Jet Time Evolution and Perturbative Hadronization

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In collaboration with

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OUTLINE

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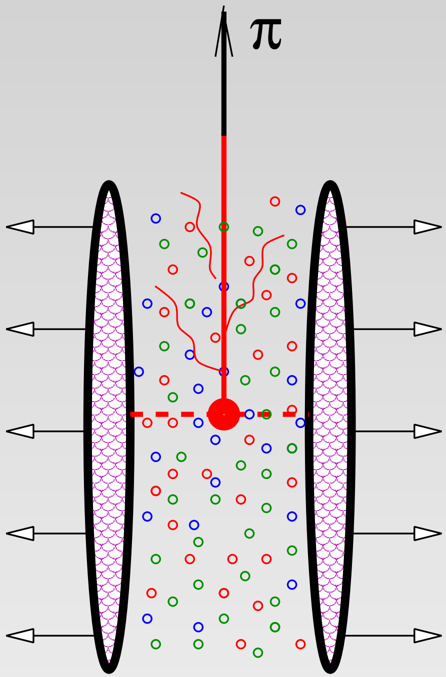
- Upper bound for the effect of induced energy loss
- High-p_T hadrons in heavy ion collisions: More energetic partons hadronize faster

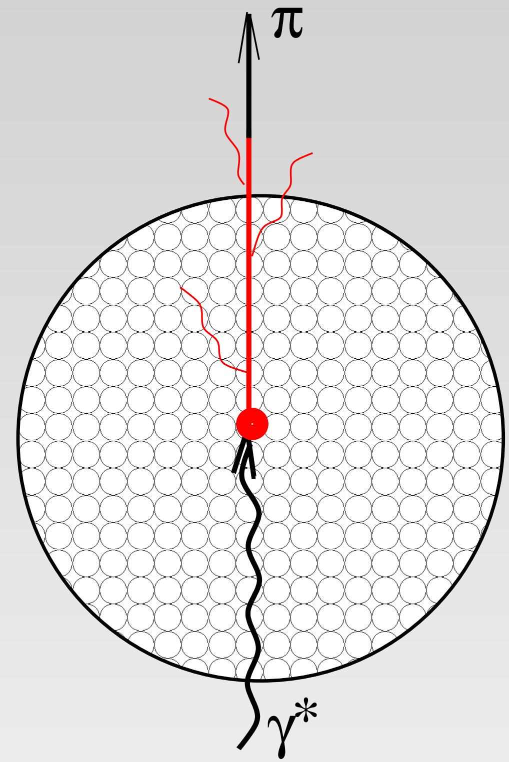
Jet quenching in heavy ion collisions and DIS on nuclei



RHIC − LHC

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

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

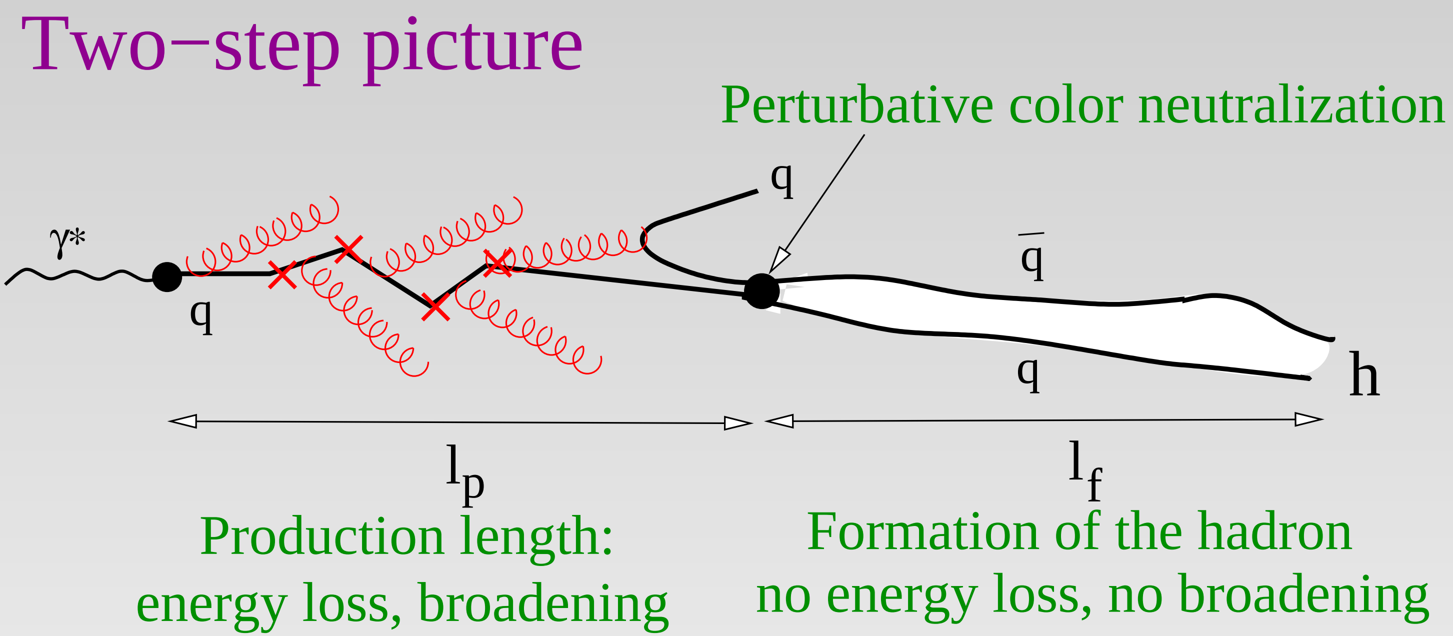


HERMES − JLAB

$E_\pi < 20$ GeV/c

The density, geometry, kinematics are known. Q^2 and ν are uncorrelated. The best model-killer!

Jet quenching in DIS



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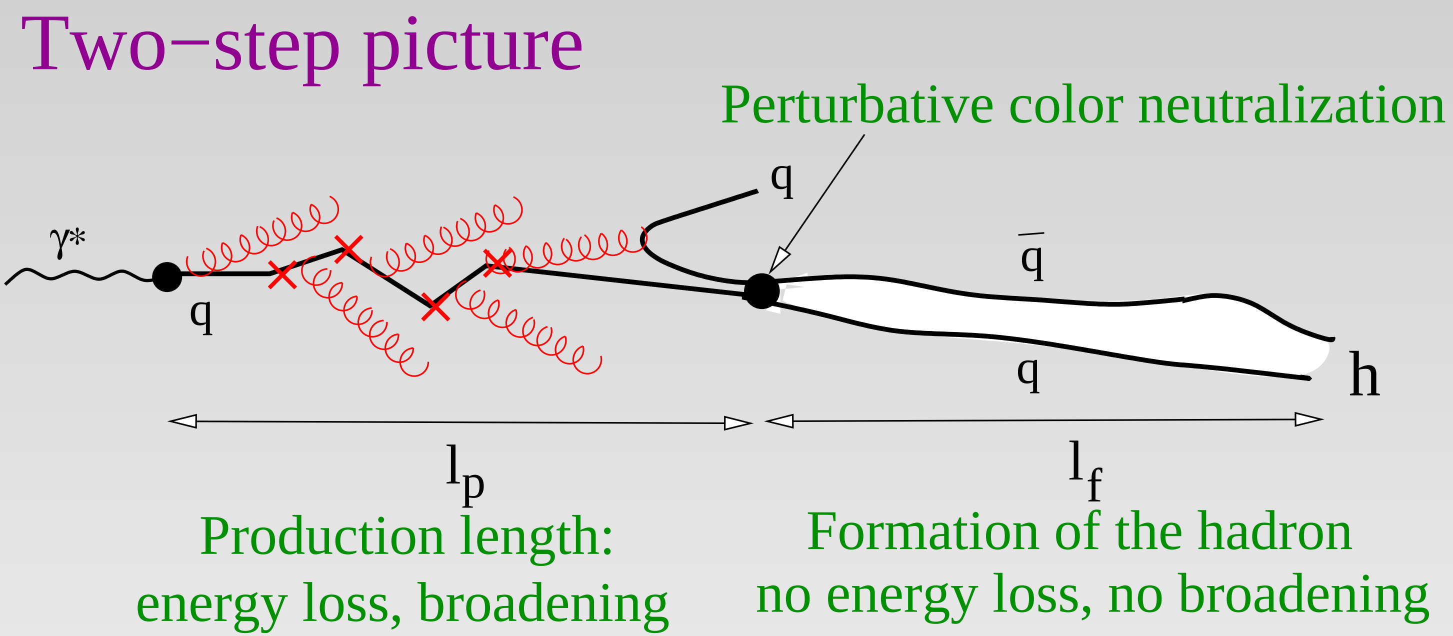

Two sources of jet quenching:

(i) energy loss of the parton prior production of a pre-hadron (no absorption);

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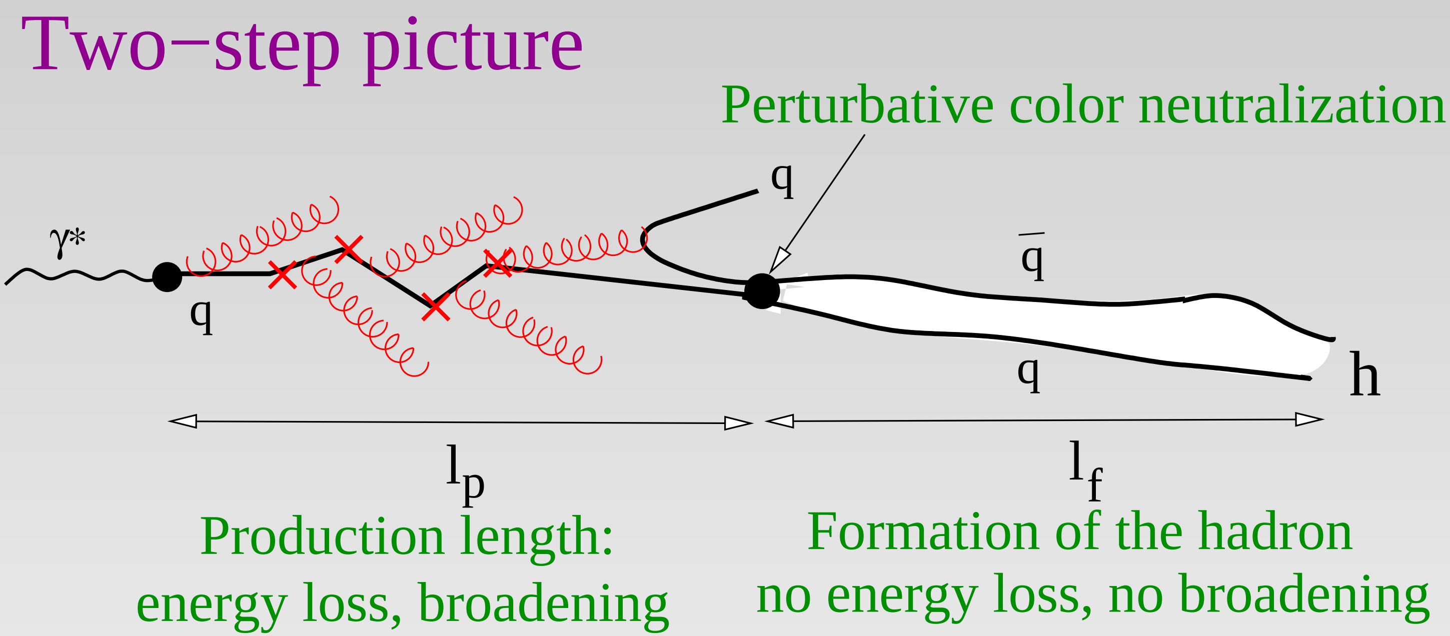

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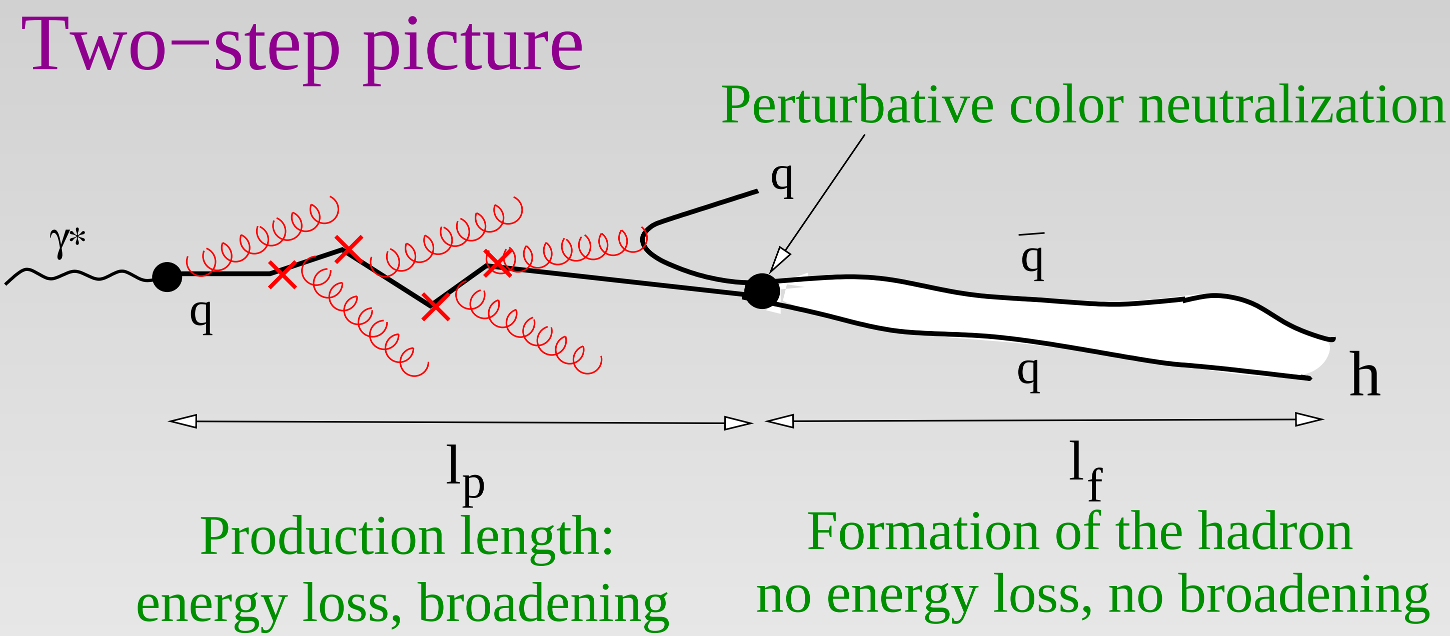

Two sources of jet quenching:

(i) energy loss of the parton prior production of a pre-hadron (no absorption);

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

In the energy loss scenario one assumes (ad hoc) that color neutralization always happens outside of the medium

$l_p \gg R_A$

Jet quenching in DIS

If the hadron takes the main fraction of the jet energy,

$$z_h = \frac{E_h}{E_{\gamma^*}} \longrightarrow 1\,,$$

then energy conservation becomes an issue:

$$l_p\,\frac{dE}{dz} < E_{\gamma^*}\,(1 - z_h)$$

The main contribution to the rate of energy loss, $\frac{dE}{dz}$ comes from vacuum energy loss which follows the strong kick given to the quark in DIS.

$$\left.\frac{dE}{dz}\right|_{vac} = \frac{2\alpha_s}{3\pi}\,Q^2$$

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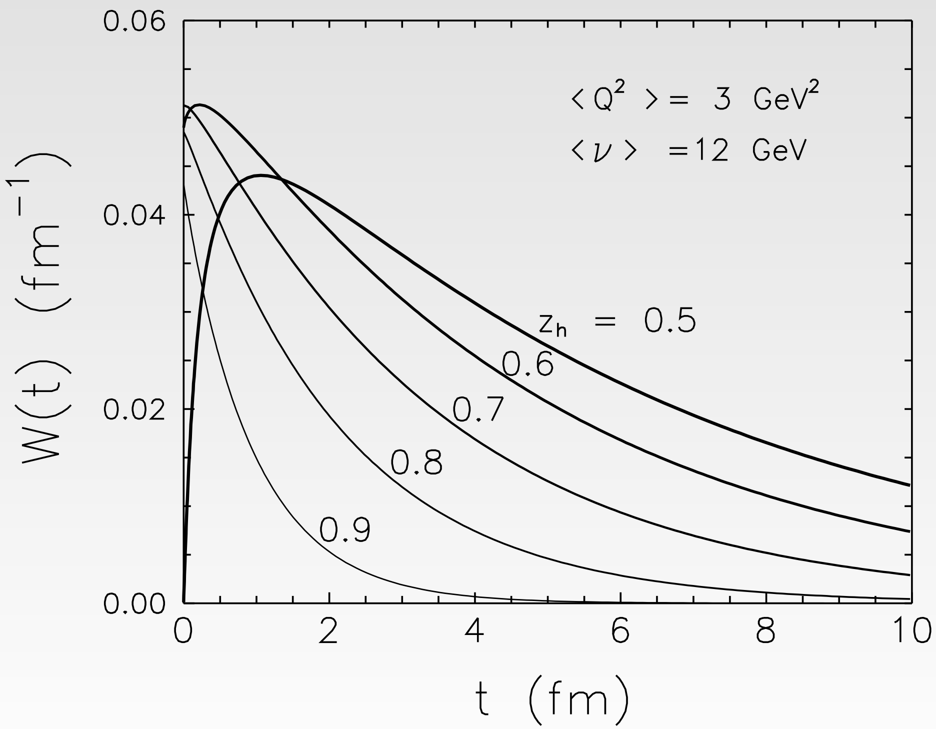
Jet quenching in DIS

Thus, the mean production length rises with E_{γ^*}, but it contracts as function of the hard scale Q^2 and z_h,

$$\langle l_p \rangle \leq \frac{3\pi}{2\alpha_s} \frac{E_{\gamma^*}}{Q^2} (1 - z_h)$$

The amount radiated energy fluctuates, and l_p may be rather long, even if $\langle l_p \rangle$ is vanishing.



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Perturbative hadronization

The production and formations times are frequently mixed up. The former, $\boldsymbol{l_p}$, is the time of color neutralization, while the latter, $\boldsymbol{l_f}$, is the time scale for formation of the hadronic wave function.

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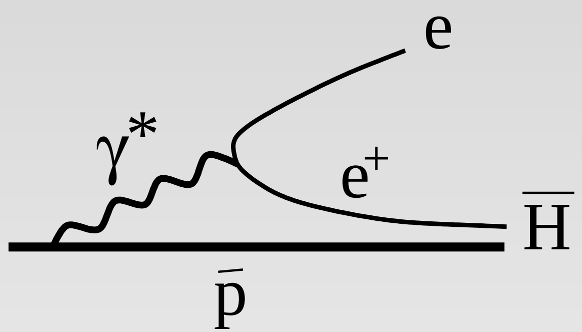
- QED analog for perturbative hadronization: production of antihydrogen



S.Brodsky, Ch.Munger, I.Schmidt

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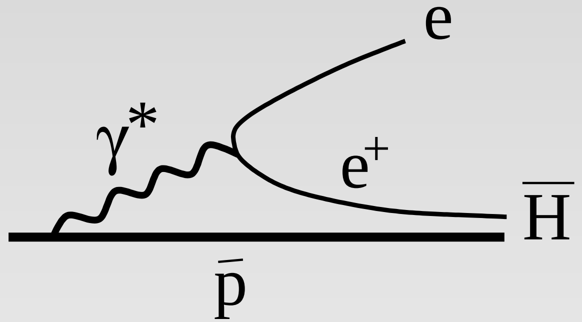
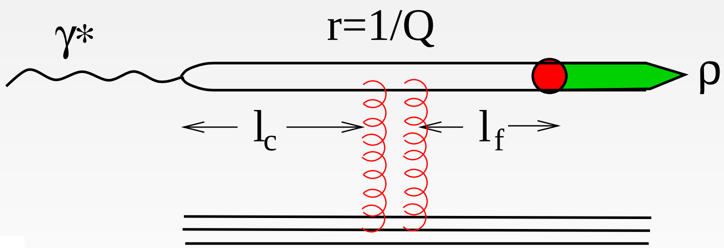
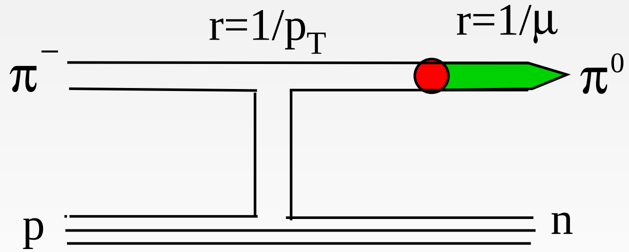


S.Brodsky, Ch.Munger, I.Schmidt

- In QCD perturbative hadronization leads to **Color Transparency** which has been well detected in data





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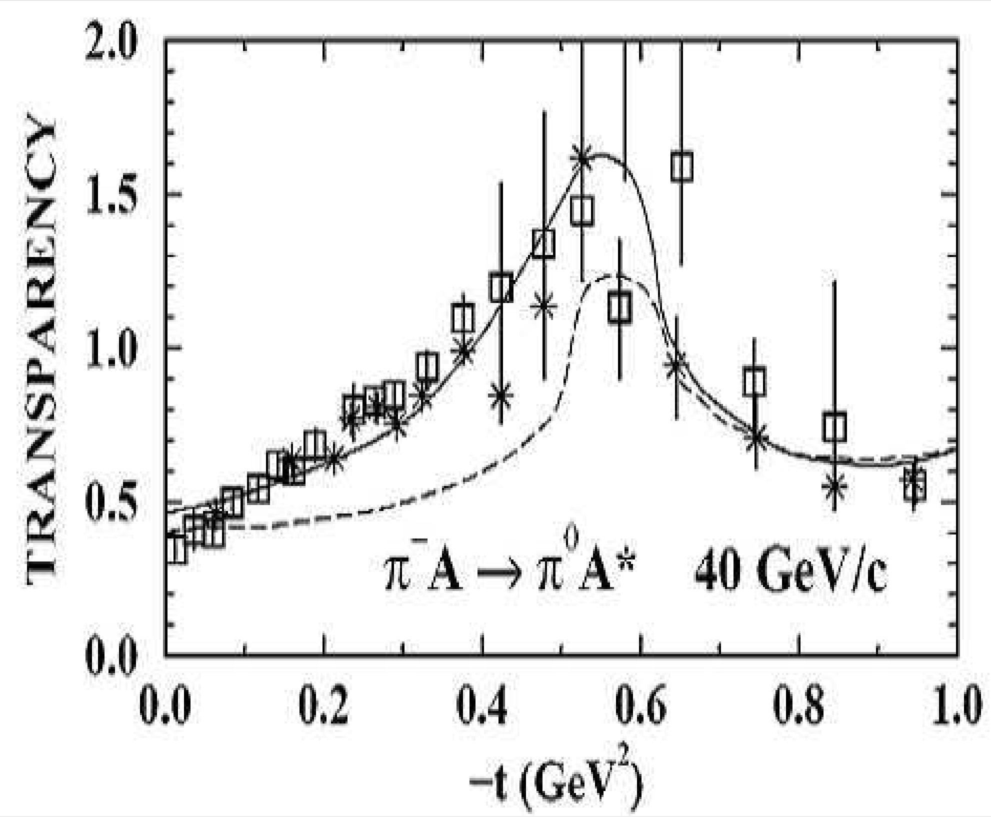
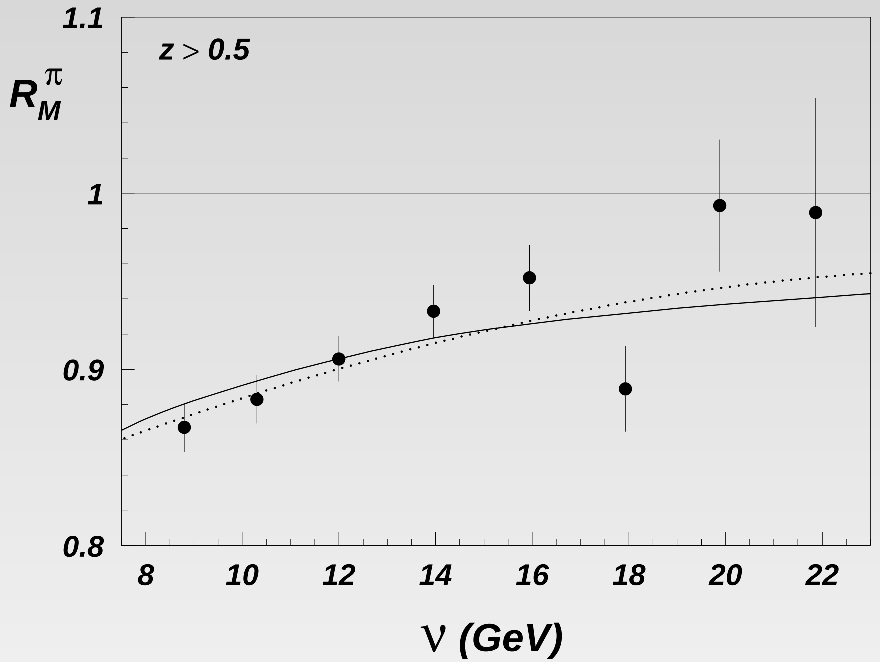
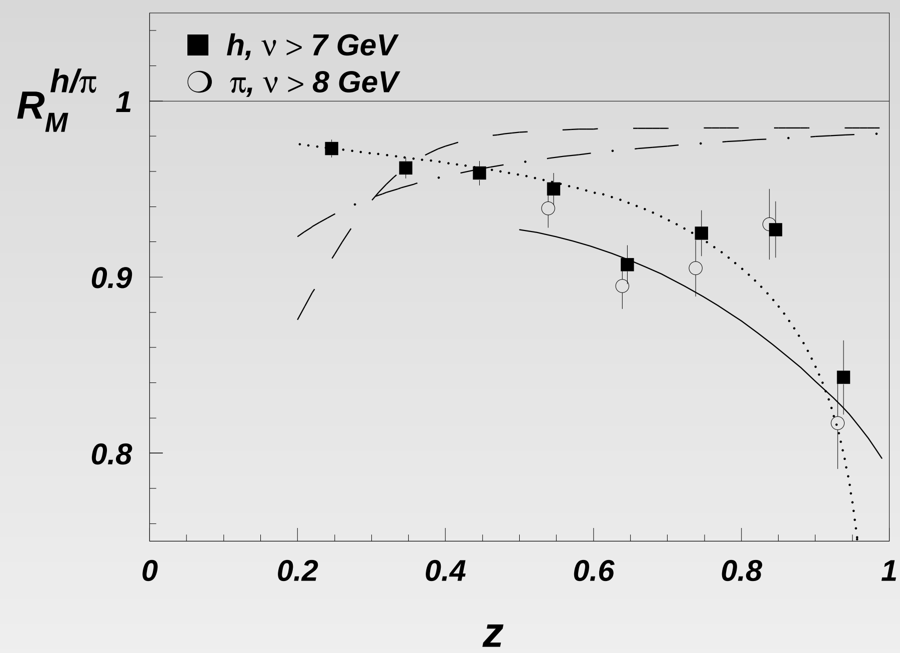


Hadronization at $z_h \longrightarrow 1$: quasi-free charge exchange pion scattering at large p_T, in nuclear environment, π^-"p" $\longrightarrow \pi^0 n$. Comparison with the Glauber model expectation (dashed) is an evidence for a perturbative dipole, rather than pion, propagating through the nucleus.

Jet quenching in DIS

The HERMES data have been well predicted by this model.





Predictions KNP-1995 (solid curves) and HERMES data for nitrogen.

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Jet quenching in DIS

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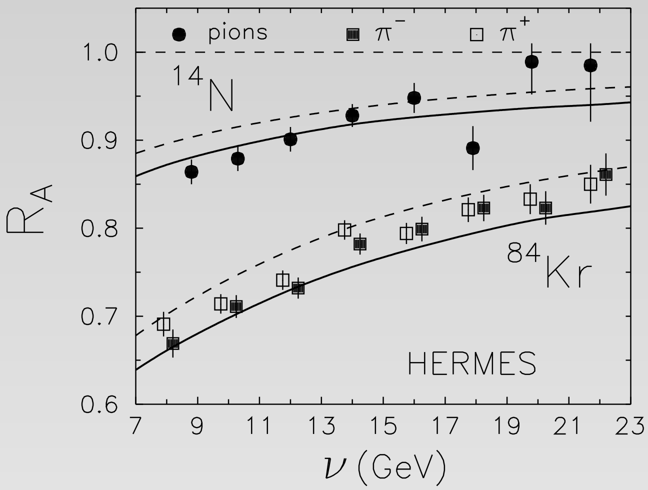

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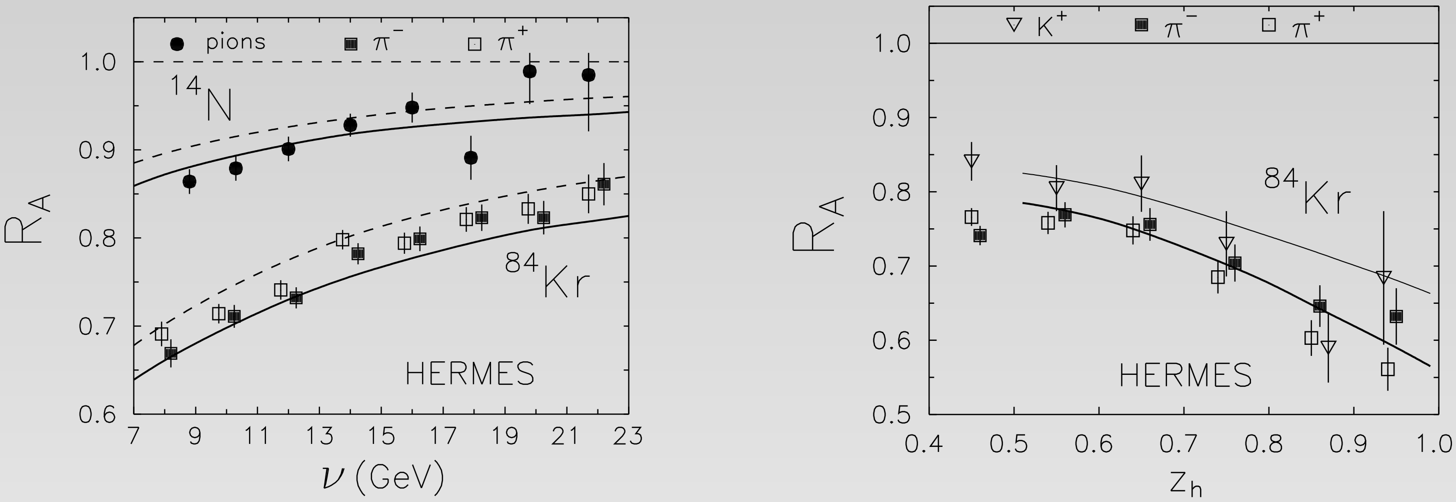

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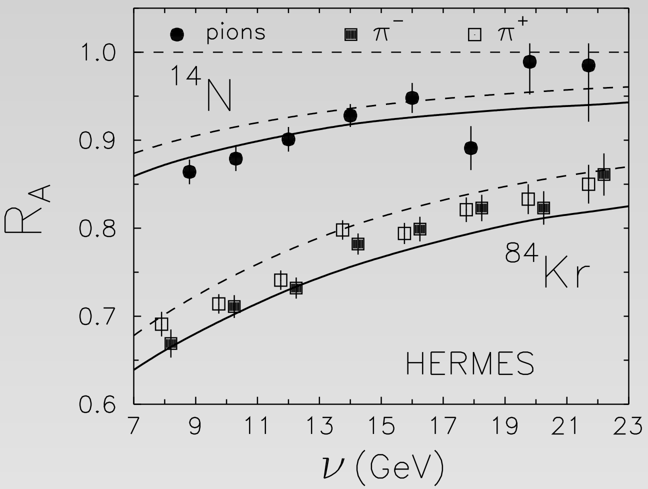

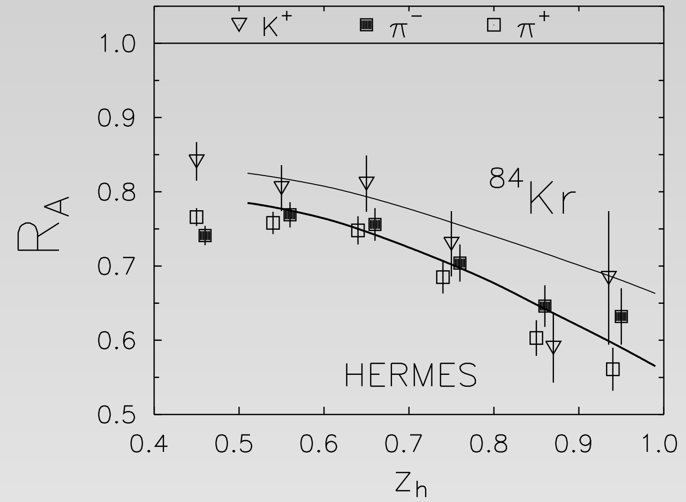

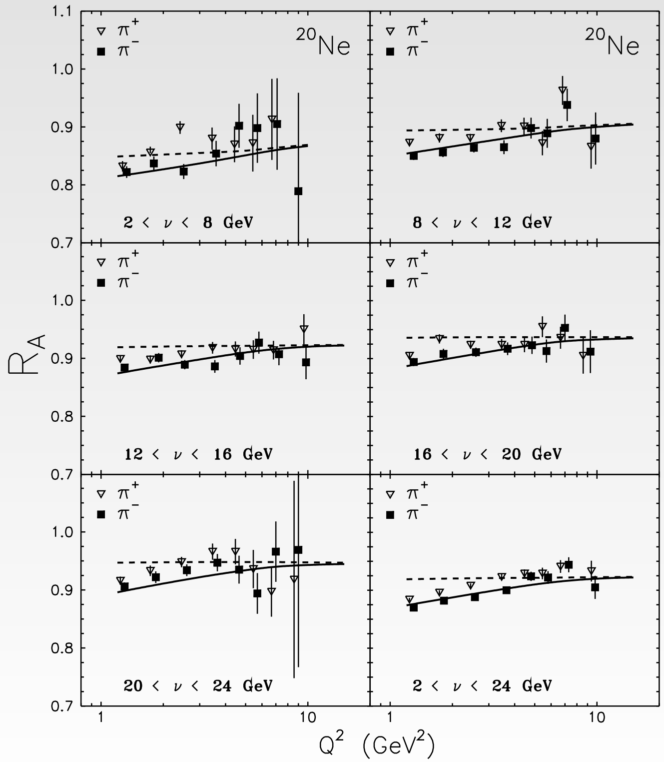

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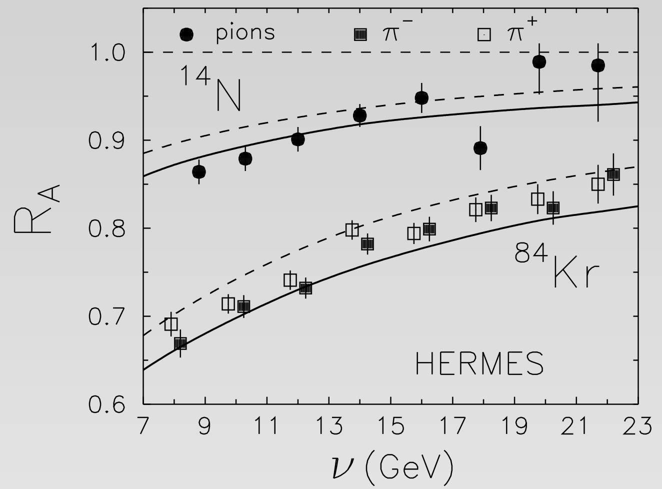

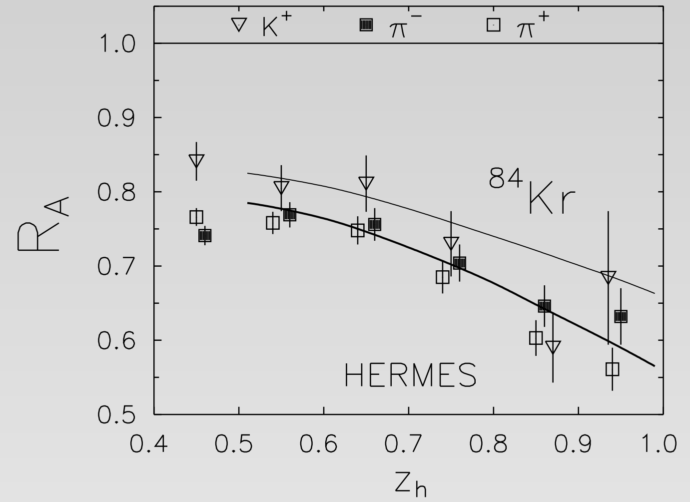

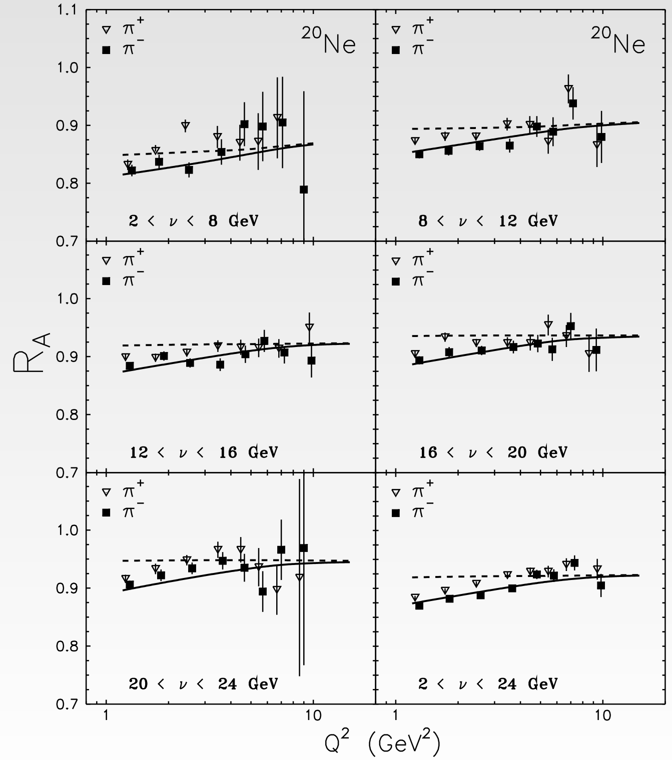

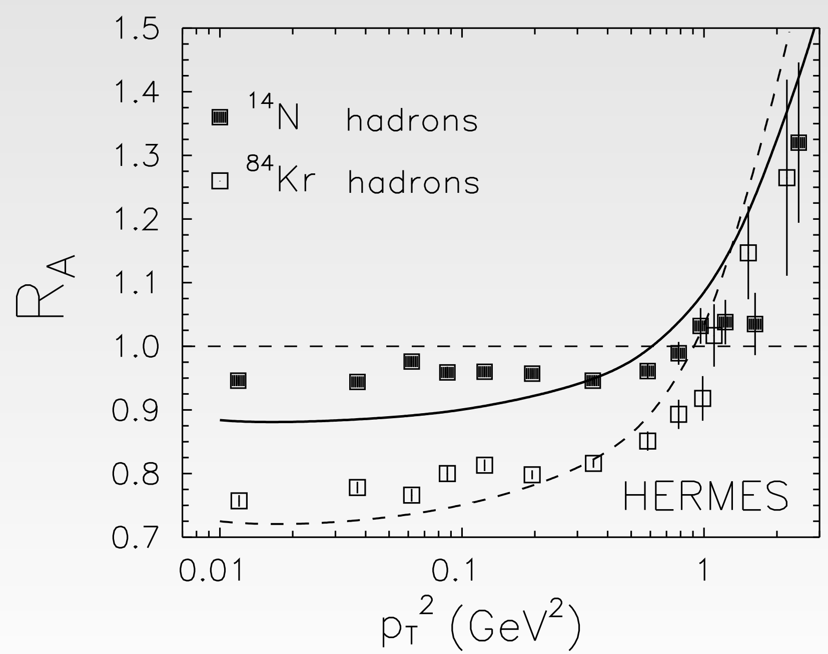

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Nuclear broadening of p_T

M.Johnson, BK, A.Tarasov
PR C63(2001)035203

$$\frac{dN_q}{d^2k_T} = \int d^2r_1\, d^2r_2\, e^{i\,\vec{k}_T\,(\vec{r}_1-\vec{r}_2)}\, \Omega^q_{in}(\vec{r}_1,\vec{r}_2)\, e^{-\frac{1}{2}\,\sigma(\vec{r}_1-\vec{r}_2,x)\,T_A(b)}$$

Dipole cross section $\sigma(r_T, x)$ is fitted to data for $F_2^p(x, Q^2)$. $\Omega^q_{in}(\vec{r}_1,\vec{r}_2)$ is the density matrix describing the impact parameter distribution of the quark in the incident hadron,

$$\Omega^q_{in}(\vec{r}_1,\vec{r}_2) = \frac{\langle k_0^2\rangle}{\pi}\, e^{-\frac{1}{2}(r_1^2+r_2^2)\langle k_0^2\rangle}\ ,$$

where $\langle k_0^2\rangle$ is the mean value of the parton primordial transverse momentum squared.

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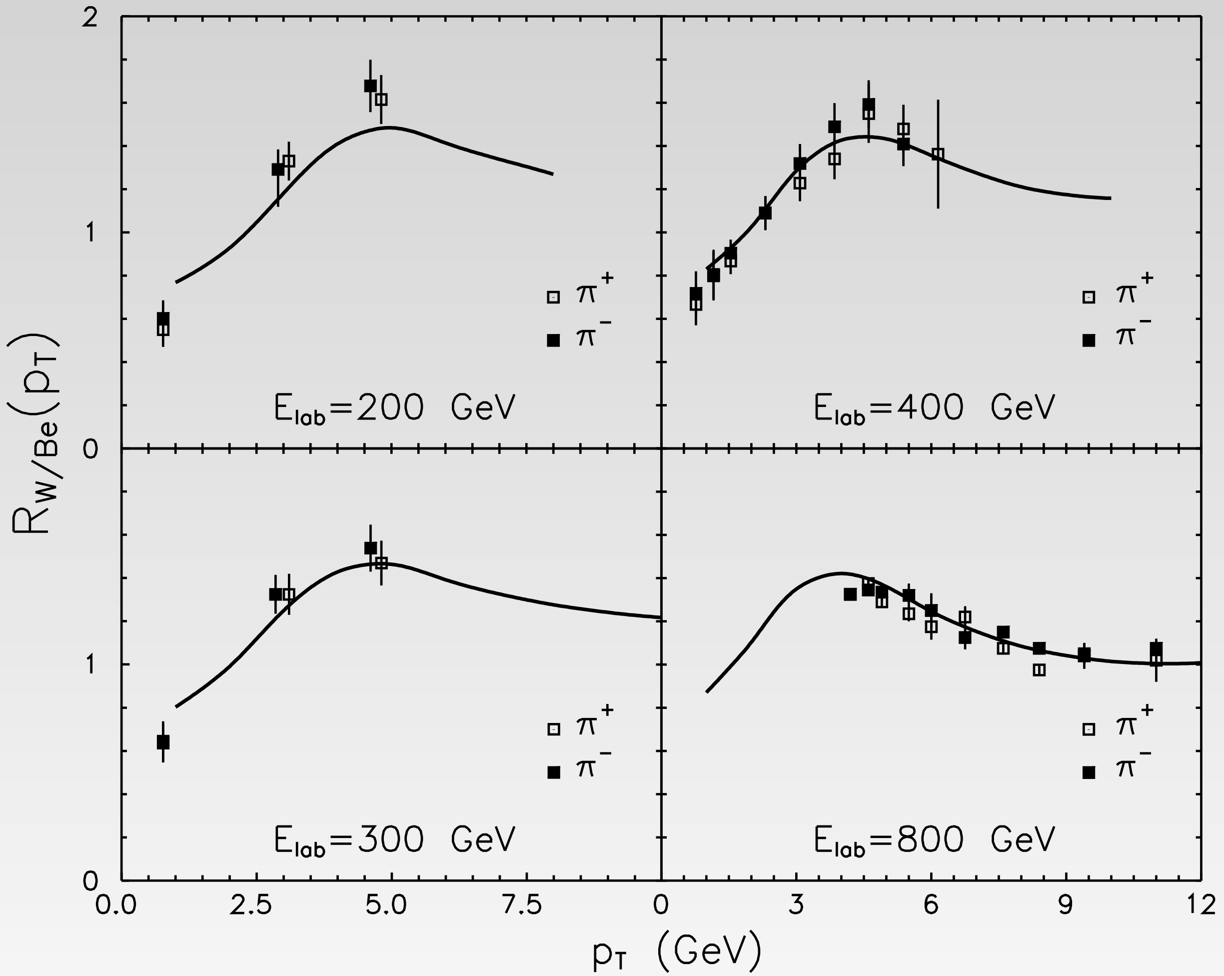
Cronin effect in pA collisions

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



No fit to the data to be explained.

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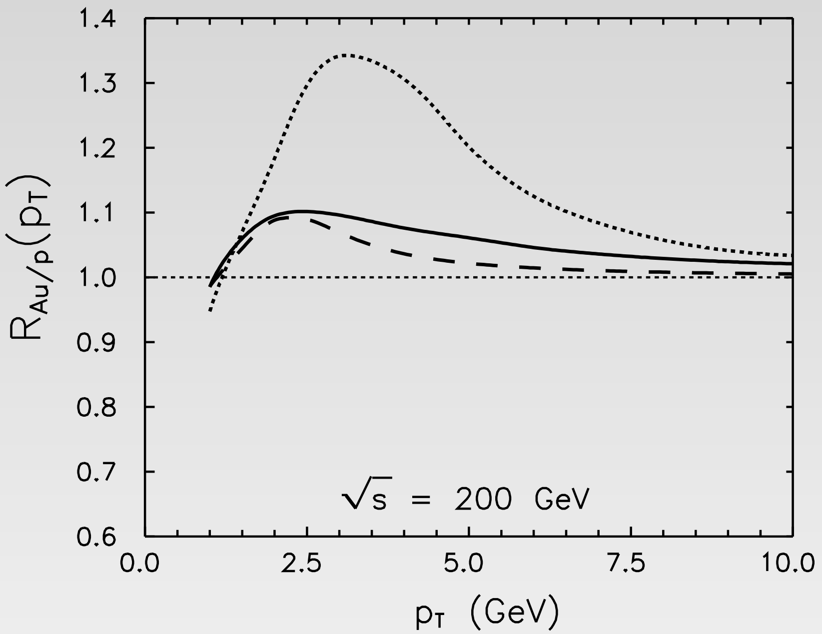
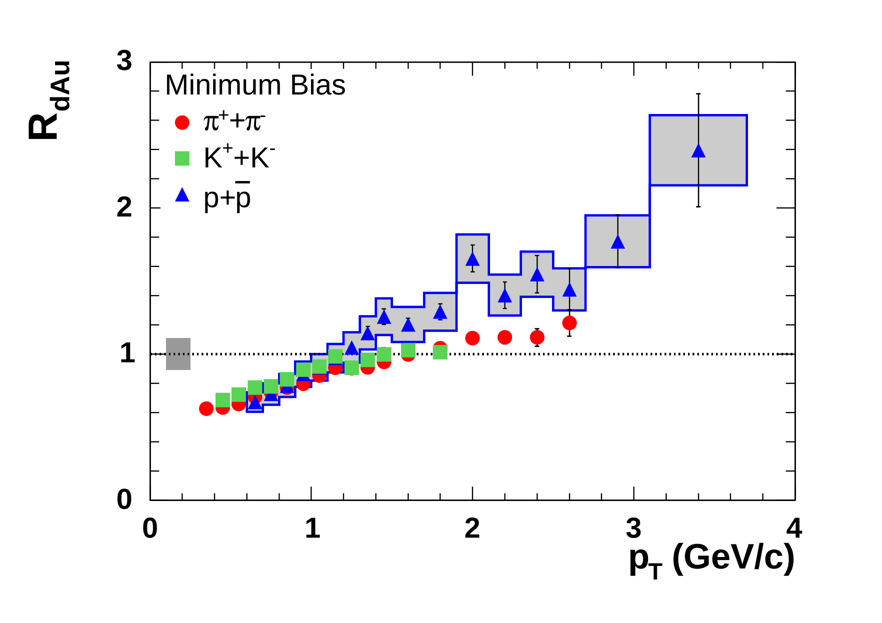
Cronin effect at RHIC



A much weaker Cronin enhancement was predicted for RHIC.



PHENIX results

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Jet quenching in DIS

What would be a smoking gun measurement for $\boldsymbol{l_p}$?

Jet quenching in DIS

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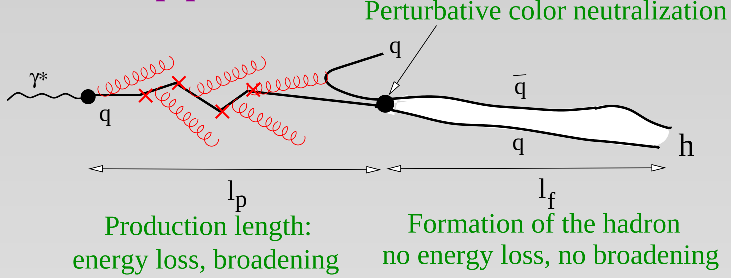
Since $\Delta p_T^2 \propto l_p$, broadening provides direct information

Two−step picture



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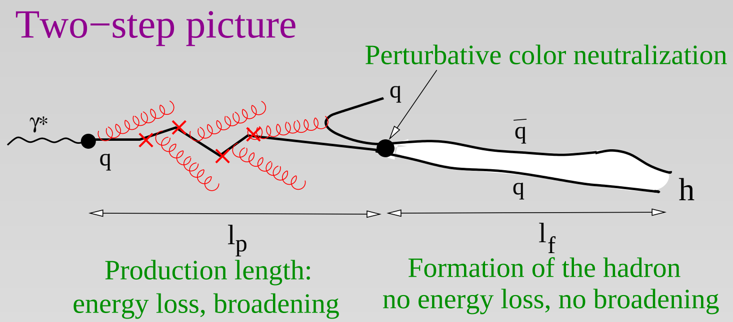

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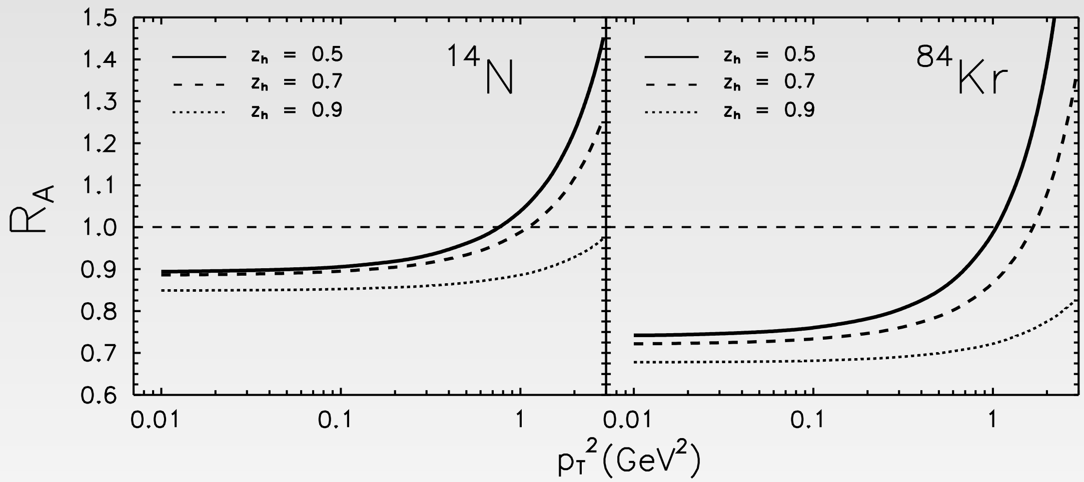

Expectations for HERMES

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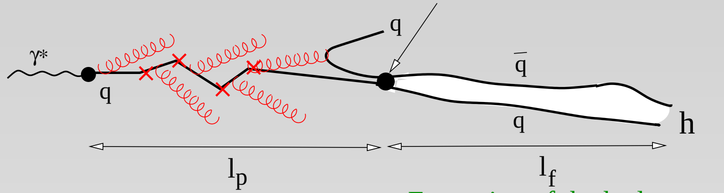

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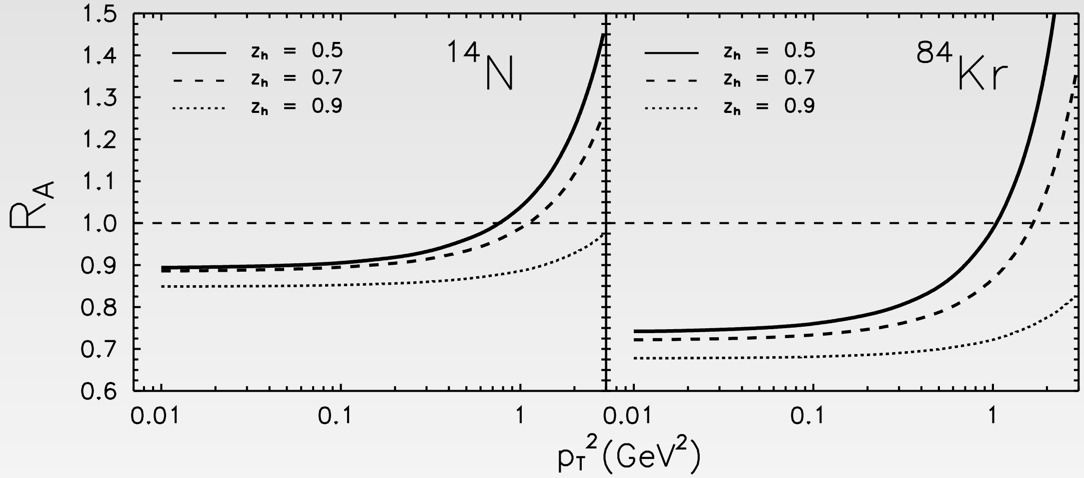

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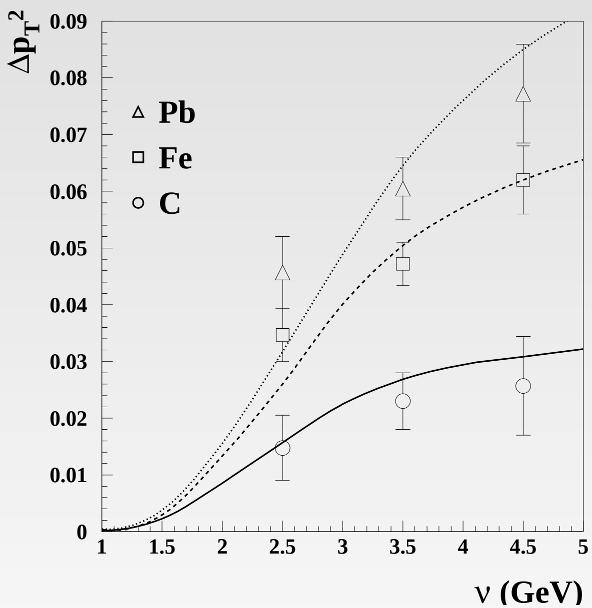

Preliminary results from CLAS & preliminary calculations.

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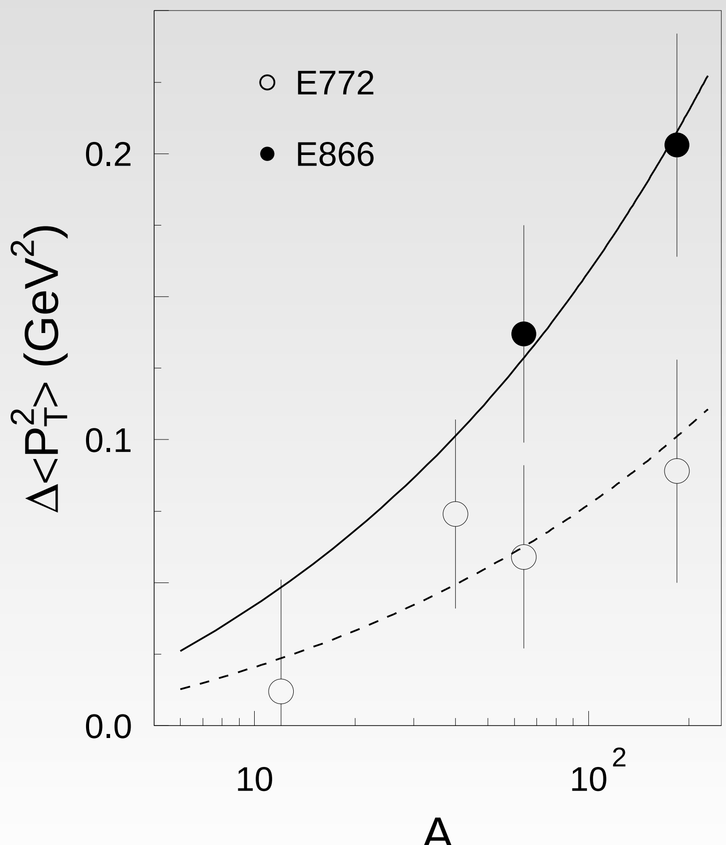
Induced energy loss in DIS

The rate of medium-induced energy loss is very small,

$$\left.\frac{dE}{dz}\right|_{ind} = \frac{3\alpha_s}{8}\,\Delta p_T^2 \qquad \text{(BDMPS, 1994)}$$

Data for Drell-Yan reaction show that even for heavy nuclei broadening is small,

$$\Delta p_T^2 \sim 0.1\,\mathrm{GeV}^2$$



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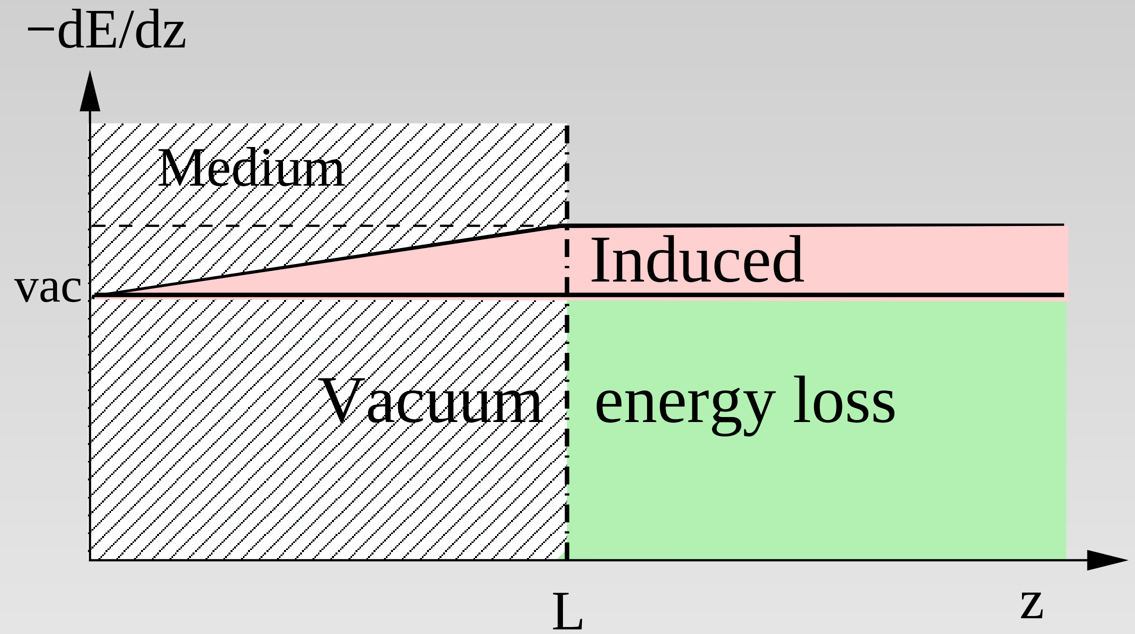
Induced energy loss in DIS

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



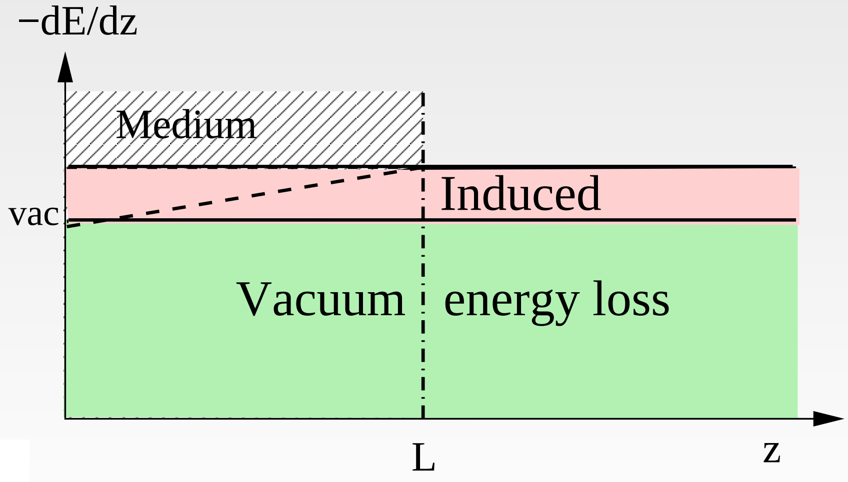
What happens afterwards?

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.

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.

Medium generated DGLAP evolution

We arrive at a constant rate of energy loss corresponding 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 via of DGLAP equations

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

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.

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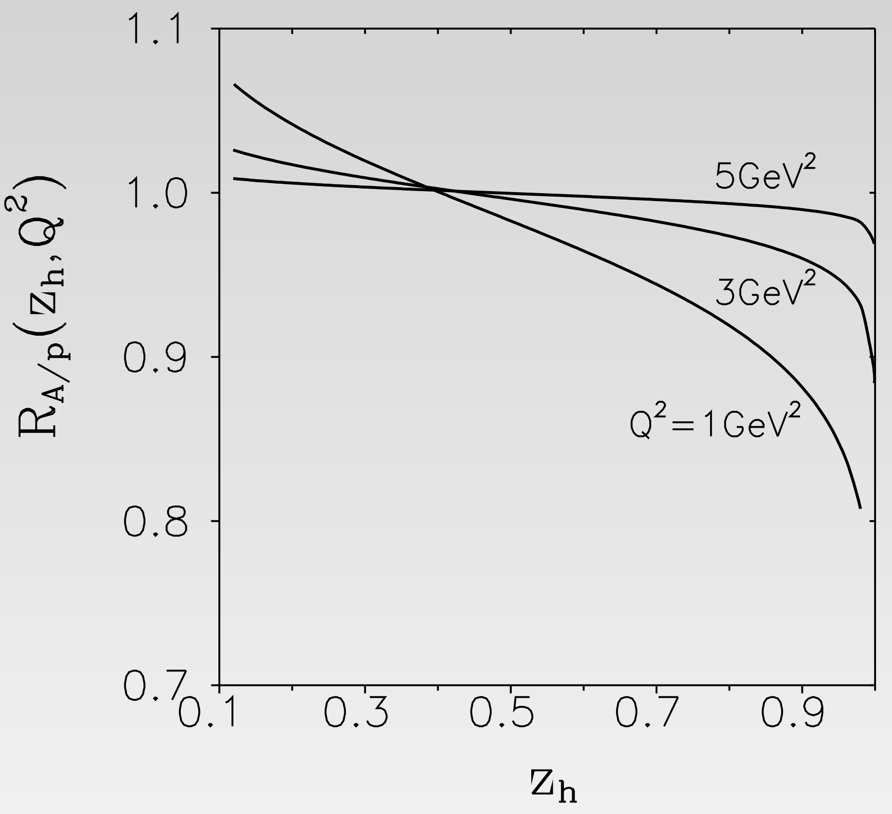
Medium generated DGLAP evolution



Ratio of the nuclear-modified to vacuum fragmentation functions calculated for lead. The modification is far too small in comparison with data.

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Heavy ion collisions

Peculiar behavior of l_p in high-p_T collisions

Heavy ion collisions

Peculiar behavior of l_p in high-p_T collisions

- In the string model $l_p \propto E/\kappa$, i.e. the production length always rises with the jet energy.

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Heavy ion collisions

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- In pQCD $l_p \propto E/Q^2$, i.e. the production also length rises with jet energy, unless Q^2 rises faster than E.

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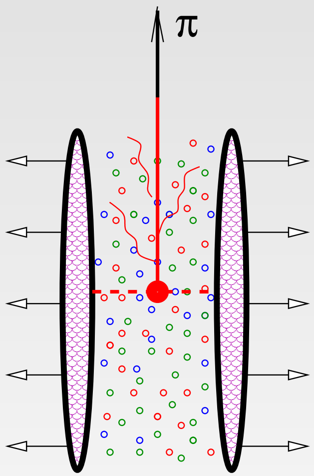
- In pQCD $l_p \propto E/Q^2$, i.e. the production also length rises with jet energy, unless Q^2 rises faster than E.
- In 90^0 parton-parton scattering with large p_T, the transverse momentum plays roles of both, jet energy, $E = p_T$, and its virtuality, $Q = p_T$. Thus, the production length shrinks, rather than rises, with p_T,



$$\langle l_p \rangle \propto \frac{1}{p_T}$$

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Time evolution of a high-p_T jet

The mean time of radiation of a gluon:

$$\langle l_c \rangle = \int_{\Lambda^2}^{Q^2} dk^2 \int_0^1 dx \, \frac{dn}{dx\, dk^2} \, l_c(x, k^2) = \frac{E}{\Lambda^2} \, \frac{1}{\ln(Q/\Lambda) \;\; \ln(Q\Lambda/4E$$

where

$$l_c = \frac{2Ex(1-x)}{k^2} \; ; \qquad \frac{dn}{dx\, d^2k} = \frac{\gamma}{x\, k^2} \; ; \qquad \gamma = \frac{3\alpha_s}{\pi^2}$$

The mean coherence length of gluon radiation is long.

However, this is not the same as production length of a colorless dipole with large $z_h > 0.5$, which takes the main fraction of the jet energy. In this case energy conservation becomes an issue.

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Time evolution of a high-p_T jet

How much energy is radiated over path length L?

$$\Delta E(L) = E \int_{\Lambda^2}^{Q^2} dk^2 \int_0^1 dx\, x \,\frac{dn}{dx\, dk^2}\; \Theta\left(L - \frac{2Ex(1-x)}{k^2}\right)$$

The rate of energy loss is constant for each interval of k^2,

$$\frac{dE}{dL\, dk^2} = \frac{1}{2}\gamma$$

Radiation of gluons with given transverse momentum $\boldsymbol{k}$ is continuing with the constant rate $\gamma/2$ until the maximal length $L_{max}(k^2) = 2E/k^2$ is reached.

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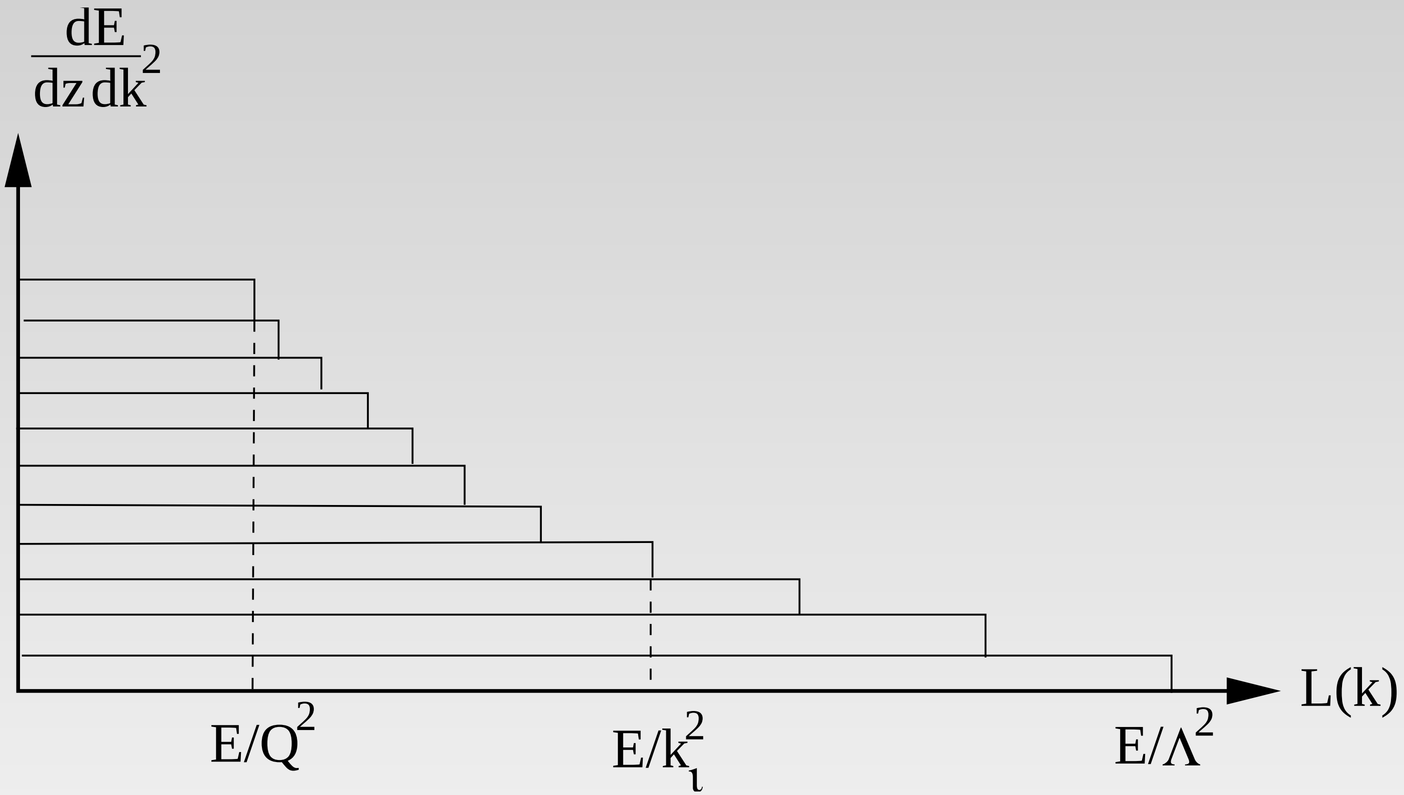
Time evolution of a high-p_T jet



L-dependence for the rate of energy loss for different intervals of transverse momentum $\boldsymbol{k_i^2}$

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Time evolution of a high-p_T jet

The total energy radiated over this maximal path length is

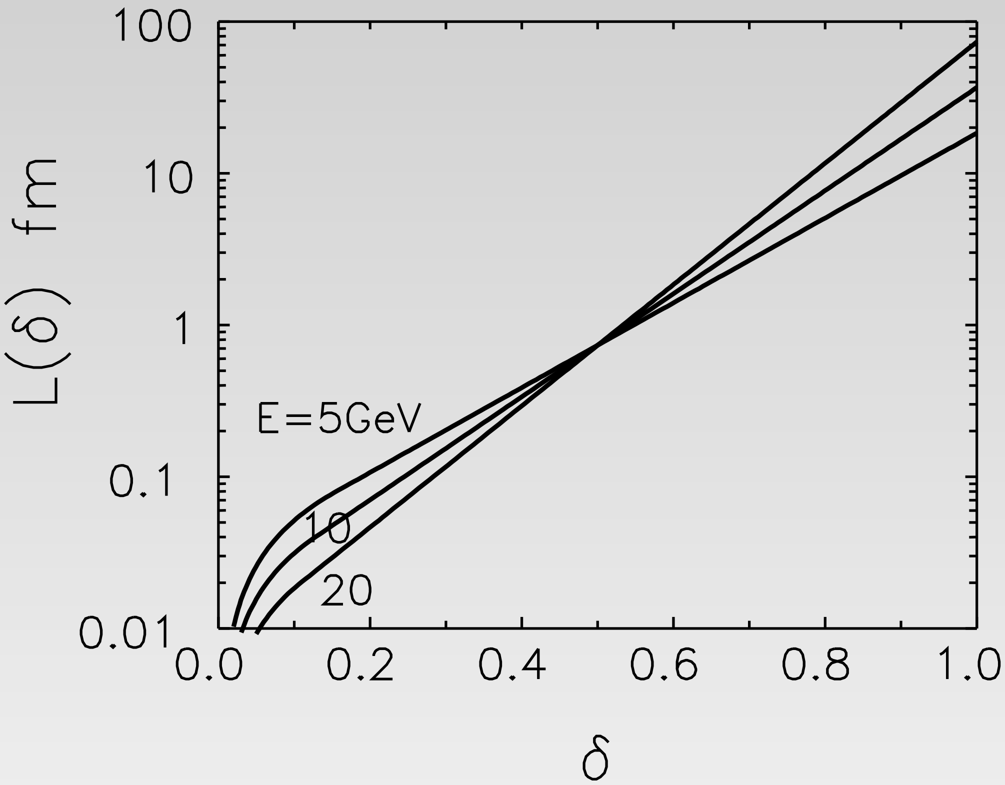
$$\Delta E_{tot} = \int_{\Lambda^2}^{Q^2} dk^2 \, \frac{1}{2} \gamma \, \frac{2E}{k^2} = \gamma \, E \, \ln \frac{Q^2}{\Lambda^2}$$

How long does it take to radiate fraction δ of the total emitted energy? The answer depends on how large is δ. For $Q = E$

$$L = \delta \frac{4}{E} \ln \frac{E}{\Lambda} \qquad \text{if} \quad \delta < 1/\ln\left(\frac{Q^2}{\Lambda^2}\right)$$

$$L = \frac{2}{Ee} \left(\frac{E}{\Lambda}\right)^{2\delta} \qquad \text{if} \quad \delta > 1/\ln\left(\frac{Q^2}{\Lambda^2}\right)$$

Time evolution of a high-p_T jet



The path length needed to radiate fraction $\boldsymbol{\delta}$ of the total vacuum energy loss.

More than a half of the total energy is lost within $\mathbf{1}$ **fm** !

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Heavy ion collisions

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- However, contraction of the production length makes the path available for absorption of the colorless pre-hadron longer. This leads to a reduction of $R_{AA}(p_T)$. Usually attenuation caused by absorption is quite a strong effect, however one should incorporate it with a precaution.

Summary

- Production of leading hadrons in hard reactions involve two stages of time development: (i) propagation of a parton though the medium accompanied with vacuum and induced gluon radiation; (ii) perturbative color neutralization followed by evolution and attenuation of the (pre)hadron in the medium.

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- Shortness of the production (color neutralization) length is the main source of nuclear suppression of leading hadrons observed in DIS. There is no room for induced energy loss.
- 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 time scale of vacuum gluon radiation in high-p_T jets is very short, lesst than 1 fm.
  The production time of leading pre-hadrons is even shorter by factor $(1 - z_h)$.

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Color Transparency

The produced colorless dipole (pre-hadron) has a small size $r_T \sim 1/p_T$) and interacts weakly, $\sigma(r_T) = C\, r_T^2$. In situation when the virtuality and the jet energy are of the same order, Lorentz time dilation cannot "freeze" the initial transverse size which evolves quickly.

Attenuation of a dipole propagation over pathlength L and evolving from initial size r_1 up to a final size r_2 is controlled by the light-cone Green function

$$G(\vec{r}_2, \vec{r}_1; L) = \frac{a}{\pi \sinh(\Omega L)} \exp\left\{ -a \left[(r_1^2 + r_2^2) \coth(\Omega L) - \frac{2\vec{r}_1 \cdot \vec{r}_2}{\sinh(\Omega L)} \right] \right\} ,$$

where

$$a = \frac{\sqrt{-iC\,\rho_0}}{4}; \qquad \Omega = \frac{4ia}{p_T}$$

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