Final results from HERMES on hadronization in nuclear environment

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(on behalf of the HERMES Collaboration)

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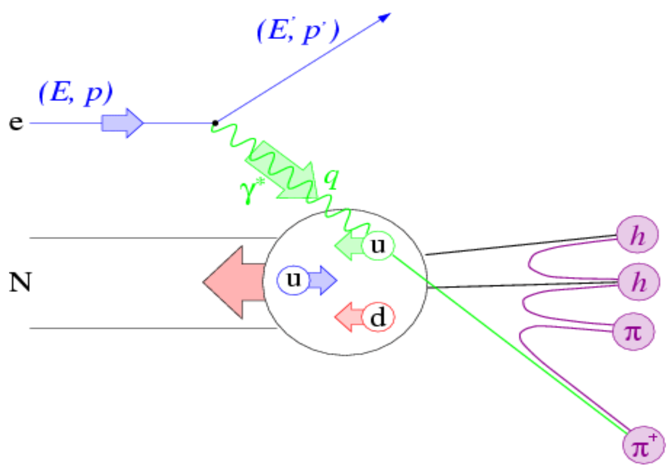
Motivation

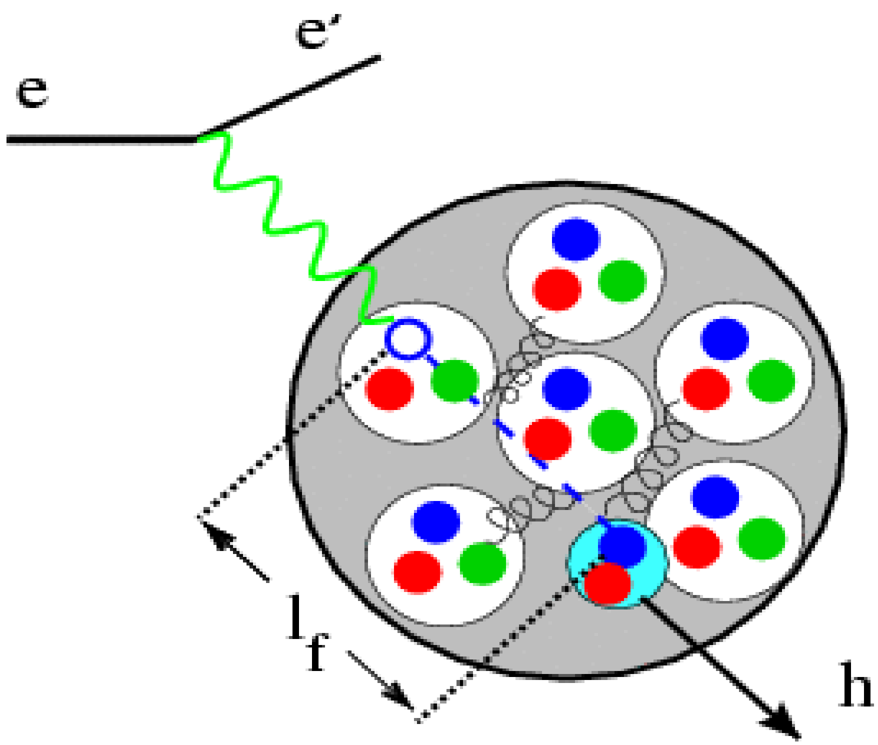
- Understanding of the hadronization process:
  - parton energy-loss mechanisms in nuclear matter
  - space-time evolution of the hadron formation process

- Hadronization as a non-perturbative QCD problem:
  - Approximative theoretical approaches used
  - Experimental data necessary to gauge available models
  - HERMES offers suitable energy range, set of nuclear targets, and PID for hadrons; clean initial state:
    - Beam energy of 27.6 GeV
    - Deuterium, Helium 4, Neon, Krypton, Xenon
    - Identified hadrons: π^+, π^-, π^0, K^+, K^-, p, p_{bar}



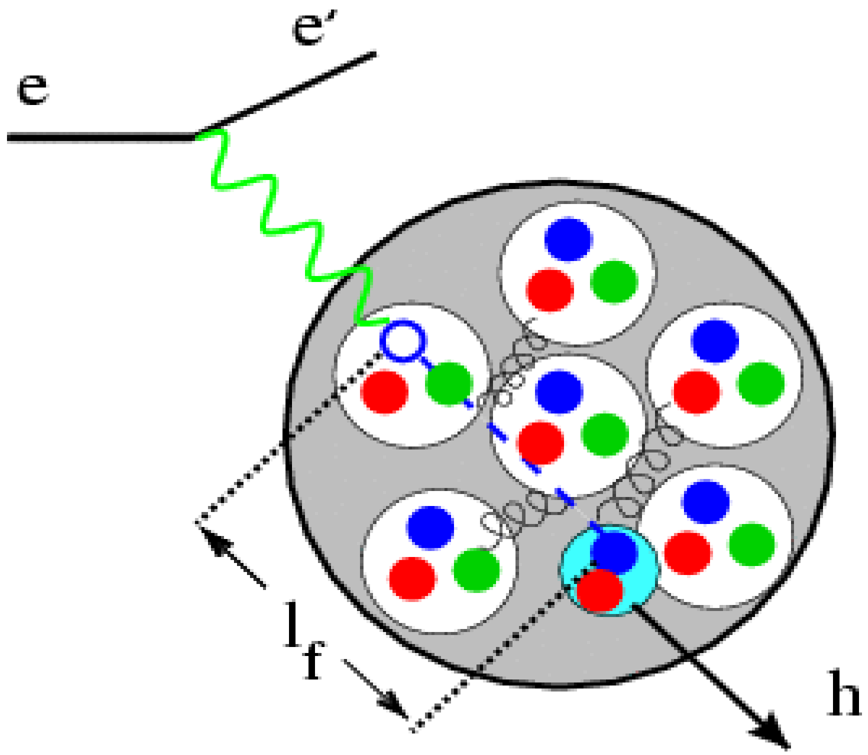
- $\nu = E - E'$
- $-Q^2 = q^2 = (p - p')^2$
- $z = E_h/\nu$

Nucleus as a laboratory



- Nucleus as an ensemble of targets
- Scattering on a quark
- Quark energy loss
- Fragmentation quark to hadron ("pre-hadron" formation)

Nucleus as a laboratory



- Pre-hadron (hadron) can experience absorption in nuclear medium
- Hadron-nucleon cross-section is known
- Formation time from DIS to final hadron:

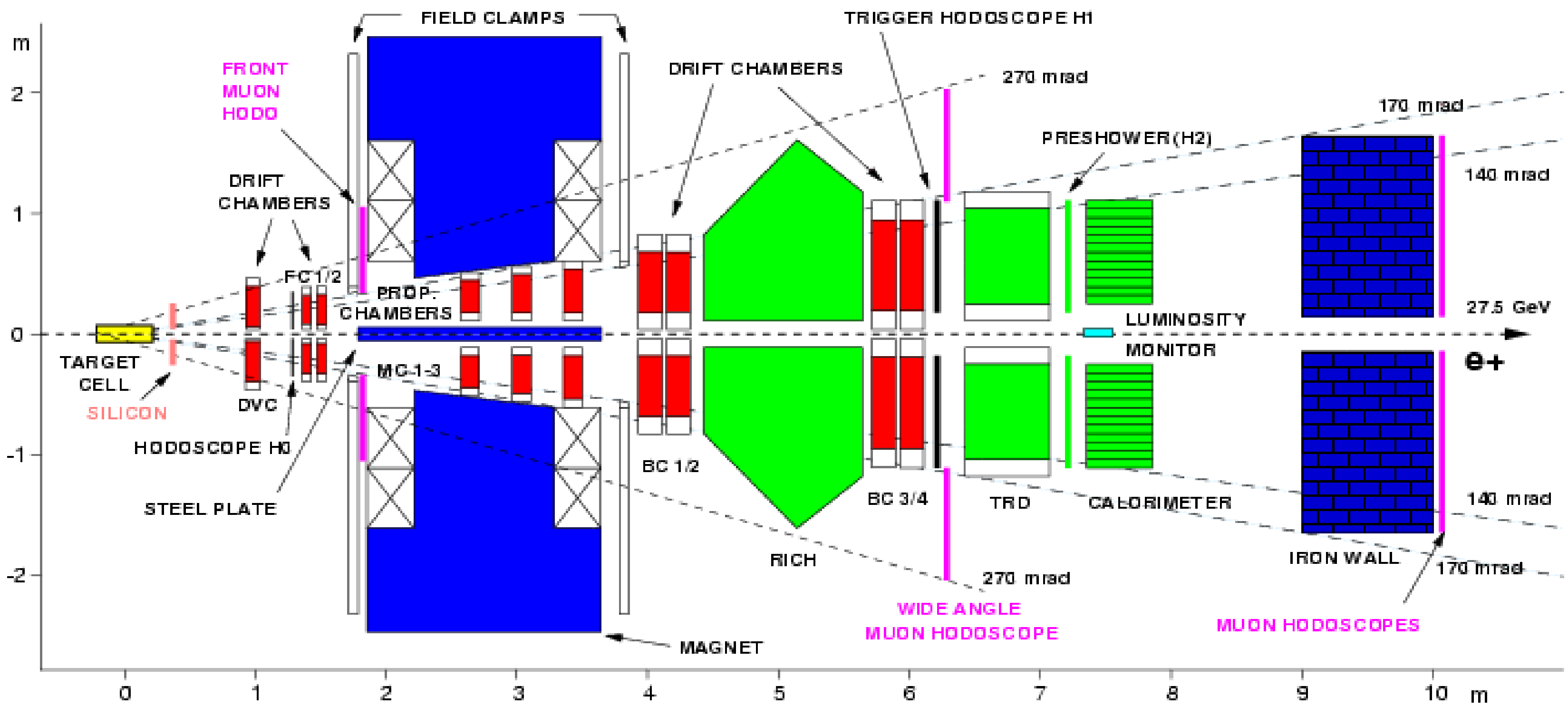
$$\tau_c = \nu(1-z)/\kappa$$

Multiplicity ratio

- Experimental access to the hadronization process through the measured multiplicity ratio:

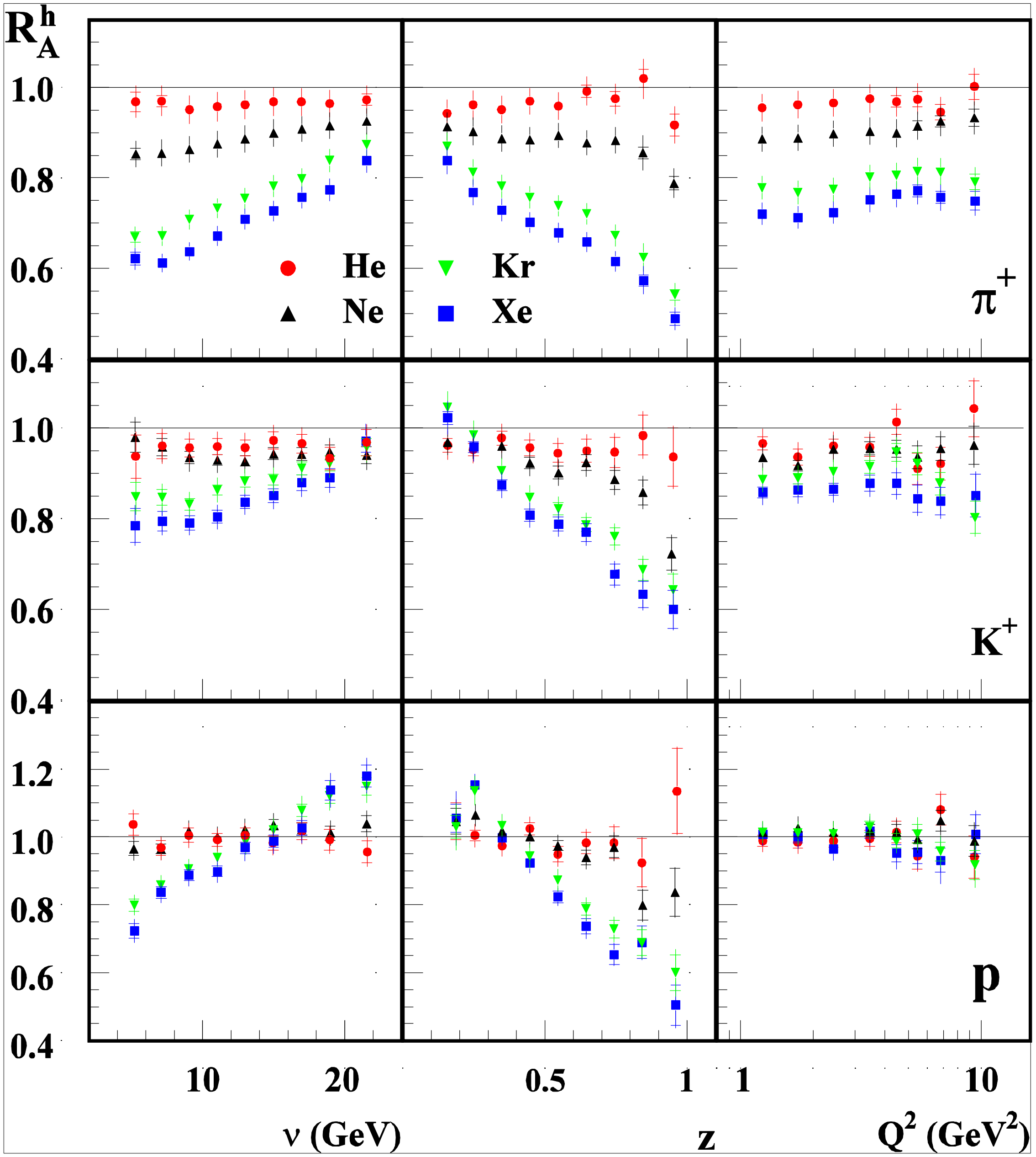
$$R_A^h(\nu, z, Q^2, p_t^2; f) = \frac{\left\{ \dfrac{N_h^{SIDIS}(\nu, z, Q^2, p_t^2; f)}{N_h^{DIS}(\nu, Q^2)} \right\}_A}{\left\{ \dfrac{N_h^{SIDIS}(\nu, z, Q^2, p_t^2; f)}{N_h^{DIS}(\nu, Q^2)} \right\}_D}$$

The HERMES Set-Up



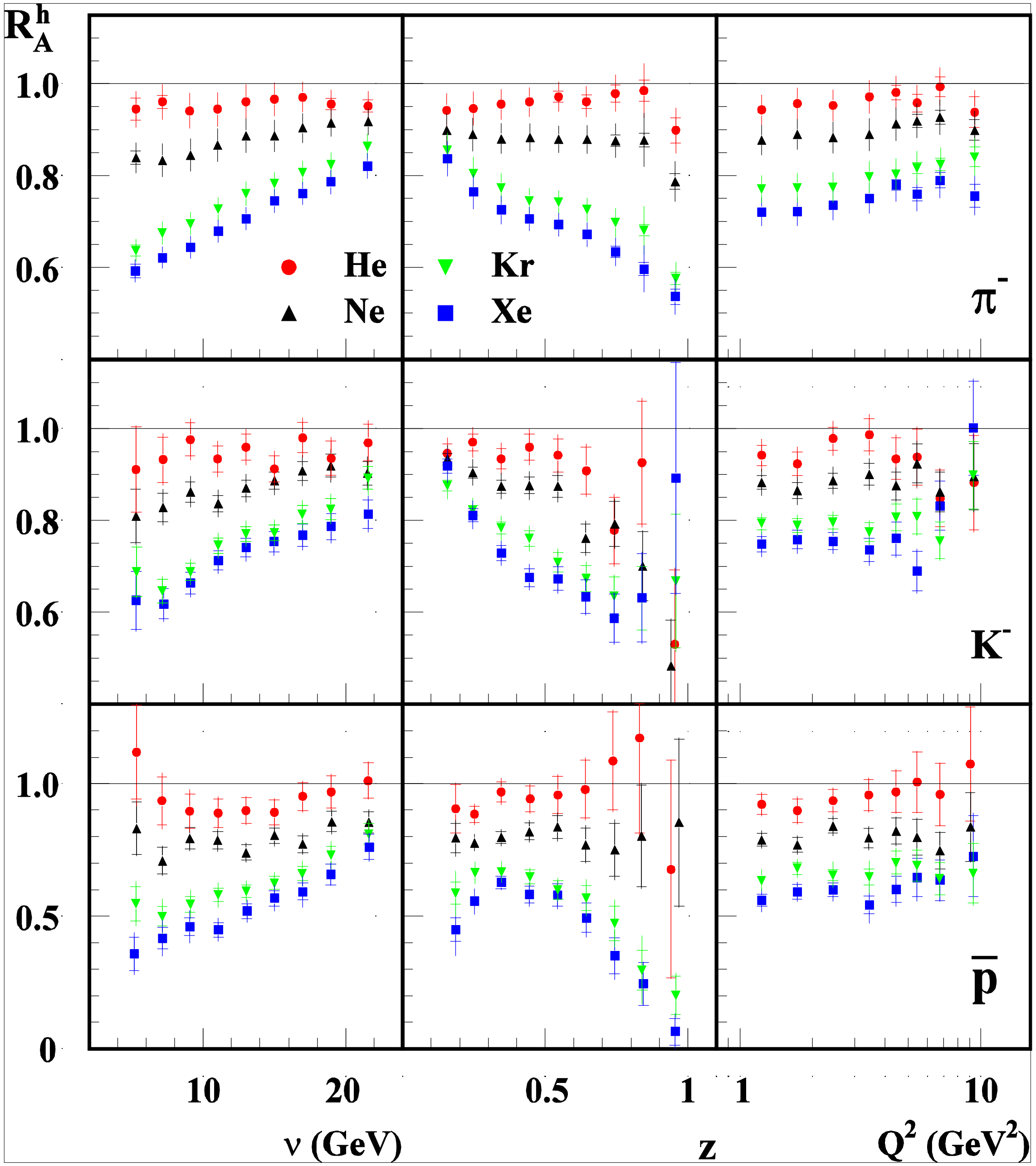
- Positron/electron beam with energy of 27.6 GeV
- Internal storage cell, pure gas targets: Deuterium, Helium 4, Neon, Krypton, Xenon
- Luminosity up to 10^33
- Hadron identification using RICH

R_A^h: positively charged hadrons



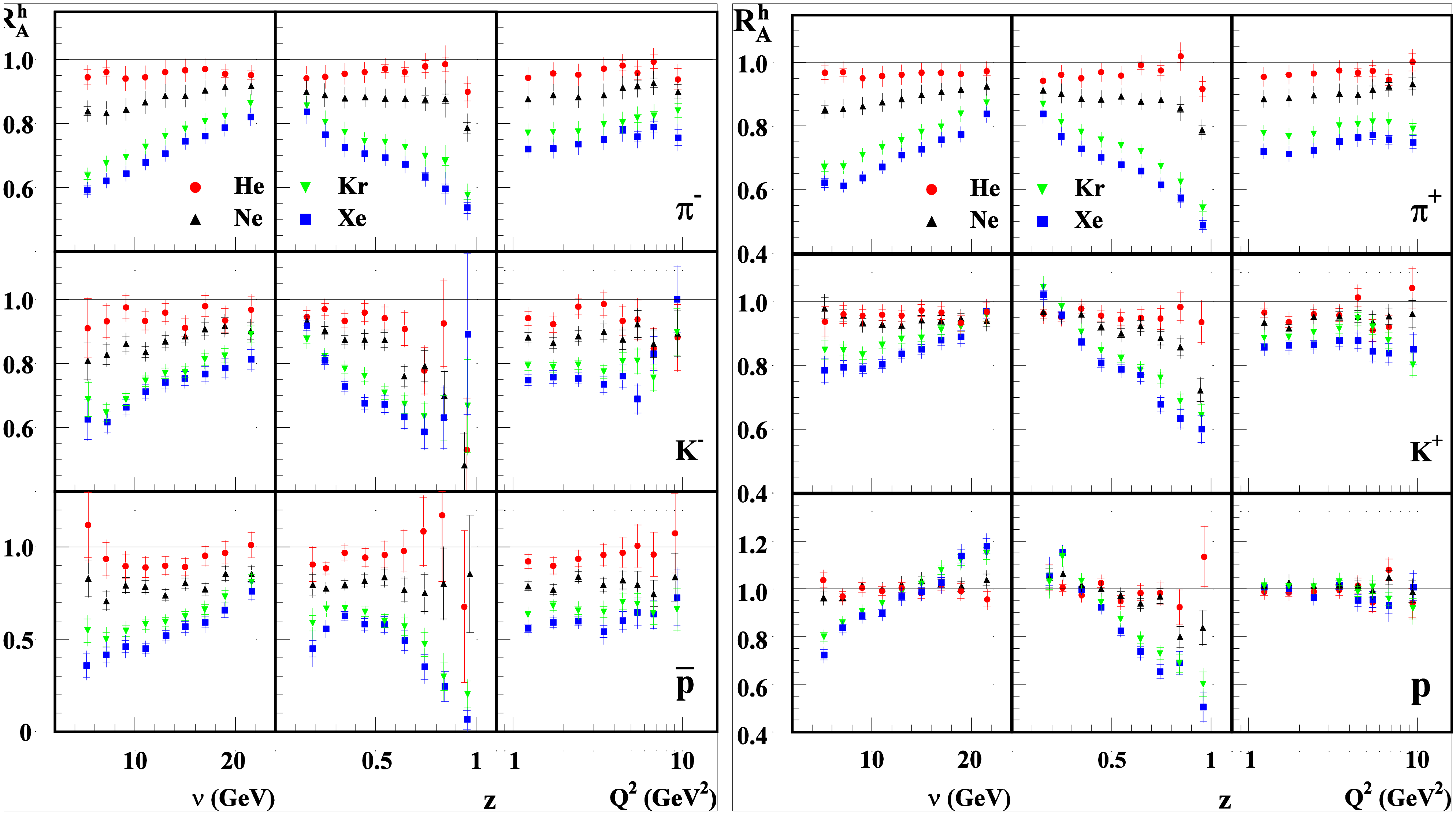
- Multiplicity ratio increases with increasing ν;
- Decrease with larger *z* values
- Strong atomic mass number dependence of the attenuation.

R_A^h: negatively charged hadrons

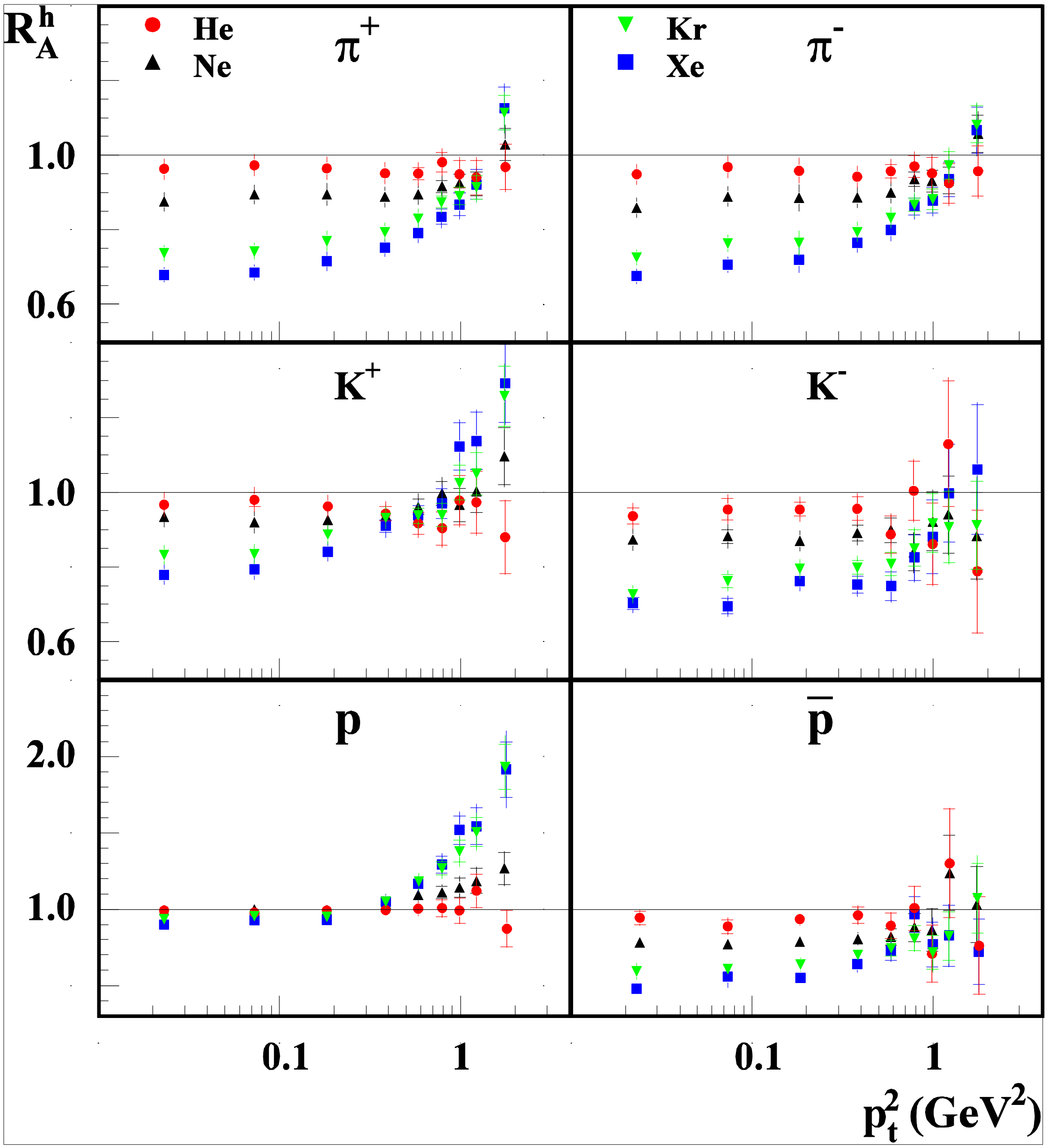


- $\pi^+ = \pi^- = \pi^0 \sim K^-$
- $K^+ > K^-$
- Total σ_h :
  - $\sigma_{\pi+} = \sigma_{\pi-} = 20$ mb
  - $\sigma_{K+} = 14$ mb, $\sigma_{K-} = 20$ mb;
  - $\sigma_p = 32$ mb, $\sigma_{p-} = 42$ mb
- Production mechanisms for p and p_{bar} differ

R_A^h: positive/negative hadrons

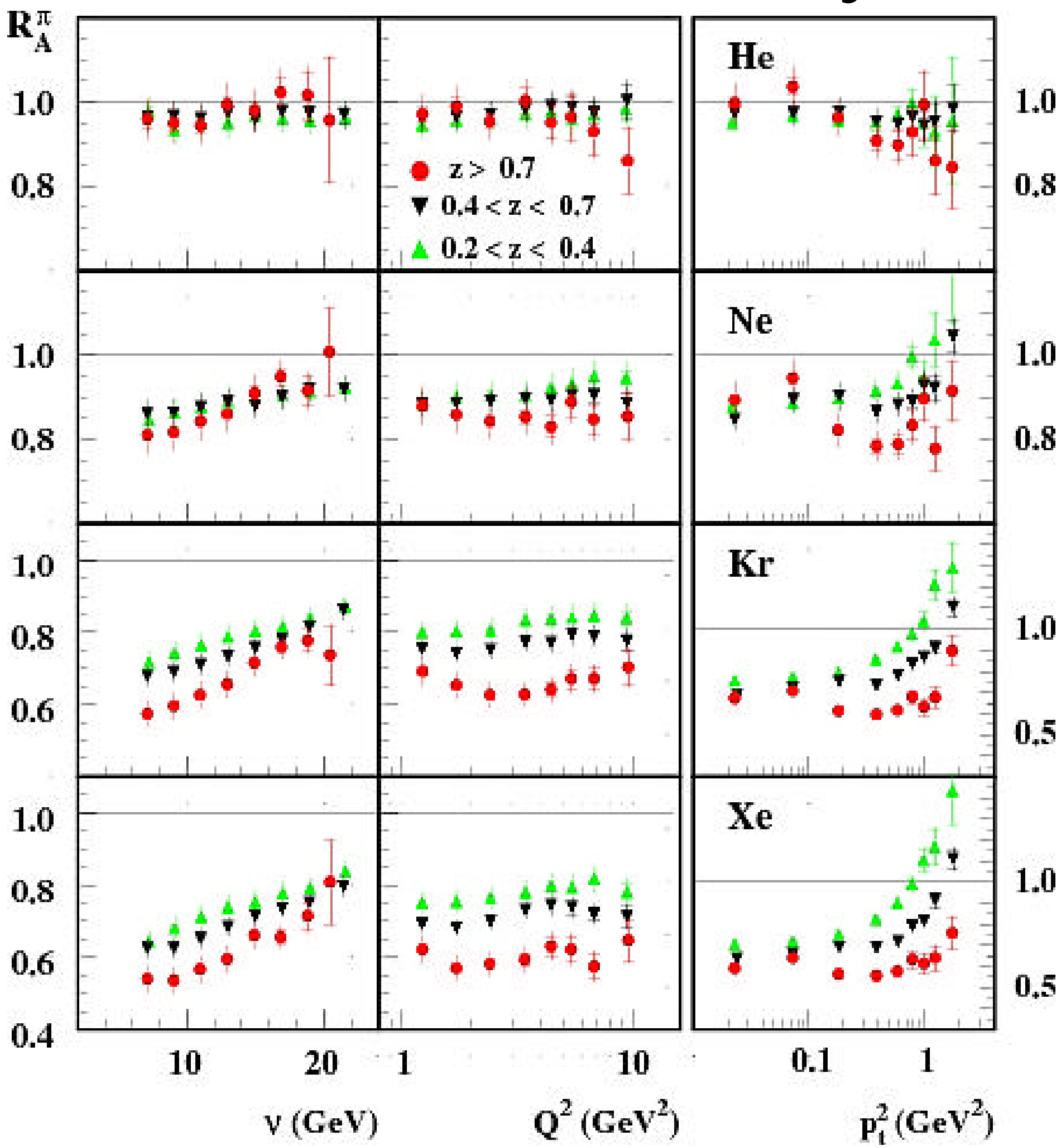


p_t^2 - dependence



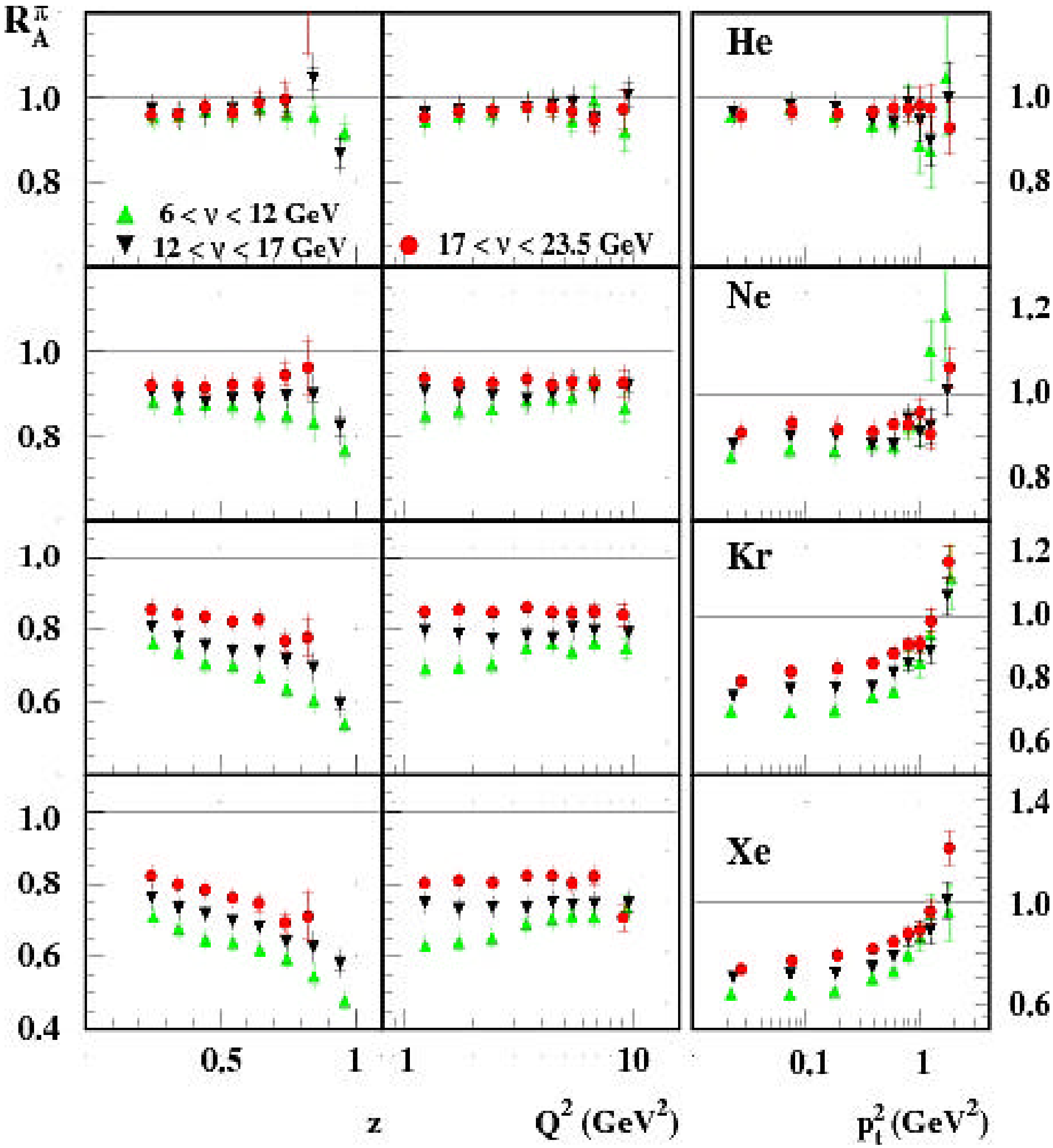
- Large increase of the multiplicity ratios with p_t^2
- Nuclear p_t^2 broadening.

2D-analysis: *z*-ranges



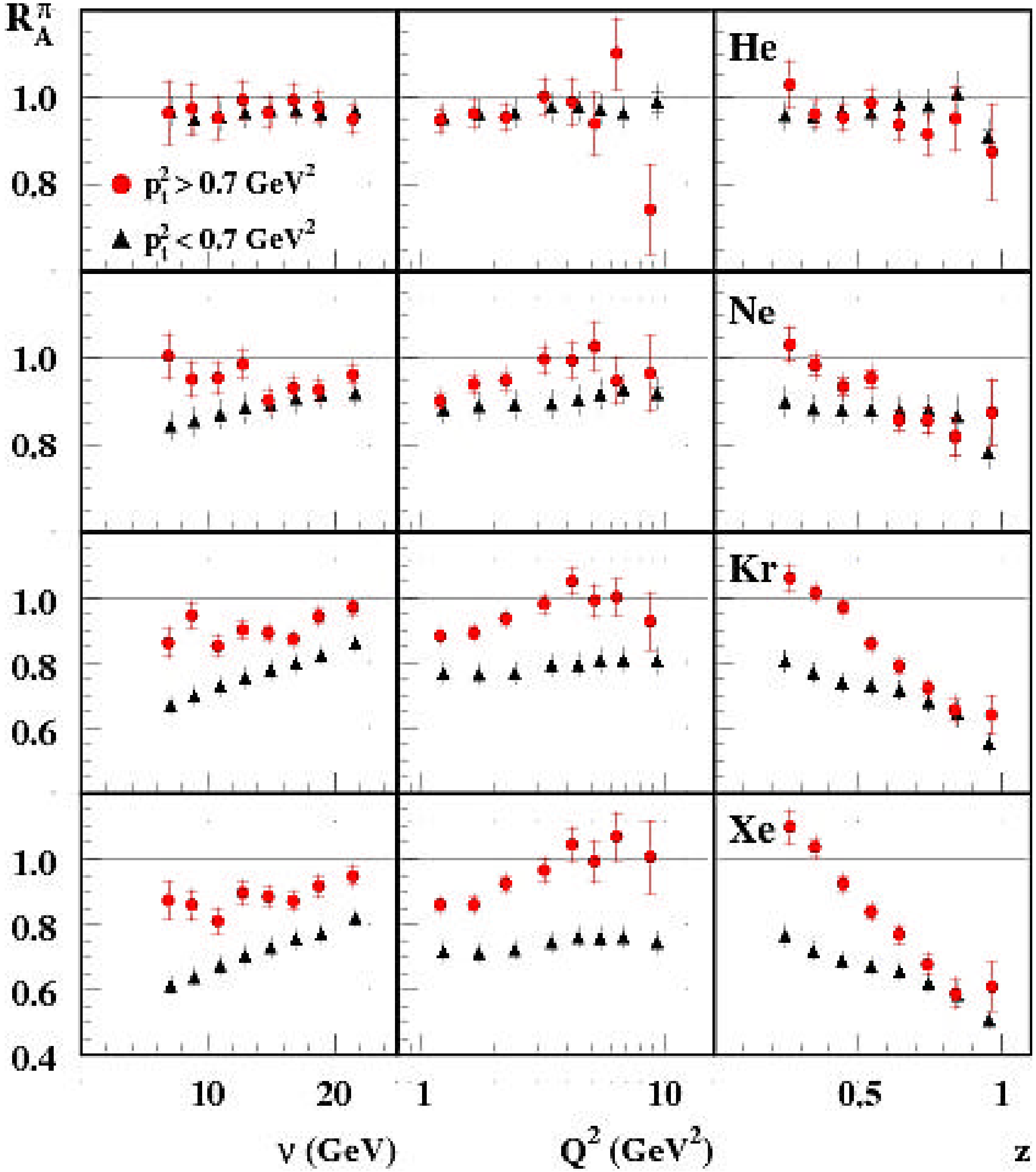
- Positive ν slope for all *z*-bins
- Within the uncertainties, the Q^2 -dependence is similar for all *z*-bins
- No broadening of p_t^2 for highest *z*-range
- Highest *z*-bin (red points) – drop in p_t^2 – possible contribution of pions from exclusive ρ0–decay.

2D-analysis: ν -ranges



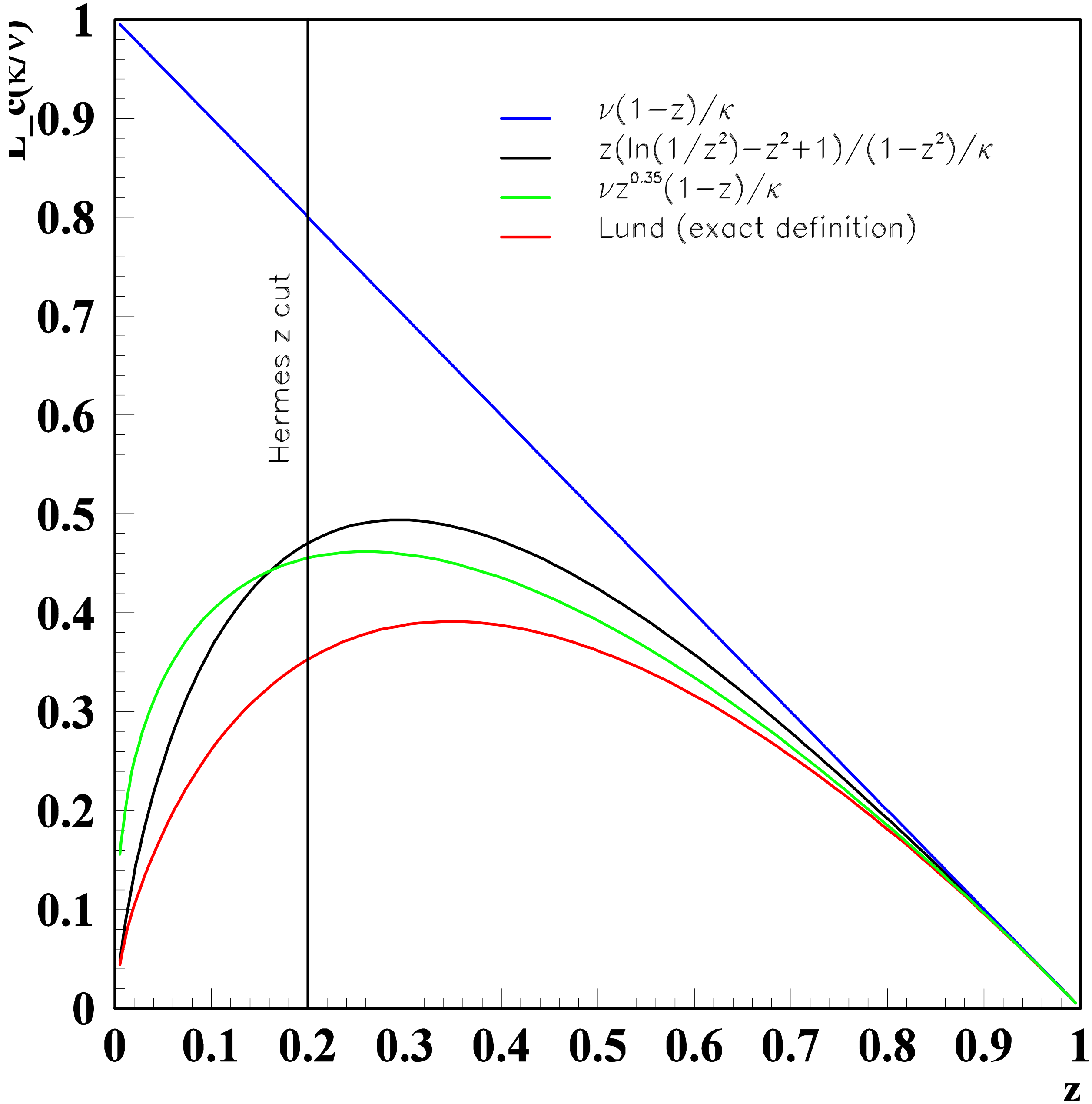
- Q^2 and p_t^2 dependences are similar for different values of ν
- Different slopes of the z-dependence in different ν-bins.
- First part of the z–dependence at high ν might reflect partonic mechanism; drop at higher z in the lowest ν-bin due to hadron absorption.

2D-analysis: p_t^2 -ranges



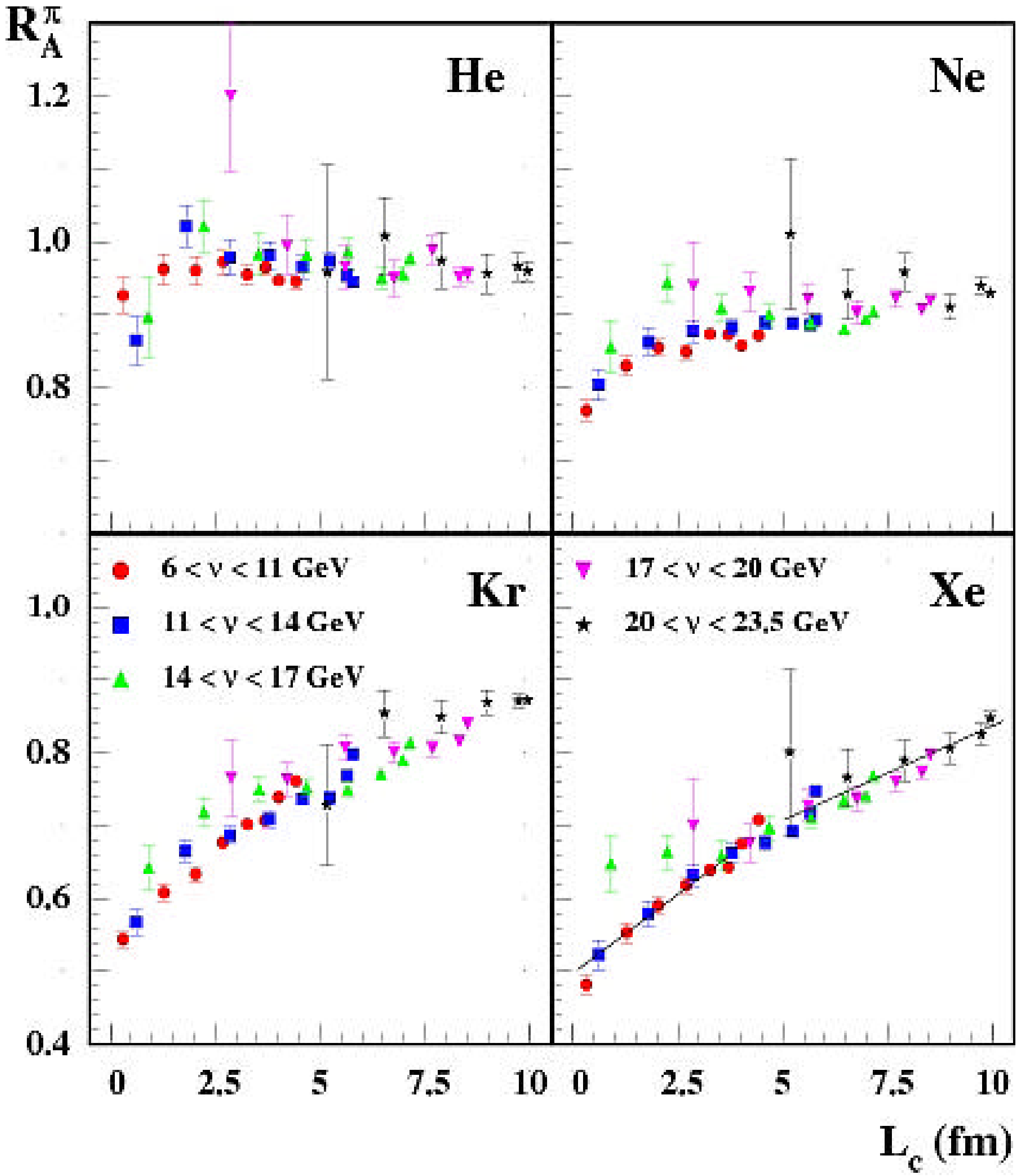
- Larger R at higher p_t^2 and..
- .. smooth ν-dependence (red points)
- - related to the p_t^2 broadening which is correlated with ν
- Broadening gone at high z – parton can't lose energy at z->1 (Kopeliovich)

Formation length: definition and kinematics



- Several definitions for the formation lenght
- The *z*-dependence, normalized by κ/ν
- In leading hadron approximation, z>0.5; polynomial approximation according to Accardi; exact Lund definition.
- Different location of the function maximum
- In HERMES kinematics, unambiguous (monotonous) function

Nuclear Attenuation dependence on the formation length

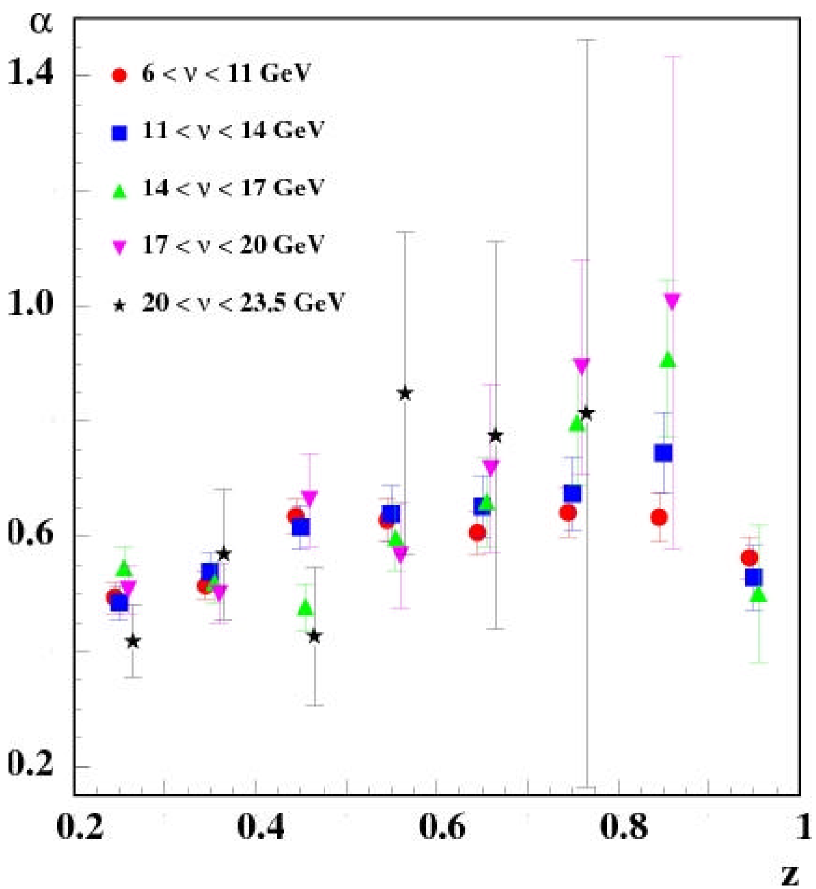


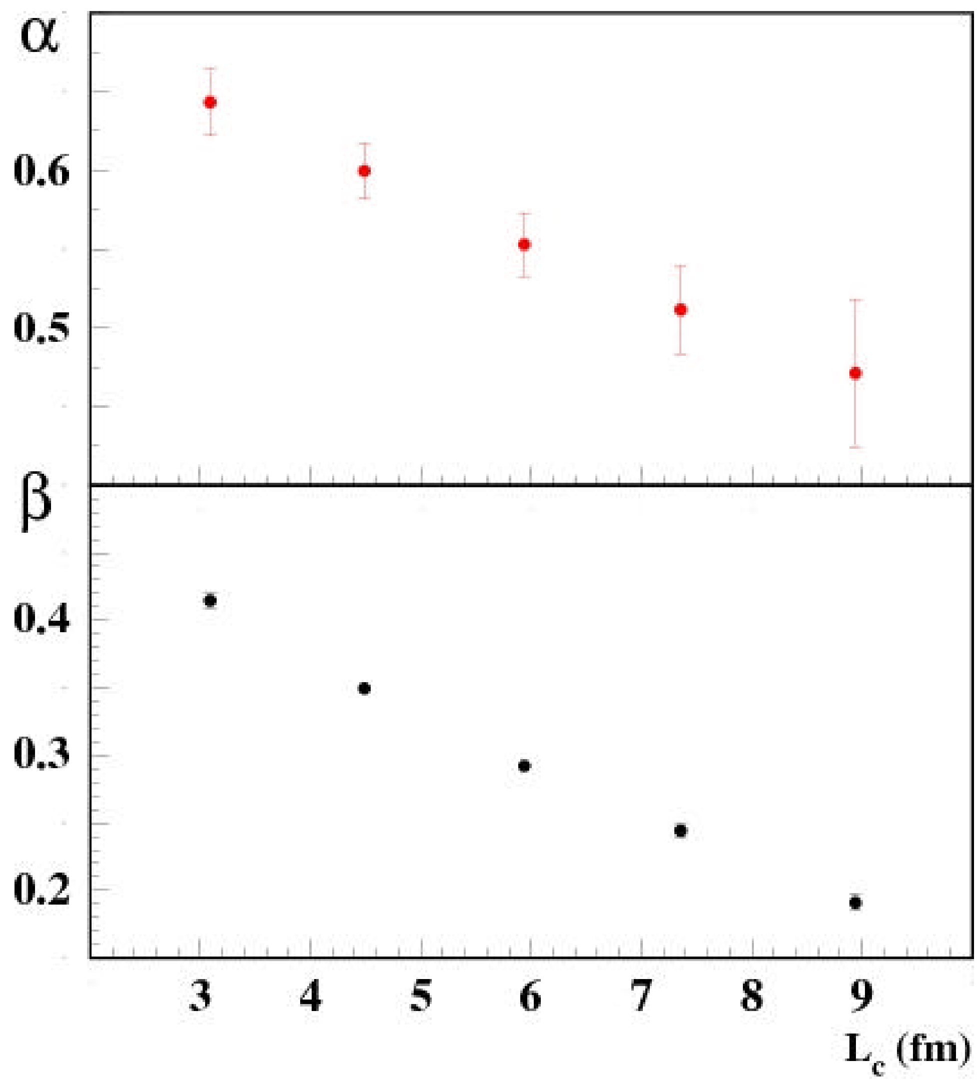
- Scaling behavior for different ν and *z* ranges
- Atomic mass number depedence
- Even at large values of formation length, does not reach 1: still attenuated.
- Partonic mechanism plays a role (pre-hadron in nuclear environment)
- Substantial L-dependence
- The correlated ν, *z* – dependence presented as a function of one variable -
- - the formation length in Accardi approximation

A-dependence

- Two-dimensional binning
- Value of R in each ν, *z* bin – for the fit
- Parametrization according to:

$$R_A^p = \exp\left[-b\,(A/100)^a\right]$$





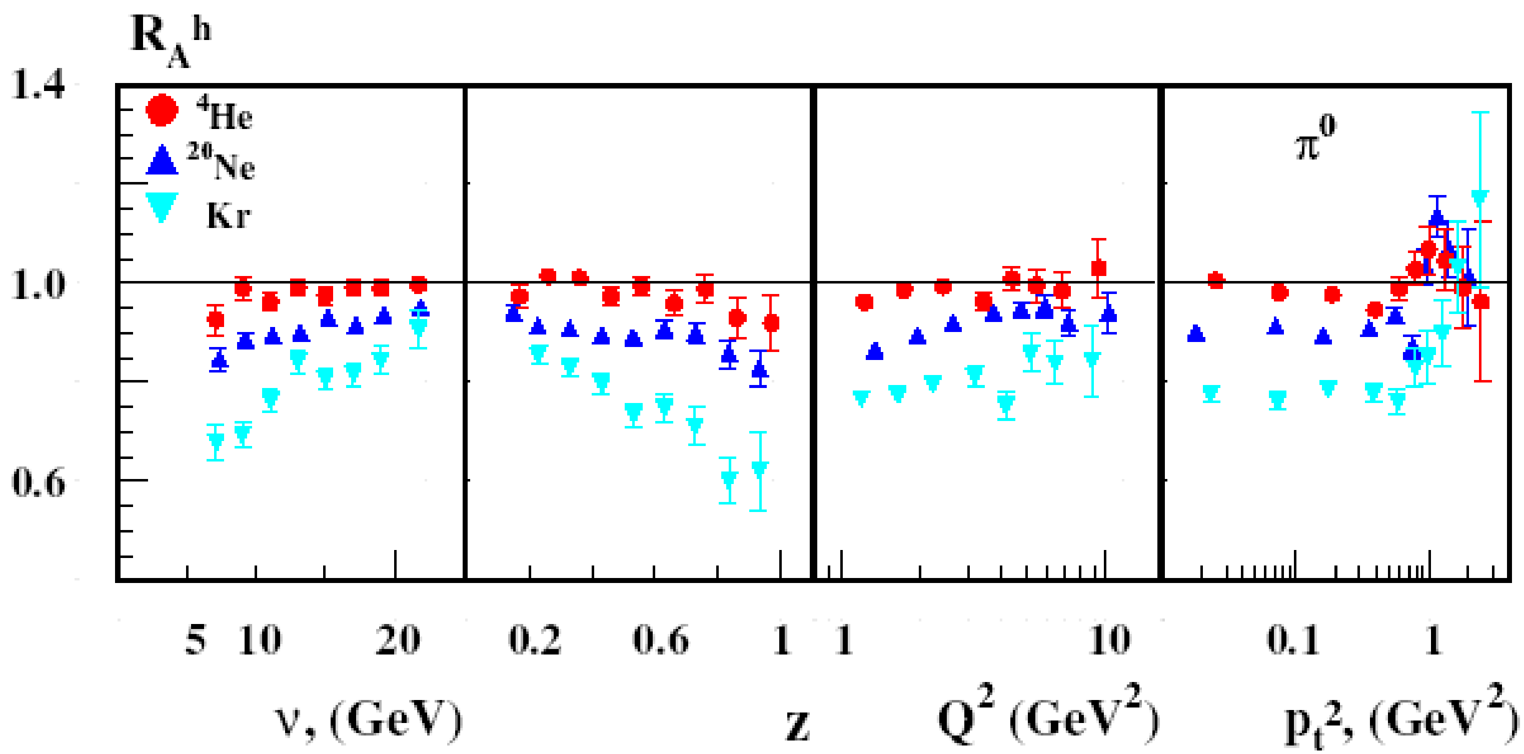
Conclusion

- Major dataset, detailed studies of hadronization on many nuclear targets, basis for theoretical studies.
- Substantial nuclear attenuation observed as a function of kinematic variables such and as ν, z, p_t^2 and Q^2
- Increase of the formation length with higher ν results in less suppression of the hadron yield
- Broadening of p_t^2 due to re-scattering, as observed in *pA* scattering and heavy-ion collisions – Cronin effect
- For the first time, detailed two-dimensional studies of the nuclear attenuation is performed as functions of ν and z, which should assist the refining of theoretical models
- Observed a substantial A-dependence of nuclear attenuation
- For the first time, the formation length dependence of the nuclear attenuation has been studied,
- and the L-dependence of the α parameter in the A^{a} parameterization
- Paper out soon

Theory overview

- Rescaling model
  - Gluon radiation and absorption of the produced hadron (A. Accardi et al)
- FF modification model
  - Modification of parton FF to account for energy loss: multiple scattering and gluon bremsstrahlung. (X.-N. Wang et al)
- Gluon Bremsstrahlung model
  - Vacuum and induced energy loss, attenuation of colorless pre-hadrons in nuclear medium (B. Kopeliovich et al)
- FSI by means of BUU transport
  - Full coupled-channel treatment of FSI by means of BUU transport model, where while interacting with the nucleon, hadron may not only be absorbed but can also be decelerated in an elastic or inelastic collision (T.Falter et al)
- String models
  - Colorless pre-hadronic system – string – propagates in nuclear medium, multiple interactions and gluon radiation (e.g. B.Andersson et al, T. Sjostrand et al, A. Bialas et al)

Results: neutral pions



- Multiplicity ratio for π^0 is consistent with the one for the charged pions