Studies of hadronization in nuclei at HERMES

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(on behalf of the HERMES collaboration)

- Why?
- How?
- What?
- Next?

Hadronization workshop Trento, Oct. 2005

Motivation

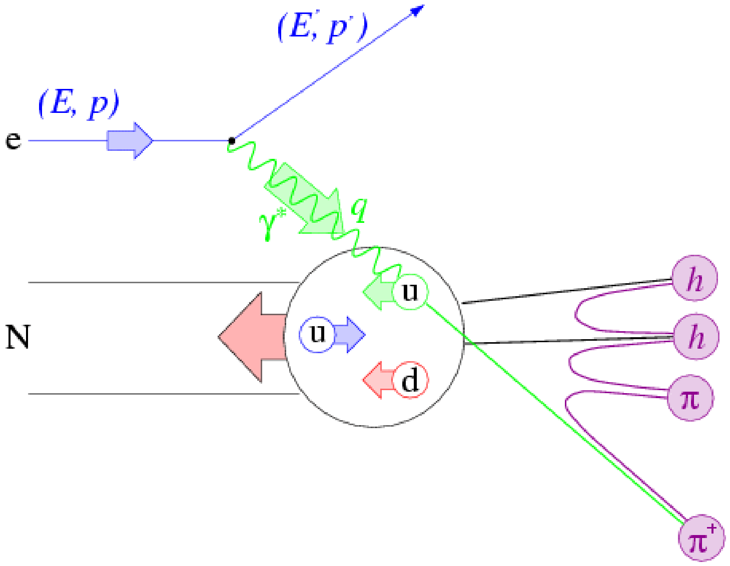
Hadronization is a non-perturbative QCD phenomenon
  - Want to know space-time evolution of the hadron formation process
  - Use nuclei as time/length-scale probe

Hadronization in relativistic heavy-ion collisions possible probe of different state of matter
  - Nuclei (cold nuclear matter) reference point

Experimental data needed to gauge calculations
  - HERMES offers suitable energy range, set of nuclear targets, and hadron identification; clean initial state

Method

Semi-Inclusive Deep Inelastic Scattering (SIDIS)



Variables:

$$\nu = E - E'$$

$$-Q^2 = q^2 = (p - p')^2$$

$$z = E_h / \nu$$

$$p_t^2$$

In free space described by $\sigma \Box \sum_f e_f^2 q_f(x) D_f^h(z)$

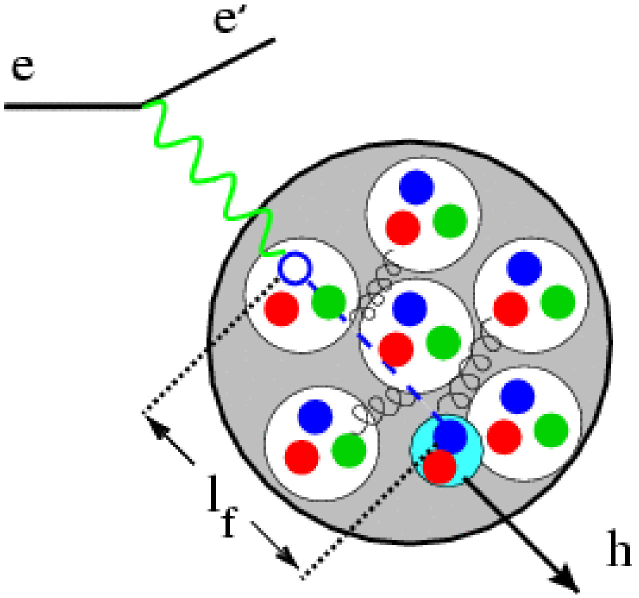
Hadronization (in a nucleus)

quark ‘production’

quark energy loss

(pre)hadron formation

reactions (absorption) of produced (pre)hadrons

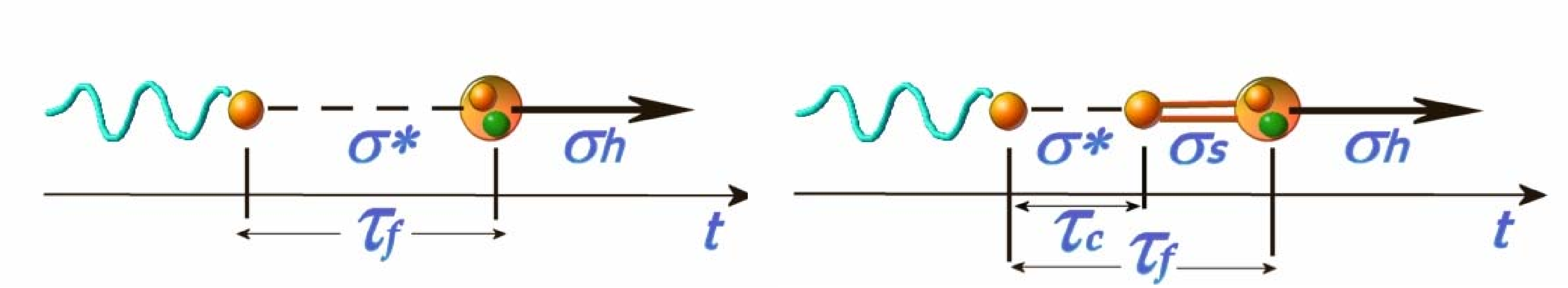


Models

Phenomenological

A. Bialas and T. Chmaj, PhL 133B (1983) 241
A. Bialas and M. Gyulassy, NPh B291 (1987) 793

one or two time scales plus corresponding cross sections



Energy loss type

X. Guo and X.N. Wang, PRL 85 (2000) 3591
E. Wang and X.N. Wang, PRL 89 (2002)162301
F. Arleo EPJ C30 (2003) 213

gluon radiation and quark-quark interaction
effective (increased) z in fragmentation function $D_f^h(z_{eff})$

Models

Energy loss and absorption

A. Accardi, V. Muccifora, H.J. Pirner, NPh A720 (2003)131

B.Z. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki,
NPh A740 (204) 211

nuclear absorption cross sections after ‘formation’ time

‘Full FSI’

T. Falter, W. Cassing, K. Gallmeister, U.Mosel, PR C70 (2004) 054609

coupled-channel treatment of FSI
by means of BUU transport model

Studying hadronization in nuclei

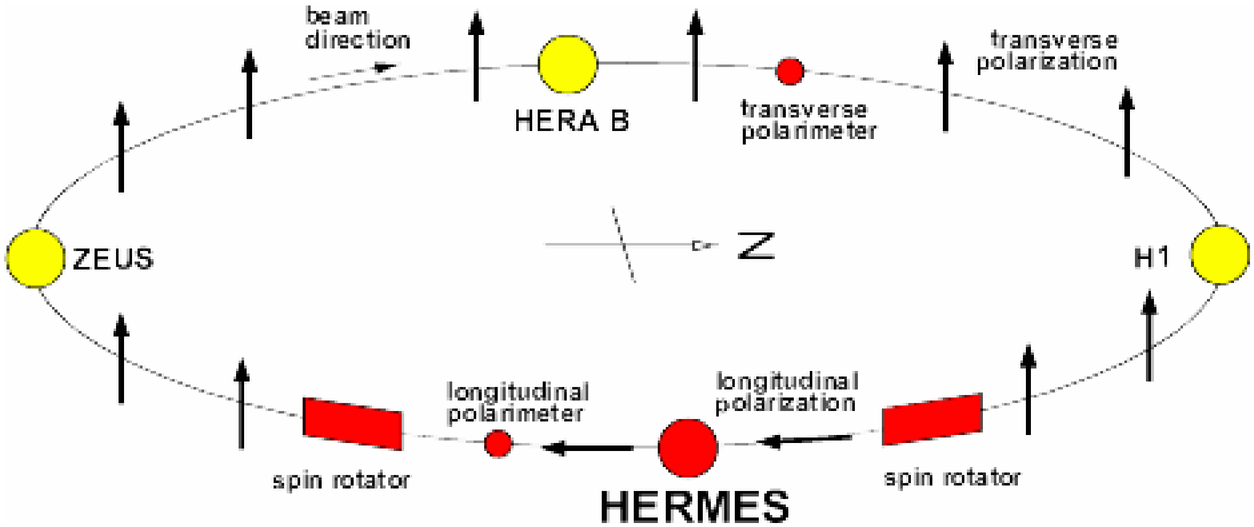
Measure <u>nuclear attenuation</u> in (e,e'h) SIDIS reaction

$$R_A^h(\nu, z, Q^2, p_t^2; \phi) = \frac{\left\{ \dfrac{N_h^{SIDIS}(\nu, z, Q^2, p_t^2; \phi)}{N_h^{DIS}(\nu, Q^2)} \right\}_A}{\left\{ \dfrac{N_h^{SIDIS}(\nu, z, Q^2, p_t^2; \phi)}{N_h^{DIS}(\nu, Q^2)} \right\}_D}$$

Depending on the size of the nucleus different length scales probed

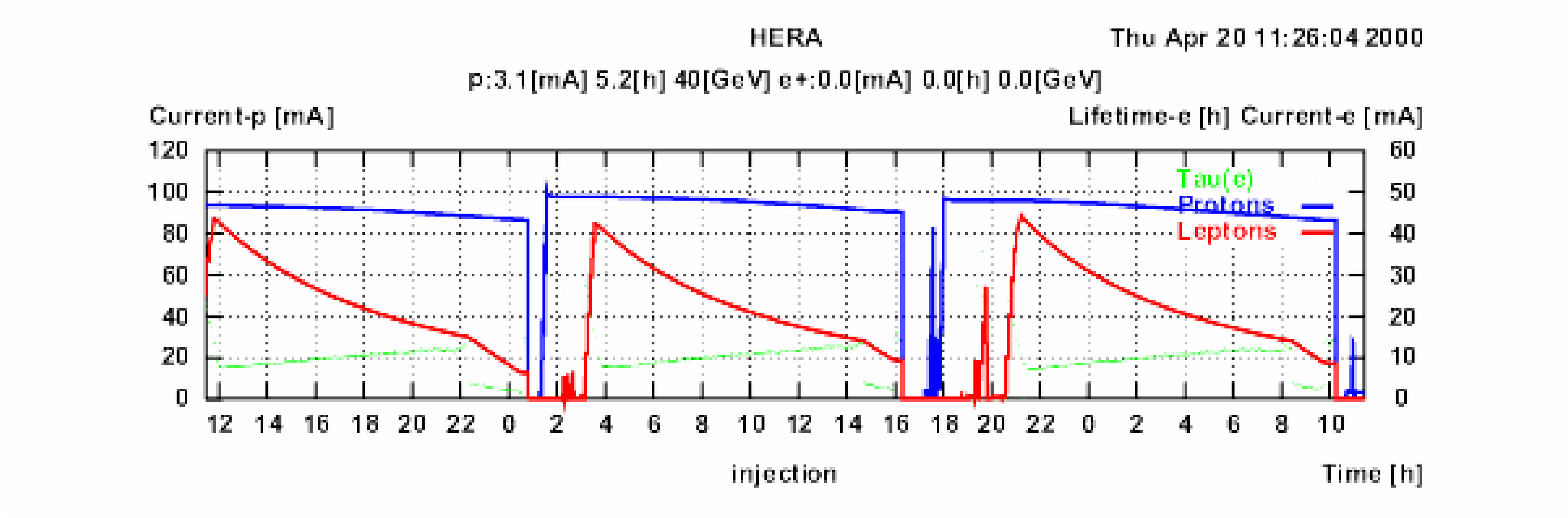
HERMES at DESY

HERMES studies the spin structure of the nucleon … but not only..

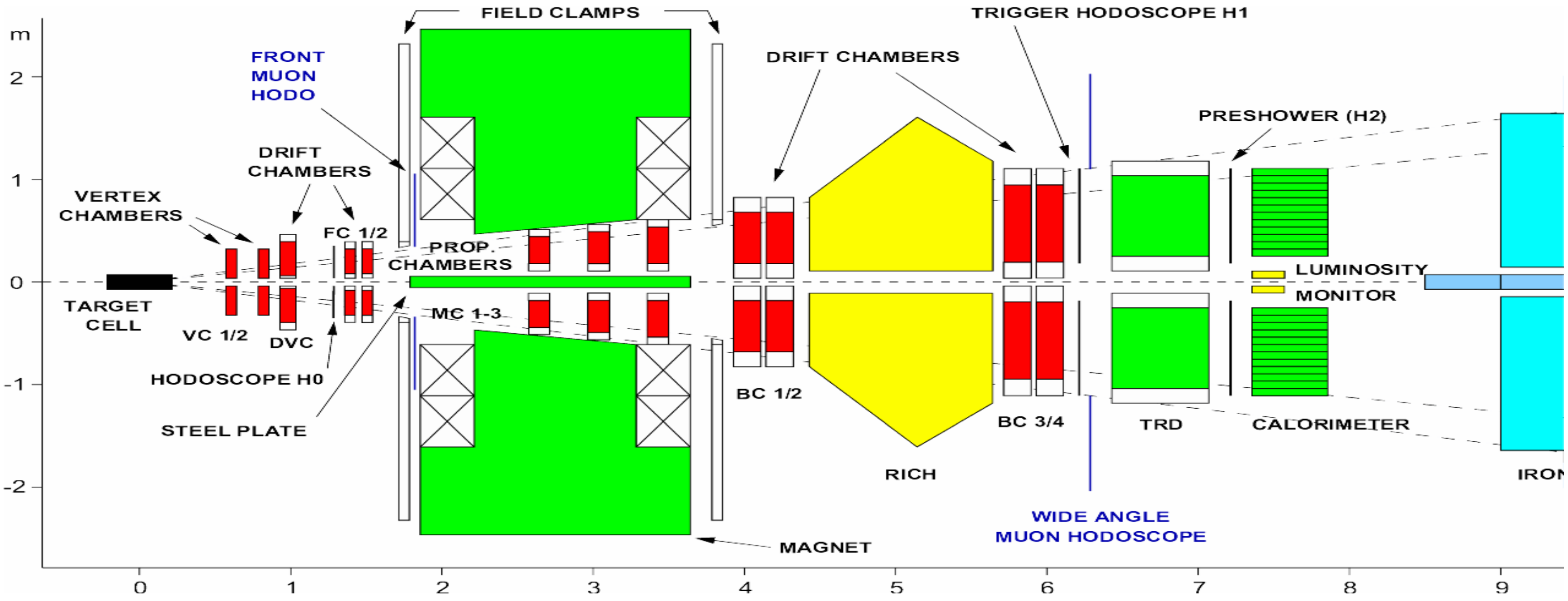


$E = 27.5$ GeV e^+ (e^-)
$I \sim 30$ mA
p beam of 920 GeV,
not used by HERMES

Internal target polarized and unpolarized gas.
Last part of the fill:high-density unpolarized runs.



HERMES Spectrometer



- e$^+$ identification: >99% efficiency, <1% contamination
- Particle IDentification: RICH (< '98 Čerenkov), TRD,
  Preshower, e.m. Calorimeter

HERMES experiments

SIDIS on nuclei: A(e,e'*h*) with $h = \pi^+, \pi^-, \pi^0, K^+, K^-, p, \bar{p}$

Studied in D, He, N (only all *h* or π), Ne, Kr (1997-2000)
D, Kr, Xe (2004)

$E_e = 27.6$ GeV; some 12 GeV data on N and Kr

$2\ (5) < \nu < 23.5$ GeV
$0.1\ (0.2) < z < 1.1$
$Q^2 > 1.0\ \mathrm{GeV}^2$
$W > 2$ GeV

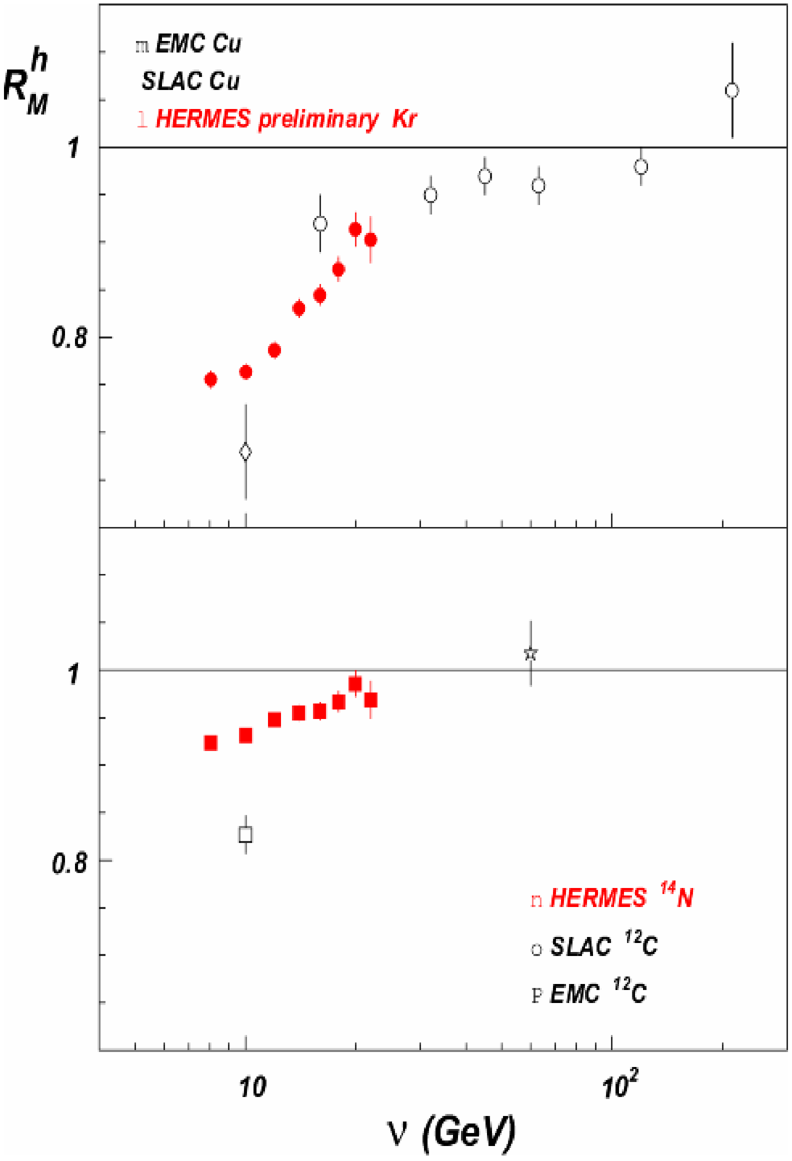
Analysis

Calculate $R_A^h(\nu, z, Q^2, p_t^2; \phi)$ for all *h*

Corrections (largely cancel in double ratio):

radiative effects
exclusive ρ production

Hadron attenuation vs transfer energy ν



HERMES, EPJ C 20 (2001) 479.
HERMES, Ph.L. B 577 (2003) 37.
EMC Coll. Z.Phys. C52 (1991) 1.
SLAC PRL 40 (1978) 1624.

- Increase of R with ν consistent with the EMC data at higher energy.

- Discrepancy with SLAC mainly due to the EMC effect

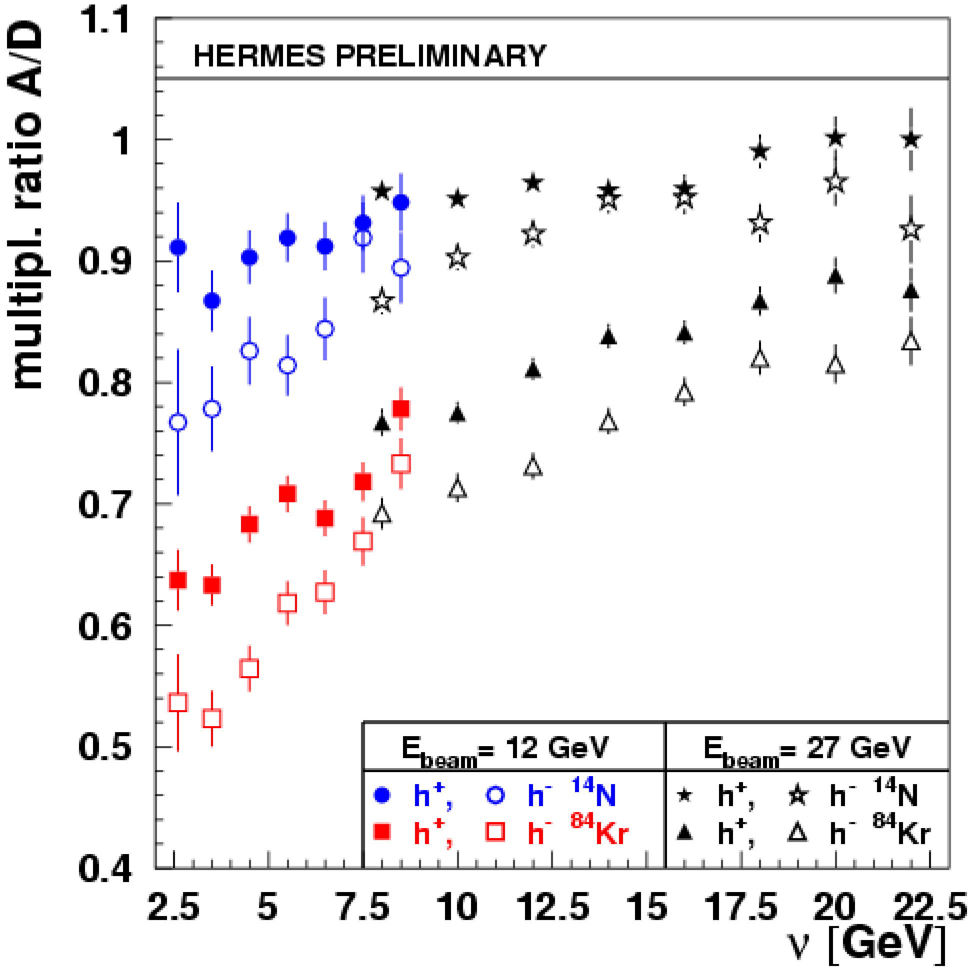
- HERMES kinematics optimal to study medium effects.

12 GeV

Data on N and Kr

Average Q^2 lower at 12 GeV

Good agreement



Target fragmentation

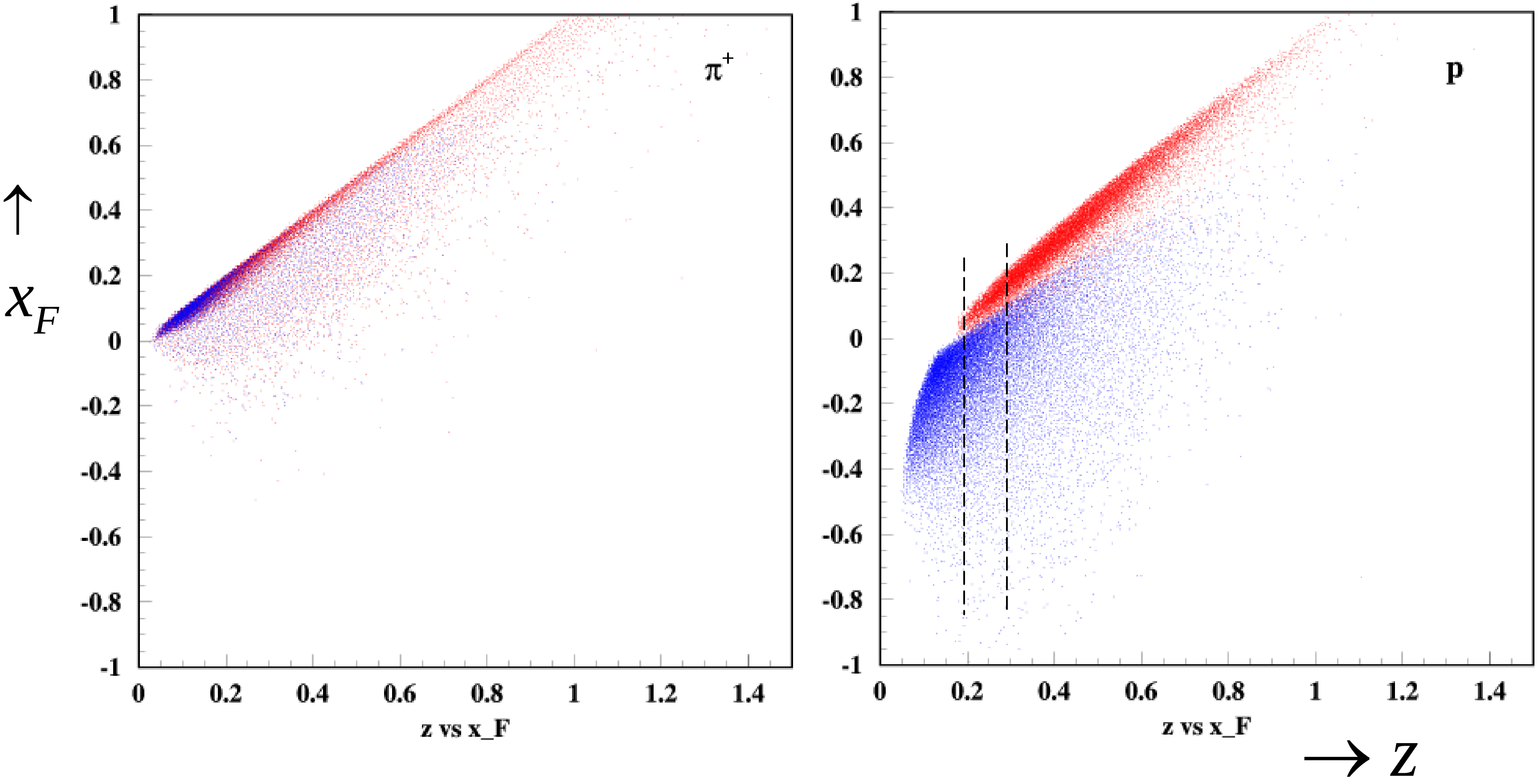
Investigate by looking at x_F

For pions very strong correlation of x_F with z

Suggestion from data for proton that value of R stable when $x_F > 0$

x_F coverage/dependence

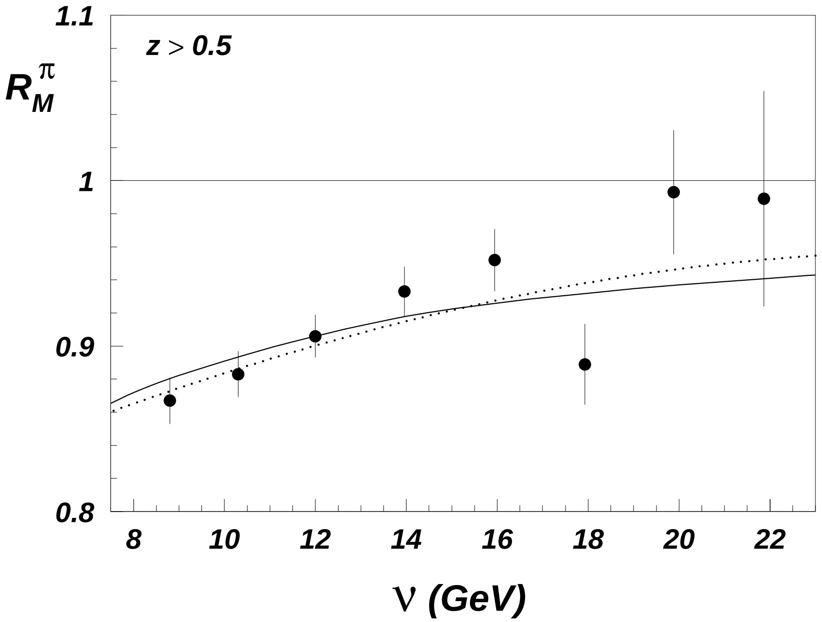
Correlation between z and x_F for pions and protons

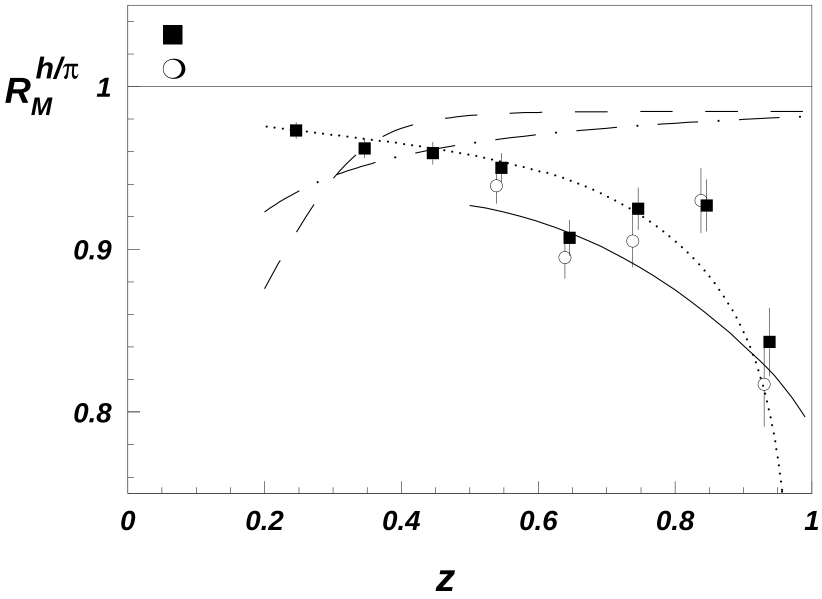


First data and analysis EJP C20 (2001) 479

Results for N (all hadrons or pions)

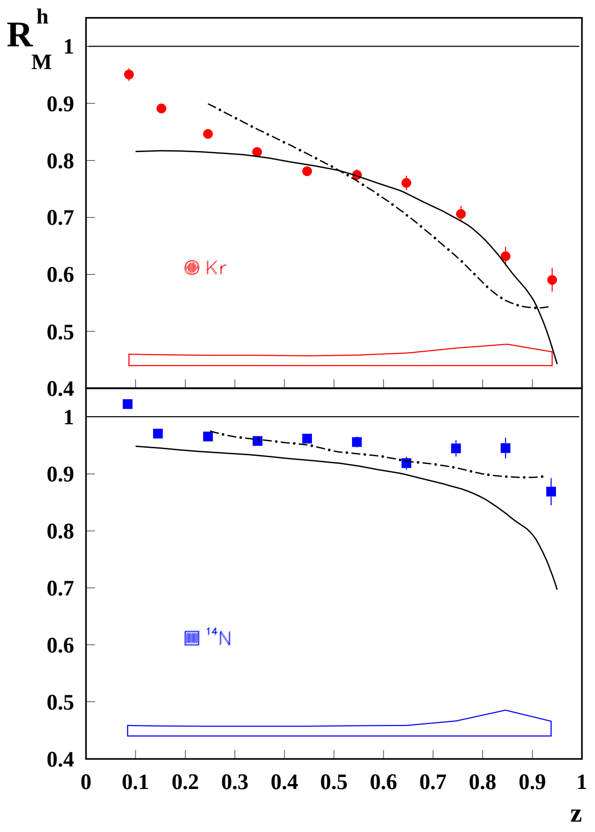
'Time scale' analysis and comparison with gluon Bremsstrahlung model

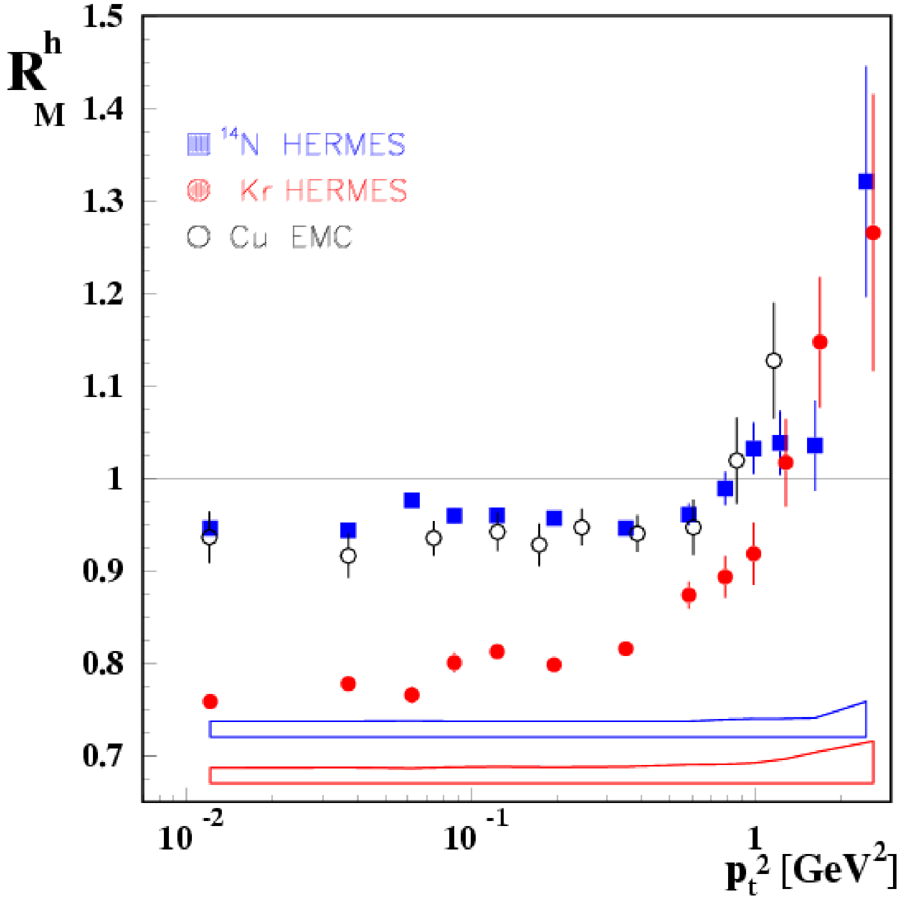




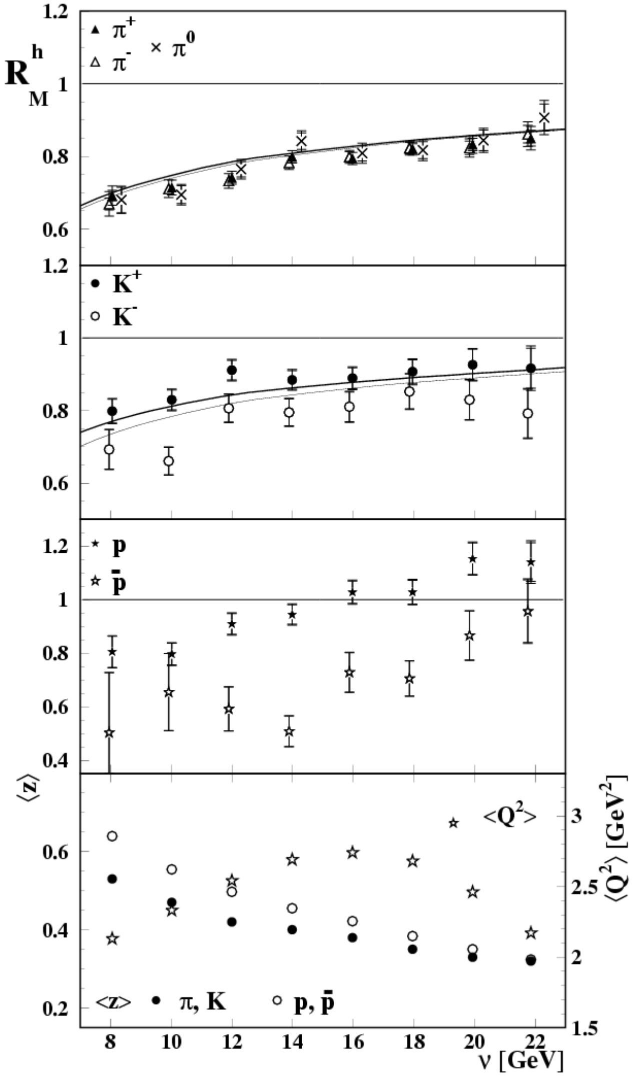
More detailed studies PhL B577 (2003) 37

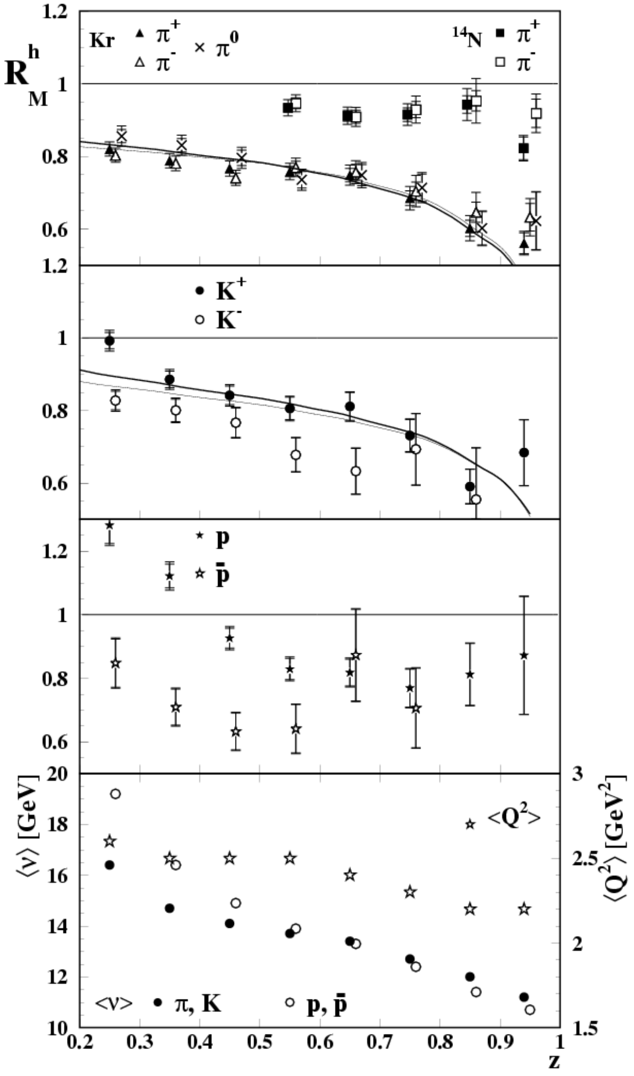
Kr data with PID from RICH



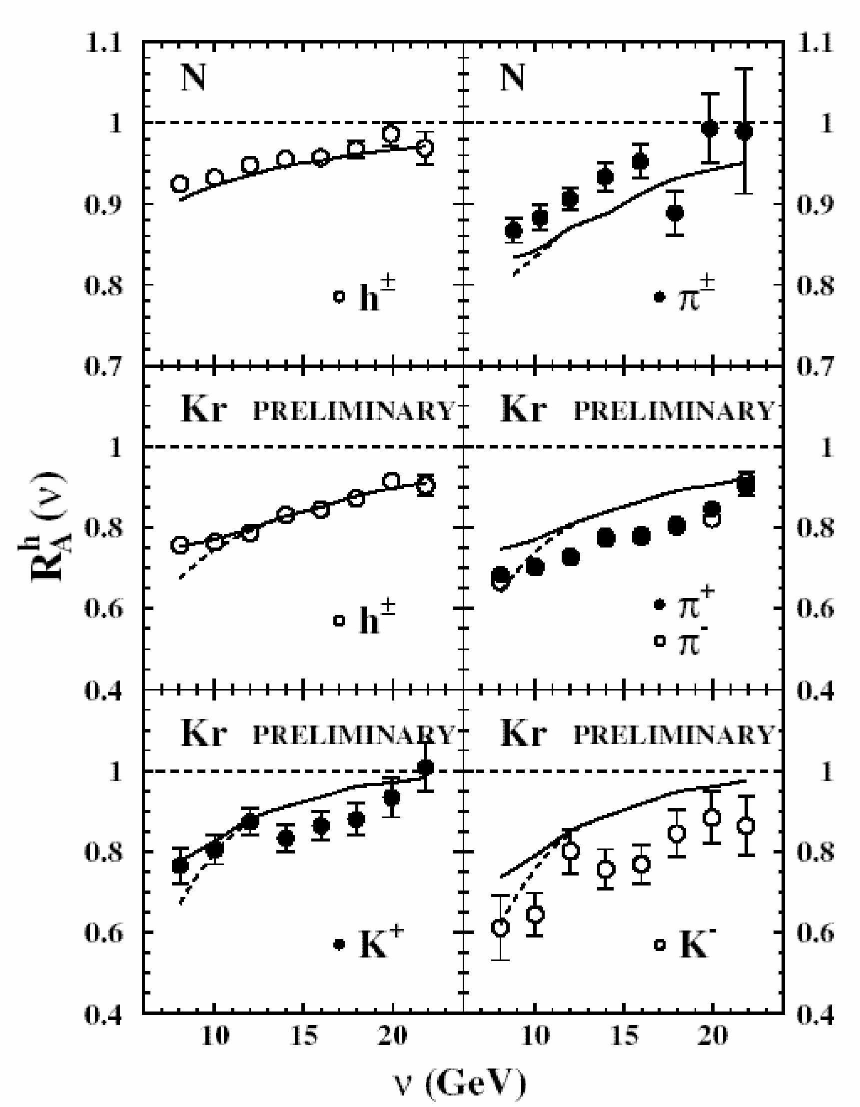


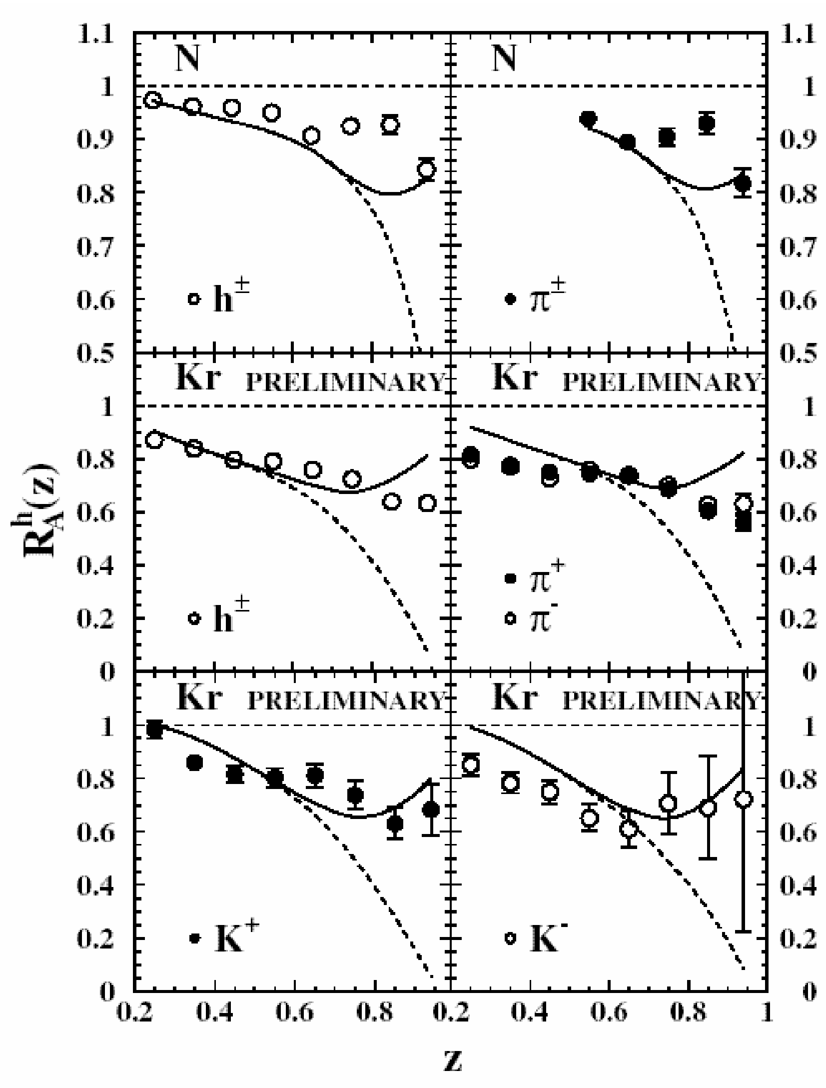
ν and z dependence



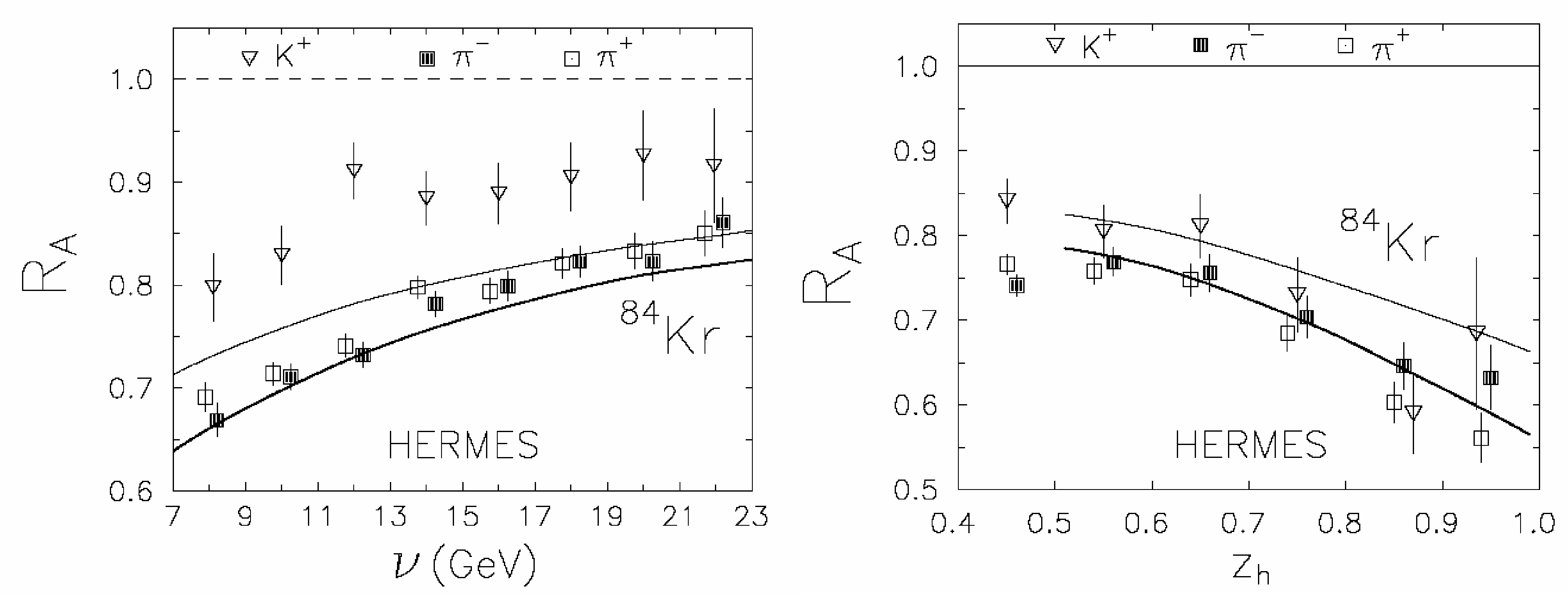


Comparison of published data with models: ‘Arleo’

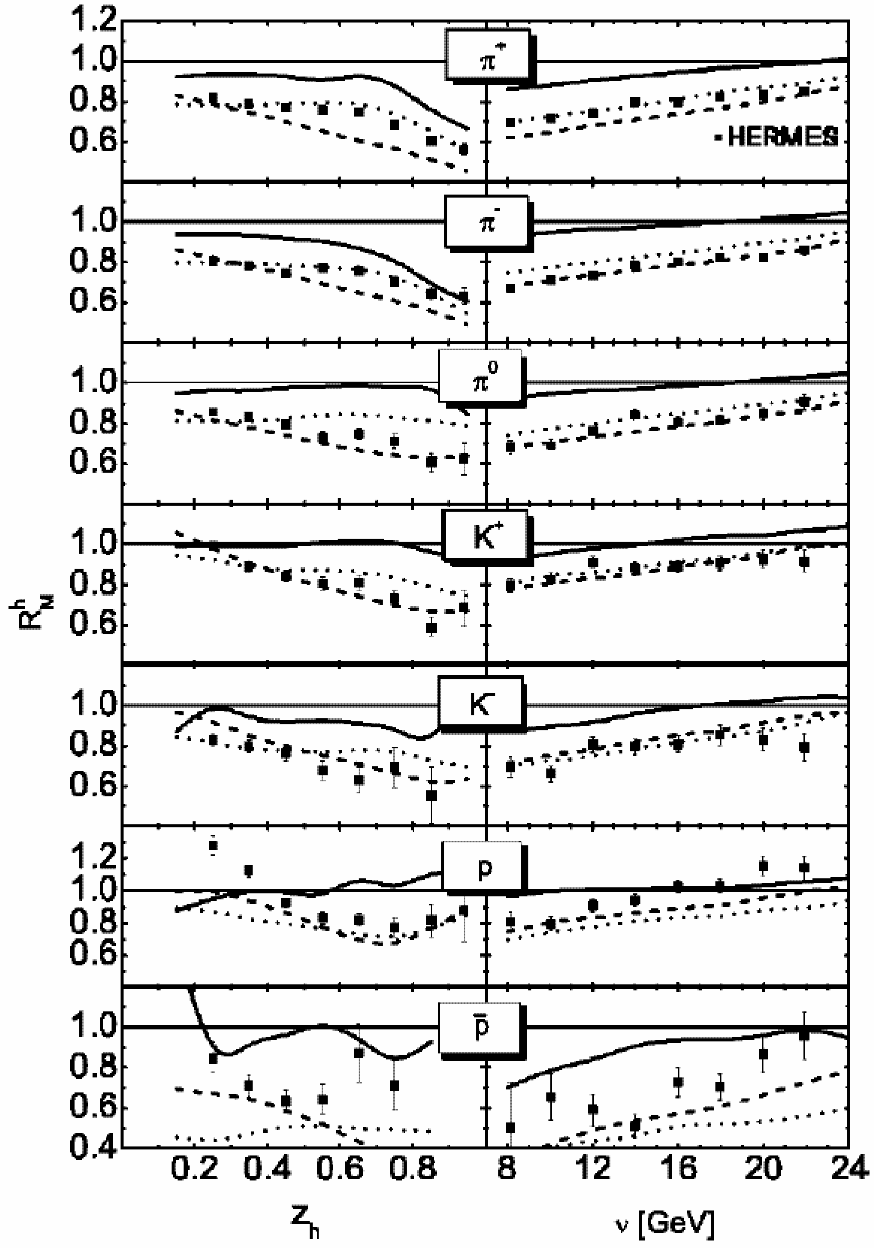




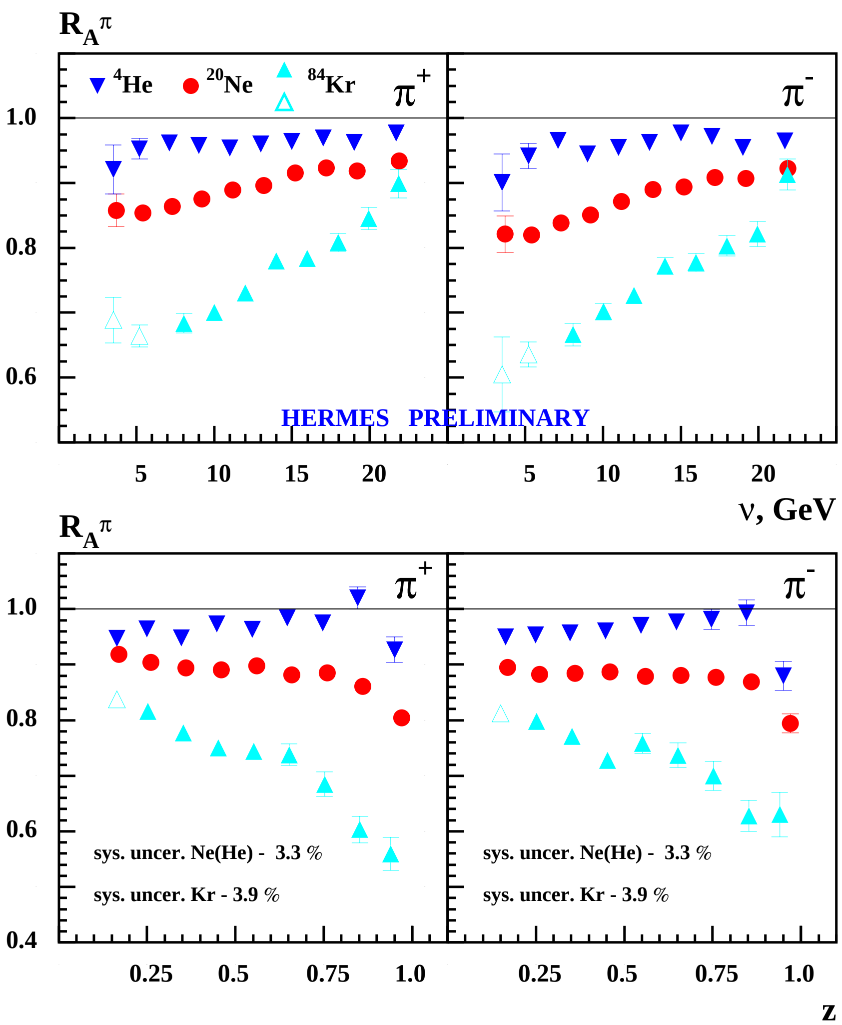
Comparison of published data with models: ‘Kopeliovich’

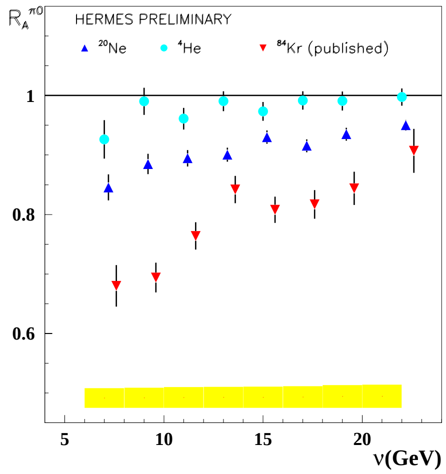


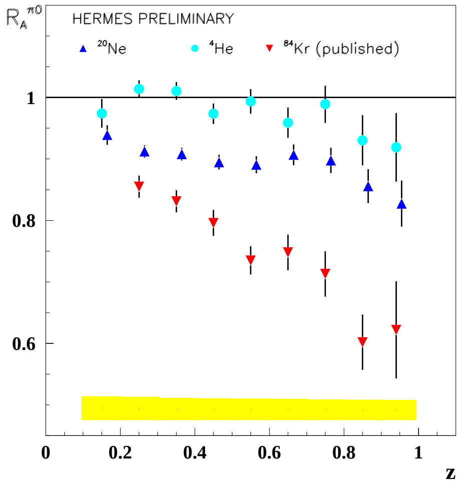
Comparison of published data with models: ‘Falter’



Results for He, Ne, Kr: pions







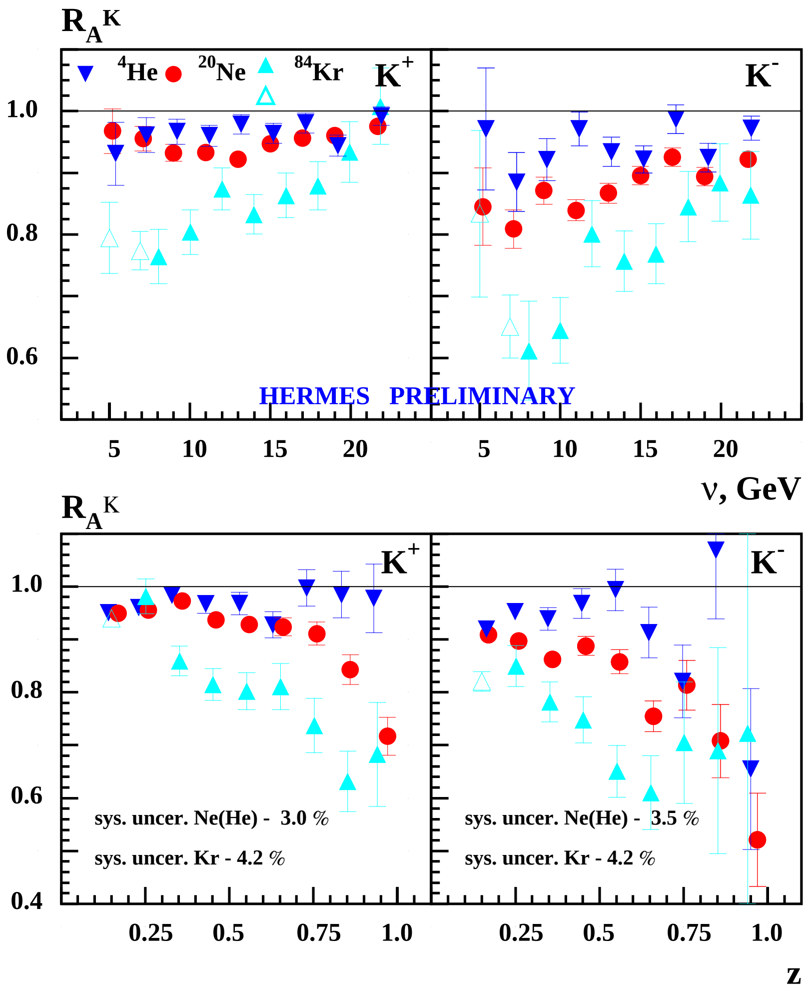
π^+/π^- ratio

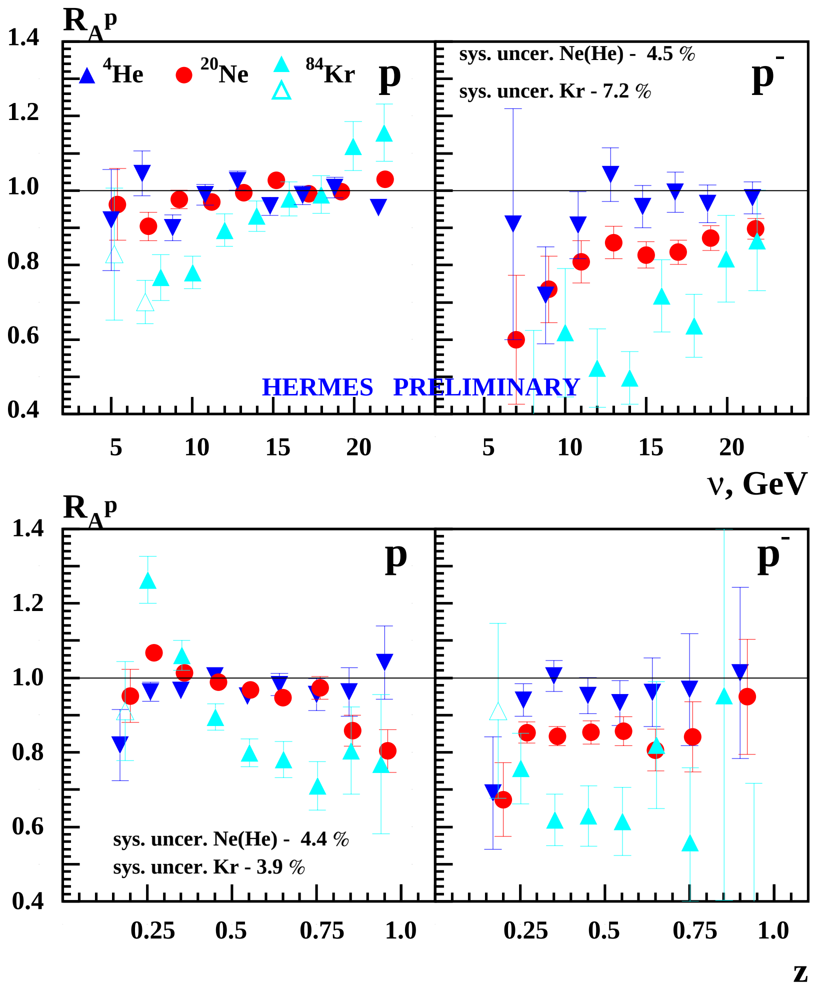
Based on ^{3,4}He data some more π^+ produced on protons compared to neutrons

Nuclear effects: at lower p_π $R(\pi^-) < R(\pi^+)$ for Ne ($N \approx Z$)

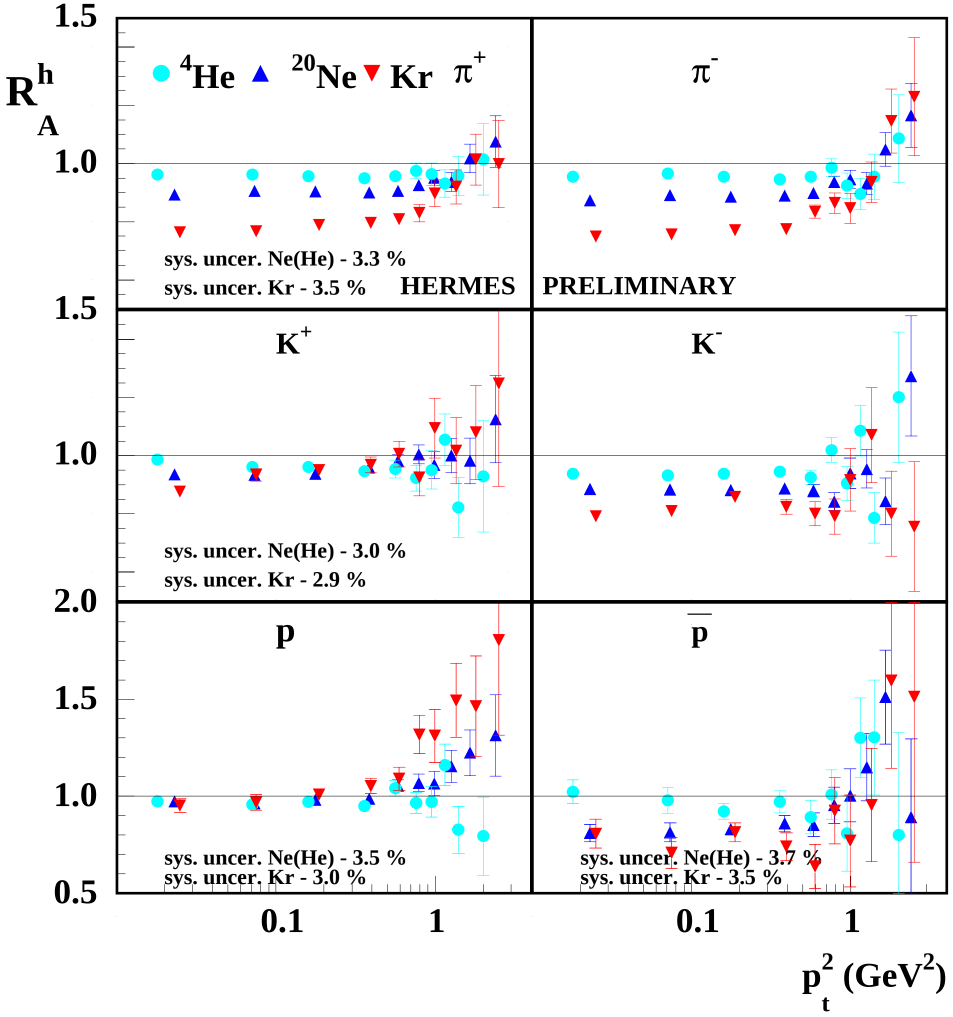
Overall very little difference between $R(\pi^-)$ and $R(\pi^+)$ for same nucleus

He, Ne, Kr: other hadrons





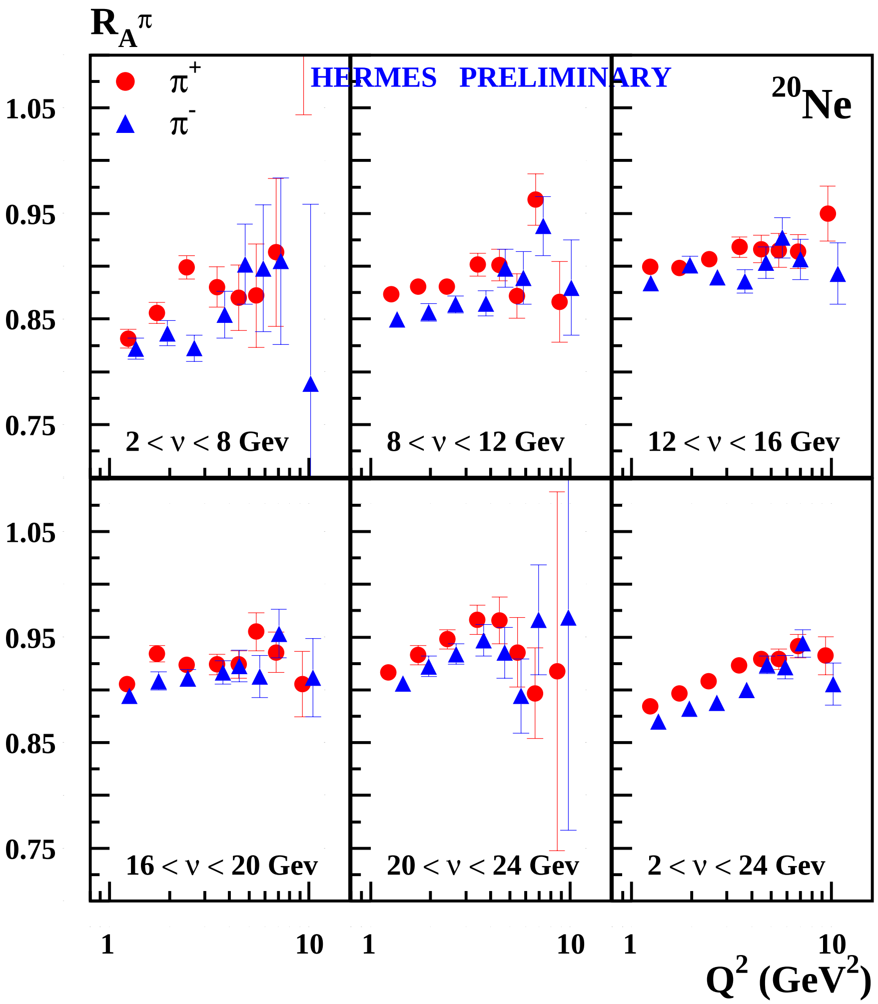
$p_t{}^2$ distribution



- Large increase of the multiplicity ratios with $p_t{}^2$
- Nuclear $p_t{}^2$ broadening; Cronin effect.

Hadronization workshop Trento, Oct. 2005

Q^2 dependence



Q^2 dependence weak,

little or not dependent on ν

Double-hadron attenuation

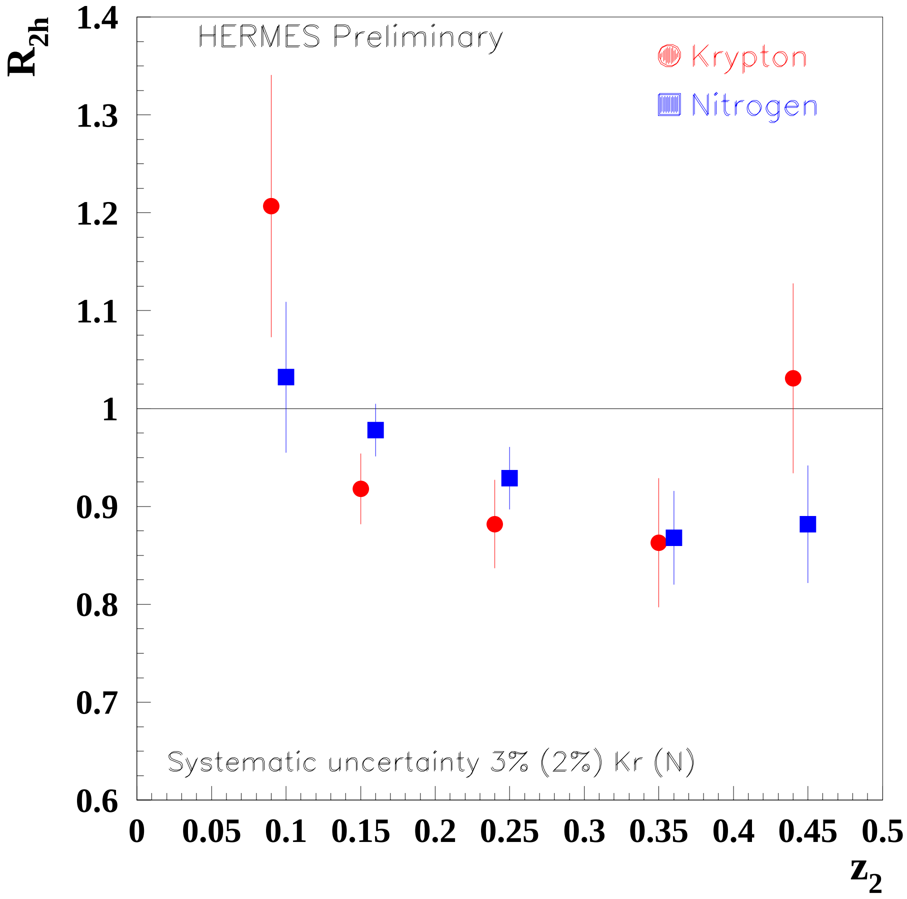
$$R_{2h}(z_2) = \left(\frac{d^2N(z_1, z_2)}{dN(z_1)}\right)_A \Big/ \left(\frac{d^2N(z_1, z_2)}{dN(z_1)}\right)_D$$

Additional way to study hadronization

R_{2h} sensitive to model assumptions :

- Partonic energy loss: slight A dependence of double-hadron to single-hadron ratio on a nuclear target (correlated (?))
- Absorption in final state: the ratio decreases with A (uncorrelated)

Double-hadron attenuation



- Ratio is generally below unity
- No significant difference between nuclei
- Mass dependence substantially smaller than for single-hadron case
- Double-hadron ratio: new way to differentiate contributions of different mechanisms

A-dependence

Try fit: $R_A = \exp[-\beta A^{\alpha}] \approx 1 - \beta A^{\alpha}$

Globally $\alpha \approx 0.55$ - 65 (0.05) (for pions)

Caveats:

- $R_A = M_A/M_D$: attenuation in D?
- Simple formula's such as

  $1 - R_A \sim L^2 \sim A^{2/3}$ (energy loss models)

  $1 - R_A \sim L \sim A^{1/3}$ (absorption models)

  too simple!

a) $L \sim A^{1/3}$?

Based on nucleus as a hard sphere

With realistic matter distribution (diffuse surface) $L_{eff} \sim A^{0.45}$

b) Including distribution of formation length, also in absorption models, $1 - R_A \sim A^{2/3}$ (for hard sphere)

(Accardi et al., hep-ph/0502072)

- And: if more than one mechanism, depending on traversed distance, A-dependence will be more complicated than 'simple' A^{α} .

Summary

- Substantial nuclear attenuation depending on the kinematic variables ν, z, p_t^2 and Q^2
- Attenuation increases with atomic mass A
- Decrease of attenuation with higher ν
- Increase of attenuation with higher z
- Weak dependence on Q^2
- Broadening of p_t^2 distribution

Outlook

- Increased statistics on Krypton, as well as new data on Xenon to be released very soon
- Detailed analysis (2-dimensional) of the high-statistics data samples (especially for pions)
- Global A-dependence as function of ν and z for various hadrons