Electroproduction of hadrons in nuclei

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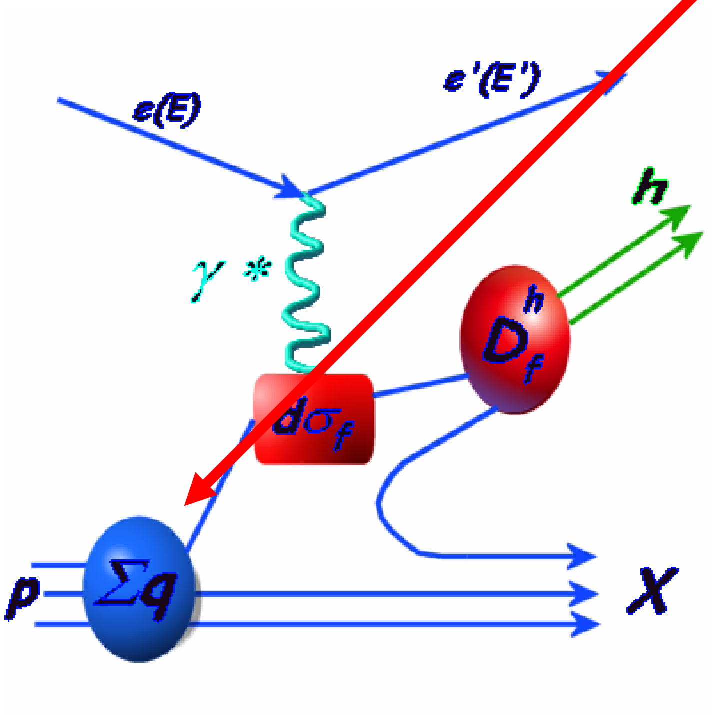
- Fragmentation Function modifications in the nuclear medium
- HERMES recent and new results
- Expectations from CLAS
- Interpretations

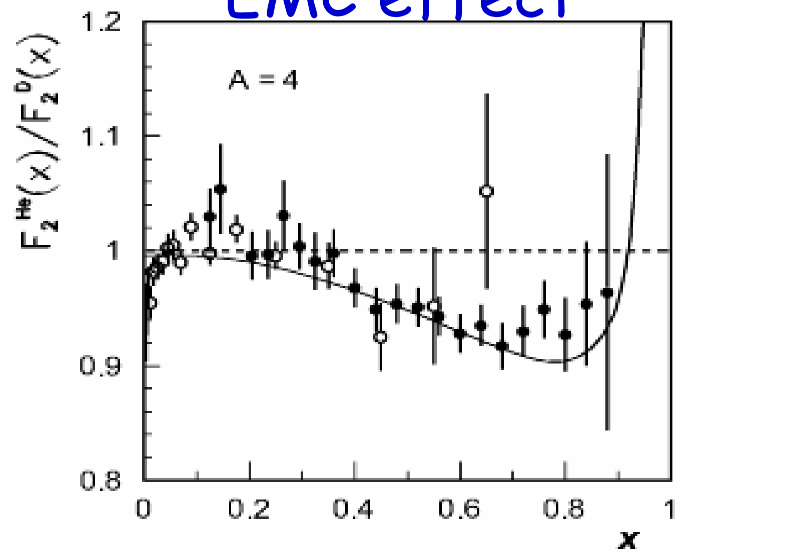
Workshop on In-Medium Hadron Physics. Giessen, 11-13 November 2004

DF on Nucleon & Nuclear Medium

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



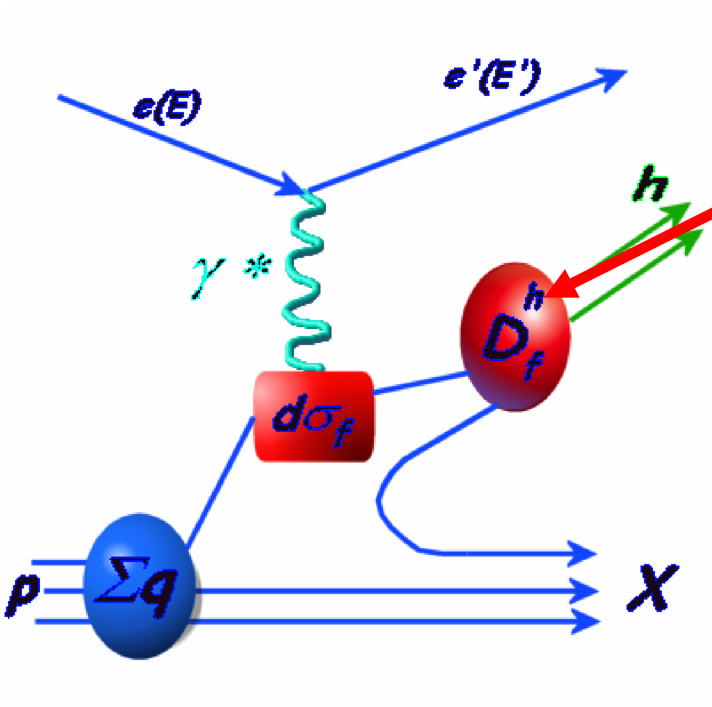
Inclusive DIS on nuclei:
EMC effect



Medium modifications of Distribution Functions :
interpretation at both hadronic (nucleon's binding, Fermi motion, pions) and partonic levels (rescaling, multi-quark system)

Fragmentation Functions on Nucleon

$$d\sigma^{h}(z) \propto \sum_f q_f(x) \otimes d\sigma_f \otimes D_f^h(z)$$



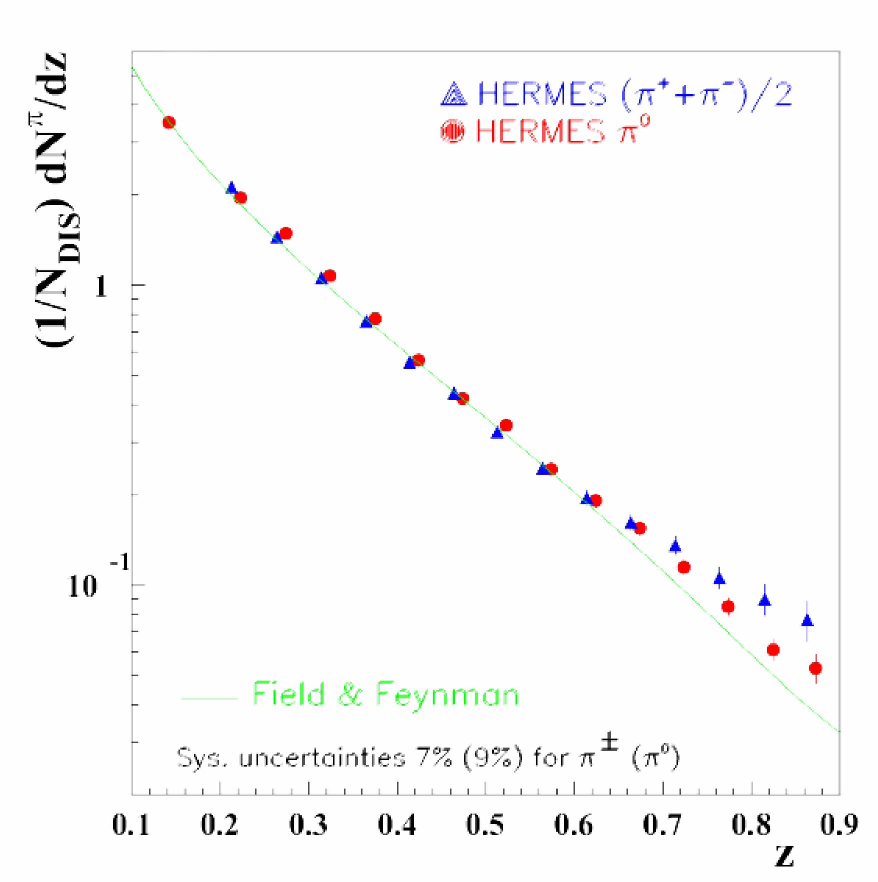
FFs are measured with precision in e+e-
FFs follow pQCD Q^2-evolution like DFs
FFs scale with $z=E_h/\nu$ like DFs with x
FFs probabilistic interpretation like DFs

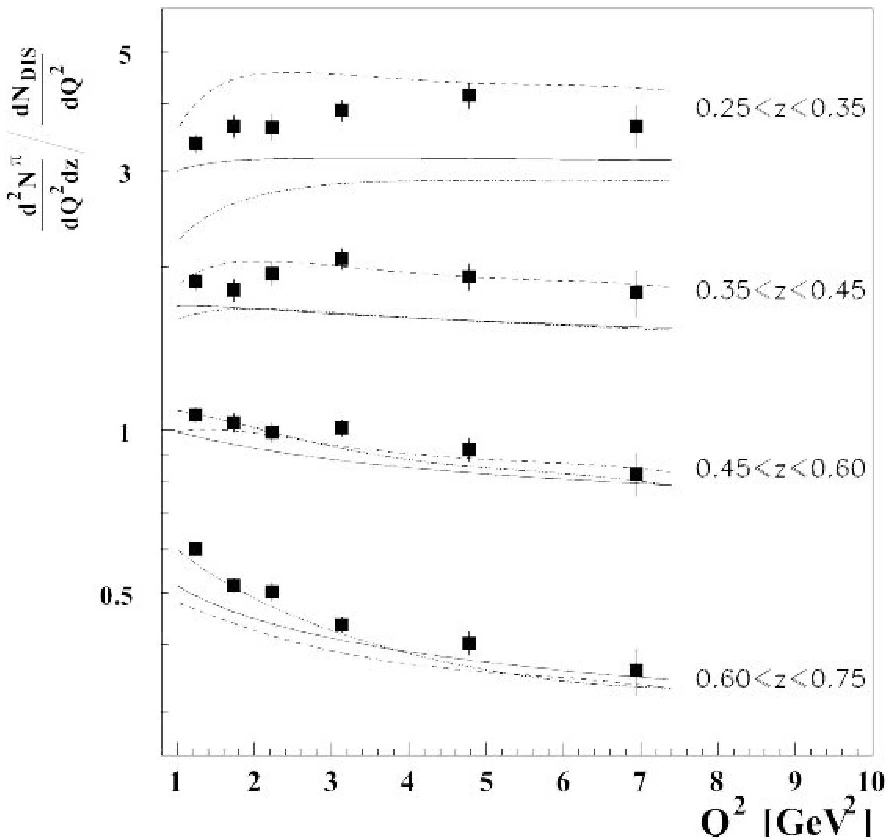
SIDIS multiplicities are also good measurements of FFs:

$$\frac{1}{N_{DIS}} \frac{dN^h(x,z)}{dz} = \frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}$$

SIDIS multiplicities on Nucleon

(HERMES: EPJ C21(2001) 599).

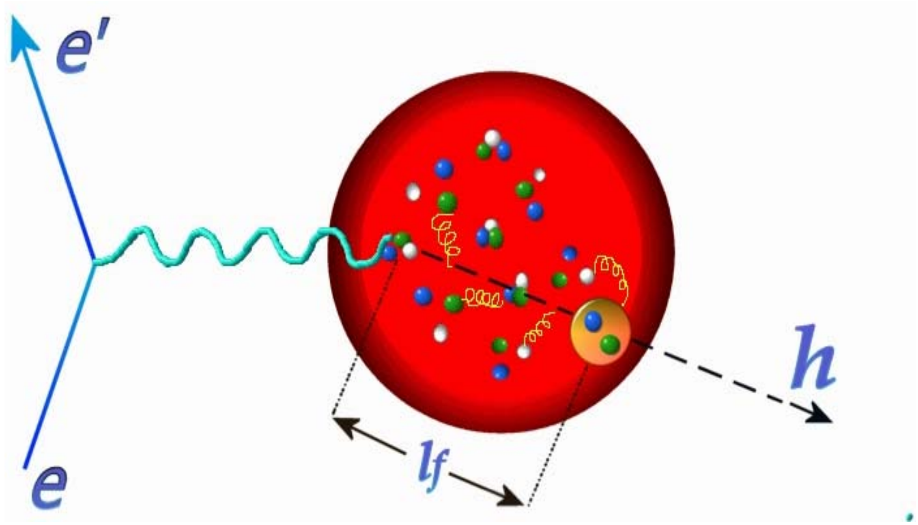




What happens in a nuclear medium ?

Nuclear Attenuation

Observation: reduction of multiplicity of fast hadrons due to both *hard partonic* and *soft hadron interaction.*



Production and Formation Times + FF modifications are crucial for the understanding of the space-time evolution of the hadron formation process

Hadron multiplicity ratio

Experimental observable: hadron multiplicity ratio in nuclei and deuterium

$$R_M(z,\nu) = \frac{\dfrac{N_h(z,\nu)}{N_{DIS}}}{\dfrac{N_h(z,\nu)}{N_{DIS}}} = \frac{\left.\dfrac{1}{\sigma_{DIS}}\dfrac{d^2\sigma_h}{dzd\nu}\right|_A}{\left.\dfrac{1}{\sigma_{DIS}}\dfrac{d^2\sigma_h}{dzd\nu}\right|_D} = \frac{\left.\dfrac{\Sigma e_f^2 q_f(x) D_f^h(z)}{\Sigma e_f^2 q_f(x)}\right|_A}{\left.\dfrac{\Sigma e_f^2 q_f(x) D_f^h(z)}{\Sigma e_f^2 q_f(x)}\right|_D}$$

Determine R_M versus:

Leptonic variables : ν (or x) and Q^2

Hadronic variables : z and P_t^2

Different nuclei : size and density

Different hadrons : flavors and mixing of FFs

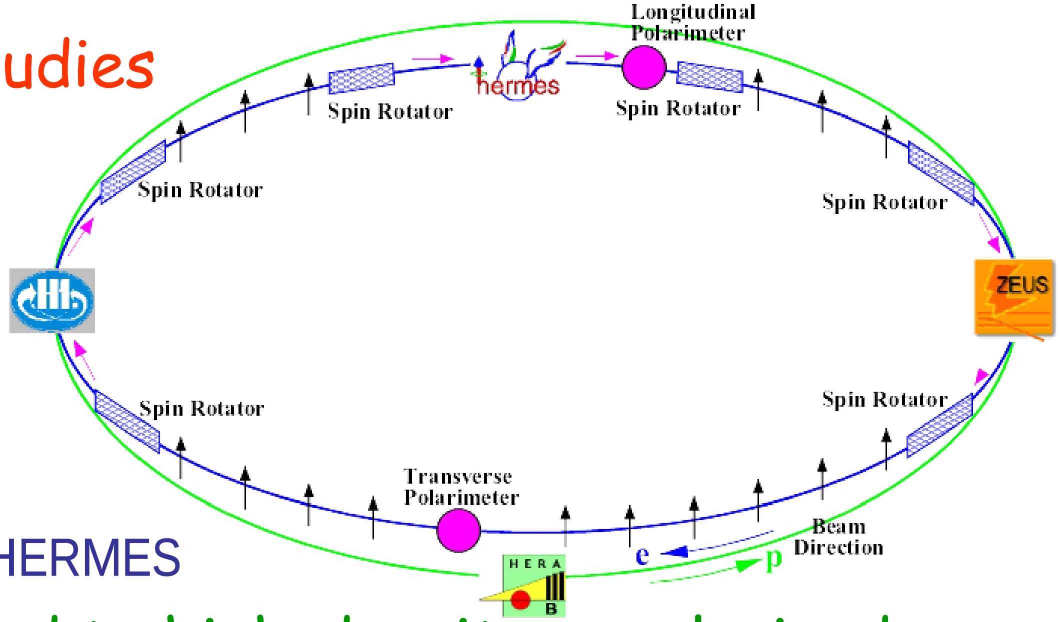
Experiments

- SLAC: 20 GeV e^--beam on Be, C, Cu Sn PRL 40 (1978) 1624
- EMC: 100-200 GeV μ-beam on Cu Z.Phys. C52 (1991) 1.
- WA21/59: 4-64 GeV $\nu(\bar{\nu})$-beam on Ne Z.Phys. C70 (1996) 47.
- HERMES: 27.6 or 12 GeV e^+-beam on He, N, Ne, Kr, Xe.
  EPJ C20 (2001) 479. PLB 577 (2003) 37.
  http://www-hermes.desy.de/notes/pub/trans-public-subject.html#HADRON-ATTENUATION
- CLAS: 5.4 GeV e^--beam on C, Fe, Pb
  E-02-104

- The energy range (ν 3-25 GeV) is well suited to study medium effects.
- Measurements over the full z range
- Possibility to use several different gas targets
- PId: π^+, π^-, π^0, K^+, K^-, p, $\bar{p}$

HERMES @ HERA

It is an experiment which studies the spin structure of the nucleon and not only …

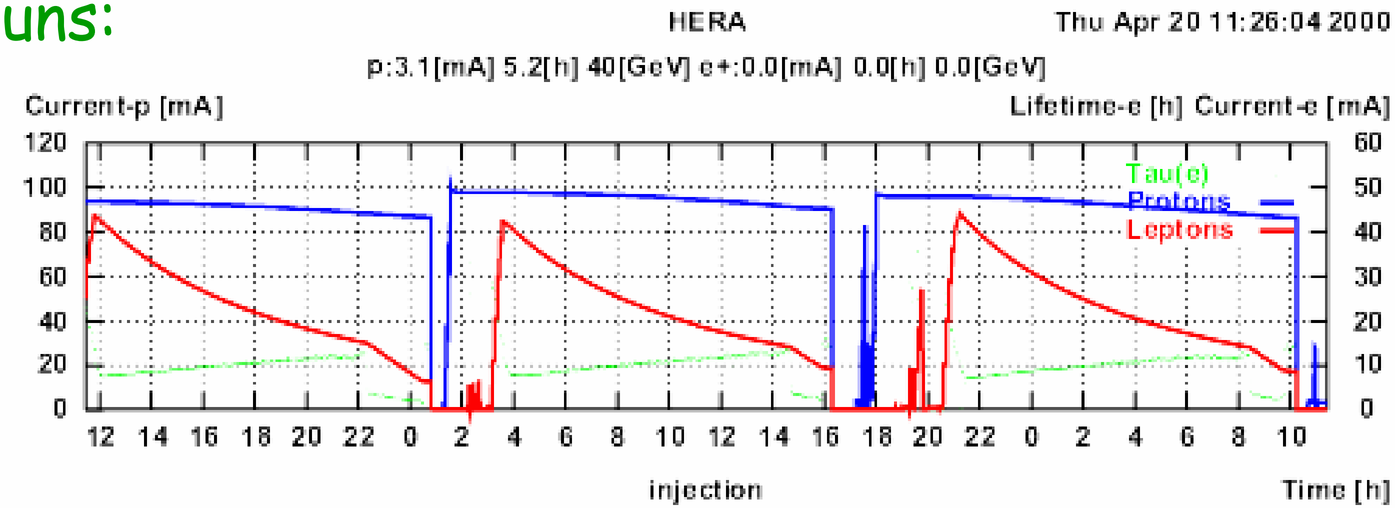


E=27.5 12 GeV e^+ (e^-)

I ~ 30 mA

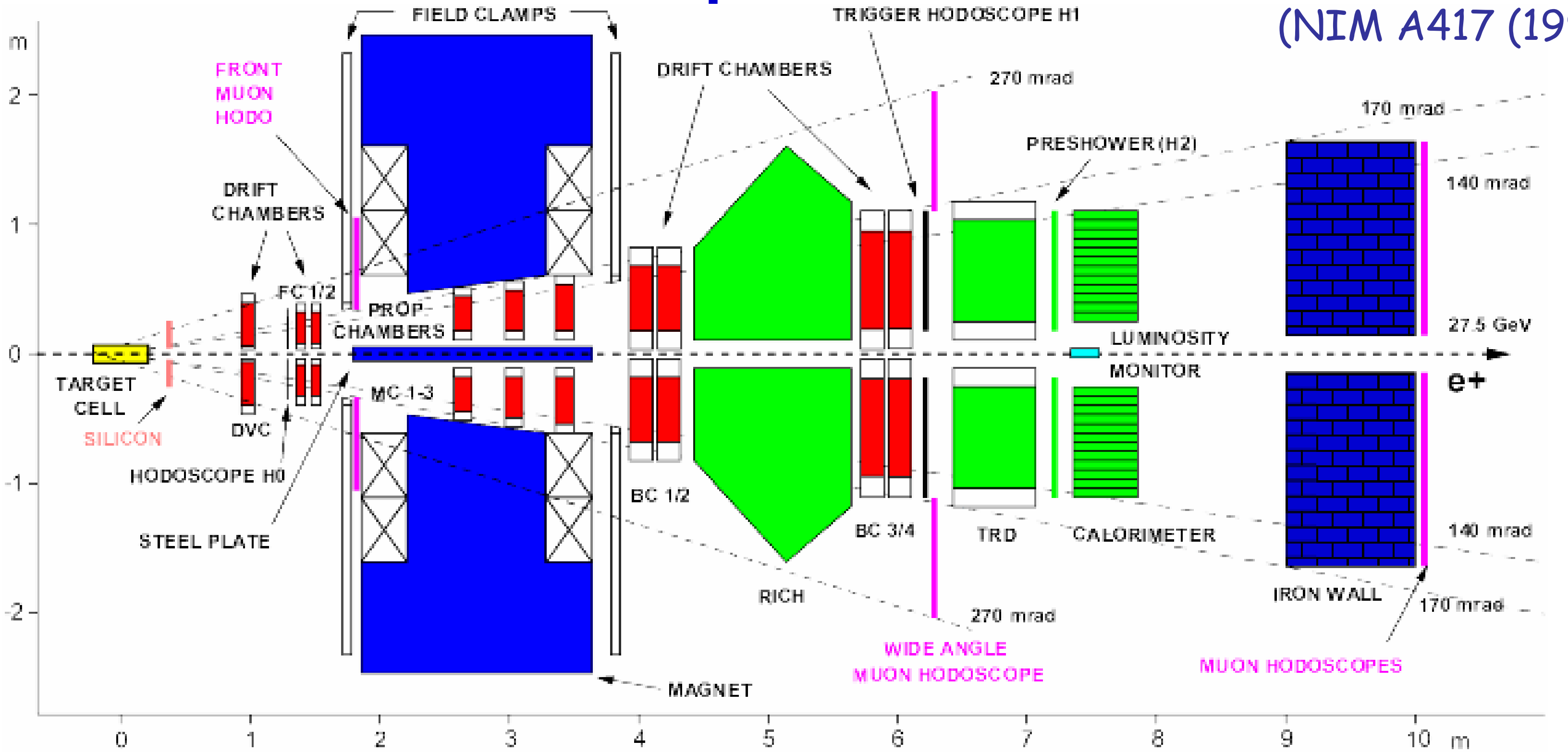
p beam of 920 GeV, not used by HERMES

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



The Spectrometer

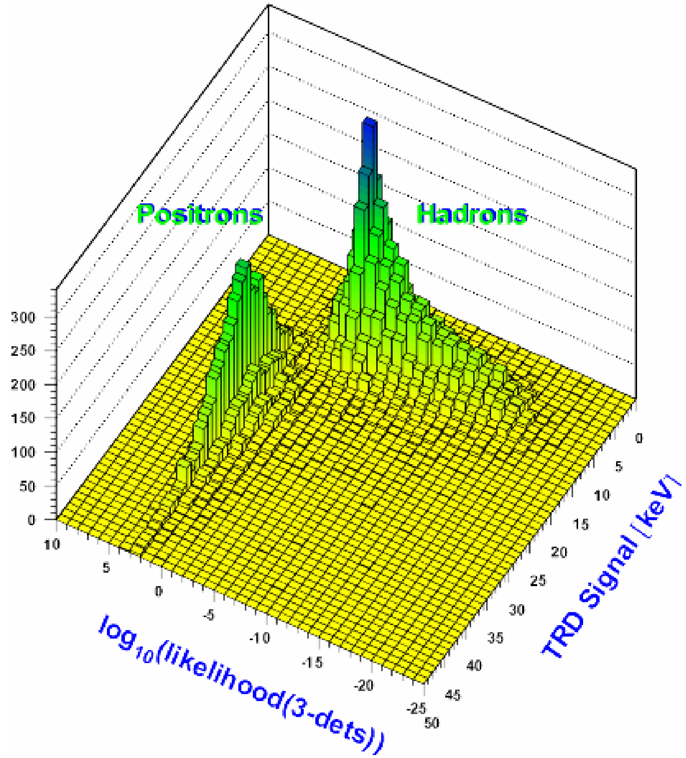
(NIM A417 (1998) 230)

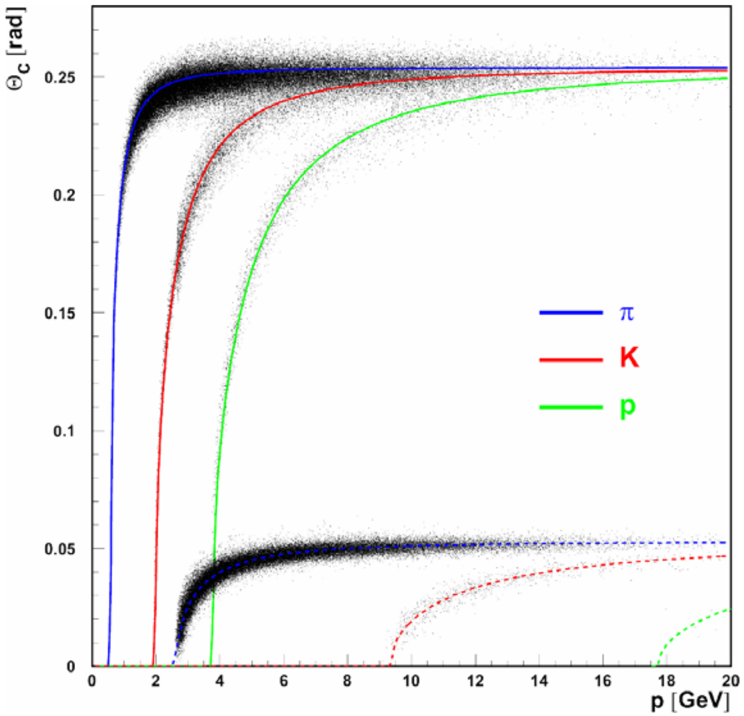


- e+ identification: 99% efficiency and < 1% of contamination
- PID: RICH, TRD, Preshower, e.m. Calorimeter
- For N target: by Cerenkov π ID 4<p<14 GeV
- For He, Ne, Kr targets: by RICH π, K, p ID 2.5<p<15 GeV
- π^0 ID by e.m. Calorimeter.

Particle Identification

Positrons – hadrons separation:

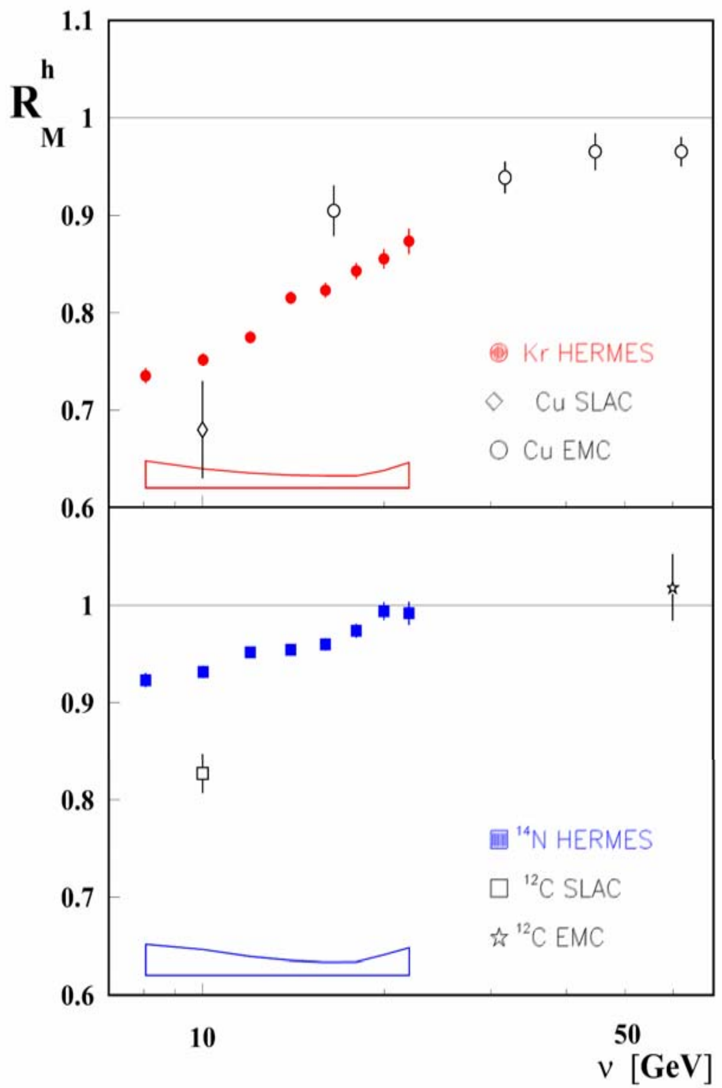




Double radiator RICH: Aerogel + C_4F_{10}. Cerenkov photons detected by ~4000 PMTs.

Detection efficiency: 99% (π), 90% (K), 85-95% (p)

Hadron multiplicity ratio vs transfer energy ν

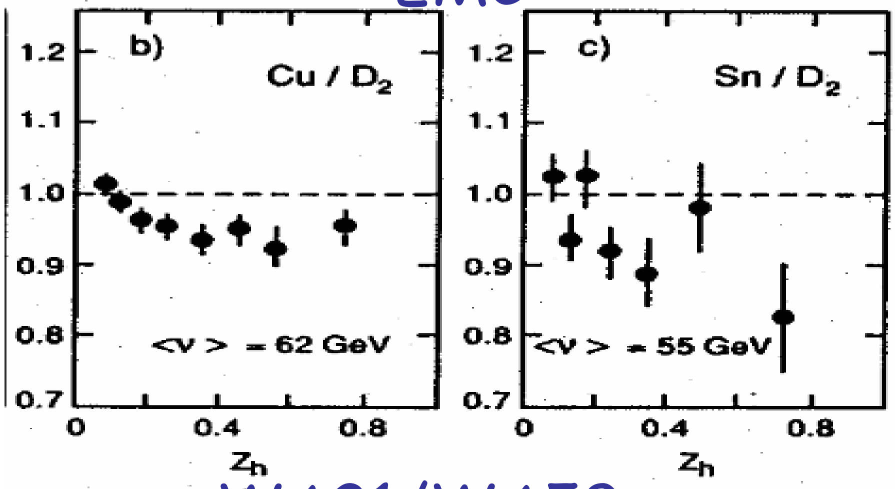


HERMES, PLB 577 (2003) 37
EMC Coll. Z.Phys. C52 (1991) 1.
SLAC PRL 40 (1978) 1624

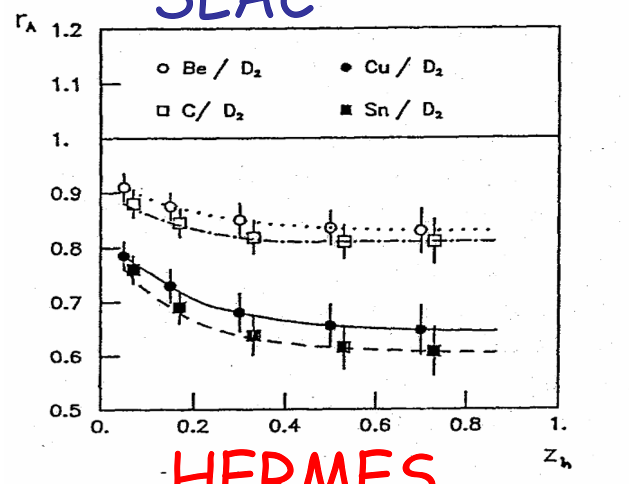
- Clear nuclear attenuation effect for charged hadrons.
- Increase with ν consistent with EMC data at higher energy
- Discrepancy with SLAC due to the *EMC effect,* not taken into account at that time
- HERMES kinematics is well suited to study quark propagation and hadronization

Hadron Multiplicity Ratio vs $z=E_h/\nu$

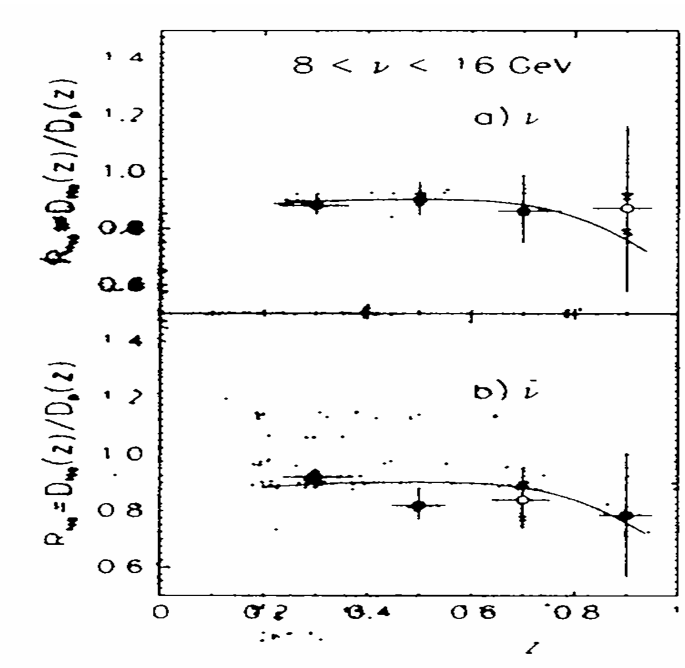
EMC



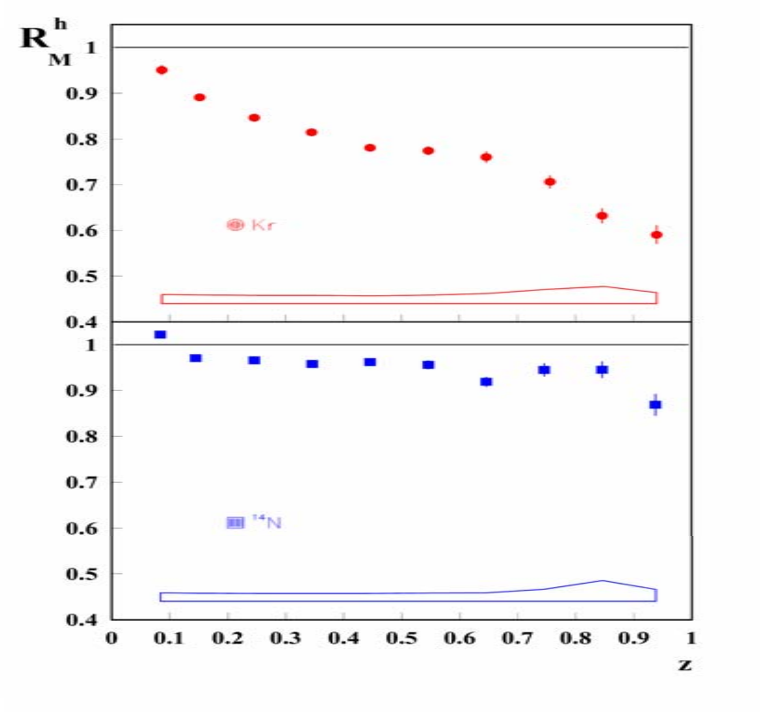
SLAC



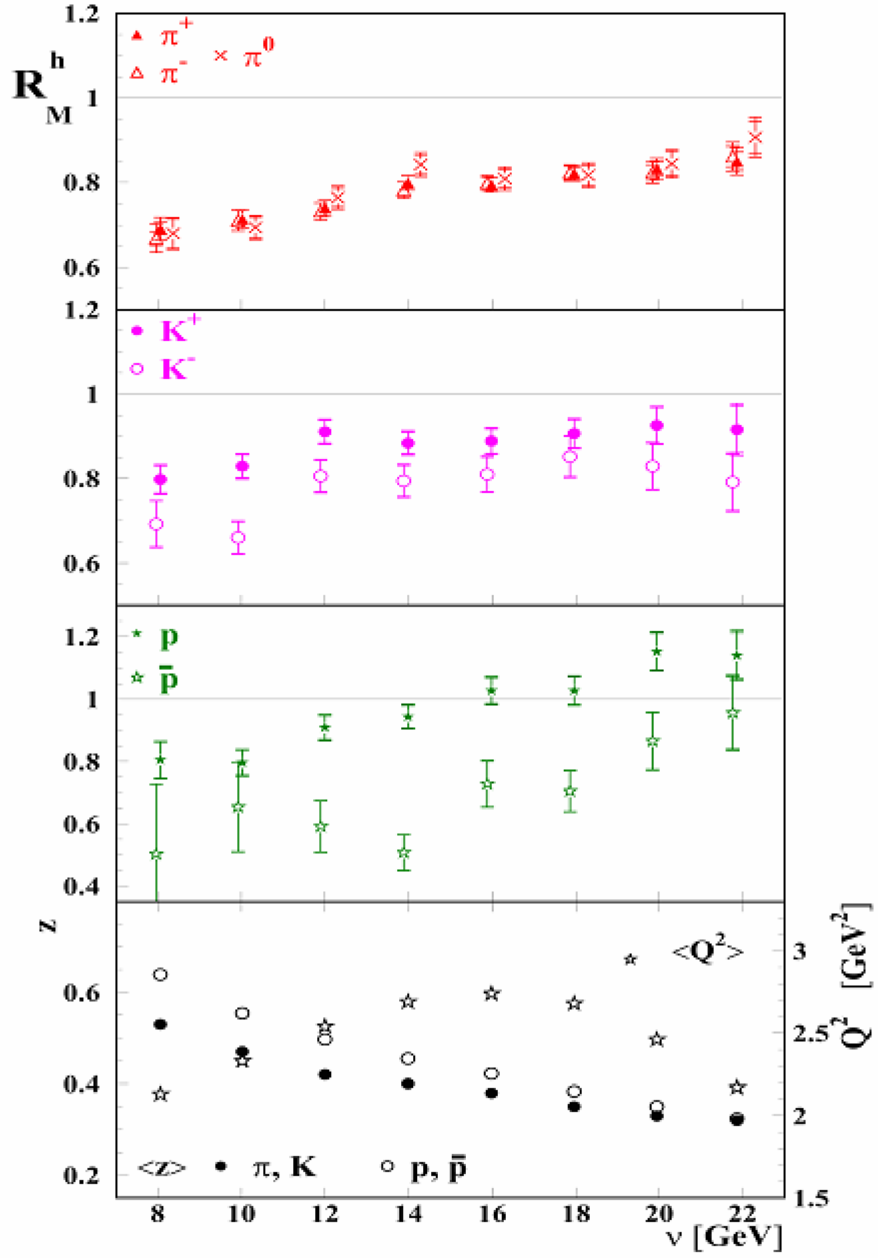
WA21/WA59



HERMES



Multiplicity ratio for identified hadrons vs ν



HERMES, PLB 577 (2003) 37

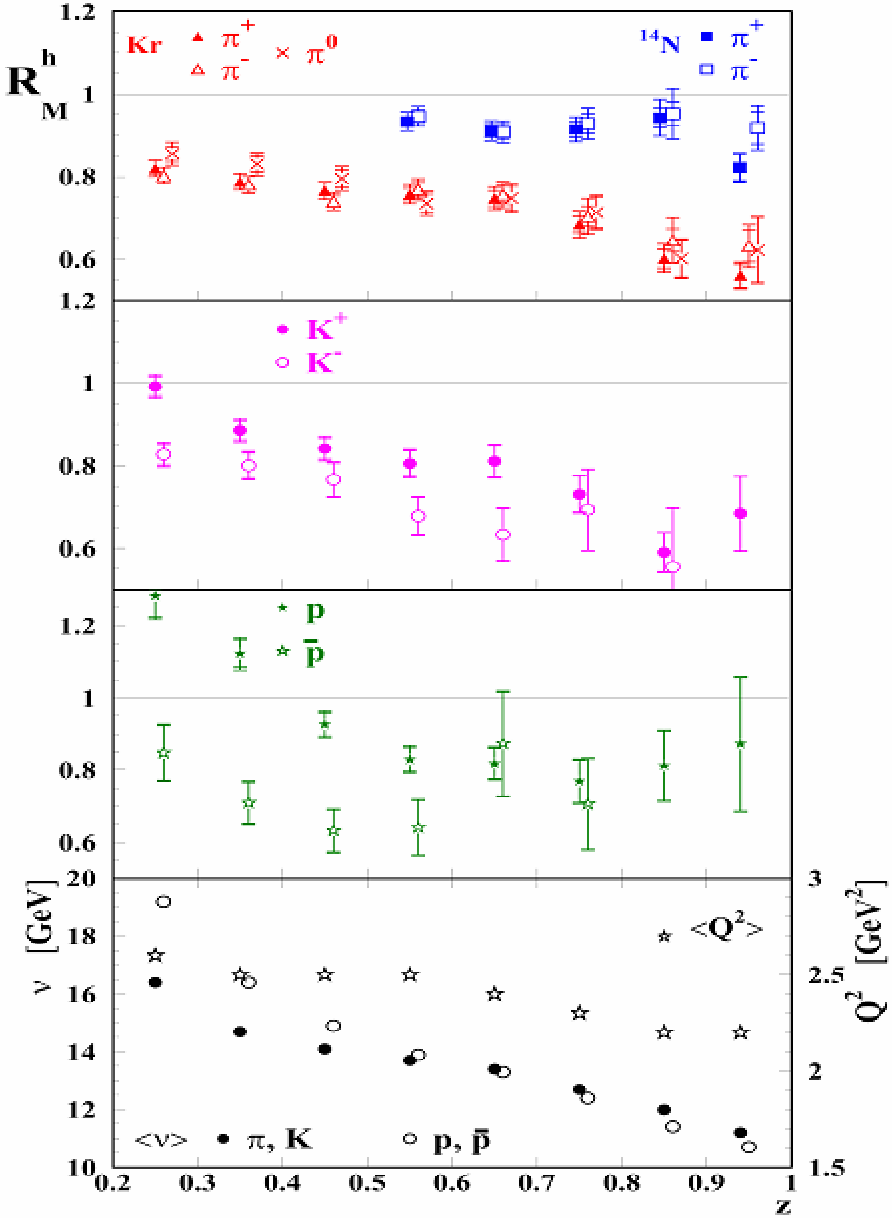
<u>Experimental findings</u>:

$\pi^+ = \pi^- = \pi^0 \sim K^-$

$K^+ > K^-$

$p > \bar{p}$, $p > \pi$, $p > K$

Multiplicity ratio for identified hadrons vs z



HERMES, PLB 577 (2003) 37

Different FF modification for *quark* and *anti-quark*

Different τ_p and τ_h for mesons and baryons

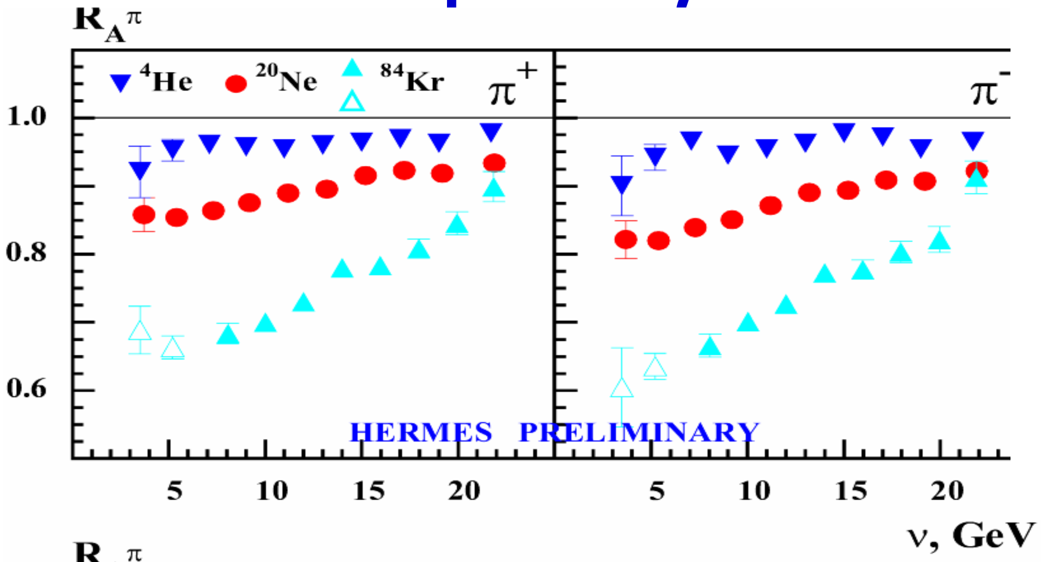
Different σ_h:

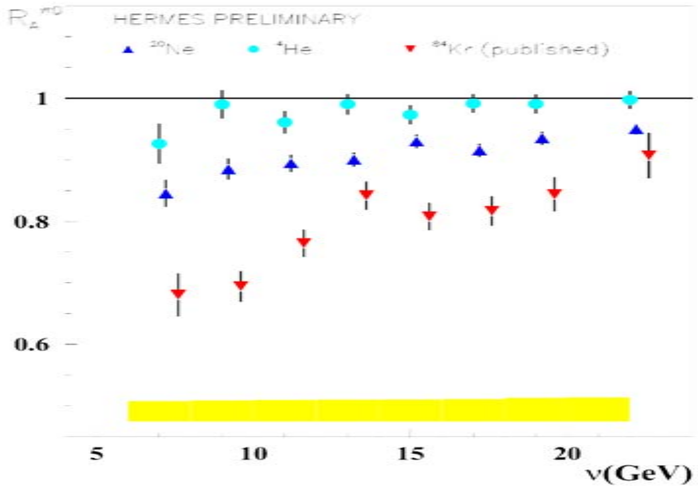
$\sigma_{\pi+} = \sigma_{\pi-} \approx 20$ mb

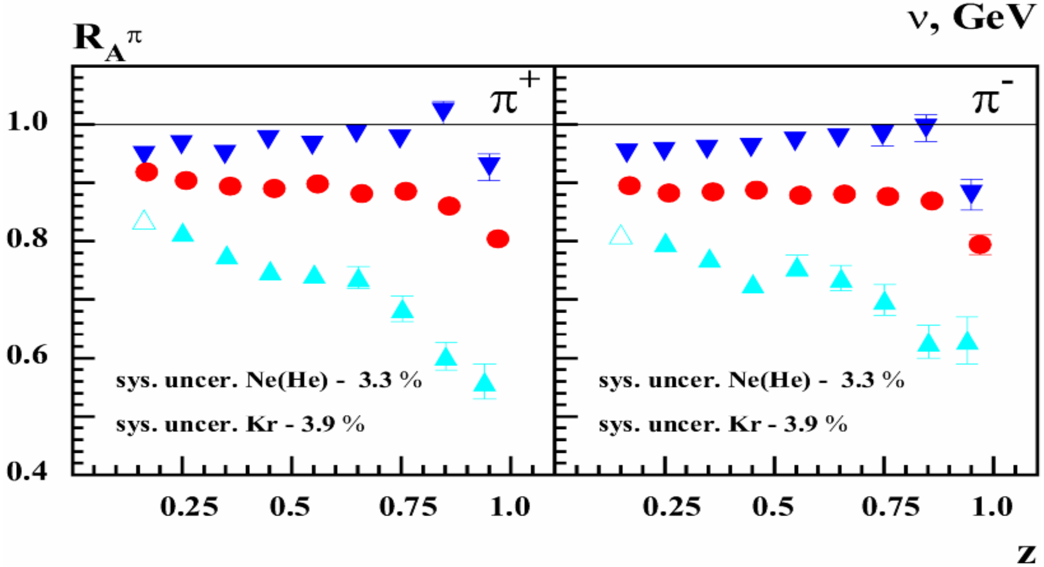
$\sigma_{K+} \approx 17$ mb, $\sigma_{K-} \approx 23$ mb

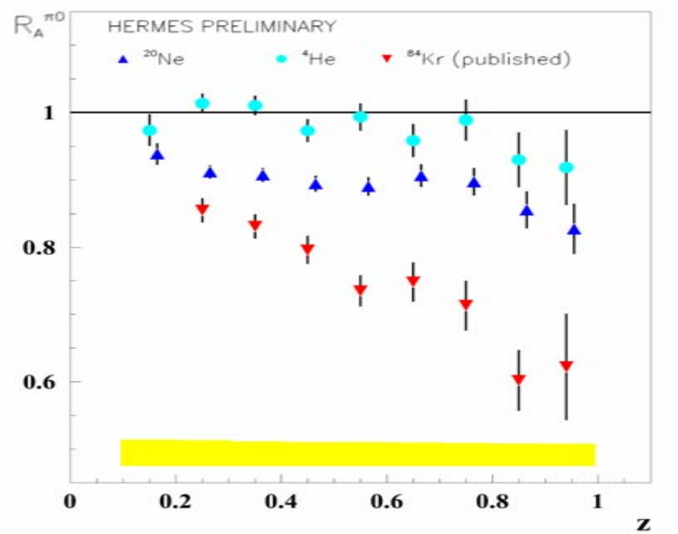
$\sigma_p \approx 40$ mb, $\sigma_{p-} \approx 60$ mb

Multiplicity ratio on He, Ne, Kr





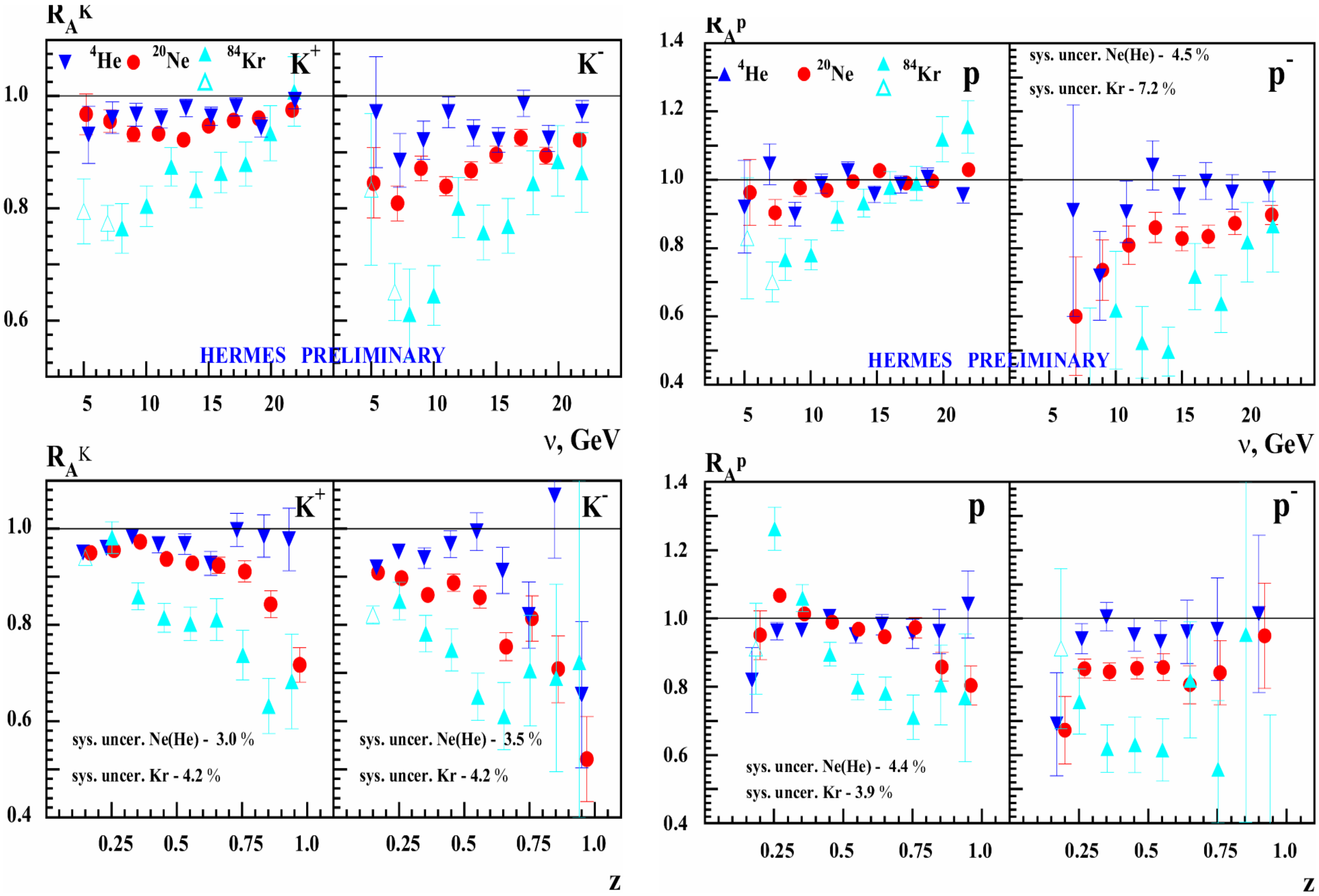




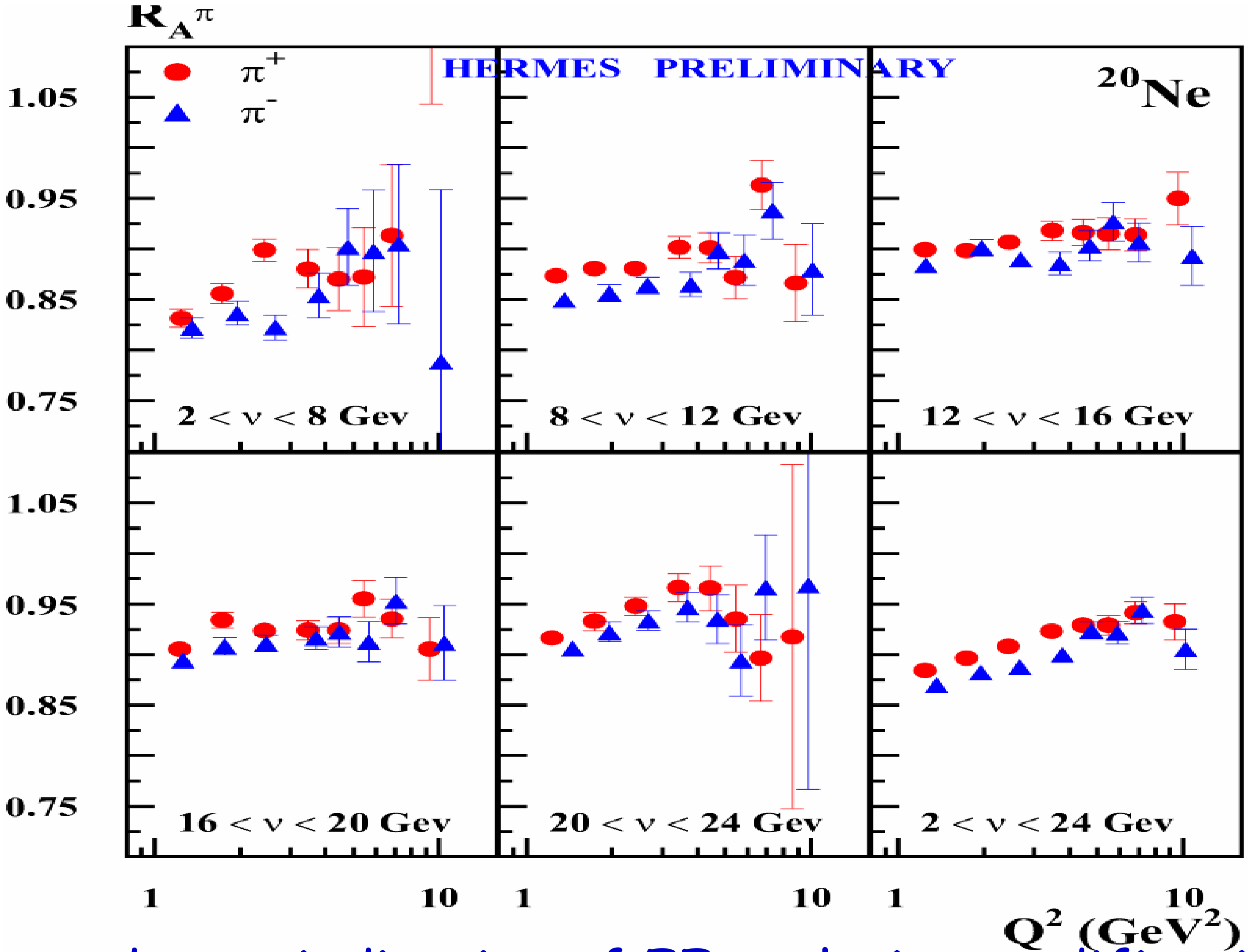
nuclear attenuation: $1-R^h = A^\alpha$

Data suggest α~2/3

Multiplicity ratio on He, Ne, Kr



Multiplicity ratio vs Q^2

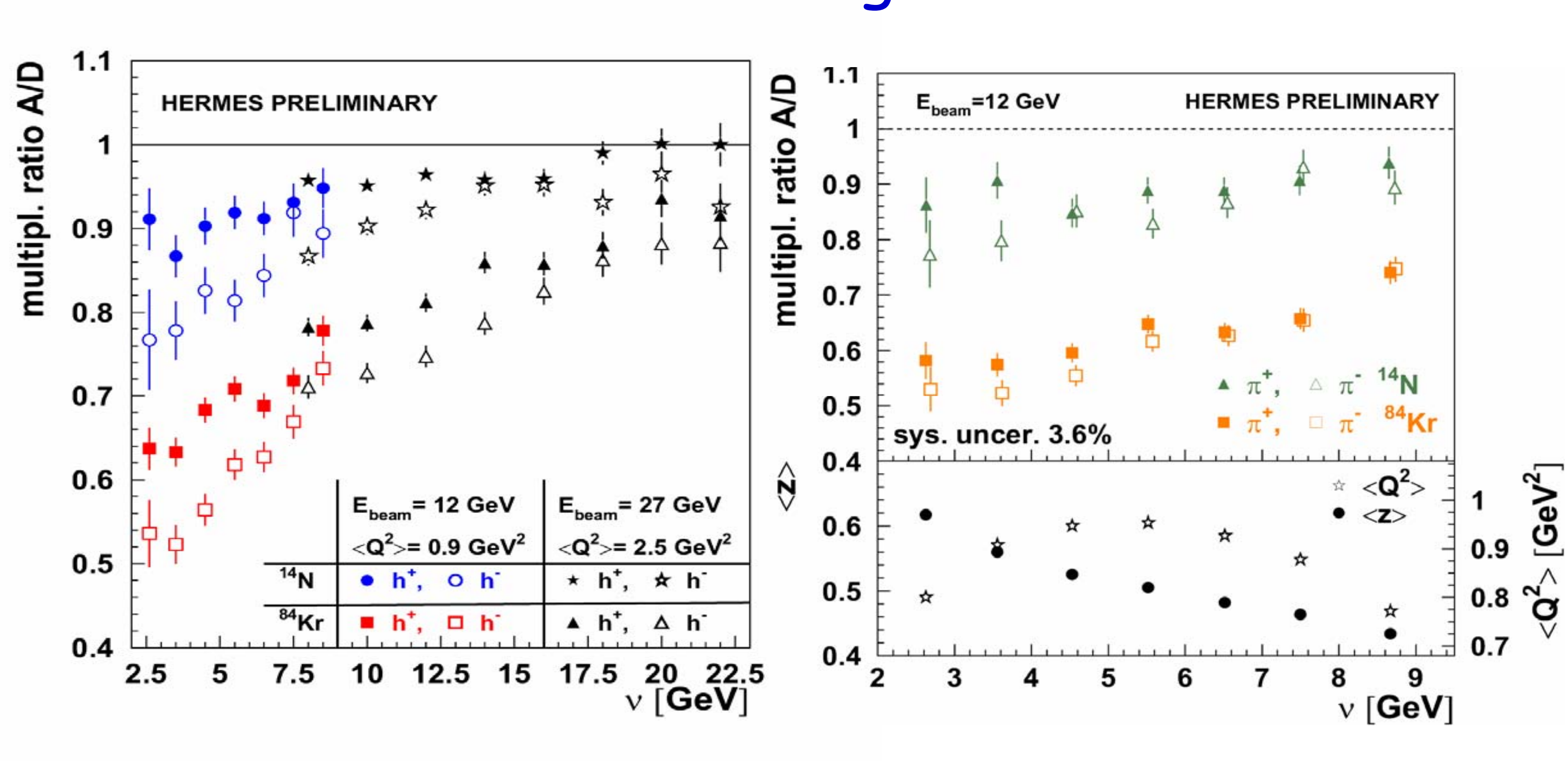


Q^2 Dependence: indication of FF evolution modification

Stronger at small ν (large x); weaker at high ν (small x)

Hadrons and Pions @ E_{beam}=12 & 27 GeV

Extension of the ν range down to 2 GeV

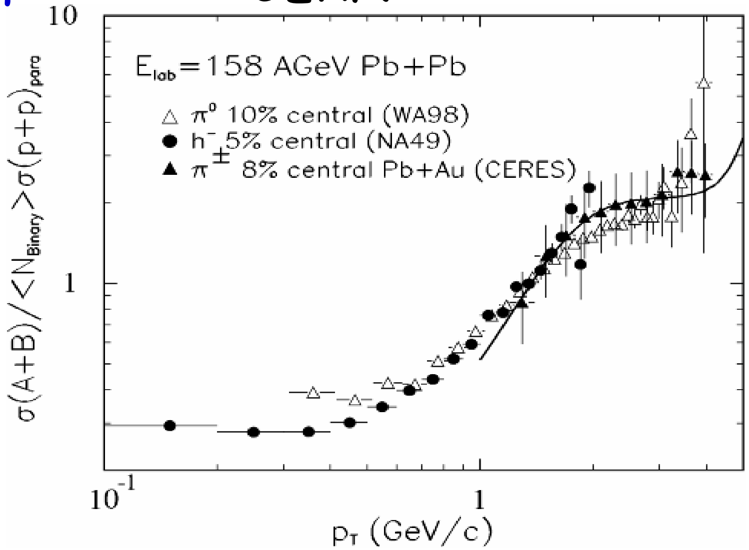


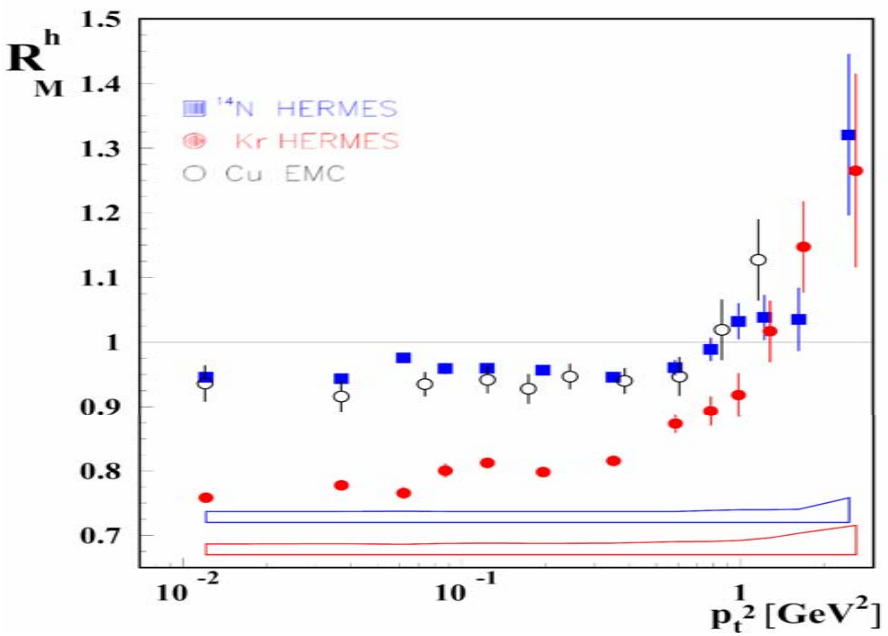
- Measurements are still in progress at HERMES
  $2<\nu<23$ GeV $Q^2<10$ GeV^2

Multiplicity Ratio vs p_t^2

In pA and AA collisions hadrons gains extra transverse momentum due to the multiple scattering of projectile partons propagating through the nucleus (Cronin effect.)

CERN

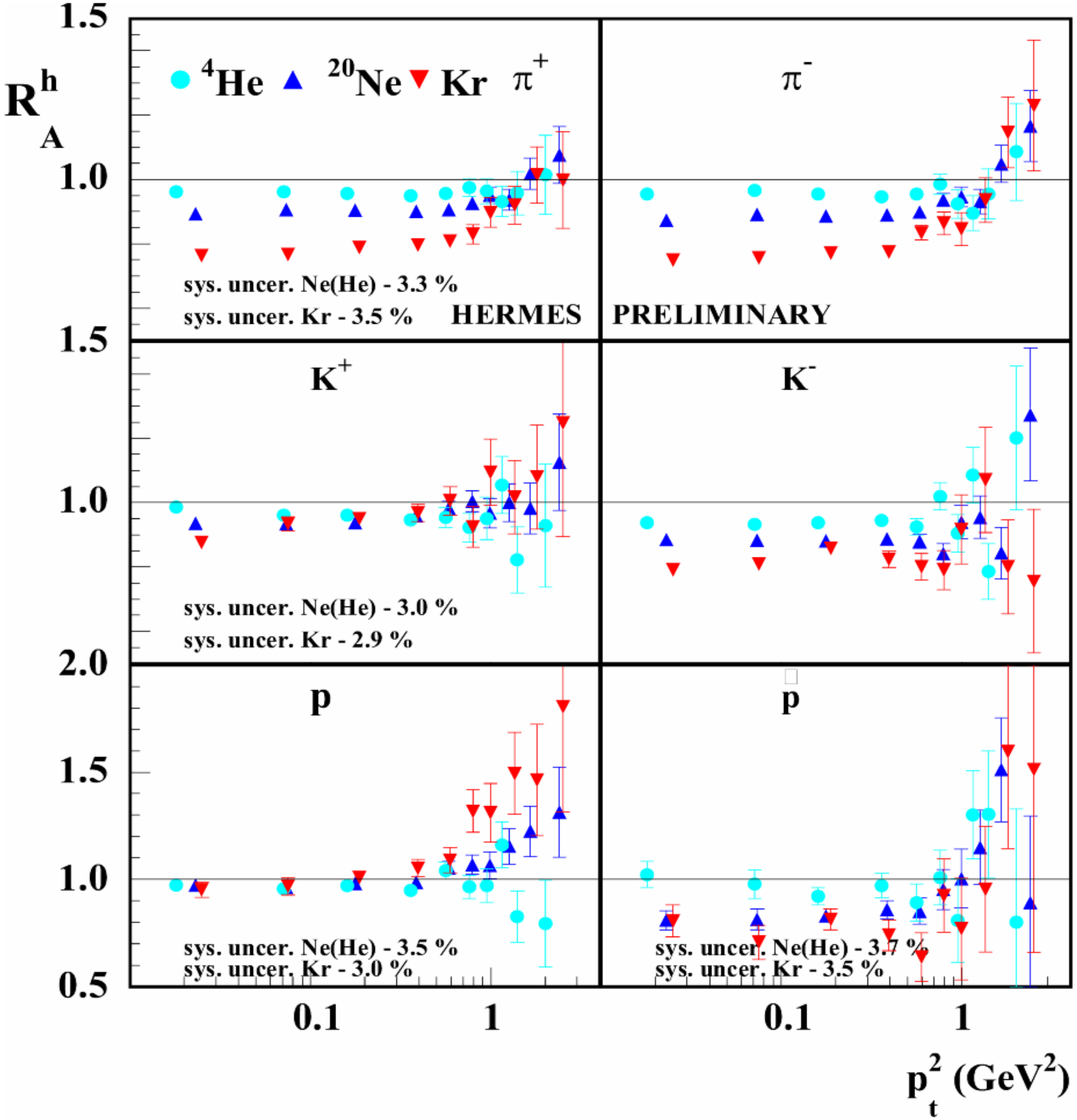




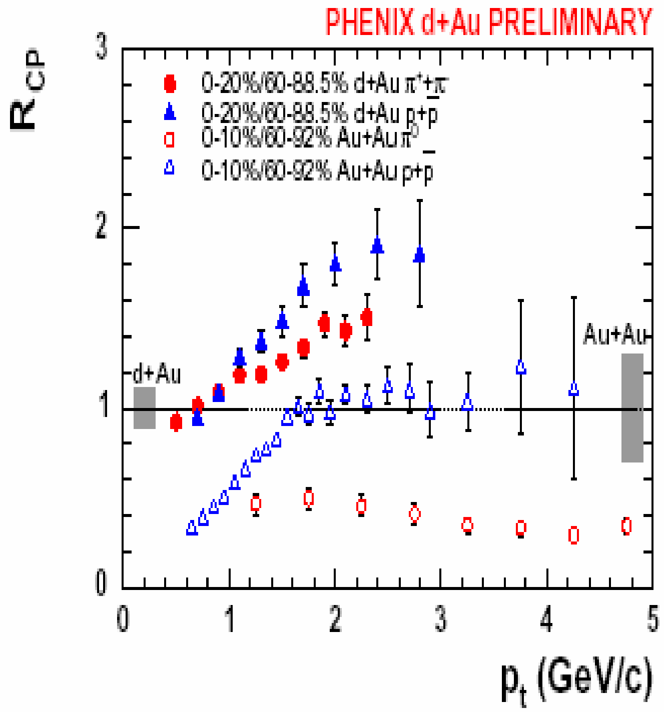
SIDIS show a p_t enhancement similar to that observed in AA scattering.
The enhancement in AA is typically explained at p_t~1-2 GeV assuming ISI.

In SIDIS Cronin only from FSI : no multiple scattering of the incident particle nor interaction of its consituents.

P_t dependence for identified hadrons



Nucl-ex/0403029



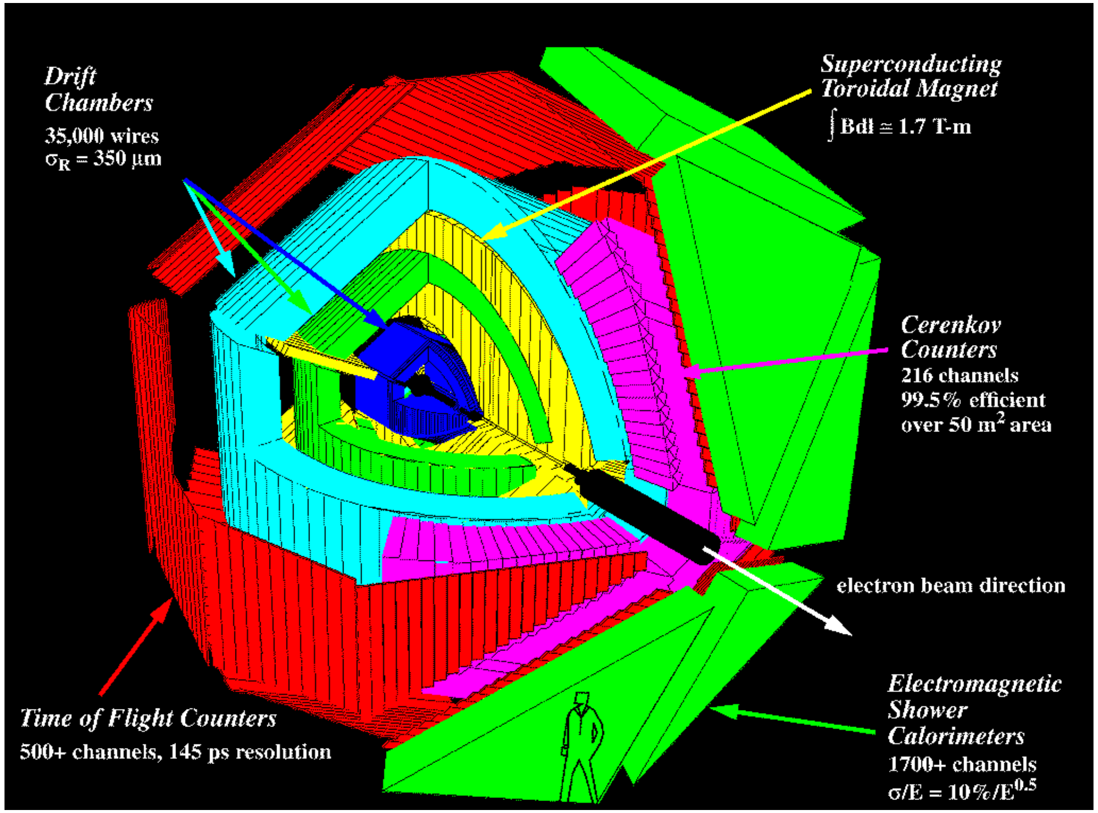
Dependence of the Cronin effect on the hadron species.
Cronin effect for protons larger than for pions.

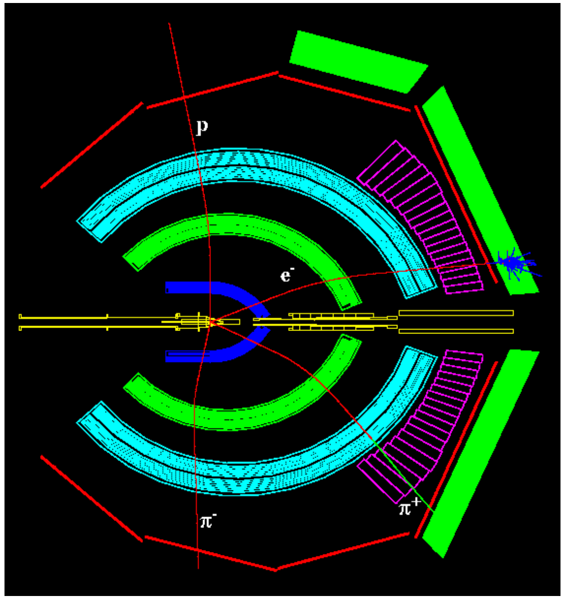
Experiments with CLAS and CLAS++

(NIM A503 (2003) 513)

5.4 GeV exp. in 2003
$Q^2 \leq 4$ GeV^2, $\nu \leq 5$ GeV

11 GeV in 2010-2012
with Jlab upgrade
$Q^2 \leq 9$ GeV^2, $\nu \leq 9$ GeV



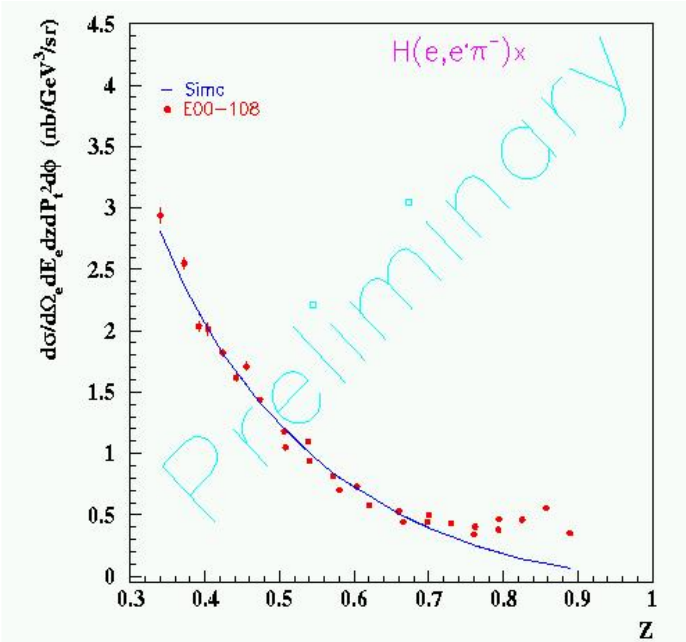


- Charged particle angles 8° - 144°
- Neutral particle angles 8° - 70°
- Momentum resolution ~0.5% (charged)
- Angular resolution ~0.5 mr (charged)
- Identification of p, π^+/π^-, K^+/K^-, e^-/e^+

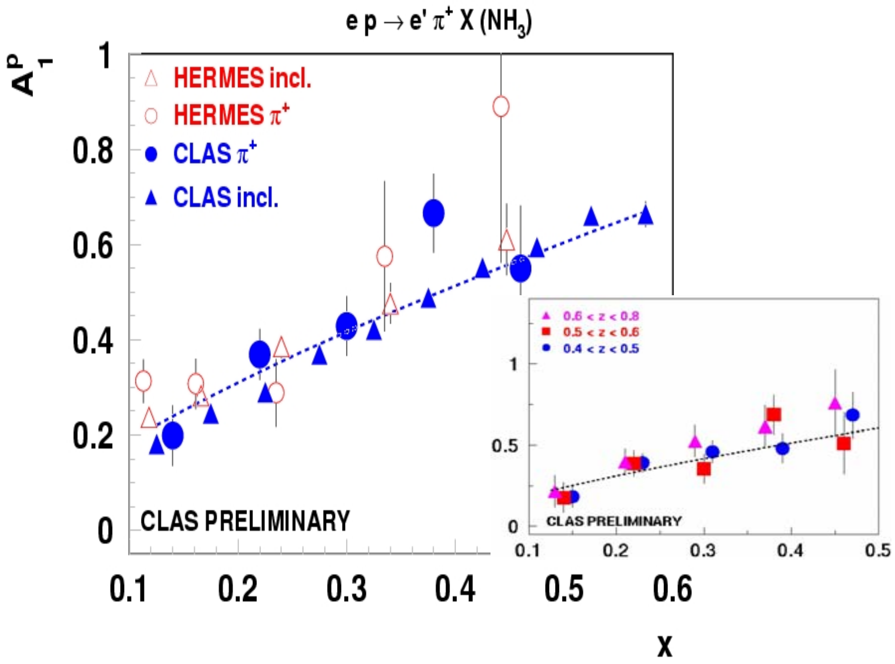
Factorization issues at Jlab

Given the relatively low energy of Jlab (max 6 GeV) the factorization of SIDIS into DF and FF maybe questionable

$$\sigma^{eH\to ehX} = \sum_q f^{H\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to h}$$



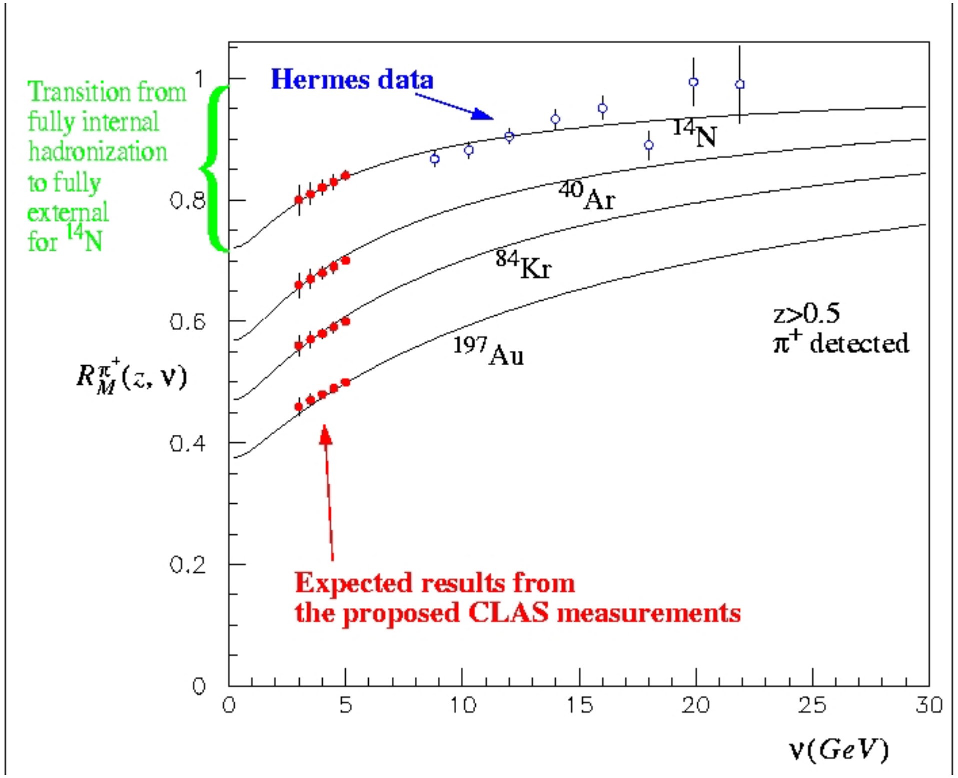
Cross section reproduced by Monte-Carlo based on LO *x*-*z* factorization (Hall C).

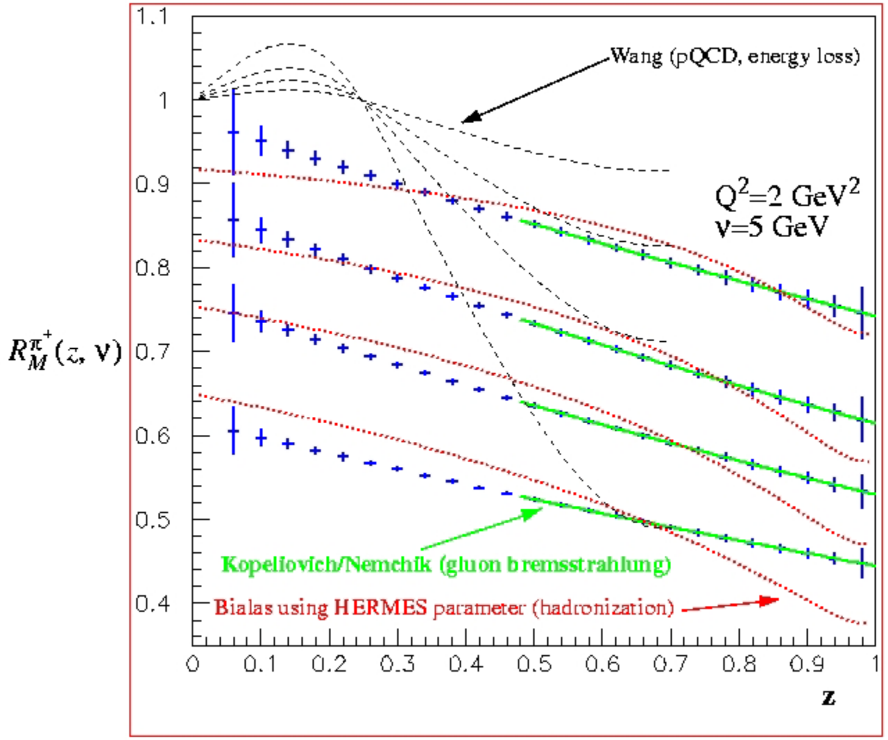


Semi-inclusive asymmetry $A_1^p(\pi^+)$ agrees with HERMES falls on the same curve as inclusive A_1^p; no *z*-dependence observed

LO x-z factorization is not (much) violated at 6 GeV

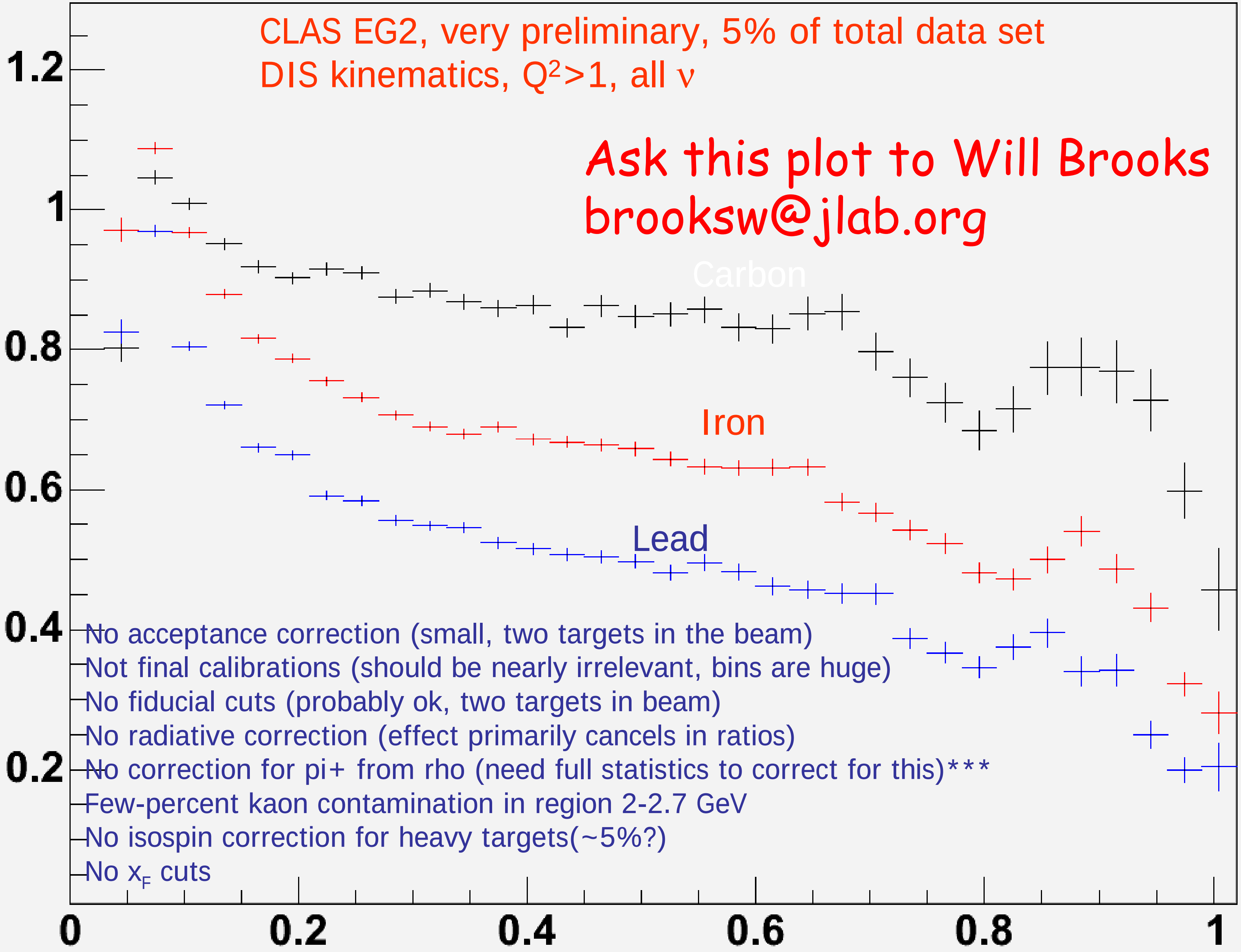
Anticipated CLAS Data





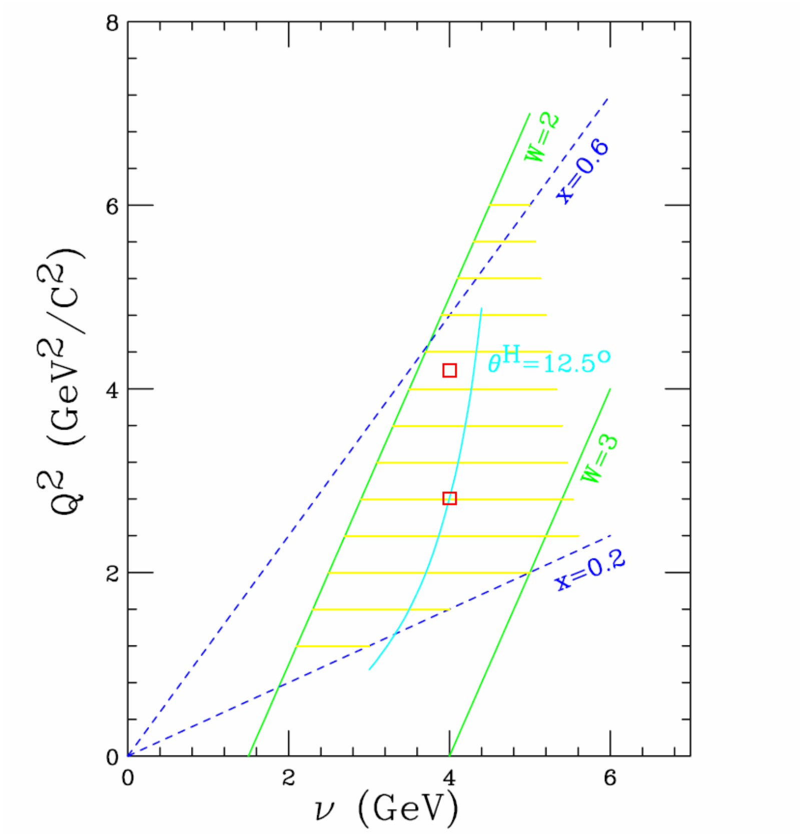
Can measure $\pi^{+,-,0}$, η, ω, η', ϕ, $K^{+,-,0}$, p, Λ, $\Sigma^{+,0}$, $\Xi^{0,-}$

Multiplicity ratio for pion+:



Expectations from Hall-A E04-002

For fixed kinematics a high precision meas. at large z



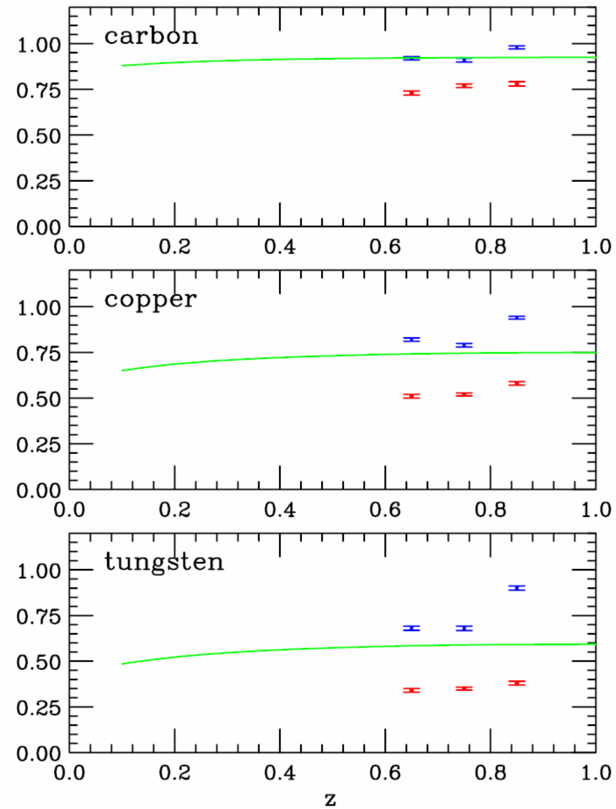
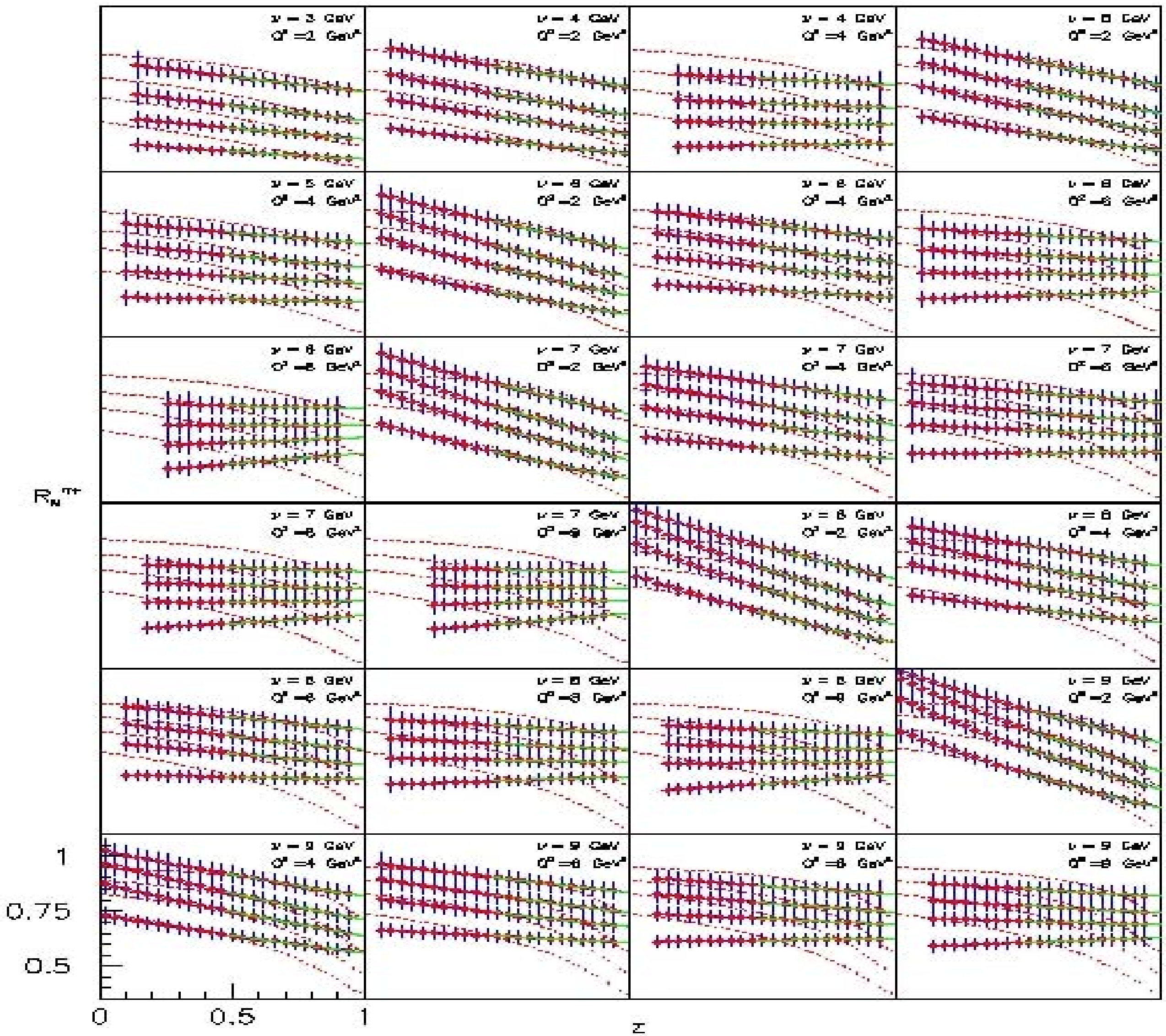


Figure 8: Attenuation of π^+ (blue x, larger) and proton (red o, smaller) in carbon (top), copper (central) and tungsten (bottom) as a function of z for $Q^2 = 2.81(GeV/c)^2$, $\nu = 4$ GeV and P_T= 0-0.25 GeV/c.

Expectations from CLAS++ upgrade



Models based on pre-hadronic interaction

B. Kopeliovich et al.: hep-ph/9511214 , NPA 740, 211 (2004).
T. Falter et al.: nucl-th/0406023, PRC in print.
A. Accardi et al.: NPA 720, 131 (2003).

Important role of the pre-hadron formation and interaction :
Which time and cross section? Absorption or rescattering?
Hadron formation mainly outside the nucleus.
Induced radiation is a smaller contribution compared to absorption or rescattering.

Models based on partonic energy loss

X.N. Wang et al.: PRL 89, 162301 (2002).
F. Arleo et al.: EPJ C 30, 213 (2003).

Energy loss mechanism for the hadron suppression, parton rescattering for the enhancenment at large p_T

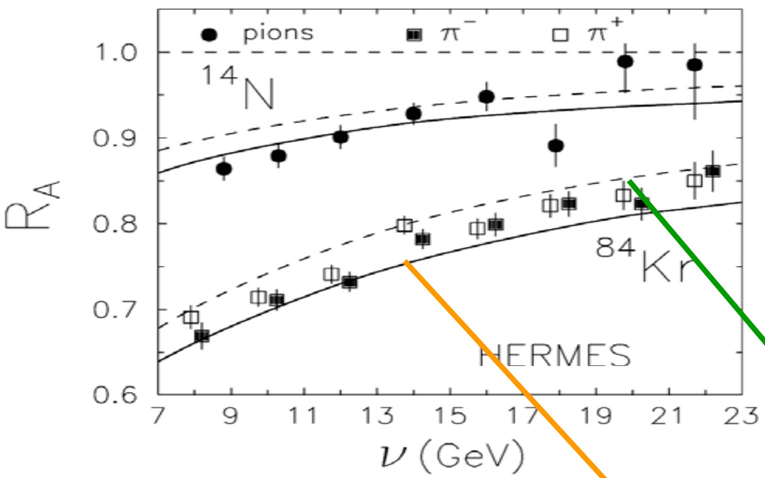
Gluon Bremsstrahlung

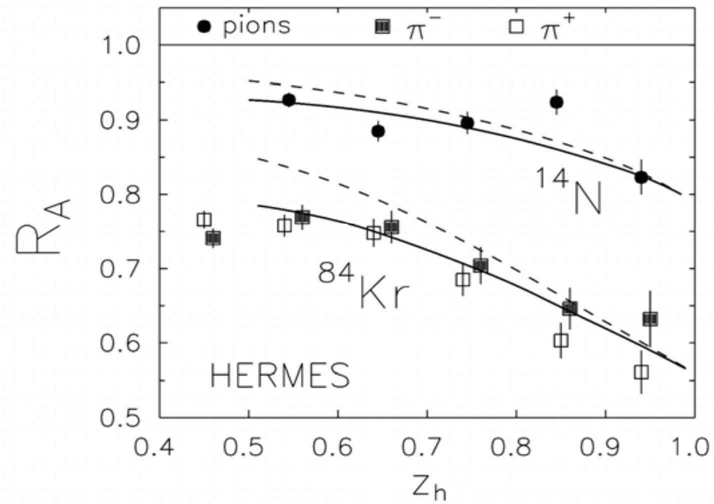
B.Kopeliovich et al.,
hep-ph/9511214
Nucl.Phys. A740 (2004) 211

FF modification: Nuclear Suppression + Induced Radiation

Nuclear suppression: interaction of the $q\bar{q}$ in the medium.

Energy loss: induced gluon radiation by multiple parton scattering in the medium



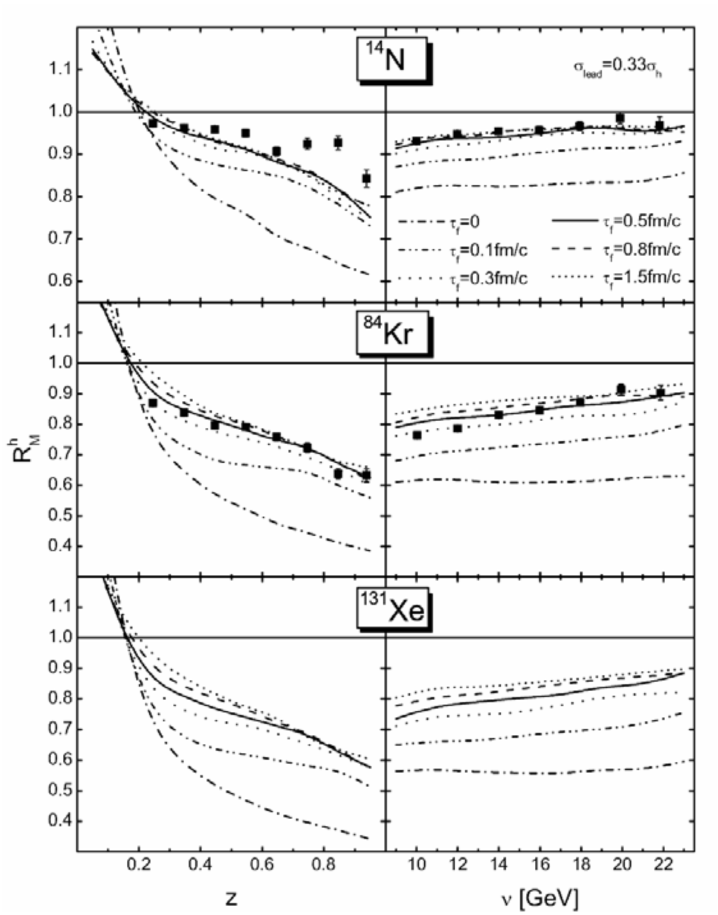


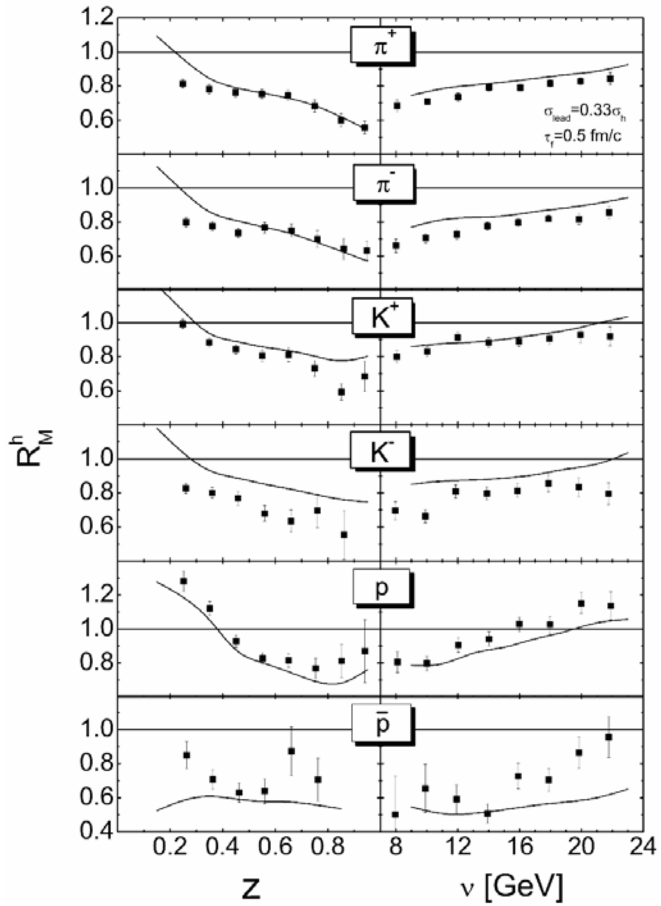
Nuclear Suppression

Nuclear Suppression + Induced Radiation

Pre-hadron FSI and formation times

T.Falter et al., PLB 594 (2004) 61
and PRC in print, nucl-th/0406023

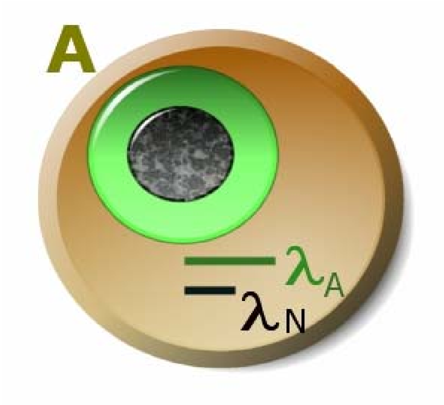




τ_p = 0 ; τ_f>0.5 fm/c compatible with data

R_M is very sensitive to the $\sigma_{pre\text{-}h}$; ($\sigma_{pre\text{-}h}$=0.33 σ_h)

Rescaling + Absorption Model

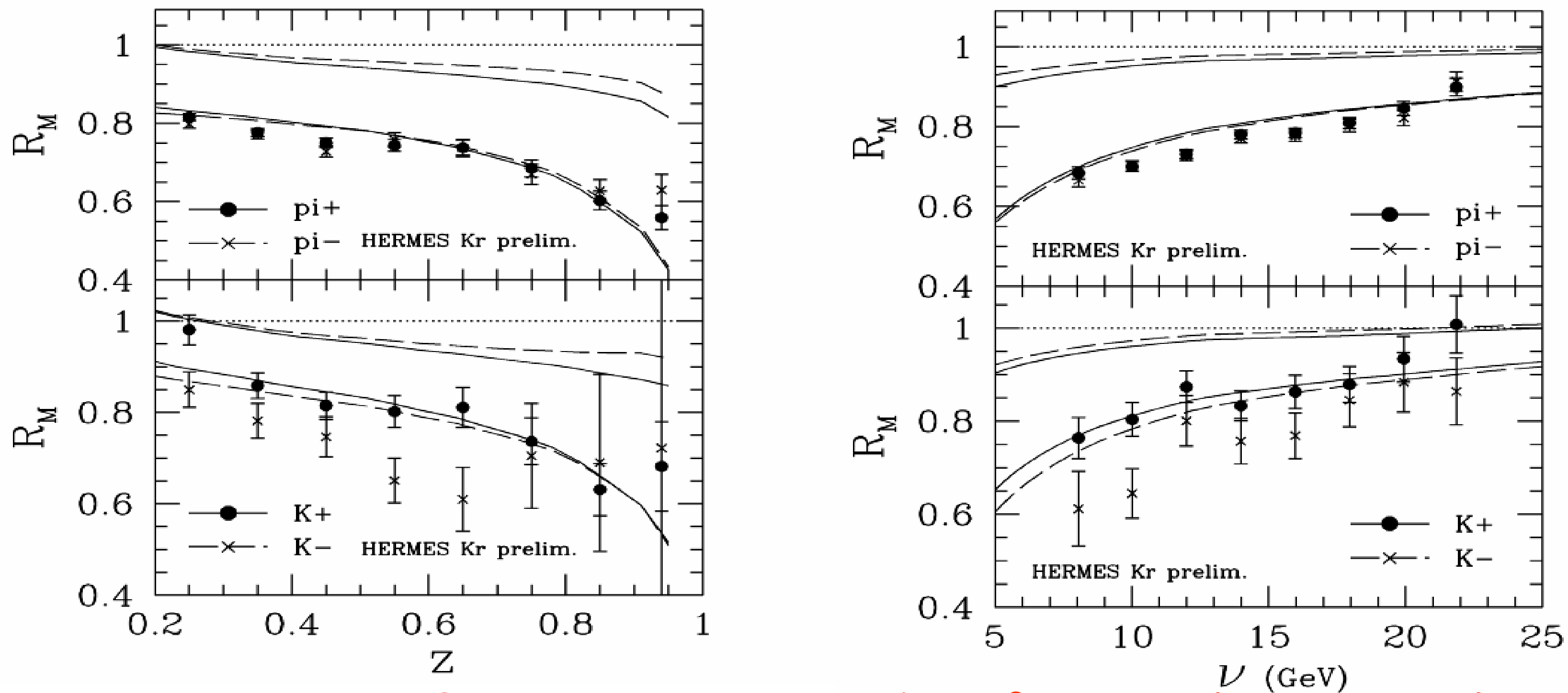


$$\lambda_A > \lambda_N\,; \qquad \xi_A(Q^2) = \left(\frac{\mu_N^2}{\mu_A^2}\right)^{\frac{\alpha_s(\mu_A^2)}{\alpha_s(Q^2)}}$$

A.Accardi et al.,
NPA720(2003)131

$$q_f^A(x,Q^2) = q_f(x,\xi_A(Q^2)Q^2)$$

$$D_f^{h|A}(z,Q^2) = D_f^h(z,\xi_A(Q^2)Q^2)$$



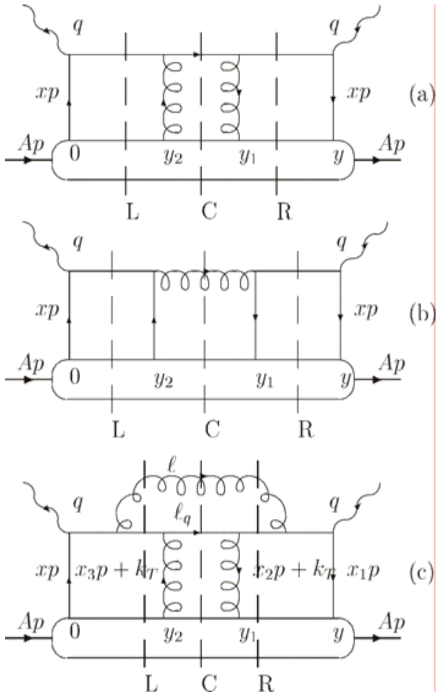
Nice agreement for p+, p-, K+ with Q^2-rescaling + nuclear absorption (lower curves).

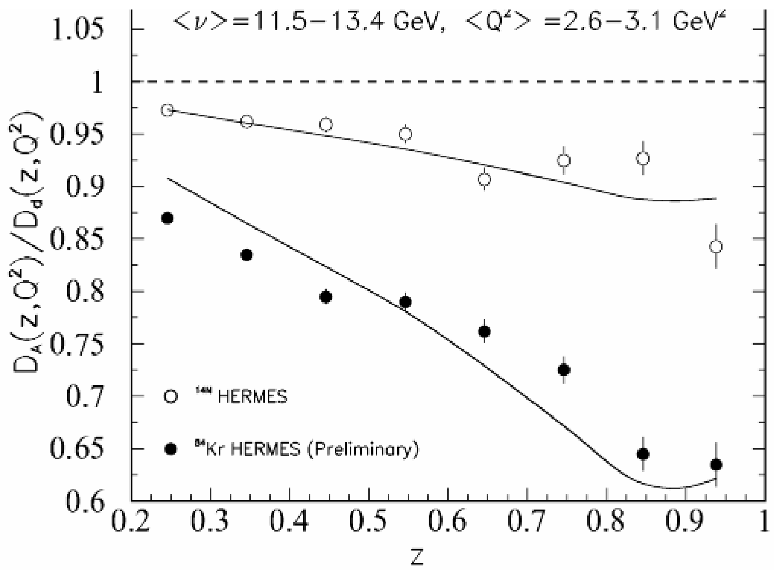
FF modification

X.N.Wang et al.,
NPA696(2001)788
PRL89(2002)162301

multiple parton scattering and induced parton energy loss (without hadron rescattering)

pQCD approach: LPM interference effect →$A^{2/3}$ dependence





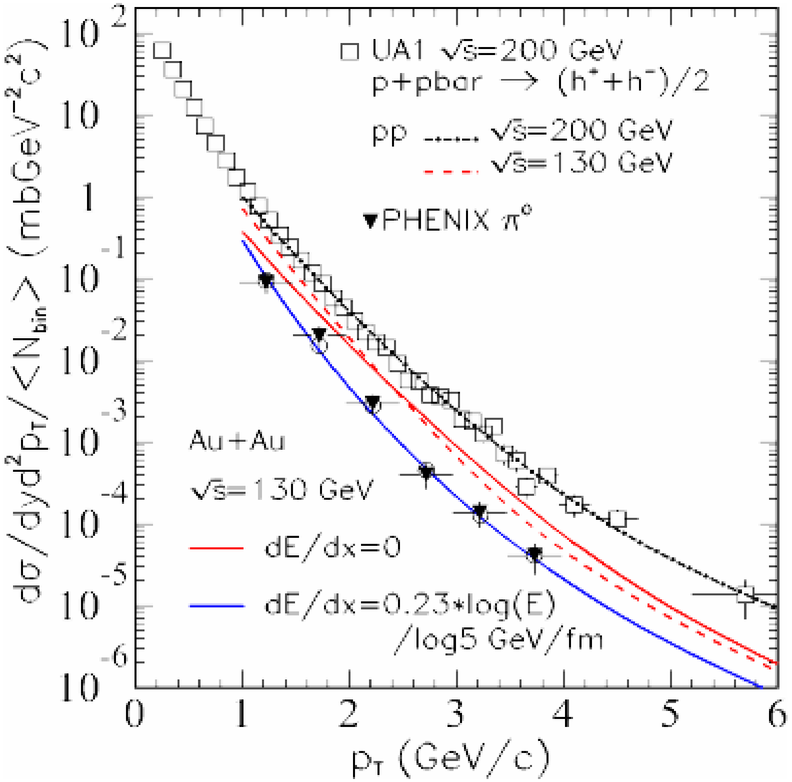
- Consistency with the quadratic nuclear size dependence $[A^{2/3}]_{th}$

- 1 free parameter C≡quark-gluon correlation strength in nuclei.
- From ^{14}N data C=0.0060 GeV^2: $\Delta E = n < \Delta z_g > \propto C \alpha_s^2 m_N R_A^2$

dE/dL and Gluon density at RHIC

$dE/dL_{PHENIX}|_{Au}$ predictions determined by using C=0.0060 GeV^2 from HERMES data.

$\langle dE/dL \rangle \approx 0.5$ GeV/fm for 10-GeV quark in Au.



PHENIX: hot, expanding system.

HERMES: cold, static system.

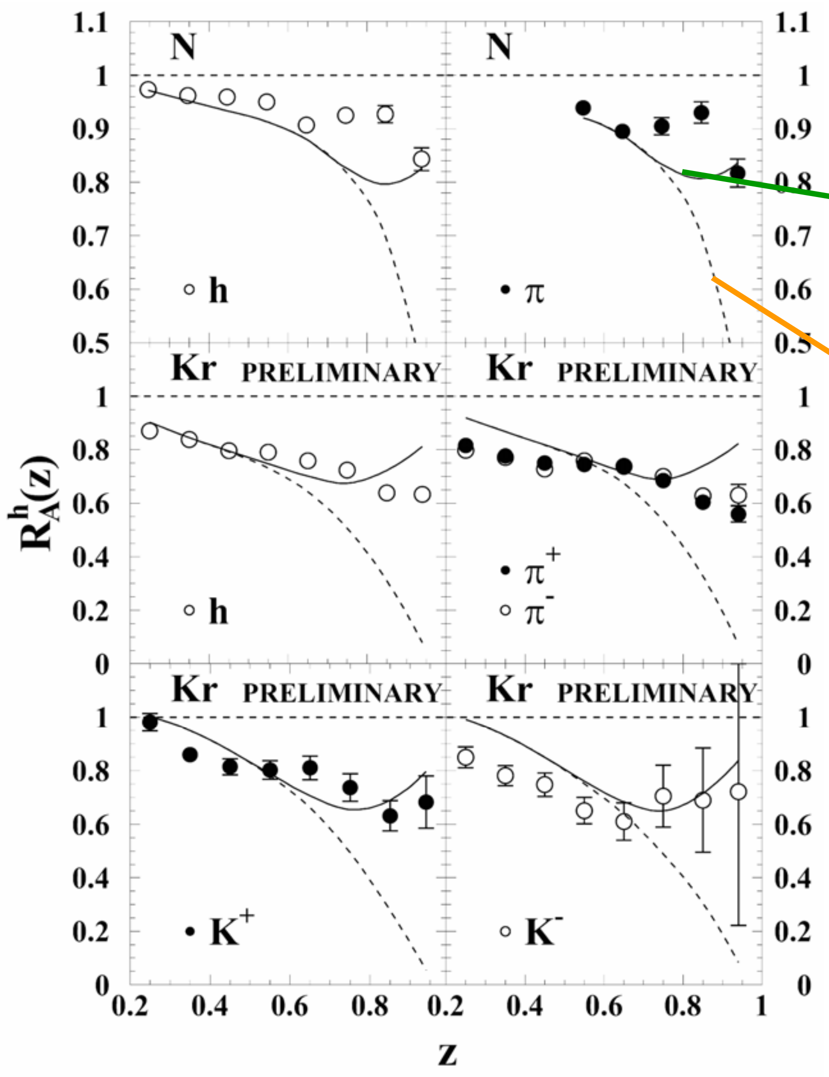
⇓

- $\Delta E_{sta} \propto \rho_0 R_A^2$; ρ_0 gluon density and $R_A \approx 6$ fm
- $\Delta E_{exp} \approx \Delta E_{sta} (2\tau_0/R_A)$; τ_0 initial formation time of dense medium

•Gluon density in hot matter much higher than in cold matter

FF modification + transport coef.

F.Arleo et al.,
NPA715(2003)899



With formation time effect

Without formation time effect

Soft gluons radiated in the dense QCD medium (gluon transport coefficient from DY)

Energy loss ~0.6 GeV/fm in agreement with X-N Wang

Nice agreement with both HERMES and old EMC data

Disentangling hadronic and partonic effects

$$R_{2h}(z_2) = \frac{\left(\dfrac{d^2N(z_1, z_2)}{dN(z_1)}\right)_A}{\left(\dfrac{d^2N(z_1, z_2)}{dN(z_1)}\right)_D}$$

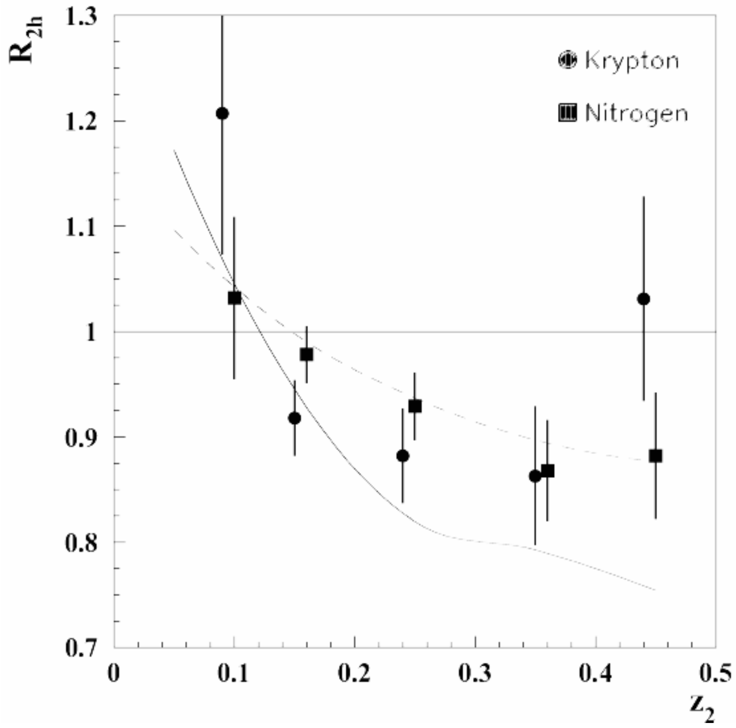
Number of events with at least 2 hadrons ($z_{leading}=z_1>0.5$)

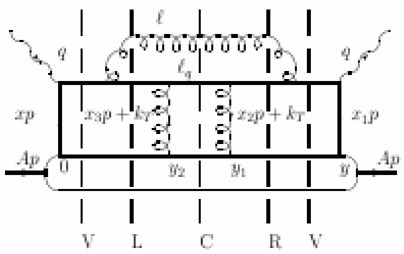
Number of events with at least 1 hadron ($z_1>0.5$)

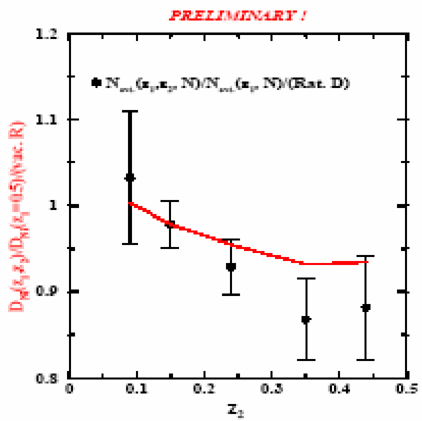
If only hadronic effect: double-hadron over single hadron ratio is expected to be much smaller in nucleus compared to deuterium.

If only partonic effect: double-hadron over single hadron ratio in nucleus and deuterium is expected to be close to unity.

Two hadron production (prelim.)

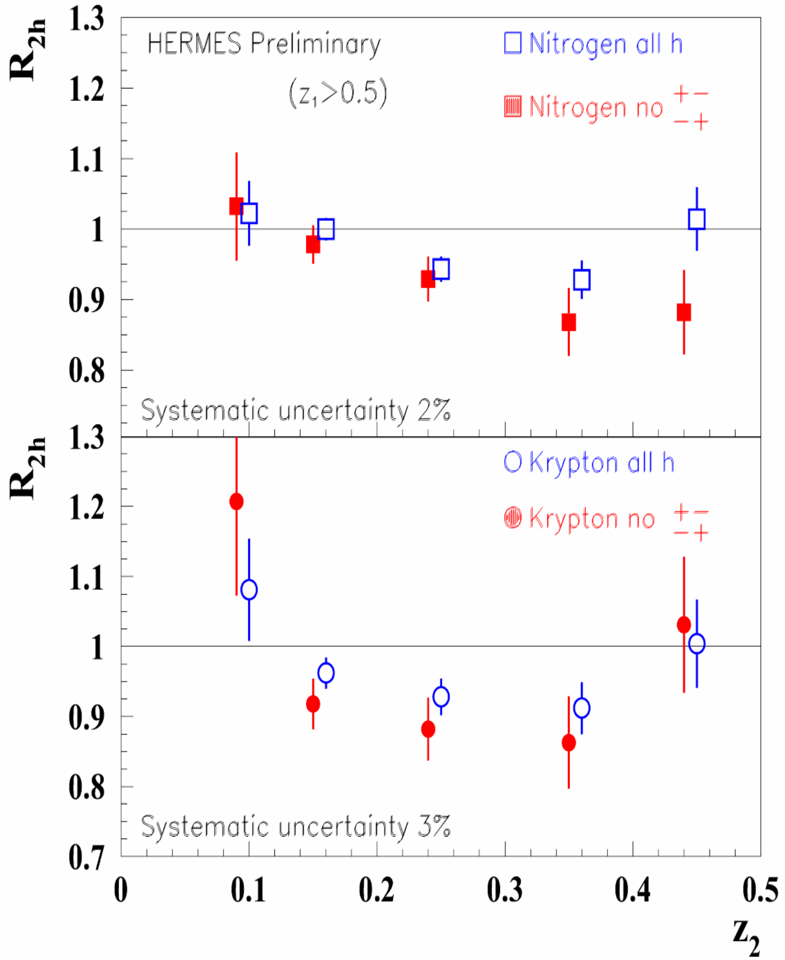


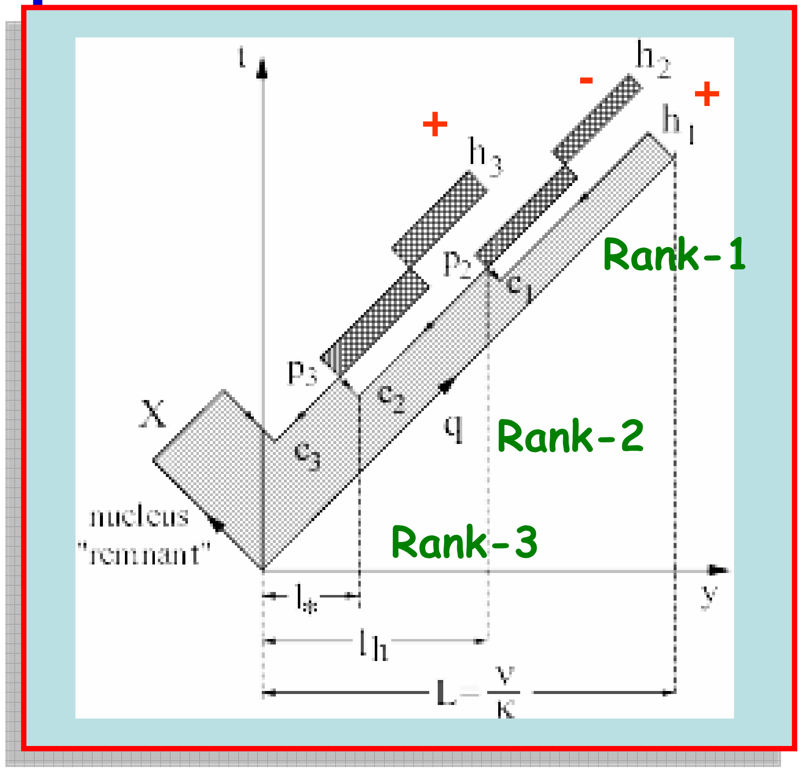




- Small effect in R_{2h} compared to single hadron multiplicity
- Small A-dependence (also confirmed by first Xe data)
- Curves from Falter et al. with per-hadronic FSI described with a transport code
- Curve from Majumder et al. (hep-ph/0410078) with partonic energy loss

Two hadron production





All h→ rank 1,2,3

No +- and -+ → no rank 2, only 1,3

•Small additional reduction for higher rank (produced before, more inside the nucleus)

Summary and outlook

HERMES is providing new results on hadron production in e-nucleus interaction:

- Nuclear attenuation in a wide kinematical range, vs ν, z, Q^2, p_t^2 for ^4He, ^{14}N, ^{20}Ne, ^{84}Kr (^{131}Xe is coming)
- First measurement with identified hadrons : π^+, π^-, π^0, K^+, K^-, p, $\bar{p}$.
- First observation of hadron-type attenuation .
- First clear observation of the Cronin effect in SIDIS.
- Effect in Ratio of double/single hadron production in *A* over D is small and with almost no *A*-dependence.

Measurements are also in progress at Jlab !

- Nuclear modification of the quark Fragmentation Functions
- Pre-hadronization and final hadronization times
- Partonic energy loss and scattering