T^2$ and present implicitly in the DGLAP.

One can use the phenomenological fragmentation function which obeys the DGLAP evolution and is fitted to data. For KKP parametrization,

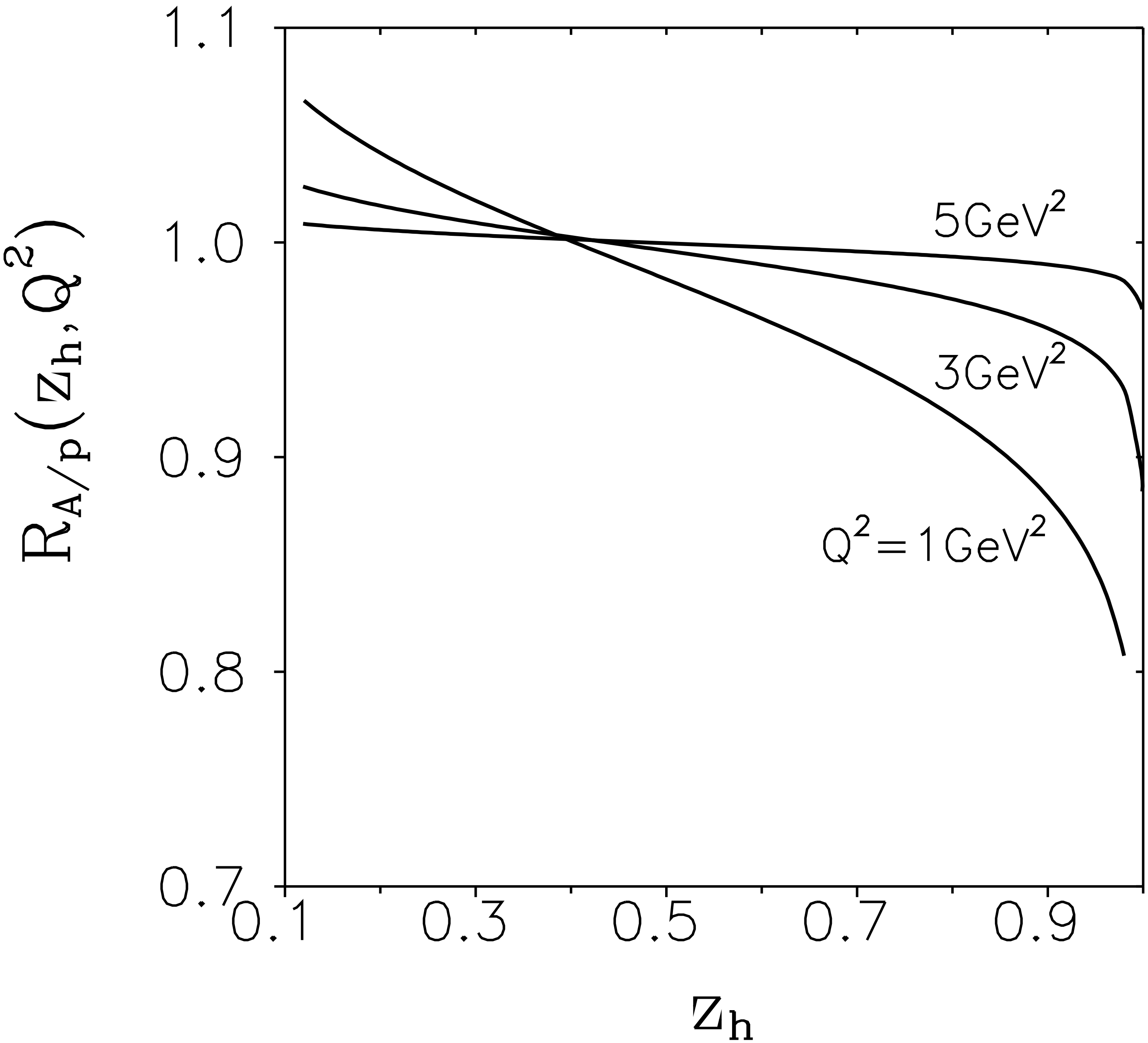
$$R(z_h, Q^2) \equiv \frac{\widetilde{D}_i^h(z_h, Q^2)}{D_i^h(z_h, Q^2)} \approx \left[\frac{(1-z_h)^{\lambda_1}}{z_h^{\lambda_2}}\right]^{\frac{\Delta p_T^2}{Q^2 \ln(Q^2/\Lambda^2)}}$$

For pion production by light quarks

$$\begin{aligned} \lambda_1(Q^2) &= 0.64 + 0.15\bar{s} - 0.51\bar{s}^2 \\ \lambda_2(Q^2) &= 0.3 + 0.04\bar{s} + 0.38\bar{s}^2 \end{aligned}$$

$$\bar{s} = \ln\left[\frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)}\right] \; ,$$

$$Q_0^2 = 2\,\mathrm{GeV}^2, \; \Lambda = 213\,\mathrm{MeV}$$



Ratio of the nuclear-modified to vacuum fragmentation functions calculated for lead.

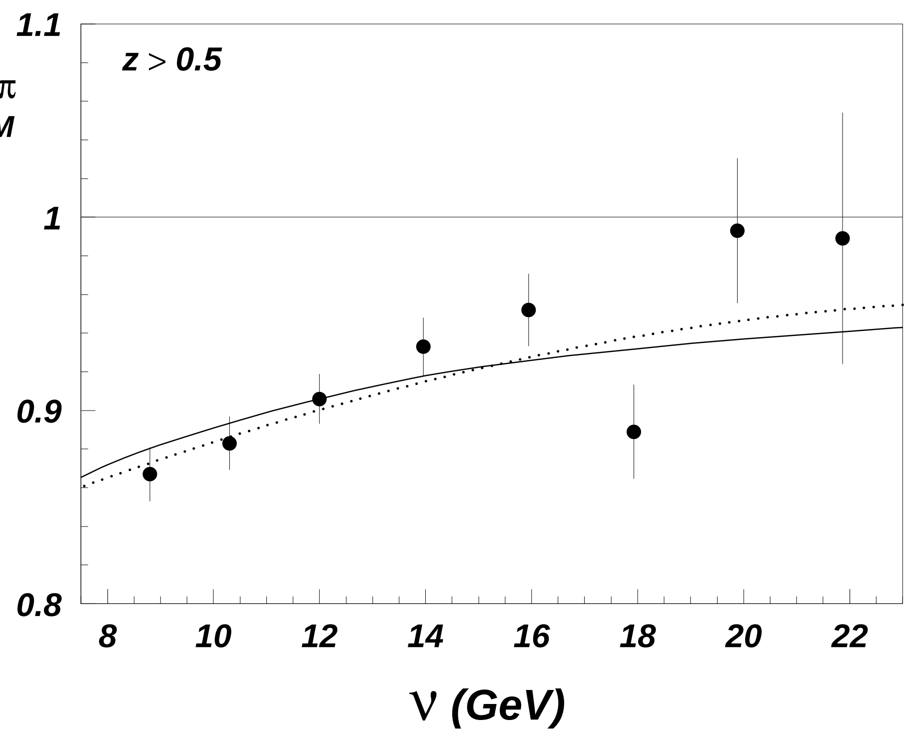
Thus, the energy loss scenario leads to an incorrect interpretation of nuclear suppression in inclusive hadron production in DIS and heavy ion collision.

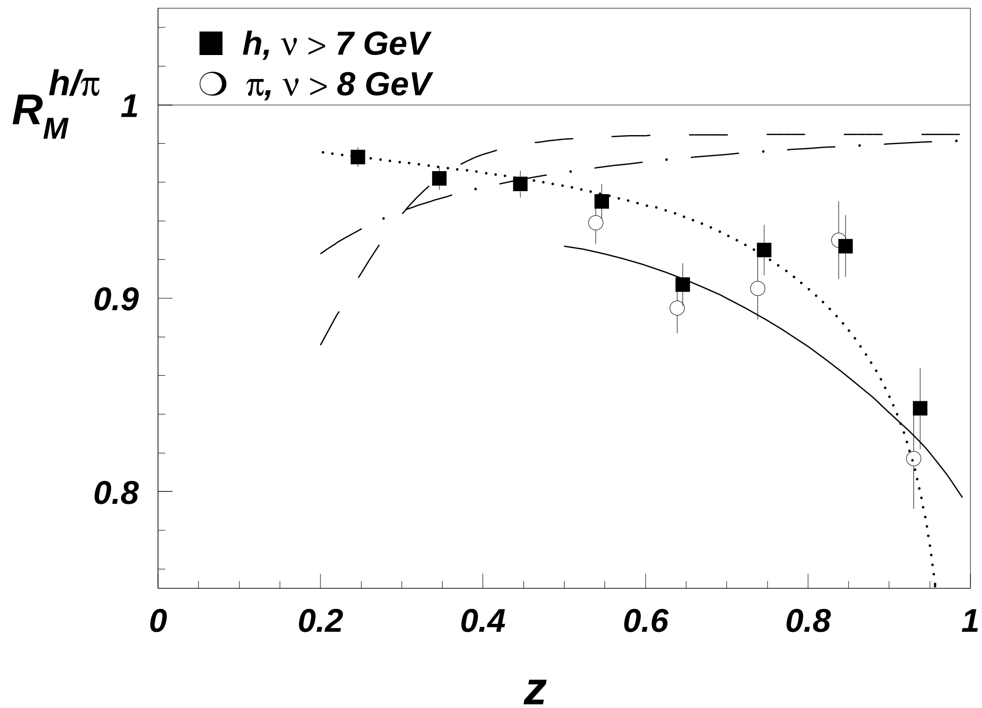
- **The color neutralization length is rather short and, in particular, is vanishing for jets produced in heavy ion collisions. There is no room for induced energy loss**

- **Even if the perturbative stage of hadronization were long (like in DIS at small x), the usual recipe for modification of the fragmentation function is incorrect and grossly overestimates the nuclear effects. The precise upper bound for the effects of induced energy loss is far too weak to explain the observed hadron suppression in DIS on nuclei and in heavy ion collisions.**

If so, where does the suppression come from ?

Absorption of the pre-hadron propagating through the medium well explains the nuclear suppression observed by HERMES, EMC and at JLAB.





Solid curves are the parameter-free prediction made 5 years prior the experiment.

A cold nuclear matter is an example of rather delute medium. What happens in the limit of very dense medium which is likely to be created in heavy ion collisions?

A tiny dipole (pre-hadron) of a size $r^2 \sim 1/p_T^2$ is produced. This initial size is not important, but what is important is the jet energy. The dipole is expanding with transverse momentum $p_T \sim E$ and longitudinal momentum $p_L \sim E$. Therefore it will evolve almost instantaneously. However, the longitudinal energy E is able to freeze sizes $r^2 > L/E$ over a path length L. This L-dependent effective size of the dipole cotrols the absorption factor,

$$S(L) = \exp\left(-\frac{C\,L^2\,\rho}{E}\right)$$

In the limit of very dense medium $\rho \to \infty$ the nuclear suppression factor seems to vanish, $R_{AA} \to 0$, since only the very surface of the medium contributes.

However, one should not rely on mean values when the result is so small, **fluctuations** are to be included. The vacuum energy loss fluctuates and the production length l_p has a distribution. The tail of this distribution starts working for a dense medium. The nonzero probability to propagate distance l_p with no radiation,

$$W(l_p) = e^{-\langle n_g(L)\rangle} \propto l_p^{-\ln(E/\Lambda)} \tag{1}$$

Then

$$R_{AA} \propto \frac{1}{\ln(E/\Lambda) - 1} \tag{2}$$

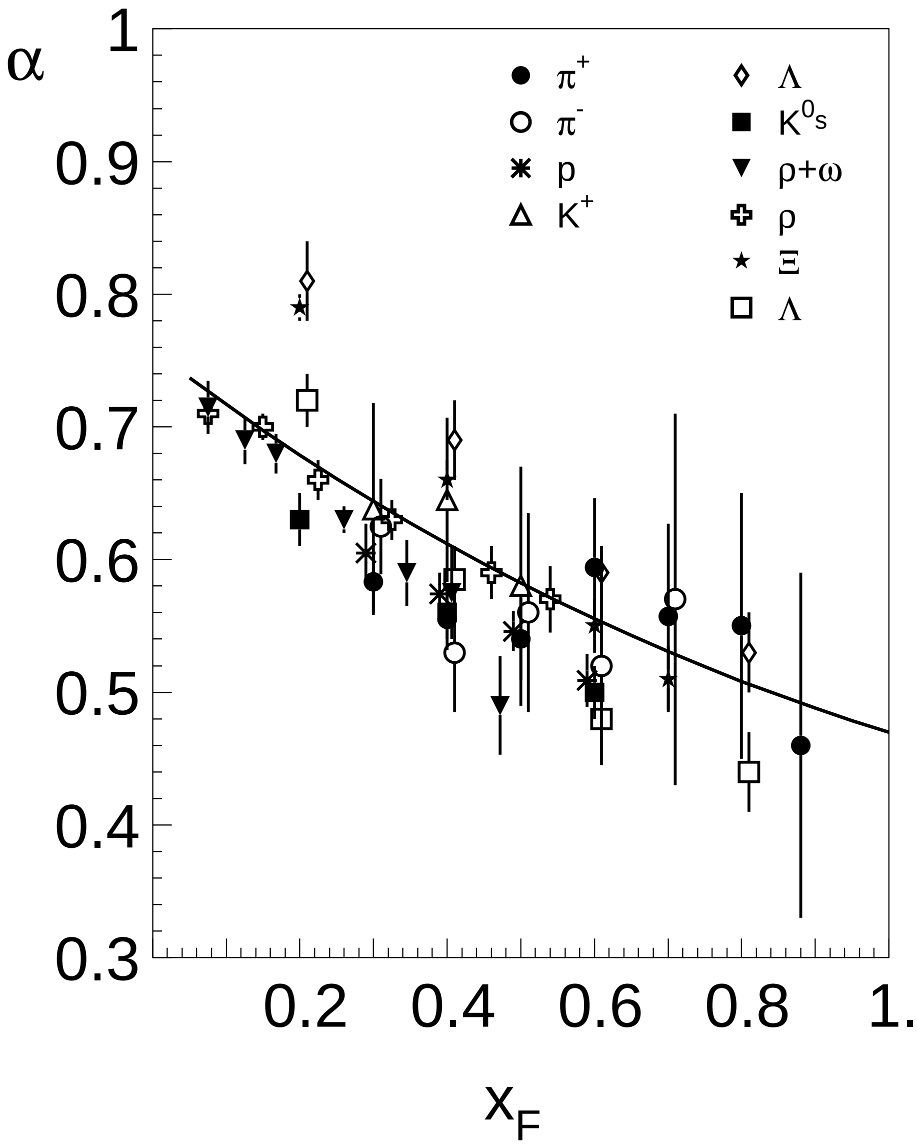
Thus, dependent on the medium density one can get any p_T dependence of nuclear suppression, from rising (delute medium) ddown to steeply falling (dense medium).

Obvious expectations: a universal flavor-independent suppression at high p_T, same suppression for pairs as for a single hadron, large v_2, etc.

On the contrary to the energy loss scenario, a falling p_T-dependence of R_{AA} is expected at LHC.

Induced energy loss proportional to energy

If the energy is high compared to virtuality (small x), induced energy loss may be important.



A-dependence of leading hadron production in pA collisions at energies $E_{lab} = 40 - 400\,\text{GeV}$.

Nuclei are able to resolve higher Fock states compared to a proton target. The higher Fock states expose a steeper fall of at $x_1 \to 1$, this is why the ratio $R_{A/p}(x_1)$ drops at $x_1 \to 1$.

Every rescattering inside the nucleus brings an extra Sudakov suppression factor

$$S(x_F) = (1 - x_F)^{dn_G/dy} \ . \tag{3}$$

The height of the gluon plateau was estimated by Gunion and Bertsch

$$\frac{dn_G}{dy} = \frac{3\alpha_s}{\pi} \ln\left(\frac{m_\rho^2}{\Lambda_{QCD}^2}\right) \approx 1 \ . \tag{4}$$

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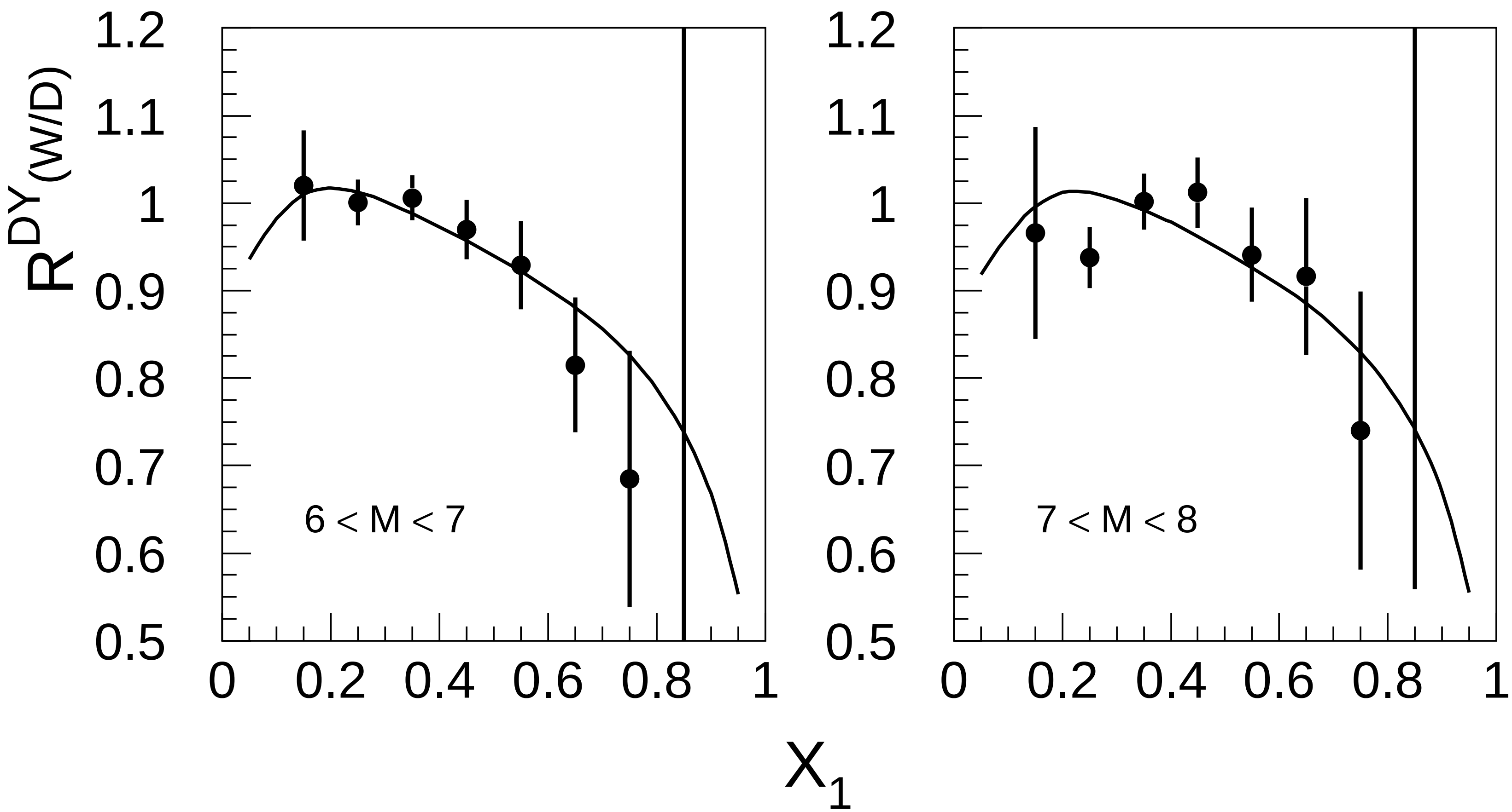
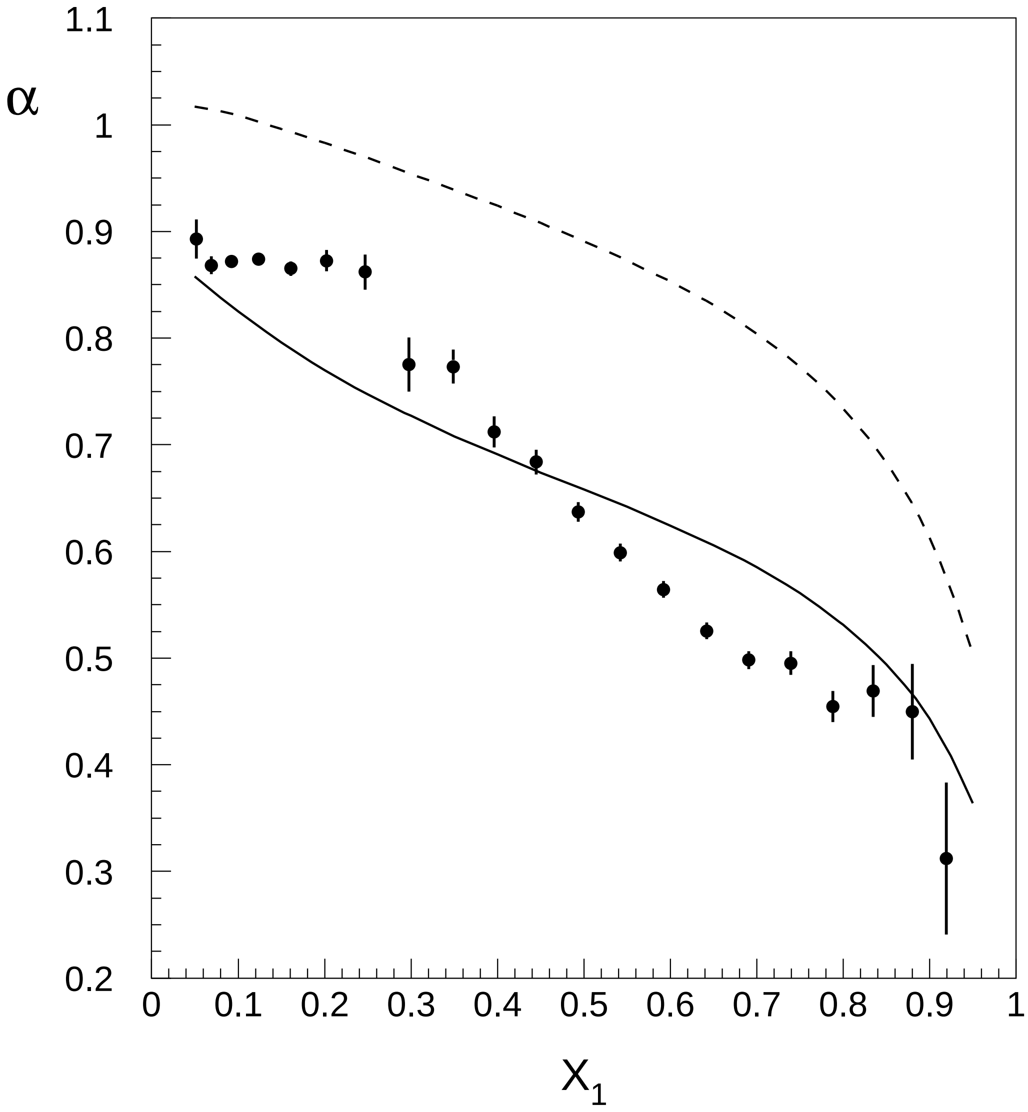
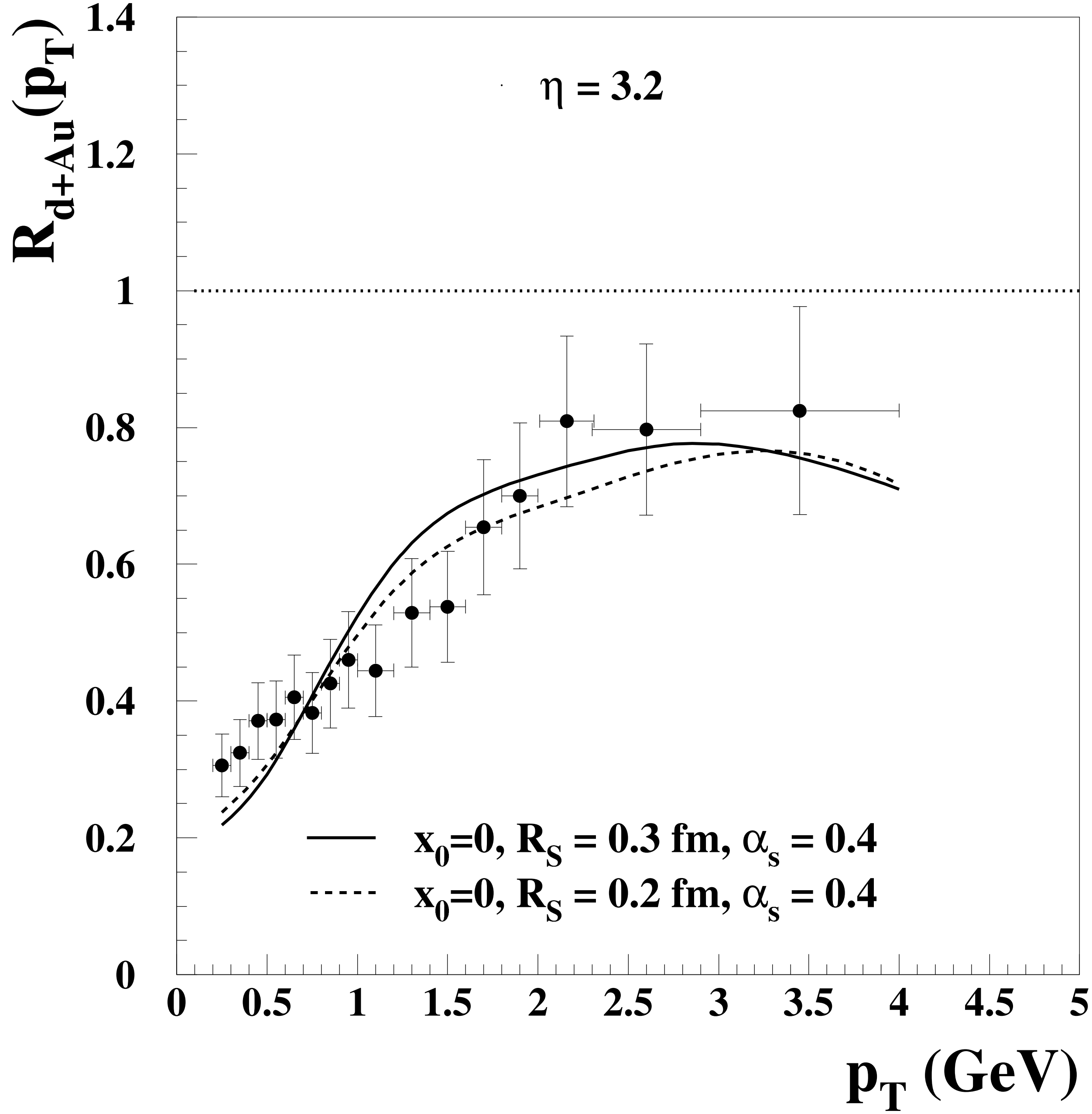
Nuclear suppression of Drell-Yan pairs in pA collisions.



Nuclear suppression of J/Ψ in pA collisions.



Cronin effect at forward rapidities.



Conclusions

- **The time scale of vacuum gluon radiation in high-p_T jets is very short $\sim 1/p_T$.**
- **The production time of leading pre-hadrons is even shorter, $l_p \sim (1 - z_h)/p_T$**
- **Maximizing the induced energy loss one can reach a calculable upper bound for the modification of the fragmentation function. It shows that the effects of induced energy loss are far too weak to explain the observed nuclear suppression of leading hadrons.**
- **The popular ad hoc prescription for incorporation of the induced energy loss into the modified fragmentation function grossly overestimates the upper bound for nuclear suppression.**

- **Shortness of the production (color neutralization) length is the main source of nuclear suppression of leading hadrons observed in DIS.**
- **Dependent on medium density the nuclear suppression ratio can either rise with p_T (delute medium), or fall (dense medium). In the latter case fluctuations of the vacuum energy loss play major role.**
- **There is room for induced energy loss in production of leading particles at high energies and not very large virtualities. The effective induced energy loss turns out to be proportional to energy.**