

Accessing characteristics of hadronization from DIS

Valeria Muccifora

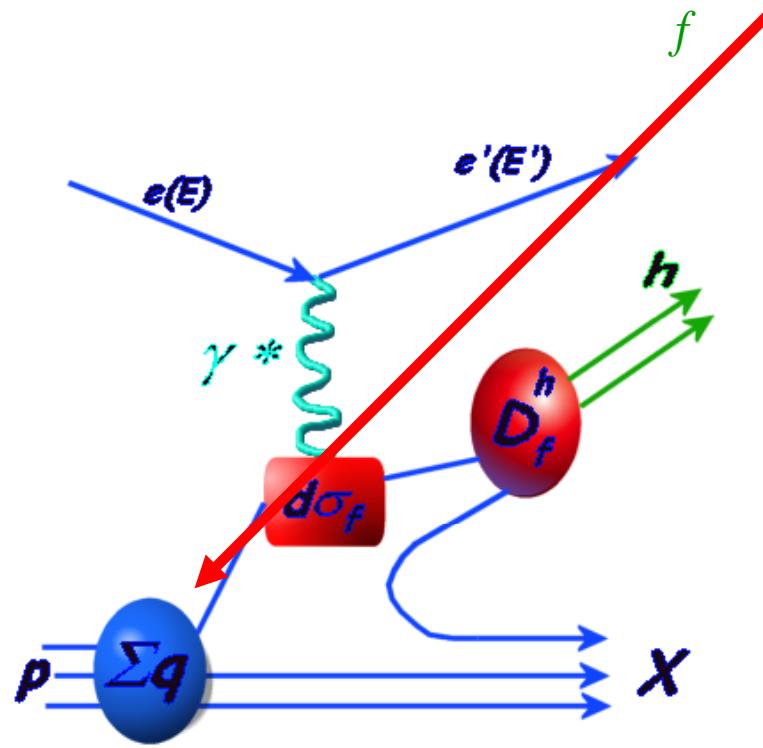


- Semi-Inclusive DIS and FF in nuclei
- The hadronization process
- Hadron production in semi-inclusive measurements on nuclei.
- Status of the theoretical models
- Connections with heavy ion measurements.

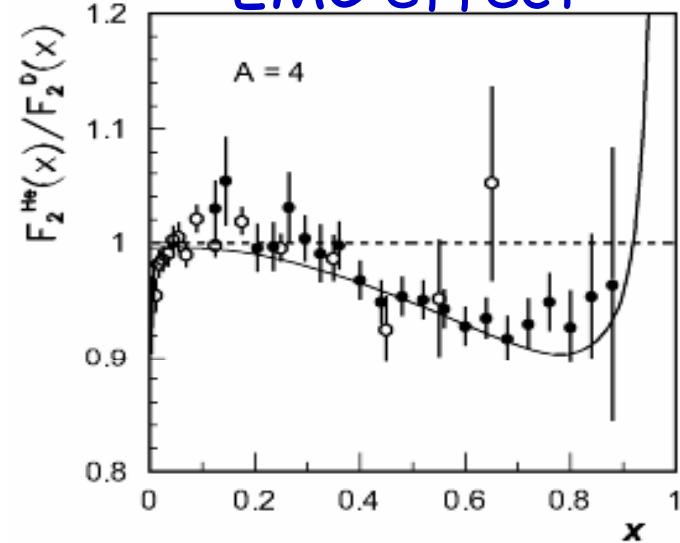
ECT* parton fragmentation process in the vacuum and in the medium

DIS and DF on Nucleon & Nuclear Medium

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



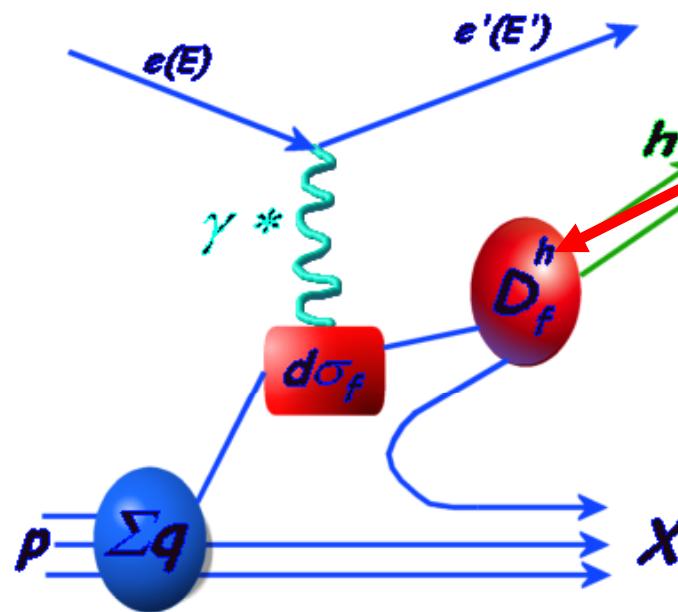
Inclusive DIS on nuclei:
EMC effect



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

SIDIS and 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 $z = E_h/v$ like DFs with x
 FFs probabilistic interpretation like DFs

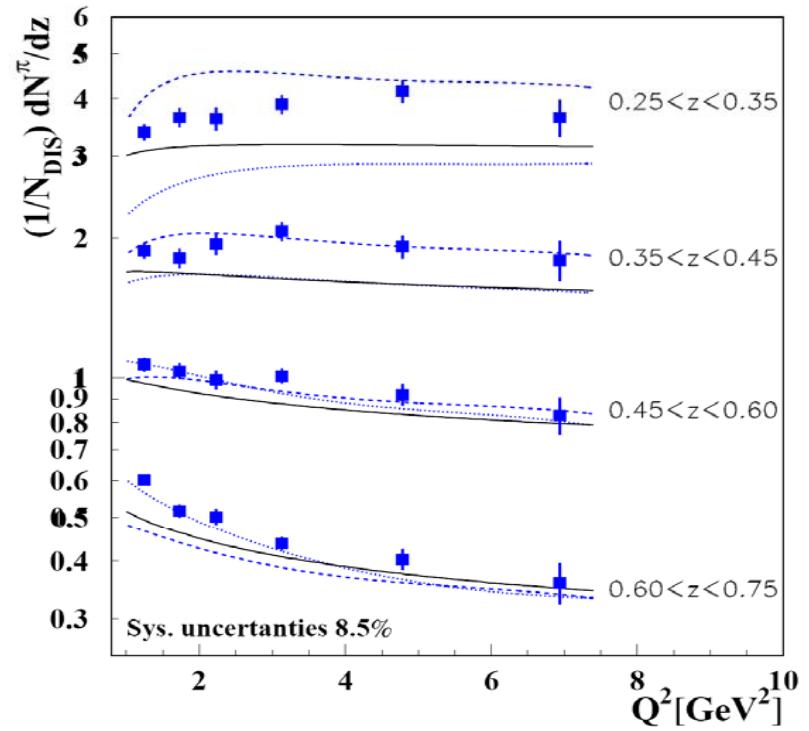
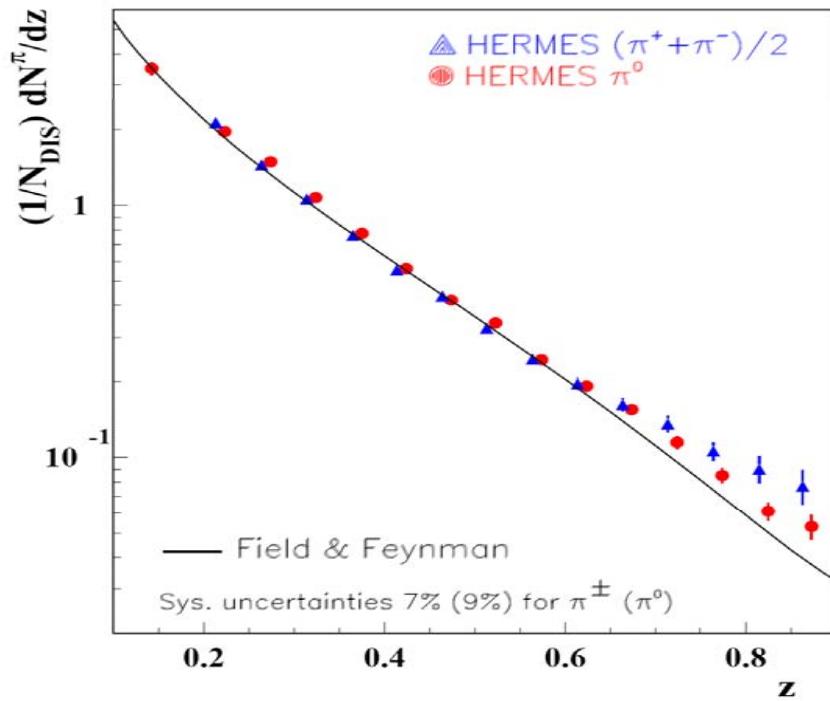
SIDIS multiplicities are also good measurements of FFs:

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

SIDIS Multiplicities and FFs

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

Particle Data Group, Review of particle physics, Jour. of Phys. G 33 2006 ,199



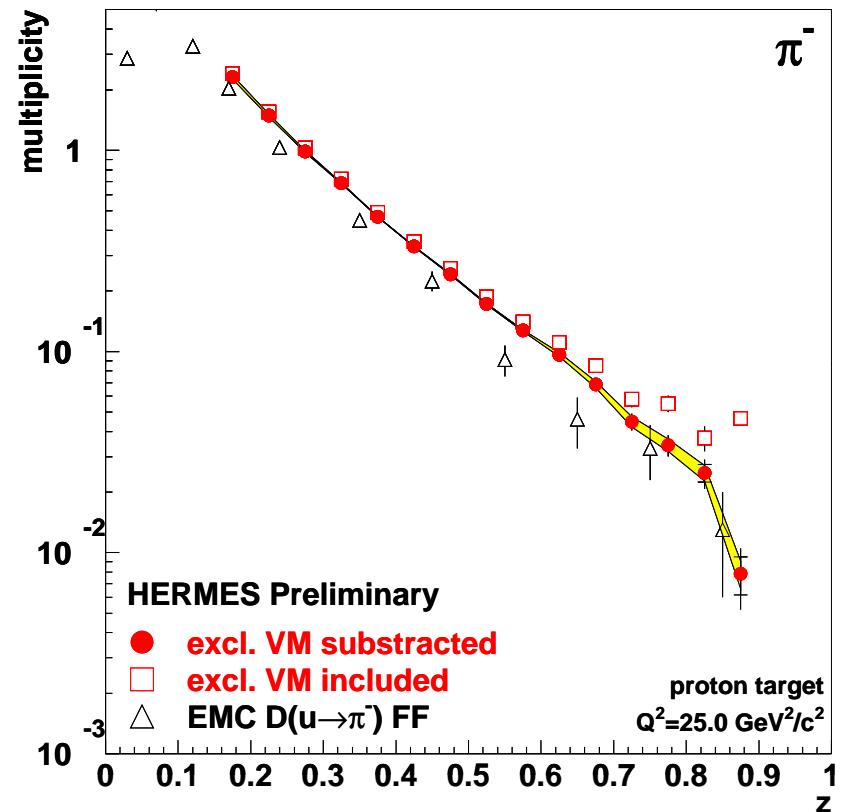
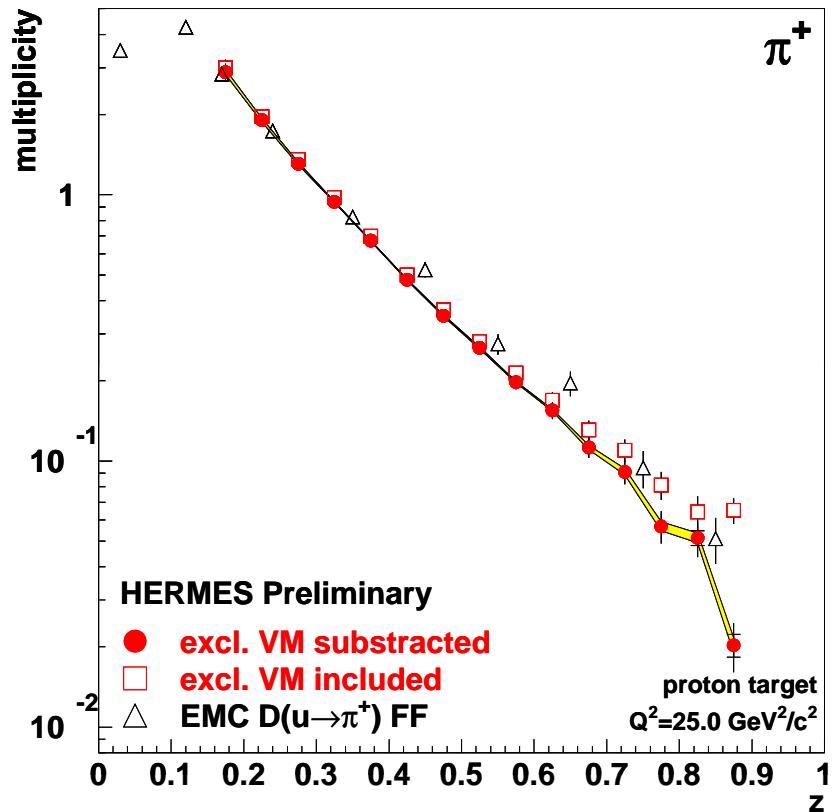
Isospin invariance in the production of charged and neutral pions

Q^2 -behaviour resembles that of the NLO QCD evolution of FFs
predicted by models based on e^+e^- data at much higher energies.

(E. Aschenauer's talk

HERMES: News on fragmentation from nucleons to nuclei)

$\pi^{+/-}$ Multiplicities vs. z

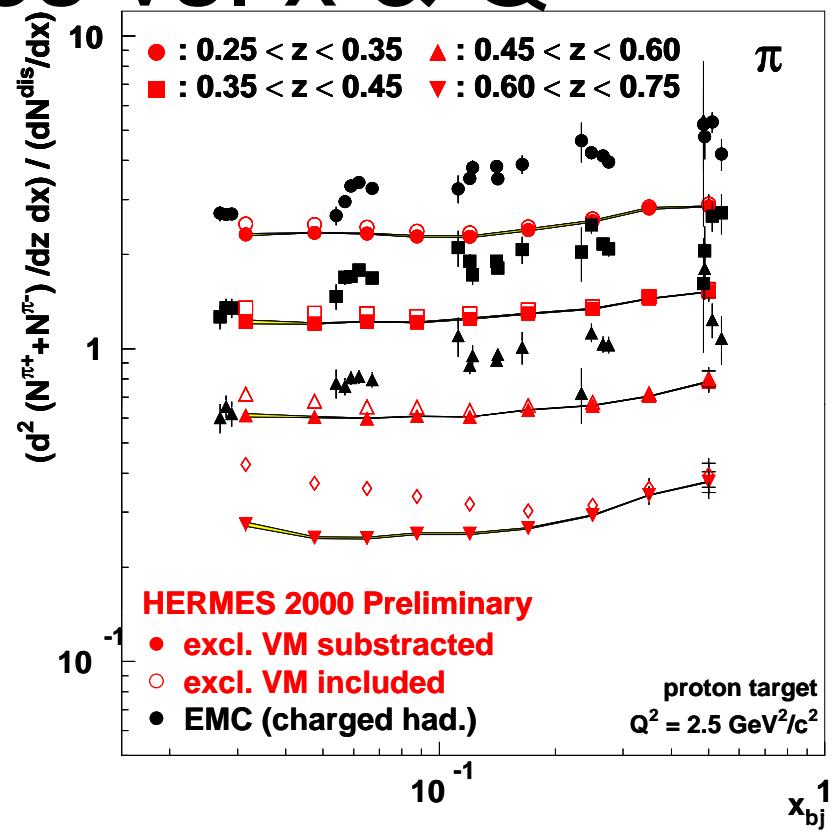
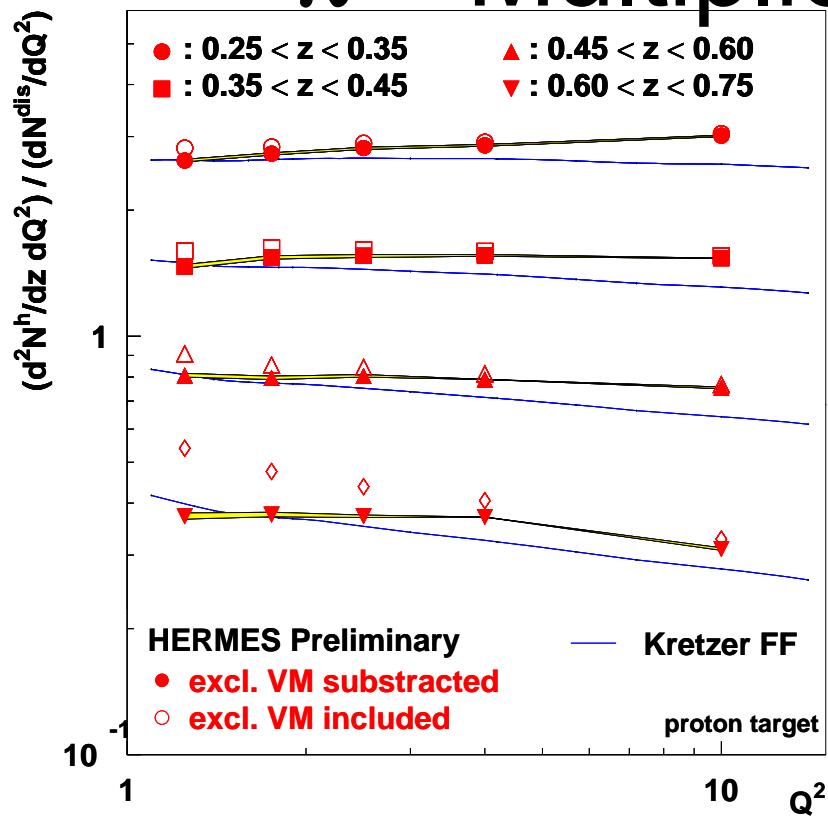


- EMC: Fragmentation Fct. $D_u^{\pi^{+/-}}$ (Nucl. Phys. B321 (1989) 541)
- syst. error dominated by PID unfolding

E. Aschenauer's talk

HERMES: News on fragmentation from nucleons to nuclei)

$\pi^{+/-}$ Multiplicities vs. x & Q^2

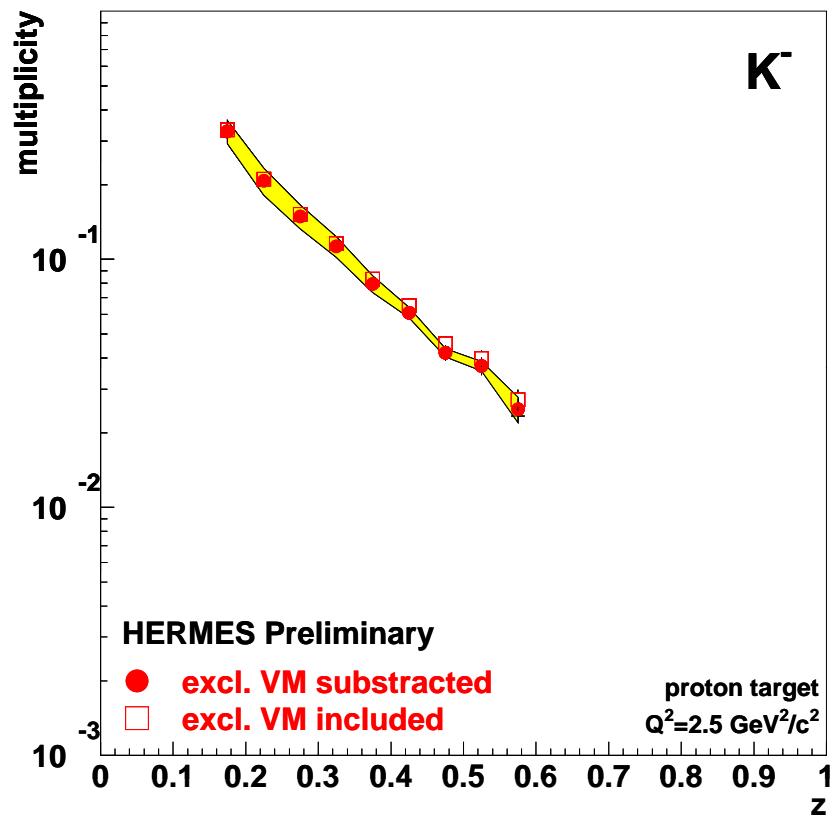
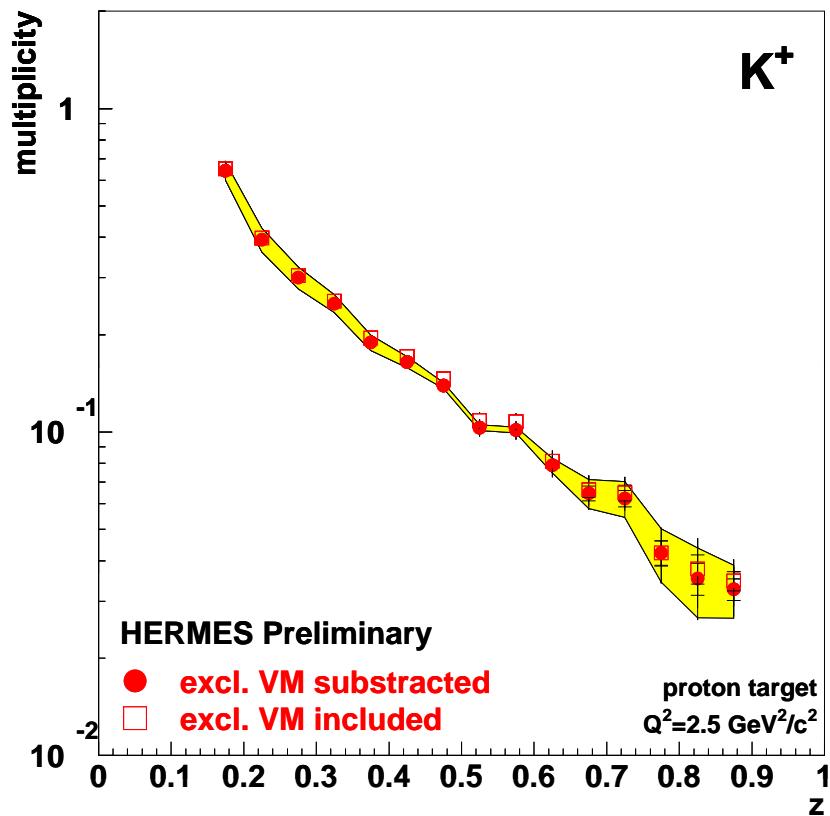


- reasonable agreement using Kretzer FF
- weak x dependence

E. Aschenauer's talk

HERMES: News on fragmentation from nucleons to nuclei)

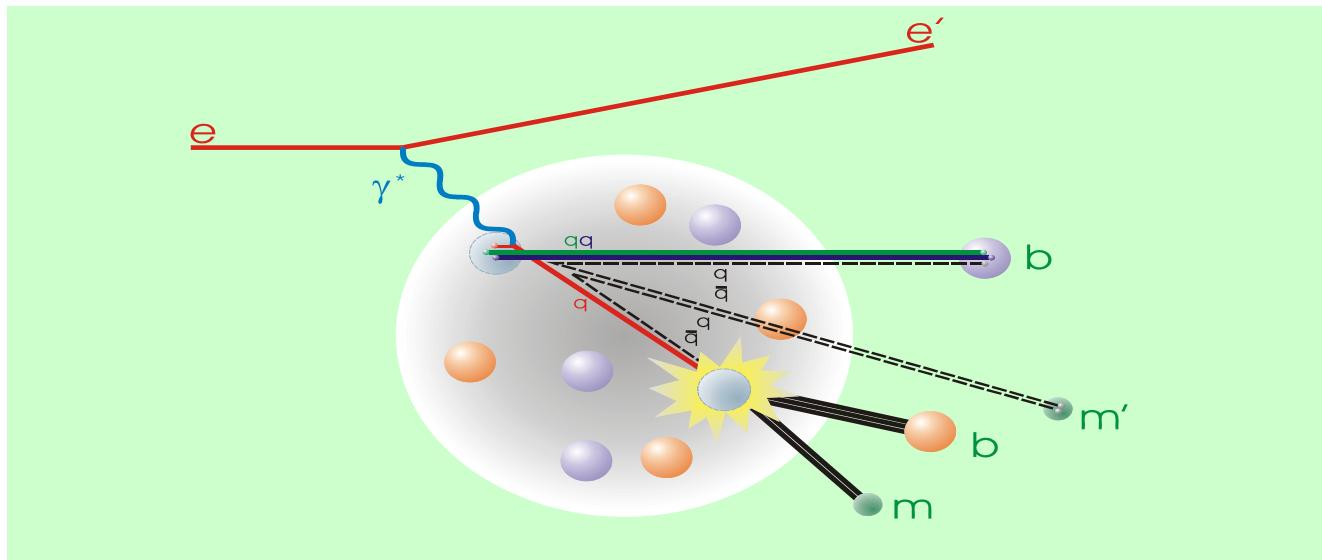
$K^{+/-}$ Multiplicities vs. z



- factor 2/(10) more statistics on tape already analyzed
- syst. error dominated by PID unfolding

Nuclear SIDIS: hadronization mechanism

Nucleus acts as an ensemble of targets: reduction of multiplicity of fast hadrons (an experimental observable) due to both *hard partonic* and *soft hadron interaction*



All nuclear effects in
Semi-Inclusive
DIS are FSI

- Underlying effects in the nuclear medium are better tested: static and known density of the system
- Input for HIC in modification of partonic distribution functions (EMC eff., shadowing, gluon saturation at low x , ...)
- Input for HIC in modification of partonic fragmentation functions (parton energy loss and scattering, pre-hadronic formation and interaction, formation times)

Nuclear SIDIS: quark-gluon dynamics

.Partonic energy loss via gluon emission

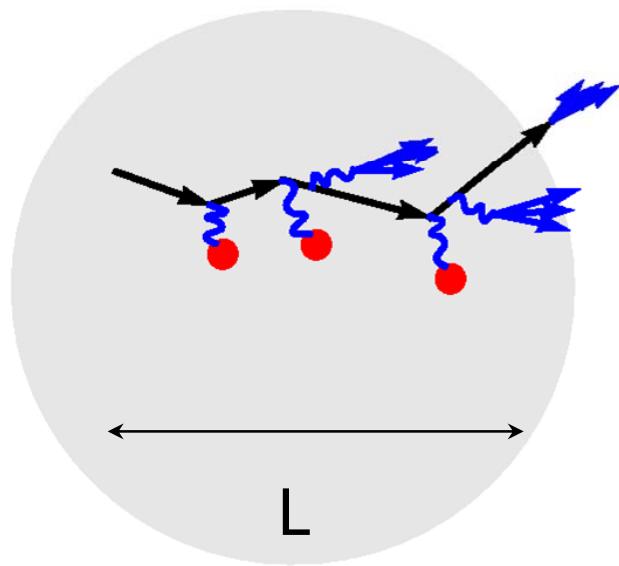
.Quark gluon correlations

- Struck quark emits gluons in vacuum because of confinement
- In nuclear medium, multiple scattering induce additional gluon radiation → L^2 - QCD LPM effect
- dE/dx that can be connected to the transverse momentum squared of the parton

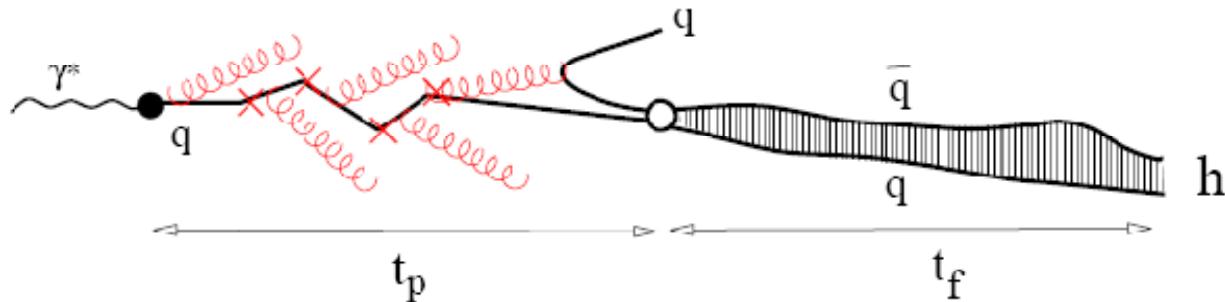
$$dE/dx \approx \frac{\alpha_s}{\pi} N_c \langle p_T^2 \rangle_L$$

$$\Delta \langle p_T^2 \rangle = \langle p_T^2 \rangle^{eA} - \langle p_T^2 \rangle^{eN} \approx \frac{4\pi^2 \alpha_s}{3} \frac{\sum_q e_q^2 T_{qf}^A(x, Q^2)}{\sum_q e_q^2 q^A(x, Q^2)}$$

(an experimental observable)



Nuclear SIDIS: Space time evolution of hadronization



- Parton propagation ($t < t_p$):

- Gluon radiation (mainly energy loss)
- Partonic scattering (mainly p_t broadening)

- Pre-hadron propagation ($t_p < t < t_f$):

- Off shell and virtual hadrons
- Colorless $q\bar{q}$
- Increasing transverse dimension & interaction probability

- Hadronic FSI ($t > t_f$):

- Full hadronic cross section (10-30 mbarn)
- Mainly formed after several tens of fm i.e. out of the nucleus

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.

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- •HERMES: 27.6 GeV $e^+(e^-)$ on He, N, Ne, Kr, Xe
 - EPJ C20 (2001) 479 (Topcite) Single (charged) hadron attenuation
 - PLB 577 (2003) 37 (Topcite) Single (charged and identified) hadron attenuation
 - PRL 96 (2006) 162301 Double hadron (correlation) attenuation
 - NPB 780 (2007) 1 Data summary paper, multidimensional analysis
 - arXiv:0704.3712v2[hep-ex] P_t broadening (preliminary)
(see G.Elbakian's Talk)

- CLAS: 5.4 GeV e^- -beam on C, Fe, Pb
 - Fisika B13 (2004) 321
 - (see K. Hicks's talk)

Hadron multiplicity ratio

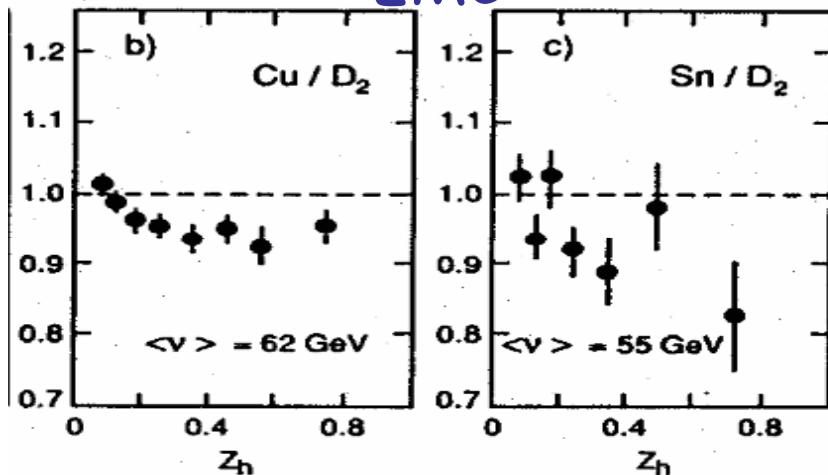
Experimental observable: hadron multiplicity ratio in nuclei and deuterium

$$R_M(z, v) = \frac{\frac{N_h(z, v, Q^2, p_t^2)}{N_{\text{DIS}}(v, Q^2)}_A}{\frac{N_h(z, v, Q^2, p_t^2)}{N_{\text{DIS}}(v, Q^2)}_D} \propto \frac{\frac{1}{\sigma_{\text{DIS}}} \frac{d^2\sigma_h}{dzdv}\Big|_A}{\frac{1}{\sigma_{\text{DIS}}} \frac{d^2\sigma_h}{dzdv}\Big|_D} \propto \frac{\frac{\sum e_f^2 q_f(x) D_f^h(z)}{\sum e_f^2 q_f(x)}\Big|_A}{\frac{\sum e_f^2 q_f(x) D_f^h(z)}{\sum e_f^2 q_f(x)}\Big|_D}$$

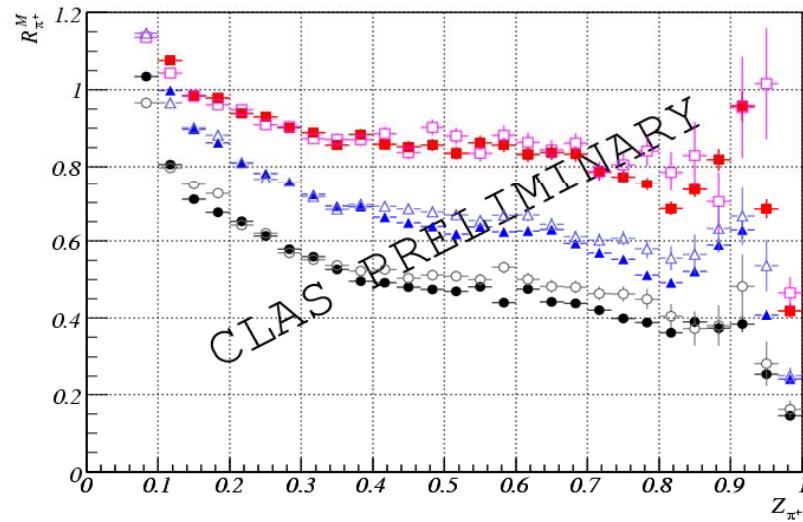
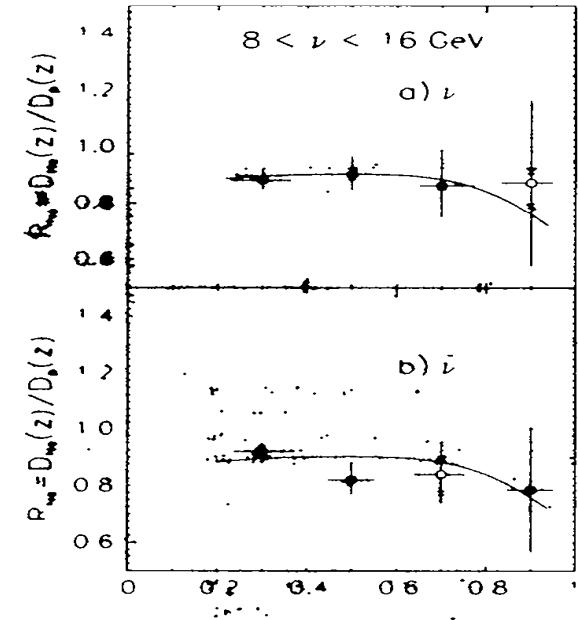
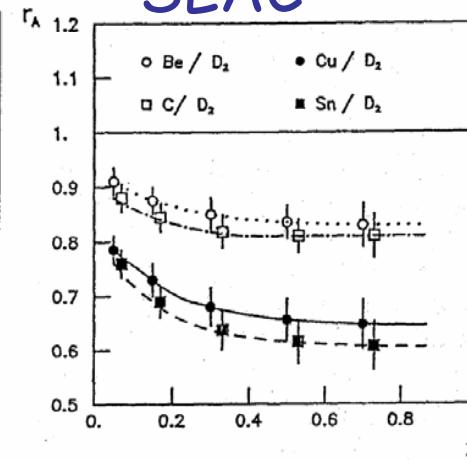
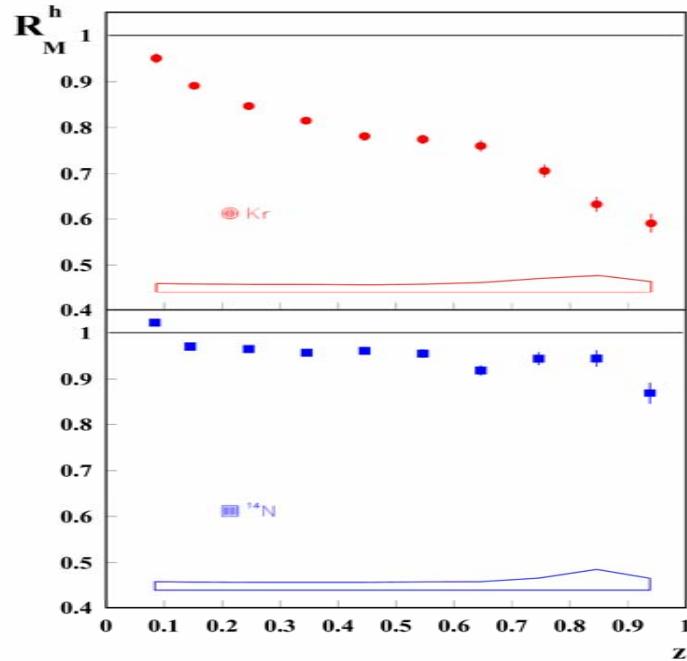
- Leptonic variables : v (or x) and Q^2
- Hadronic variables : z and p_t^2
- Different nuclei : size and density
- Different hadrons : flavors and mixing of FFs
- Double-ratio: approx evaluation of FF medium modification
- Systematic uncertainties are minimize in the double-ratio

Hadron Multiplicity Ratio vs $z = E_h/v$

EMC SLAC WA21/WA59



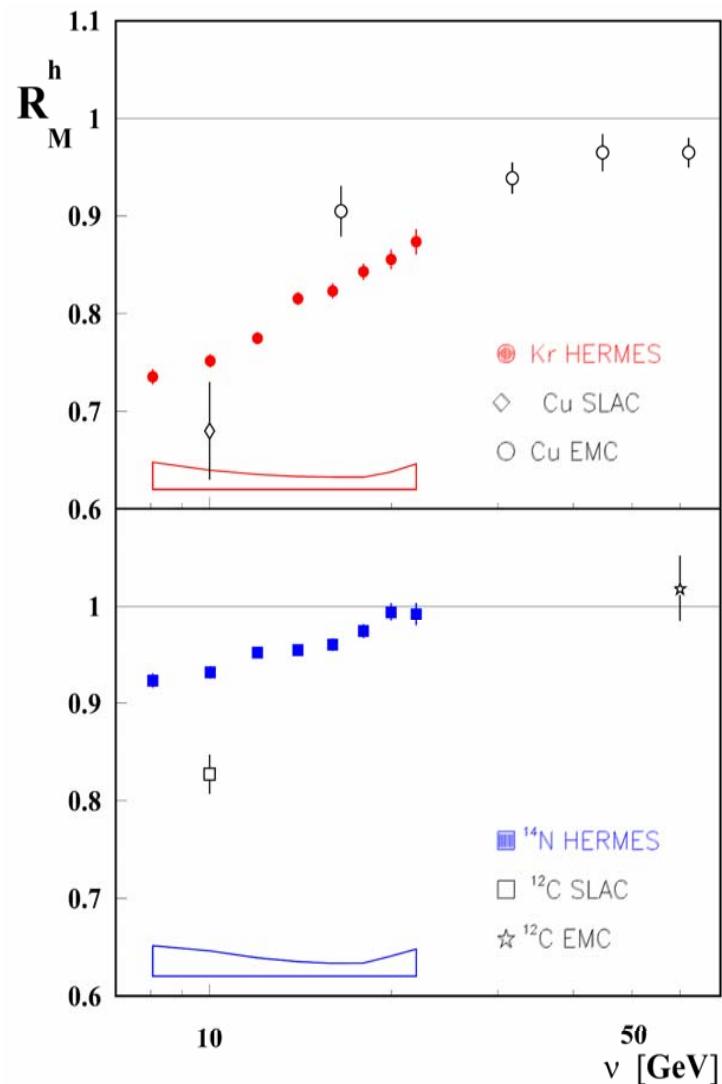
HERMES





- ➊ The energy range (ν 3-27 GeV) is well suited to study medium effects.
- ➋ Measurements over the full z range
- ➌ Possibility to use several different gas targets
- ➍ PID: π^+ , π^- , π^0 , K^+ , K^- , p , \bar{p}

HERMES (first data) 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

Multiplicity ratio for identified hadrons vs ν

HERMES, PLB 577 (2003) 37

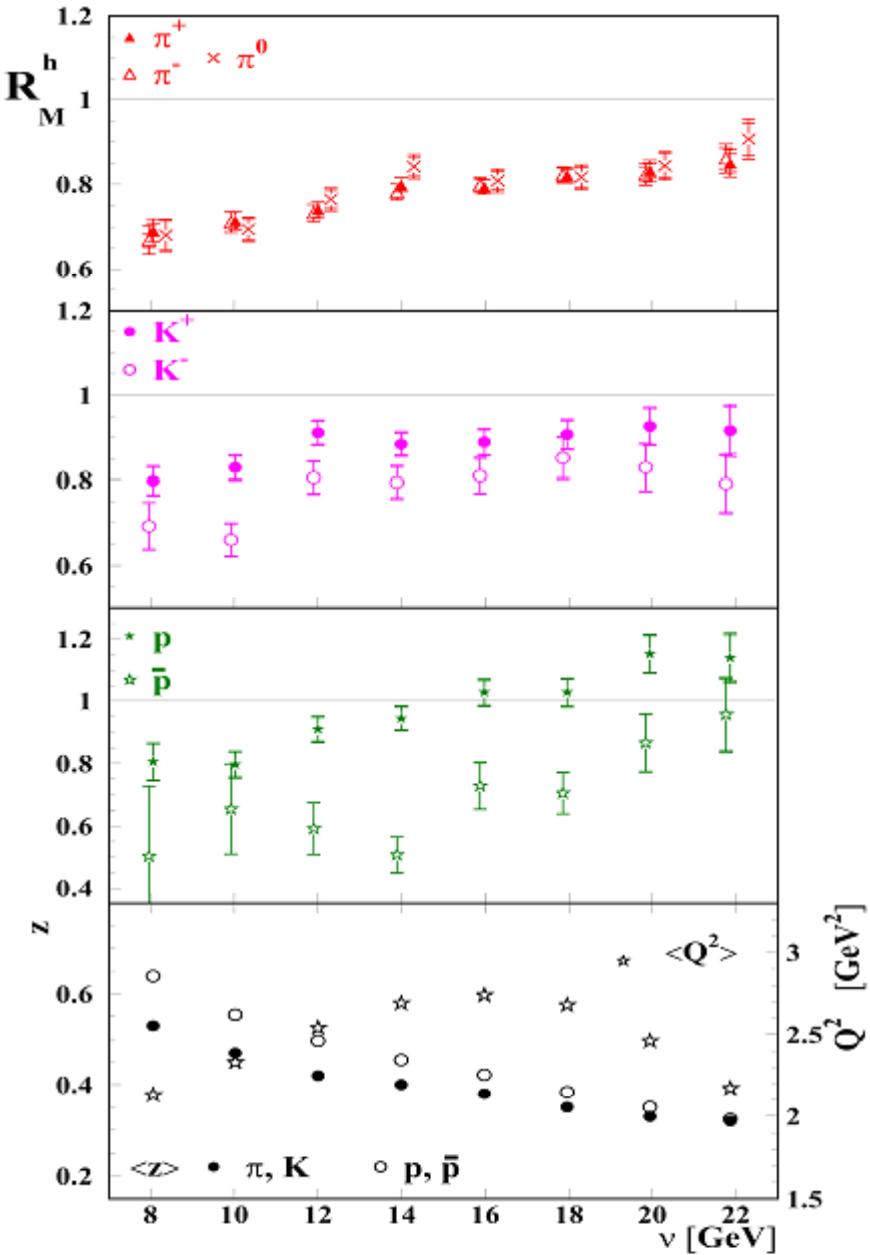
Krypton

Experimental findings:

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

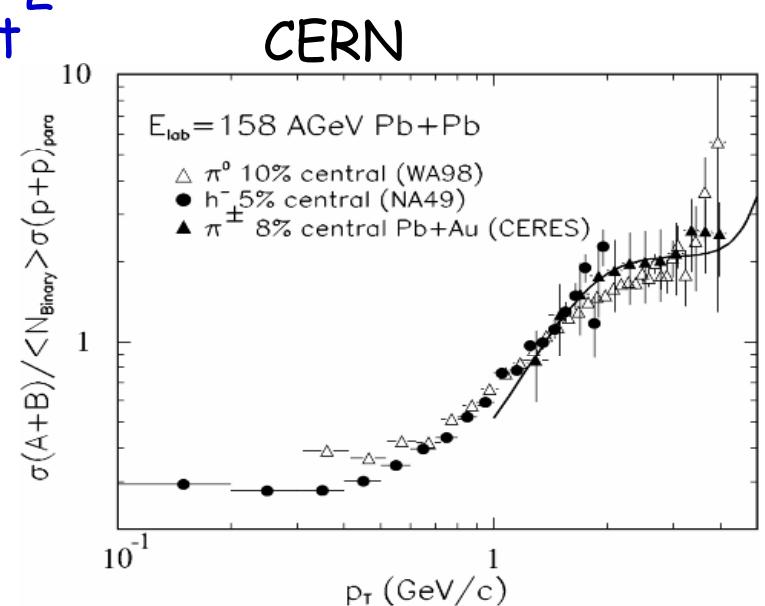
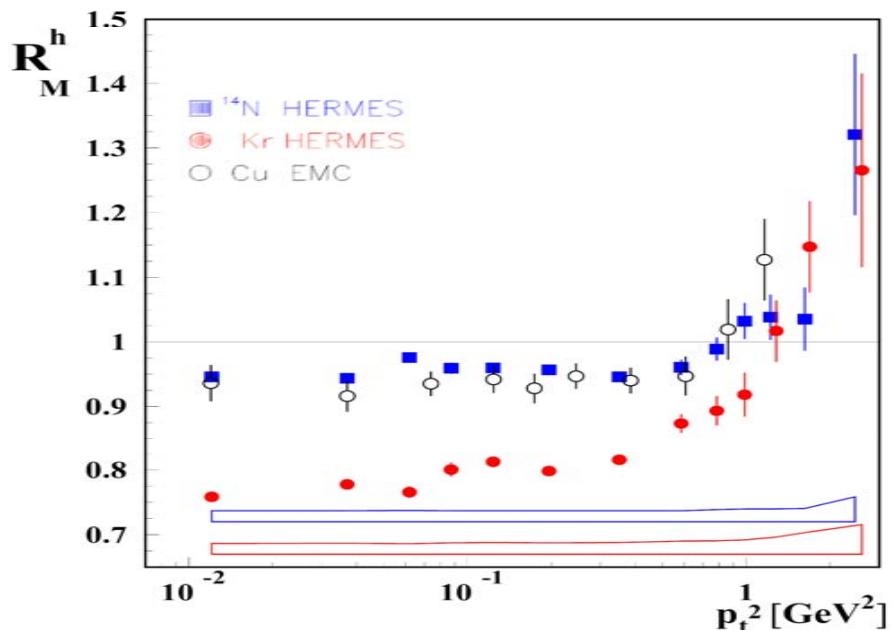
$$K^+ > K^-$$

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



Multiplicity ratio vs p_t^2

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



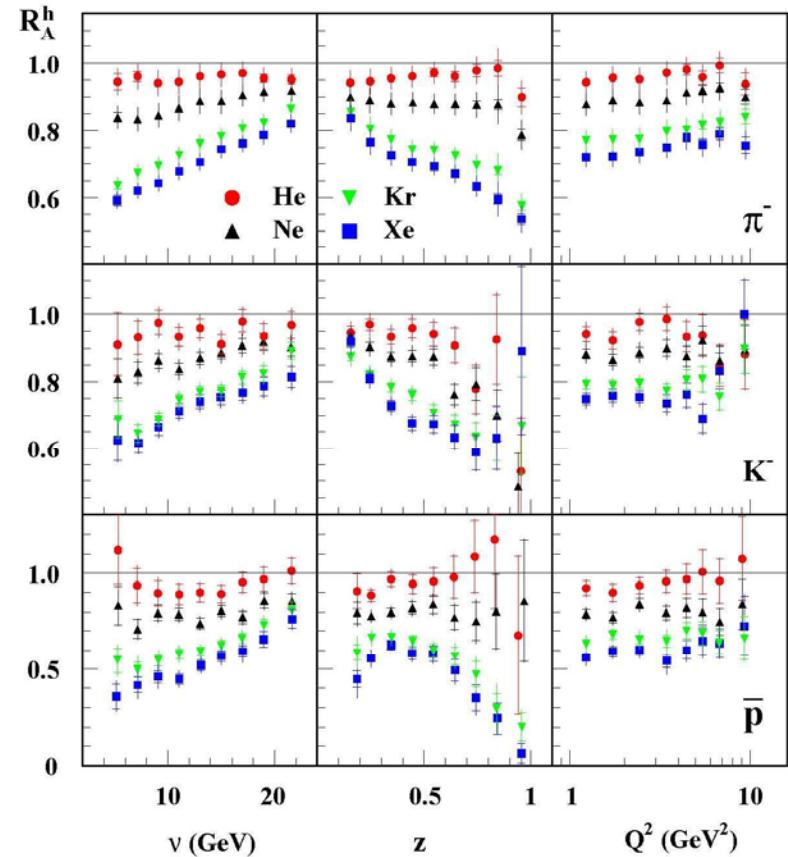
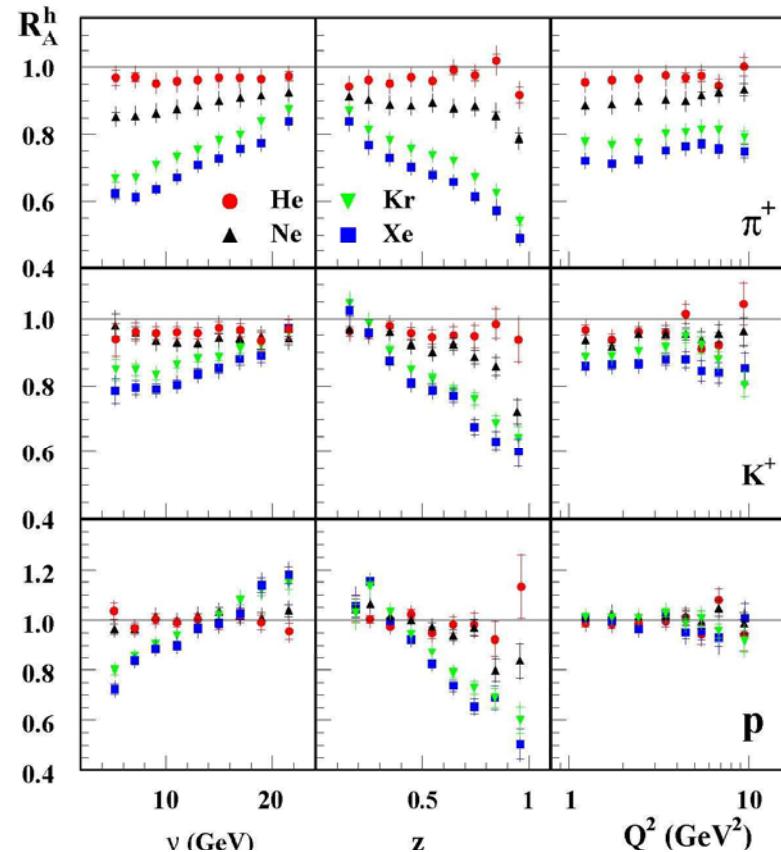
HERMES, PLB 577 (2003) 37

- DIS shows a p_t enhancement similar to that observed in HIC (SPS, RHIC non-central)

In DIS neither multiple scattering of the incident particle nor interaction of its constituents → FSI contribution to the Cronin

Multiplicity ratio : vs v, z, Q^2 for different hadrons

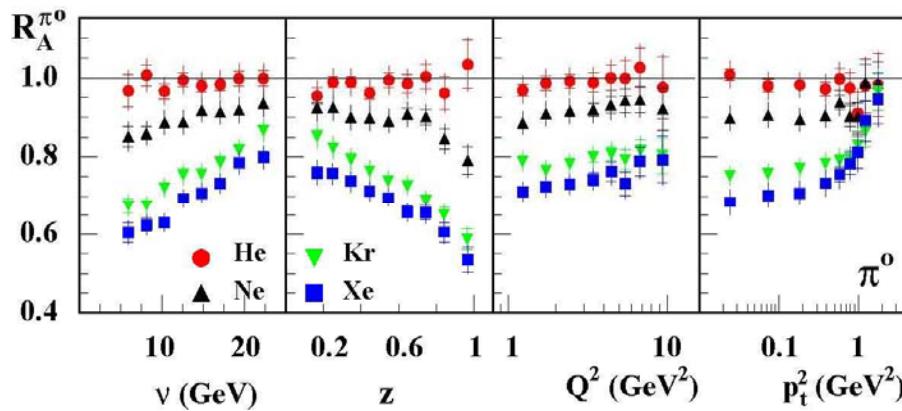
HERMES. NPB 780 (2007) 1



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

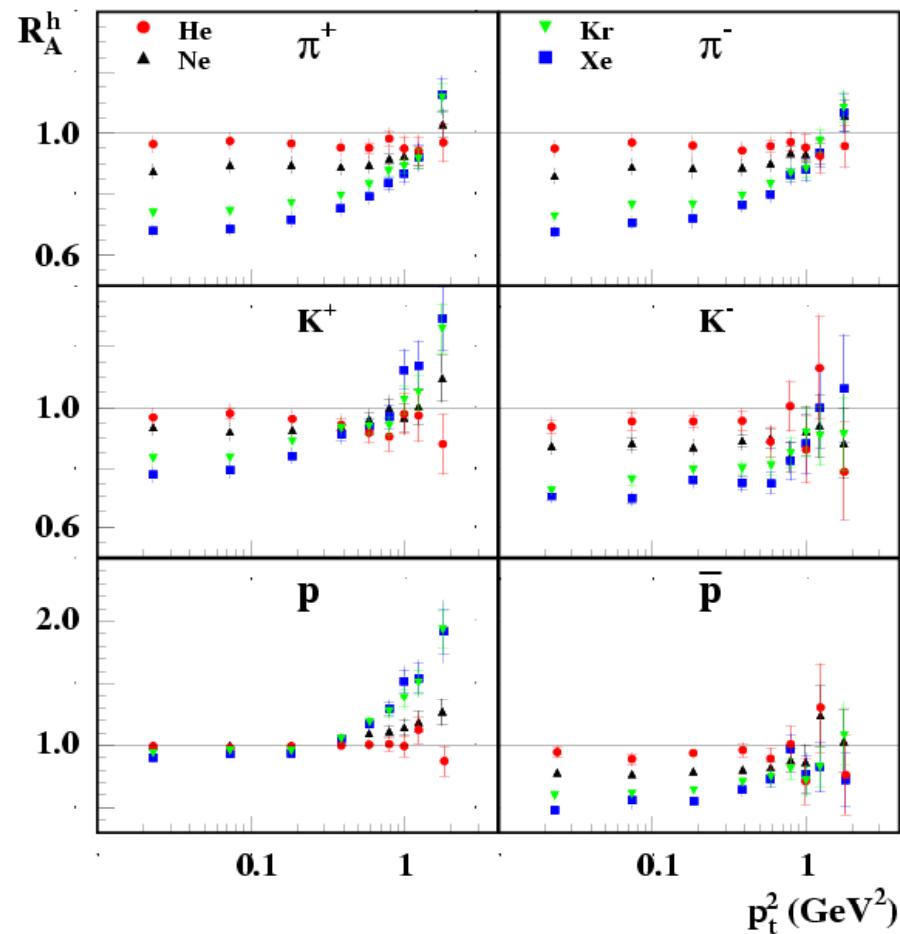
$$K^+ \neq K^-$$

$$p \neq \bar{p}$$



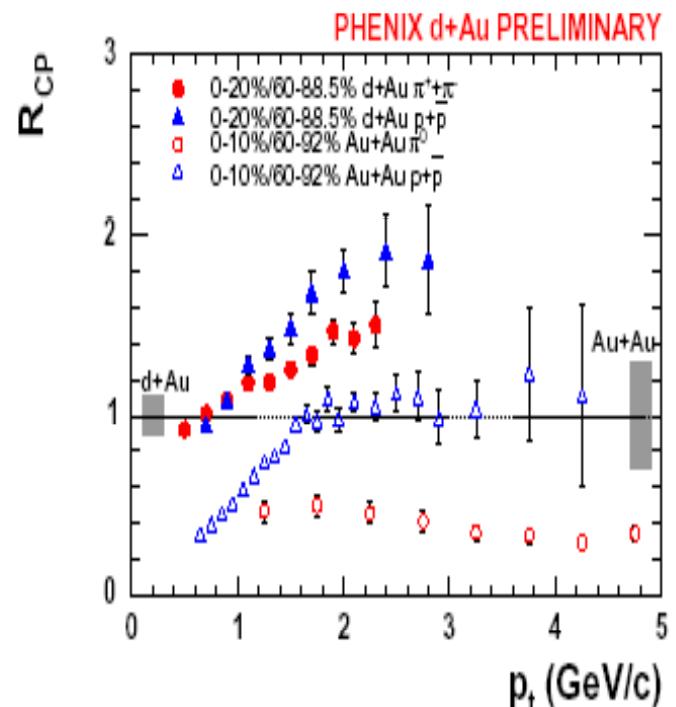
P_+ dependence for identified hadrons

HERMES, NPB 780 (2007) 1



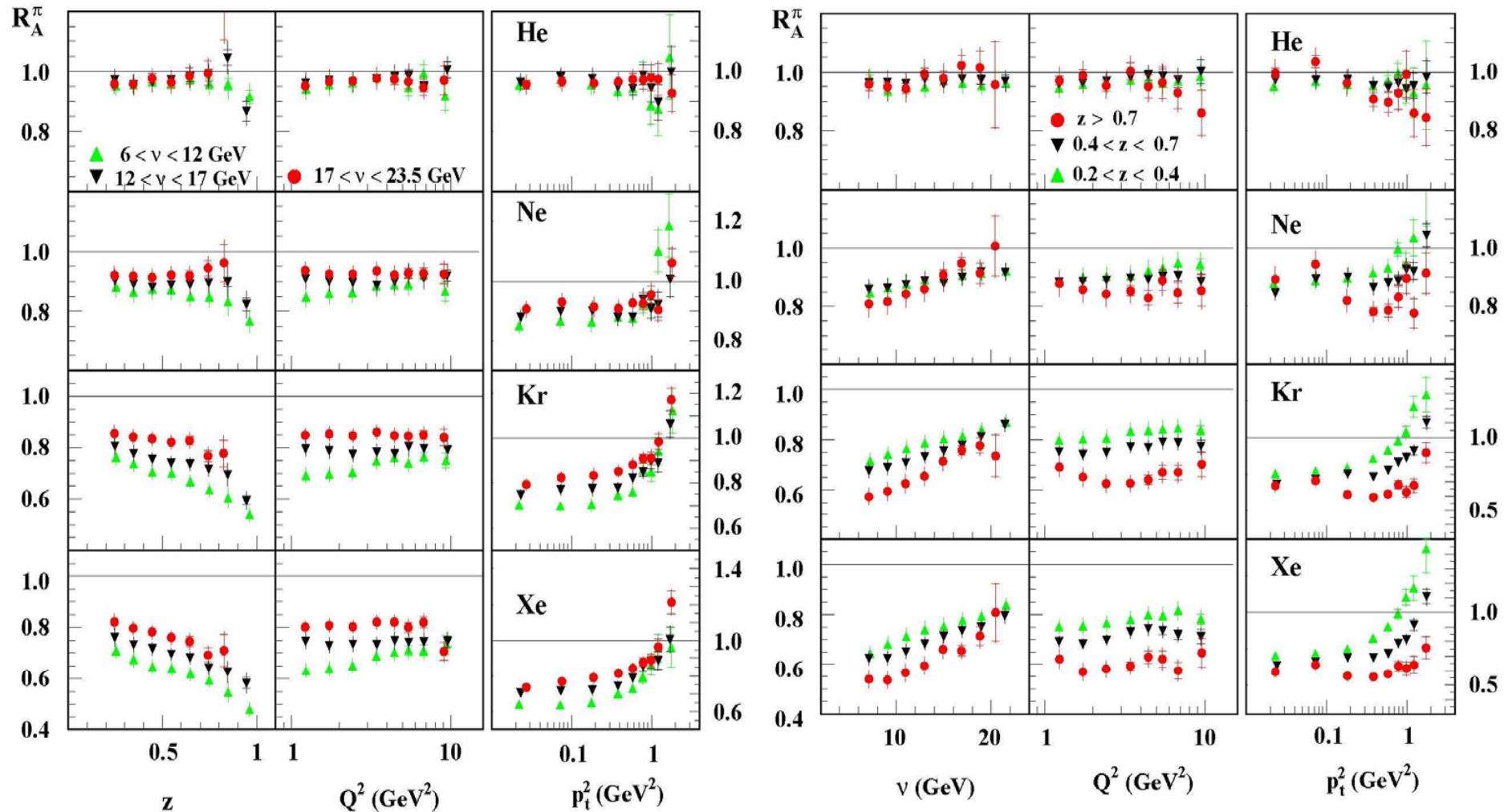
Cronin effect larger for protons

Nucl-ex/0403029



Multiplicity ratio two-dimensional

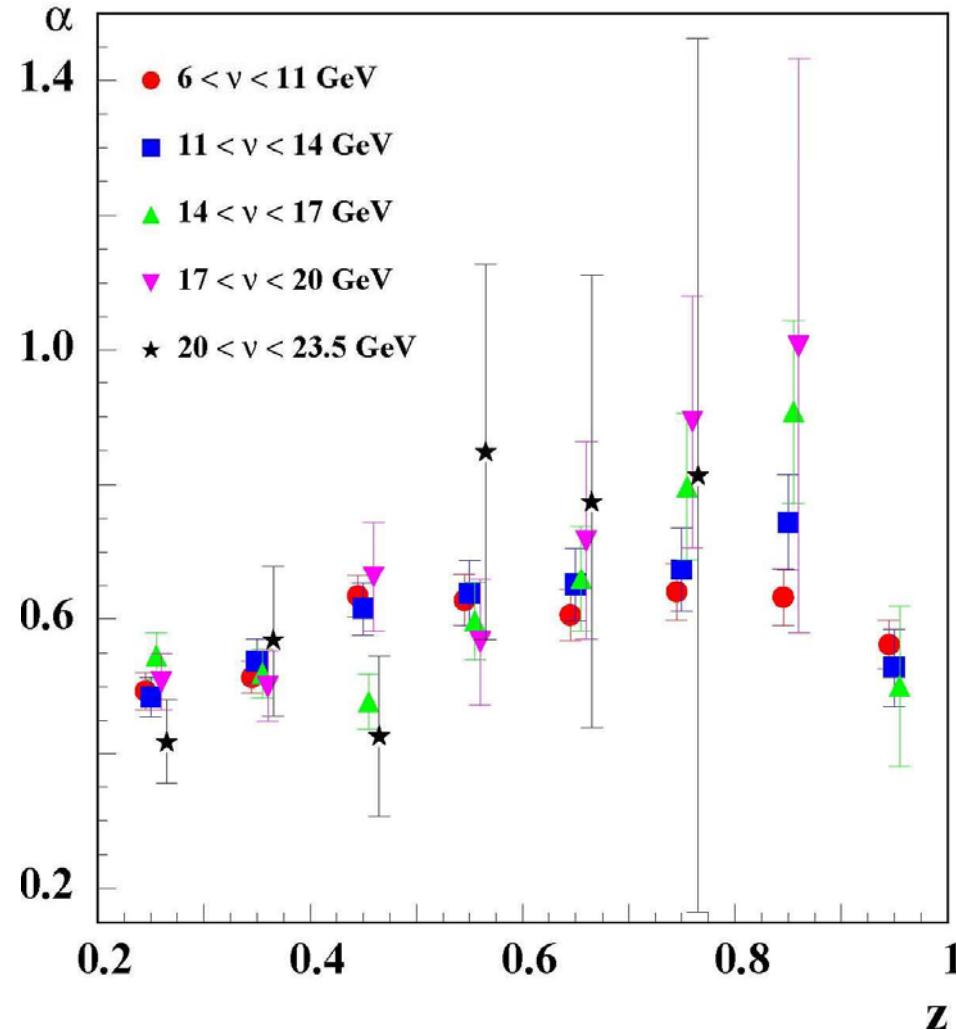
HERMES, NPB 780 (2007) 1



Reduce the correlation between z and v

A dependence of nuclear attenuation $1-R_M$

HERMES, NPB 780 (2007) 1

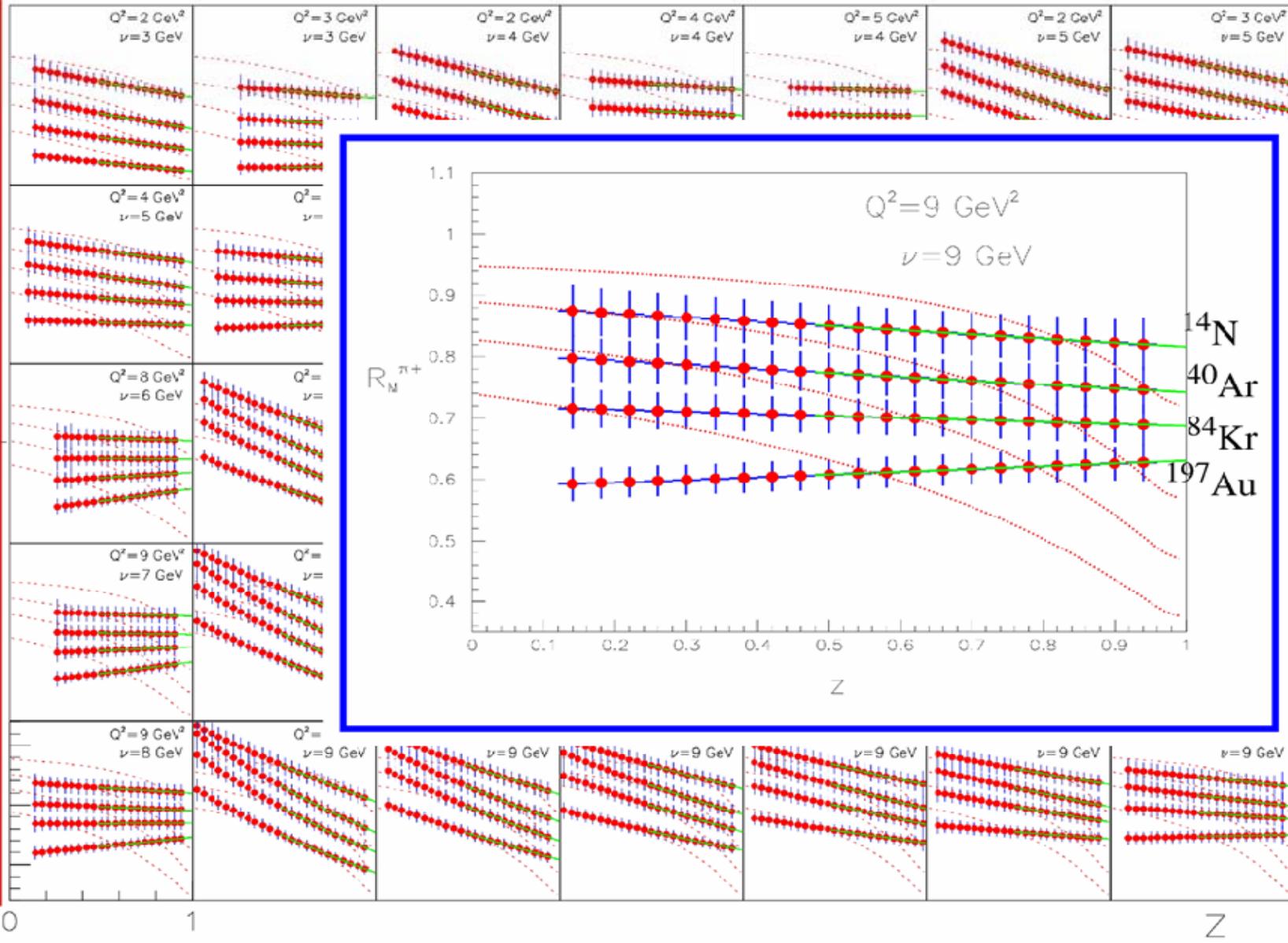


Data support a quadratic dependence on nuclear size
 A^α with $\alpha \sim 2/3$



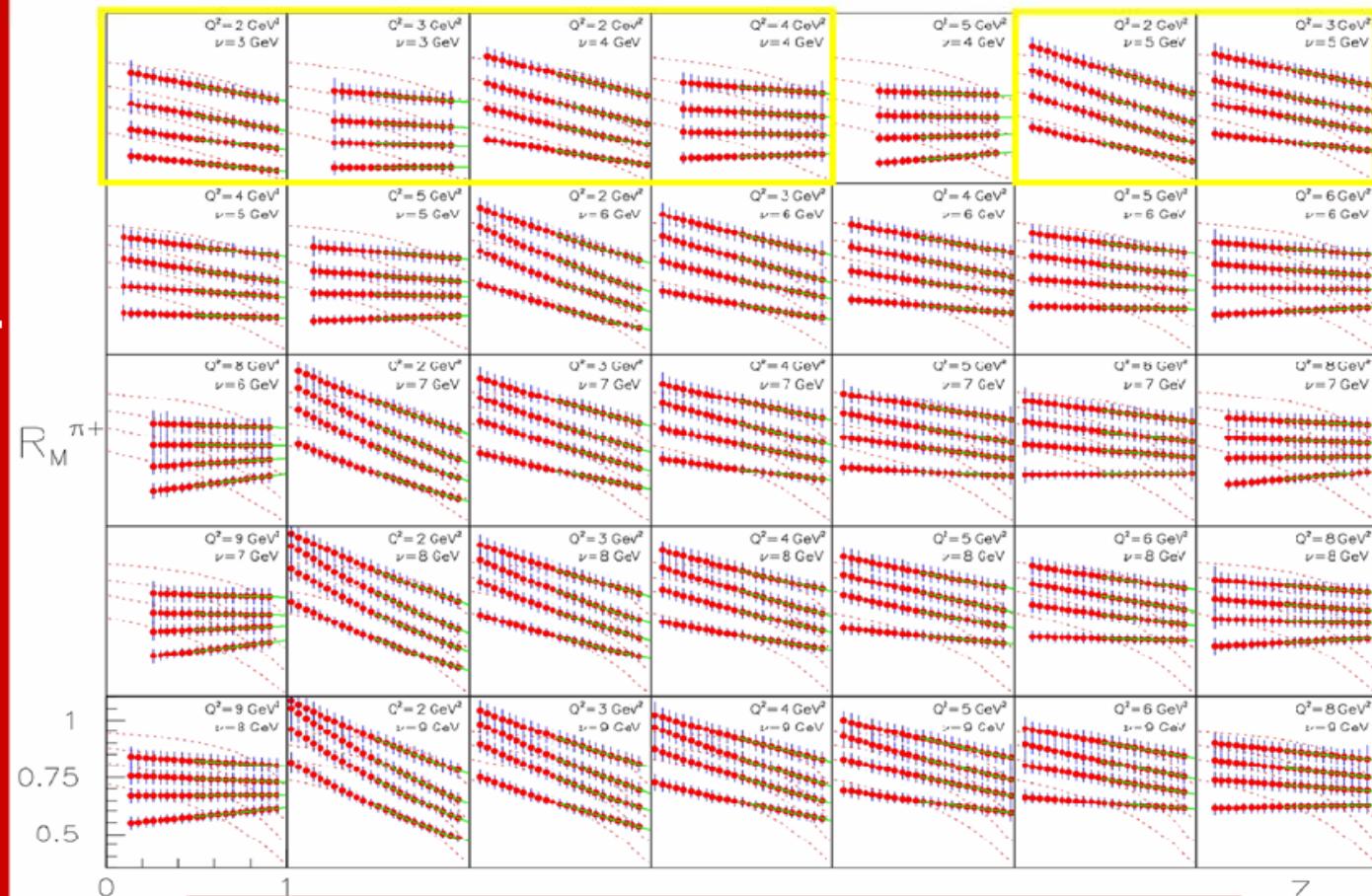
- Larger geometrical acceptance → detects more secondary particles from FSI.
- High statistics and wide range of final states:
 $\pi^+, \pi^-, \pi^0, K^+, K^-, K^0, p, \Lambda, \Sigma^{+0}, \Xi^{-0}$.
- 6 GeV beam : $Q^2 < 4 \text{ GeV}^2, v < 5 \text{ GeV}$.
12 GeV beam : $Q^2 < 9 \text{ GeV}^2, v < 9 \text{ GeV}$.

12 GeV Anticipated Data



12 GeV Anticipated Data

Examples of Experimental Data and Theoretical Predictions



Bins in yellow are accessible at 6 GeV

★ Theoretical
Models
At work

V. Muccifora



Models based on partonic energy loss

X.N. Wang *et al.* (PRL 89, 162301 (2002))

F. Arleo *et al.* (EPJ C 30, 213 (2003))

Models based on (pre)-hadronic interaction

B. Kopeliovich *et al.* (NPA 740, 211 (2004))

T. Falter *et al.* (PLB 594 (2004) 61)

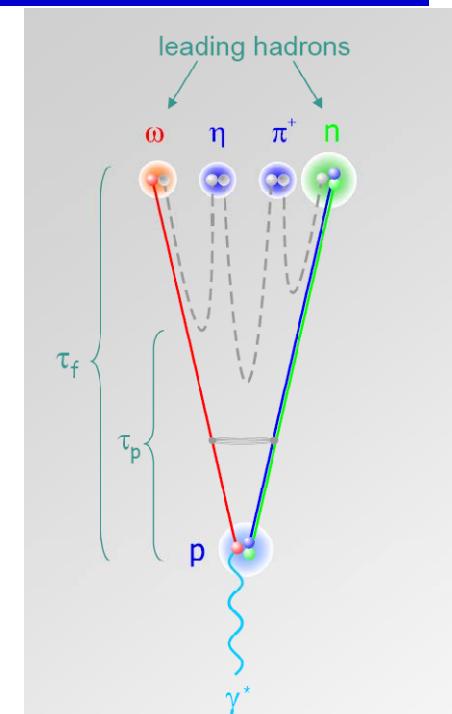
A. Accardi *et al.* (NPA 720, 131 (2003); NPA 761, 67 (2005))

N. Akopov *et al.* (Eur.Phys. J 44(2005) 219)

H.J. Pirner, D.Grunewald (hep-ph/0608033)

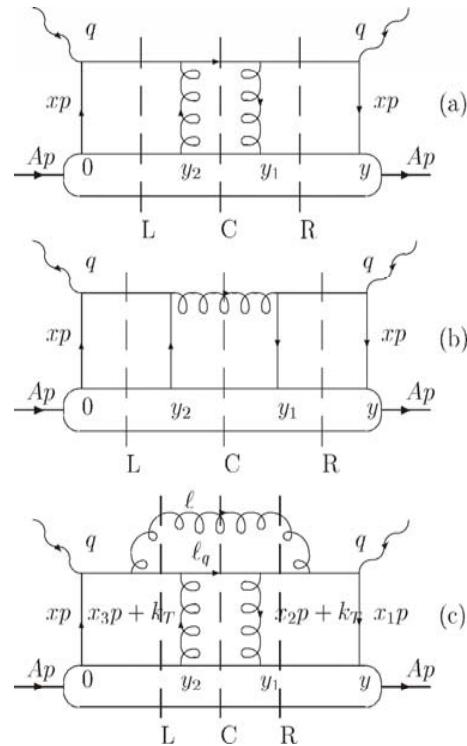
B. Kopeliovich *et al.* (NPA 782, 224 (2007))

K.Gellmeister, U. Mosel (nucl-th/0701064; nucl-th/07122200)



FF modification

FF and their QCD evolution are described in the framework of multiple parton scattering and induced radiation



Rescattering without gluon-radiation: p_T -broadening.

Rescattering with another q : mix of quark and gluon FF.

Gluon-rescattering including gluon-radiation: dominant contribution in QCD evolution of FF.

Importance to measure the full kinematical/dynamical dependence :

- transverse broadening : high energy
- mixing of hadron species : good PID
- hadron suppression at large z / enhancement at low z : full momentum acceptance

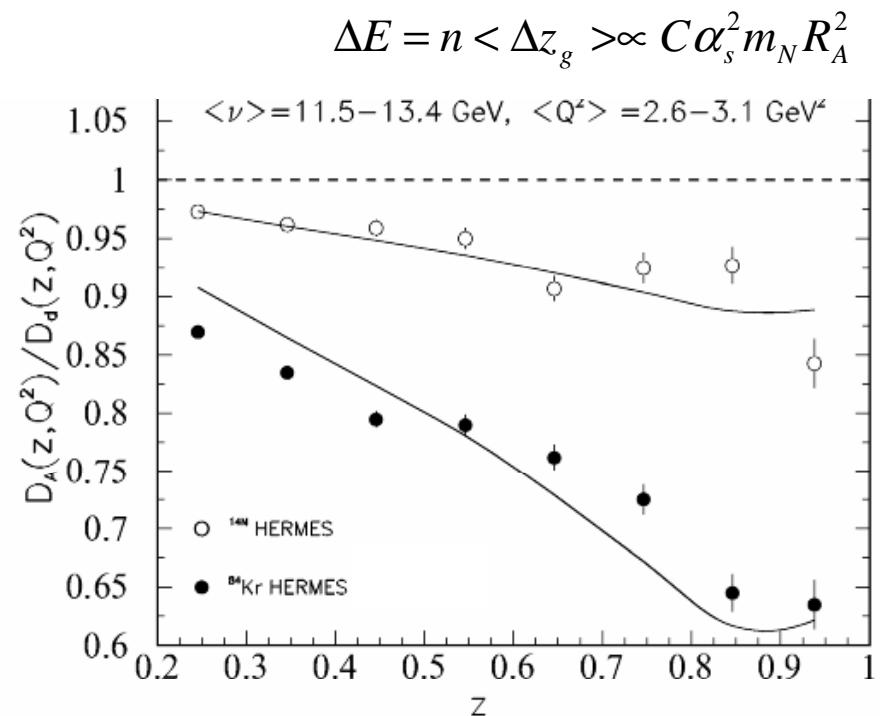
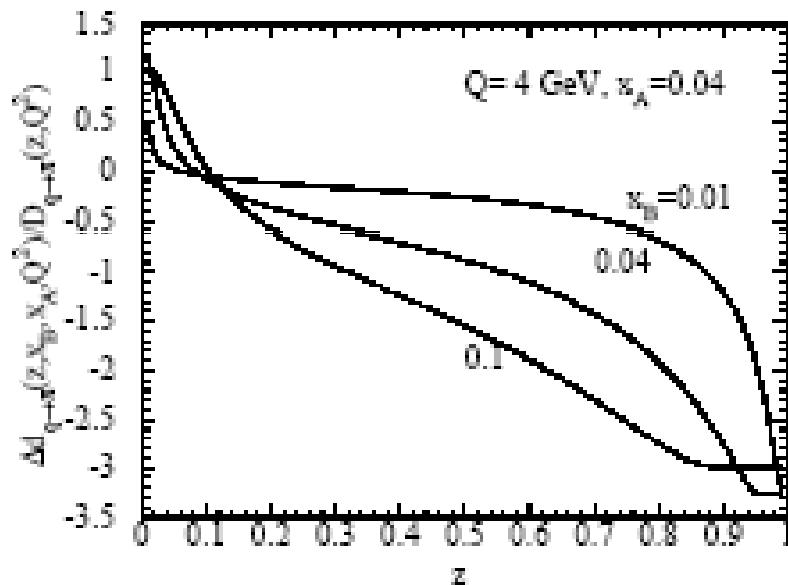
FF modification

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

Parton energy loss :

Landau-Migdal-Pomeranchuk interference pattern

H-T term in the QCD evolution equation of FFs $\rightarrow A^{2/3}$ dependence

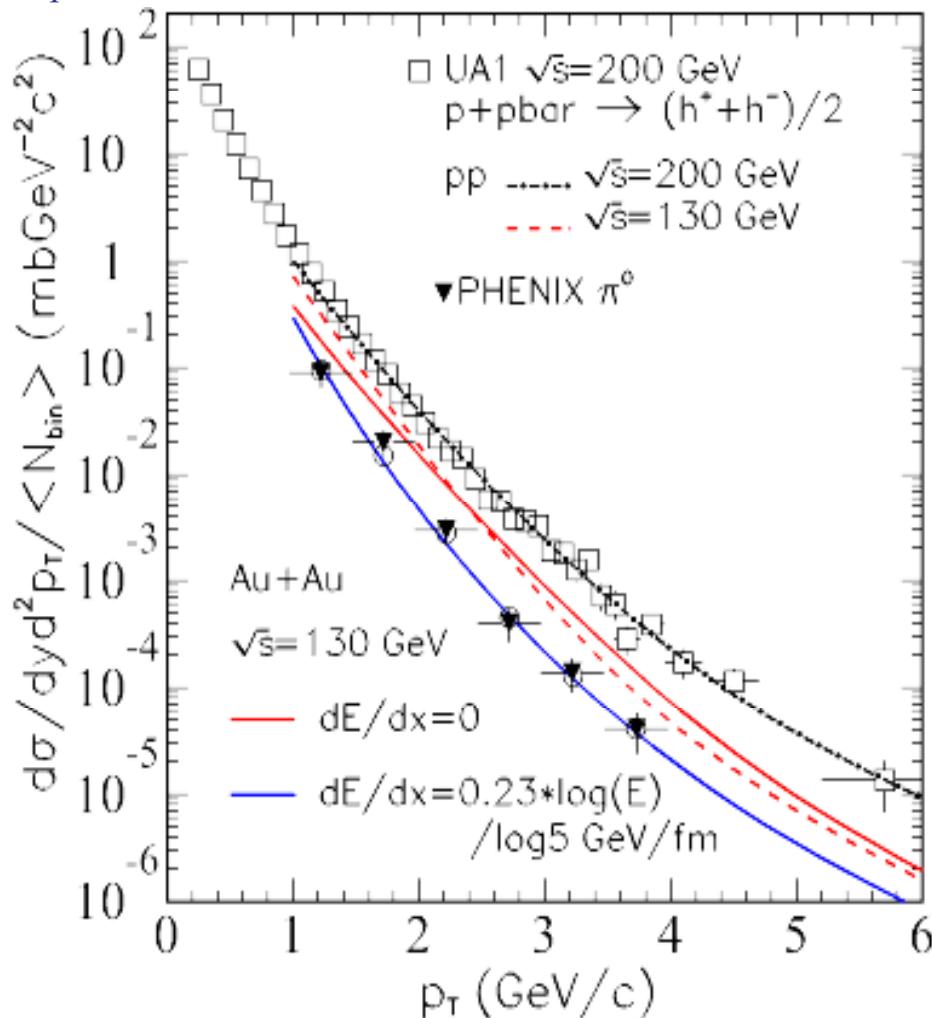


- 1 free parameter $C \equiv$ quark-gluon correlation strength in nuclei
- From ^{14}N data $C = 0.0060 \text{ GeV}^2$:
- HERMES : cold static nuclei $\Delta E_{\text{sta}} \propto \rho_0 R_A^{-2}$; ρ_0 gluon density and $R_A \approx 6 \text{ fm}$
 $\langle dE/dL \rangle \approx 0.5 \text{ GeV/fm}$ for 10 GeV quark in Au

dE/dL and Gluon density at RHIC

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

$$\Delta E_{\text{exp}} \approx \Delta E_{\text{sta}} (2\tau_0/R_A) \propto 2\rho_0 R_A \tau_0$$



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

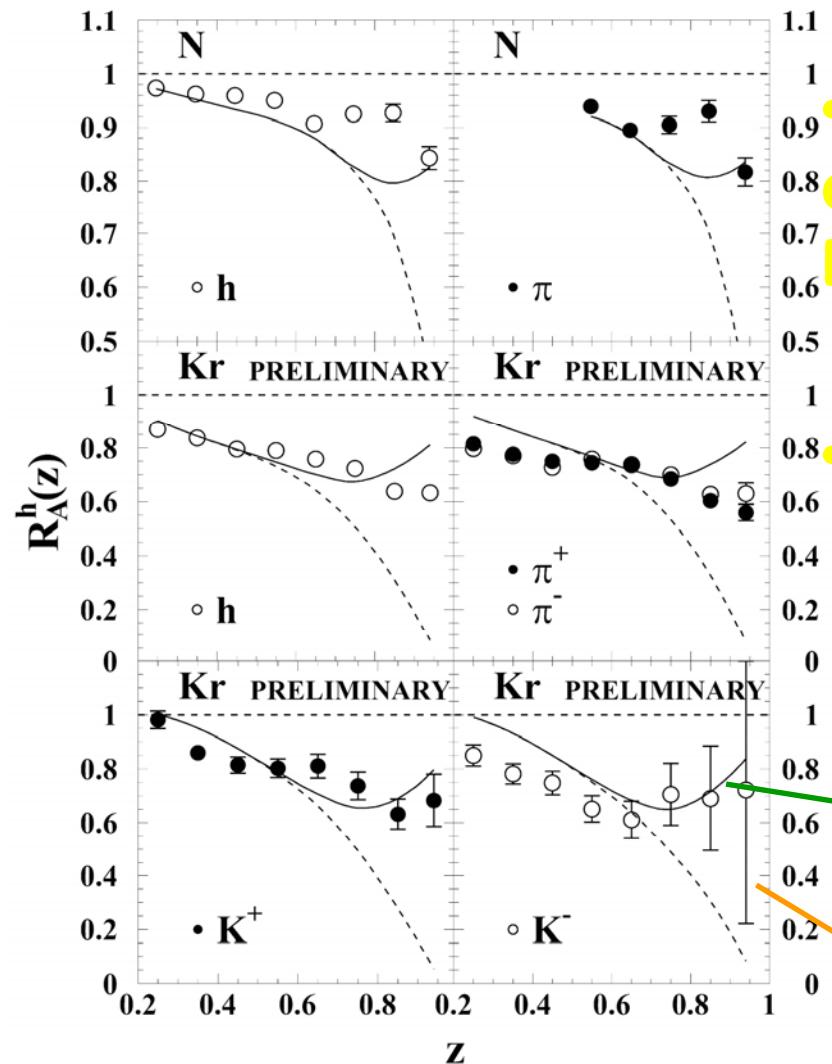
$\langle dE/dL \rangle \approx 0.5 \text{ GeV/fm}$ for
10 GeV quark in Au

- Cold \leftrightarrow Hot nuclear matter correlation
- Gluon density in Au+Au ~ 30 times higher than in cold matter

FF modification + formation time effect

F.Arleo, JHEP 0211, (2002) 044

F.Arleo, EPJ C30, (2003) 213



• Probability distribution in the energy loss computed in the BDMS formalism

• Gluon transport coefficient fixed from Drell-Yan
 $q=0.72 \text{ GeV/fm}^2$

With formation time effect

Without formation time effect

Gluon Bremsstrahlung

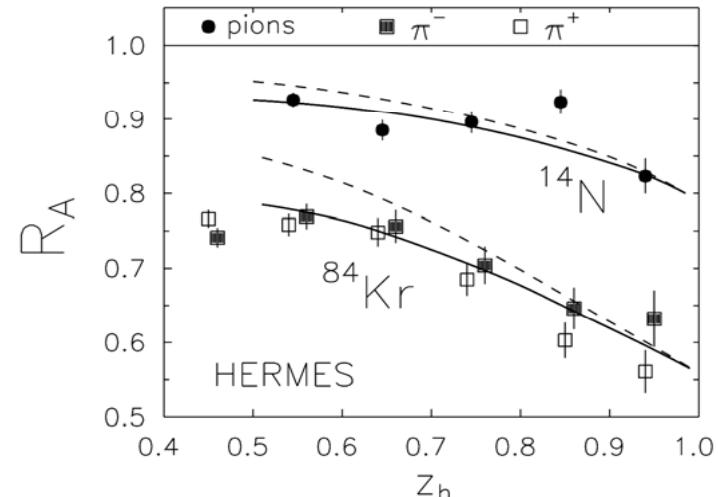
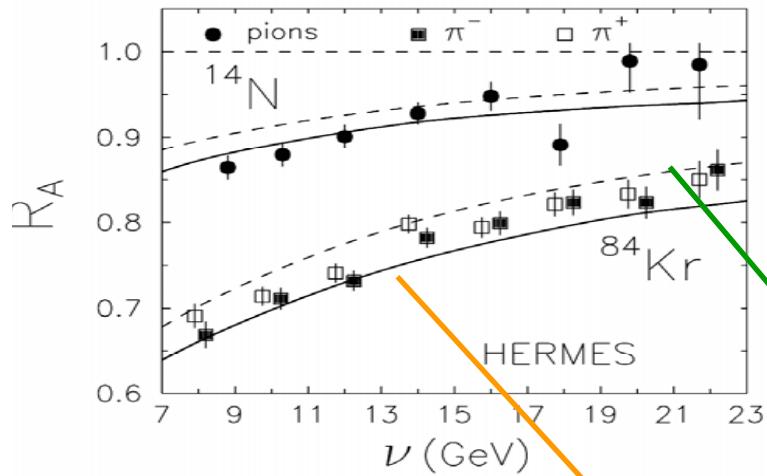
FF modification: Nuclear Suppression + Induced Radiation

B.Kopeliovich et al.,
hep-ph/9511214
NPA 740, 211 (2004)

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

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

Pre-hadron production time: $\langle \tau_p \rangle \propto (1-z)zv/Q^2$



Nuclear Suppression

Nuclear Suppression + Induced Radiation

FSI in BUU Transport model

T.Falter et al. PLB 594 (2004) 61

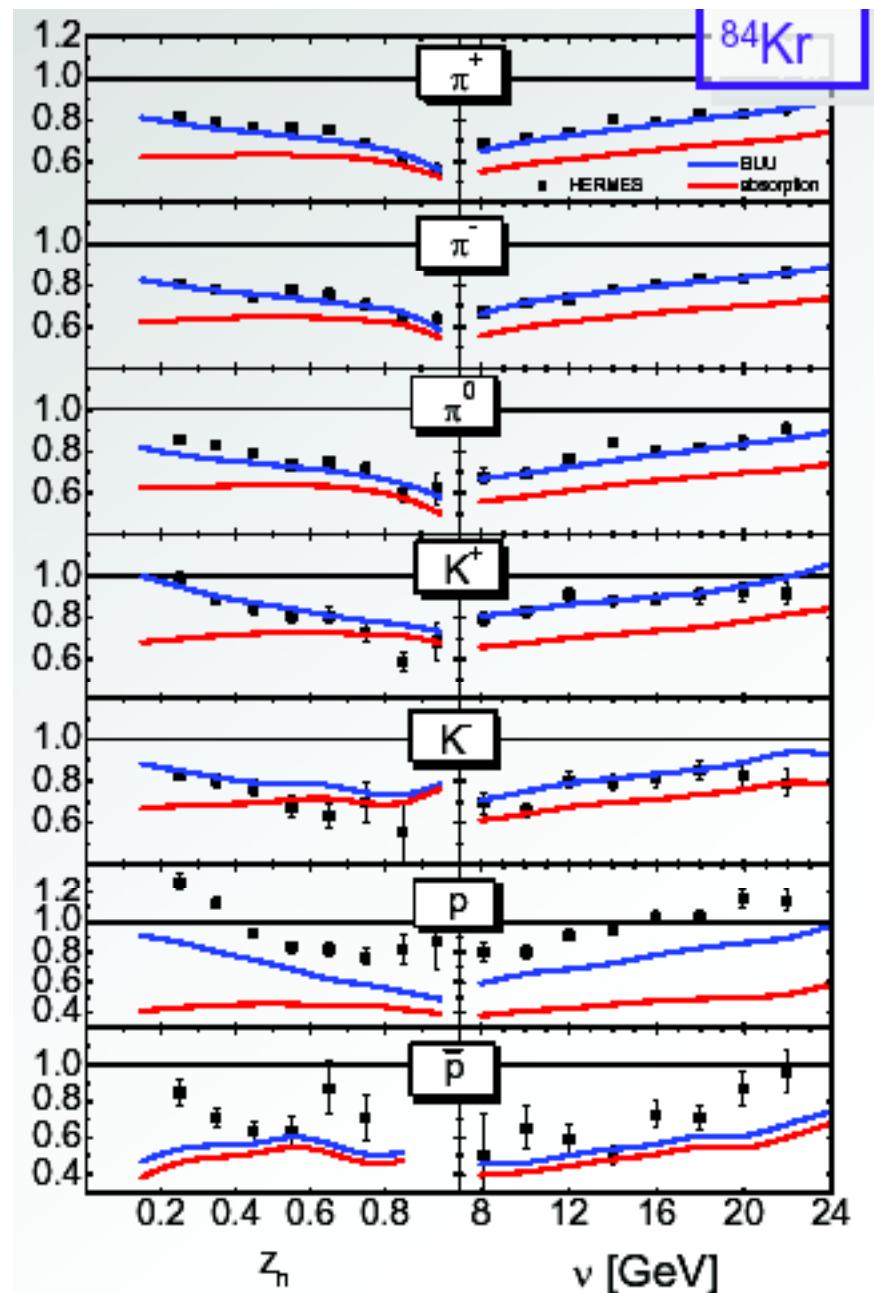
—Propagation of final state X within BUU transport model.

— pre-hadron $\tau_p = 0$
hadron $\tau_F = E_h/m_h \tau_0$
 $\tau_0 = 0.5$ fm

Leading pre-hadron interacts during τ_F with reduced cross Section $\sigma^{\text{lead}} = 0.33\sigma^h$

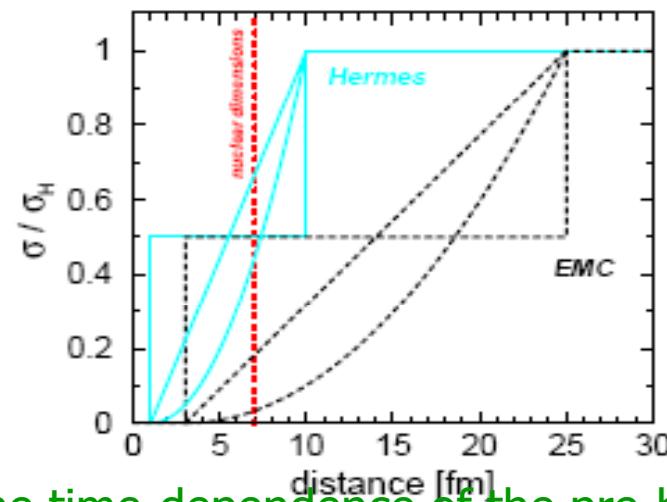
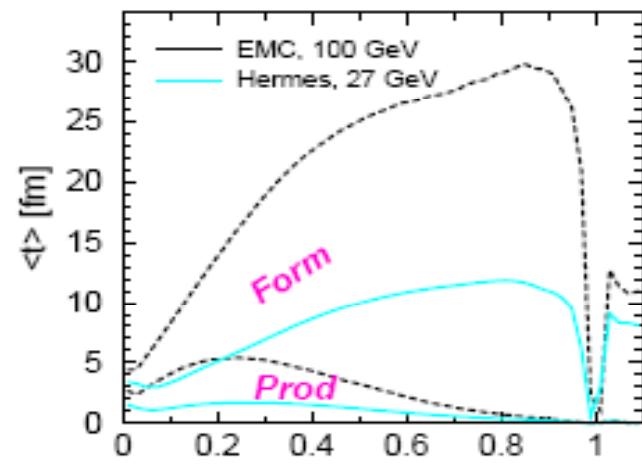
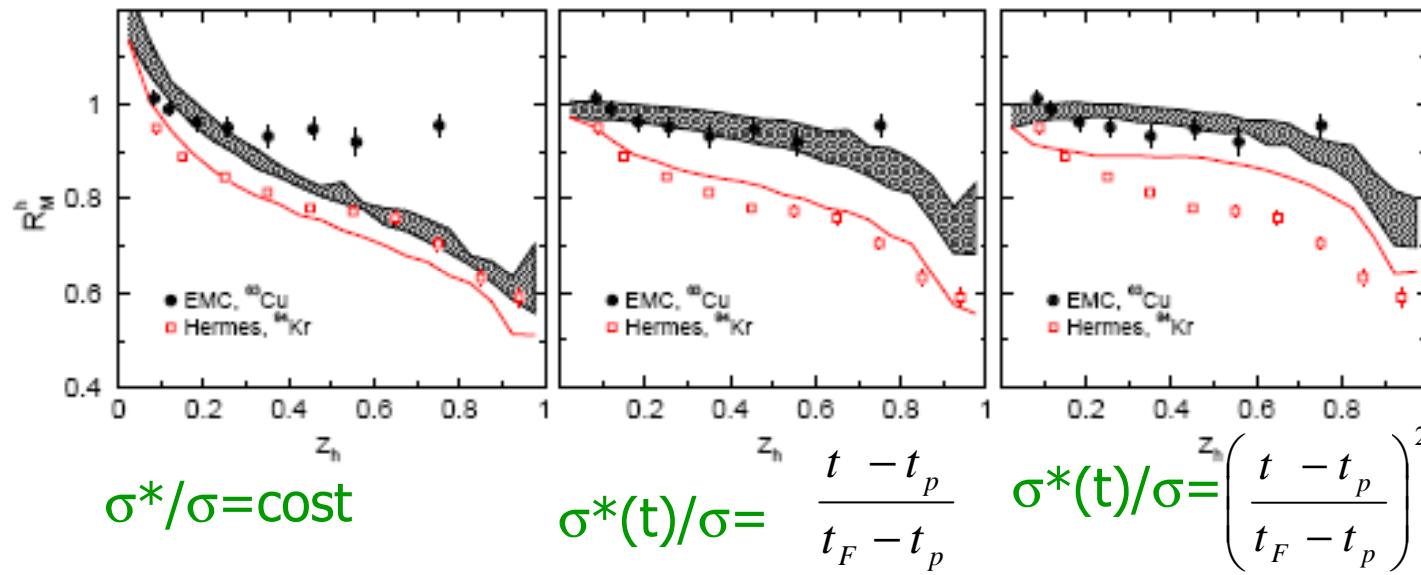
— purely absorptive FSI

• Prediction for A^α -dependence $1-R_M$
 $\alpha = 0.22-0.29$ at $z=0.95$



FSI in GiBUU Transport model

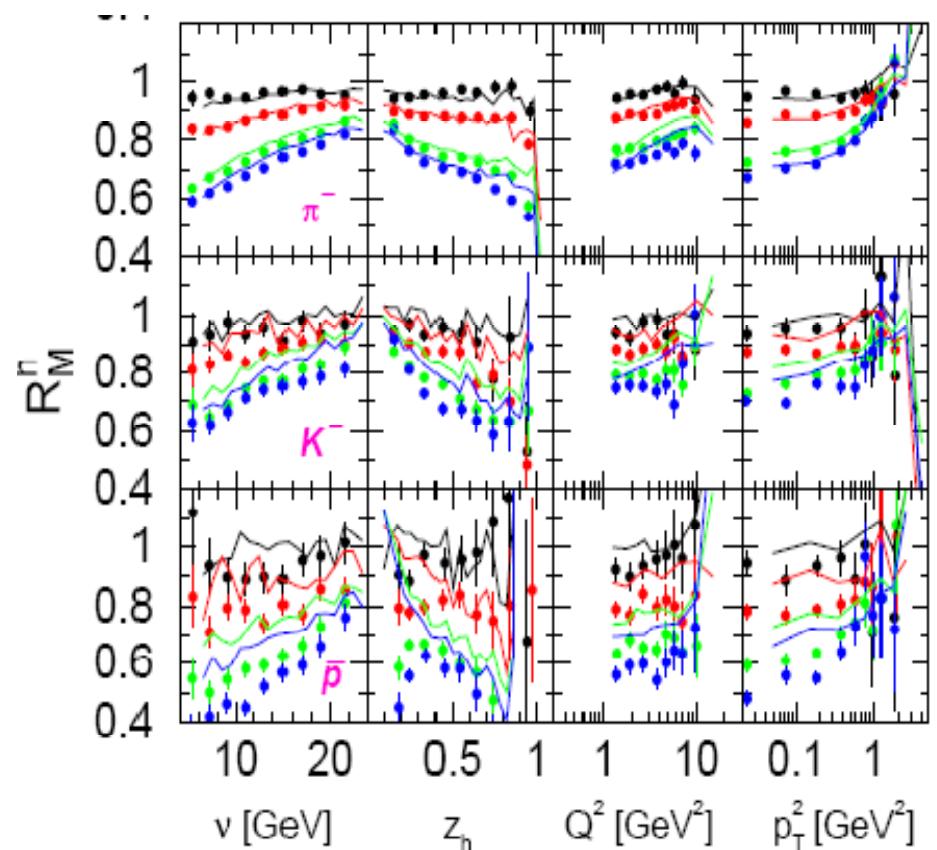
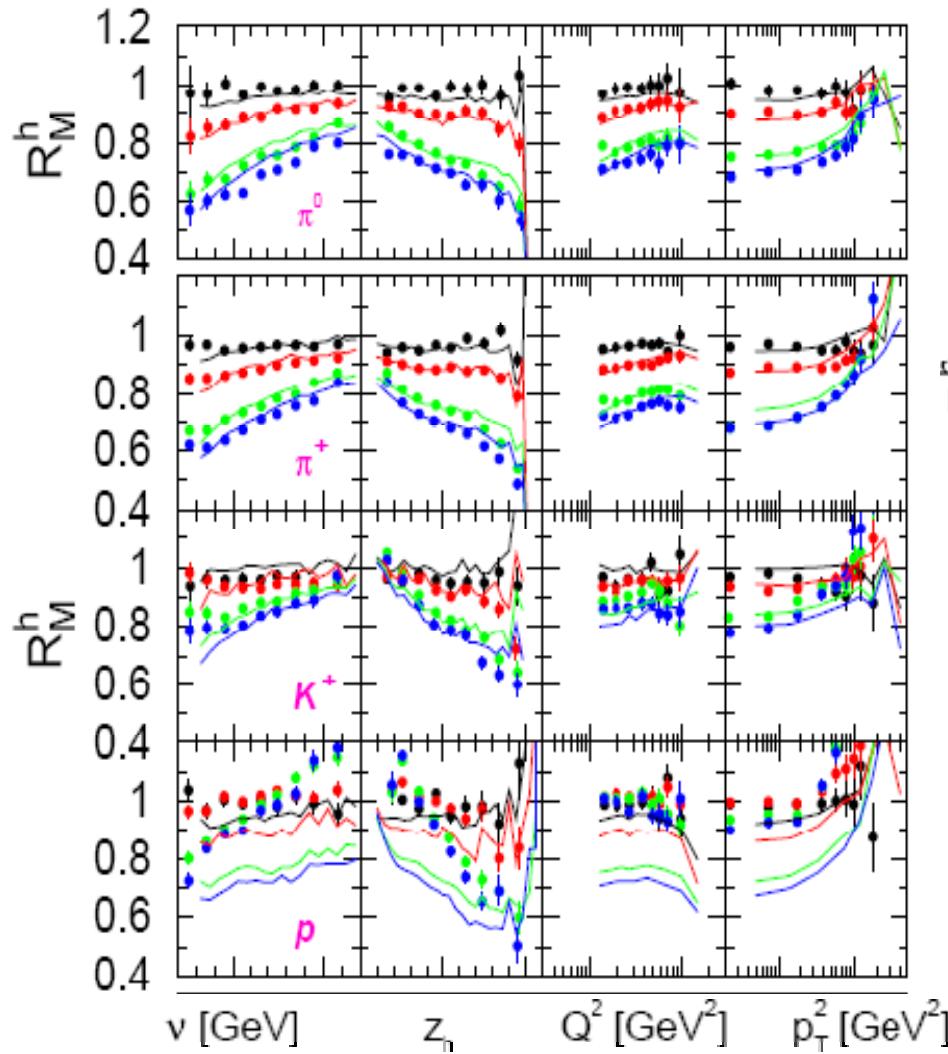
K.Gallmeister et al. nucl-ph/07122200



- Sensitivity to different scenarios for the time-dependence of the pre-hadronic cross section
- At lower beam energies less sensitivity to pre-hadronic interaction as hadronization happens in medium.

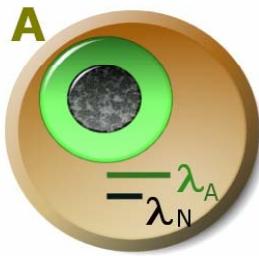
FSI in GiBUU Transport model

K.Gallmeister et al. nucl-ph/0712220C



Rescaling + Absorption Model

A.Accardi et al.,
NPA761(2005)67

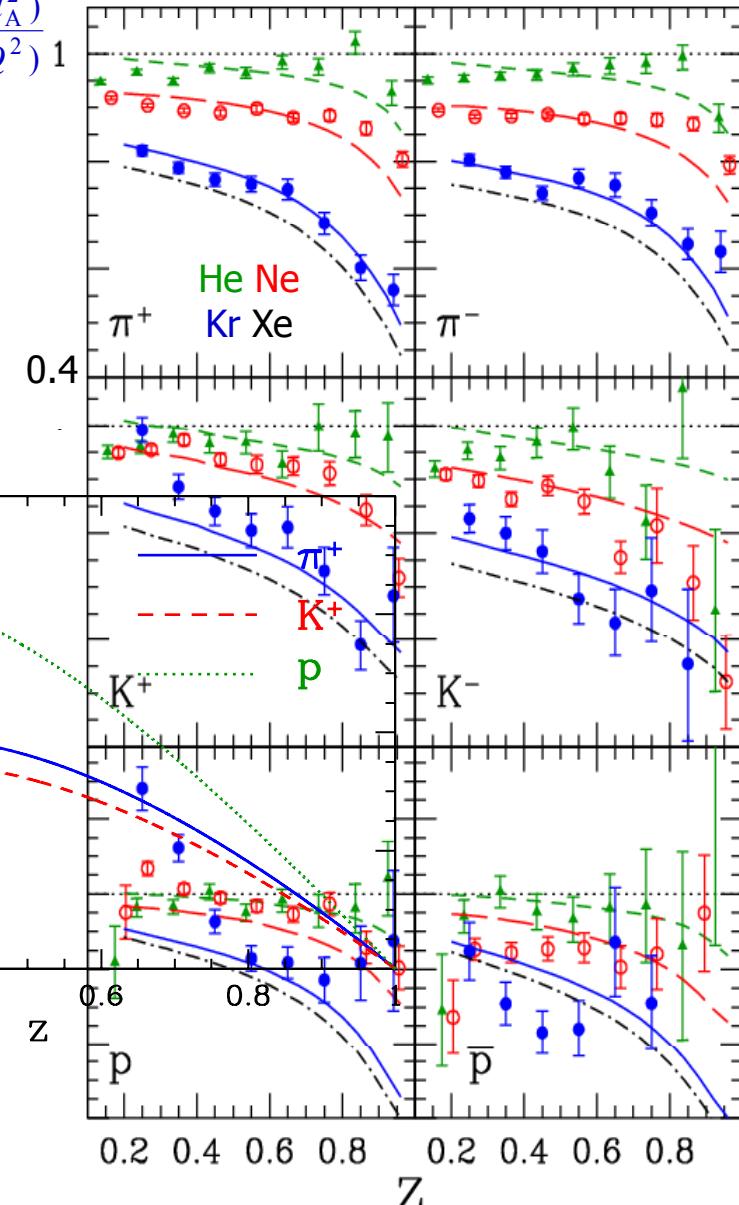
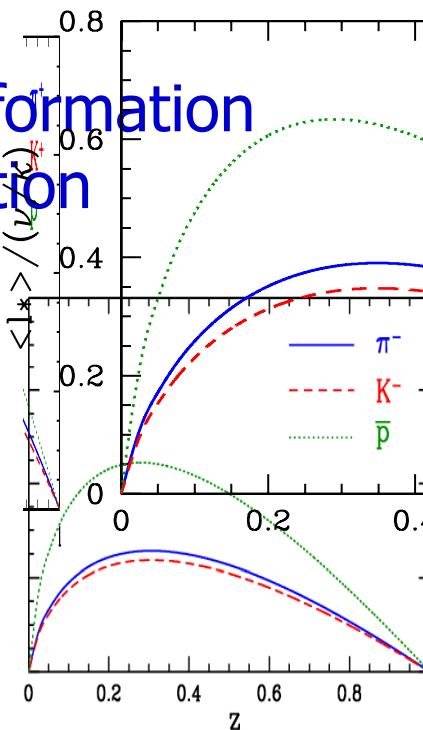
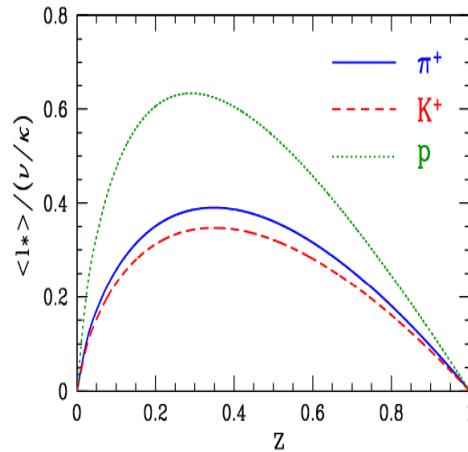


$$\lambda_A > \lambda_N ; \quad \xi_A(Q^2) = \left(\frac{\mu_N^2}{\mu_A^2} \right)^{\frac{\alpha_s(\mu_A^2)}{\alpha_s(Q^2)}} 1$$

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

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

Flavor dependent formation length and absorption



Higher Twist Effects

D.Grunewald, H.J.Pirner hep-ph/0608033

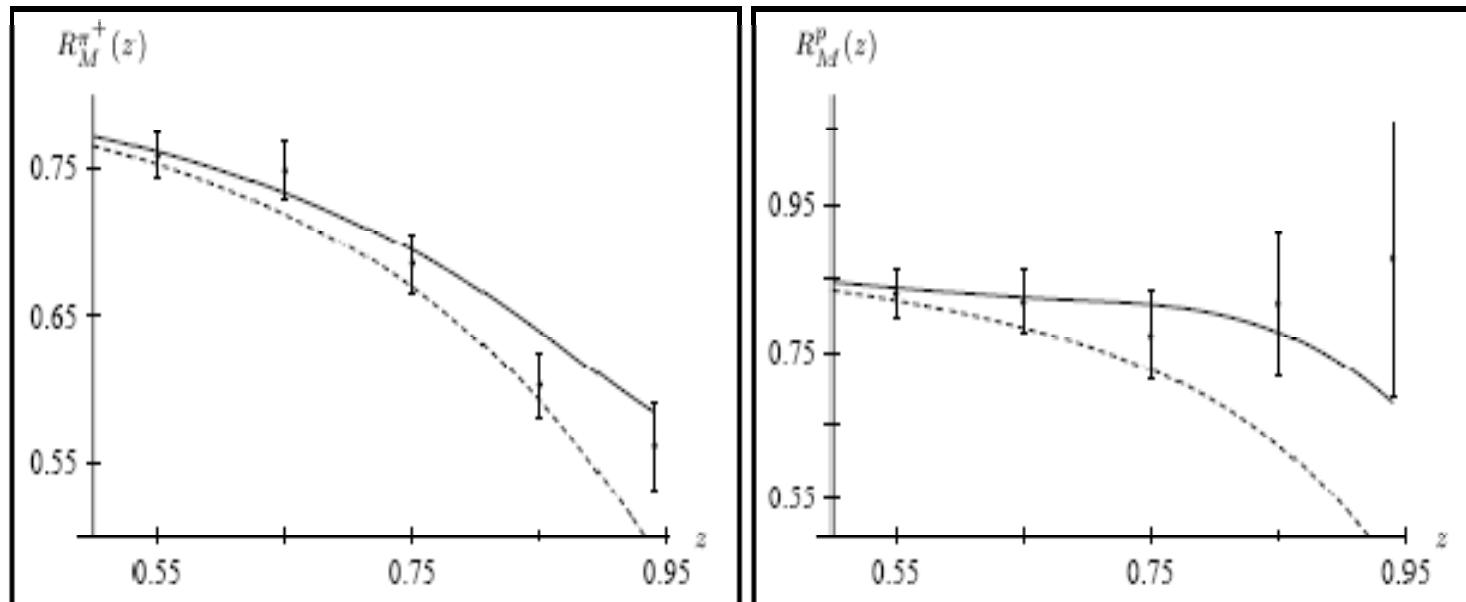
$$D_{h/q}(z, Q^2) = D^{LT}(z, Q^2) + D^{HT}(z, Q^2)$$

$$D_\pi^{HT}(z, Q^2) = 1/3 F_\pi(Q^2)$$

$$D_N^{HT}(z, Q^2) = 1/3 F_N(Q^2)$$

@ $Q^2=2\text{GeV}^2$ $D^{LT}(z, Q^2) \propto (1-z)$ \rightarrow for $z > 0.7$ HT direct productions takes over.

π and p at HERMES for Kr



- Dashed lines: LT FF of A.Accardi et al., NPA761(2005)67
- Solid lines: LT+ HT FF of D.Grunewald, H.J.Pirner hep-ph/0608033

V. Muccifora



A -dependence in absorption models

- Common expectation in absorption models: $1-R_M \propto L \propto A^{1/3}$ has been shown to fail

[A.Accardi et al., NPA761(2005)67,
H.P.Blok , L.Lapikas P.R.C 73 038201 (2006),
H.J.Pirner,D.Grunewald hep-ph:0608033]:

- Analytical calculation

$$1-R_M = c_1 A^{2/3} + c_2 A^{4/3} + O[A^2]$$

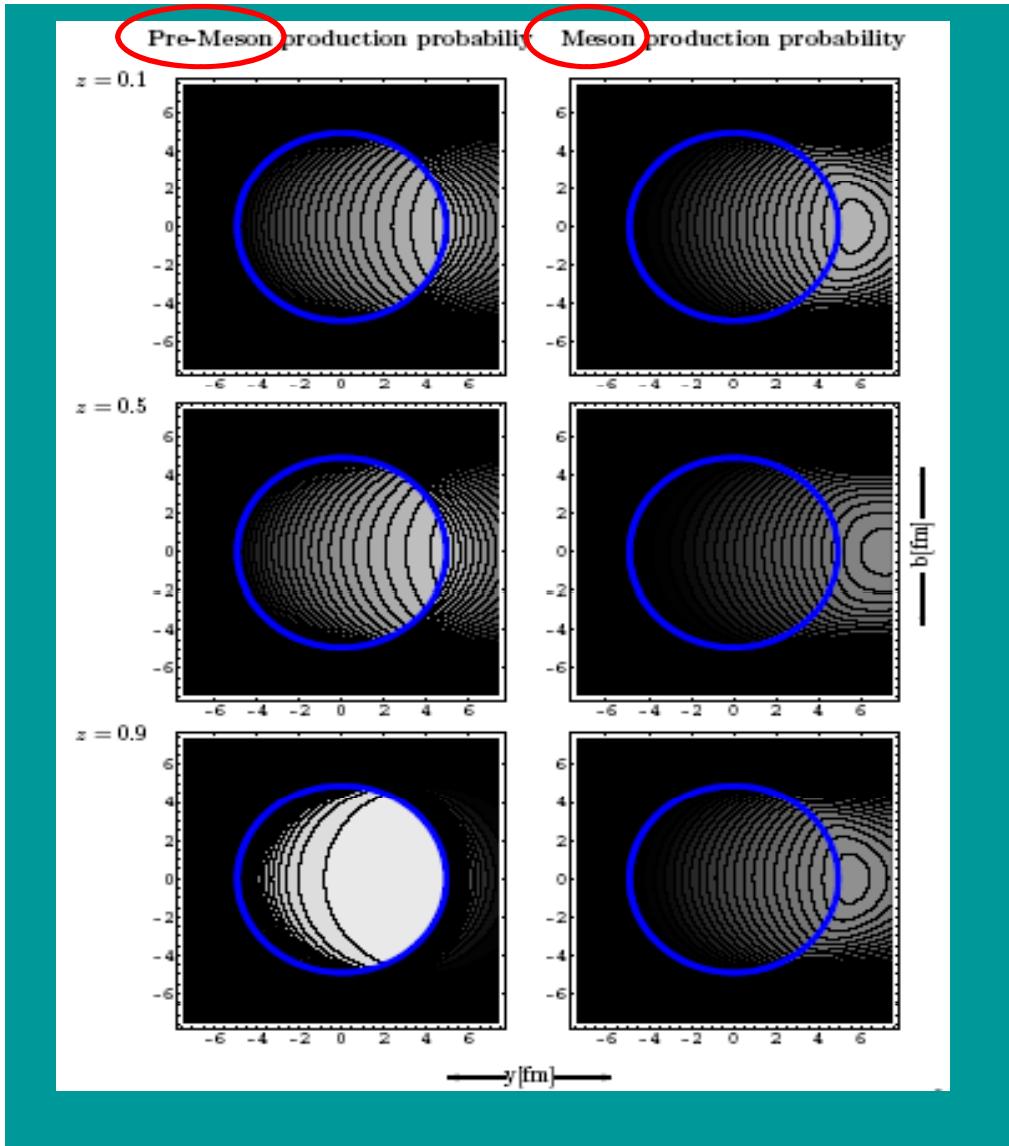
$c_2(z) \ll c_1(z)$, quickly convergence over the z range \rightarrow

$$1-R_M = c A^\alpha \quad \text{with } c \sim c_1(z) \text{ and } \alpha \sim 2/3.$$

z	Theory			
	He (N)	Ne	Kr	Xe
0.25	0.9 ± 0.9	0.70 ± 0.13		
0.35	0.8 ± 0.9	0.72 ± 0.13		
0.45	0.8 ± 0.9	0.73 ± 0.13		
0.55	0.9 ± 0.7	0.71 ± 0.13		
0.65	1.1 ± 0.8	0.70 ± 0.10		
0.75	1.4 ± 0.9	0.68 ± 0.08		
0.85	1.9 ± 1.2	0.65 ± 0.06		
0.95	3.3 ± 1.6	0.57 ± 0.05		

Pre-Hadron and Hadron-Production probabilities (at HERMES energies for Kr target)

D.Grunewald, H.J.Pirner hep-ph/0608033



Different formation areas:

- Hadrons are mostly produced outside the nucleus
 - Pre-hadrons forms inside the nucleus
- $A^{2/3}$ -dependence in the absorption models:
mostly pre-hadrons from the away surface of the nucleus contribute.

Models based on pre-hadronic interaction

- Induced radiation << absorption or rescattering
- Color neutralization inside the medium
- Pre-hadron formation and interaction $\rightarrow A^{2/3}$
- Hadron formation mainly outside the nucleus
 - \Rightarrow Strong dependence on the pre-hadron interaction cross section, formation times.

Models based on partonic energy loss

- Energy loss mechanism mainly, competing processes play a modest role.
- Energy loss mechanism for the hadron suppression $\rightarrow A^{2/3}$
 - \Rightarrow Strong dependence on the gluon transport coefficient that reflects the medium gluon density

Observables sensitive to the model assumptions.

- Double/single hadron production
A.Majumder and X.N.Wang hep-ph/0410078.
- p_t -broadening and its z -dependence.
B.Z.Kopeliovich et al. NPA 740, 211 (2004).

Double hadron/single hadron production

$$R_{2h}(z_2) = \frac{\left(\frac{dN^{z_1>0.5}(z_2)/dz_2}{N^{z_1>0.5}} \right)_A}{\left(\frac{dN^{z_1>0.5}(z_2)/dz_2}{N^{z_1>0.5}} \right)_D}$$

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

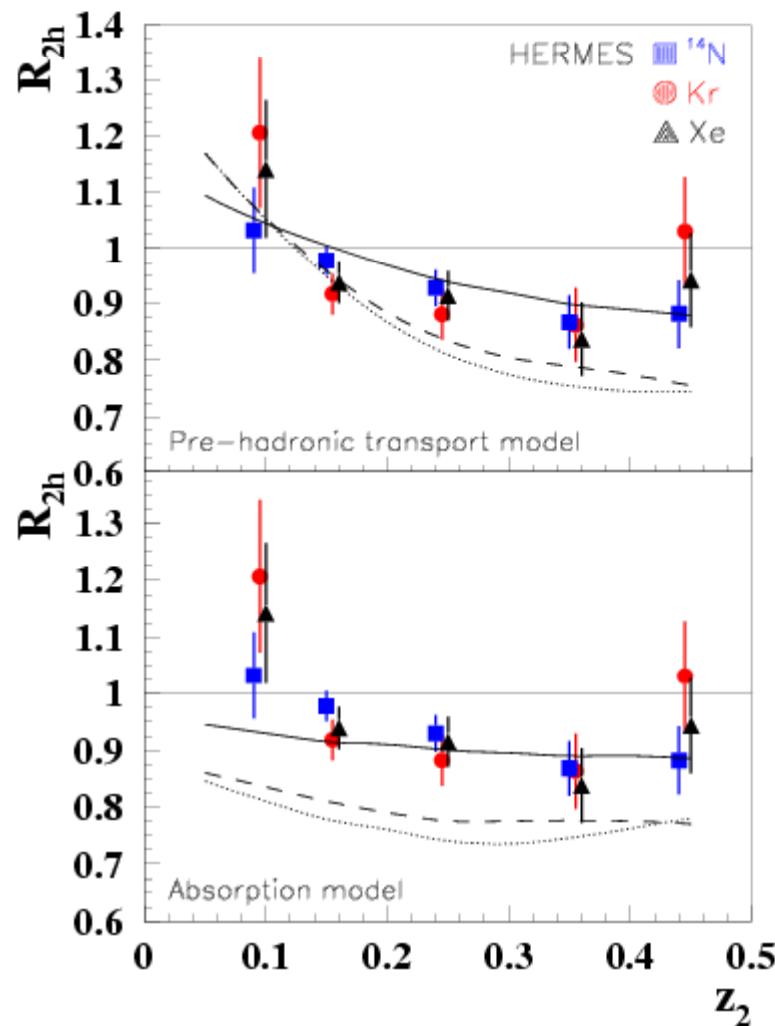
Number of events with at least 1 hadron ($z_1>0.5$)

If final hadron absorption effect: the requirement of additional sub-leading hadrons would suppress the two-hadron yield from heavier nuclei \rightarrow double-hadron over single hadron ratio is expected to be smaller in nucleus compared to deuterium.

If Energy loss effect: the attenuation does not depend on the number of hadrons involved \rightarrow double-hadron over single hadron ratio in nucleus and deuterium is expected close to unity.

Double/single hadron production

HERMES Phys. Rev. Lett. 96(2006) 162301



Reduction of R_{2h}
compared to 1

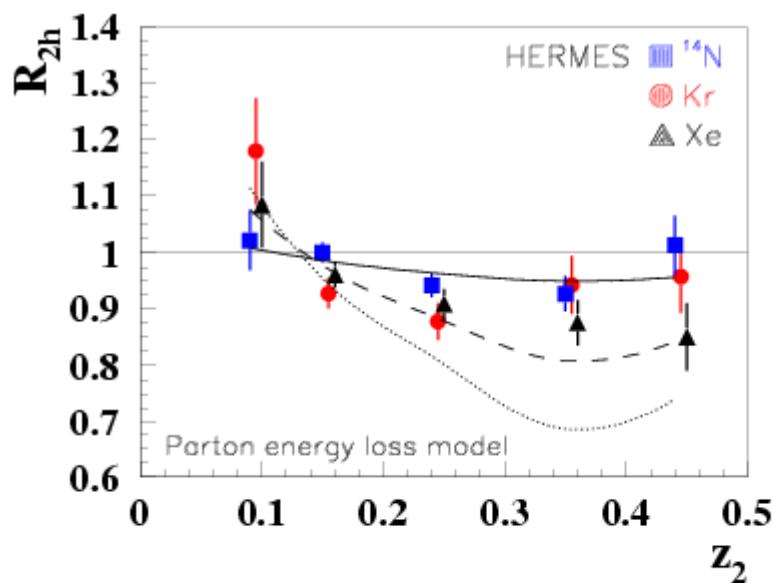
Small variation with A .

T.Falter, W.Cassing, K. Gallmeister and
U.Mosel nucl-th/0406023

Double/single hadron production

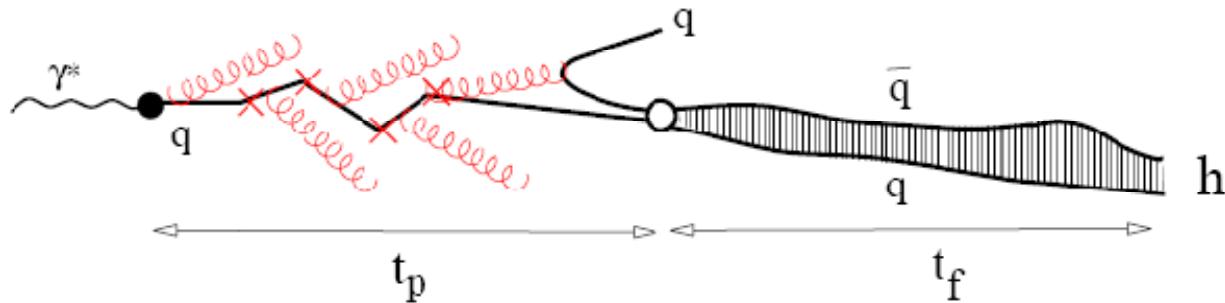
HERMES Phys. Rev. Lett.96(2006) 162301

.Majumder, Eur. Phys. J. C 43 ,
259 (2005)



Contrary to naïve
expectations this models
predicts a significant A-
dependence.

Pt-broadening vs $A^{1/3}$

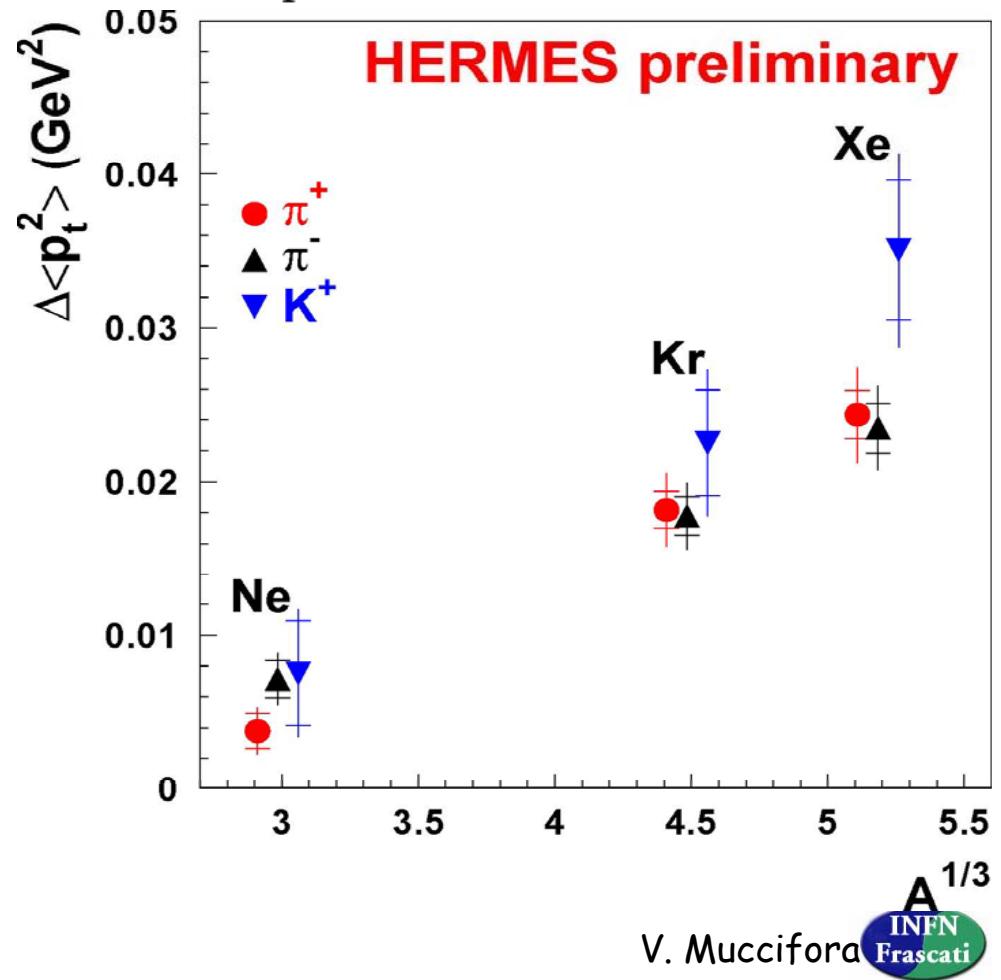


$$\Delta \langle p_t^2 \rangle = \langle p_t^2 \rangle_A - \langle p_t^2 \rangle_D$$

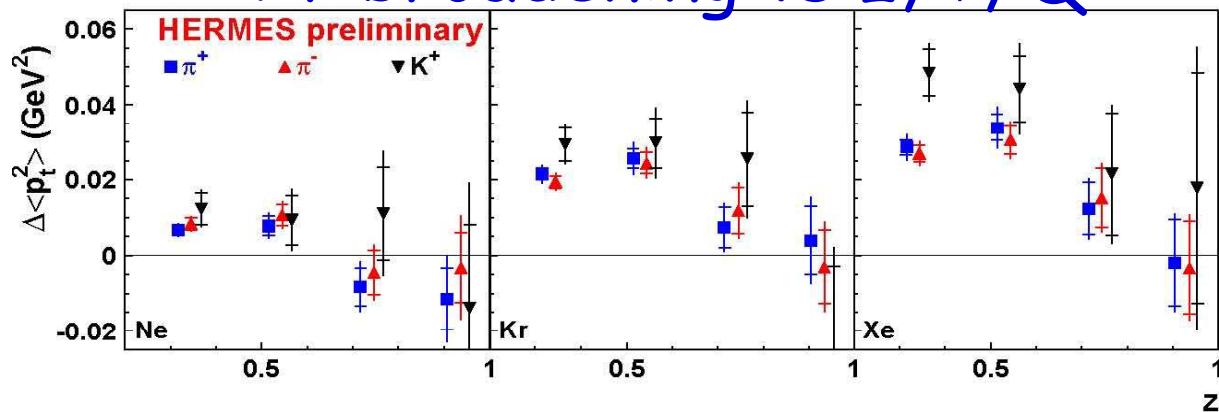
$$\Delta \langle p_t^2 \rangle \sim t_p \propto v z (1-z)$$

Mainly partonic scattering.

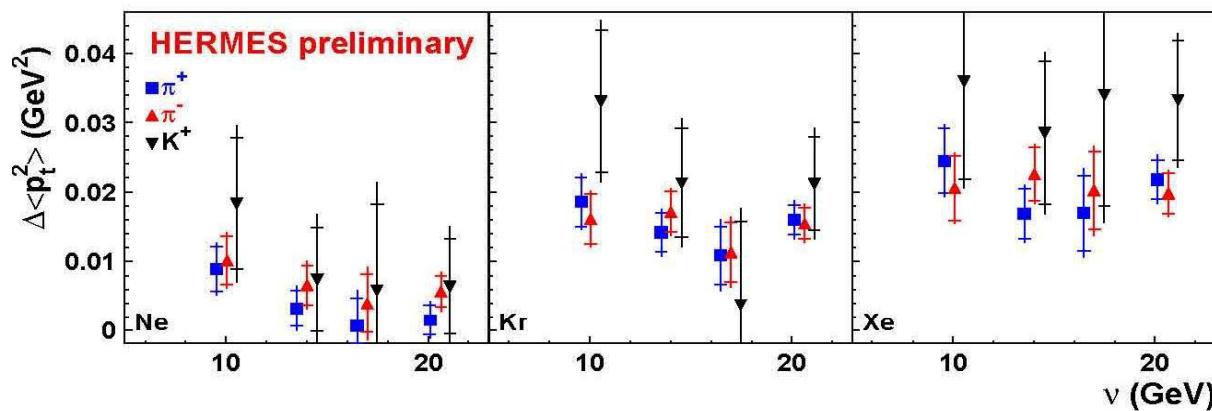
In later stages no broadening:
prehadron-nucleon elastic cross section very small compared to the quark cross section



Pt-broadening vs z, v, Q²

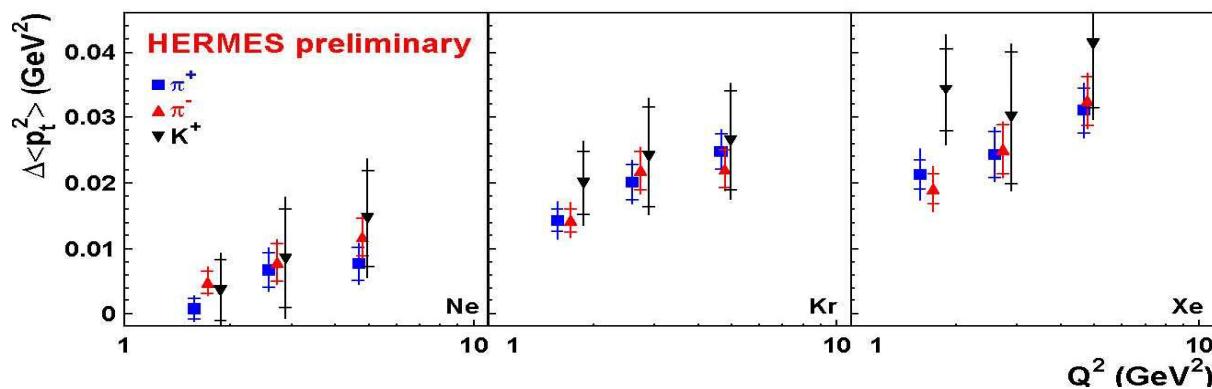


No effect at $z=1$
 $(t_p \propto v z(1-z) \rightarrow 0)$



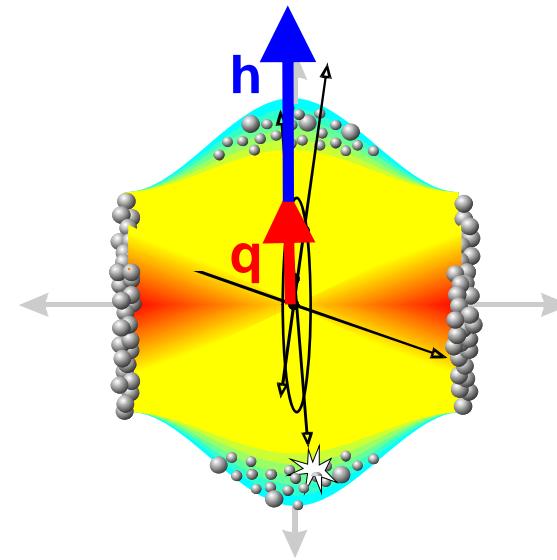
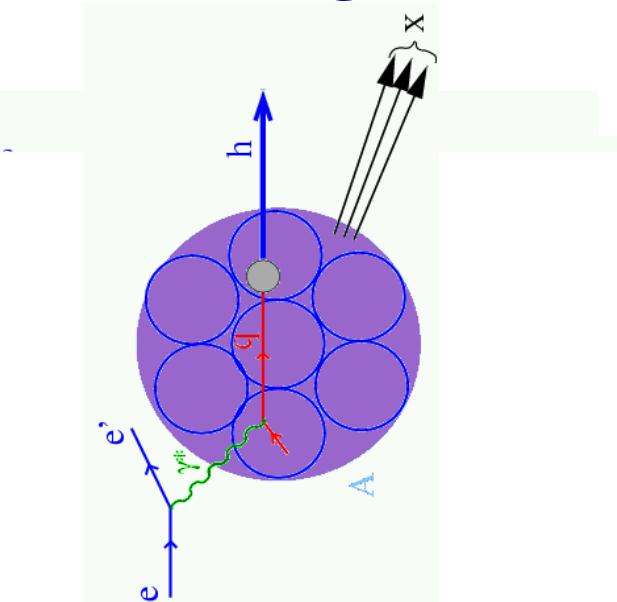
$\Delta \langle p_t^2 \rangle$ up to 0.25 GeV²

No v dep. @ $\langle z=0.4 \rangle$:
 pre-hadron formation
 mainly at the surface.



Increase with Q^2 :
 enhanced Δp_t^2 due to
 parton evolution in the
 medium with scattering
 (H.J.Pirner's talk)

SIDIS connections with HIC



$$E_q = \blacksquare = E_e - E_{e'} \quad \text{⌚ 13 GeV}$$

$$E_h = z \blacksquare \quad \text{⌚ 2 - 15 GeV}$$

$$E_q = p_T / z$$

$$E_h = p_T \quad \text{⌚ 2 - 20 GeV}$$

$$E_h = zv(\text{DIS}) \approx p_T (\text{HIC})$$

→ the relevant energies are few – few tens of GeV

HERMES kinematics is relevant to RHIC mid-rapidity

...but beware the virtuality...

$Q^2 = \blacksquare q^2$ is measured

$Q^2 \quad \text{⌚ } E_q^2 \star (p_T/z)^2$

...and the rapidity...

always forward rapidity

rapidity can change

DIS and HIC kinematics

•A.Accardi, nucl-th:0706.3227

- DIS invariants in terms of parton rapidities and transverse momenta

$$x_B = \frac{p_T}{\sqrt{s}} (e^{-y_2} + e^{-y_1})$$

$$Q^2 = p_T^2 (1 + e^{y_1 - y_2})$$

$$\nu = \frac{p_T \sqrt{s}}{2M} e^{y_1}$$

$$y = \frac{1}{1 + e^{y_2 - y_1}}$$

$$z_h = z$$

- NN -collision variables in term of DIS invariant:

$$p_T^2 = (1 - y) Q^2$$

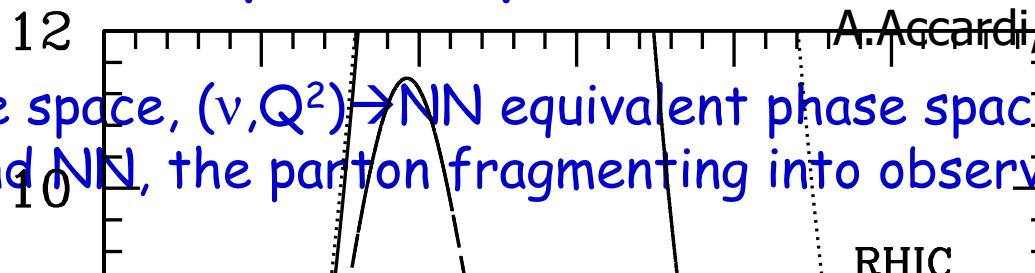
$$y_1 = -\log \frac{Q \sqrt{s}}{2 M E_e^{tr}} \frac{(1 - y)^{1/2}}{y}$$

$$y_2 = y_1 + \log \frac{(1 - y)}{y}$$

$$z = z_h$$

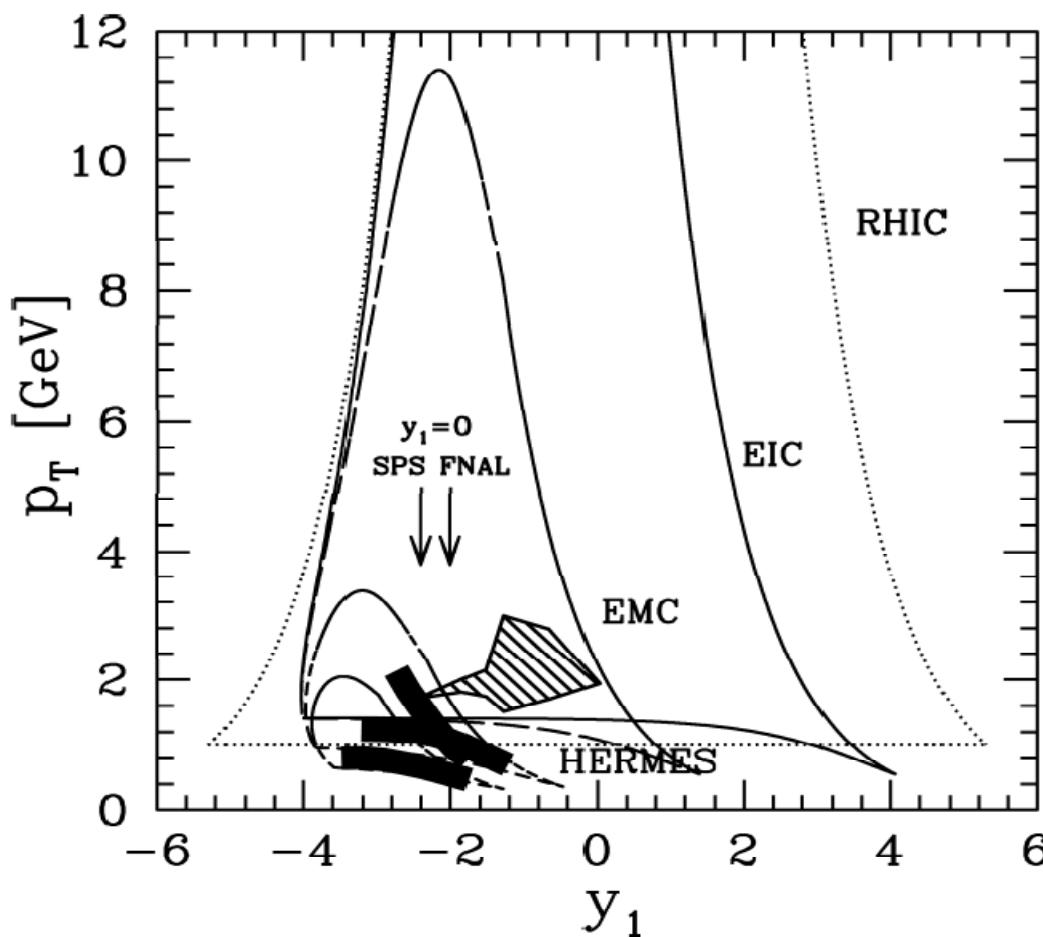
$$y = \frac{\nu}{E_e^{tr}}$$

RHIC equivalent phase space of DIS experiments



A. Accardi, nucl-th:0706.3227

- Given DIS phase space, $(v, Q^2) \rightarrow$ NN equivalent phase space, (p_T, y_1)
- Both for DIS and NN, the parton fragmenting into observed hadron is identified.



Shaded regions: regions explored at HERMES ($E_e^{tr} = 27$ and $E_e^{tr} = 12$ GeV) at EMC ($100 < E_e^{tr} < 280$ GeV).

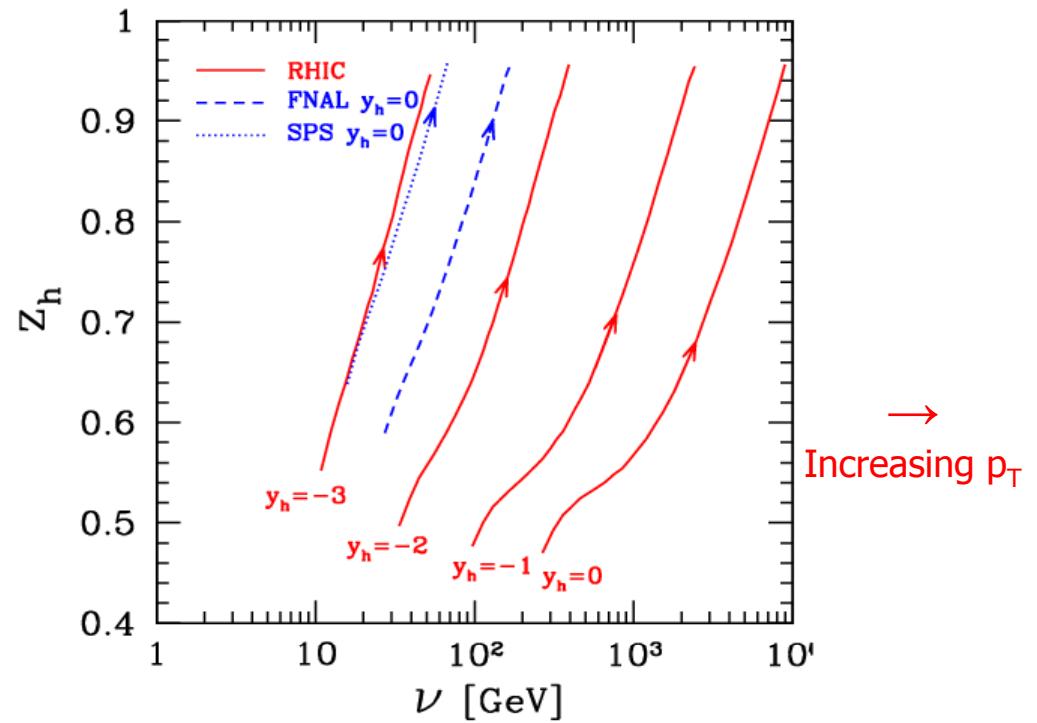
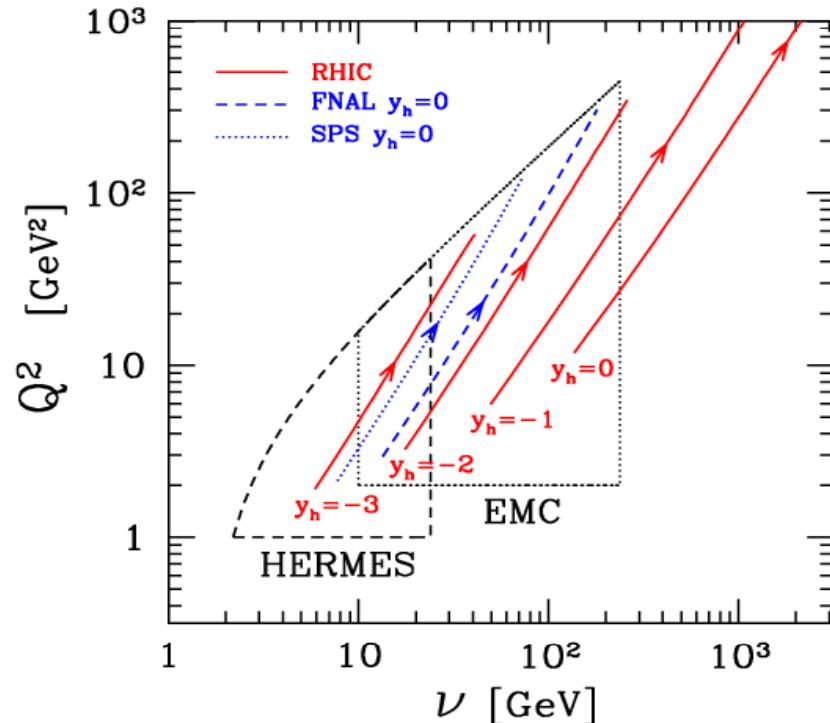
At HERMES $y_1 < 0$ $p_T < 3$
At EMC @ $y_1 > 0$ $p_T < 2$

$$\log \frac{Q\sqrt{s}}{2M E_e^{tr}} \frac{p_T}{y_{max}}$$

DIS equivalent phase space of NN experiments

A.Accardi, nucl-th:0706.3227

- Given NN (p_T, y_1) phase space \rightarrow DIS equivalent phase space, (v, Q^2, y, z_h)
- Define trajectories in NN and project them into $\text{DIS}(v, Q^2)$ (v, z_h) phase spaces.

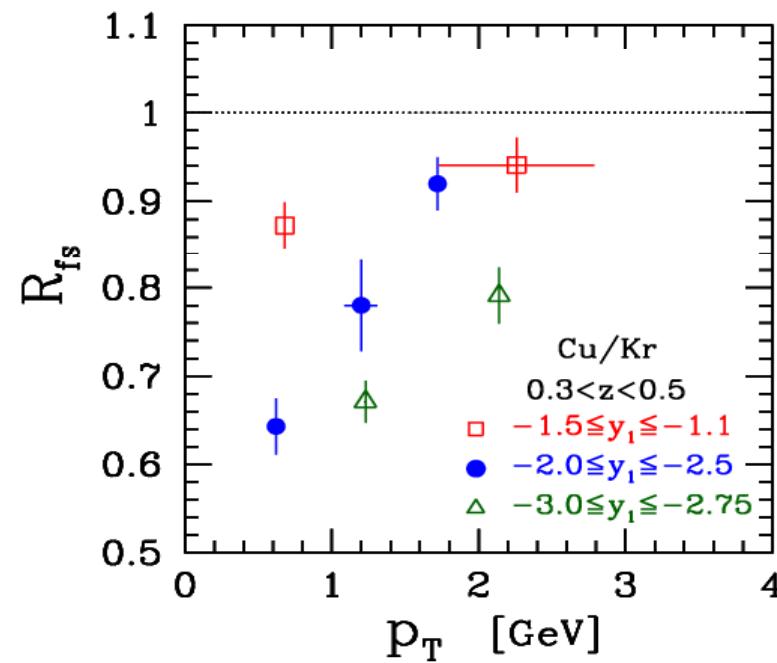
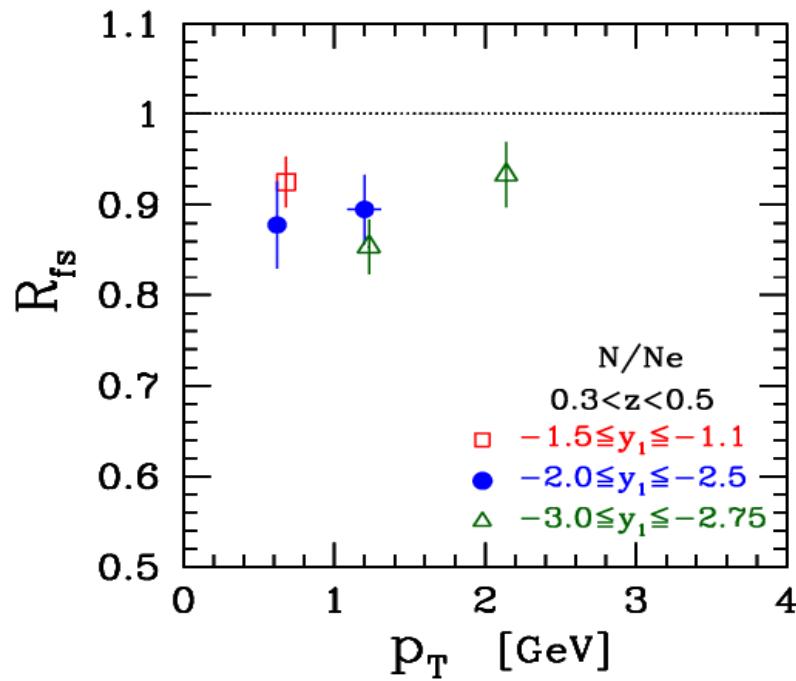


RHIC trajectories at $y_h \leq -2$ span $v \leq 60 \text{ GeV}$ and $z_h \geq 0.5$ where EMC and HERMES have shown non negligible cold nuclear matter suppression of hadron production

At higher rapidity the larger spanned values of v will make cold nuclear matter effect less prominent

Cold jet quenching in d+A collisions

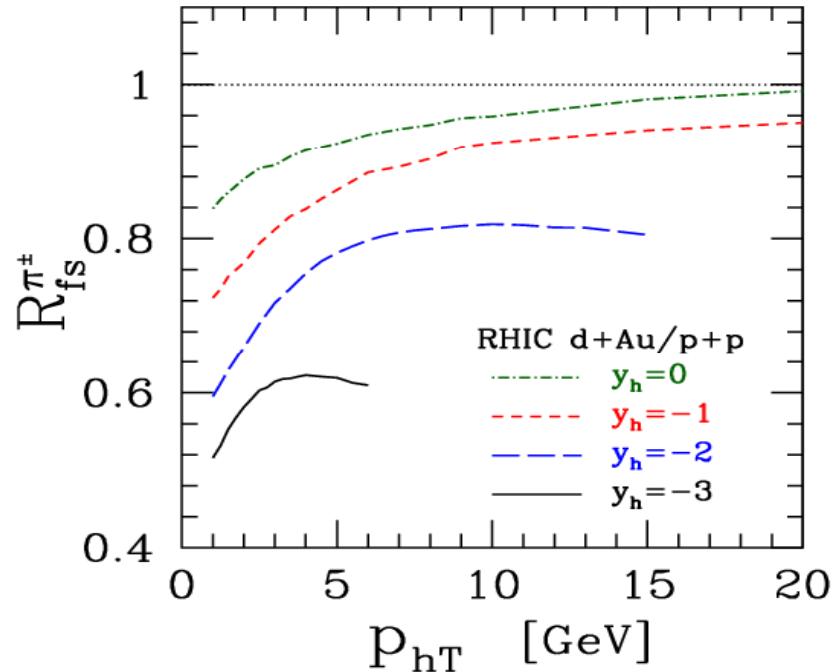
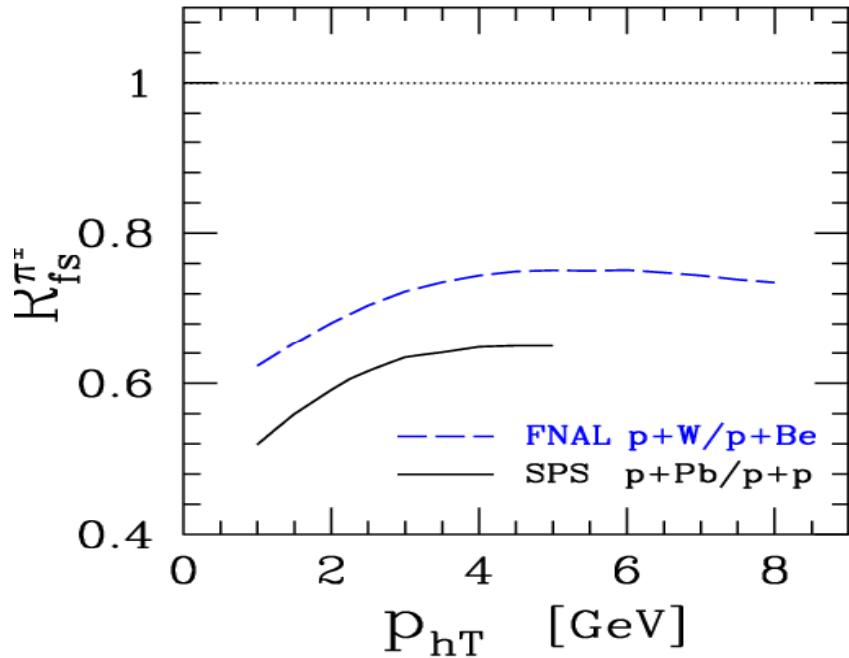
A.Accardi, nucl-th:0706.3227



- The cold nuclear quenching increases with decreasing y_1 .
- Limited p_T coverage...

Cold jet quenching in A+A collisions

- Computed cold matter final state energy loss effect R_{fs} in BDMS framework:



- Substantial final state hadron quenching for midrapidity hadrons at SPS and FNAL at for $y_h \leq 2$ at RHIC.
- 5% effect at RHIC at $y_h = 0$.

Summary

Lepto-production in nuclei is a powerful tool for studying space-time evolution of hadronization process

Nuclear attenuation by HERMES in a wide kinematical range,
vs. v , z , Q^2 , p_t^2 for ${}^4\text{He}$, ${}^{14}\text{N}$, ${}^{20}\text{Ne}$, ${}^{84}\text{Kr}$, ${}^{131}\text{Xe}$

First measurement with identif. hadrons: π^+ , π^- , π^0 , K^+ , K^- , p , \bar{p}

First clear observation of the Cronin effect in SIDIS

First direct measurement of the p_t - broadening in SIDIS

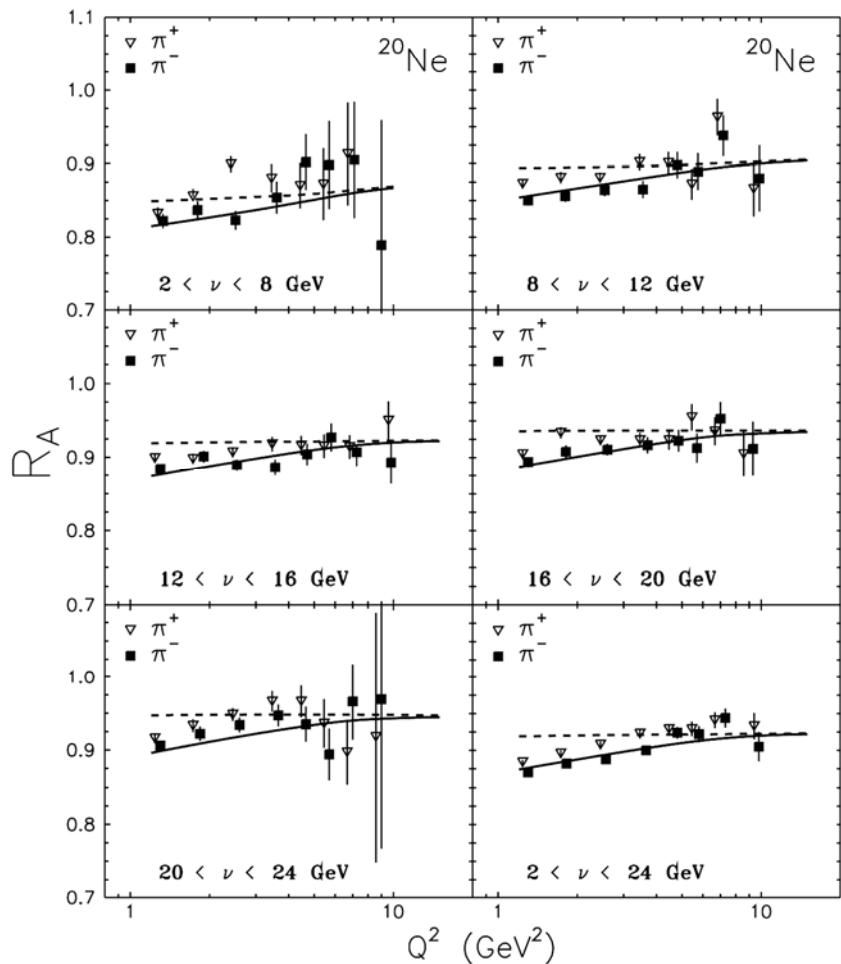
The combination of HERMES and the upcoming JLab data will provide new insight into hadronization in cold nuclear matter.

Possibility to formulate consistent picture of Fragmentation Function modification in cold and hot nuclear matter

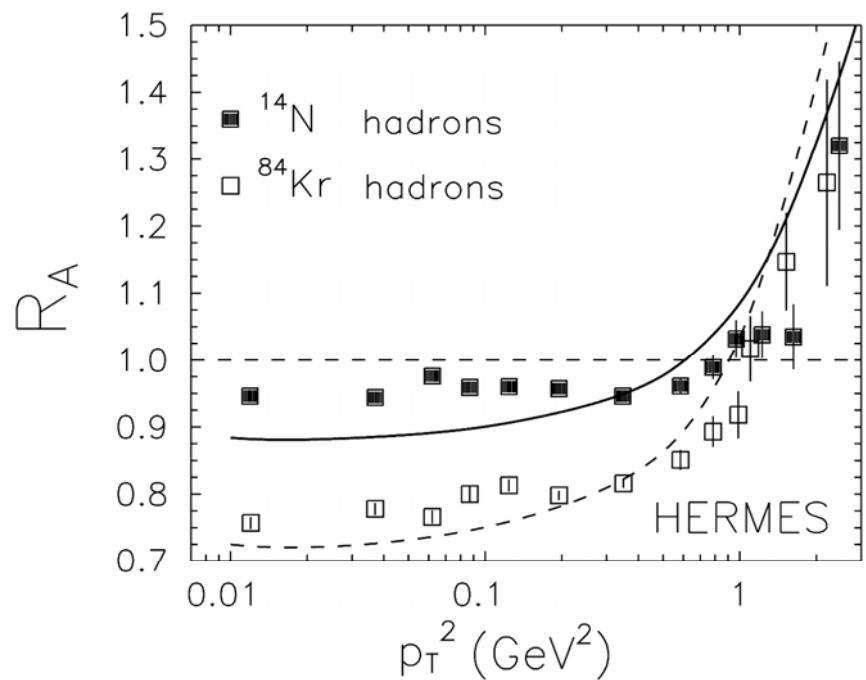


Back slides

Gluon Bremsstrahlung



Q^2 -dependence: mainly due to Induced Radiation.

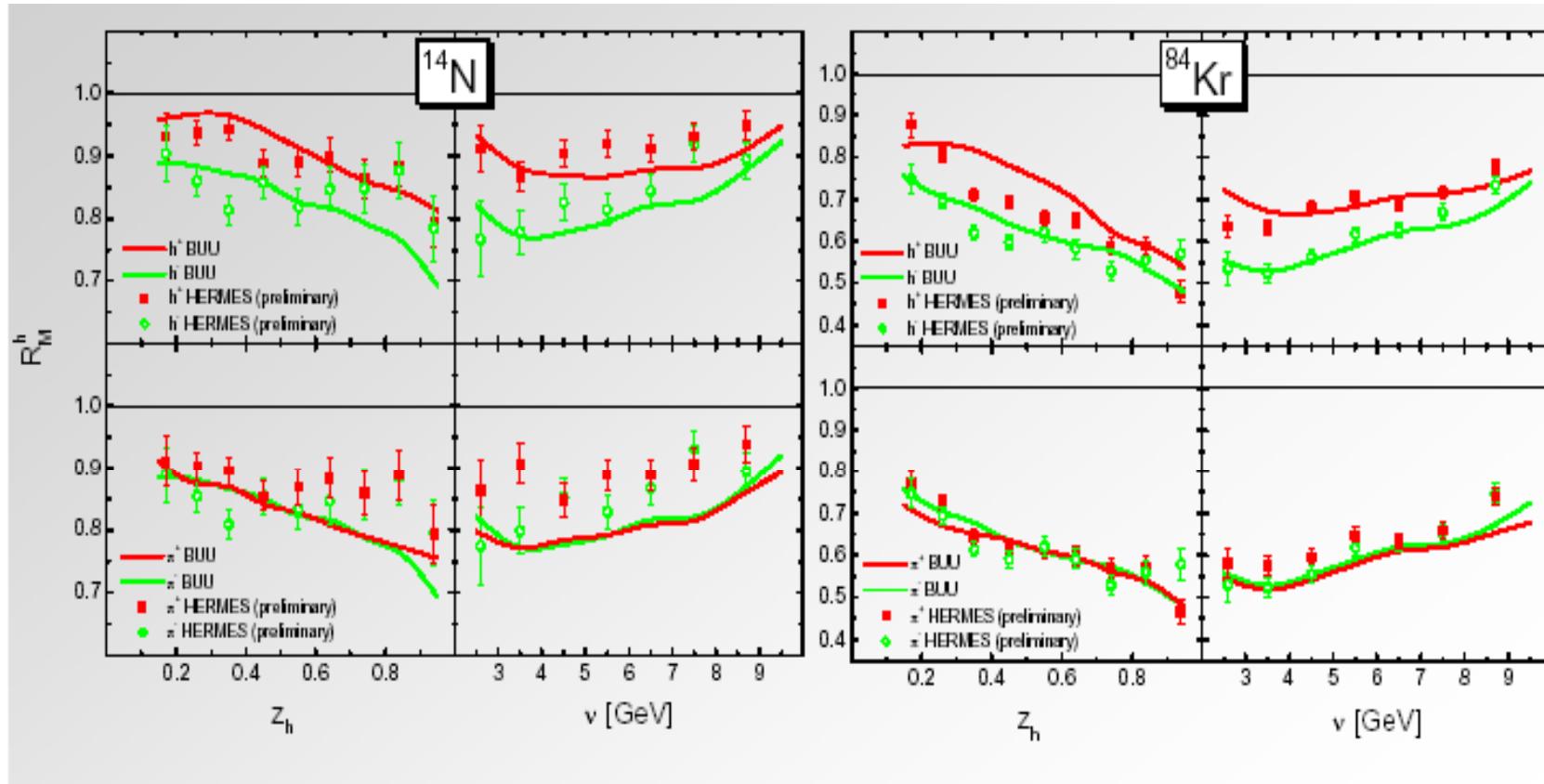


Good description of ν , z , Q^2 and P_t -dependence .

FSI in BUU Transport model

T.Falter et al.,
nucl-th/0406023

HERMES @ 12 GeV ($\tau_f=0.5$ fm/c)



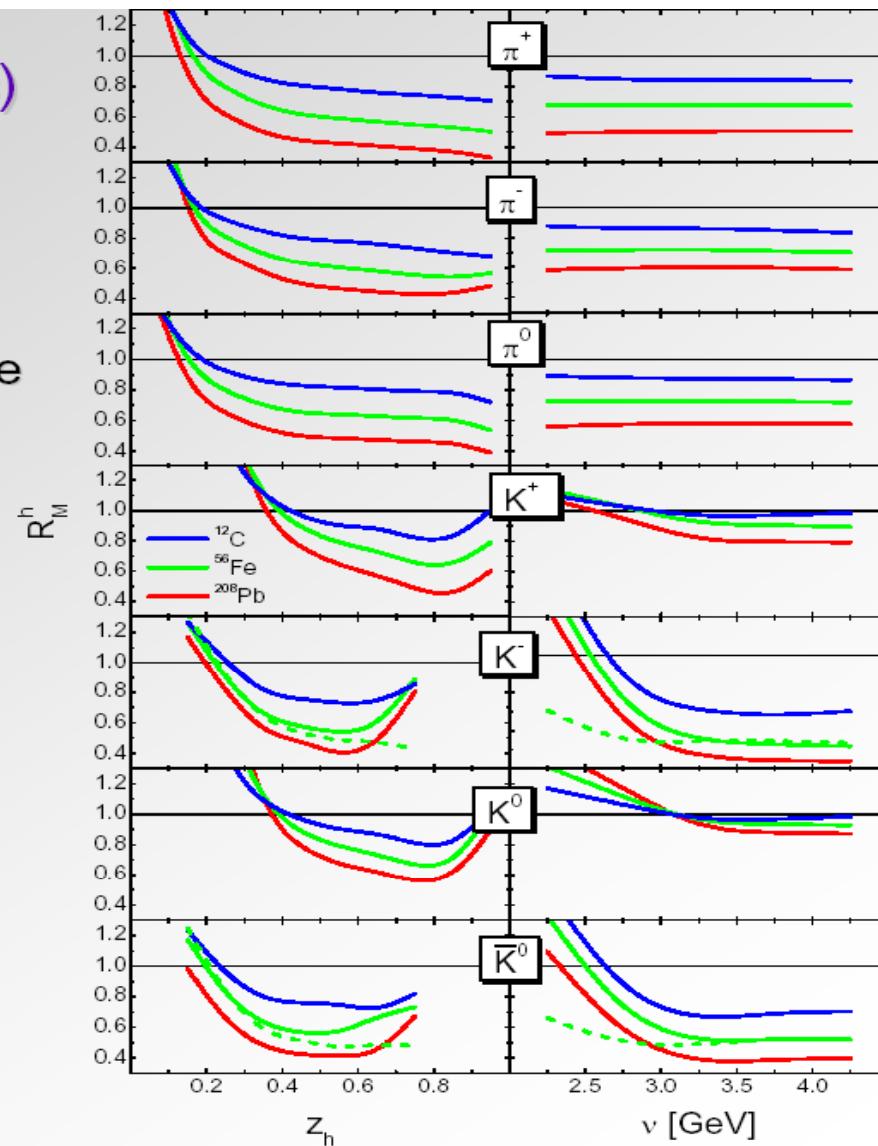
Model seems to work also at lower energy

FSI in BUU Transport model

T.Falter et al.,
nucl-th/0406023

- Jefferson Lab ($\tau_f = 0.5$ fm/c)

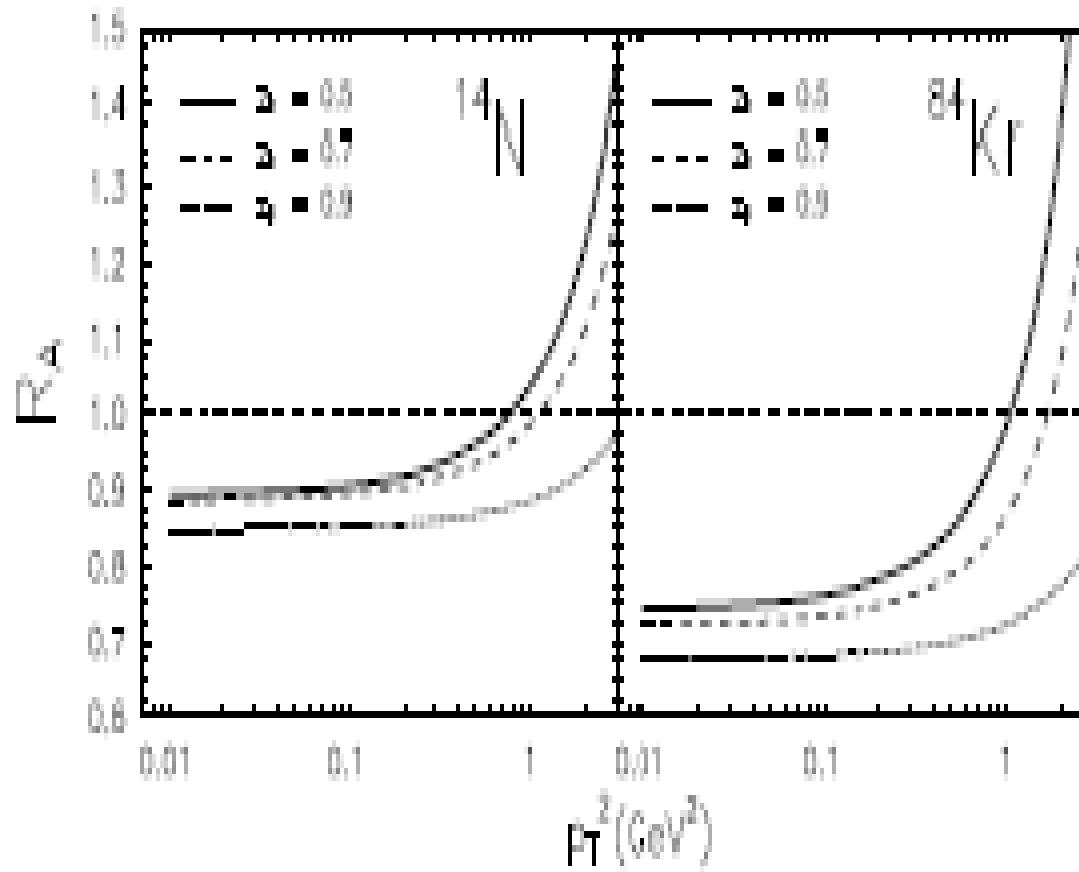
- CLAS detector
 - larger geometrical acceptance
 - detects more secondary particles from FSI
- CEBAF
 - lower energy
 - strong effect of Fermi-motion



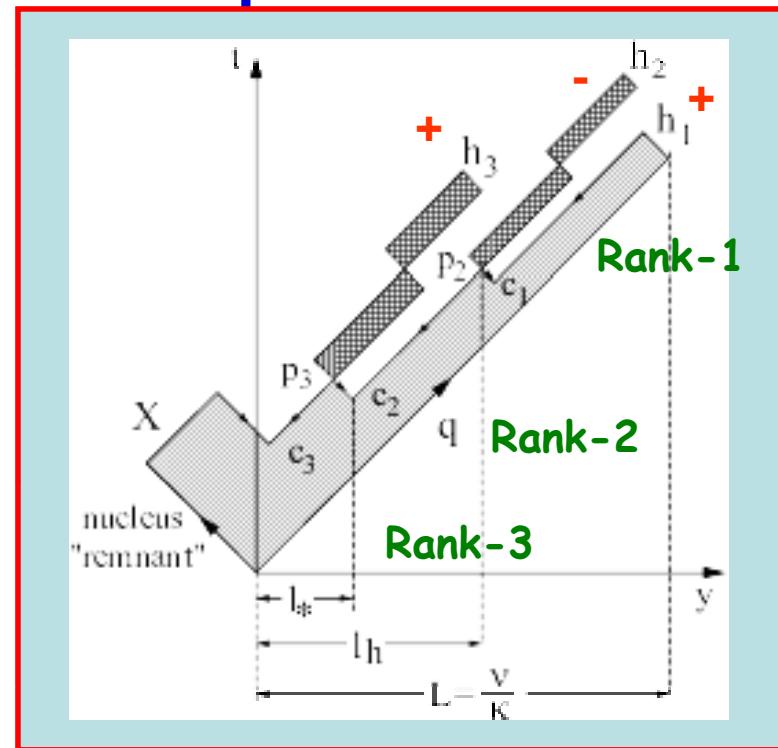
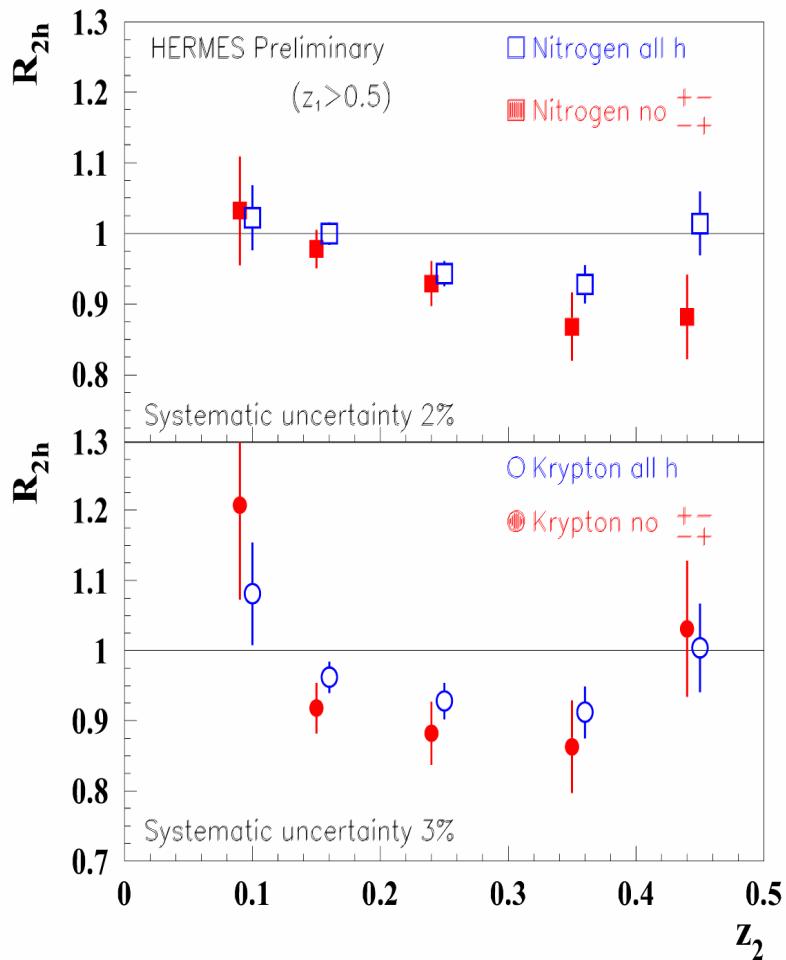
Pt-broadening predictions

B.Kopeliovich et al. NPA 740,211 (2004)

t_p effect in the p_t -broadening: $t_p \propto v_z(1-z) \rightarrow 0$



Double/single hadron production



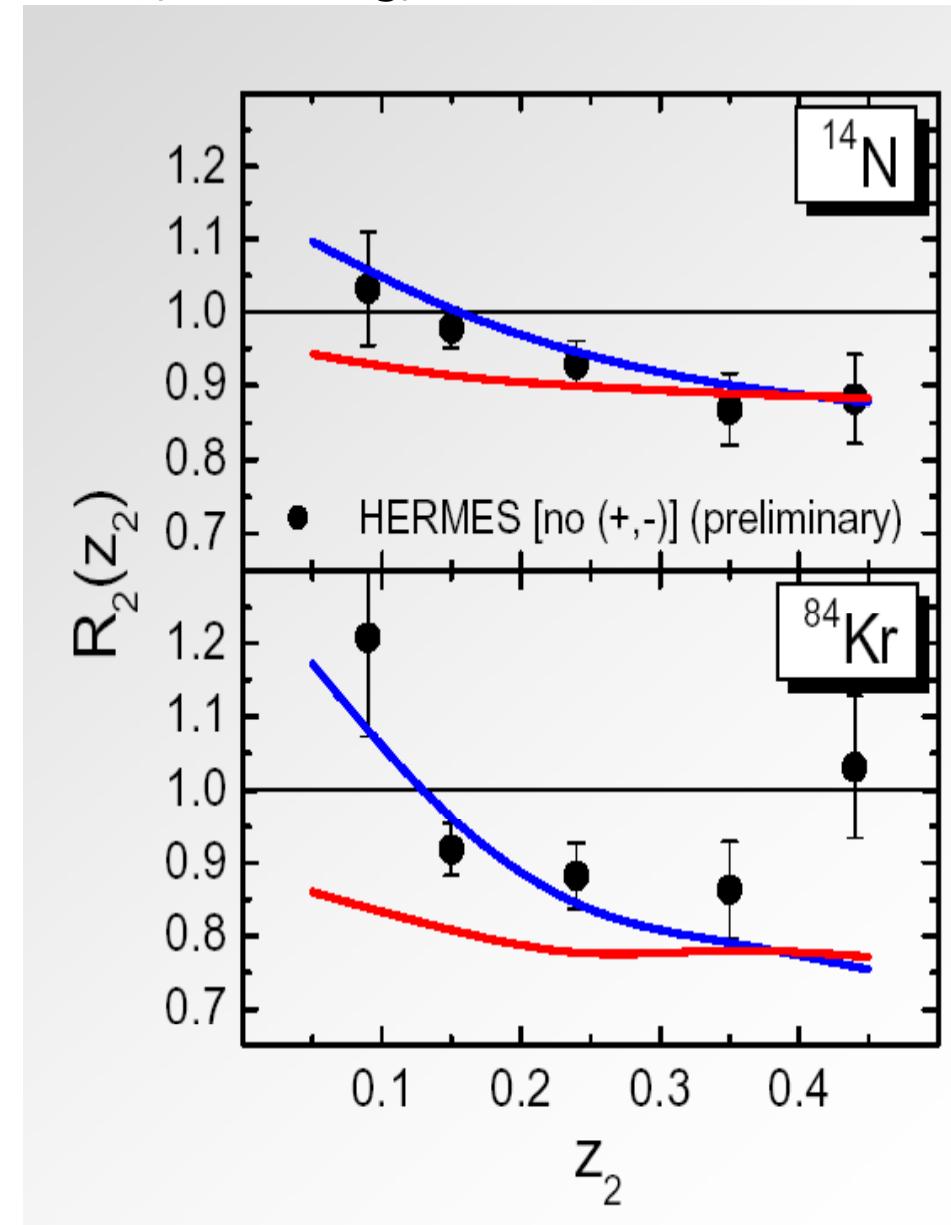
All $h \rightarrow$ rank 1,2,3

No $+$ - and $-+$ \rightarrow no rank 2, only 1,3

- Stronger reduction for higher rank (produced before, more inside the nucleus)

Double/single hadron production

T.Falter, W.Cassing, K. Gallmeister and U.Mosel nucl-th/0406023.



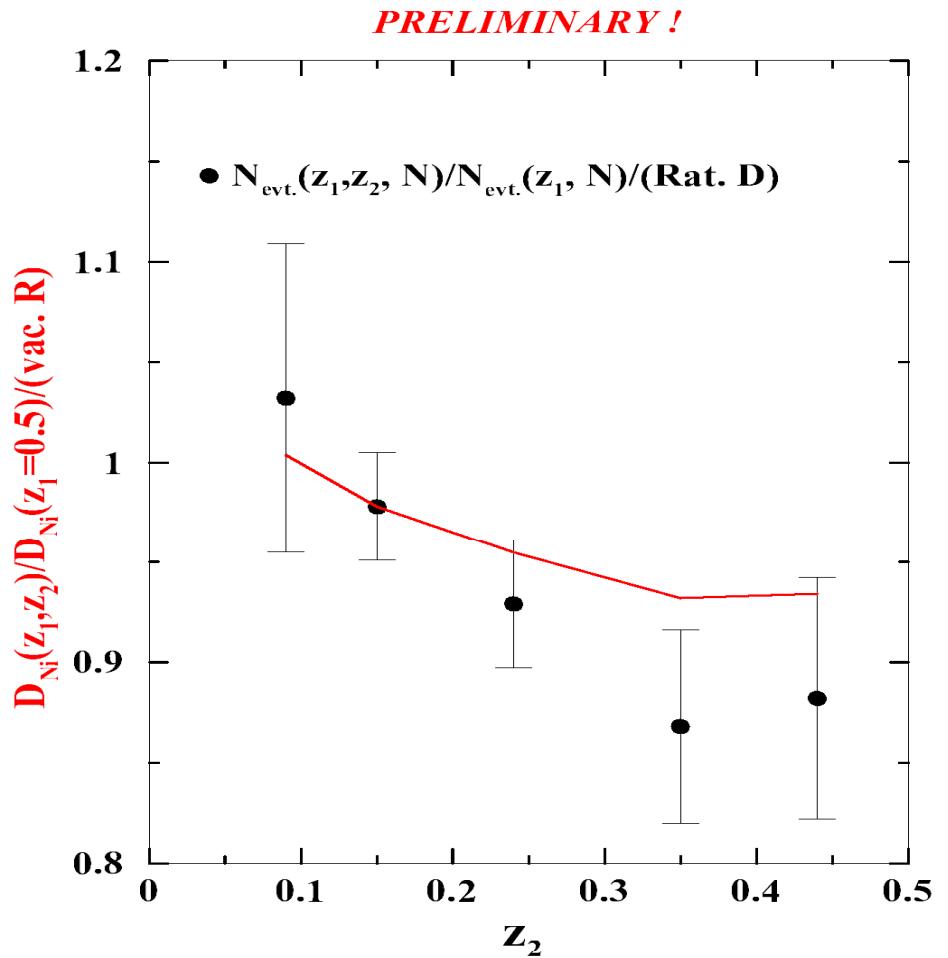
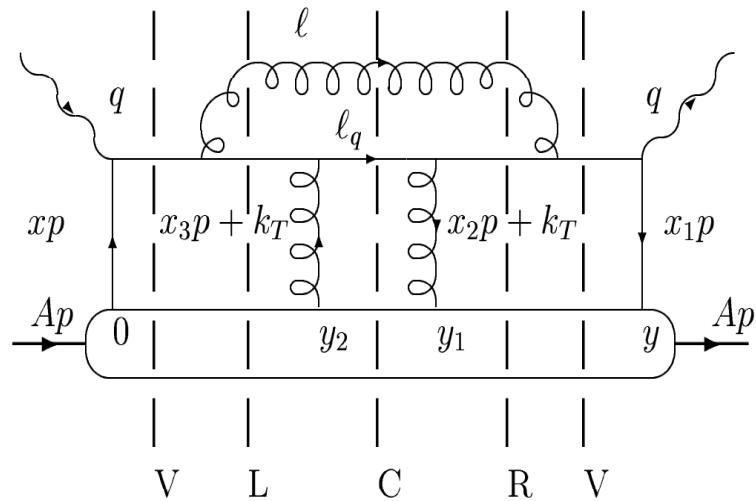
FSI in BUU Transport model

- pre-hadron $\tau_F=0.5$ fm,
 σ^* by constituent quark model:
 $\sigma_{\text{meson}}^* = \#q_{\text{orig}}/2 \sigma_{\text{meson}}$
- purely absorptive FSI

Double/single hadron production

A.Majumder and X.N.Wang hep-ph/0410078.

- Computation of dihadron FF and its modification from higher twist correction in DIS



HERMES @ HERA

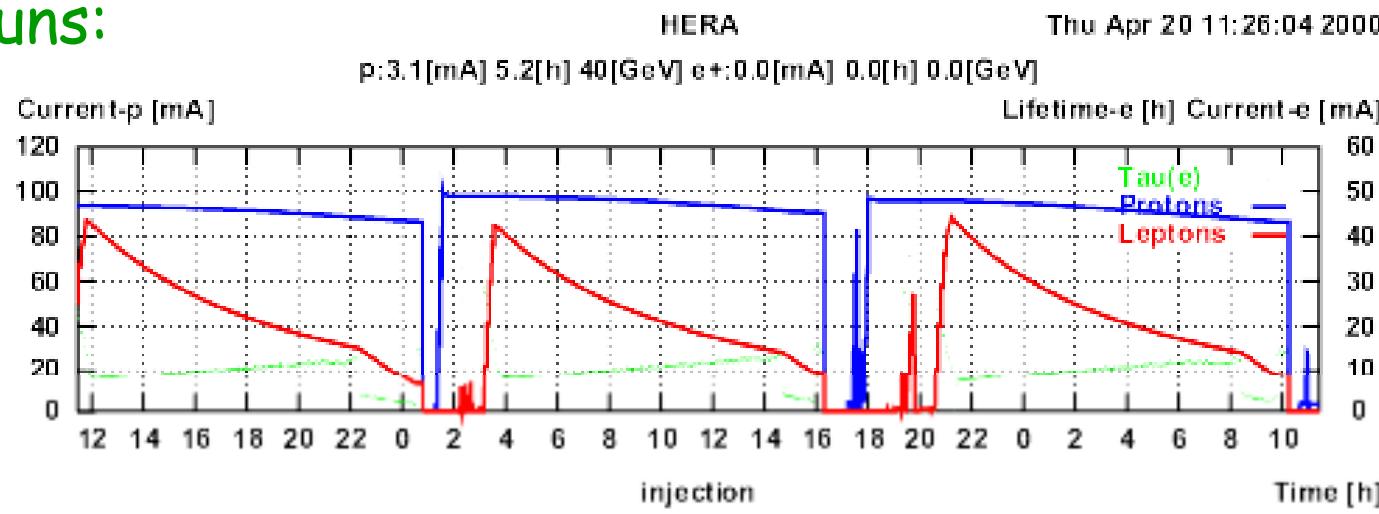
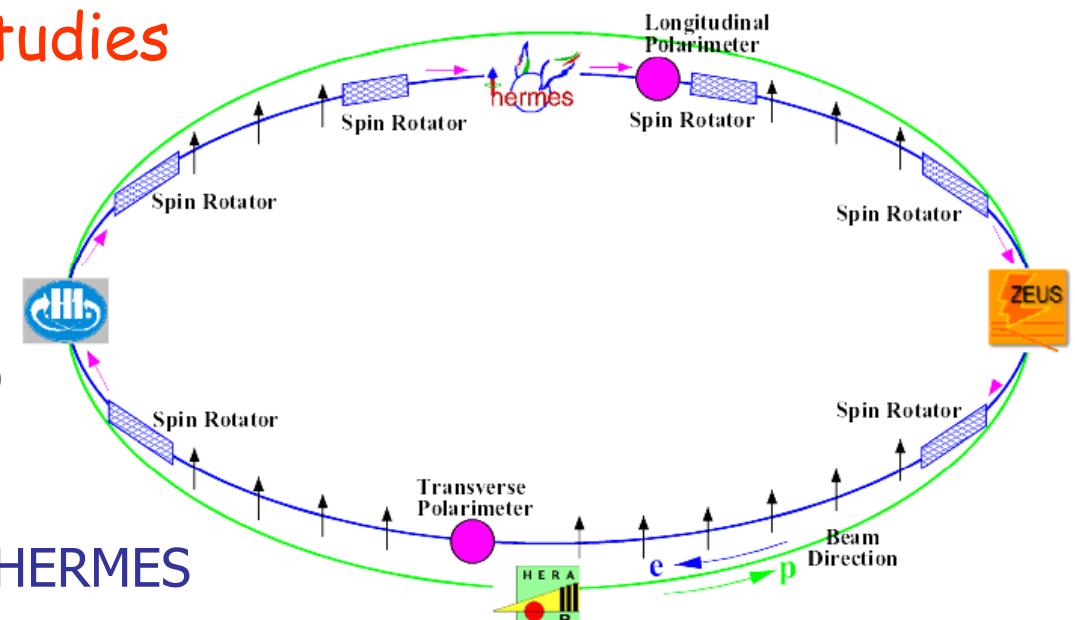
It is an experiment which studies
the spin structure of the
nucleon
and not only ...

E=27.5 12 GeV e⁺ (e⁻)

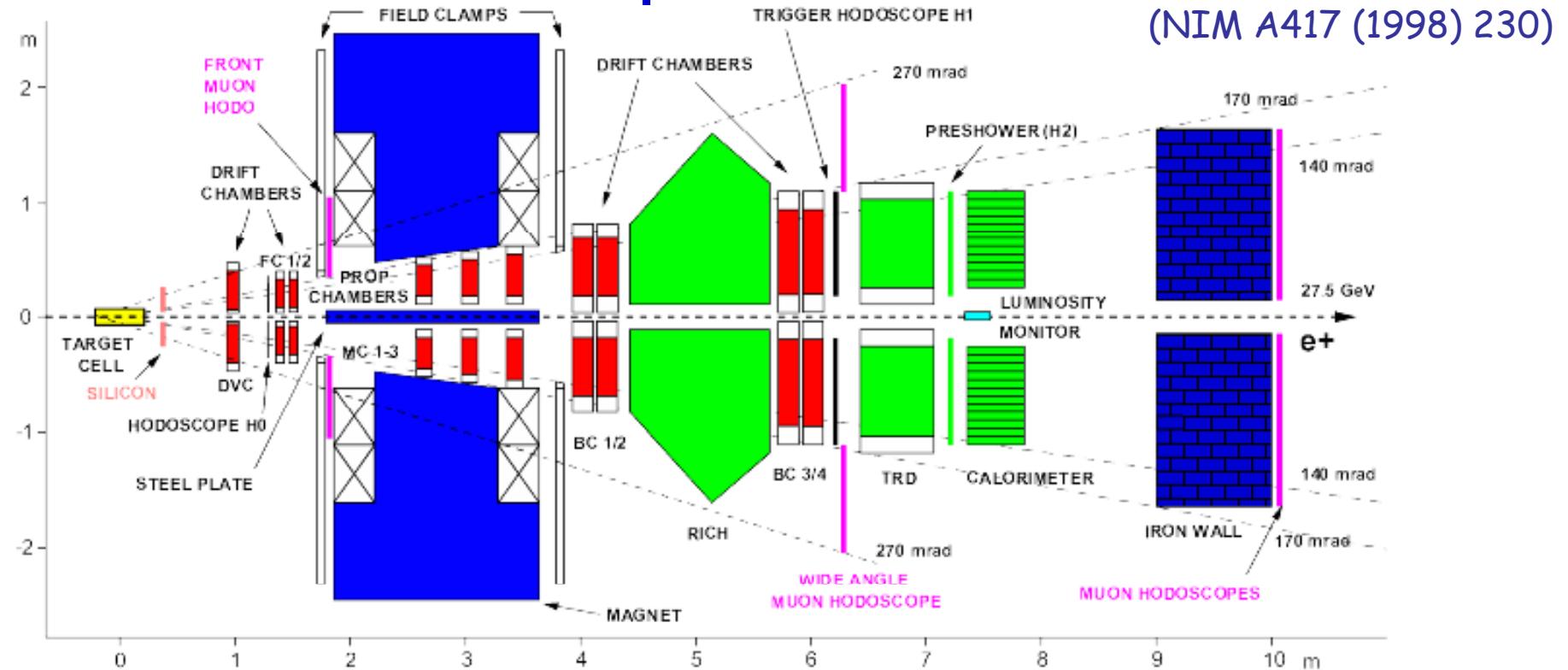
I ~ 30 mA

p beam of 920 GeV, not used by HERMES

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

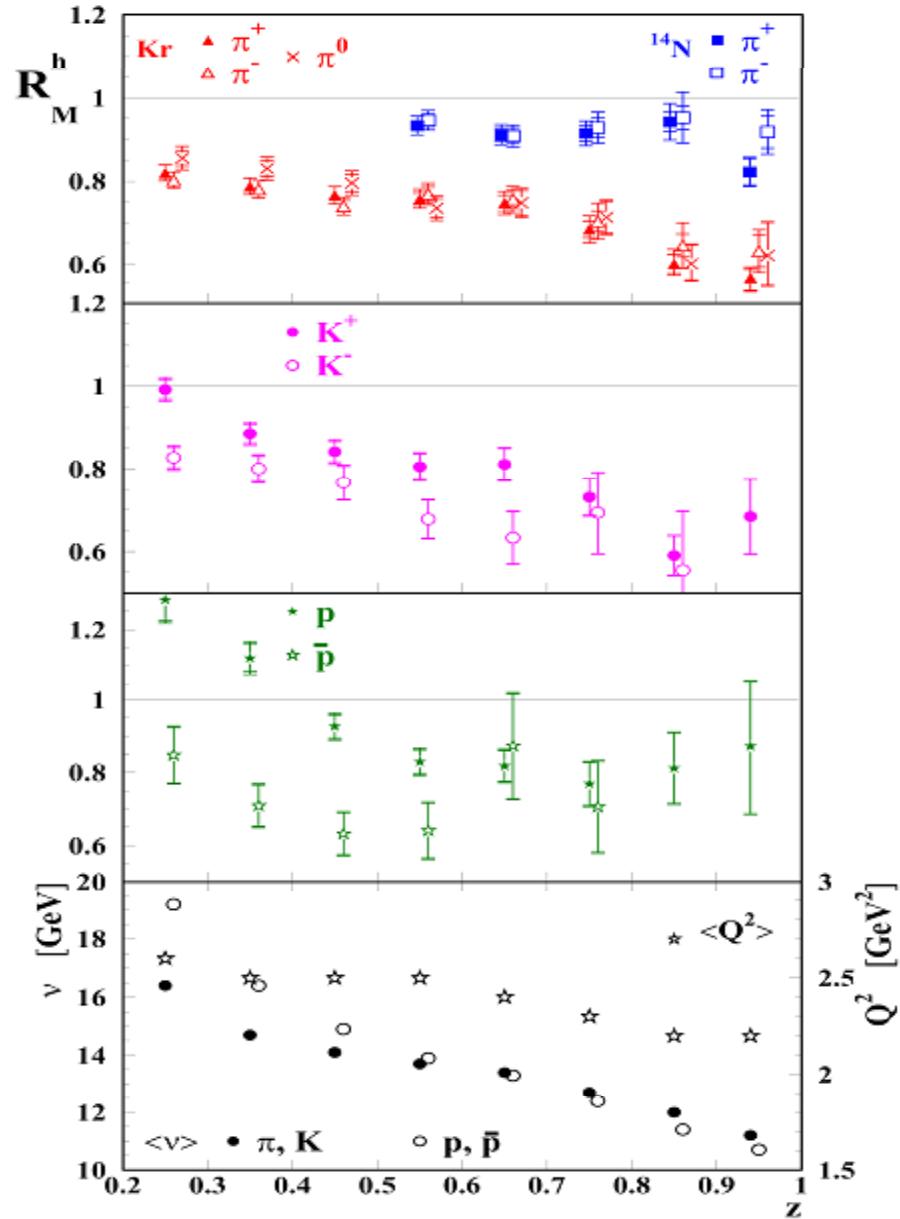


The Spectrometer



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

Multiplicity ratio for identified hadrons vs z



HERMES, PLB 577 (2003) 37

Different FF modification for quark and *anti-quark*

Different τ_h for mesons and baryons

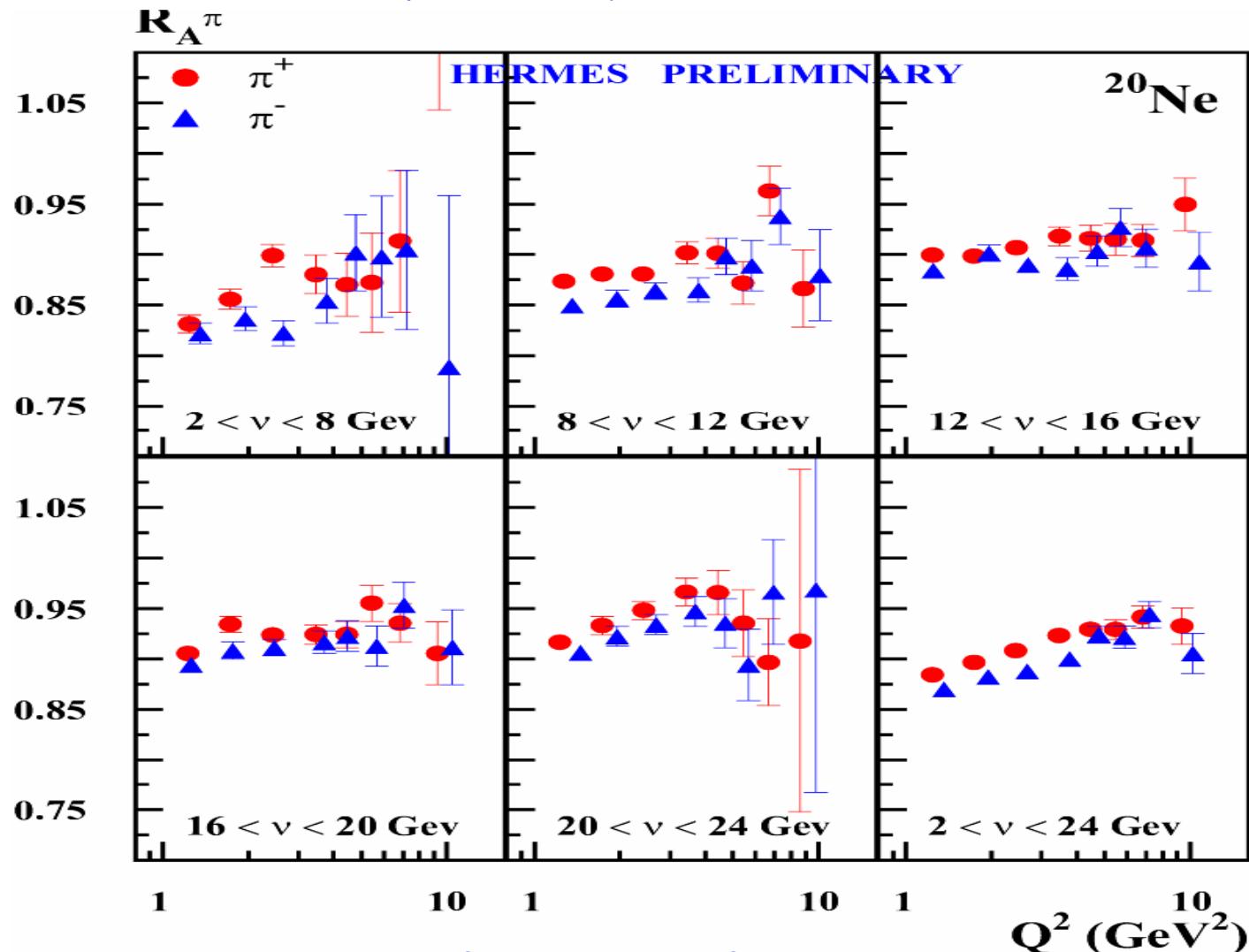
Different σ_h :

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

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

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

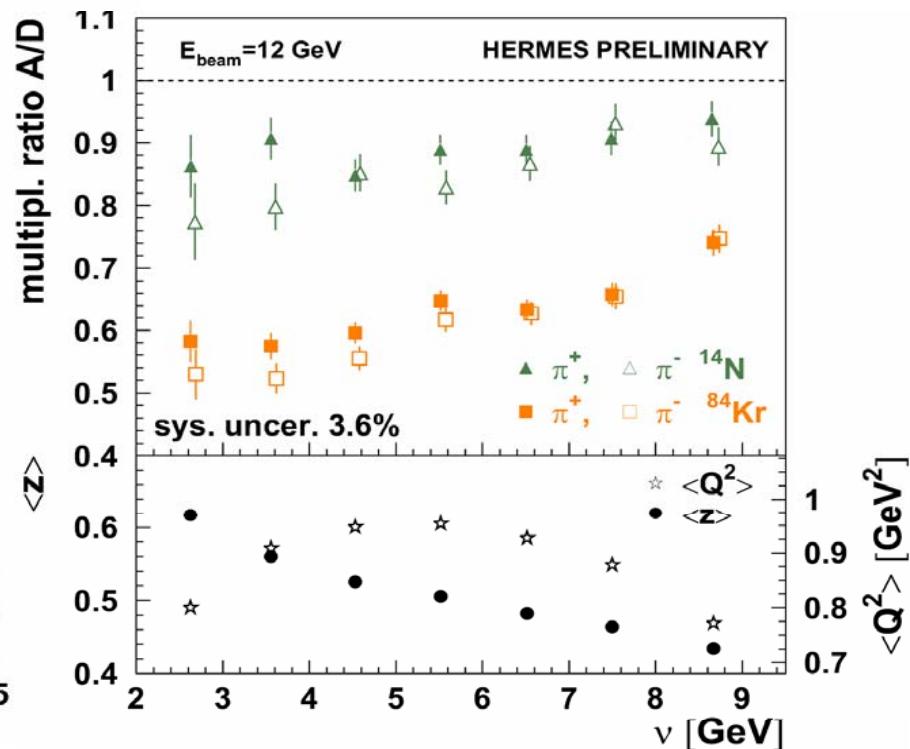
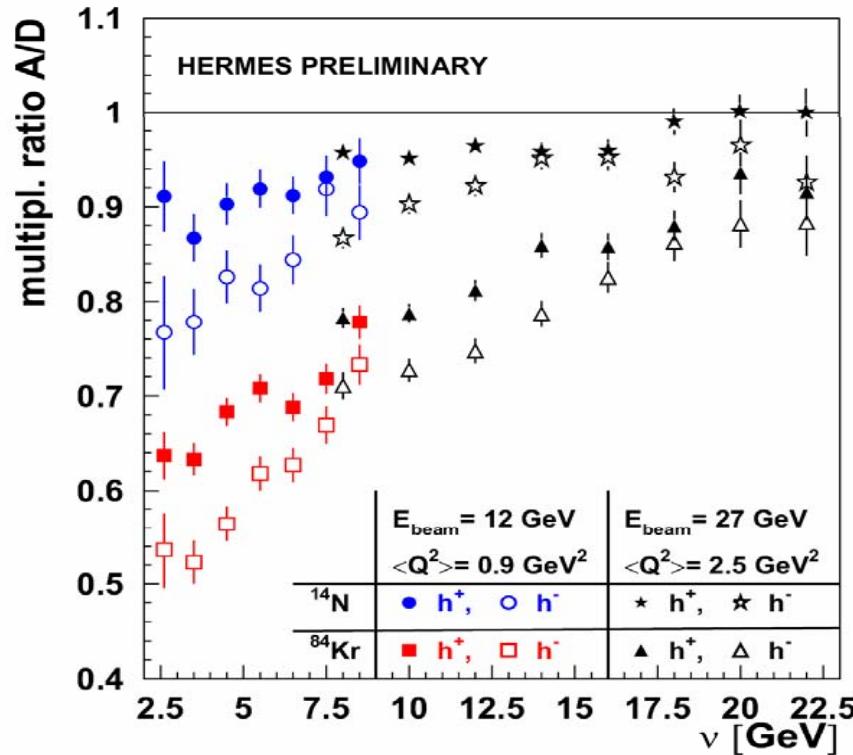
Multiplicity ratio vs Q^2



Dependence on $1 < Q^2 < 10 \text{ GeV}^2$:
stronger at small v , weaker at high v

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

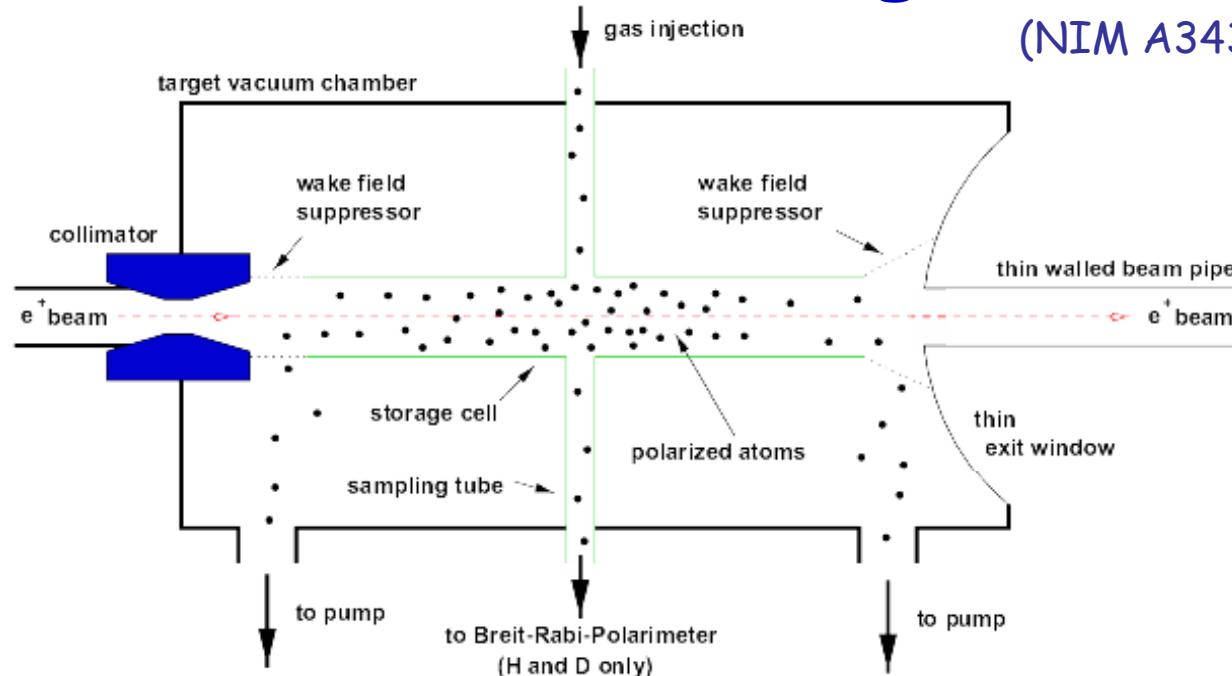
Extension of the v range down to 2 GeV



- Measurements are in progress at HERMES
 $2 < v < 23 \text{ GeV}$ $Q^2 < 10 \text{ GeV}^2$

The Internal Target

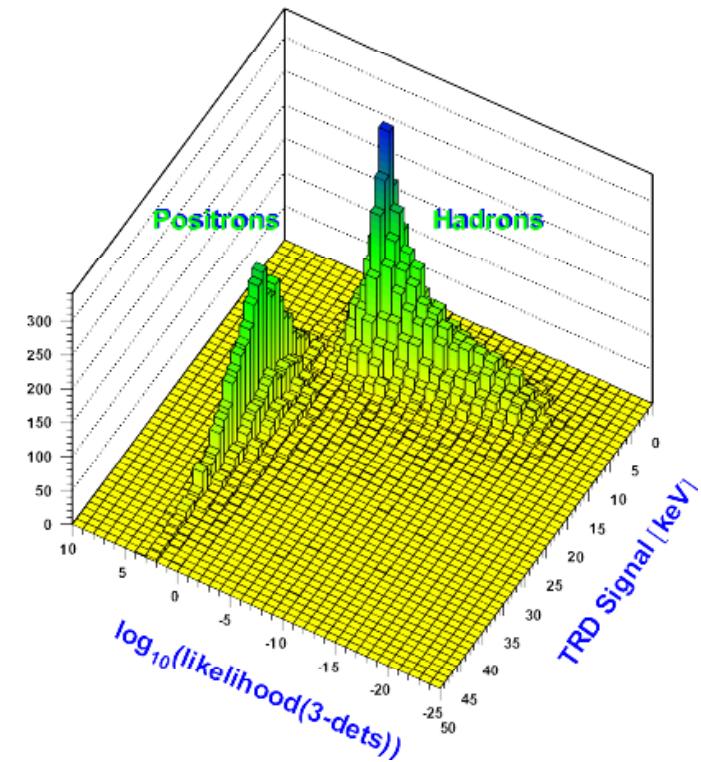
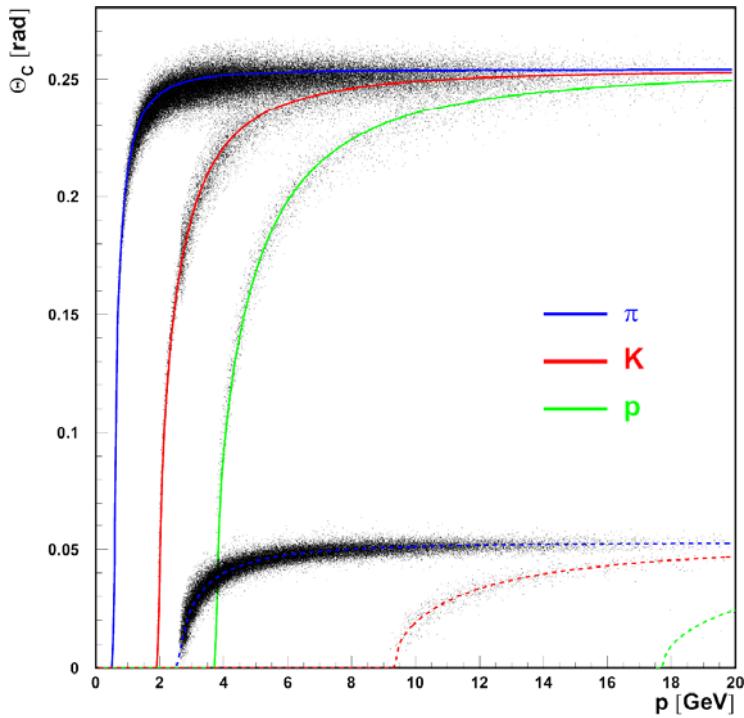
(NIM A343 (1994) 334)



- Internal storage cell
- Pure gas target, no dilution factor
- Nuclear targets: (H, D), ${}^3\text{He}$, ${}^4\text{He}$, ${}^{14}\text{N}$, ${}^{20}\text{Ne}$, ${}^{40}\text{Ar}$, ${}^{84}\text{Kr}$, ${}^{131}\text{Xe}$
- Densities: $\sim 10^{15} - 10^{17}$ nucl*cm $^{-2}$

Particle Identification

Positron - hadrons separation:



Double radiator RICH: Aerogel + C_4F_{10} . Cerenkov photons detected by ~4000 PMTs.
Detection efficiency: 99% (π), 90% (κ), 85-95% (p)

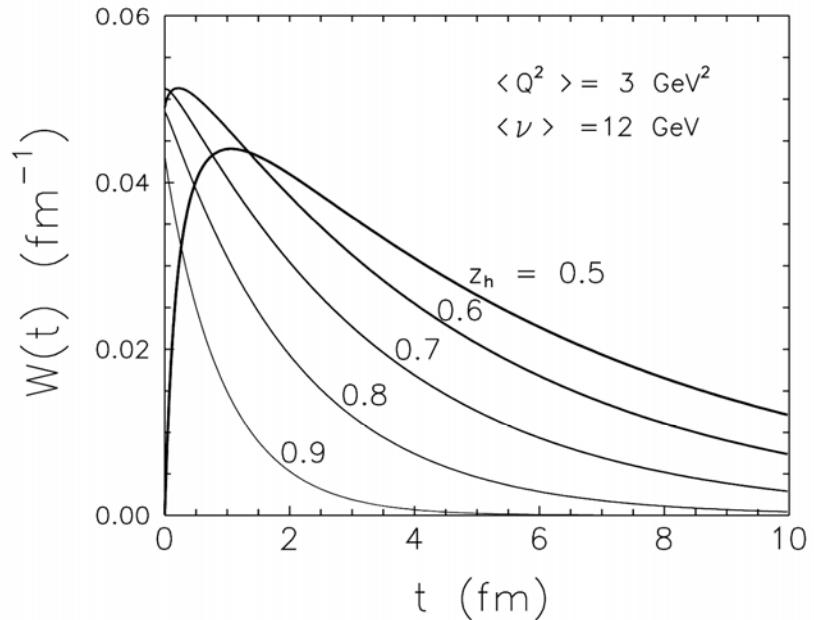
Gluon Bremsstrahlung

FF modification: Nuclear Suppression + Induced Radiation

- Vacuum energy loss: $q \rightarrow q\bar{q}$.
 ($dE/dz \sim 2.5 \text{ GeV/fm}$ by E772/E866 for DY on nuclei)
- Energy loss induced by multiple interactions in the medium
 (rising in p_t)
- Color Transparency of the $q\bar{q}$ ($\sim 1/Q^2$)

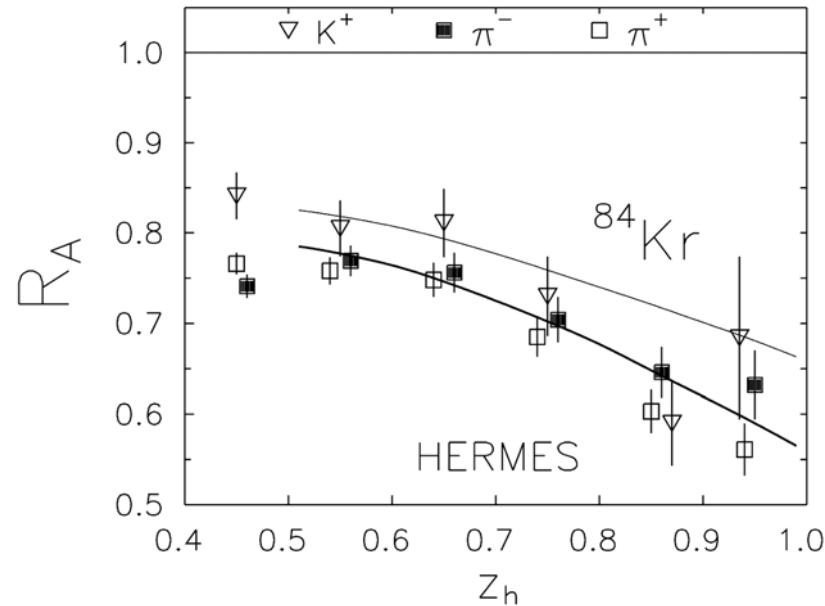
$$\tilde{D}_{h/q}(z_h, Q^2) =$$

$$\int_0^\infty dt W(t, z_h, Q^2)$$



Gluon Bremsstrahlung

B.Kopeliovich et al.,
hep-ph/9511214
hep-ph/0311220

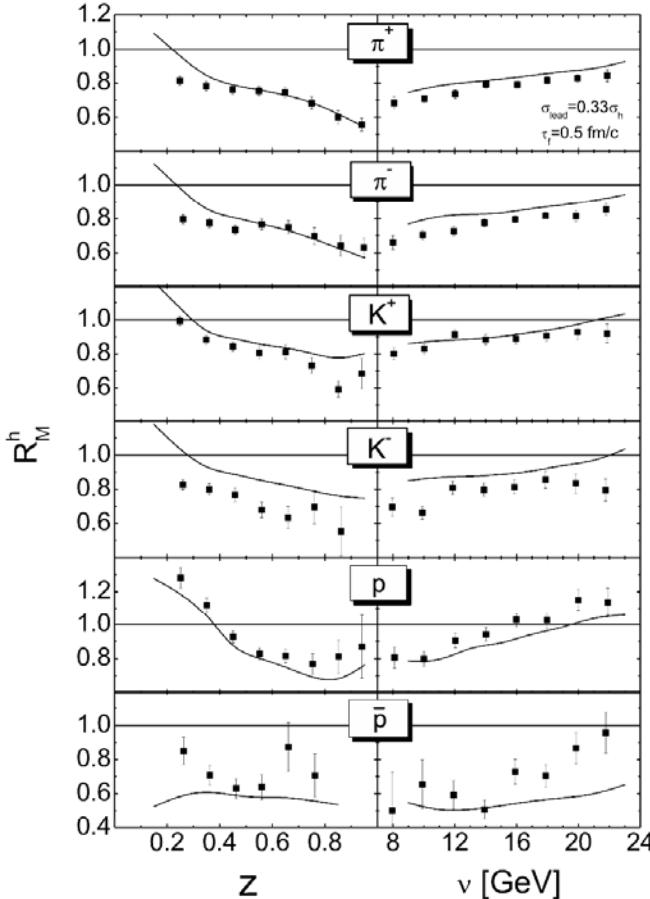
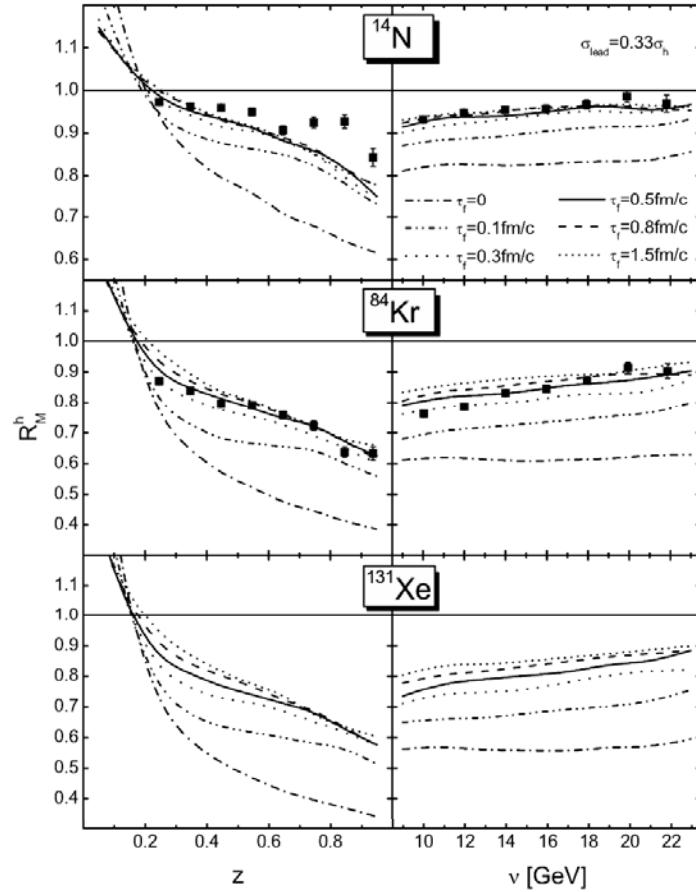


Only prediction for h containing target valence quark.

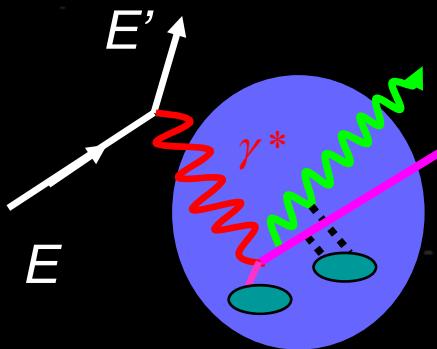
Good agreement also for K^+

(Pre-)Hadron FSI and formation times

T.Falter et al., nucl-th/0303011



R_M is very sensitive to the $\sigma_{\text{pre-h}}$; ($\sigma_{\text{pre-h}}=0.33 \sigma_h$)
 $\tau_f > 0.5 \text{ fm/c}$ compatible with data



DIS Tomography

$\nu = E - E'$ - energy transfer

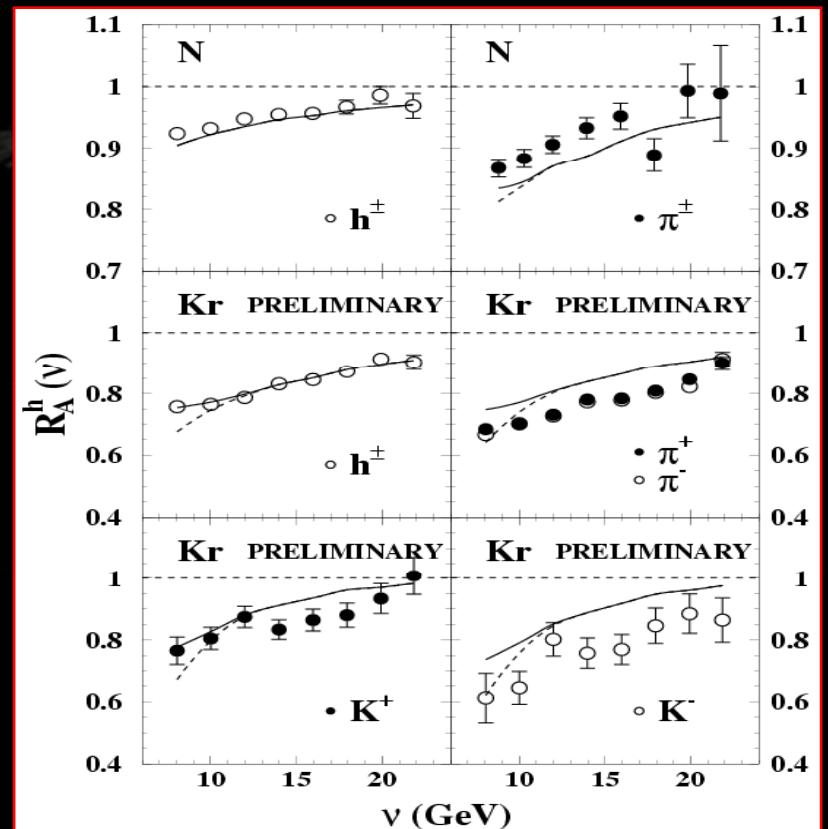
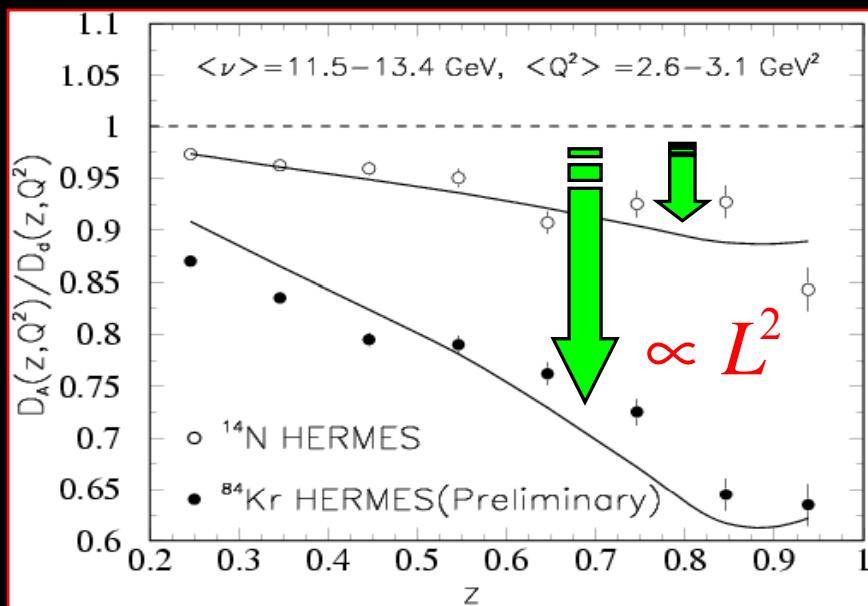
$\langle \Delta z \rangle$ - radiative energy loss fraction

$$\Delta E = \nu \langle \Delta z \rangle = (E - E') \langle \Delta z \rangle$$

$$x_B = Q^2 / (2 p \cdot q), \quad x_A = 1 / (m_N R_A)$$

$$\langle \Delta z \rangle = \tilde{C}(Q^2) \frac{C_A \alpha_s^2(Q^2)}{N_c} \frac{x_B}{Q^2 x_A^2} 6 \ln \frac{1}{2 x_B}$$

$$\langle -dE/dL \rangle_{cold} \approx 0.5 - 0.6 \text{ GeV/fm}$$



F.Arleo, Eur.Phys.J. C30 (2003)

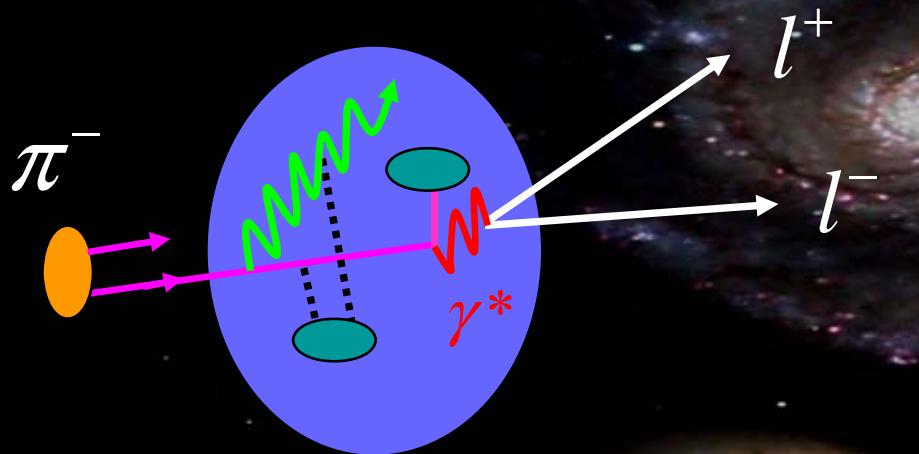
E.Wang, X.-N.Wang, Phys.Rev.Lett. 89 (2002)

Ivan Vitev, ISU

FROM DRELL-YAN TO DIS

- Gluon transport coefficient fixed from Drell-Yan

$$\hat{q} = 0.14 \text{ GeV}^2 / \text{fm}$$

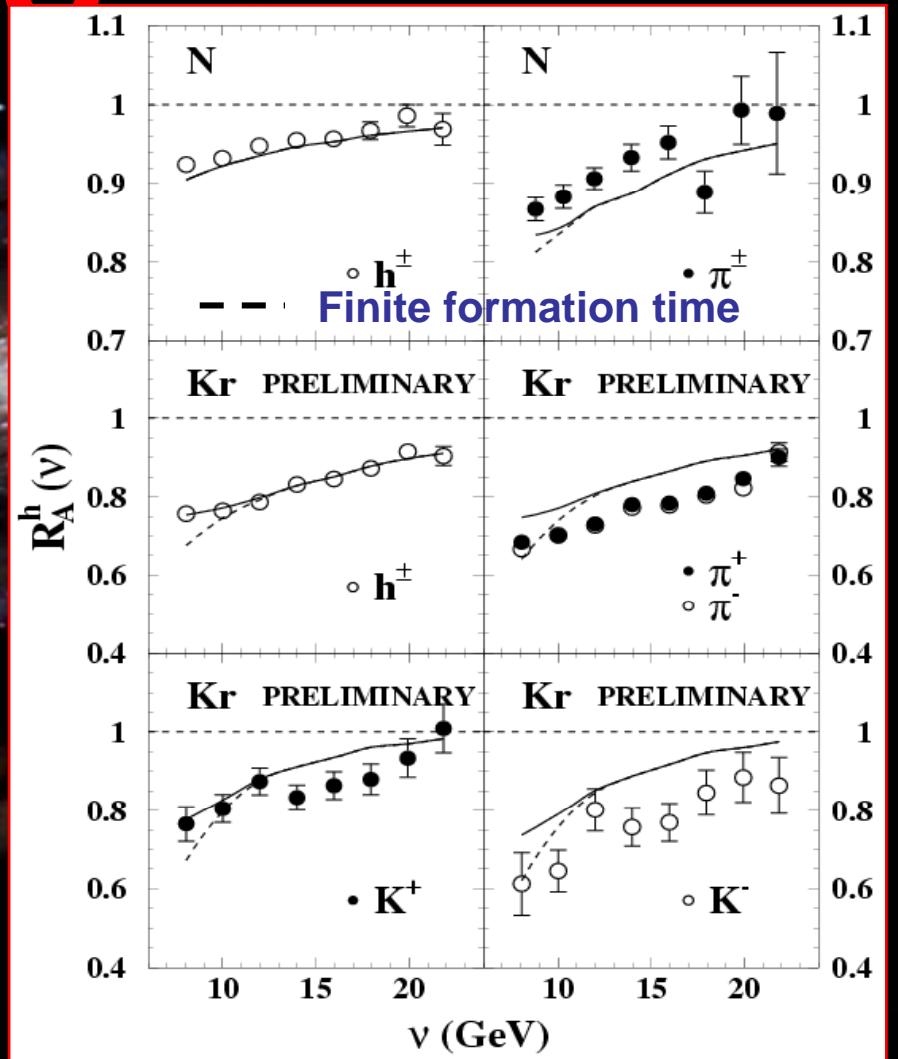


Large number of scatterings approximation

$$\langle -dE / dL \rangle_{final} \approx 3 \langle -dE / dL \rangle_{initial}$$

$$\langle -dE / dL \rangle_{cold}^{final} \approx 0.6 \text{ GeV / fm}$$

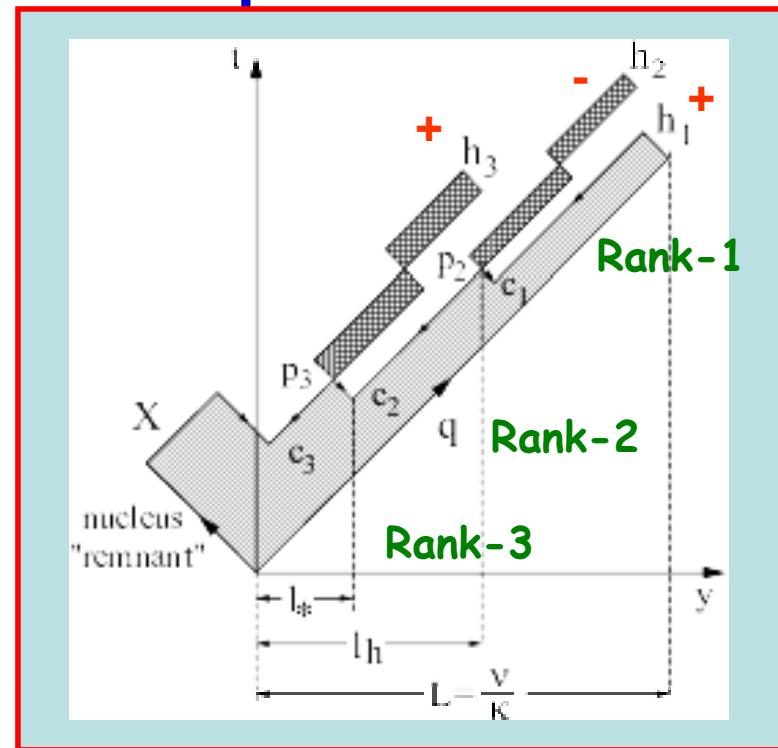
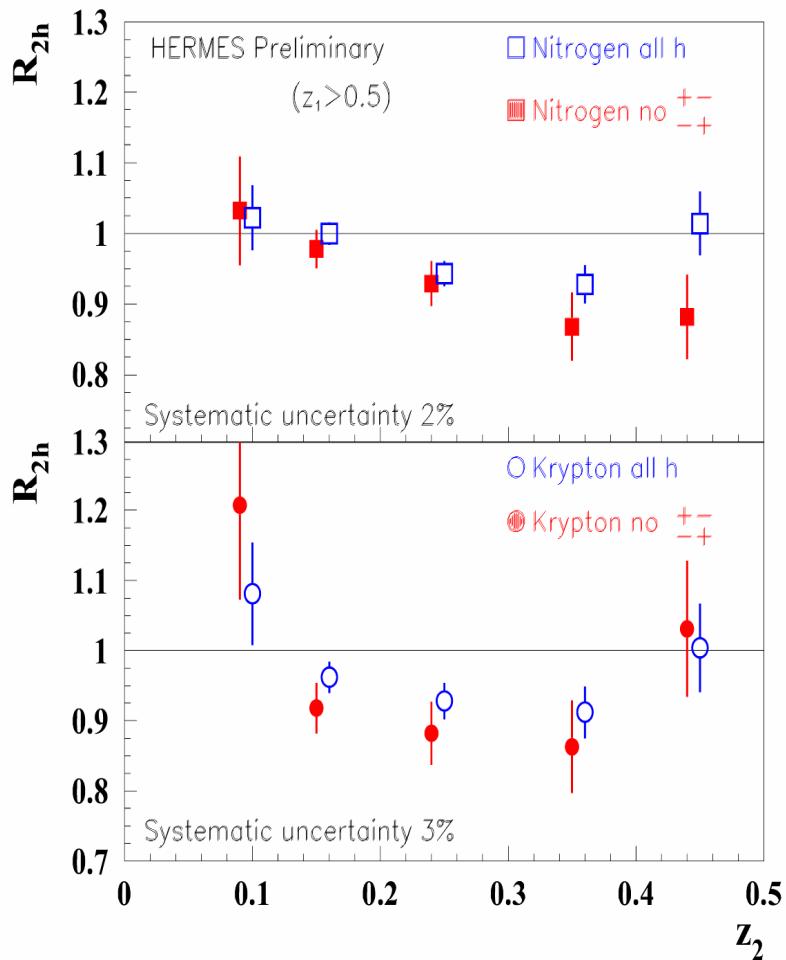
ASTROCRUISE



F.Arleo, Eur.Phys.J. C30 (2003)

Ivan Vitev, ISU

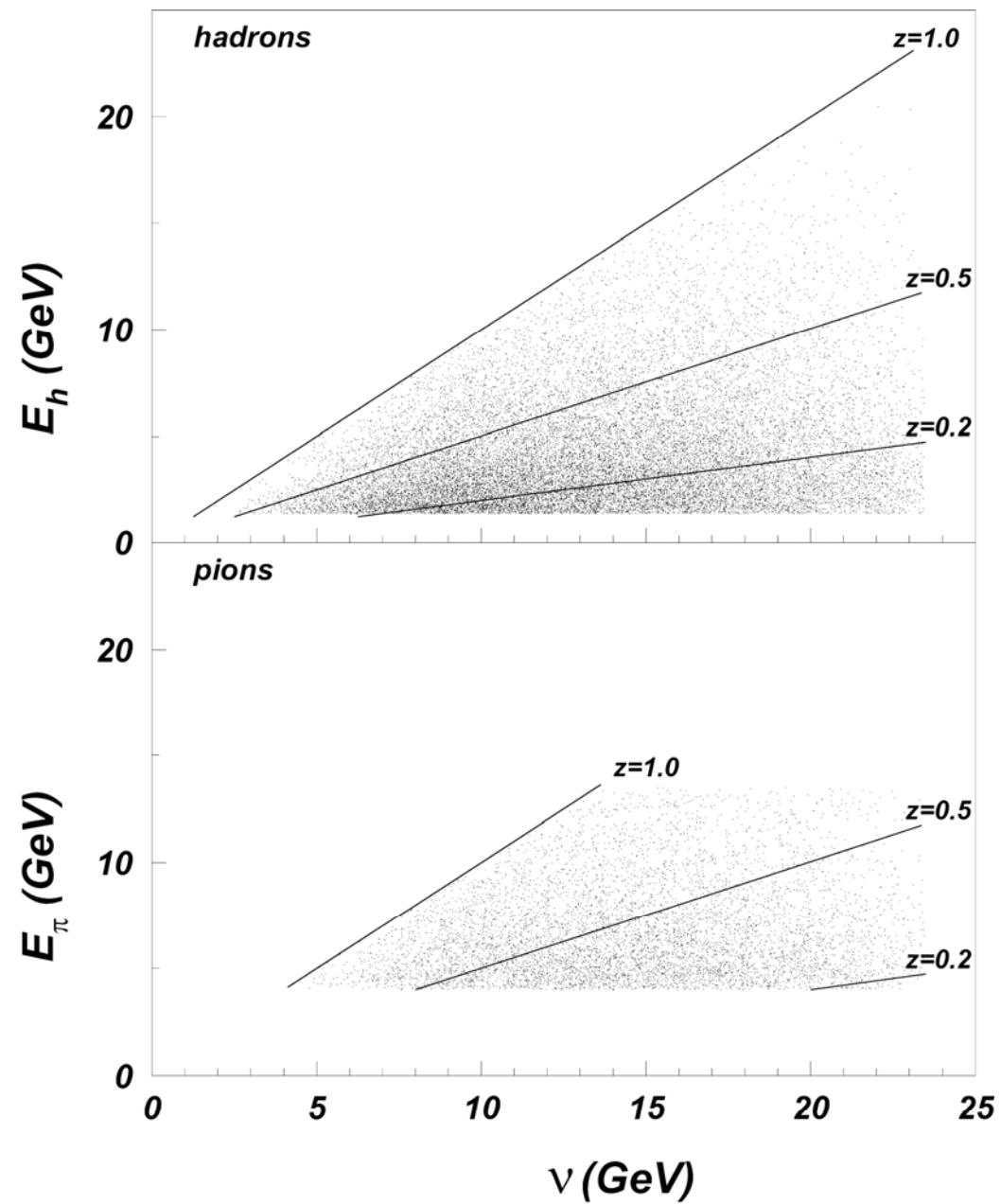
Double/single hadron production



All $h \rightarrow$ rank 1,2,3

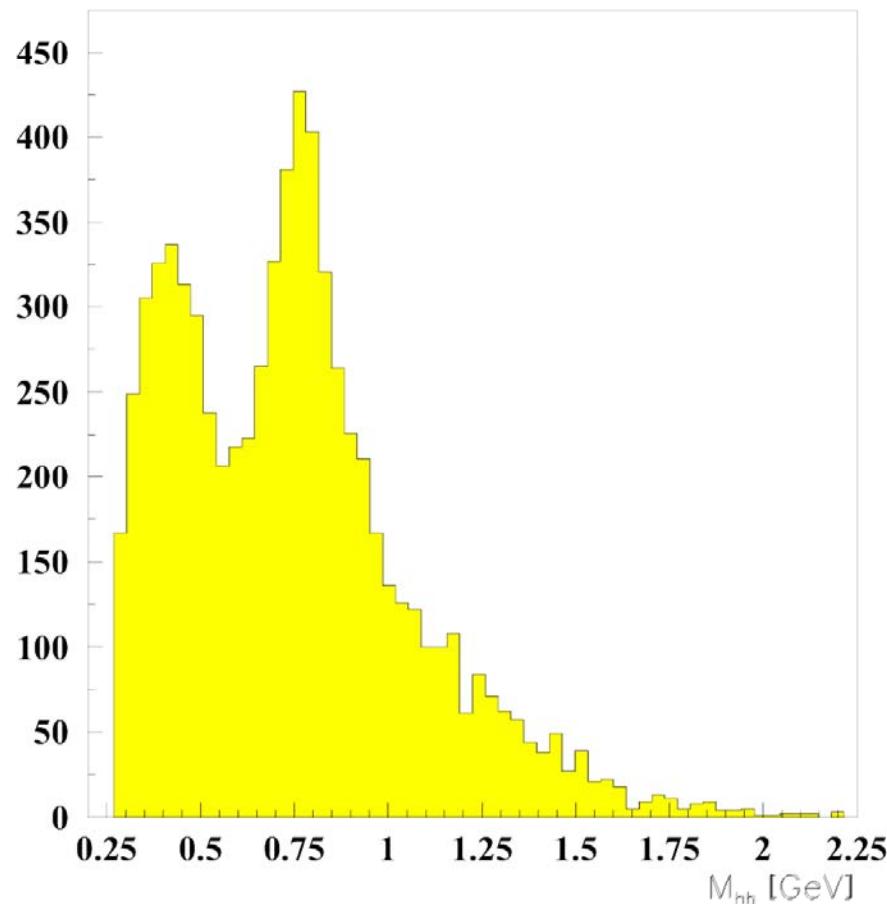
No $+\pm$ and $-\pm$ \rightarrow no rank 2, only 1,3

- Stronger reduction for higher rank (produced before, more inside the nucleus)

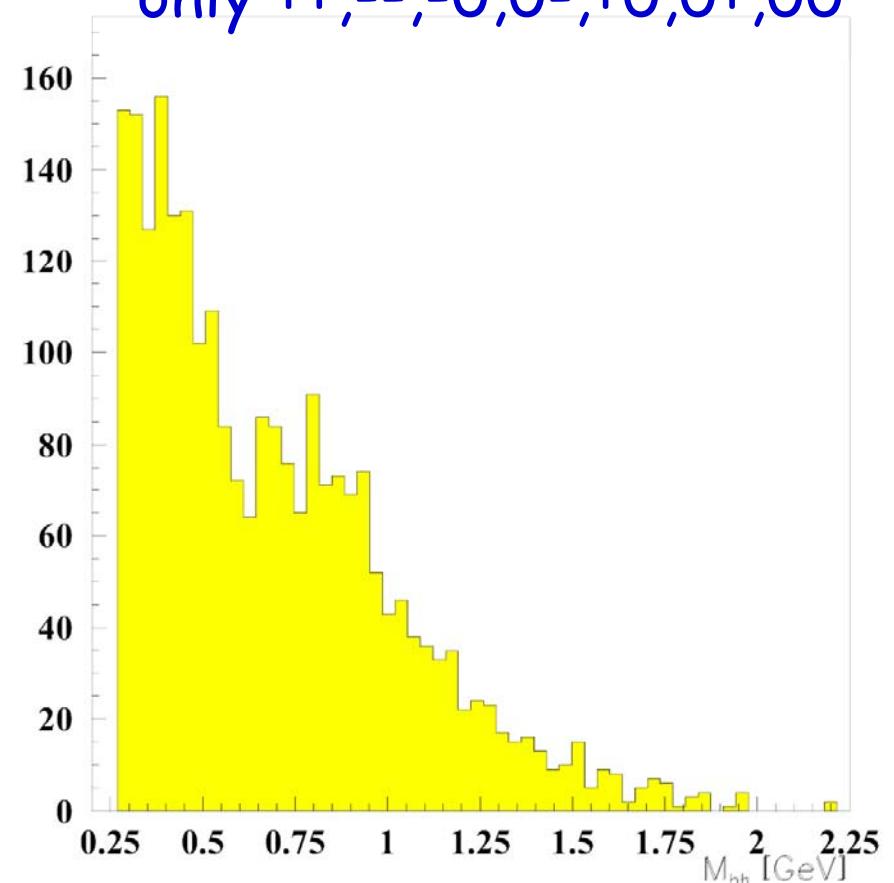


ρ^0 and particle rank

$z_1 > 0.5$, all h

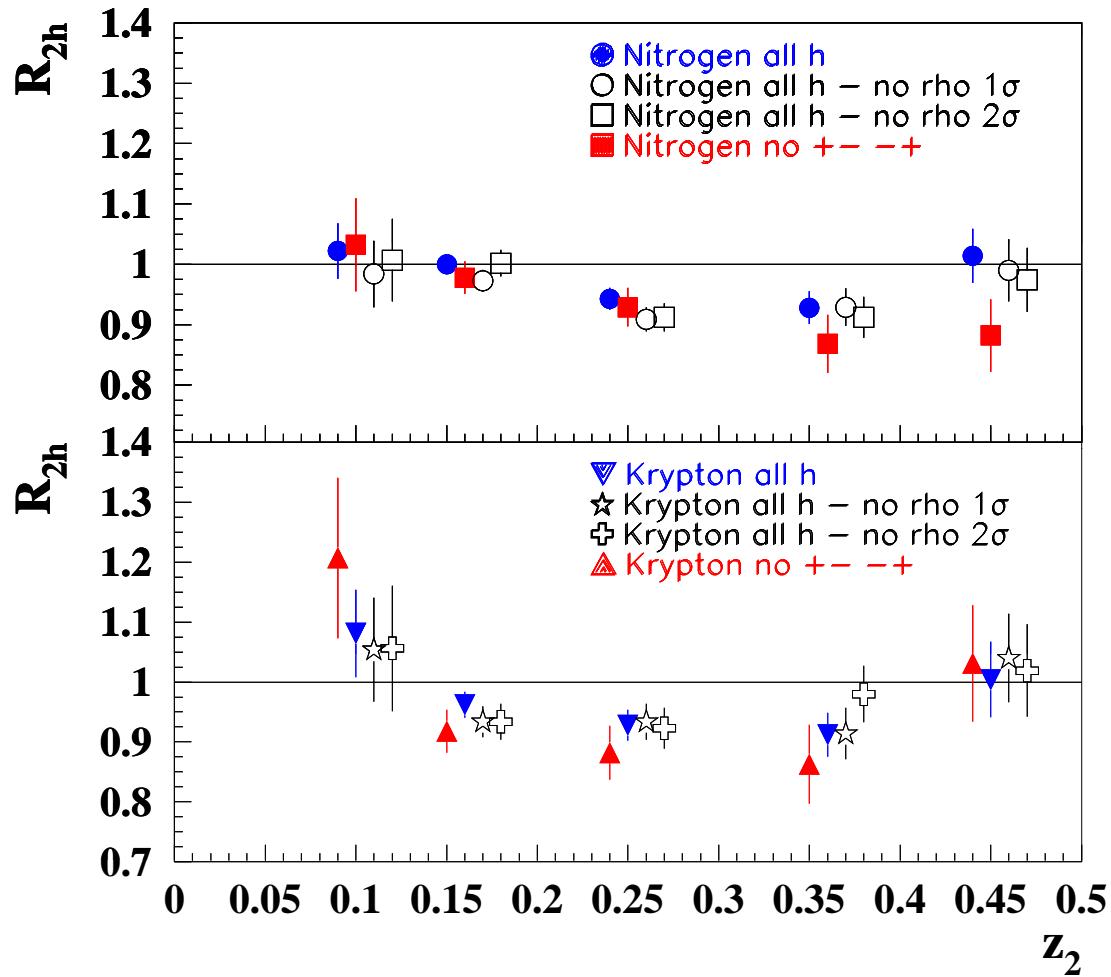


$z_1 > 0.5$,
only ++,--,0,0-,+0,0+,00



Clear ρ^0 suppression excluding +-,-+
Signals from ρ^+ and ρ^-

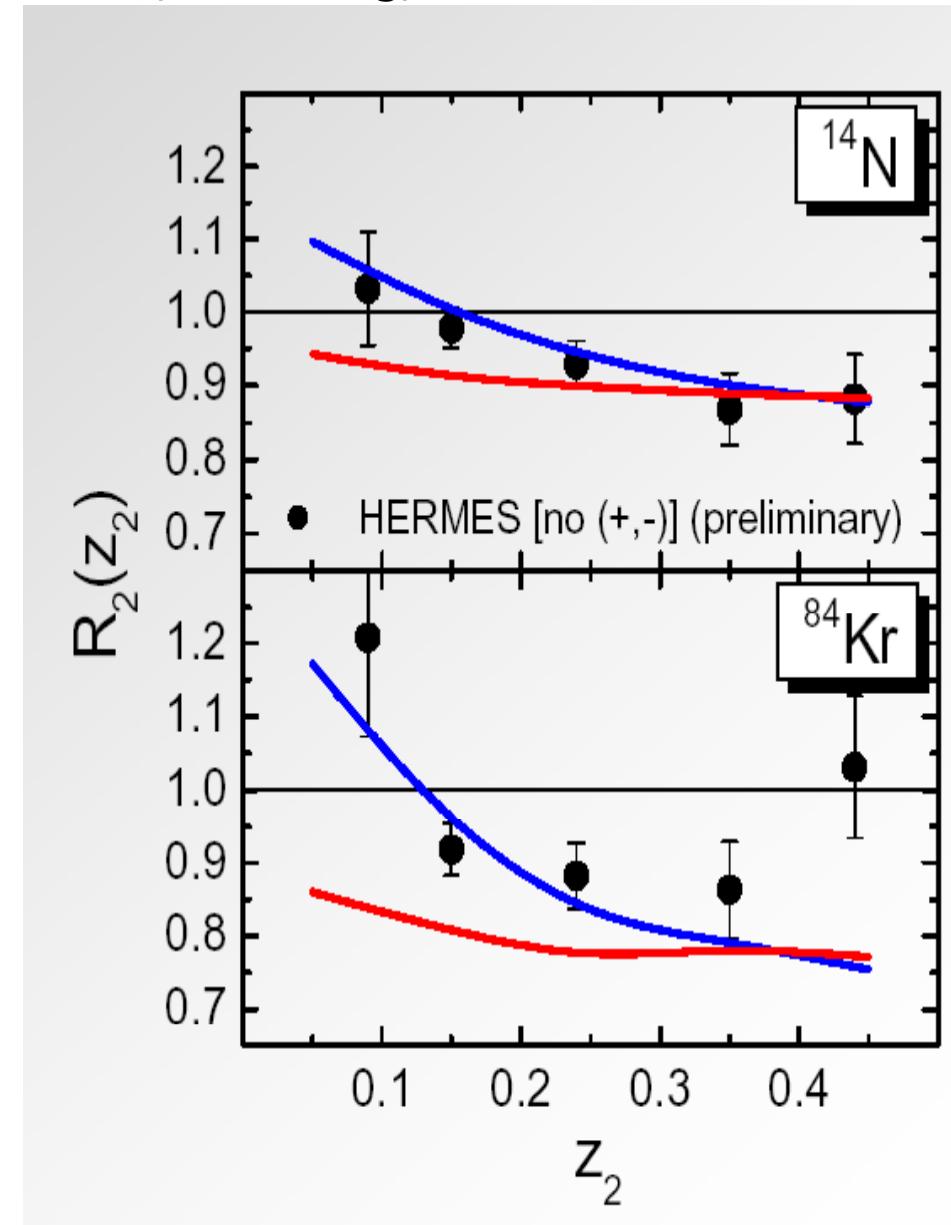
ρ^0 and particle rank



The ρ^0 contribution does not affect the results significantly;
The differences between all-h and +-,-+,... are not due to the
 ρ^0 contribution.

Double/single hadron production

T.Falter, W.Cassing, K. Gallmeister and U.Mosel nucl-th/0406023.



FSI in BUU Transport model

- pre-hadron $\tau_F=0.5$ fm,
 σ^* by constituent quark model:
 $\sigma_{\text{meson}}^* = \#q_{\text{orig}}/2 \sigma_{\text{meson}}$
- purely absorptive FSI

Double/single hadron production

A.Majumder and X.N.Wang hep-ph/0410078.

- Computation of dihadron FF and its modification from higher twist correction in DIS

