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Space-Time Characteristics of Hadronization from Nuclear Deep-Inelastic Scattering

"Electromagnetic Studies of Nuclear Systems"
Workshop Milos Island, Greece

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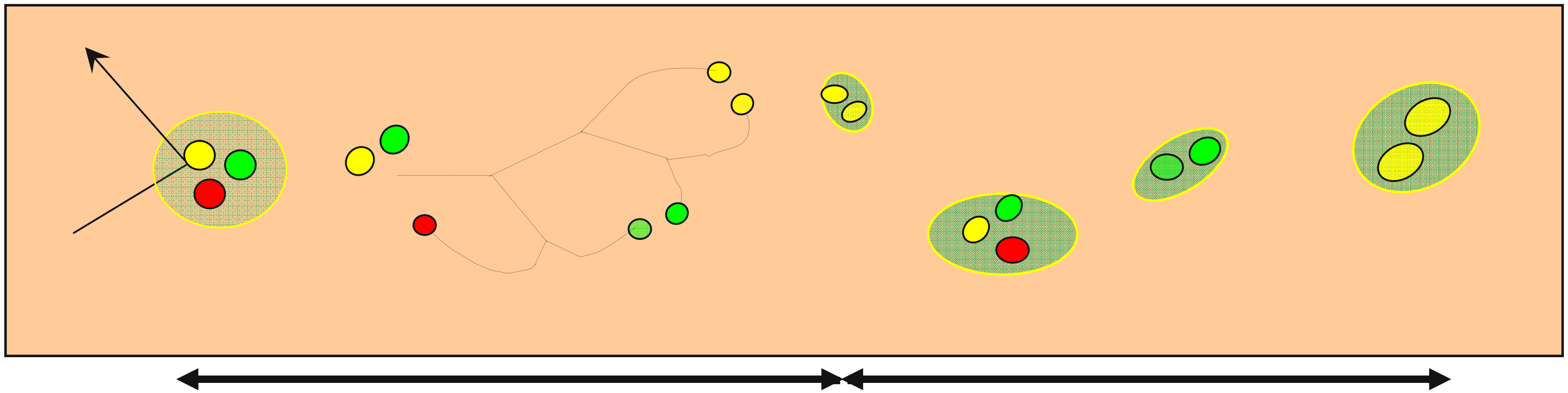
Time-distance scales of Hadronization



Production length

Time required to produce colorless "pre-hadron", signaled by **medium-stimulated energy loss** via gluon emission

Formation length

Time required to produce fully-developed hadron, signaled by **CT** and/or **usual hadronic interactions**

It is essentially unknown what these time scales are!

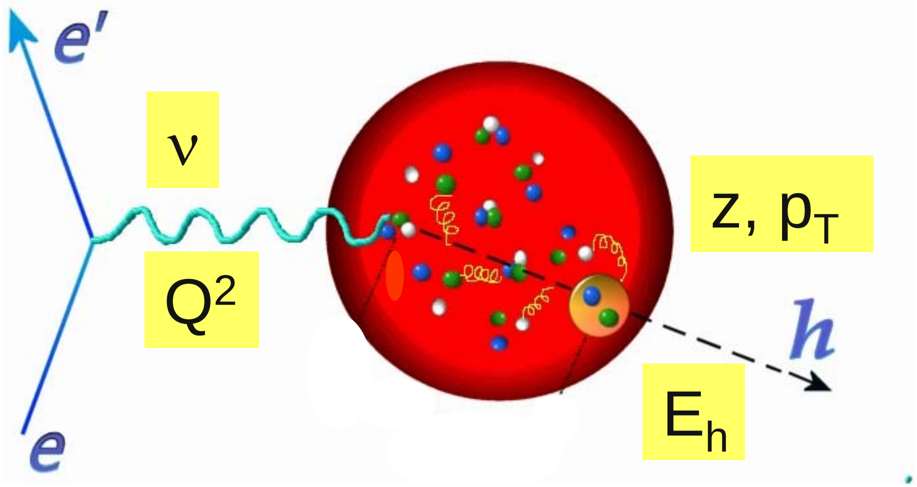
Experimental studies of quark propagation and hadron formation can isolate the production length and the formation length

Main Physics Focus

- **How long can a light quark remain deconfined?**
  - The **production time τ_p** measures this
  - Deconfined quarks lose energy via gluon emission
  - **Measure τ_p** and dE/dx via **medium-stimulated gluon emission**

- **How long does it take to form the color field of a hadron?**
  - The **formation time τ_f^h** measures this
  - Hadrons interact strongly with nuclear medium
  - **Measure τ_f^h** via **hadron attenuation in nuclei**

Experimental Variables



- ν – **energy transferred by the electron**
  = initial energy of struck quark, > 2 GeV here

- **Q^2** – **four-momentum transferred by the electron**,
  ~1/(spatial resolution) of the probe, > 1 GeV² here

- **$z = E_{hadron}/\nu$, the fraction of the struck quark's initial energy that is carried by hadron**; **0<z<1**

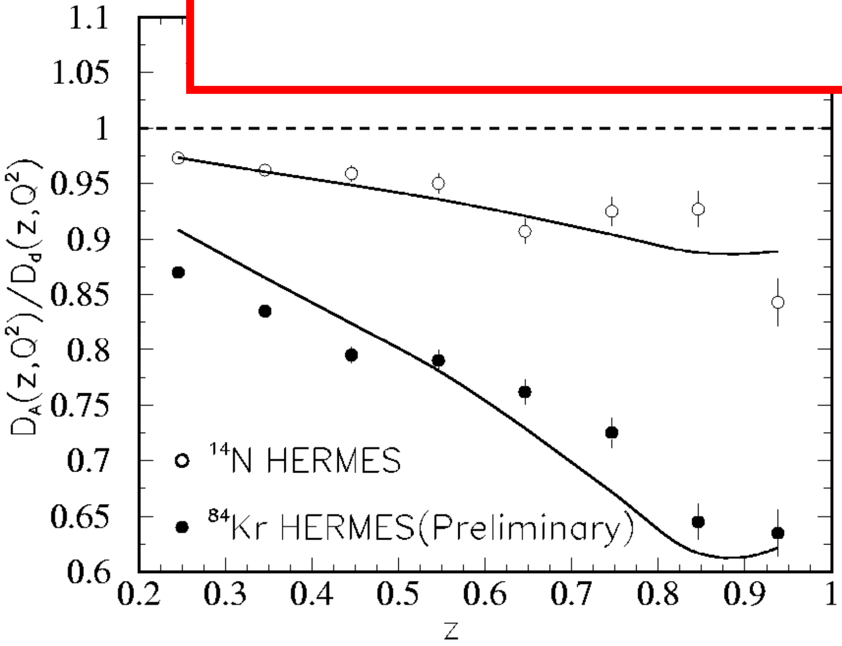
- **p_T** – **hadron momentum transverse to virtual photon direction**

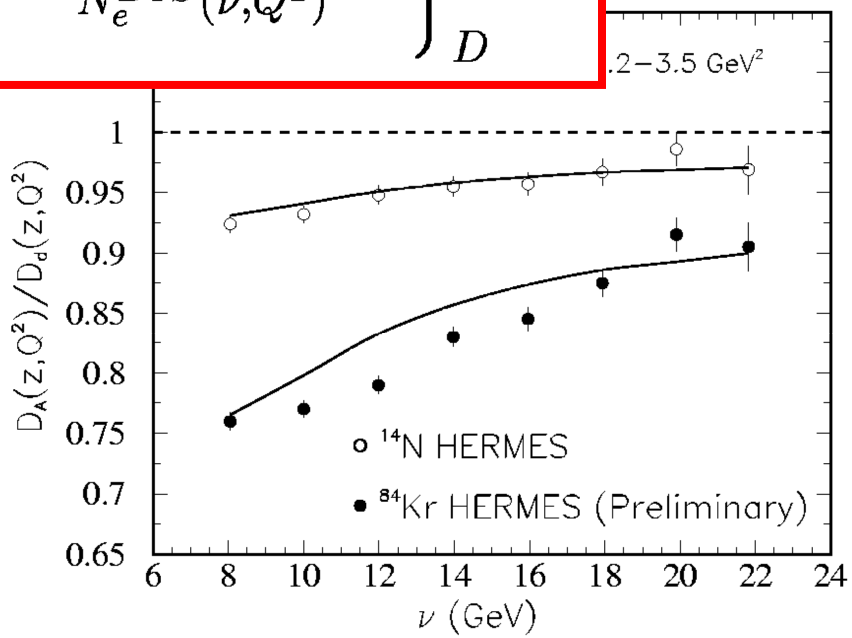
Observable Number 2 – Hadronic Multiplicity Rati

$$l_p \approx \frac{\nu(1-z)}{dE/dx}$$

$$\left\{\frac{N_h(z,\nu)}{N_e^{DIS}(\nu)}\right\}$$

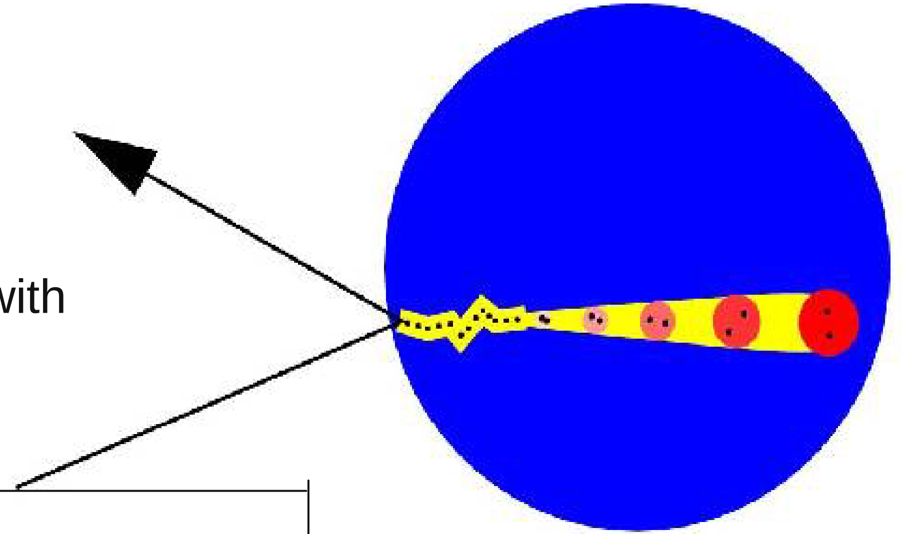
$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{\dfrac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_A}{\left\{\dfrac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_D}$$

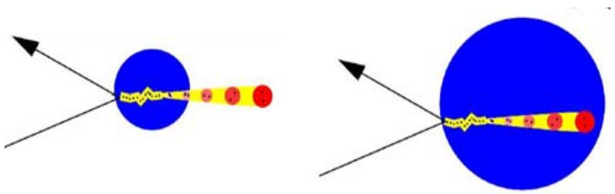




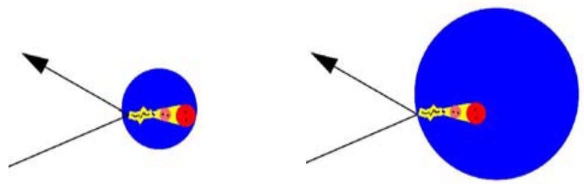
Hadron Attenuation – Physics Picture

- Hadrons lost from incident flux through
  - Quark energy loss
  - Interaction of pre-hadron or hadron with medium





z_h~0.5, larger ν, less attenuation



$z_h \rightarrow 1$, smaller ν, more attenuation

Analysis Strategy

$$\Delta p_T^2\Big|_h \Rightarrow \tau_p(\nu, z, Q^2)$$

$$\tau_p + R_M^h \Rightarrow \tau_f^h(\nu, z, Q^2, p_T)$$

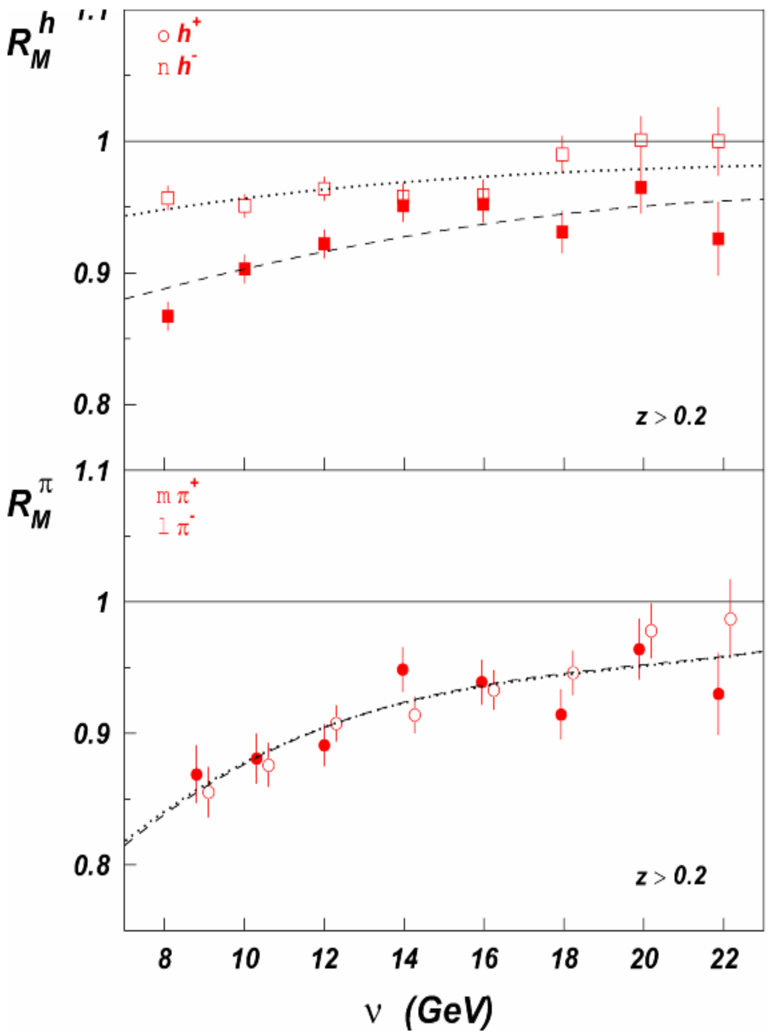
Experimental Studies

Experimental avenues

- **Semi-inclusive deep inelastic scattering on nuclei**
  - *1970's CERN EMC eA → e'Xh, energy transfer ~35-145 GeV*
  - *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*
- **Relativistic heavy ion reactions**
  - *2000's BNL RHIC AA → everything, 200 GeV/u colliding beams*

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

Charged hadron/pion on ^{14}N

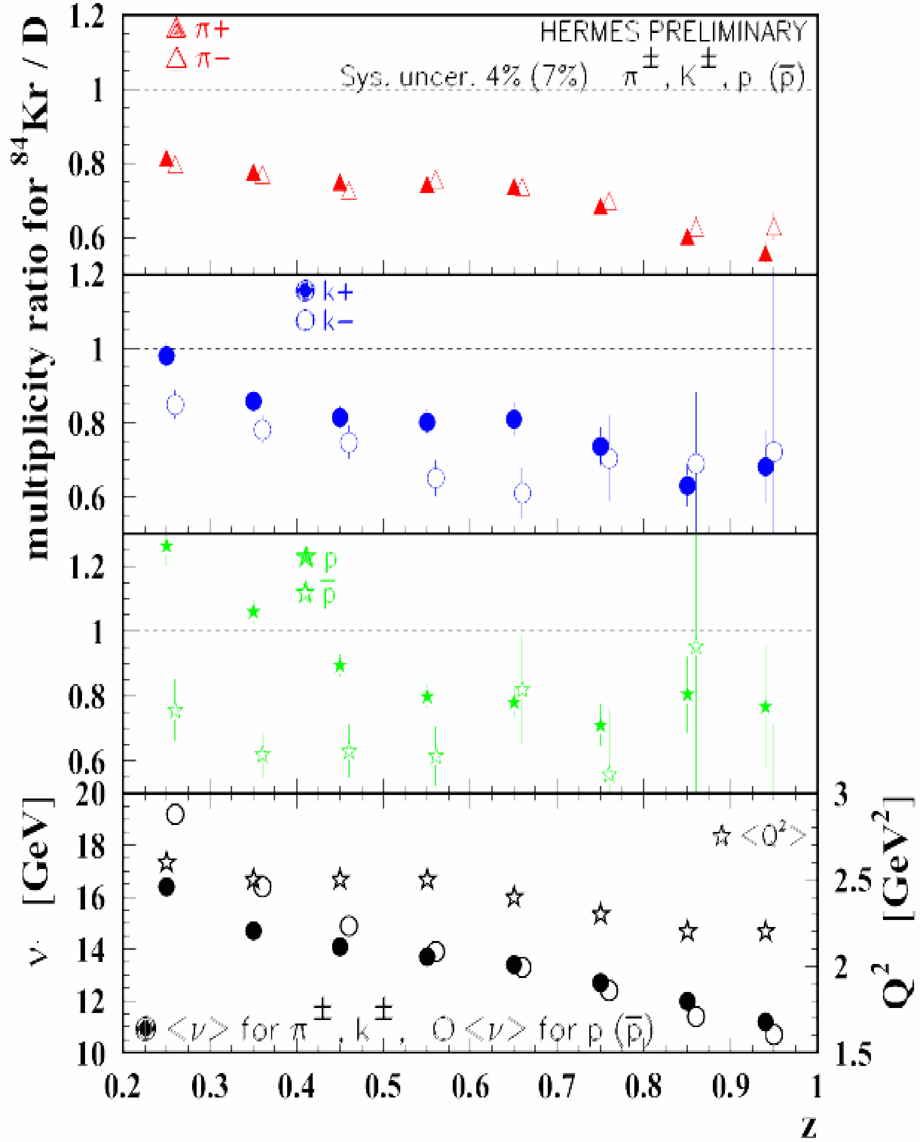


No difference between π^+ and π^-

Difference between $h^+(\pi^+,K^+,p)$ and $h^- (\pi^- ,K^-,p-)$.

$\Rightarrow$ different behavior for different hadrons

Attenuation on ^{84}Kr vs z with hadron ID



Possible interpretations:

- Different FF modification for q and $\bar{q}$.
- Different t_f for mesons and baryons.
- Different hadronic cross sections:

$\sigma_{\pi^+} = \sigma_{\pi^-} \approx 20$ mb.
$\sigma_{K^+} \approx 17$ mb $\sigma_{K^-} \approx 23$ mb.
$\sigma_p \approx 40$ mb $\sigma_{\bar{p}} \approx 60$ mb

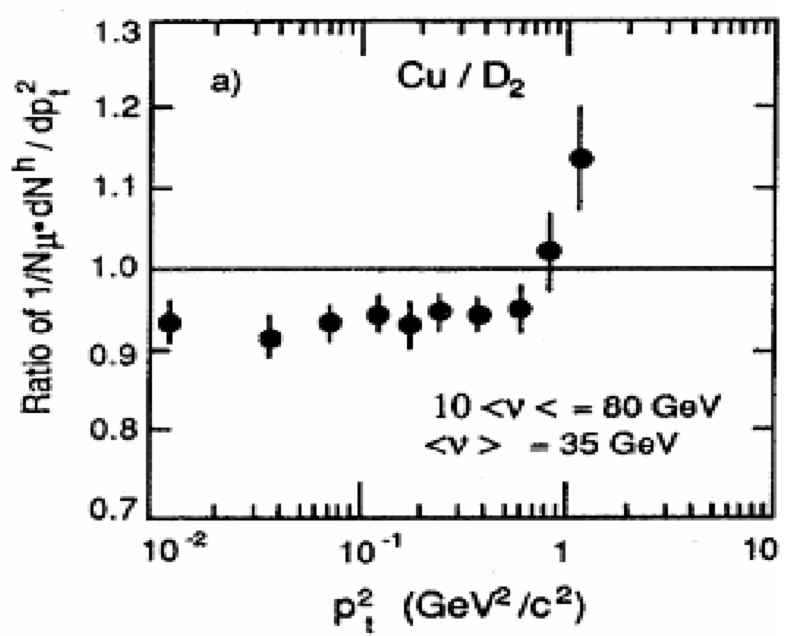
Attenuation vs p_t^2 ('Cronin effect')

In the lepton-nucleon scattering neither multiple scattering of the incident particle nor interaction of its constituents complicate the interpretation.

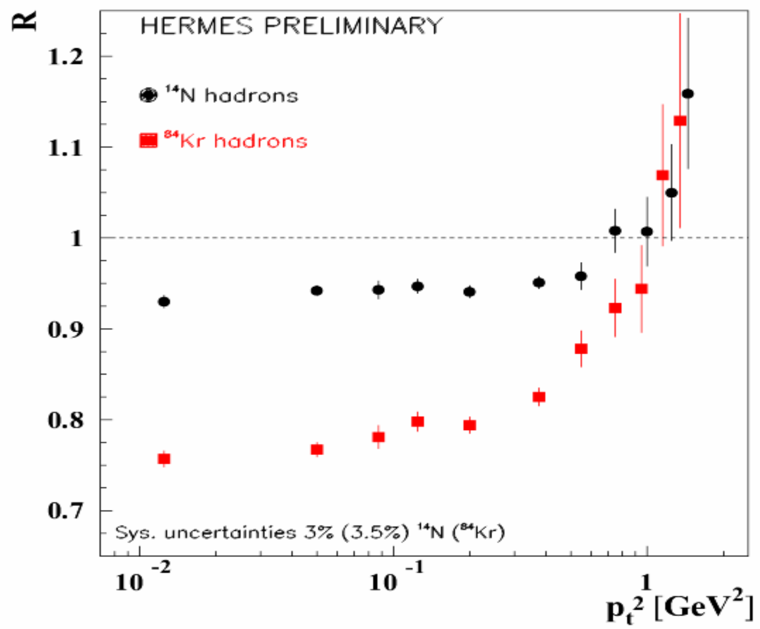
⇓

Clean and reliable information on quark transport in 'cold' nuclear matter.

EMC



HERMES



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)*

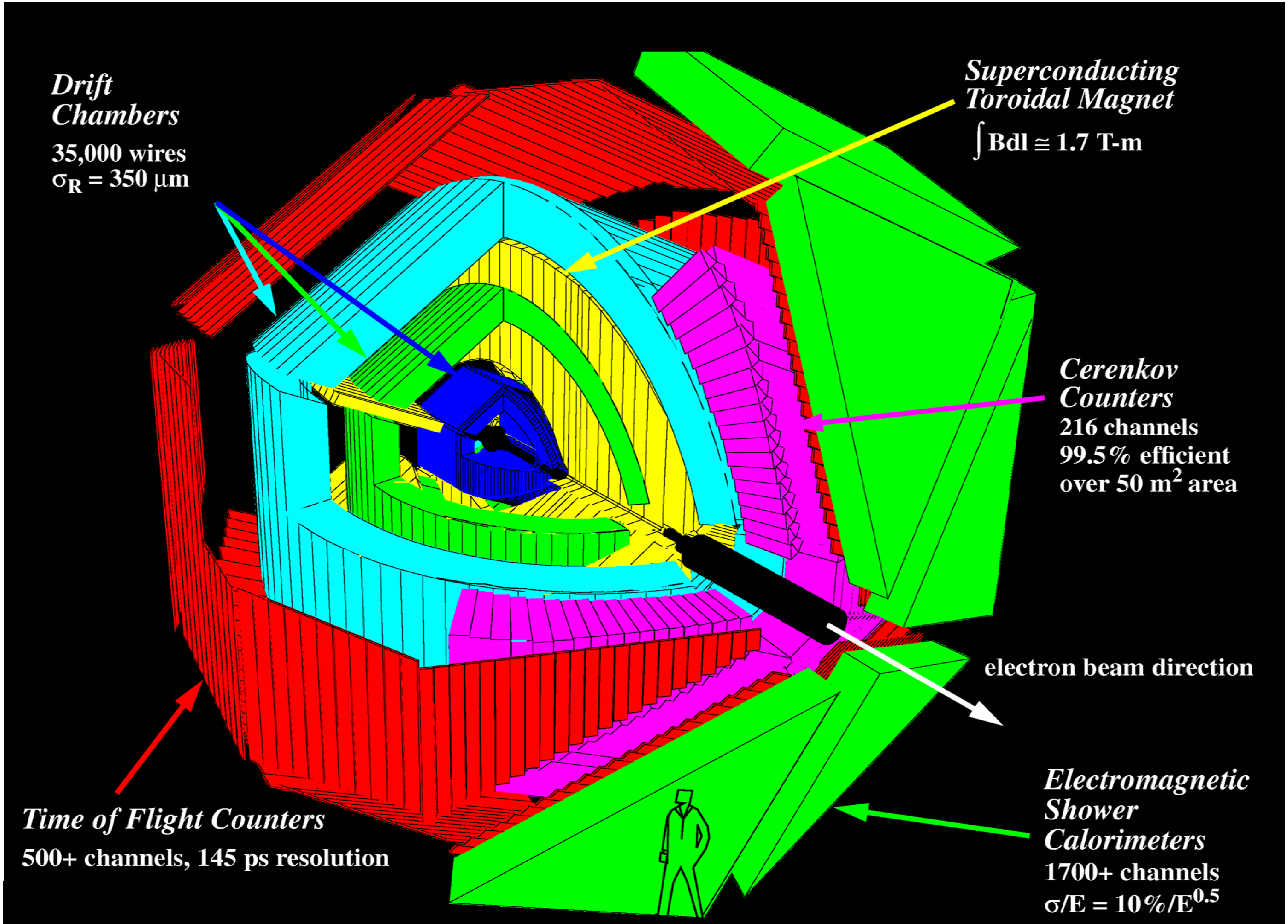
  Gluon emission, partial deconfinement, nuclear absorption

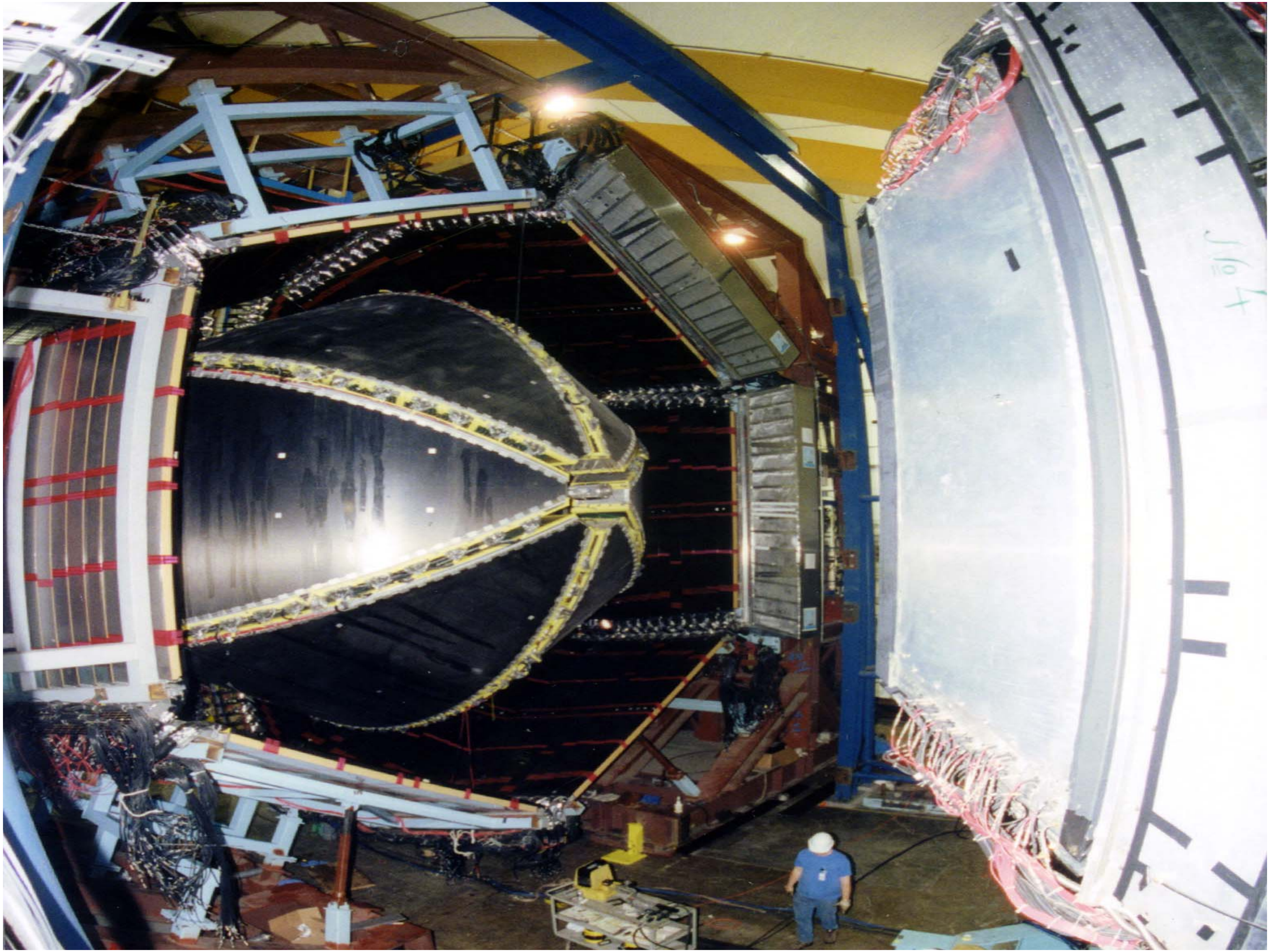
- **PYTHIA-BUU Coupled Channel Model** *(T. Falter, W. Cassing, K. Gallmeister, U. Mosel)*

  Fundamental interaction + coupled channel nuclear final state interaction

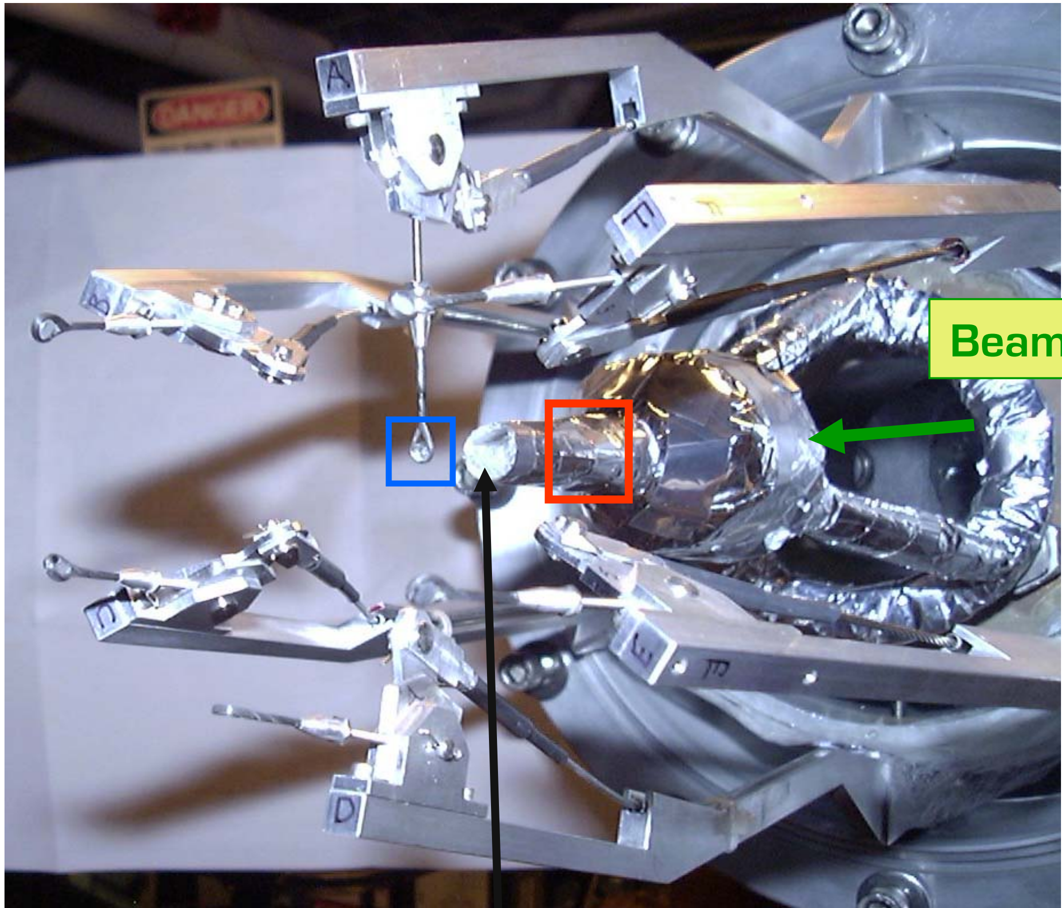
Comparison of HERMES/DESY and CLAS/Jefferson Lab

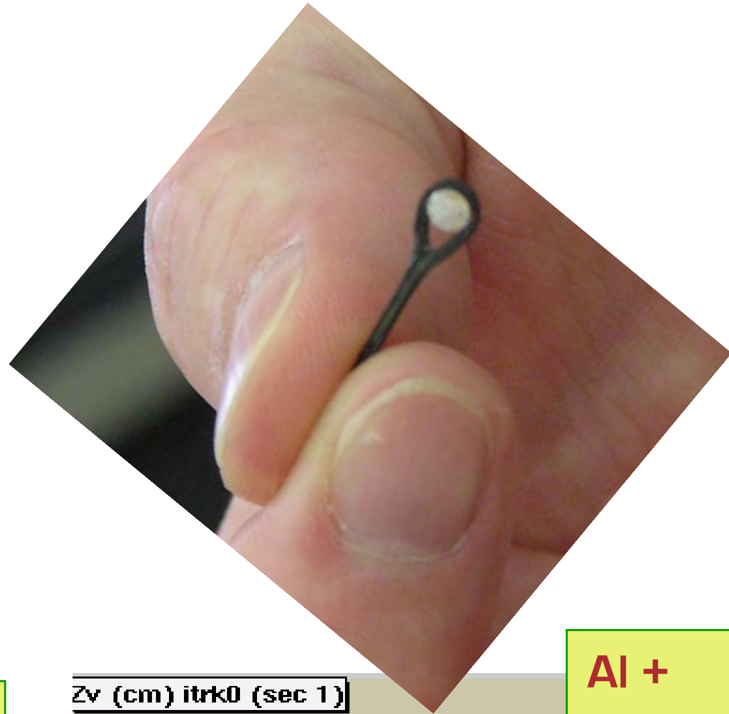
- HERMES has higher beam energy (27 GeV and 12 GeV, vs. 5 GeV)
  - Much wider range in ν
  - Factorization ~ large range in z (vs. ~0.4-0.7 for JLab)
  - Access to higher W
- **HERMES can identify a wider range of particle species**
- **CLAS has higher luminosity (10^{34}/cm^2/s, ~factor 100)**
  - **Can 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**
- **CLAS can use solid targets**
  - **Access to heaviest nuclei (^{208}Pb vs. ^{131}Xe)**

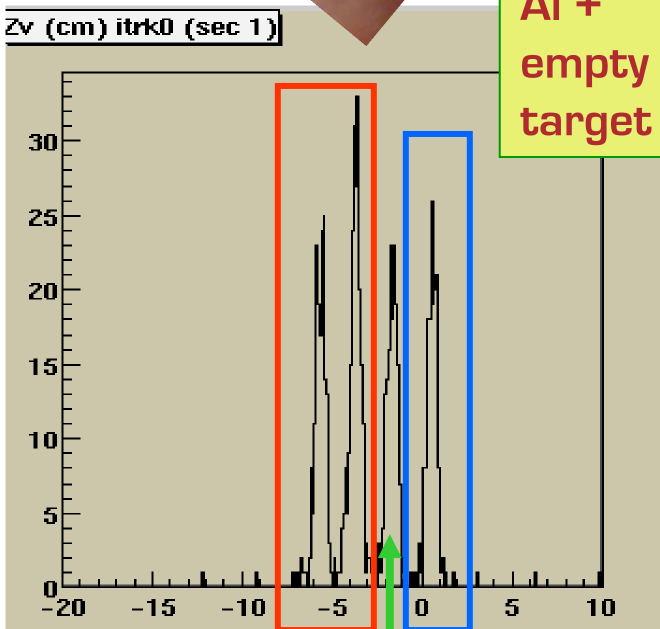

Drift Chambers
35,000 wires
σR = 350 μm
Superconducting Toroidal Magnet
∫Bdl ≅ 1.7 T-m
Cerenkov Counters
216 channels
99.5% efficient
over 50 m2 area
electron beam direction
Electromagnetic Shower Calorimeters
1700+ channels
σ/E = 10%/E0.5
Time of Flight Counters
500+ channels, 145 ps resolution



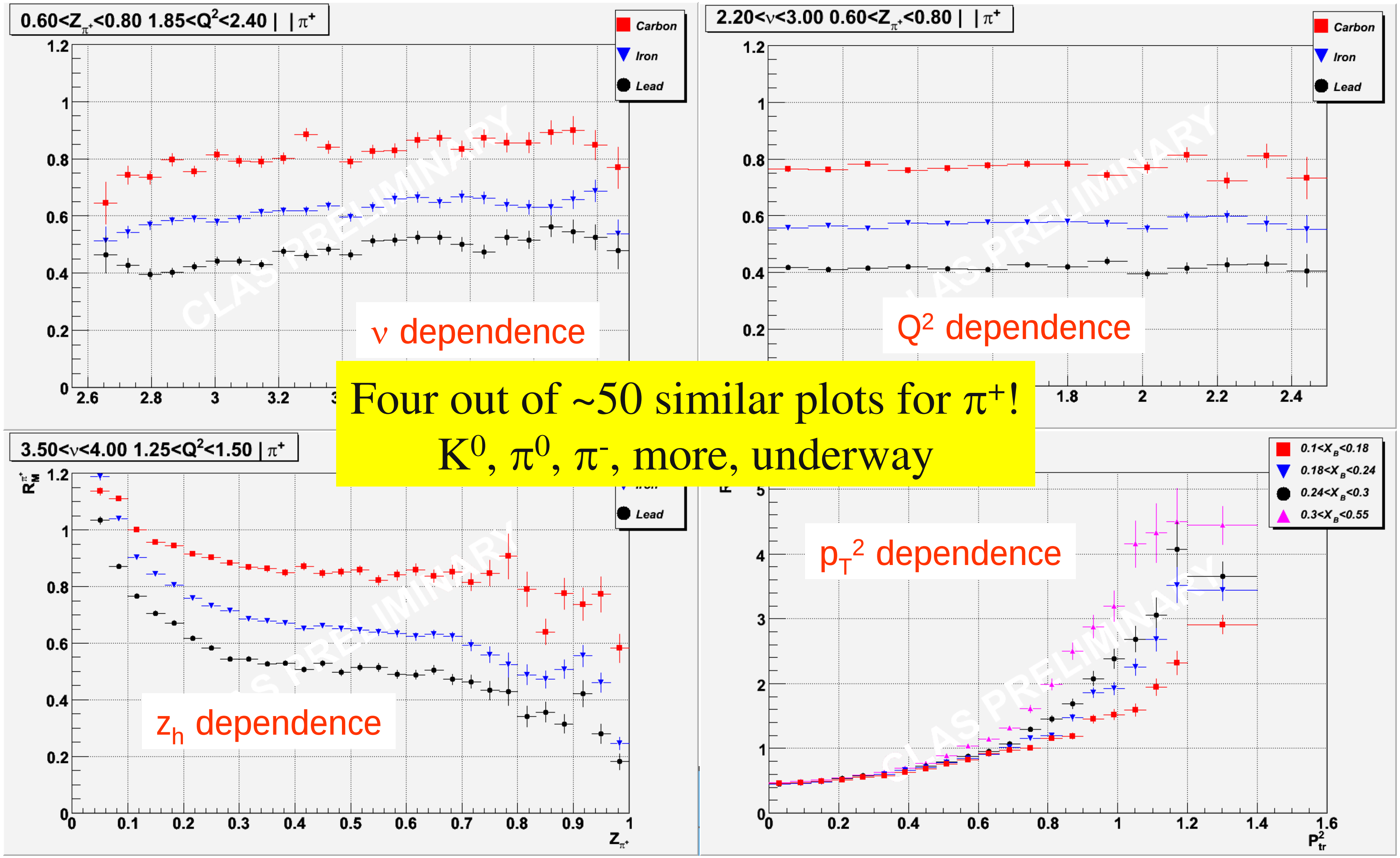
EG2 Targets


Beam

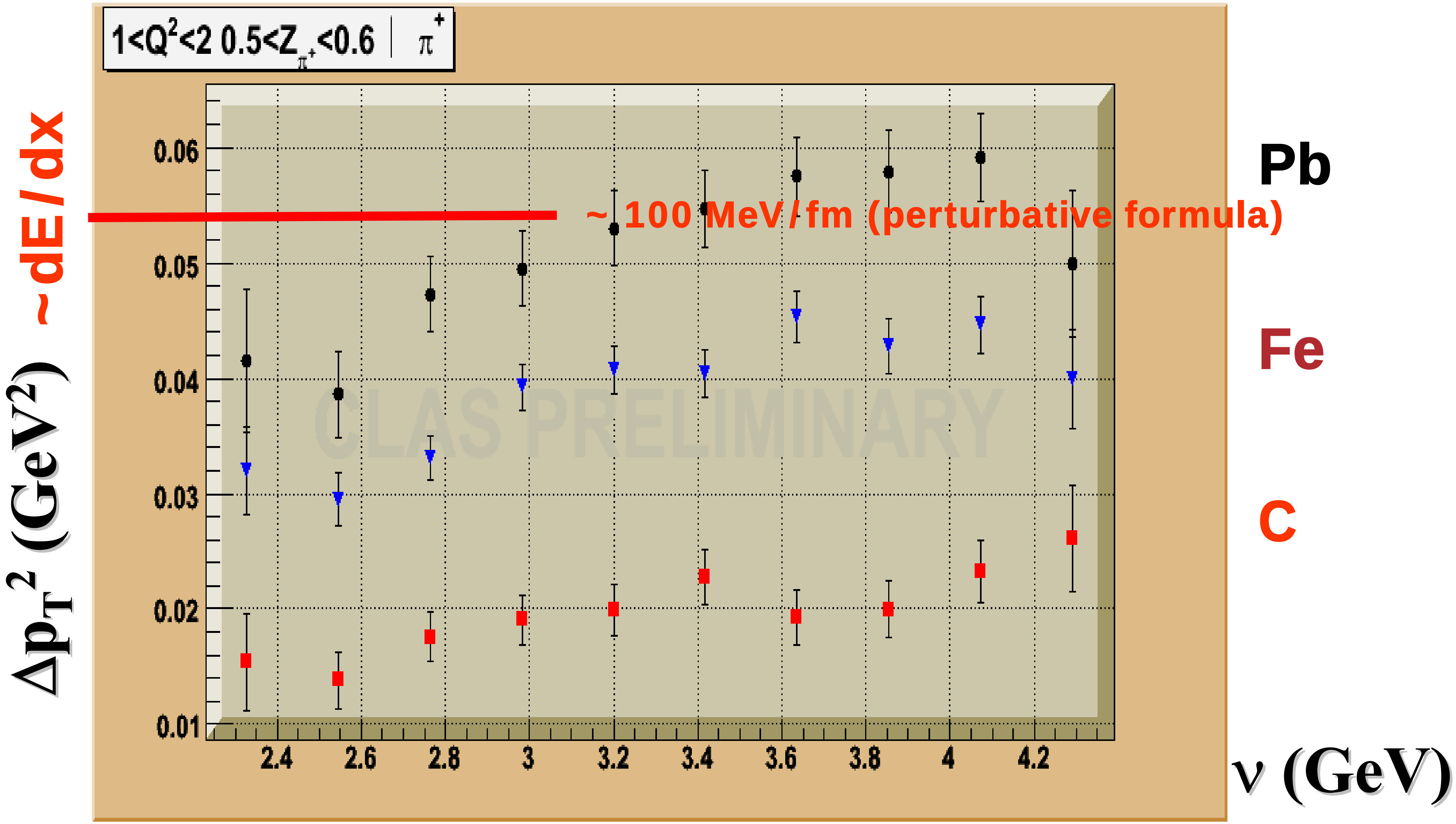



Zv (cm) itrk0 (sec 1)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
Al + empty target
Reference foil

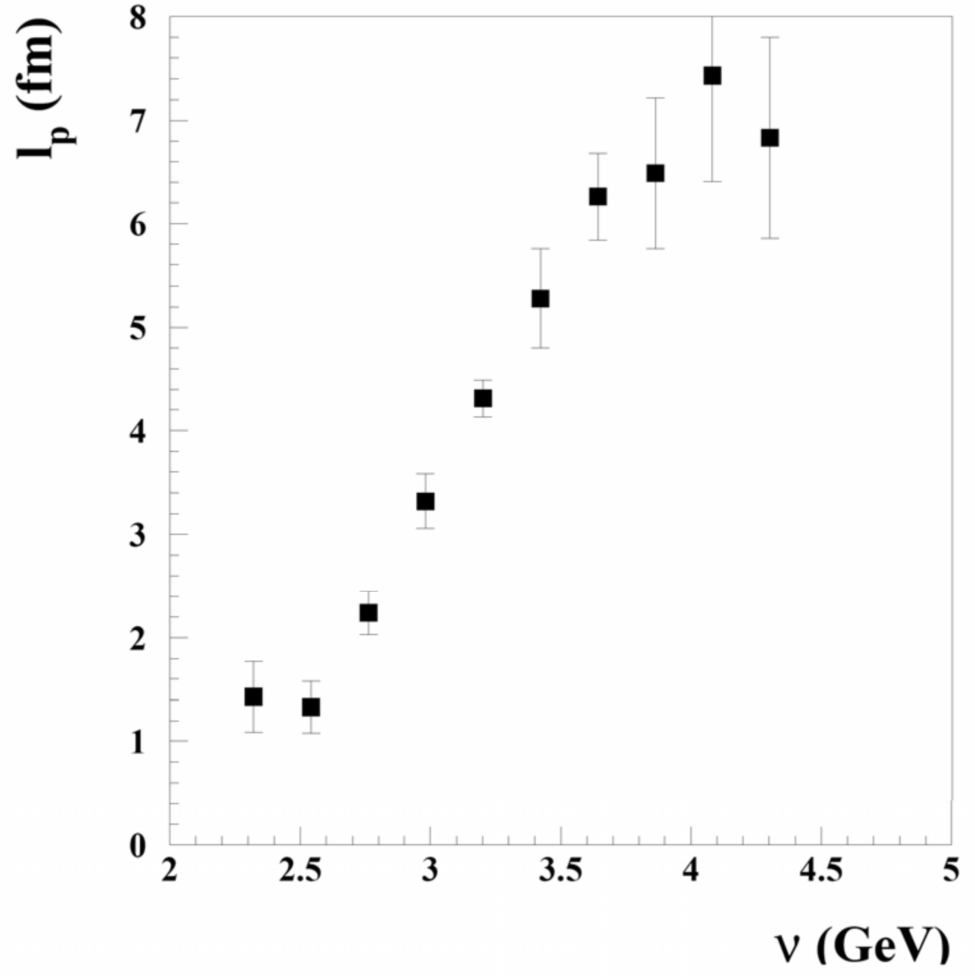
Examples of multi-variable slices of preliminary CLAS 5 GeV data for $R^{\pi+}$



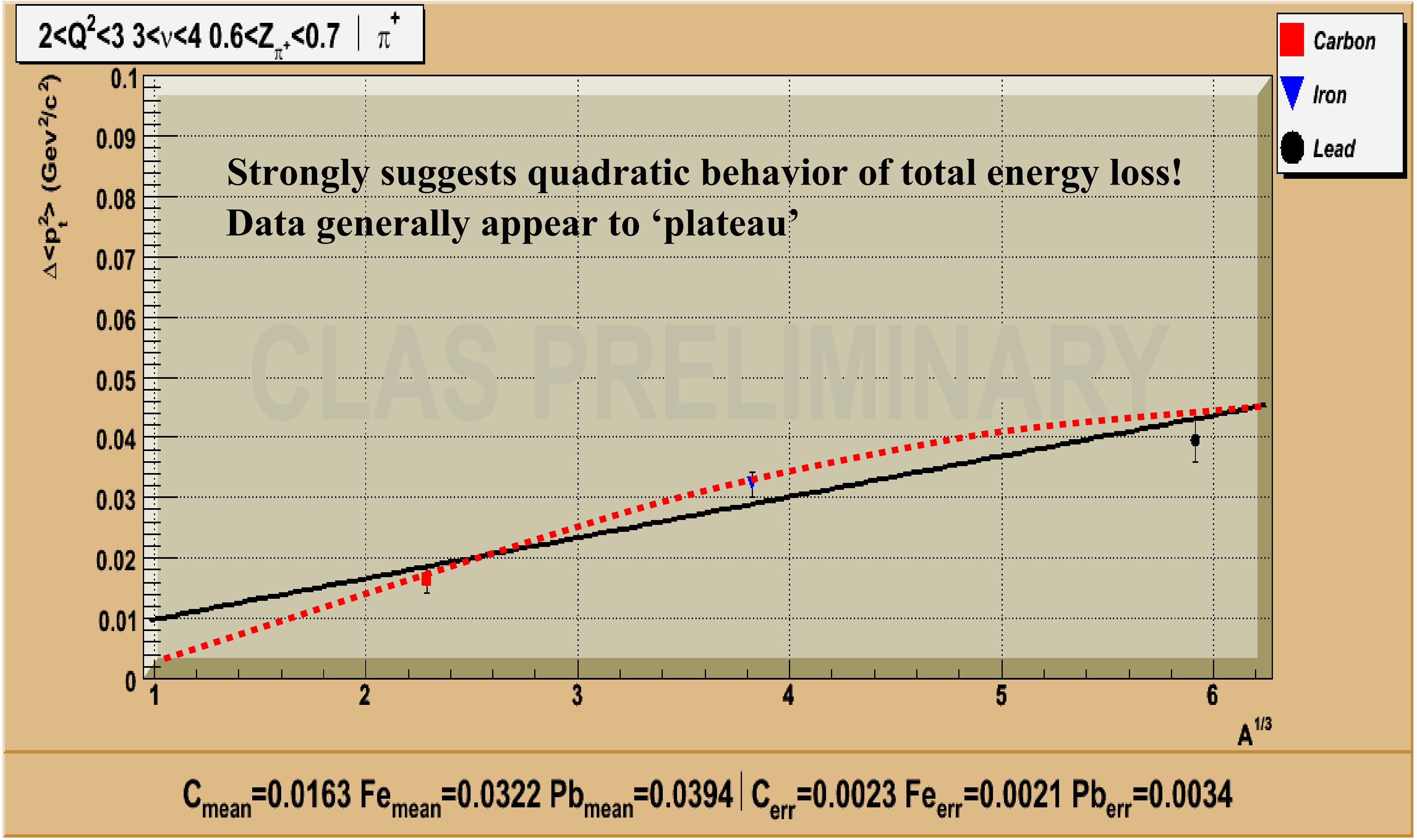
Δp_T^2 vs. ν for Carbon, Iron, and Lead



Production length from JLab/CLAS 5 GeV data (Kopeliovich, Nemchik, Schmidt, hep-ph/0608044)



Δp_T^2 vs. $A^{1/3}$ for Carbon, Iron, and Lead

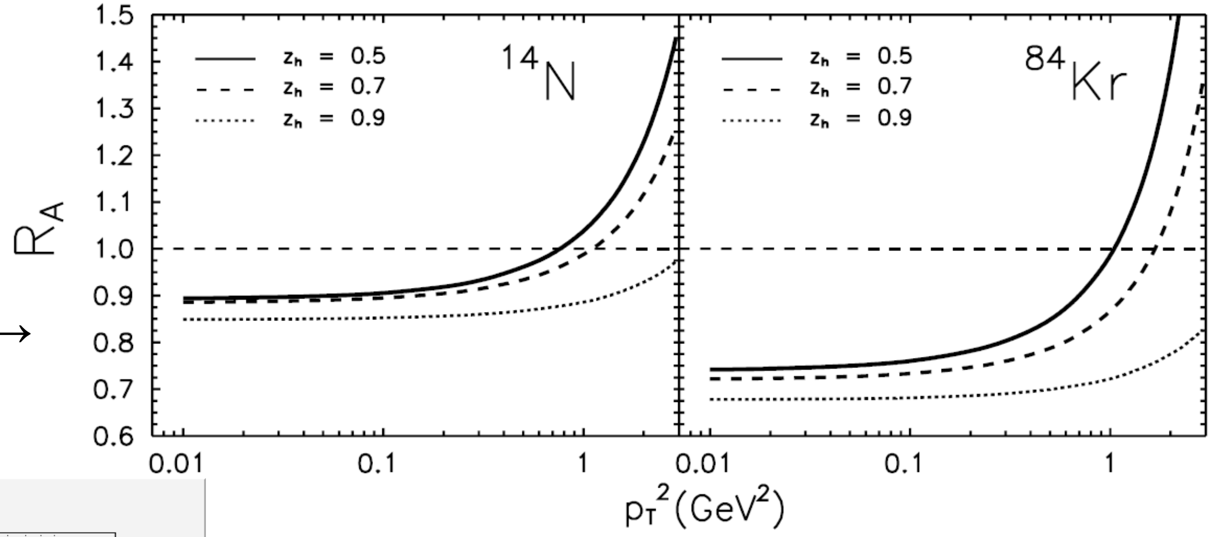


Only statistical errors shown

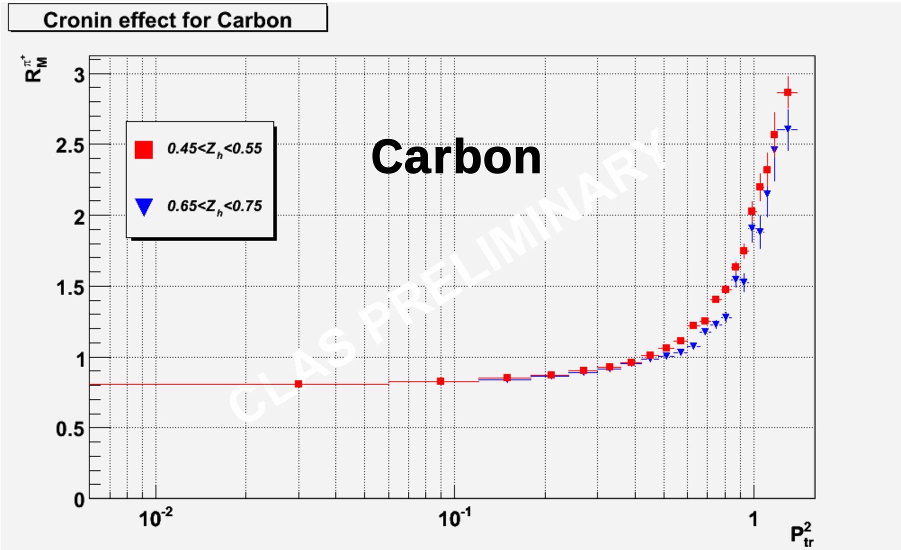
B.Z. Kopeliovich et al. / Nuclear Physics A 740 (2004) 211–245

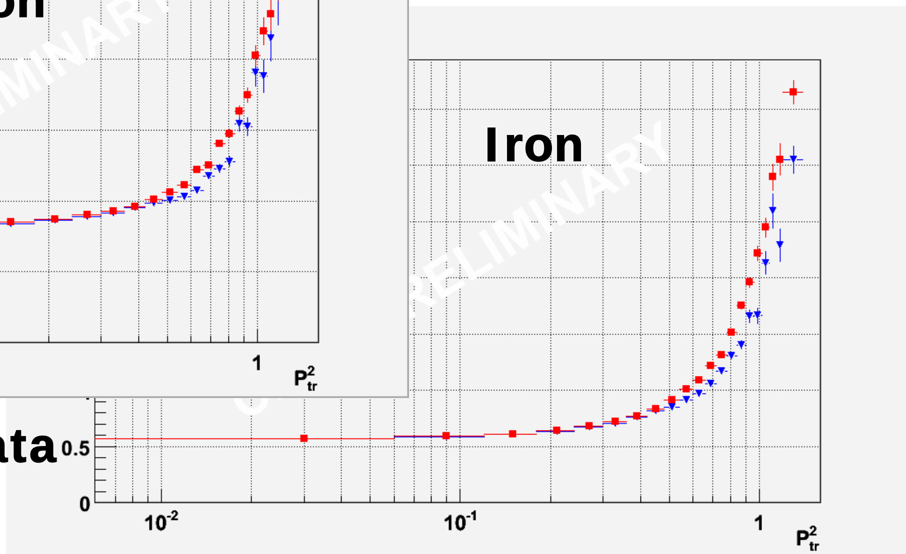
Cronin Effect – Dependence on Z

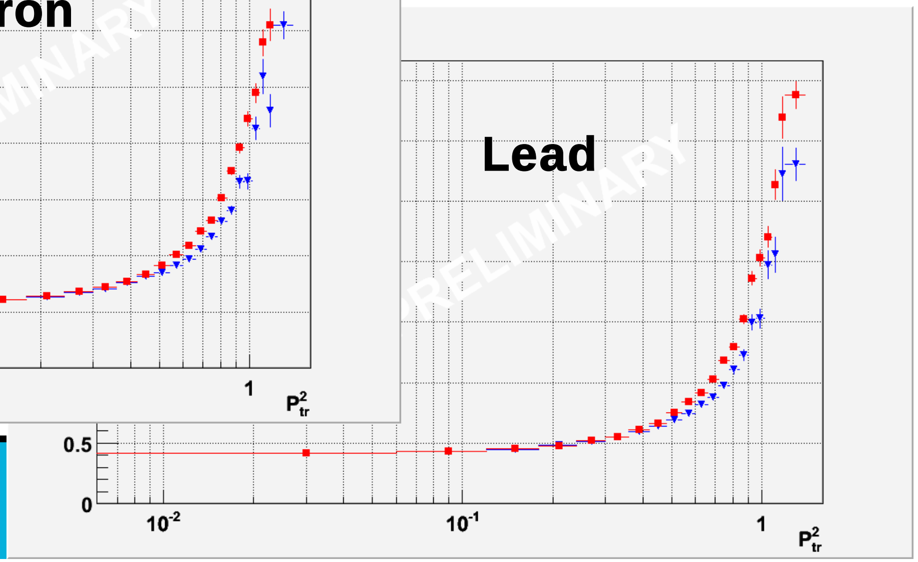
Theoretical *prediction* →



Strong evidence for reaction mechanism

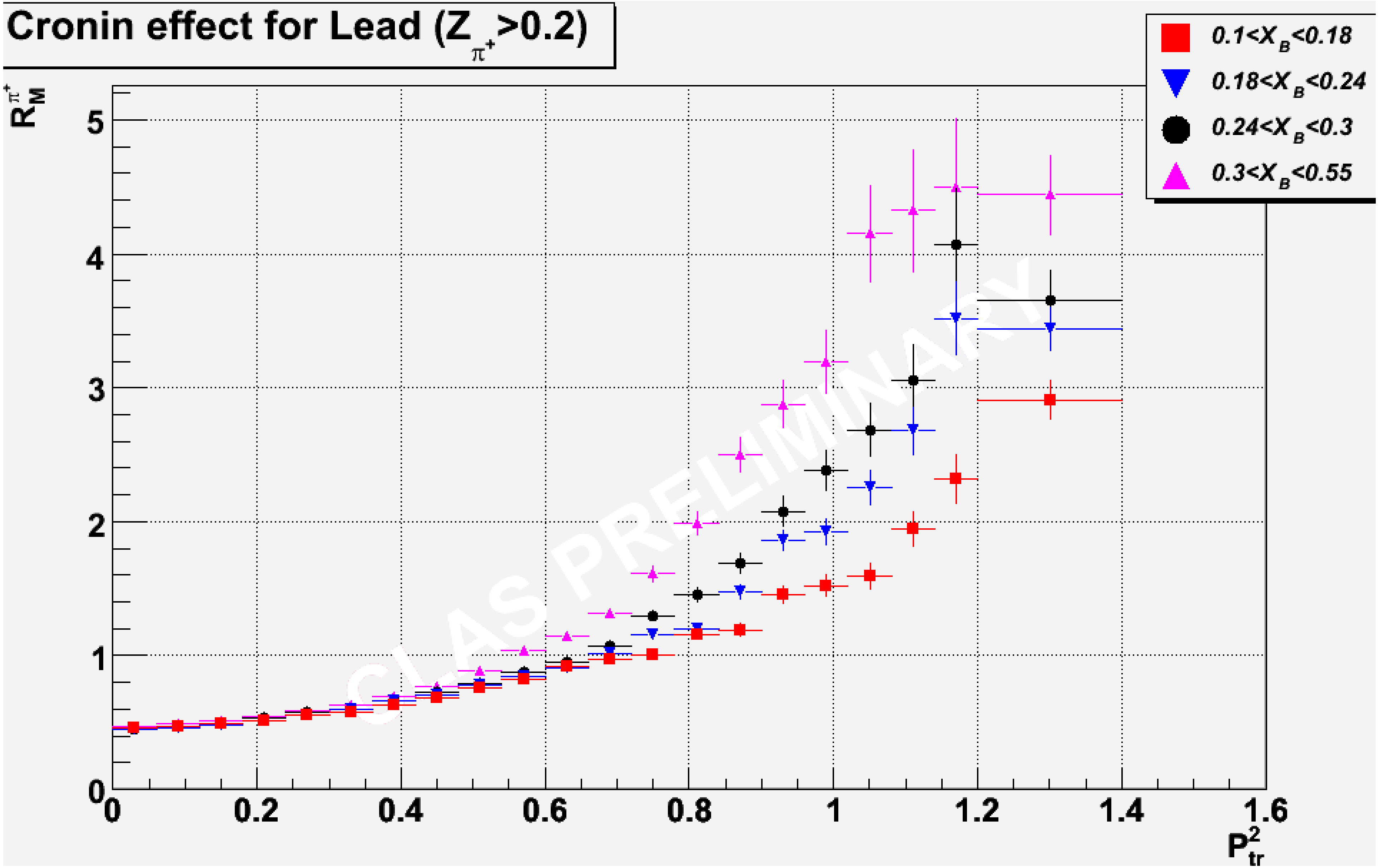






CLAS preliminary data
z=0.5 and 0.7

Cronin Effect – Dependence on A, x, and Q^2



Physics Insights from CLAS Data

- **Precision measurement of p_T broadening:**
  - dE/dx ~100 MeV/fm at 6 fm for few-GeV quarks at zero temperature; more theoretical work needed for quantitative extraction
  - Quadratic dependence of ΔE clearly seen
  - Enabled first extraction of deconfined quark lifetime τ_p

- **New information on Cronin effect**
  - Dependence on A, Q^2, x, z has been observed

- **Multivariable formation lengths accessible through R_M**
  - Comprehensive analysis framework needed

Connections to Relativistic Heavy Ion Physics

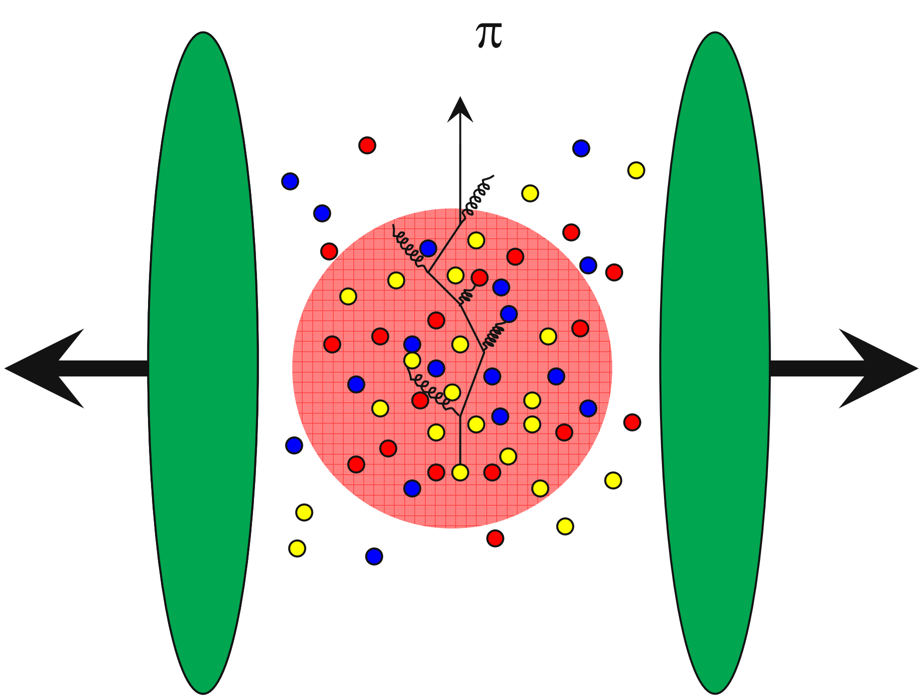
- Radiative energy loss – quantitative baseline in well-understood cold system

- Detailed understanding of hadron formation

- Nuclear DIS is closely related to propagation of partons in AA collisions

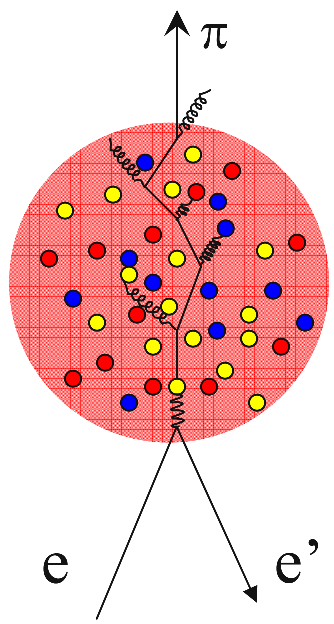
Relevance to RHIC and LHC

Relativistic Heavy-Ion Collisions



$E_\pi = p_T < 20$ GeV/c

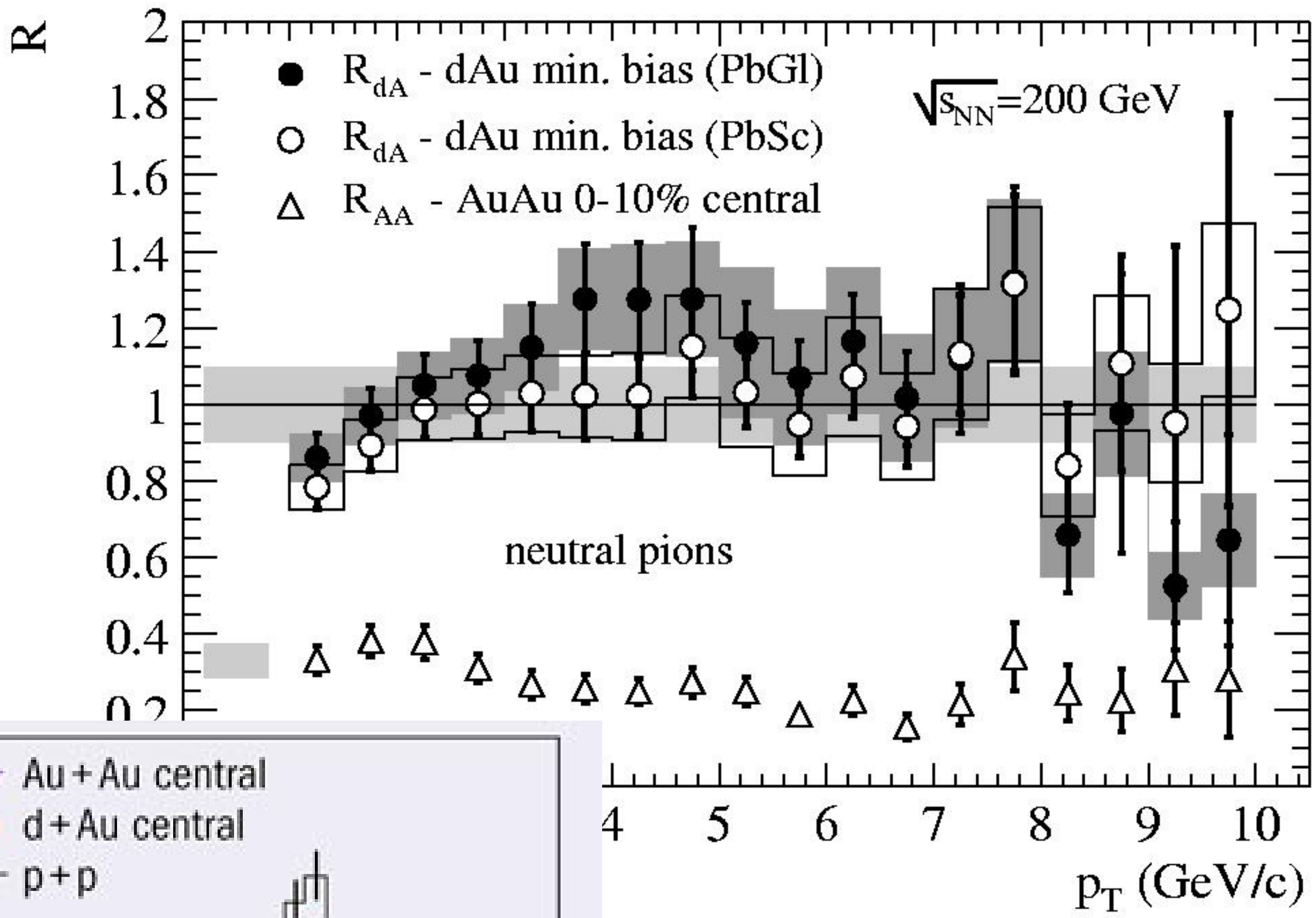
Deep Inelastic Scattering



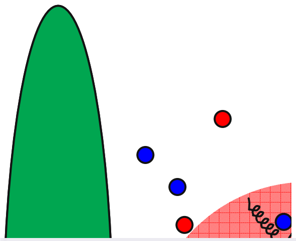
Initial quark energy is known
Properties of medium are known

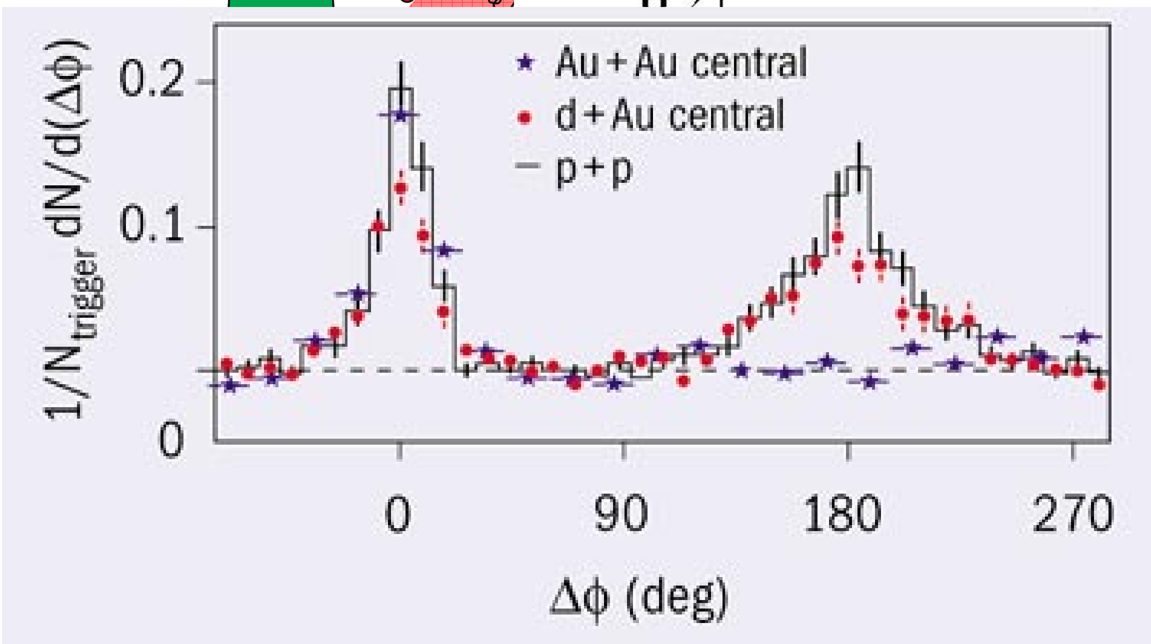
$E_\pi < 20$ GeV/c

Releva



R
R_{dA} - dAu min. bias (PbGl)
R_{dA} - dAu min. bias (PbSc)
R_{AA} - AuAu 0-10% central
$\sqrt{s_{NN}}$=200 GeV
neutral pions
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
4
5
6
7
8
9
10
p_T (GeV/c)





Au + Au central
d + Au central
p + p
$1/N_{trigger}$ dN/d(Δφ)
0.2
0.1
0
0
90
180
270
Δφ (deg)

Connection to Relativistic Heavy Ion Physics

- One proposed signature of the Quark Gluon Plasma is jet quenching: the suppression of high p_T jets

- Jet quenching caused by radiative energy loss would be an indication of high partonic density, e.g., QGP

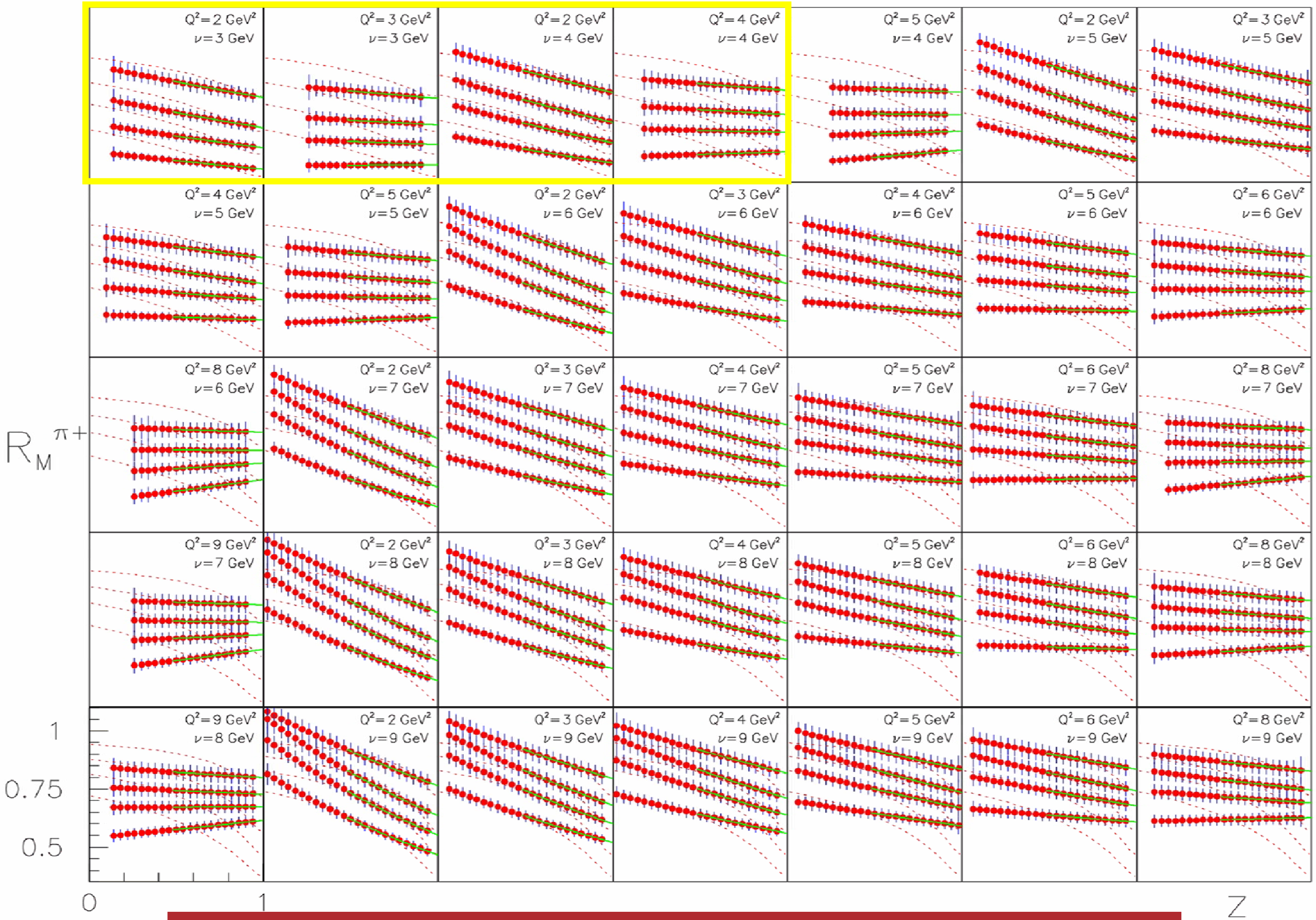
- Hadron formation might give an alternative explanation for jet quenching

Future Prospects

- Ongoing HERMES analyses will be released/published, e.g.,
  - Transverse momentum broadening
  - Two-hadron correlations
  - Data for ^{131}Xe
- New Drell-Yan experiment - E906
  - Lower energy run will significantly simplify dE/dx extraction
- The 12-GeV upgrade of Jefferson Lab (including CLAS)
  - Factor of 10 luminosity increase to 10^{35} /cm^2/s
  - Improved particle identification
  - Access to higher mass hadrons
  - Much bigger range of DIS kinematics

12 GeV Anticipated Data

Examples of Experimental Data and Theoretical Predictions



Argonne NATIONAL LABORATORY π^+

Bins in yellow accessible at 5 GeV

Conclusions

- ☺ New opportunities to learn space-time physics related to confinement and to hadron structure – τ_p and τ_f
- ☺ New insights from HERMES data
- ☺ Massive new data set from CLAS will stimulate much more theoretical progress
- ☺ Future measurements: Drell-Yan, and JLab at 12 GeV

THE END

Target Frame DIS Kinematics

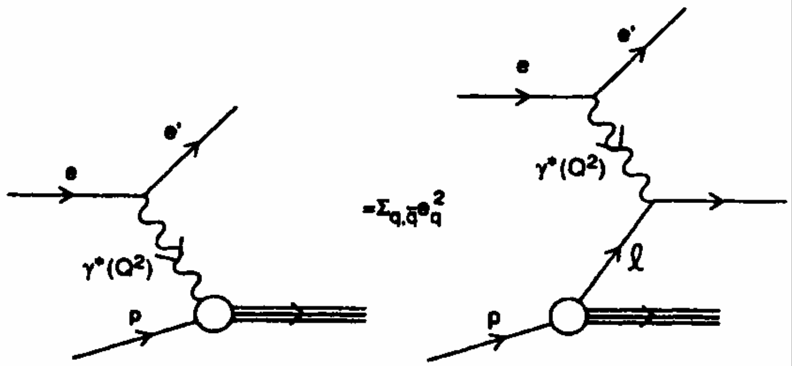


FIG. 1. DIS in the infinite-momentum frame.

See "*Space-time structure of deep-inelastic lepton-hadron scattering*," Del Duca, Brodsky, Hoyer PRD 46 (1992) p. 931

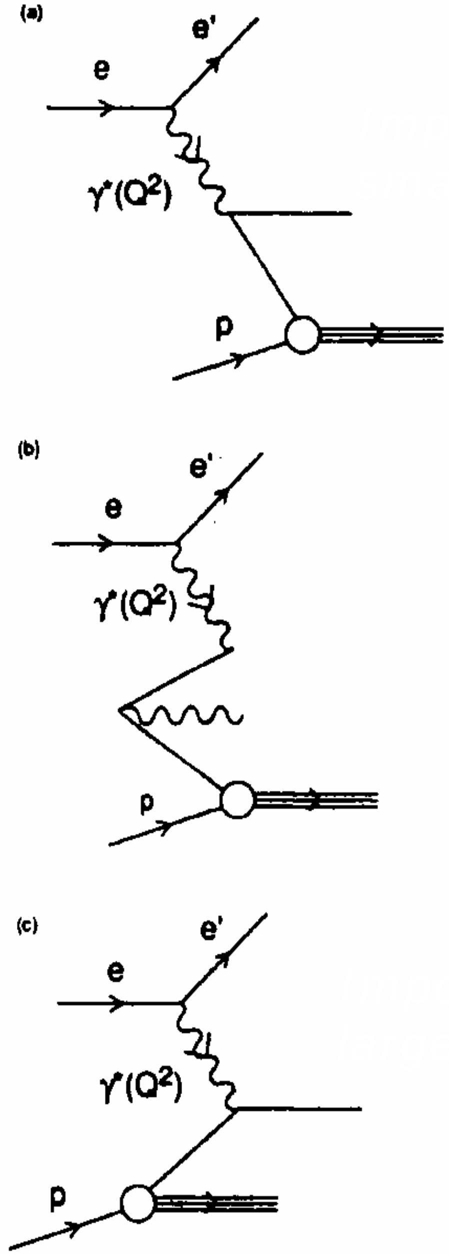


FIG. 2. Time-ordered contributions to DIS in the target rest frame.

Energy Loss in QCD

- Partonic energy loss in QCD is well-studied: dozens of papers over past 15 years
- Dominant mechanism is gluon radiation; elastic scattering is minor
- Coherence effects important: QCD analog of LPM effect

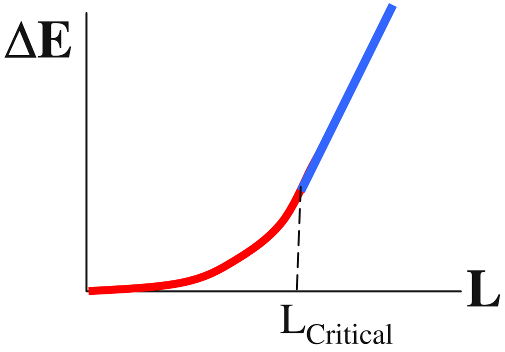
$$\ell_c \approx \frac{\omega}{\langle k_\perp^2 \rangle_{\ell_c}}$$ Coherence length ~ formation time of a gluon radiated by a group of scattering centers

Three regions: if mean free path is λ, and medium length is L, then →

$\ell_c < \lambda$	Incoherent gluon radiation
$\lambda < \ell_c < L$	Coherent gluon radiation
$\ell_c > L$	'Single-scatter' gluon radiation

Two conditions emerge: $-\frac{dE}{dx} \propto L \qquad L < L_{Critical}$

$$-\frac{dE}{dx} \propto \sqrt{E} \qquad L > L_{Critical}$$



Baier, Schiff, Zakharov, Annu. Rev. Nucl. Part. Sci. 2000. 50:37-69

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

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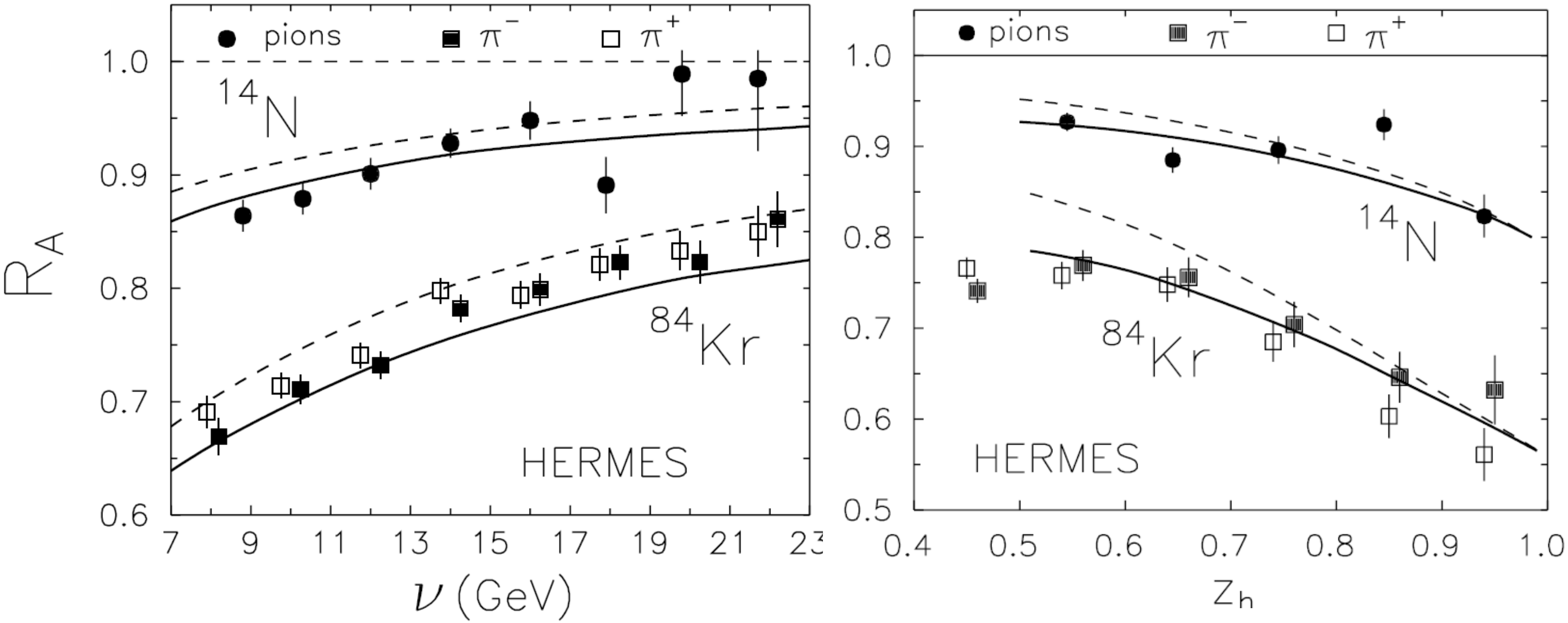
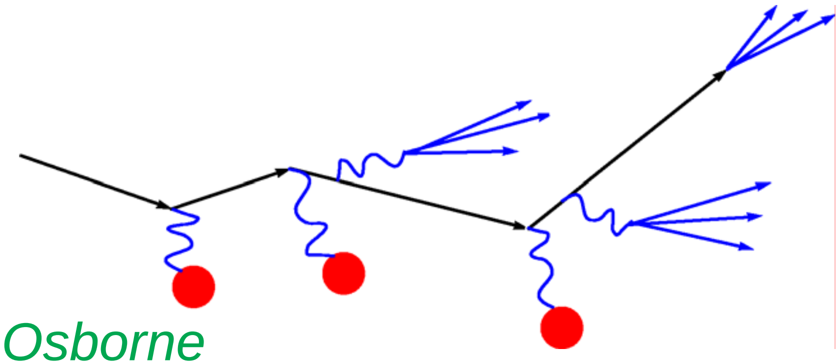


Prediction was made 5 years before data were taken!

Twist-4 pQCD Model

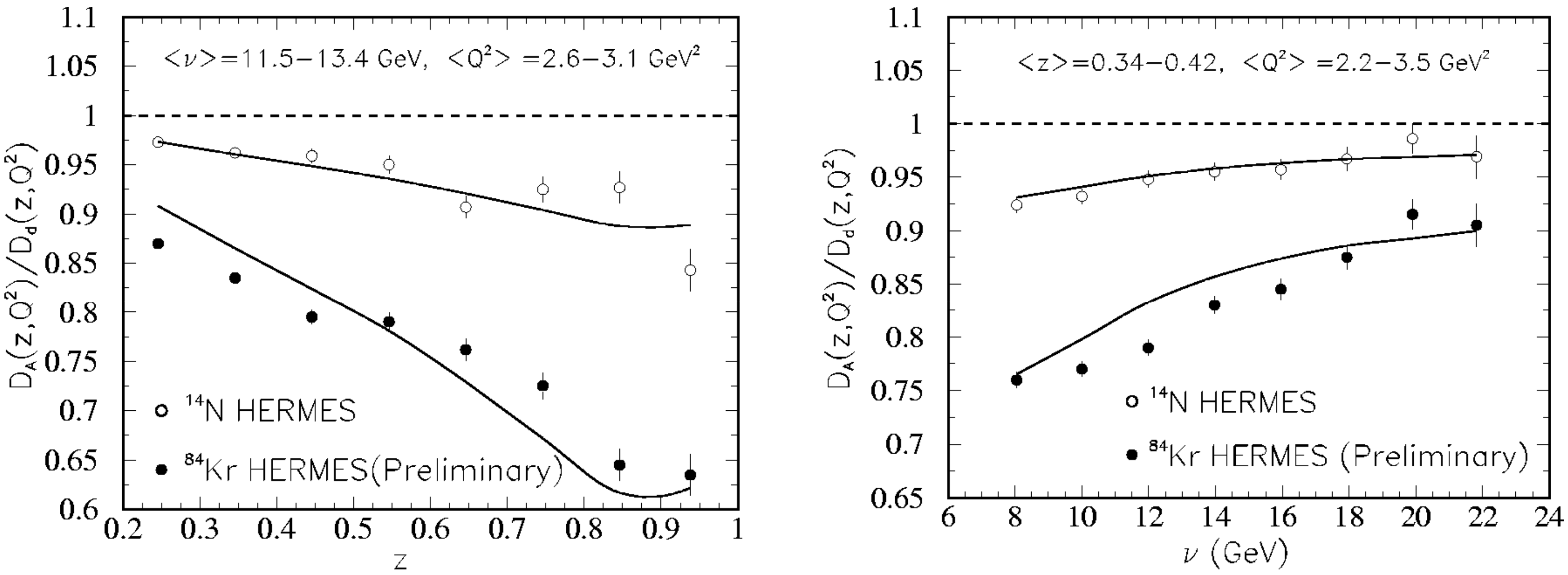


Authors: X.-N. Wang, E. Wang, X. Guo, J. Osborne

- 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

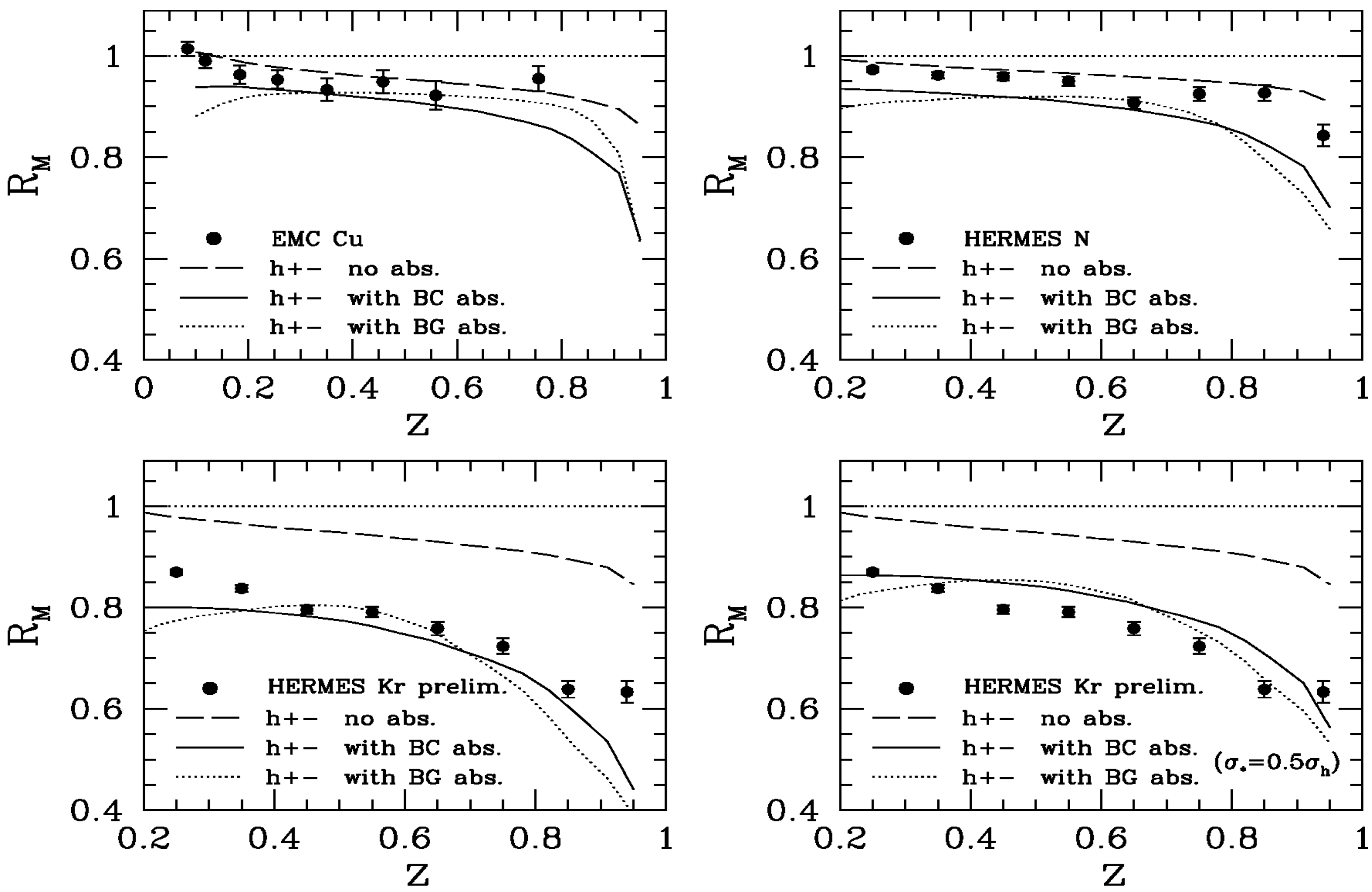


Rescaling Models

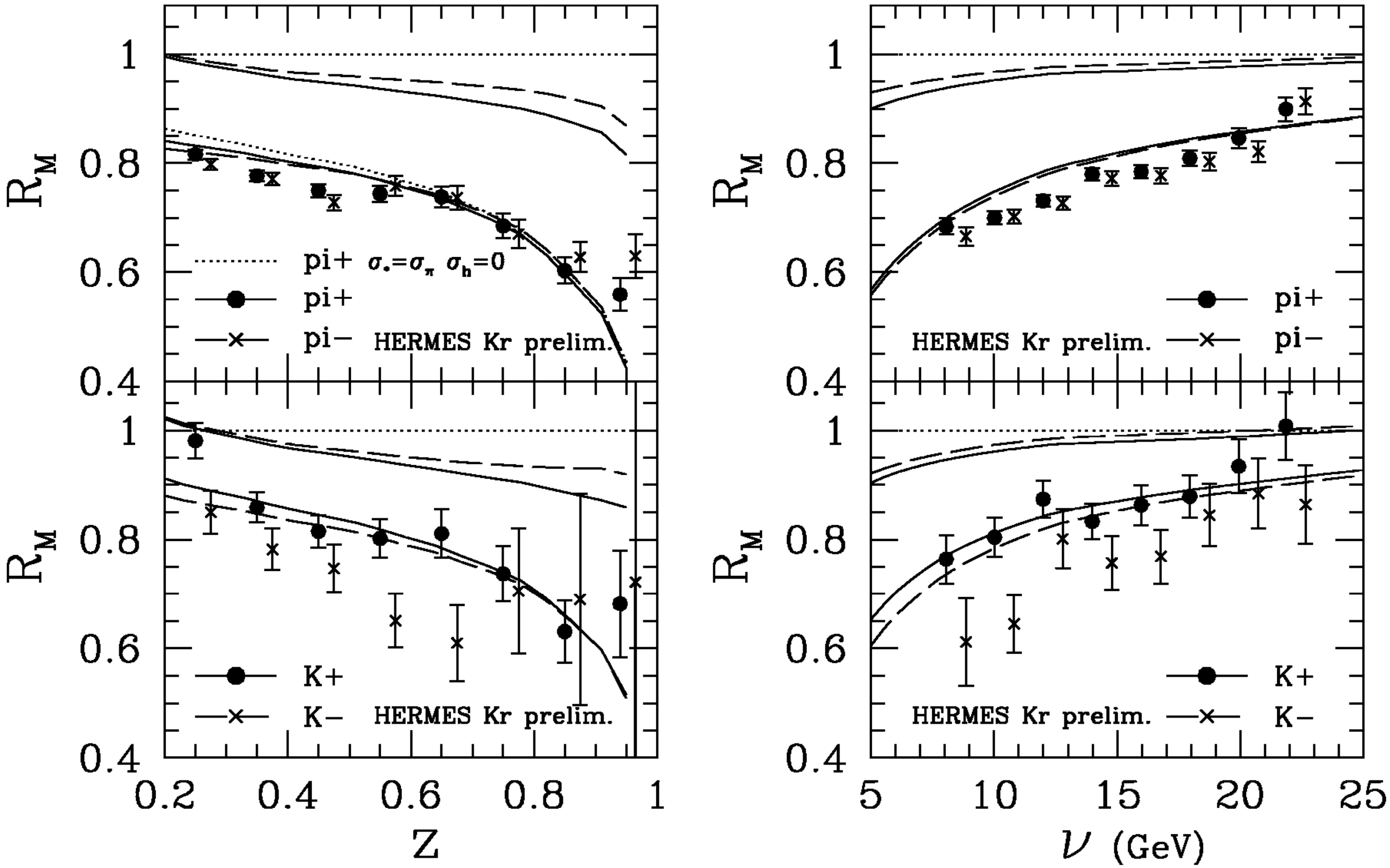
- *Authors: A. Accardi, H. Pirner, V. Muccifora*
  - Rooted in work by Nachtmann, Pirner, Jaffe, Close, Roberts, Ross, de Deus, from 1980's

- **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



Rescaling Model, HERMES Flavor-separated Kr Data



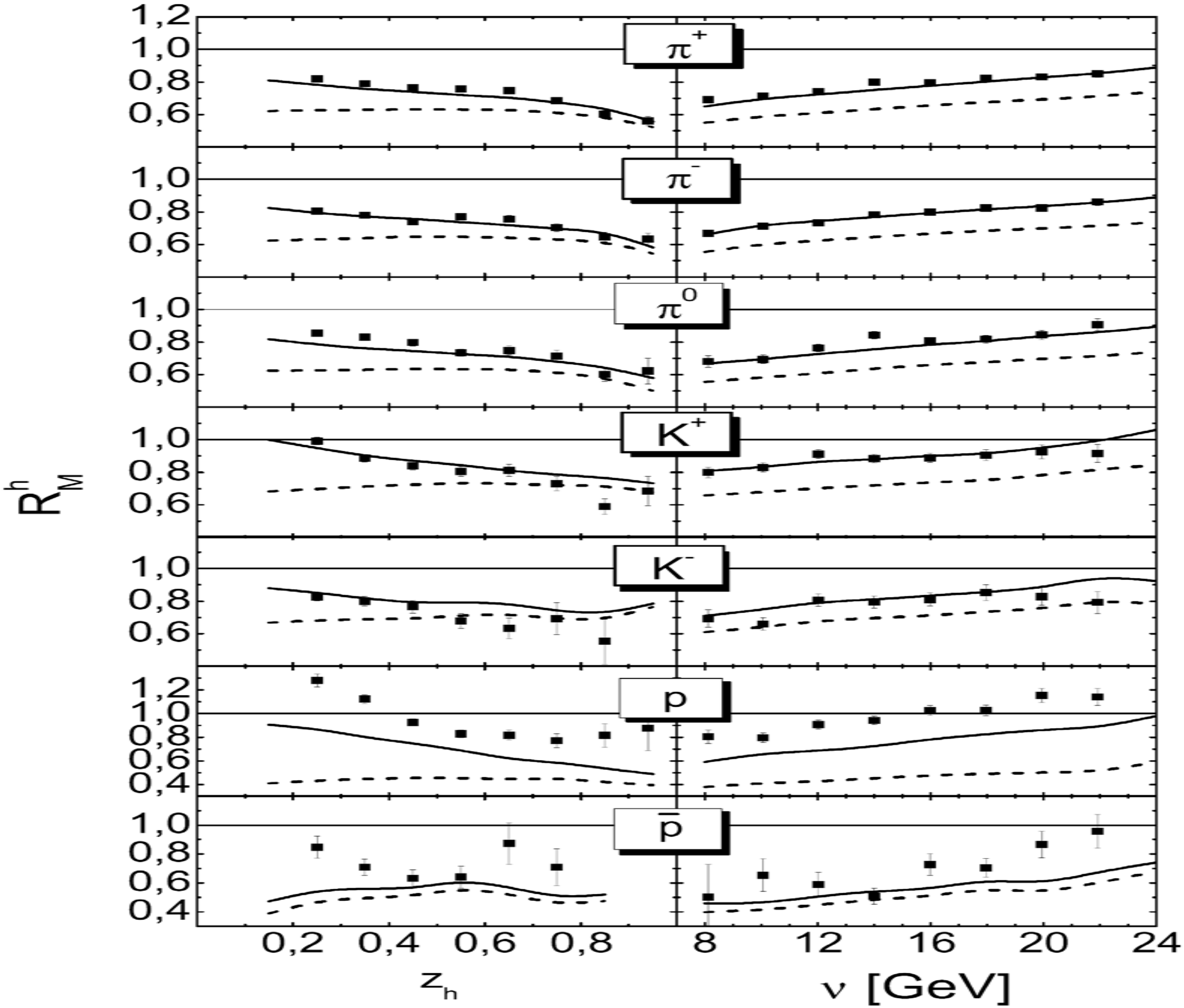
PYTHIA-BUU Coupled Channel Model

Authors: T. Falter, W. Cassing, K. Gallmeister, U. Mosel

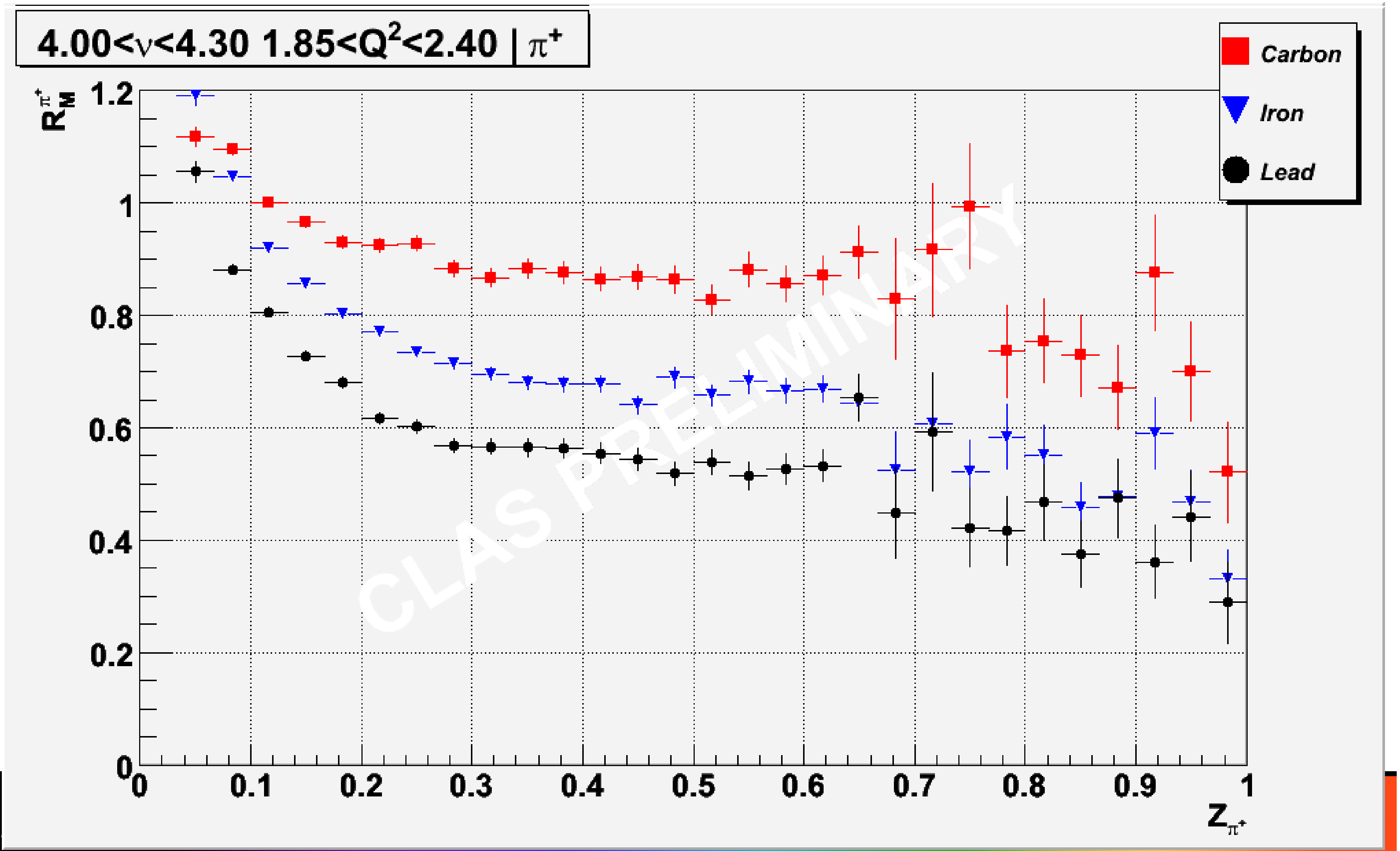
- PYTHIA-BUU
  - PYTHIA for e-p interaction
  - BUU (Boltzmann-Uehling-Uhlenbeck) coupled channel transport model for final state interactions

- Can describe the data without modification of fragmentation functions, hadron formation time ~0.5 fm in hadron rest frame

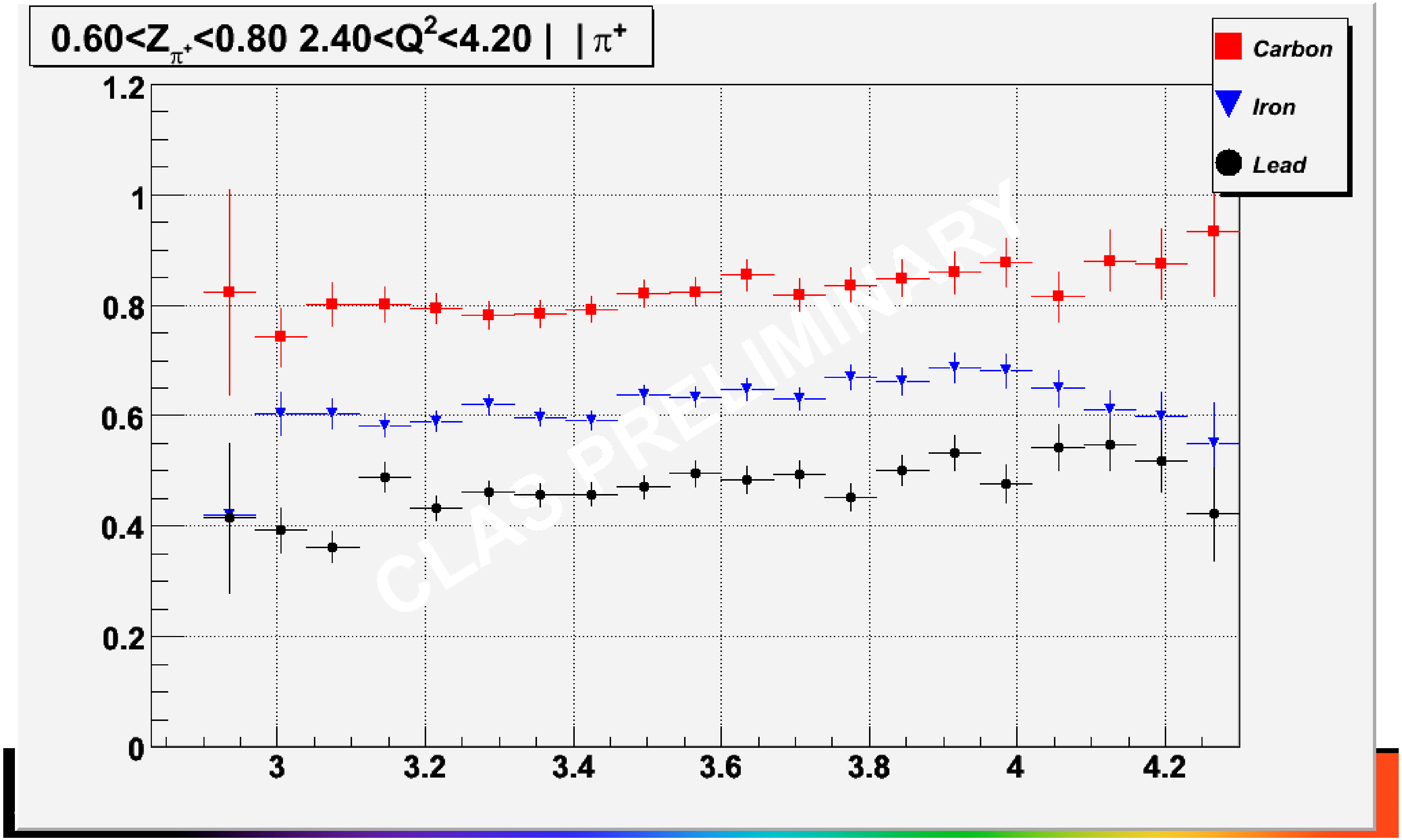
PYTHIA-BUU Coupled Channel Model and Hermes Kr Data



Multiplicity Ratio Dependence on Z



Hadronic Multiplicity Ratio vs. ν



Hadronic multiplicity ratio – dependence on Q^2