Hadronization

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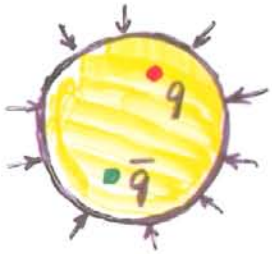
Nonperturbative models

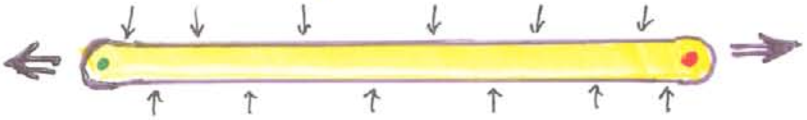
MIT Bag

Assuming that the valence quarks in the hadron suppress vacuum fluctuation and vary the density of energy, the latter becomes different inside and outside the hadron: $B = \varepsilon_{in} - \varepsilon_{out} = \frac{M_h}{\frac{4}{3}\pi R_h^3}$

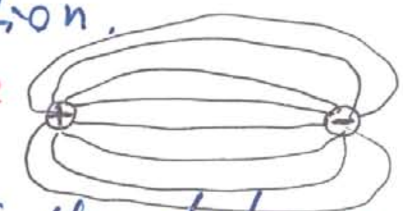


Vacuum presses on the bubble trying to squeeze it. However, the energy of the chromo-electric and -magnetic field rises leading to equilibrium.

If the quarks are pulled away, the same boundary condition leads to formation of a tube of a constant X-section.



Compare to QED



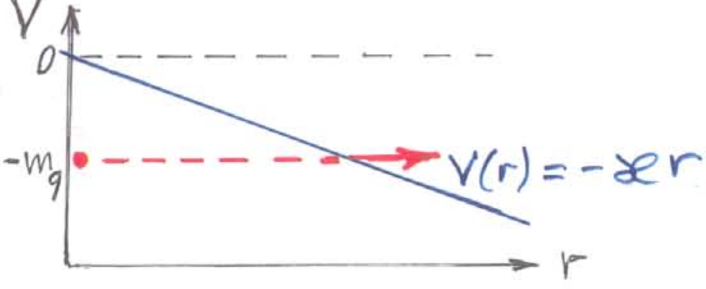
Usually the transverse size of the tube is not important, and one can call it a **string**.

The important parameter is the density of energy stored in the string per unit of length - string tension.

$\varkappa \approx 1 \, \frac{GeV}{fm}$ - from the slope of Regge trajectories: $\varkappa = (2\pi \alpha_R')^{-1}$

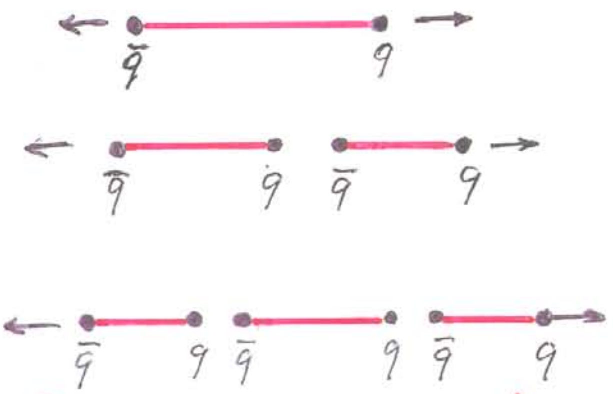
calculations on the lattice give the same.

One cannot make the string very long, since it easily breaks up due to the Schwinger process of quark tunneling from vacuum.



The decay rate per unit of time and length

$$P = \frac{\alpha_s \varkappa}{2\pi^2} e^{-\frac{\pi m_T^2}{2\varkappa}}$$



$$m_T^2 = m_q^2 + p_T^2 ; \quad \alpha_s = \frac{g^2}{4\pi}$$

The K/π ratio

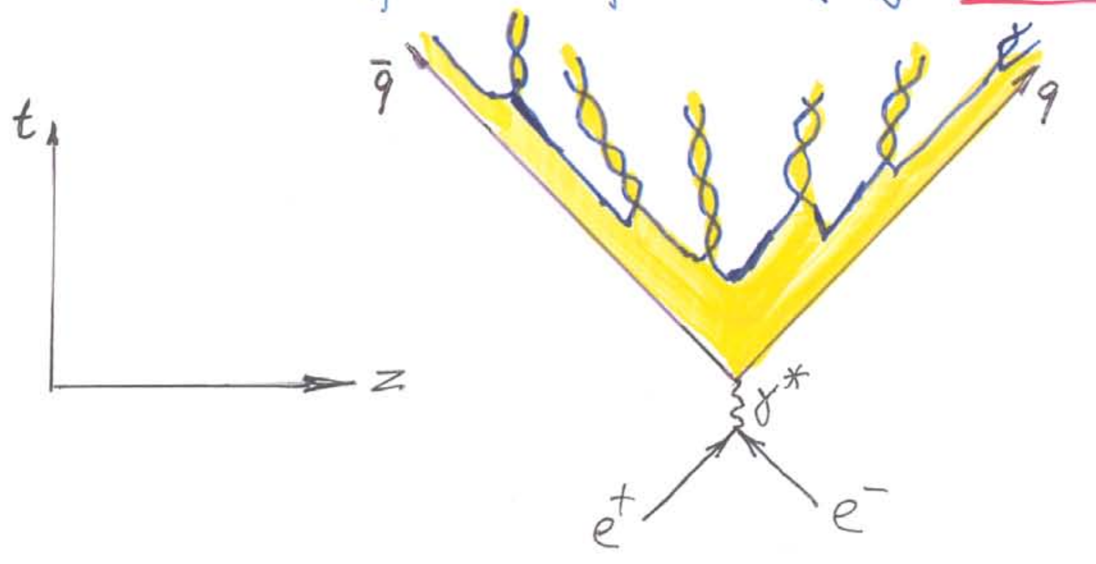
$$R_{K/\pi} = e^{-\frac{\pi \Delta m^2}{2\varkappa}} \approx \frac{1}{3}$$

in accordance with data.

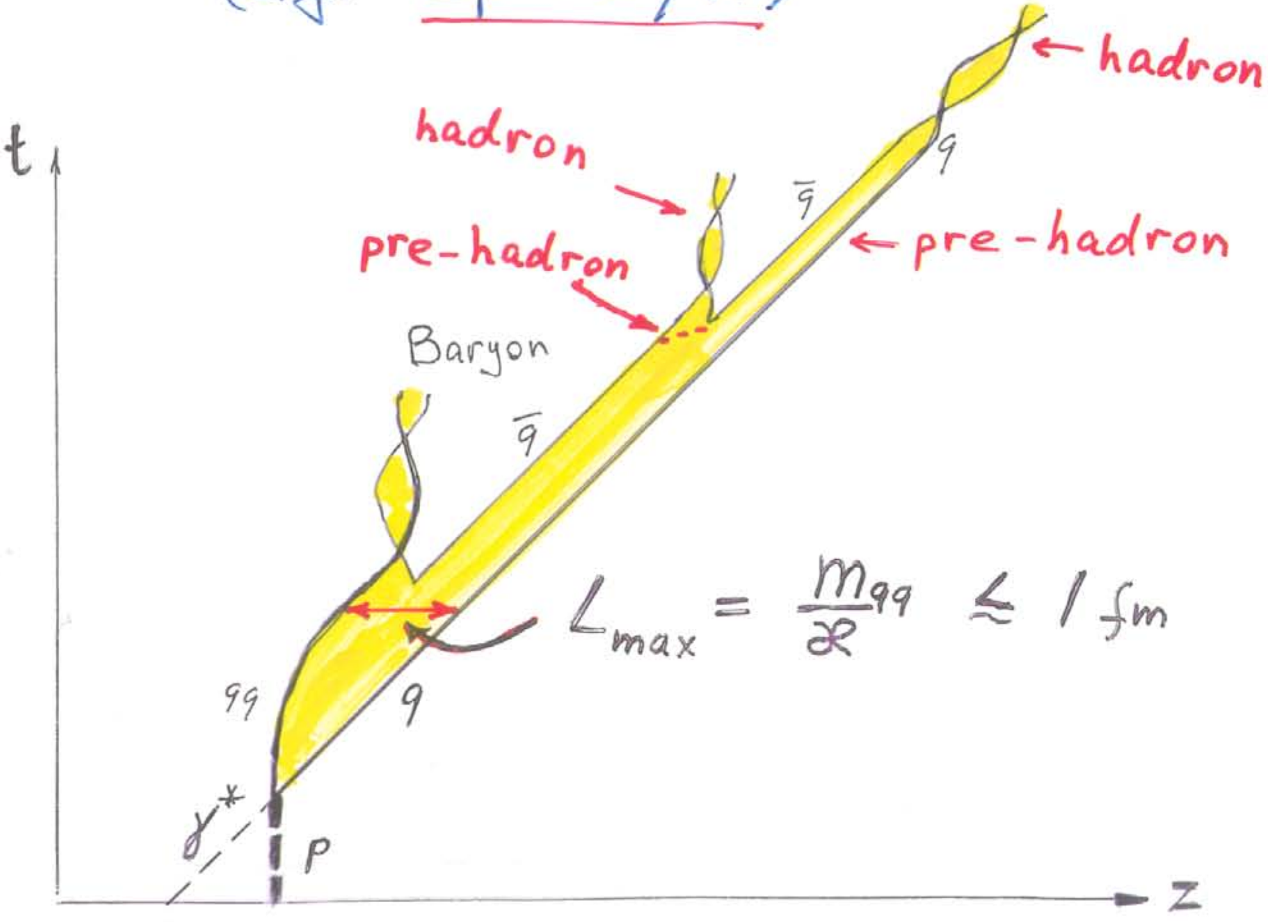
The Schwinger phenomenon is the real reason for confinement

Space-time development of hadronization

- The center-of-mass frame (e.g. $e^+e^- \to q\bar{q}$)



- The rest frame of the target
  (e.g. $ep \to e'qX$)



$$L_{max} = \frac{m_{qq}}{\varkappa} \lesssim 1\,fm$$

In each $q\bar{q}$ pair produced from vacuum the $\bar{q}$ becomes a slow end of the leading heavy string, while the q becomes a fast end of the light slow string. The latter becomes a **hadron later,** when it develops the wave function (YO-YO in terms of the classical string model).

Correspondingly, hadronization is characterized with two time scales.

Production time, t_p, is related to the moment of $q\bar{q}$ production on mass shell. The slow string, which is just a colorless $q\bar{q}$ dipole, may be called **pre-hadron.**

Formation time, t_f, of the hadronic wave function. It is longer than production, $t_f > t_p$.

The momenta of produced (pre) hadrons in a jet rise in geometrical progression. Correspondingly,

$$t_p \approx \frac{p_q}{2\varkappa}\, z_h \qquad\qquad z_h = \frac{p_h}{p_q} \leq 1$$

The formation time is also proportional to z_h:

$$t_f = \frac{p_q}{\mu^2}\, z_h$$

! This relation between t_p and t_f drastically changes at large $z_h \to 1$.

Indeed, due to the retarding force from the string the leading quark keeps losing energy with a constant rate

$$\frac{dE}{dt} = -\varkappa$$

At $z_h \to 1$ no energy loss is permitted, therefore the pre-hadron must be produced momentarily

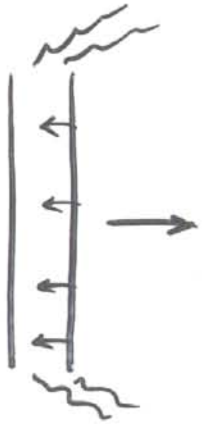
$$t_p \underset{z_h \to 1}{=} \frac{p_q}{\varkappa}\,(1 - z_h)$$

F. Niedermayer
B. K.
1983

- String model or pQCD?

Can one describe a hard reactions within a nonperturbative string model?

QED analogy: a big capacitor



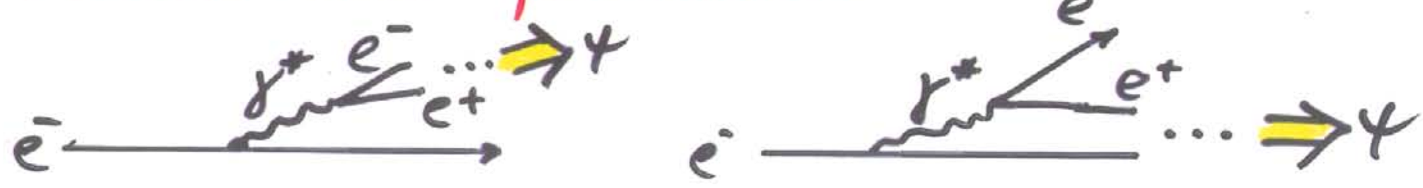
The retarding force from the static field is the main source of energy loss. Bremsstrahlung from the edges can be neglected. This may be QED analogy to color strings.

Point-like charges lose energy mainly via radiation, the contribution of the static field is small

Perturbative hadronization

Although hadronization is usually considered as a manifestation of confinement, it also may be a perturbative process.

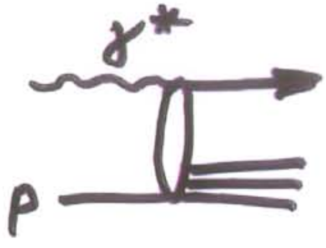
Positronium production



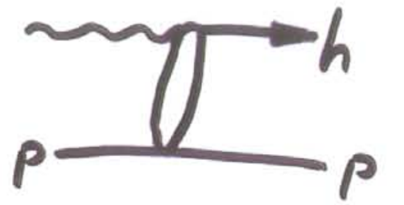
Of course, formation of the wave function is always nonperturbative.

Inclusive production of leading hadrons has a limiting case of exclusive process.

$$z_h = \frac{P_h^+}{P_{\gamma^*}^+}$$

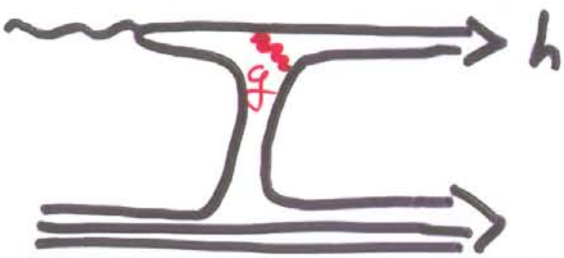


$$\xrightarrow[z_h \to 1]{}$$



Subject to Color Transparenc
E665, HERMES . . .

$\longrightarrow$



Instantaneous production

Slower $q\bar{q}$ pairs
are produced earlier.

The less z_h is, the more $q\bar{q}$ pairs is produced, the longer it takes.

The pre-hadron (a $q\bar{q}$ dipole) is produced perturbatively with a size $\bar{r}(Q^2, z_h)$ controlled by Q^2 and z_h.

In the limit $z_h \to 1$ $\bar{r} \sim \frac{1}{Q}$

! The string model contradicts data on
• CT at large z_h.

pQCD model for hadronization

In the large N_c limit each radiated gluon can be replaced by a color-octet $q\bar{q}$ pair (10% accuracy)

The gluon cloud is replaced by a cloud of $q\bar{q}$ dipoles (colorless).

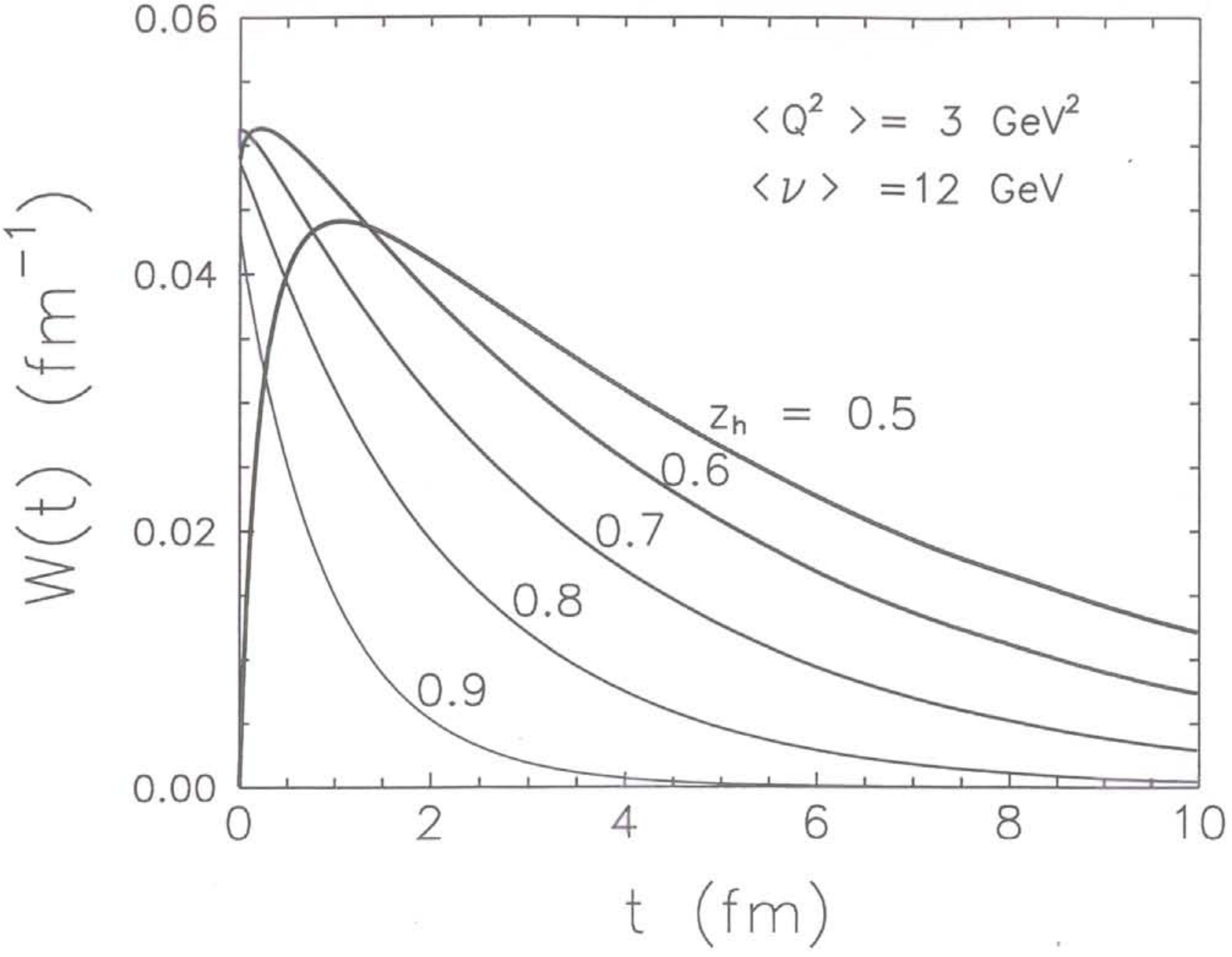
The one which contains the leading quark is projected to the light-cone wave function of the leading hadron

$$\Psi_h(\beta, \ell_T) = \frac{\beta(1-\beta)}{\beta(1-\beta)+a_0} \exp\left[-\frac{1}{8} \frac{R_h^2 \ell_T^2}{\beta(1-\beta)+a_0}\right]$$

The fragmentation function

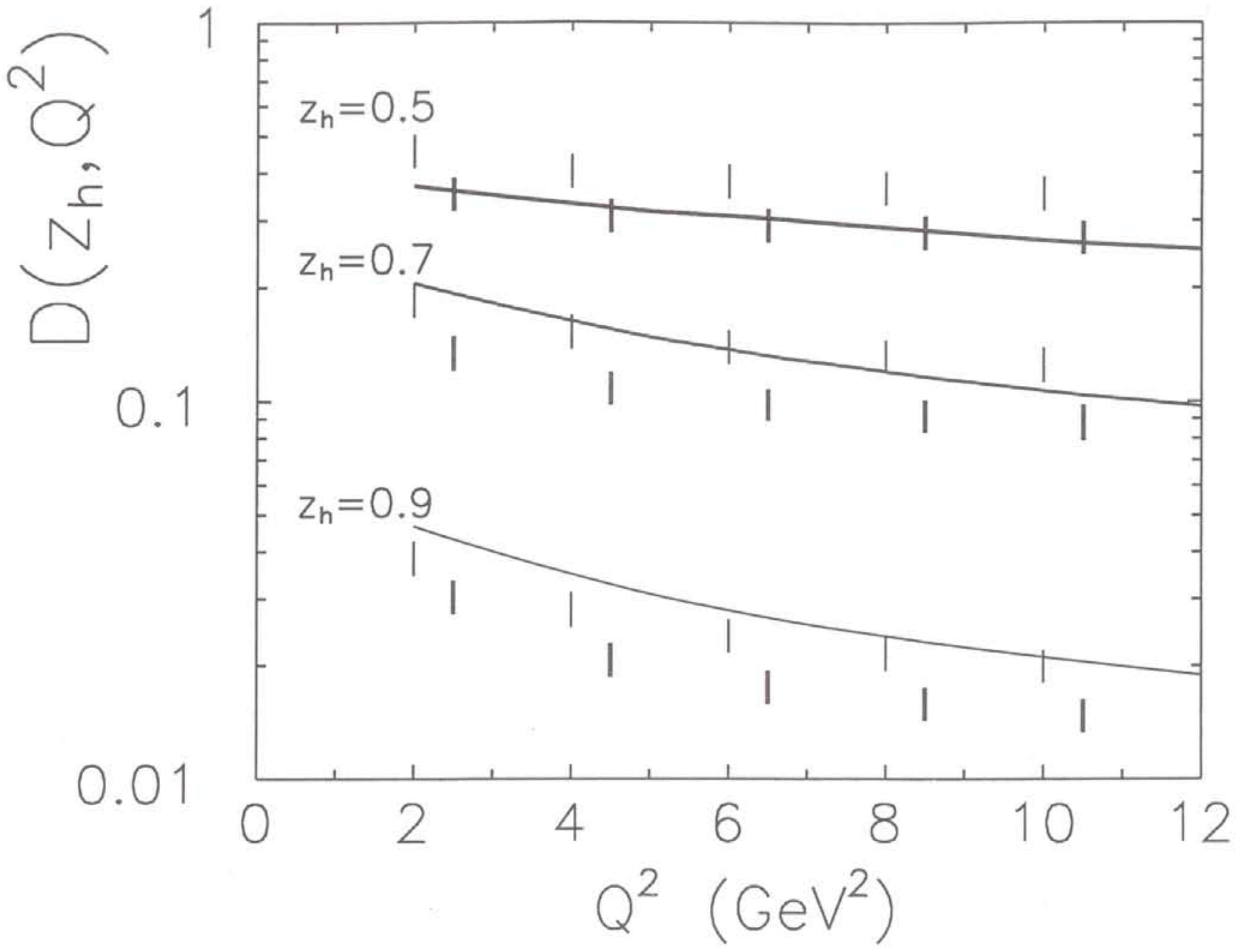
$$D_{h/q}(z_h, Q^2) = \int dt\, W(t, z_h, Q^2)$$

$$W(t, z_h, Q^2) = N \int \frac{d\alpha}{\alpha} \delta\left[z_h - \left(1-\frac{\alpha}{2}\right) \frac{E_q(t)}{E_q(0)}\right]$$
$$\times \int\limits_{\Lambda^2}^{Q^2} \frac{dk_T^2}{k_T^2} \frac{1}{t_c} e^{-\frac{t}{t_c}} \int d\ell_t^2\, \delta\left[\ell_T^2 - \frac{9}{16} k_T^2\right] \int\limits_0^1 d\beta\, \delta\left(\beta - \frac{\alpha}{2-\alpha}\right) |\Psi_h(\beta, \ell_T)|^2 S(z_h, t)$$



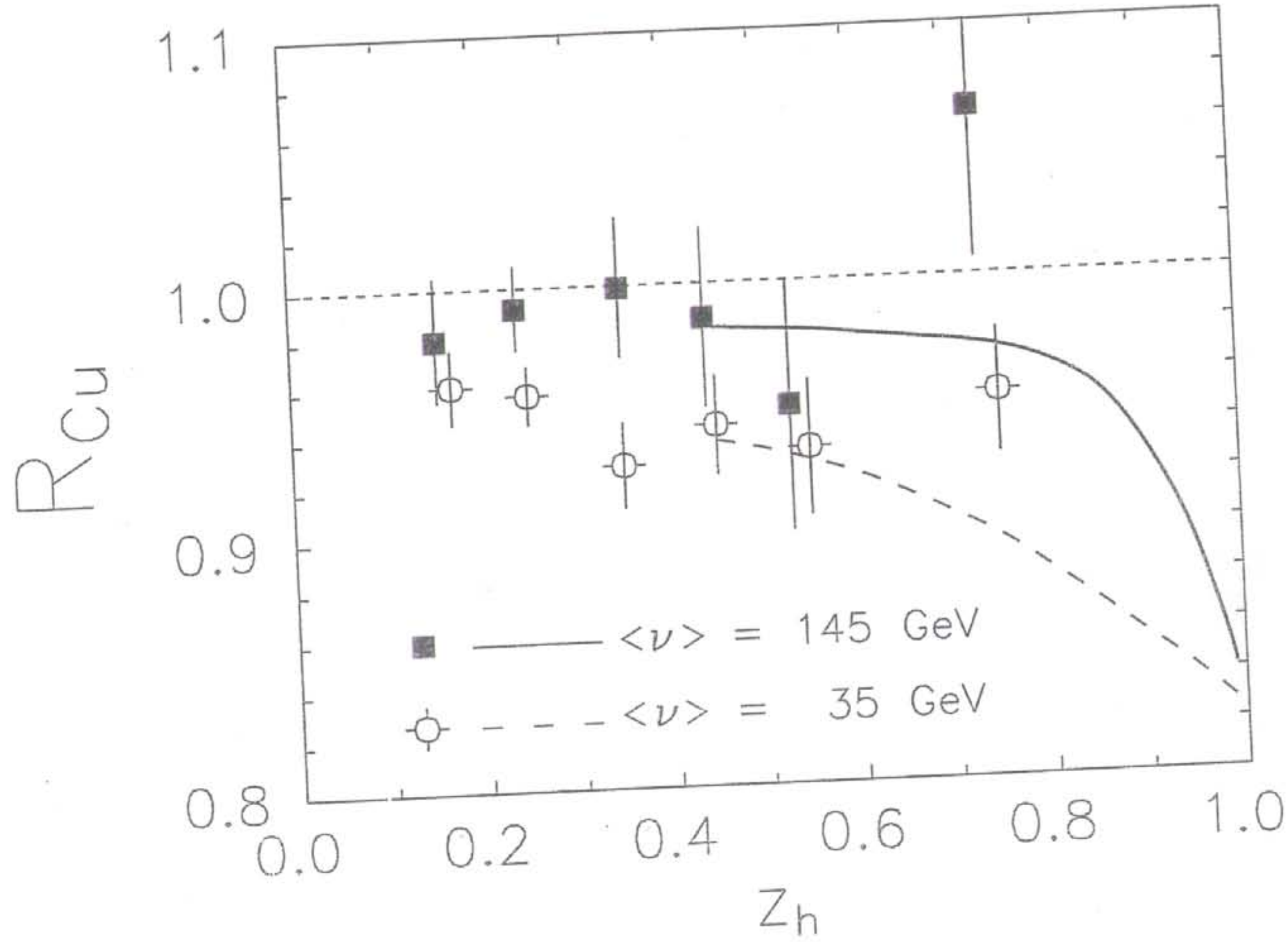
The production time distribution function

$t_p = \langle t \rangle$ shrinks at $z_h \to 1$

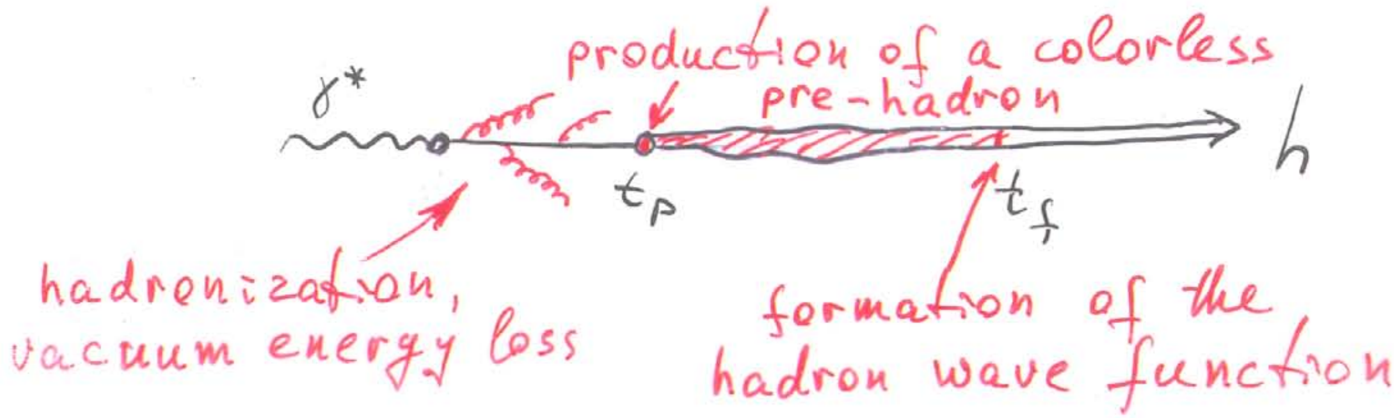


❙ B. Kniehl, G. Kramer, B. Potter, 2001
Global analysis

Pre-HERMES era



One should discriminate between production and formation times



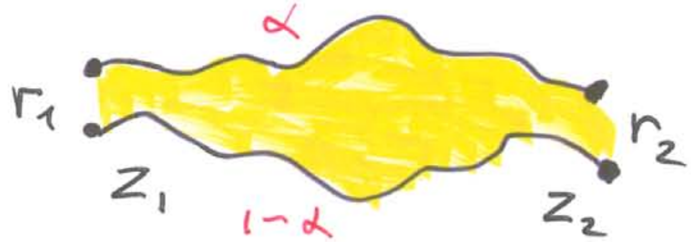
production of a colorless pre-hadron

hadronization, vacuum energy loss

formation of the hadron wave function

attenuation of the pre-hadron

The light-cone Green function $G(\vec{r}_1, z_1; \vec{r}_2, z_2)$ describes propagation and evolution of a $q\bar{q}$ in an absorptive medium



B. Zakharov & B.K. 1991

B.K., J. Raufeisen, A. Tarasov 1998

. . . . .

One should sum up all trajectories.

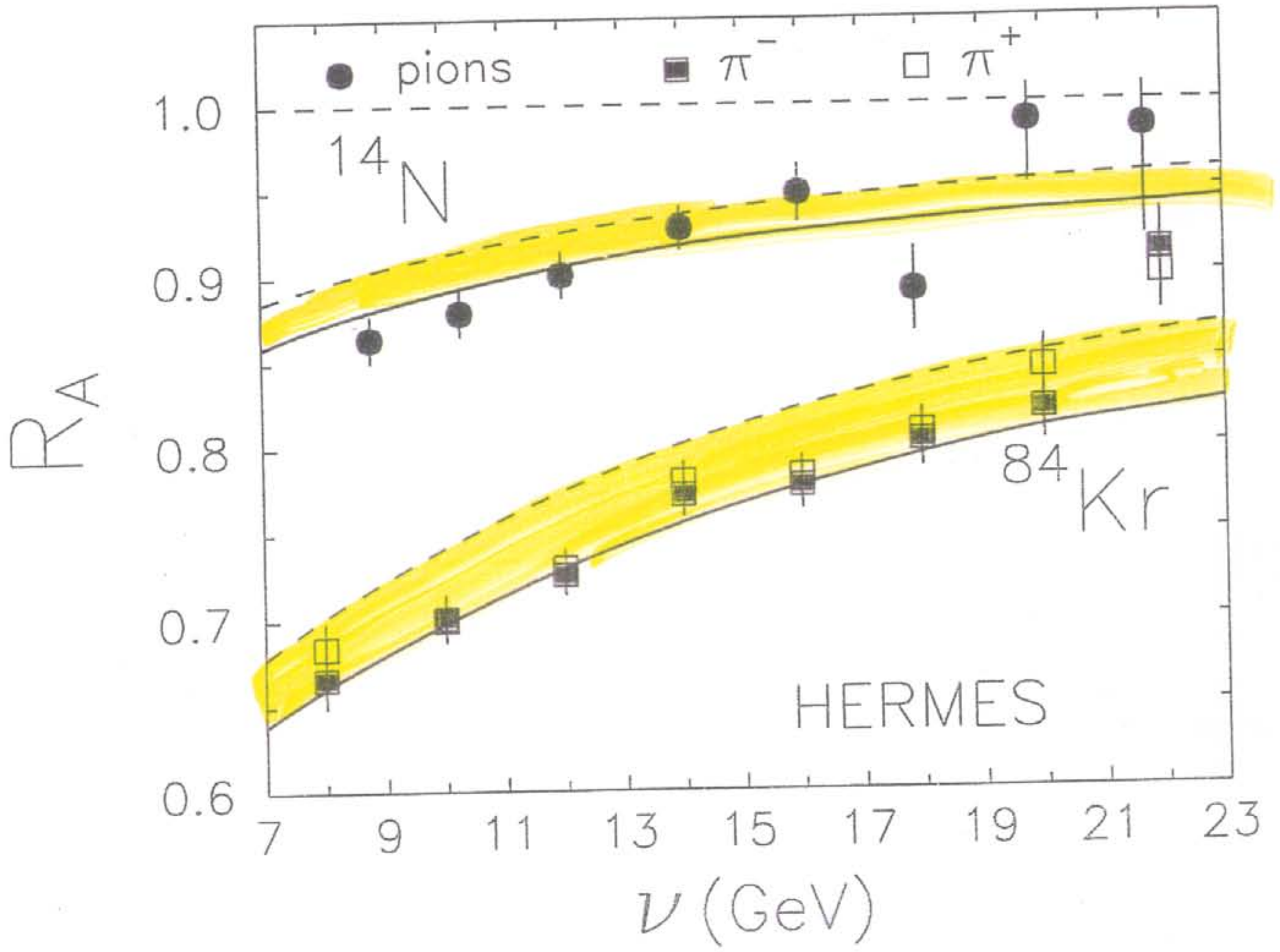
$$i\frac{d}{dz_2} G(\vec{r}_1, z_1; \vec{r}_2, z_2) = \left[\frac{m_q^2 - \Delta_{r_2}}{2E_q\alpha(1-\alpha)} + V_{q\bar{q}}(z_2, \vec{r}_2, \alpha)\right] \times G(\vec{r}_1, z_1; \vec{r}_2, z_2)$$

$$\mathrm{Im}\, V_{q\bar{q}} = -\frac{1}{2}\sigma_{q\bar{q}}(\vec{r}, s)\,\rho_A(z_2)$$

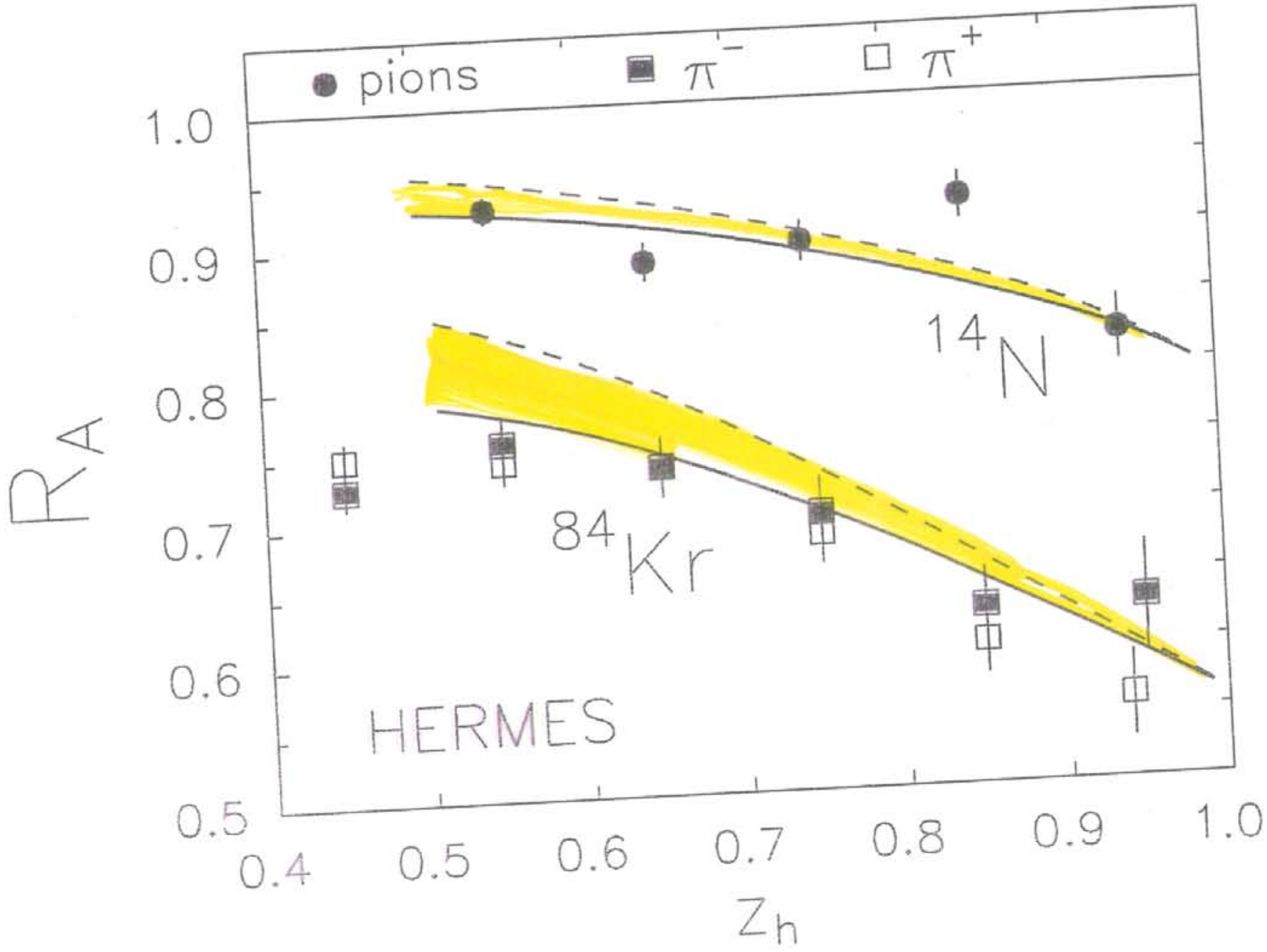
The initial size $r_1^2 \sim \frac{1}{Q^2}$, so **color transparency** is at work,

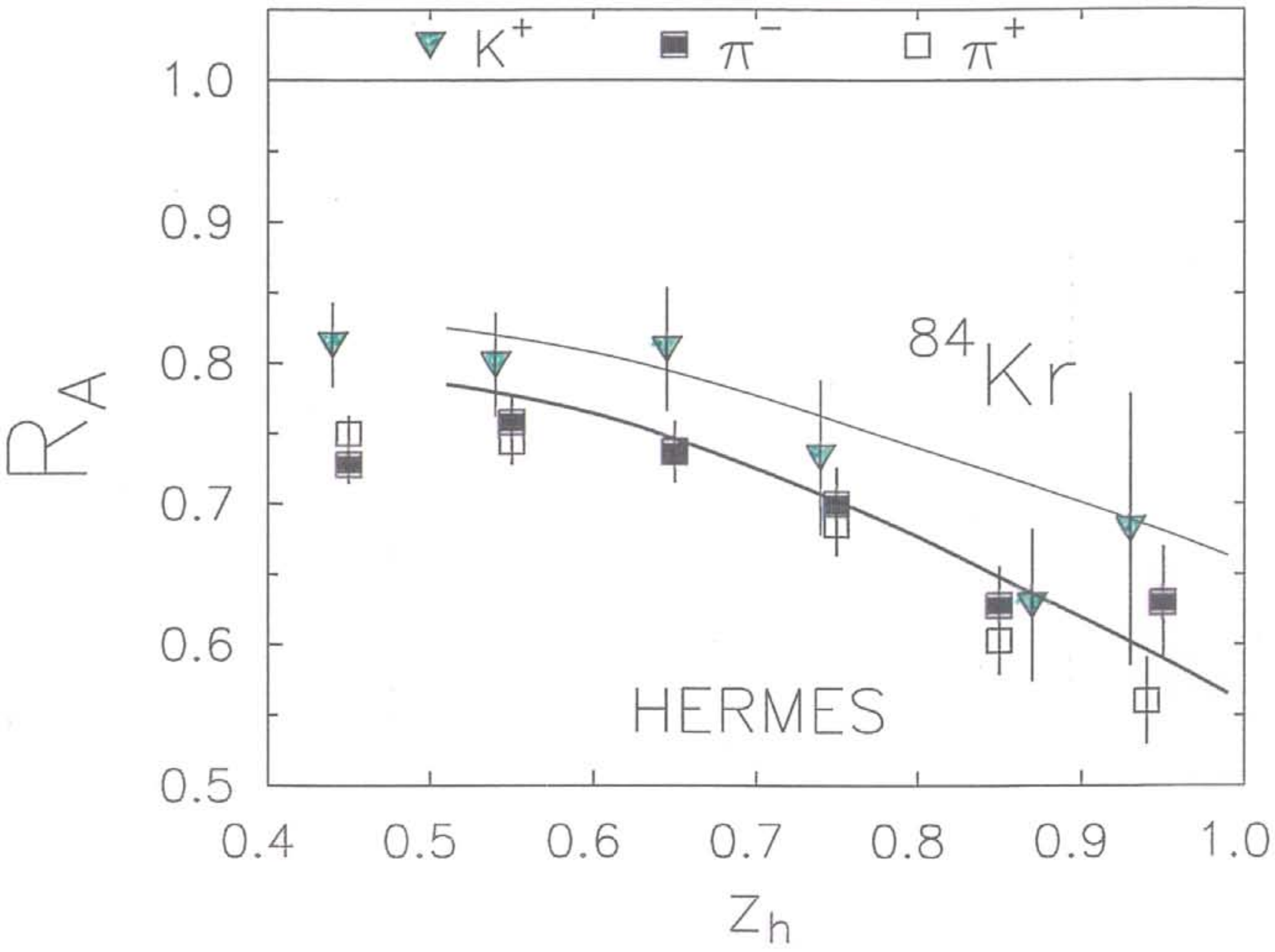
$\sigma_{q\bar{q}} \sim r^2$

B.K., J. Nemchik
& E. Predazzi:
1996



🟨 induced energy loss in accordance with BDMS

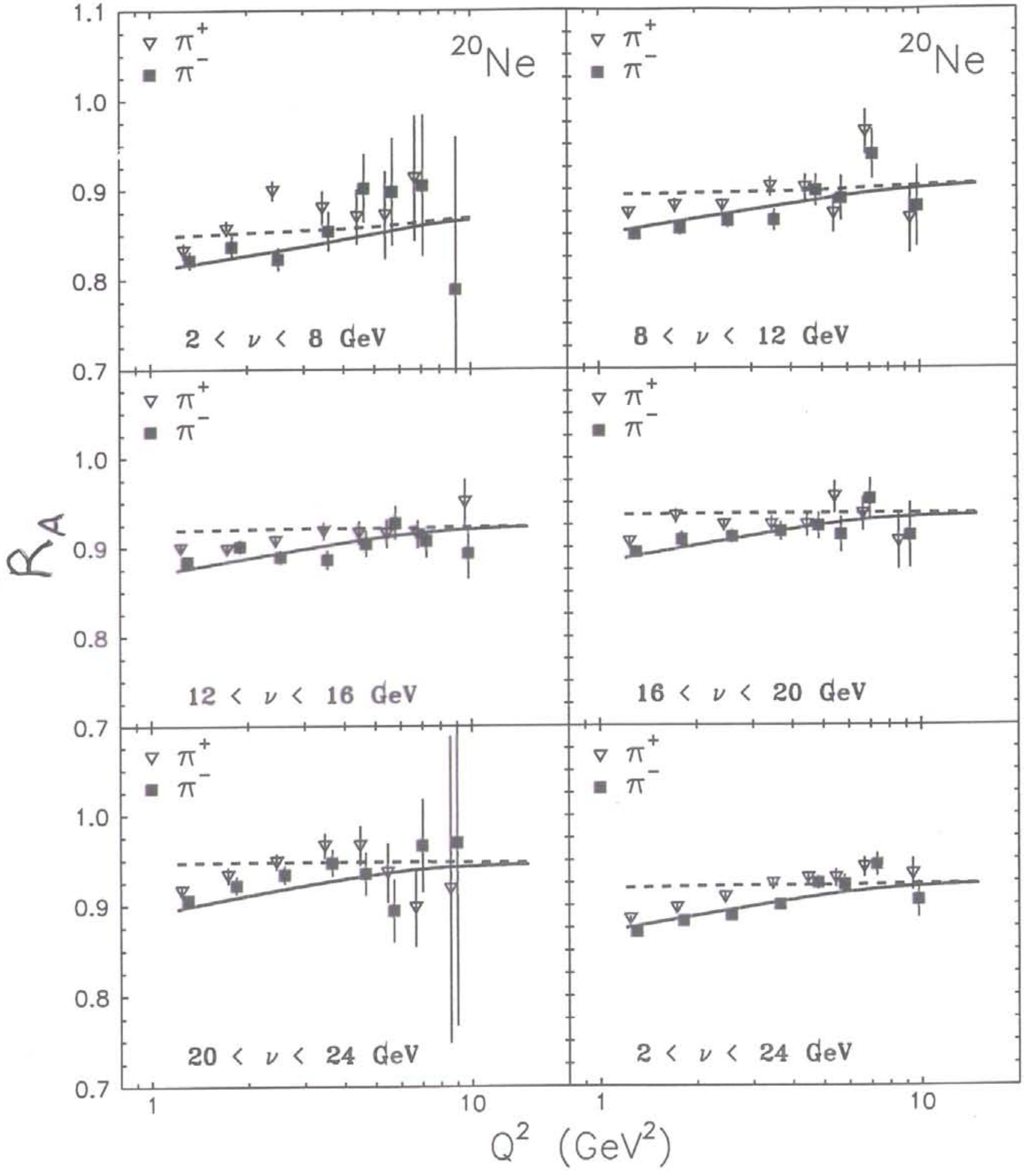

● pions
■ π⁻
□ π⁺
1.0
0.9
0.8
0.7
0.6
0.5
R_A
0.4
0.5
0.6
0.7
0.8
0.9
1.0
z_h
14N
84Kr
HERMES



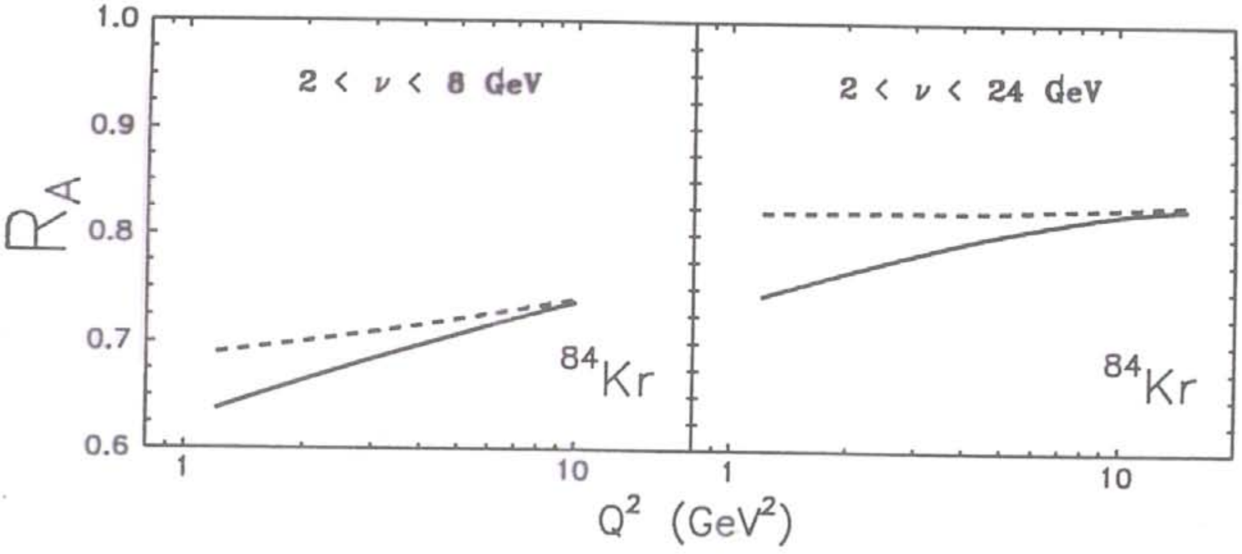
Signatures of a short production time: flavor dependence

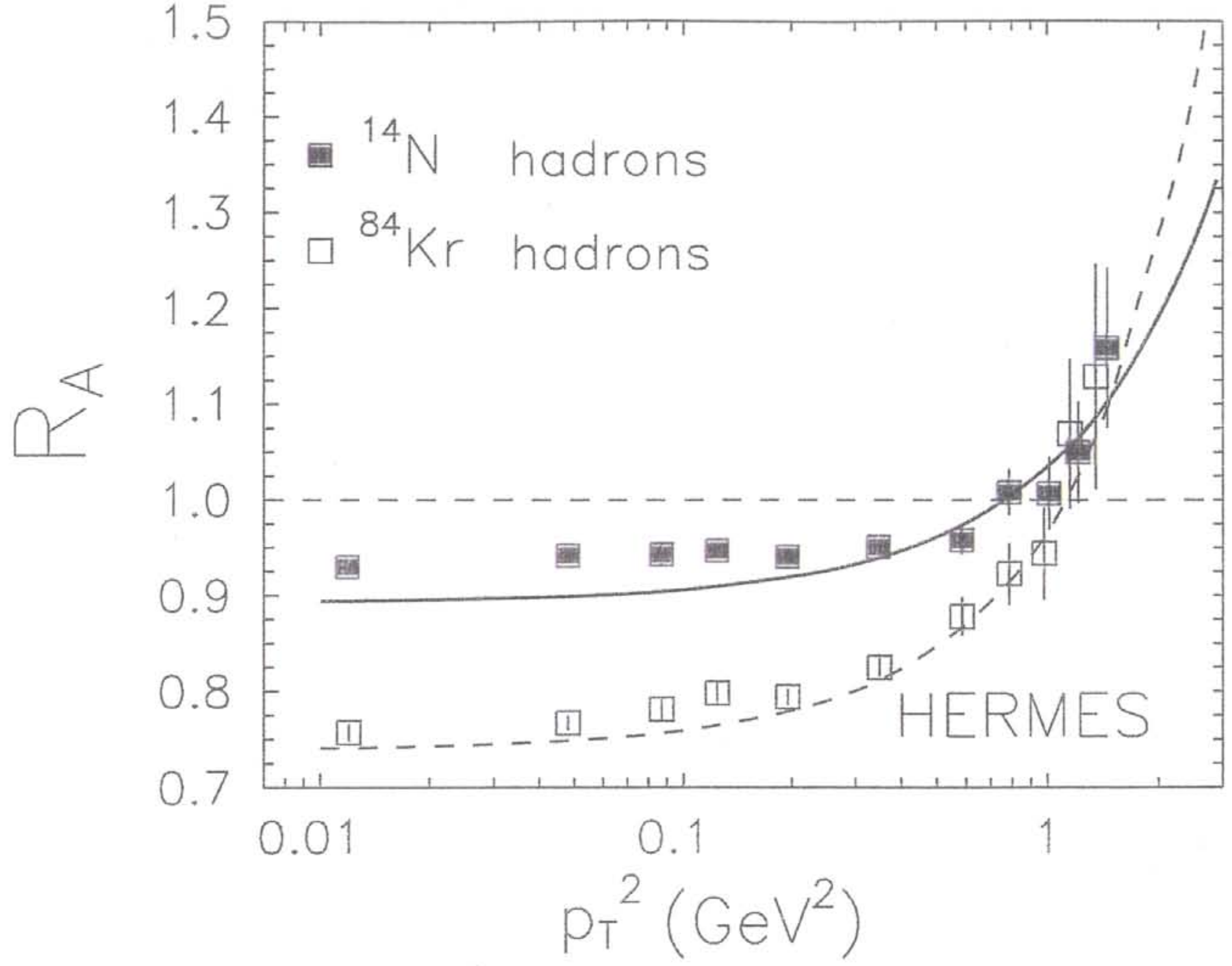
Kaons having a smaller absorption cross section, are less suppressed.

The energy loss scenario (Wang & Wang) predicted an increasing with Q^2 nuclear suppression



The contraction of ℓ_p with Q^2 and CT partially compensate each other.

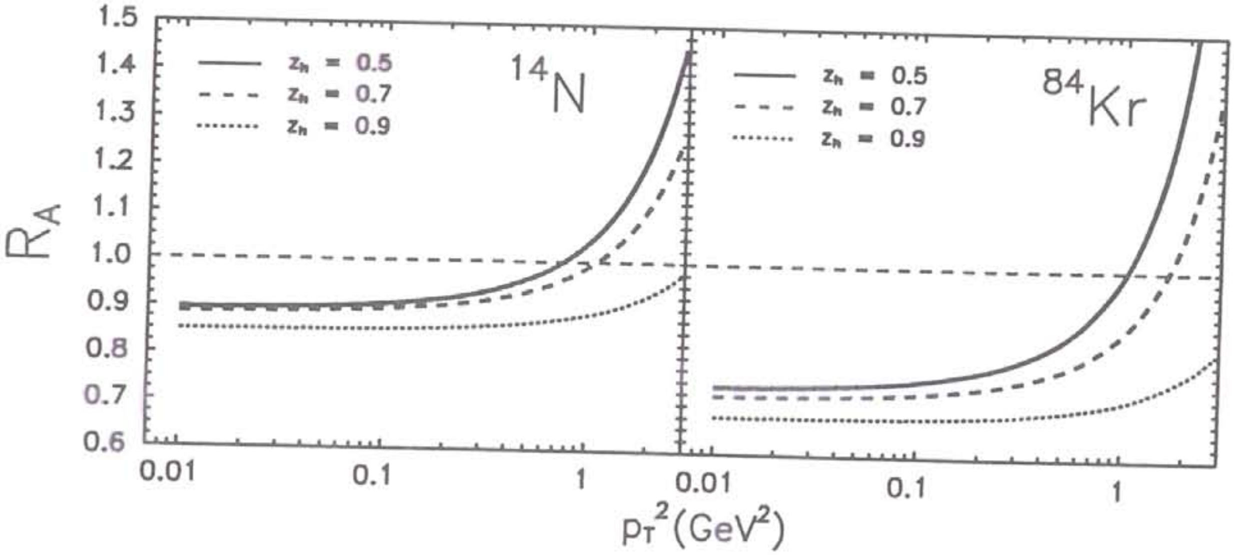

2 < ν < 8 GeV
2 < ν < 24 GeV
R_A
1.0
0.9
0.8
0.7
0.6
^{84}Kr
^{84}Kr
1
10
1
10
Q^2 (GeV^2)



P_T broadening is calculated in the dipole approach with no free parameters

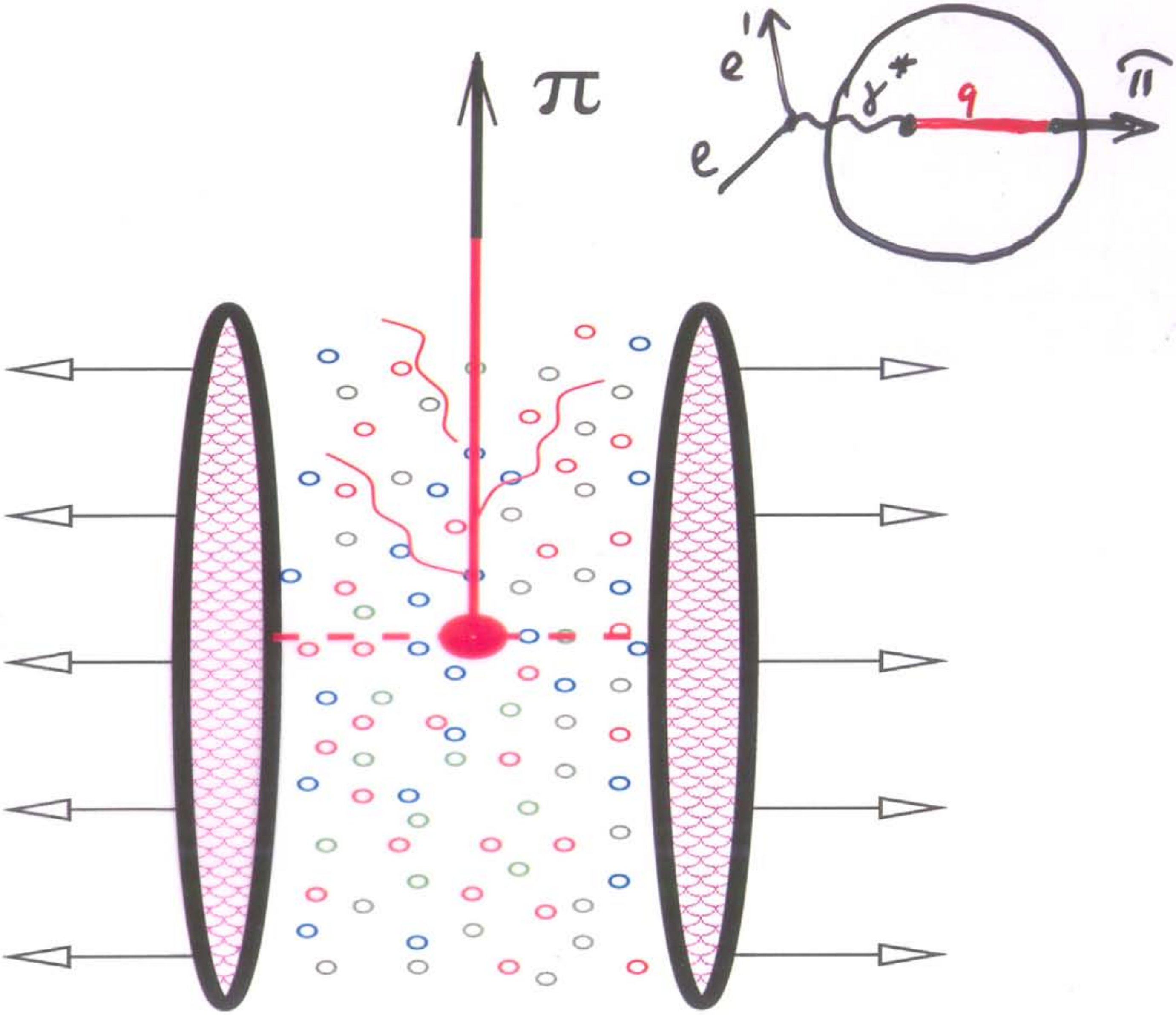
$$\frac{d\sigma}{dP_T^2} = \int d^2r\, d^2r' \underset{\nearrow\, e^{i\vec{P}_T(\vec{r}-\vec{r}\,')}}{\,}\Omega(\vec{r},\vec{r}\,') \exp\left[-\tfrac{1}{2}\sigma_{q\bar{q}}^{N}(\vec{r}-\vec{r}\,')\, T_A(b)\right]$$

$\sigma_{q\bar{q}}^{N}(r)$ is the total cross section of interaction of a $q\bar{q}$ dipole with separation $\vec{r}$. It is fitted to $F_2^p(x, Q^2)$. Gluon radiation is included.



1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
R_A
z_h = 0.5
z_h = 0.7
z_h = 0.9
^{14}N
z_h = 0.5
z_h = 0.7
z_h = 0.9
^{84}Kr
0.01
0.1
1
0.01
0.1
1
p_T^2(GeV^2)

Jet quenching in quark-gluon plasma



Inclusive hadron production in DIS is a perfect laboratory to test our ideas.

Very similar kinematics to what one has in high-p_T hadron production in heavy ion collisions.

Less unknowns: the initial quark energy and the properties of the medium are known.

! The new important feature of hadronization of high-p_T partons produced in pp, or AA collisions is a different energy dependence.

In DIS $$t_p = \frac{P_q}{\frac{2\alpha_s}{3\pi} Q^2}(1-z_h)$$

There are two dimensional parameters.

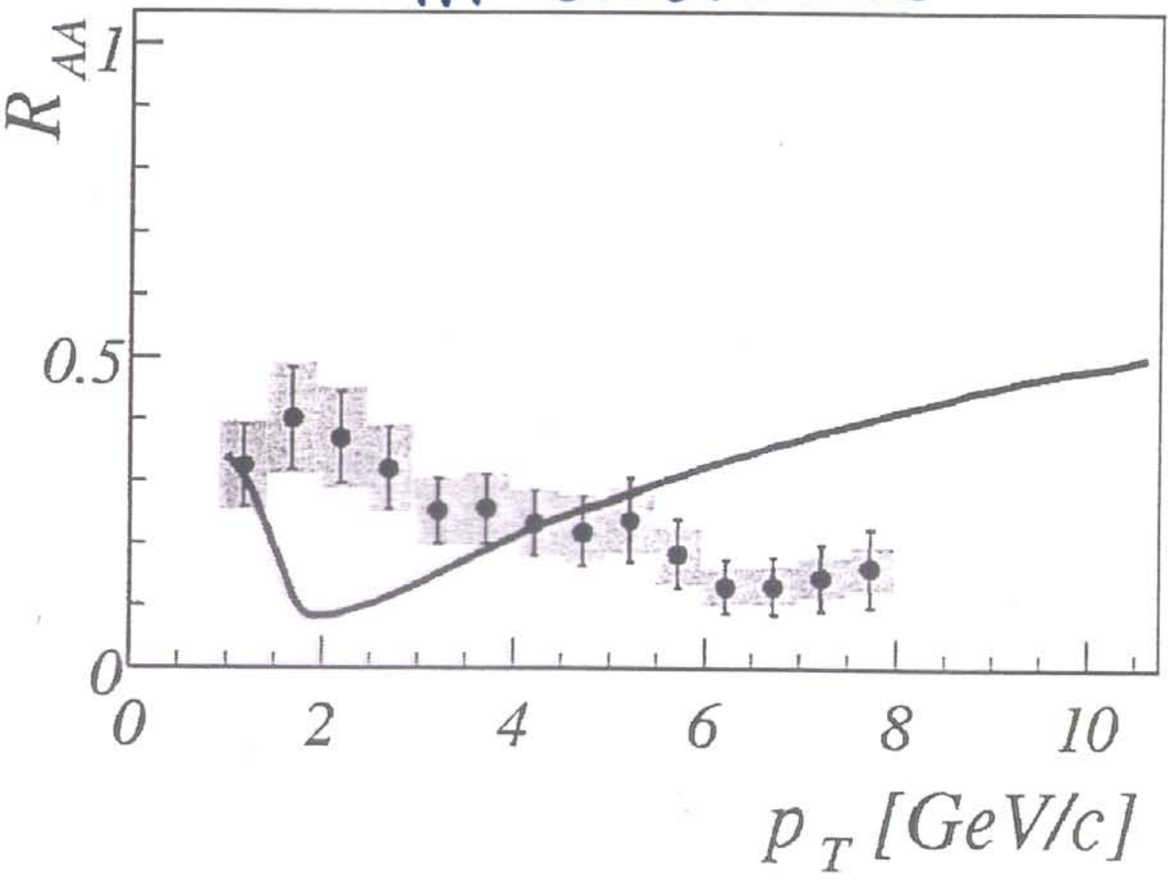
In high-p_T parton scattering there is only <u>one</u> dimensional parameter p_T

$$P_q = P_T$$
$$Q^2 = P_T^2$$

Thus, $t_p \propto \frac{1}{P_T}$, i.e. the production time <u>shrinks</u> with p_T!

One may expect a <u>falling</u> p_T-dependence for R_{AA} compared to <u>rising</u> $R_A(\nu)$ in DIS.

Wang & Wang predictions for HI collisions



Conclusions

- Although there is no doubt (theoretically) that at the energies of Jlab - HERMES the production time of pre-hadrons is usually rather short, few fm, it would be very imortant to have detailed data sensitive to the space-time development of hadronization.

- In DIS at high Q^2 a perturbative description is more appropriate than the string model. The production time is shorter, $t_p \sim \frac{\nu}{Q^2}(1-z_h)$, but color transparency partially compensate this.

- The model for perturbative hadronization suggested prior the experiment correctly predicted, A-, ν-, Q^2-, z_h-, flavor-, and p_T-dependence of data.
- The pure energy loss scenario fails to explain Q^2- and flavor-dependence
- High-p_T jets in heavy ion collisions are characterized by even shorter production time which shrinks as $\frac{1}{p_T}$.