Jet Quenching:
Controvercial Issues

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OUTLINE

- **Hadronization in vacuum: energy loss, coherence:**

  String model, Gluon bremsstrahlung
- **Medium-induced energy loss:**

  String model, Gluon bremsstrahlung
- **Energy loss scenario:**

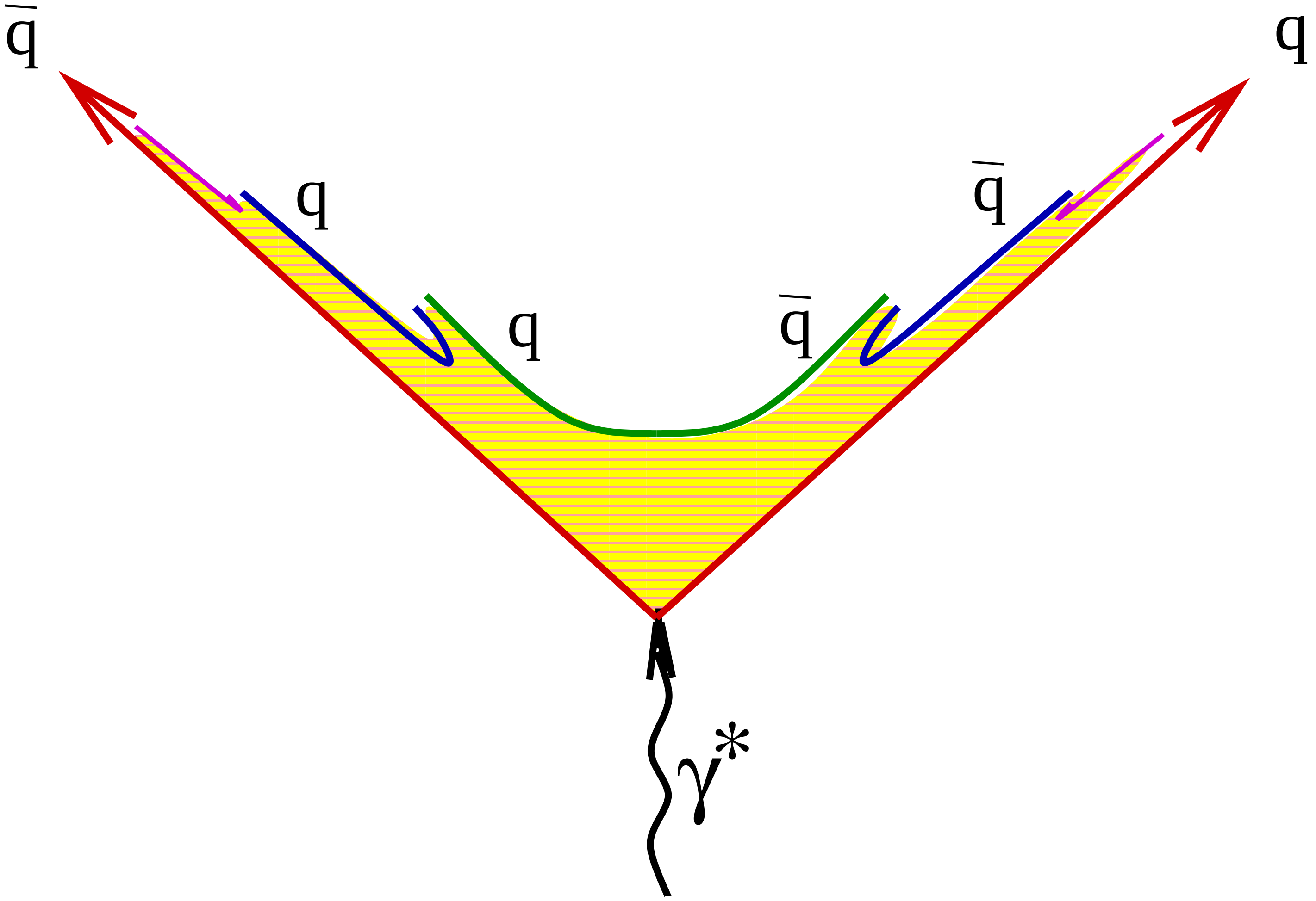
  Where does hadronization start?
- **Upper bound for modification of the fragmentation function:** Medium induced DGLAP evolution
- **Perturbative versus nonperturbative hadronization:**

  Production of pre-hadrons and wave function formation
- **Peculiarities of high-p_T hadrons in heavy ion collisions:**

  Radiation of gluonic bursts

Why Hadronization?

This is the main manifestation of the confinement. Color charges cannot be separated by much more than 1 fm, since light quarks easily pop up from vacuum.



The interaction always ends up with colorless hadrons.

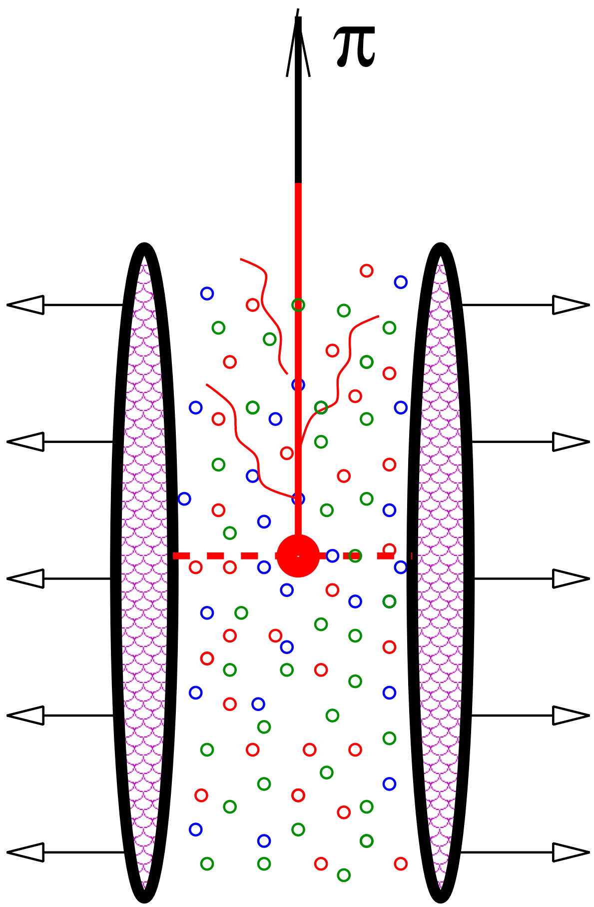
Why Nuclei?

Our detectors are placed a distances $\mathbf{10^{15}}$ times further away from the origin than the hadronization stage. Are we able to trace back these 15 orders to test reliably our ideas about the hadronization dynamics?

Nuclei provide a unique opportunity to place detectors at a tiny distance, within the range of the hadronization process and perform direct measurements. These are the multiple scattering centers separated by only $1-2\,\mathrm{fm}$.

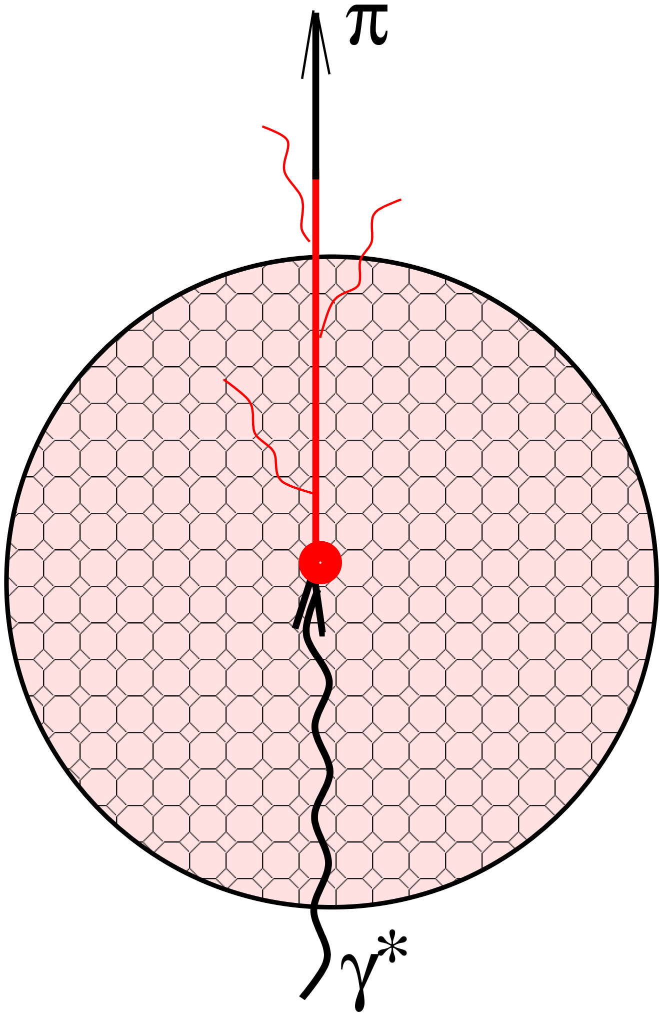
More motivation

High-p_T hadrons in HI collisions and DIS on nuclei.



RHIC

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



HERMES & JLAB

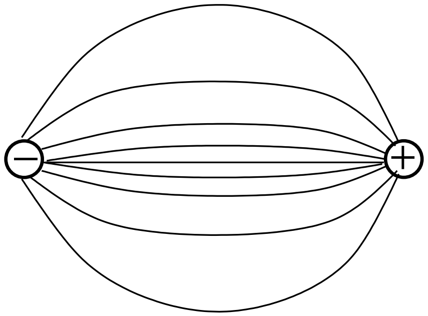
$E_\pi < 20$ GeV/c

Models for hadronization

- **String model**

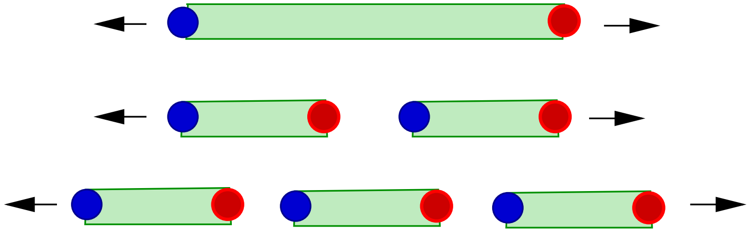
$$V(r) = \frac{\alpha}{r}$$

QED



QCD

$$V(r) = \kappa\, r$$



Schwinger phenomenon
quark tunnelling from vacuum

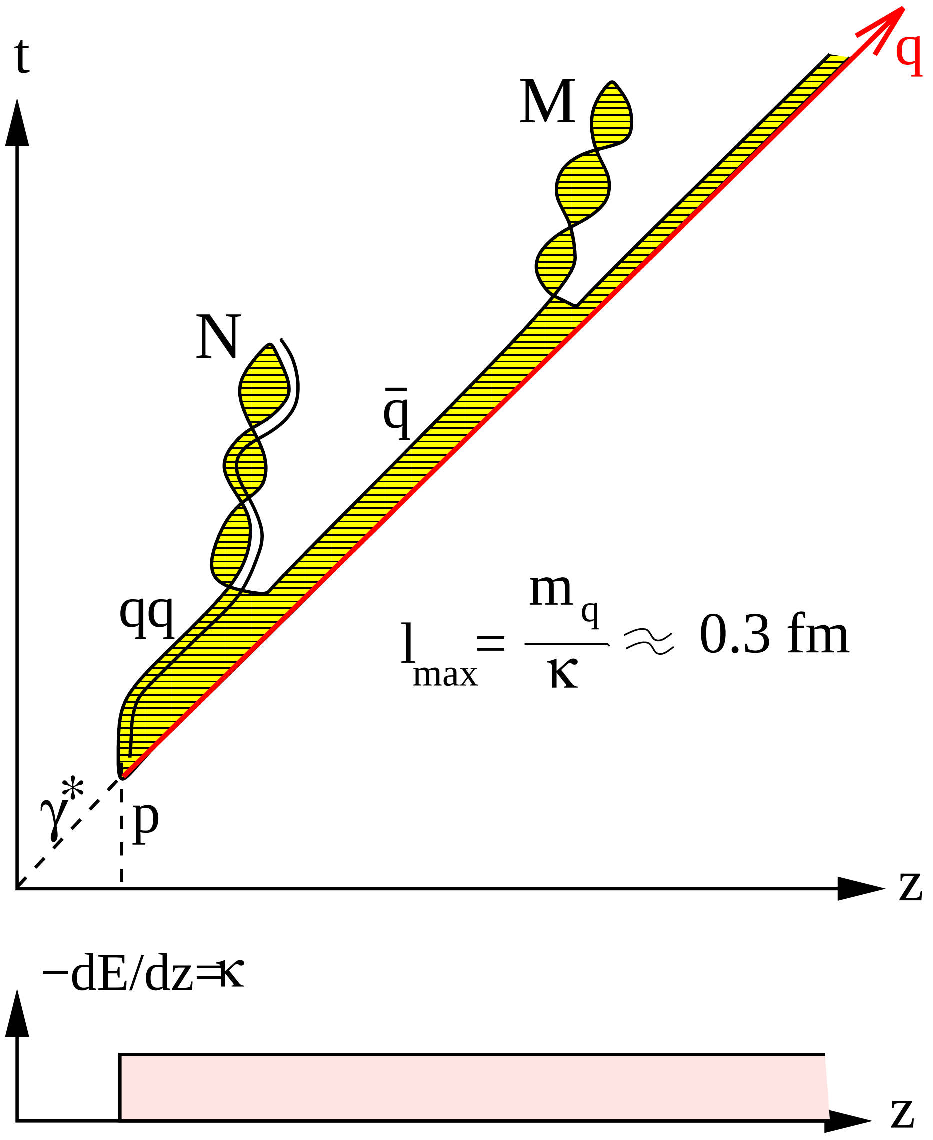
Energy of the string per unit of length, string tension

$$\kappa = \frac{1}{2\,\pi\,\alpha'_R} \approx 1 \text{ GeV}/ \text{ fm}$$

Schwinger formula for the probability of quark pair creation per unit of time and unit of length

$$W = \frac{\kappa}{2\pi^3} \exp\left(\frac{\pi m_q^2}{2\kappa}\right)$$

Space-time development of hadronization and vacuum energy loss



String tension provides a constant rate of energy loss

How long does it take to produce the final hadron?

Since the quark keeps losing energy (about 1 GeV or more per each fm.), in a while it wastes so much, that becomes unable to produce any hadron with energy $z_h\,E$, if z_h is large.

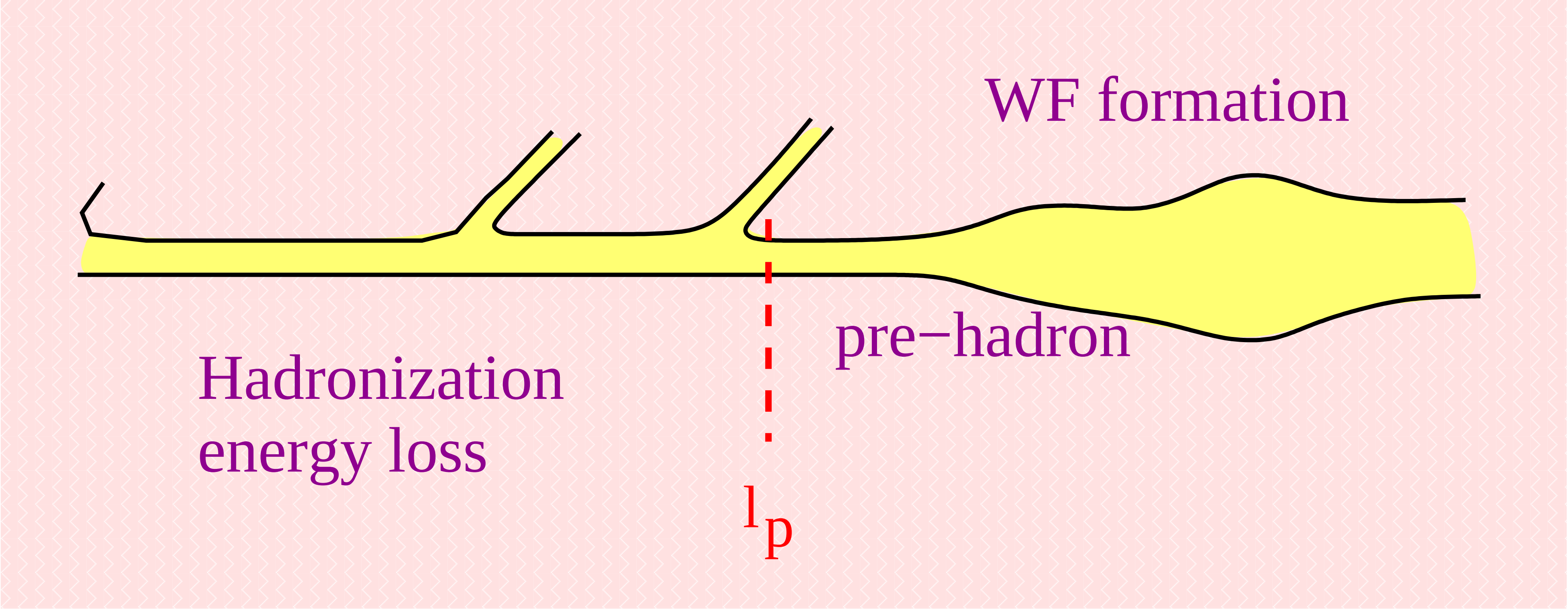
Thus, only the distance

$$l_p = \frac{E}{\kappa}\,(1 - z_h)$$

called production length, is available for hadronization and energy loss. Then the quark picks up an antiquark and creates a colorless pre-hadron which does not radiate.

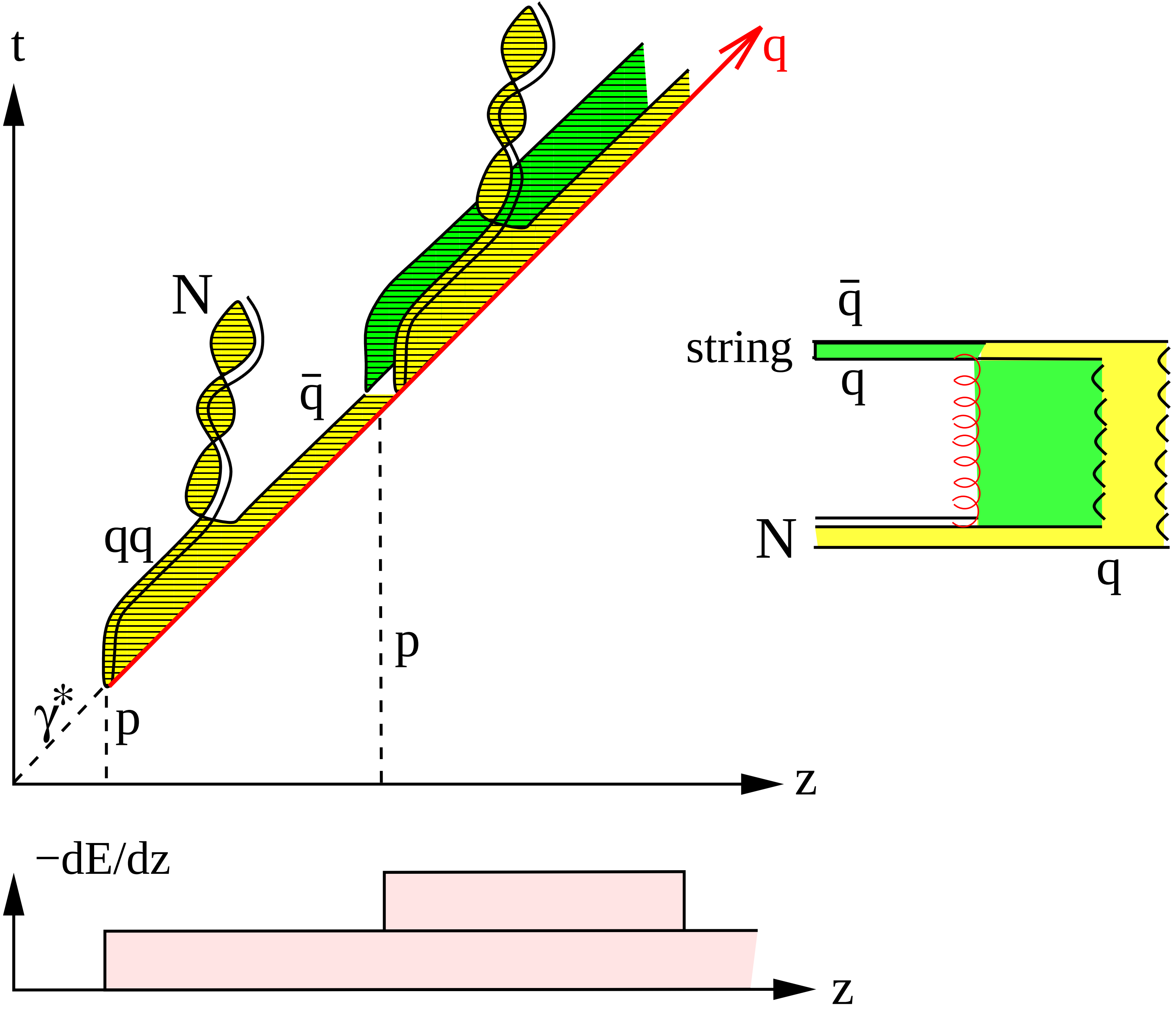
It takes, however, a much longer time, called formation time/length, to form the hadronic wave function,

$$l_f = \frac{z_h\,E}{m_{h^*}^2 - m_h^2}$$



Production of the pre-hadron at distance l_p is of great importance, since it stops energy loss and starts attenuation. The creation of a colorless pre-hadron with $z_h \to 1$ is a suppressed rare fluctuation. Any inelastic interaction of the pre-hadron in the medium leads to a degradation of its momentum and should be forbidden. The survival probability (no interaction) is controlled by the pre-hadron size.

What happens if the string multiply interacts during hadronization, at $l < l_p$?



? How much additional energy loss is induced by the multiple interactions of the quark in the medium?

- NOTHING!

Indeed, the leading quark is always attached to only one string and is losing energy with the same rate $dE/dz = -\kappa$, independently of the interactions.

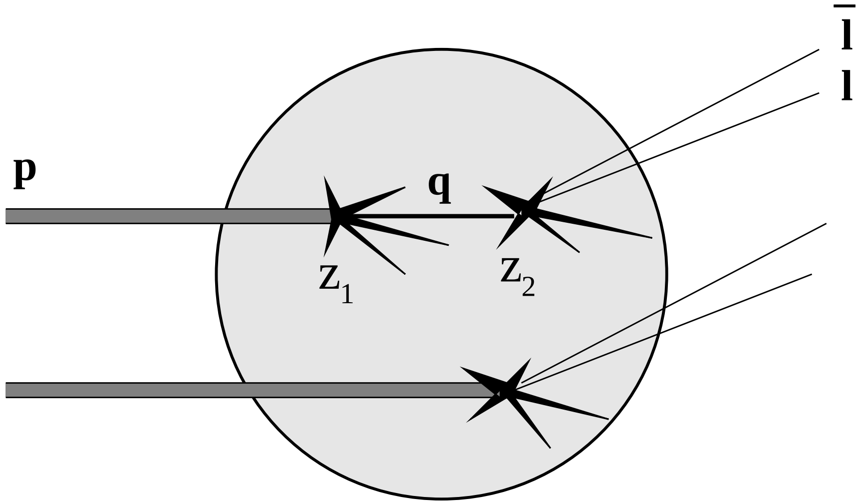
However, the medium induces production of extra particles, who pays for that?

Every time when quark experiences inelastic collision it starts hadronization from the very beginning, but with a reduced starting energy, $\tilde{E} = E - \kappa\Delta z$. It generates a less energetic jet, and this is the cost of extra particle production. The modified fragmentation function,

$$D(z_h) \Rightarrow D\left(\frac{z_h}{1-\kappa L/E}\right)$$

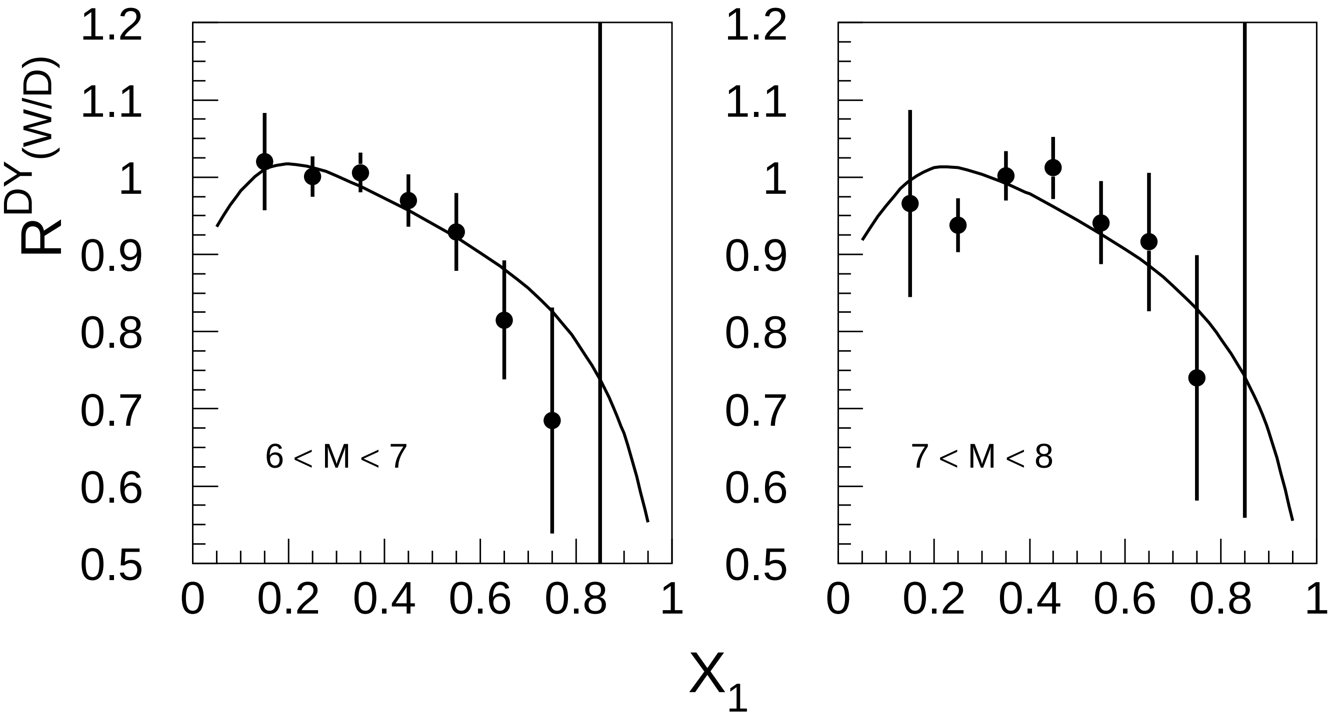
Notice: the energy loss rate here, κ, is not induced, but vacuum, $dE/dz|_{vac} = -\kappa$.

Example: initial state interaction in Drell-Yan reaction



$$-\frac{dE}{dz} = 2.7 \pm 0.4 \pm 0.5\,\frac{\text{GeV}}{\text{fm}}$$

$E = 800\,\text{GeV}$



A quark is not a point-like particle, it has a structure which depends on our resolution.

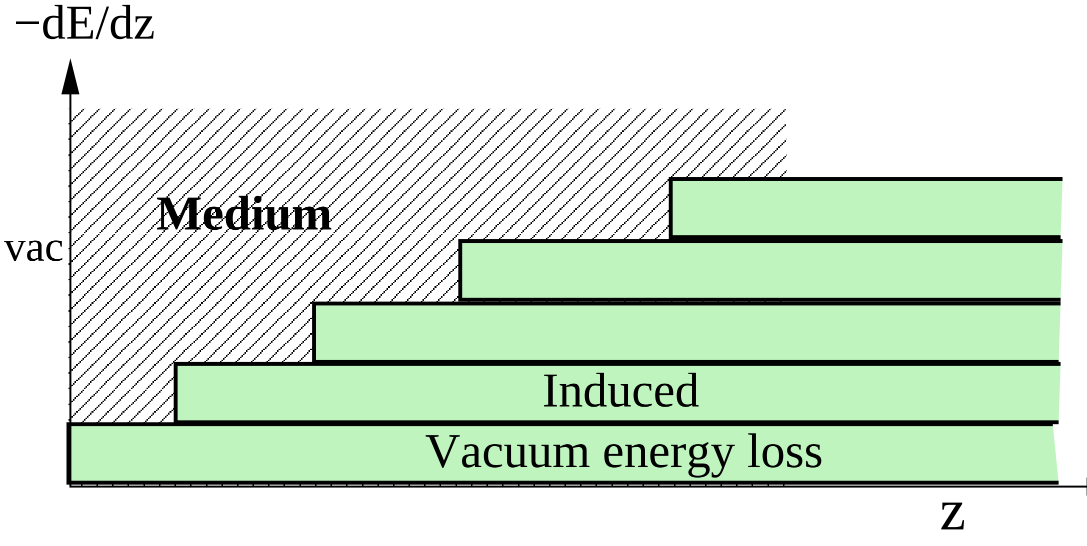
Fock state decomposition: $|q\rangle = |q\rangle_0 + |qG\rangle + |qq\bar{q}\rangle + \ldots$ In every rescattering the quark picks up a new couple of strings, so the energy loss rate steadily rises,

$$-\frac{dE}{dz} = \kappa\left[1 + 2\sigma\,\rho_A\,z\right]$$

The total energy loss on path length L is

$$\Delta E(L) = \underset{\substack{\uparrow\\ \text{vacuum}}}{\kappa}\,L + \sigma_{in}^{\pi N}\rho_A\,\underset{\substack{\uparrow\\ \text{induced}}}{L^2}$$

The pre-factor in the induced term $\kappa\sigma_{in}^{\pi N}\rho_A \approx 0.15\,\mathrm{GeV}/\,\mathrm{fm}^2$ for cold nuclear matter.



It is quite doubtful that one can apply the string model to DIS, i.e. treat this process on a pure nonperturbative basis. And of course no strings should be expected inside a dense medium (QGP).

Energy loss in pQCD .

After a quark gets a hard kick 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.

The amount of energy loss over path length L reads,

$$\Delta E_{vac}(L) = E\int d^2k \int\limits_0^1 dx\, x\, \frac{dn_g}{dx\, d^2k}\, \Theta(L - l_c) = \frac{3\alpha_s}{2\pi}\, L\, Q^2$$

Thus, the rate of energy loss in vacuum is constant,

$$\left(\frac{dE}{dz}\right)_{vac} = -\frac{3\alpha_s}{2\pi}\, Q^2$$

Amazing, the rate of gluon radiation is steeply falling, $dn_g/dz \propto 1/z$, but the rate of energy loss remains unchanged, like in the string model.

What is in common between these so different approaches? - Lorentz Invariance

dE/dt is Lorentz invariant, and has dimension $[M^2]$. The only quantity available in pQCD satisfying these conditions is Q^2. In the case of nonperturbative QCD it is κ or might be another characteristic parameter of QCD vacuum.

Medium induced radiation

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.

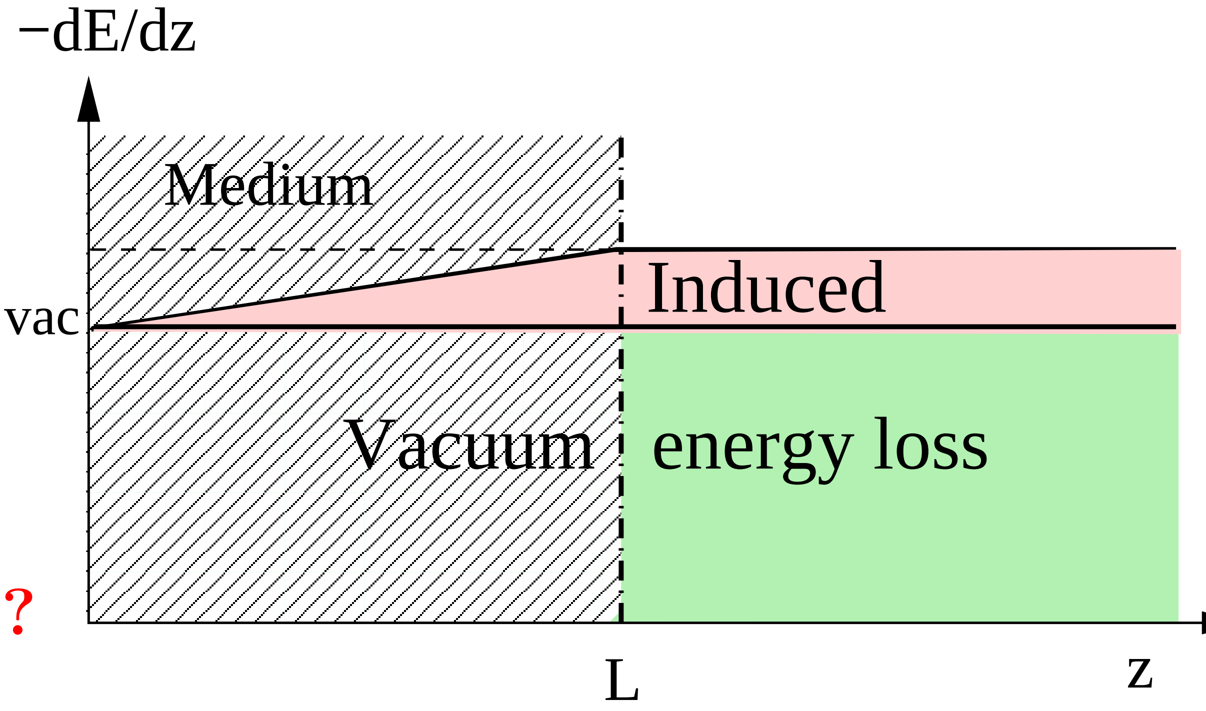
- This can be also understood as another possibility to construct a Lorentz invariant combination,

$$-\frac{dE}{dz} \propto \rho\, z$$

- Notice that there is one more boost-invariant combination for induced energy loss, $\rho\, E$, since energy is also the zero component of a 4-vector. However, this combination does not have the dimension of dE/dz, so it should be square-rooted, $dE/dz \propto \sqrt{\rho E}$. This possibility is realised in QED. The reason for rising energy dependence of the energy loss rate is rather obvious. The radiation spectrum in non-abelian theory peaks at the rapidities of the colliding particles, while in an abelian case it make a plateau in rapidity. Thus, in QED photons carry away a finite fraction of the electron momentum, therefore the energy loss must rise with energy.

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

$$\widetilde{D}_i^h(z_h, Q^2) = \int\limits_0^1 \frac{d\epsilon}{1-\epsilon} W(\epsilon)\, D_i^h\left(\frac{z_h}{1-\epsilon}, Q^2\right) \ ,$$

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

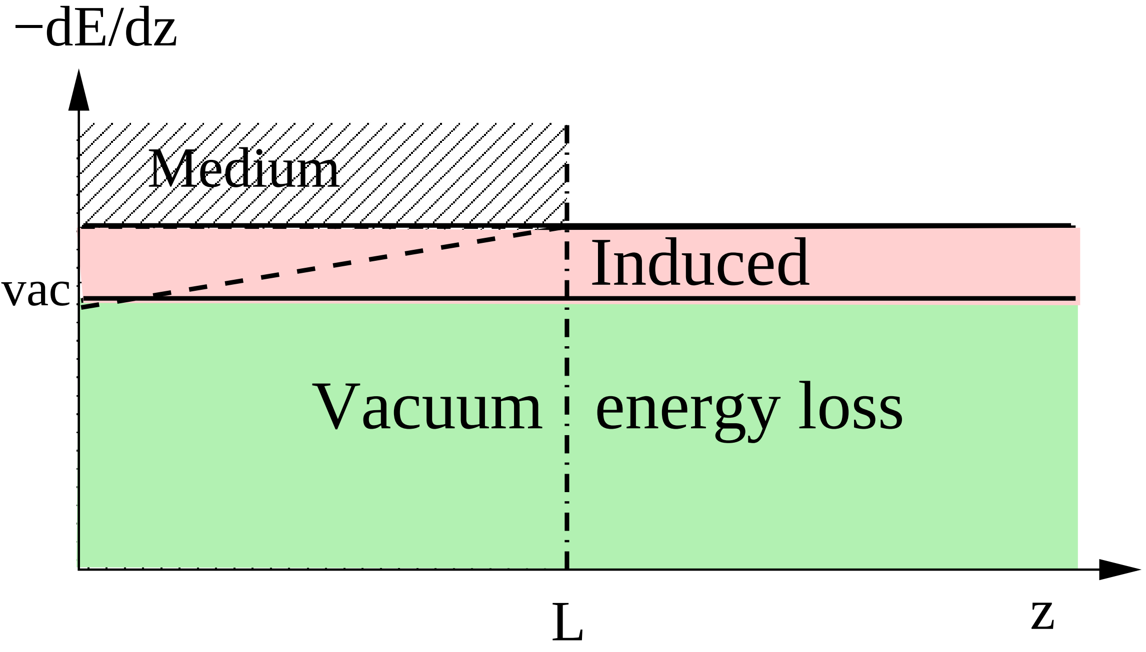
This prescription assumes a two-stage hadronization: first induced energy loss in the medium, then hadronization which starts from the very beginning at the medium surface and continues in vacuum, but with a reduced starting energy.

This remind the result of the string model, but that was vacuum energy loss, while induced was zero.
Quite a difference!

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

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

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,

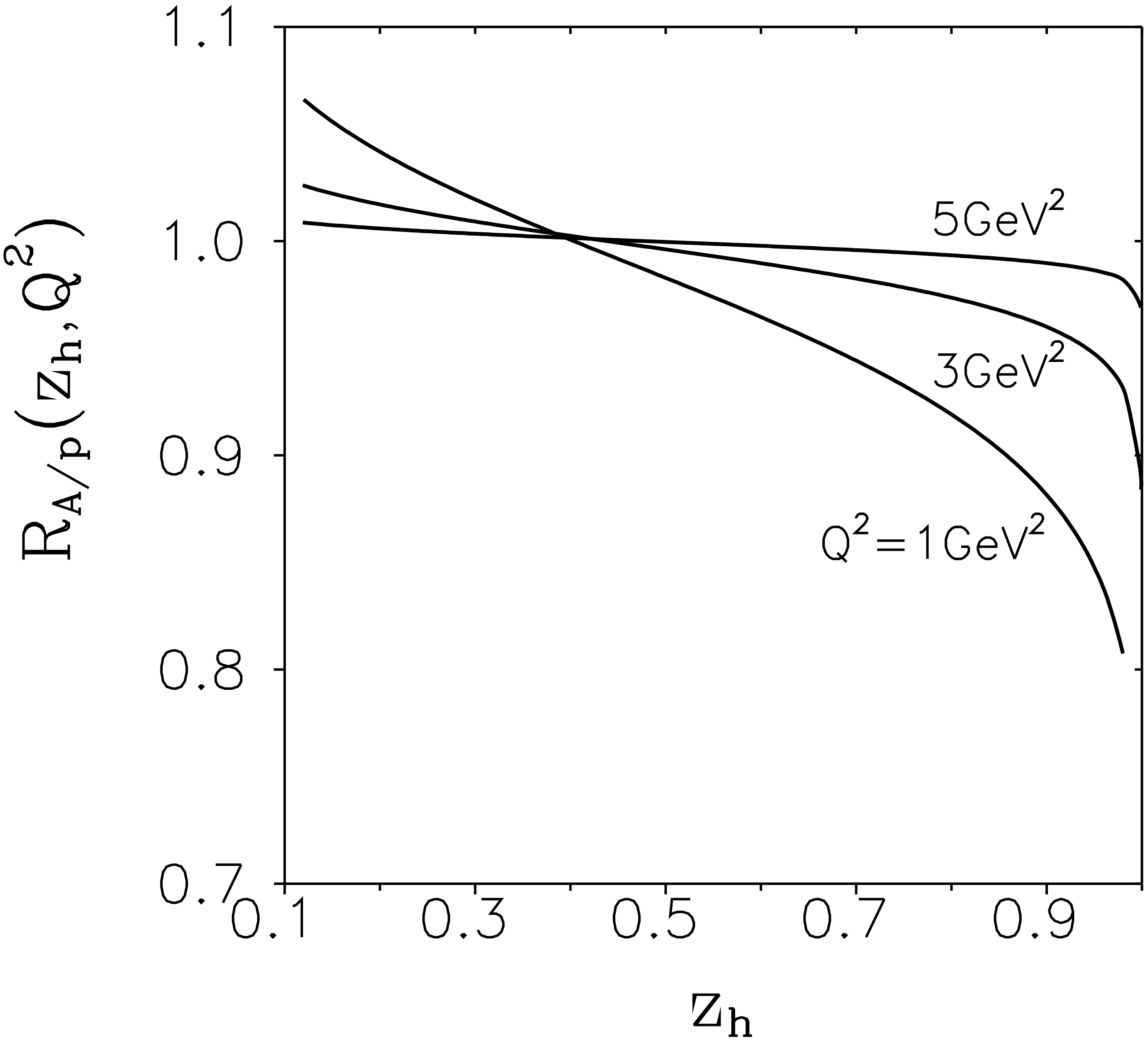
$$R(z_h, Q^2) \equiv \frac{\widetilde{D}_i^h(z_h, Q^2)}{D_i^h(z_h, Q^2)} \approx \left[\frac{(1-z_h)^{\lambda_1}}{z_h^{\lambda_2}}\right]^{\frac{\Delta p_T^2}{Q^2 \ln(Q^2/\Lambda^2)}}$$

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.

One can conclude that the procedure of redefining the argument of of the fragmentation function is incorrect. It provides wrong dependences on jet energy and Q^2 and grossly overestimates the leading hadron suppression related to medium induced energy loss.

The precise upper bound for the effects of induced energy loss is found to be far too weak to explain the observed hadron suppression in DIS on nuclei and in heavy ion collisions.

Where does the suppression come from ?

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 $z_h = 1$,

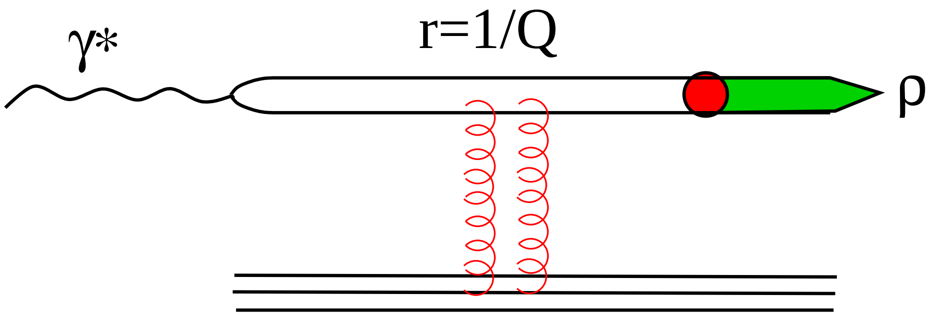
$$l_p = \frac{E}{|dE/dz|}(1 - z_h)$$

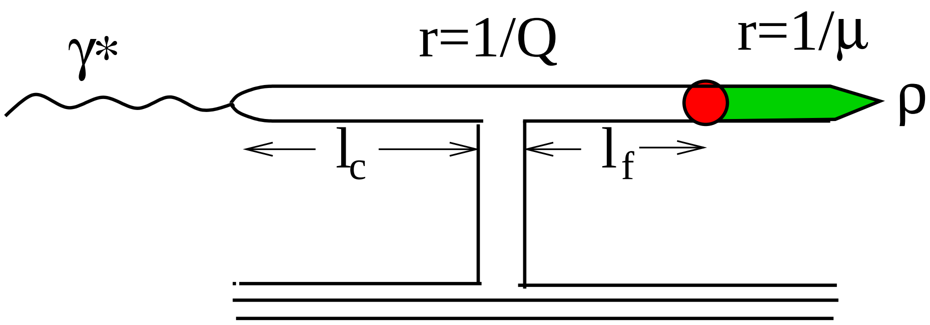
Here dE/dz includes both vacuum and induced energy losses. At high Q^2 the former is much larger than the latter, so $l_p \propto E/Q^2$.

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.

Color transparency is an important effect to be included, since it may substantially increase the survival probability of the pre-hadron in the medium.

A point-like colorless dipole cannot interact with external color fields, therefore its interaction cross section vanishes quadratically (non-abeliance) with the dipole size, $r_T \to 0$,

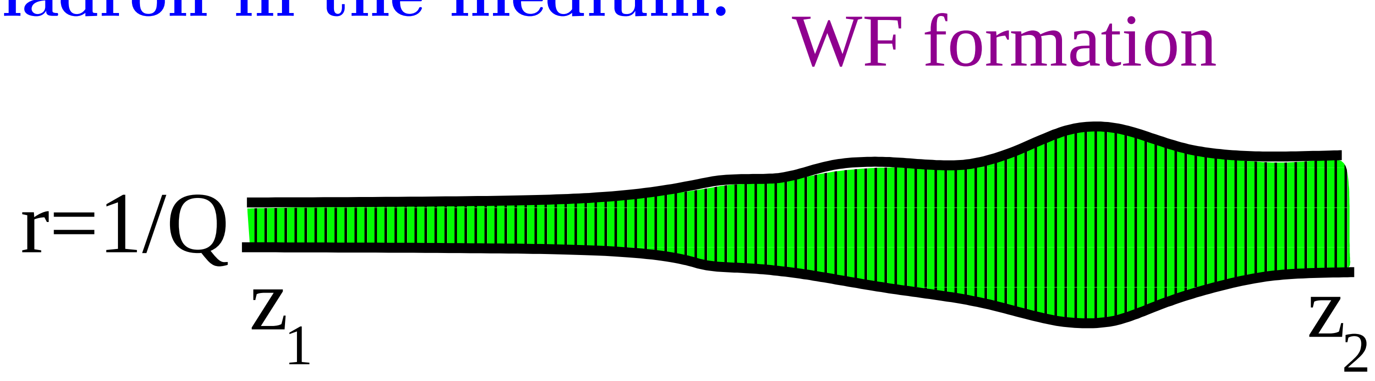
$$\sigma(r_T) = C\, r_T^2 = \frac{C}{Q^2}$$

Thus, a small-size pre-hadron produced inside a medium may escape it with survival probability,

$$S = \exp\left[-\frac{C}{Q^2}\int\limits_z^\infty dz'\,\rho(z')\right]$$

Another important effect is the evolution of the pre-hadron size during propagation through the medium. This can be accurately calculated employing the light-cone Green function technique.

Formation of the wave function and attenuation of the pre-hadron in the medium.



The survival probability for propagation through the medium between points z_1 and z_2,

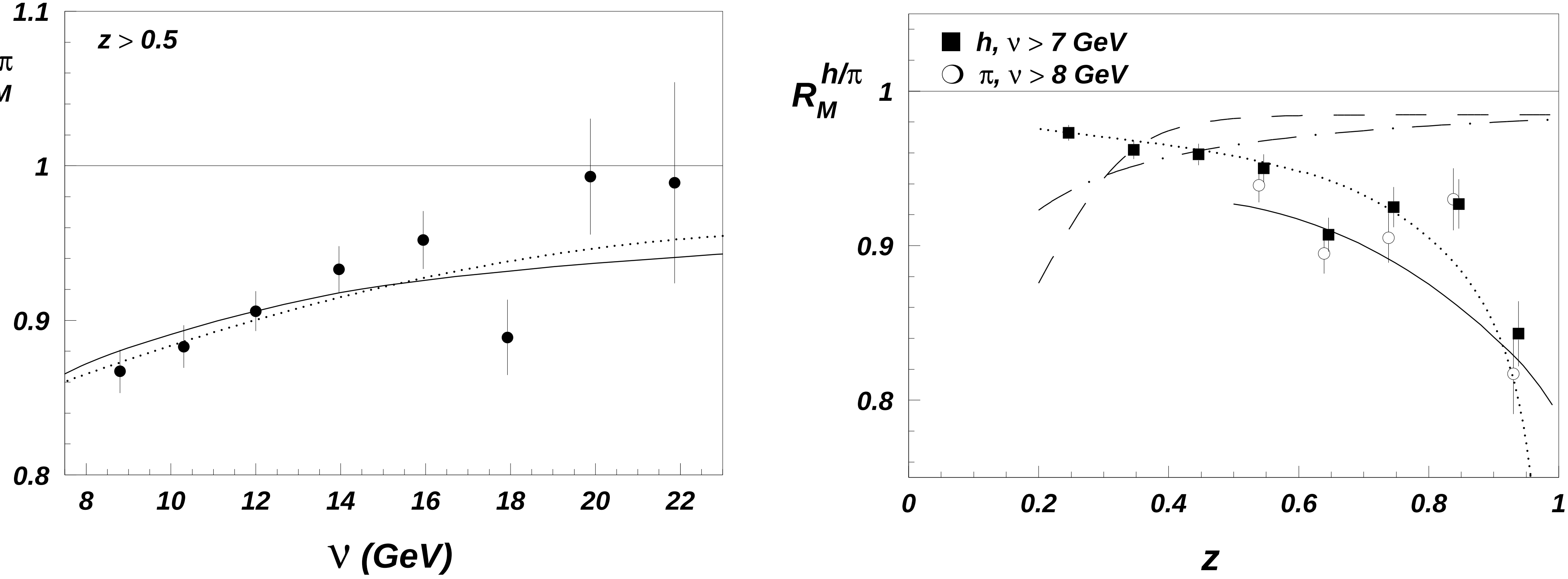
$$S(z_1, z_2) = \frac{\int_0^1 dx \int d^2r_1\, d^2r_2\, \Psi_h^*(r_2) G_{\bar{q}q}(r_2, z_2; r_1.z_1) \Psi_{in}(r_1)}{\int_0^1 dx \int d^2r_1\, d^2r_2\, \Psi_h^*(r_2) \Psi_{in}(r_1)}$$

The light-cone Green function $G_{\bar{q}q}(r_2, z_2; r_1.z_1)$ satisfies the 2-dimensional Schrödinger equation,

$$i\frac{d}{dz_2} G_{\bar{q}q} = \left[\frac{Q^2 x(1-x) + m_q^2 - \Delta_r}{2Ex(1-x)} + V_{\bar{q}q}(z_2, \vec{r}, x)\right] G_{\bar{q}q}$$

The potential $V_{\bar{q}q} = -\frac{i}{2}\sigma_{\bar{q}q}(r)\rho(z)$ provides absorption.

Can absorption explain the nuclear suppression observed by HERMES, EMC and at JLAB?



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

eculiarities of high-p_T hadron production in heavy ion collisions

How long is the production length in this case?

REMINDER: Energy conservation, imposes restriction on the production length,

$$l_p \leq \frac{E}{|dE/dz|}(1 - z_h) \propto \frac{E}{Q^2}$$

In the case of 90^o parton scattering (in c.m.)

$$\begin{aligned} E &= p_T \\ Q^2 &= p_T^2 \end{aligned}$$

Thus, the production length shrinks with p_T,

$$\boxed{l_p \propto \frac{1}{p_T}}$$

This is a very counter-intuitive result: the time scale of jet development does not rise with the jet energy, but shrinks.

Why should it rise?

Intuition: Because the Lorentz factor delays all processes

- Not all!

The coherence length for gluon radiation

$$l_c^g = \frac{2\omega}{k_T^2}$$

In the process in question $\langle k_T^2 \rangle \sim p_T^2$, $\omega \lesssim E = p_T$

The Lorentz factor doesn't rise, but falls with p_T.

Thus, the mean radiation time of gluons shrinks as well, $l_c^g \propto 1/p_T$, **i.e. most of gluons are radiated instantaneously as a burst.**

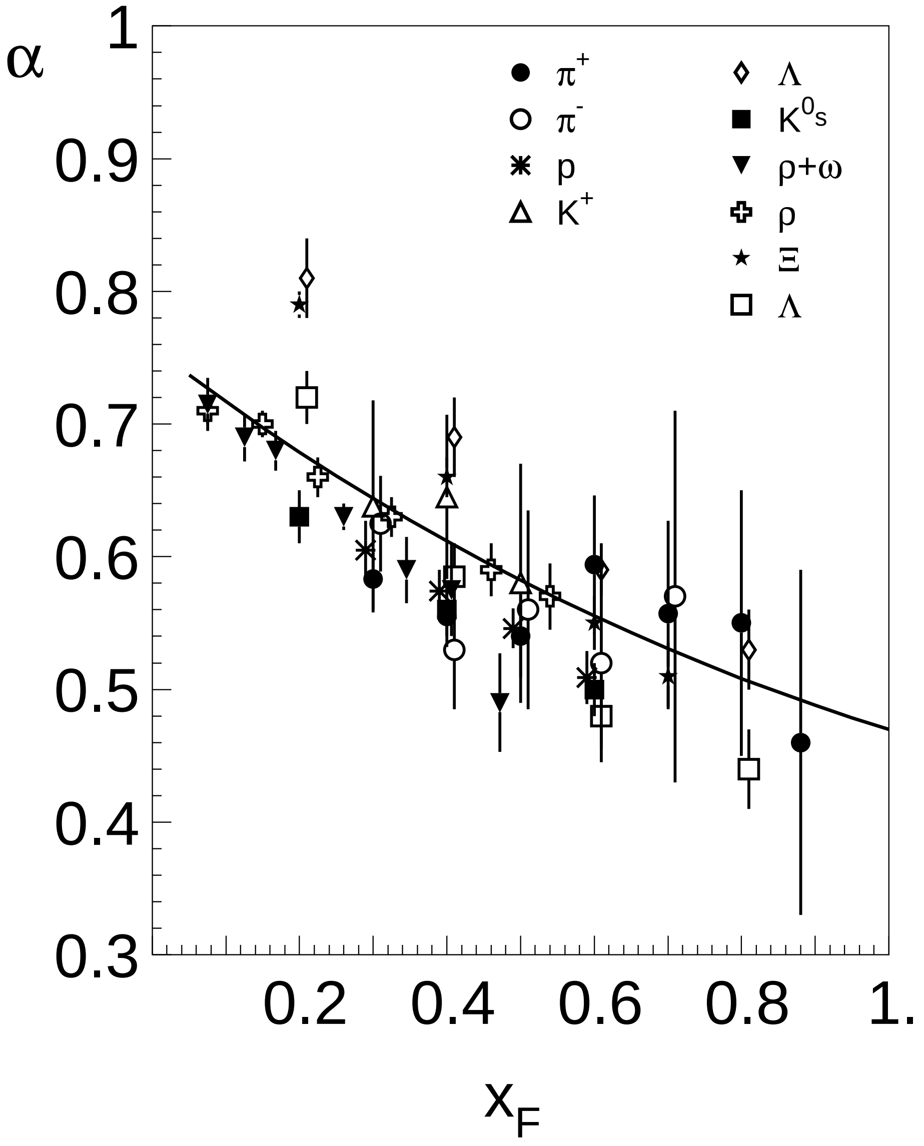
Induced energy loss is irrelevant to explanation of nuclear suppression of high-p_T hadrons in HI collisions. A colorless dipole of tiny size $r \sim 1/p_T$ is produced next to the origin. This dipole quickly evolves and the mean size controlling the attenuation depends on p_T and the medium density.

- **Attenuation of the dipole, rather than energy loss, is the source of nuclear suppression in heavy ion collisions.**

The attenuation is very strong, since it is exponential, therefore one might not need a very high density medium to explain data.

Why do we believe that a dense matter is created in heavy ion collisions at RHIC?

Suppression by factor **3-5** may not be an evidence for high density.



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

Conclusions

- **Vacuum energy loss has a constant rate which rises with the hard scale of the reaction. This is an important part of the medium-modified fragmentation function and should not be forgotten.**
- **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 strongly violates the upper bound.**

- **Shortness of the production (color neutralization) length is the main source of nuclear suppression of leading hadrons observed in DIS.**
- **Contrary to the simple intuition, the time scale of jet development and the production length shrink $\propto 1/p_T^2$ in heavy ion collisions.**
- **For this reason there is no room for induced energy loss in heavy ion collision. The observed suppression should be related to attenuation of the colorless dipoles produced shortly after the high-p_T parton collision.**

Outlook

The nuclear suppression of high-p_T hadrons observed at RHIC remains unexplained and has to be understood without any ad hoc procedures. Otherwise, an incorrect interpretation may produce wrong information about the properties of the created medium. More work to be done.