Nuclear medium effects on hadronization

Hadron attenuation and p_t-broadening

Yves Van Haarlem

Carnegie Mellon University

for the HERMES collaboration

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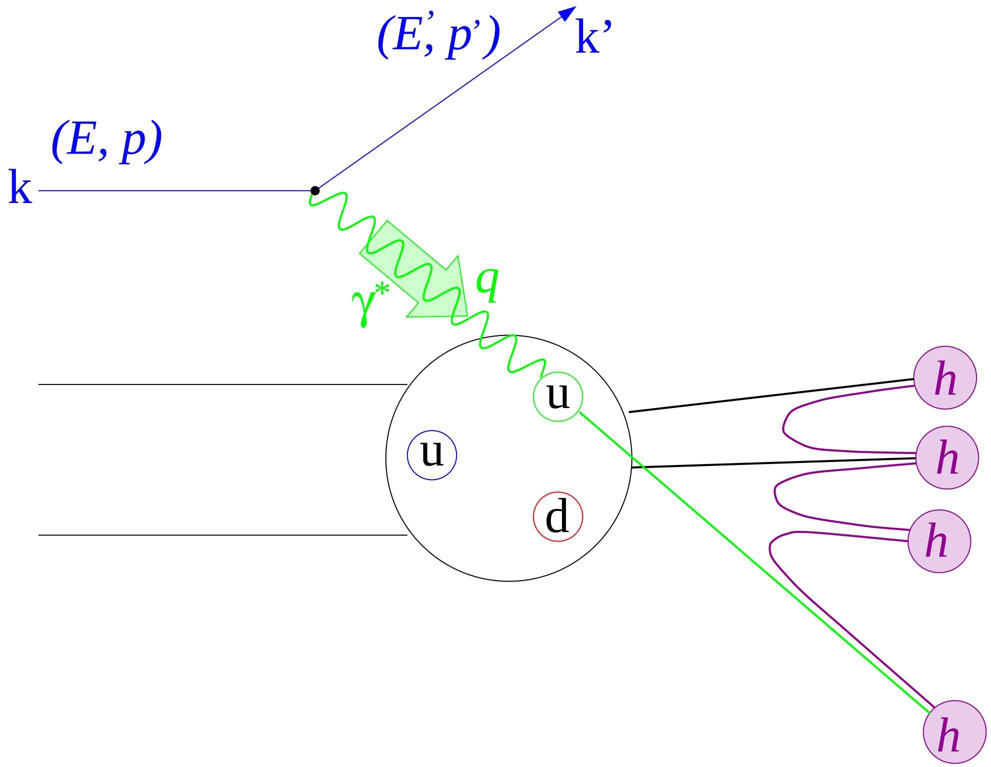
Outline

- (nuclear) SIDIS
- Nuclear effects
- Models
- Experiment
- Results

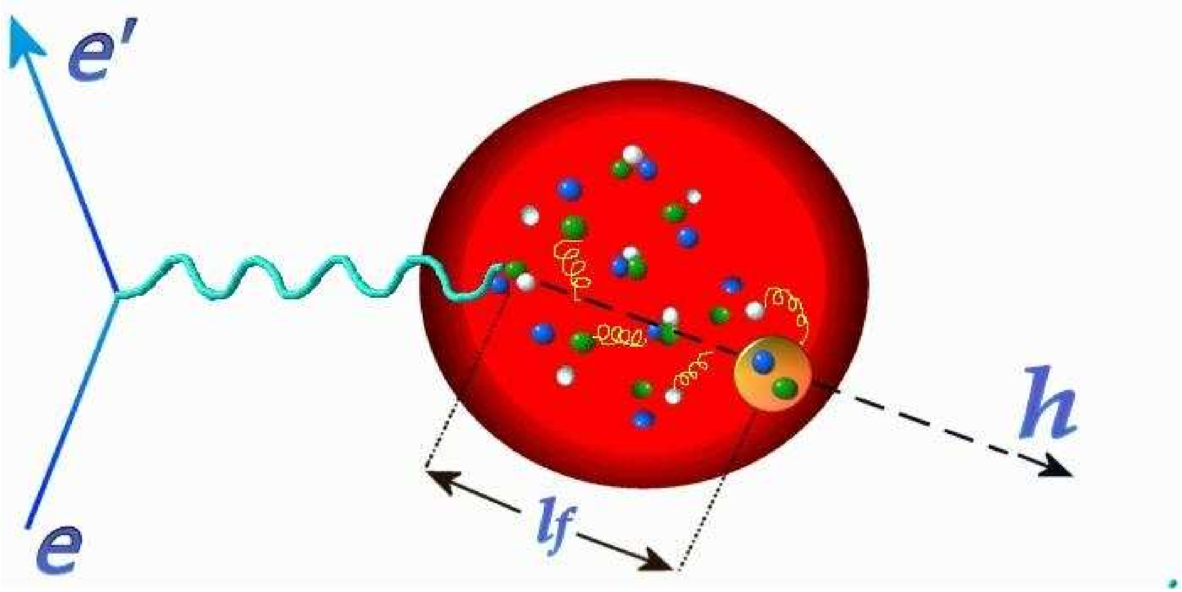
Semi-inclusive Deep-Inelastic Scattering (DIS)



$$d\sigma \propto \sum_f e_f^2 \cdot q_f(x_{bj}, Q^2) \cdot \sigma \cdot D_f^h(z, Q^2)$$

- $e^{\pm}$ + N $\rightarrow$ $e^{\pm}$ + h + X
- $q^2 = -Q^2$: squared 4-momentum transfer
- ν = $E_{\gamma *}$ = $E - E'$ (target rest frame)
- W^2 = $(\mathbf{N} + \mathbf{q})^2$: squared invariant mass $\gamma^* N$
- $x_{bj} = \frac{Q^2}{2M\nu}$
- z = $\frac{E_h}{\nu}$
- p_t: momentum of hadron transverse to γ^*

Nuclear semi-inclusive DIS as hadronization laboratory



- Investigate hadronization with a nucleus
- Nano lab to study hadronization

  ⇒ Multiple scattering centers (1-2 fm)

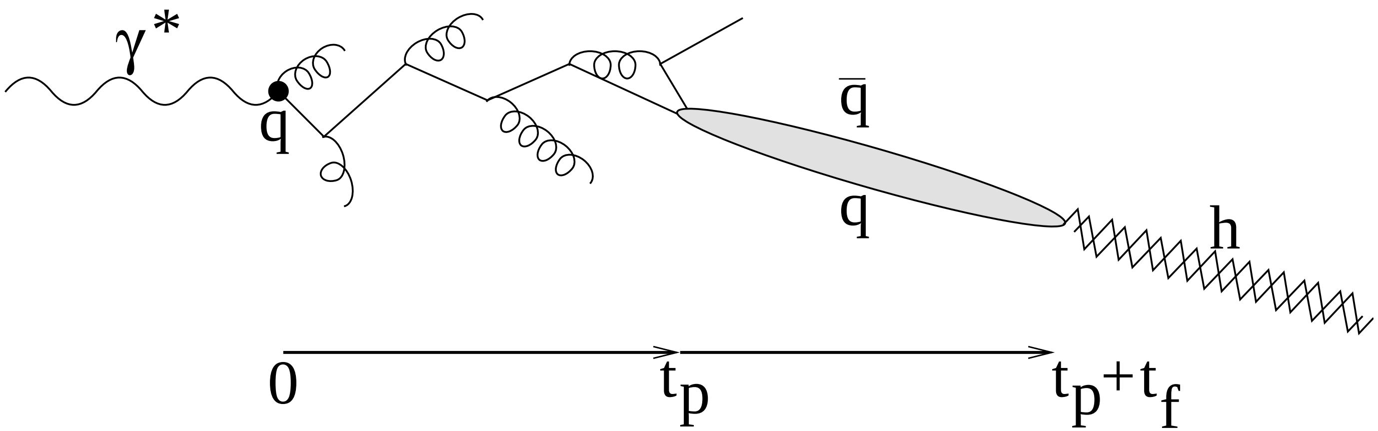
- Nuclear effects like:

  ⇒ EMC effect: $\frac{\sigma_A}{\sigma_N}(x_{bj}) \neq 1$

  ⇒ Nuclear attenuation

  ⇒ p_t-broadening

Space-time evolution of hadronization



- Parton propagation ($t < t_p$)

  $\Rightarrow$ Gluon radiation

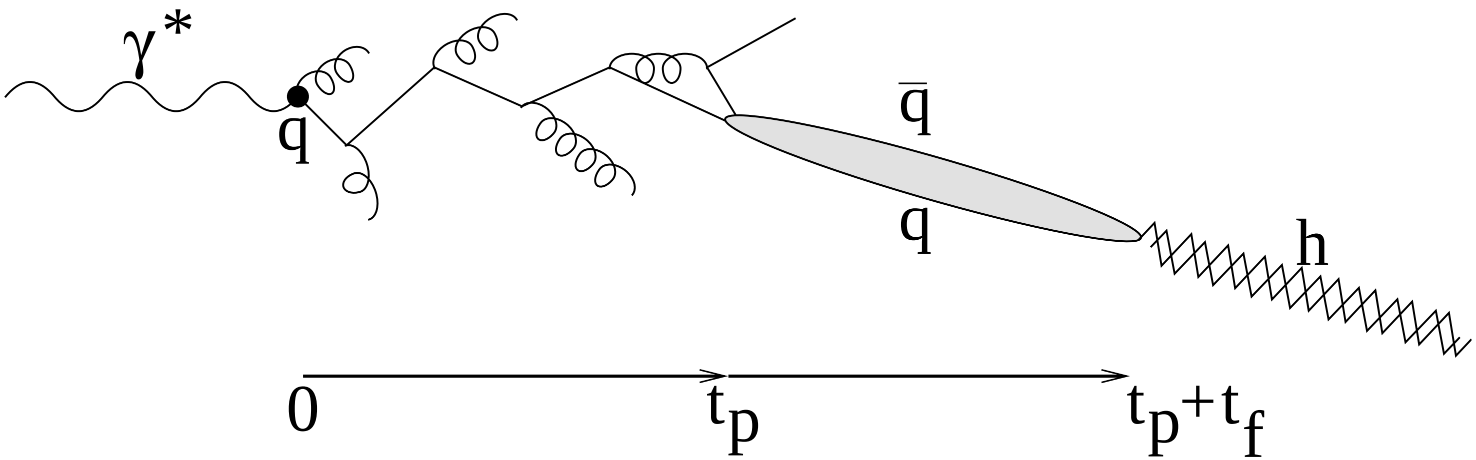
- pre-hadron ($t_p < t < t_p + t_f$)

  $\Rightarrow$ Off-shell hadron
  $\Rightarrow$ Virtual hadron
  $\Rightarrow$ Colorless $q\overline{q}$

- Final state hadron ($t > t_p + t_f$)

  $\Rightarrow$ Known hadron-nucleon cross section

Space-time evolution of hadronization: hadron attenuation



- $R^h(z,\nu,Q^2,p_t^2,\phi_h) = \dfrac{\left[\dfrac{N_h(z,\nu,Q^2,p_t^2,\phi_h)}{N_{\mathrm{DIS}}(\nu,Q^2)}\right]_{\mathrm{A}}}{\left[\dfrac{N_h(z,\nu,Q^2,p_t^2,\phi_h)}{N_{\mathrm{DIS}}(\nu,Q^2)}\right]_{\mathrm{D}}}$

$\Rightarrow$ Called hadron multiplicity ratio

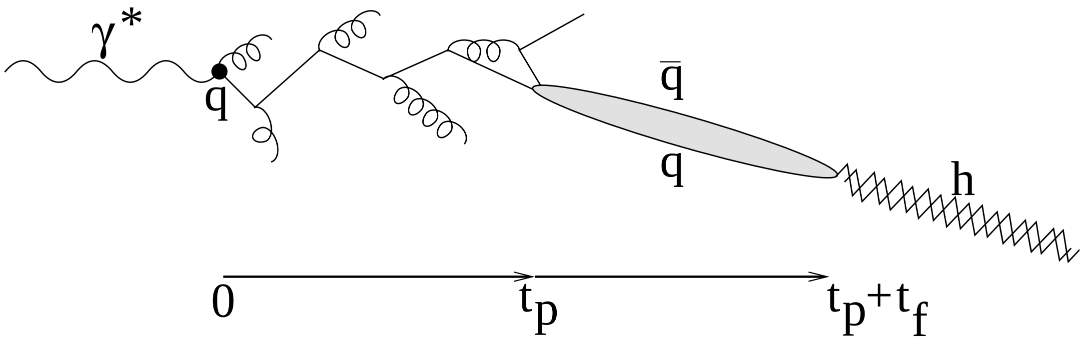
$\Rightarrow$ Effect: hadron attenuation

  $*$ Shift to lower energy

  $*$ Absorption (e.g. $K^- p \rightarrow \Lambda$)

$\Rightarrow$ Sensitive to $t_p + t_f$

Space-time evolution of hadronization: p_t-broadening



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

  $\Rightarrow$ Called p_t-broadening

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

  $\Rightarrow$ In later stages no broadening occurs
  - $*$ Inelastic scattering suppressed
  - $*$ $\sigma_{elastic}$ very small
    - $\cdot$ Pions mfp $>$ 20 fm

- R^h and t_p access to t_f

Models: partonic/hadronic oriented

Partonic

- Parton energy loss

  ⇒ F. Arleo
  JHEP **11** (2002) 44

  ⇒ X.N. Wang and X. Guo
  Nucl.Phys.A **696** (2001) 788

Hadronic

- PYTHIA + BUU transport model

  ⇒ T. Falter et al.
  Nucl.Phys.B **594** (2004) 61

- Rescaling + nuclear absorption

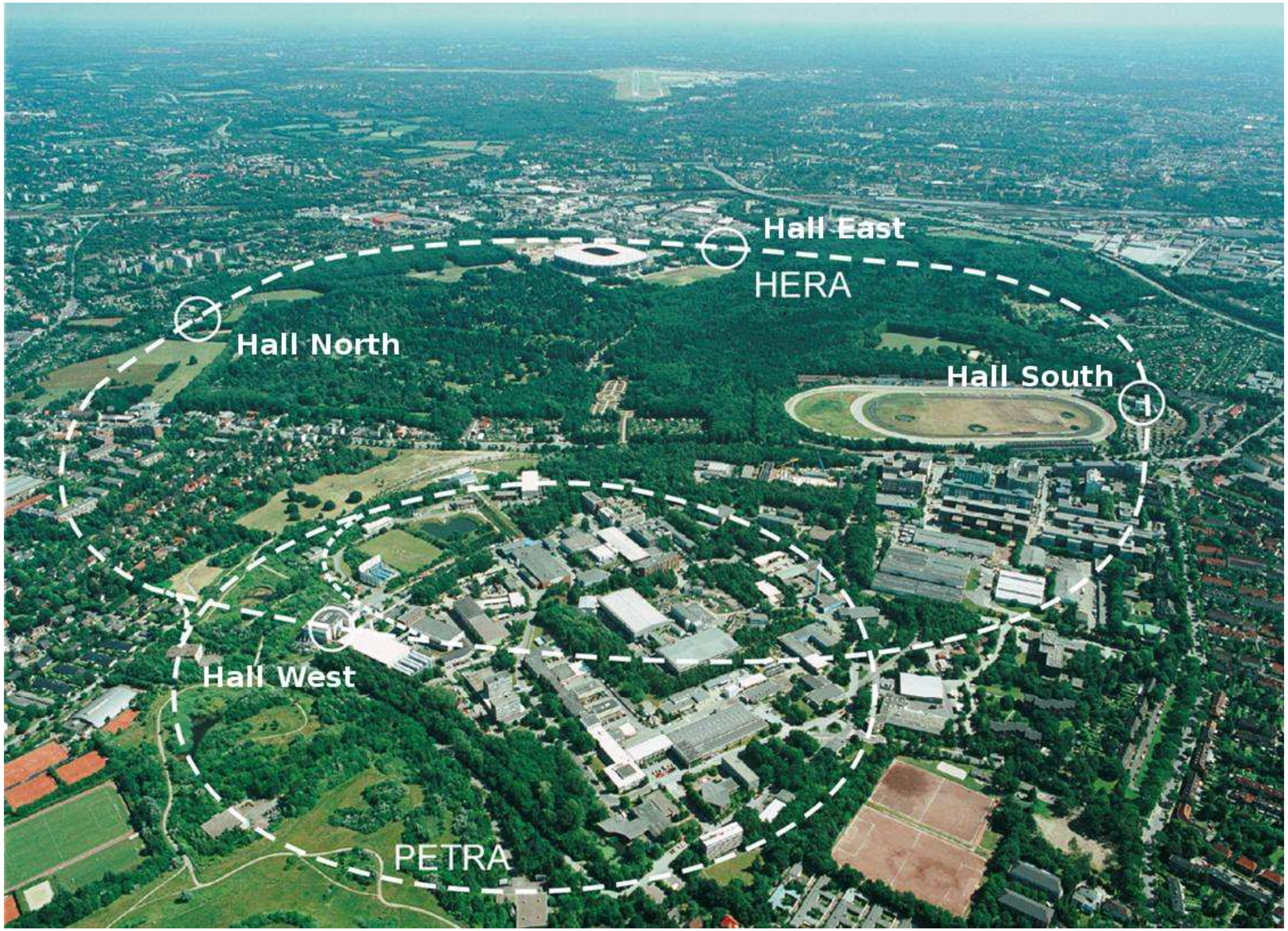
  ⇒ J. Dias De Deus
  Phys.Lett.B **166** (1986) 98

  ⇒ A. Accardi et al.
  Nucl.Phys.A **720** (2003) 131

- Gluon bremsstrahlung

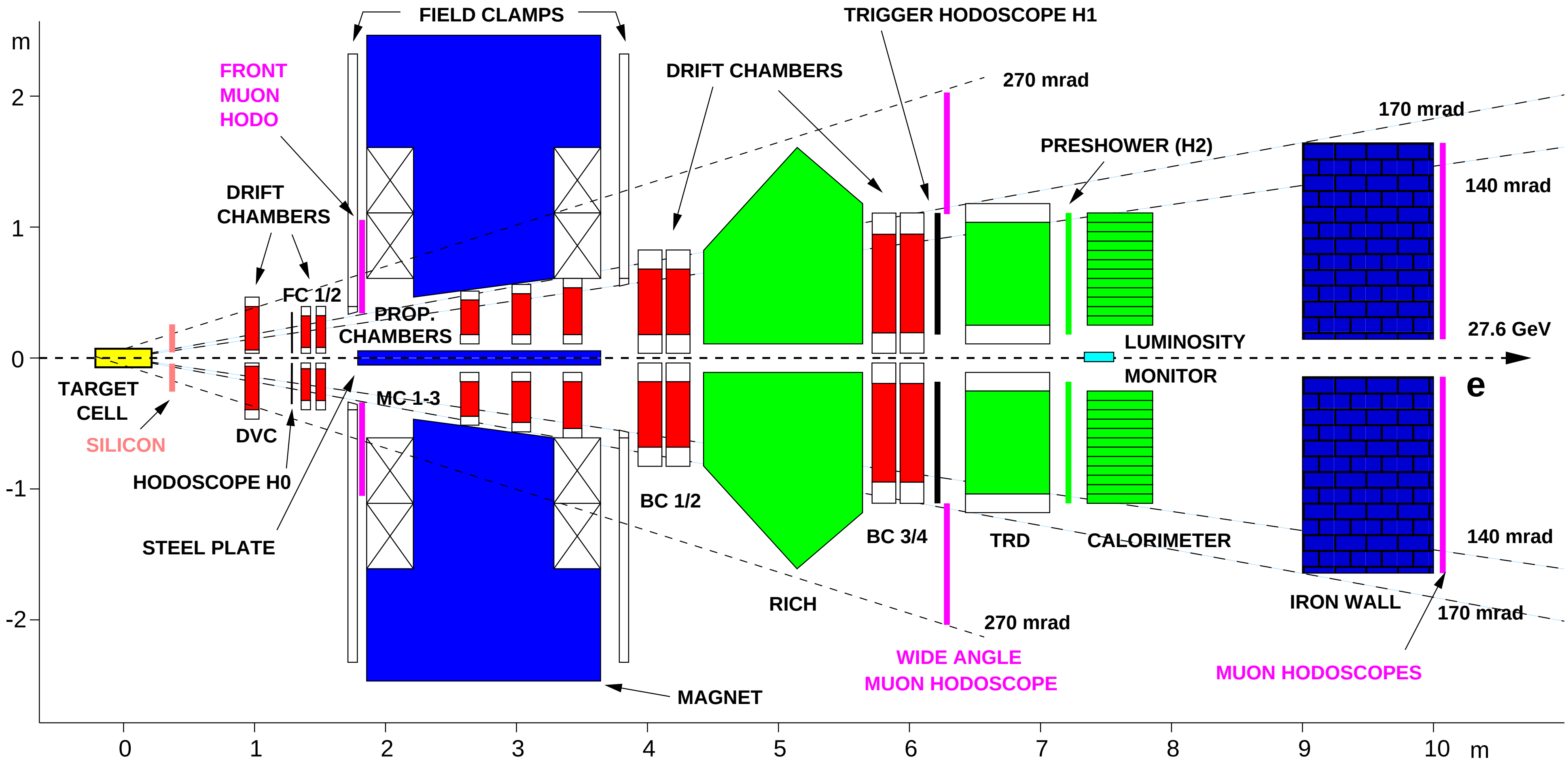
  ⇒ B.Z. Kopeliovic et al.
  Nucl.Phys.A **740** (2003) 211

Experimental setup



Was operational until June 30, 2007, 23:00h

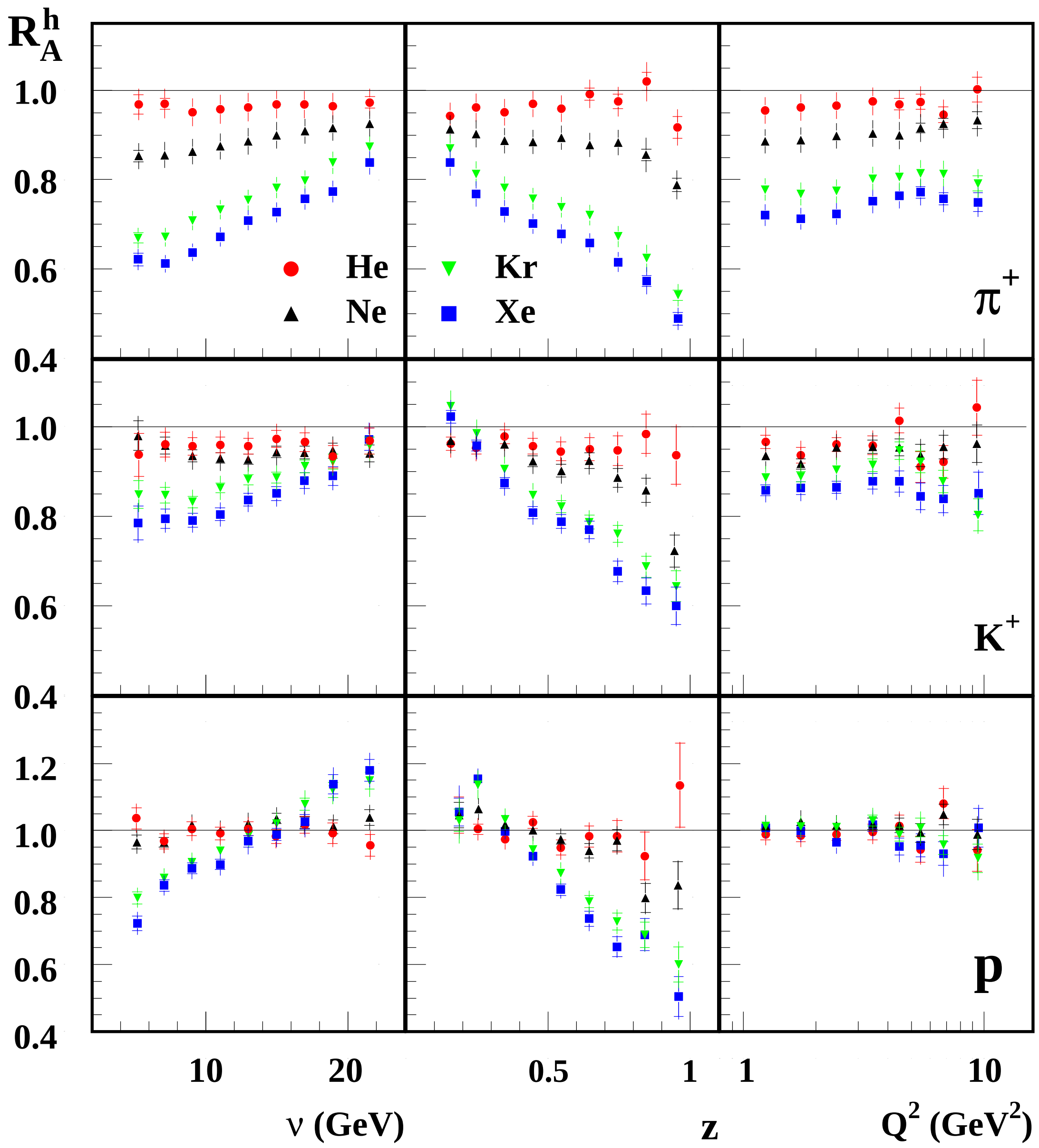
Side view of the HERMES spectrometer



Tracking Momentum measurement Particle identification (l/h $>$ 98%)

27.6 GeV $e^{\pm}$ on “fixed” gas target: H , D, ^{3}He, ^{4}He, N, Ne, Kr, Xe

Multiplicity ratio: kinematic dependencies



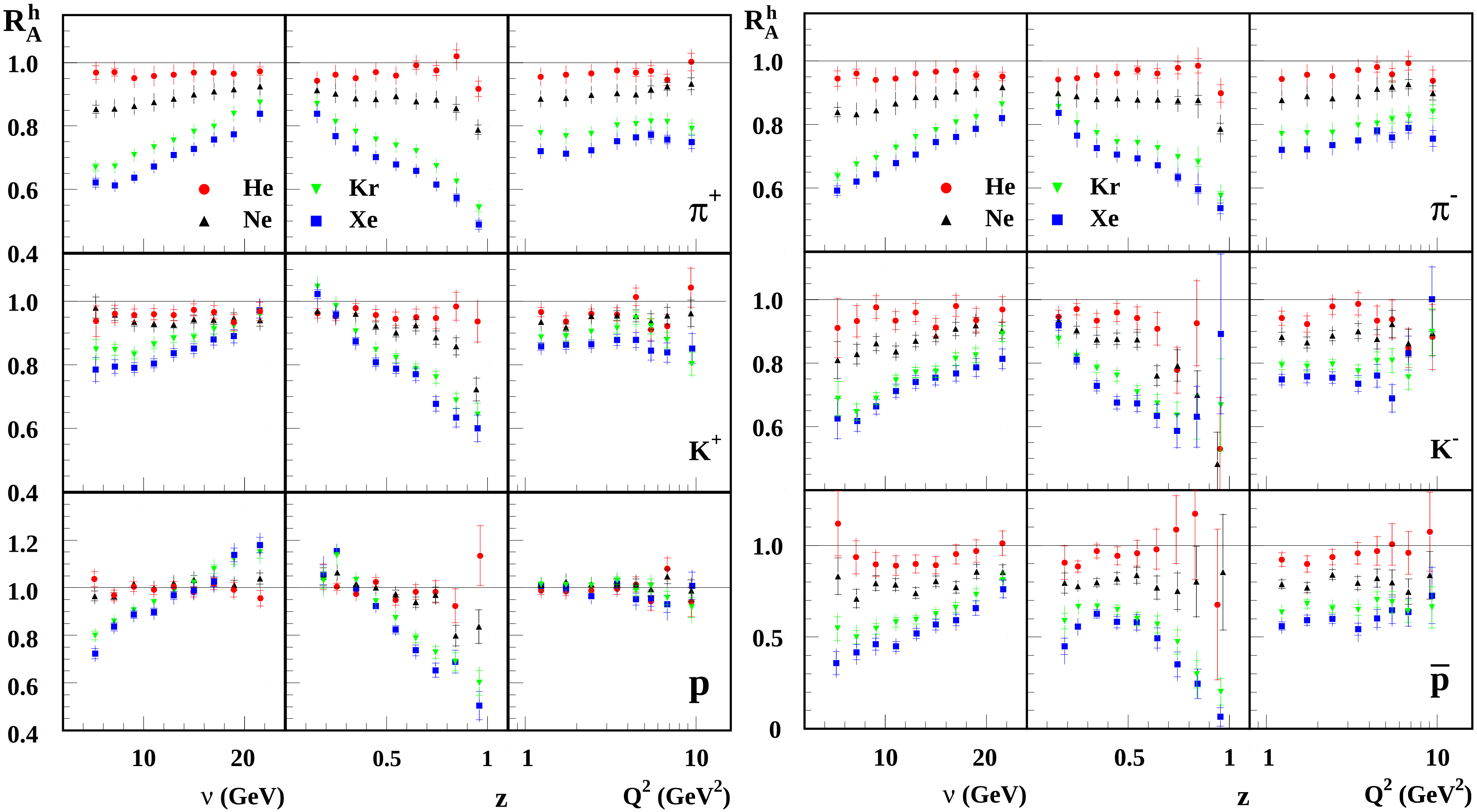
- $$R^h = \frac{\left[\frac{N_h(z,\nu,Q^2,p_t^2,\phi_h)}{N_{\mathrm{DIS}}(\nu,Q^2)}\right]_A}{\left[\frac{N_h(z,\nu,Q^2,p_t^2,\phi_h)}{N_{\mathrm{DIS}}(\nu,Q^2)}\right]_D}$$
- Clear A-dependence
- ν-dependence

  ⇒ Lorentz-boost

  ⇒ Hadron formed outside nucleus
- z-dependence

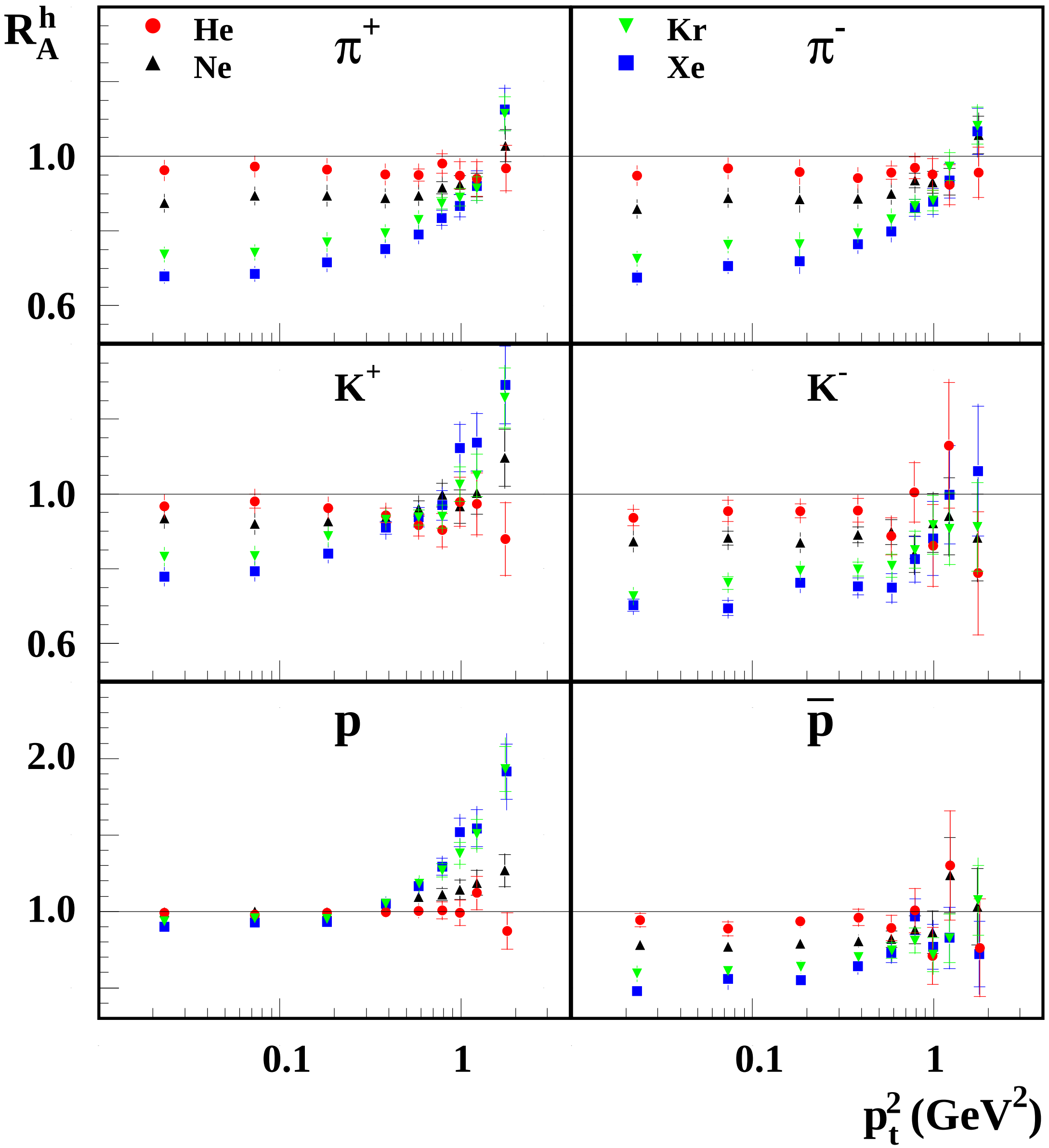
  ⇒ $z \to 1$ no interaction
- Small Q^2 dependence

Multiplicity ratio: different hadrons



$\pi^+ = \pi^-$ $K^+ \neq K^-$: $pK^- \to \Lambda$ $p \neq \bar{p}$: p in nucleus

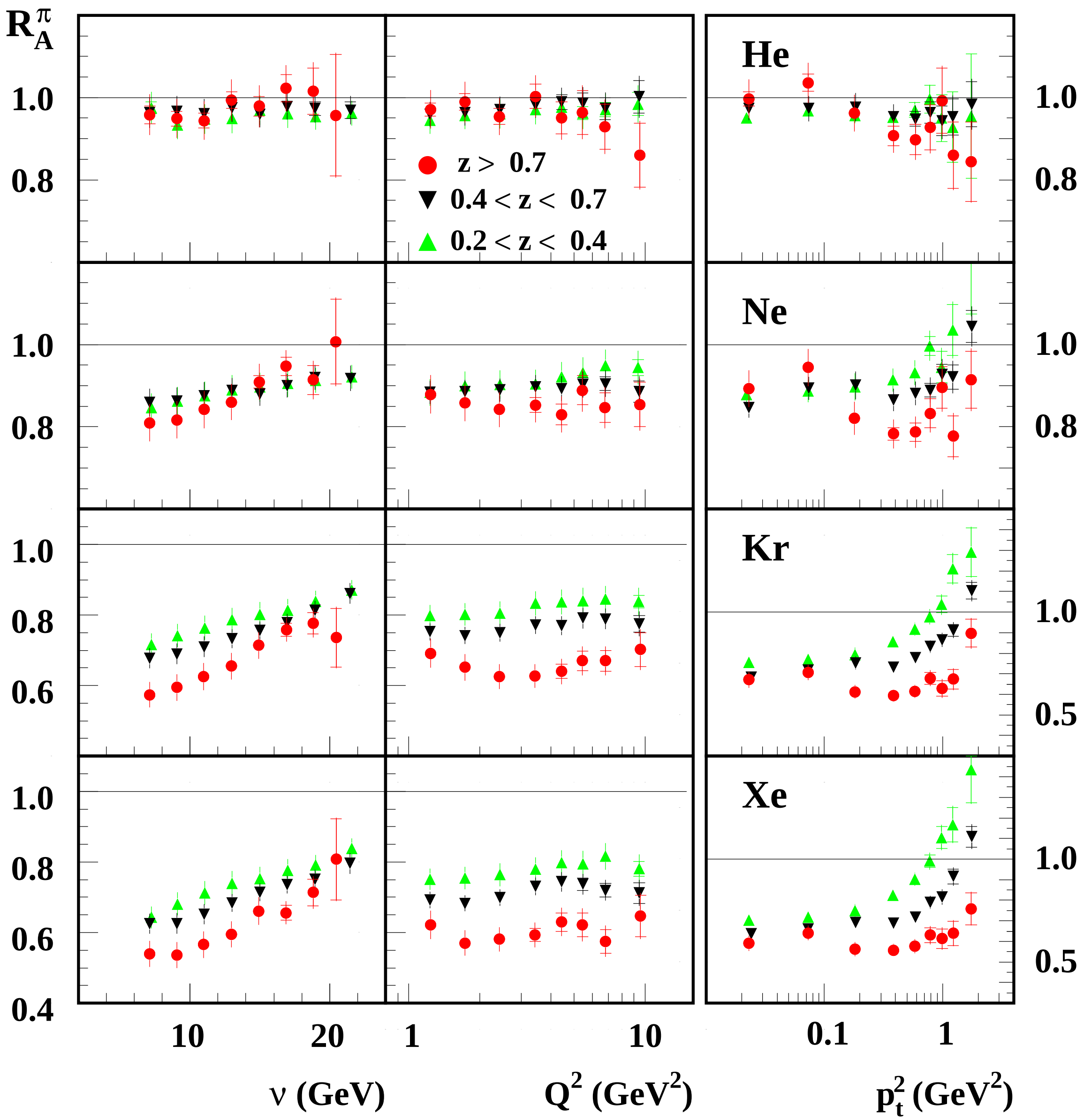
Cronin effect



- Cronin effect without ISI
- First measurement
  for different hadron types
- Higher for p

  $\Rightarrow$ consistent with ion-ion

Multiplicity ratio 2D

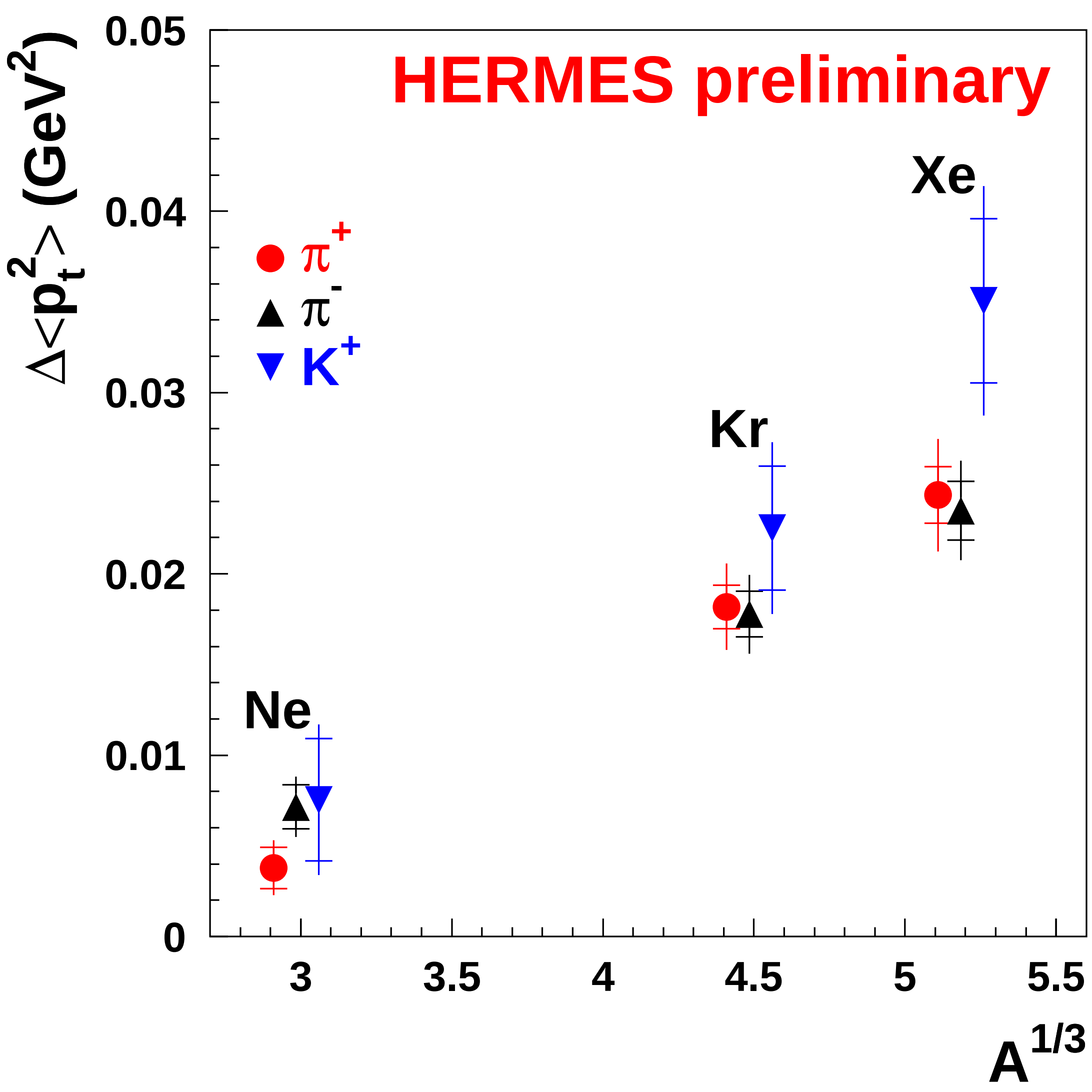


- 2D plot - $\pi^{\pm}$

  $\Rightarrow$ Excellent statistics example plot

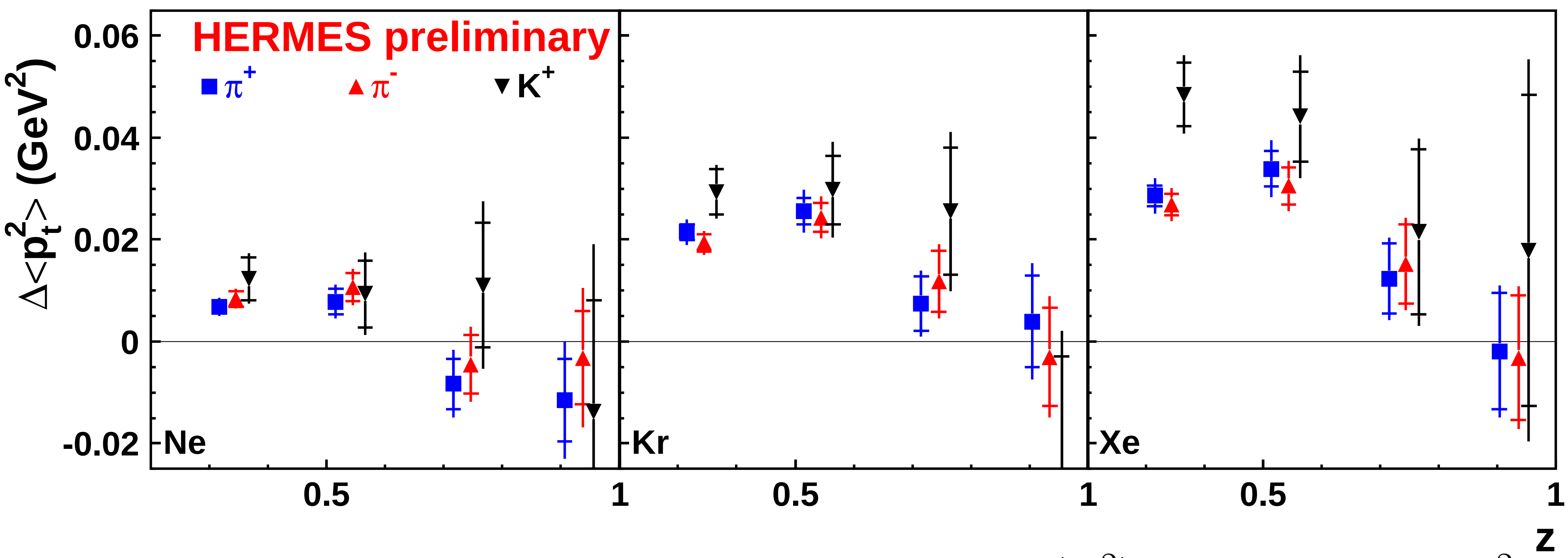
- Cronin effect reduced at high z

p_t-broadening versus A$^{1/3}$



- $\Delta\langle p_t^2\rangle^h = \langle p_t^2\rangle_A^h - \langle p_t^2\rangle_D^h$
- First measurement of p_t-broadening in DIS
- Linear vs A$^{1/3}$
- $\langle p_t^2\rangle$ around 0.25 GeV^2 - large effect
- $\langle Q^2\rangle$ = 2.4 GeV^2
- $\langle \nu\rangle$ = 14.5 GeV
- $\langle z\rangle$ = 0.39

p_t-broadening versus z

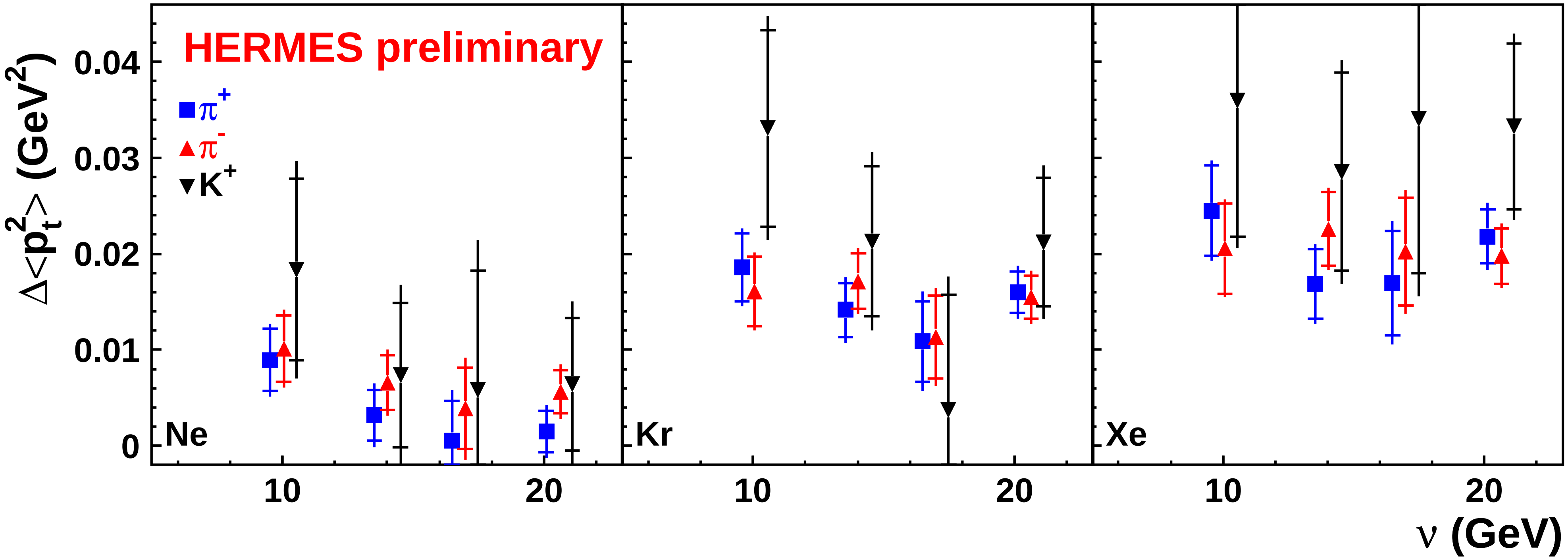


- $\langle Q^2 \rangle^\pi$ = 2.4 $\rightarrow$ 2.1 GeV^2
- $\langle \nu \rangle^\pi$ = 15 $\rightarrow$ 11 GeV
- $\langle Q^2 \rangle^{K^+}$ = 2.5 $\rightarrow$ 2.5 GeV^2
- $\langle \nu \rangle^{K^+}$ = 15 $\rightarrow$ 12 GeV

- Broadening dominated by gluon radiation

$\Rightarrow$ $z \rightarrow 1$: broadening to zero
$\Rightarrow$ therefore $t_p \rightarrow 0$

p_t-broadening versus ν

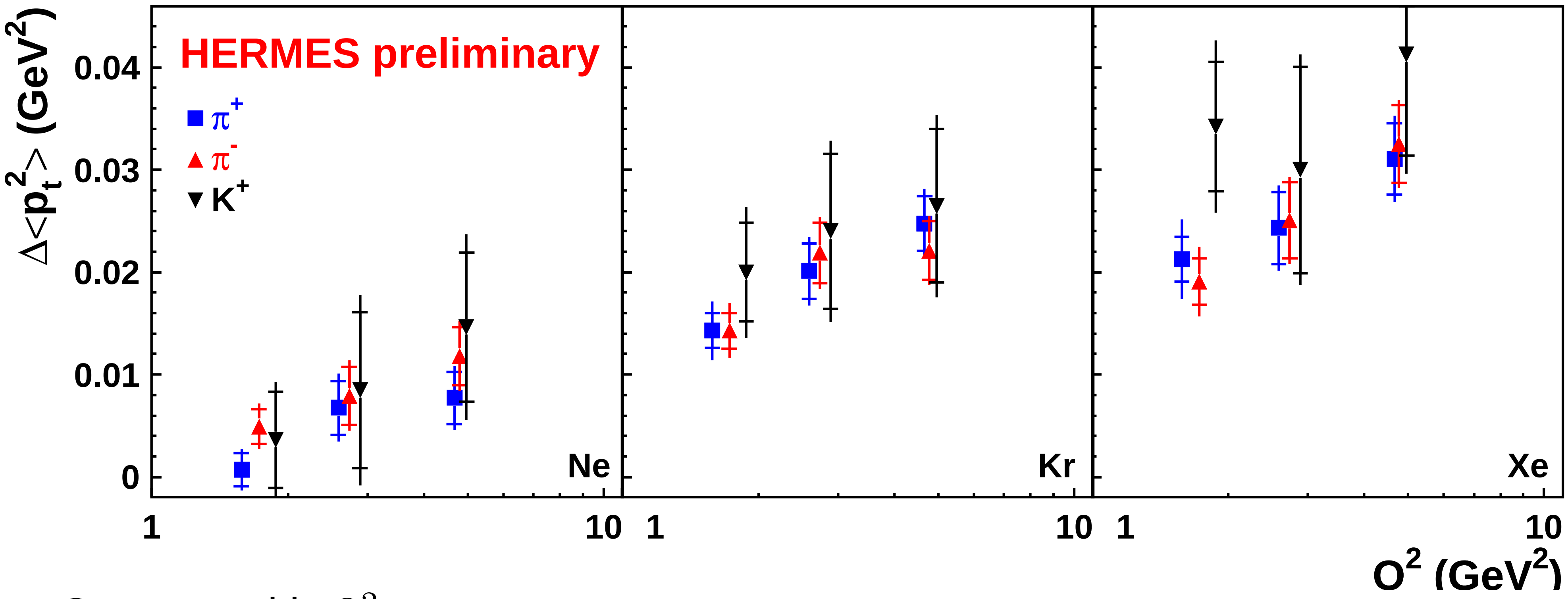


- $\langle Q^2 \rangle^{\pi}$ = 2.1 $\rightarrow$ 2.4 GeV^2
- $\langle z \rangle^{\pi}$ = 0.46 $\rightarrow$ 0.34
- $\langle Q^2 \rangle^{K^+}$ = 2.1 $\rightarrow$ 2.4 GeV^2
- $\langle z \rangle^{K^+}$ = 0.46 $\rightarrow$ 0.37

- Broadening is constant

$\Rightarrow$ pre-hadron formed outside nucleus
$\Rightarrow$ In favor of partonic effects

p_t-broadening versus Q^2



- Goes up with Q^2
- Gluon-bremsstrahlung model

$\Rightarrow$ $t_p \downarrow$ with Q^2
$\Rightarrow$ Other behaviors are fine (A$^{1/3}$, ν, z)
$\Rightarrow$ BUT $\langle z \rangle$ not above 0.5

- $\langle \nu \rangle$ = 14 $\rightarrow$ 15 GeV
- $\langle z \rangle$ = 0.40 $\rightarrow$ 0.39

Conclusions

- HERMES provides the largest data set concerning the space-time evolution of hadronization.

$\Rightarrow$ Final attenuation results using all HERMES data

- $\ast$ Different hadron types
- $\ast$ Versus several kinematic variables
- $\ast$ 2D analysis
- $\ast$ Excellent statistics

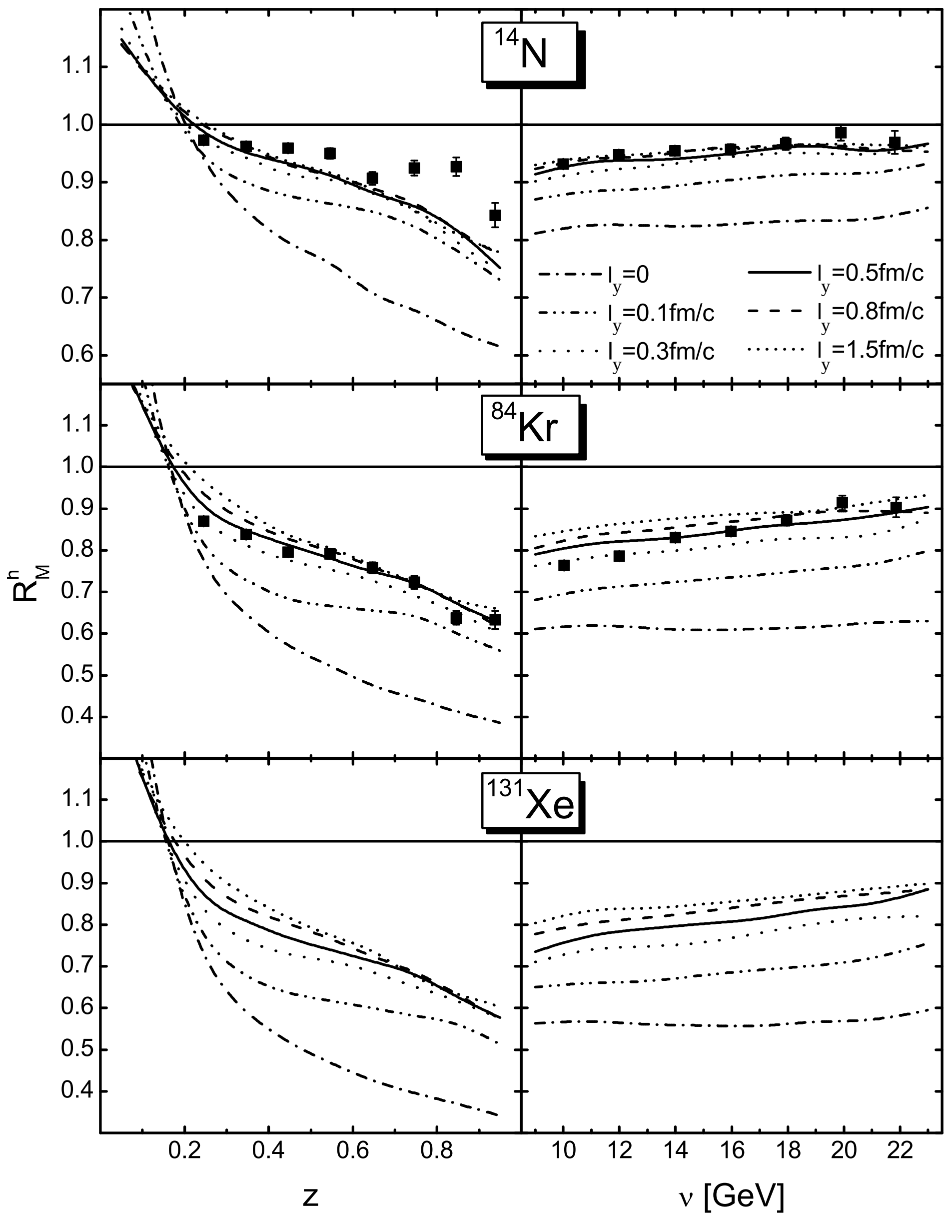
Nucl. Phys. B 780 (2007) 1-27

$\Rightarrow$ First direct measurement of p_t-broadening in semi-inclusive DIS

- $\ast$ Different hadron types
- $\ast$ Versus several kinematic variables
- $\ast$ A clear signal of broadening is observed
- $\ast$ Constraint on pre-hadron mechanism

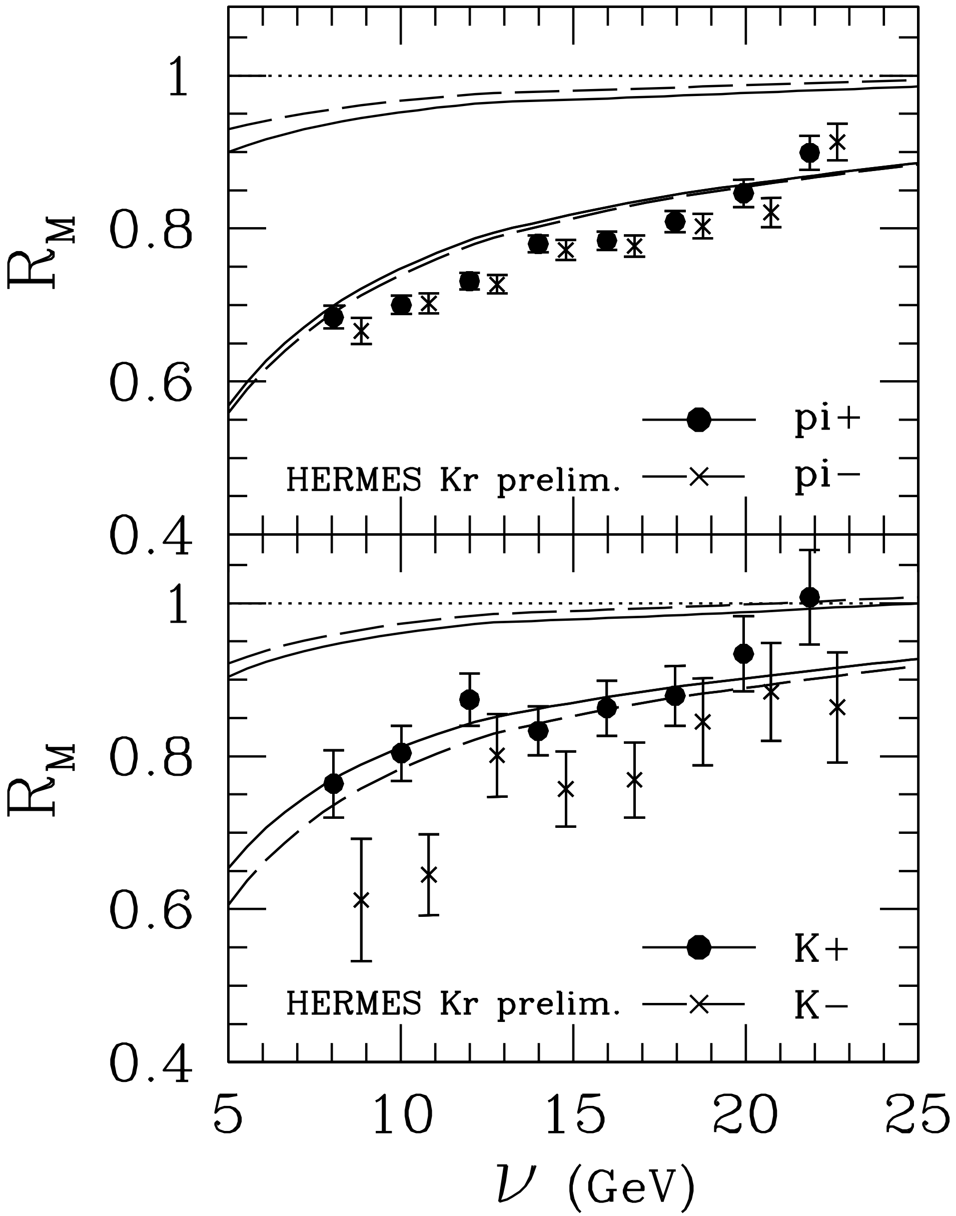
arXiv:0704.3712 [hep-ex]

Additional: BUU



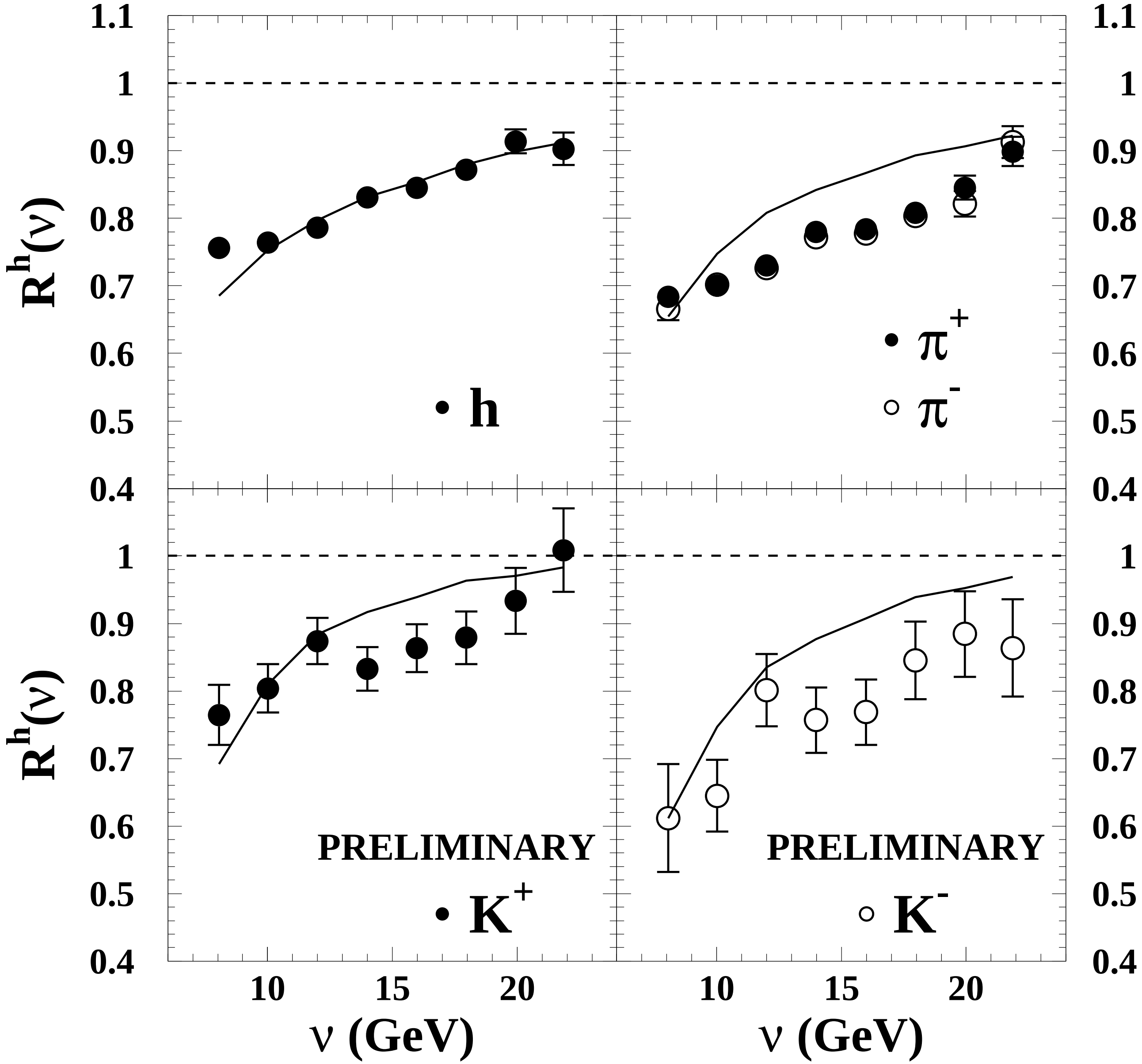
- $t_p = 0$
- $\sigma_{prehadron} = 0.33 \cdot \sigma_{hadron}$

Additional: rescaling

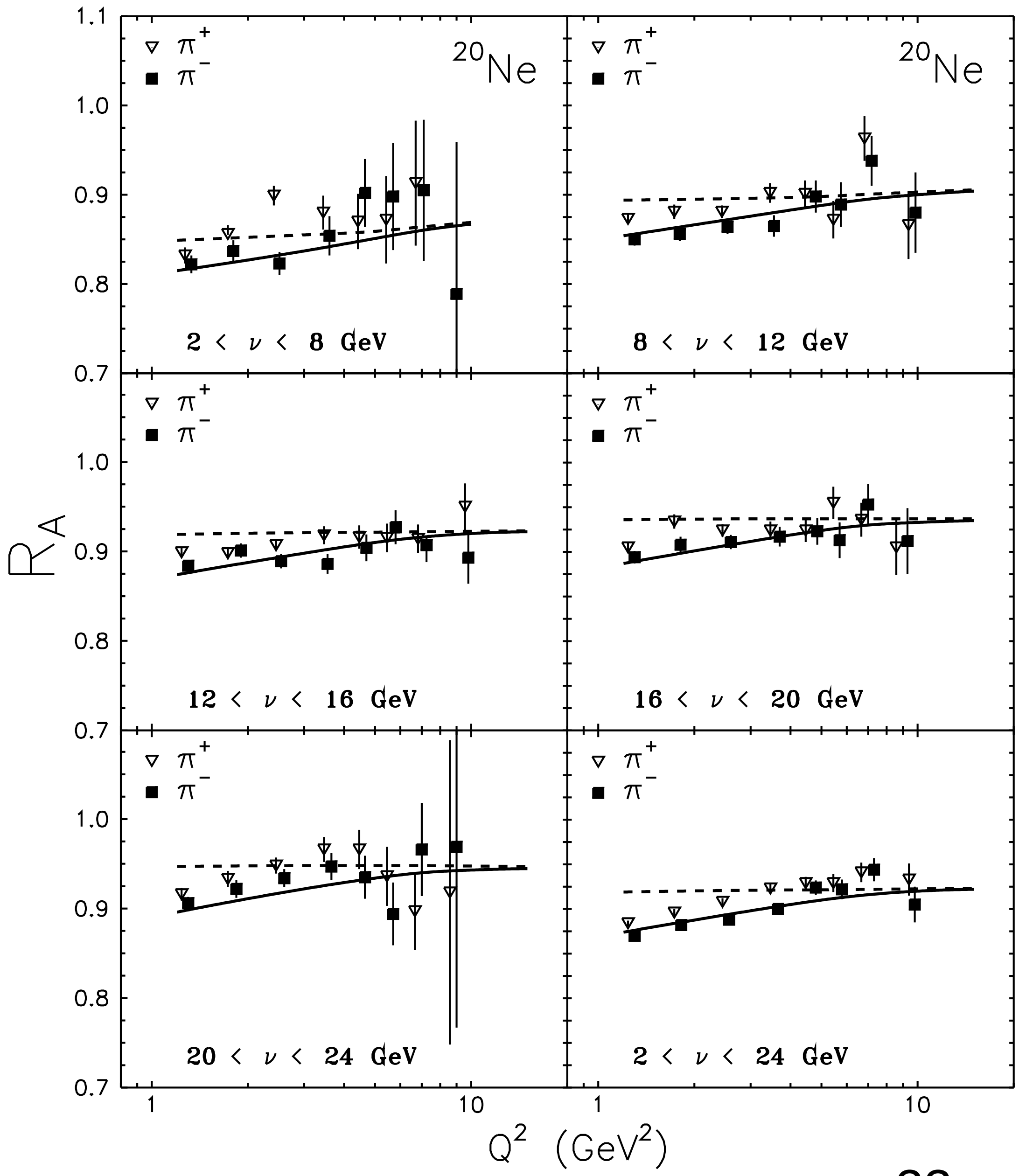


- with/without nuclear absorption

Additional: parton energy loss



Additional: Gluon bremsstrahlung



- with/without induced gluon radiation