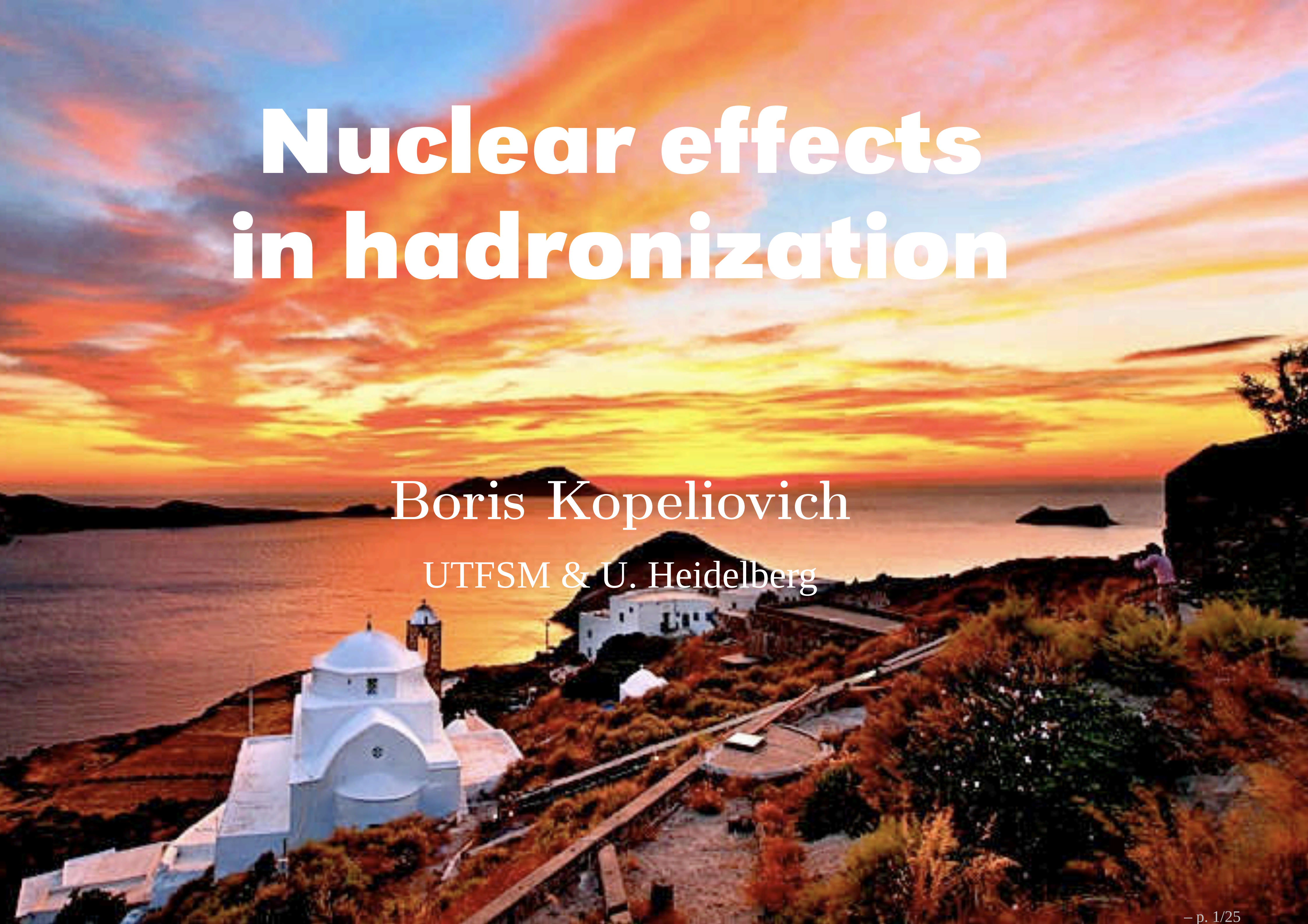

Nuclear effects in hadronization

Boris Kopeliovich

UTFSM & U. Heidelberg

In-medium hadronization

The hadronization proces lasts a short time of several fms, while detectors are installed at macroscopic distances, so one cannot access many of the details of hadronization dynamics. Nuclei provide a unique opportunity to place additional detectors, which are the bound nucleons, next to the origin of the jet.

- Therefore, experiments with nuclear targets can provide precious information about the space-time development at the early stage of the hadronization process. They also establish a base line for the jet quenching effect in heavy ion collisions.

Semi-inclusive hadron production in DIS (SIDIS) is probably the most precise tool for such studies. The typical observable is the multiplicity ratio,

$$R_A(z_h, p_T) = \frac{d\sigma(\gamma^* A \to hX)/dz_h d^2p_T}{A\, d\sigma(\gamma^* N \to hX)/dz_h d^2p_T},$$

where $z_h = p_h^+/p_{\gamma^*}^+ \approx E_h/E_{\gamma^*}$.

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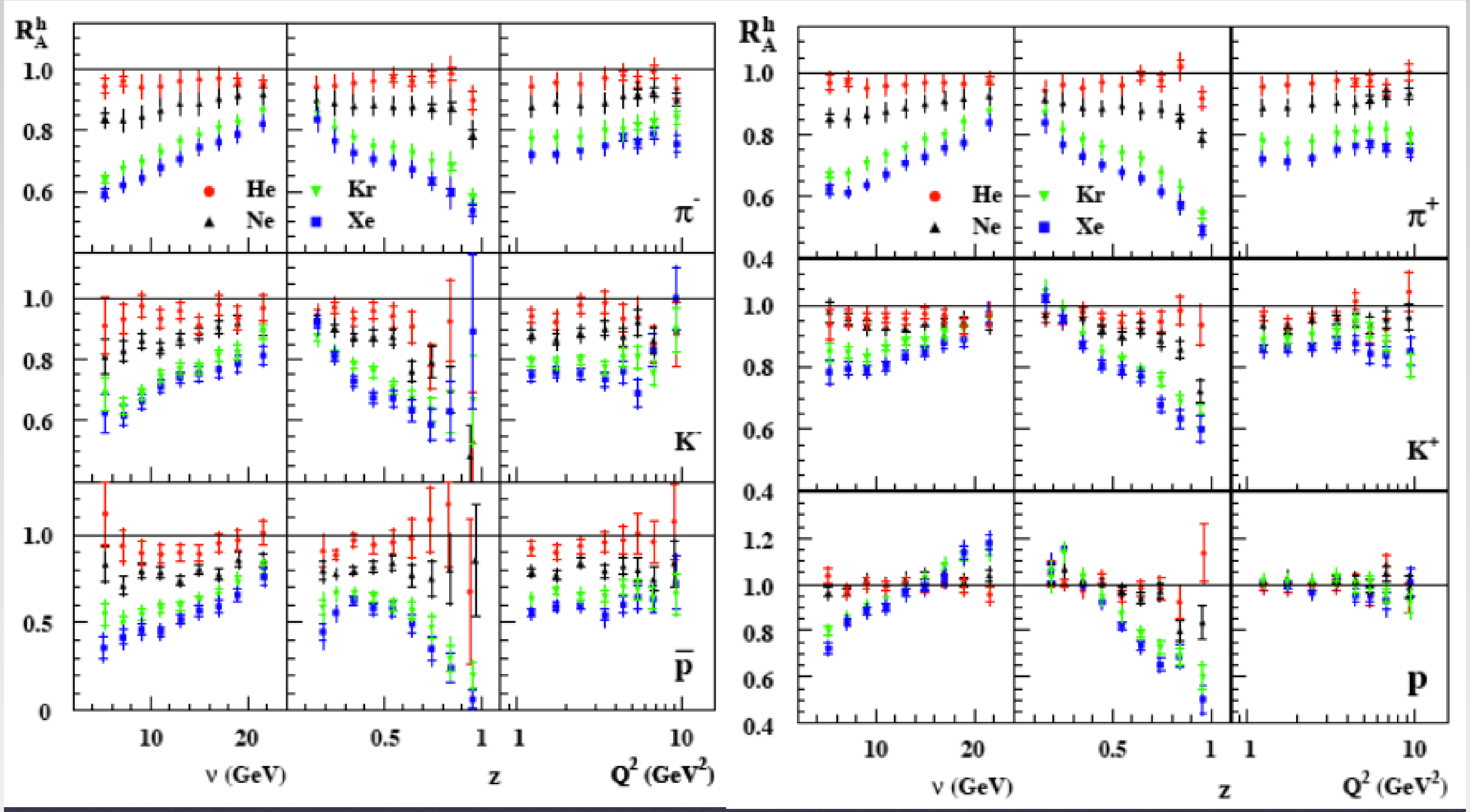
Hadron attenuation



HERMES data for He, Ne, Kr, Xe: π^{+-}, K^{+-}, p, antiproton

pions act similarly, K^+ vs. K^-, proton vs. antiproton

(each 1-D plot is integrated over all other variables)

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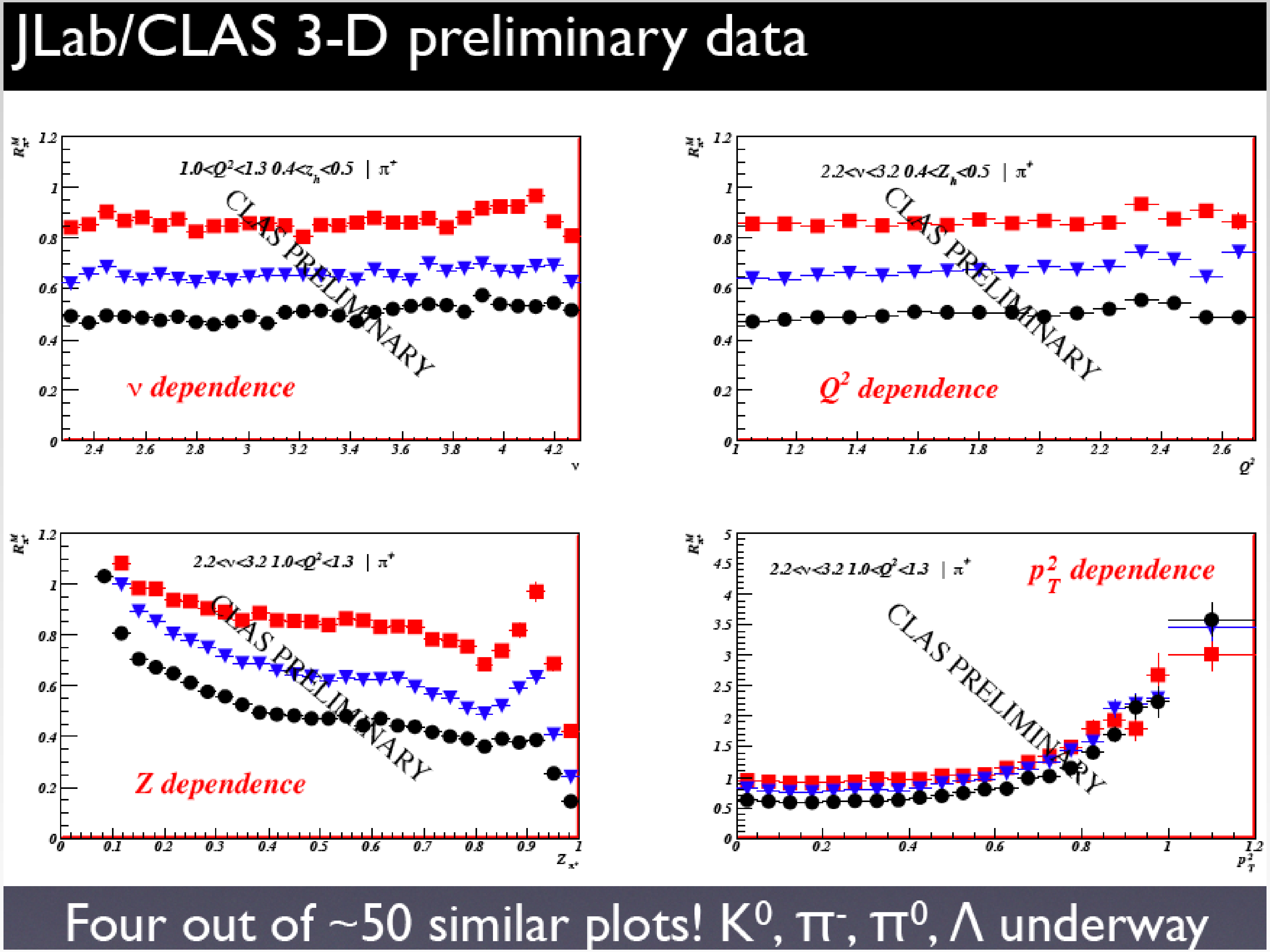
Data from CLAS



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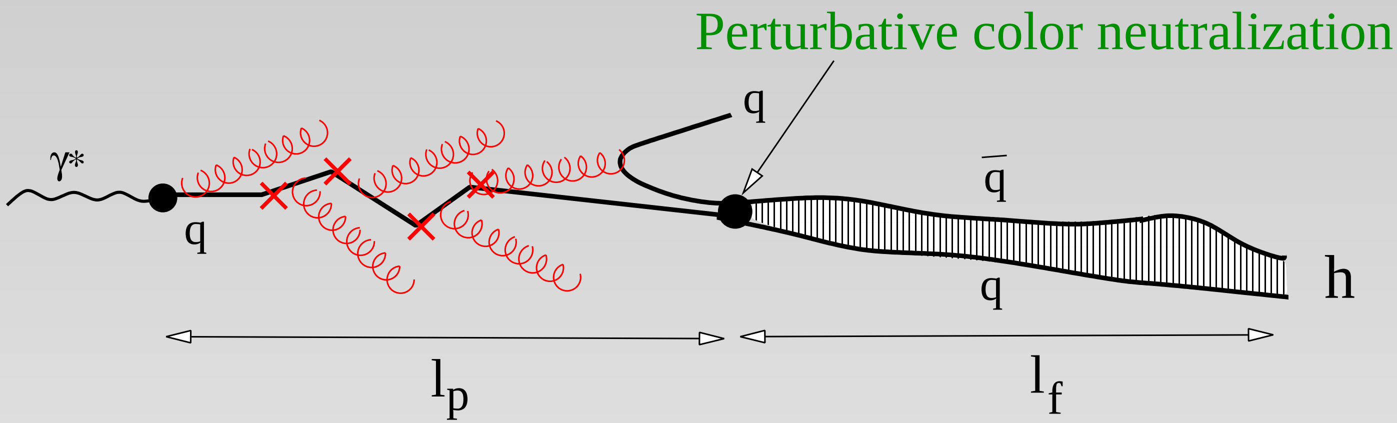
Hadron attenuation in SIDIS



A simplified (classical) picture of in-medium hadronization.

Two stages of leading hadron production:

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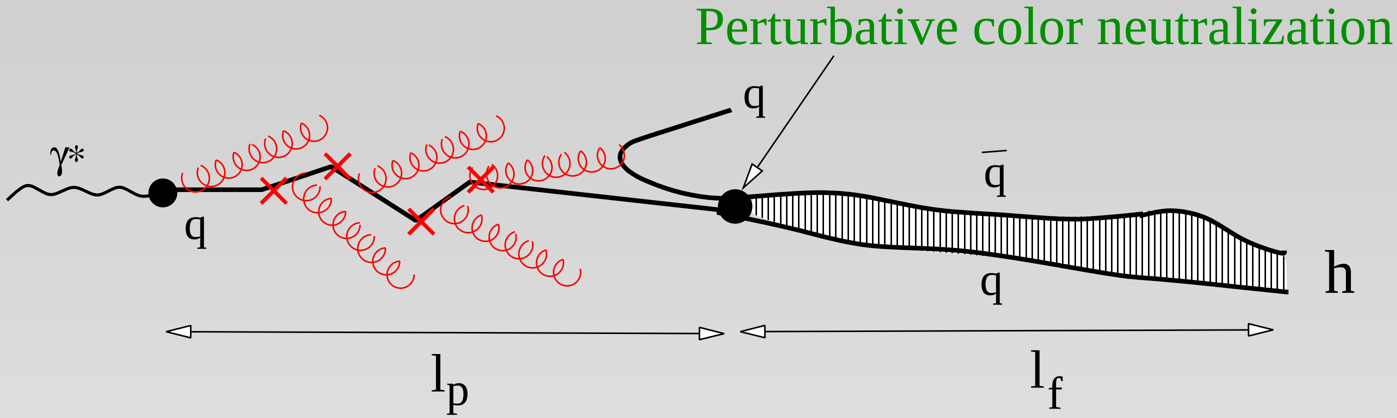
Hadron attenuation in SIDIS



A simplified (classical) picture of in-medium hadronization.

Two stages of leading hadron production:

(i) The parton originating from a hard reaction is regenerating its color field via gluon radiation, which leads to vacuum energy loss. Multiple interactions in the medium induce an additional radiation and energy loss;

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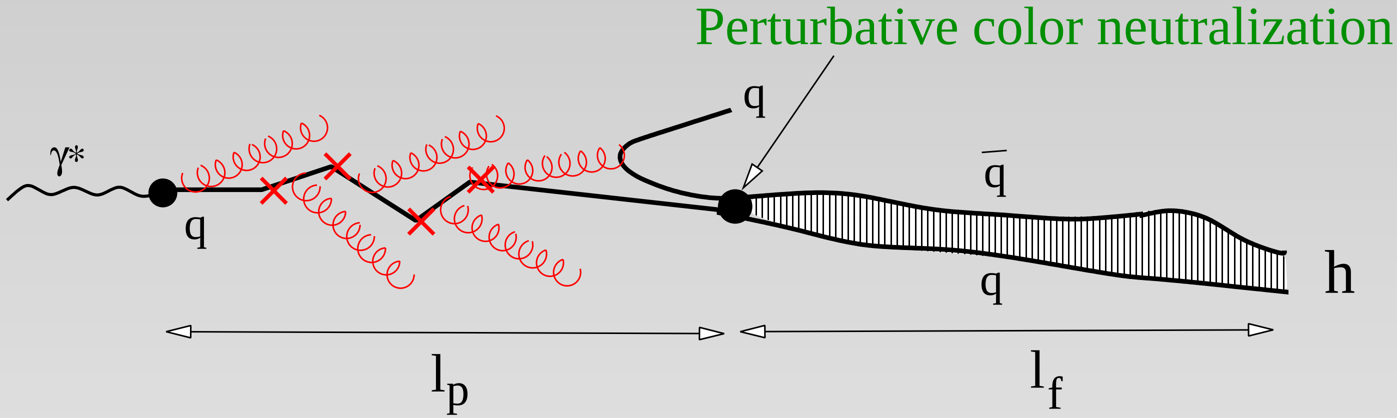
Hadron attenuation in SIDIS



A simplified (classical) picture of in-medium hadronization.

Two stages of leading hadron production:

(i) The parton originating from a hard reaction is regenerating its color field via gluon radiation, which leads to vacuum energy loss. Multiple interactions in the medium induce an additional radiation and energy loss;

(ii) The leading quark picks up a sea antiquark, and the produced colorless dipole (pre-hadron) attenuates in the medium (absorption). The dipole is forming the hadron wave function over a path length which considerably exceeds the nuclear size.

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Production length scale

If the hadron takes the main fraction of the jet energy, $z_h \longrightarrow 1$, then energy conservation becomes an issue:

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

The main contribution to the rate of energy loss, $\frac{dE}{dz}$ (z is longitudinal coordinate), comes from vacuum energy loss, which may have either a nonperturbative origin (string tension),

$$-\frac{dE}{dz}\bigg|_{vac} \approx 1\,\mathrm{GeV/\,fm},$$

or perturbative (color field regeneration),

$$-\frac{dE}{dz}\bigg|_{vac} = \frac{2\alpha_s}{3\pi}\,Q^2,$$

or both.

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Broadening in a nuclear medium

A parton experiencing multiple interactions in the medium increases its mean p_T^2 linearly with the path length L (Brownian motion). The coefficient was calculated within the dipole approach (M.Johnson, B.K., A.Tarasov, 2001),

$$\Delta p_T^2 = 2\, C(E)\, \rho_A\, L.$$

$$C(E) = \left.\frac{\partial \sigma_{\bar{q}q}(r_T, E)}{\partial r_T^2}\right|_{r_T=0} = \frac{\sigma_{tot}^{\pi p}(E)}{R_0^2(E)} \left[1 + \frac{3R_0^2(E)}{8\langle r_{ch}^2\rangle_\pi}\right]$$

where $R_0(E) = 0.88\,\mathrm{fm} \times (E_0/E)^{0.14}$; $E_0 = 500\,\mathrm{GeV}$.

The energy dependence is steep at high energies, $C(E) \propto E^{0.36}$.

It results from gluon radiation which also contributes to broadening. The dipole cross section $\sigma_{\bar{q}q}(r_T, E)$ is fitted to data for real photoproduction and to $F_2^p(x, Q^2)$.

- Thus, the dipole phenomenology has a good predictive power for the magnitude of broadening.

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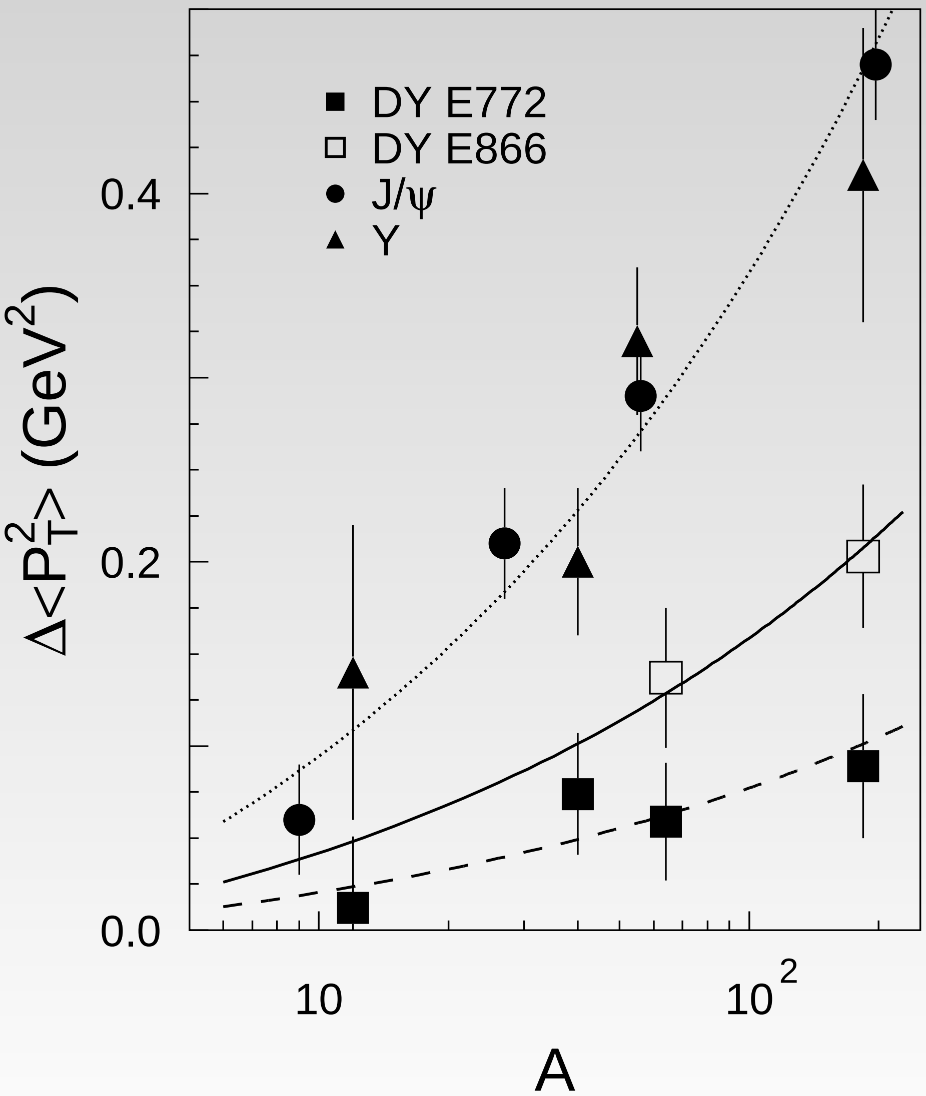
Broadening in the Drell-Yan reaction

The dipole approach predicted broadening twice as large as was measured in the E772 experiment. However, later, data from the E866 experiment confirmed the prediction.

Gluon broadening is expected to be $\mathbf{9/4}$ times larger than for quarks. Data for $\boldsymbol{J/\Psi}$ and $\boldsymbol{\Upsilon}$ production confirm this as well.



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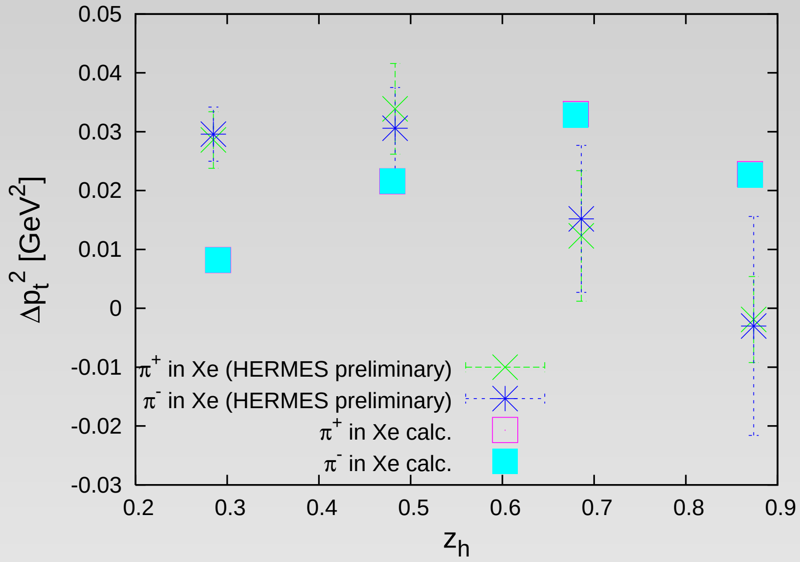
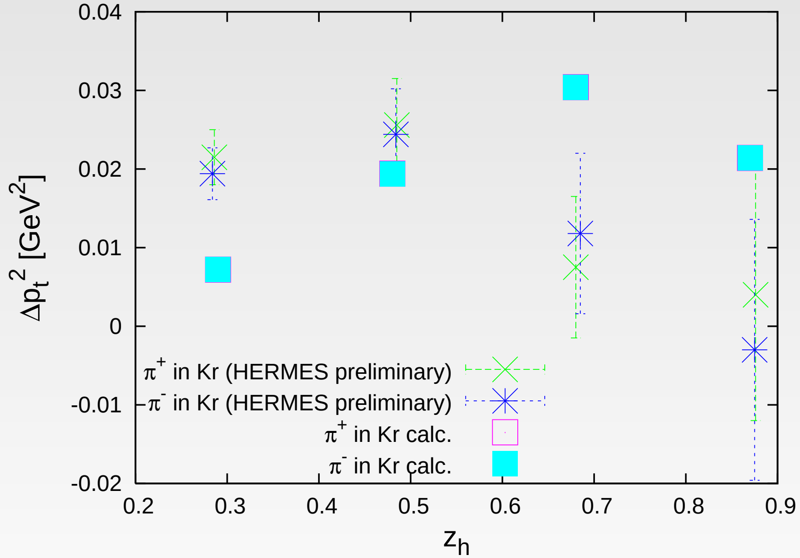
Probing the production length

Broadening originates mainly from the first stage of hadronization. After the color of the leading quark is neutralized broadening of the pre-hadron proceeds with a very small elastic cross section and can be disregarded. Thus, broadening is a sensitive probe for the production length, $\Delta p_T^2 \propto l_p$, which was predicted to shrink for leading hadrons, $l_p(z_h) \propto (1 - z_h)$ (B.K., F.Niedermayer, 1984). This effect is confirmed by HERMES data (!hadronic broadening is z_h^2 times less than the quark one).





S.Domdey, D.Grünewald, B.K., H.J.Pirner, 2009

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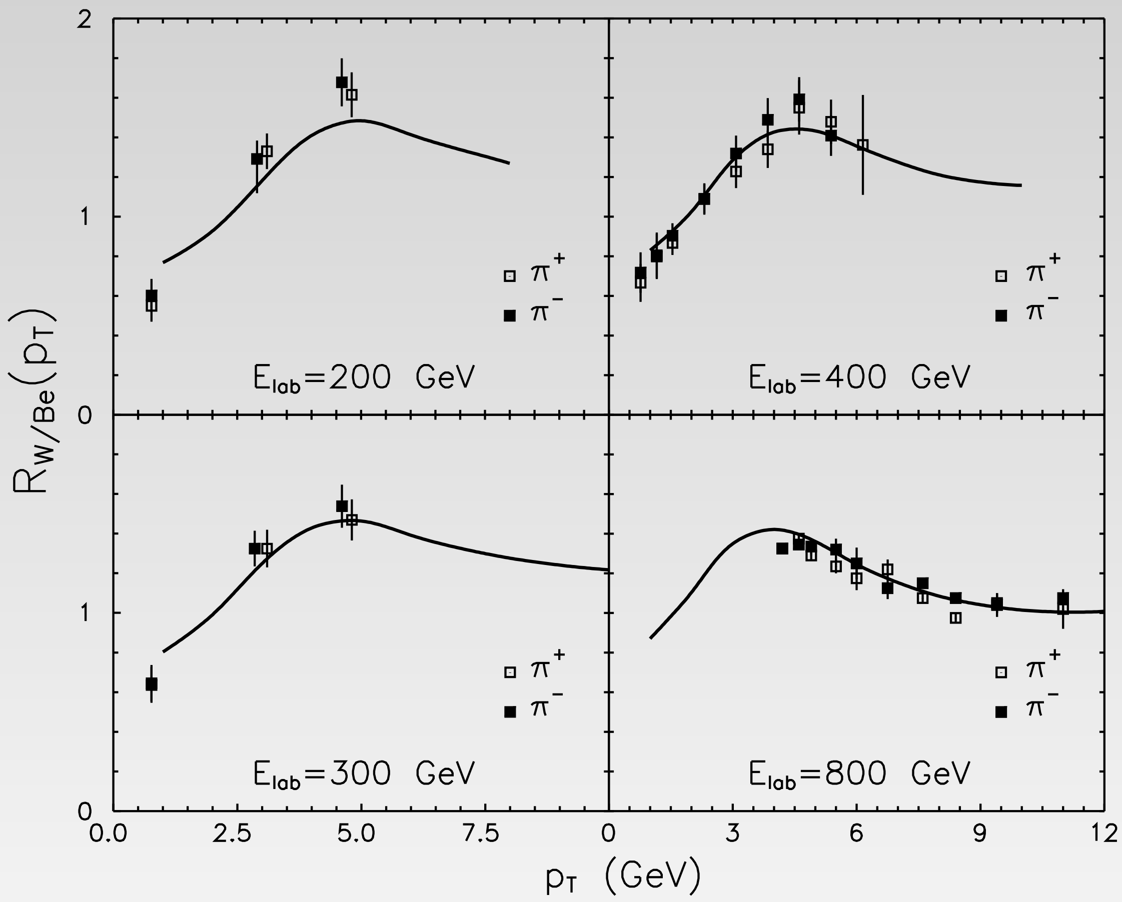
Cronin effect in pA collisions

Broadening in hadron-nucleus collisions, known as Cronin effect, can also be calculated in a parameter free way, i.e. with no fit to the data to be explained.



BK, J.Nemchik, A.Schäfer, A.Tarasov, 2002

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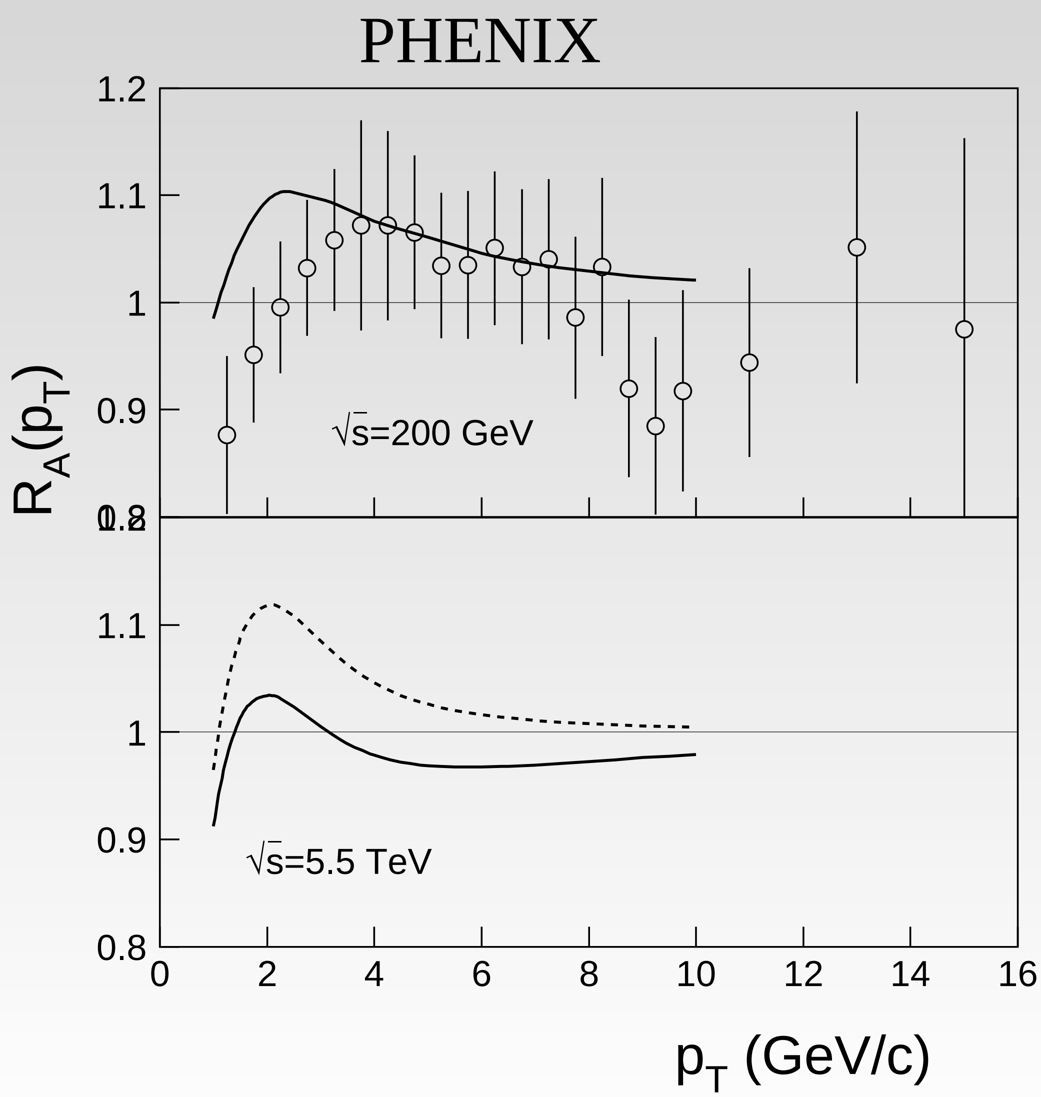
Cronin effect at RHIC/LHC

A much weaker Cronin enhancement $\sim$ **10%** was predicted for RHIC. Later was confirmed by PHENIX data on dAu collisions.

Due to gluon shadowing even a weaker effect is expected at LHC.



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Comparative analysis of broadening

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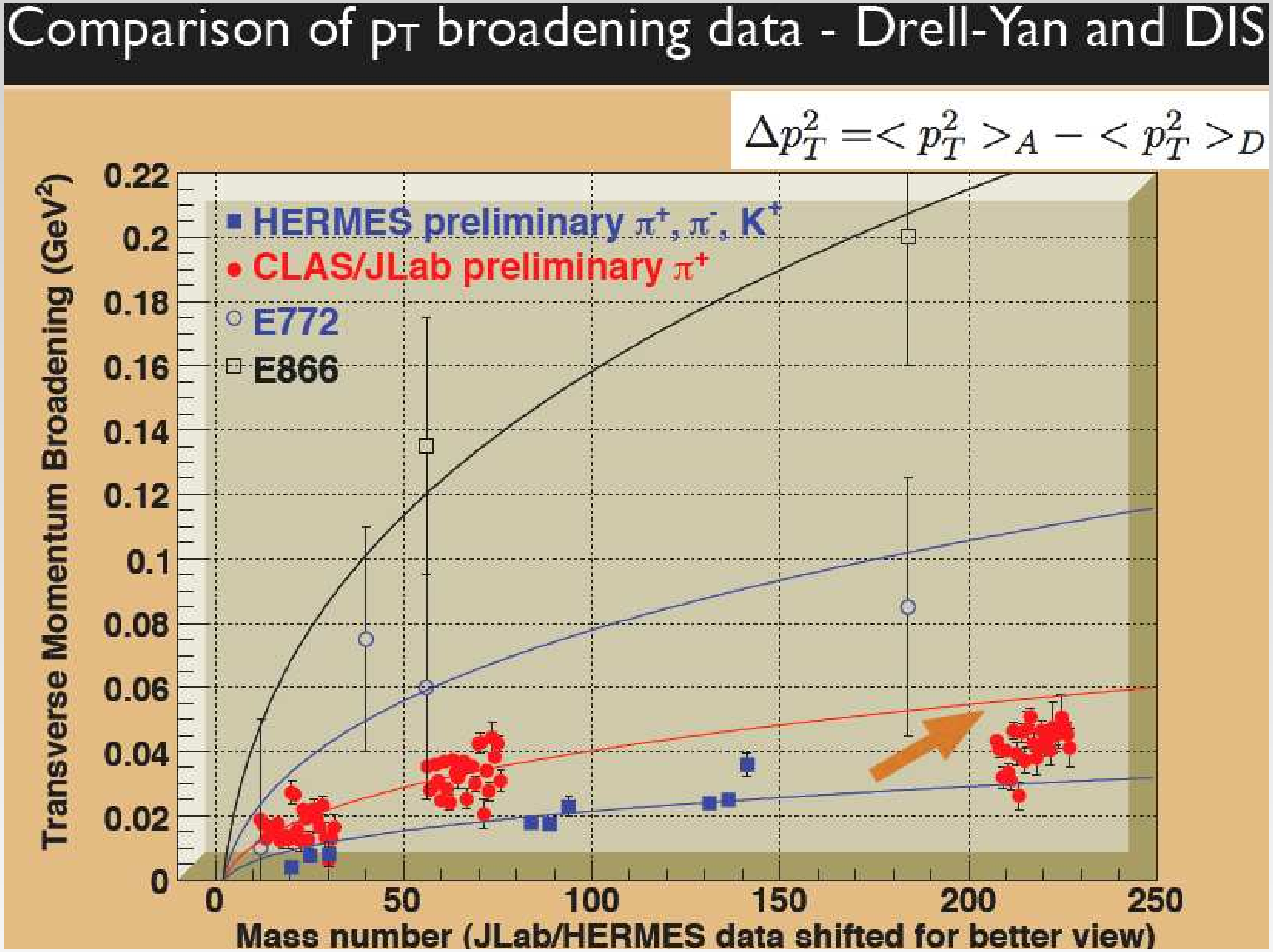

Comparison of Drell-Yan and SIDIS agrees with the predicted energy dependence.

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Induced energy loss

Getting additional multiple kicks in the medium the parton radiates more than in vacuum and is losing more energy. Thus broadening results in an induced energy loss, relates as,

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

Broadening measured in the HERMES experiment is very small, $\Delta p_T^2 < 0.06\,\mathrm{GeV}^2$, several times smaller than measured in Drell Yan reaction at 800 GeV. Then the induced energy loss is vanishingly small, $-dE/dz|_{ind} \lesssim 0.04\,\mathrm{GeV/\,fm}$, compared to the value $-dE/dz|_{ind} = 0.5\,\mathrm{GeV/\,fm}$ (X.N.Wang & E.Wang, 2002) needed to describe HERMES data on nuclear attenuation.

- Thus, the brand-new HERMES data on broadening rule out the energy loss scenario as a dominant mechanism for hadron attenuation observed in the HERMES experiment.

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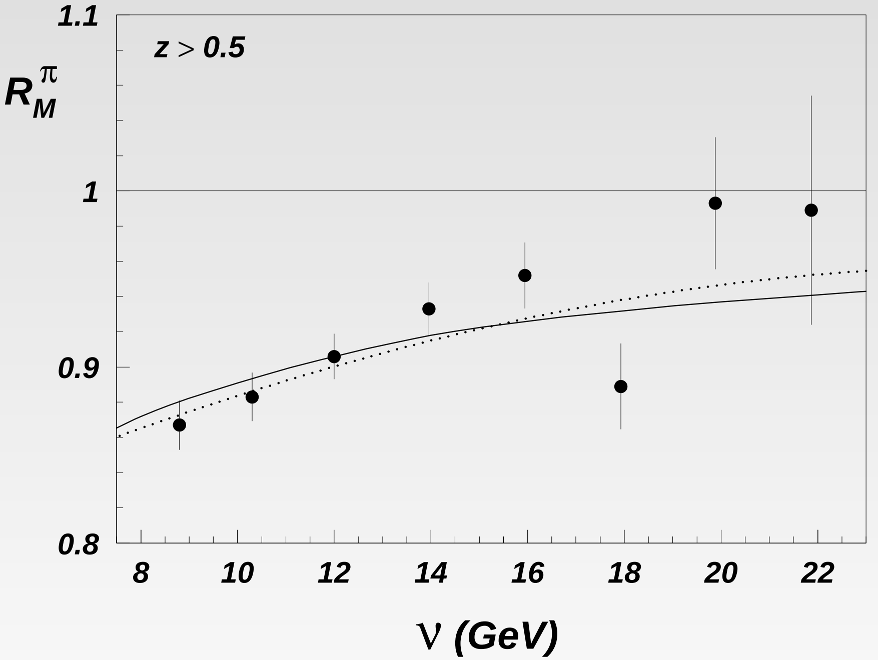
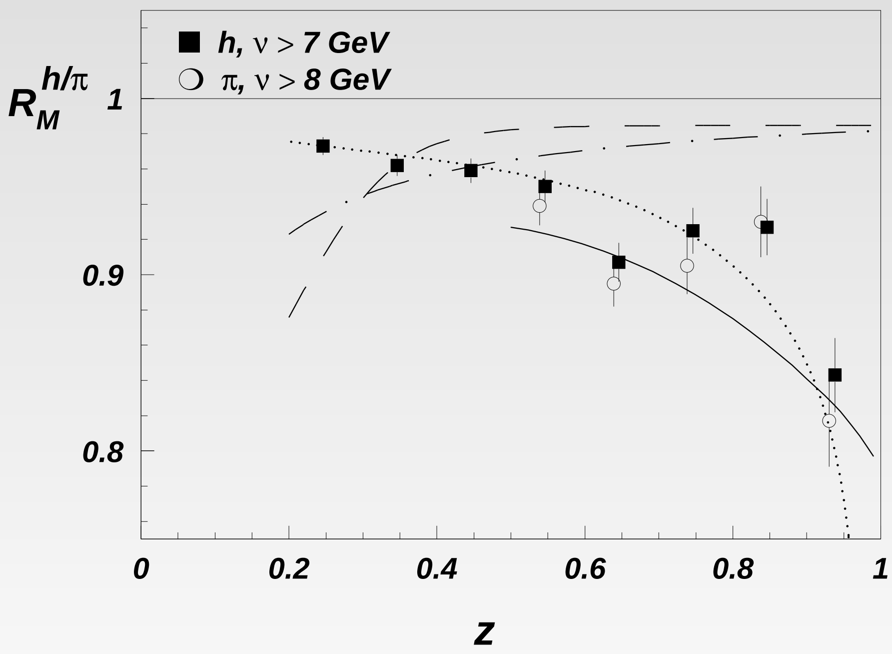
Attenuation of pre-hadrons

The propagation of a "breathing" dipole through a medium is described summing up all possible paths of the q and $\bar{q}$. Combining with the above evaluation of the production length this approach makes a good job predicting nuclear attenuation in SIDIS (B.K., J.Nemchik, E.Predazzi, 1995).

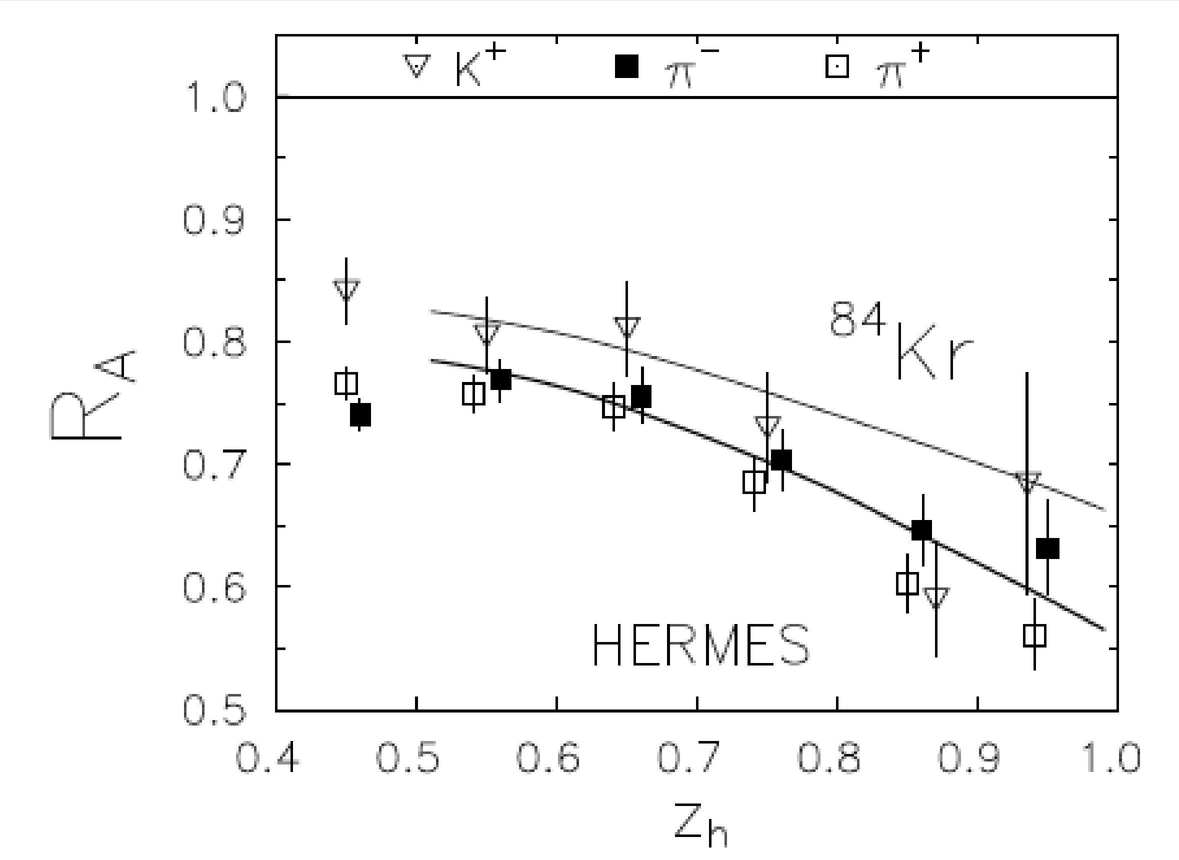




Solid curves: KNP-1995; Data: HERMES-2001for nitrogen.

Attenuation of pre-hadrons

The model also describes well the observed flavor dependence. The weaker attenuation of K^+ is another evidence for importance of absorption of the pre-hadron (K^-s are produced by a different mechanism).



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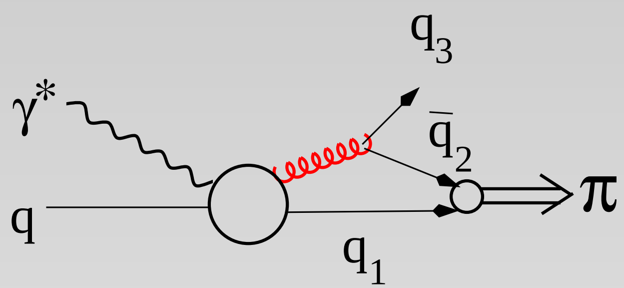
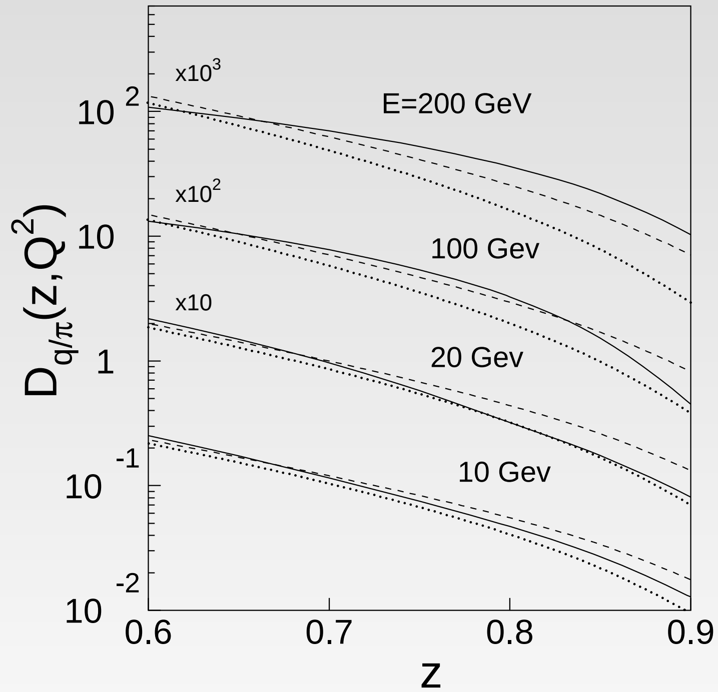
Perturbative fragmentation

Leading pion production $\gamma^* p \to \pi X$ in Born approximation results from radiation of a gluon which splits into $\bar{q}_2 q_3$. The produced colorless dipole $q_1\bar{q}_2$ is then projected to the pion wave function (E.Berger, 1980). Full calculations includes: (i) normalization; (ii) higher order terms in $(1 - z_h)$ expansion; (iii) realistic light-cone pion wave function; (iv) higher-twist terms; (v) effects of nonperturbative interaction between the partons; (vi) energy loss. The result agrees with the phenomenological fragmentation functions fitted to data (B.K., H.J.Pirner, I.Potashnikova, I.Schmidt, A.Tarasov, 2007-2009)





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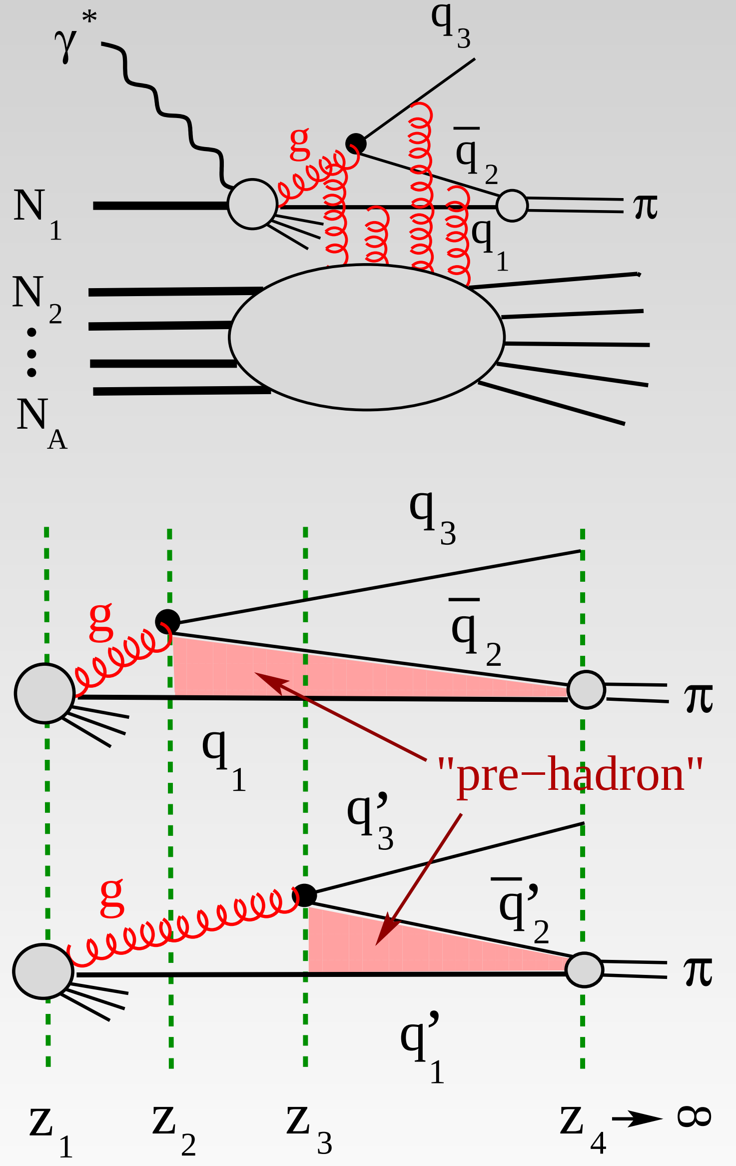
Quantum-mechanics of absorption

The model of nuclear attenuation discussed above is semi-classical, since treats the space-time development probabilistically. It is not correct to say that the pre-hadron is produced either inside, or outside the medium. Both can happen simultaneously.

Indeed, the cross section is a product of two amplitudes which may have different coordinates, $z_2 \neq z_3$, for pre-hadron production. Accordingly, the cross section contains three terms corresponding to pre-hadron production in both amplitudes outside (σ_1), or inside (σ_2) the nucleus, and the inside-outside interference (σ_3).



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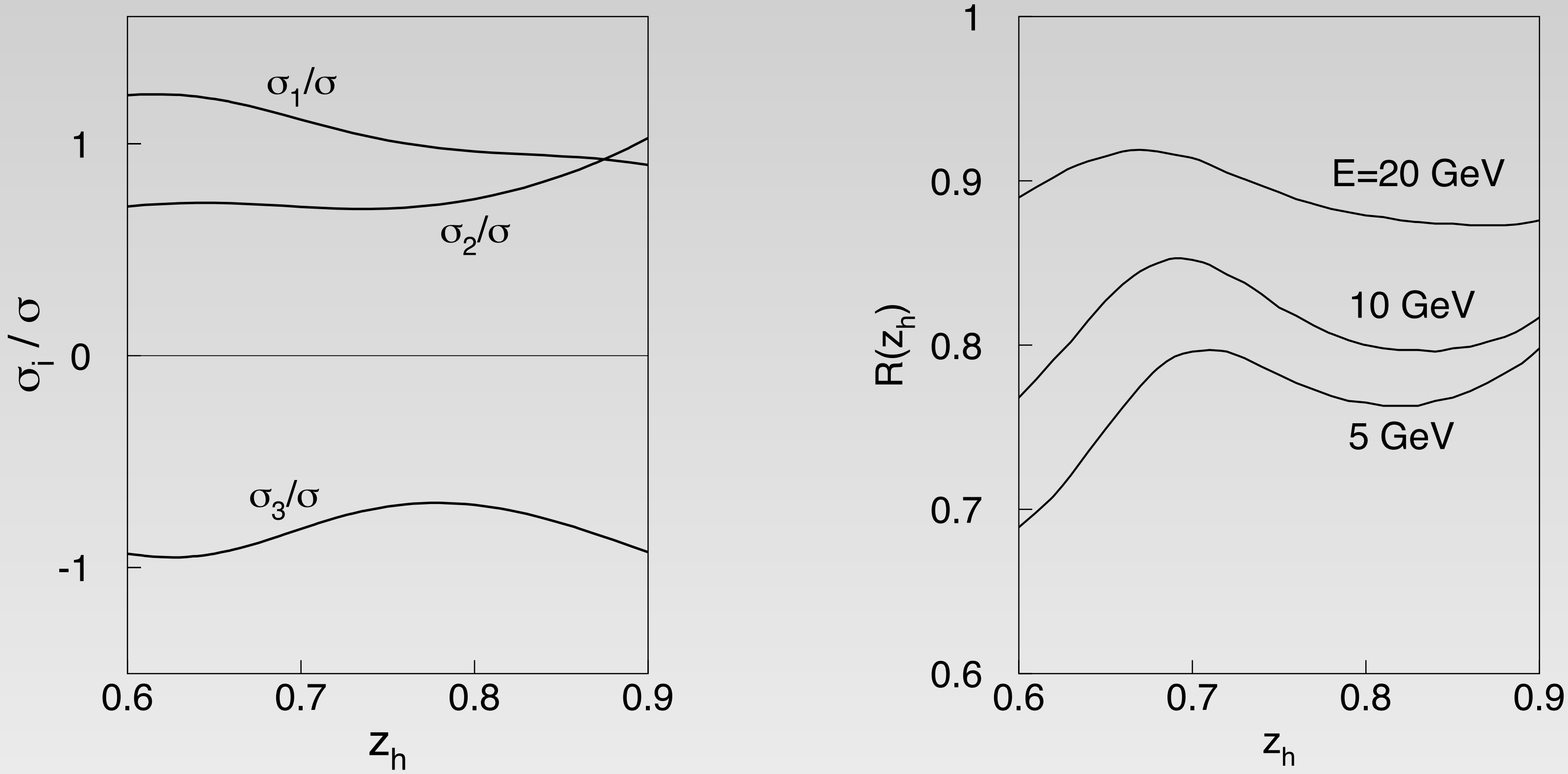
Quantum-mechanical treatment



The relative contributions of inside and outside productions, and their interference ($\boldsymbol{\sigma = \sigma_1 + \sigma_2 + \sigma_3}$) are of the same order of magnitude, however the interference term is negative.

- The effects of energy loss and non-perturbative interaction between partons are to be added.

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Summary

- The dipole formalism describes well in a parameter free way data on broadening of partons in nuclear matter observed in variety of processes and in a wide energy range.

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Summary

- The dipole formalism describes well in a parameter free way data on broadening of partons in nuclear matter observed in variety of processes and in a wide energy range.
- Smallness of broadening observed by HERMES rules out the explanation of HERMES data on hadron attenuation solely by induced energy loss.
- The semi-classical model which employs a probabilistic description for the space-time development of the hadronization process, but describes the quantum-mechanical evolution of the pre-hadron, well explains data on hadron attenuation in a parameter free way.

Summary

- Although the perturbative mechanism predicts too flat z_h dependence of the fragmentation function, introduction of a nonperturbative interaction between partons and energy loss results in a good agreement with data.

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Summary

- Although the perturbative mechanism predicts too flat z_h dependence of the fragmentation function, introduction of a nonperturbative interaction between partons and energy loss results in a good agreement with data.
- The full quantum-mechanical description of in-medium hadroniztion demonstrates that interference between inside and outside production of the pre-hadron has negative sign and is 100% important. It also leads to a nontrivial z_h dependence of nuclear effects.

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Summary

- Although the perturbative mechanism predicts too flat z_h dependence of the fragmentation function, introduction of a nonperturbative interaction between partons and energy loss results in a good agreement with data.
- The full quantum-mechanical description of in-medium hadroniztion demonstrates that interference between inside and outside production of the pre-hadron has negative sign and is 100% important. It also leads to a nontrivial z_h dependence of nuclear effects.

Outlook: The nonperturbative corrections, interaction among the partons and energy loss, must be introduced. The result can be used as a starting function for the DGLAP evolution to a higher scale to be compared with data.

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Backups: Time evolution of a high-p_T jet

The mean time of radiation of a gluon:

$$\langle l_c \rangle = \int\limits_{\Lambda^2}^{Q^2} dk^2 \int\limits_0^1 dx \, \frac{dn}{dx\, dk^2} \, l_c(x, k^2) = \frac{E}{\Lambda^2} \, \frac{1}{\ln(Q/\Lambda)\ \ln(Q\Lambda/4E^2)}$$

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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Backups: 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 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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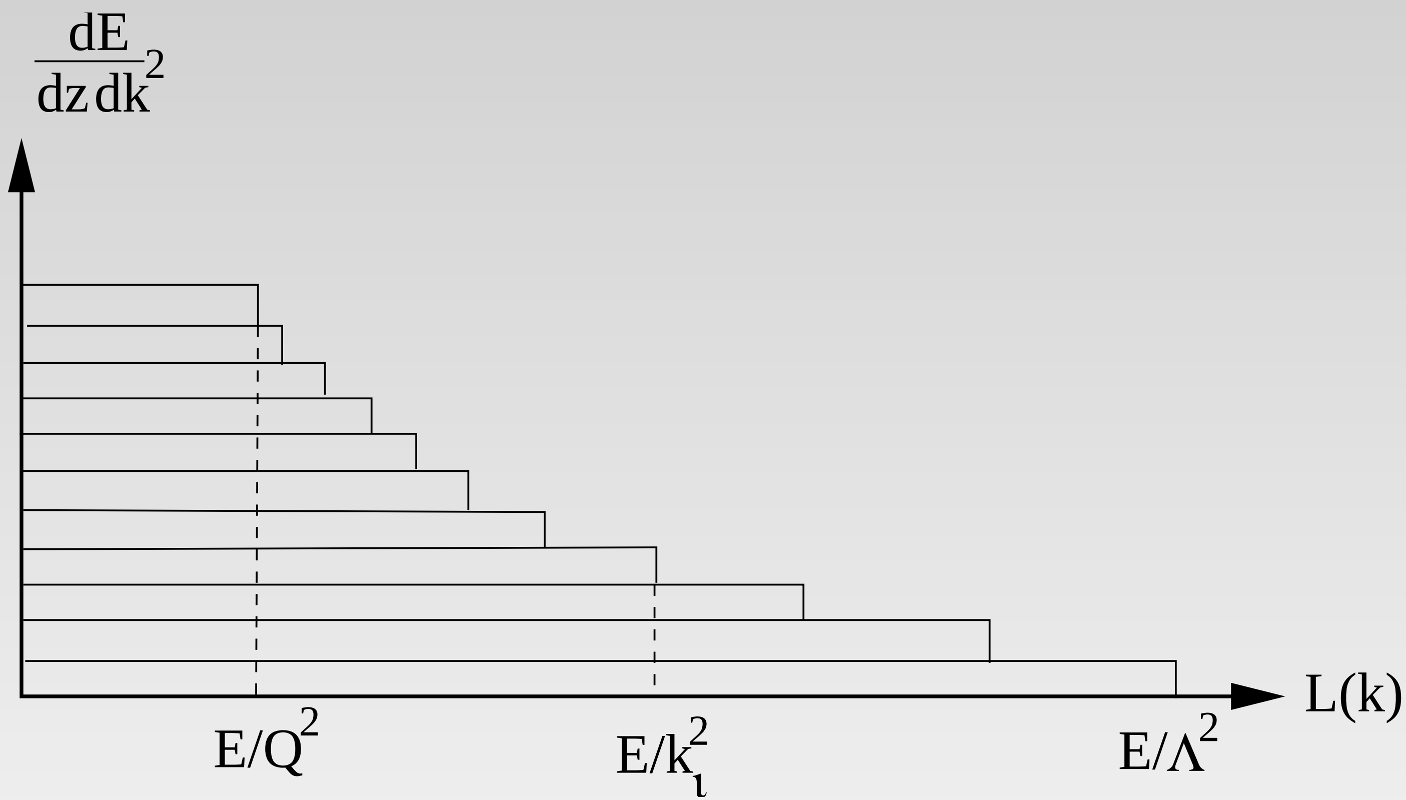
Backups: Time evolution of a high-p_T jet



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

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Backups: 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 $Q = E$

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

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

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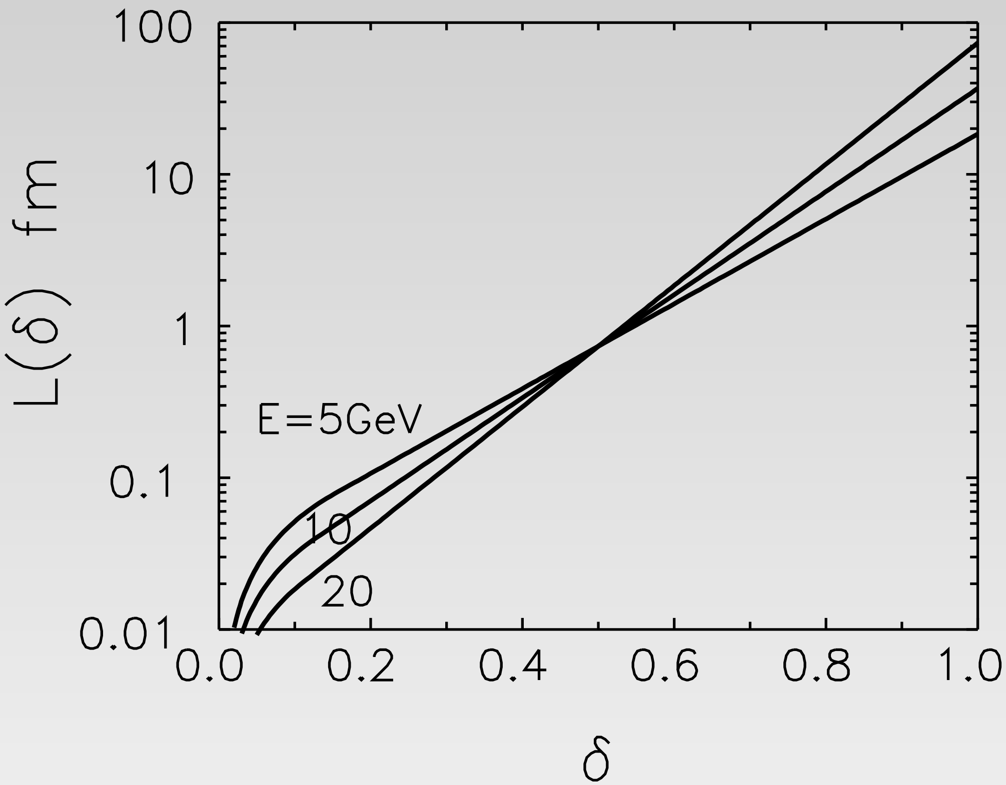
Backups: Time evolution of a high-p_T jet



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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