Hadron Production in nuclear DIS at HERMES

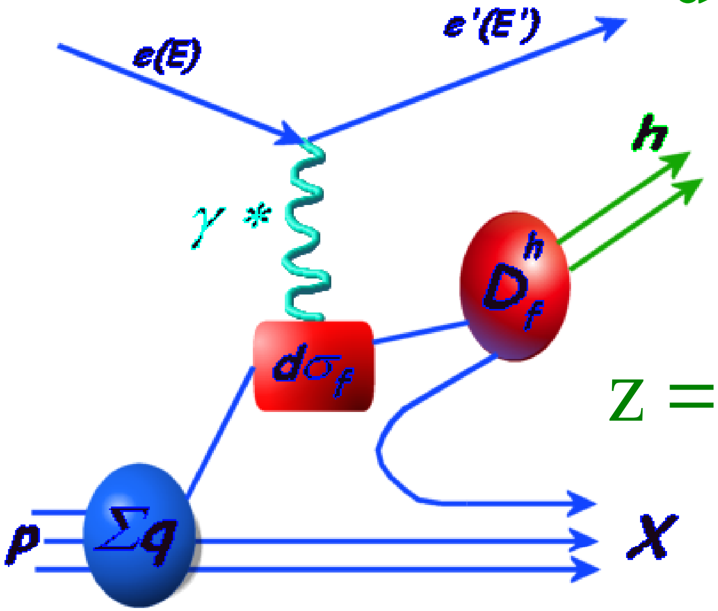
Valeria Muccifora
On behalf of HERMES Collaboration

- Semi-Inclusive DIS and FF in nuclei
- Single Hadron Attenuation
- Data Interpretations
- P_T broadening

Fragmentation Functions on Nucleon

• Semi-Inclusive DIS -> Parton Fragmentation Functions

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



$$z = E_h/\nu \qquad x = Q^2/2M\nu \qquad \nu = E - E'$$

FFs are measured with precision in e+e-
FFs follow pQCD Q^2-evolution like DFs
FFs scale with z like DFs with x
FFs probabilistic interpretation like DFs

What happens in a nuclear medium ?

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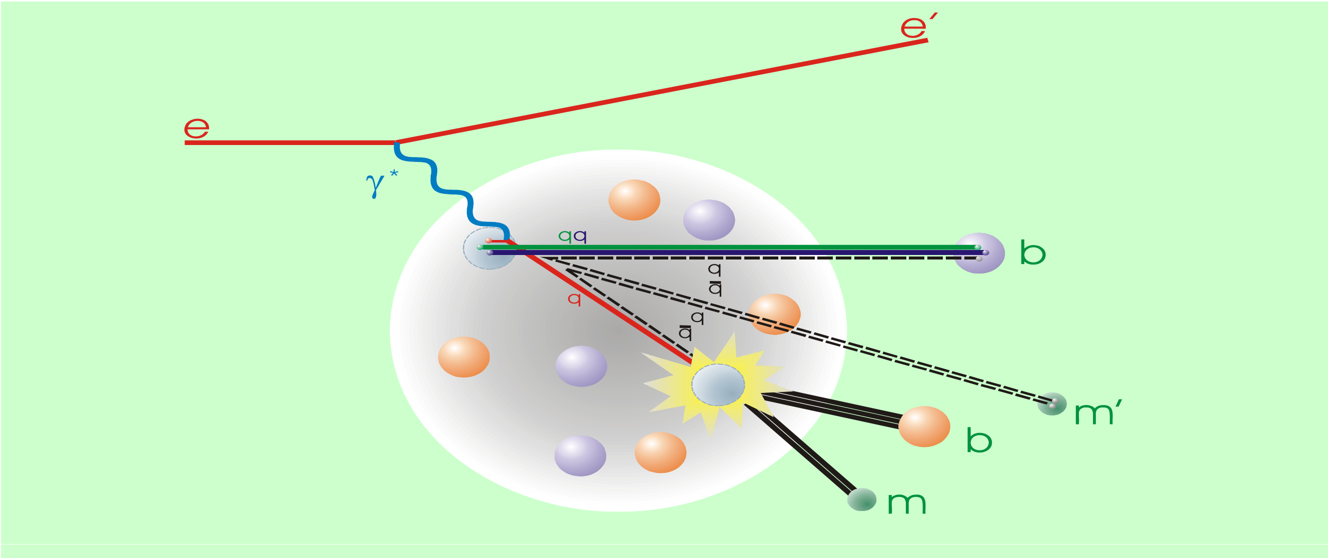
Nuclear Attenuation (quenching)

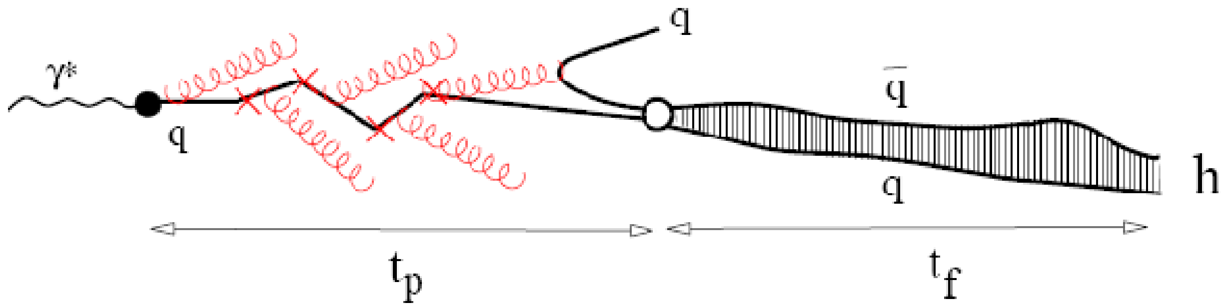
<u>Observation</u>: reduction of multiplicity of fast hadrons due to both *hard partonic* and *soft hadron interaction.*



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, kinematic defined
- 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, hadron formation time)

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 qqbar

➢Increasing transverse dimension & interaction probability

•Hadronic FSI ($t>t_f$):

➢Mainly formed after several tens of fm i.e. out of the nucleus

➢Full hadronic cross section (10-30 mbarn)

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Nuclear SIDIS: Experiments

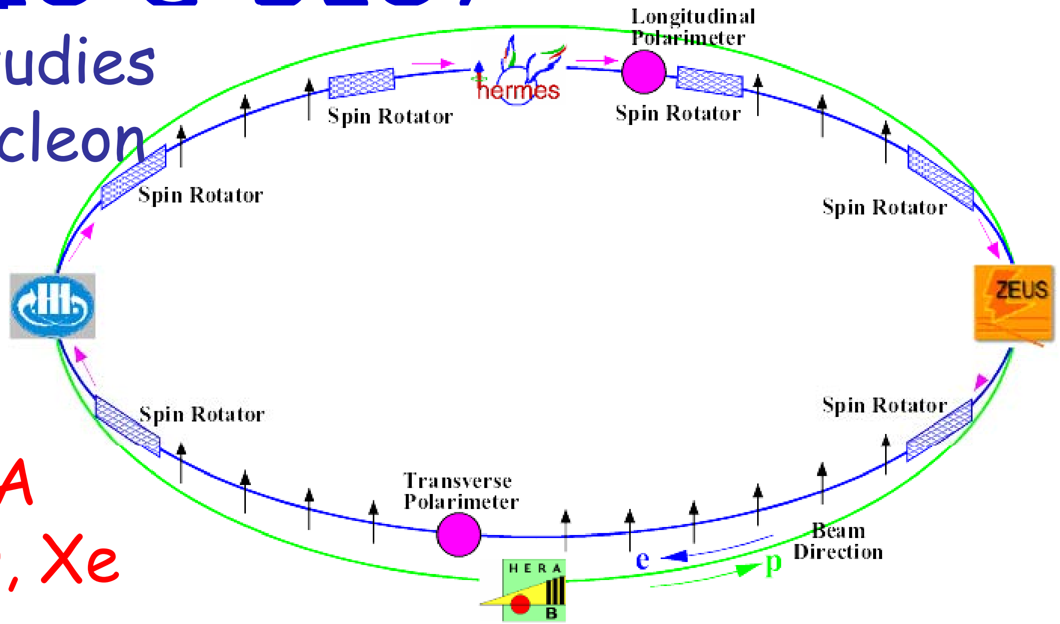
- SLAC: 20 GeV e^--beam on Be, C, Cu Sn   PRL 40 (1978) 1624
- EMC: 100-200 GeV μ-beam on Cu   Z.Phys. C52 (1991) 1
- WA21/59: 4-64 GeV ν-beam on Ne   Z.Phys. C70 (1996) 47
- HERMES: 27.6 GeV e^{+-}-beam on He, N, Ne, Kr, Xe

EPJ C20 (2001) 479	(Topcite)	Single hadron attenuation
PLB 577 (2003) 37	(Topcite)	Single hadron attenuation
PRL 96 (2006) 162301		Double hadron (correlation) attenuation
NPB accepted, arXiv:0704.3270		Data summary paper
arXiv:0704.3712v2[hep-ex]		P_t broadening (preliminary)

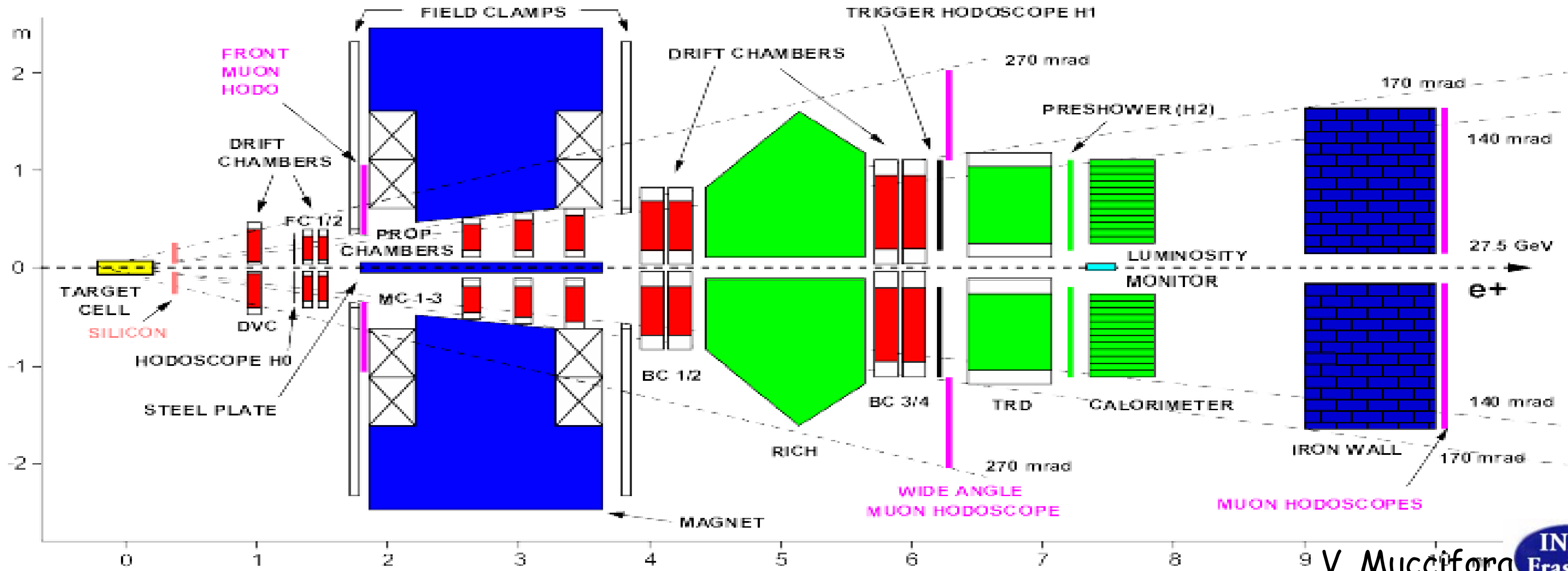
- CLAS: 5.4 GeV e^--beam on C, Al, Fe, Pb
  E-02-104

HERMES @ DESY

It is an experiment which studies the spin structure of the nucleon (see Marianski's talk)
… but not only …



Beam: 27.6 GeV e+, I_e~40 mA
Targets: H, D, He, N, Ne, Kr, Xe



- The energy range (ν 3-27 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, $\bar{p}$

Hadron multiplicity ratio

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

Double-ratio: approx evaluation of FF medium modification
Systematic uncertainties are minimize in the double-ratio

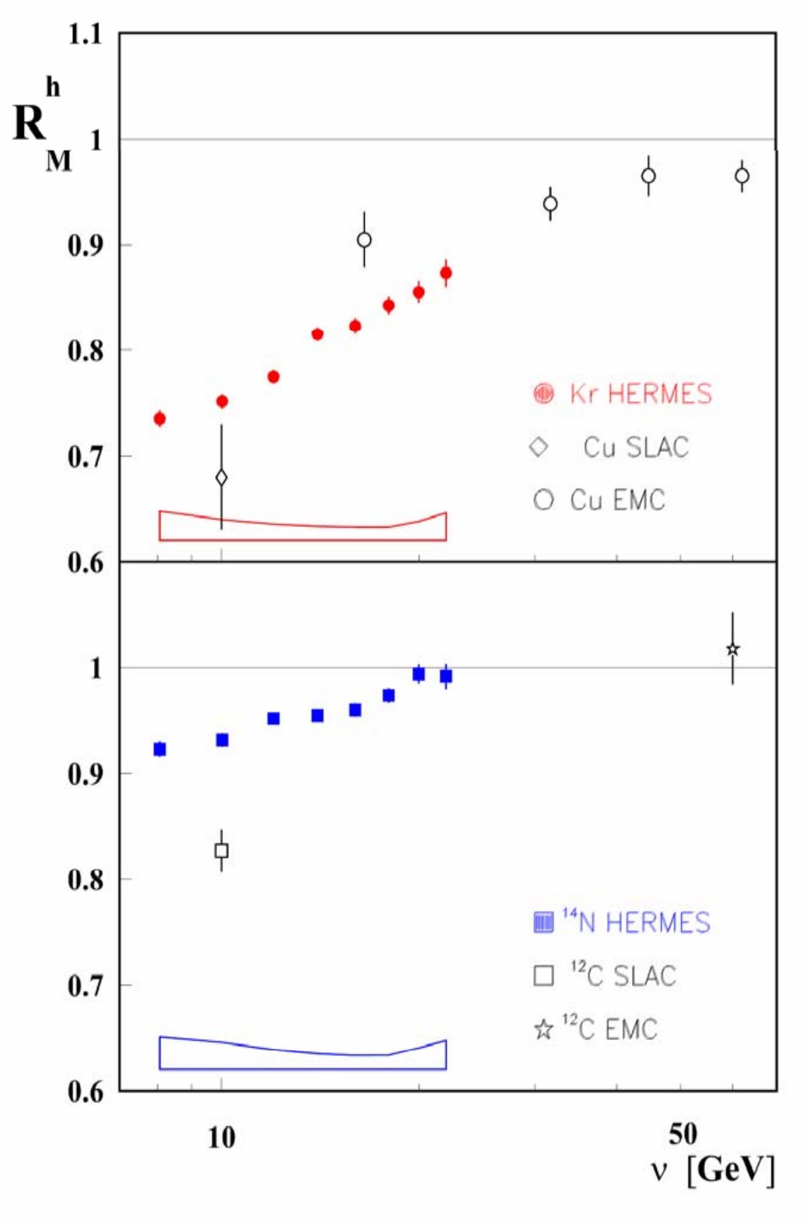
Leptonic variables : ν (or x) and Q^2

Hadronic variables : z and P_t^2

Different nuclei : size and density

Different hadrons : flavors and mixing of FFs

Multiplicity ratio for charged hadrons vs ν
HERMES (first data) vs SLAC/EMC



- 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

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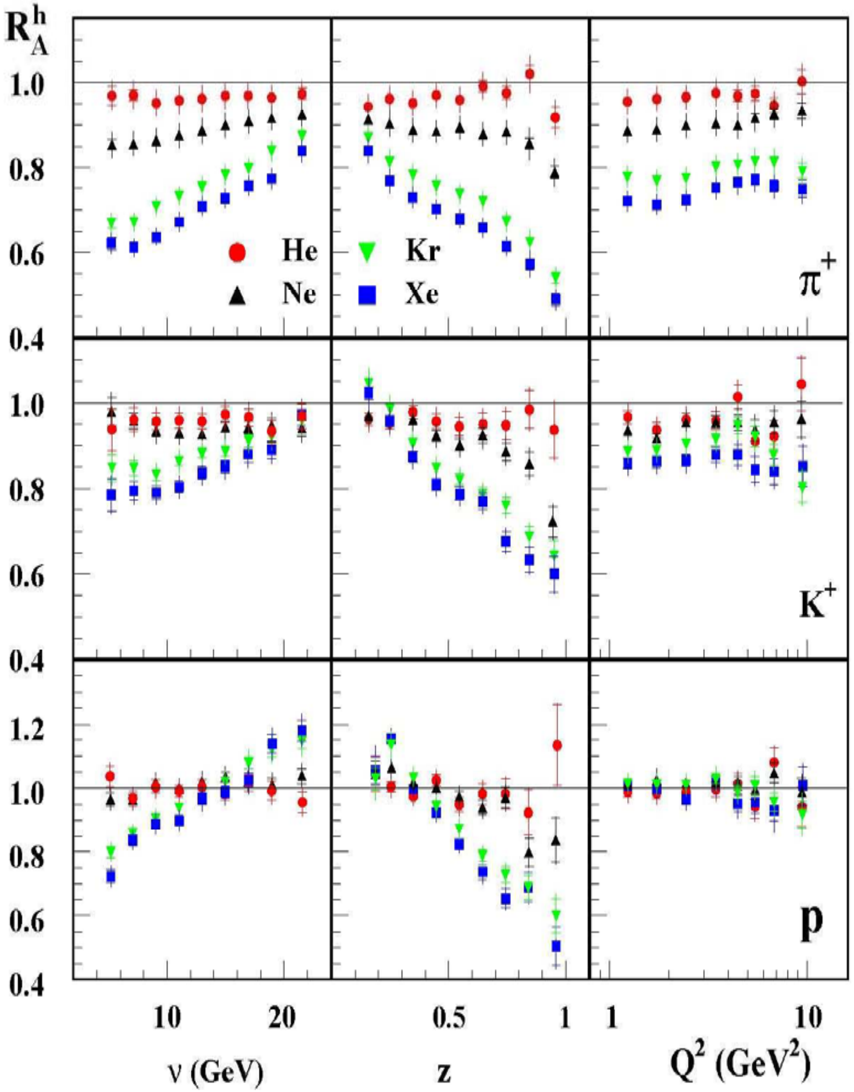
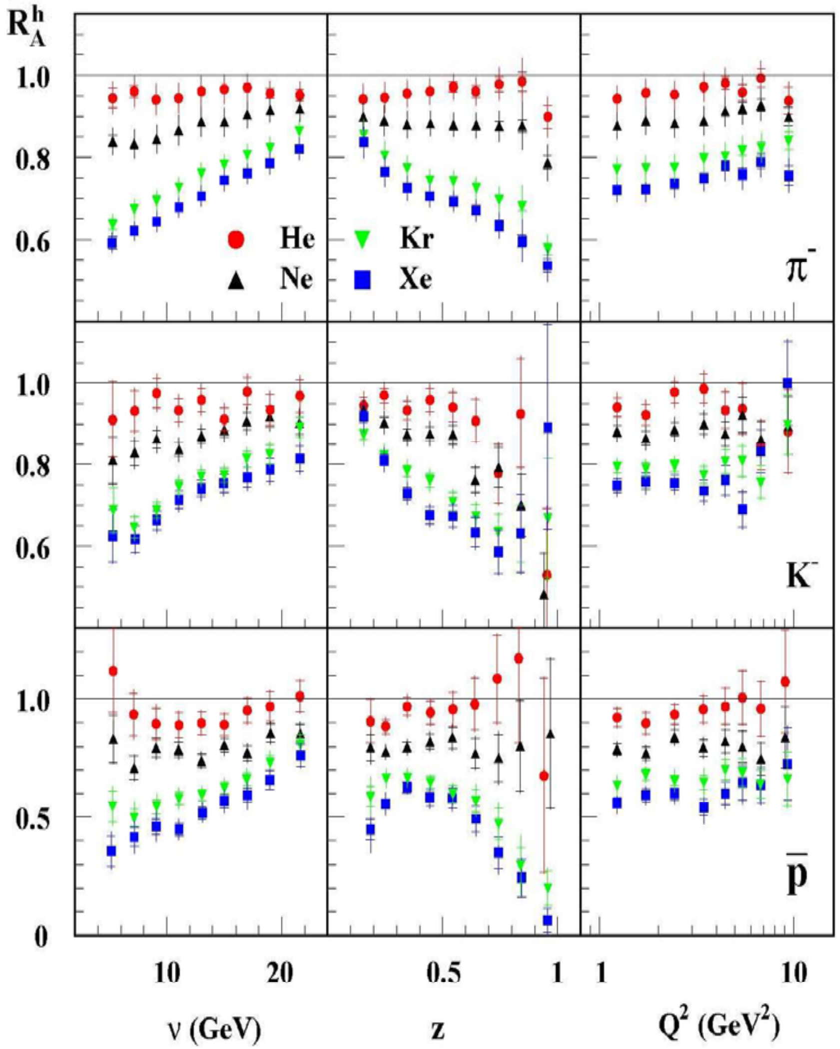
Multiplicity ratio vs ν,z, Q2 : different hadrons





$\pi^+ = \pi^- = \pi^0$ $K^+ \neq K^-$ $p \neq \bar{p}$

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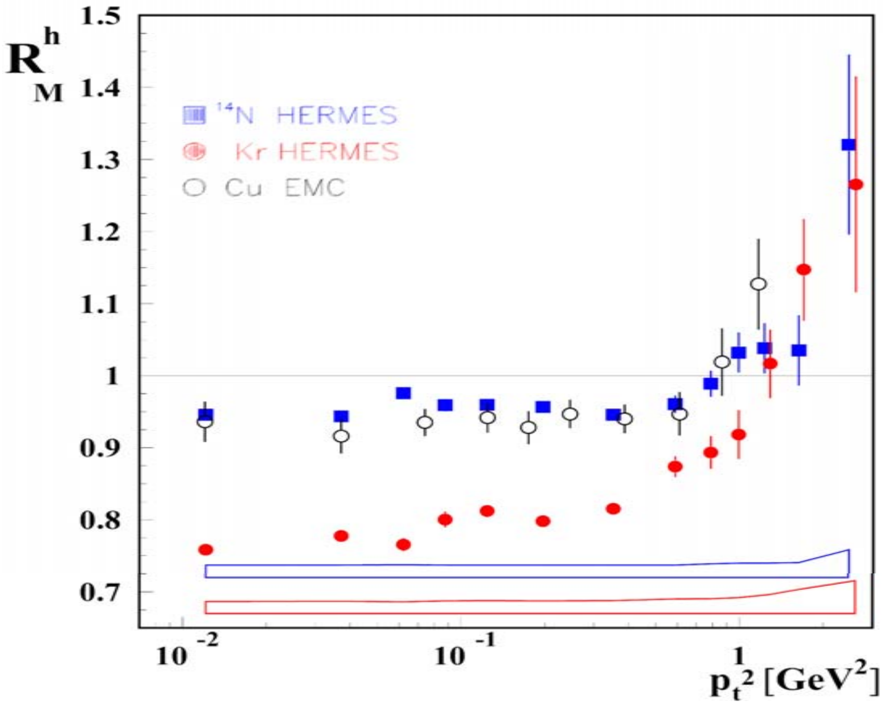
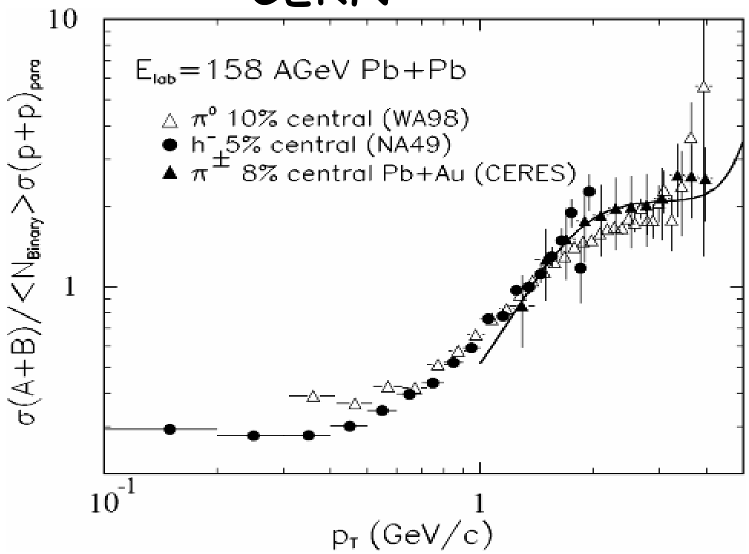
Multiplicity Ratio vs. p_t^2

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



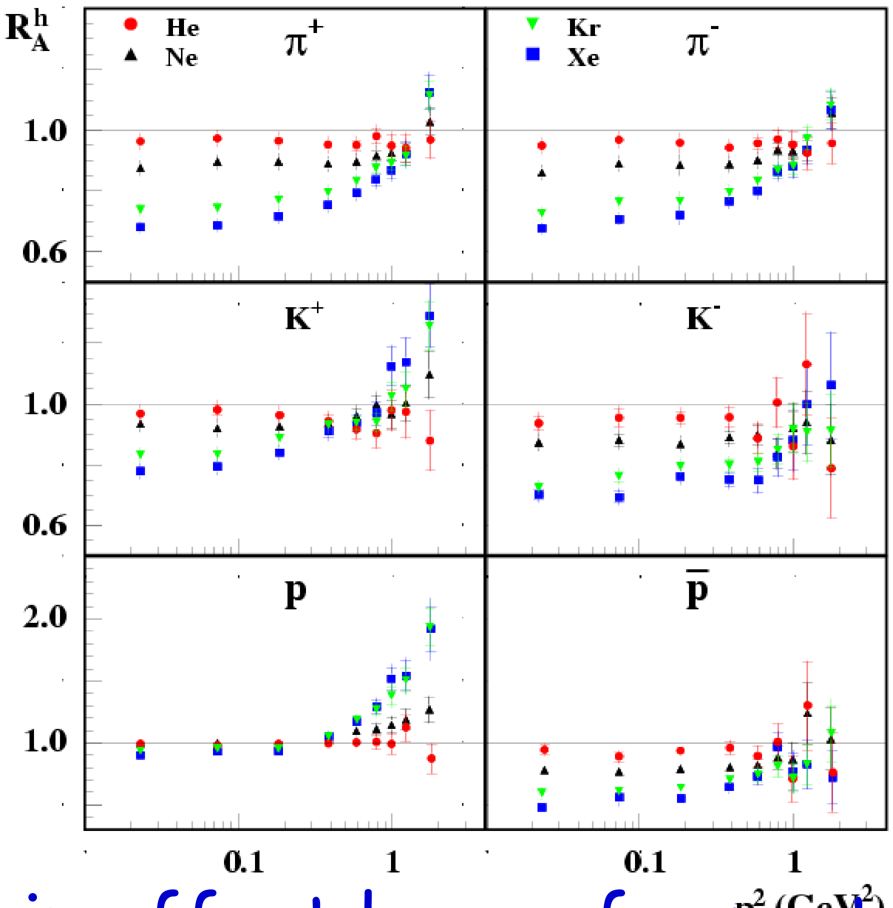
CERN



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

Pt dependence for identified hadrons



Cronin effect larger for protons

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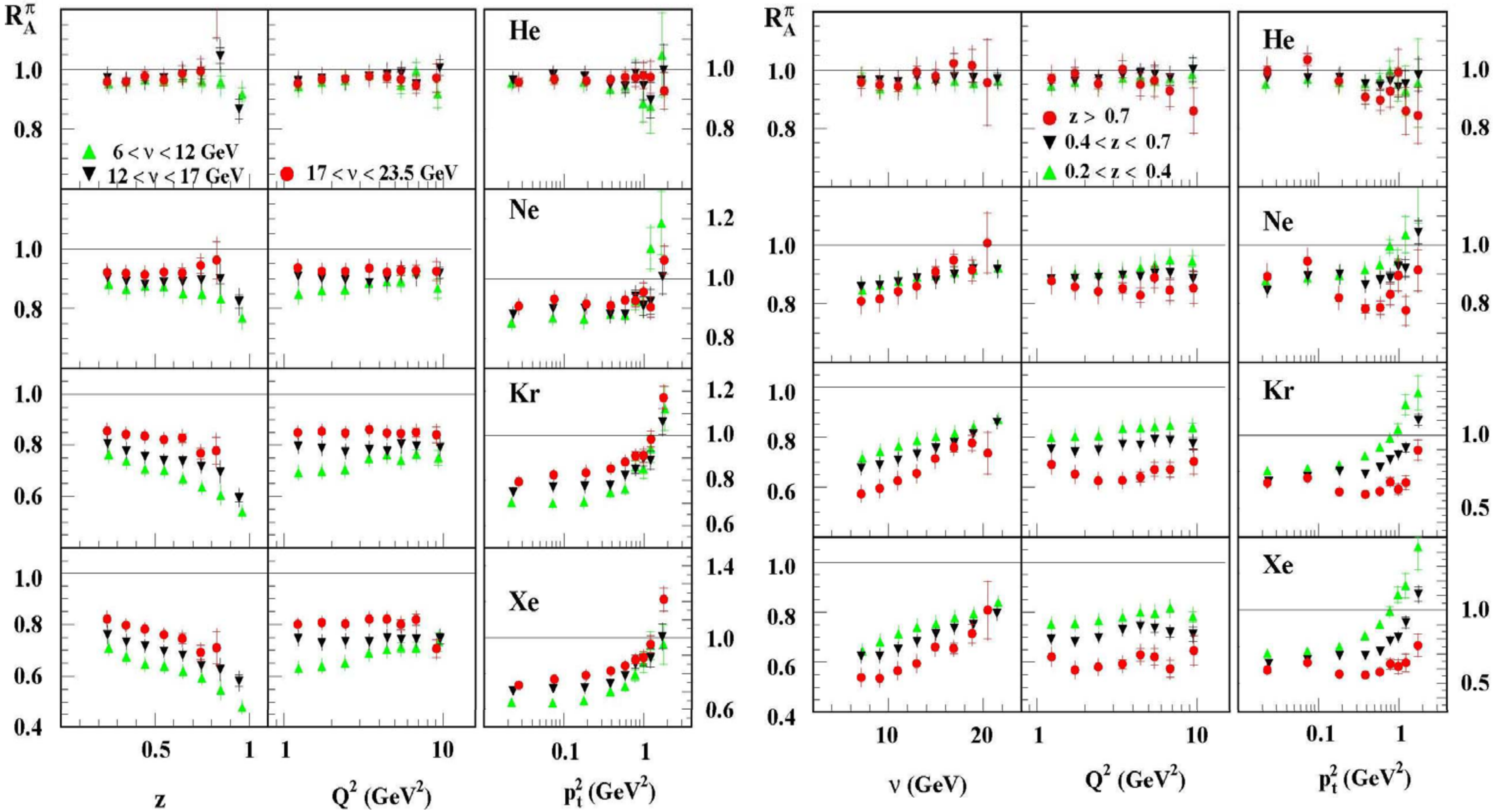
Multiplicity ratio 2D



Reduce the correlation between z and ν

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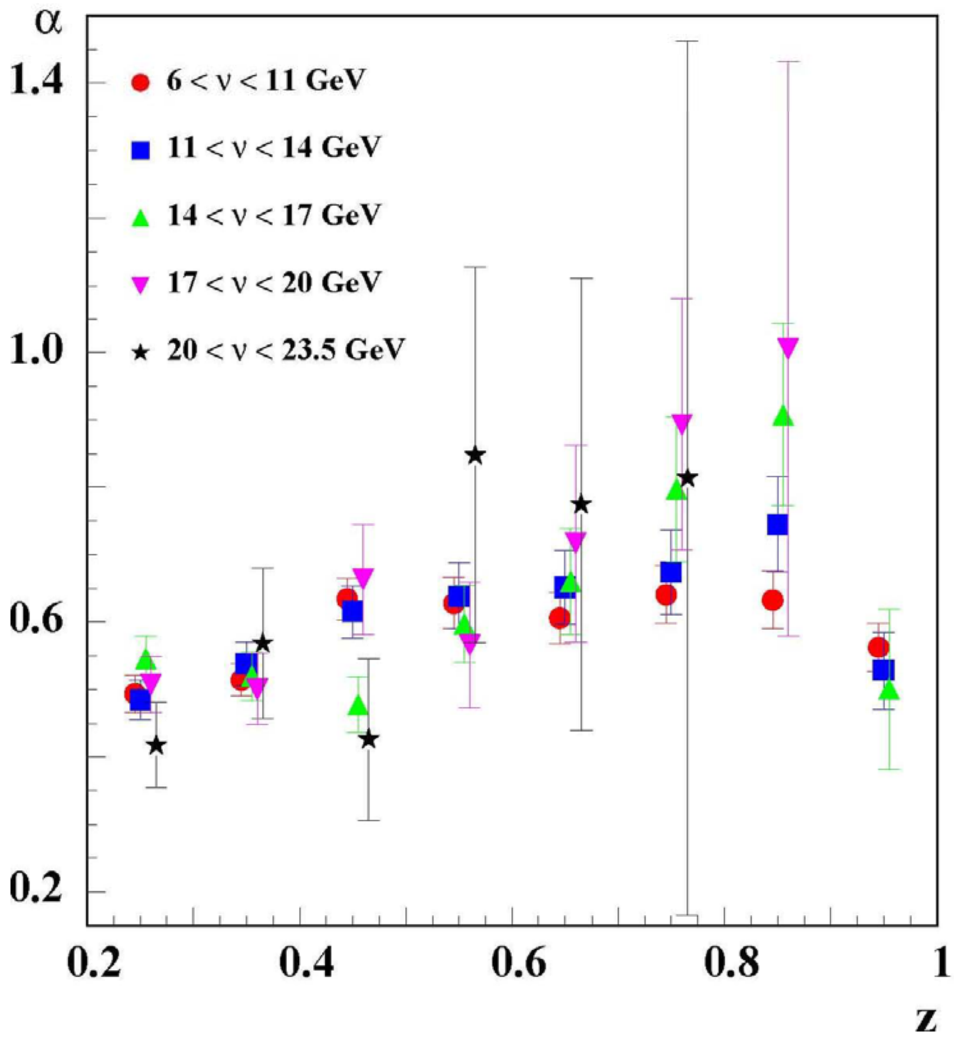
A dependence of attenuation $1\text{-}R_M$



Data support a quadratic dependence on nuclear size

A^{α} with α ~2/3

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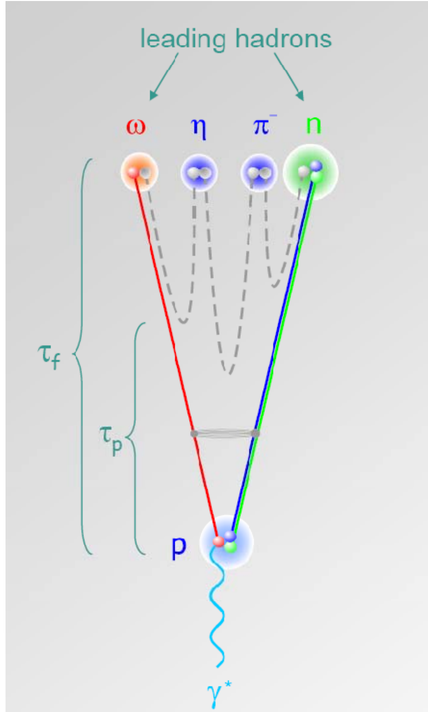
Models based on pre-hadronic interaction

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))

-Induced radiation « absorption or rescattering
-Color neutralization inside the medium
-Pre-hadron formation and interaction
-Hadron formation mainly outside the nucleus
Time? Cross section? AbsorptionvsRescattering



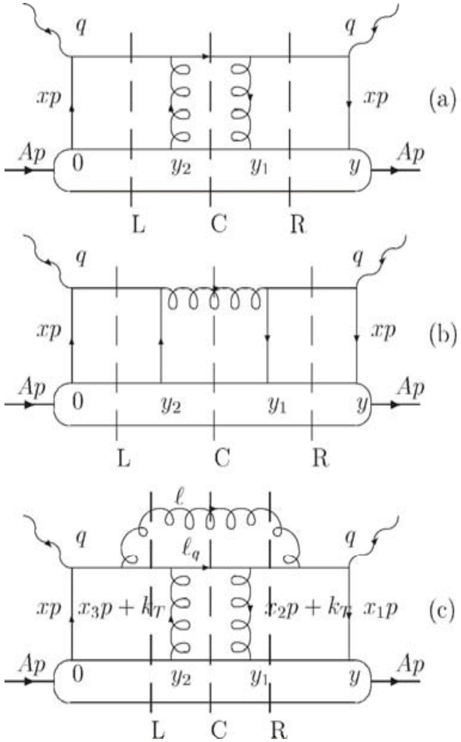
Models based on partonic energy loss

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 $A^{2/3}$
-Parton rescattering → enhancement at large p_T $A^{1/3}$
gluon transport coefficient?(the medium gluon density)

FF modification

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

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
•longitudinal effect (hadron suppression at large z/ enhancement at low z) : full momentum acceptance

FF modification

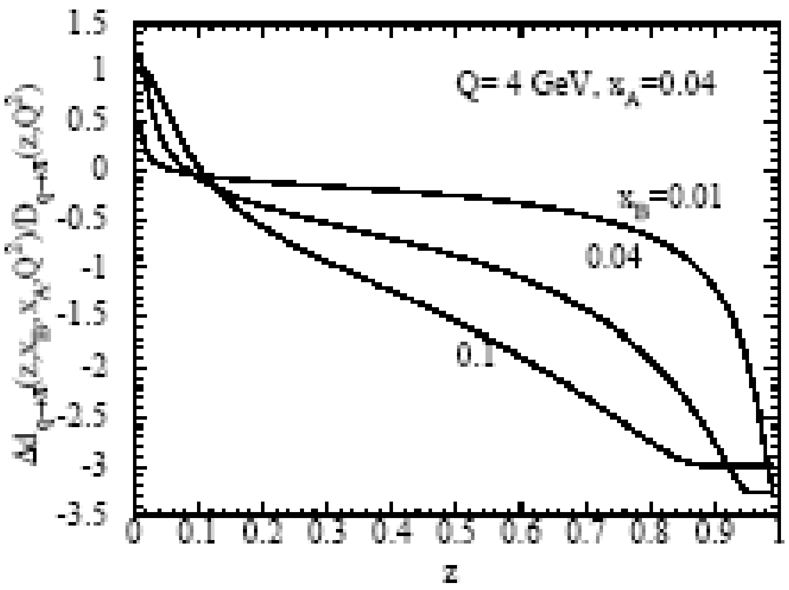
X.N.Wang et al., NPA696(2001)788 PRL89(2002)162301

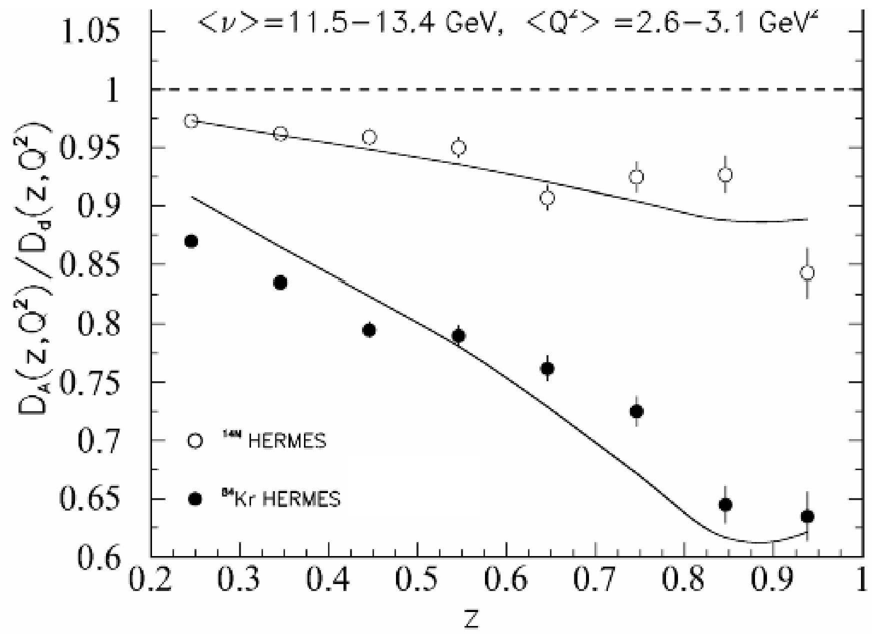
Parton energy loss :

Landau-Migdal-Pomeranchuk interference pattern

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

$$\Delta E = n < \Delta z_g > \propto C\alpha_s^2 m_N R_A^2$$

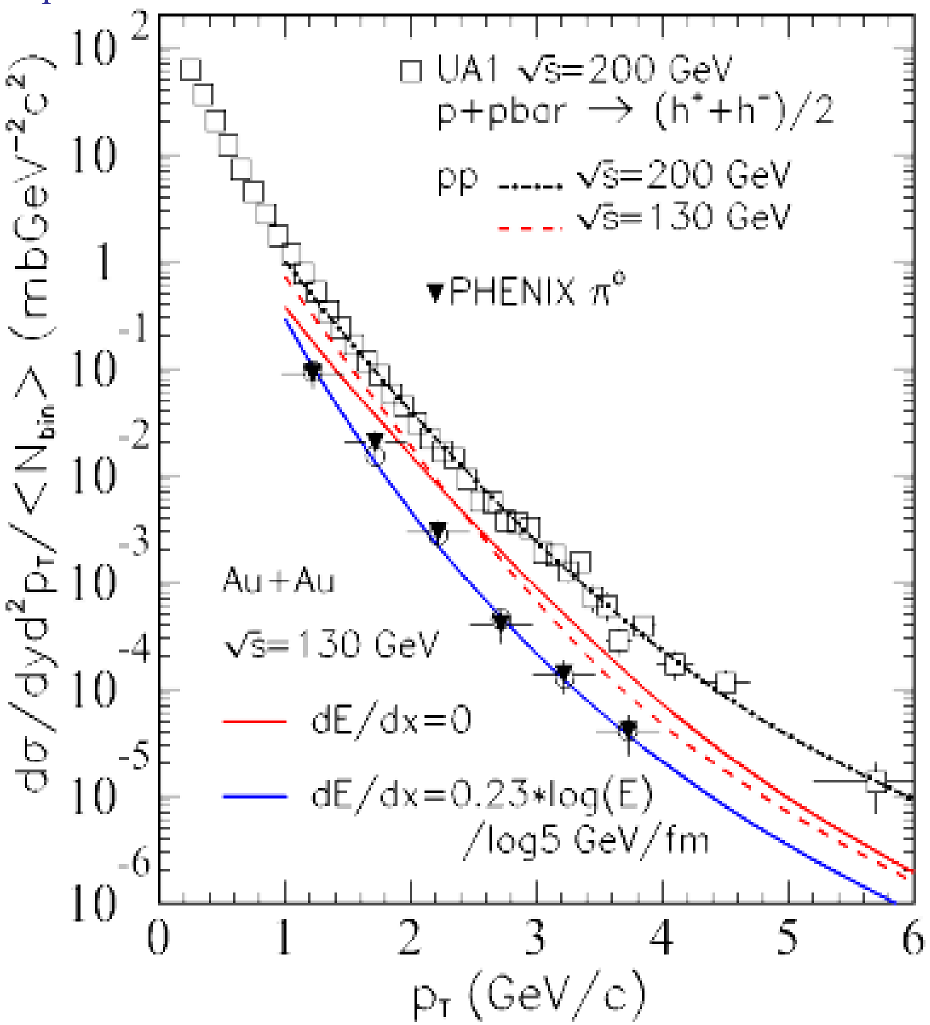




- 1 free parameter C≡quark-gluon correlation strength in nuclei
- From ^{14}N data C=0.0060 GeV^2:
- HERMES : cold static nuclei $\Delta E_{sta} \propto \rho_0 R_A^2$; ρ_0 gluon density and $R_A \approx 6$ fm
- RHIC : hot expanding $\Delta E_{exp} \approx \Delta E_{sta}\,(2\tau_0/R_A)$; τ_0 initial medium formation time

dE/dL and Gluon density at RHIC

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

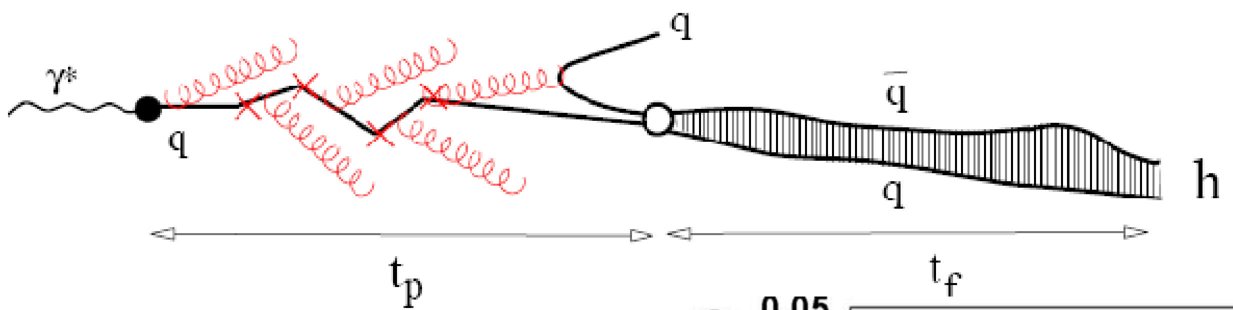


$dE/dL_{PHENIX}|_{Au}$ predictions by using C=0.0060 GeV^2 from HERMES data

<dE/dL>≈0.5 GeV/fm for 10 GeV quark in Au

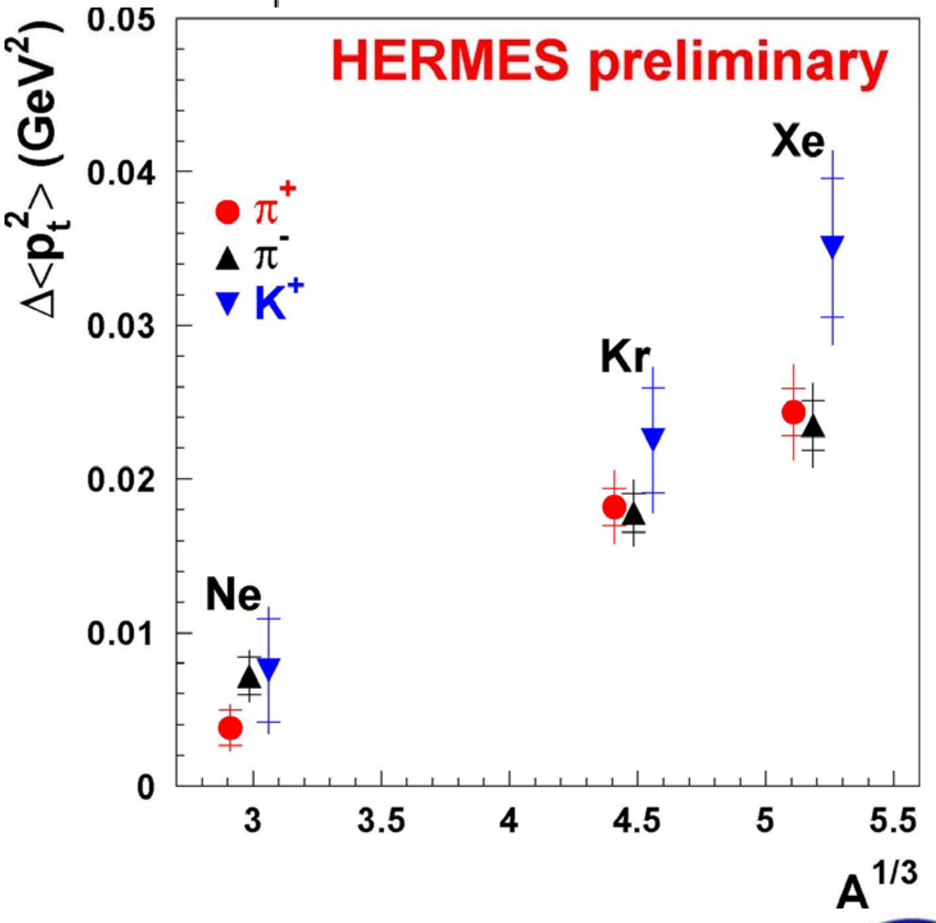
- Cold <--> Hot nuclear matter correlation
- Gluon density in Au+Au~30 times higher than in cold matter

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



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

$\Delta\langle p_t^2\rangle \sim t_p$



Mainly partonic scattering :

Incoherent →linear in nuclear size

In later stages no broadening:

Elastic scattering very small

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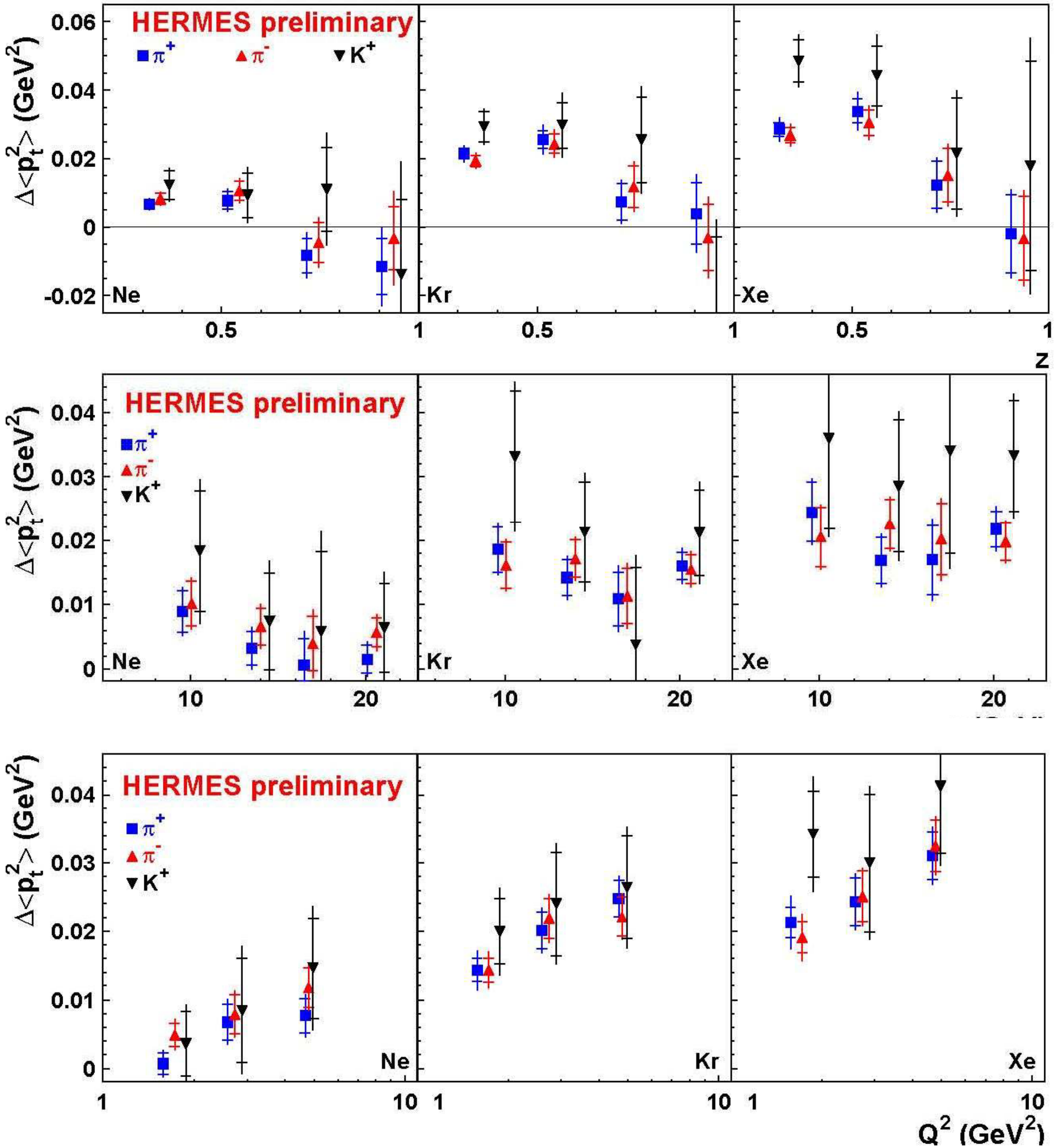
Pt-broadening vs z, ν, Q^2



No effect at z=1

($t_p \propto \nu z(1-z) \to 0$)

$\Delta\langle pt^2\rangle$ up to 0.025 GeV^2

No ν dep. @ <z=0.4> : pre-hadron formation mainly at the surface.

Increase with Q2: gluon radiation

Clear evidence for partonic effects

Constraints on pre-hadronic effects

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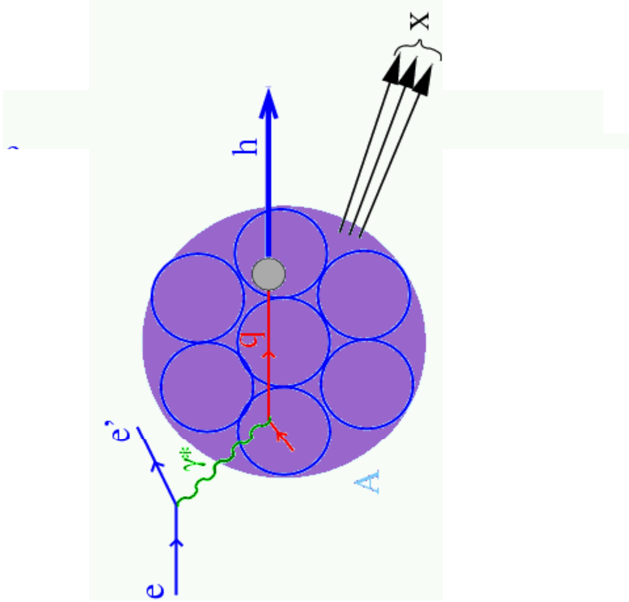
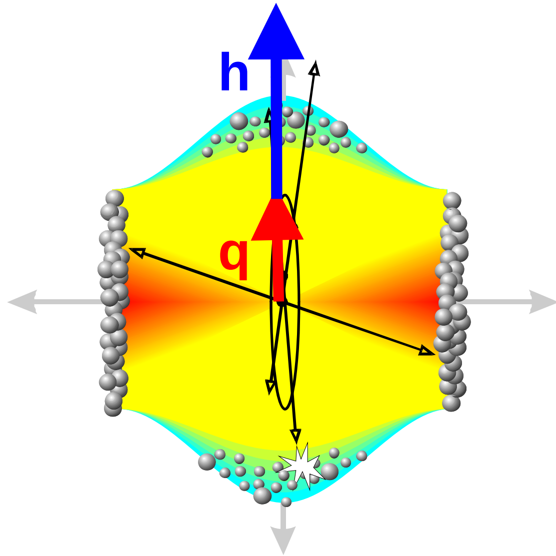
DIS vs HIC





E_q = ■ = E_e-$E_{e'}$ 🕓 13 GeV

E_h = z ■ 🕓 **2 - 15 GeV**

$E_q = p_T / z$

$E_h = p_T$ 🕓 **2 - 20 GeV**

HERMES kinematics is relevant to Ion-Ion mid-rapidity

...but beware the virtuality...

Q^2 = 📭 q^2 is measured

Q^2 🕓 $E_q^{\,2}$ ✪ $(p_T/z)^2$

...and the rapidity...

always forward rapidity

rapidity can change

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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. ν, z, Q^2, p_t^2 for ^{4}He, ^{14}N, ^{20}Ne, ^{84}Kr, ^{131}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 pt- broadening in SIDIS

HERMES provide information on partonic propagation, energy loss and scattering and constraints in pre-hadronic effects

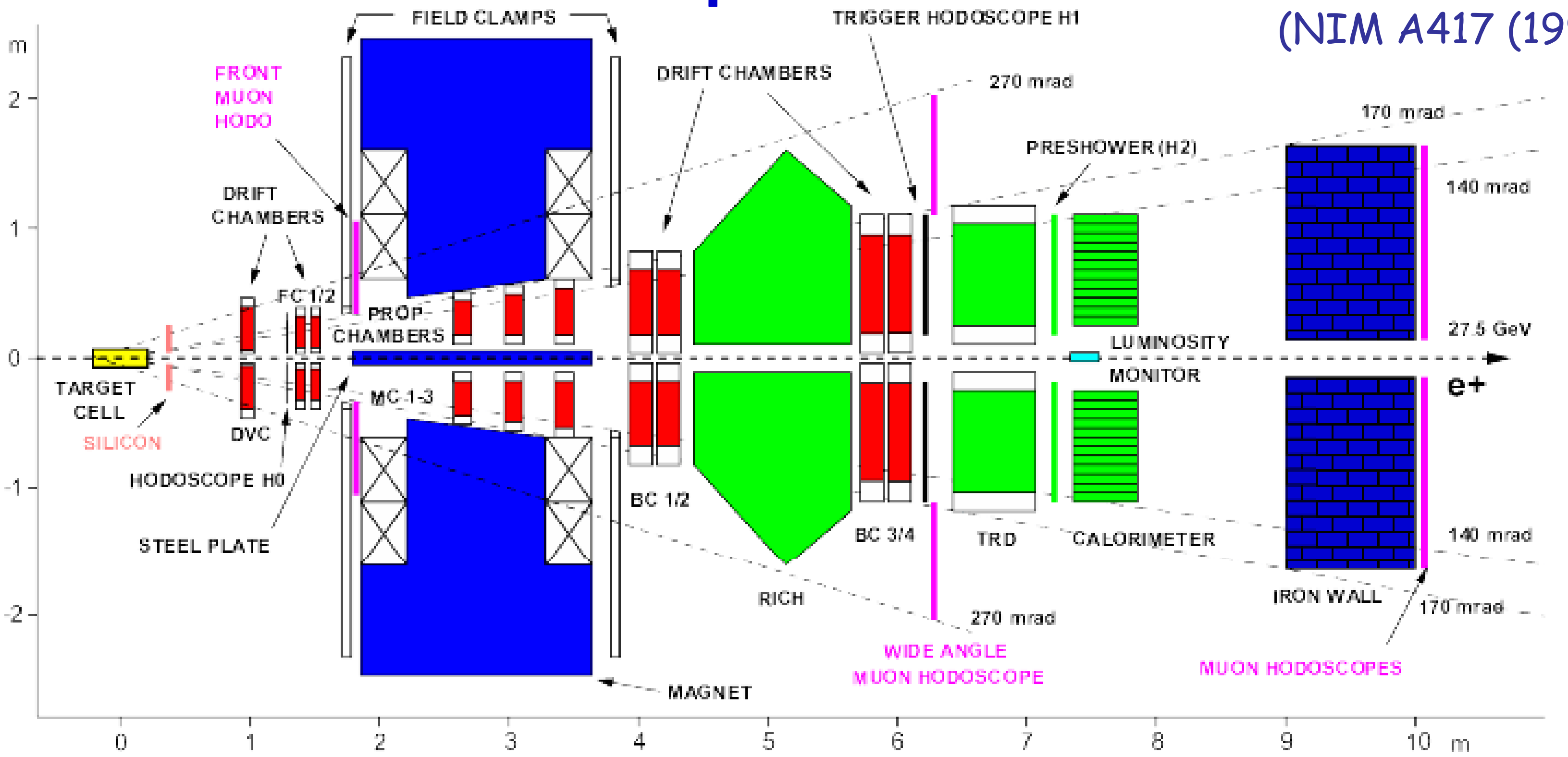
HERMES kinematics is relevant to ion-ion mid-rapidity

Possibility to formulate consistent pictures of nuclear effects in cold and hot nuclear matter

BACKSLIDES

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 target: by RICH π, K, p ID 2.5<p<15 GeV
- π^0 ID by e.m. Calorimeter.

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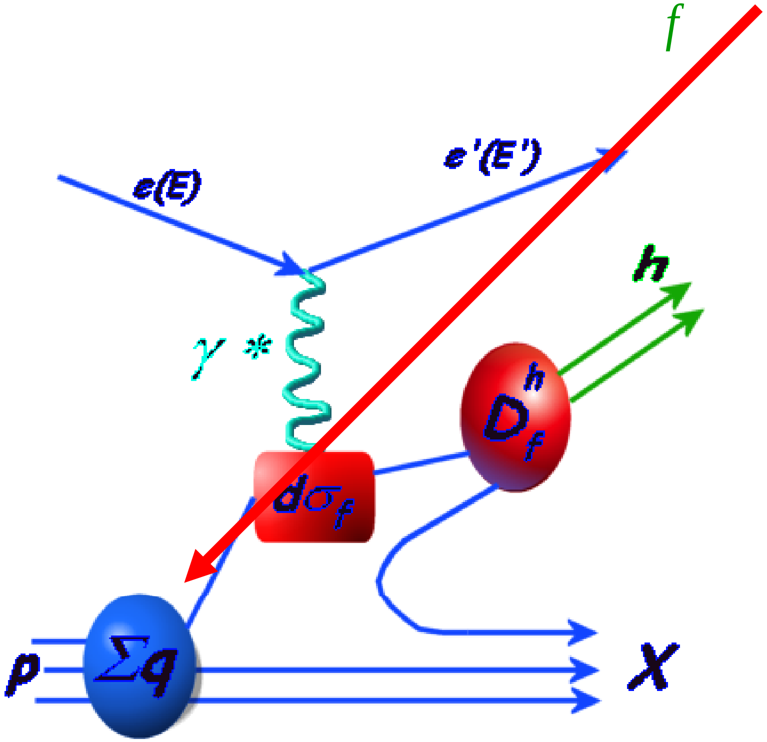
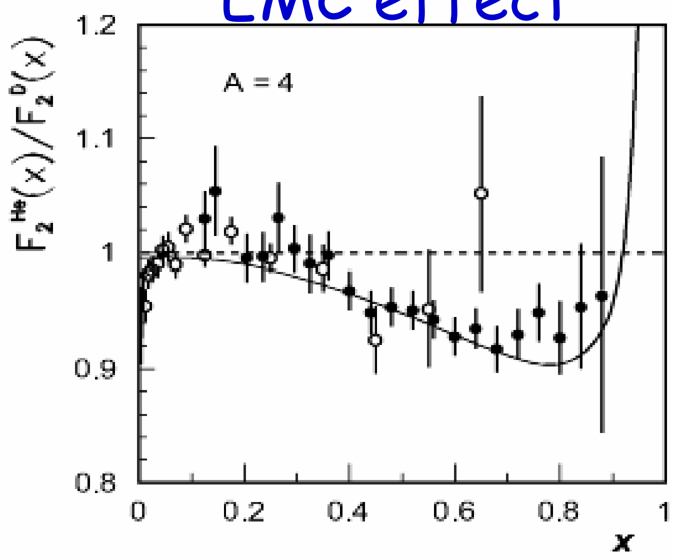
DF on Nucleon & Nuclear Medium

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



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)

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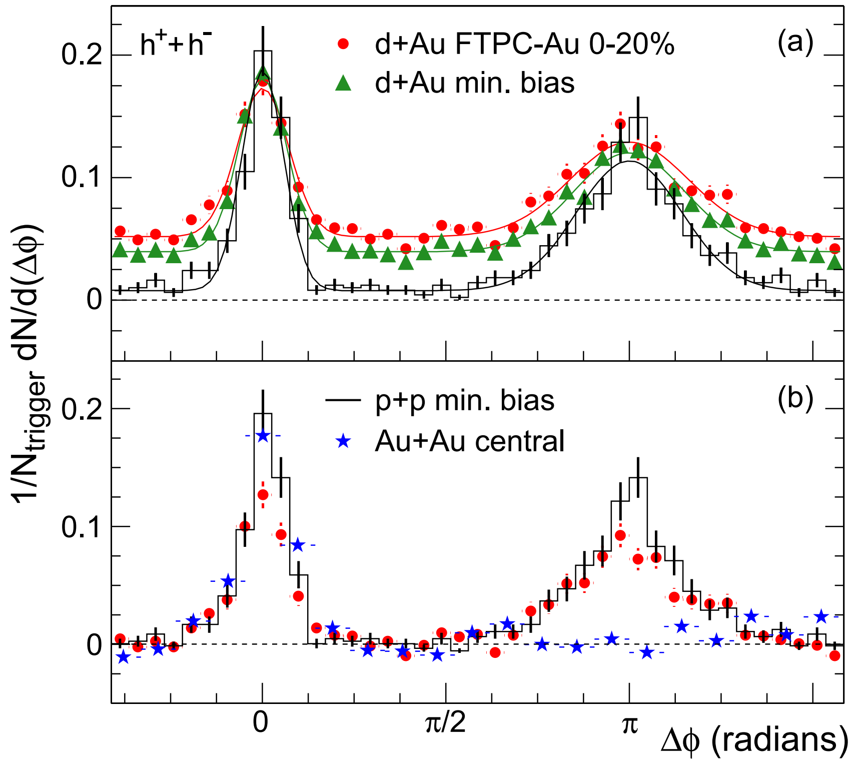
Disentangling hadronic and partonic effects



In central Au-Au the opposite-side pair are suppressed due to FSI, while the same-side pairs exhibit jet-like correlations similar to p+p and p+d collisions.

X.N.Wang, Phys. Lett. B579 (2004) 299 : If hadron interaction is responsible for the hadron suppression, it would destroy the jet structure i.e. the correlation between leading and subleading hadrons.

In cold nuclear matter → double- hadron correlation

- If partonic effects dominate: prod. of double-hadron is correlated
- If absorption dominates: prod. of double-hadron is UNcorrelated

Double-hadron ratio

$$R_{2h}(z_2) = \frac{\left(\dfrac{d\ N(z_2)^{z1>0.5}}{dN^{z1>0.5}}\right)_A}{\left(\dfrac{dN(z_2)^{z1>0.5}}{dN^{z1>0.5}}\right)_D}$$

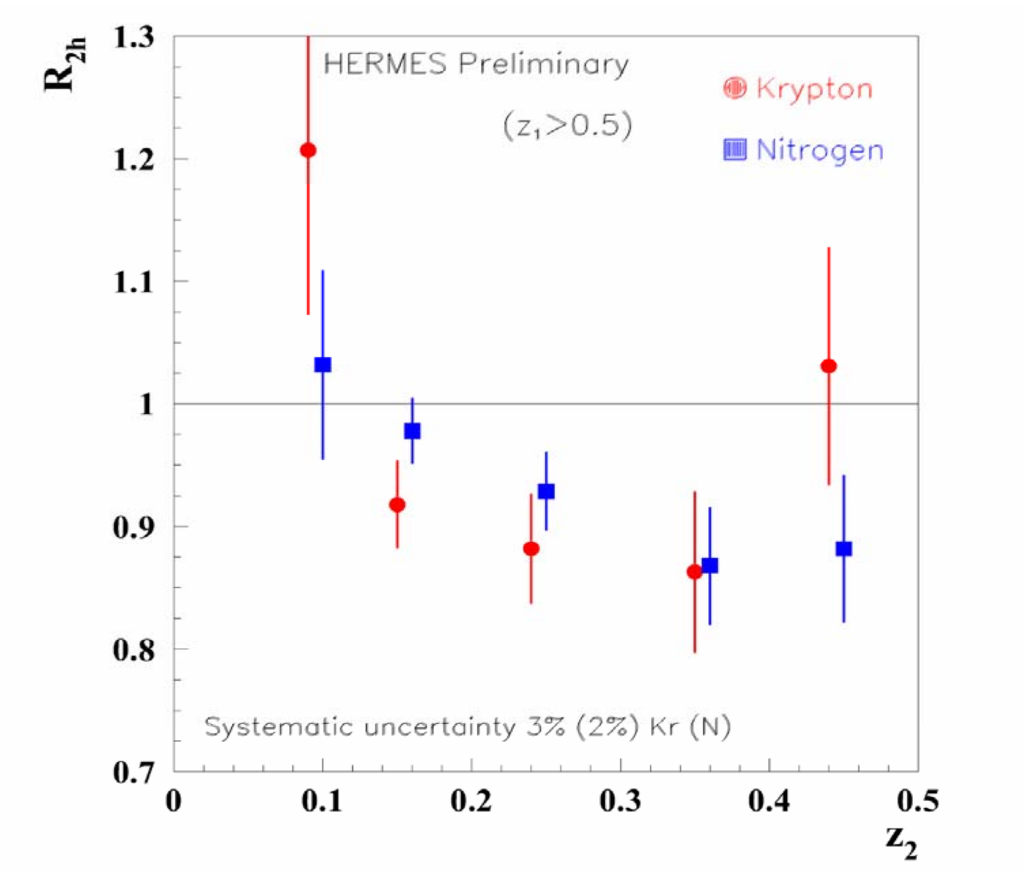
Number of events with at least 2 hadrons ($z_{leading}=z_1>0.5$)

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

If final hadron absorption: double-hadron over single hadron ratio should decrease with *A*, since the effect on the two hadrons is uncorrelated .

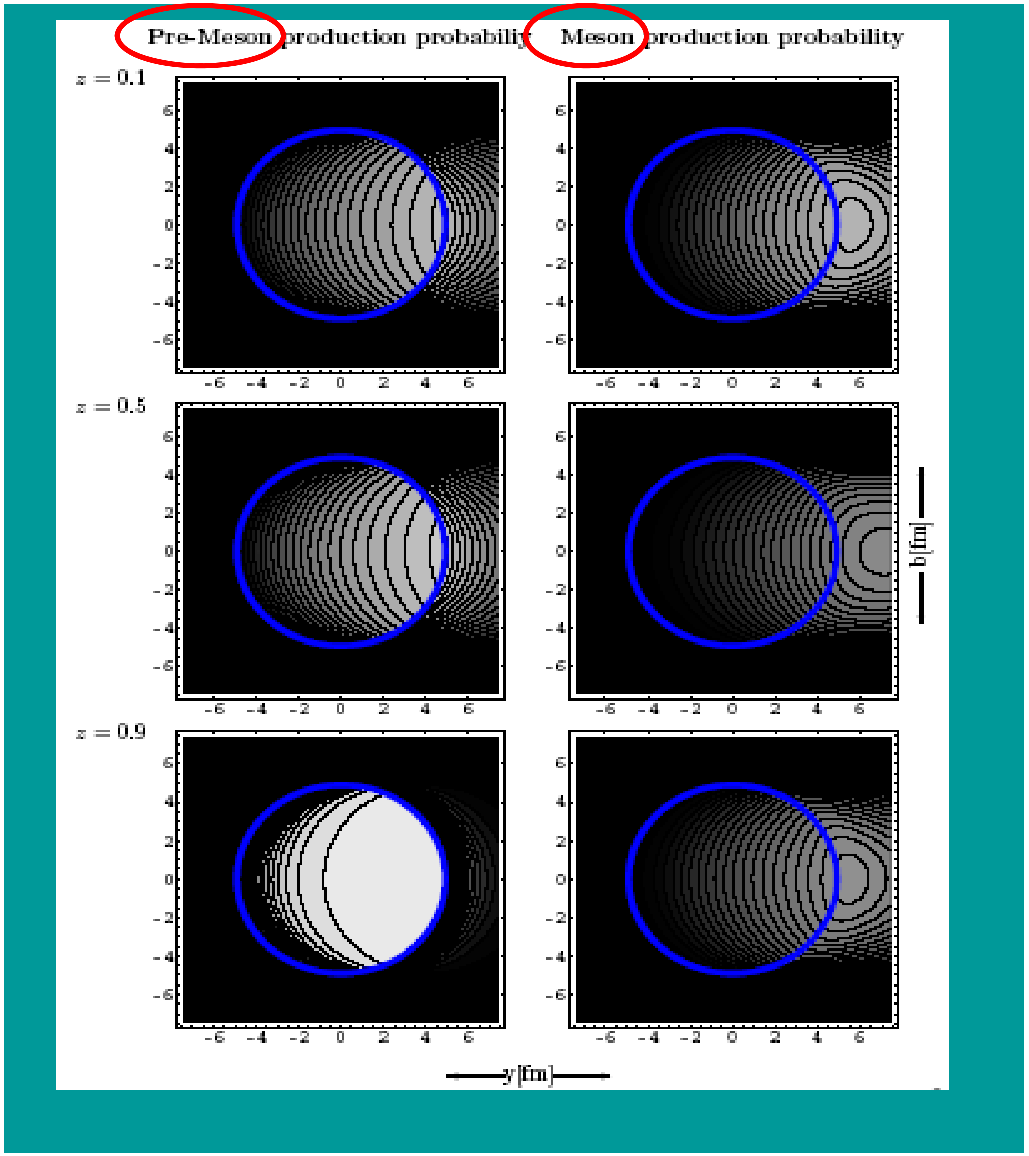
If Energy loss effect: double-hadron over single hadron ratio in nucleus and deuterium should be only slightly *A*-dependent.

Double-hadron ratio



- Reduction of R_{2h} compared to unity.
- Small variation with *A*.
- The nuclear effect in the double-hadron ratio is much smaller than for the single-hadron attenuation.

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



Accardi et al., NP A761 (2005) 67

•Hadrons are mostly produced outside the nucleus

•Nuclear effect are true FF modification

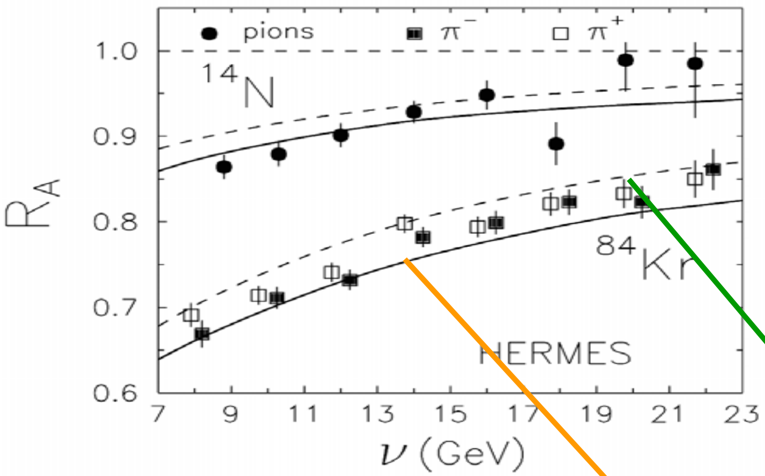
Gluon Bremsstrahlung

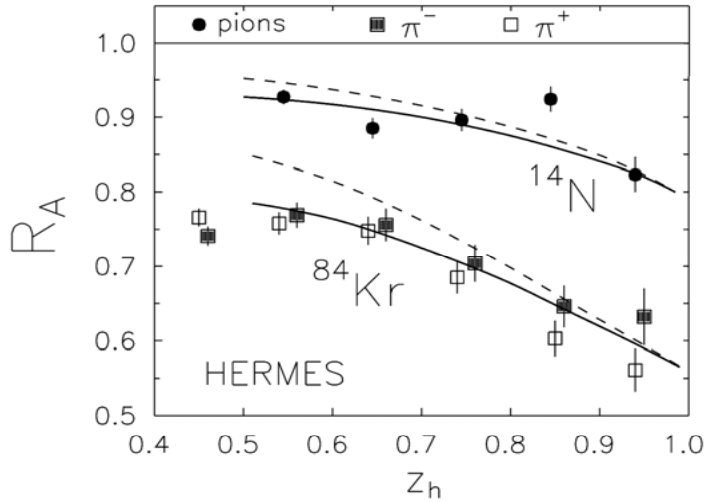
B.Kopeliovich et al.,
hep-ph/9511214
NPA 740, 211 (2004)

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



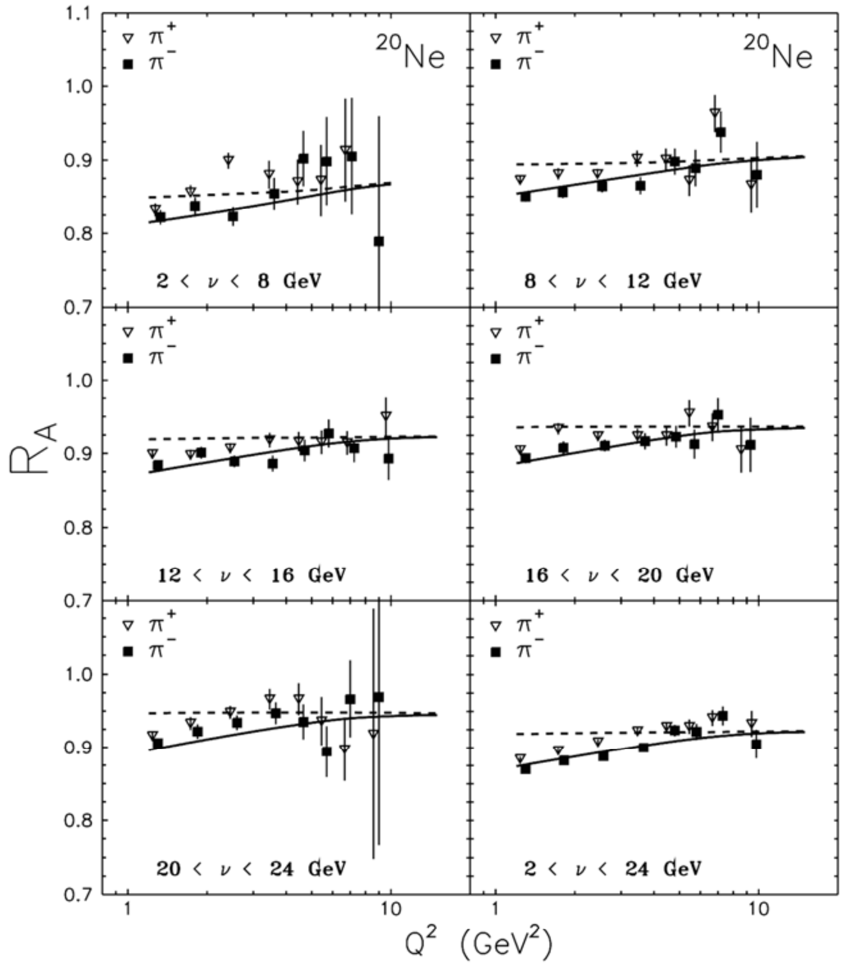


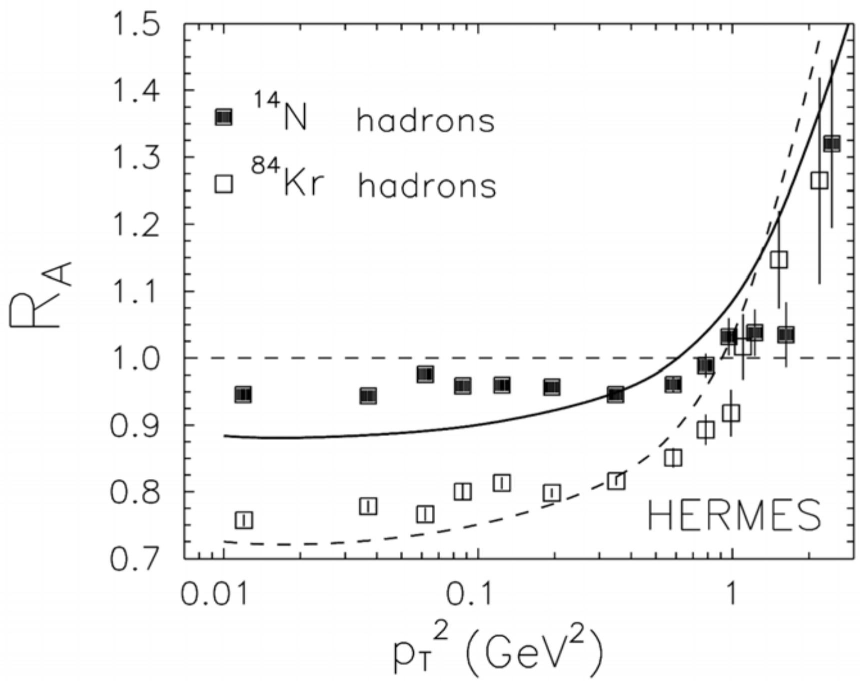
Nuclear Suppression

Nuclear Suppression + Induced Radiation

Gluon Bremsstrahlung

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





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

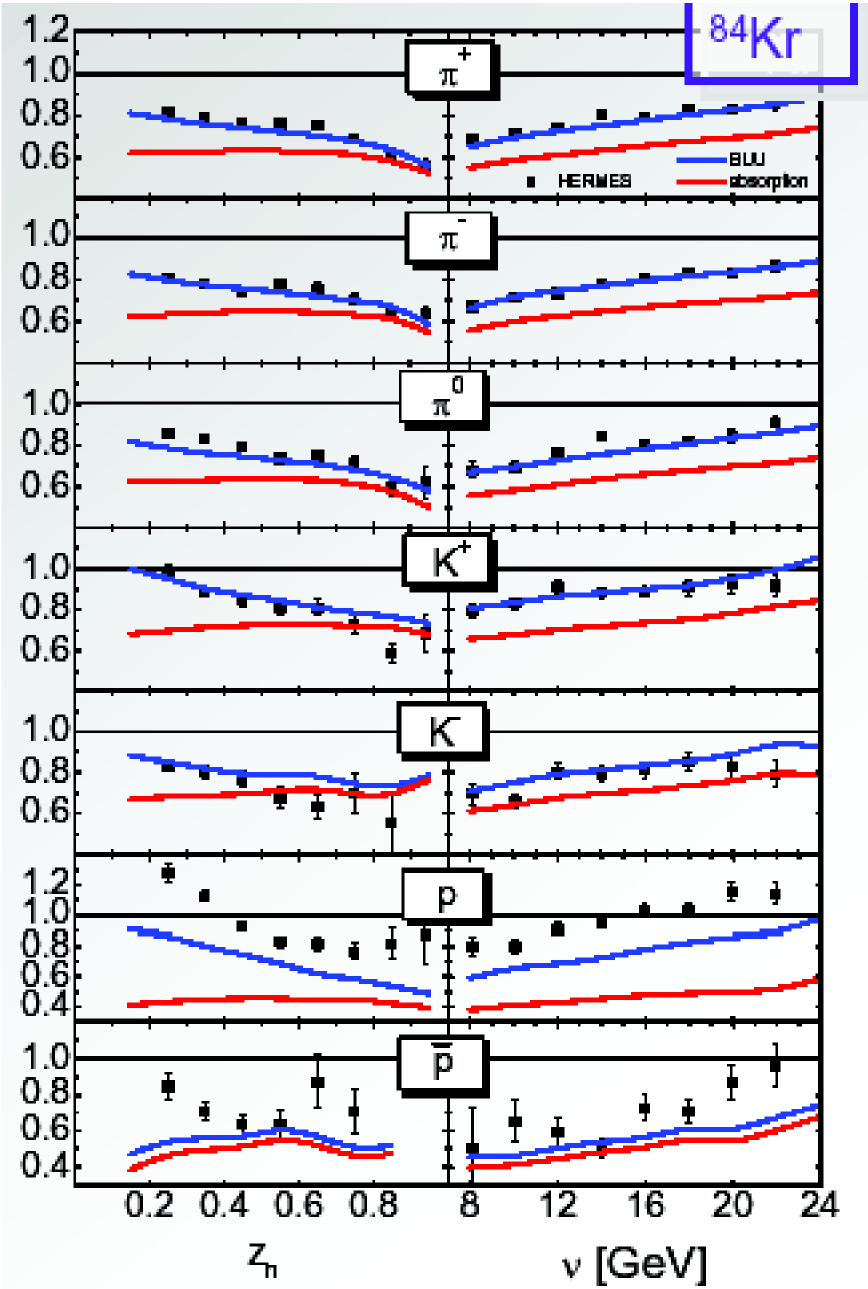
γ-A eA reaction splitted in 2 parts:

-γ*N $\rightarrow$ X using PYTHIA & FRITIOF

-propagation of final state X within BUU transport model.

• ___ pre-hadron τ_F=0.5 fm, σ^* by costituent quark model: σ^*_{meson}=#q_{orig}/2 σ_{meson}

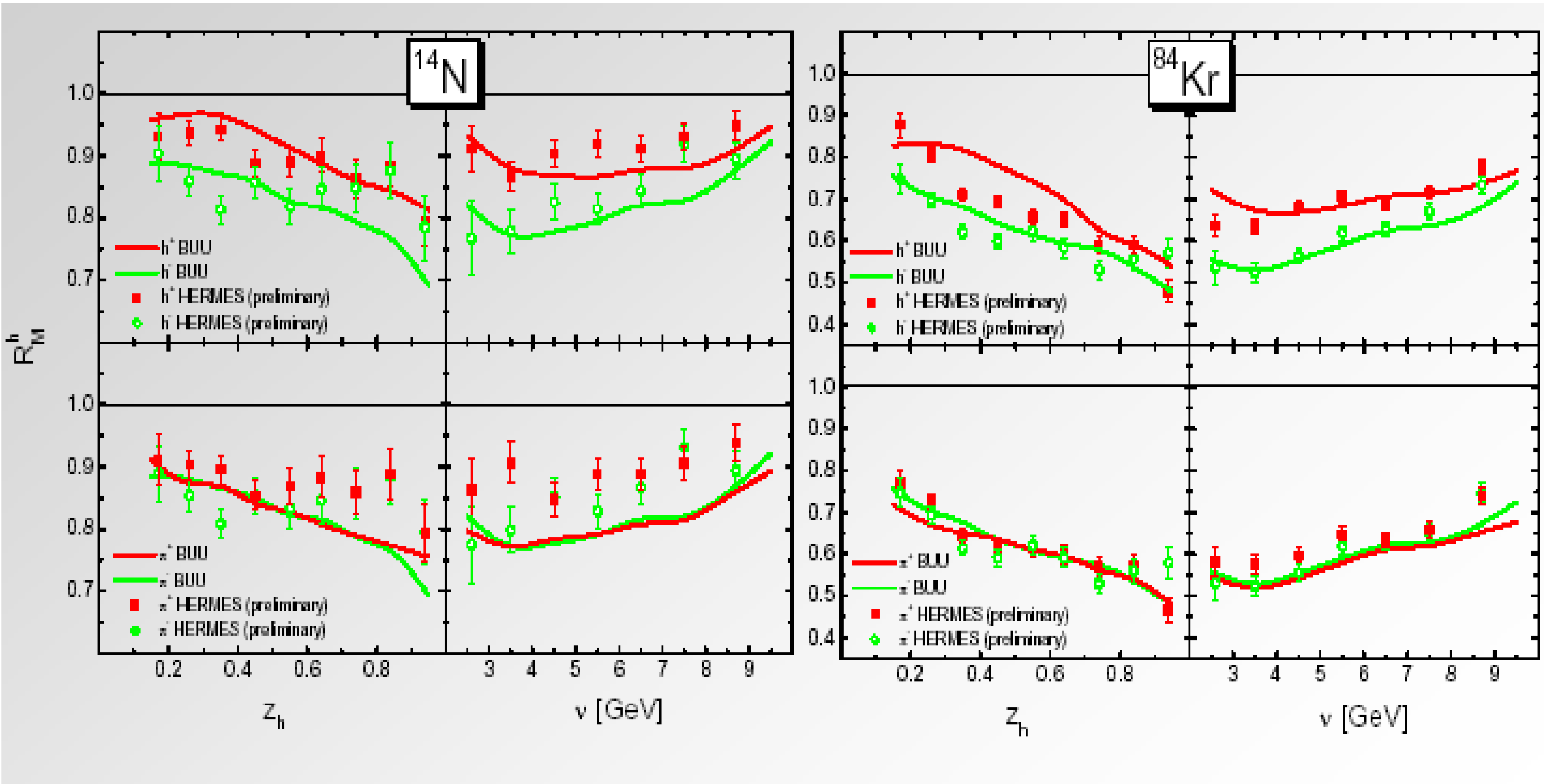
• ___ purely absorbitive FSI



FSI in BUU Transport model

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

HERMES @ 12 GeV (τ_f=0.5 fm/c)



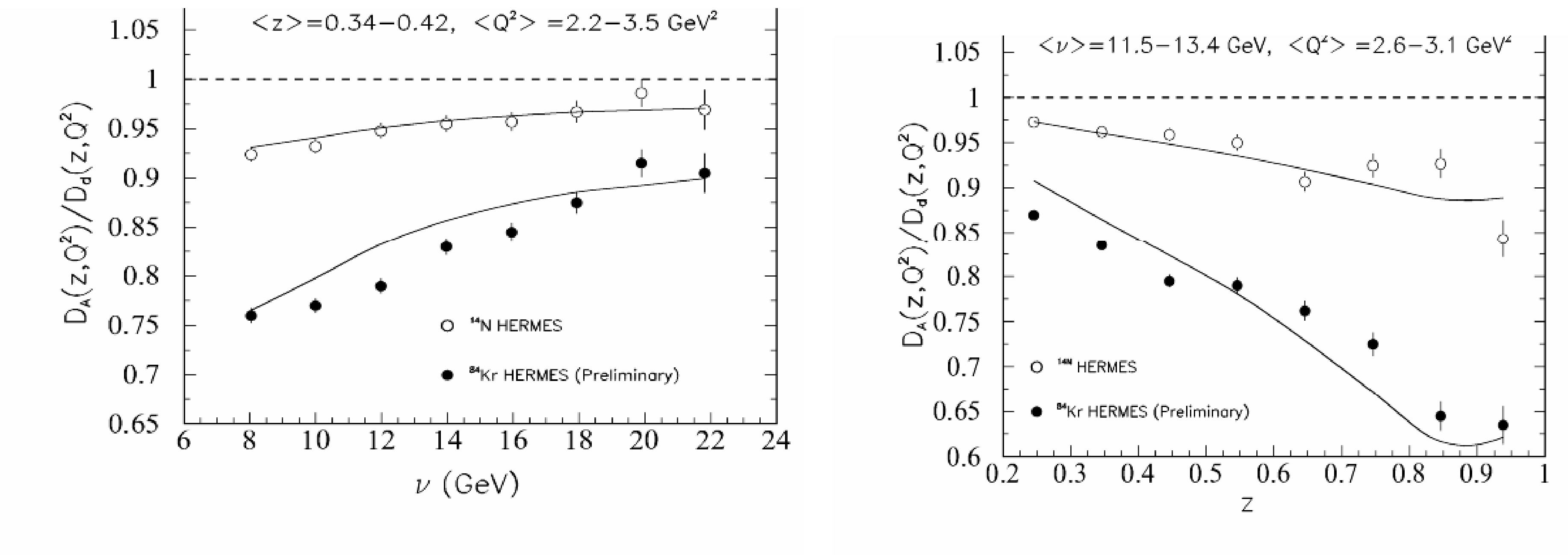
Model seems to work also at lower energy

FF modification

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

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

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



•1 free parameter C≡quark-gluon correlation strength in nuclei.

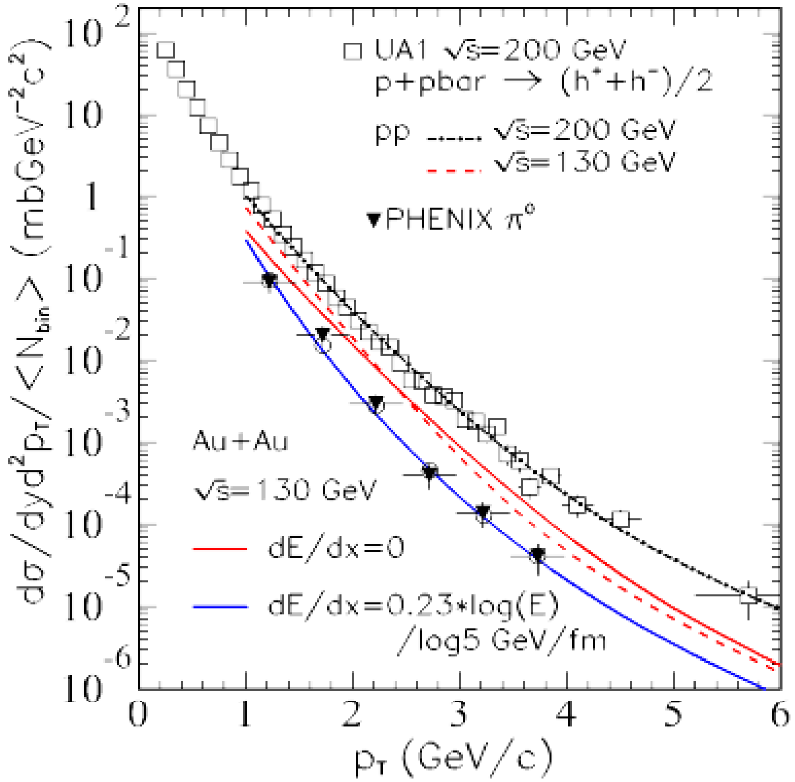
•From ^{14}N data C=0.0060 GeV^2: $\Delta E = n < \Delta z_g > \propto C\alpha_s^2 m_N R_A^2$

<dE/dL>≈0.5 GeV/fm .

dE/dL and Gluon density at RHIC

E.Wang , X.N. Wang PRL 89 (2002) 162301.

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



PHENIX: hot, expanding system.
HERMES: cold, static system.

⇓

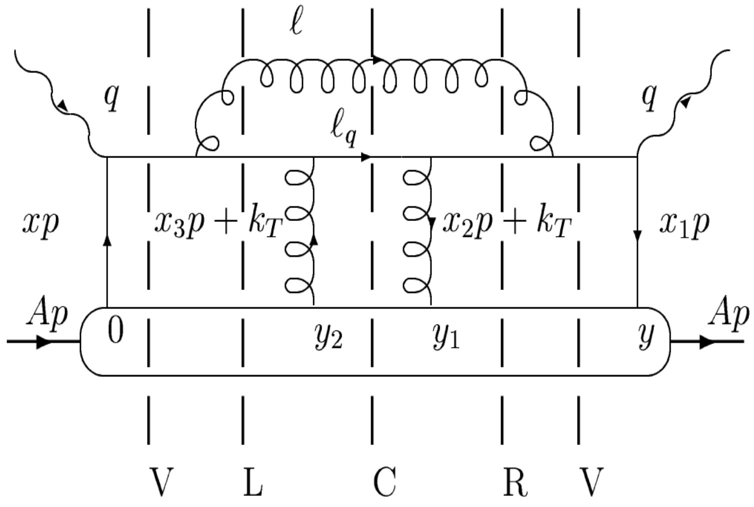
- $\Delta E_{sta} \propto \rho_0 R_A^2$; ρ_0 gluon density and $R_A \approx 6$ fm
- $\Delta E_{exp} \approx \Delta E_{sta} (2\tau_0/R_A)$; τ_0 initial formation time of dense medium

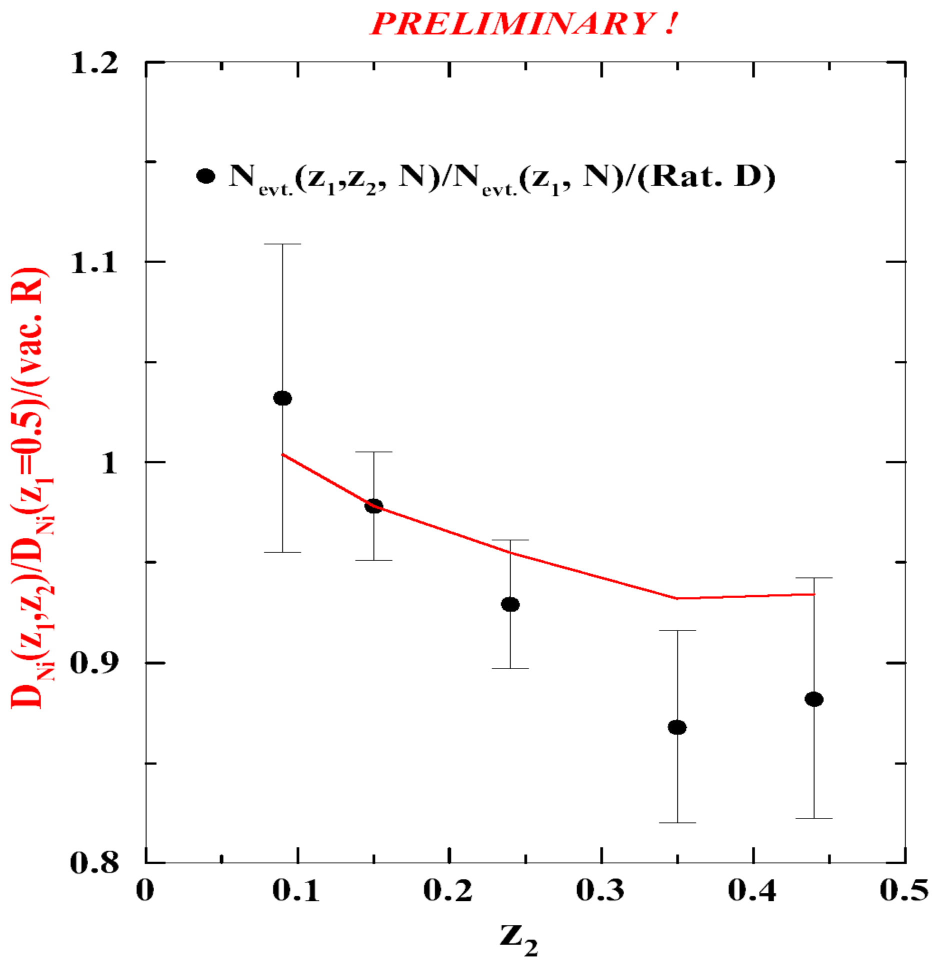
•Gluon density in Au+Au~15 times higher than in cold matter

Double/single hadron production

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

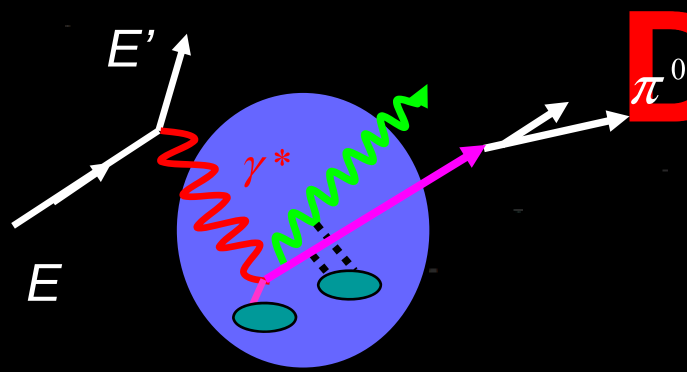
- Computation of dihadron FF and its modification from higher twist correction in DIS





INFN Frascati

DIS Tomography



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

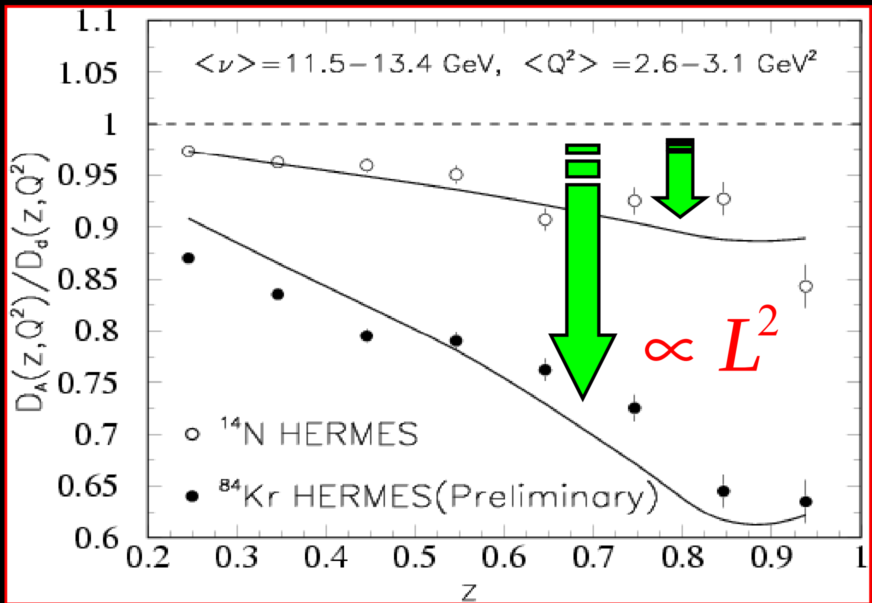
$\langle \Delta z \rangle$ - radiative energy loss fraction

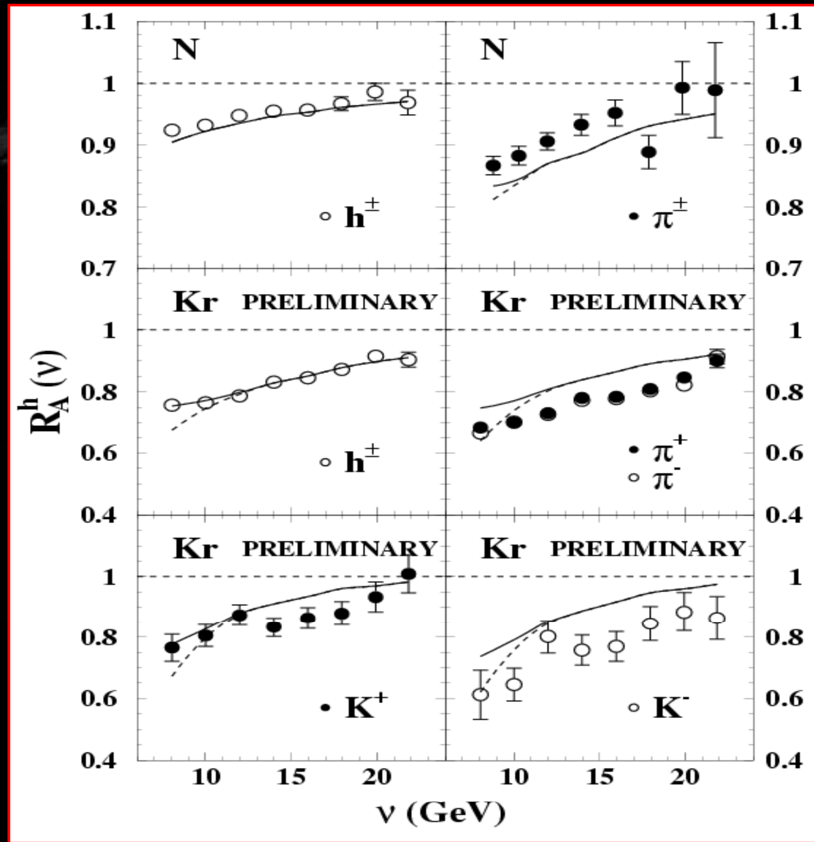
$$x_B = Q^2/(2p\cdot q), \quad x_A = 1/(m_N R_A)$$

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

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

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





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