Hadron Formation in DIS in a Nuclear Environment

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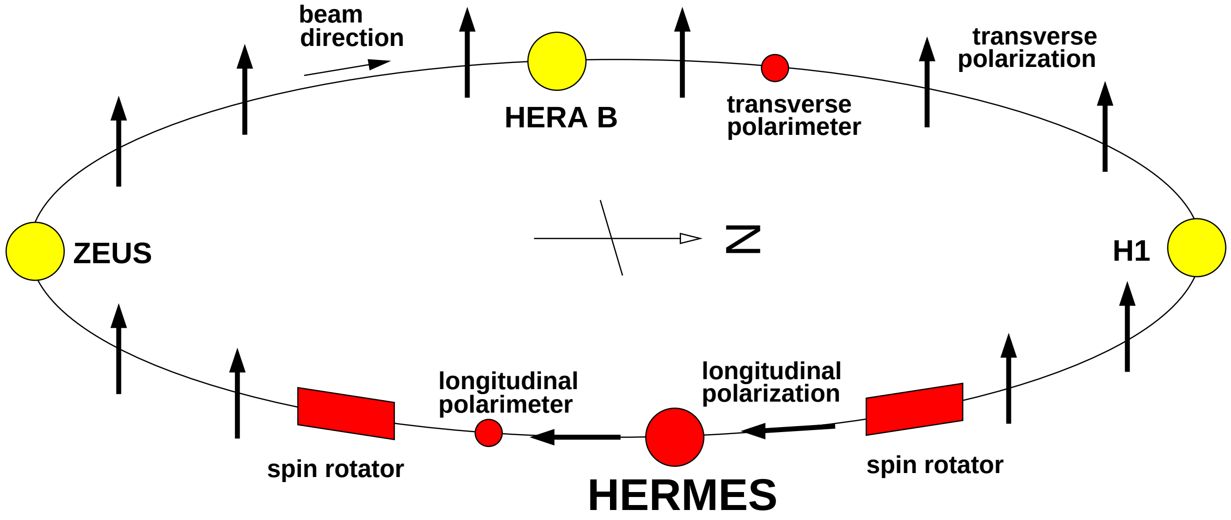
on behalf of the HERMES Collaboration
INFN Frascati

DIS2001
Bologna, April 2001

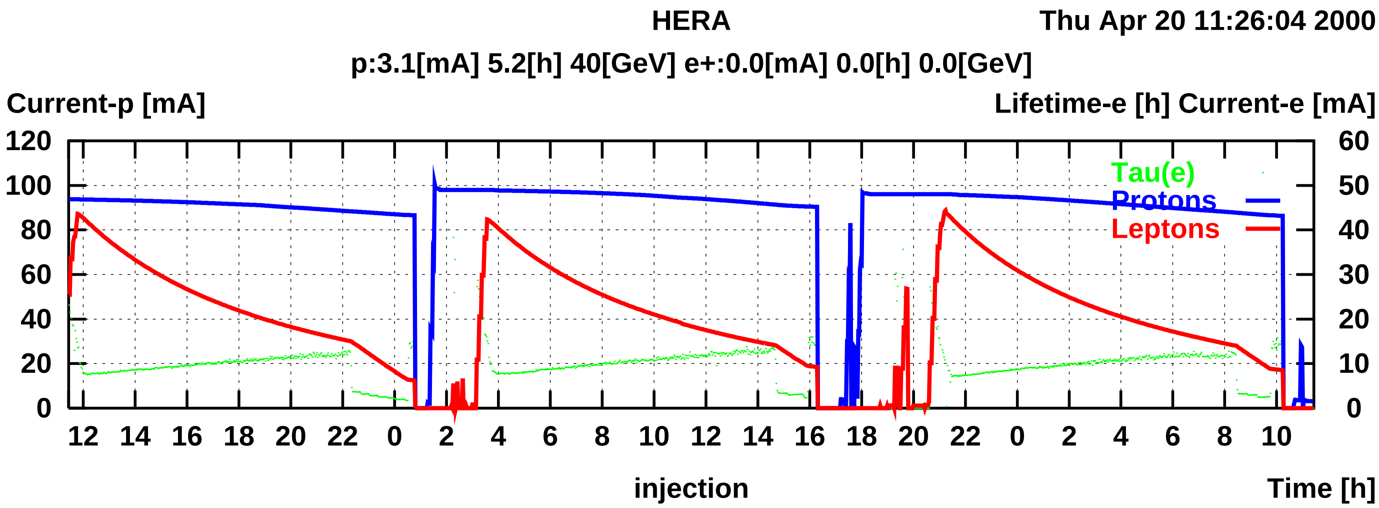
- Hadron formation studied by the HERMES experiment in semi-inclusive DIS on nuclei
$\rightarrow$ Nuclear Attenuation of the multiplicity of fast charged hadrons and pions.

- Models for the Nuclear Attenuation.
- Results for the Nuclear Attenuation on ^{14}N.
- Results for the Nuclear attenuation on ^{84}Kr.
- Nuclear Attenuation as function of ν, z.
- Nuclear Attenuation for charged hadrons and pions.
- Nuclear Attenuation as function of p_t.

HERA at DESY

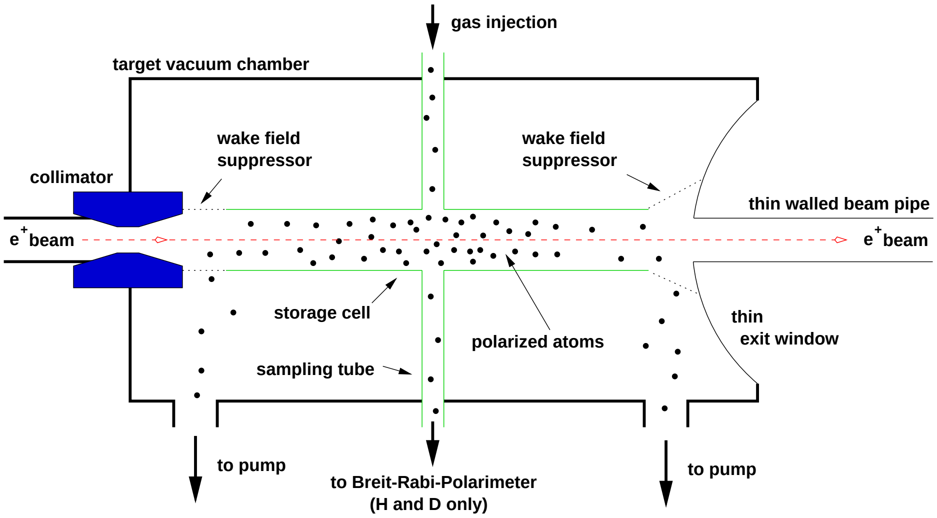


- 27.5 GeV e^{+} (e^{-}), I∼30 mA.
- Self-polarization by emission of synchrotron radiation, $P_b(t) = p_b^{max}[1 - exp(t/\tau)]$
- Spin rotators → longitudinal polarization at HERMES IP



- Last part of the fill dedicated to high-density unpolarised target runs

The Internal Target



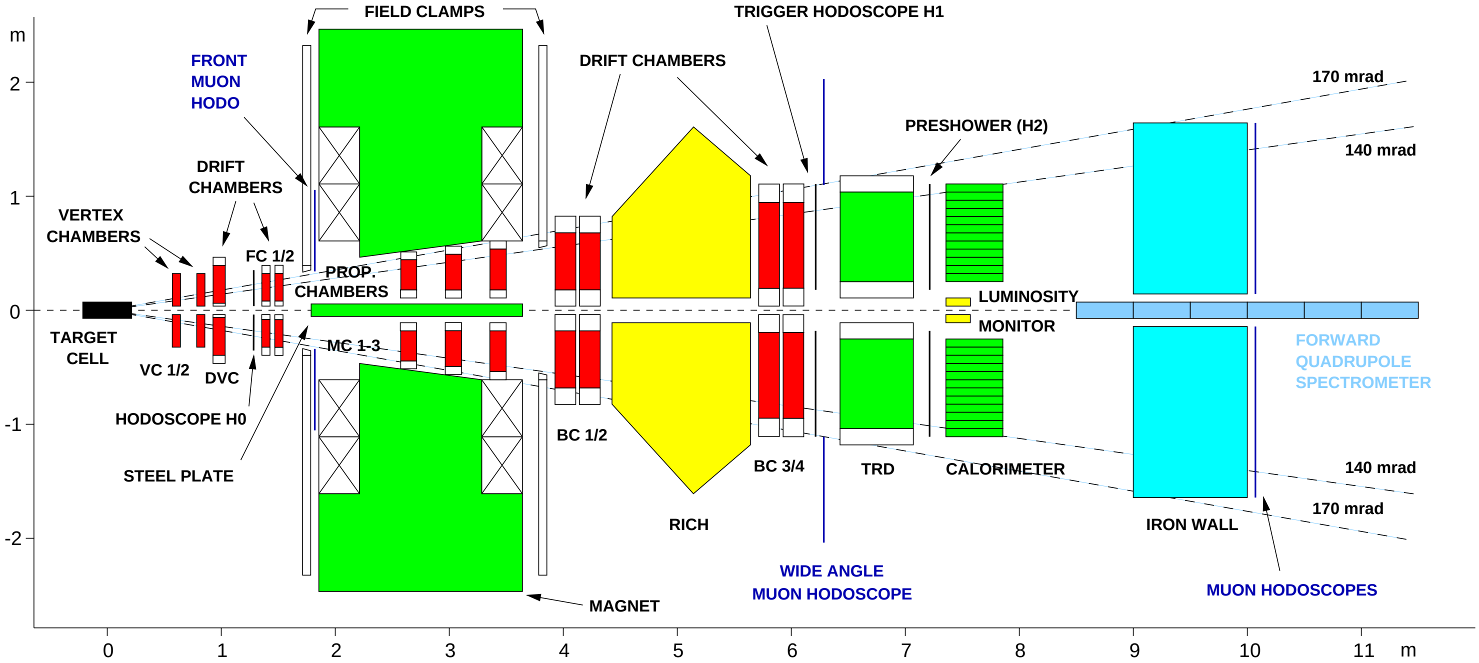
- Internal storage cell
- Laser driven $^3\vec{He}$ $(P \sim 50\%)$ in 95.
- Atomic beam source for $\vec{H}$ in 96-97 and $\vec{D}$ in 98-00 with high polarisation $(P > 90\%)$
- **Unpolarised high density nuclear target (H, D, ^{3}He, ^{14}N, ^{84}Kr, ^{20}Ne, ^{40}Ar, ^{131} Xe) runs started in 97.**

$$Densities: \begin{cases} \sim 10^{14} \div 10^{15} \;\; nucl \cdot cm^{-2} & (polarised) \\ \sim 10^{15} \div 10^{16} \;\; nucl \cdot cm^{-2} & (unpolar.) \end{cases}$$

NIM A343 (1994) 334

SPECTROMETER

(HERMES coll. NIM A417 (1998) 230)



- **kinematic:** $0.004 < x < 0.8$ for $Q^2 > 0.2$ $W^2 > 4$
- **Tracking**: 57 tracking planes, $\delta P/P = (0.7 - 1.3)\%$, $\delta\theta < 0.6$ mrad
- **Particle identification**: **Cerenkov (RICH 98), TRD, Preshower, e.m. Calorimeter**

  e^+ identification: 99% efficiency and $< 1\%$ of contamination

  RICH: π, k, p separation on the full acceptance

  ^{14}N results are related 95-97 data taking period.
  ^{84}Kr results are related 99 data taking period.

NIM A417 (1998) 230

hermes

RICH

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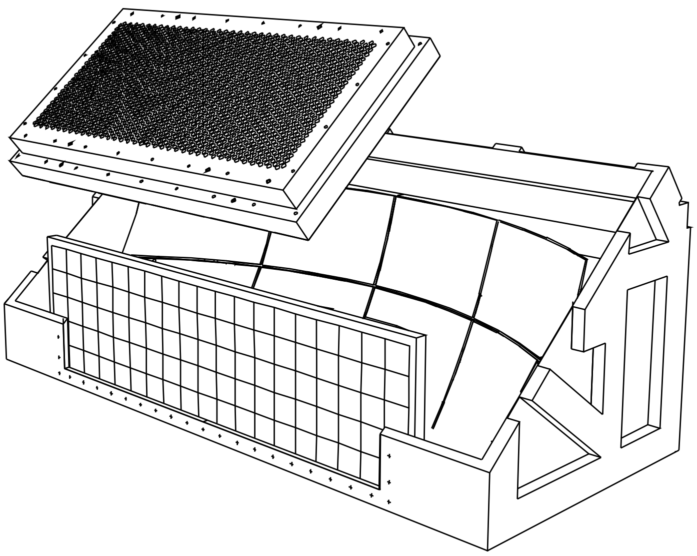
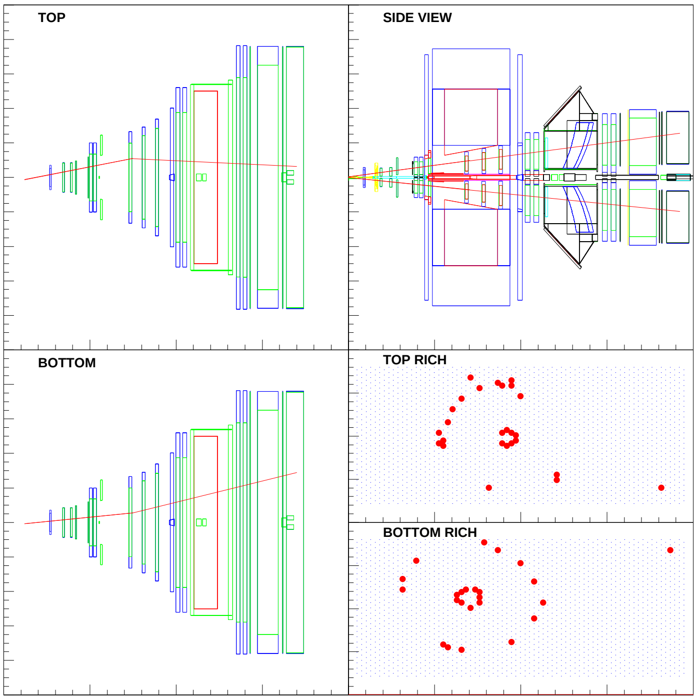
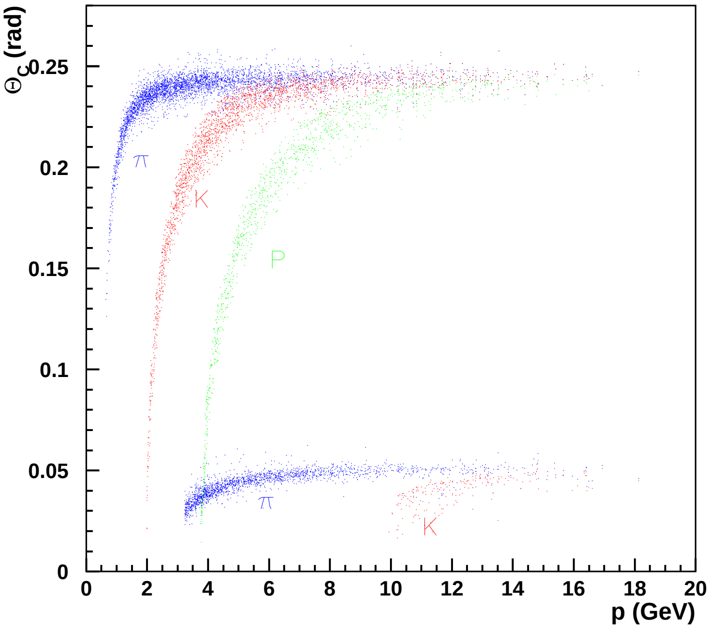
The RICH, at HERMES, has a double radiator : Aereogel (n=1.03) and C_4F_{10} gas (n=1.0014). Čerenkov photons are detected by two matrix of $\sim$ 4000 PMTs.

Detection efficiencies : 85% (π), 93%(K), 73%(p)

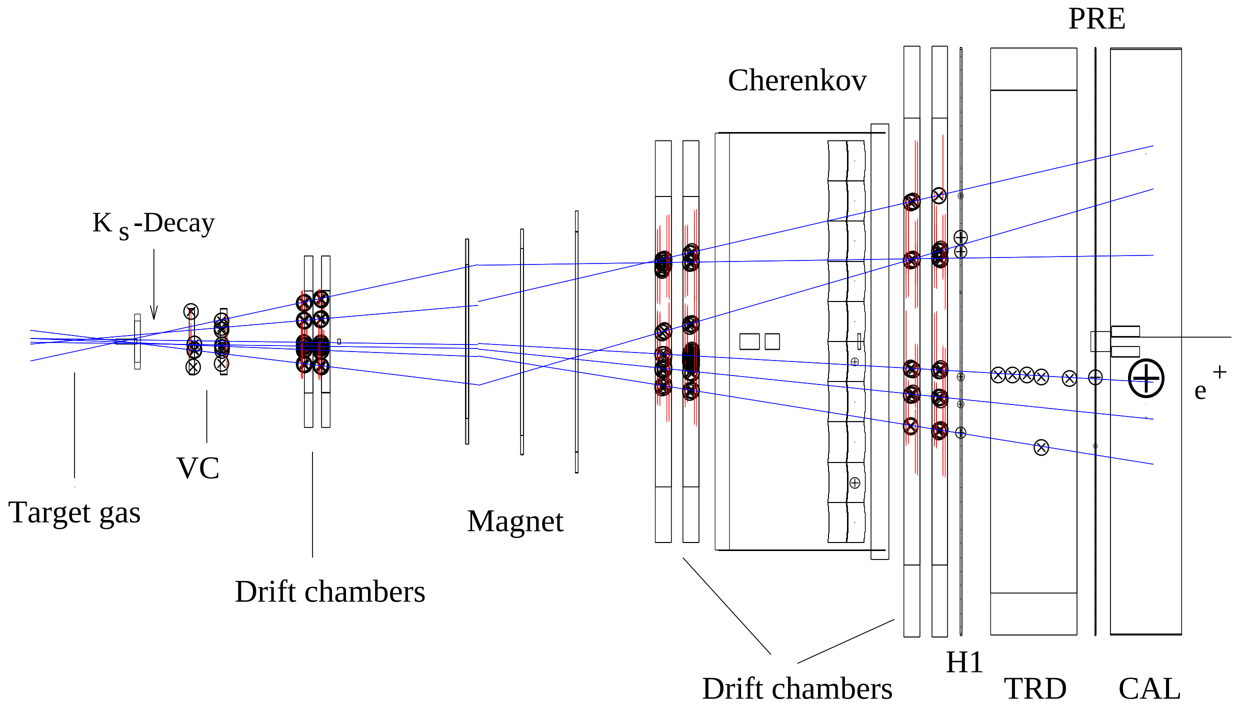




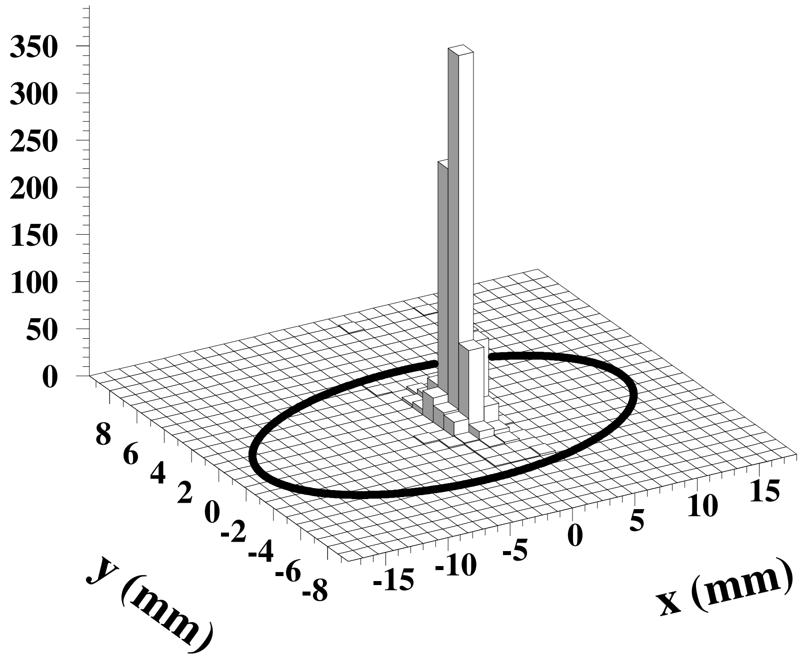


Valeria Muccifora, DIS2001

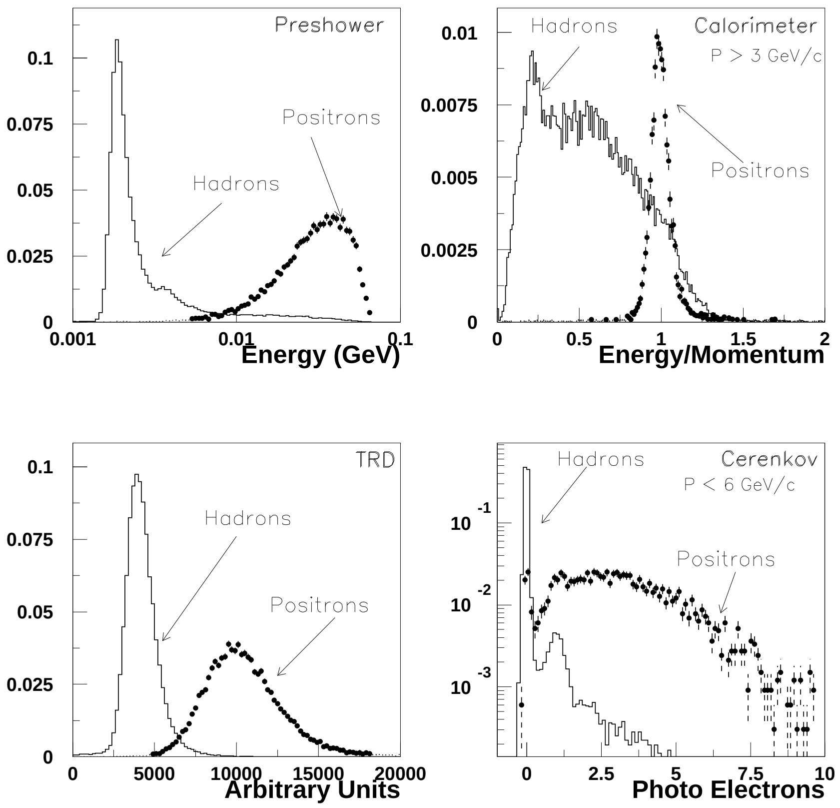
Track Reconstruction



Vertex reconstruction:

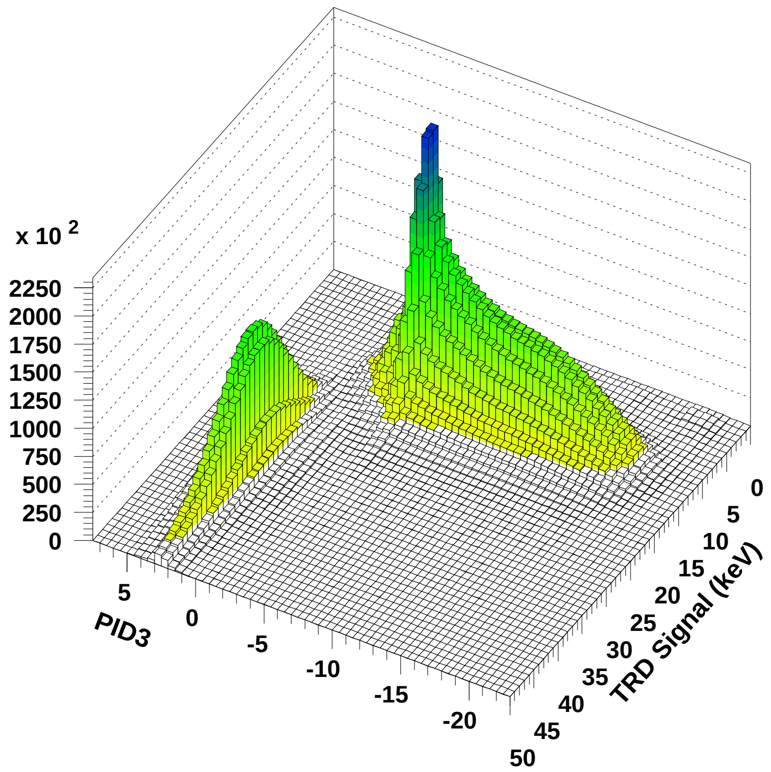


Particle Identification



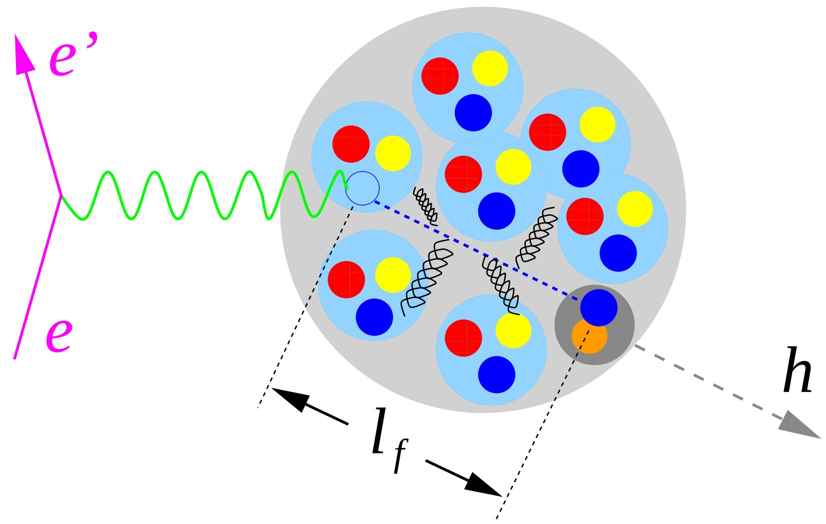
Combined likelihood and TRD:

$$PID3 = log_{10}\left(\frac{P_{e+Cer}\cdot P_{e+Pre}\cdot P_{e+Cal}}{P_{h\ Cer}\cdot P_{h\ Pre}\cdot P_{h\ Cal}}\right)$$



Hadron production in DIS on nuclei

- The struck parton is subjecting to a sequence of hard parton- and soft hadron-production processes.
- Nucleus acts as an ensemble of targets for the struck quark or the produced hadron.



Reduction of the multiplicity of the fast forward hadrons Nuclear Attenuation.

$$R_A(z,\nu) = \frac{\left.\frac{1}{\sigma}\frac{d^2\sigma}{dz d\nu}\right|_A}{\left.\frac{1}{\sigma}\frac{d^2\sigma}{dz d\nu}\right|_D} = \frac{\left.\frac{1}{N_e}\frac{d^2 N_h}{dz d\nu}\right|_A}{\left.\frac{1}{N_e}\frac{d^2 N_h}{dz d\nu}\right|_D} = \frac{\left.\frac{\sum e_f^2 q_f(x) D_f^h(z)}{\sum e_f^2 q_f(x)}\right|_A}{\left.\frac{\sum e_f^2 q_f(x) D_f^h(z)}{\sum e_f^2 q_f(x)}\right|_D}$$

$q_f(x)$ quark Distribution Functions, $x = Q^2/2m\nu$
$D_f^h(z)$ Fragmentation Functions, $z = E_h/\nu$

- $\tau_f = l_f/c$ formation time.
  $\sigma_{quark-nucleon}$, $\sigma_{hadron-nucleon}$

Formation times

- Quantitative information on the hadron formation time is needed for the interpretation of relativistic heavy ion collisions.

- Initial energy density of the Quark Gluon Plasma:

$$\epsilon \sim \frac{\frac{dE_t}{d\eta}}{F_p \cdot c \cdot \tau_0}$$

E_t transverse energy $E_t = \sum_i E_i \cdot sin\theta_i$
F_p area of the projectile, η rapidity,
τ_0 proper time at which a plasma is produced (estimated to be $\sim 1fm/c$).

- The plasma formation time estimated to be comparable to the hadron formation time.

- The hadron formation time (from $p - A$ reactions and lepton-nucleus scattering) it is not known to better than a factor of 2.

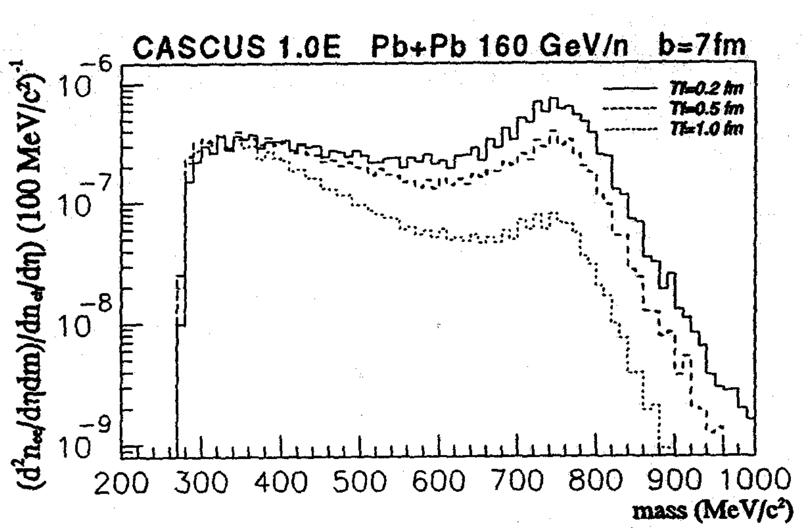
H.R. Schmidt and J. Schukraft J. Phys. G: Nucl. Part. Phys. 19 (1993) 1705-1795.

Formation times

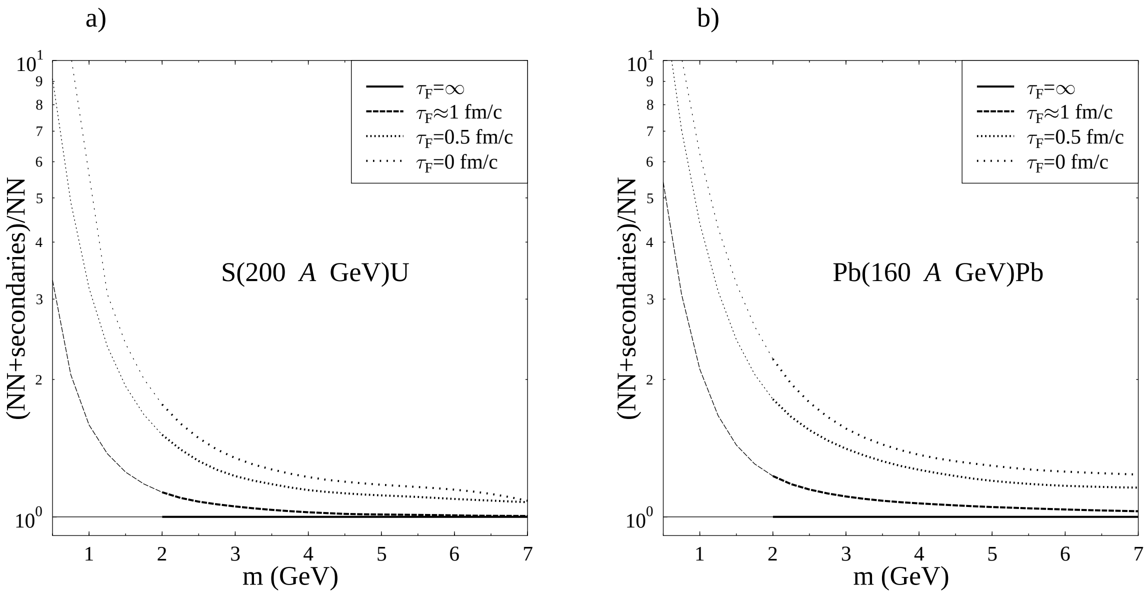
τ_f of pions produced in heavy collisions modified the mass spectrum of dileptons produced via $\pi^+\pi^- \rightarrow e^+e^-$.

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

Spieles et al,hep-ph/9706525



- τ_f strongly influences the shape and magnitude of the dilepton produced in $\pi^+\pi^-$ annihilition.



- Also at higher mass, a τ_f reduction increases dilepton yield due to the larger number of hadron-hadron interactions.

Models for nuclear attenuation

Hadron formation in DIS occurs at energy momentum scales where pQCD is not applicable:

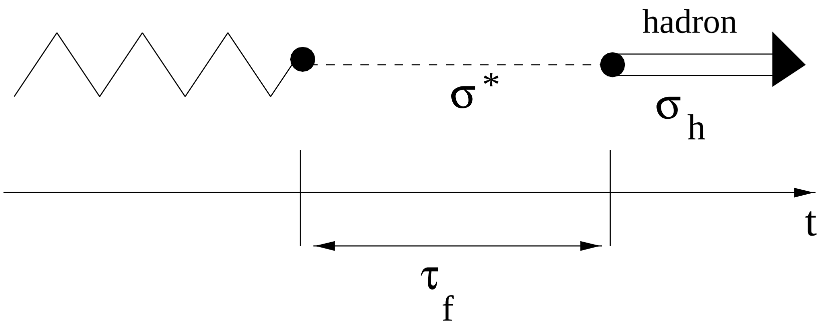
→ Phenomenological intranuclear reinteraction models

Bialas and Chmaj P.L. B 133 (1983) 241

- DIRECT PRODUCTION (one-time-scale model)

  Hadrons directly produced and interacting with typical hadronic inelastic cross section $\sigma_h \sim 20$ mb.

$$\tau_f \propto \frac{E_h}{m_h}; \quad \tau_f \propto \frac{E_q}{m_q}$$



$$R_A = 2\pi \int_0^{\infty} bdb \int_{-\infty}^{\infty} dl \rho(b,l)[P_A(b,l)]^{A-1}$$

Probability of no-interaction:

$$P_A = 1 - \sigma^* \int_l^{\infty} dl' \rho_A(b,l') P_q(l'-l) - \sigma_h \int_l^{\infty} dl' \rho_A(b,l') P_h(l'-l)$$

$\rho_A(b,l)$: normalized nuclear density

(b,l): position of the scattering

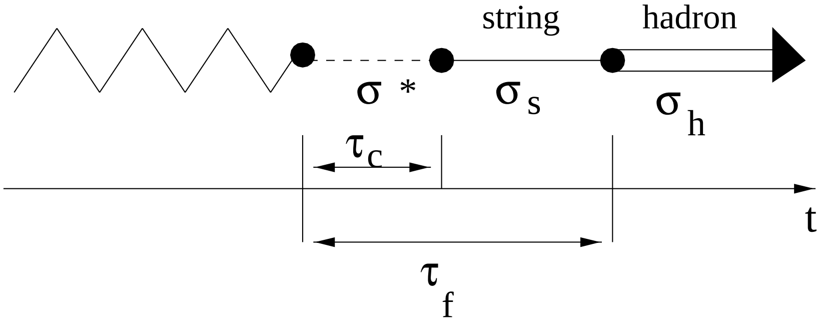
- τ_f can be derived by a fit using σ^* and τ_f as free parameters

Models for nuclear attenuation

- STRING MODELS (two-time-scales τ_c, τ_f models)

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

  The constituents of the hadron are formed at different time τ_c, τ_f.



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

string constant $\kappa \approx 1\ GeV/fm$

$$R_A = 2\pi \int_0^{\infty} bdb \int_{-\infty}^{\infty} dl\rho(b,l)[P_A(b,l)]^{A-1}$$

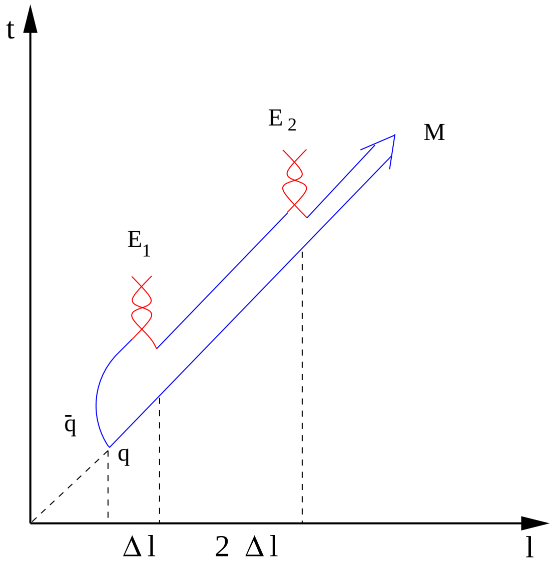
$$P_A = 1 - \sigma^* \int_l^{l_c} dl' \rho_A(b,l') - \sigma_s \int_{l_c}^{l_f} dl' \rho_A(b,l') -$$

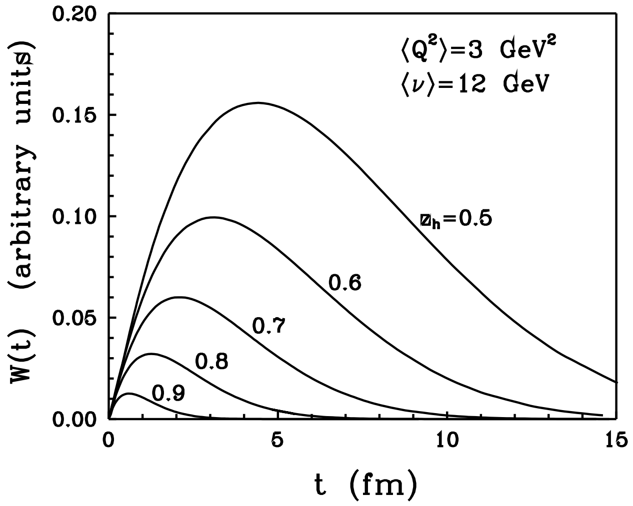
$$\sigma_h \int_{l_f}^{\infty} dl' \rho_A(b,l')$$

- τ_f can be derived by a fit using σ^*, σ_s, and τ_f as free parameters

Models for nuclear attenuation

- GLUON BREMSSTRAHLUNG MODEL
  (B.Kopeliovich et al., hep-ph/9511214)
  QCD inspired model for "leading-meson" (high z) formation and subsequent rescattering.





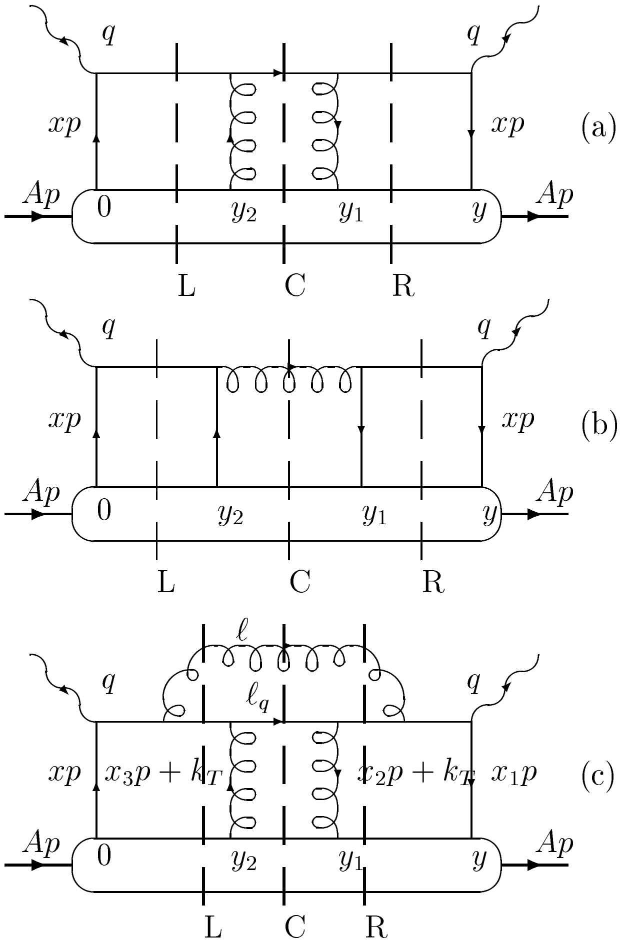
$E_1 \simeq \xi \Delta l$, $E_2 \simeq \xi 2\Delta l$, $-\xi = \frac{dE}{dl} \sim 1\ GeV/fm$

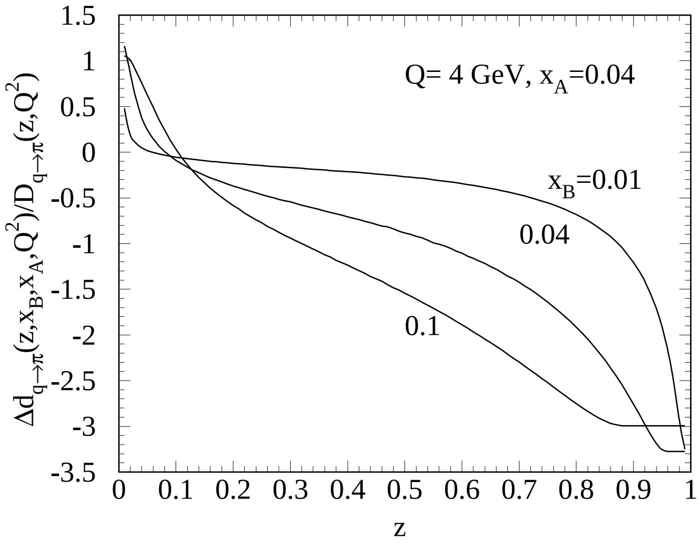
Highly virtual quark reaches its mass shell by the emission of gluons. It is *time* and *energy* dependent.

- The initial q combines with q or $\bar{q}$ from the last emitted gluon $\Rightarrow$ final meson.
- If a high-z meson is formed, the initial q cannot radiate many gluons $\Rightarrow$ high-z meson production is suppressed.

Models for nuclear attenuation

- Fragmentation Functions Modification
  (Guo & Wang, PRL 85 (2000) 3591)
  The modification of quark fragmentation functions and their QCD evolution equations are described in the framework of multiple parton scattering (HT effects).





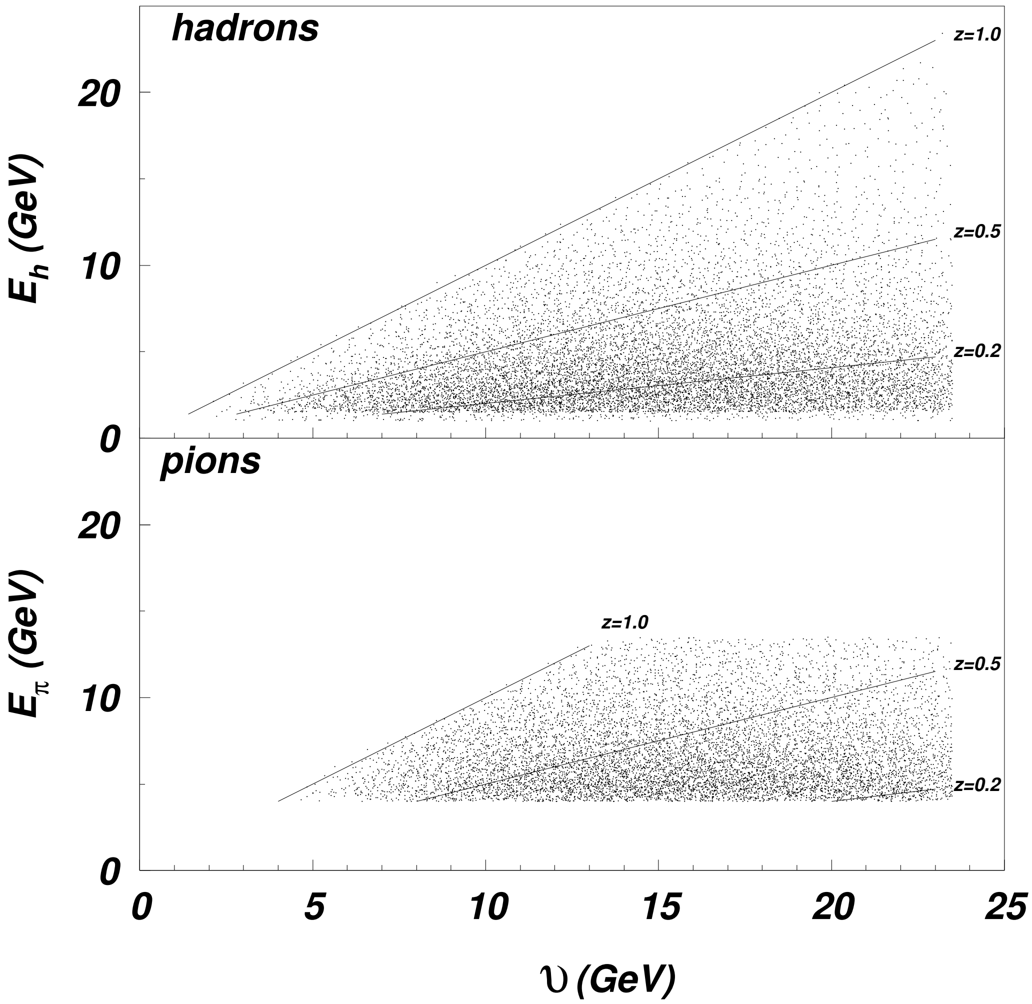
- The FF modification increases for smaller $x_A = \frac{1}{MR_A}$.

- The FF modification scales $\propto A^{2/3}$.

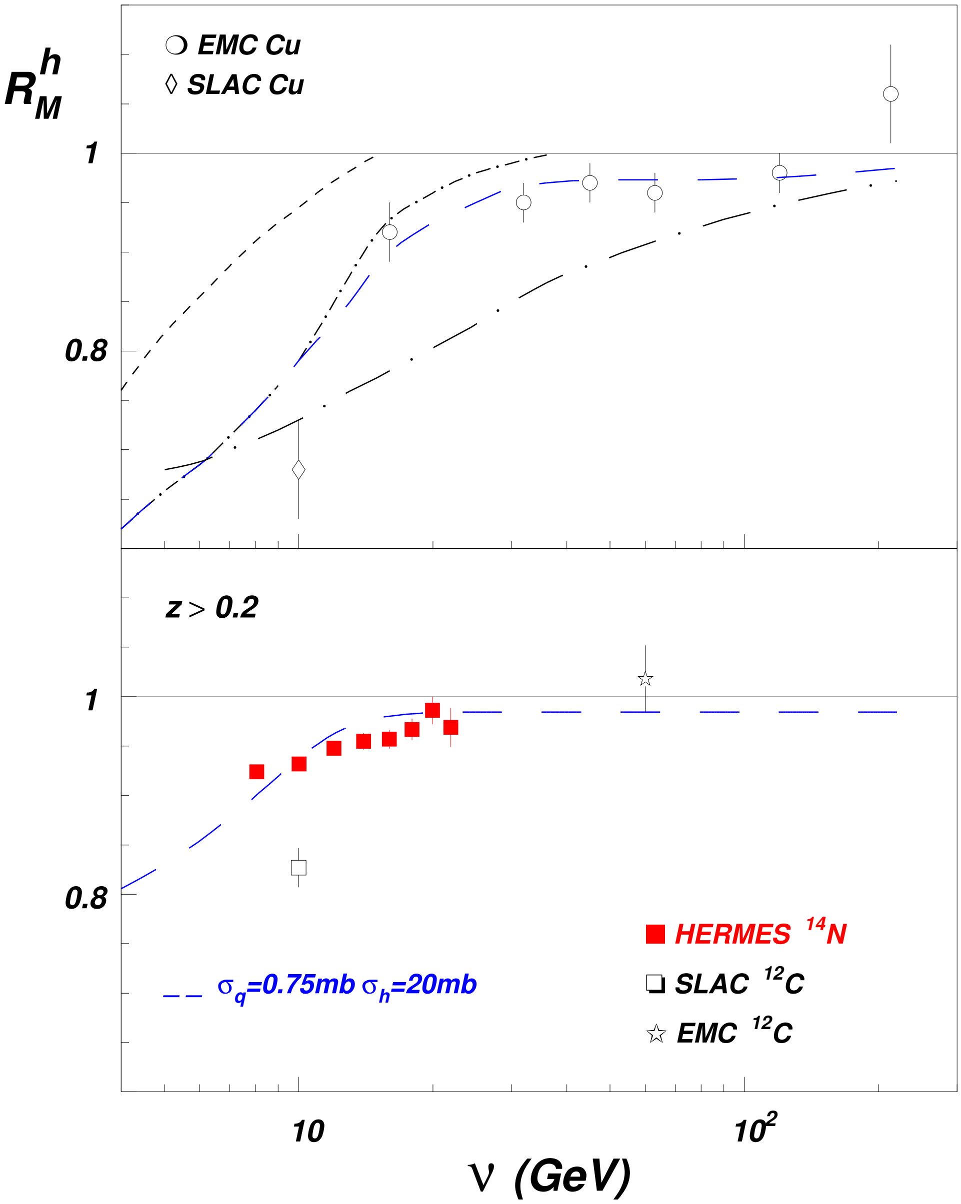
Data selection

- ^{14}N and D targets ($\sim 10^{15}\ nucl/cm^2$)
- $Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2, $x > 0.06$, $y < 0.85$

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



Attenuation Ratio *vs* ν

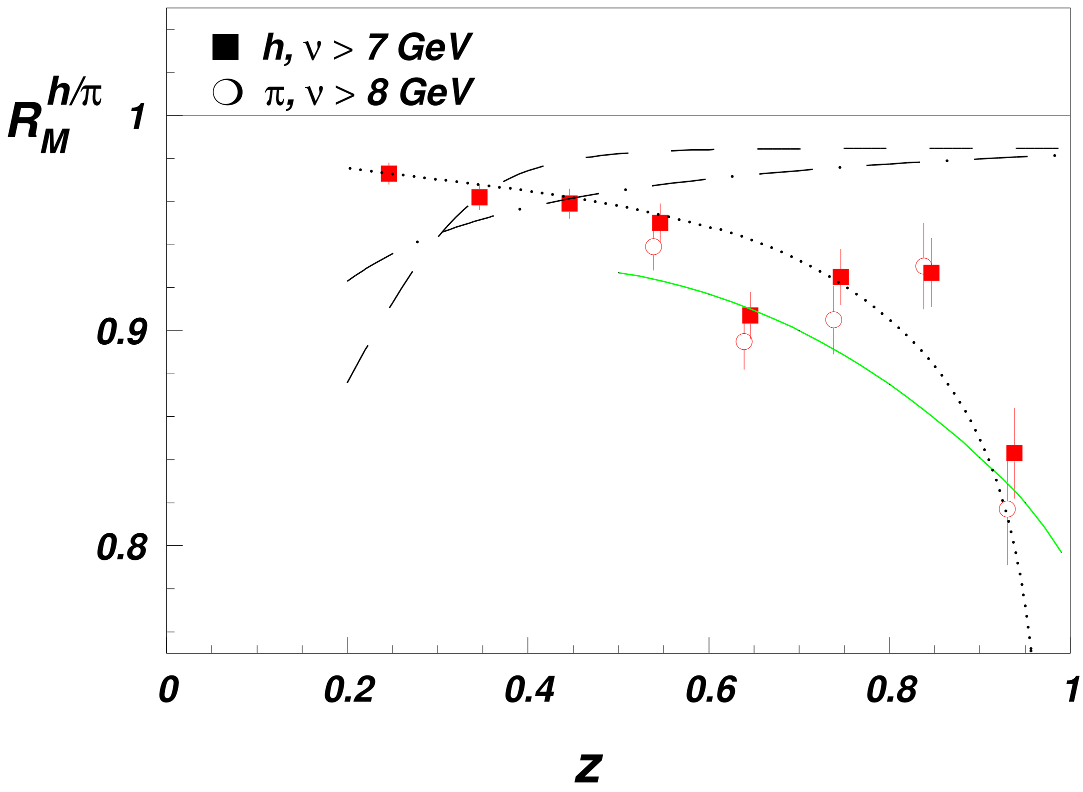


- Significant fast hadron attenuation at low ν.
- Accuracy of HERMES data adequate to constrain model predictions.

Submitted to Eur. Phys. Jour. C; hep-ex/0012049

Attenuation Ratio

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

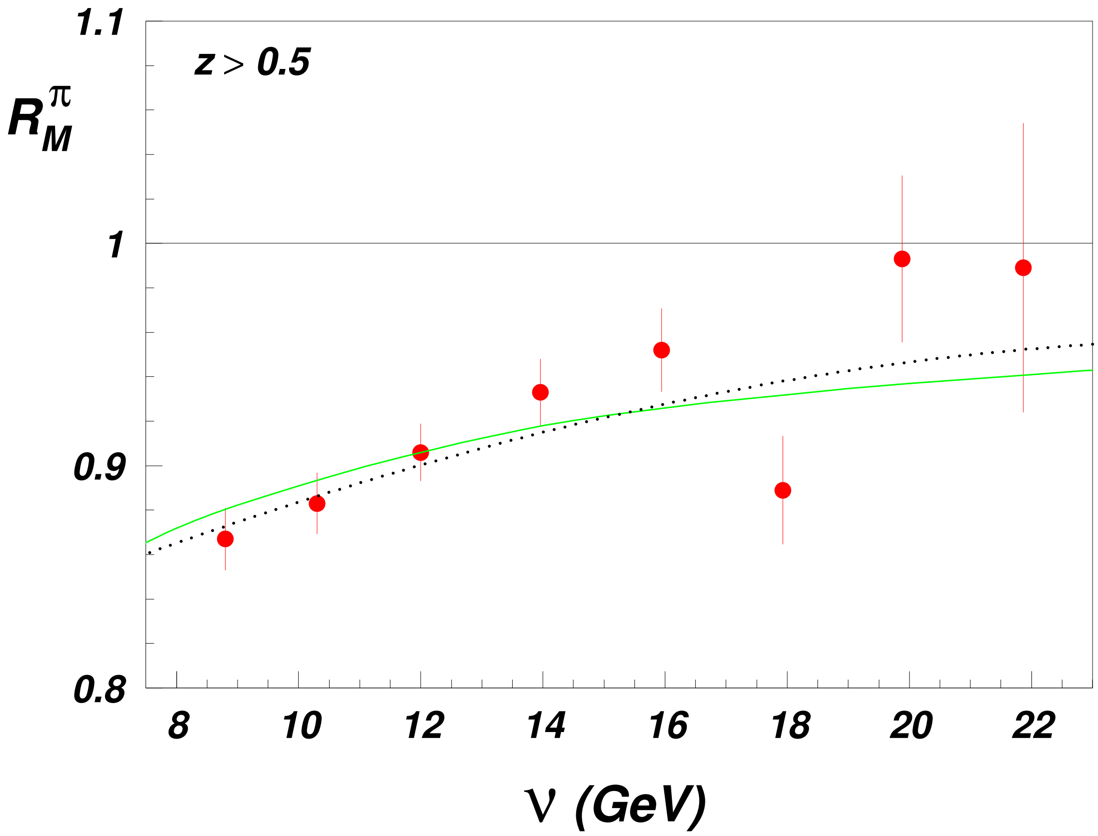


line type	t_f^h (fm/c)	σ_q	σ_s	σ_h
— · — · —	$c_h \times z\nu$	0	–	20
— — — —	$(1 - \ln(z))z\nu/(\kappa c)$	0.75	20	20
· · · · · · · · · ·	$c_h \times (1 - z)\nu$	0	–	25

- Significant attenuation of fast forward hadrons
- HERMES data provide information in the unexplored region $z > 0.8$ where the model predictions strongly differ
- Good agreement with the *gluon-bremsstrahlung model*

Pion Attenuation Ratio

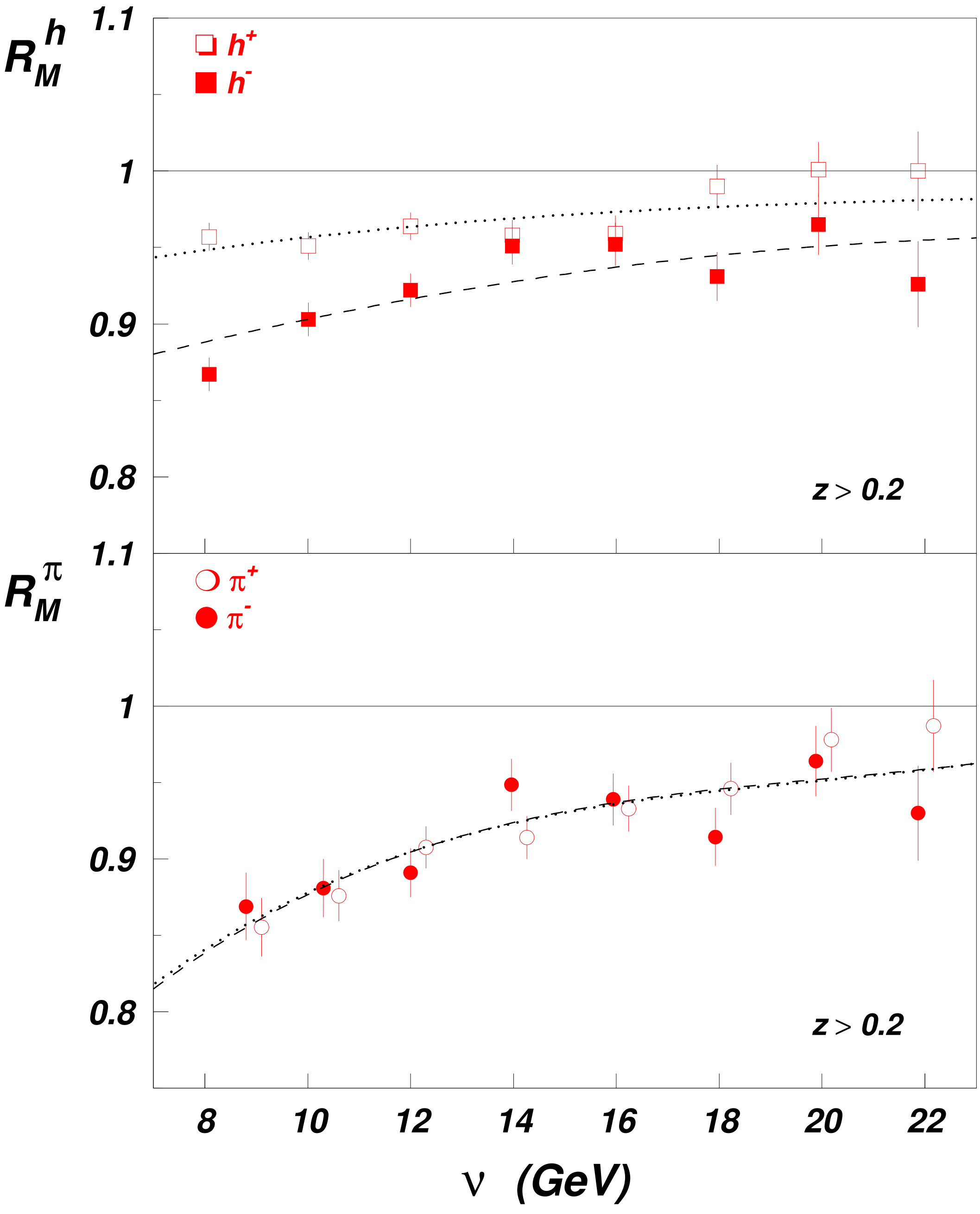
vs ν



line type	t_f^h (fm/c)	σ_q	σ_h
$\cdots\cdots\cdots$	$c_h \times (1-z)\nu$	0	25

- First measurement of pion attenuation
- Agreement with the *gluon-bremsstrahlung model*

Attenuation Ratio vs ν for + and − charge



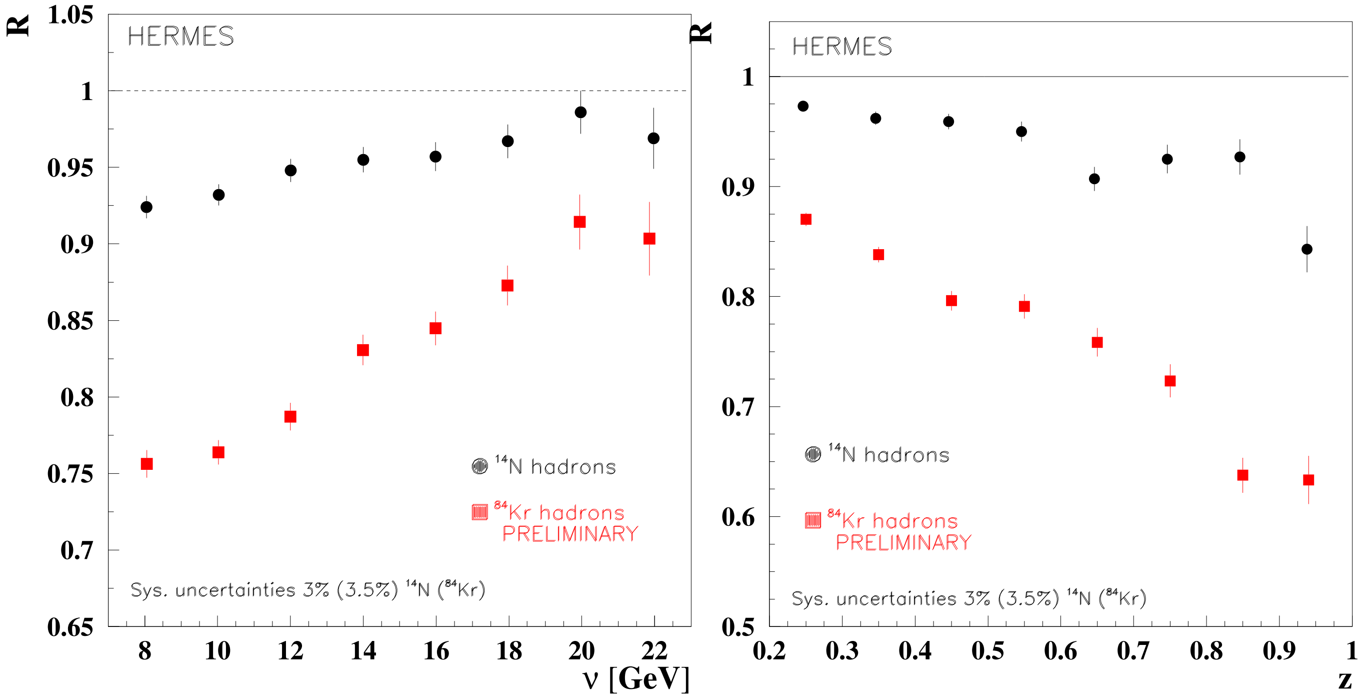
- $h^+(\pi^+, K^+, p) \Leftrightarrow h^-(\pi^-, K^-, \bar{p})$: for the first time a possible dependence on the m_h.
  Protons seem to be less attenuated $\Rightarrow$ longer formation time.
- No significant difference between π^+ and π^- $\Rightarrow$ formation time is charge-independent.

Formation time

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

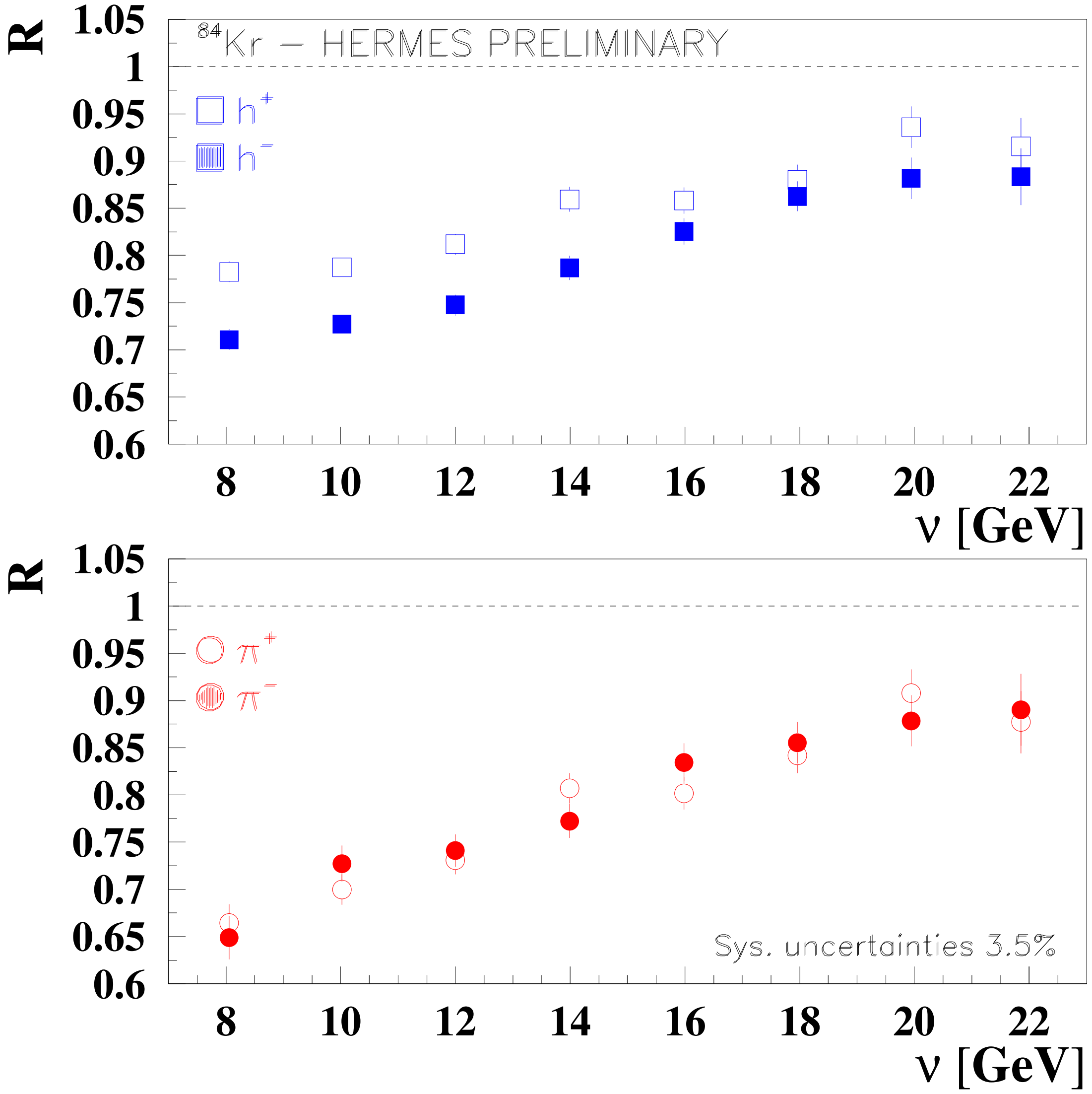
- Equality of the formation time of positive and negative pions.
- Large difference between the formation time of positive and negative hadrons
- Additional measurements of hadronization in various nuclei with pion, kaon and proton identification (RICH) will clarify the issue concerning formation-time differences of different kind of hadrons.

Attenuation ratio vs ν and z for Kr



- Consistent behavior with the ^{14}N analysis but stronger attenuation (~ 3 times) on ^{84}Kr.
- The Fragmentation Function modification in nuclei scales as $A^{2/3}$: $(Kr/N)^{2/3} \simeq 3.3$
  Guo & Wang [PRL 85 (2000) 3591]

Attenuation Ratio *vs* ν for + and − charge for Kr



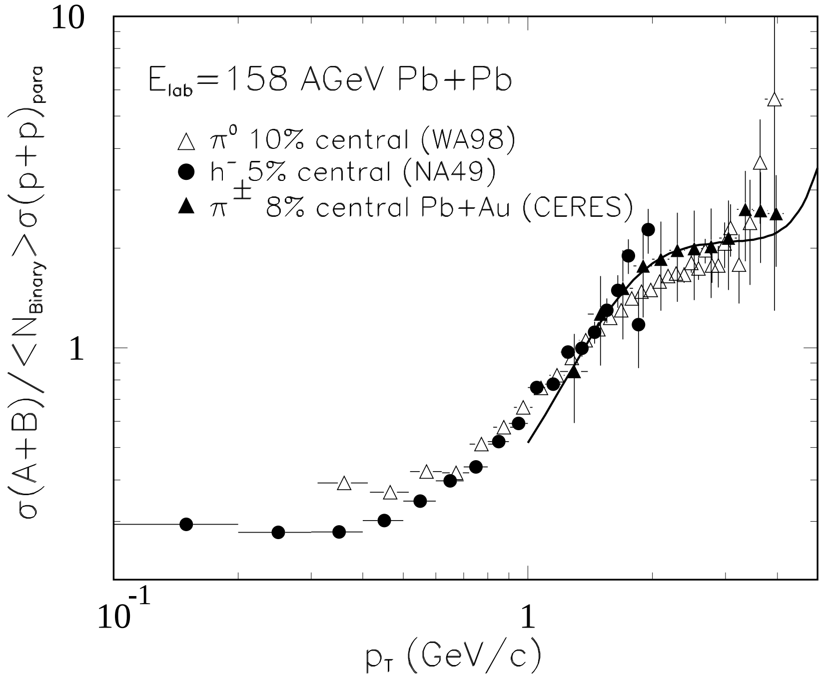
- Consistent behavior with the ^{14}N for h^+, h^-, π^+ and π^-
- No significant difference between π^+ and π^- identified by RICH

Cronin effect

Enhancement at high p_t of particle production in high-energy proton-nucleus collision (pA) relative to proton-proton (pp)

Recent model of multiple parton scattering within the Glauber formalism well describes the p_t enhancement:

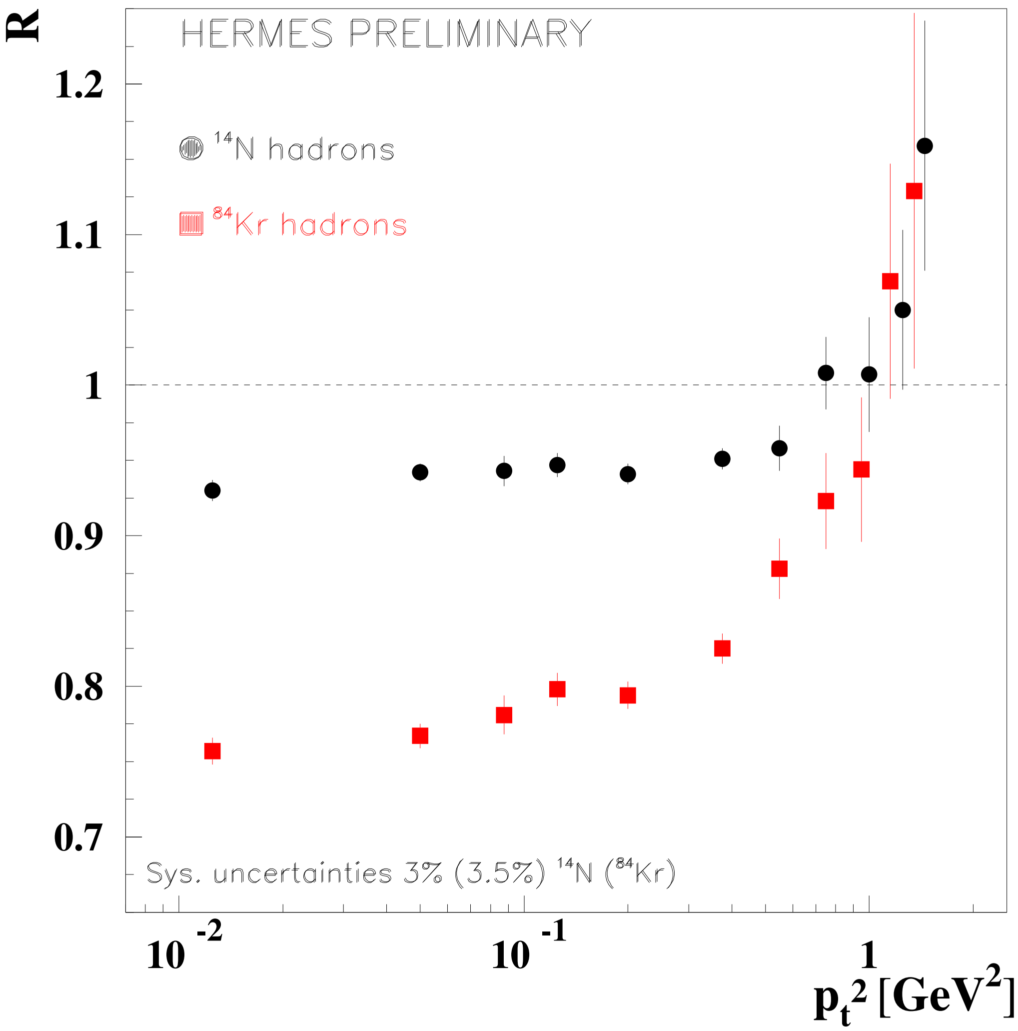
E. Wang and X.N. Wang nucl-th/0104031



- The spectra are enhanced at large p_t (hard) by multiple scattering while suppressed at low p_t (soft) by absorptive correction with the transition occurring at a scale $\sim$ 1-2 GeV/c.
- hA data indicate that the hard component of incoherent parton scattering becomes dominant at $p_t \sim$ 1-2 GeV .

Attenuation Ratio *vs* p_t^2

In the lepton nucleon scattering neither multiple scattering of the incident particle nor interaction of its constituents complicate the interpretation.



The p_t enhancement is similar to that observed in hadron nucleus scattering but is smaller in magnitude

The $p_t{}^2$ enhancement supports the hypothesis of the rescattering of either hadrons and quarks in the final state (Cronin effect).

Conclusions

- Significant nuclear attenuation, in a new region of the kinematical plane, has been found by semi-inclusive production in ^{14}N and ^{84}Kr.
- First observation of a stronger nuclear attenuation in the high z region.
- First observation of the fast pion nuclear attenuation, no difference between π^+ and π^- (different pion identification for ^{14}N and ^{84}Kr).
- First observation of a possible dependence of the nuclear attenuation on the hadron mass interpreted in terms of different formation times between protons and pions. $\rightarrow$ this issue will be clarified by the new RICH data.
- The comparison between ^{14}N and ^{84}Kr is in agreement with the mass number dependence of the possible modification of the FF.
- Cronin effect is observed: p_t enhancement supports the hypotesis of the rescattering of either hadrons and quarks in the final state.
  The transition between hard and soft processes occurs around p_t=1GeV.

  In the next future:
- Data on K, p and $\bar{p}$.
- Additional HERMES data: ^4He, ^{20}Ne...