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Hadronization in Nuclei

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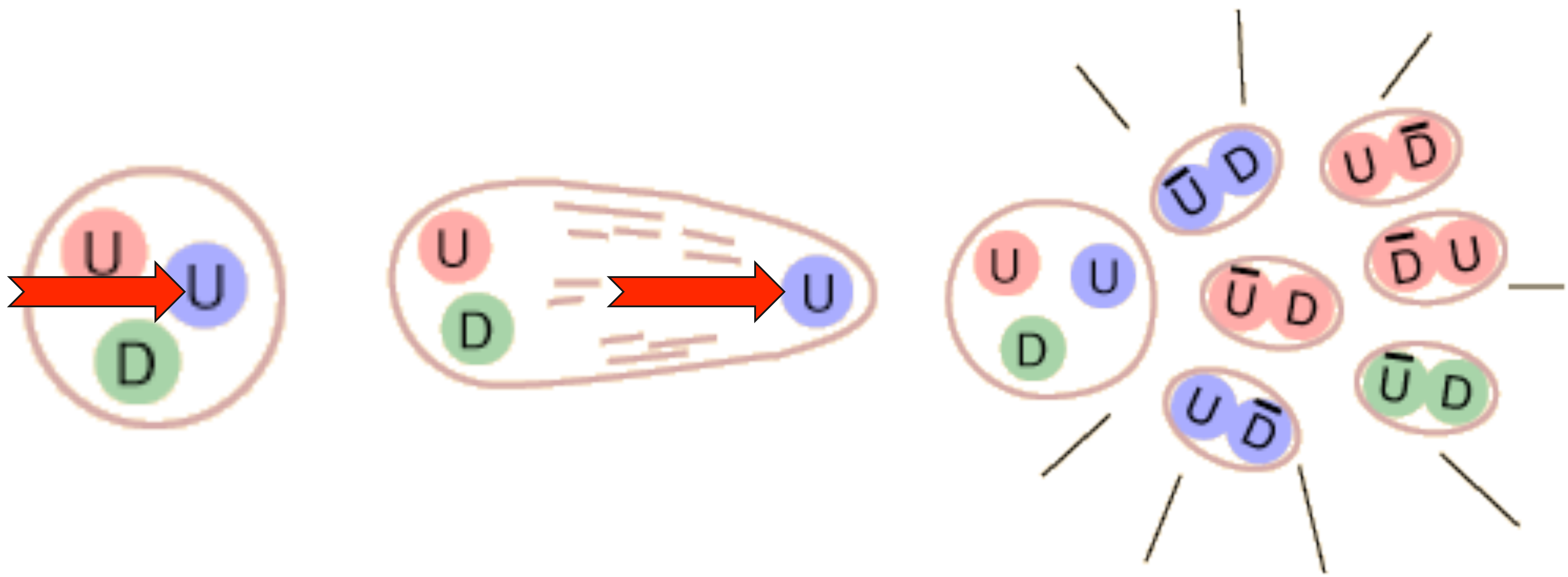
Outline

- Introduction
- Physical pictures
- Parton propagation: p_T broadening
- Hadron formation: multiplicity ratios
- Future prospects

Hadronization is a manifestation of confinement !



How do energetic quarks transform into hadrons ?

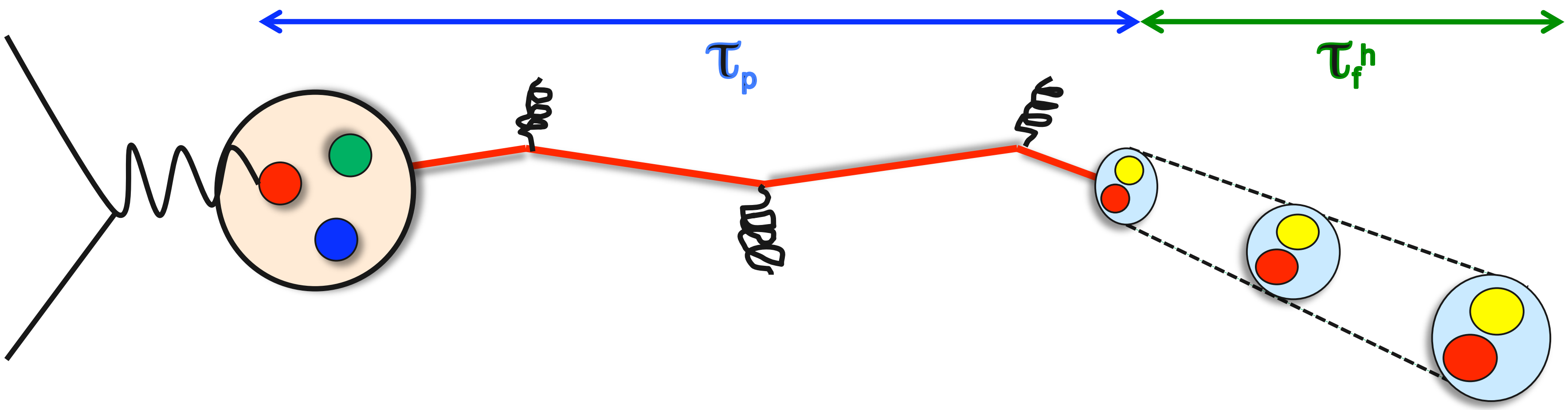
Important Questions

- What is the lifetime of an energetic free quark?
- How long does it takes to form a hadron starting from an energetic light quark?
- What is the dynamic leading to color confinement?

Important Consequences

- Provides complementary way of studying confinement (the traditional way being the study of hadron spectrum)
- Testing and calibrating theoretical tools used to determine the properties of Quark-Gluon Plasma
- Reduce systematic uncertainties in neutrino experiments using nuclear targets

Physical picture – Semi Inclusive DIS in the vacuum



- Production time τ_p

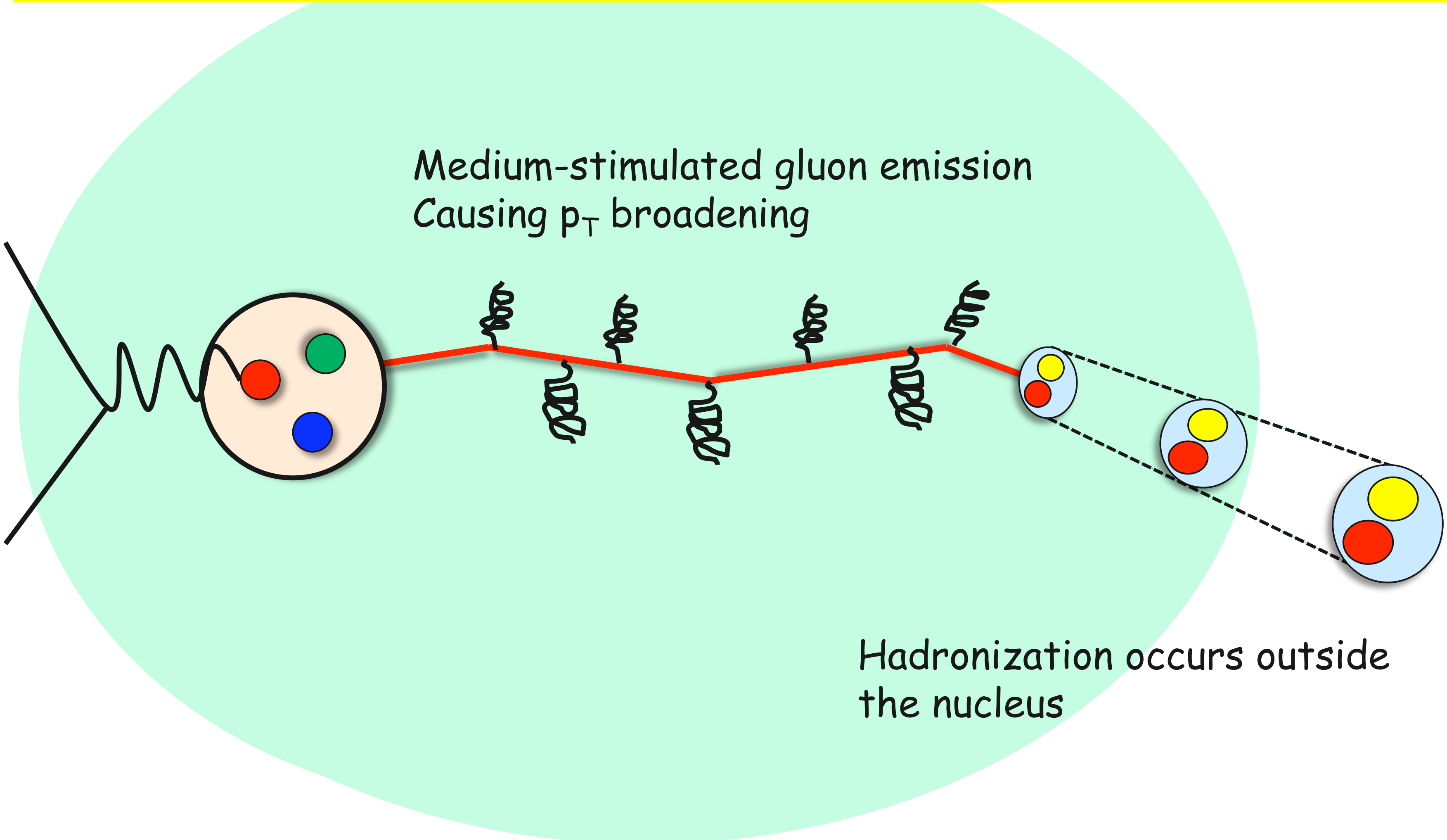
  the time interval during which the quark is deconfined

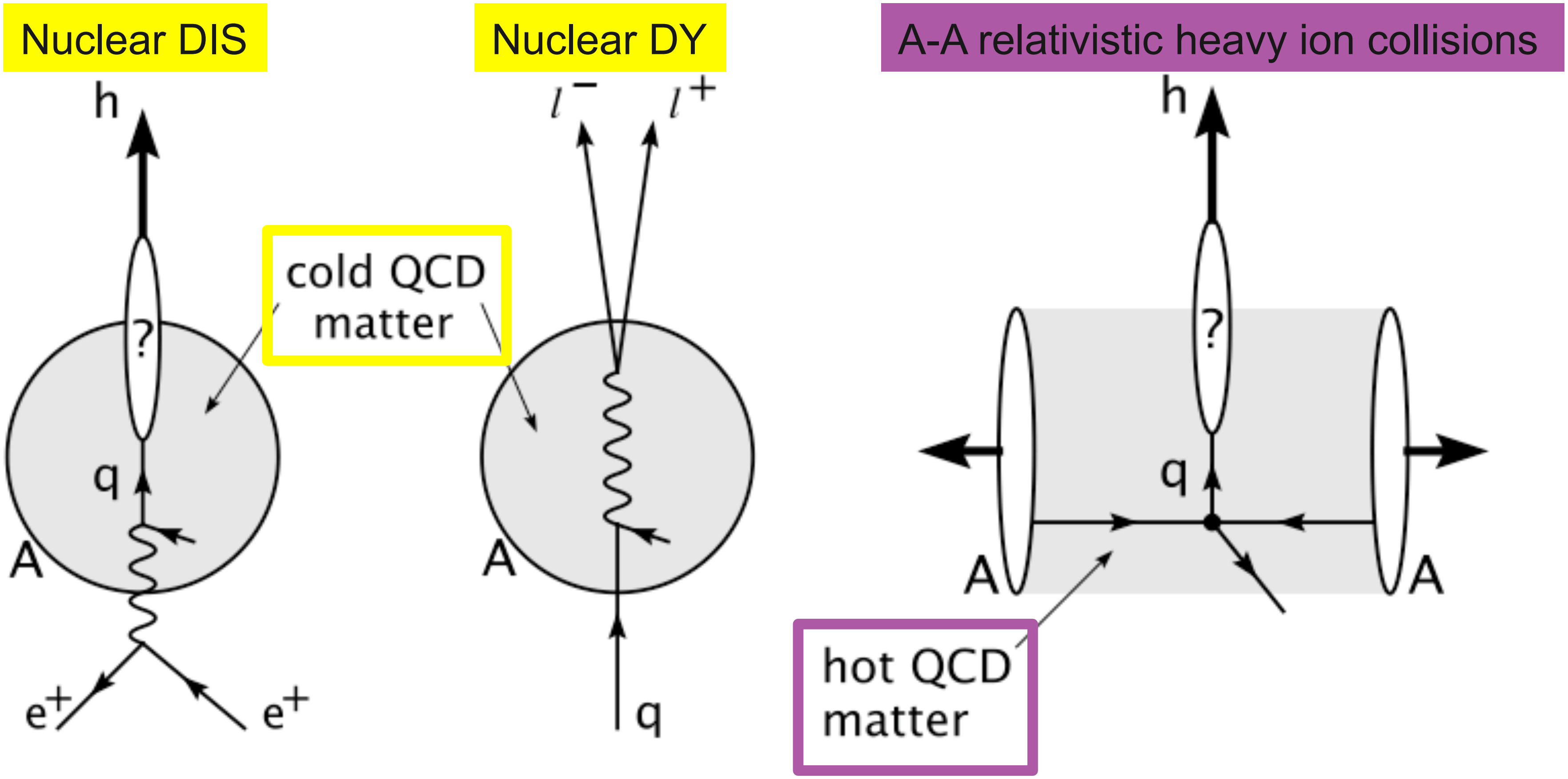
- Formation time τ_f^h

  the time required to form the color field of the hadron

Physical picture – Semi Inclusive DIS in the medium

- *Use nuclei as spatial filters with known properties: size, density and interactions*
- *Take advantage of the unique kinematical window*





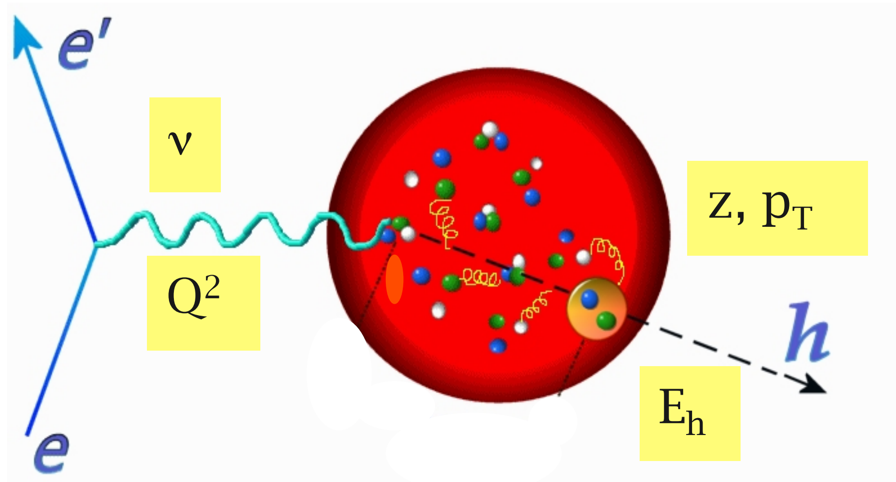
In medium hadronization
p_T broadening

No **in medium hadronization**
p_T broadening

Parton propagation in hot dense medium

Courtesy of A. Accardi, F. Arleo, W. K. Brooks, D. D'Enterria and V. Muccifora, arXiv:0907.3534

Summary of the Experimental techniques



- Identify quark propagation phase by p_T broadening
- Identify hadron formation phase by hadron attenuation
- Extract characteristic times and reaction mechanisms using the variation of these observables with nuclear size

Experimental Studies

Semi-inclusive deep inelastic scattering on nuclei

- *1970's SLAC eA → e'Xh, energy transfer ~35-145 GeV*
- *1990's CERN EMC μA → μ'Xh, energy transfer ~35-145 GeV*
- *1990's WA21/59 (4- 64 GeV) ν beam on Ne target*
- *2000's HERA HERMES $e^+A \rightarrow e^{+\prime}Xh$, 12 and 26 GeV beam*
- *2000's Jefferson Lab CLAS, eA → e'Xh, 5 GeV beam*

Drell-Yan reaction

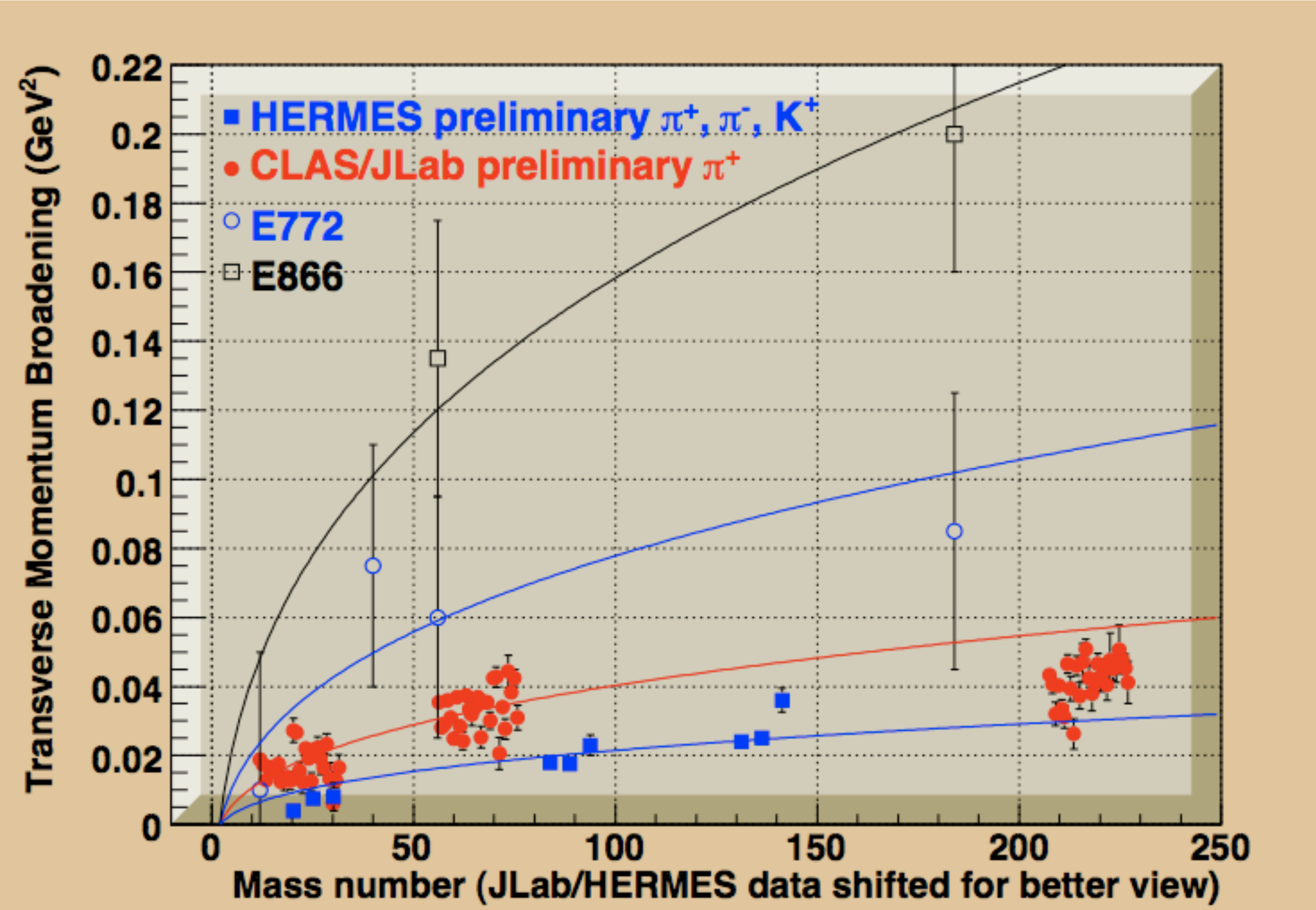
- *1980's CERN SPS NA-10 spectrometer:* $\pi A \rightarrow X\mu^+\mu^-$, *140 and 280 GeV beam*
- *1990's Fermilab* $pA \rightarrow X\mu^+\mu^-$, *800 GeV beam*

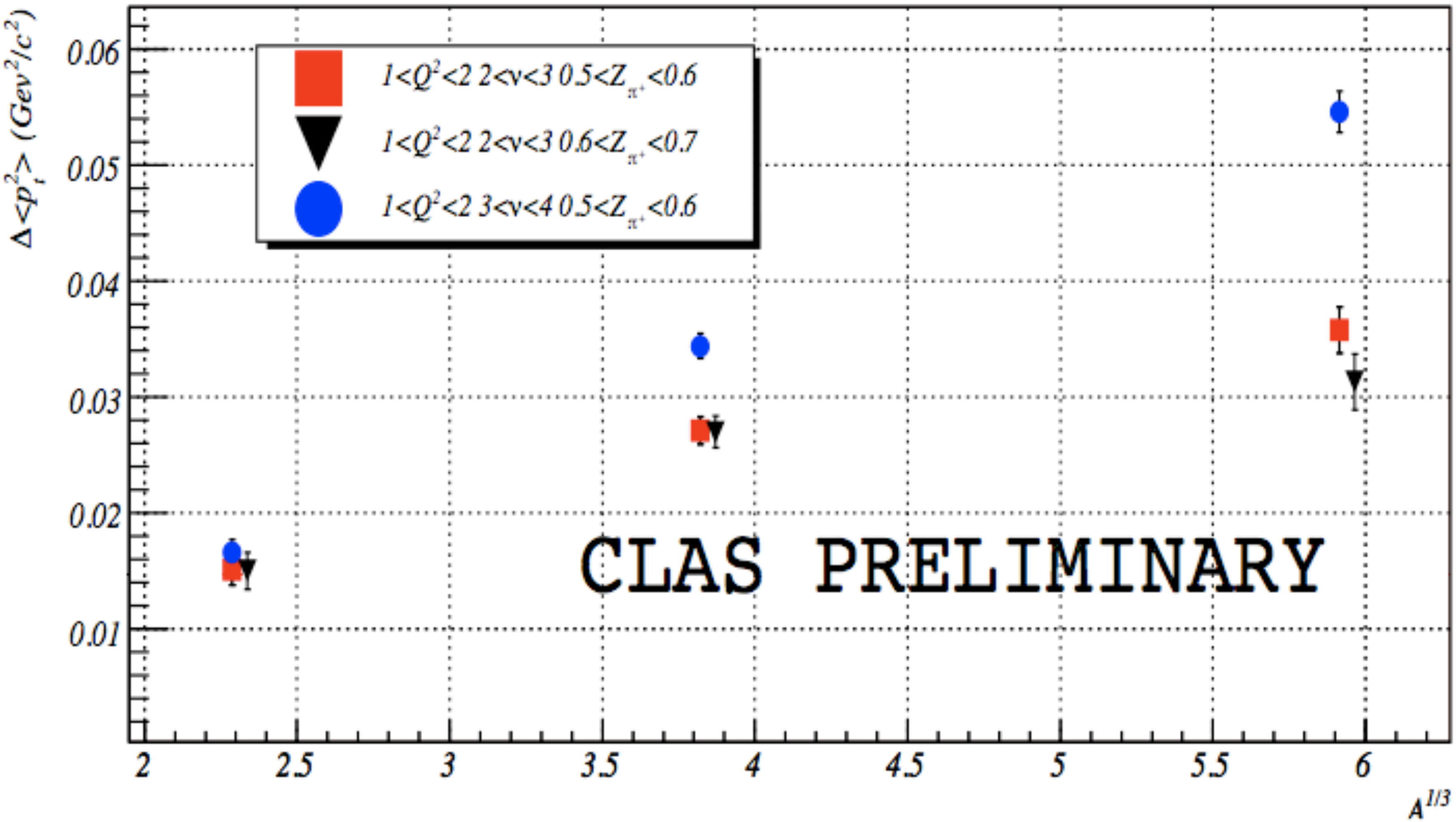
International, multi-institutional quest for 30 years, but most progress since 2000

Parton Propagation:

p_T Broadening

$$\Delta p_T^2 = < p_T^2 >_A - < p_T^2 >_D$$

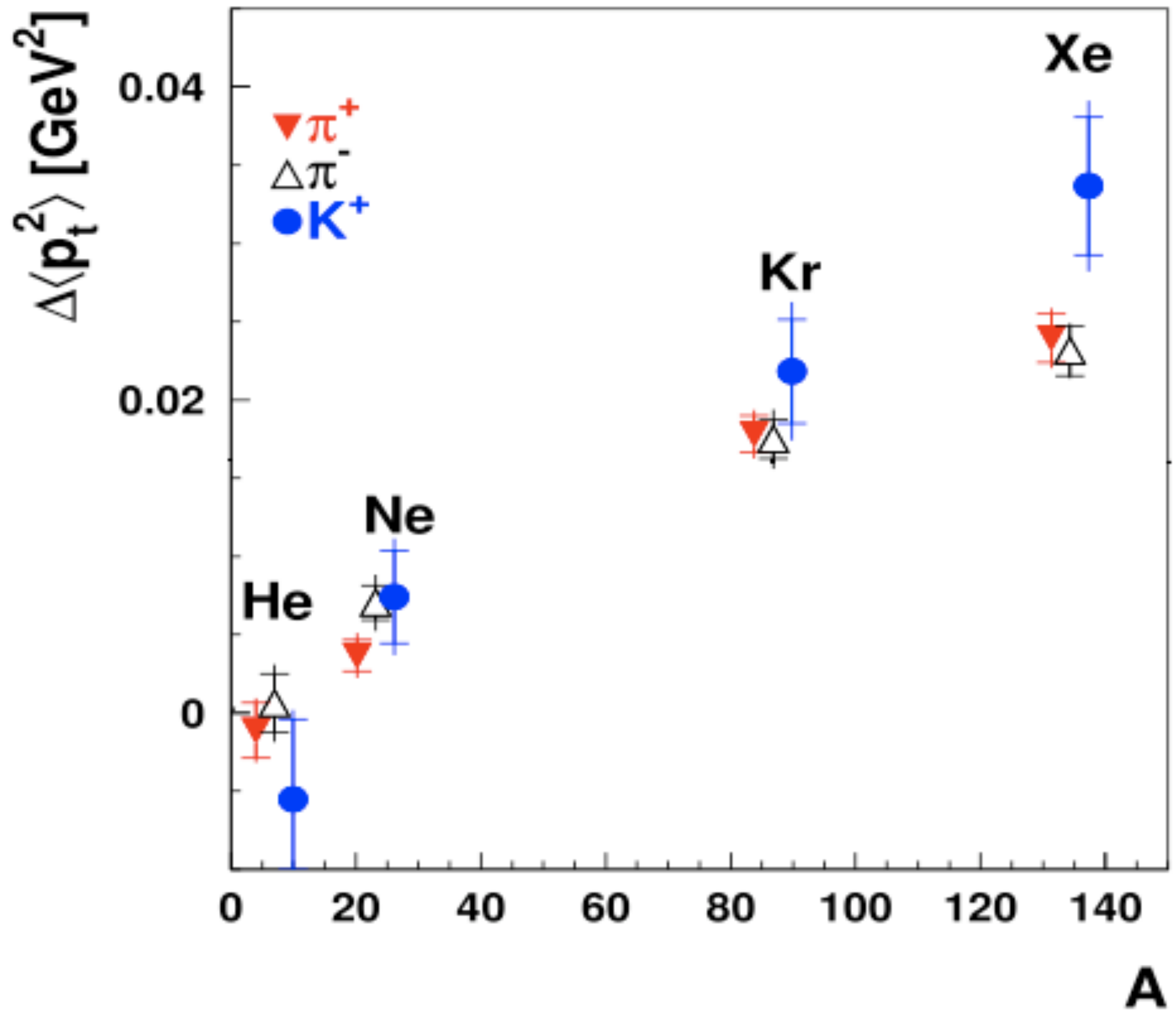




JLab/CLAS data :
3 dimensional variable dependences

$$\tau_p \approx \frac{\nu z}{Q^2}(1-z)$$

HERMES p_T broadening results for different hadrons



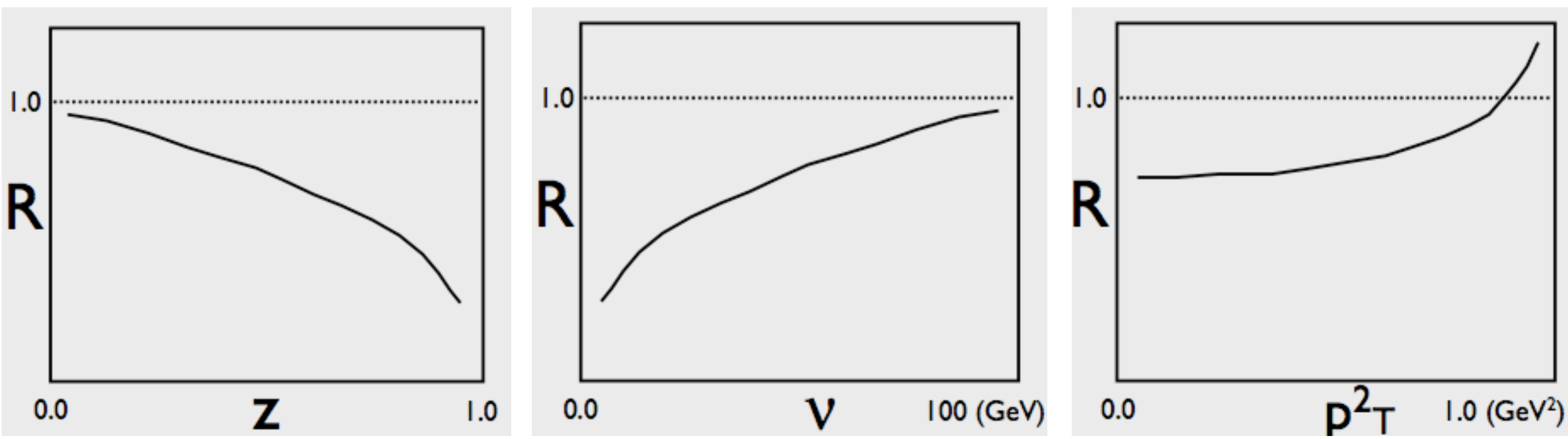
Hadron Attenuation:

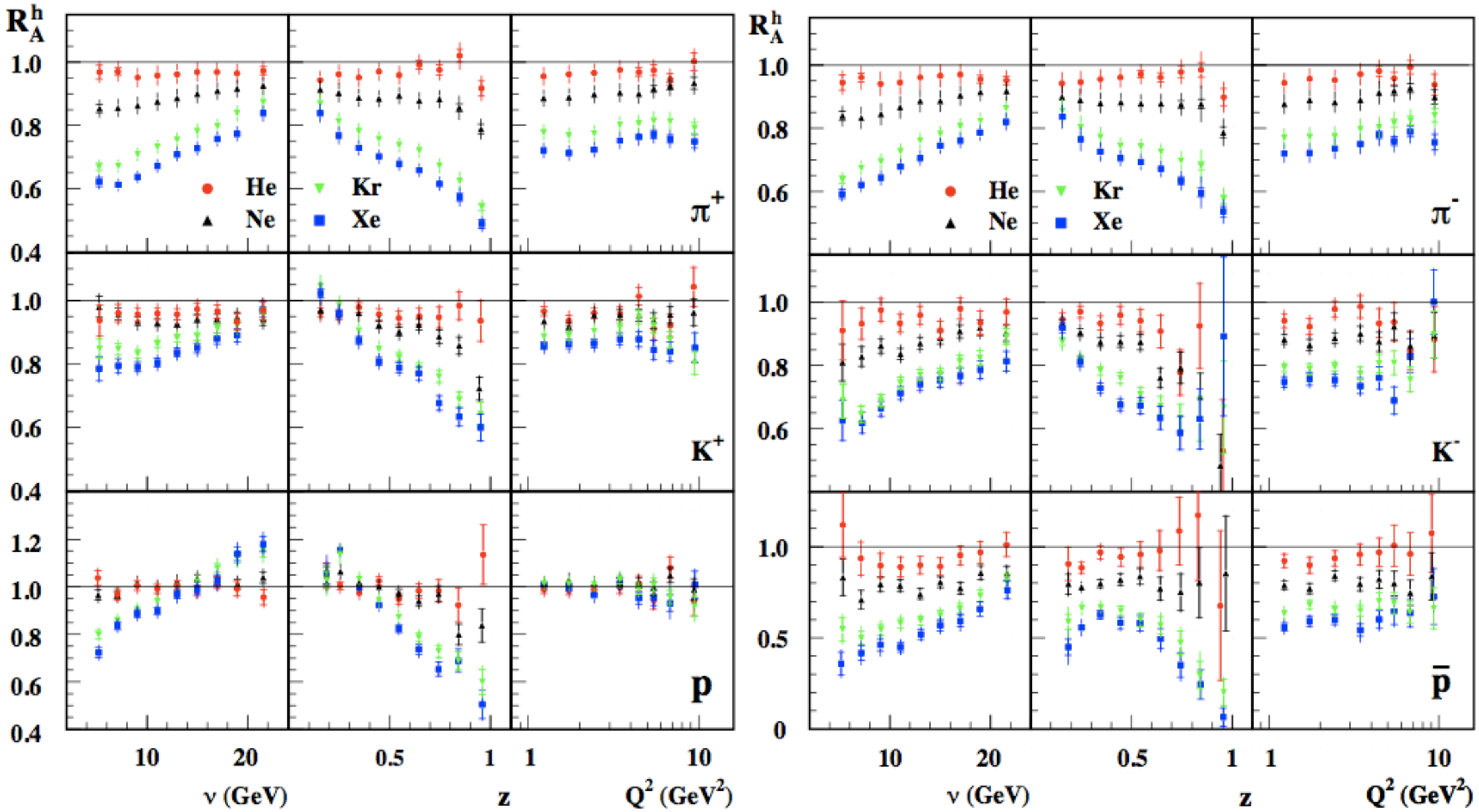
Multiplicity Ratios

Hadronic multiplicity ratio

$$\tau_p \approx \frac{\nu z}{Q^2}(1-z)$$

$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{\frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_A}{\left\{\frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_D}$$





HERMES 1-D multiplicity ratios:

pions act similarly

Differences are observed between K^+ and K^- and protons and anti-protons

Sample of Models

- **Gluon Bremsstrahlung Model** (B. Kopeliovich, J. Nemchik *E. Predazzi, A. Hayashigaki)*

  Gluon radiation + hadronization model

- **Twist-4 pQCD Model** *(X.-N. Wang, E. Wang, X. Guo, J. Osborne)*

  Medium-induced gluon radiation only

- **Rescaling Models** *(A. Accardi, H. Pirner, V. Muccifora)*

  Gluon emission, partial deconfinement, nuclear absorption

- **PYTHIA-BUU Coupled Channel Model** *(T. Falter, W. Cassing, K. Gallmeister, U. Mosel)*

  Fundamental interaction + coupled channel nuclear final state interaction

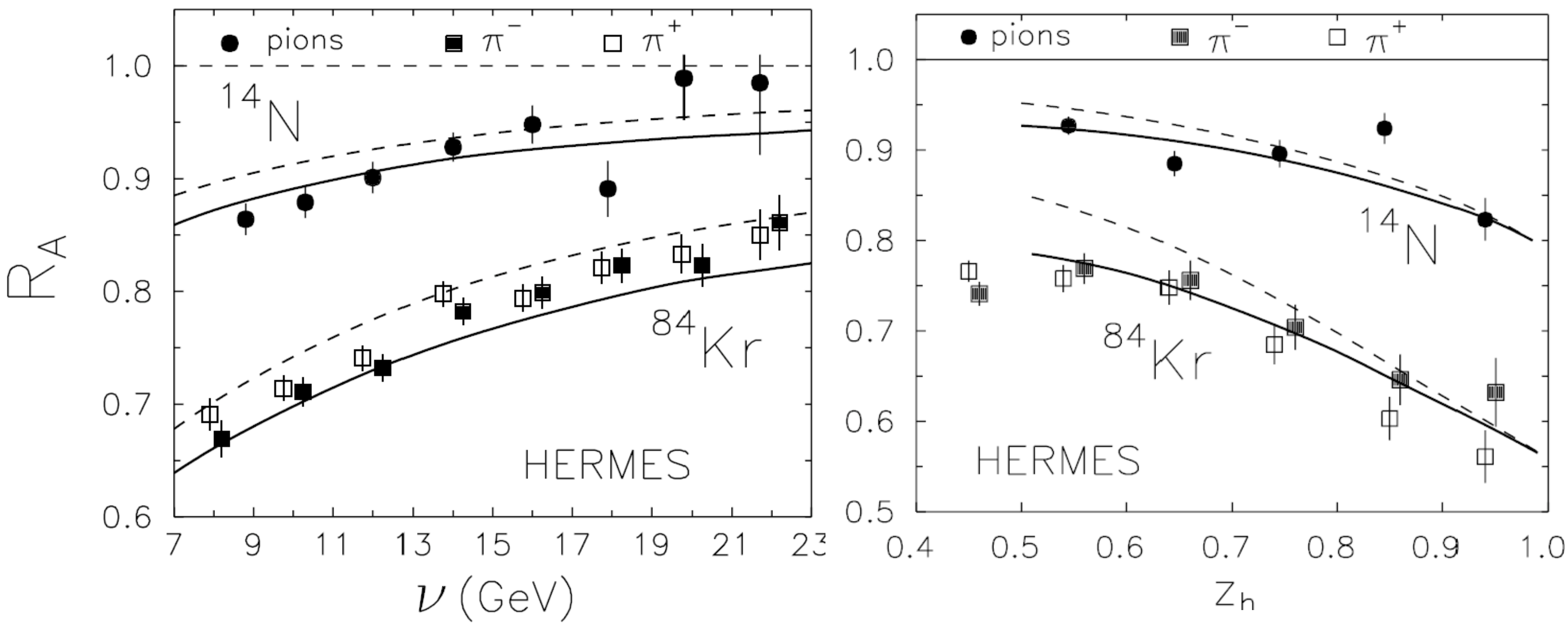
Gluon Bremsstrahlung Model

Authors B. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki

- Time and energy dependent model for energy loss by gluon emission coupled to a hadron formation scheme
- **Gluon emission:**
  - Two time constants
  - Q^2 dependence
- **Hadron formation:**
  - **Color dipole cross section**

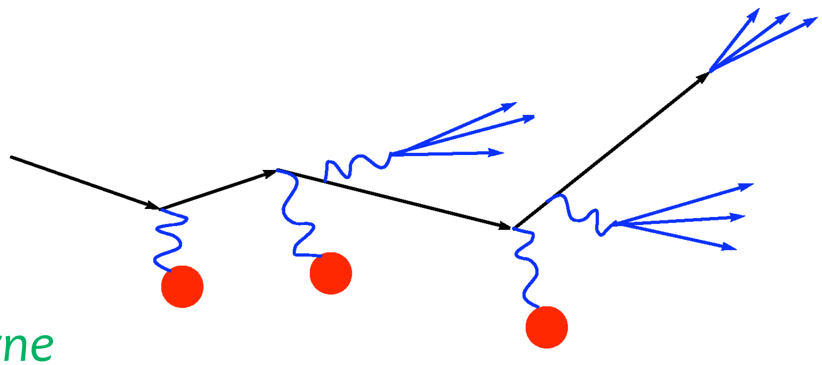
Gluon Bremsstrahlung Model and HERMES Data

B.Z. Kopeliovich et al. / Nuclear Physics A 740 (2004) 211–245



Prediction was made 5 years before data were taken!

Twist-4 pQCD Model

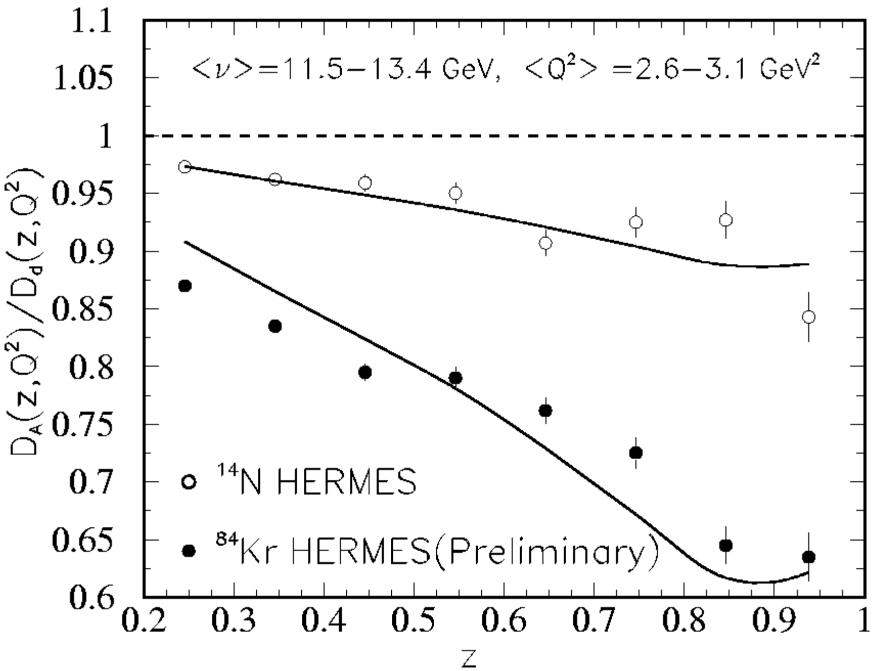


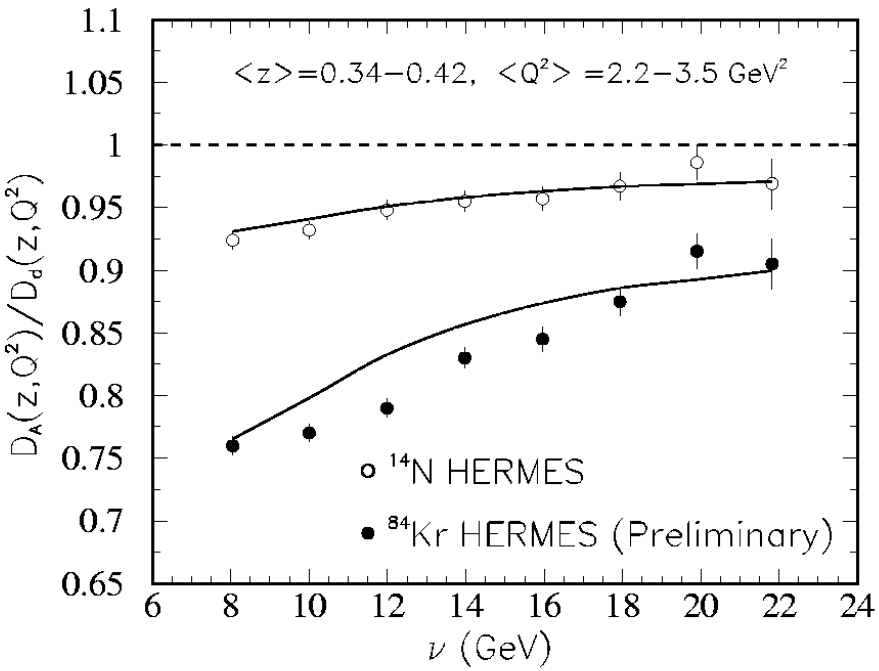
Authors: X.-N. Wang, E. Wang, X. Guo, J. Osborne

- No hadronization in this picture:
  - Hadrons form outside nucleus
  - Energy loss from medium-stimulated gluon radiation causes nuclear attenuation
- Leading twist-4 modifications to pQCD fragmentation functions due to induced gluon radiation from multiple scattering
- Strength of a quark-gluon correlation function is a free parameter

Other similar efforts: F. Arleo, U.A. Wiedemann

Twist-4 pQCD Model



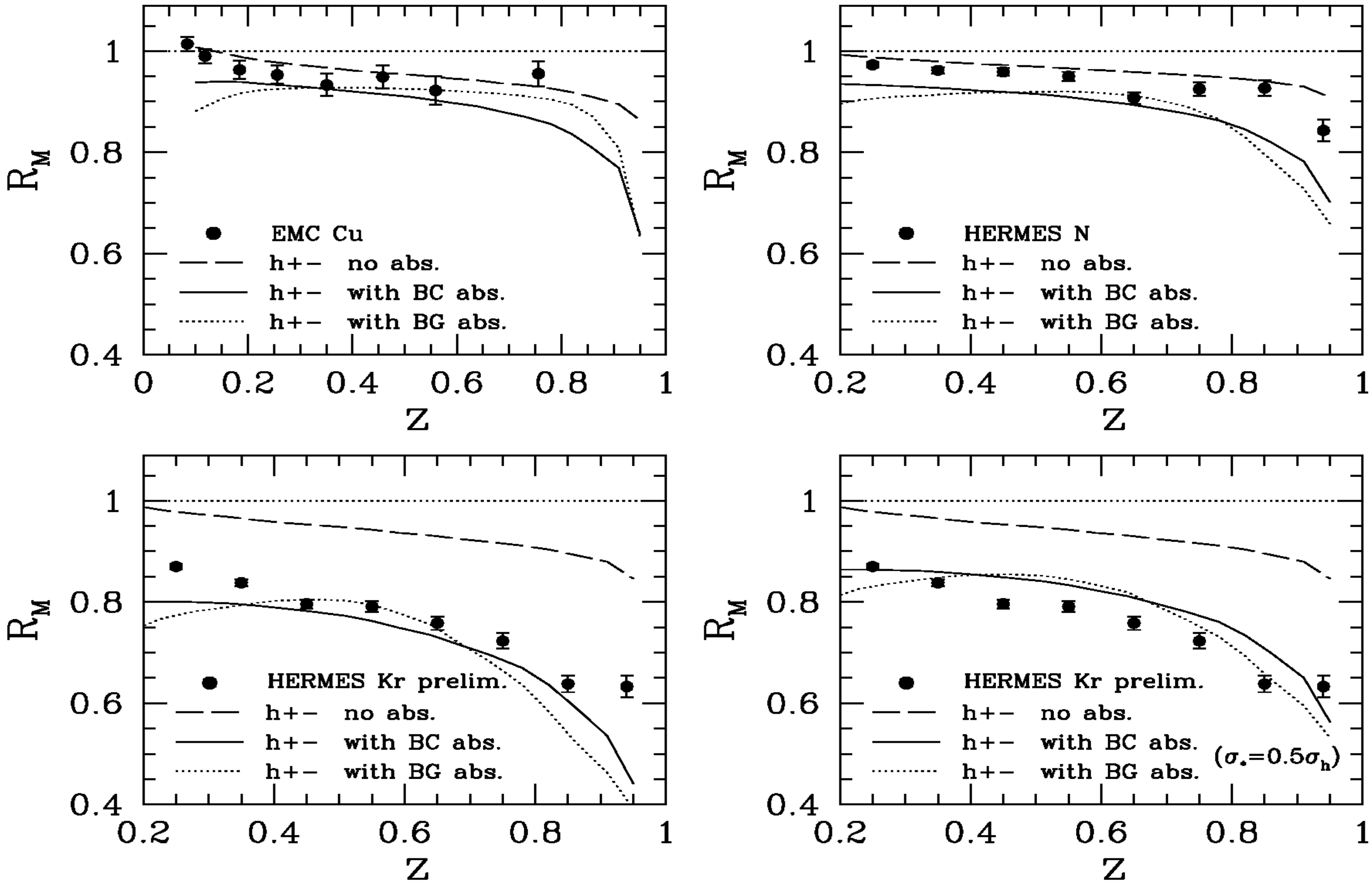


Rescaling Models

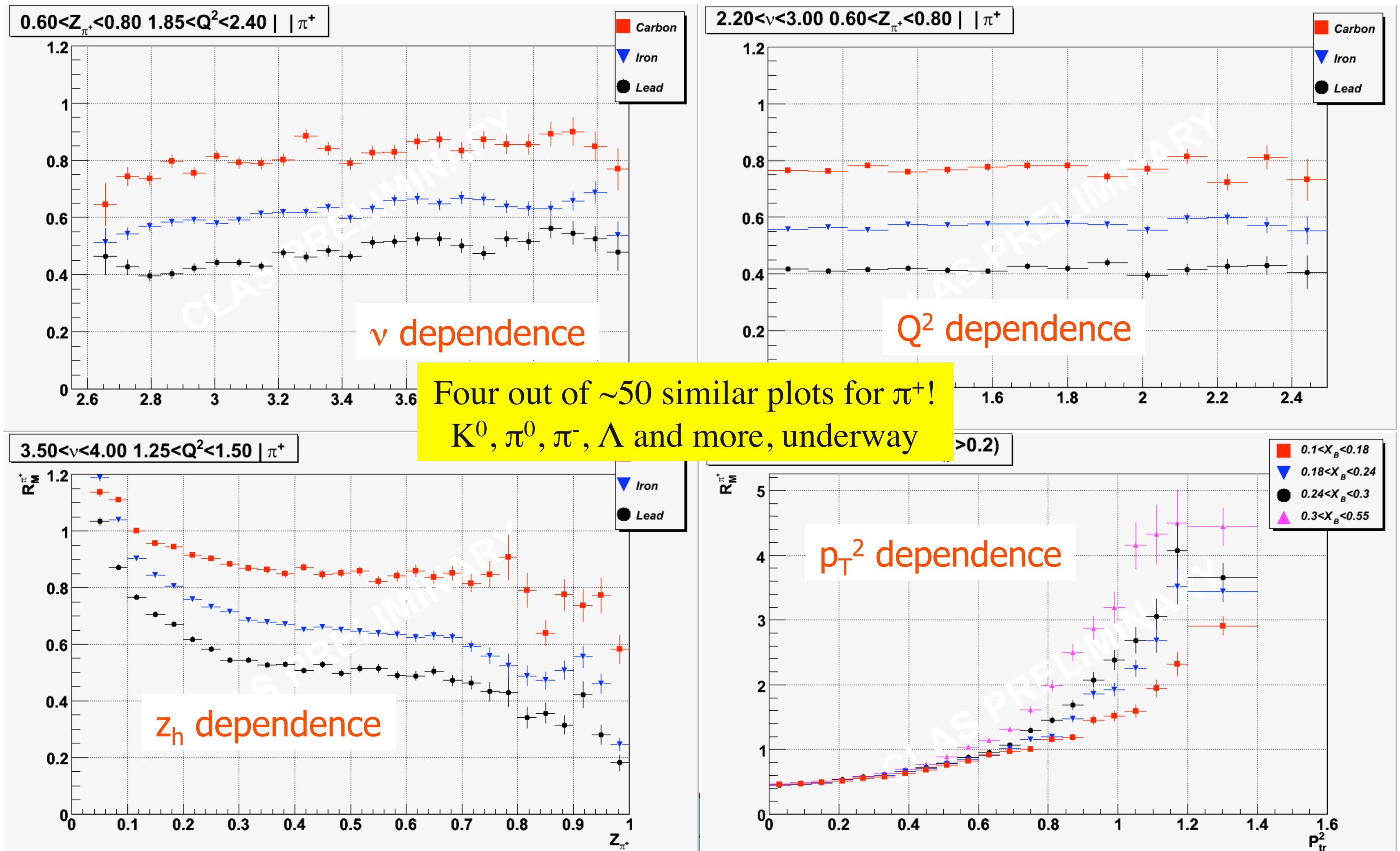
- *Authors: A. Accardi, H. Pirner, V. Muccifora*
  - Rooted in work by Nachtmann, Pirner, Jaffe, Close, Roberts, Ross, de Deus, from 1980's

- **Nuclear attenuation comes from:**
  - Partial deconfinement of quarks in nucleus in combination with gluon radiation
  - Nuclear re-interaction and absorption

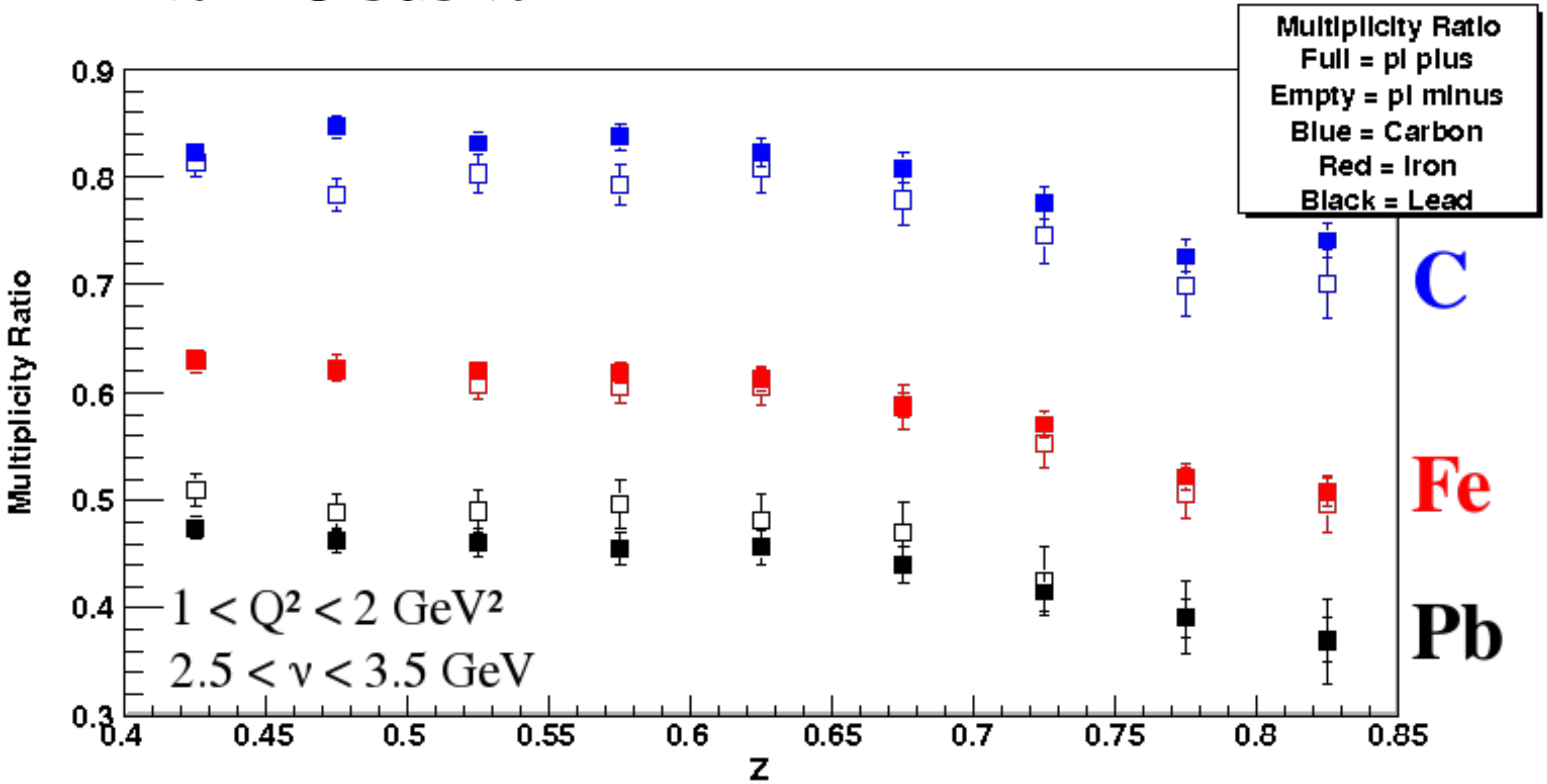
Rescaling Model, EMC/HERMES Data



Examples of multi-variable slices of preliminary CLAS 5 GeV data for $R^{\pi+}$



π^+ versus π^-



CLAS very preliminary: statistical errors only!

no acceptance or radiative corrections applied

Future prospects

- FNAL: E906 Drell-Yan at 120 GeV
  - ✓ Lower energy run will significantly simplify dE/dx extraction and remove ambiguity between shadowing and energy loss
- LHC RHI data
- RHIC upgrades
- JLab 12 GeV upgrade – CLAS12 in Hall B
  - ✓ 10 times more luminosity than CLAS and 1000 times more than HERMES
  - ✓ Improved particle identification
  - ✓ Access to higher masses
  - ✓ Much larger kinematical range
- **Future electron-ion collider**

Summary

- HERMES has higher beam energy (27 GeV and 12 GeV, vs. 5 GeV)
  - Much wider range in ν
  - Factorization ~ large range in z (0.2 – 0.8 vs. ~ 0.4 - 0.7 for JLab)
  - Access to higher W
  - Wide range of particle species
- CLAS has higher luminosity ($10^{34}/cm^2/s$, ~factor 100)
  - Can do 3 and 4-fold differential binning (vs. 1-D or 2-D for HERMES)
  - Access to higher Q^2 (good statistics for 4 GeV^2) and higher p_T^2
  - Can use solid targets (access to heaviest nuclei)
- Production and formation times extractions look promising
- The future will be even brighter, stay tuned!

Acknowledgments

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