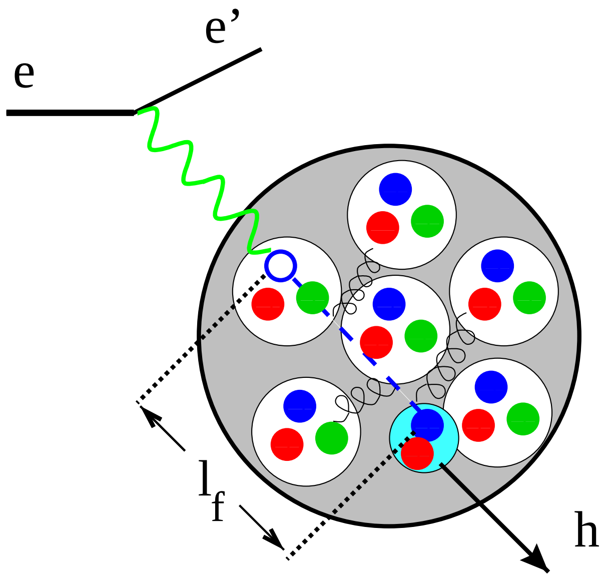
Hadron Formation in Nuclei in Deep-Inelastic Scattering

Erika Garutti (NIKHEF)
on behalf of the HERMES collaboration

- Nuclear Attenuation on ^{14}N and ^{84}Kr
- Kinematic dependences
- Opposite charged state
- Hadron Formation Times
- Link to relativistic heavy-ion physics
- Conclusions and Outlook

Baryons 2002, Jefferson Lab, Newport News.

Hadron Production in DIS on nuclei



$$R_A(z,\nu) = \frac{\left(\frac{1}{N_e}\frac{d^2N_h}{dz\,d\nu}\right)_A}{\left(\frac{1}{N_e}\frac{d^2N_h}{dz\,d\nu}\right)_D}$$

Formation time:

$$\boxed{\tau_f = \frac{l_f}{c}}$$

Nuclear Attenuation: reduction of multiplicity of the fast forward hadrons due to

1) hard partonic interactions

2) soft hadron interactions.

Fragmentation Functions from SIDIS multiplicities

$$\frac{1}{N_{DIS}}\frac{dN_h(x,z)}{dz} = \frac{\sum_q e_q^2 \overbrace{q_f(x)}^{DF} \overbrace{D_f^h(z)}^{FF}}{\sum_q e_q^2 q_f(x)}$$

Motivation

- Why is formation time of interest?
  - fundamental quantity
  - dependence on hadron type
  - comparison to model prediction $\Longrightarrow$
  - link to Heavy Ion physics
- Formation time in Heavy Ion physics:
  - initial energy density in Quark Gluon Plasma

$$\epsilon = \frac{m_T}{\tau_0 \cdot A} \frac{dN}{dy}$$

m_T = transverse mass

A = collision area of two nuclei

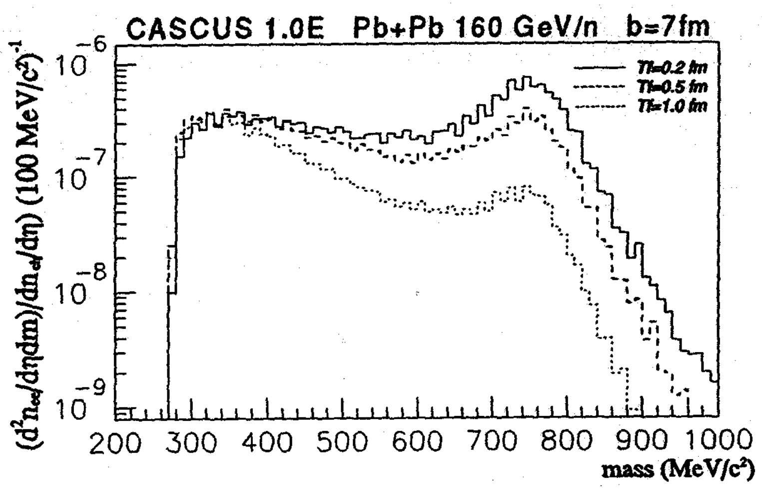
$\frac{dN}{dy}$ = rapidity density

τ_0 plasma formation time.

$\Longrightarrow$ Estimate $\tau_0 \sim \tau_f$ (?)

  - impact of τ_f^π in dilepton spectrum

(P. Filip, J. Pisut Phys. Lett. B 411 (1997) 187)

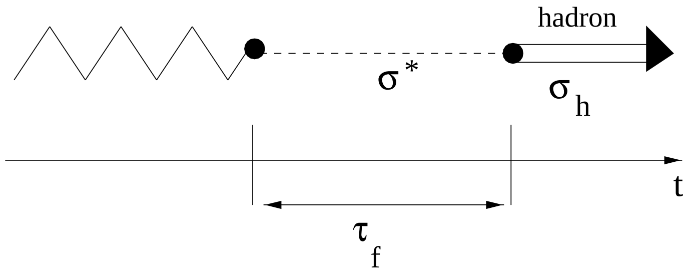


Nuclear Attenuation Models

DIRECT PRODUCTION (one-time-scale model):

(Bialas and Chmaj Phys. Lett. B 133 (1983) 241)

Hadrons produced after τ_f with $\sigma_h \sim 20mb$



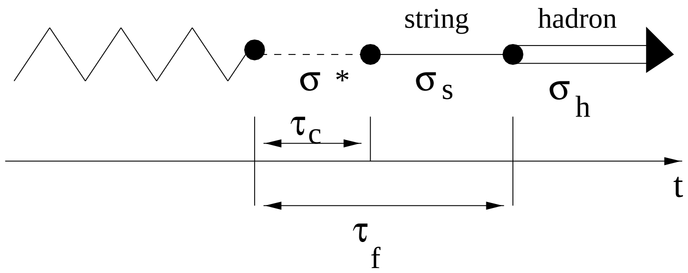
$$\tau_f \sim \frac{E_h}{m_h} = \frac{z\nu}{m_h}$$

τ_f from fit to $R_A(z,\nu)$ with σ^* and τ_f free

STRING MODEL (two-time-scale model):

(Bialas and Gyulassy, Nuc. Phys. B 291 (1987) 793)

Hadron constituents formed at τ_c and τ_f



$$\tau_f - \tau_c = c\frac{E_h}{k} = c\frac{z\nu}{k}$$

$k \sim 1$ GeV/fm

τ_f from fit to $R_A(z,\nu)$ with σ^*, σ_s and τ_f free

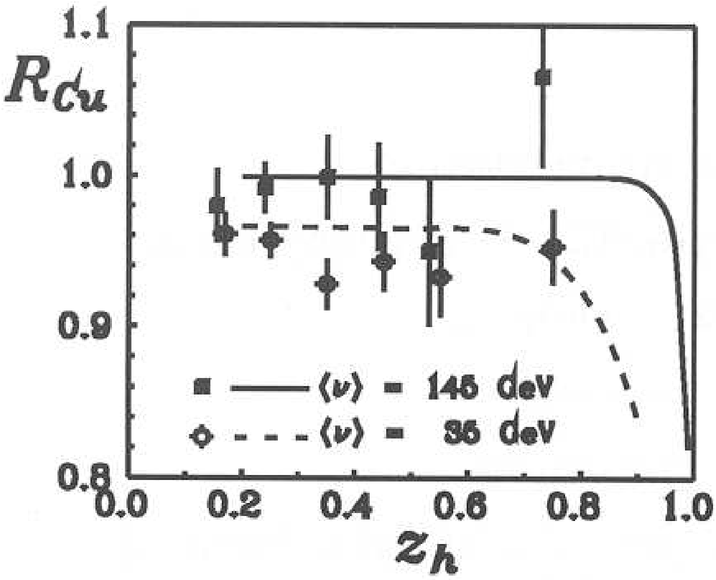
Nuclear Attenuation Models

GLUON BREMSSTRAHLUNG :

(B.Kopeliovich et al., hep-ph/9511214)

pQCD based model for high-z mesons:

Highly virtual quark looses energy via gluon emission till final meson is formed



Nuclear Suppression

+

Induced Radiation:

$$\frac{dE}{dt} = \frac{-\epsilon\nu(1-z)}{t}$$

$$\Downarrow$$

$$\boxed{\tau_f \sim \nu(1-z)}$$

Suppression of high-z mesons

$\Rightarrow$ high-z: quarks emit only few gluons

$\Rightarrow$ corresponds to small τ_f

$\Rightarrow$ long time for hadron-Nucleus interaction:

$\Longrightarrow$ Strong Suppression

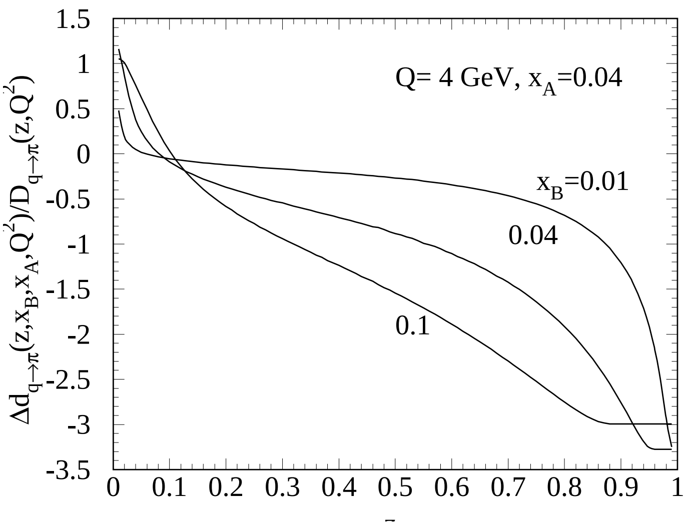
Nuclear Attenuation Models

Fragmentation Function MODIFICATION :

(Guo & Wang, PRL 85 (2000) 3592)

Modification of $D_f^h(z)$ in medium due to multiple parton scattering (in QCD).

$$\bar{D}_f^h(z) \equiv D_f^h(z) + \Delta D_f^h(z)$$



$$\Delta D_f^h(z) \propto \frac{\Delta d_h(z, x_B, Q^2)}{x_A^2}$$

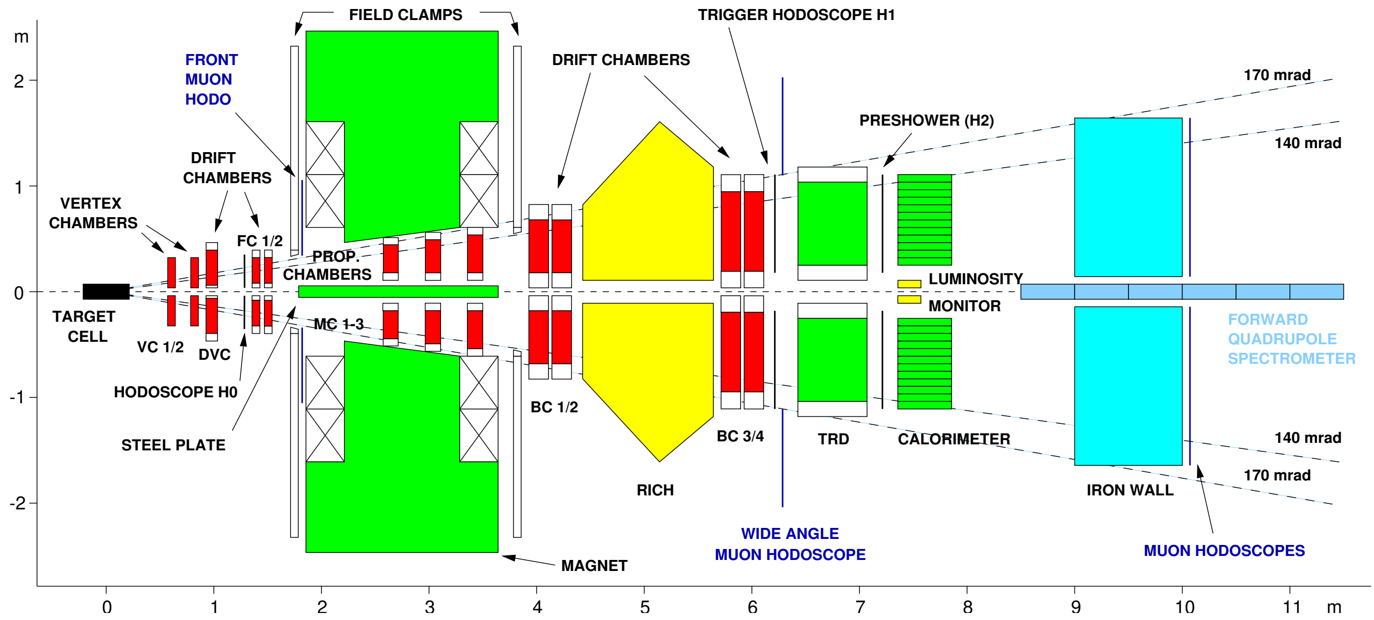
$$x_A = \frac{\hbar c}{m_p \, r_0 \, A^{1/3}}$$

$\Longrightarrow$ $D_f^h(z)$ **modification scales** $\propto A^{2/3}$

$\Longrightarrow$ $D_f^h(z)$ **modification increases for small** ν

HERMES experiment

(HERMES coll. NIM A417 (1998) 230)



- **Tracking:** $\delta P/P =$(0.7-1.3%), $\delta\theta <$0.6 mrad

- **Particle ID:**
  - e^+ identification: 99% eff., $<$ 1% cont.
  - **RICH:** detection eff. 85% (π), 93% (K), 73% (p)

- **Unpolarized Target:** $\rho \sim 10^{15} - 10^{16}$ nucl·cm^{-2}

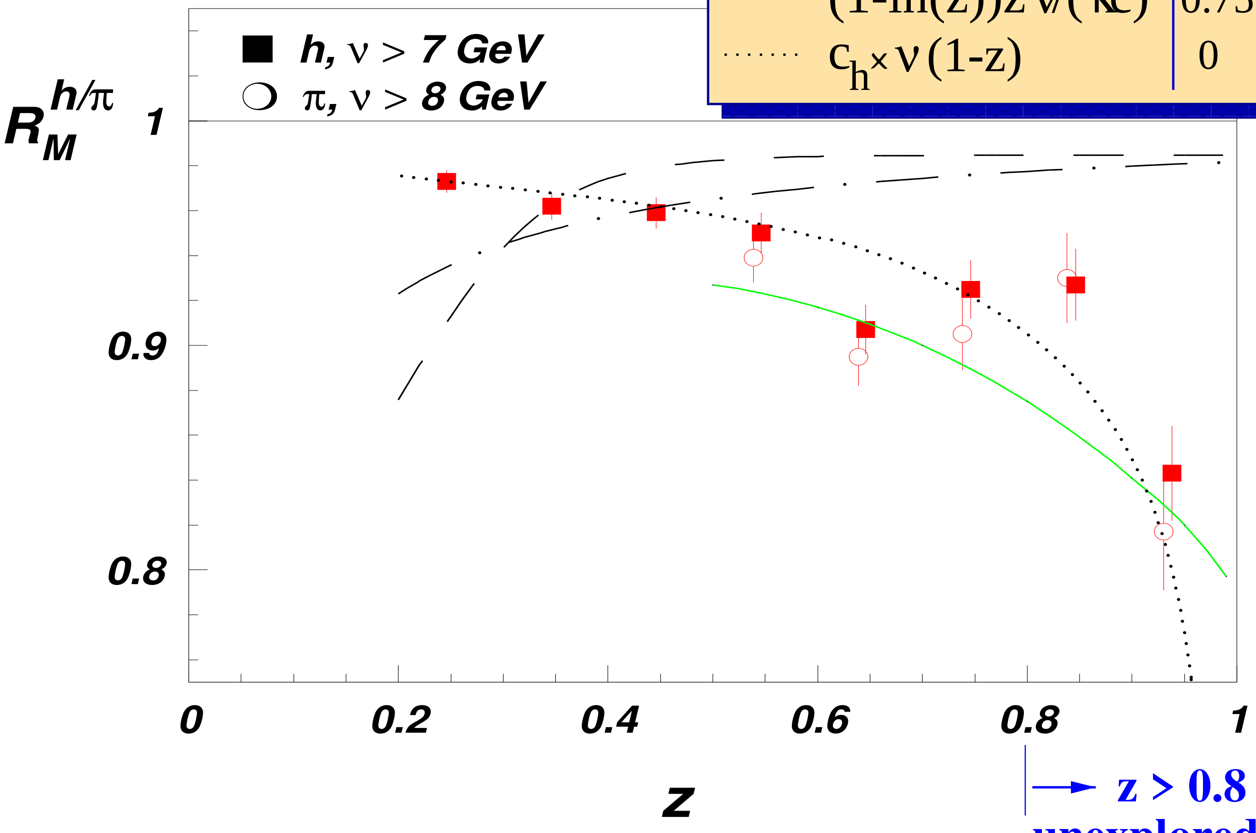
- **Target Type:** ^2H, ^3He, ^{14}N, ^{20}Ne and ^{84}Kr

Attenuation Ratio $vs\ z = \frac{E_h}{\nu}$

Data selection:

- h and π ID with Cerenkov:
  $E_h > 1.4\ GeV,\ 4 < E_\pi < 13.5\ GeV$
- $Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2, $x > 0.06$, $y < 0.85$

	τ_f (fm/c)	σ_q	σ_s	σ_h
-·-·-	$c_h \times z\nu$	0	-	20
- - - -	$(1-\ln(z))z\nu/(\kappa c)$	0.75	20	20
·······	$c_h \times \nu(1-z)$	0	-	25

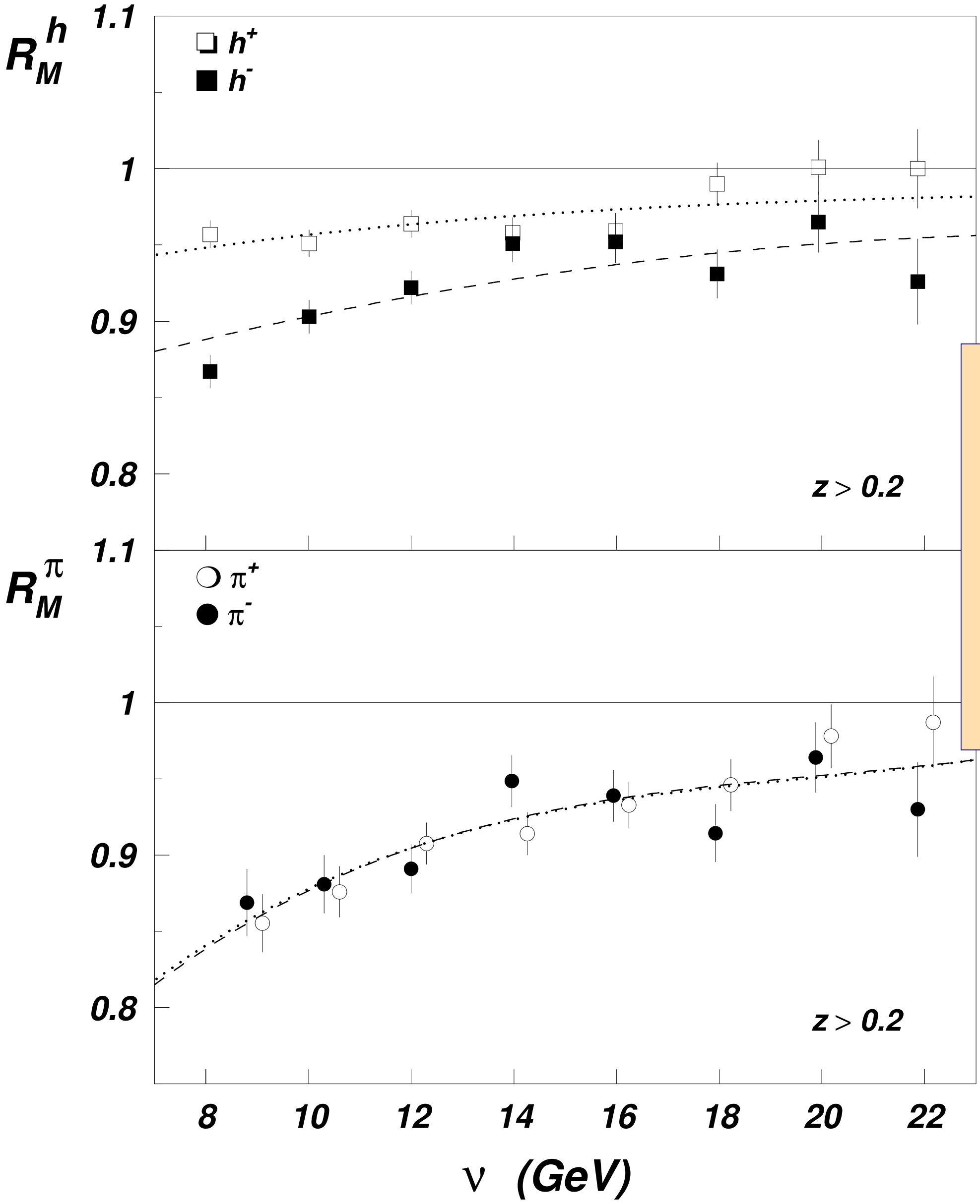


→ z > 0.8
unexplored region

Agreement with gluon bremsstrahlung model

Formation Time

Model used: $\tau_f = c_h \cdot \nu(1-z)$

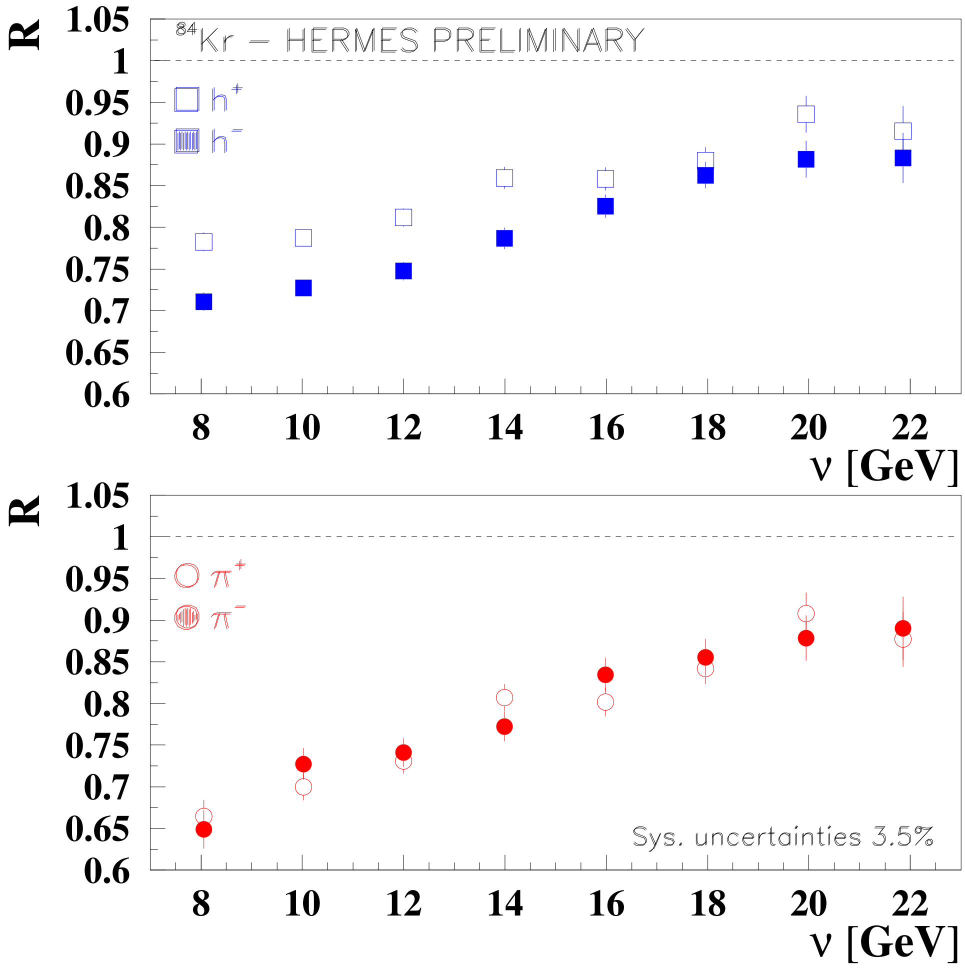


Formation time

	c_h [fm/ GeV·c]
h^+	3.49±0.51
h^-	1.32±0.16
π^+	1.37±0.18
π^-	1.38±0.21

- One-time-scale model with $\sigma_q = 0$, $\sigma_h = 25$ mb
- i.e. $\nu = 14$ GeV, $z = 0.5 \implies \tau_f^\pi = 3 \cdot 10^{-23}$ sec

h and π separation performed with the RICH

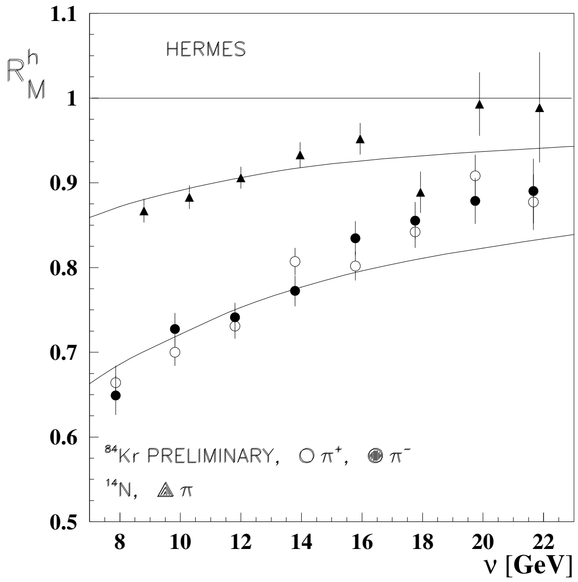


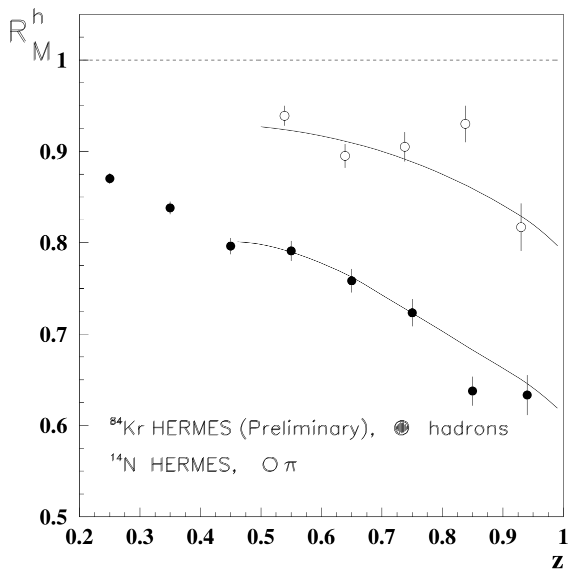
- Behavior of ^{14}N data confirmed by ^{84}Kr.
- Attenuation on pions: π^+ and π^- are equally attenuated.

Pion Attenuation
vs Gluon bremsstrahlung

Data compared to gluon bremsstrahlung calculation

(B.Kopeliovich et al.)





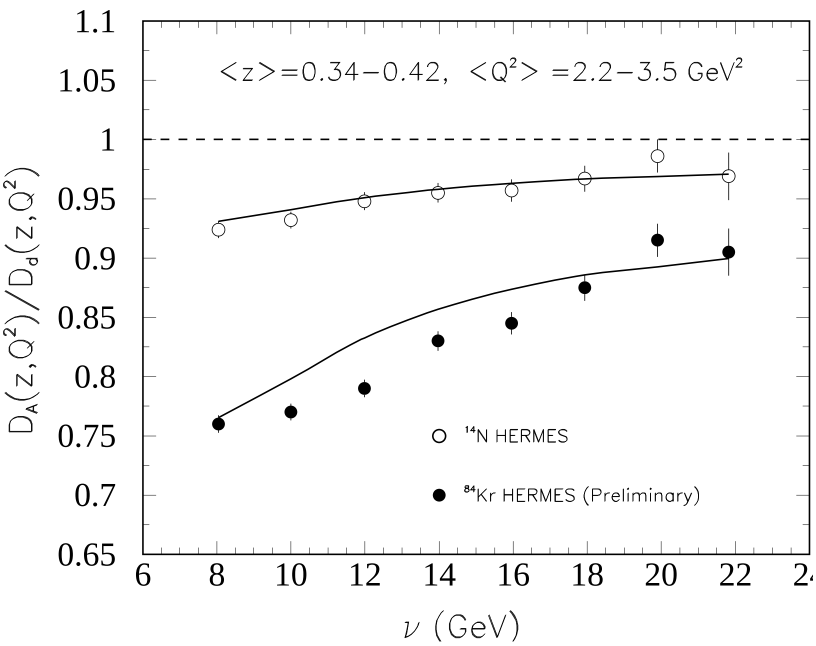
Formation time of pions:

HERMES: $c_\pi = 1.37 \pm 0.18$ (fm/GeV·c)

Theory: $c_\pi = 1.35$ (fm/GeV·c)

Prediction available only for fast pions ($z > 0.5$).

Hadron Attenuation $vs\ D_f^h(z)$ modification

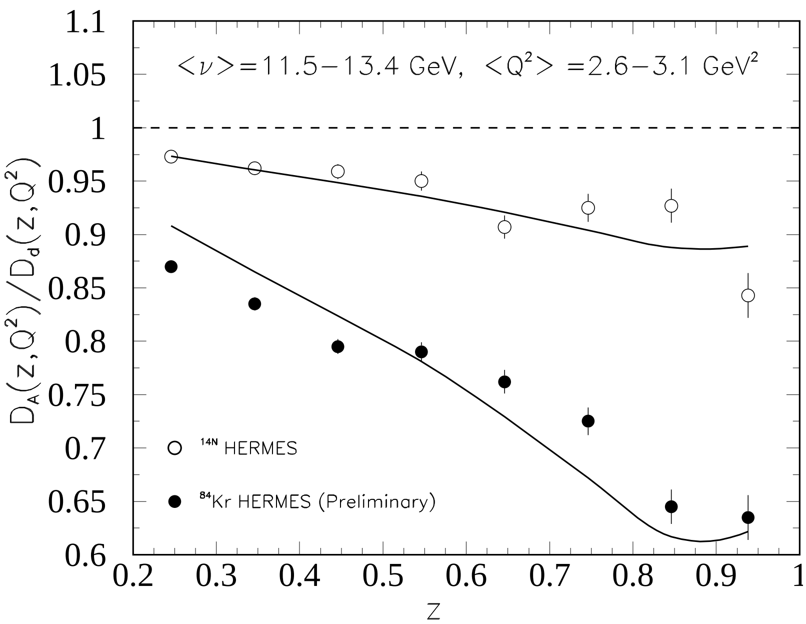


curve:
$D_f^h(z)$ modification model
(no hadron rescattering)

Prediction: $D_f^h(z) \sim A^{2/3}$ (Guo & Wang, PRL 85 (2000) 3592)

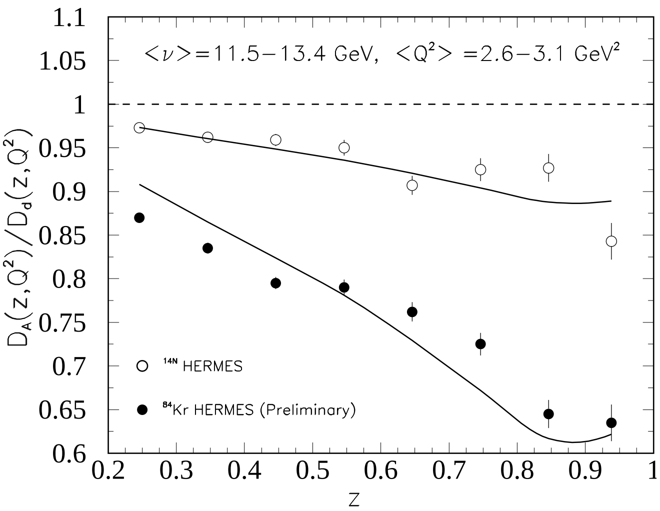
from the data:
$(R_{Kr}/R_N)^{2/3} \simeq 3.6$
(at average kinematics)

consistent with:
$(A_{Kr}/A_N)^{2/3} \simeq 3.3$



(X.N. Wang, hep-ph/0111404)

Parton energy loss calculated from DIS data:

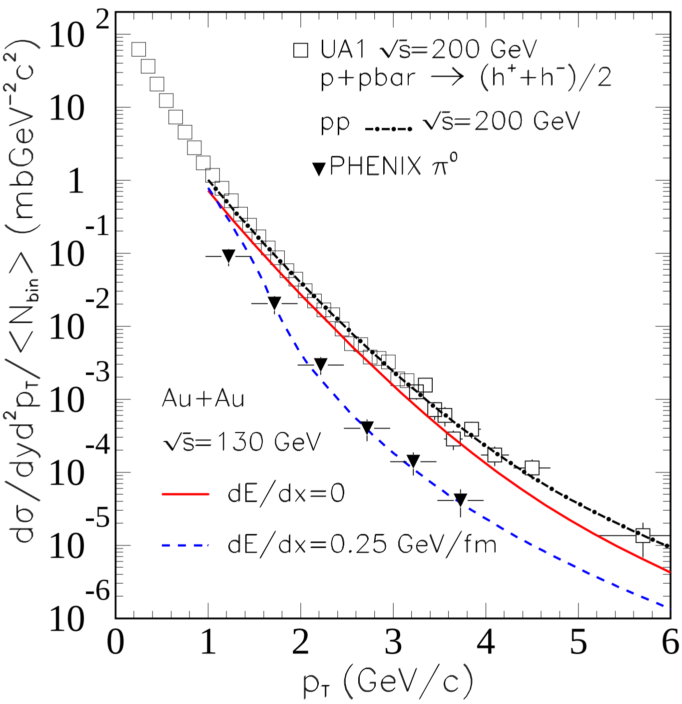


$$\bar{D}_f^h(z) \approx \frac{1}{1-\Delta E/E} D\left(\frac{z}{1-\Delta E/E}\right)$$

$$\Downarrow$$

$$\boxed{dE/dx \approx 0.3 \text{ GeV/fm}}$$

Compared to hadron yield in Au+Au collision:



expanding system:

$$\boxed{dE/dx \approx 0.25 \text{ GeV/fm}}$$

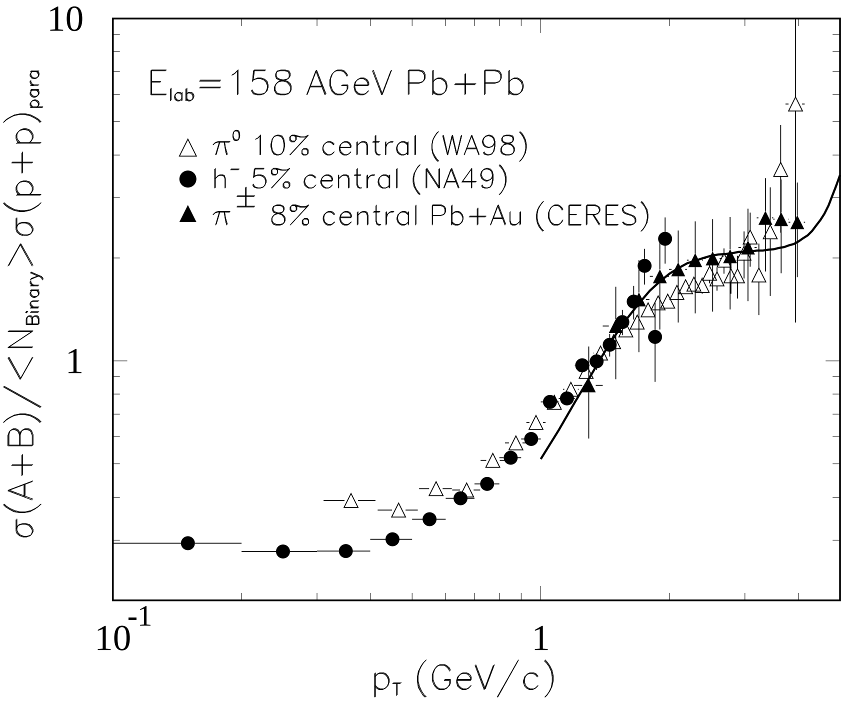
+ absorbptive processes
+ expantion correction:

$$\left.\frac{dE}{dx}\right|_{Au-Au} \approx 20 \cdot \left.\frac{dE}{dx}\right|_{eA}$$

Gluon density in Au+Au is 20 times that inside cold nuclear matter.

Cronin Effect

Heavy-Ion Collisions:
Enhancement at high p_t in AA collisions relative to pp collisions.



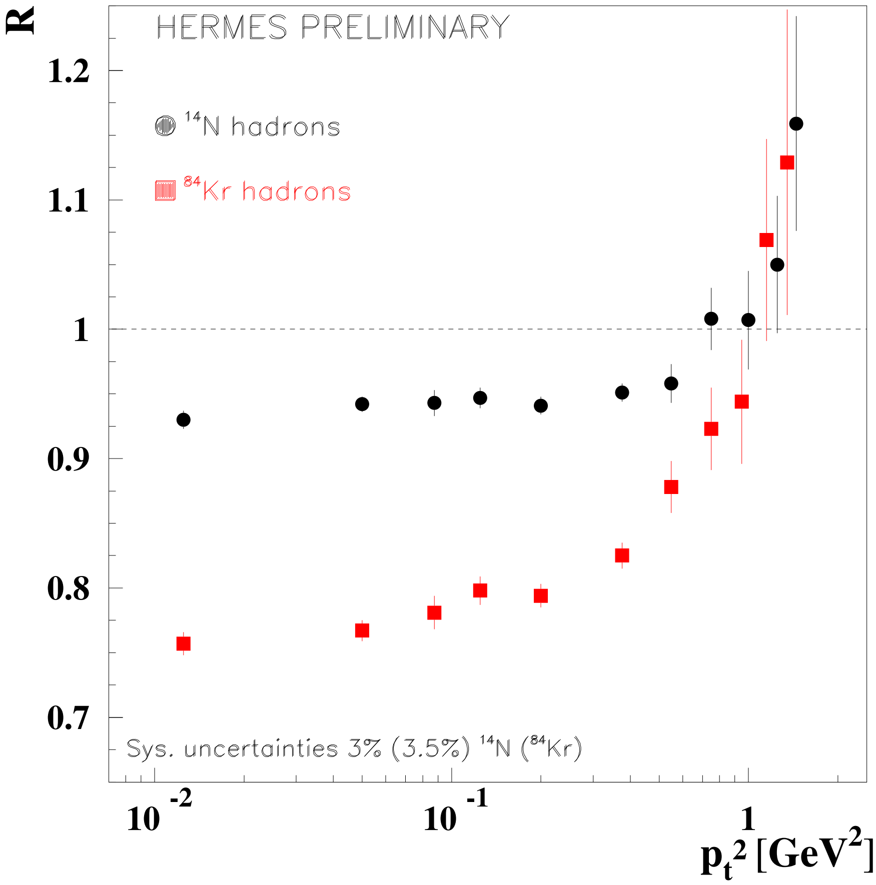
Agreement with multiple parton scattering model:

(E. Wang and X.N. Wang nucl-th/0104031)

Transition at $p_t \sim$ 1-2 GeV/c.

Hadron Attenuation vs p_t^2

Cronin effect in DIS on nuclei:



- Similar p_t^2-enhancement as in heavy-ions collisions
- Clean information on quark transport in cold nuclear matter

Conclusions & Outlook

- Strong nuclear attenuation at high z.
- Similar attenuation for fast π^+ and π^-.
- Observed: $R^{h+} > R^{h-}$
  Interpretation: $\tau_{h+} > \tau_{h-}$

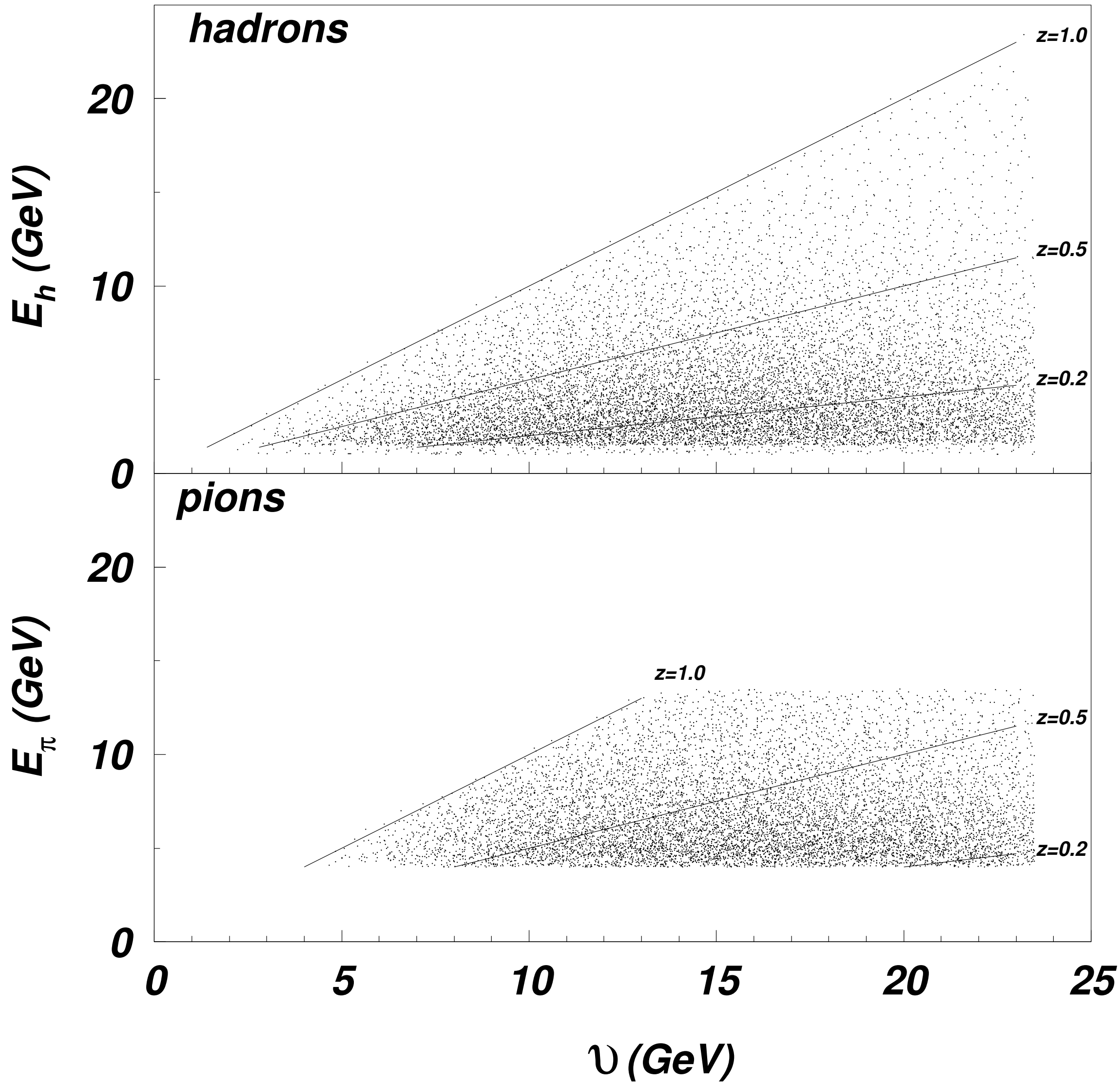
  Future $\Rightarrow \pi\,, K\,, p$ separation from the RICH.

- Gluon bremsstrahlung model describes ν and z dependence of nuclear attenuation.
- Comparison between ^{14}N and ^{84}Kr in agreement with the $D_f^h(z)$ modification model.
- Observed Cronin effect with a transition between hard and soft processes around $p_t = 1$ GeV.

  more to come:

- Additional HERMES data on ^{4}He and ^{20}Ne.
- Particle ID for $K\,, p$ and $\bar{p}$.

Kinematics



$$\begin{cases} h^{\pm}: & E > 1.4\,GeV, \;\rightarrow\; z_{min} = 0.2,\; \upsilon_{min} = 7\,GeV \\ \pi^{\pm}: & 4 < E < 13.5\,GeV, \;\rightarrow\; z_{min} = 0.5,\; \upsilon_{min} = 8\,GeV \end{cases}$$