Nuclear effects at HERMES

Hadron attenuation and p_t-broadening

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for the HERMES collaboration

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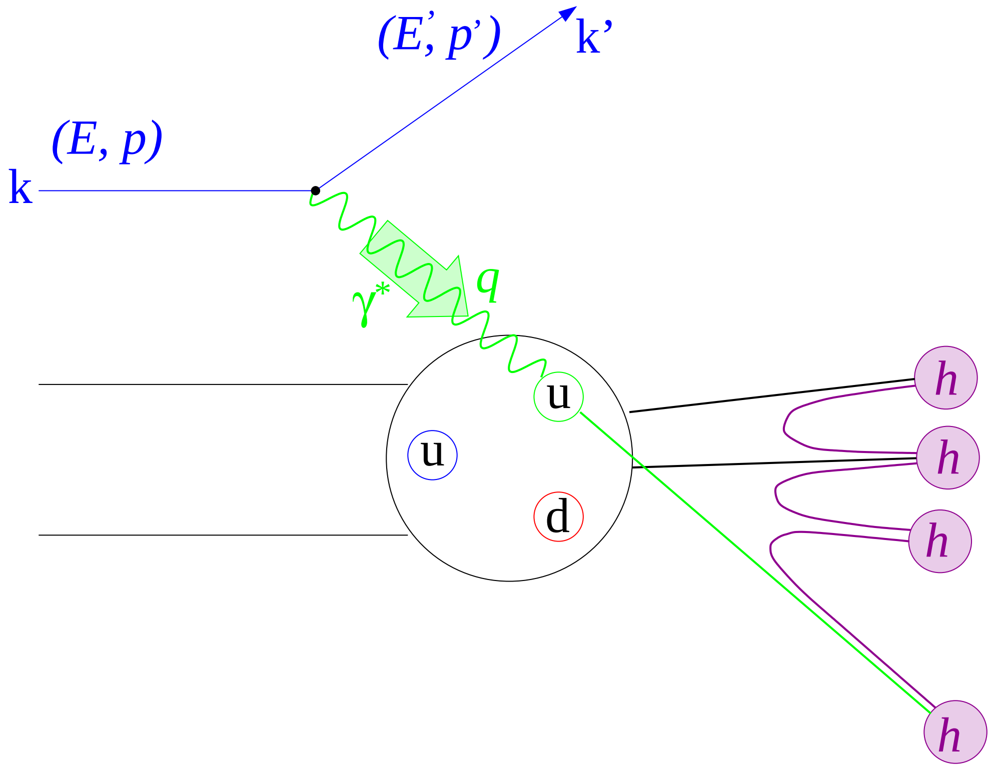
Outline

- (nuclear) SIDIS
- Nuclear effects
- Models
- Set up and analysis
- Results

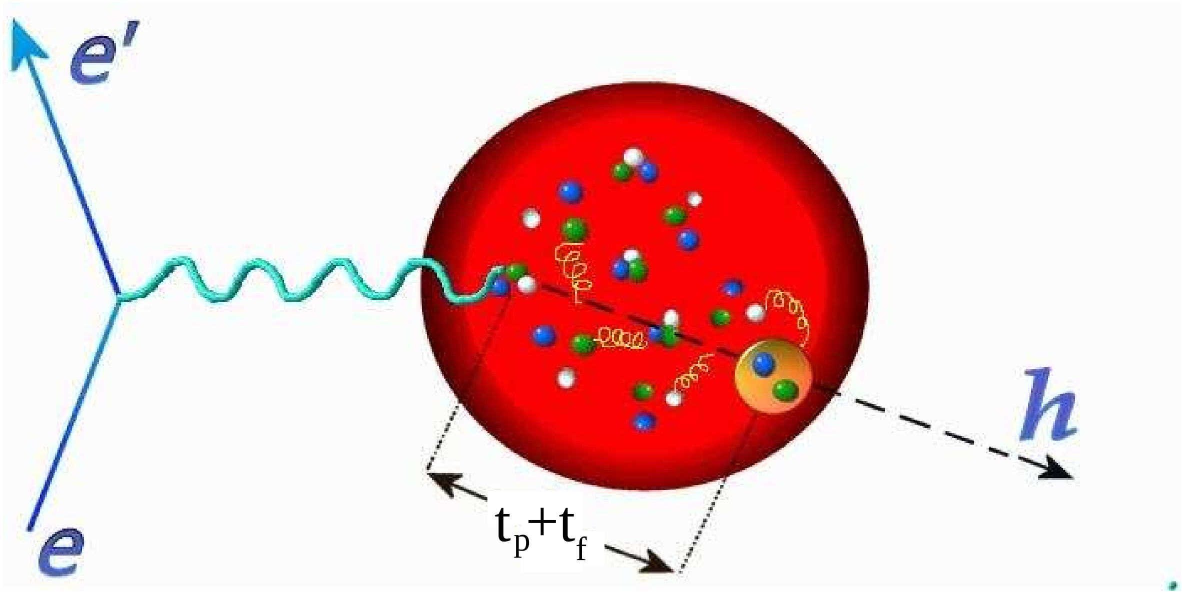
Semi-inclusive Deep-Inelastic Scattering (DIS)



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

- $e^{\pm}$ + 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)

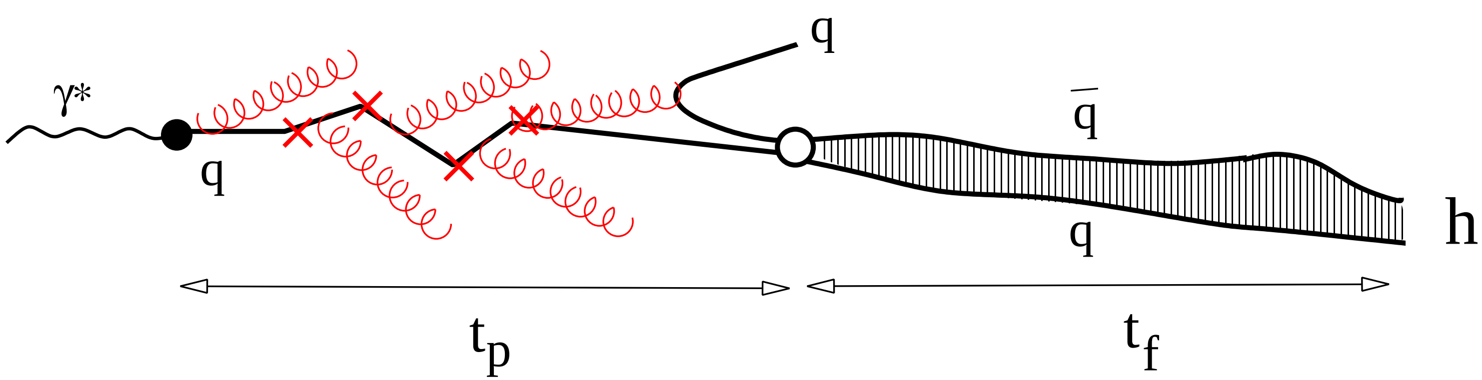
- Nuclear effects like:

  ⇒ 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

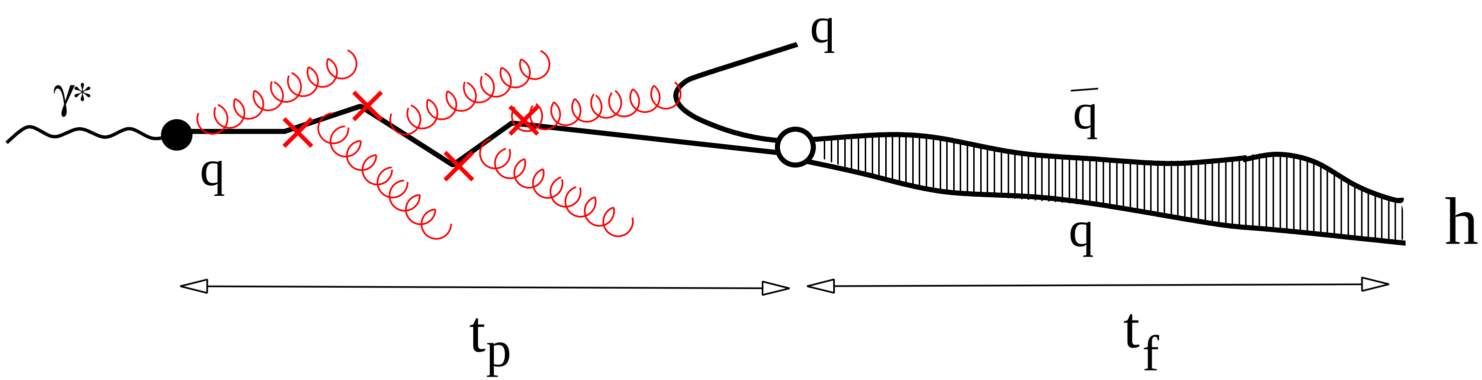
- pre-hadron ($t_p < t < t_f$)

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

- Final state hadron ($t > t_f$)

  $\Rightarrow$ Known hadron-nucleon cross section

Space-time evolution of hadronization: hadron attenuation



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

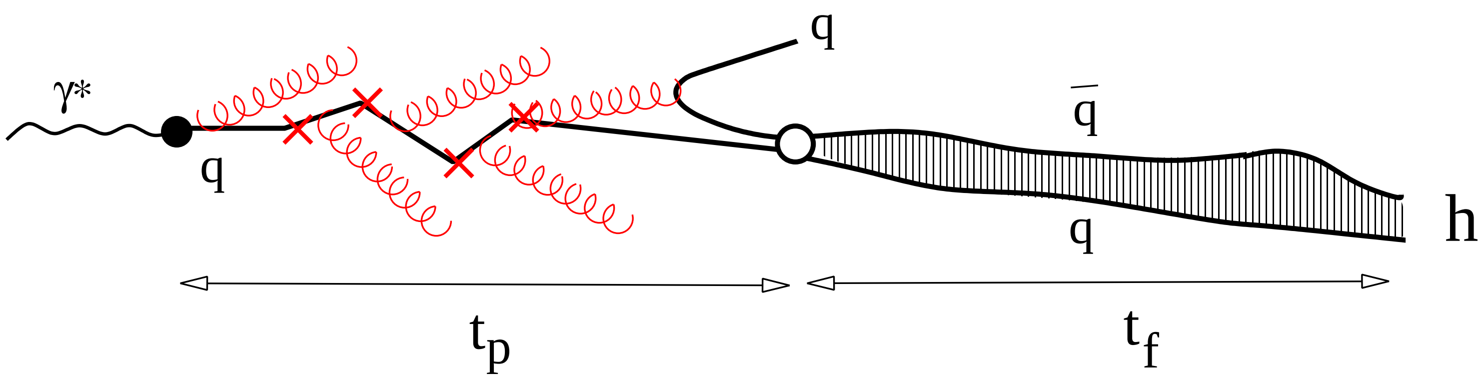
  $\Rightarrow$ Called hadron multiplicity ratio

  $\Rightarrow$ 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

- $R^h + t_p$ 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

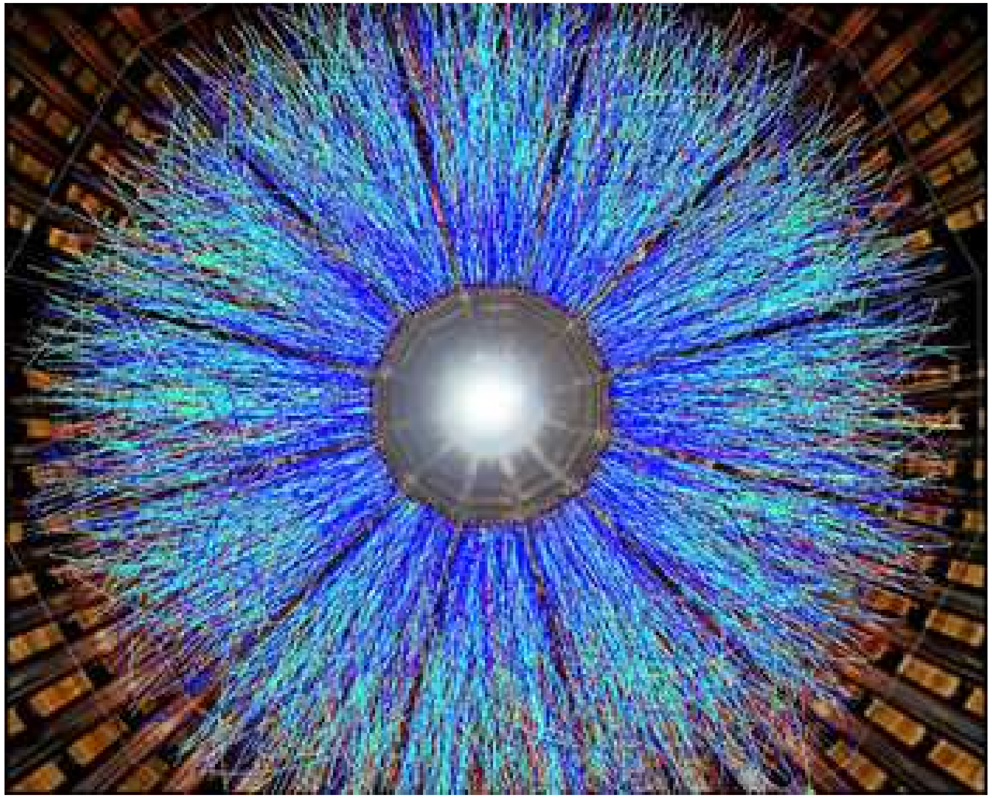
  ⇒ J. Dias De Deus
  Phys.Lett.B **166** (1986) 98

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

- Gluon bremsstrahlung

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

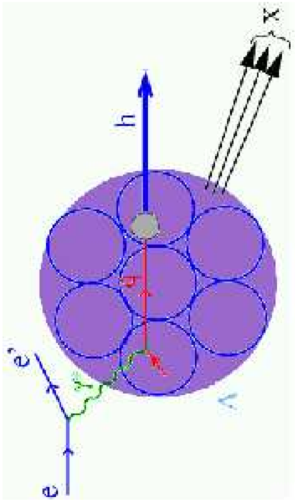
More reasons for nuclear semi-inclusive DIS

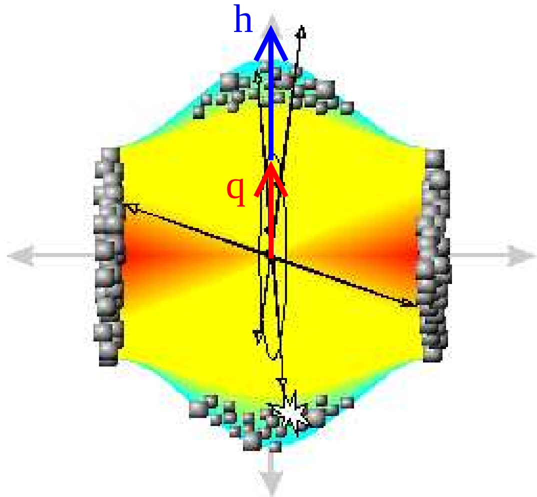


Gold-gold collision at RHIC
$\sim$ 1500 tracks

- Cold nuclear matter
- No Initial State Interactions
  - $\Rightarrow$ Clean
  - $\Rightarrow$ Initial state kinematics known
- At HERMES no jets
  $\rightarrow$ $\langle$1 event$\rangle$: 3.5 tracks
- Helps understanding ion-ion collisions

Cold versus hot nuclear matter



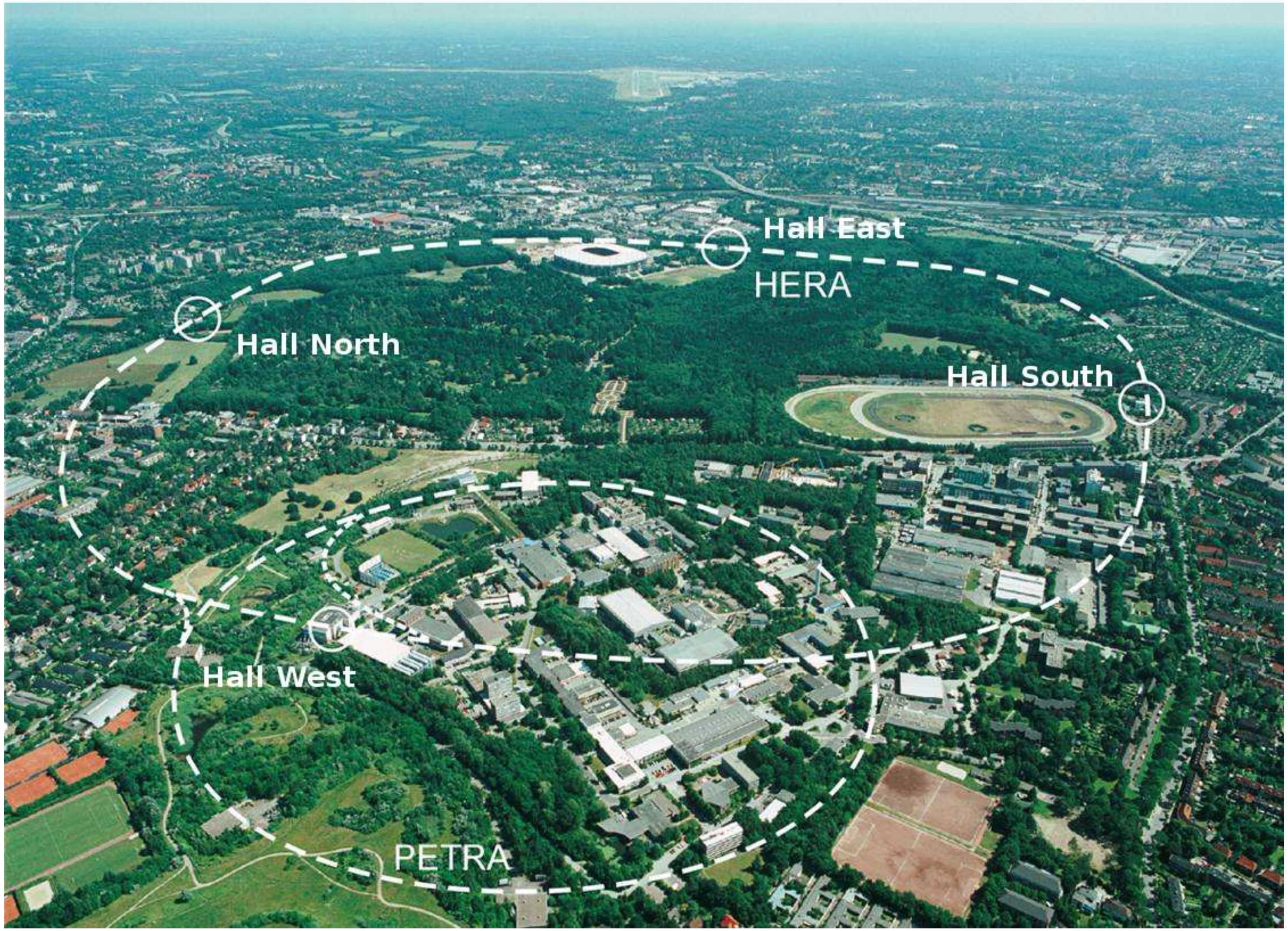


- $E_q = \nu =$13 GeV
- $E_h = z\nu =$ 2-15 GeV
- Q^2 is known
- Always forward pseudorapidity

- $E_q \propto \frac{p_t}{z}$
- $E_h = p_t =$ 2-20 GeV
- $Q^2 \equiv E_q^2 \propto (\frac{p_t}{z})^2$
- All pseudorapidities

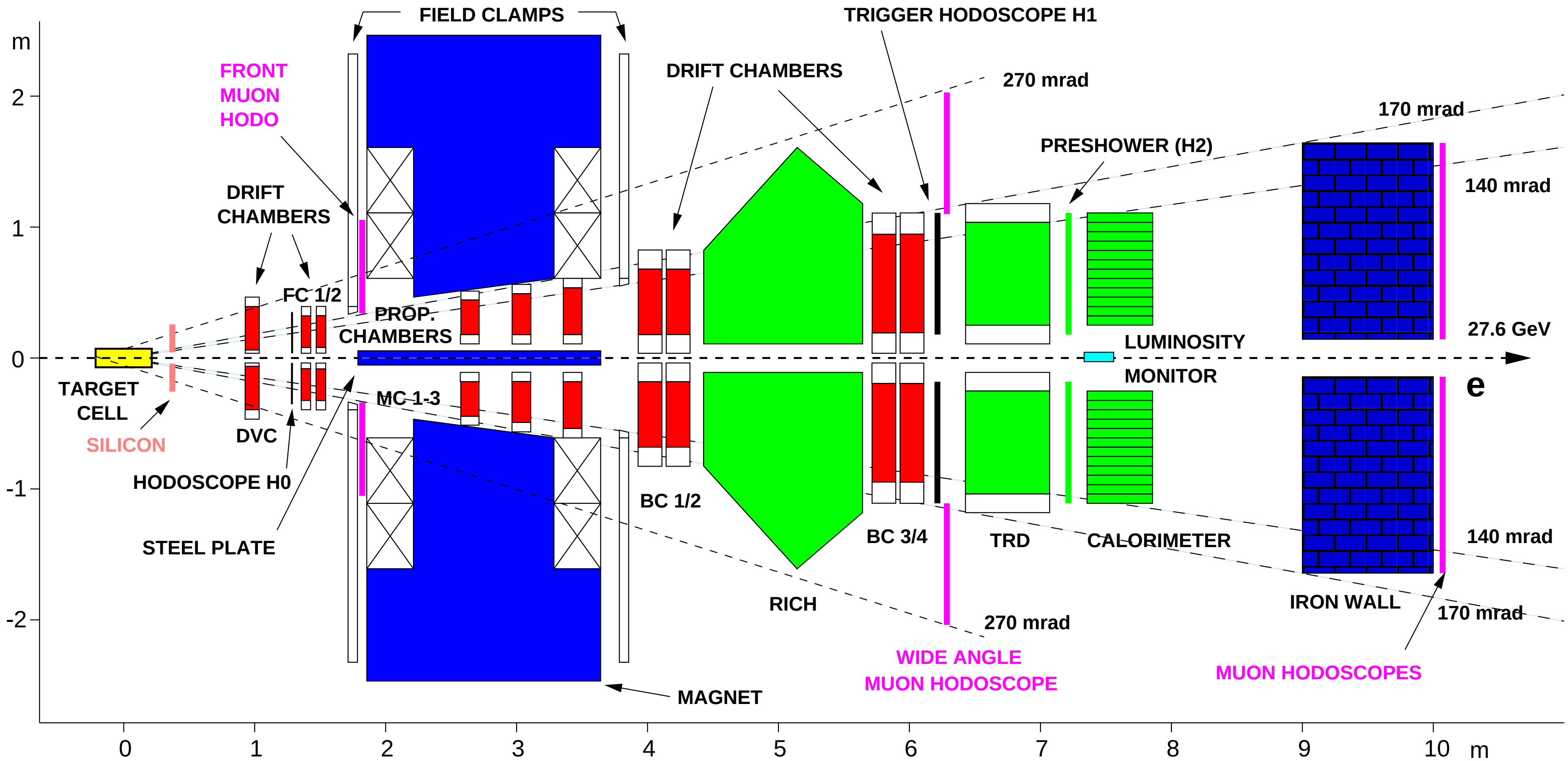
$\Rightarrow$ HERMES **kinematics is relevant for ion-ion in mid-rapidity**

Set up to measure nuclear effects



Operational till July 2, 2007, 10:00 am

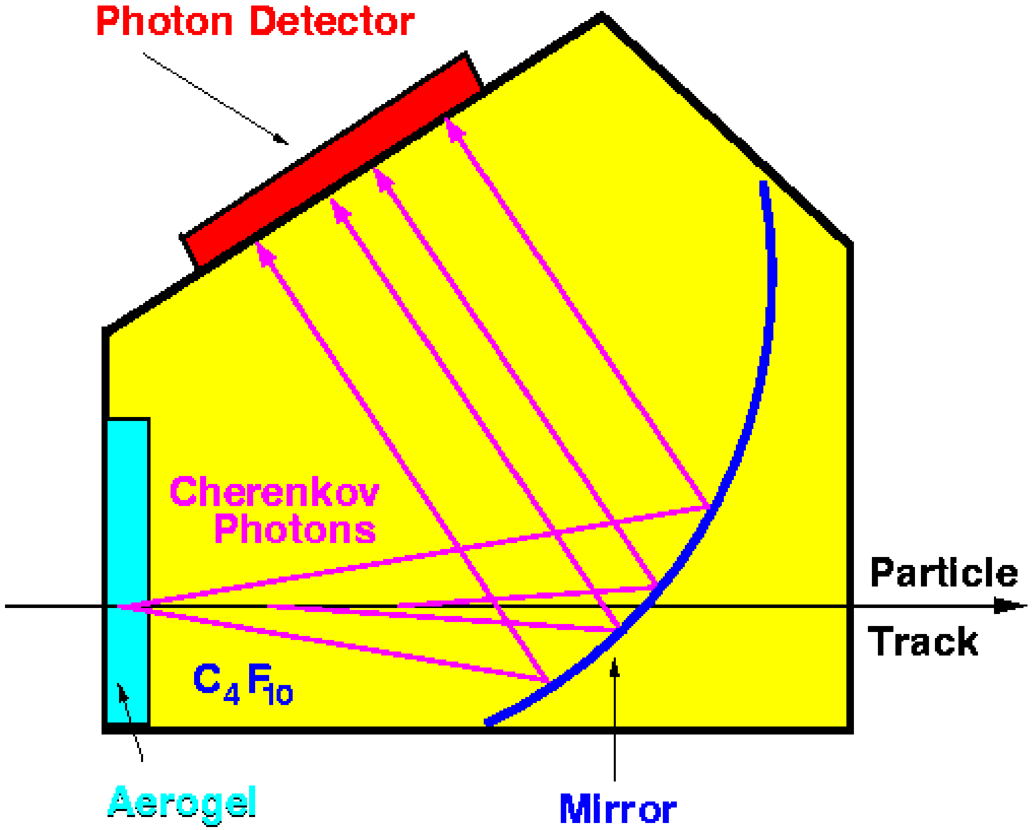
Side view of the HERMES spectrometer



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

Hadron identification with RICH



- Used for π, K, p identification
- Efficiencies

  $\Rightarrow$ π: $\sim$98%
  $\Rightarrow$ K: $\sim$88%
  $\Rightarrow$ p: $\sim$85%

Kinematic cuts

- Inclusive

  $\Rightarrow$ $1 < Q^2 < 10$ GeV^2

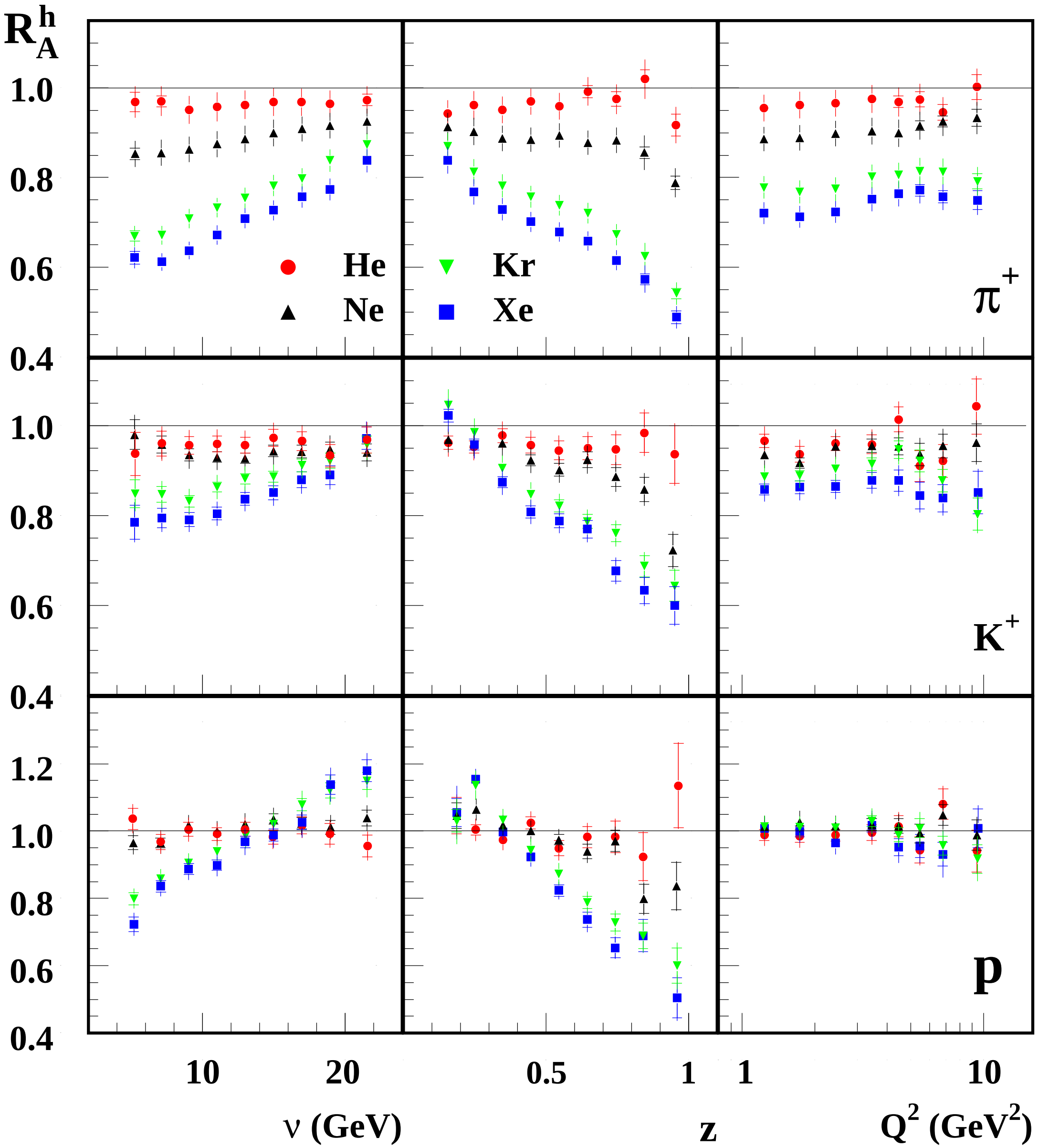
  $\Rightarrow$ $W > 2$ GeV
  - $*$ No resonances

  $\Rightarrow$ $\nu < 23$ GeV
  - $*$ Radiative effects

- Semi Inclusive

  $\Rightarrow$ $0.2 < z < 1.0$
  $\Rightarrow$ $2 < p^{\pi,K,p} < 15$ GeV

Multiplicity ratio: kinematic dependencies



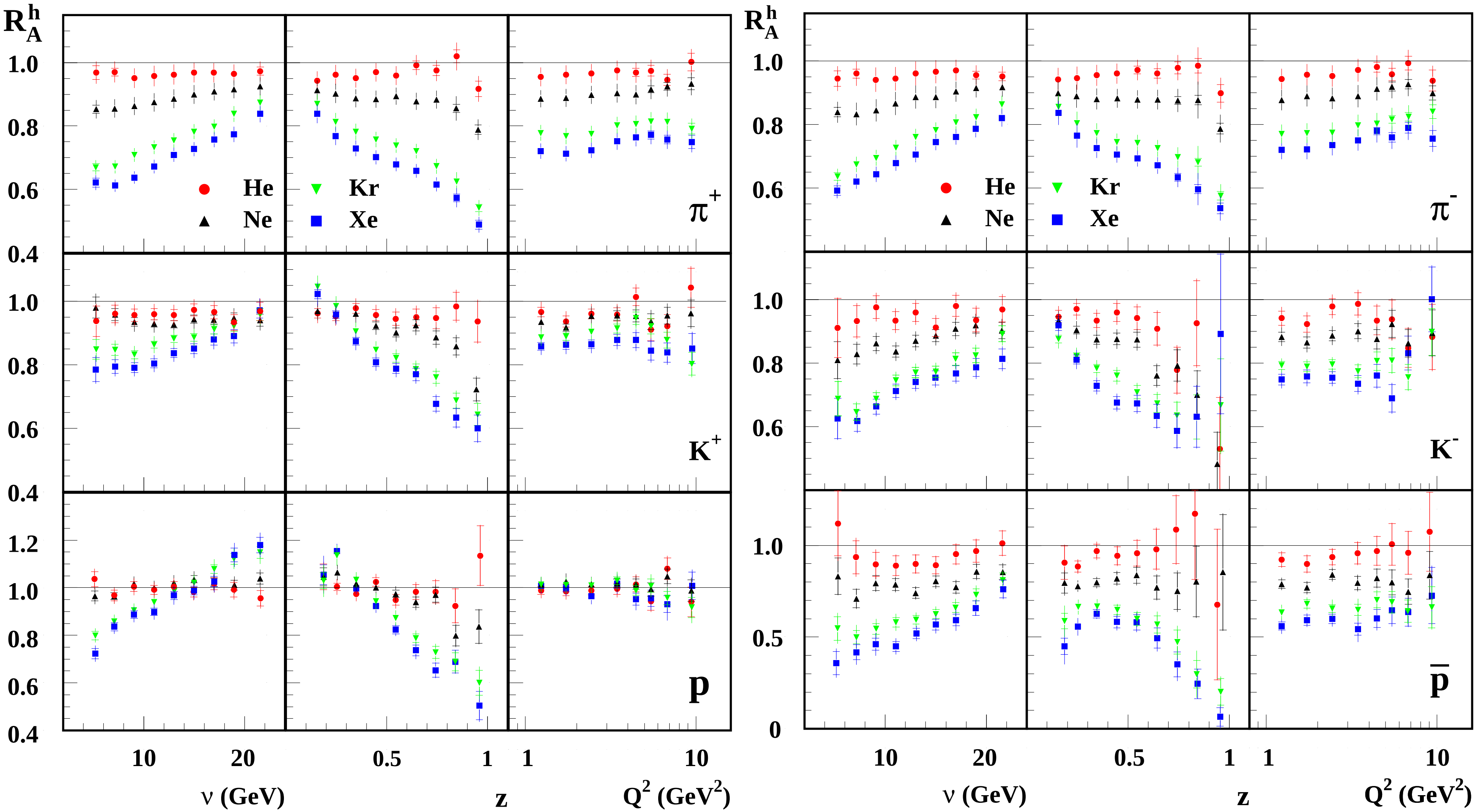
- $R^h = \frac{\left[\frac{N_h(z,\nu,Q^2,p_t^2,\phi_h)}{N_{\mathrm{DIS}}(\nu,Q^2)}\right]_A}{\left[\frac{N_h(z,\nu,Q^2,p_t^2,\phi_h)}{N_{\mathrm{DIS}}(\nu,Q^2)}\right]_D}$
- Clear A-dependence
- ν-dependence

  $\Rightarrow$ Lorentz-boost

  $\Rightarrow$ Hadron formed outside nucleus
- z-dependence

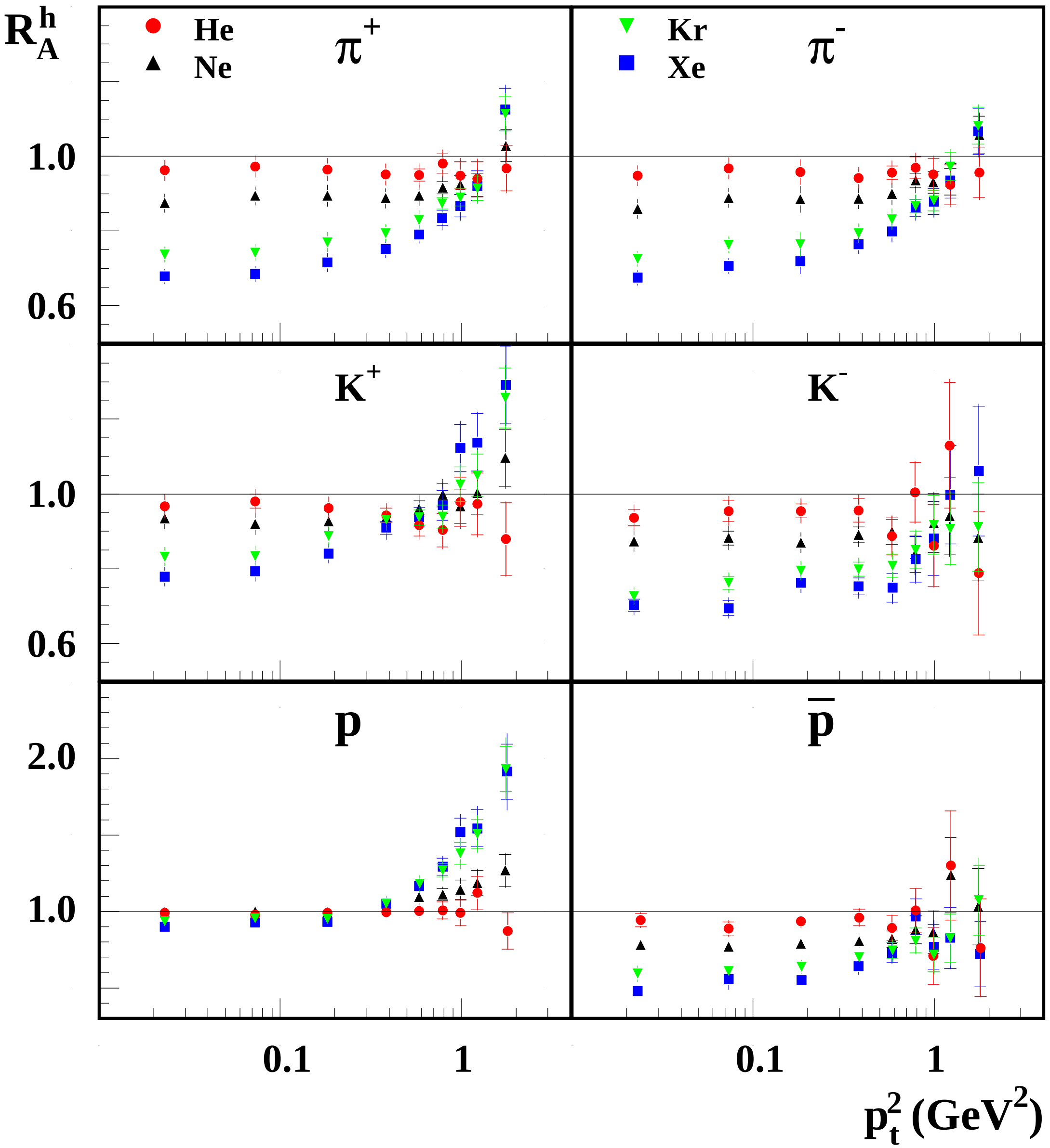
  $\Rightarrow$ $z \rightarrow 1$ no interaction
- Small Q^2 dependence

Multiplicity ratio: different hadrons



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

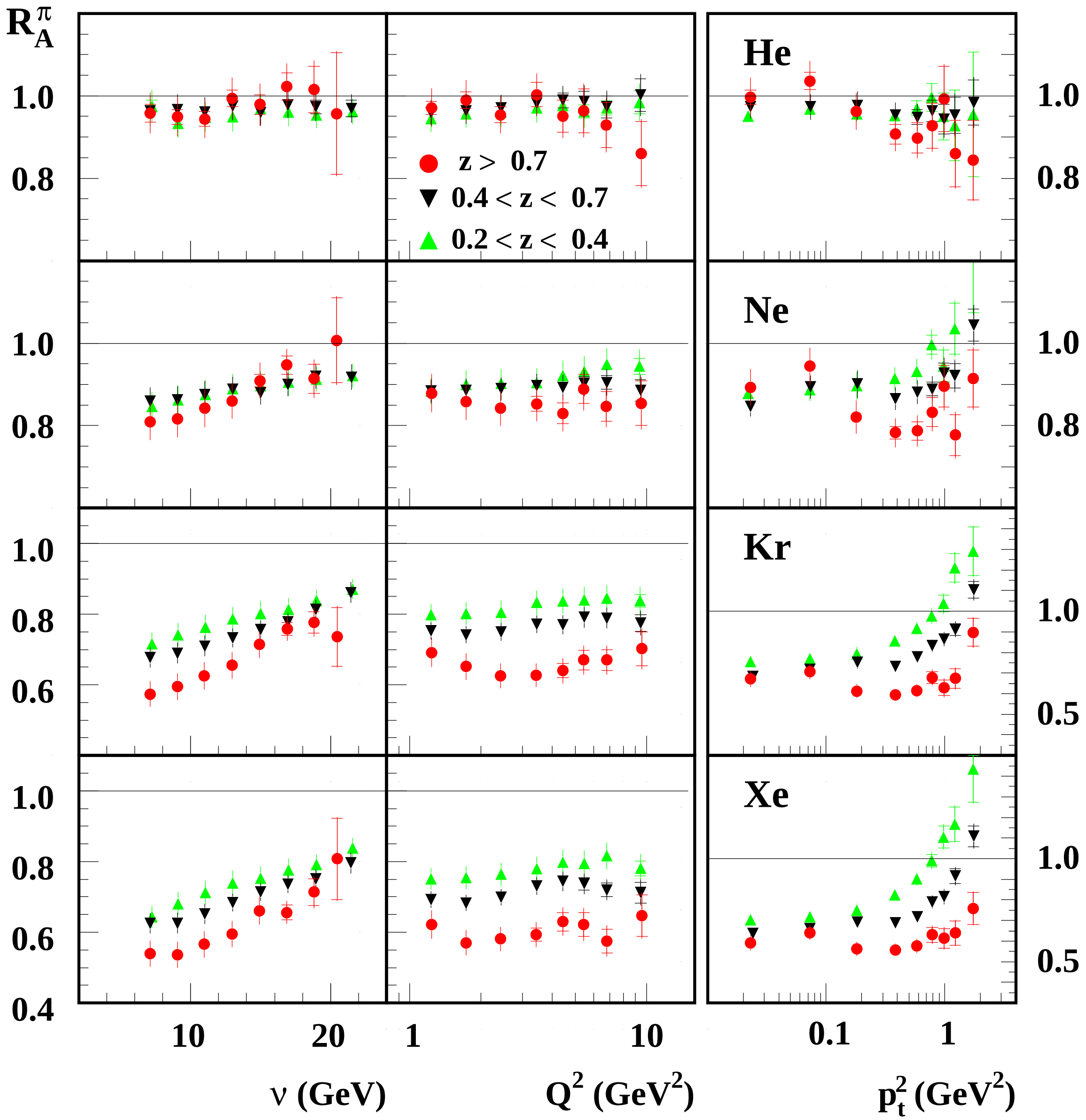
Cronin effect



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

  $\Rightarrow$ consistent with ion-ion

Multiplicity ratio 2D

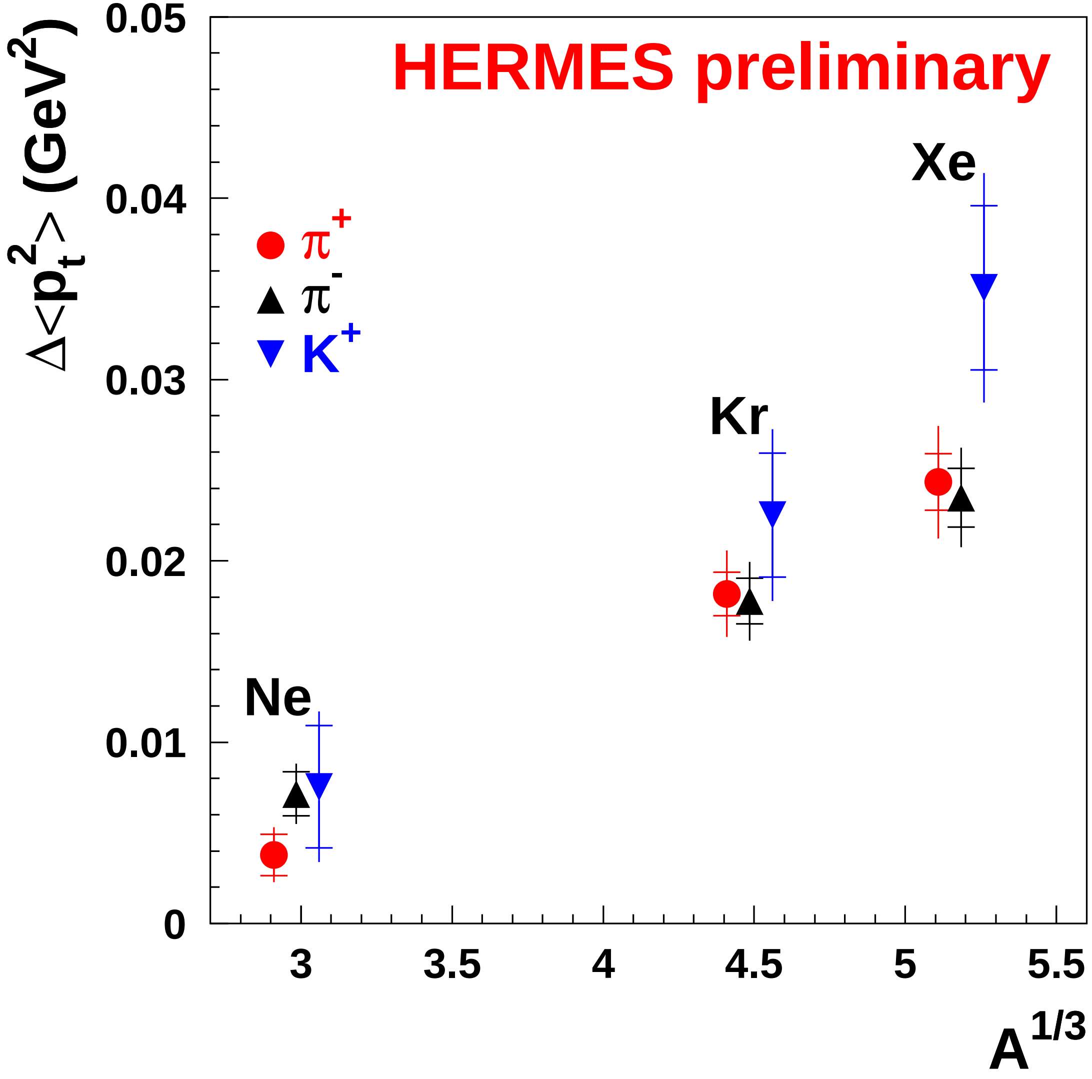


- 2D plot - $\pi^{\pm}$

  $\Rightarrow$ Excellent statistics example plot

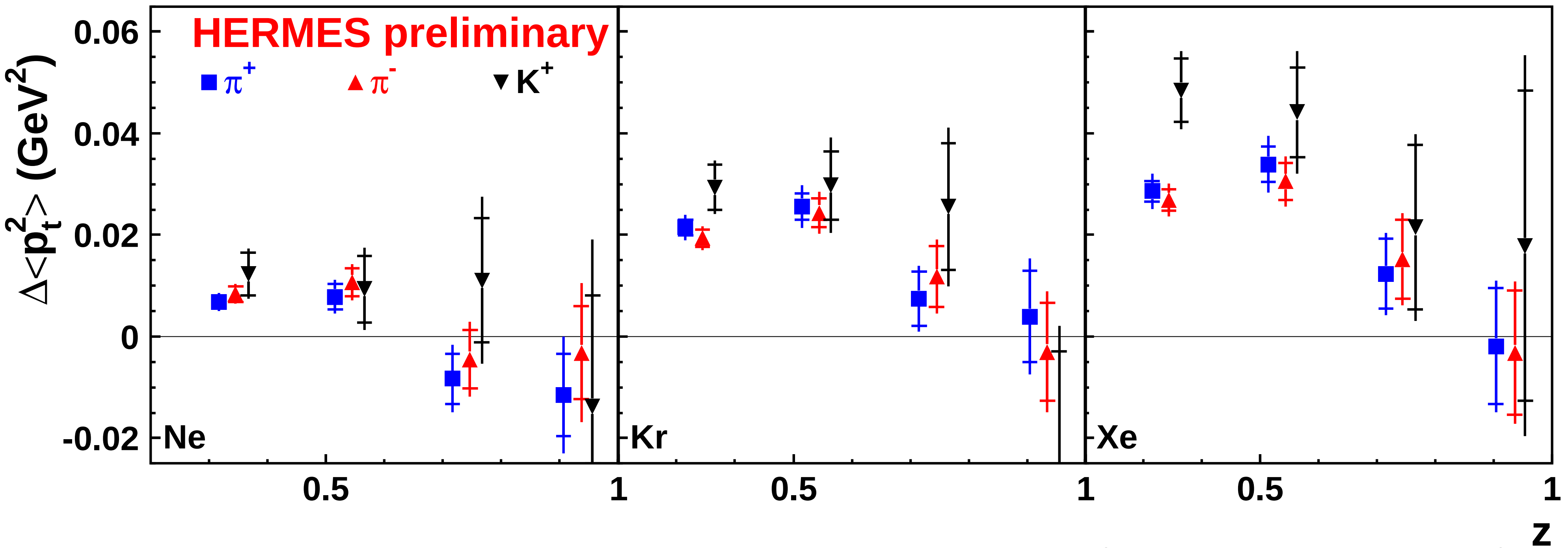
- Cronin effect reduced at high z

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

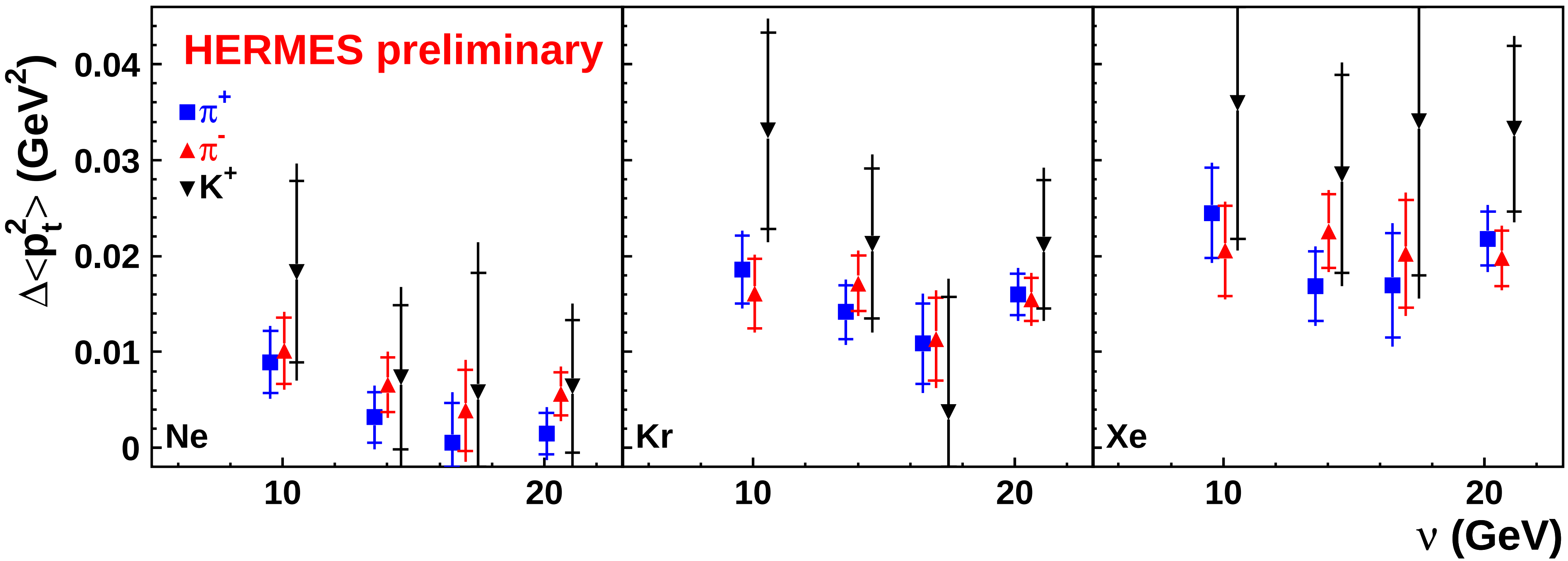


- Broadening dominated by gluon radiation

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

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

p_t-broadening versus ν

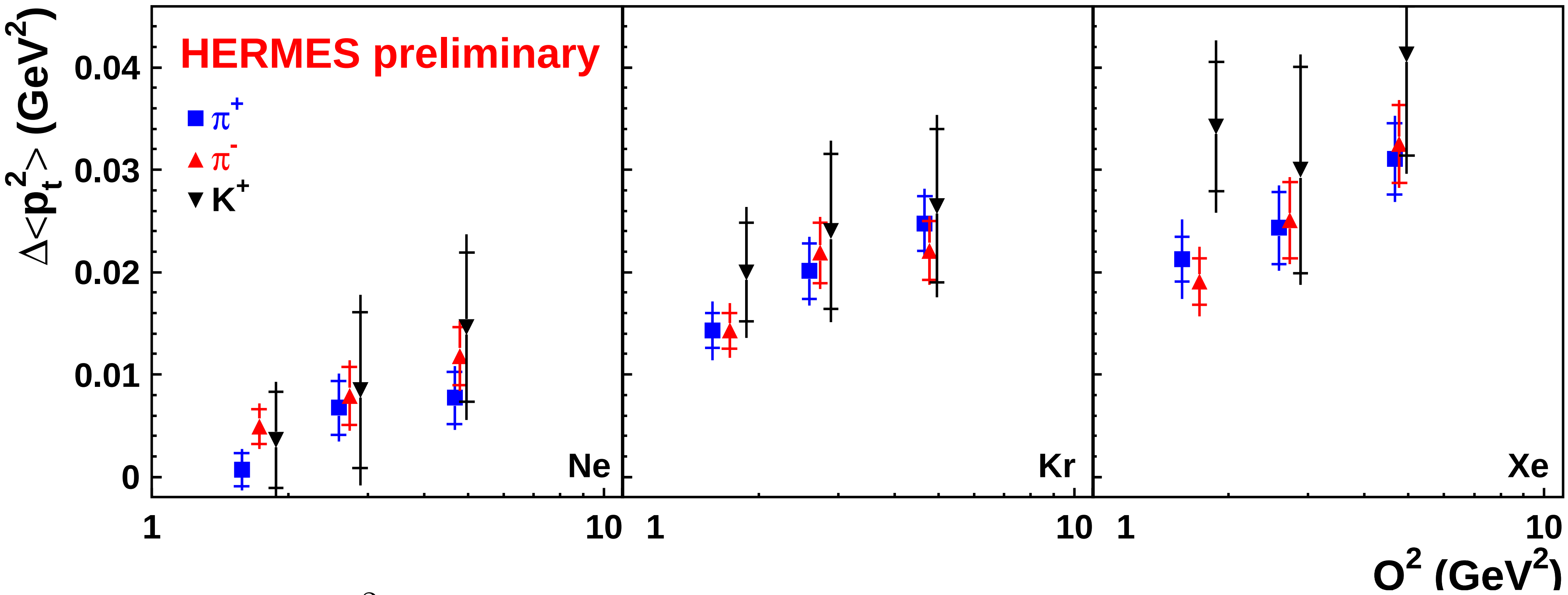


- $\langle Q^2\rangle^{\pi}$ = 2.1 $\rightarrow$ 2.4 GeV^2
- $\langle z\rangle^{\pi}$ = 0.46 $\rightarrow$ 0.34
- $\langle Q^2\rangle^{K^+}$ = 2.1 $\rightarrow$ 2.4 GeV^2
- $\langle z\rangle^{K^+}$ = 0.46 $\rightarrow$ 0.37

- 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

- $*$ Different hadron types
- $*$ 2D analysis
- $*$ Excellent statistics
- $*$ Submitted to Nucl.Phys.B

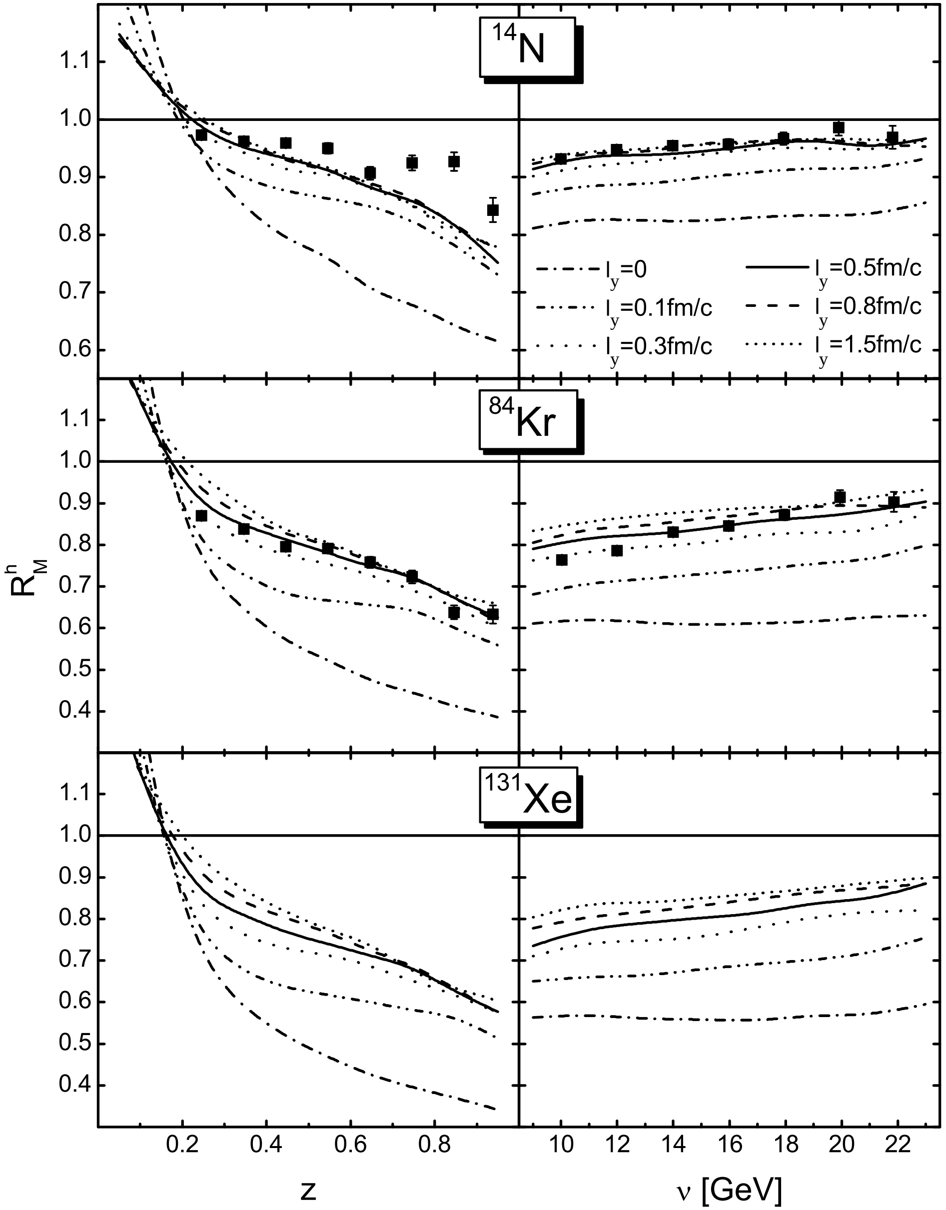
arXiv:0704.3270 [hep-ex]

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

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

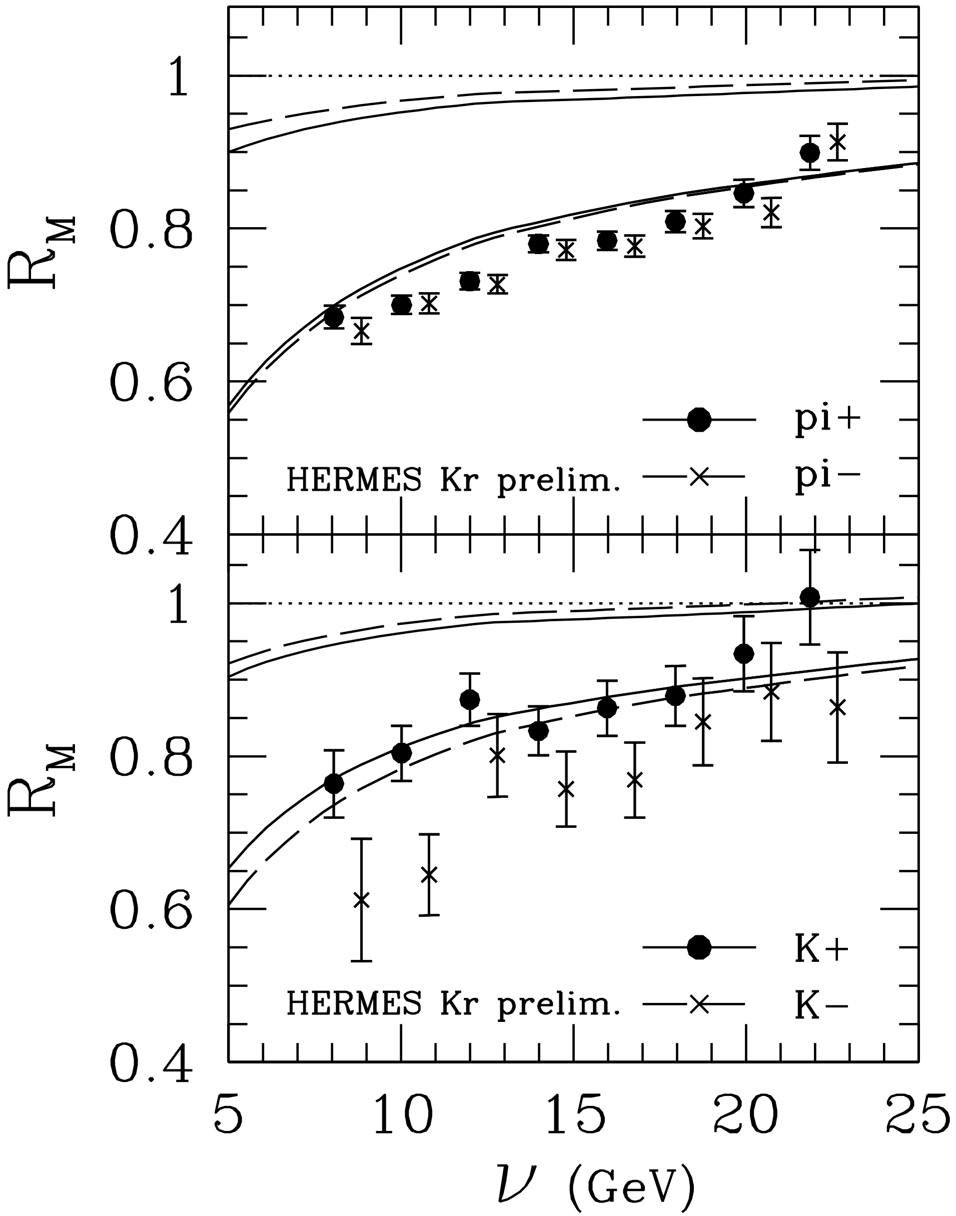
arXiv:0704.3712 [hep-ex]

Additional: BUU



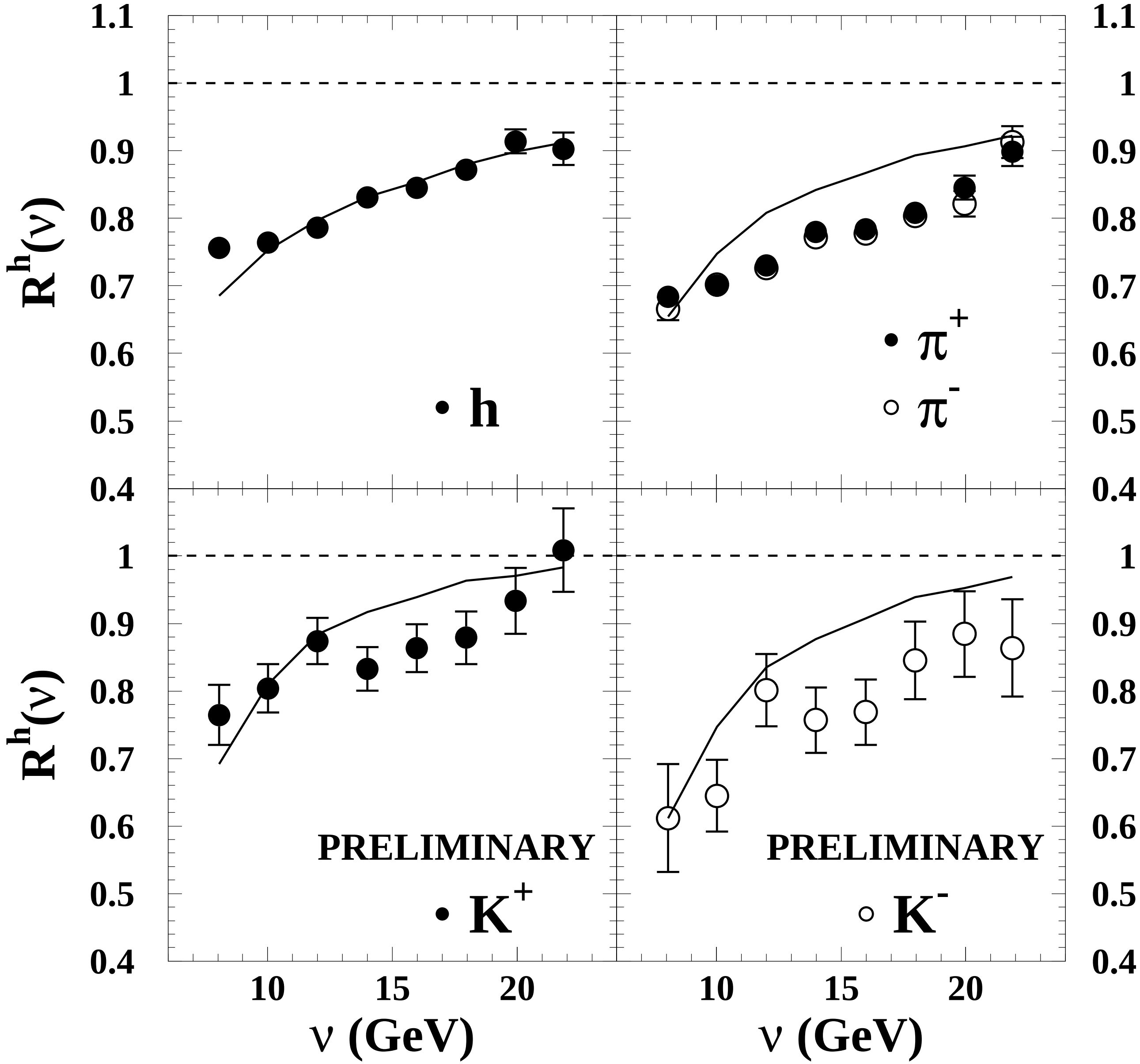
- $t_p = 0$
- $\sigma_{prehadron} = 0.33 \cdot \sigma_{hadron}$

Additional: rescaling

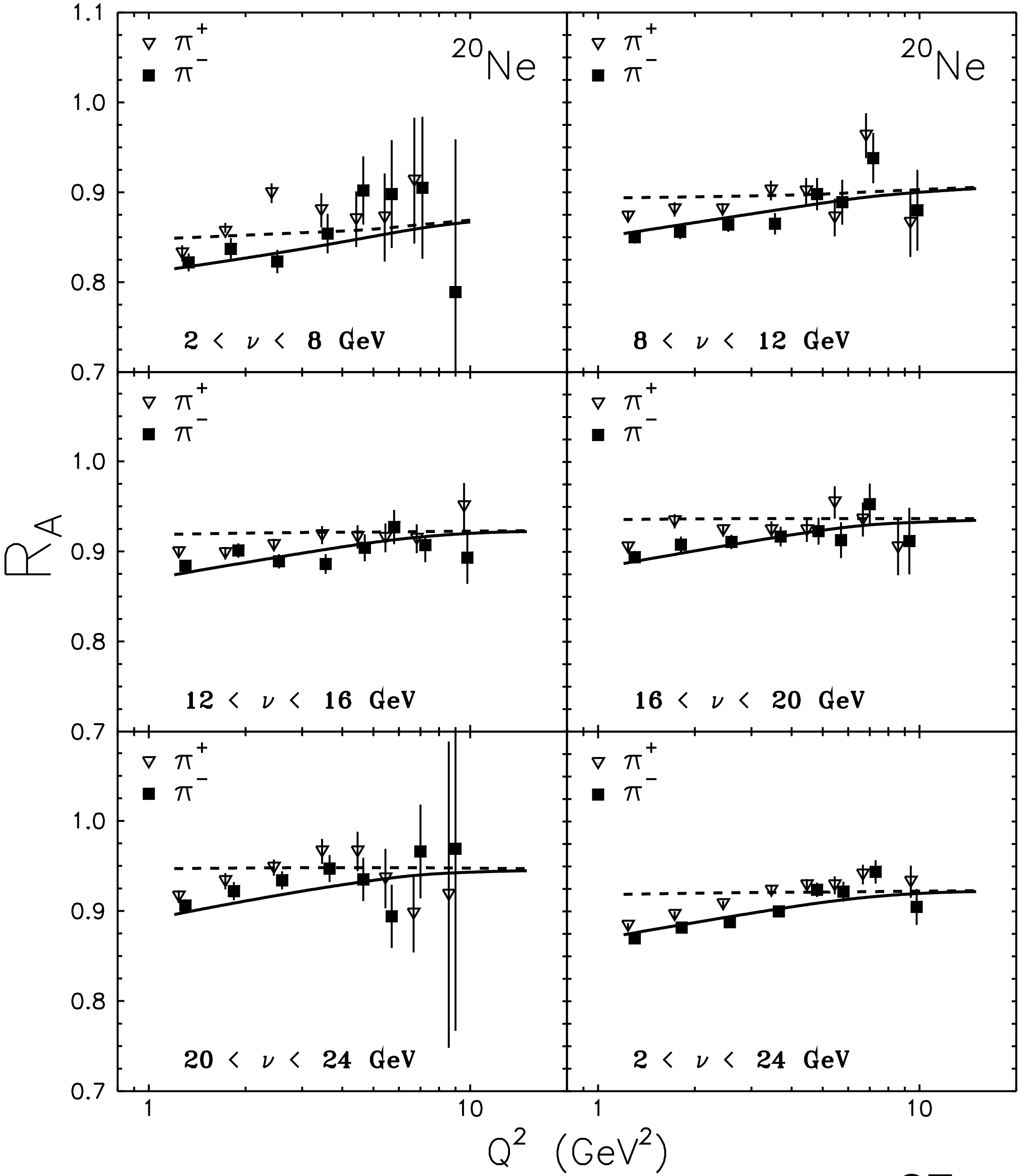


- with/without nuclear absorption

Additional: parton energy loss



Additional: Gluon bremsstrahlung



- with/without induced gluon radiation