Accessing space-time characteristics of hadronization from data

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- The hadronization process
- Role of nuclear DIS
- Hadron production in semi-inclusive measurements on nuclei.
- Status of the theoretical models

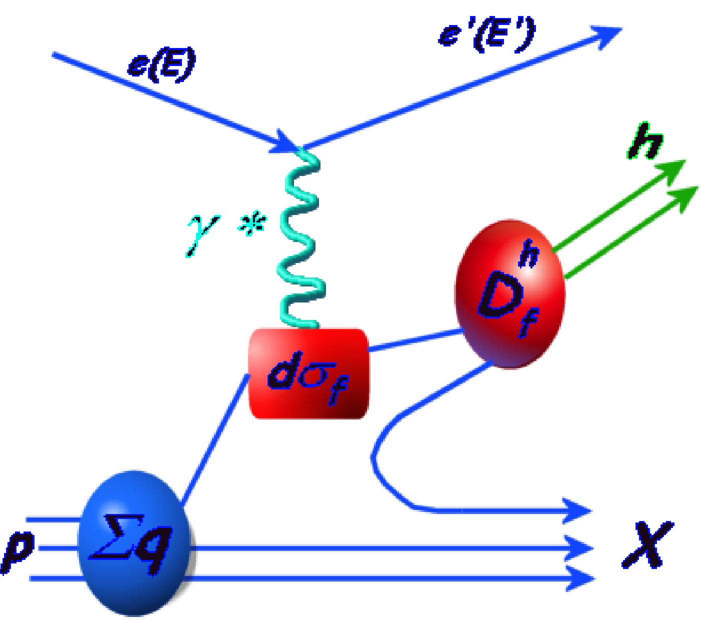
Hadronization

•Hadronization: The process by which energetic quarks evolve into hadrons -> Fundamentally non perturbative Generally described through phenomenological models.

•Lepton DIS: Less ISI than in hA interactions -> partonic/hadronic FSI in ‘clean’ nuclear environment.

•Semi-Inclusive DIS ->Parton Fragmentation Functions

$$d\sigma^{h}(z) \propto \sum_{f} q_{f}(x) \otimes d\sigma_{f} \otimes D_{f}^{h}(z$$

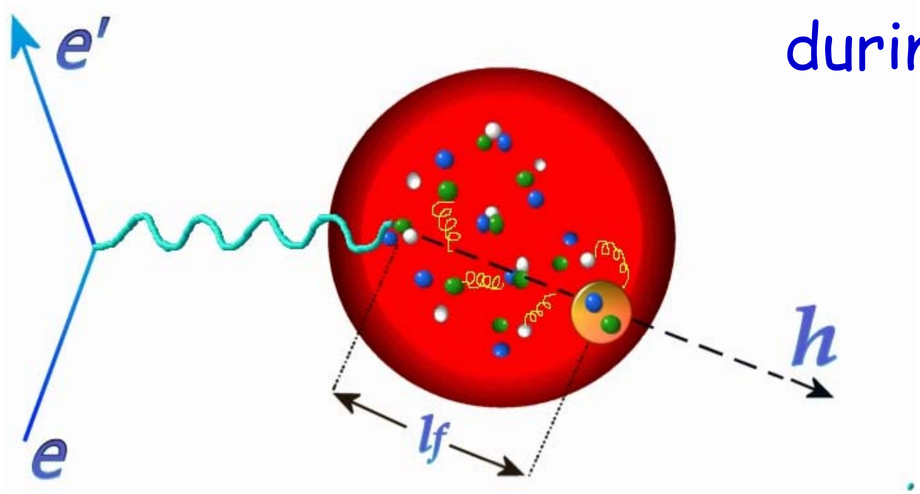


$$z = E_h / \nu$$

DIS and hadronization distance scales

Determine the scale of hadronization using nuclei

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

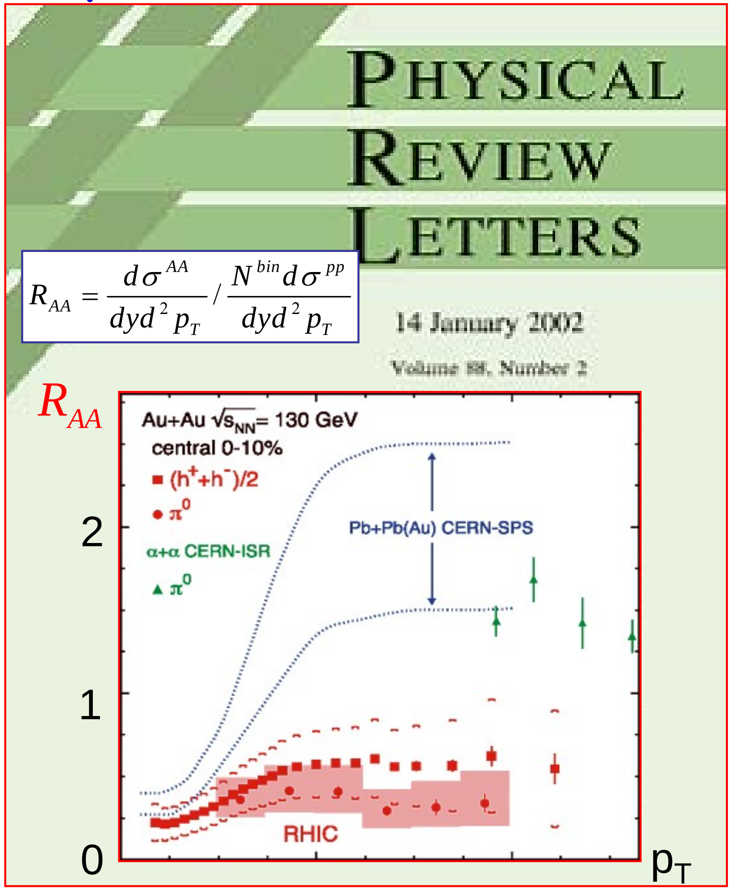


Interactions with the medium during l_f → space-time picture of hadronization

Connections to Relativistic Heavy Ions

Nuclear SIDIS is related to parton progation in AA collisions

- P_T (A-A) $\approx$ $E_h = z\nu$(DIS) → the relevant energies are few - few tens of GeV.
- Jet quenching (suppression of high P_T hadrons) and depletion of the Cronin effect at RHIC:



Jet quenching, ascribed to radiative energy loss, would be an indication of high partonic density, e.g. QGP.

(Pre-)hadron interaction in the nuclear medium might give alternative explanation.

W.Cassing, K.Gallmeister, C. Greiner NPA 735, 277 (2004).

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Hadron multiplicity ratio

Experimental observable: hadron multiplicity ratio in nuclei and deuterium

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

Determine R_M versus:

Leptonic variables: ν=E-E' , Q^2

Hadronic variables $z=E_h/\nu$, P_t^2

Flavor

Different nuclei

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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.

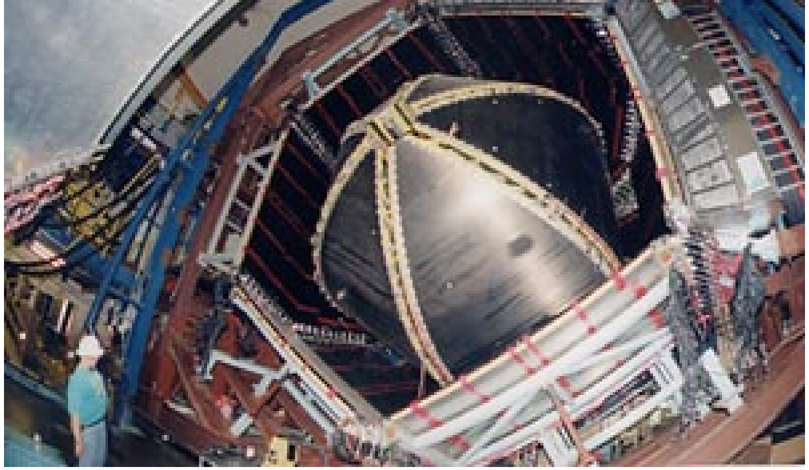
- WA21/59: 4-64 GeV $\nu(\bar{\nu})$-beam on Ne Z.Phys. C70 (1996) 47

- HERMES: 27.6 or 12 GeV e^+-beam on He, N, Ne, Kr, Xe.
  PLB 577 (2003) 37

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

- 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, $\bar{p}$

Hall B



- Larger geometrical acceptance $\rightarrow$ detects more secondary particles from FSI.

- High statistics and wide range of final states: π^+, π^-, π^0, K^+, K^-, K^0, p, Λ, Σ^{+0}, Ξ^{0-}.

- 6 GeV beam : $Q^2 < 4$ GeV^2, $\nu < 5$ GeV.
  12 GeV beam : $Q^2 < 9$ GeV^2, $\nu < 9$ GeV.

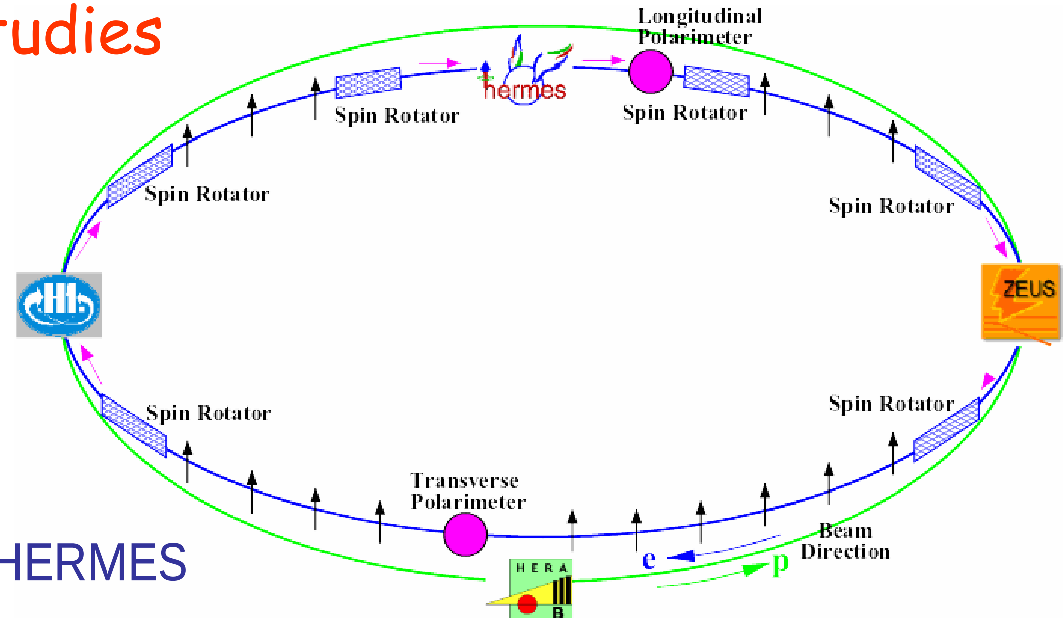
HERMES @ HERA

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

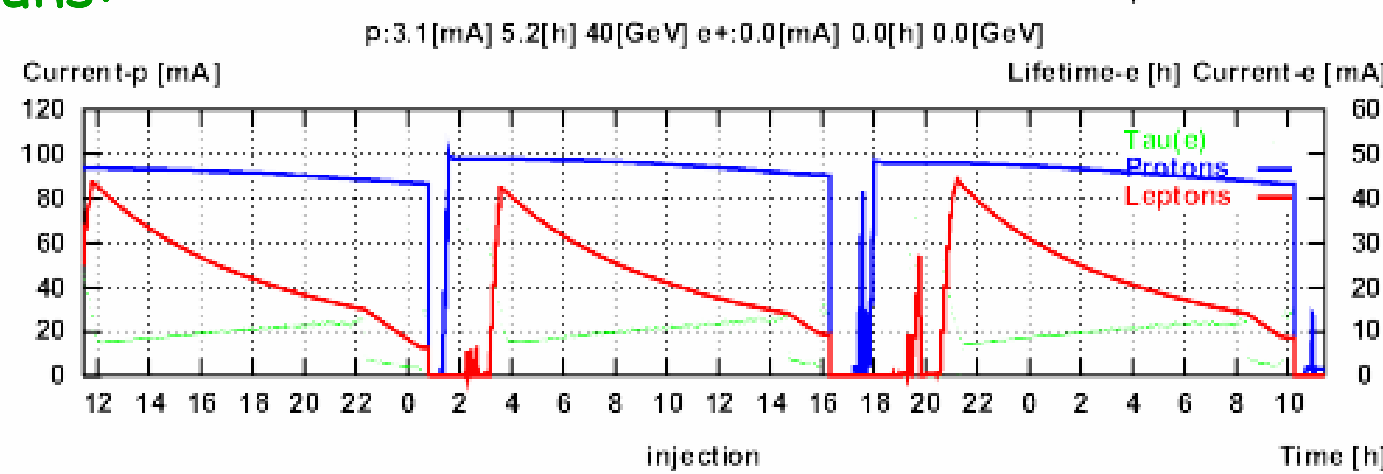
E=27.5 12 GeV e^+ (e^-)

I ~ 30 mA

p beam of 920 GeV, not used by HERMES



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



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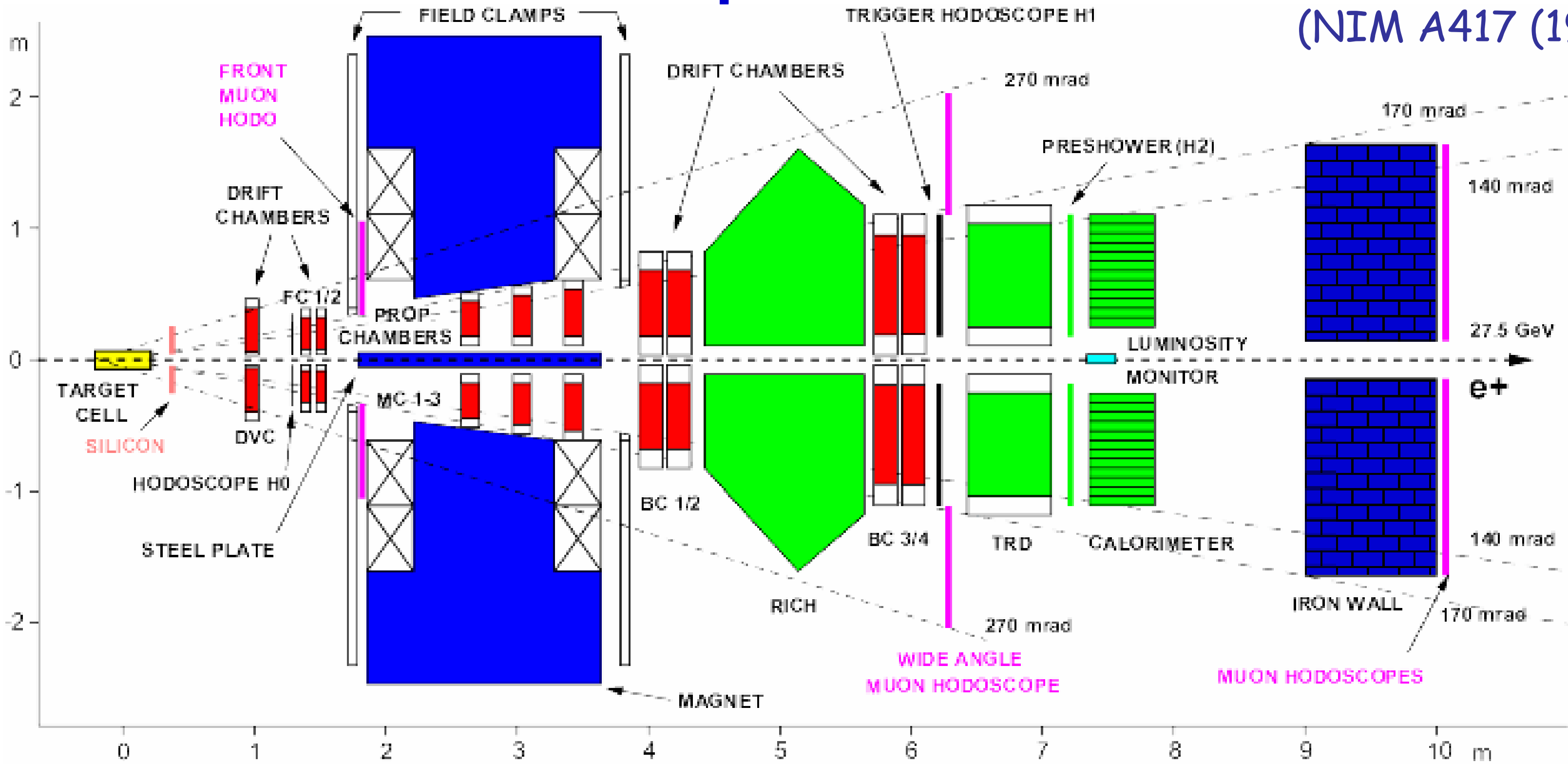
The Spectrometer

(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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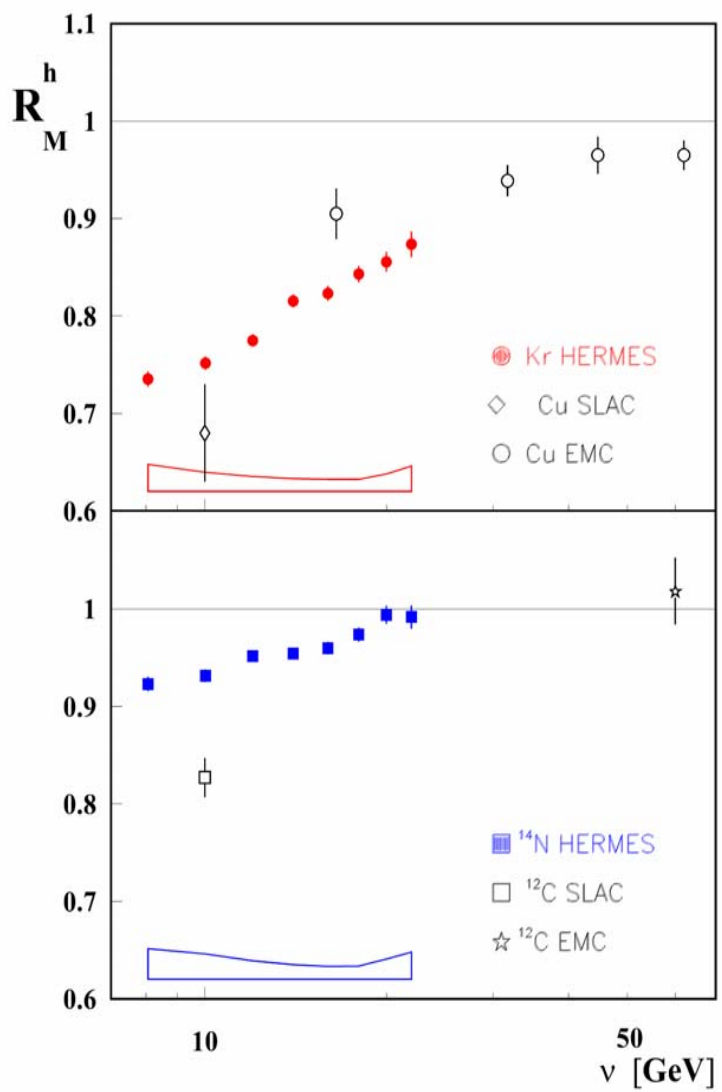
Hadron multiplicity ratio vs transfer energy ν



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

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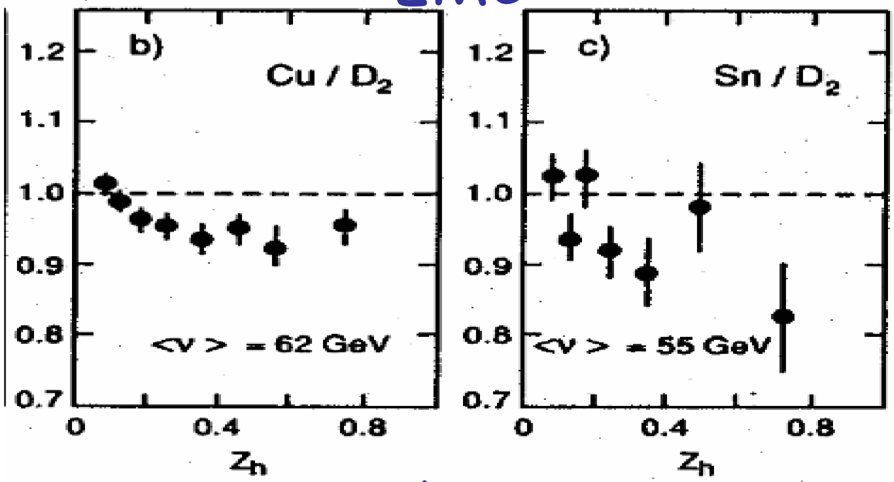
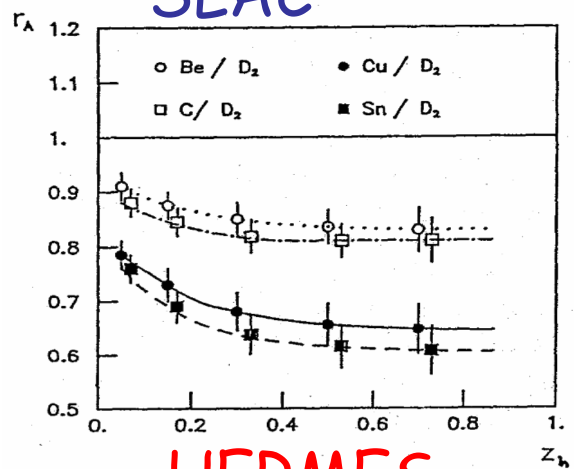
Hadron Multiplicity Ratio vs $z=E_h/\nu$

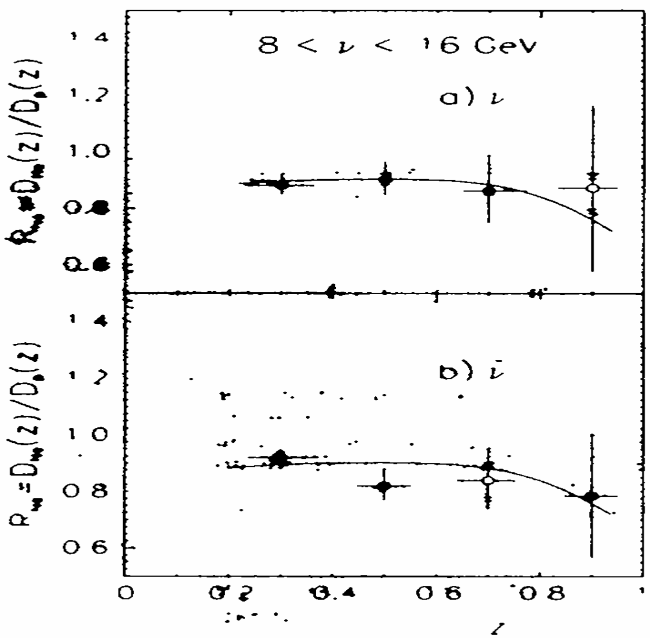
EMC



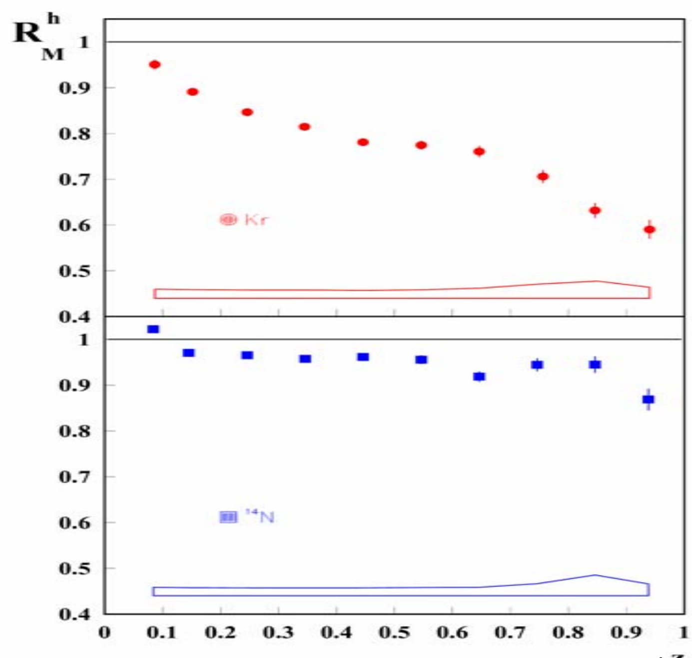
SLAC



WA21/WA59



HERMES



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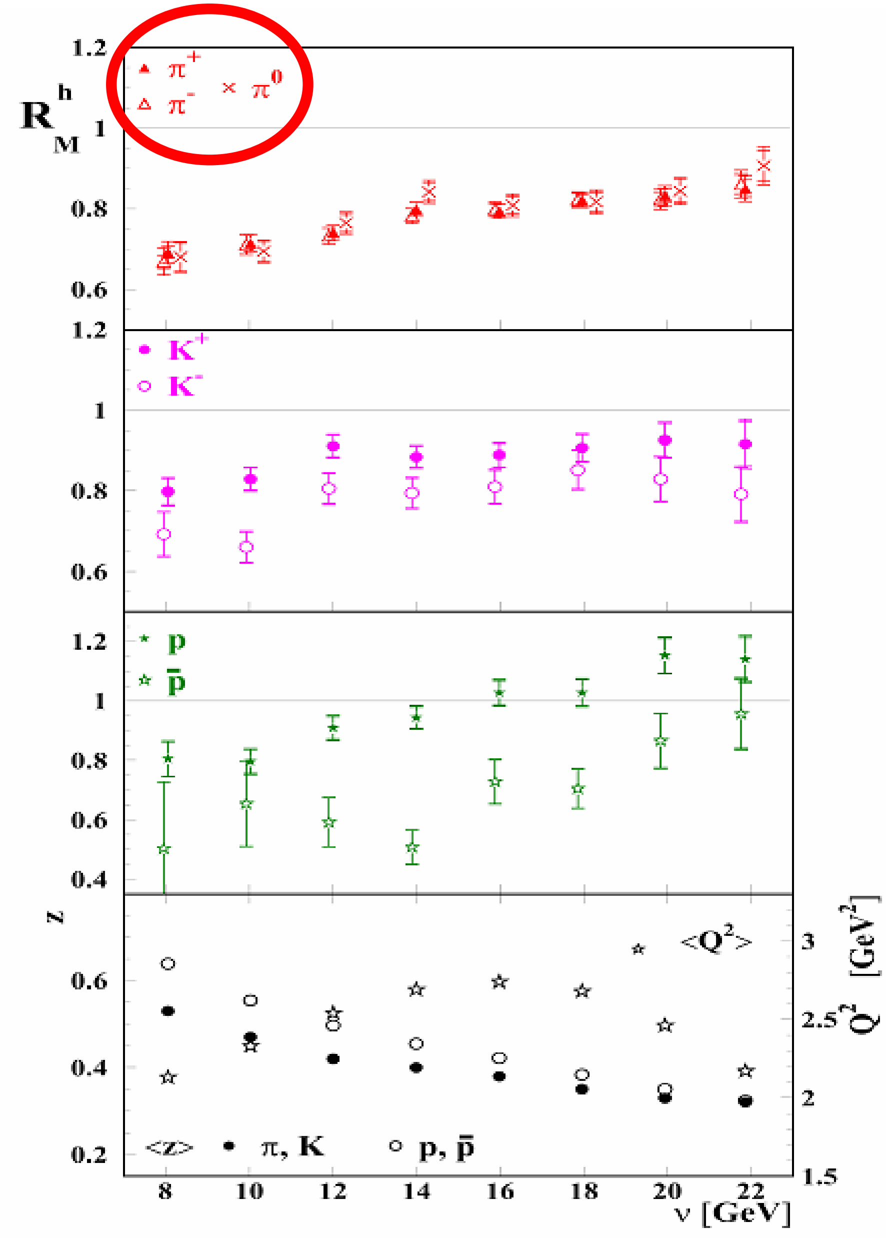
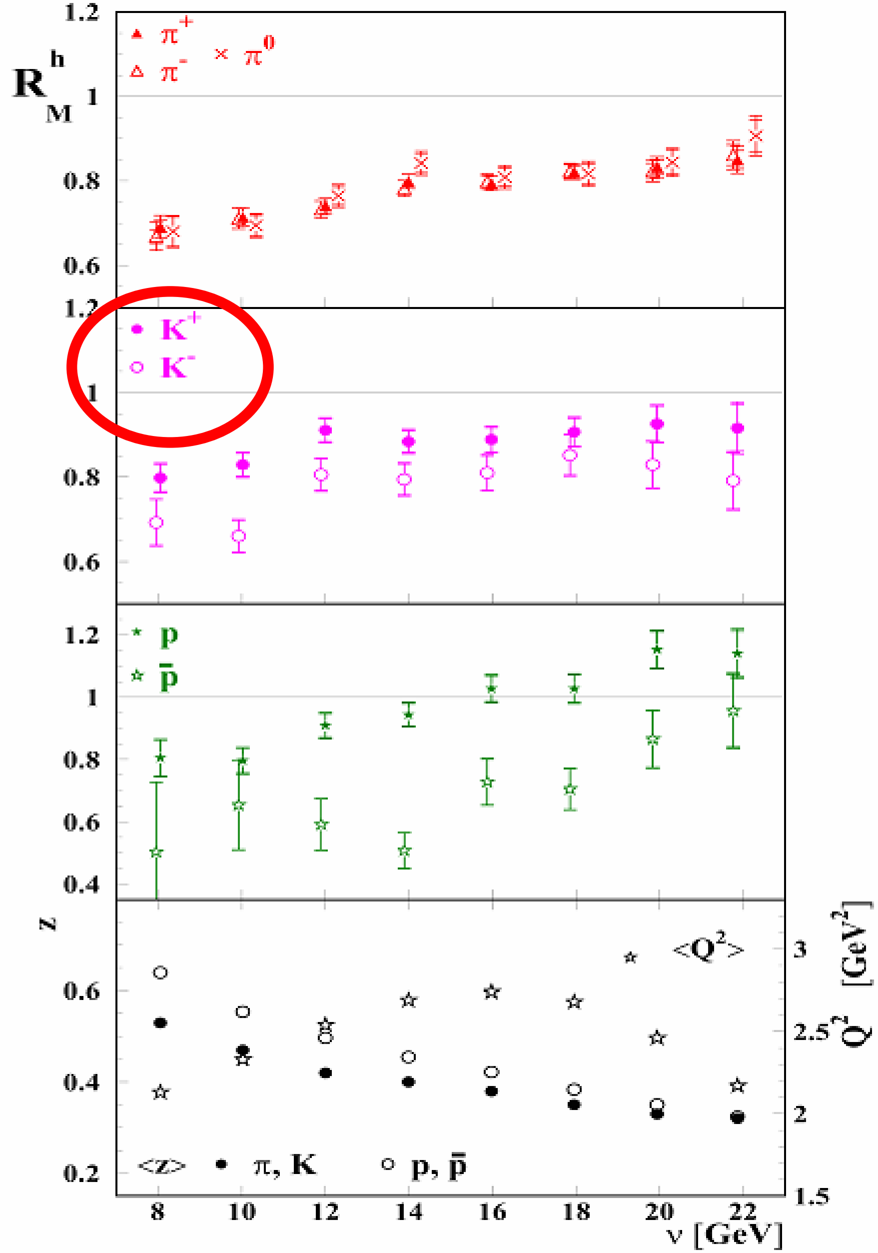
Multiplicity ratio for identified hadrons vs ν

HERMES, PLB 577 (2003) 37

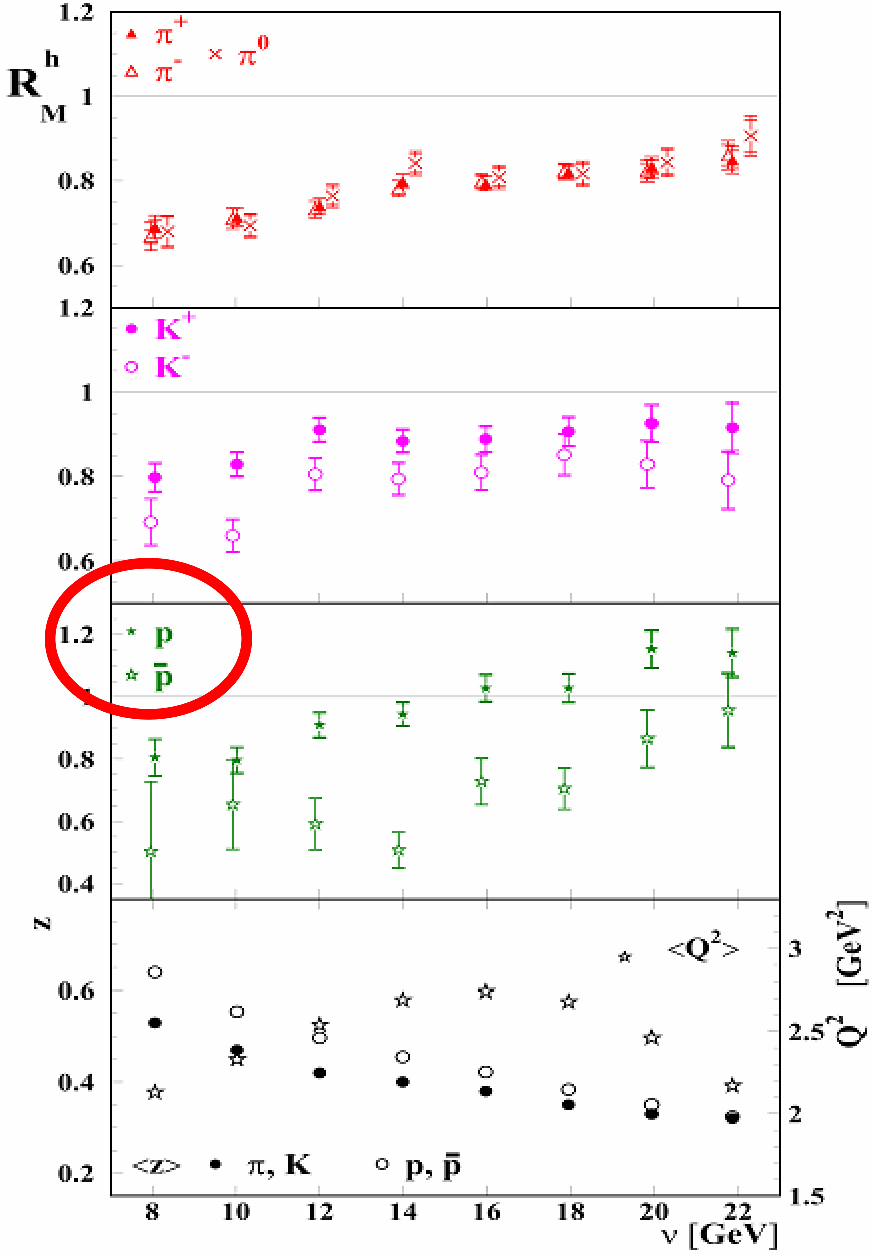


Multiplicity ratio for identified hadrons vs ν



HERMES, PLB 577 (2003) 37

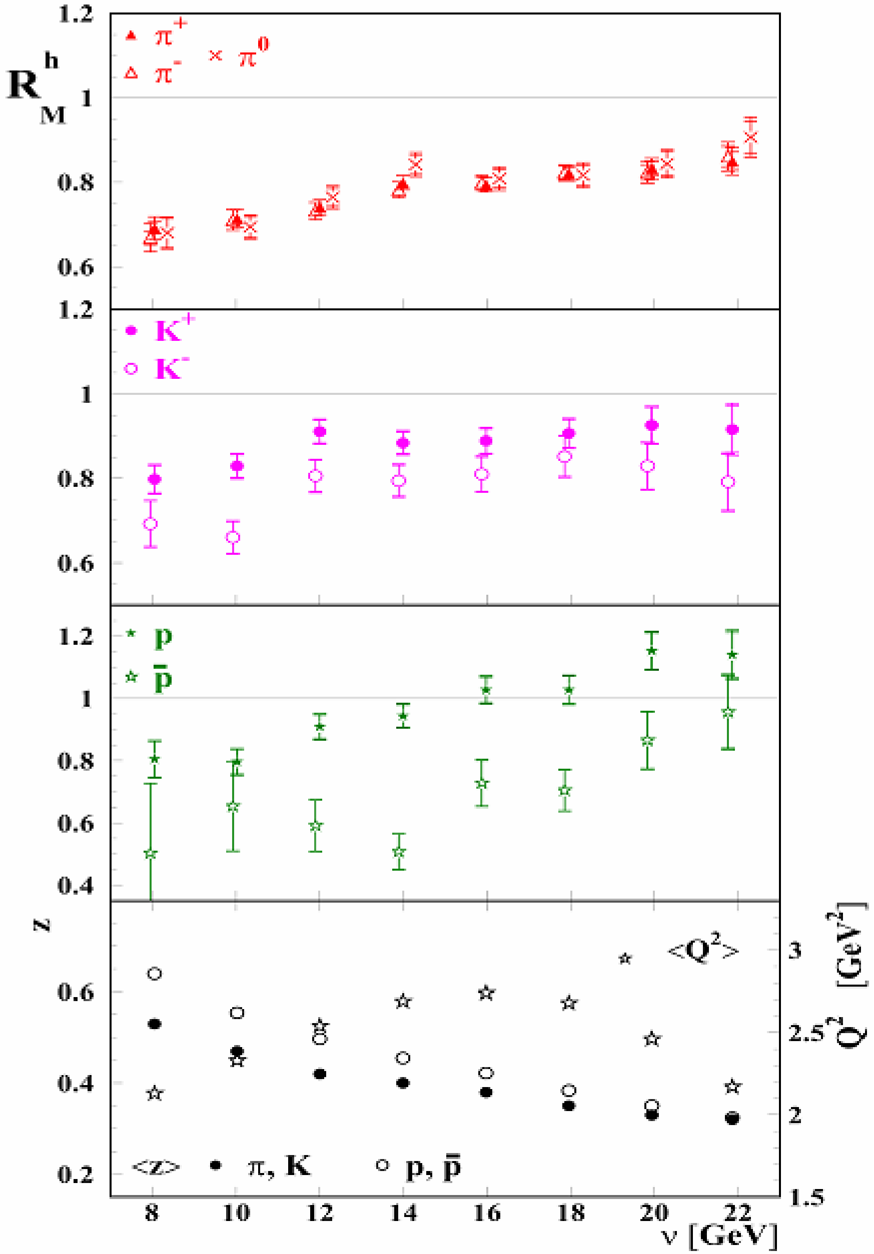
Multiplicity ratio for identified hadrons vs ν



HERMES, PLB 577 (2003) 37

Multiplicity ratio for identified hadrons vs ν

HERMES, PLB 577 (2003) 37



Experimental findings:

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

$K^+ > K^-$

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

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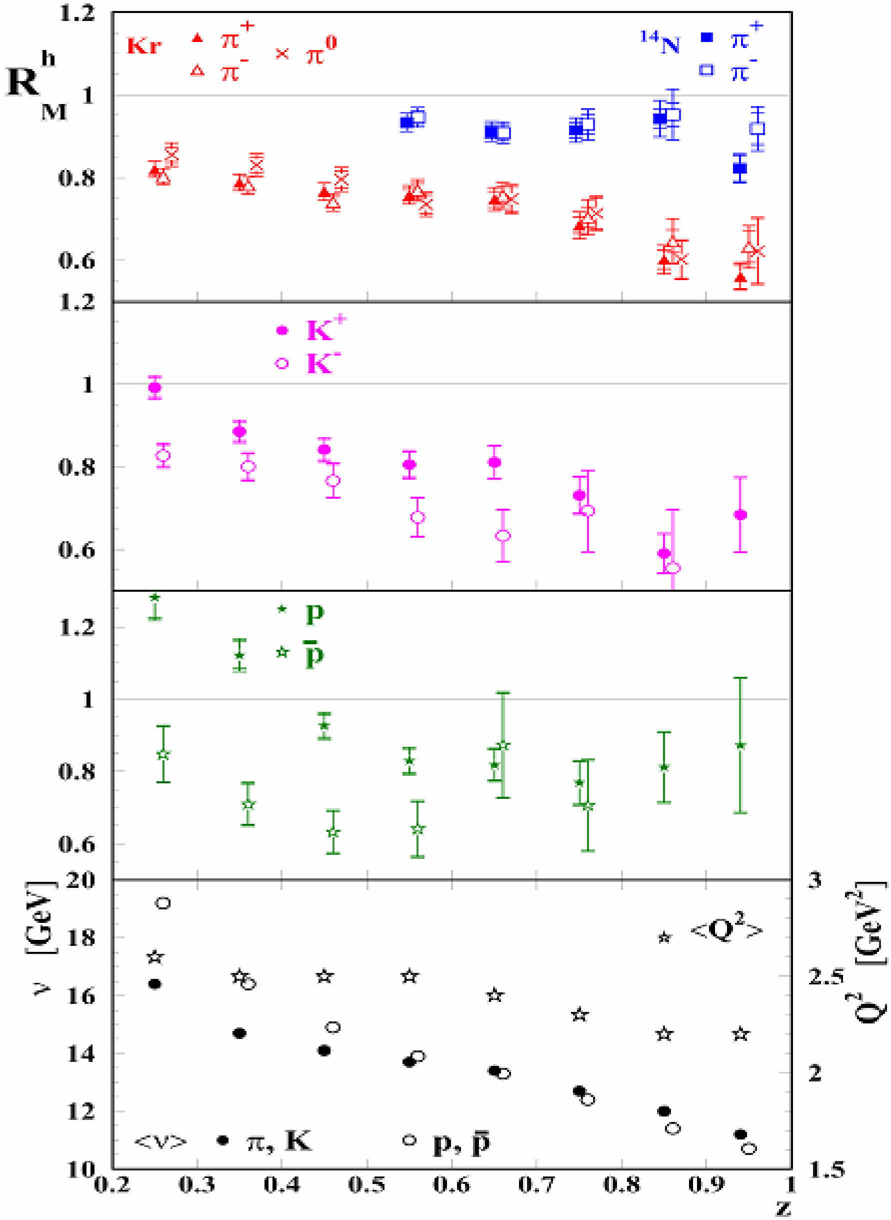
Multiplicity ratio for identified hadrons vs z



HERMES, PLB 577 (2003) 37

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

Different τ_h for mesons and baryons

Different σ_h:

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

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

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

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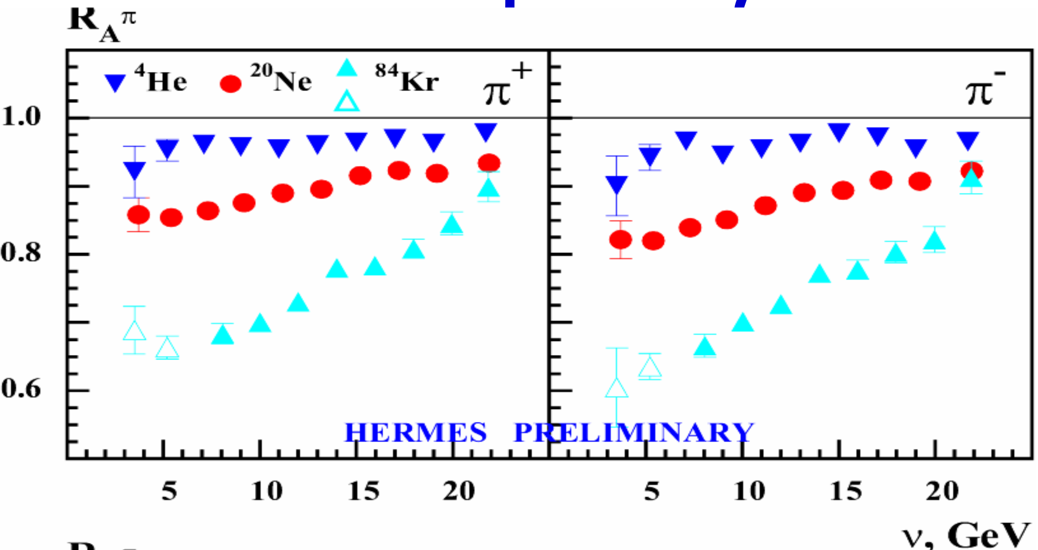
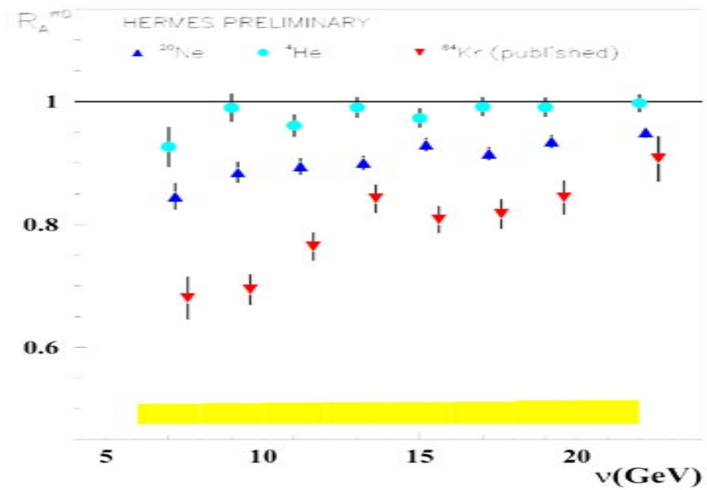
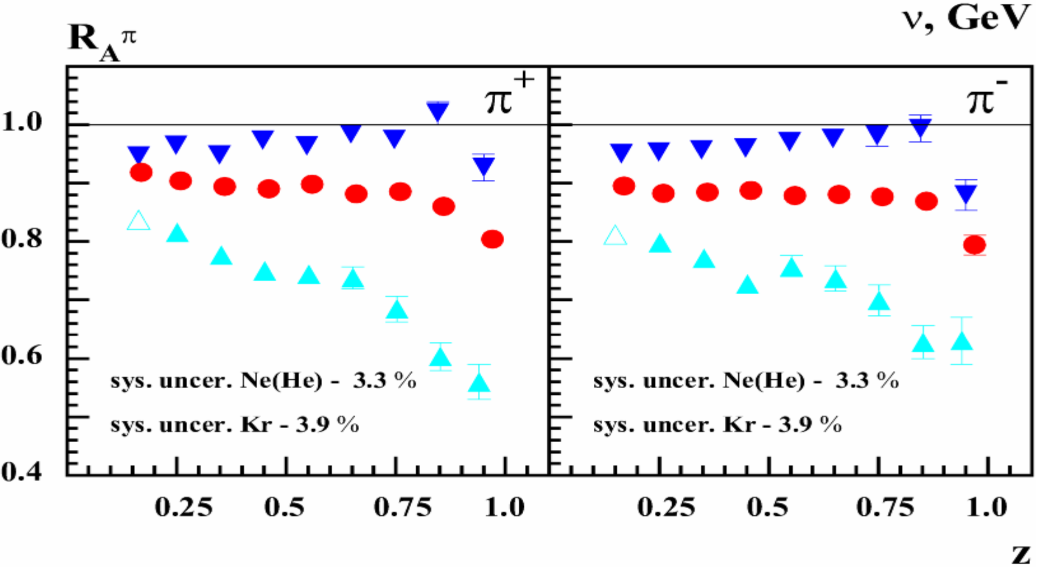
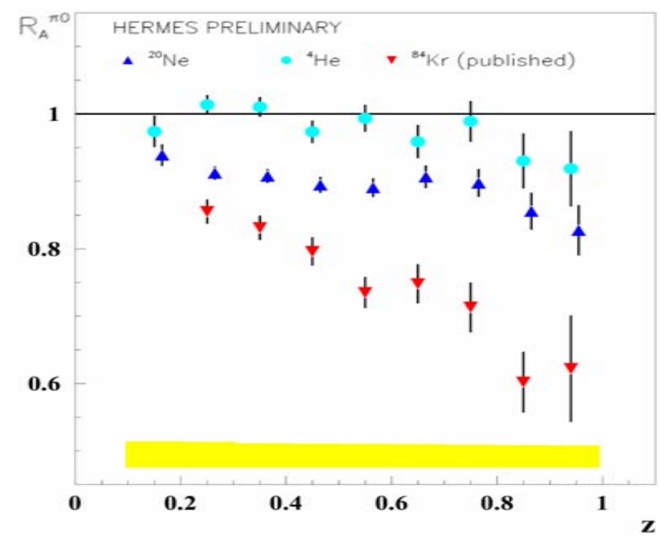
Multiplicity ratio on He, Ne, Kr









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

Data suggest $\alpha \sim 2/3$

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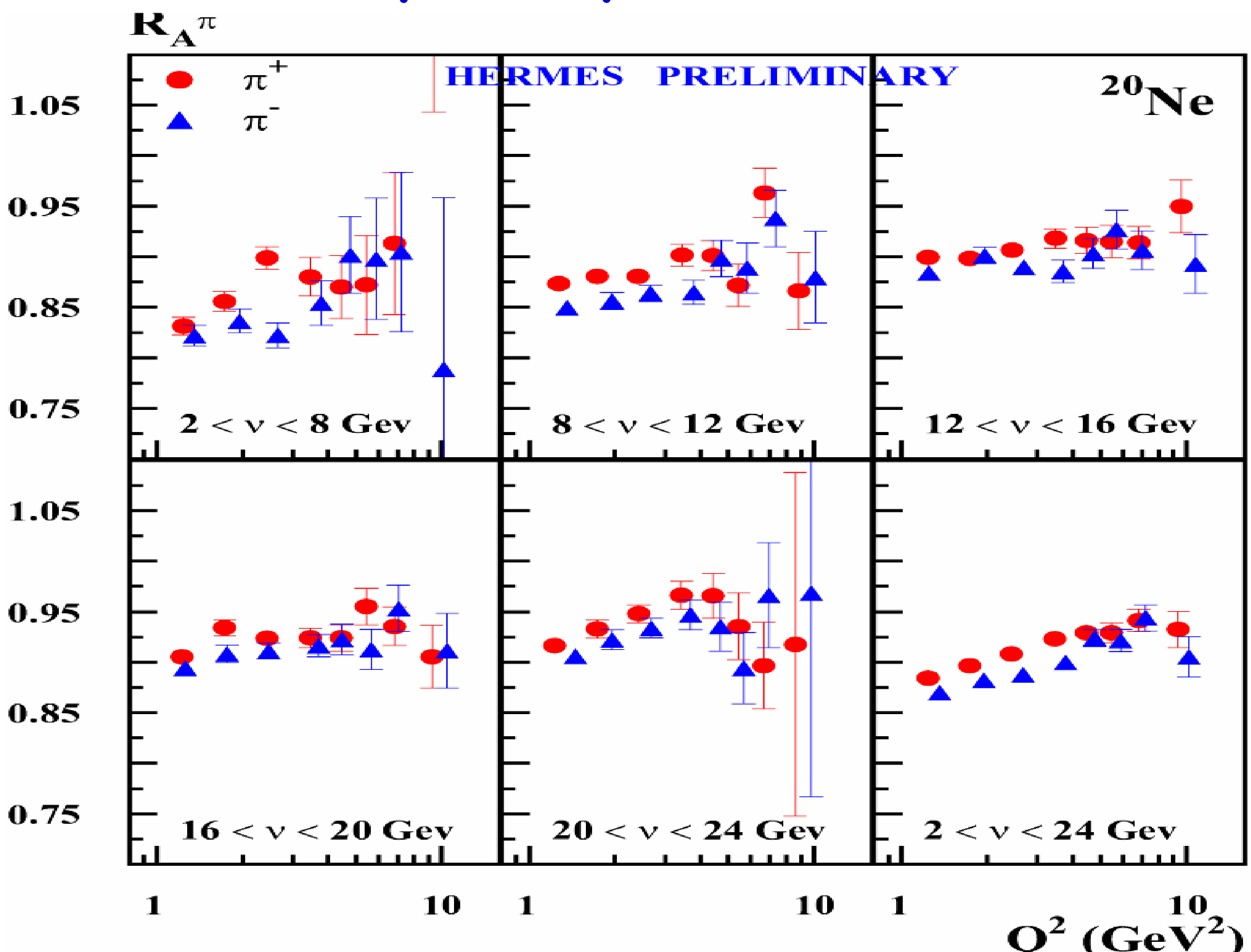
Multiplicity ratio vs Q^2



Dependence on $1<Q^2<10$ GeV^2:

stronger at small ν, weaker at high ν

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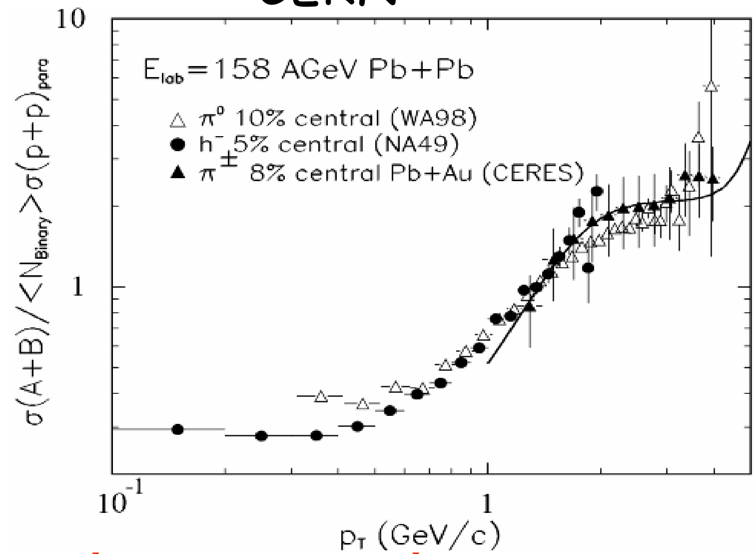
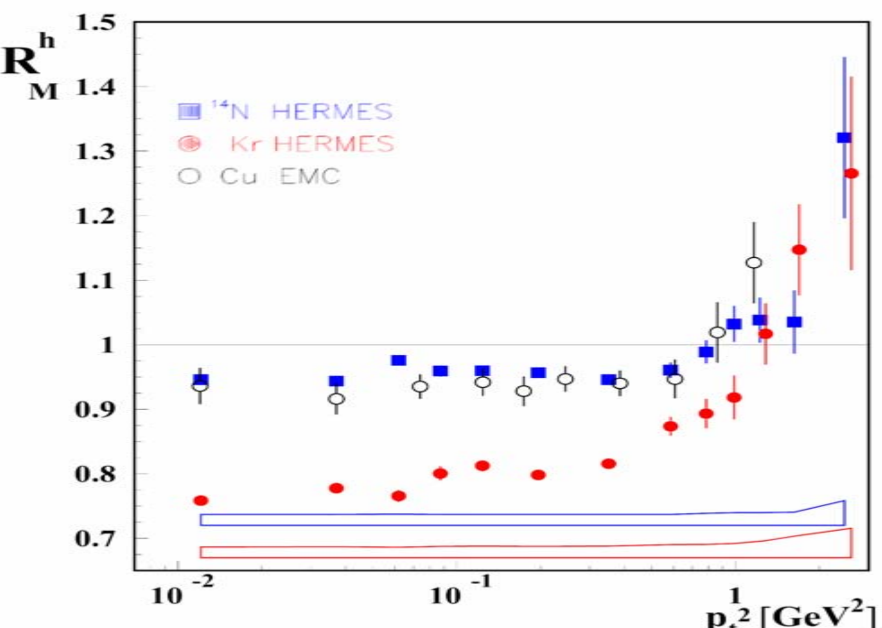
Multiplicity Ratio vs p_t^2

Cronin effect: in pA and AA collisions hadrons gain extra transverse momentum due to the multiple scattering of projectile partons propagating through the nucleus.

CERN

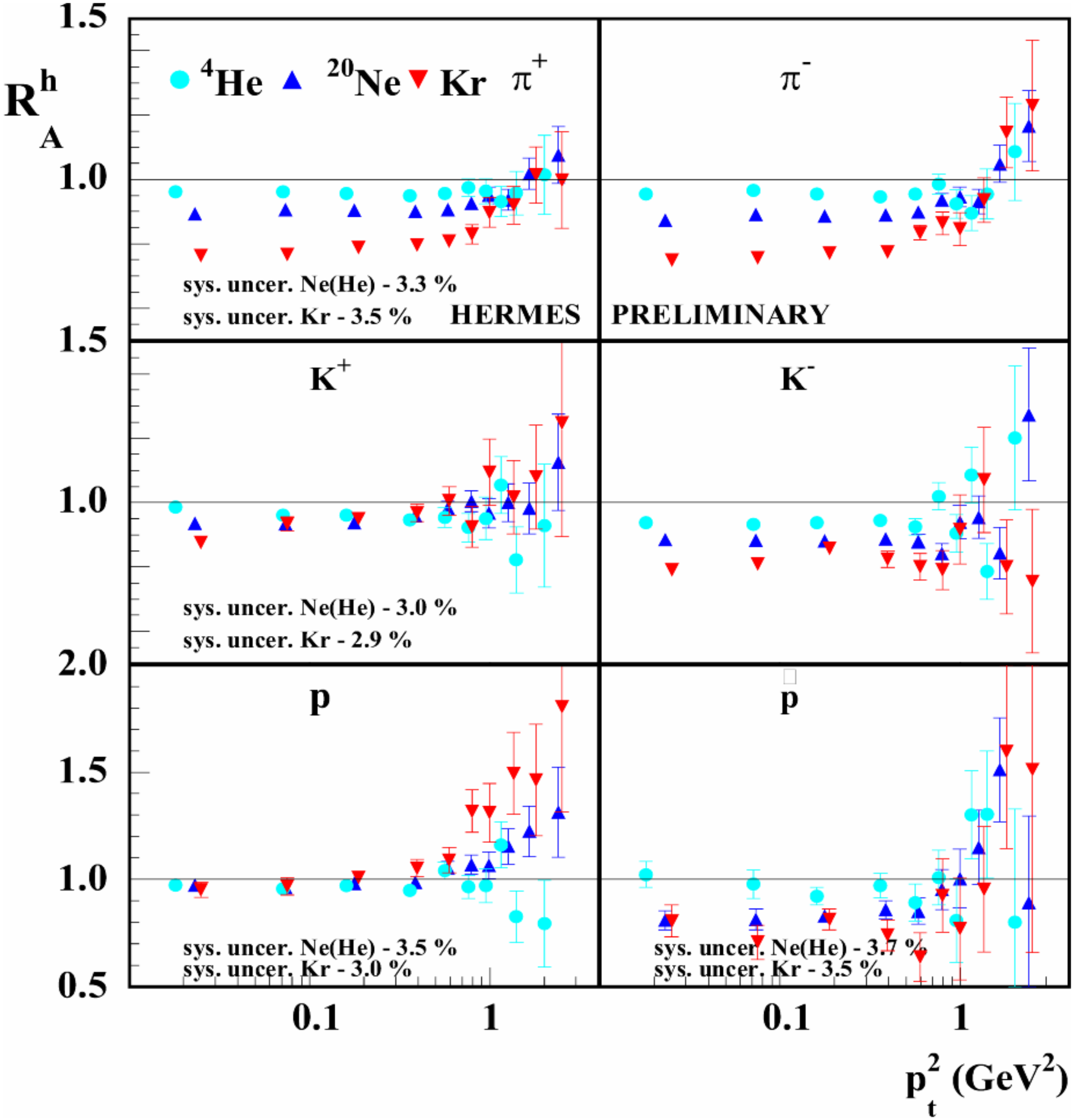




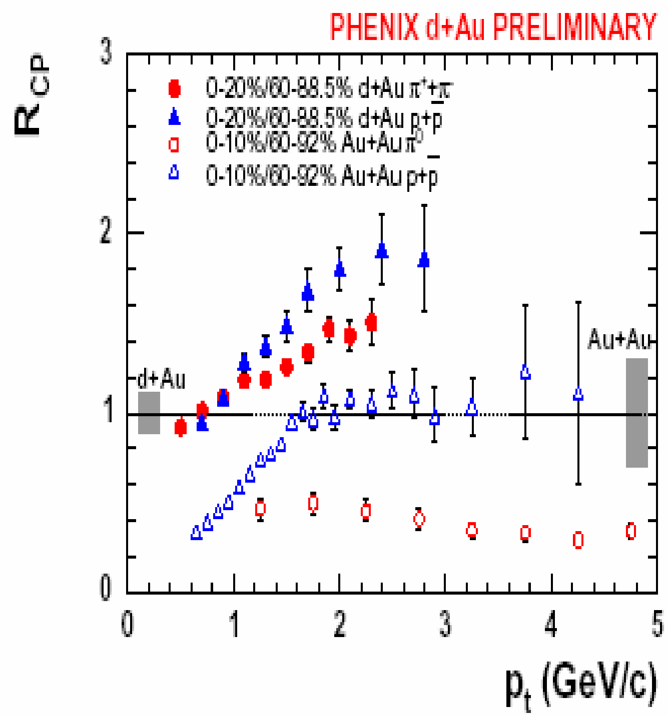
Data show a p_t enhancement similar to that observed in pA scattering at p_t~1-2 GeV.

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

P_t dependence for identified hadrons



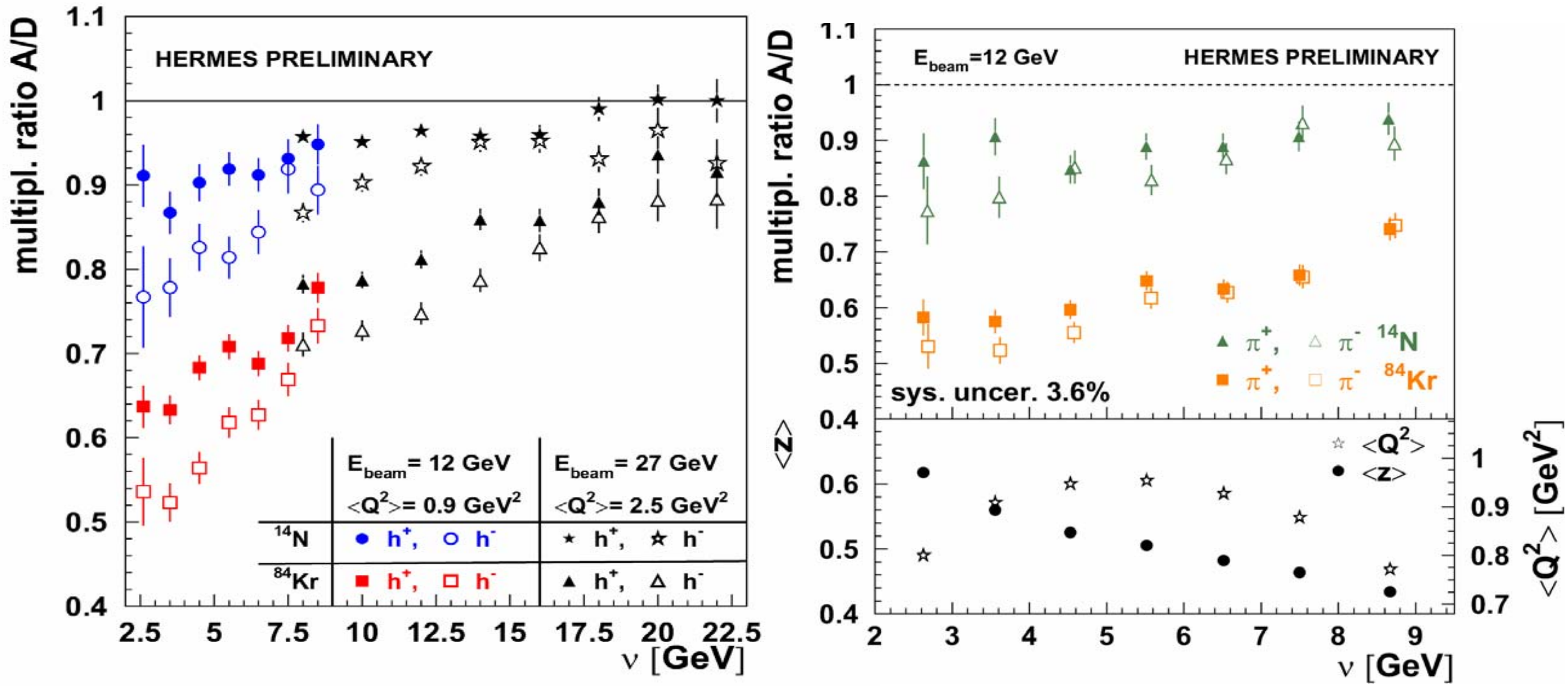
Nucl-ex/0403029



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

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

Extension of the ν range down to 2 GeV



- Measurements are in progress at HERMES

2<ν<23 GeV Q^2<10 GeV^2

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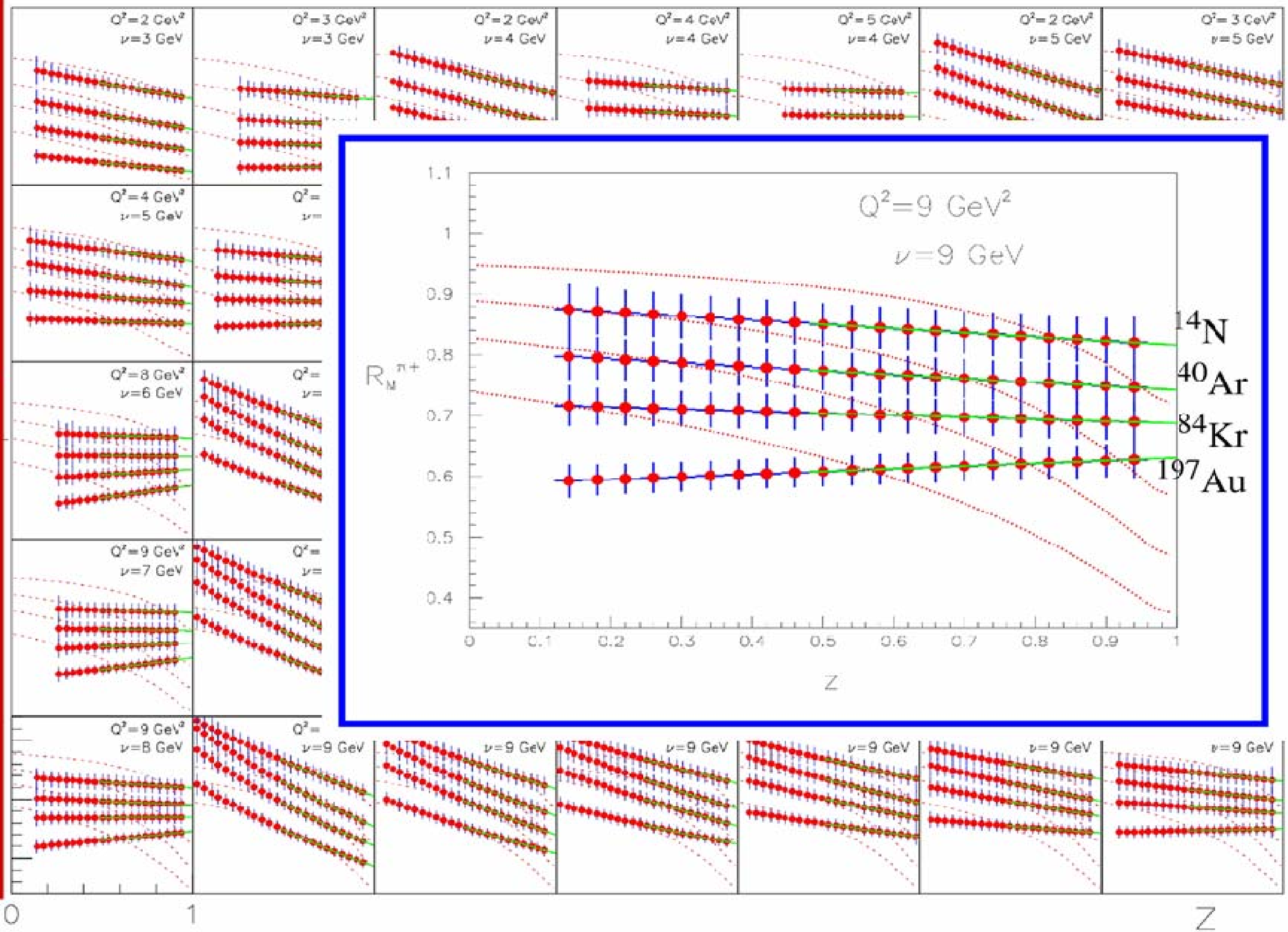
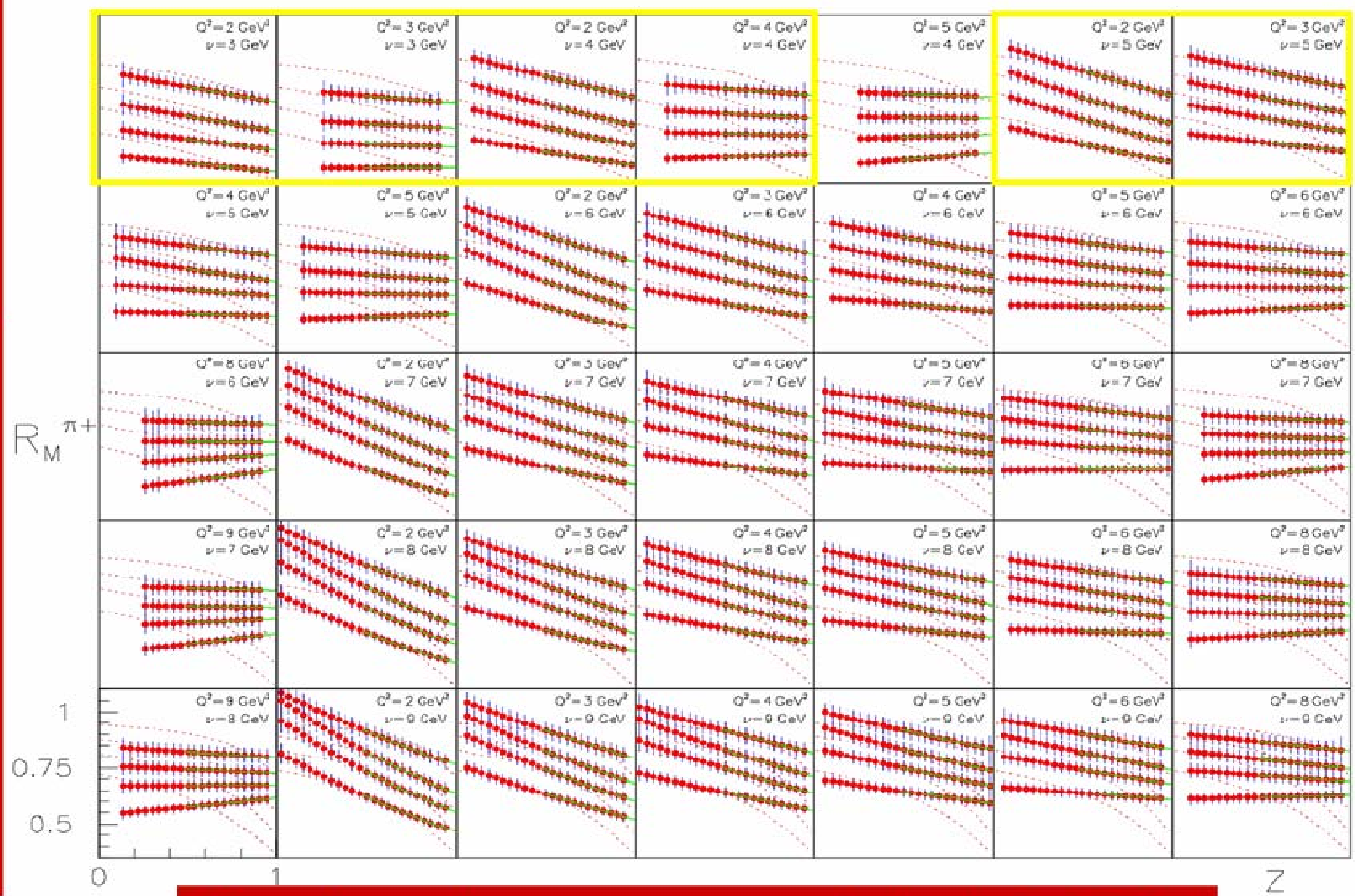
12 GeV Anticipated Data



12 GeV Anticipated Data

Examples of Experimental Data and Theoretical Predictions



Bins in yellow are accessible at 6 GeV

Theoretical Models At work

Models based on (pre-)hadronic absorption

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

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

A. Accardi et al.,: NPA 720, 131 (2003).

Models based on partonic energy loss

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

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

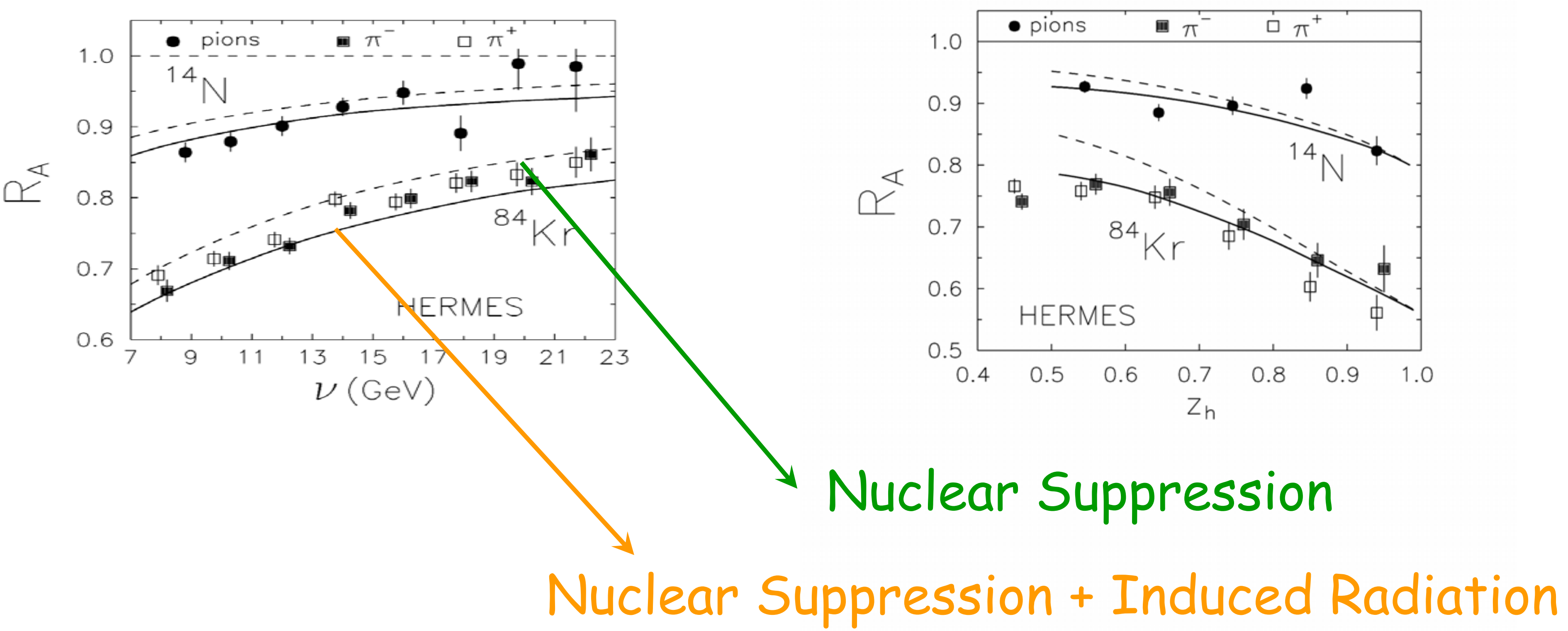
Gluon Bremsstrahlung

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

FF modification: Nuclear Suppression + Induced Radiation

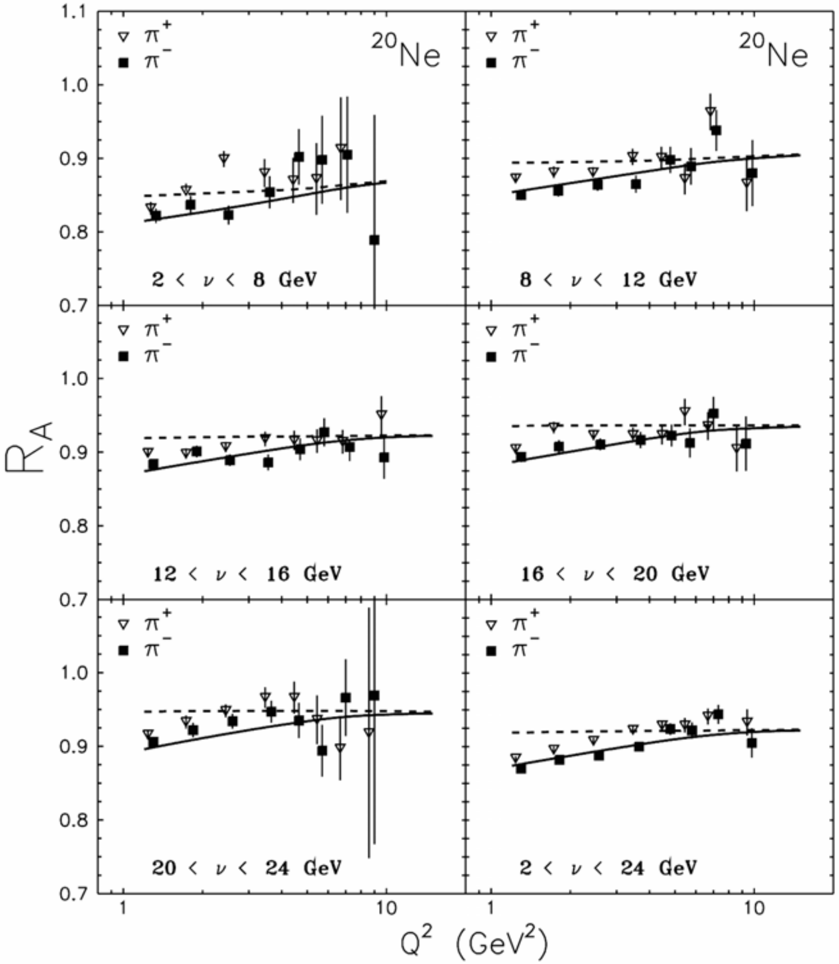
Nuclear suppression: interaction of the $q\bar{q}$ in the medium.

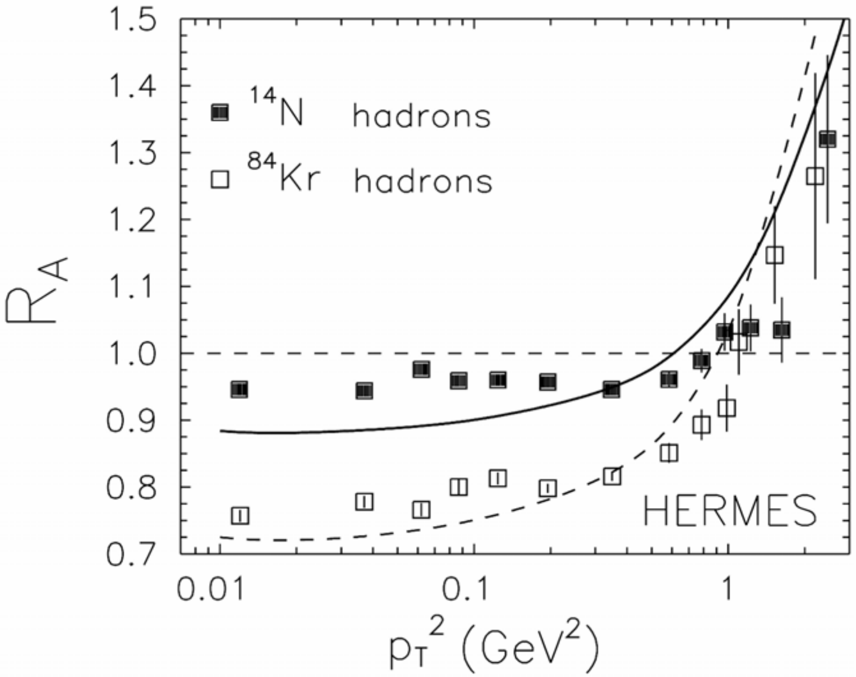
Energy loss: induced gluon radiation by multiple parton scattering in the medium



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

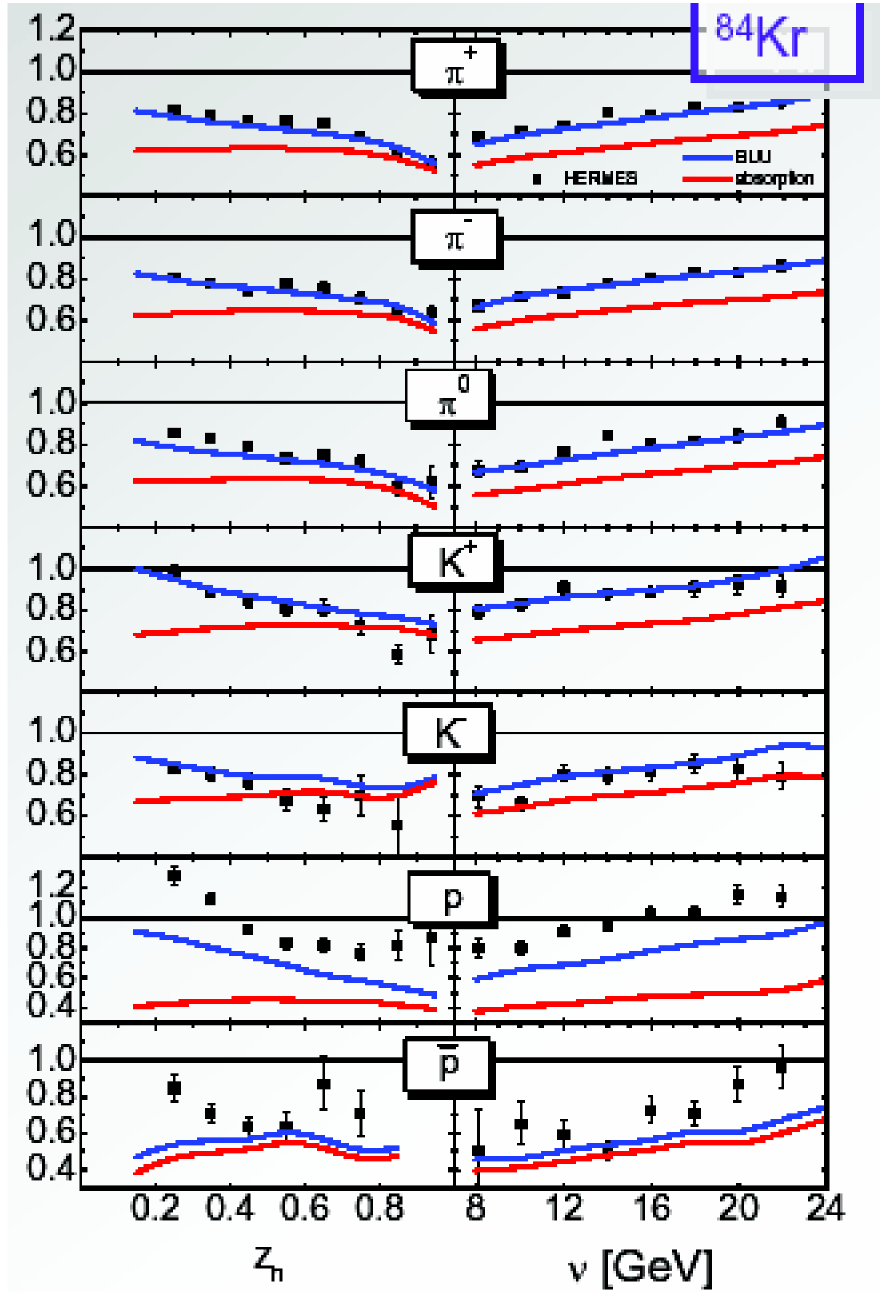
γ-A eA reaction splitted in 2 parts:

-$\gamma^*N \rightarrow X$ using PYTHIA & FRITIOF

-propagation of final state X within BUU transport model.

•____ pre-hadron τ_F=0.5 fm, σ^* by costituent quark model: $\sigma^*_{meson}=\#q_{orig}/2\ \sigma_{meson}$

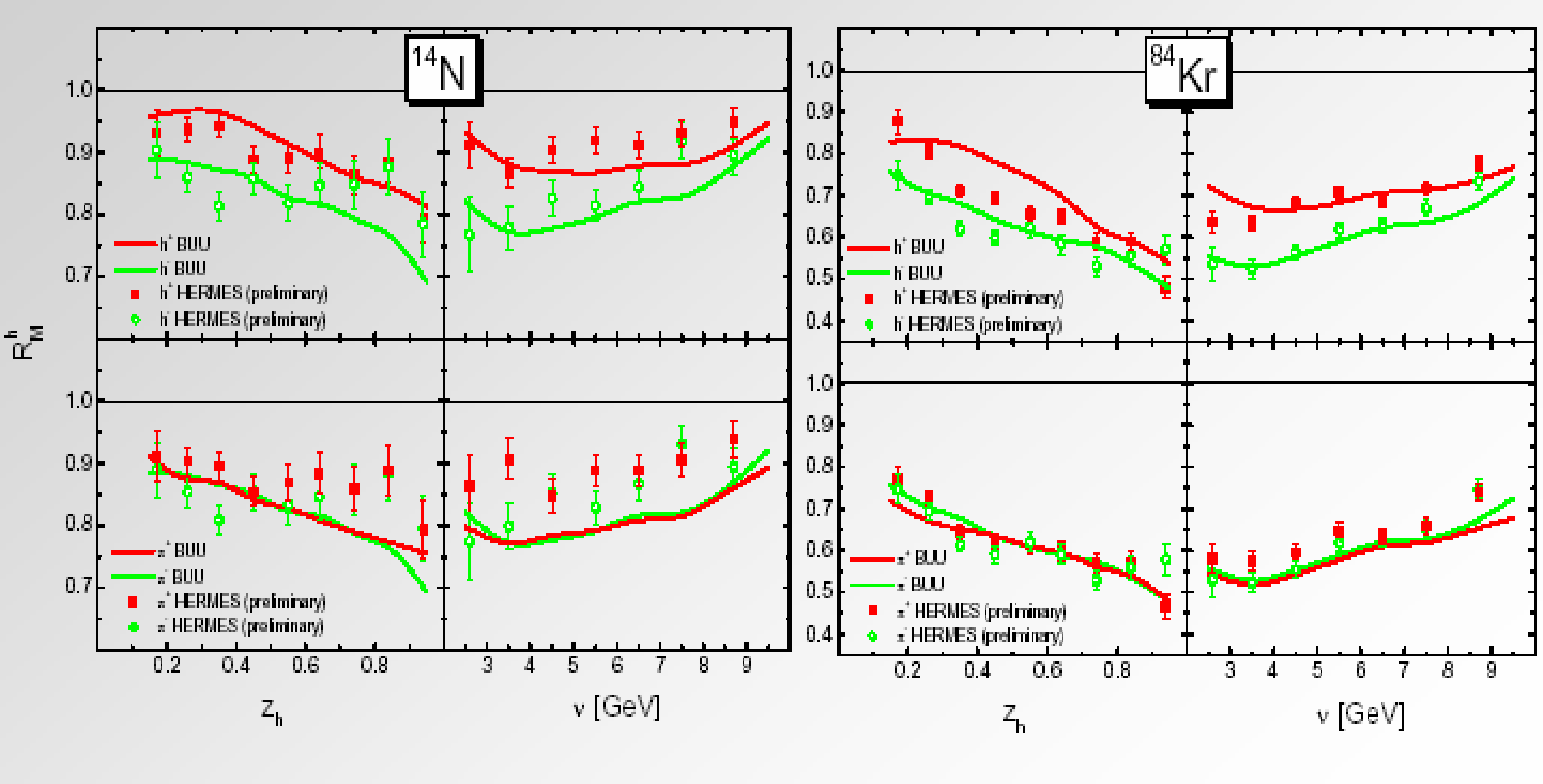
•____ purely absorbitive FSI



FSI in BUU Transport model

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

HERMES @ 12 GeV (τ_f=0.5 fm/c)

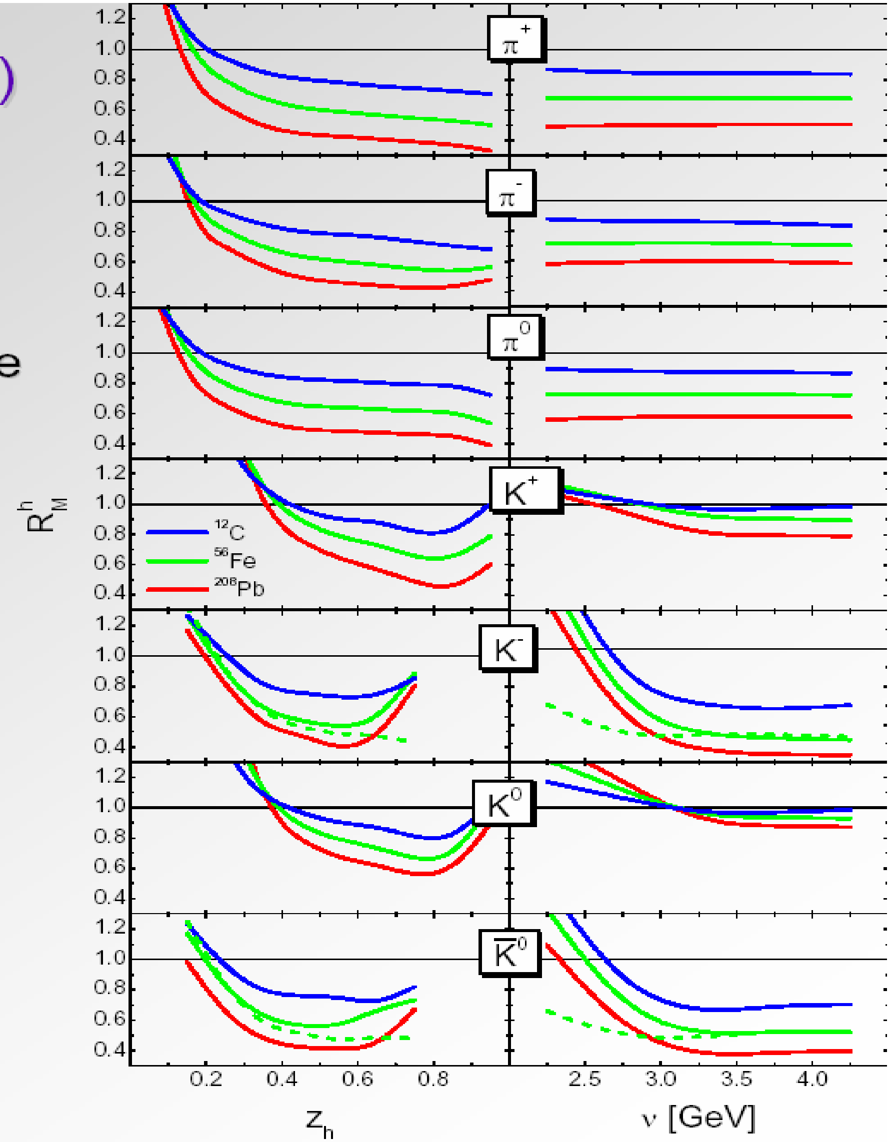


Model seems to work also at lower energy

FSI in BUU Transport model

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

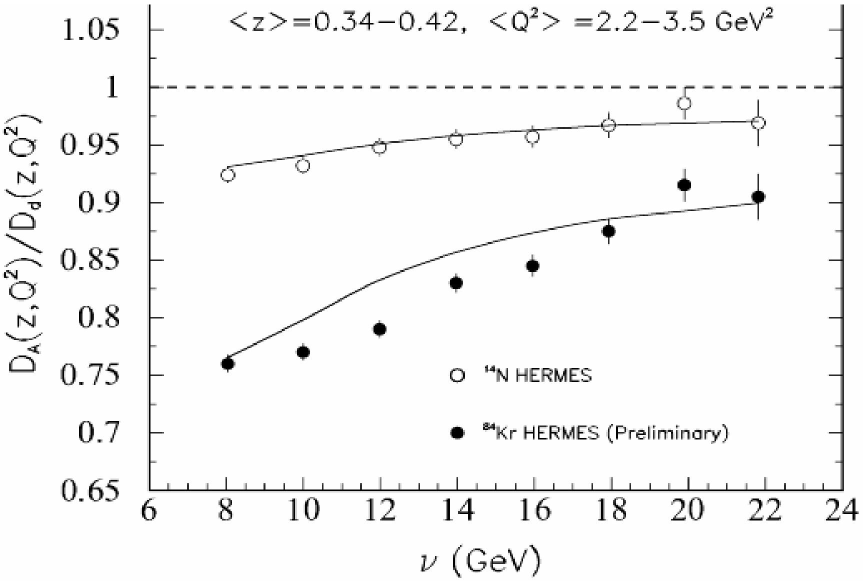
- Jefferson Lab (τ_f = 0.5 fm/c)
  - CLAS detector
    larger geometrical acceptance
    - detects more secondary particles from FSI
  - CEBAF
    lower energy
    - strong effect of Fermi-motion

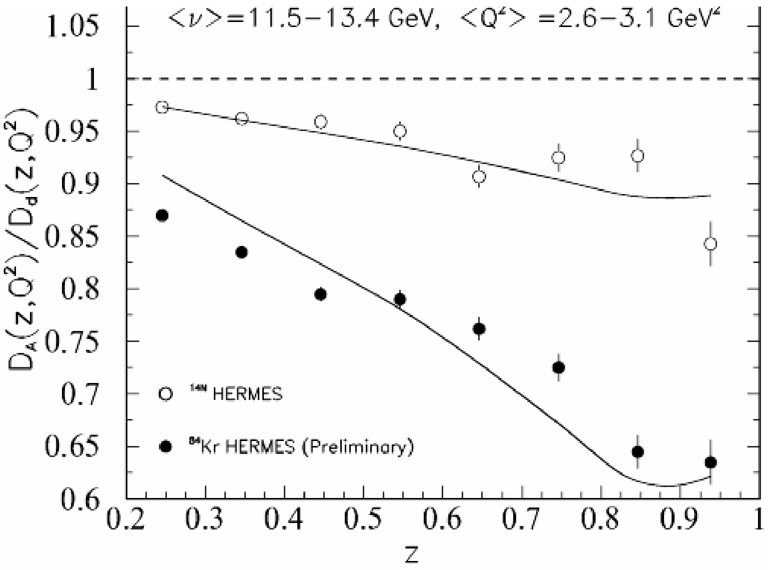


FF modification

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 →$A^{2/3}$ dependence





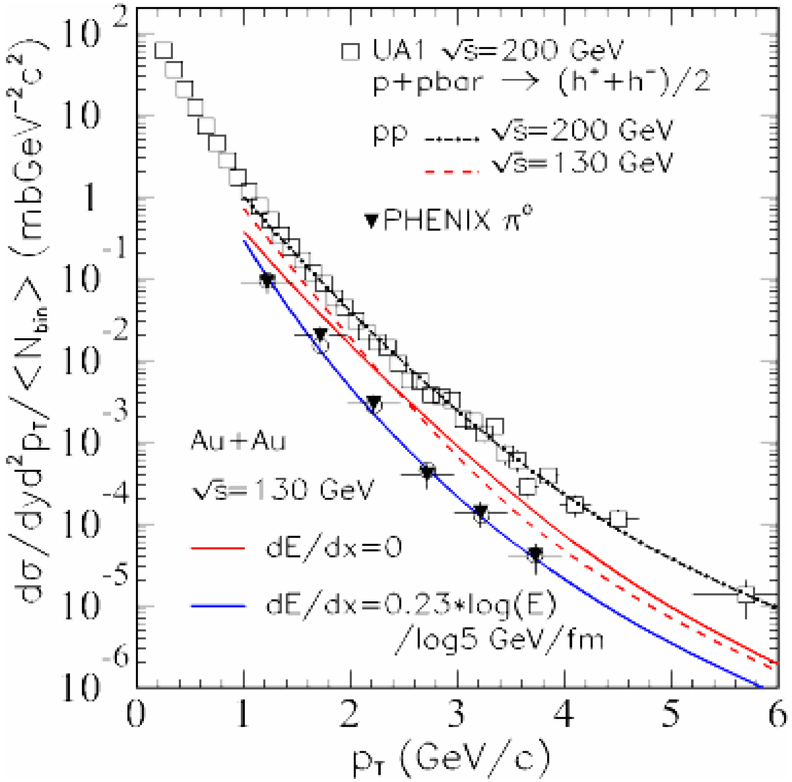
- 1 free parameter C≡quark-gluon correlation strength in nuclei.
- From ^{14}N data C=0.0060 GeV^2: $$\Delta E = n < \Delta z_g > \propto C \alpha_s^2 m_N R_A^2$$

<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.

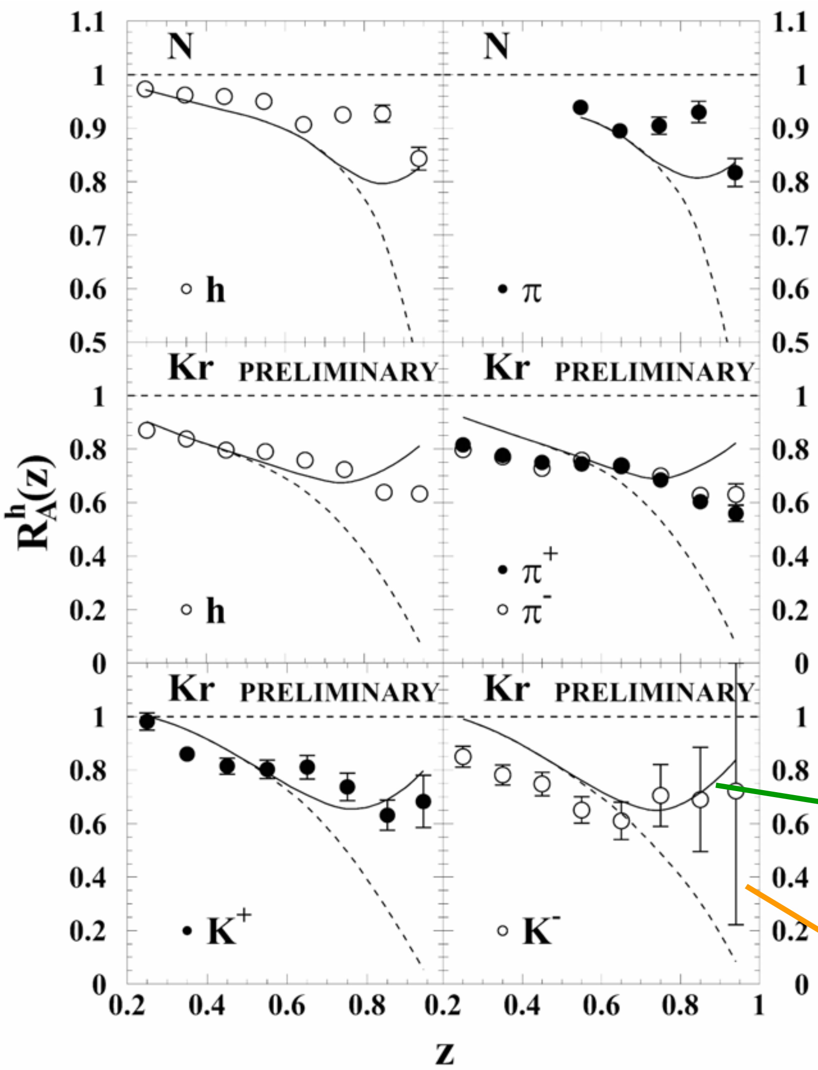
⇓

- $\Delta E_{sta} \alpha\ \rho_0 R_A^2$; 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

FF modification + formation time effect

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



- **Gluon transport coefficient fixed from Drell-Yan**

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

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

With formation time effect

Without formation time effect

Models summary.

Absorption Models:

Important role of the pre-hadron formation and interaction.
Hadron formation mainly outside the nucleus.
Induced radiation smaller contribution compared to absorption.
⇒ Strong dependence on the pre-hadron interaction cross section.

Energy loss models:

Energy loss mechanism mainly,
competing processes play a modest role.
⇒ Strong dependence on the gluon transport coefficient that reflects the medium gluon density

Observables sensitive to the model assumptions.

• Investigation of the Q^2-dependence of the nuclear effects.

• p_t-broadening and its z-dependence.
B.Z.Kopeliovich et al. NPA 740, 211 (2004).

• Investigation of the Q^2-dependence of "grey tracks" (GT) in SIDIS:
A(e,e'B)X where the recoil nucleus B does not survive, but breaks in fragments (predominantly protons) with few-hundred MeV/c momenta.
C. Ciofi degli Atti and B.Z. Kopeliovich hep-ph/0409077.

• Double/single hadron production
A.Majumder and X.N.Wang hep-ph/0410078.

Double hadron/single hadron production

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

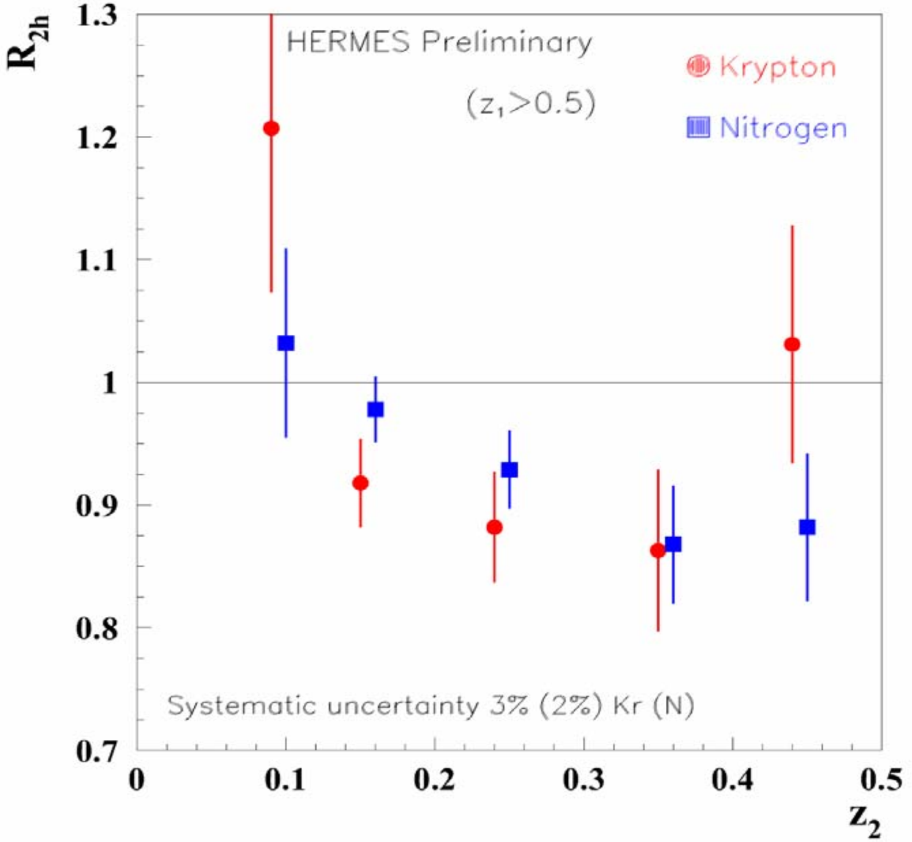
Numerator, $d^2N(z_1,z_2)$: Number of events with at least 2 hadrons ($z_{leading}=z_1>0.5$)

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

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

If Energy loss effect: double-hadron over single hadron ratio in nucleus and deuterium is expected close to unity.

Double/single hadron production



- Reduction of R_{2h} compared to 1
- Small variation with *A*.

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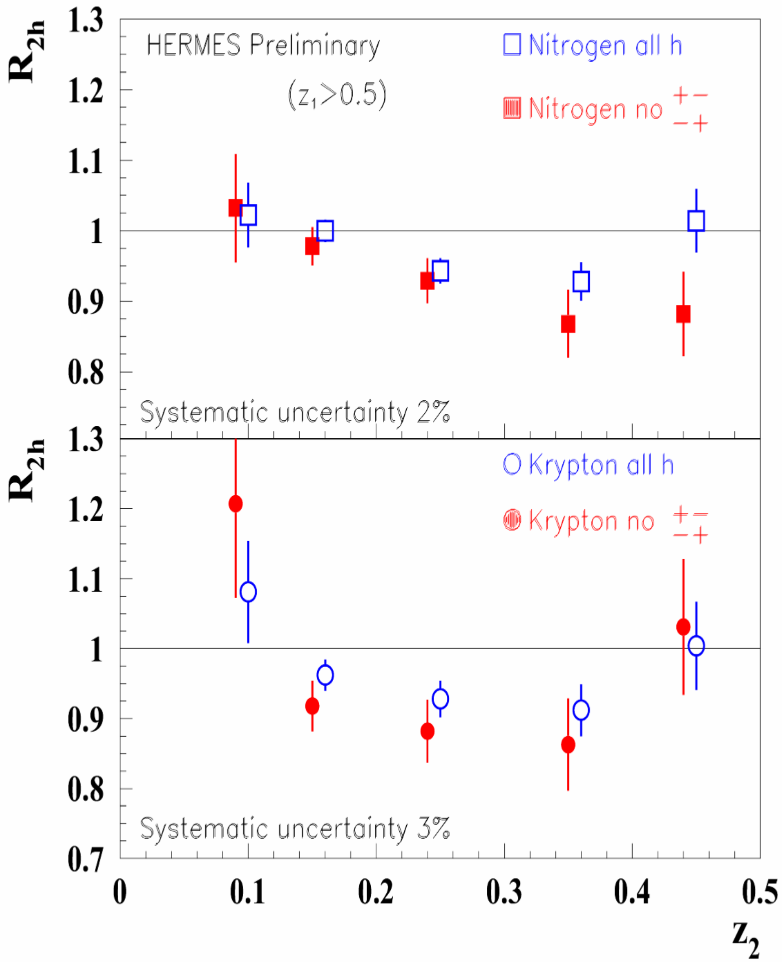
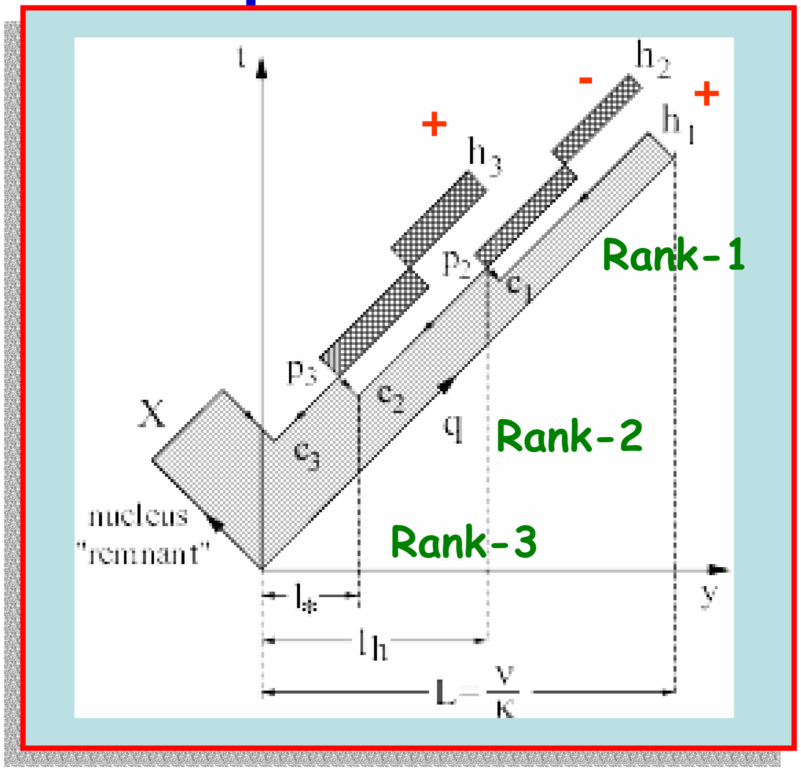
Double/single hadron production





All h→ rank 1,2,3

No +- and -+ → no rank 2, only 1,3

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

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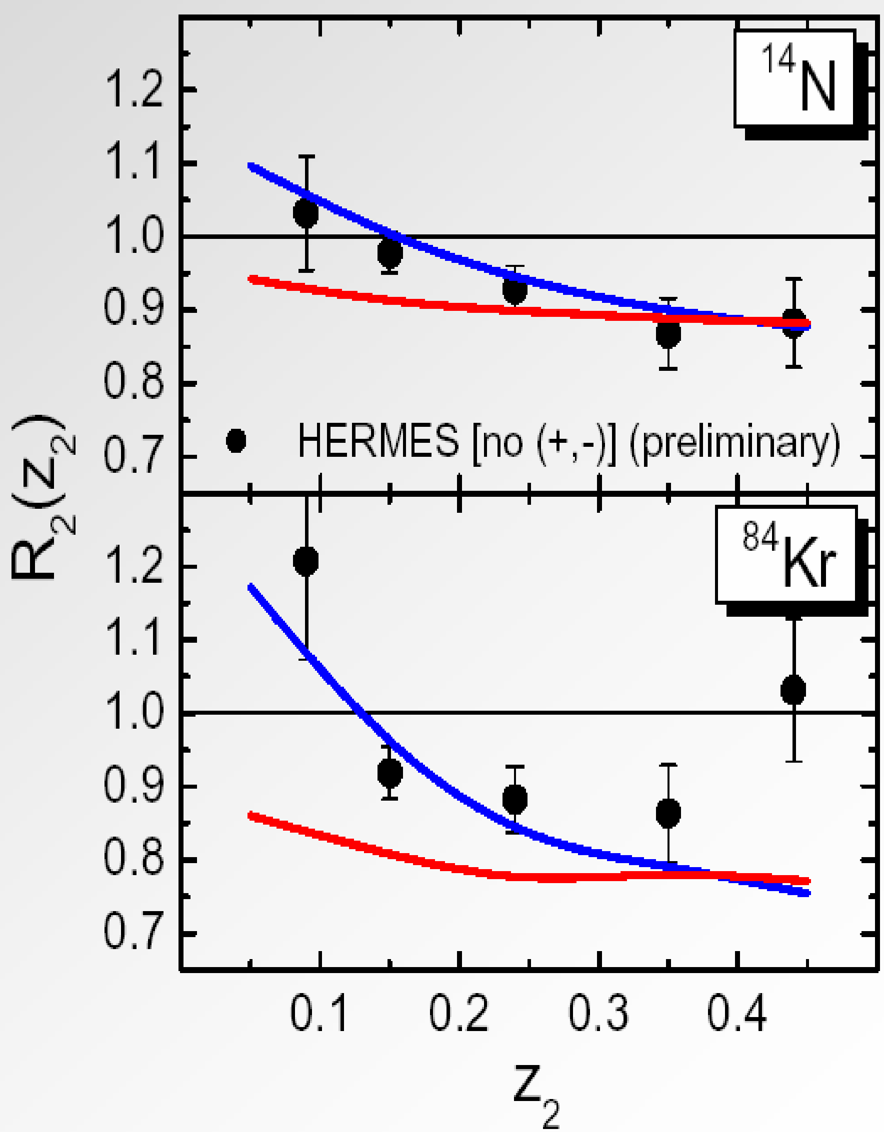
Double/single hadron production

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



FSI in BUU Transport model

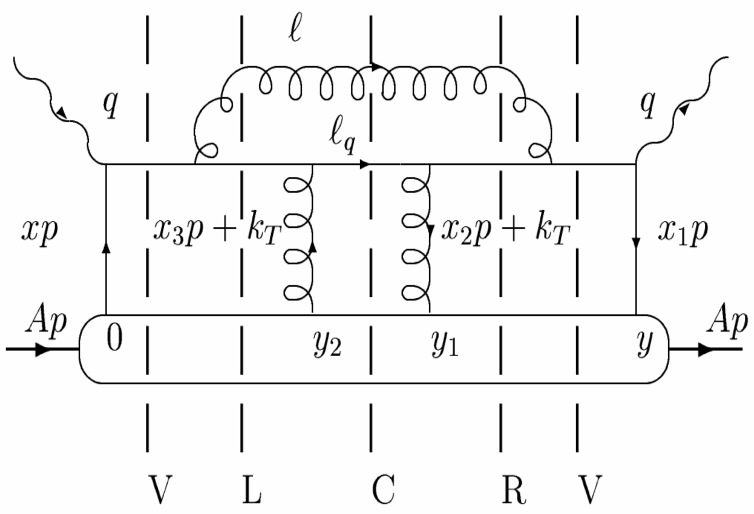
• ___ pre-hadron τ_F=0.5 fm, σ^* by costituent quark model: $\sigma^*_{meson}=\#q_{orig}/2\ \sigma_{meson}$

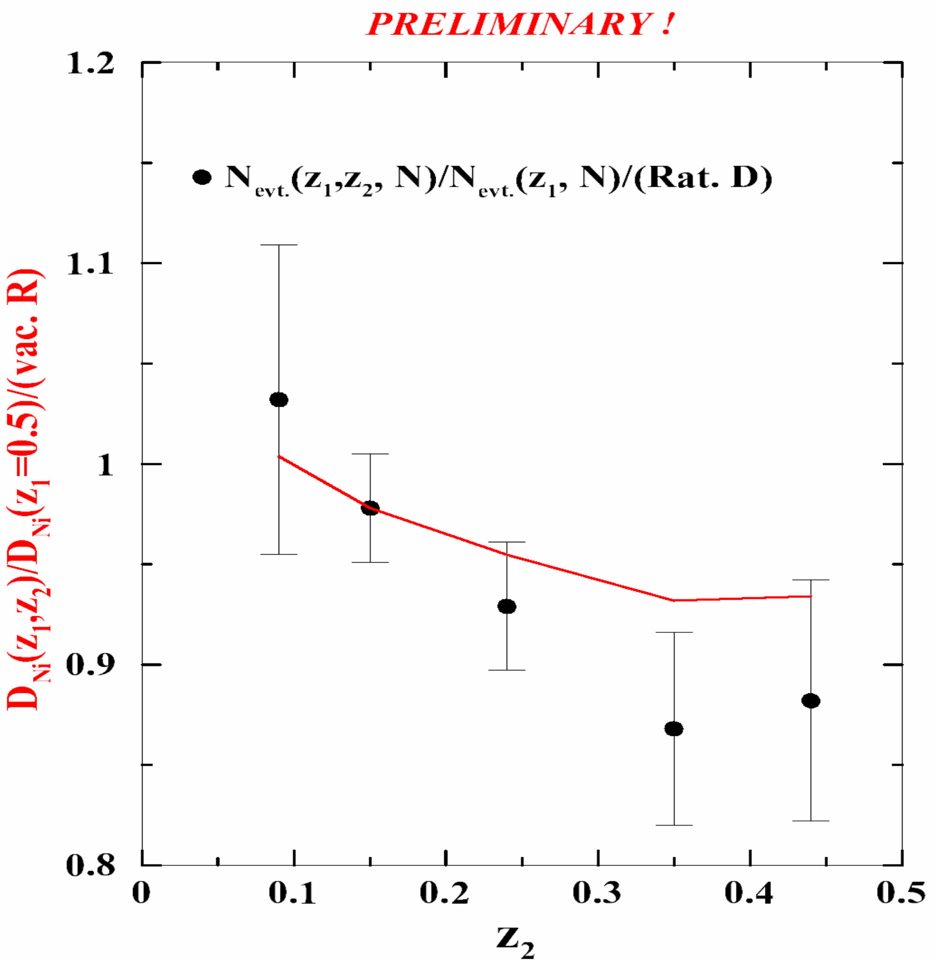
• ___ purely absorbitive FSI

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





Summary and outlook

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

- Nuclear attenuation in a new kinematical range, vs ν, z, Q^2, p_t^2, for ^4He, ^{14}N, ^{20}Ne, ^{84}Kr.
- First measurements for identified hadrons : π^+, π^-, π^0, K^+, K^-, p, $\bar{p}$.
- First observation of hadron-type dependence of the attenuation and of the Cronin effect.
- Ratio of double/single hadron production in A and D.

Measurements are in progress: D, Kr, Xe

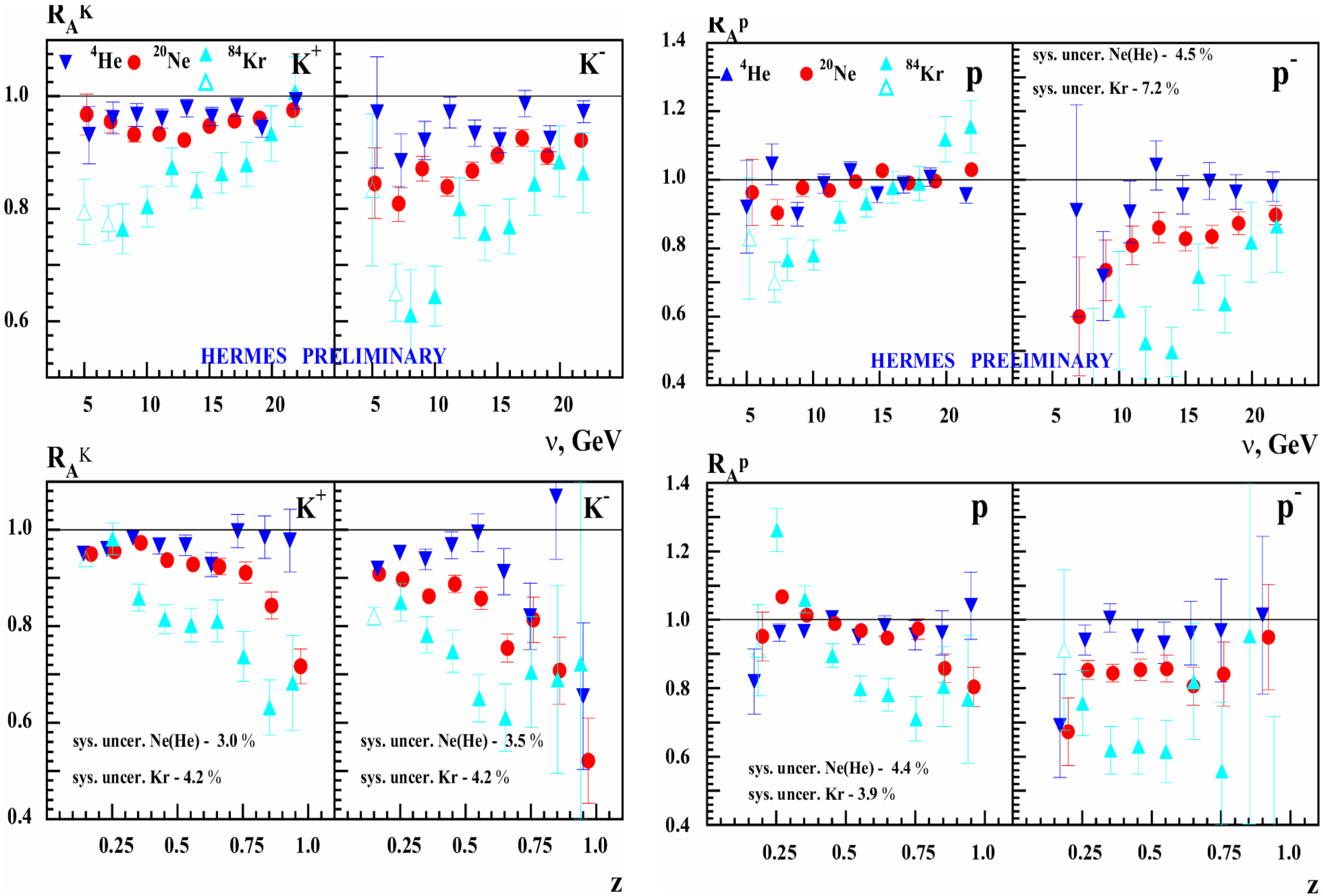
The combination of HERMES and the upcoming Jlab data will provide new insight into:

- Space-time properties of hadron formation
- Fundamental process of gluon emission.

V. Muccifora

Back slides

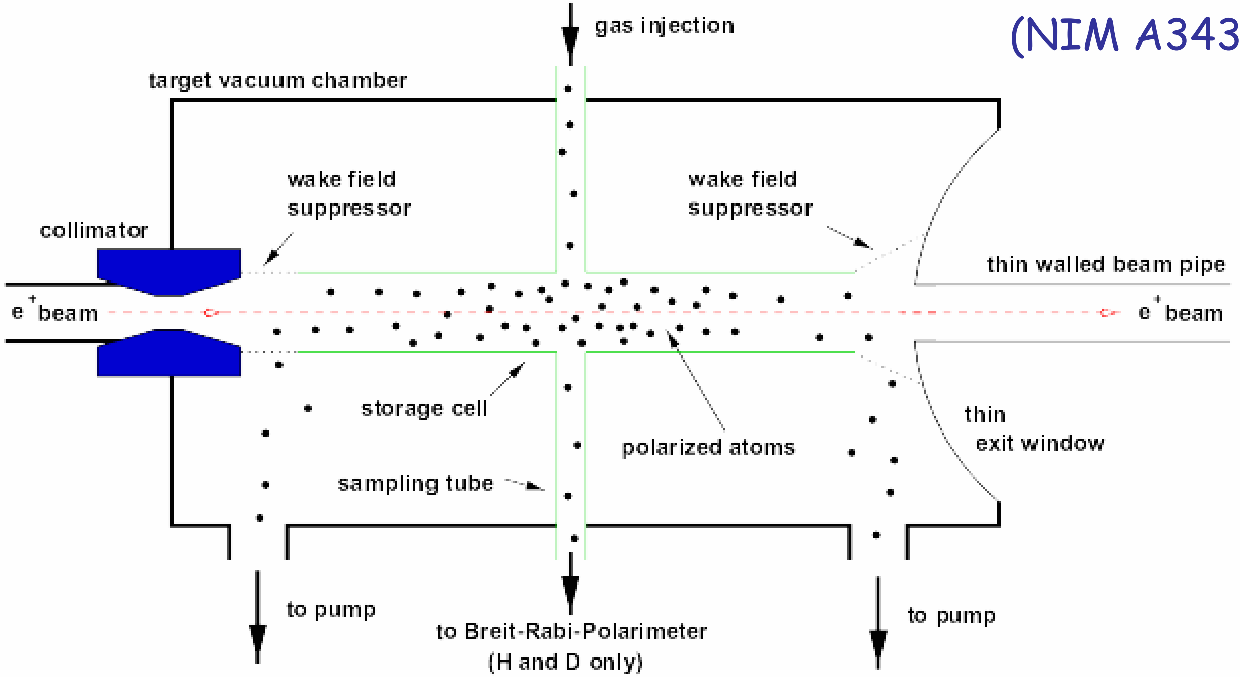
Multiplicity ratio on He, Ne, Kr



V. Muccifora

The Internal Target

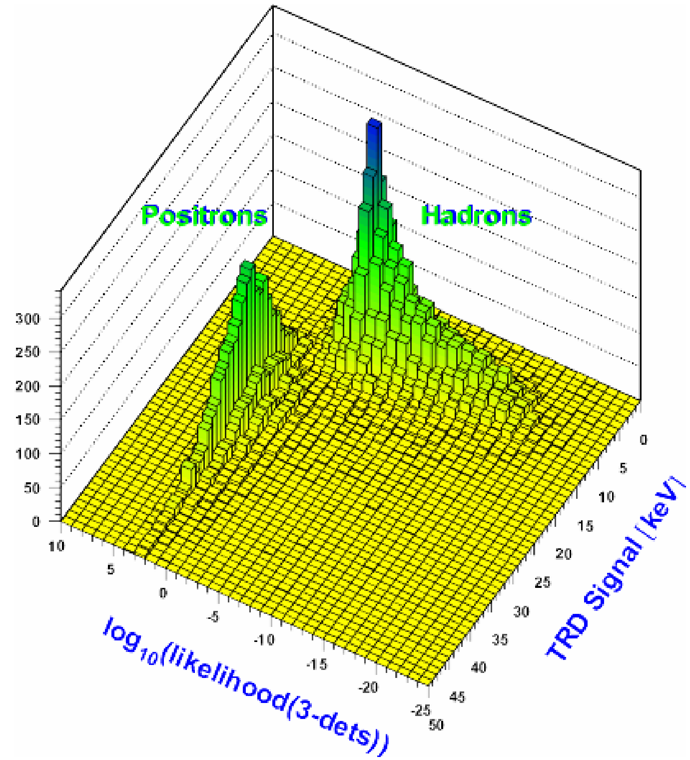
(NIM A343 (1994) 334)

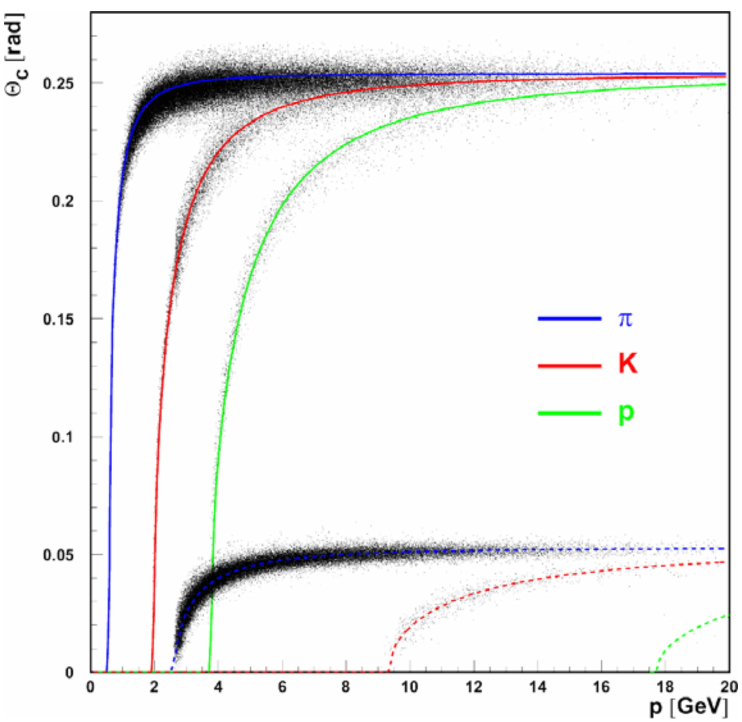


- Internal storage cell
- Pure gas target, no dilution factor
- Nuclear targets: (H, D), ^{3}He, ^{4}He, ^{14}N, ^{20}Ne, ^{40}Ar, ^{84}Kr, ^{131}Xe
- Densities: $\sim 10^{15}$ – 10^{17} nucl*cm^{-2}

Particle Identification

Positron – hadrons separation:



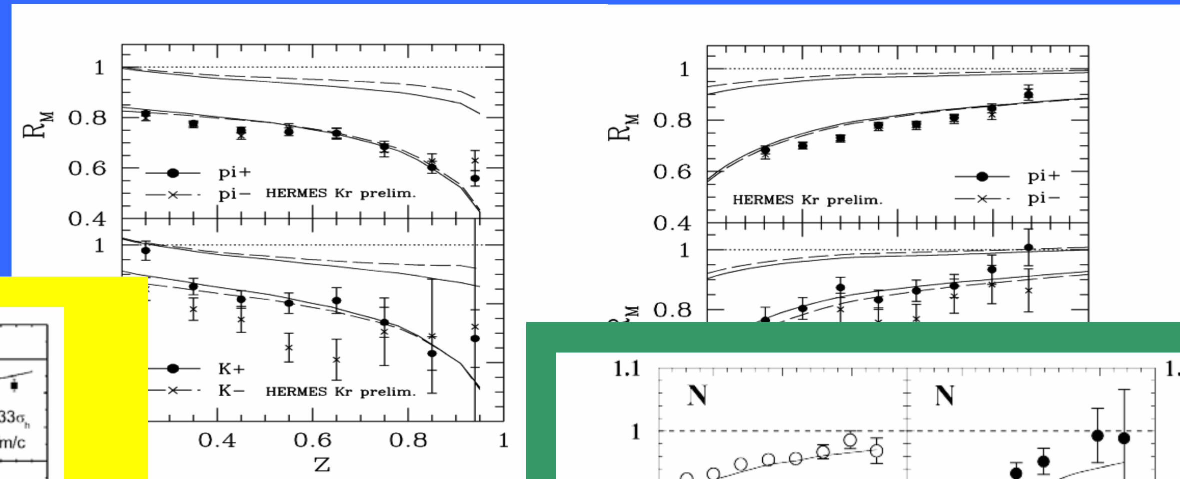


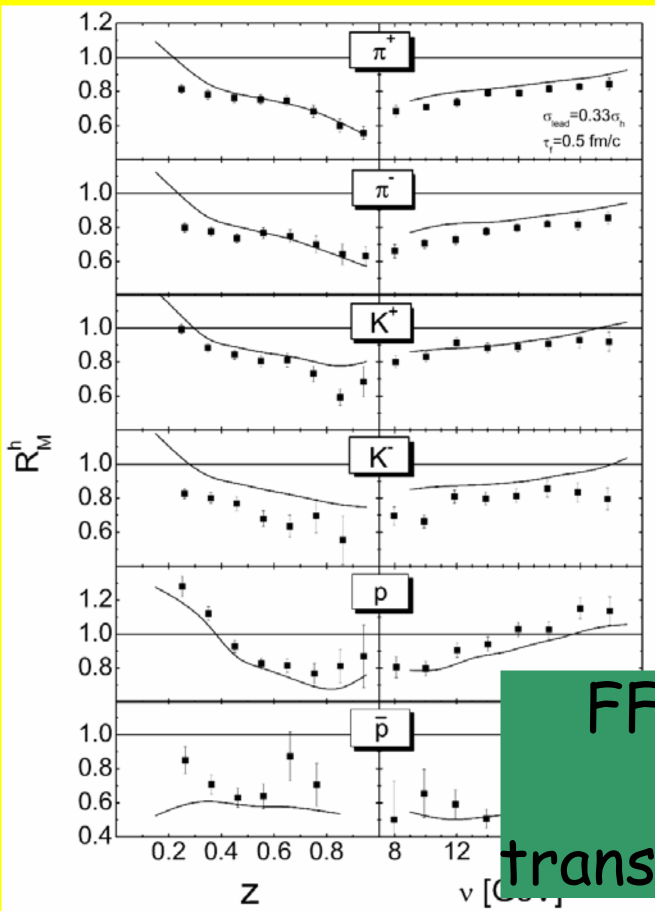
<u>Double radiator RICH</u>: Aerogel + C_4F_{10}. Cerenkov photons detected by ~4000 PMTs.

<u>Detection efficiency</u>: 99% (π), 90% (K), 85-95% (p)

Model interpretations

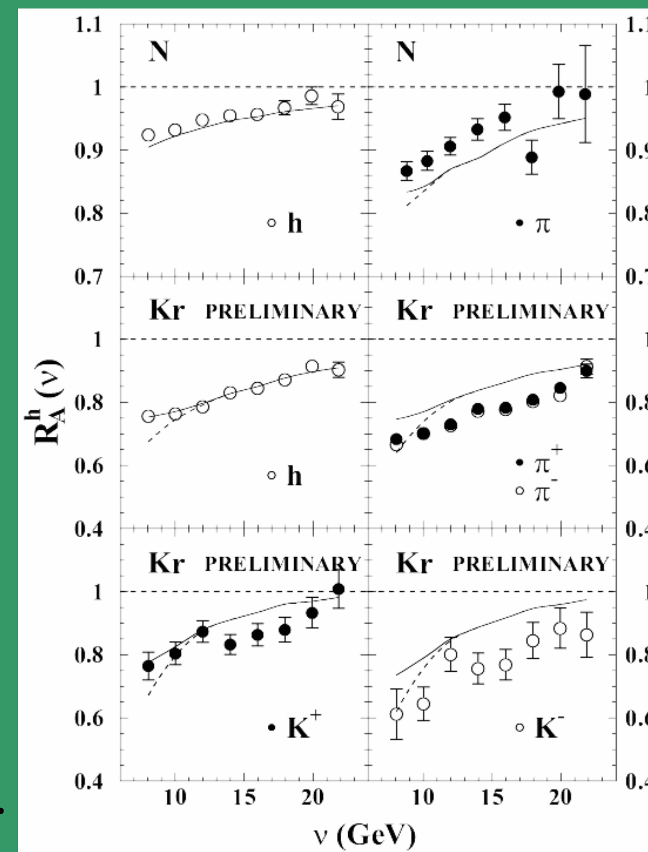
Deconfinement
and absorption



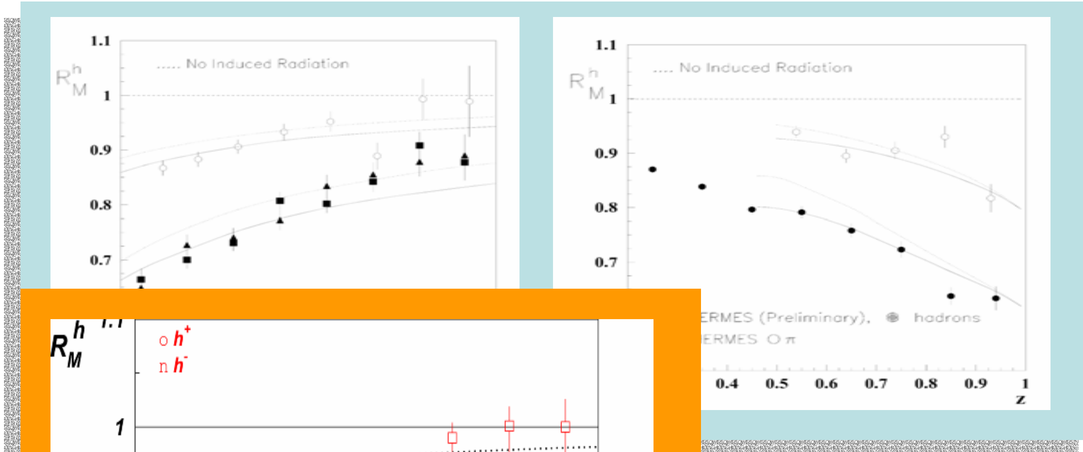


(Pre-)hadron Fi
State Interact

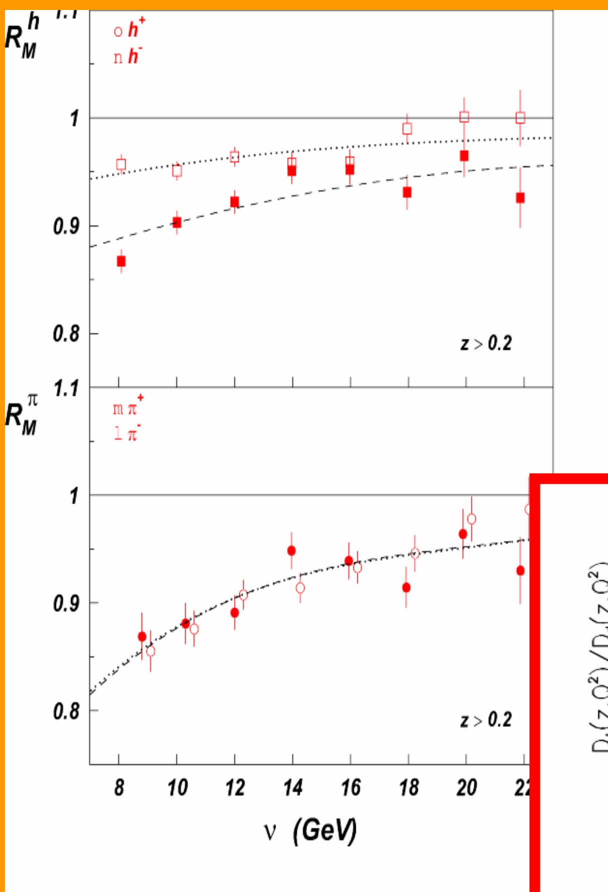
FF modification
and
transport coefficient



Model interpretations

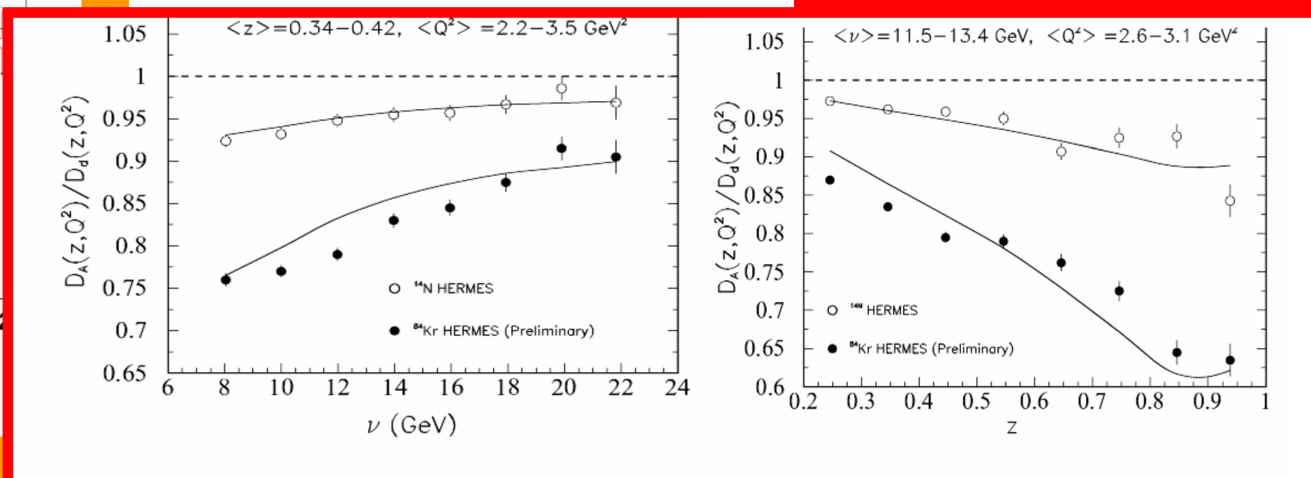


Gluon Bremsstrahlung model (energy loss, (pre-) hadron int.)



String Model (full absorption)

FF modification by pure induced energy loss



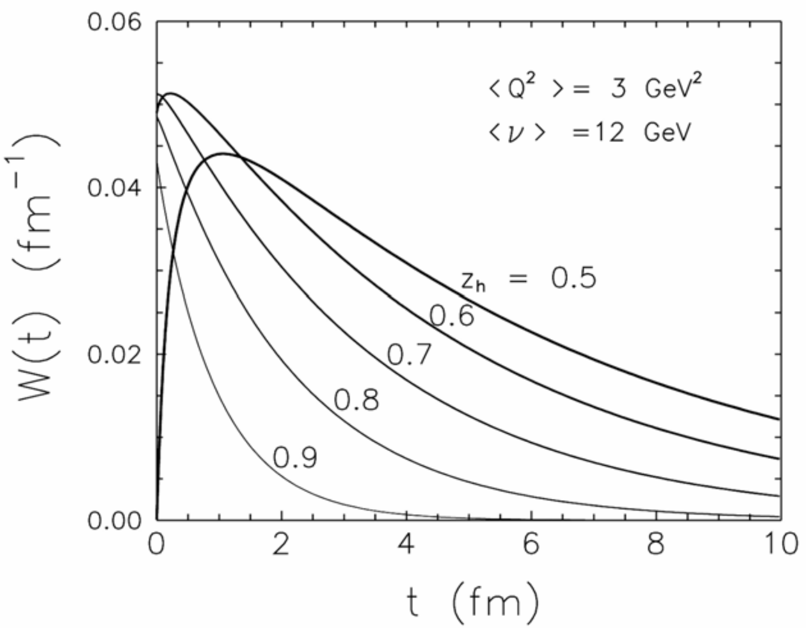
Gluon Bremsstrahlung

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

FF modification: Nuclear Suppression + Induced Radiation

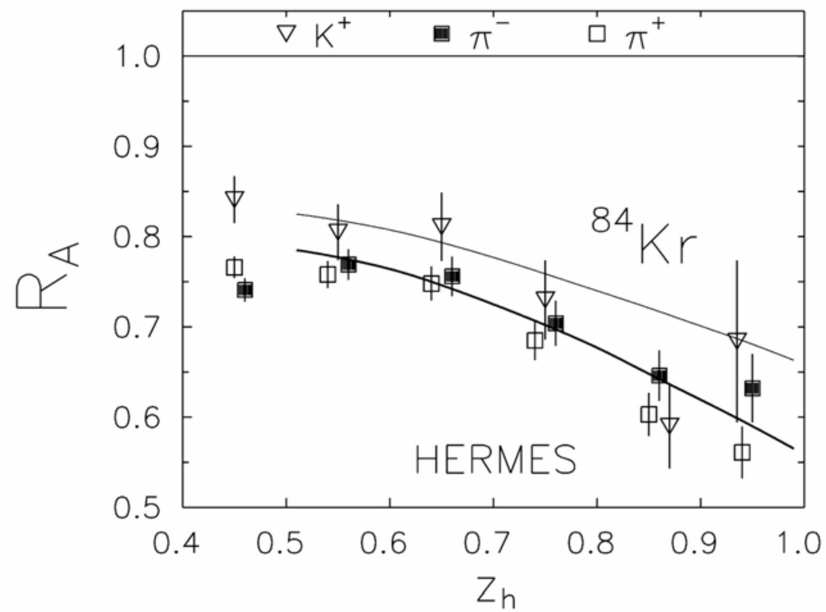
- Vacuum energy loss: $q \to gq'$.
  (dE/dz ~2.5 GeV/fm by E772/E866 for DY on nuclei)
- Energy loss induced by multiple interactions in the medium
  (rising in p_t)
- Color Transparency of the qq (~1/Q^2)

$$\tilde{D}_{h/q}(z_h, Q^2) = \int_0^\infty dt W(t, z_h, Q^2)$$



Gluon Bremsstrahlung

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



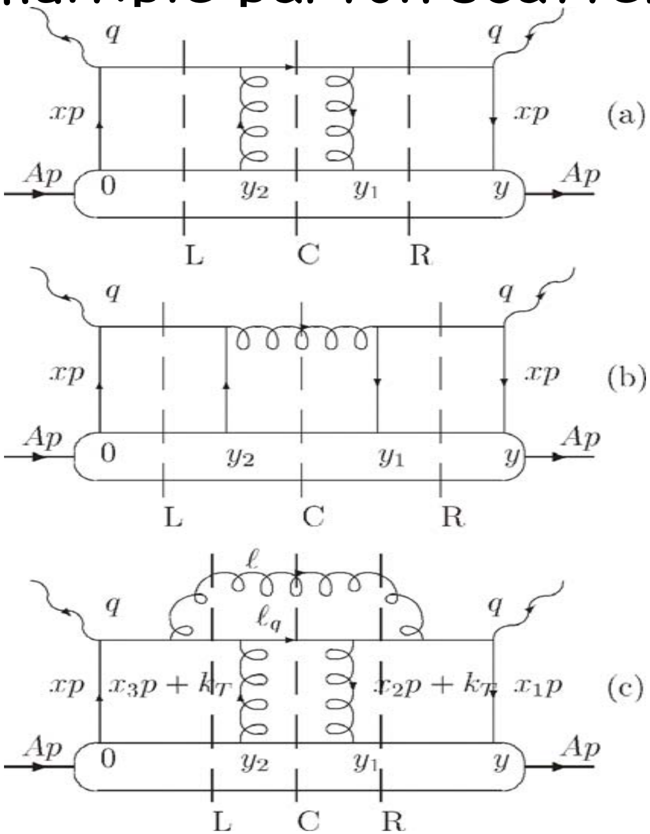
Only prediction for h containing target valence quark.

Good agreement also for K^+

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 (DGLAP).



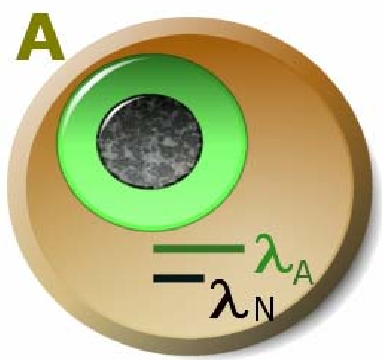
Rescattering without gluon radiation: p_t-broadening.

Rescattering with another *q*: mix of *q* and *g* FF.

g-rescattering including *g*-radiation: dominant contribution in QCD evolution of FF.

- The emitted *g* and the leading *q* propagate coherently → Landau-Pomeranchuk-Midgal interference effects.
- Different modification of quark and antiquark FF.

Rescaling + Absorption Model

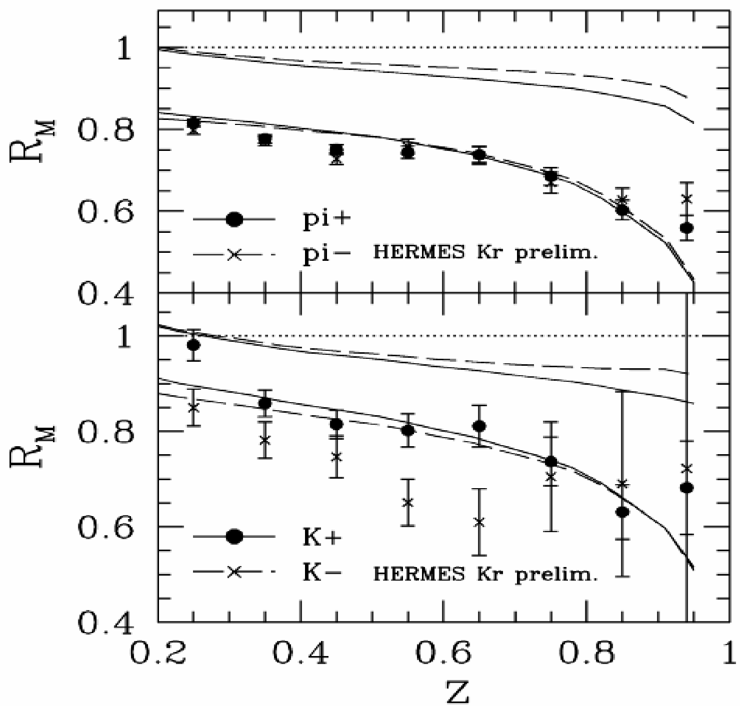


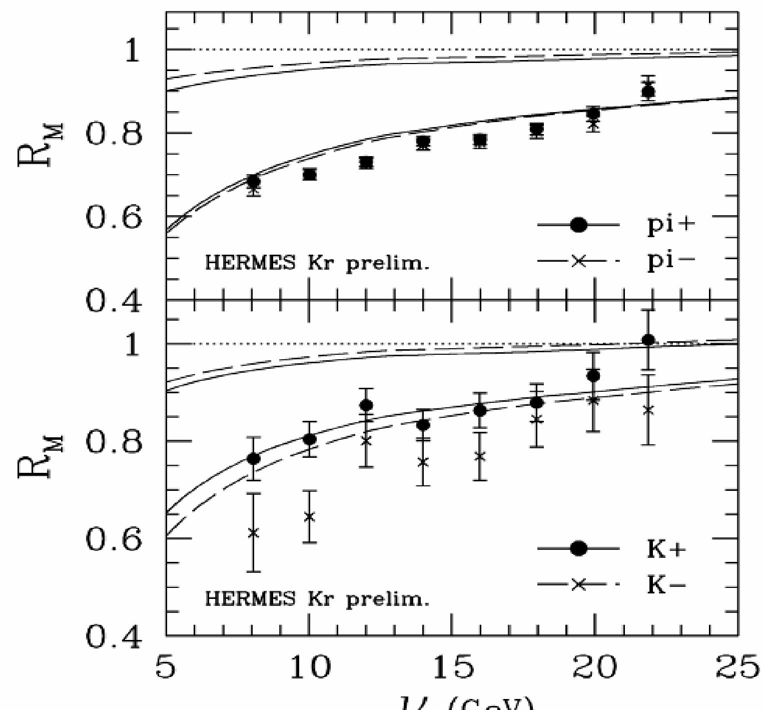
A.Accardi et al., NPA720(2003)131

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

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

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

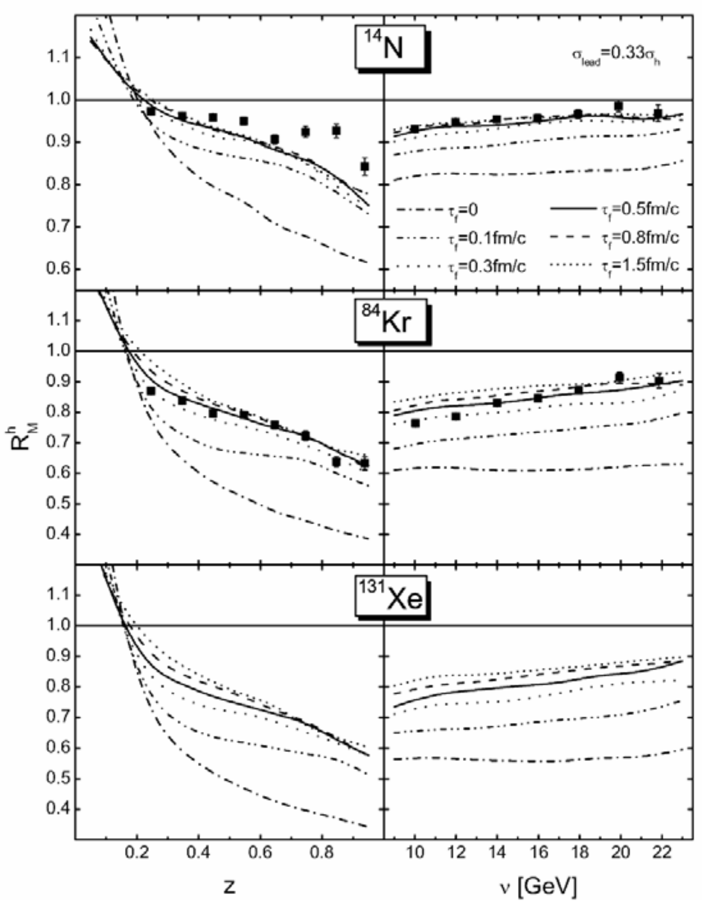


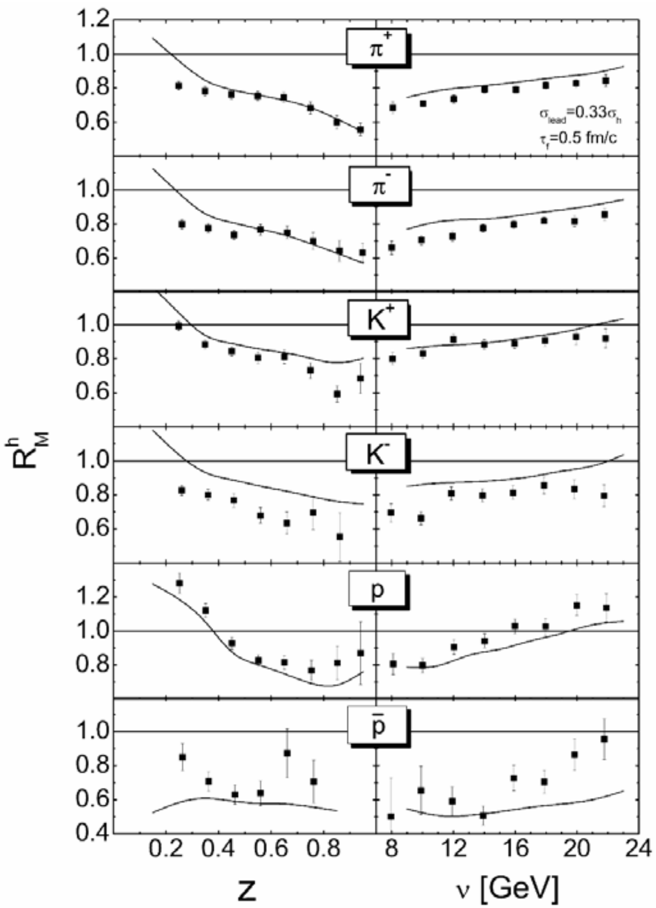


Nice agreement for p+, p-, K+ with Q^2-rescaling + nuclear absorption (lower curves).

(Pre-)Hadron FSI and formation times

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

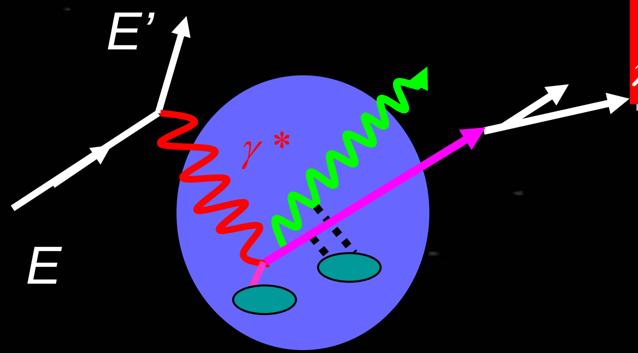




R_M is very sensitive to the $\sigma_{pre\text{-}h}$; ($\sigma_{pre\text{-}h}$=0.33 σ_h)

τ_f>0.5 fm/c compatible with data

DIS Tomography



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

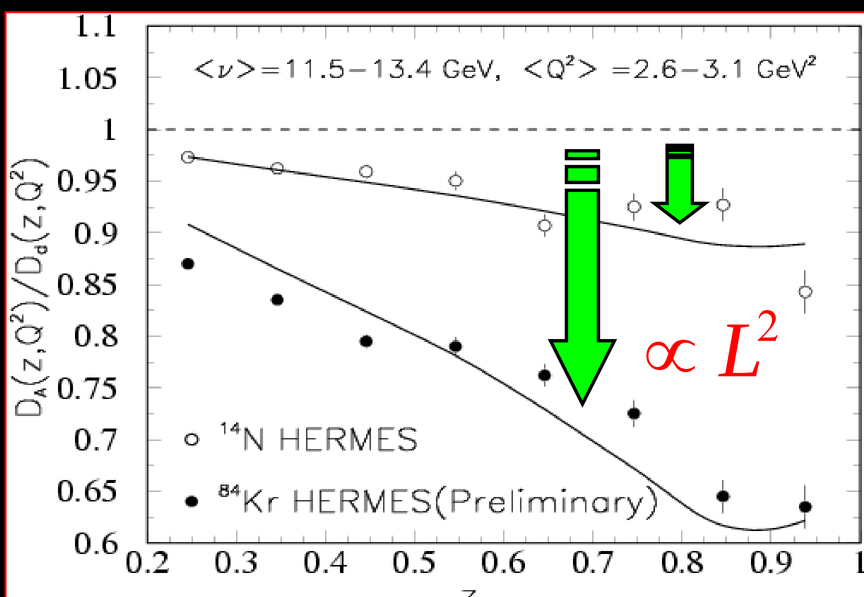
$\langle \Delta z \rangle$ - radiative energy loss fraction

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

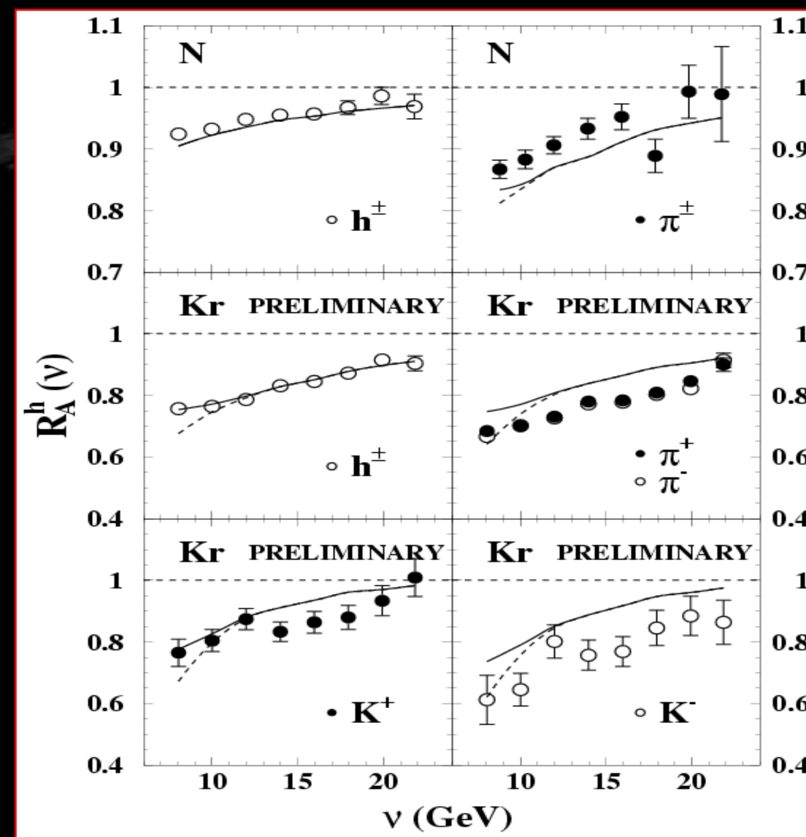
$$\langle \Delta z \rangle = \tilde{C}(Q^2)\frac{C_A \alpha_s^2(Q^2)}{N_c}\frac{x_B}{Q^2 x_A^2} 6\ln\frac{1}{2x_B}$$

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

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



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



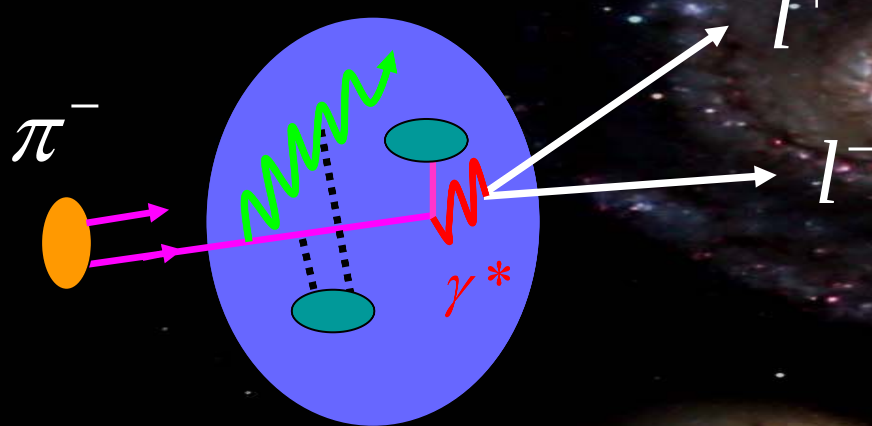
F.Arleo, Eur.Phys.J. C30 (2003)

Ivan Vitev, ISU

From Drell-Yan to DIS

- **Gluon transport coefficient fixed from Drell-Yan**

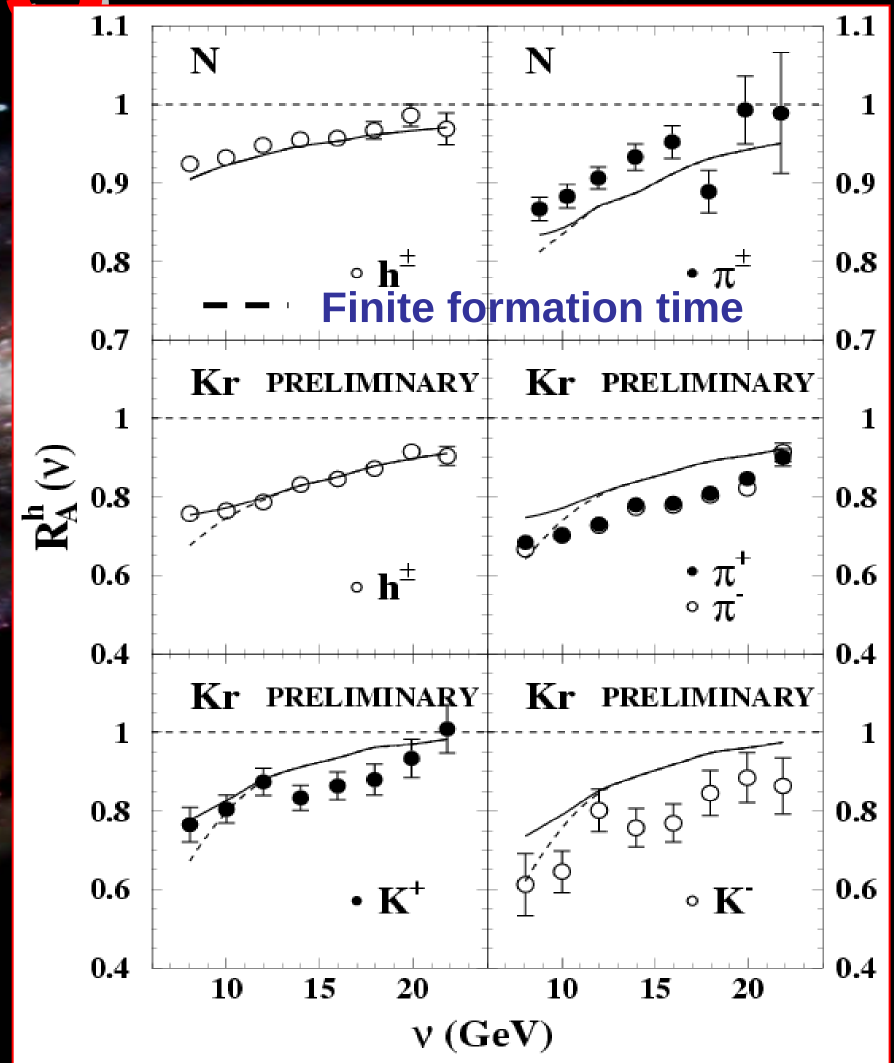
$$\hat{q} = 0.14 \ GeV^2 / fm$$



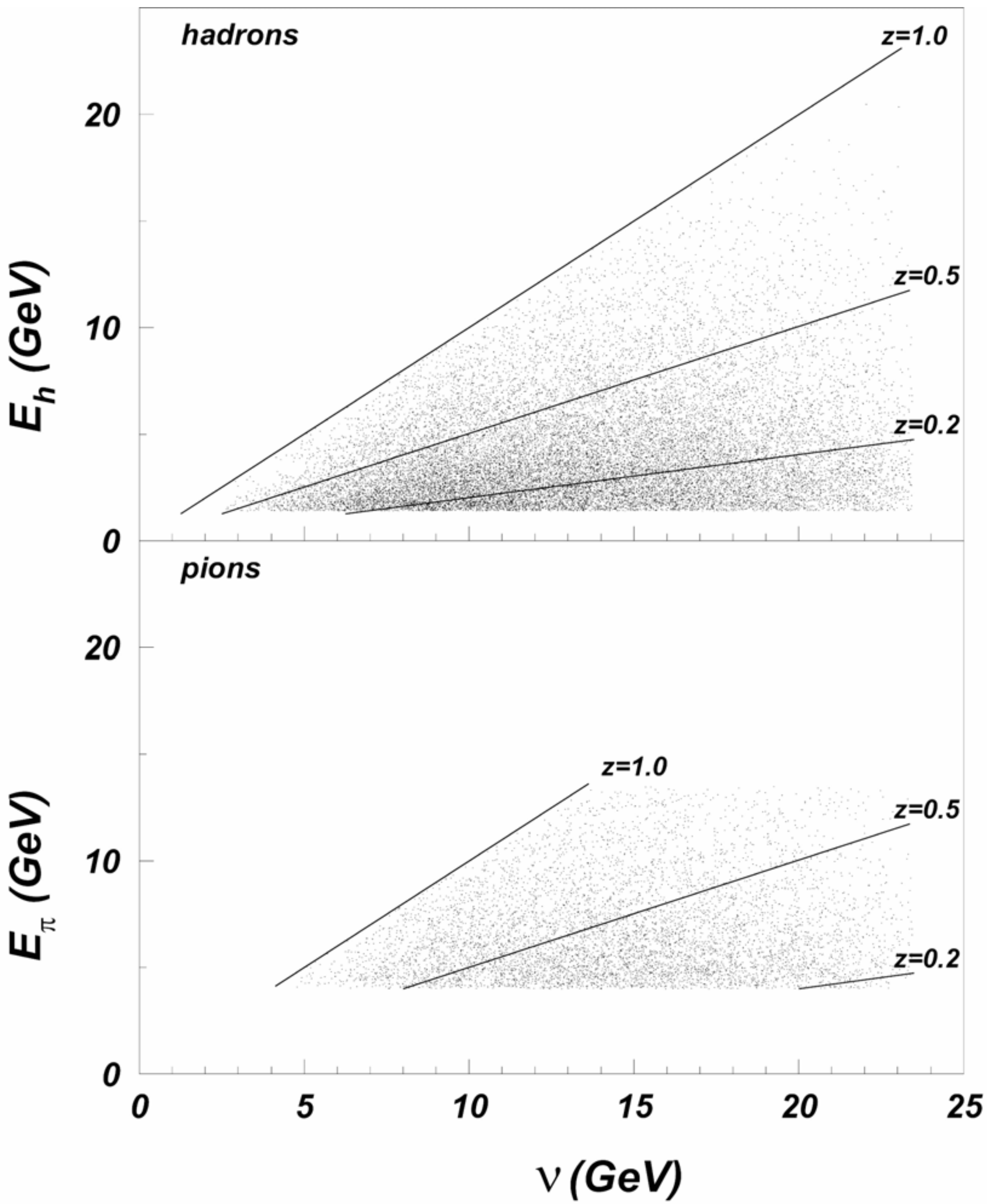
Large number of scatterings approximation

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

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



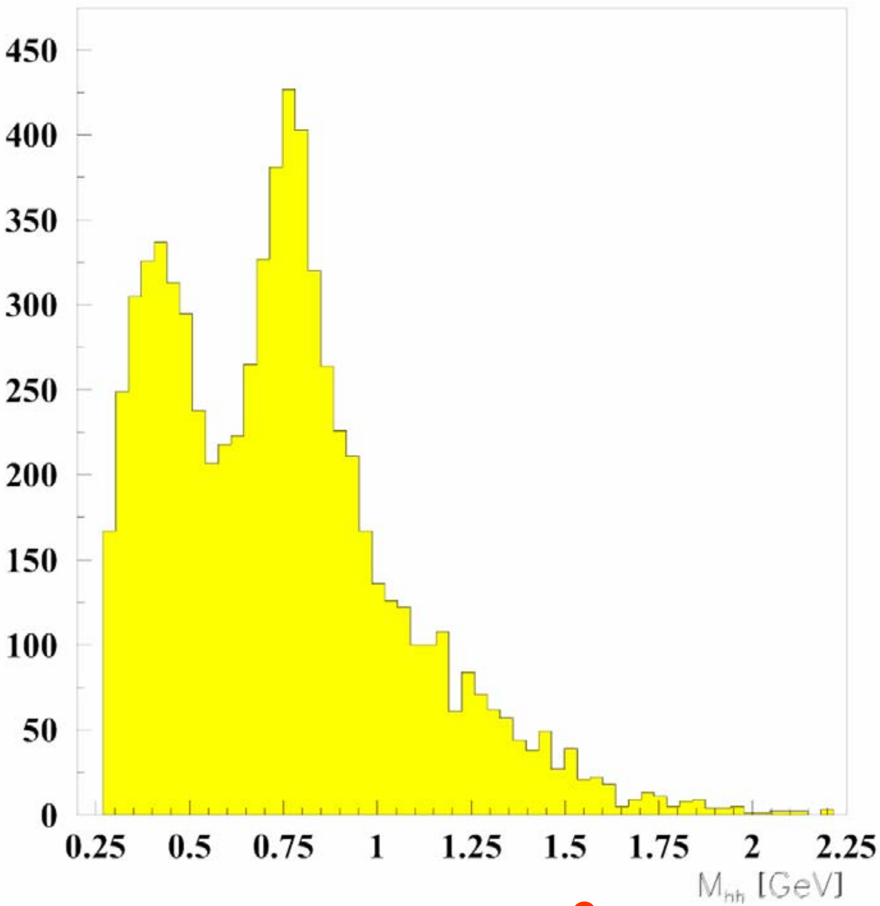
F.Arleo, Eur.Phys.J. C30 (2003)



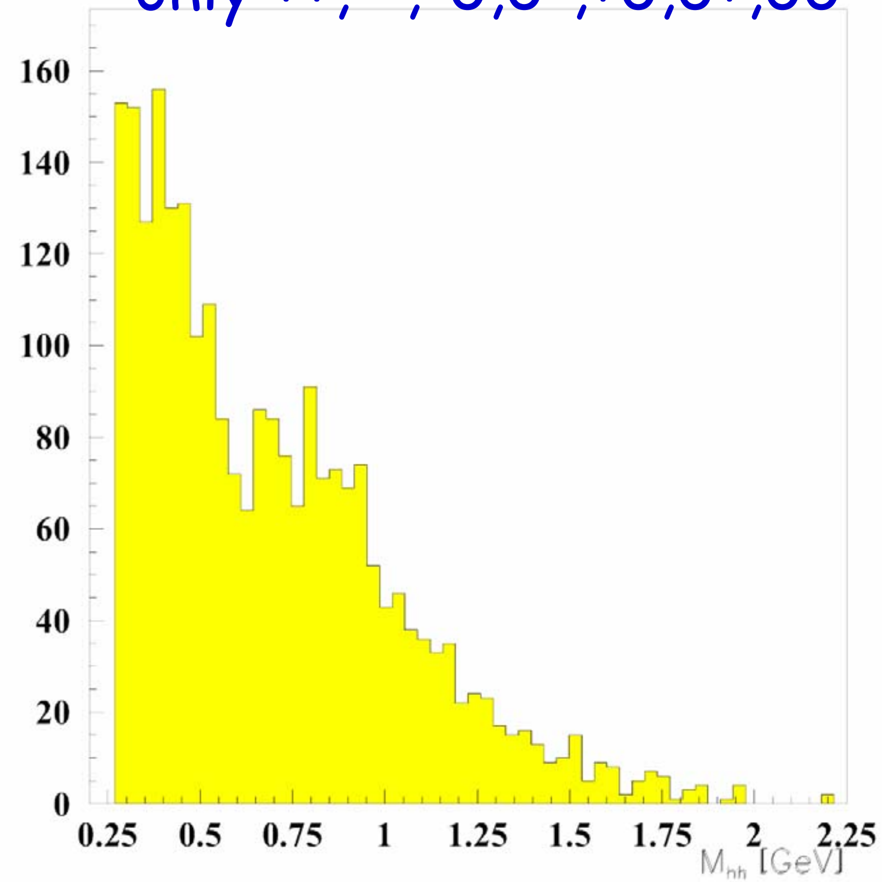
hadrons
z=1.0
z=0.5
z=0.2
E_h (GeV)
pions
z=1.0
z=0.5
z=0.2
E_π (GeV)
0
10
20
0
5
10
15
20
25
ν (GeV)

ρ^0 and particle rank

z_1>0.5, all h



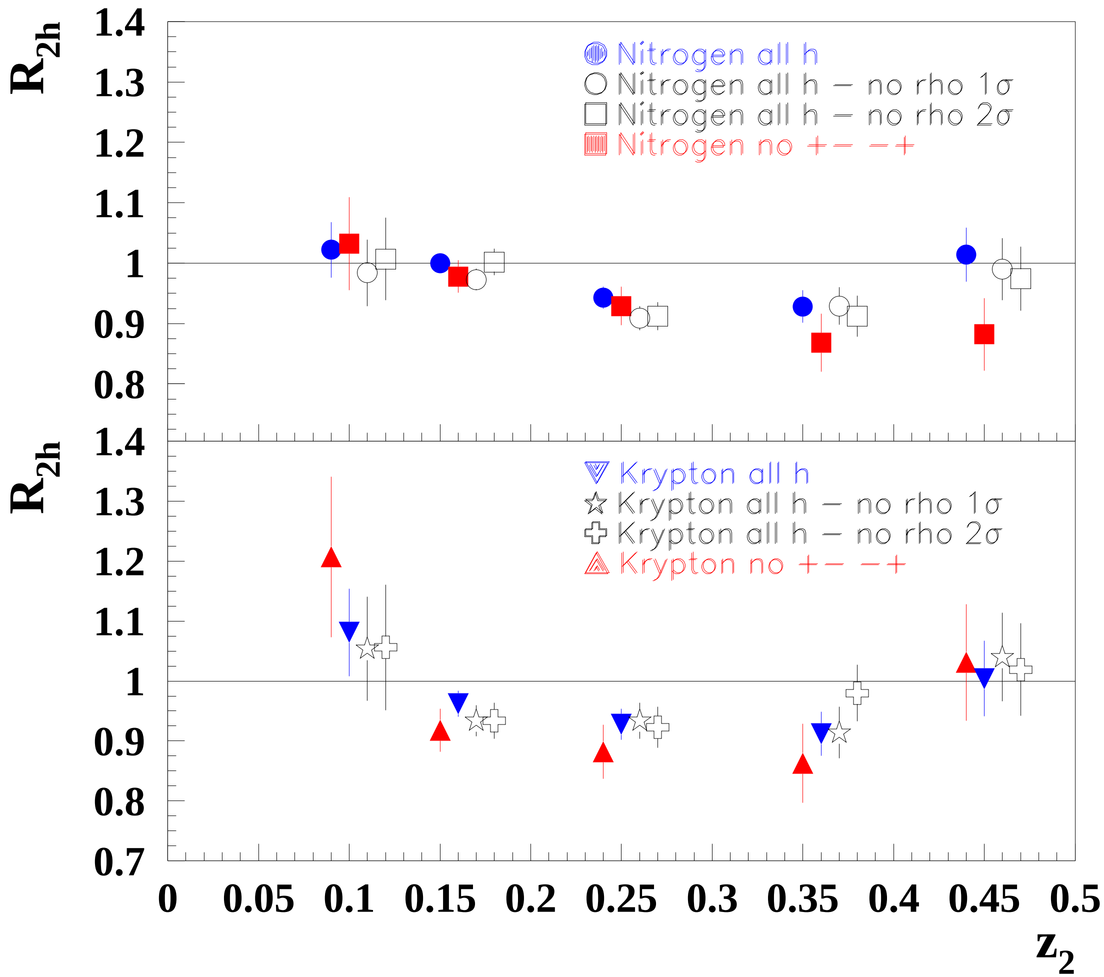
z_1>0.5,
only ++,--,-0,0-,+0,0+,00



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.