# Hadron Formation in Nuclei at

hermes

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on behalf of the HERMES Collaboration

INFN Frascati

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- Medium modification: Parton Distributions and Fragmentation Functions
- Models and predictions
- The HERMES experiment
- Semi-inclusive results for $^{14}$N and $^{84}$Kr
- Conclusions and Outlook

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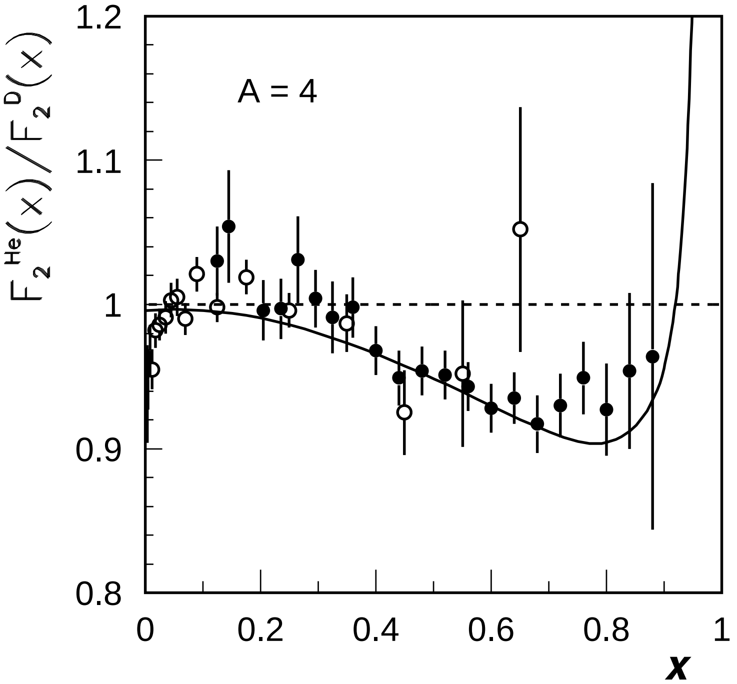
# Medium Modification of Parton Distributions

Inclusive Deep-Inelastic-Scattering (DIS) of high energy leptons on nucleons has been used from late '60s to study the Parton Distributions.

Inclusive DIS on nuclei in '80s showed a large medium effect, the EMC effect, which has been interpreted at both hadronic (nucleon's binding and Fermi motion, pions, ... ) and partonic levels (rescaling, multi-quark systems, ...).




G.A.Miller and J.R.Smith, Phys.Rev.C65(2002)015211 :

... the depletion of DIS structure function observed in the valence quark regime is due to some interesting effect involving dynamics beyond the conventional nucleon-meson treatment of nuclear physics.

# Parton Fragmentation

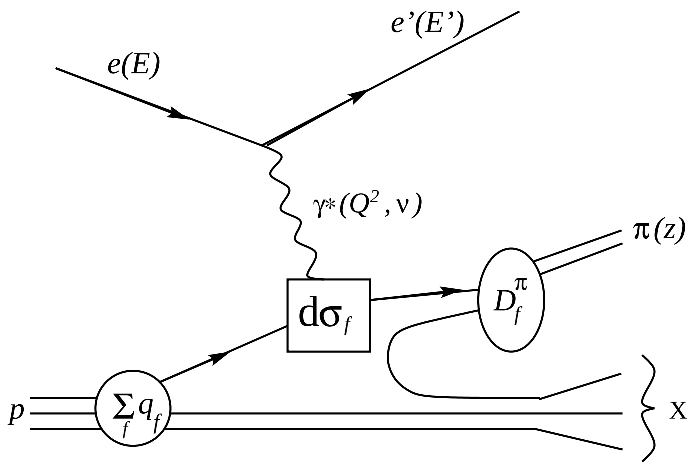
Semi-Inclusive Deep-Inelastic-Scattering (SIDIS) of high energy leptons on nucleons can be studied by:

$$d\sigma^h(z) \propto \sum_f q_f(x) \cdot d\sigma_f \cdot D_f^h(z)$$

$$\Downarrow \qquad\qquad \Downarrow$$

$$DF \qquad\qquad FF$$

$z = E_h/\nu$



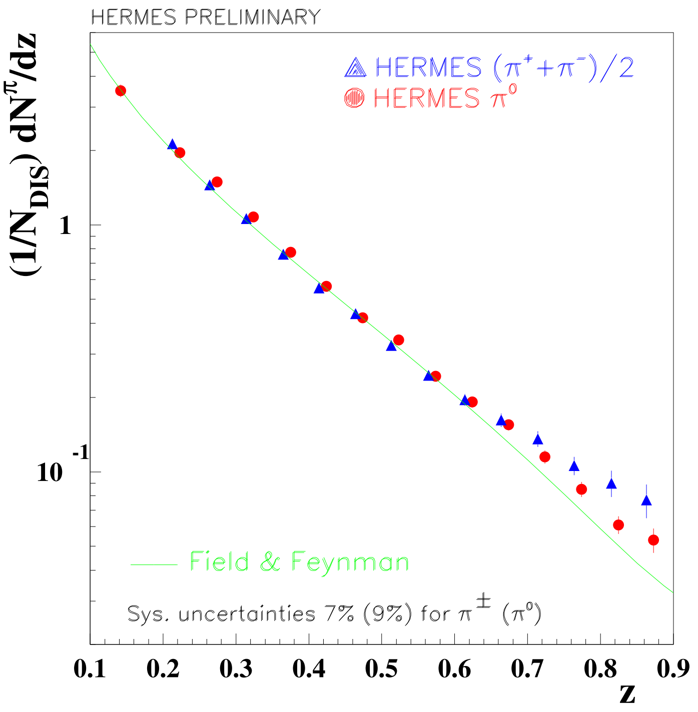

FFs are precisely measured in $e^+e^-$ and follow pQCD evolution like DFs.

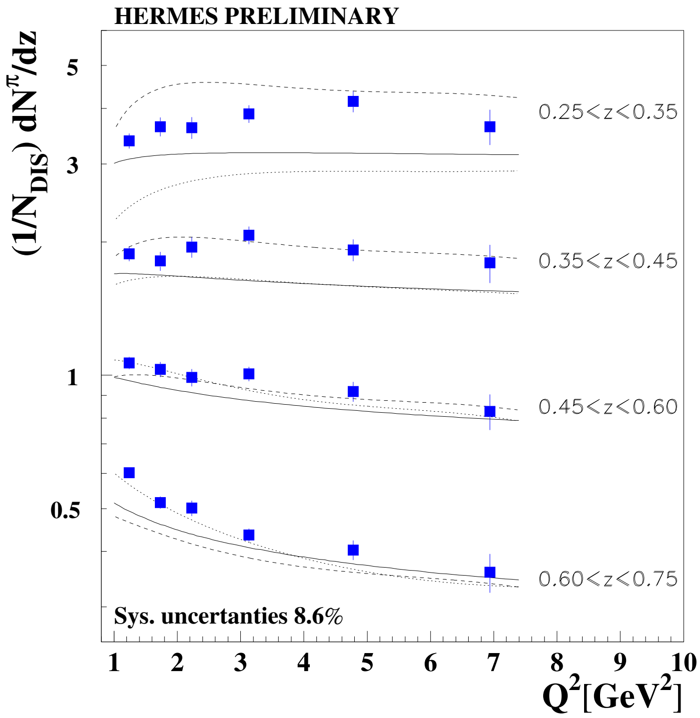
SIDIS multiplicities are also good measurements of FFs:

$$\frac{1}{N_{DIS}}\frac{dN^h(x,z)}{dz} = \frac{\sum_q e_q^2 q(x) D_q^h(z)}{\sum_q e_q^2 q(x)} \qquad (\sim D_q^{\pi^0}(z))$$

# Multiplicities $vs$ FFs

(HERMES, Eur.Phys.J. C21 (2001) 599)




Isospin invariance in the production of charged and neutral pions.

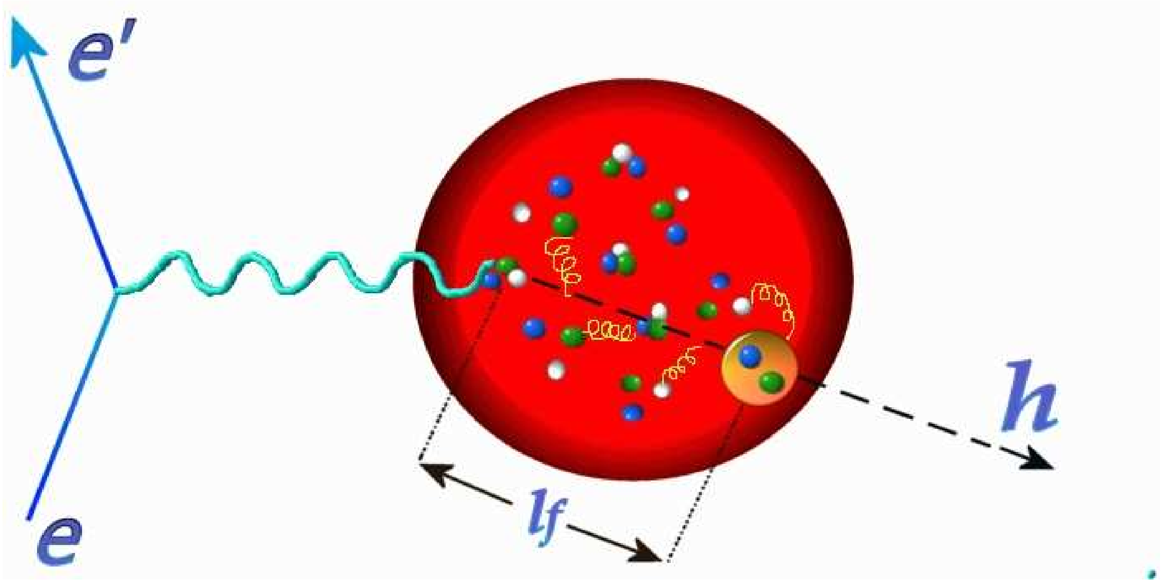
Agreement with fixed scale Field-Feynman FF parameterization.

Agreement with NLO QCD evolution of FFs measured at LEP
(KKP parameteriz.: $D(z,Q^2) = N(\bar{s}) z^{\alpha(\bar{s})}(1-z)^{\beta(\bar{s})}$).

Factorization holds in the HERMES kinematics.

# Medium Modification in Fragmentation

Nucleus acts as an ensemble of targets: reduction of multiplicity of fast hadron due to both *hard partonic* and *soft hadron interactions.*




Nuclear Attenuation :

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

The formation time ($\tau_f = l_f/c$) measurement + FFs, is crucial for the understanding of the space-time evolution of the hadron formation process.

# Formation time

...moreover

- Quantitative informations on the hadron formation time is needed for the interpretation of relativistic heavy ion collisions.
- Initial energy density of the Quark Gluon Plasma:

$$\epsilon_0 = \frac{m_T}{\tau_0 \cdot A} \frac{dN}{dy}$$

$m_T = \sqrt{m^2 + p_t^2}$ transverse mass of the particles;
$A =$ collision area of the two nuclei;
$\frac{dN}{dy} =$ rapidity density;
$\longrightarrow \tau_0$ proper time at which plasma is produced.

The plasma formation time can be related to the hadron formation time.

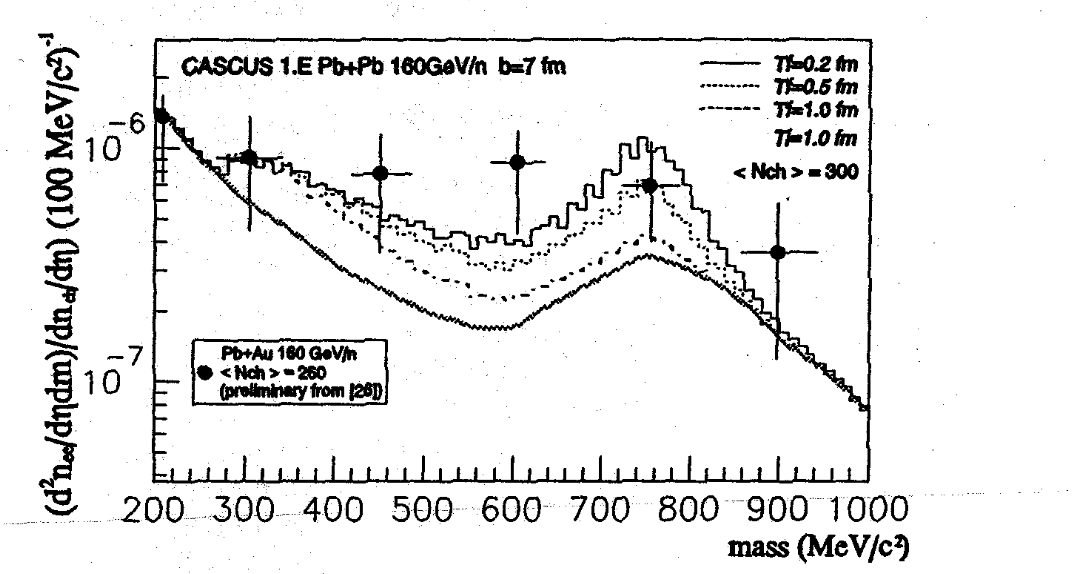
- Before the HERMES results, the hadron formation time (from $pA$ reactions and lepton-nucleus scattering) was not known better than a factor of 2.

# Formation times

$\tau_\pi$ dependence of the dilepton mass spectrum produced in heavy ion collisions at GSI.

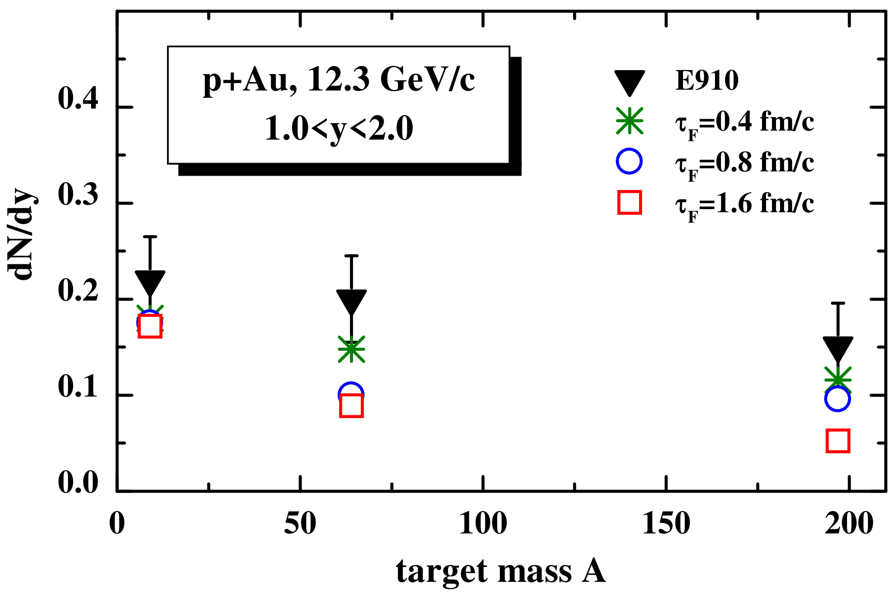
P. Filip, J. Pisut Phys. Lett. B 411 (1997) 187

Spieles et al. EPJ C5(1998) 349




$\tau_{\bar{p}}$ dependence of the antiproton yield produced in $p + A$ reactions at AGS.

Cassing et al. nucl-th/0203026



# Models for nuclear attenuation

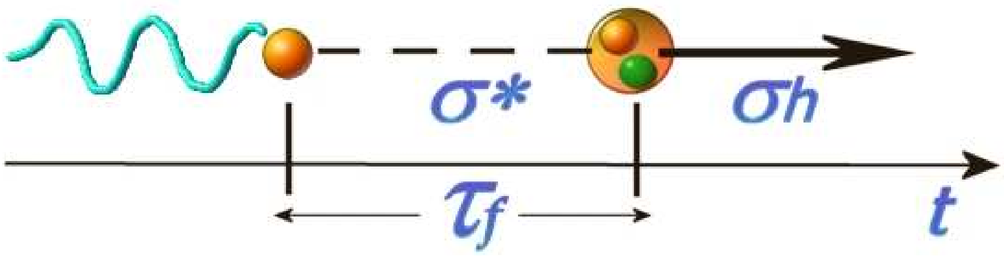
Phenomenological intranuclear reinteraction model:

(Bialas & Chmaj, PLB 133(1983) 241)

• DIRECT PRODUCTION (one-time-scale)

Hadrons are directly produced and interact with typical hadronic inelastic cross section $\sigma_h \simeq 20$ mb.

$\tau_f = \tau_0 \frac{E_h}{m_h}$ ($\tau_0$ constant characteristic for a given h)




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

Probability of non-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

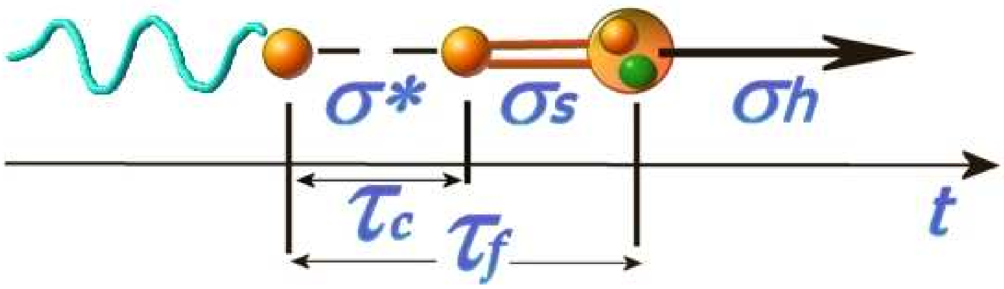
$\tau_f$ can be derived by a fit ($\sigma^*$ and $\tau_f$ as free parameters).

# Models for nuclear attenuation

• <u>STRING MODEL</u> (two-time-scale $\tau_c$, $\tau_f$)

(Bialas and Gyulassy, NPB 291(1987) 793)

The constituents of the hadron are formed at different time $\tau_c$, $\tau_f$:




$$\tau_f - \tau_c = c\frac{E_h}{\kappa} = c\frac{z\nu}{\kappa} \text{ (string constant } \kappa \approx 1\ GeV/fm)$$

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

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

$\tau_f$ can be derived by a fit ($\sigma^*$, $\sigma_s$, and $\tau_f$ as free parameters).

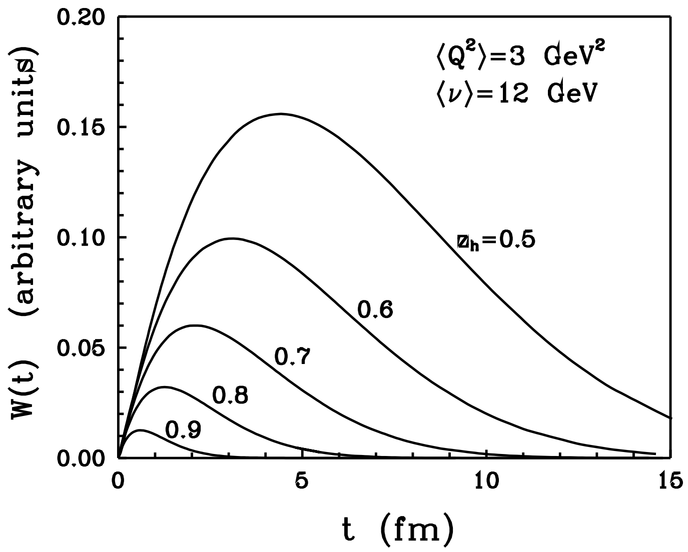
# Gluon Bremsstrahlung Model

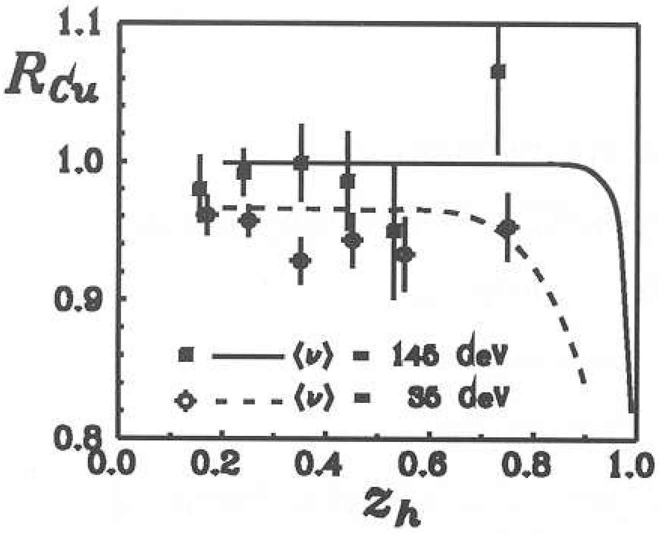
pQCD inspired model for leading mesons:

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

- Vacuum energy loss: $q \to gq'$
  ($dE/dz \sim 2.5 GeV/fm$ by E772/E866 for DY on nuclei).
- Energy loss induced by multiple interactions in the medium: rising of the parton $p_t$.
  $dE/dz \sim z$ small compared to the vacuum energy loss.
- Color Transparency ($\sim 1/Q^2$) $q\bar{q}$ at a short $\tau$.
- $q\bar{q}$ wave packet on the light-cone wave function of the $\pi$.

First idea of FF modification: $D(z) \propto \int_0^\infty dt W(t, \nu, z)$




$W(t, \nu, z)$ exhibits the $\sim \nu(1 - z)$ dependence.

A suppression at high $z$ is predicted.

High $z$ hadrons originate from quarks that have emitted only few gluons and they are correlated with small $\tau_f$.

# Gluon Bremsstrahlung Model

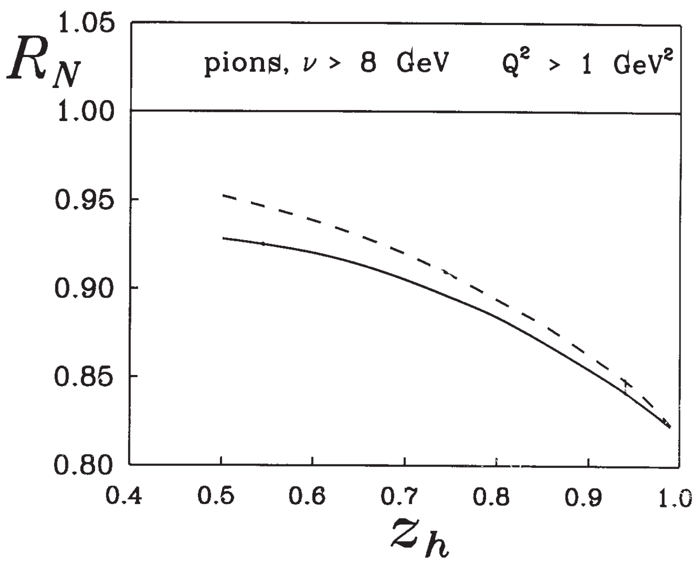
FF modification comes from: Nuclear Suppression + Induced Radiation.

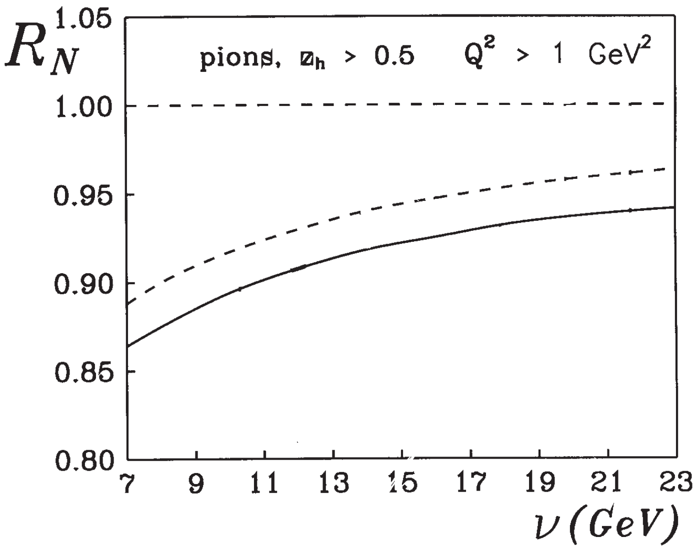
$$D_{eff}(x) =$$

$$= \int d^2b \int_0^{l_{max}} dl_{pr} \int_{-\infty}^{\infty} dz\ exp[-\int_{z+l_{pr}}^{\infty} dz' \sigma(z')\rho_A] \times$$

$$\{D_q^h(x) exp[-\int_z^{z+l_{pr}} dz_1 \sigma_q(z_1)\rho_A(b_1 z_1)] +$$

$$\int_z^{z+l_{pr}} dz_2 \sigma_q(z_2)\rho_A(b_1 z_2)\tilde{D}_q^h(x) exp[-\int_z^{z_2} dz_3 \sigma_q(z_3)\rho_A(z_3)]\}$$



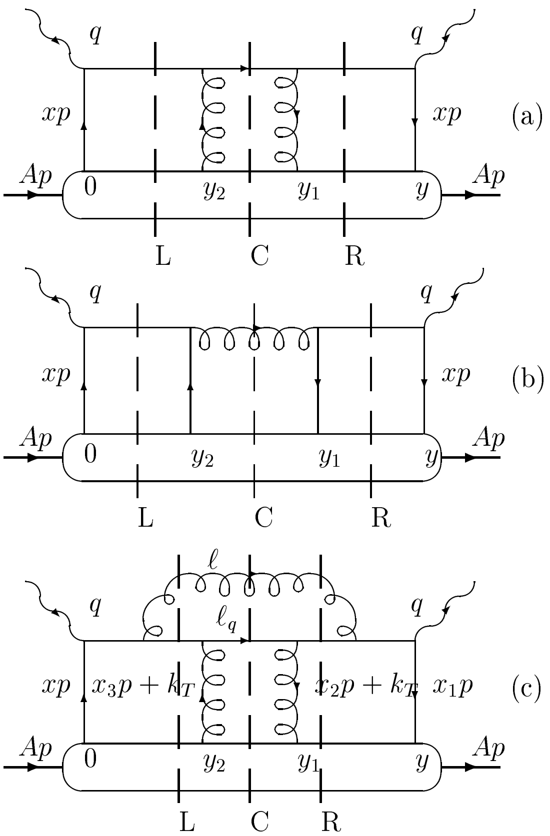

Predictions available only from fast pions ($q\bar{q}$ pair), $z > 0.5$

- The Nuclear Suppression (NS) is the dominant term;
- IR $\simeq$ 2% and constant as a function of $\nu$;
- NS flat at low $z$.

# FF Modification Model

(Guo & Wang, PRL 85 (2000) 3591)

The $D_q^h$ and their QCD evolution equations are described in the framework of multiple parton scattering and induced radiation by an additional term in DGLAP.




a) rescattering with $g$ without $g-$radiation $\rightarrow$ broadening of the transverse momentum of the leading hadron (jet).

b) rescattering with another $q$. Mix of $D_q$ and $D_g$.

c) rescattering with gluon radiation $\rightarrow$ dominant higher twist contribution in QCD evolution of $D_q^h$.

- Different modification of $D_q$ and $D_{\bar{q}}$ (different attenuation for positive and negative hadrons).
- The emitted $g$ and the leading $q$ propagate coherently through the nucleus $\rightarrow$ large interference effects (Landau-Pomeranchuk-Migdal interference).

# FF Medium effects

(Guo & Wang, PRL 85 (2000) 3591 + hep-ph/0202105)

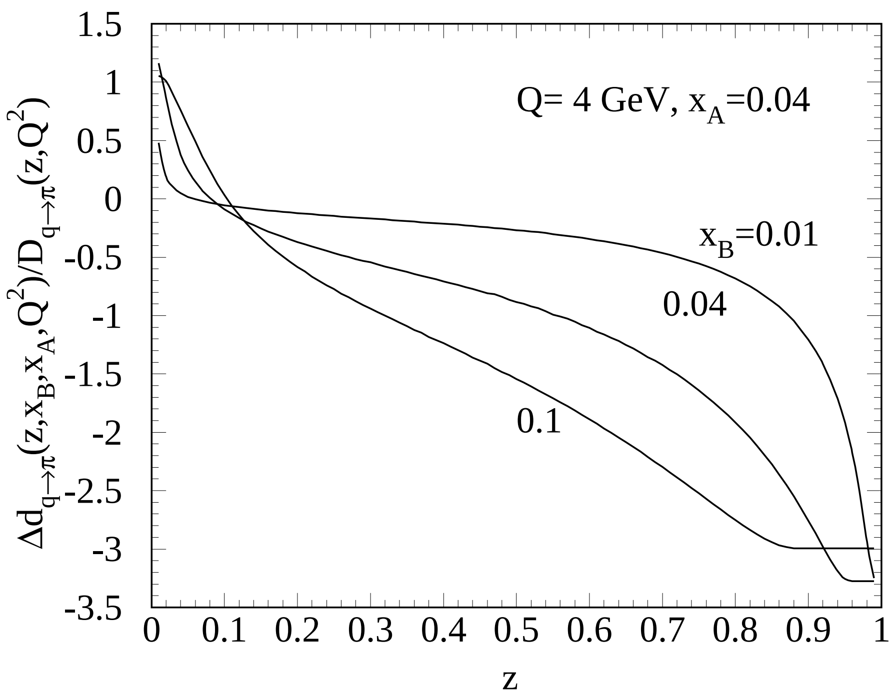
Modified effective quark fragmentation function:

$$\tilde{D}_{q\to h}(z_h, Q^2) \equiv D_{q\to h}(z_h, Q^2) + \Delta D_{q\to h}(z_h, Q^2)$$

$$\Delta D_{q\to h}(z_h, Q^2) \simeq \frac{C_A \alpha_s^2}{N_c} \frac{\tilde{C}}{Q^2 x_A^2} \Delta d_{q\to h}(z_h, x_B, x_A, Q^2).$$

($\tilde{C}$ quark-gluon correlation strength.)

Equivalent to rescale the FF for the fraction of parton energy loss $\Delta E/E$: $\tilde{D}(z) \approx \frac{1}{1-\Delta E/E} D\left(\frac{z}{1-\Delta E/E}\right)$

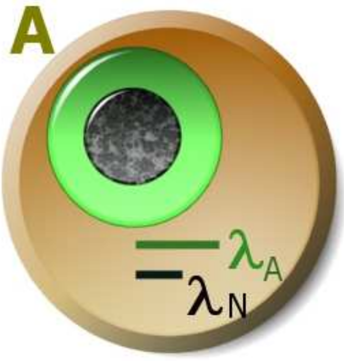



- The FF modif. increases for larger $x_B = \frac{Q^2}{2p^+q^-}$
- The FF modif. increases for smaller $x_A = \frac{1}{MR_A}$
- Due to LPM interference, the FF modification scales quadratically on the nuclear size $\propto A^{2/3}$

(A. Accardi and H.J. Pirner, nucl-th/0205008)

In QCD, $Q^2$ appears scaled either by $\Lambda$ (mass scale parameter) or by $\mu^2$ (low momentum cutoff)

$1/\mu^2 \sim \lambda^2$ quark confinement size.




In the nucleus:

$\lambda_A > \lambda_N \rightarrow Q^2$ rescaling

$q_f^A(x,Q) = q_f(x,\xi_A(Q)Q)$

$D_f^{h|A}(z,Q) = D_f^h(x,\xi_A(Q)Q)$

with the *scale factor*

$$\xi_A(Q^2) = \left(\frac{\mu_N^2}{\mu_A^2}\right)^{\frac{\alpha_s(\mu_A^2)}{\alpha_s(Q^2)}}$$

$\xi$ is determined by QCD evolution of moments of DF.

Multiplicity ratio with *rescaled* DF and *rescaled* FF:

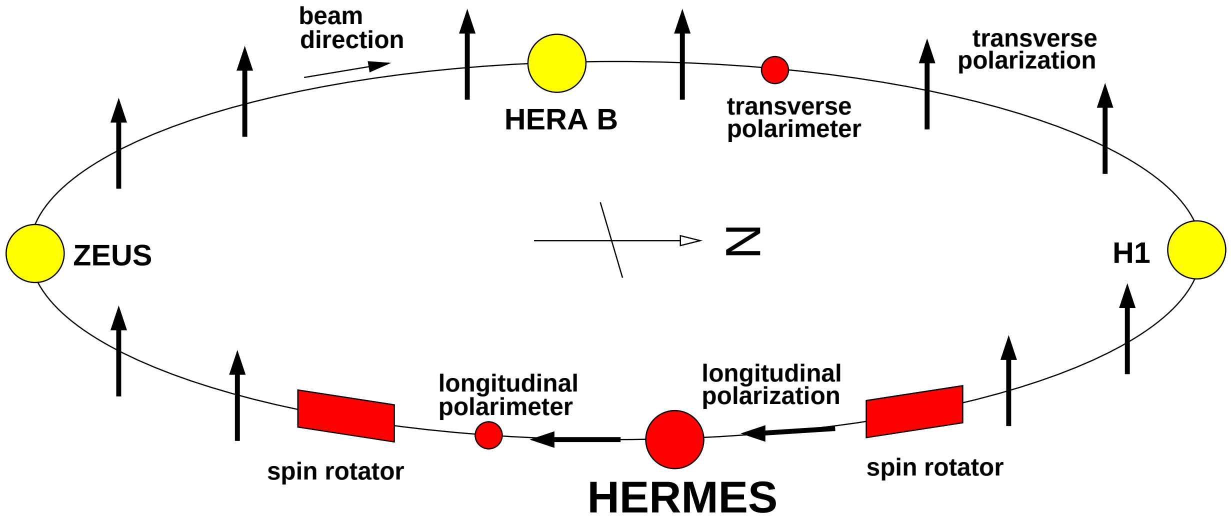
$$\frac{1}{N_A^\ell}\frac{dN_A^h}{dz} = \frac{1}{\sigma^{\gamma^* A}}\int_{\text{exp. cuts}} dx\, d\nu \sum_f e_f^2\, q_f(x,\xi_A\, Q)\,\frac{d\sigma^{\gamma^* q}}{dx\, d\nu}\, D_f^h(z,\xi_A\, Q)$$

$$\sigma^{\gamma^* A} = \int_{\text{exp. cuts}} dx\, d\nu \sum_f e_f^2\, q_f(x,\xi_A\, Q)\,\frac{d\sigma^{\gamma^* q}}{dx\, d\nu}$$

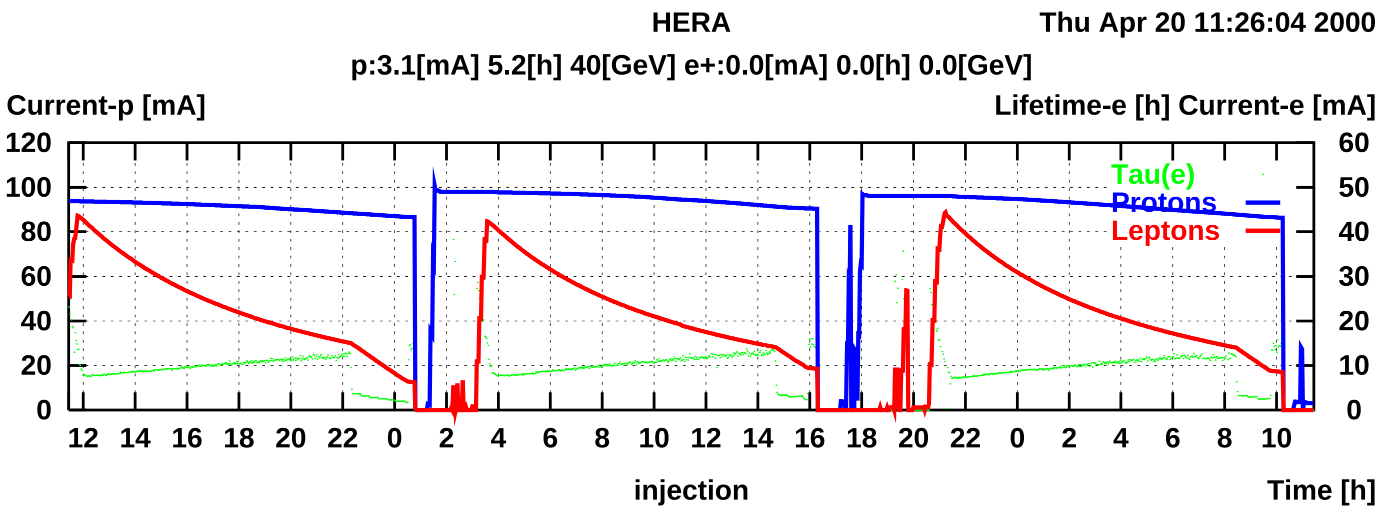
(... + Nuclear Absorption + Formation Time)

# HERMES at DESY

HERMES is an experiment at DESY which studies the spin structure of the nucleon ... and something else ...



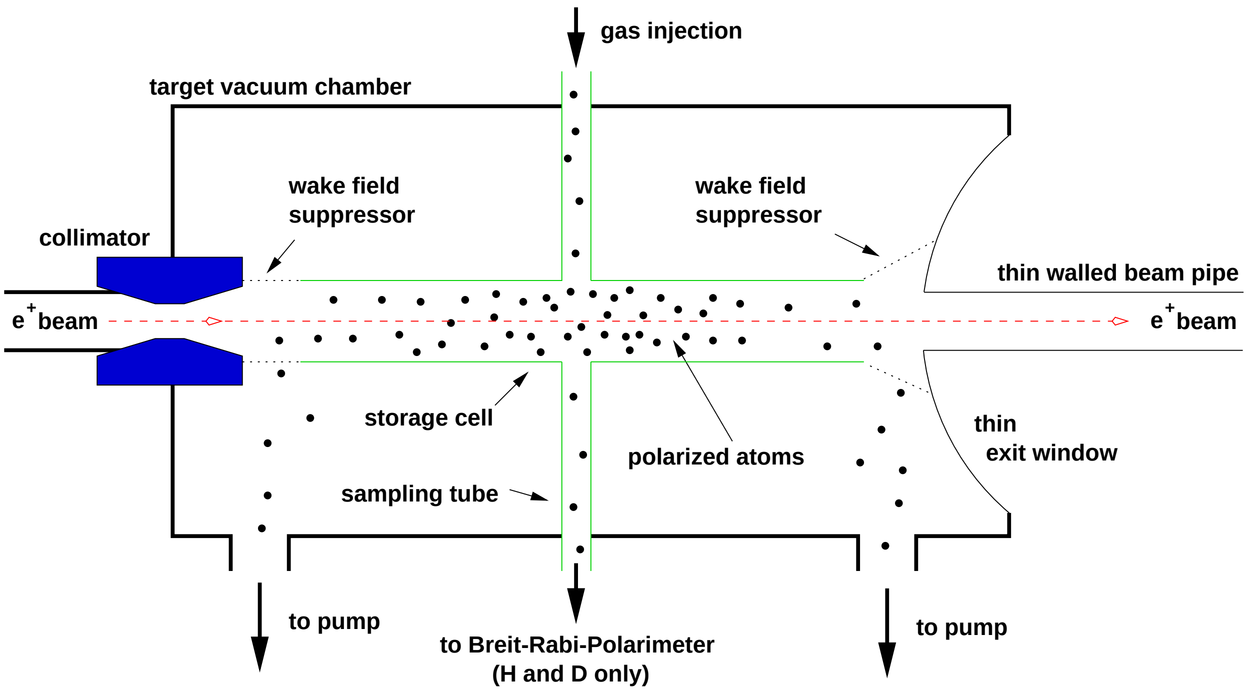

- 27.5 GeV $e^+$ ($e^-$), I$\sim$30 mA.




- Internal target, polarized and unpolarized gas.
- Last part of the fill dedicated to high-density unpolarized target runs.

# The Internal Target

(HERMES, NIM A343 (1994) 334)



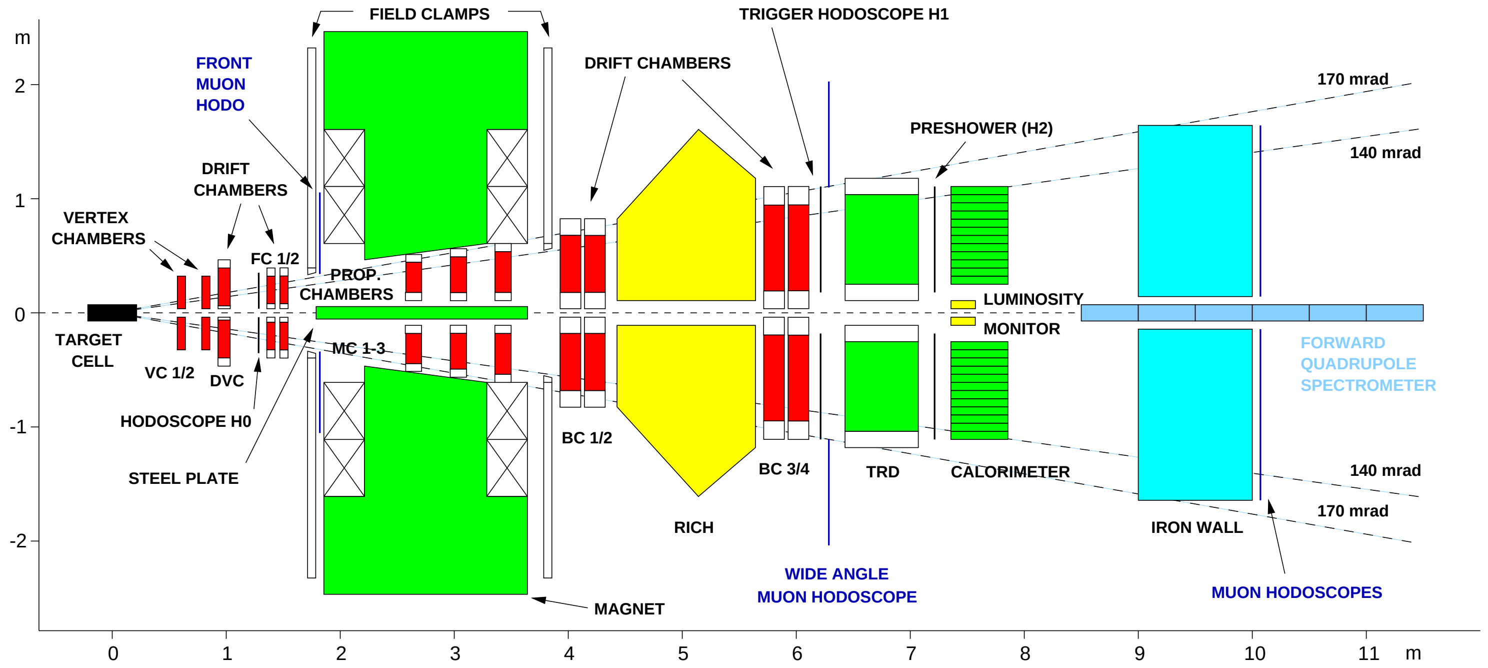

- Internal storage cell (no entrance-exit window)
- Atomic beam source for $\vec{H}$ and $\vec{D}$ with high polarization ($P > 90\%$)
- Pure gas target, no dilution factor

- **Unpolarized high density nuclear target (H, D, $^{3}$He, $^{14}$N, $^{84}$Kr, $^{20}$Ne, $^{40}$Ar, $^{131}$ Xe) runs started in 97.**

$$Densities: \begin{cases} \sim 10^{14} \div 10^{15}\ nucl \cdot cm^{-2} & (polarised) \\ \sim 10^{15} \div 10^{17}\ nucl \cdot cm^{-2} & (unpolar.) \end{cases}$$

# SPECTROMETER

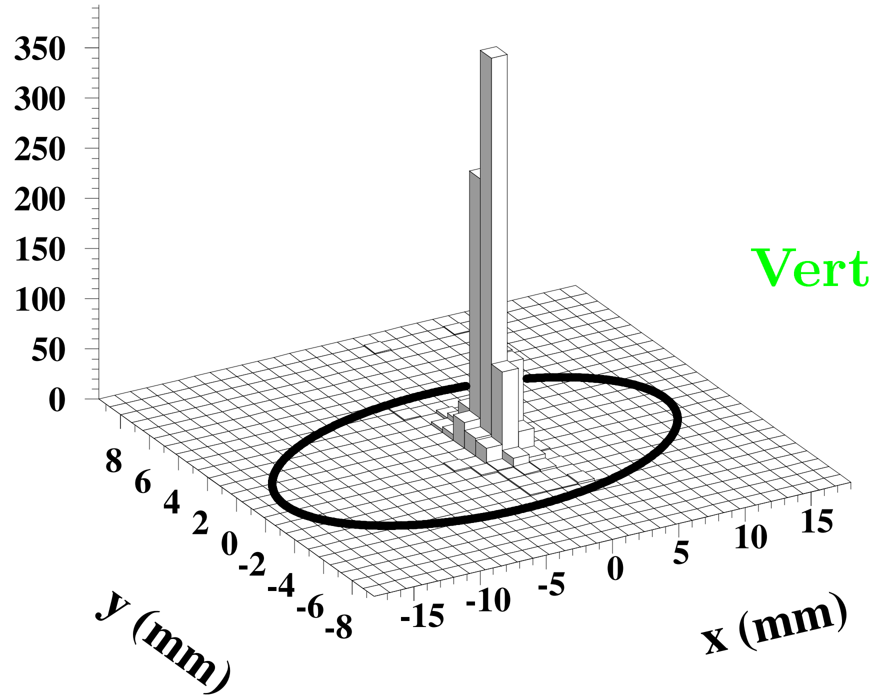
(HERMES coll. NIM A417 (1998) 230)



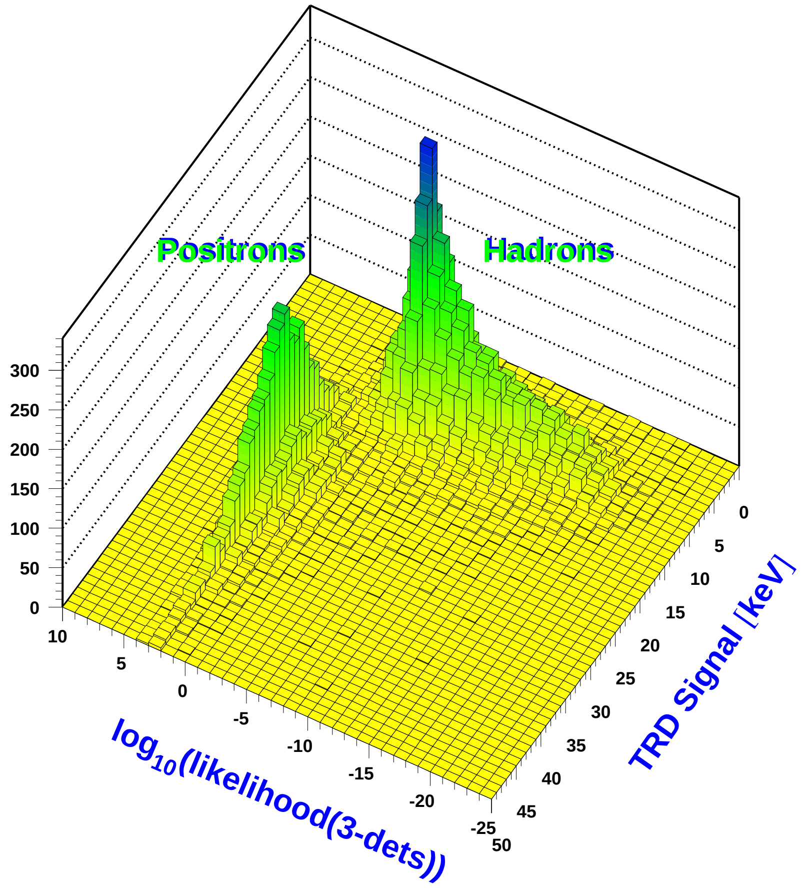

- **Kinematic:** $0.004 < x < 0.8$, $0.2 < Q^2 < 10$ GeV$^2$, $W^2 > 4$ GeV$^2$
- **Tracking**: 57 tracking planes, $\delta p/p = (0.7 - 1.3)\%$, $\delta\theta < 0.6$ mrad
- **Particle identification**: $\hat{C}erenkov$ (RICH '98), TRD, Preshower, e.m. Calorimeter

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

# Charged pions




**Vertex reconstruction**



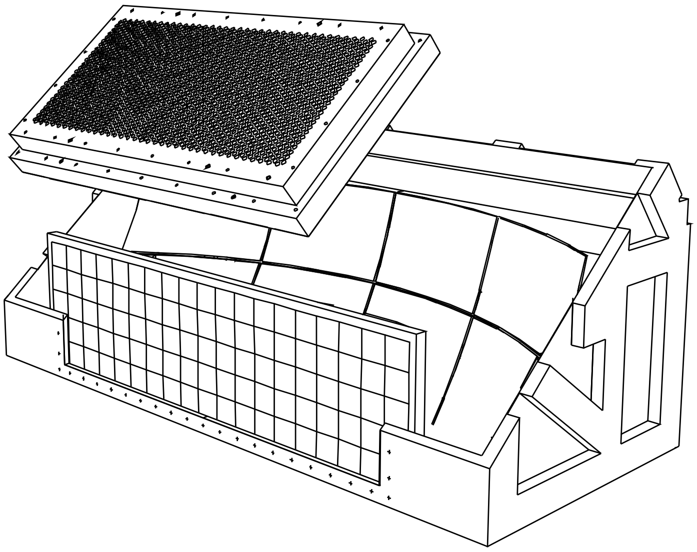

**PID from** $\hat{C}erenkov$**,**
*TRD, Preshower*
**and** *Calo*
$h$ **contamination** $\leq 1\%$
$e^+$ **efficiency** $\geq 99\%$

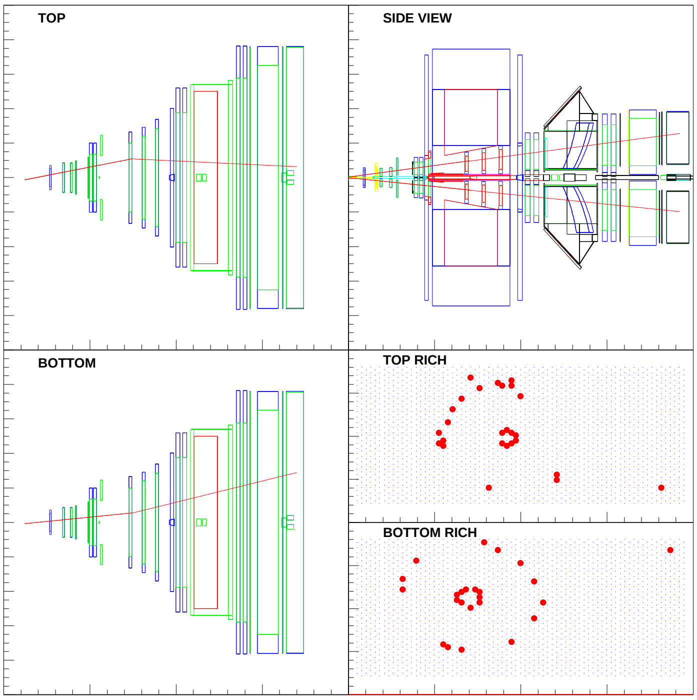
$\pi^{\pm}$ identification in $^{14}$N: $\hat{C}$erenkov threshold detector
$4 < P_{\pi^{\pm}} < 14\ GeV$.

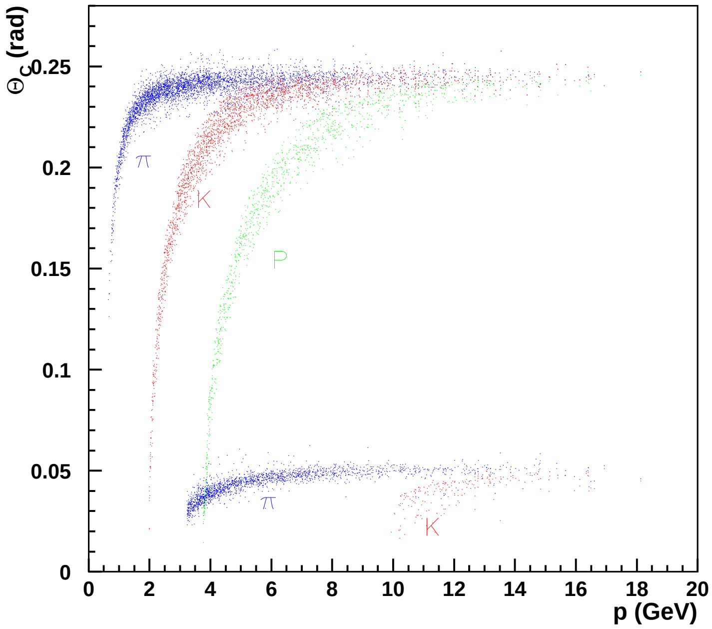
# RICH

Double radiator : Aereogel (n=1.03) and $C_4F_{10}$ gas (n=1.0014). Čerenkov photons are detected by two matrix of ~ 4000 PMTs.

Detection efficiencies : 99% ($\pi$), 90%($K$), 85-95%($p$)





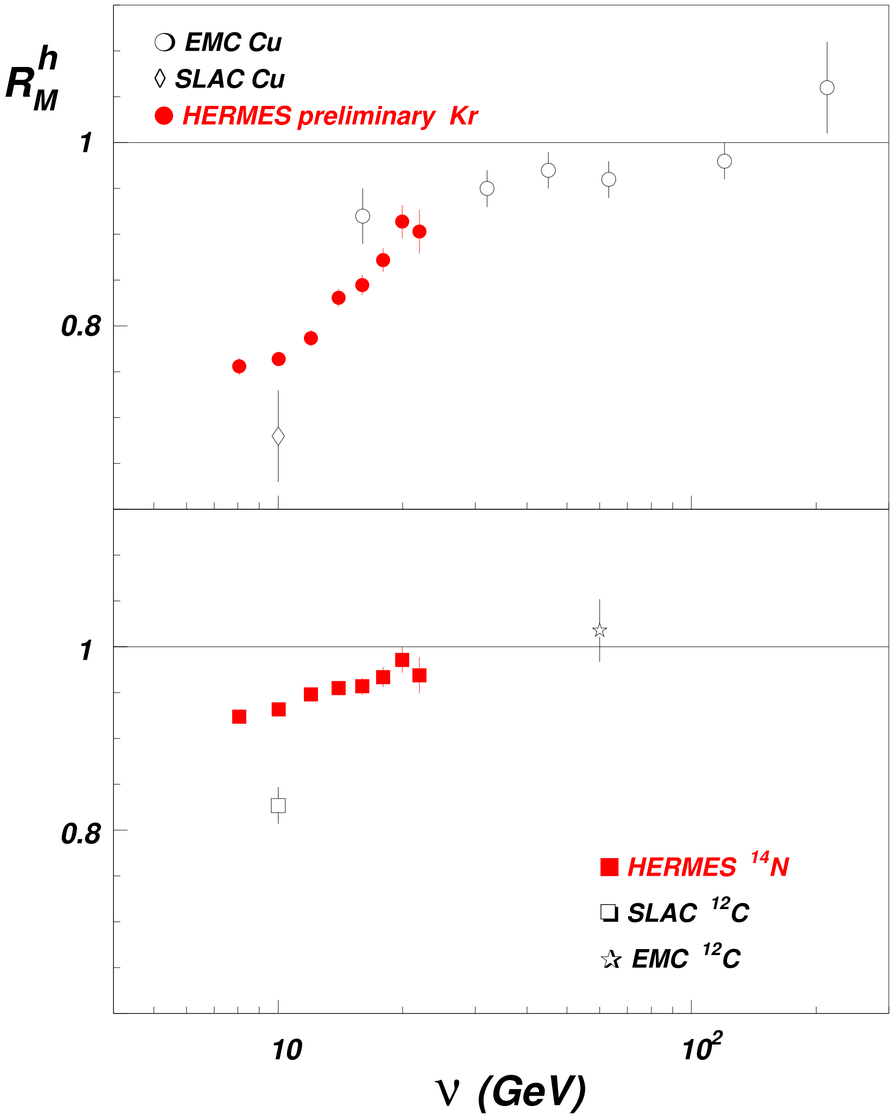




In $^{84}$Kr hadrons are identified by RICH.

# Results for Hadron Attenuation

HERMES, EPJ C 20 (2001) 479

HERMES, hep-ex/0012049

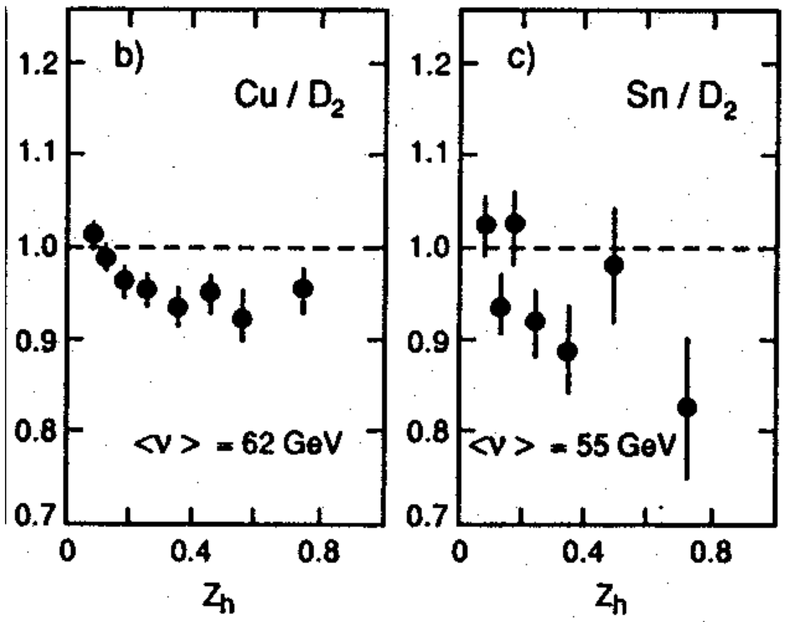



- HERMES kinematics is ideal to study medium effects in fragmentation.
- Increase with $\nu$ consistent with the EMC data taken at higher energies.
- Discrepancy with SLAC mainly due to the EMC effect.

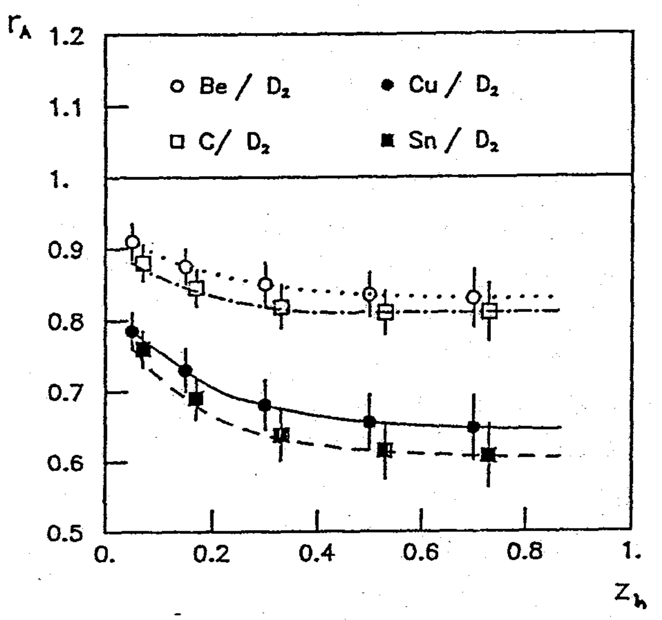
# Attenuation Ratio

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

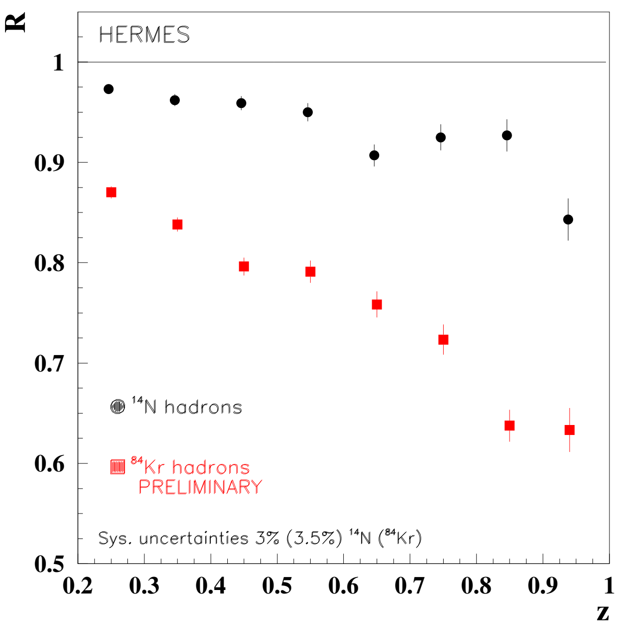
EMC




SLAC



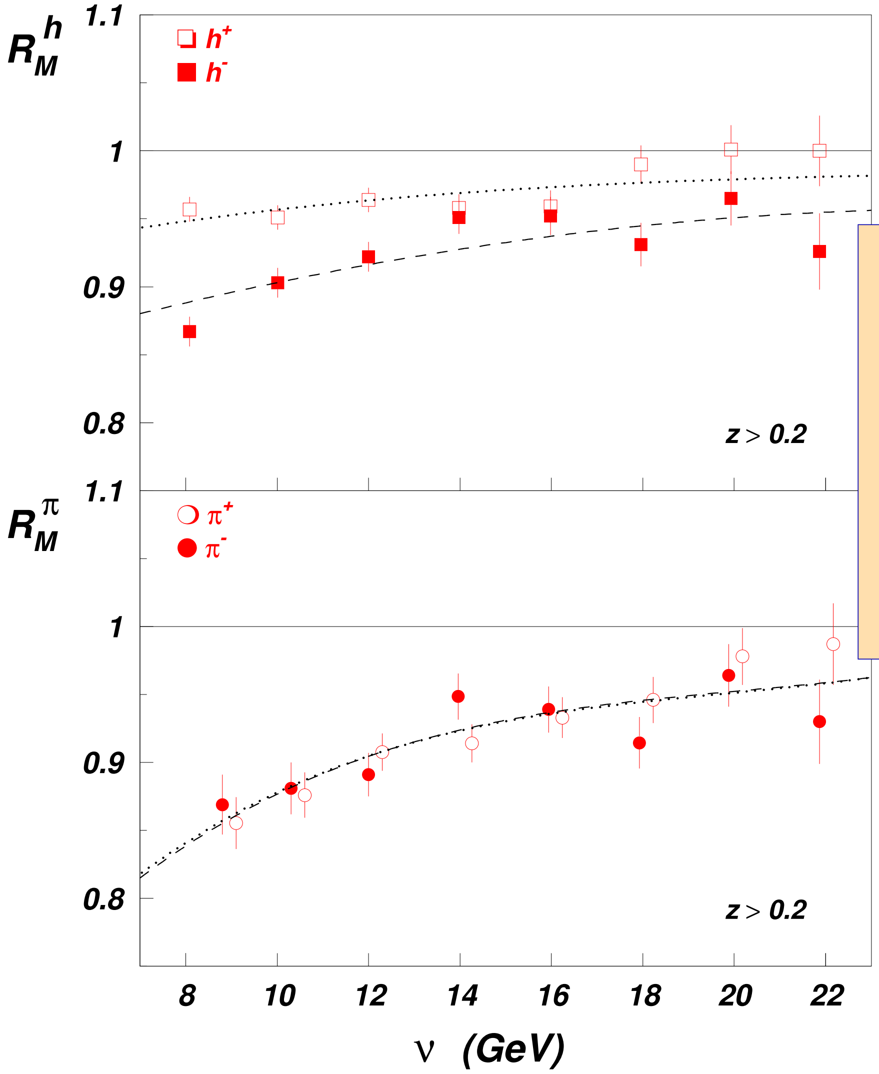

HERMES




- Significant attenuation of fast forward hadrons.
- HERMES data provide information in the unexplored region $z > 0.8$ where the model predictions strongly differ.

# Attenuation *vs* hadron/pion charge

(HERMES Coll., EPJ C20(2001)479)




**Formation time**

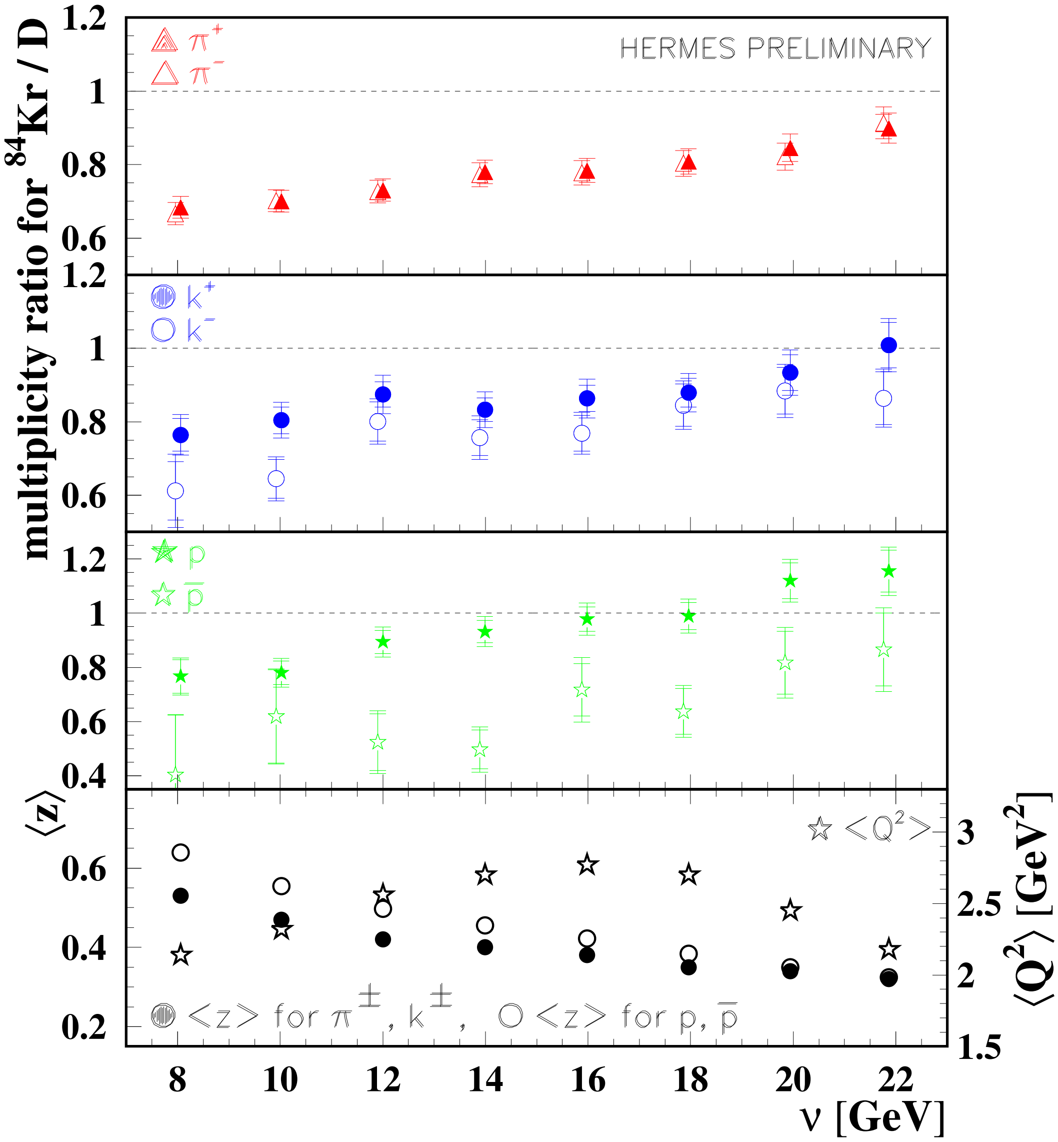
$t_h = C_h (1-z)\,\nu$

| | $C_h$ [fm/ GeV·c] |
|---|---|
| $h^+$ | **3.49±0.51** |
| $h^-$ | **1.32±0.16** |
| $\pi^+$ | **1.37±0.18** |
| $\pi^-$ | **1.38±0.21** |

- $h^+(\pi^+, K^+, p) \Leftrightarrow h^-(\pi^-, K^-, \bar{p})$:
  $\Rightarrow$ different formation times for different hadrons
  $\Rightarrow$ different FF modifications for different hadrons.
- No significant difference between $\pi^+$ and $\pi^-$.
- Measurements using different nuclei and RICH better clarify the issue concerning differences for different kind of hadrons.

# $Kr$ Attenuation *vs* $\nu$ with hadron ID

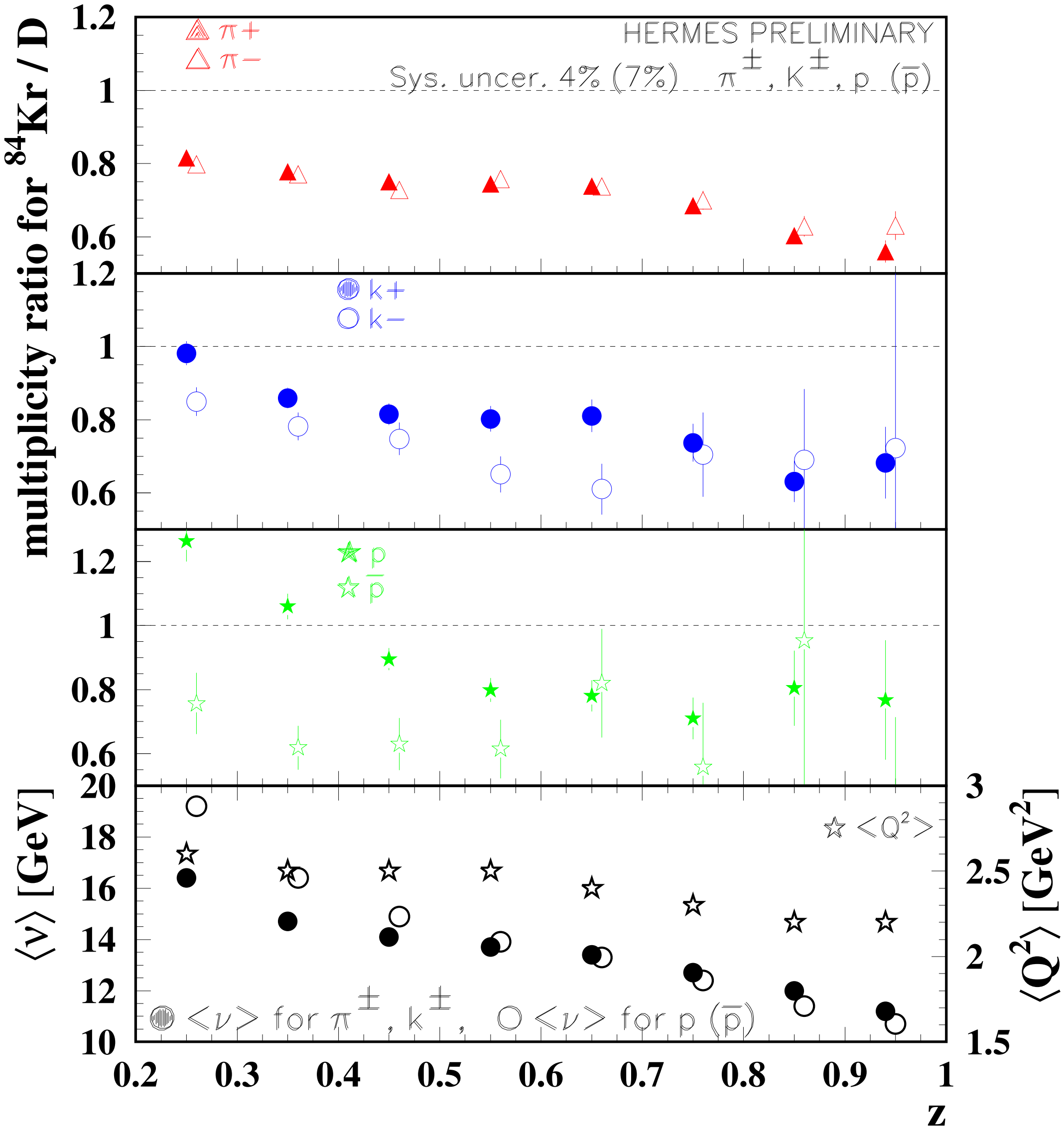
RICH ID : $\pi/K$ (2.5-15 GeV), $p/\overline{p}$ (4-15 GeV)




Experimental findings:

- $\pi^+ \approx \pi^-$ and $\pi^\pm \approx K^-$
- $K^+ > K^-$
- $p > \overline{p}$ and $p > \pi/K$

# $Kr$ Attenuation $vs$ $z$ with hadron ID

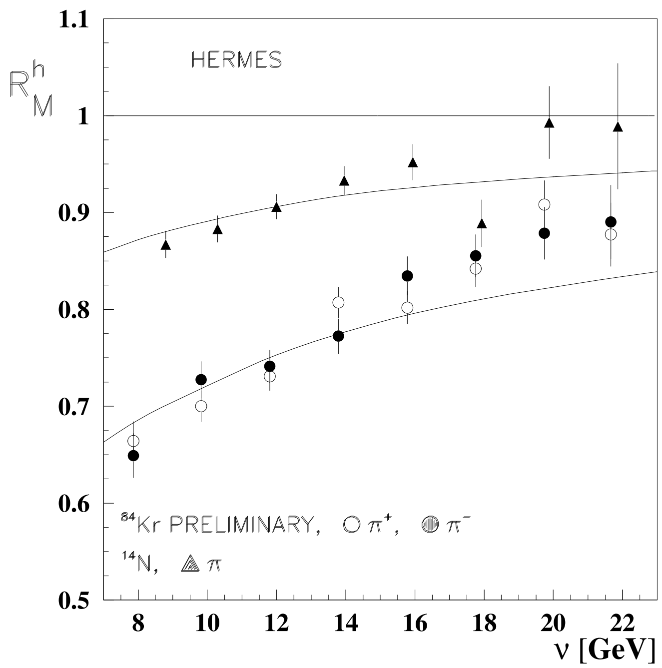


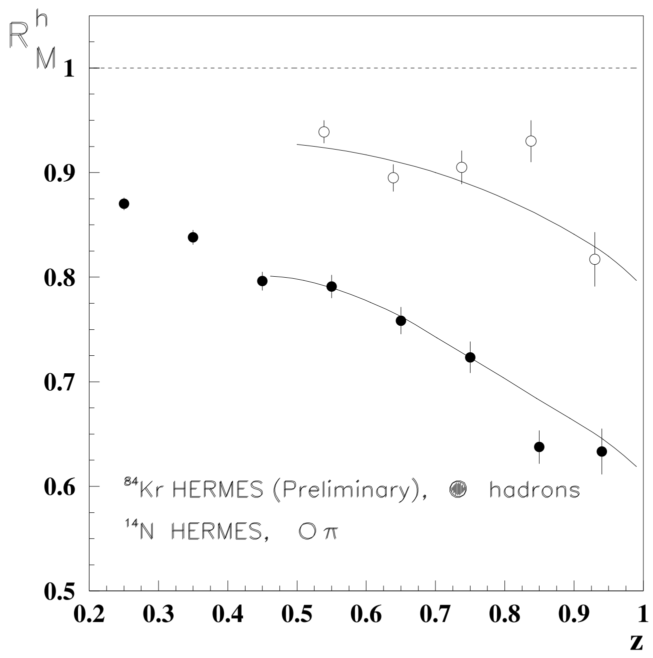

Possible contributions:

- different $D_q$ and $D_{\bar{q}}$ modification;
- different formation times for mesons and baryons;
- different hadronic cross sections:
  $\sigma_\pi^+ = \sigma_\pi^- \sim 20$ mb,
  $\sigma_k^+ \sim 17$ mb, $\sigma_k^- \sim 23$ mb,
  $\sigma_p \sim 40$ mb, $\sigma_{\bar{p}} \sim 60$ mb.

# Pion Attenuation $vs$ Gluon bremsstrahlung

Pion data are consistent with the gluon bremsstrahlung model which is a function of the Induced Radiation and Hadron Rescattering:




Comparison between the formation time of pions from HERMES and from the model:

- $c_h = 1.37 \pm 0.14$ [fm/GeV·c] (by exp fit)
- $c_h = 1.35$ (theory)

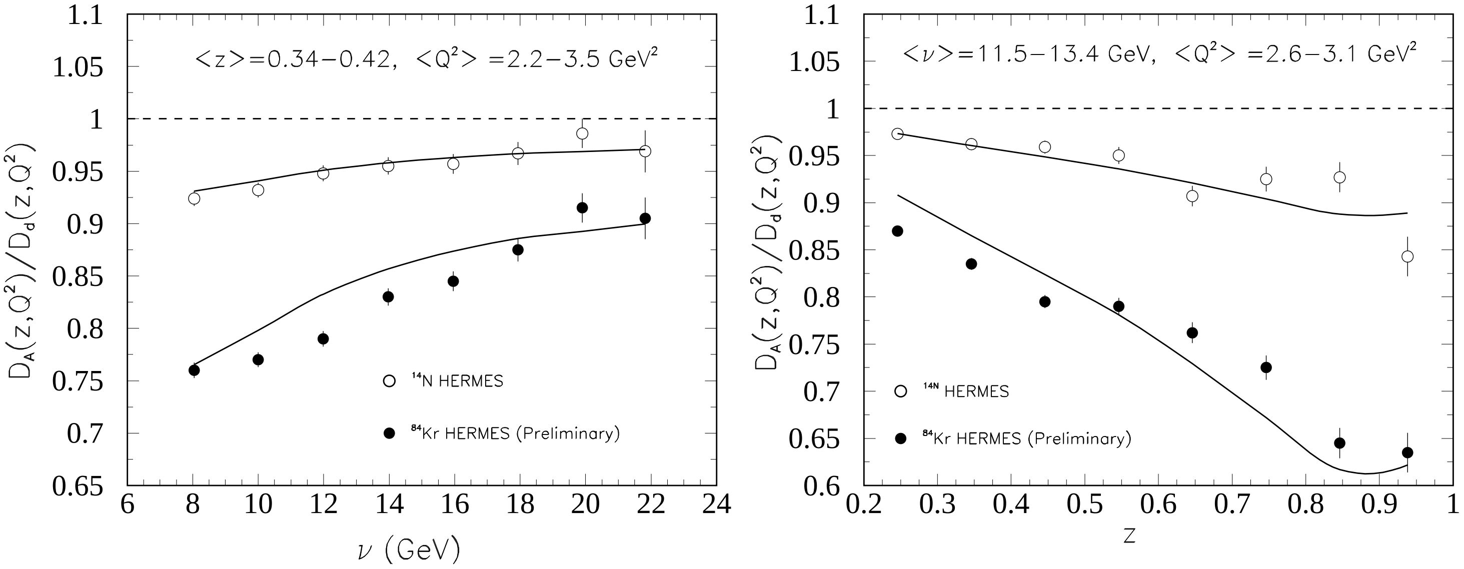
  e.g. considering typical values: $z$=0.6, $Q^2$=3 GeV$^2$, $\nu$=12 GeV $\Longrightarrow t_f^\pi \sim 6$ [fm/c]

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

# Hadron Attenuation *vs* FF modifications

(E.Wang, X.N.Wang, hep-ph/0202105)

Data are consistent with FF modification without hadron formation and re-scattering :




- Scaling law: $[R^{Kr}/R^N]_{exp} \approx 3.7 \Longleftrightarrow [A^{2/3}]_{th} = 3.3$
- only 1 free parameter $\tilde{C} \equiv$ quark gluon correlation strength inside nuclei;
- from $^{14}$N data $\tilde{C}\alpha_s^2 = 0.00065$ GeV$^2$;
- quark energy loss $\equiv$ energy of radiated gluons

$$\Delta E = \nu < \Delta z_g > \approx \tilde{C}\alpha_s^2 m_N R_A^2 (C_A/N_c) 3ln(1/2x_B)$$

$dE/dx \approx 0.3$ GeV/fm for HERMES Kr SIDIS data.

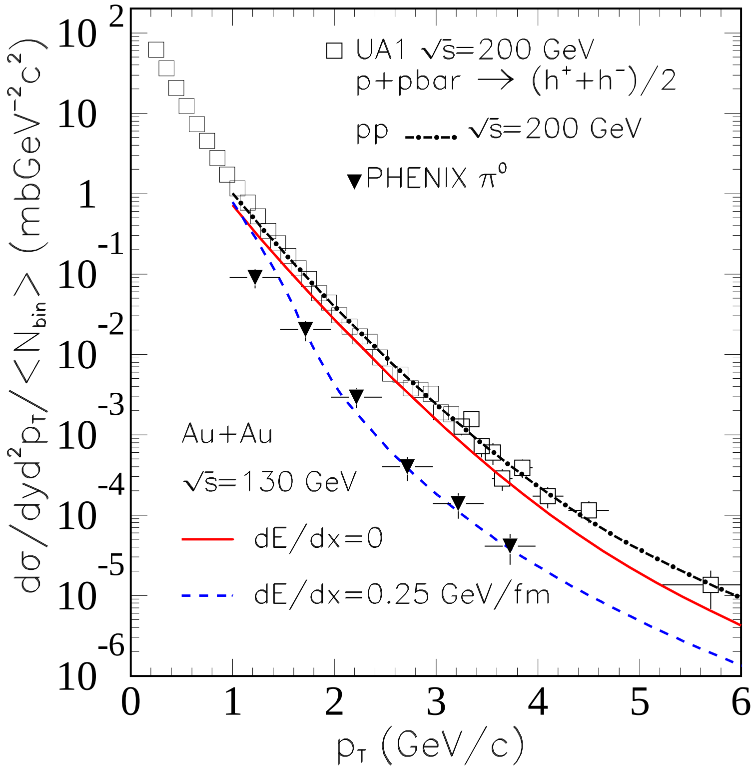
# Gluon density by dE/dx

(X.N.Wang, hep-ph/0111404, hep-ph/0202105)

Recent PHENIX data from RHIC showed strong suppression of hadron spectra.

$dE/dx_{PHENIX}|_{Au}$ prediction determined by using the $\tilde{C}\alpha_s^2 = 0.00065$ GeV$^2$ from the HERMES data.

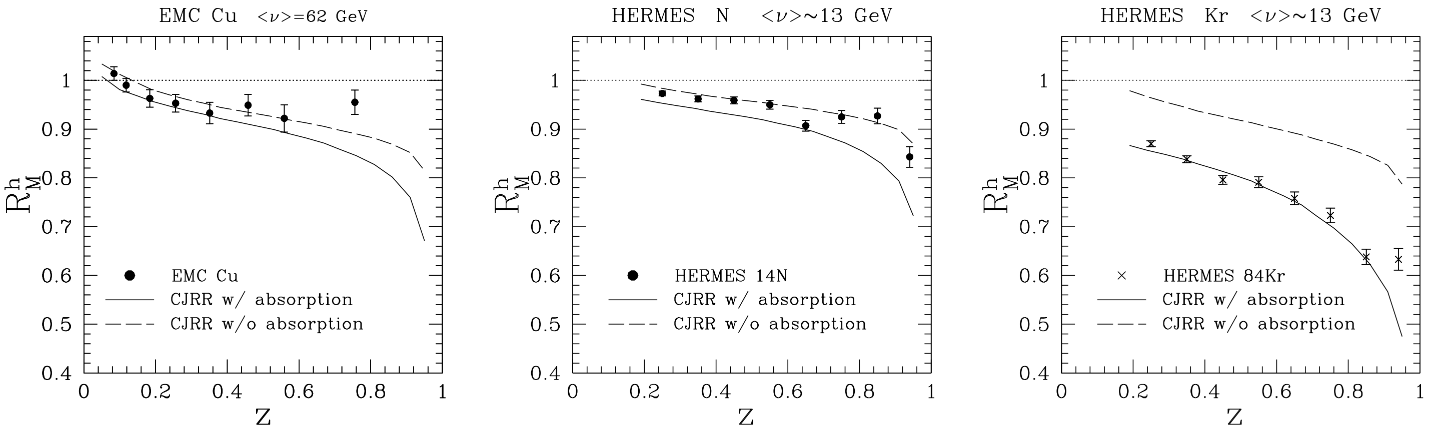
$$\tilde{D}(z) \approx \frac{1}{1-\Delta E/E} D\left(\frac{z}{1-\Delta E/E}\right)$$




- Clear agreement with data even if
  PHENIX : hot, dense, expanding system
  HERMES : cold, static system
- $\Delta E_{exp} \approx \Delta E_{sta}(2\tau_0/R_A)$ with $\tau_0 \sim 0.2$ fm initial formation time of the dense medium.

$\Longrightarrow$ gluon density in the initial hot stage of $Au + Au$ is $\sim 15$ times higher than in cold nuclear matter.

# Hadron Attenuation *vs* $Q^2$-rescaling




(GRV98 as PDF and Kretzer LO as FF)

- EMC $^{64}$Cu and HERMES $^{14}$N data are consistent with FF modification based on rescaling.
- HERMES $^{84}$Kr data need the inclusion of the hadron reinteraction:

  $\sigma_h = 20$ mb;

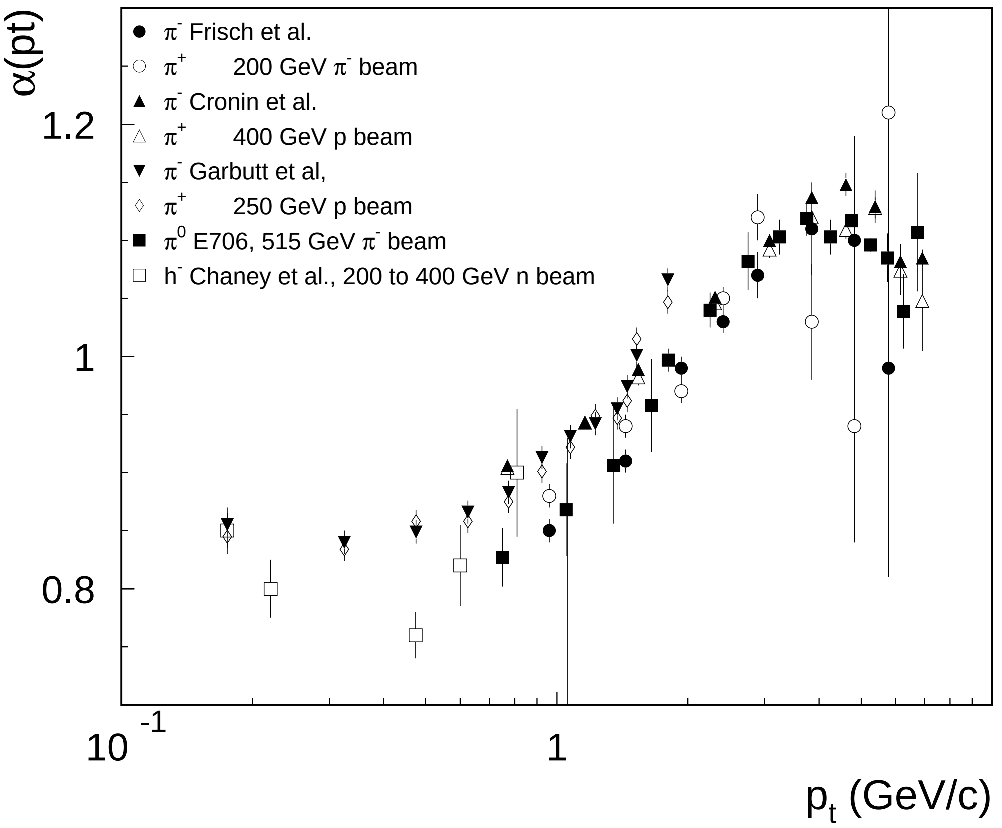
  $$\tau_F = \left(\frac{-\ln(z^2)-1+z^2}{1-z^2}\right)\frac{z\nu}{\kappa}$$

- Maximal deconfinement models (color conductivity) $\lambda_A = R_A$ are ruled out.

# Cronin effect in $pA$

Enhancement at high $p_t$ of particle produced in high-energy proton-nucleus collision ($pA$) relative to proton-proton ($pp$) one:

enhanced parameterization: $\sigma_{pA} = A^{\alpha(p_T)}\sigma_{pp}$




In $pA$ collisions the $p$ gains extra transverse momentum due to random soft collisions and the partons enter the final hard process with extra $k_T$:

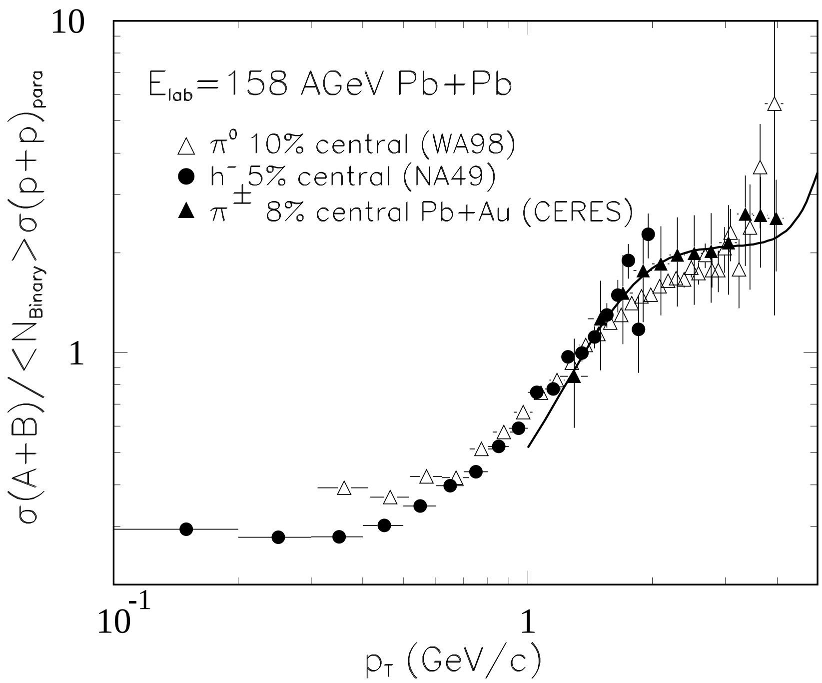
$$< {k_t}^2 >_{pA} = < {k_t}^2 >_{pp} + C h_{pA}(b)$$

$h_{pA}(b)$ is the number of effective nucleon-nucleon collisions.

# Cronin Effect in heavy ions

Enhancement at high $p_t$ of particle production in high-energy proton-nucleus heavy-ion collisions ($AA$) relative to proton-proton ($pp$).

Nuclear modification factor: $R_{AA} = \frac{d\sigma_{AA}/dyd^2p_T}{<N_{binary}>d\sigma_{pp}/dyd^2p_T}$



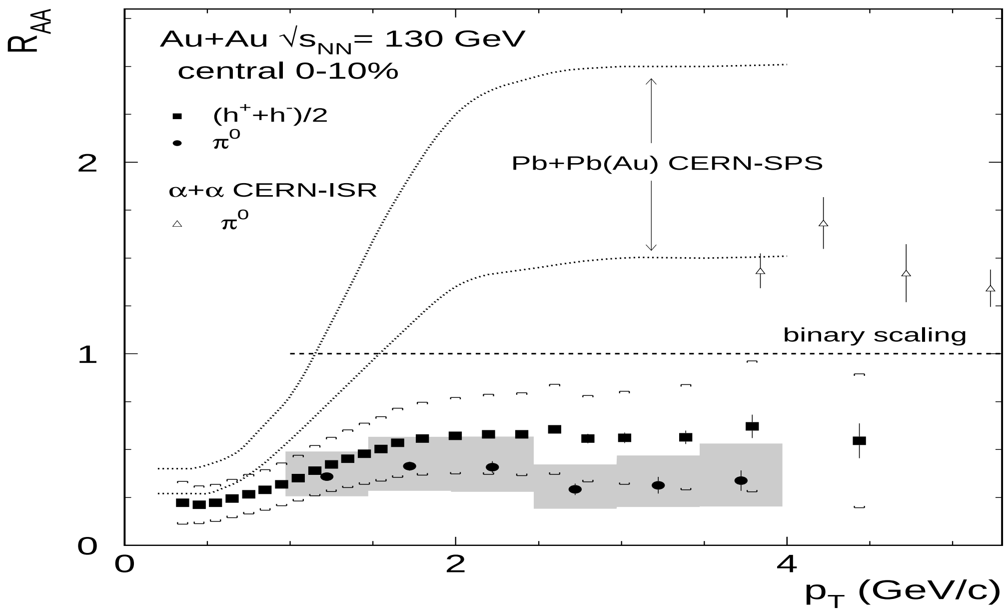

- The spectra are enhanced at large $p_t$ by multiple hard scattering.

  The hard component of incoherent parton scattering becomes dominant at $p_t \sim$ 1-2 GeV (transition region).

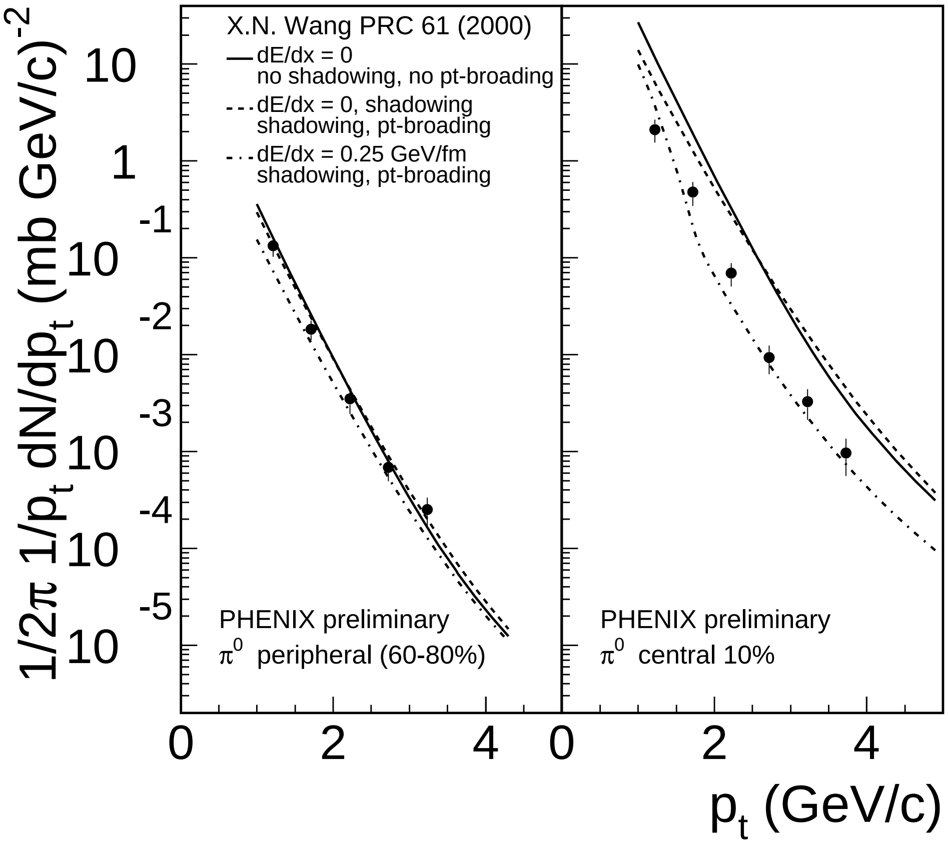
- Good description by a multiple parton scattering model (E.Wang, X.N.Wang, Phys.Rev. C64(2001) 034901) within the Glauber formalism.

# Results from RHIC

(PHENIX, PRL 88 (2002) 022301)



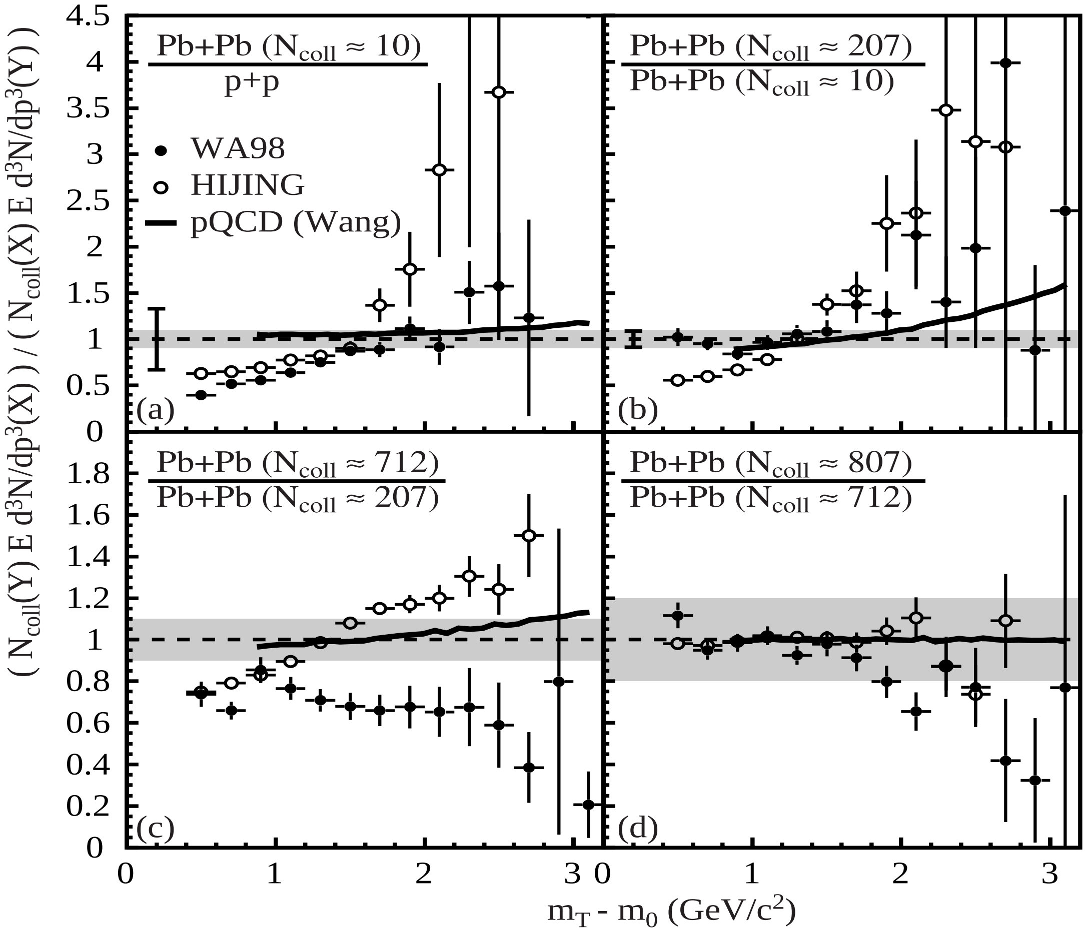

- In central collisions a depletion of high $p_t$ hadrons has been observed.




- The central data are significantly below the calculations when the energy loss and the $p_t$-broadening are not included.

# Results from WA98

(WA98, EPJ C23 (2002) 225)




- Peripheral ⇒ Medium-Central collisions: enhancement increases.
- Medium-Central ⇒ Central collisions: inverse trend.

This might be possible only if both the initial and the final state scattering are relevant (Cronin + medium suppression).

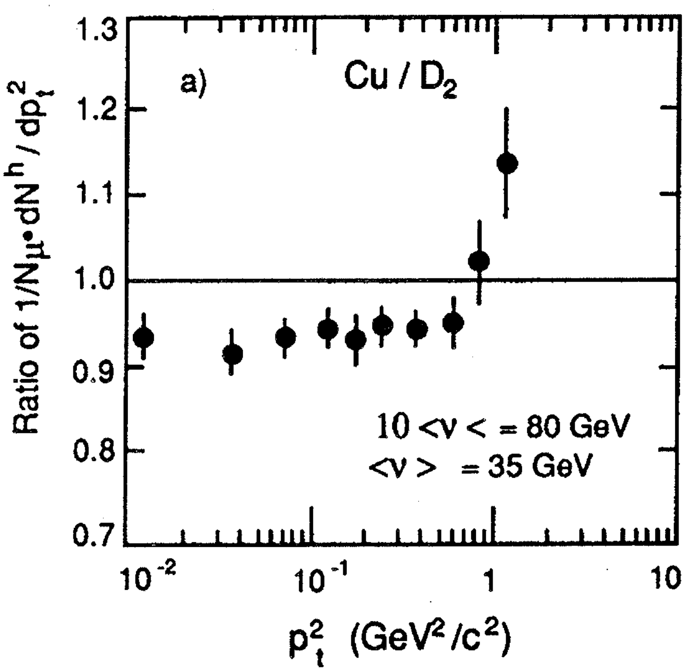
# Attenuation $vs$ $p_t^2$ (Cronin Effect)

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

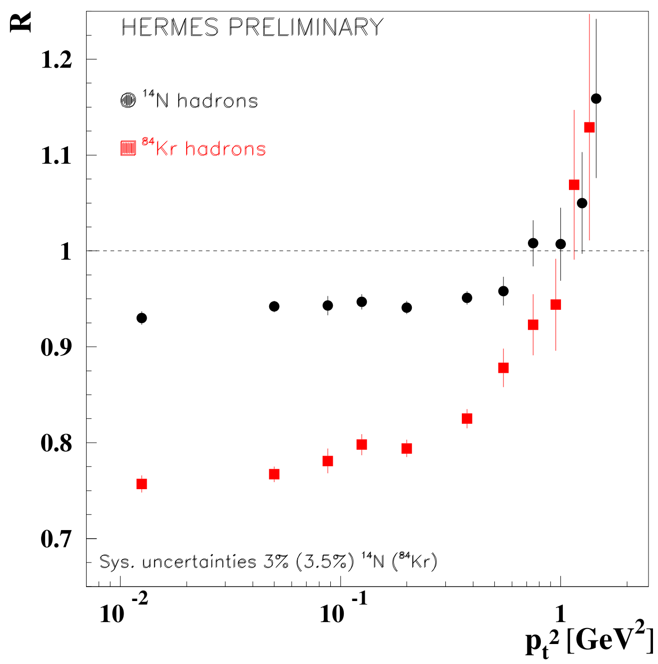
$\Downarrow$

Clean and reliable informations on quark transport in 'cold' nuclear matter.

EMC




HERMES




- The data show a $p_t$ enhancement similar to that observed in hadron-nucleus scattering (Cronin effect).
- The hard component of incoherent parton scattering becomes dominant at $p_t \sim$ 1-2 GeV.

# $p_t$-broadening in SIDIS

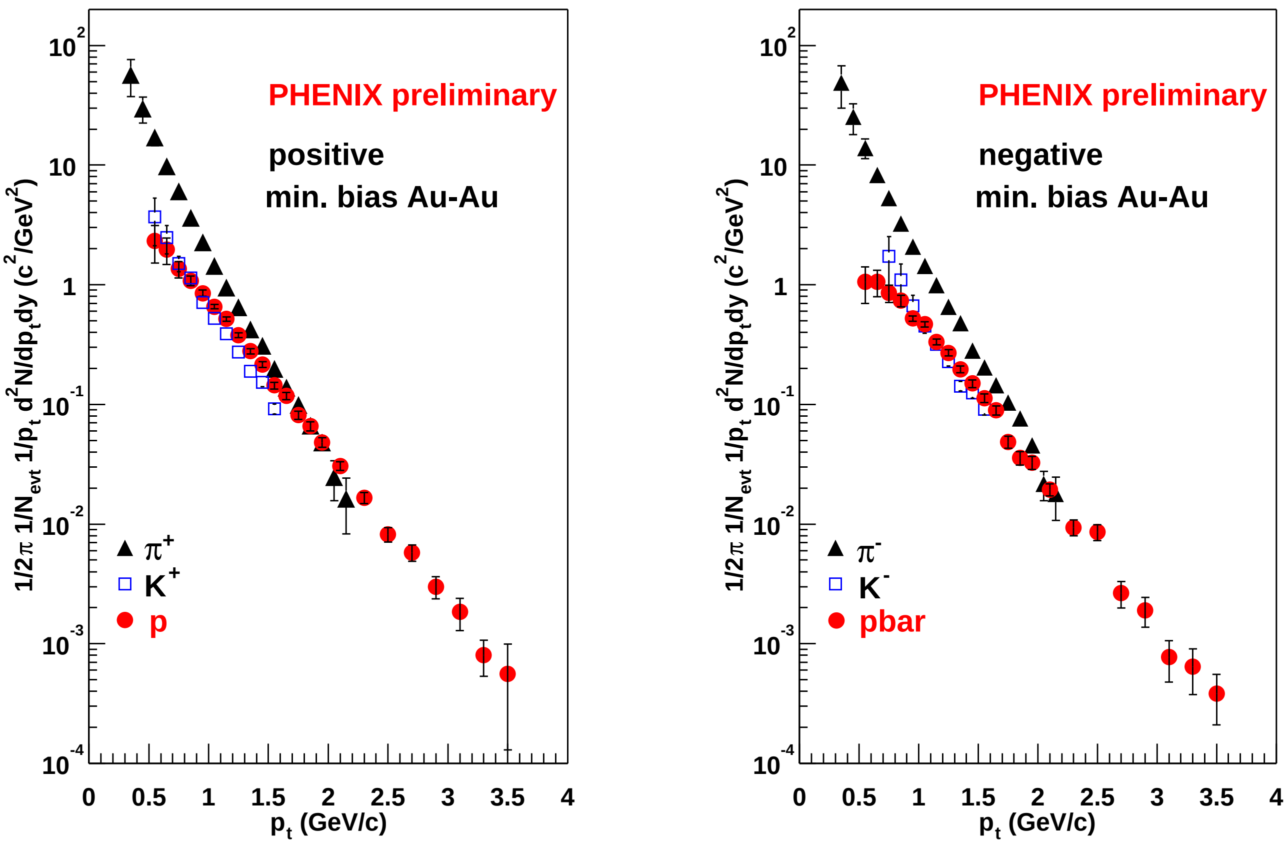
Direct measurement of multiparton correlation functions is a test for QCD factorization theorem:

- $< p_t >$ broadening depends on multiparton correlation function and to the nuclear size $\sim A^{1/3}$:

$$\Delta < p_t^2 >^{eA-eN} \propto \frac{\sum e_q^2 \int_{z_{min}}^1 dz z^2 D(z) T_{qF}^A(x, Q^2)}{\sum e_q^2 q^A(x, Q^2)}$$

- HERMES data, on 5 nuclei, will provide infos on the mass (flavor) dependence of $< p_t >$ .

  RHIC: different $< p_t >$ for pions, kaons, protons and antiprotons:



# Conclusions & Outlook

- Significant nuclear attenuation, in a new region of the kinematic plane, for $^{14}$N and $^{84}$Kr.
- First observation of a dependence of the nuclear attenuation on the hadron type.
- The Cronin effect has been observed: the transition between hard and soft processes occurs at $p_t \simeq 1$ GeV.

Near Future:

- $p_t$-broadening for $\pi$, $K$, $p$ and $\bar{p}$
- Already collected data on: $^4$He, $^{20}$Ne, ...
will provide new insights on the $A$ dependence.

The HERMES measurements are providing information on:

- Nuclear modification of Quark Fragmentation Functions.
- Hadronization times.
- Partonic energy loss and Cronin effect.

All together give unambiguous informations on quark transport in cold nuclear matter