Nuclear Effects in Hadron Production at HERMES

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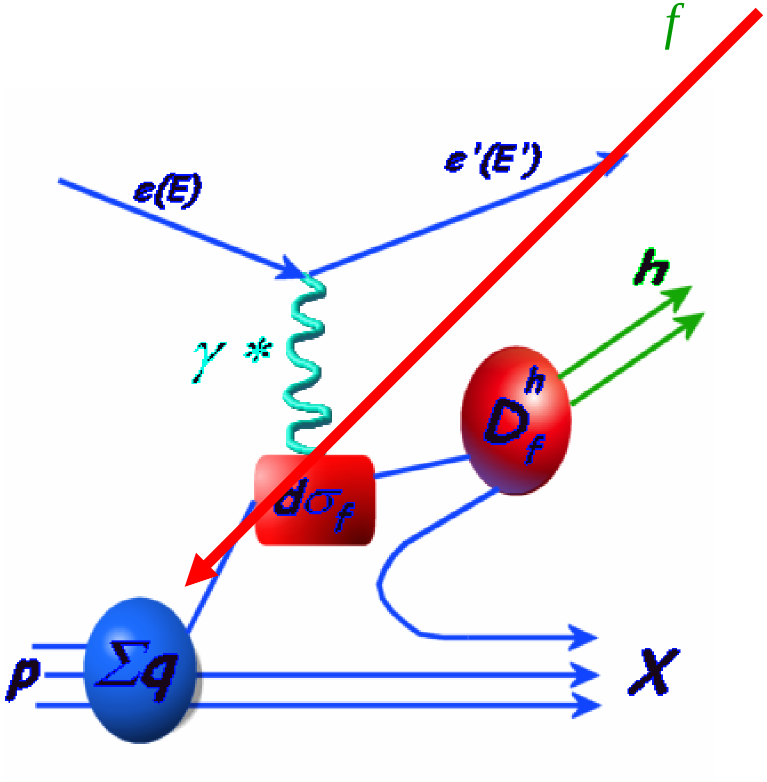
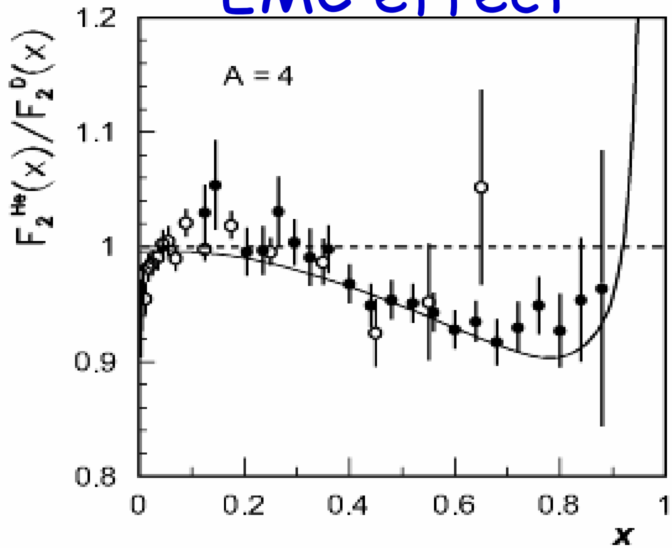
- Semi-Inclusive DIS and FF in nuclei
- Single Hadron Attenuation
- Data Interpretations
- P_T broadening

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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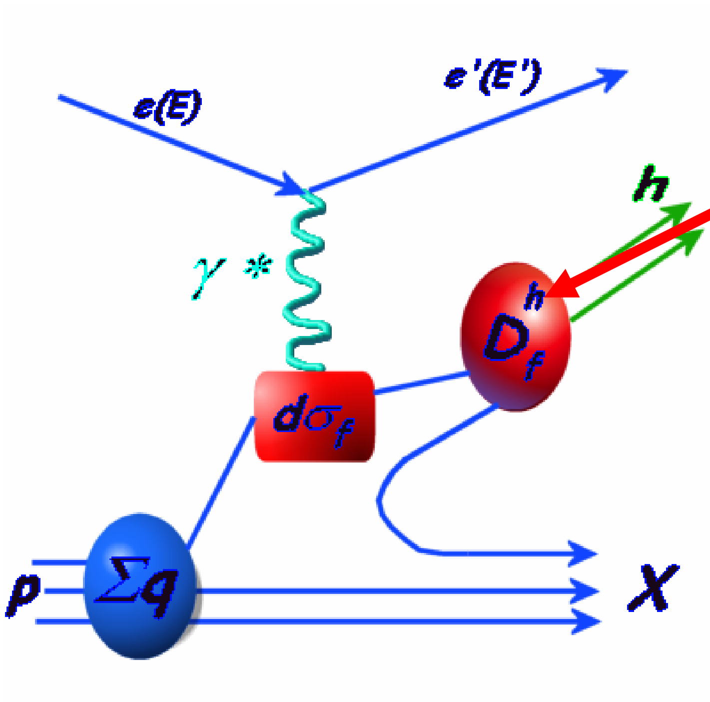
Fragmentation Functions on Nucleon

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



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

What happens in a nuclear medium ?

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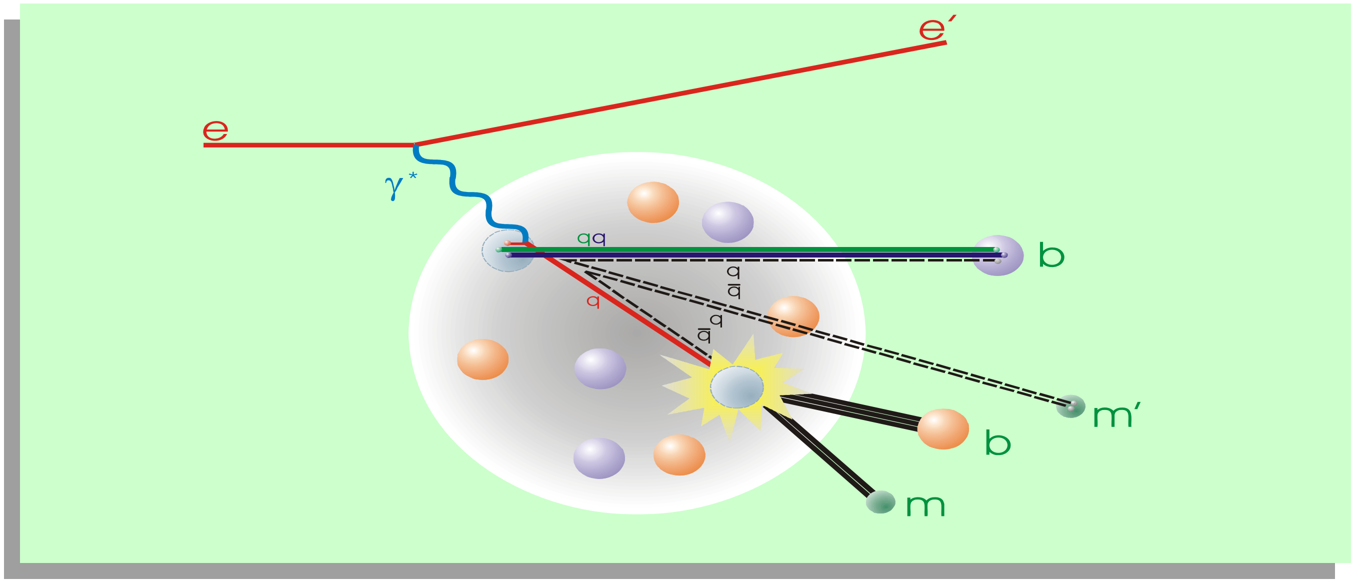
Nuclear Attenuation (quenching)

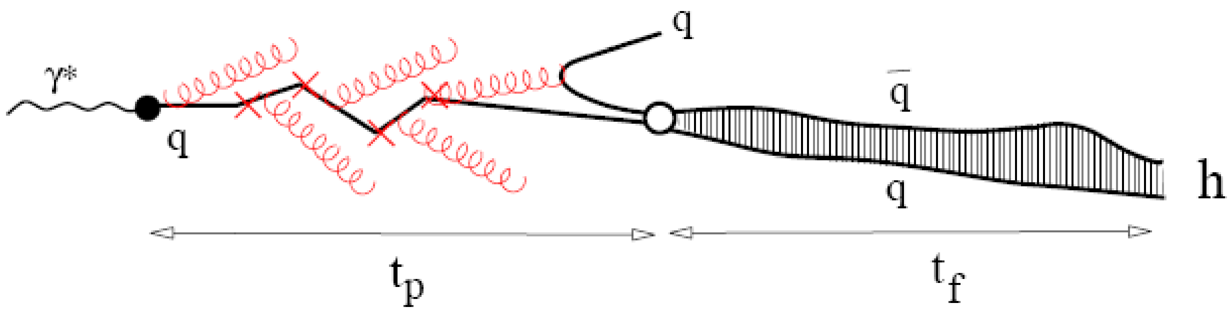
<u>Observation</u>: reduction of multiplicity of fast hadrons due to both *hard partonic* and *soft hadron interaction.*



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
- 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 $(t>t_f)$:
  - ➢Full hadronic cross section (10-30 mbarn)
  - ➢Mainly formed after several tens of fm i.e. out of the nucleus

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Experiments

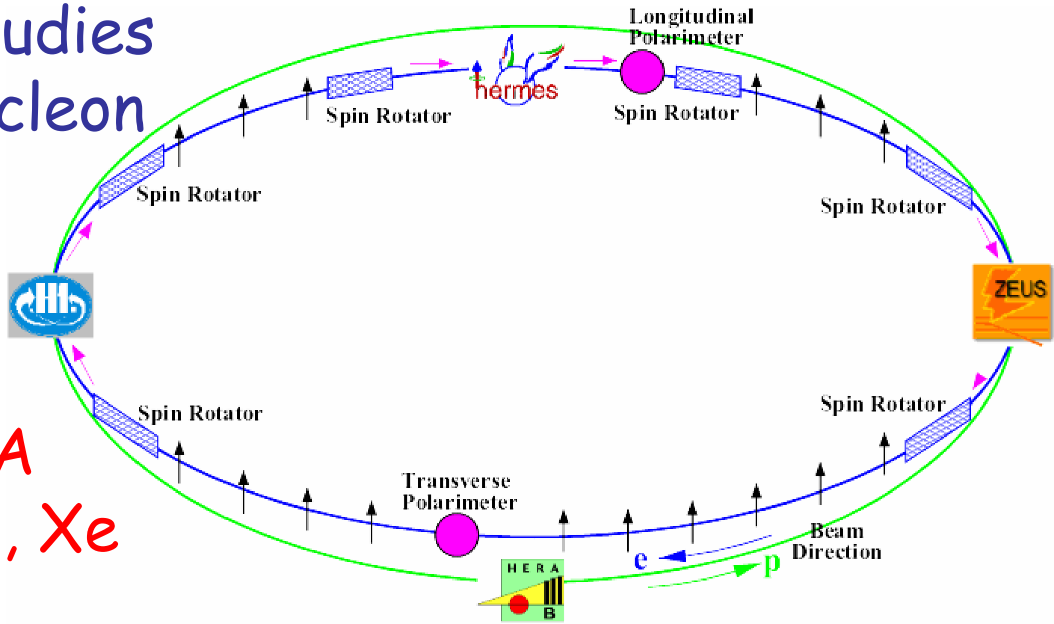
- SLAC: 20 GeV e^--beam on Be, C, Cu Sn PRL 40 (1978) 1624
- EMC: 100-200 GeV μ-beam on Cu Z.Phys. C52 (1991) 1
- WA21/59: 4-64 GeV ν-beam on Ne Z.Phys. C70 (1996) 47
- HERMES: 27.6 GeV e^{+-}-beam on He, N, Ne, Kr, Xe

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)

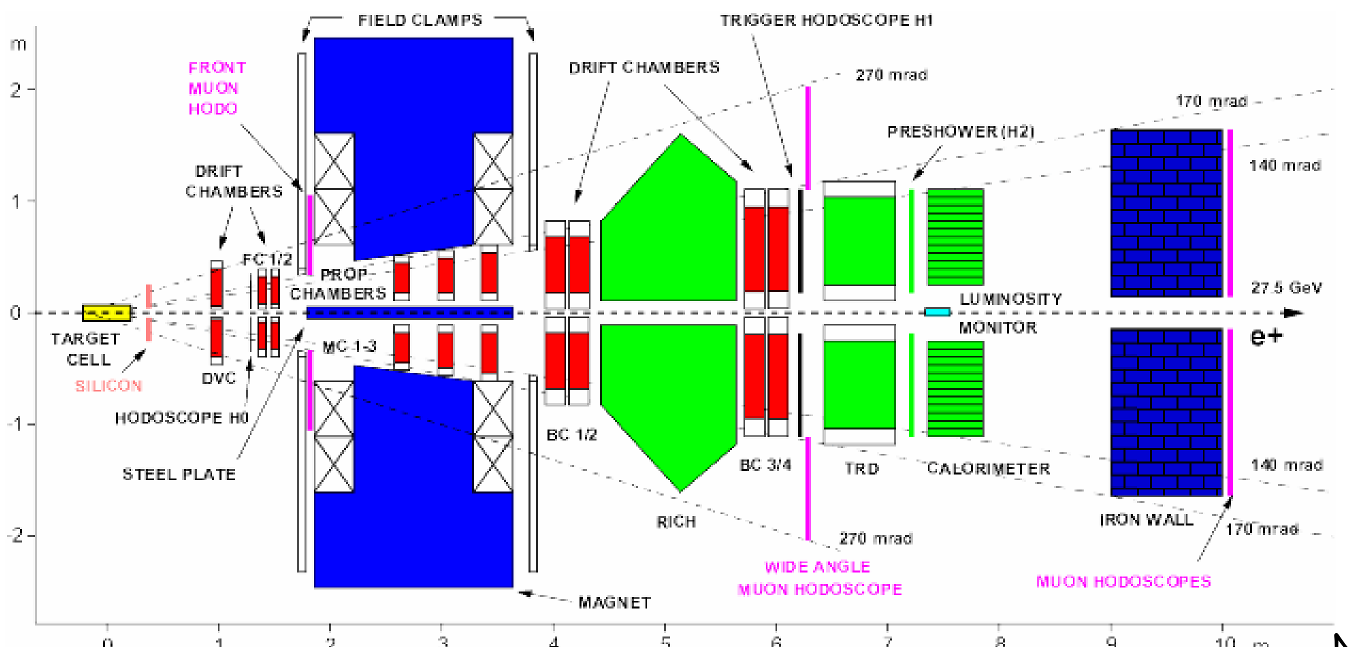
- CLAS: 5.4 GeV e^--beam on C, Al, Fe, Pb
  E-02-104

HERMES @ DESY

It is an experiment which studies the spin structure of the nucleon (see M.Contalbrigo talk)
... but not only ...



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



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Hadron multiplicity ratio

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

Leptonic variables : ν (or x) and Q^2

Hadronic variables : z and P_t^2

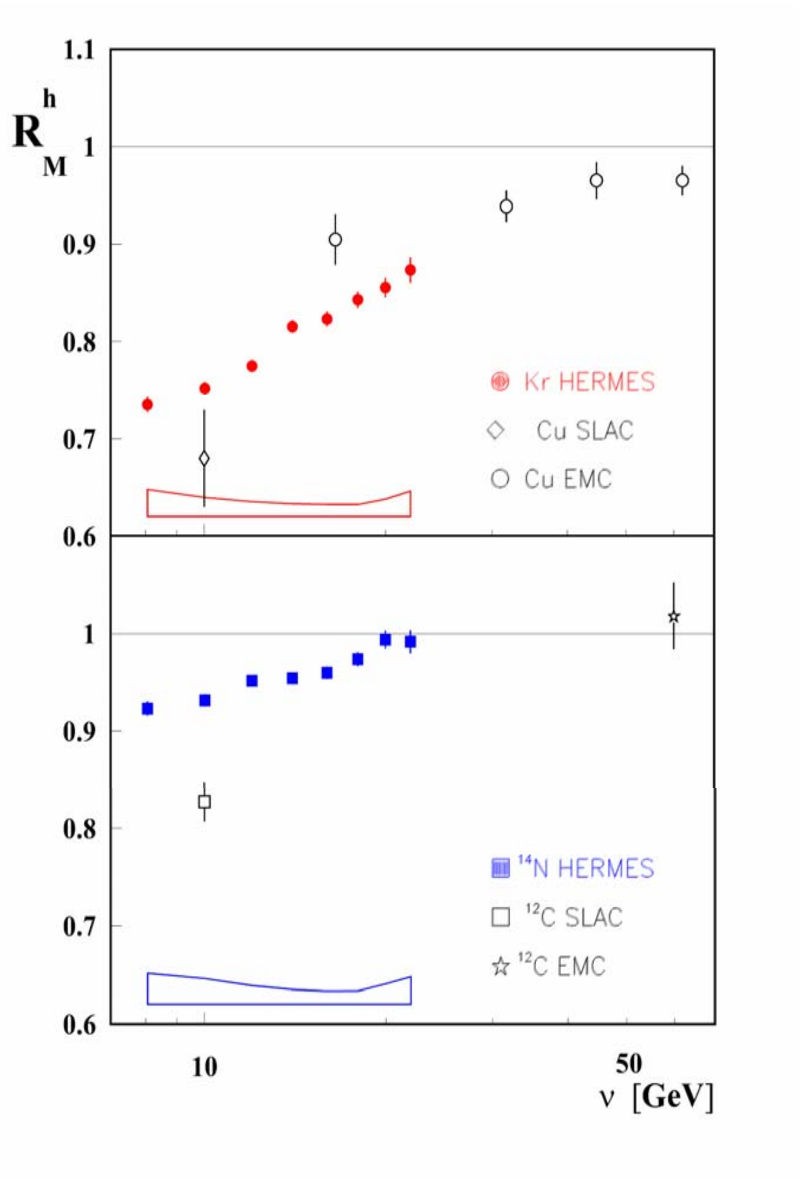
Different nuclei : size and density

Different hadrons : flavors and mixing of FFs

Double-ratio: approx evaluation of FF medium modification

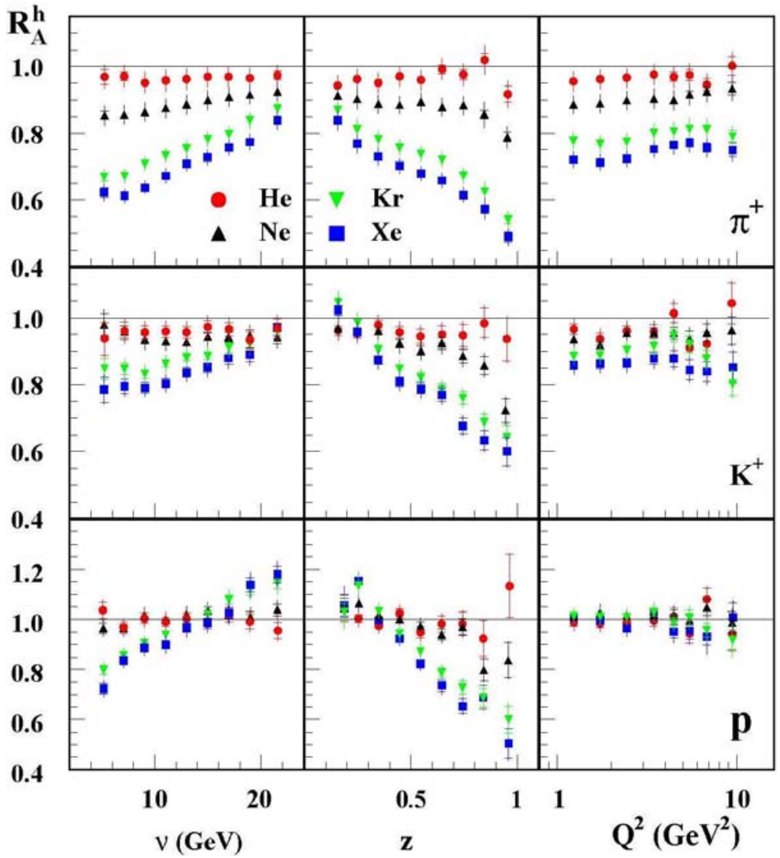
Systematic uncertainties are minimize in the double-ratio

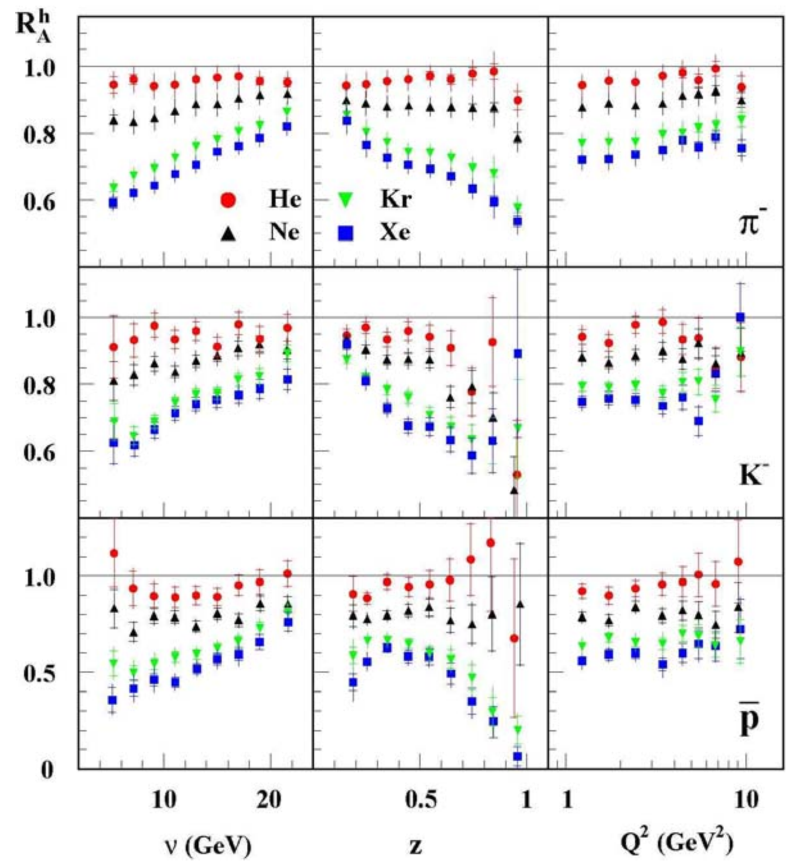
HERMES (first data) vs SLAC/EMC

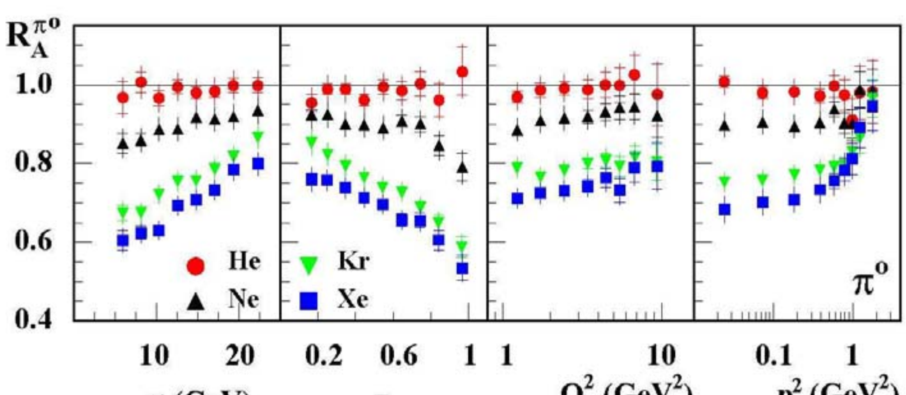


- Clear nuclear attenuation effect for charged hadrons
- Increase with ν consistent with EMC data at higher energy
- Discrepancy with SLAC due to the *EMC effect,* not taken into account at that time
- HERMES kinematics is well suited to study quark propagation and hadronization

Multiplicity ratio : different hadrons







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

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

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

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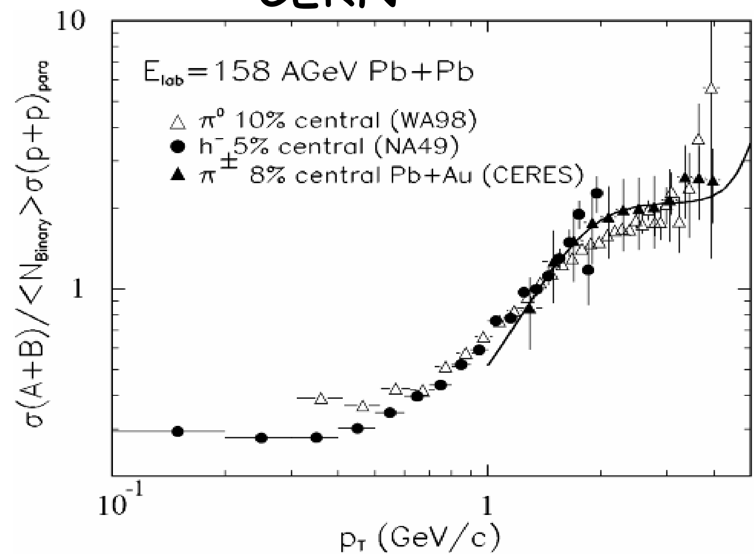
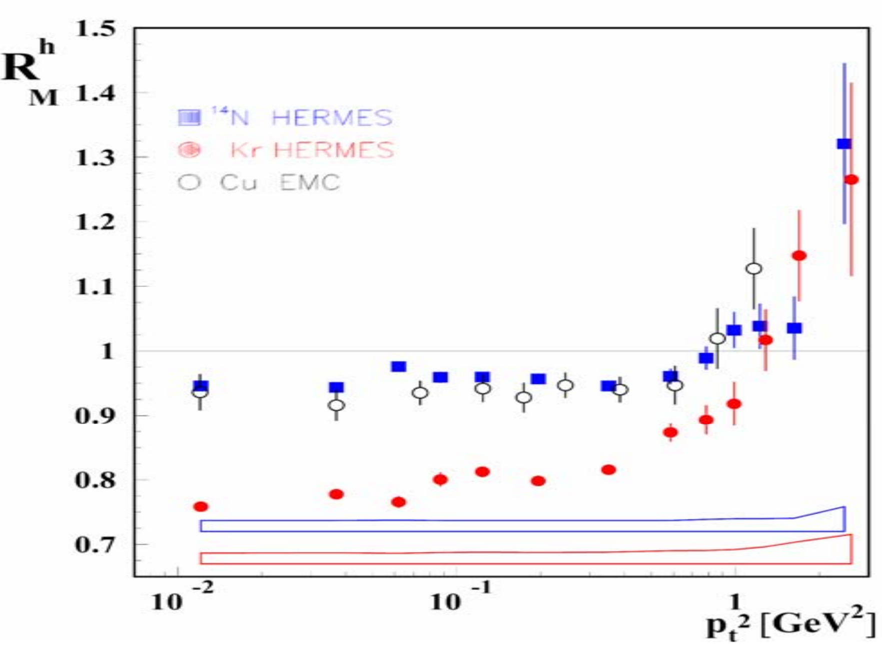
Multiplicity Ratio vs. p_t^2

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)

Larger p_t enhancement for proton vs pion

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

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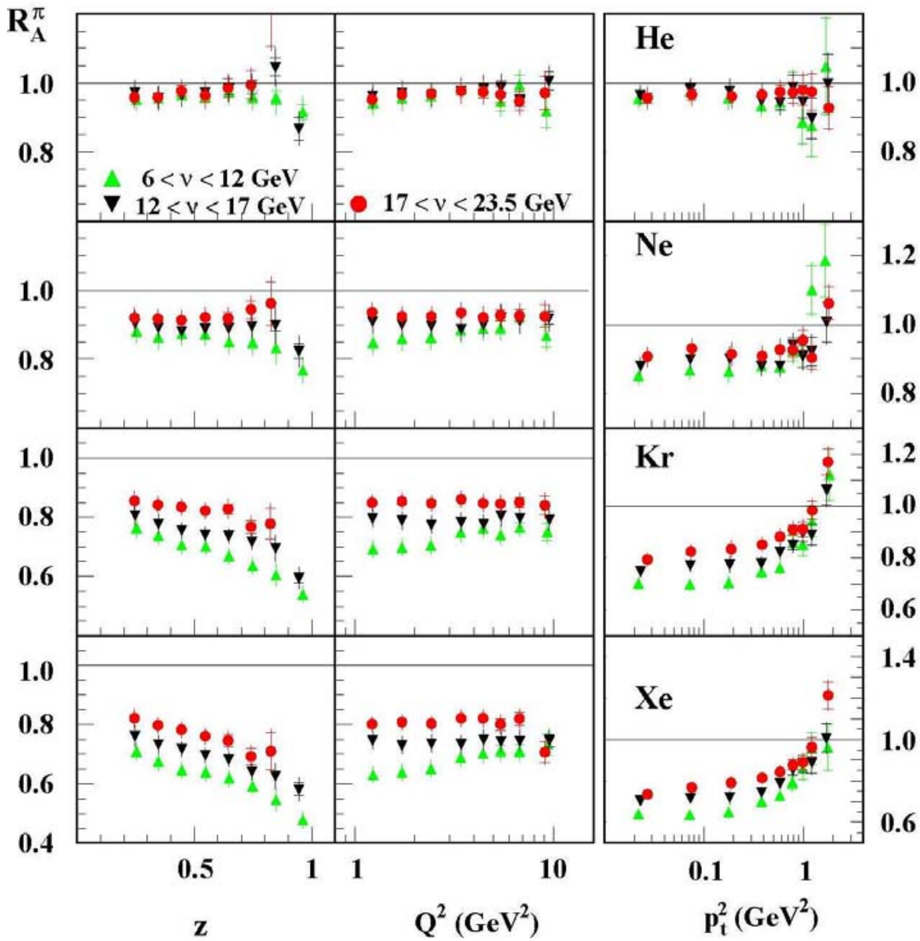
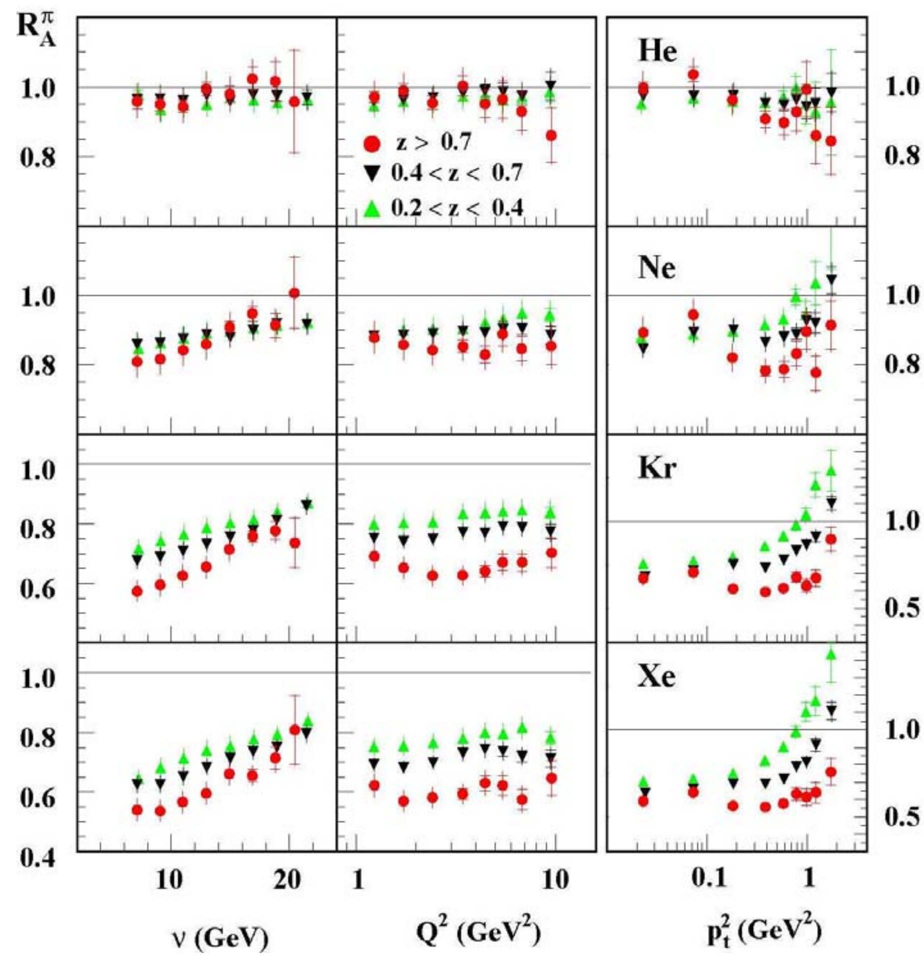
Multiplicity ratio 2D





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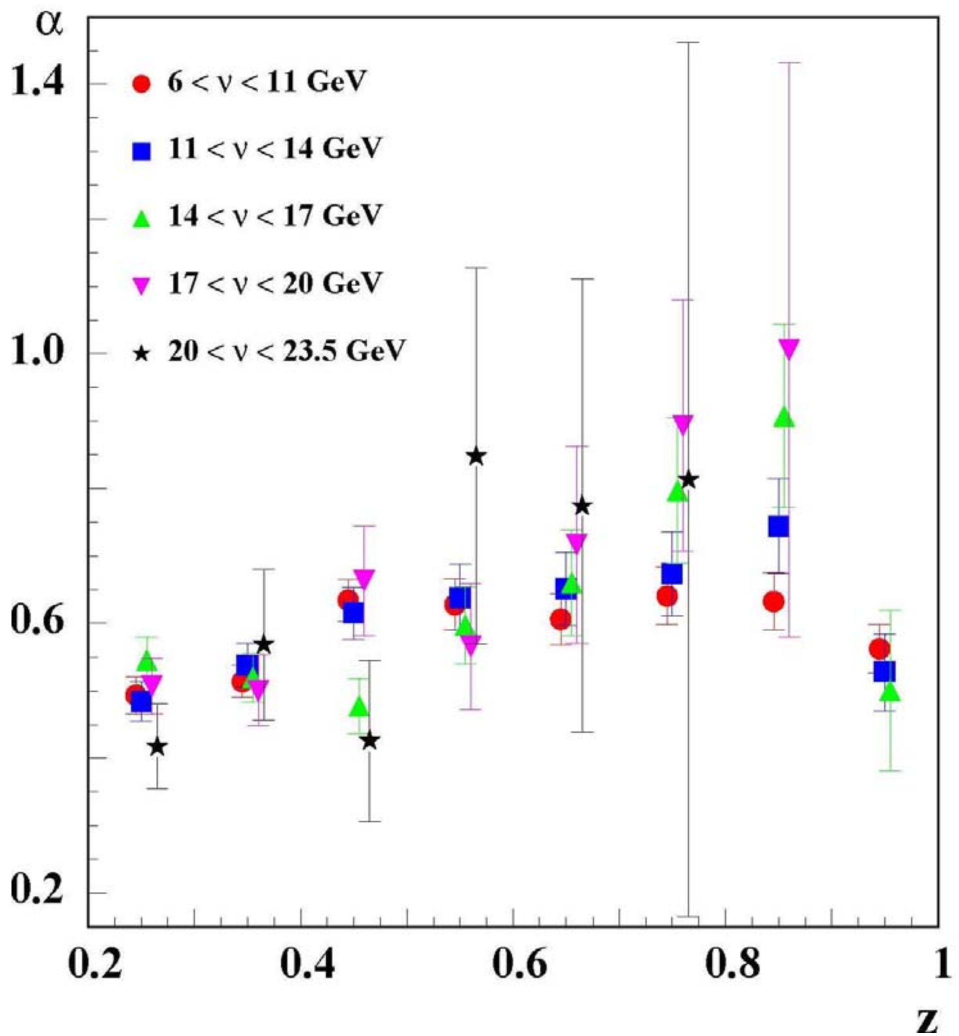
A dependence of attenuation



Data support a quadratic dependence on nuclear size A^{α} with α ~2/3

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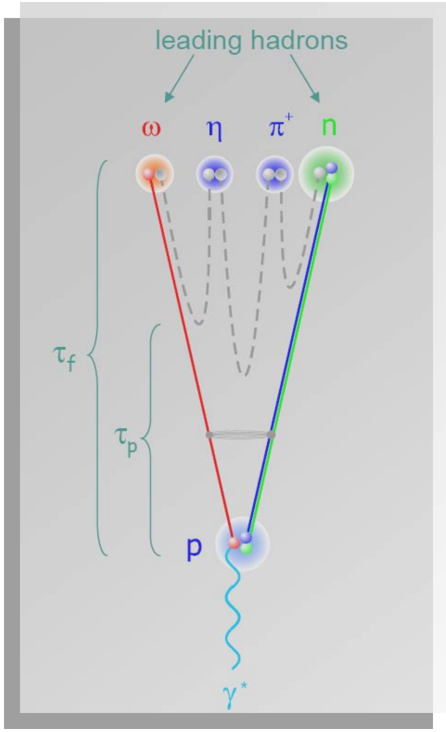
Models based on pre-hadronic interaction

B. Kopeliovich et al. (NPA 740, 211 (2004))
T. Falter et al. (PLB 594 (2004) 61)
A. Accardi et al. (NPA 720, 131 (2003))



-Color neutralization inside the medium
-Pre-hadron formation and interaction
-Time? Cross section? AbsorptionvsRescattering
-Hadron formation mainly outside the nucleus
-Induced radiation « 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 → enhancement at large p_T

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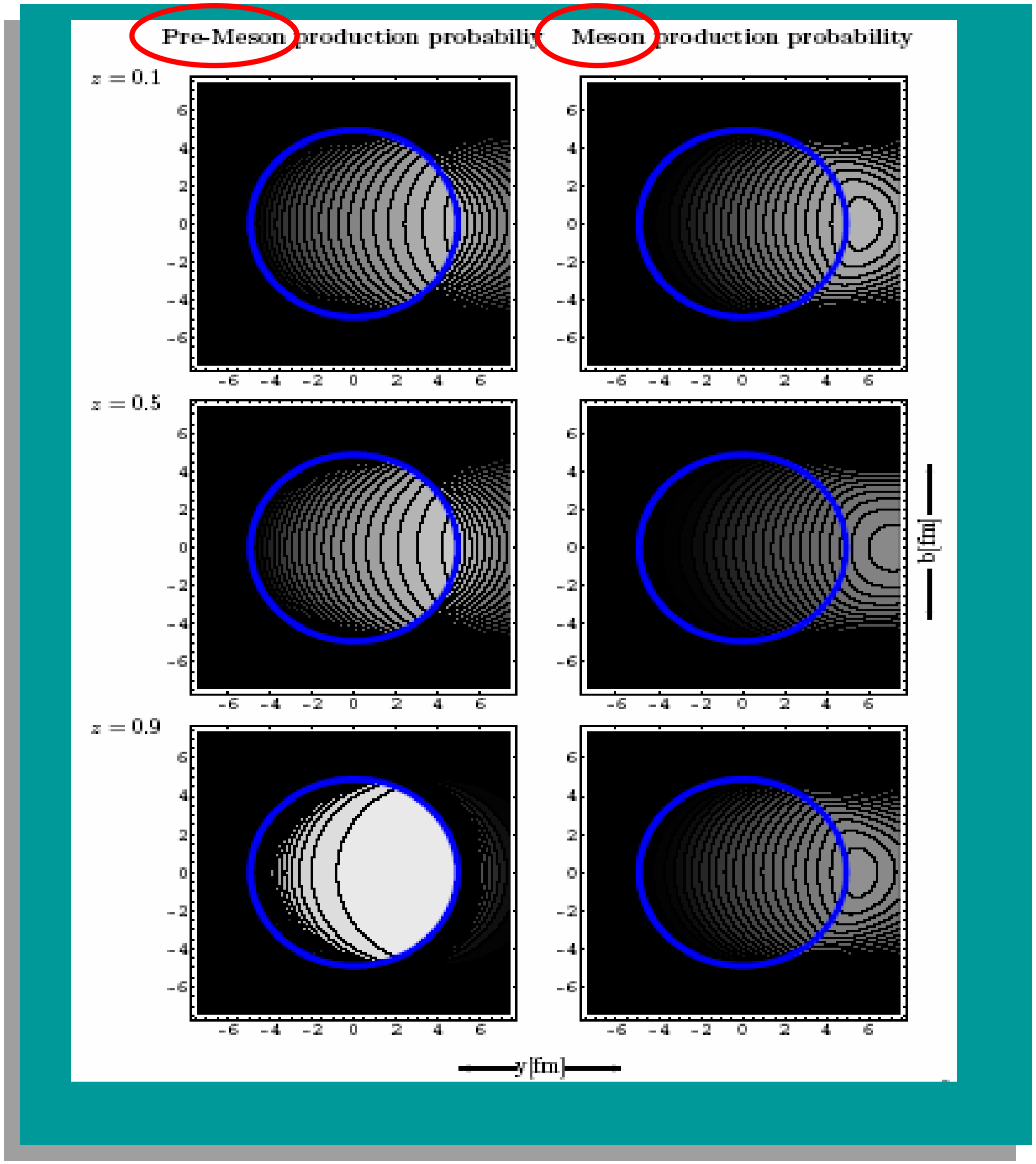
Pre-Hadron and Hadron-Production probabilities
(at HERMES energies for Kr target)



Accardi et al., NP A761 (2005) 67

- Hadrons are mostly produced outside the nucleus

- Nuclear effect are true FF modification

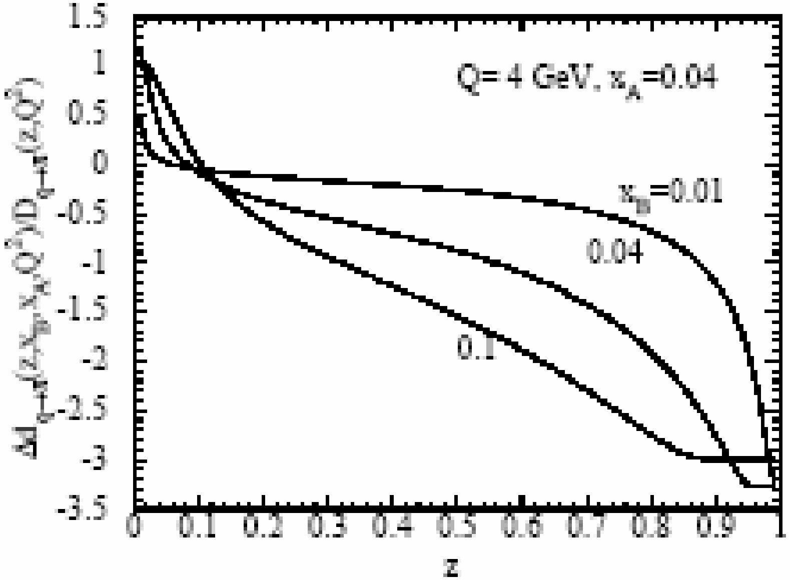
FF modification

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

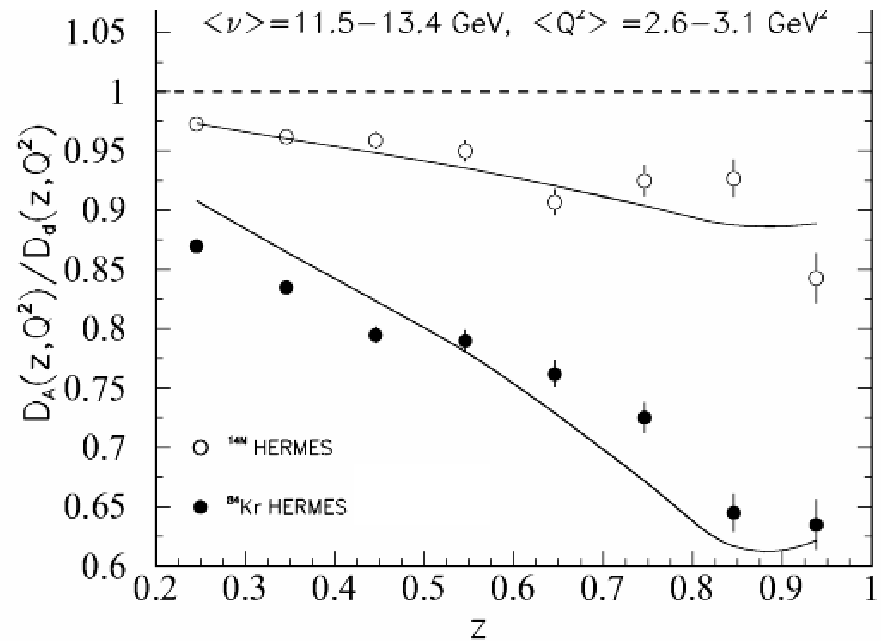
Parton energy loss :

Landau-Migdal-Pomeranchuk interference pattern

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



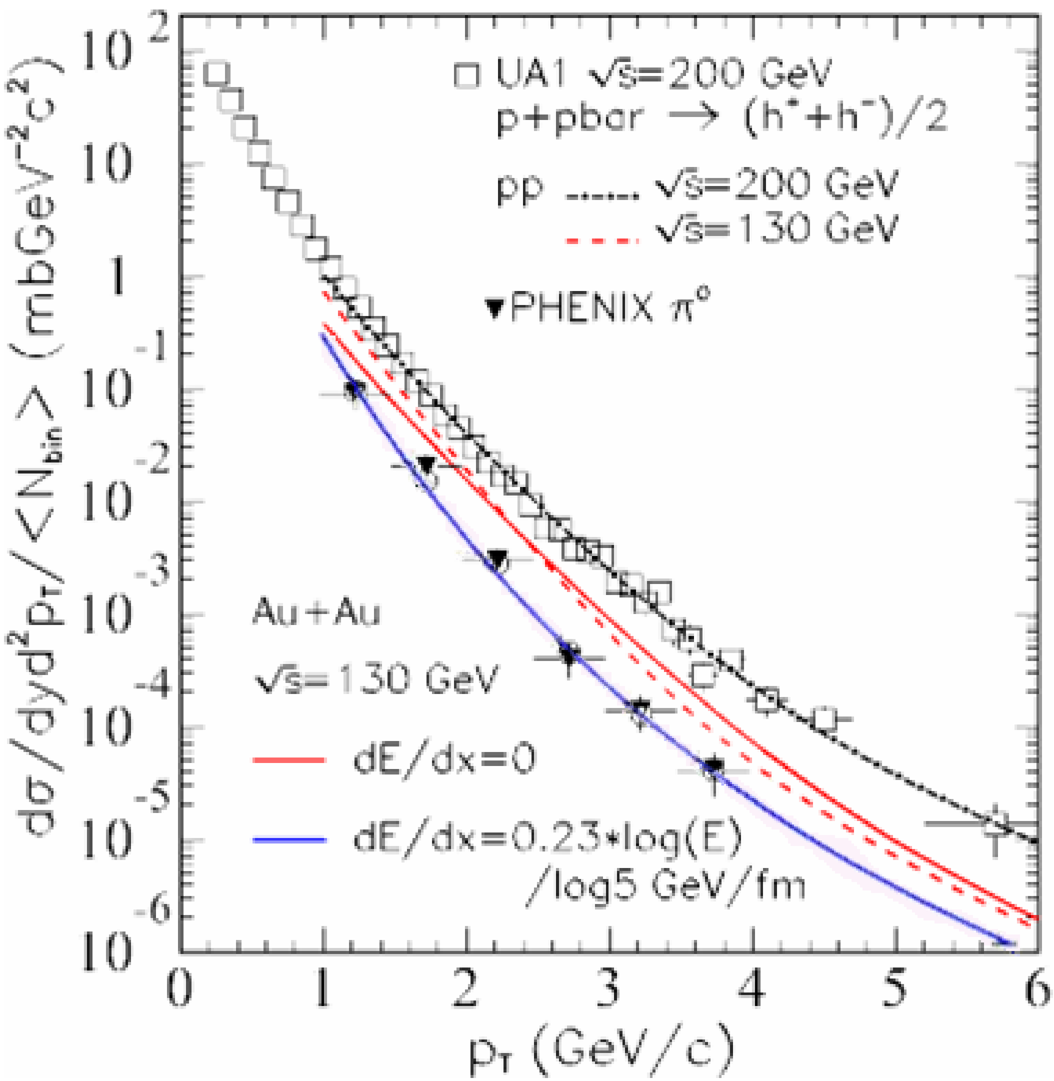
$$\Delta E = n < \Delta z_g > \propto C \alpha_s^2 m_N R_A^2$$



- 1 free parameter C≡quark-gluon correlation strength in nuclei
- From ^{14}N data C=0.0060 GeV^2:
- <u>HERMES</u> : cold static nuclei $\Delta E_{sta} \propto \rho_0 R_A^2$; ρ_0 gluon density and $R_A \approx 6$ fm
- <u>RHIC</u> : 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

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

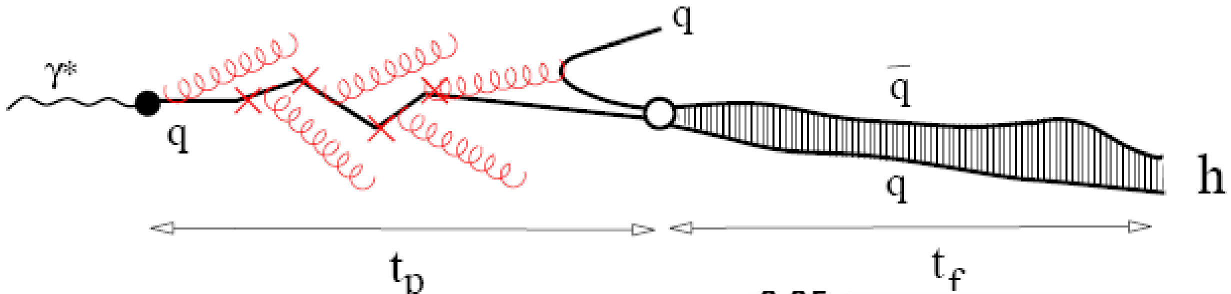


dE/dL$_{PHENIX}|_{Au}$ predictions by using C=0.0060 GeV^2 from HERMES data

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

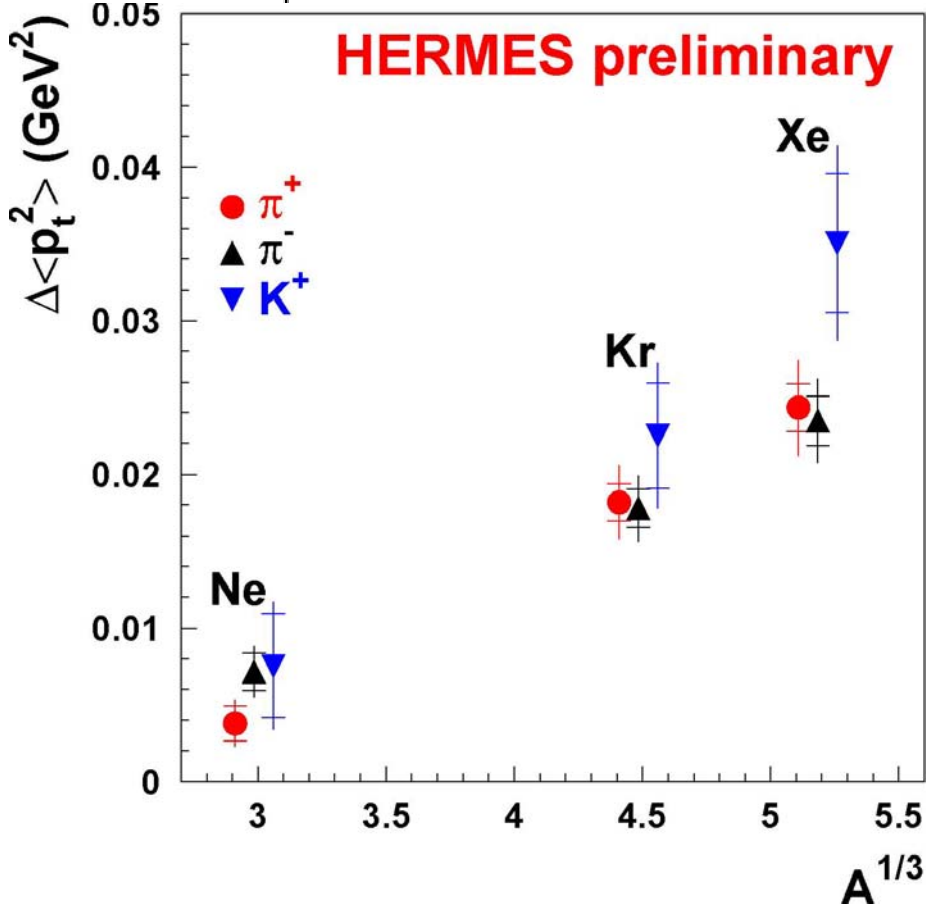
- Cold <---> Hot nuclear matter correlation
- Gluon density in Au+Au~30 times higher than in cold matter

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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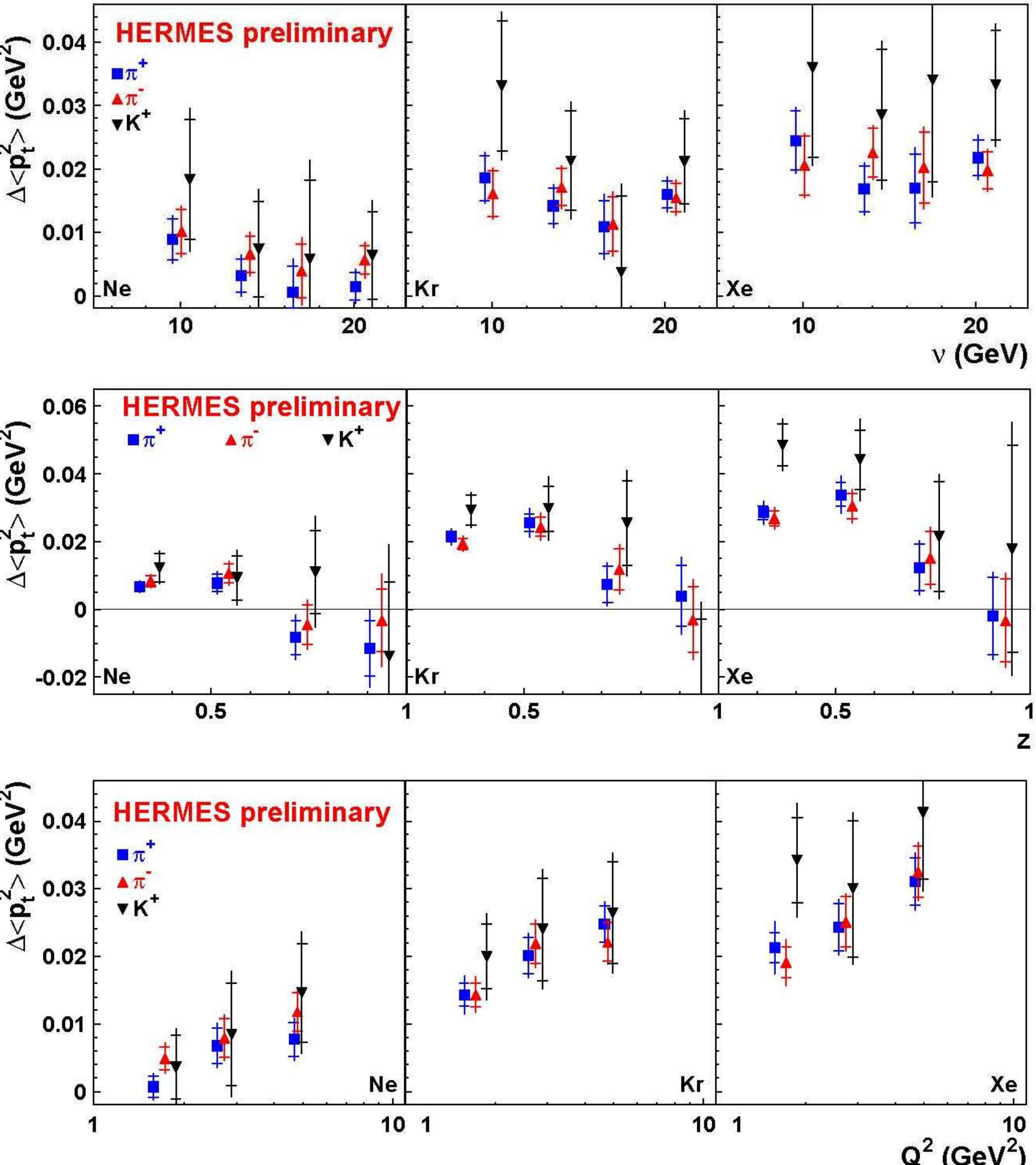

$\Delta\langle p_t^2\rangle$ up to 0.25 GeV²

No ν dep : pre-hadron formed outside

No effect at z=1 (t_p=0)

Increase with Q2: gluon radiation

Clear evidence for partonic effects

Constraints on pre-hadronic effects

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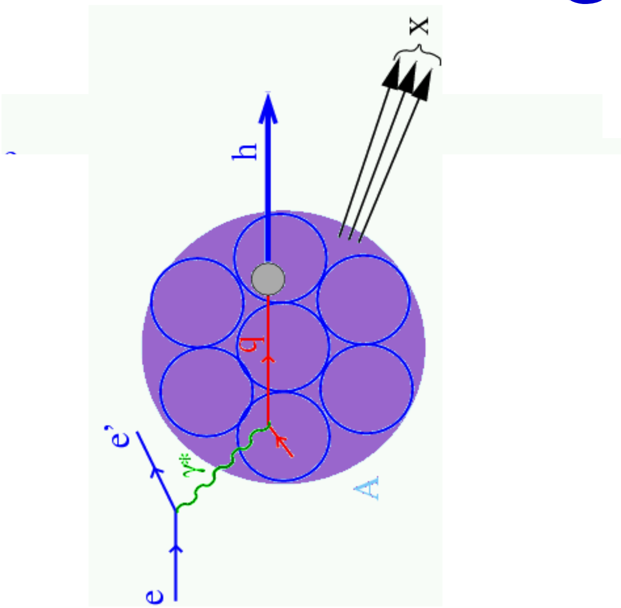
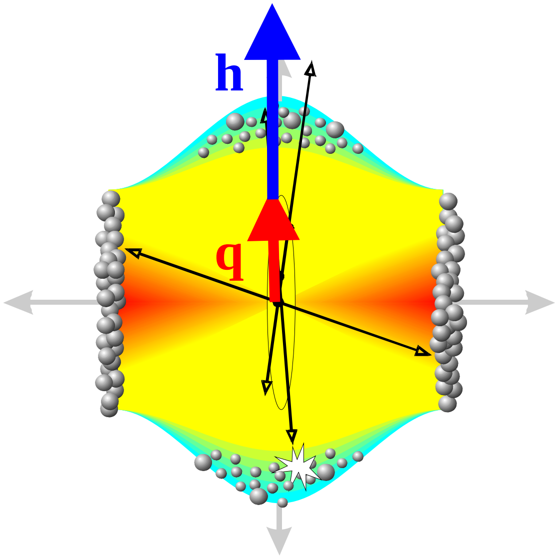
DIS vs HIC





$E_q = \nu = E_e - E_{e'} \approx 13$ GeV

$E_h = z\,\nu$ **≈ 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

$Q^2 \equiv E_q^{\,2} \propto (p_T/z)^2$

...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

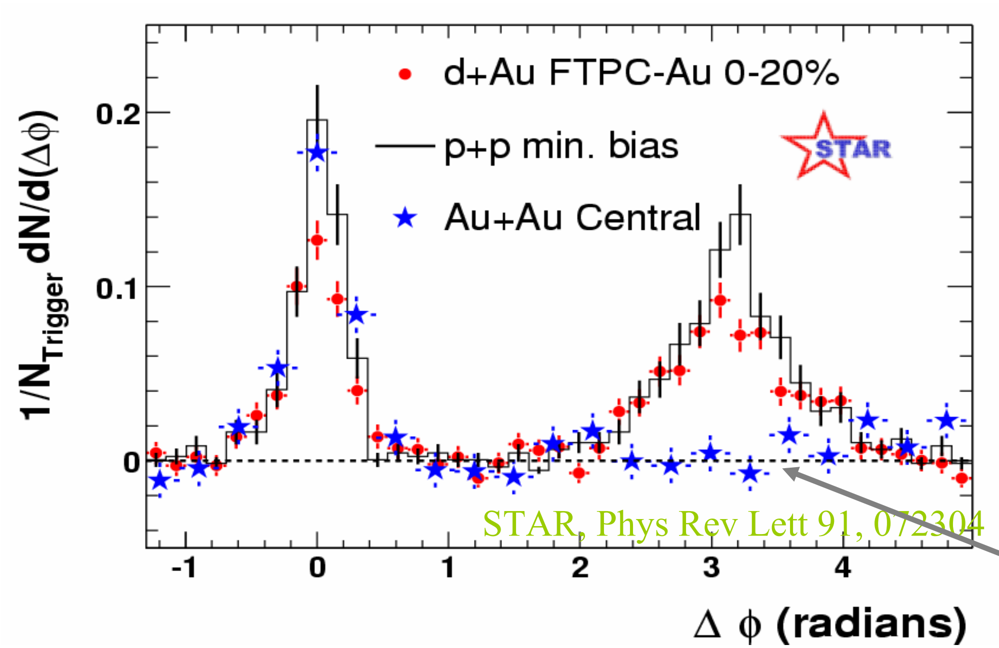
HERMES provide information on partonic propagation, energy loss and scattering and constraints in pre-hadronic effects

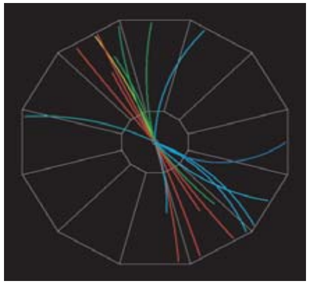
HERMES kinematics is relevant to ion-ion mid-rapidity

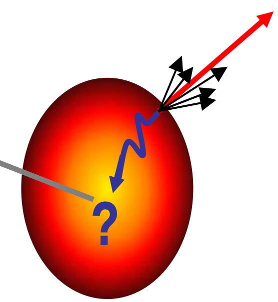
Possibility to formulate consistent pictures of nuclear effects in cold and hot nuclear matter

SPARES

Hadron correlation in HIC and DIS







HIC : two jets and double- hadron correlation in the same jet

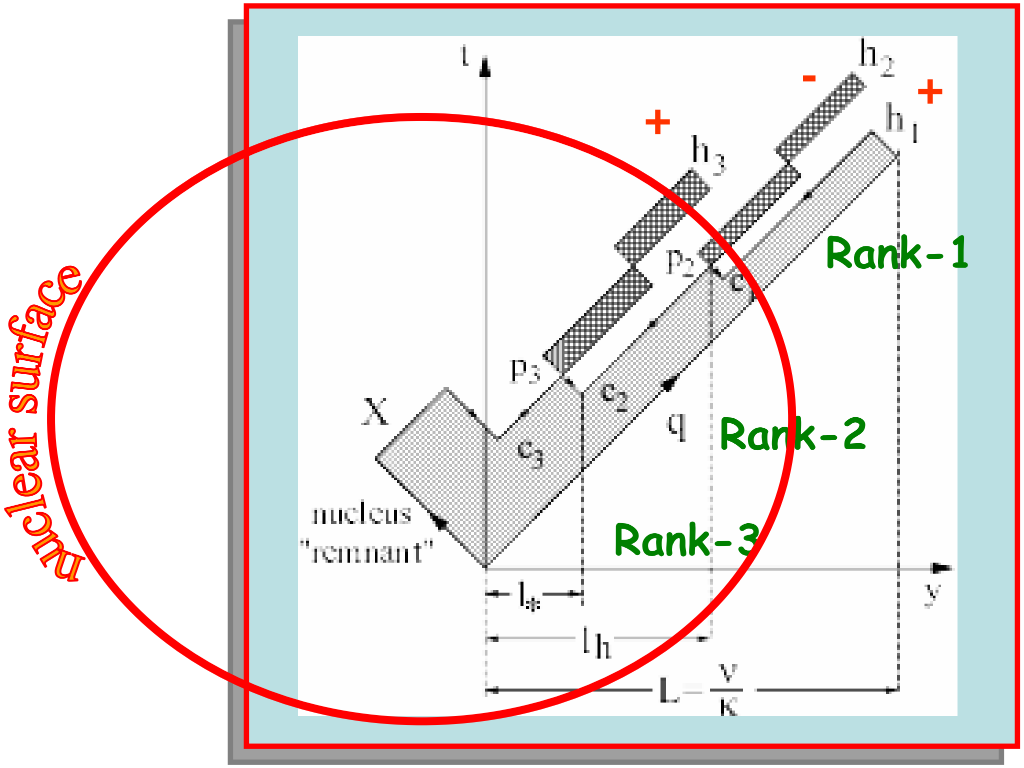
Quenching for hadrons (low p_t) from away side jet

Small effect on hadrons from the same side jet

DIS in cold nuclear matter → double-hadron in the same jet

Multiple hadrons in fragmentation

Space-time evolution within Lund string model of fragmentation:



-All h→ rank 1,2,3

-No +- and -+ → no rank 2, only 1 (leading), 3 (early formed)

-No +- reduces the Vector meson contribution to fragmentation

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

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Hadronic vs Partonic Effects

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

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

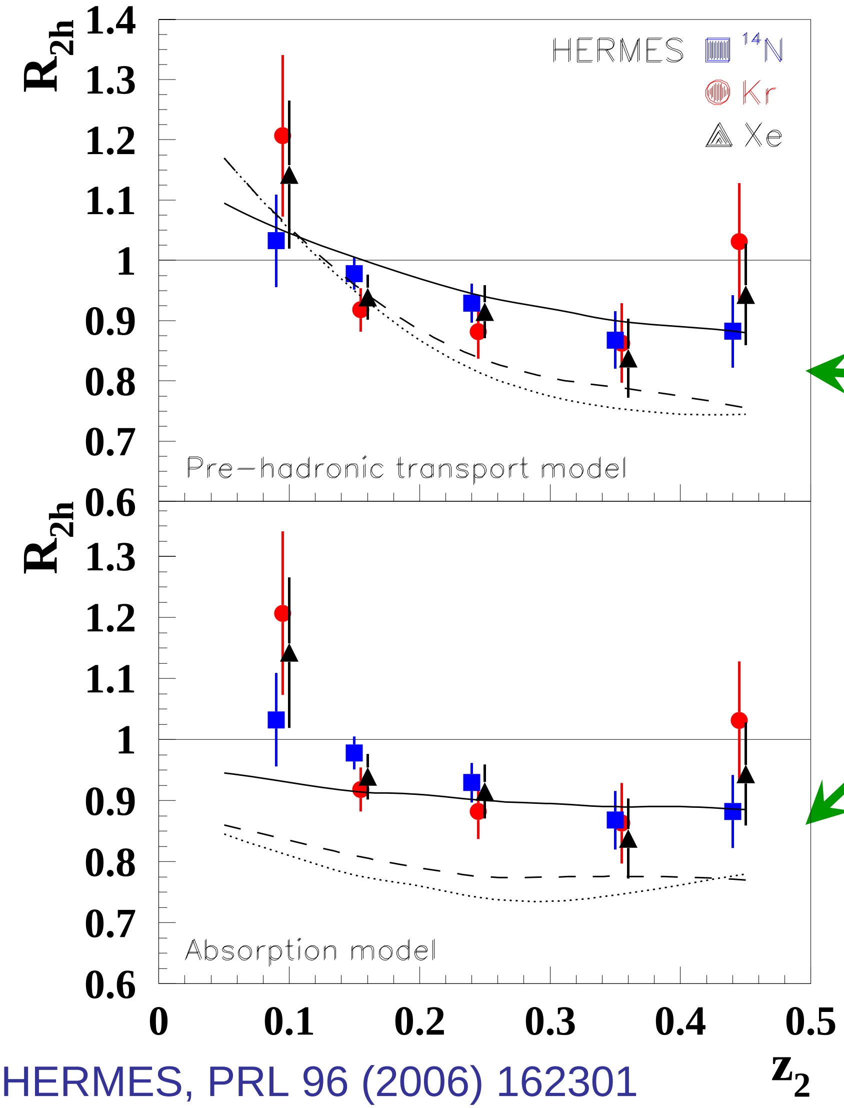
Denominator: Number of events with at least 1 hadron ($z_1 > 0.5$)

If mainly partonic effects (correlated): double-hadron over single hadron ratio in nucleus and deuterium is expected to be only slightly A-dependent.

If mainly hadronic effects (uncorrelated): double-hadron over single hadron ratio is expected to decrease with *A*.

Two-hadron production

No +- and -+ → no rank 2, only 1,3



HERMES, PRL 96 (2006) 162301

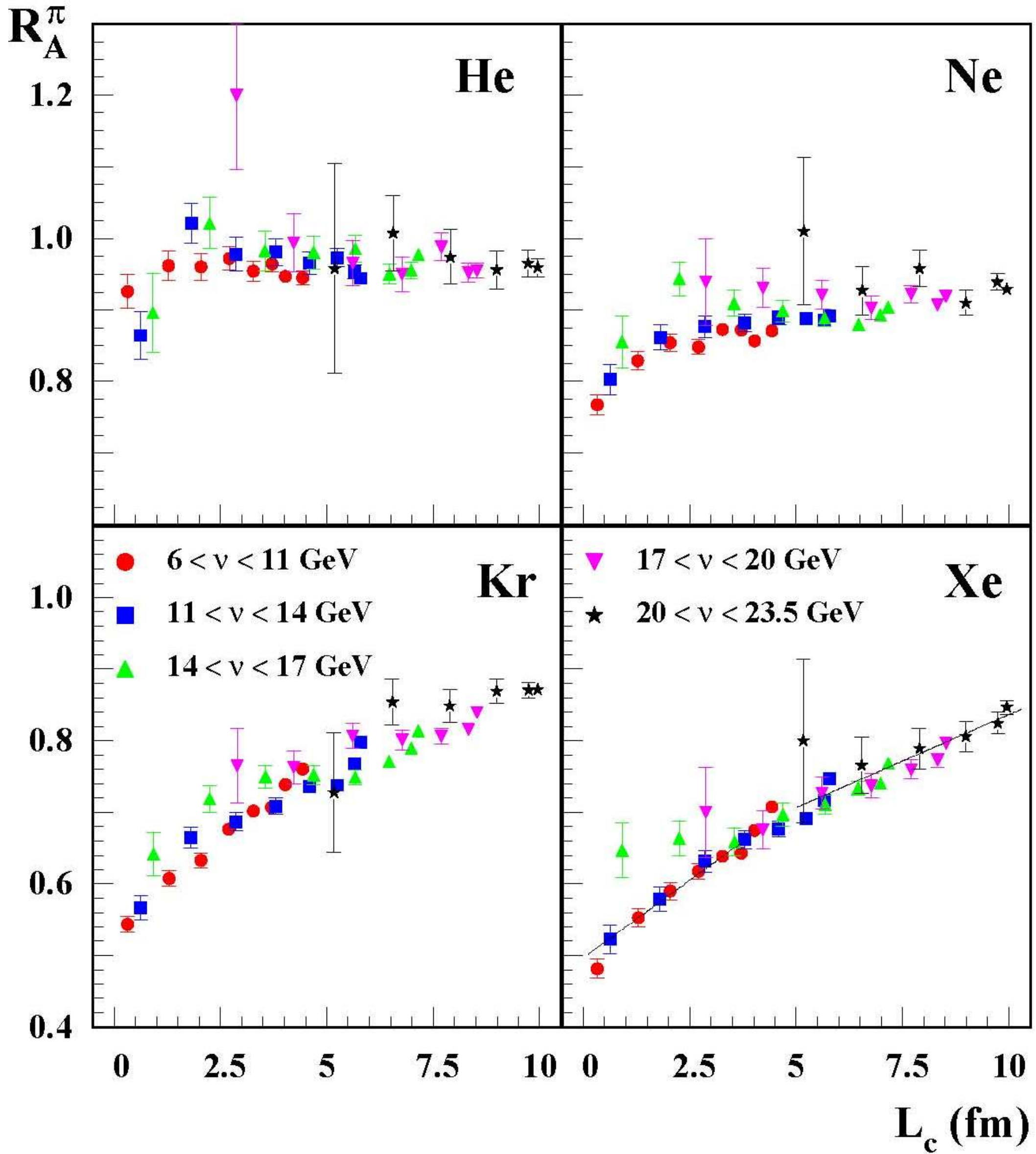
- Small nuclear effect in R_{2h} compared to single hadron multiplicity
- Small A-dependence

Pre-hadronic FSI described by a transport code

Purely absorptive treatment of hadronic FSI

Data do not support naïve expectations for pure absorptive hadronic FSI

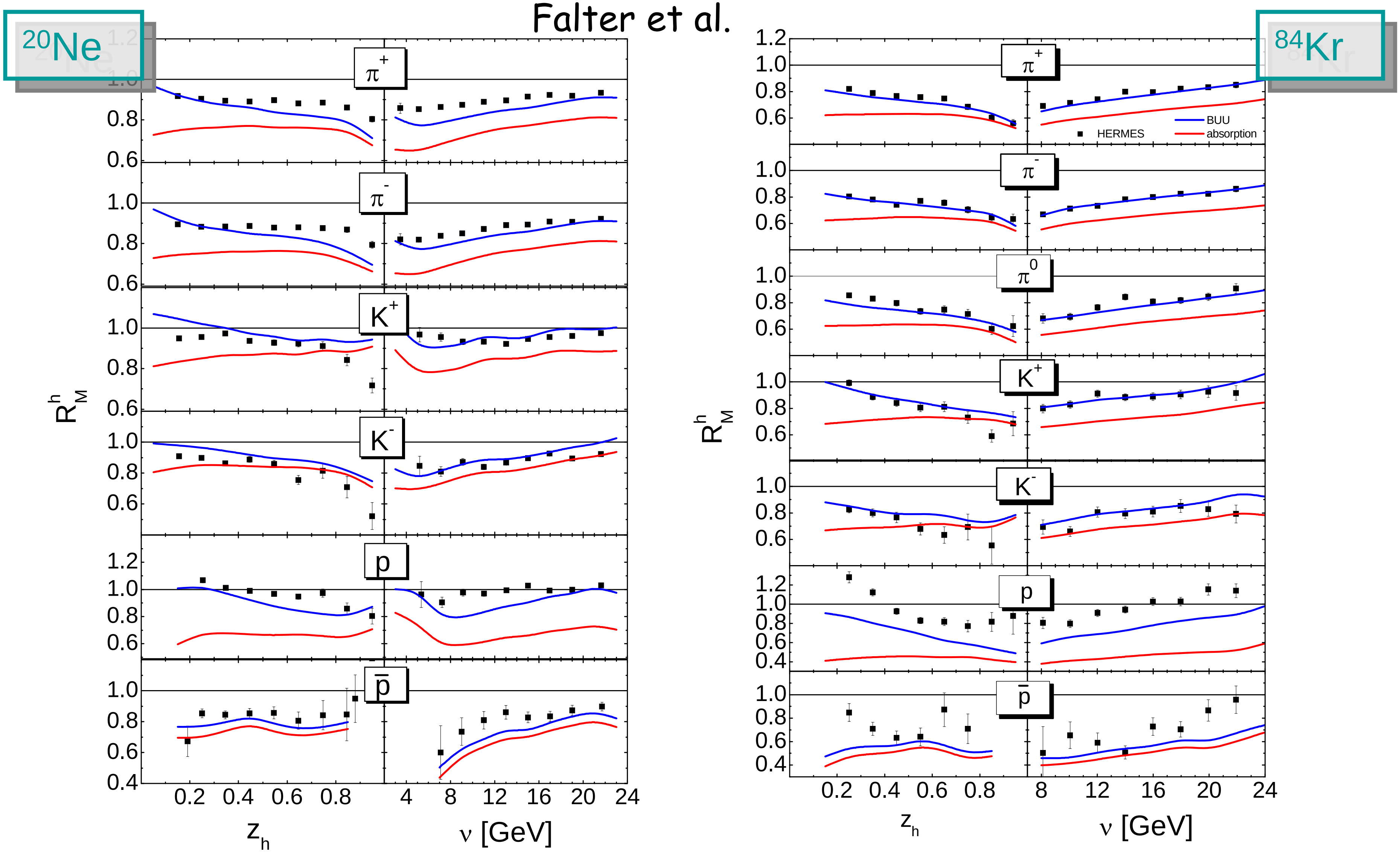
Data vs L_c



R_A^π
He
Ne
Kr
Xe
1.2
1.0
0.8
0.6
0.4
6 < ν < 11 GeV
11 < ν < 14 GeV
14 < ν < 17 GeV
17 < ν < 20 GeV
20 < ν < 23.5 GeV
0
2.5
5
7.5
10
L_c (fm)

Pre-hadronic FSI and formation times

Falter et al.



$\tau_p = 0$; $\tau_f > 0.5$ fm/c compatible with data

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

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