QCD Confinement in Forming Systems: Measuring Characteristic Times in Hadronization Processes

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Jefferson Lab Users Group Workshop
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Main Focus

- Space-time characteristics of hadronization
  - Formation times, production times for several hadron species:

“How long can a quark remain deconfined?”

“How do the color fields of hadrons form, and how long does it take?”

- Quark energy loss and multiple scattering
  - ***Deconfined quarks*** lose energy by gluon emission
  - How big is the energy loss, and how does it behave? E.g., an answer for normal nuclear density and temperature might be:

“100 MeV/fm at 5 fm, proportional to distance squared”

Determining How Confinement Assembles Hadrons

Step 1: Isolate correct interaction mechanisms - physical picture

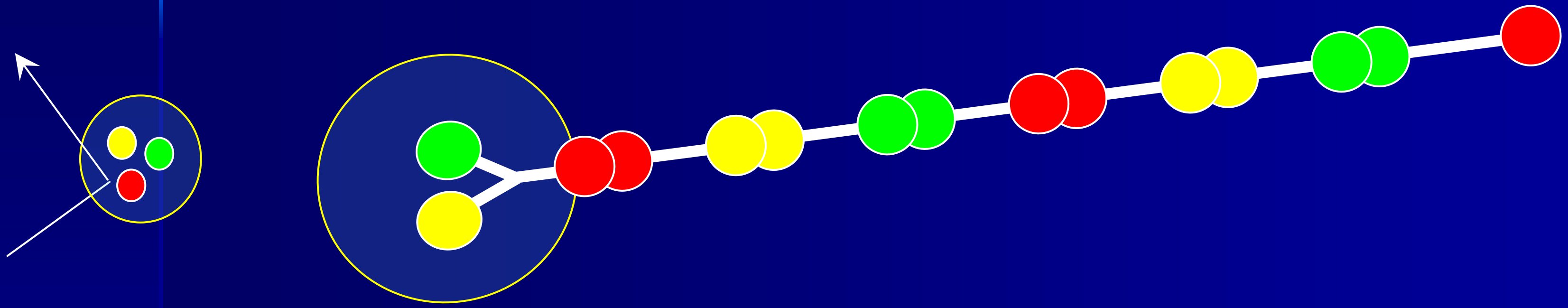
- Models
- Lattice studies require technical development, not happening soon
- Multi-hadron, multi-variable studies needed

Step 2: Extract characteristic parameters and functional dependencies

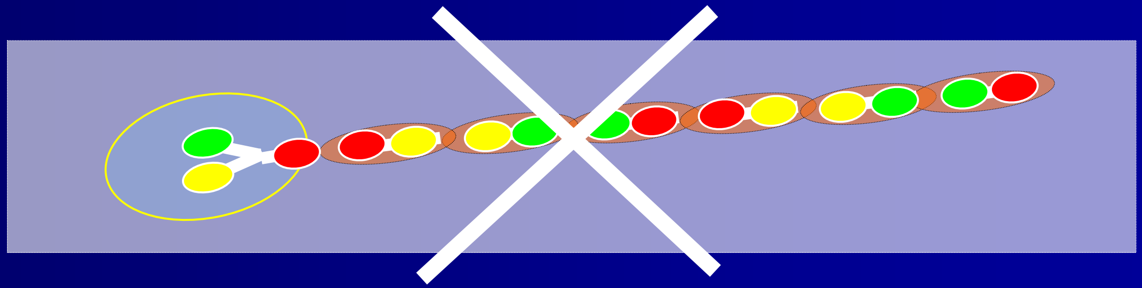
- Time/Length scales
- Flavor dependence, size dependence
- Energy loss
- Correlation functions

Interaction mechanisms

- Ubiquitous sketch of hadronization process: string/color flux tube



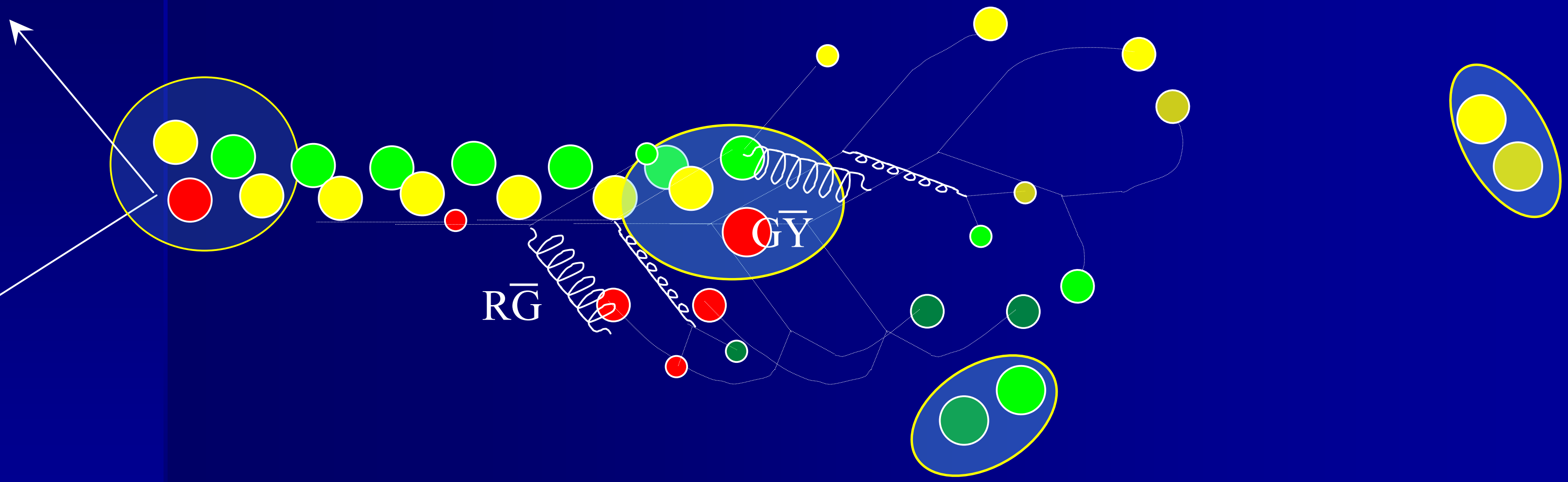
- Confinement process isn't finished yet, these are *colored* pairs:



- How do we get to colorless systems?
- Is the above picture reality, or just a nice story?(!)

Interaction mechanisms

- An alternative mechanism: “gluon bremsstrahlung model”:

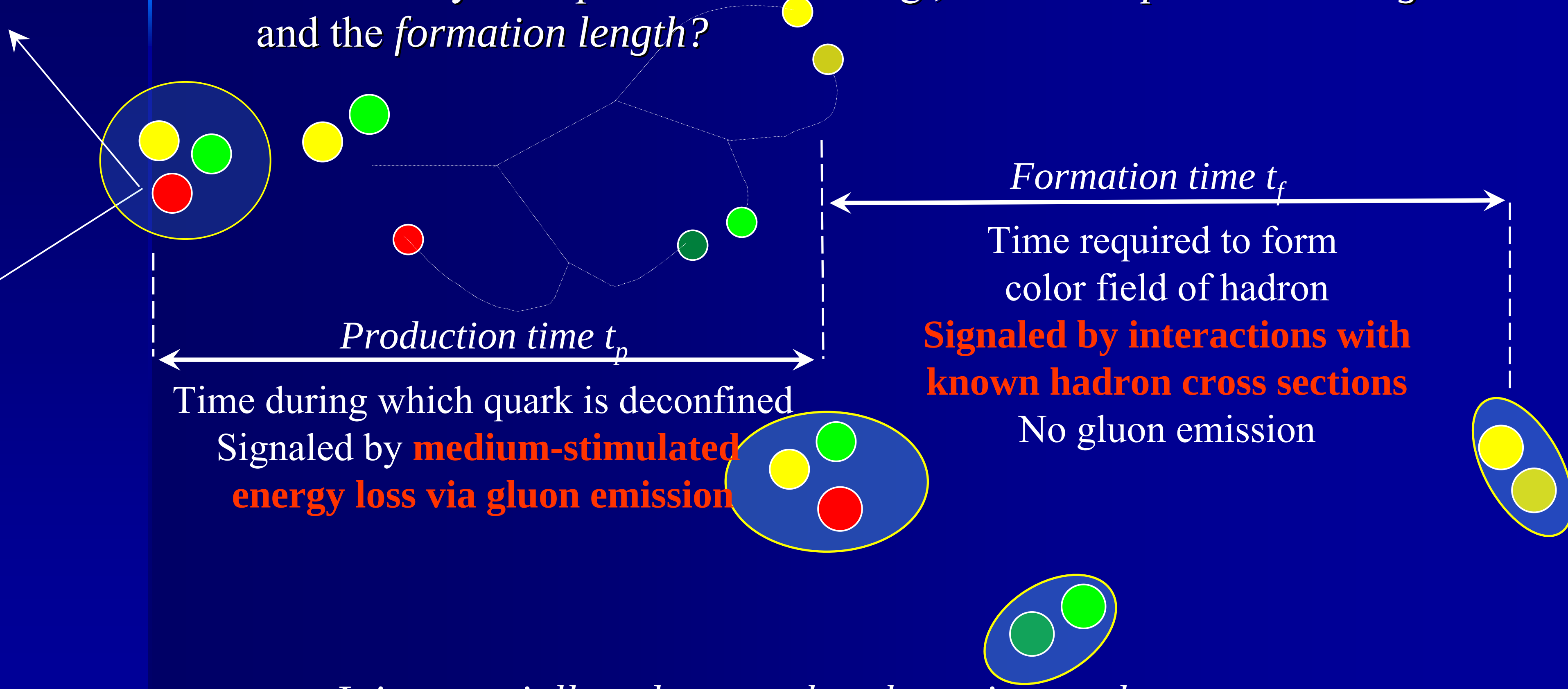


All hadron color explicitly resolved in this picture

Experimentally, it is completely unknown what the dominant mechanism is

Time scales for hadron formation

- Can identify multiple time scales? E.g., isolate the *production length* and the *formation length?*



Production time t_p

Time during which quark is deconfined
Signaled by **medium-stimulated energy loss via gluon emission**

Formation time t_f

Time required to form color field of hadron
Signaled by interactions with known hadron cross sections
No gluon emission

It is essentially unknown what these time scales are

Production times: order-of-magnitude expectations

Can estimate production time using energy conservation:

$$t_p = \frac{E_h}{\left.\frac{dE}{dx}\right|_{vacuum}}(1 - z_h)$$

Can estimate vacuum energy loss by string tension from the string model:

$$\left.\frac{dE}{dx}\right|_{vacuum} \approx \kappa \approx 1 \quad GeV/fm$$

If take, e.g., **z** = $E_{hadron}/\nu = 0.6$, $E_h = 5$ GeV, then ***$t_p \sim 2$ fm/c***

Hadron formation times: order-of-magnitude expectations

- Given hadron size R_h, can build color field of hadron in its rest frame in time no less than $t_0 \sim R_h/c$. In lab frame this is boosted:

$$t_f \geq \frac{E}{m} R_h$$

If take, e.g., the pion mass, radius 0.66 fm, E = 4 GeV, then ***t_f >20 fm/c***.

A quantum-mechanical analysis yields the same result.

- Slightly more sophisticated, if gluon emission time dominates

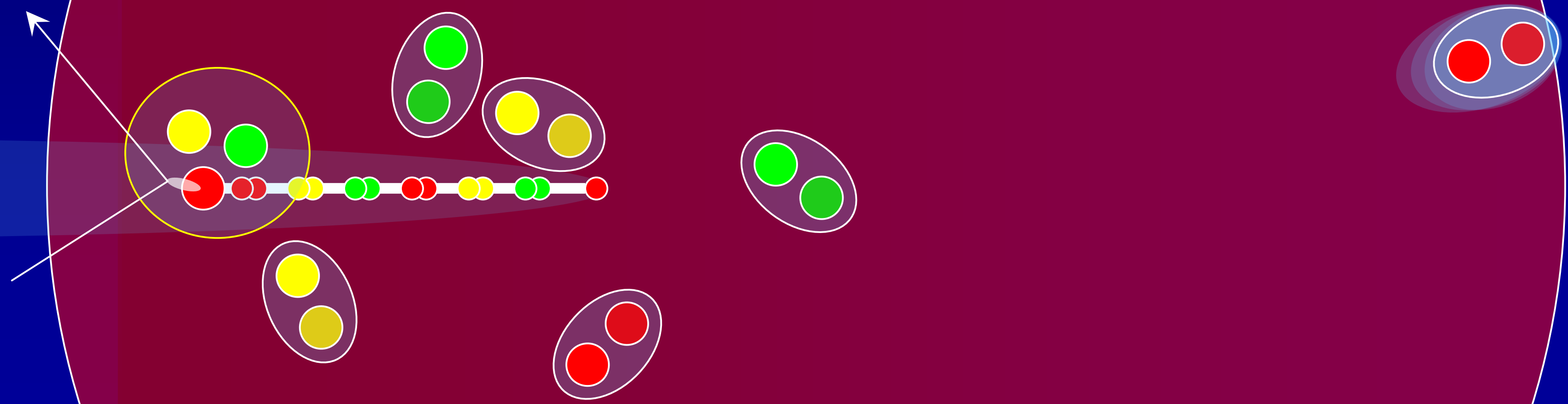
$$t_f \approx \frac{2E_h(1-z)}{k_T^2 + m_h^2}, \quad k_T \approx \Lambda_{QCD} \approx 0.2\,GeV$$

If take, e.g., pion mass, **z** = E_{hadron}/ν = 0.5, E_h = 4 GeV, then ***t_f ~ 13 fm/c***

➡ Production and formation times are well-matched to nuclear dimensions!

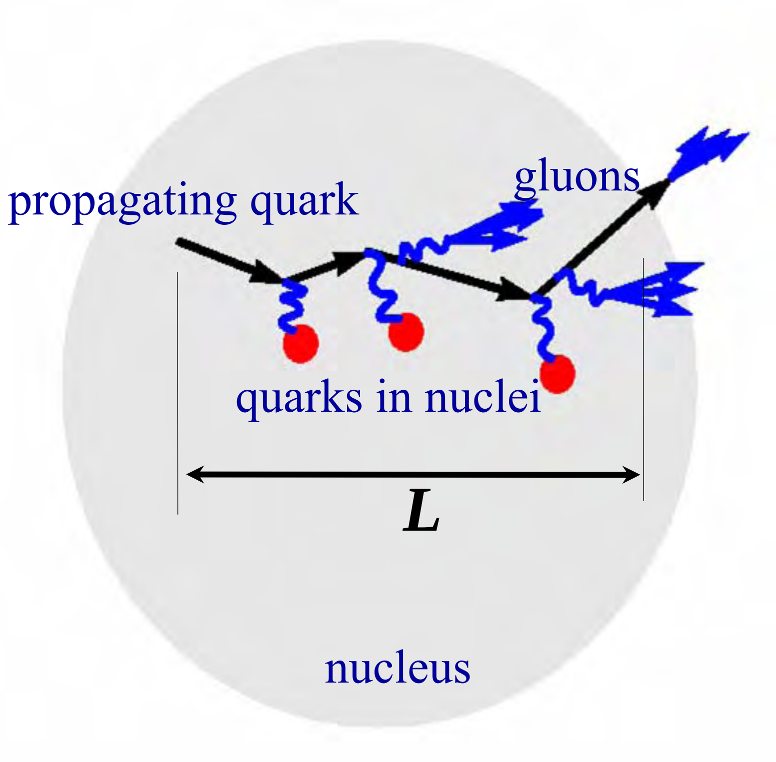
Experimental Studies: “Hadron Attenuation”

- We can learn about **hadronization distance scales** and **reaction mechanisms** from nuclear DIS
- Nucleus acts as a spatial analyzer for outgoing hadronization products



Experimental Studies: Quark Energy Loss

- Quarks lose energy by *gluon emission* as they propagate
  - In vacuum
  - Even more within a medium – proportional to the medium's gluon density



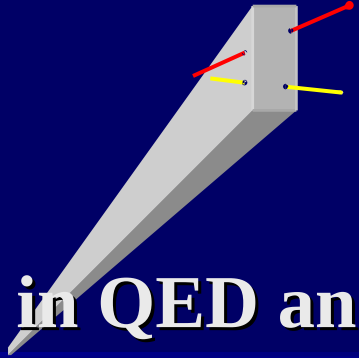
$$dE/dx \approx \frac{\alpha_s}{\pi} N_c \langle p_T^2 \rangle_L$$

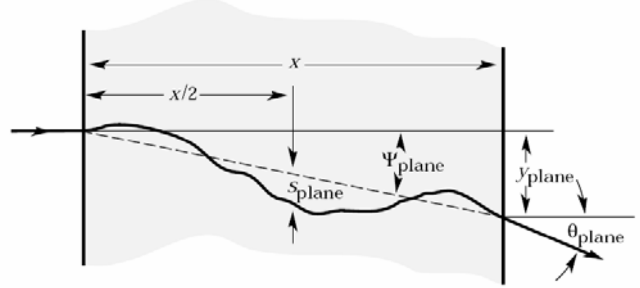
Medium-stimulated loss
Calculation by BDMPS

This can be directly measured on a series of nuclei

Signature of *production length* t_p

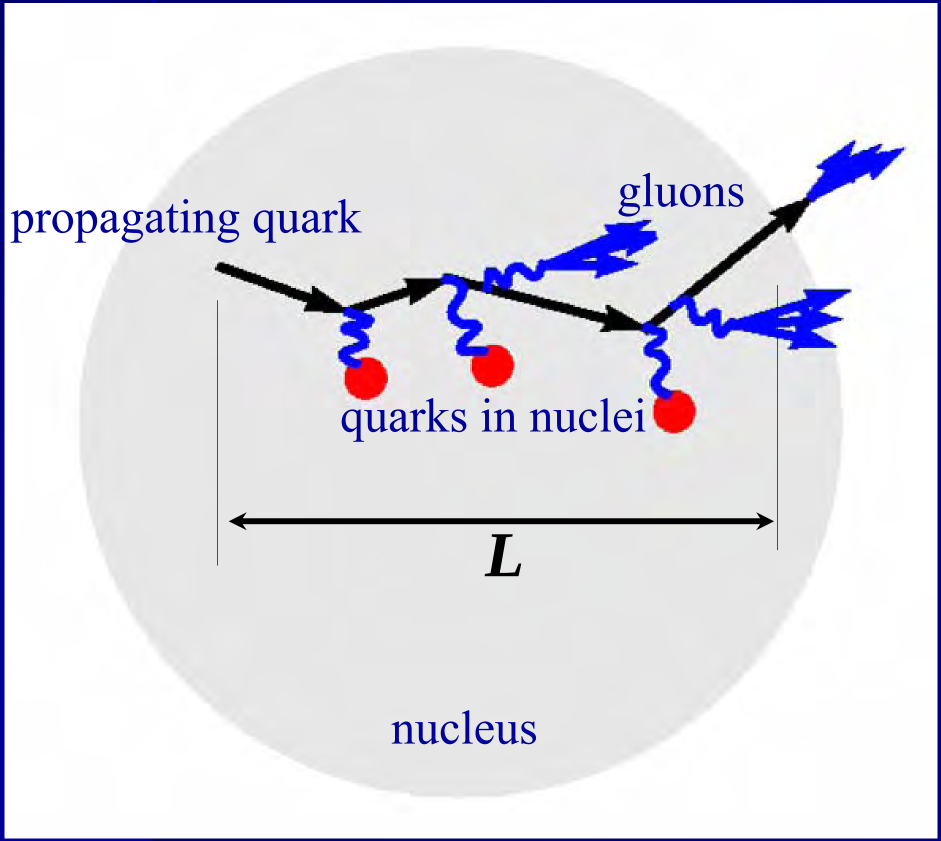
Corresponds to a quark-gluon correlation function





Analogous Processes in QED and QCD

- Analog to multiple scattering and energy loss: quark multiple scattering and quark energy loss:



- Dominant term in QED:

$$\Delta E \sim L$$

- Dominant term in QCD:

$$\Delta E \sim L^2 \ ??$$

QCD analog of LPM effect

Experiments Addressing the Same Topics

- 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
    - 2000's Fermilab $pA \rightarrow X\mu^+\mu^-$, 120 GeV beam, waiting for funding
  - 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

Parton Propagation through Strongly Interacting Matter

September 26 - October 7, 2005
Hosted by the European Centre for Theoretical Studies in Nuclear Physics (ECT*), Trento, Italy

Organizers

W.K. Brooks (Jefferson Lab)
B.Z. Kopeliovich (University of Santa Maria, Valparaiso)
U. Mosel (University of Giessen)
V. Muccifora (INFN, Frascati)
X.N. Wang (Lawrence Berkeley National Lab)

Major Topics

- jet quenching
- partonic energy loss
- hadron formation
- medium-modified fragmentation functions

Key Speakers and Participants

A. Accardi (Iowa State), J. Aichelin (Nantes), F. Arleo (Paris), I. Balitsky (Jefferson Lab/Old Dominion), J.-P. Blaizot (ECT*), H. Blok (Nikhef), S. Brodsky (Stanford), W. Cassing (Giessen), C. Ciofi degli Atti (Perugia), B. Cole (Columbia), D. d'Enterria (Columbia), P. Di Nezza (Frascati), T. Falter (Brookhaven), K. Gallmeister (Giessen), S. Gevorkyan (Dubna), P.-B. Gossiaux (Nantes), L. Grigoryan (Yerevan), D. Gruenewald (Heidelberg), A. Hayashigaki (Frankfurt), J. Qiu (Iowa), B. Jacak (Stony Brook), J. Jalilian-Marian (Seattle), C.-M. Ko (Texas A&M), A. Morsch (CERN), S. Peigne (Annecy), J.-C. Peng (Illinois), H.-J. Pirner (Heidelberg), J. Raufeisen (Heidelberg), J. Rykebusch (Ghent), K. Safarik (CERN), M. Sargsian (Florida International), I. Schmidt (Valpariso), D. Treleani (Trieste), B. Van Overmeire (Ghent), I. Vitev (Los Alamos), K. Wang (Charlottesville), K. Zapp (Heidelberg), B.-W. Zhang (Wuhan)

Sponsors

http://conferences.jlab.org/ECT/index.html

Experimental Data – CLAS (5 GeV, 11 GeV [future]) and Hermes (12 GeV, 27 GeV)

CLAS EG2

Targets

- *Two* targets in the beam simultaneously
- 2 cm LD2, upstream
- Solid target downstream
- Six solid targets:

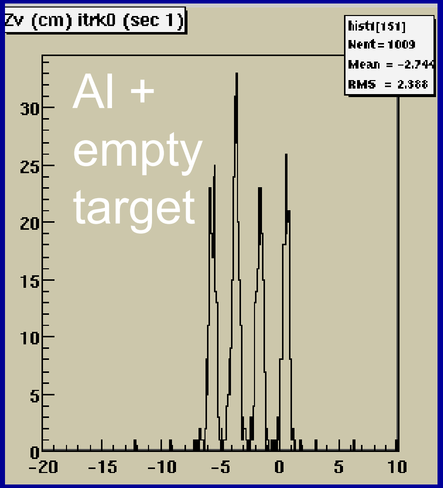
  -Carbon

  -Aluminum (2 thicknesses)

  -Iron

  -Tin

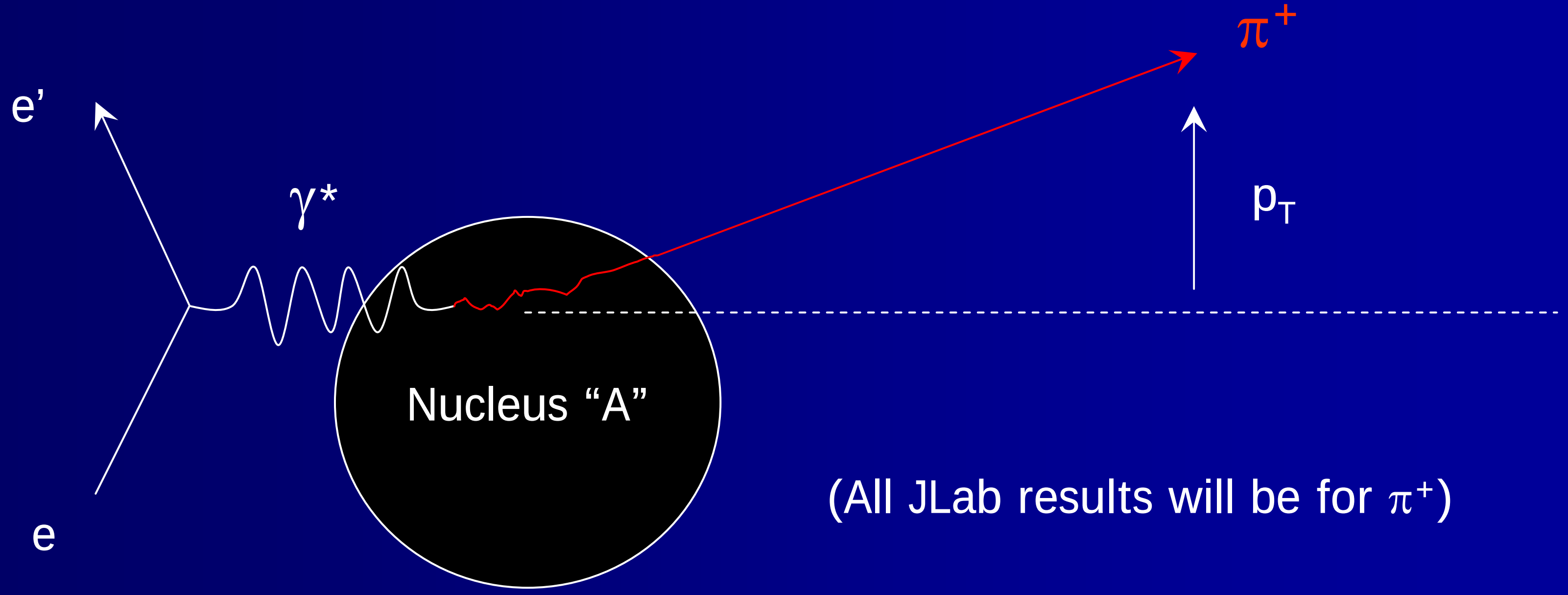
  -Lead



Observable Number 1 – “p_T Broadening”

Definition of “Transverse Momentum Broading”

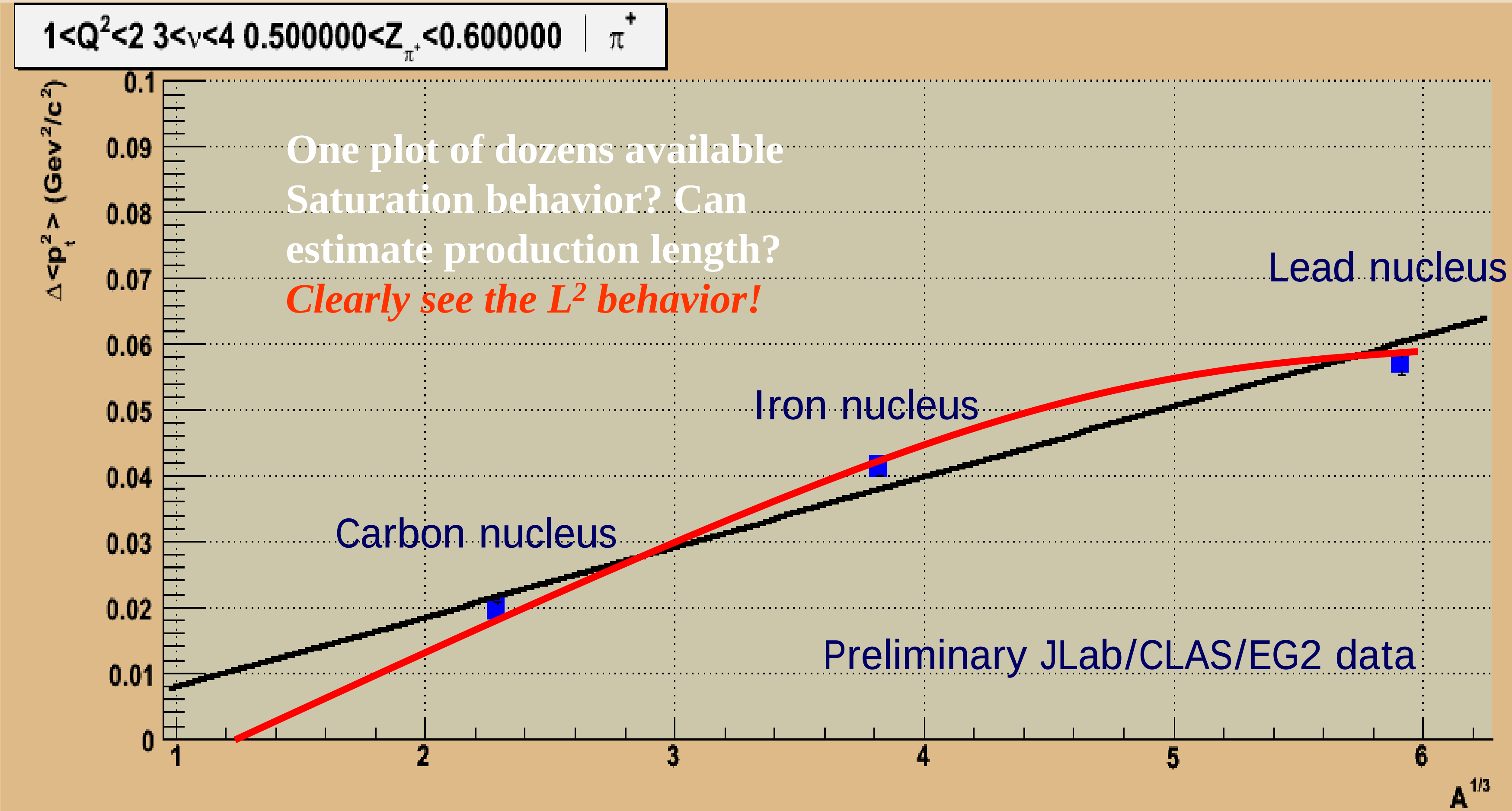
$$\Delta(p_T^2) = p_T^2(A) - p_T^2(^2H)$$



(All JLab results will be for π^+)

p_T broadening: "A" dependence, large ν, mid-z, π^+

- Transverse momentum broadening vs. nuclear radius is ~linear



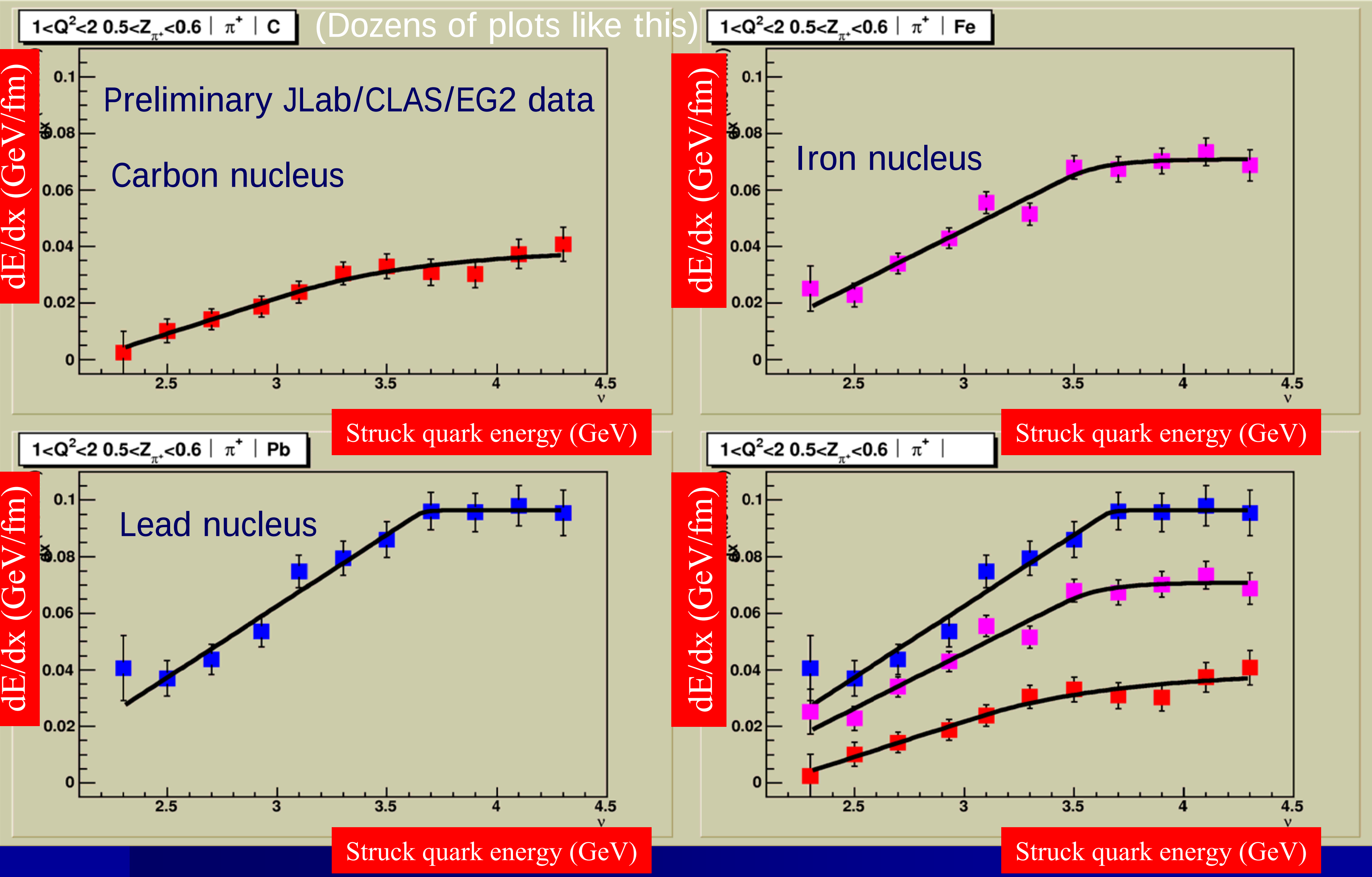
One plot of dozens available
Saturation behavior? Can estimate production length?
Clearly see the L^2 behavior!

Preliminary JLab/CLAS/EG2 data

Medium-Induced Quark Energy Loss

assuming perturbative formula $dE/dx \approx \frac{\alpha_s}{\pi} N_c \langle p_T^2 \rangle_L$

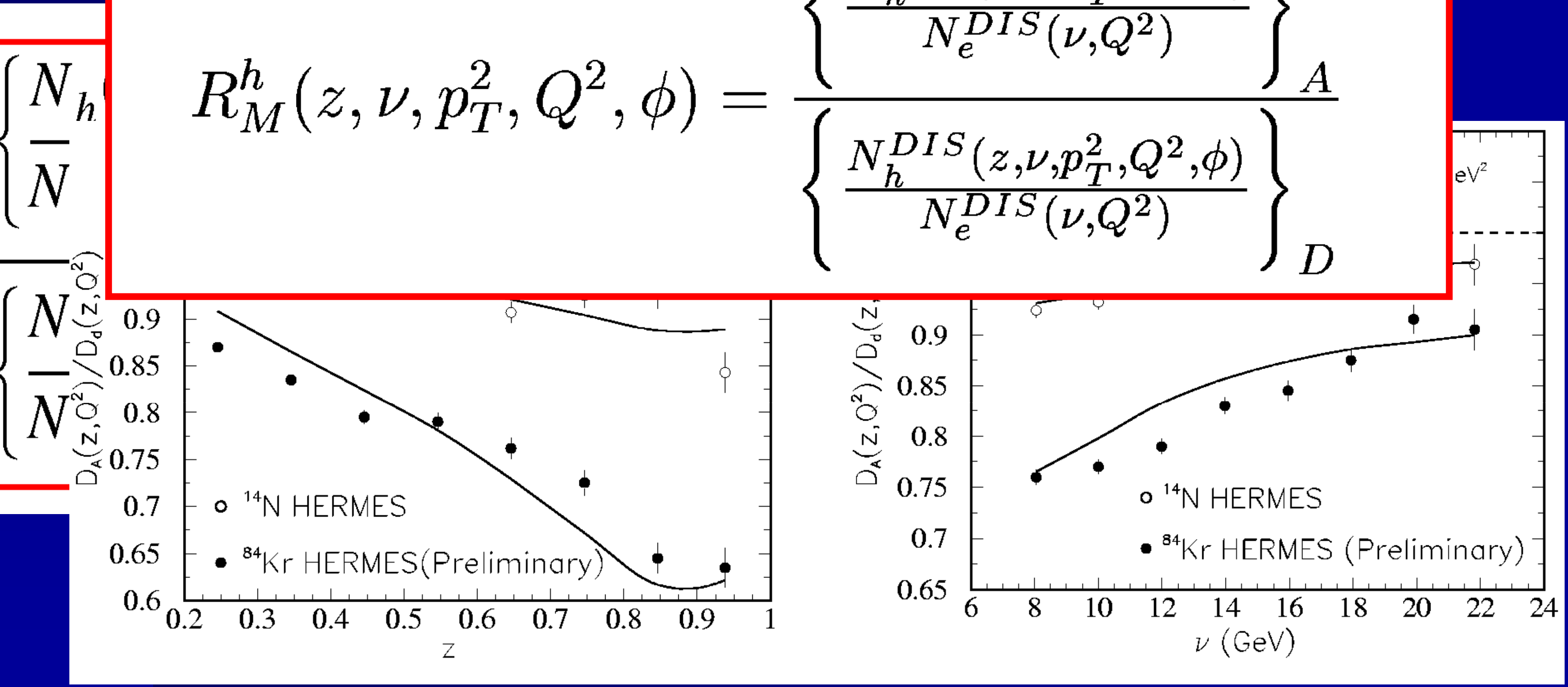
(Dozens of plots like this)



Observable Number 2 – Hadronic Multiplicity Ratio

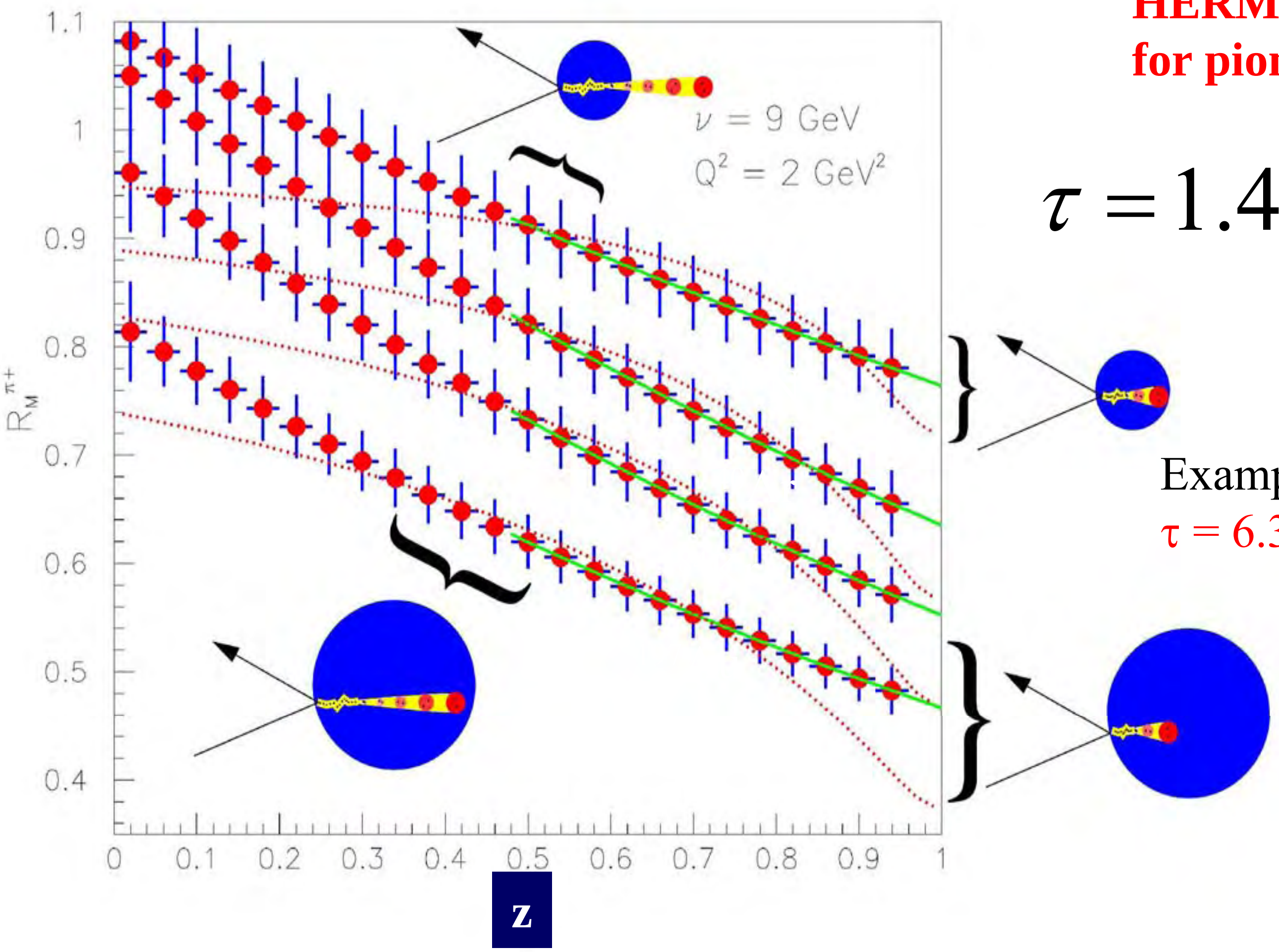
Hadronic multiplicity ratio

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



Interpretation of Hadronic Multiplicity Ratio

(concrete example in hadronization picture, for 4 nuclei)



HERMES parameterization for pion formation length:

$$\tau = 1.4 \cdot \nu \cdot (1 - z)\ fm$$

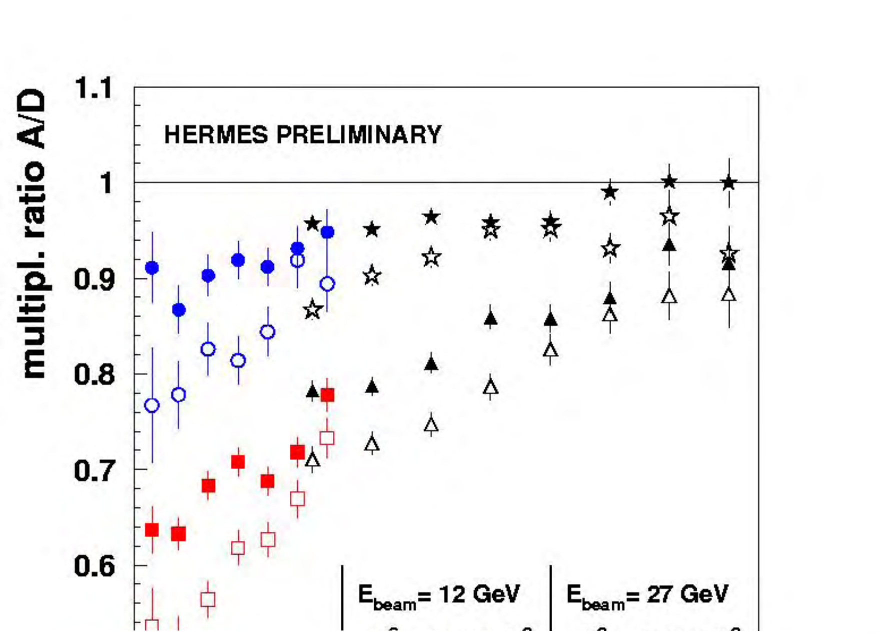
Example: z = 0.5, ν = 9 GeV,

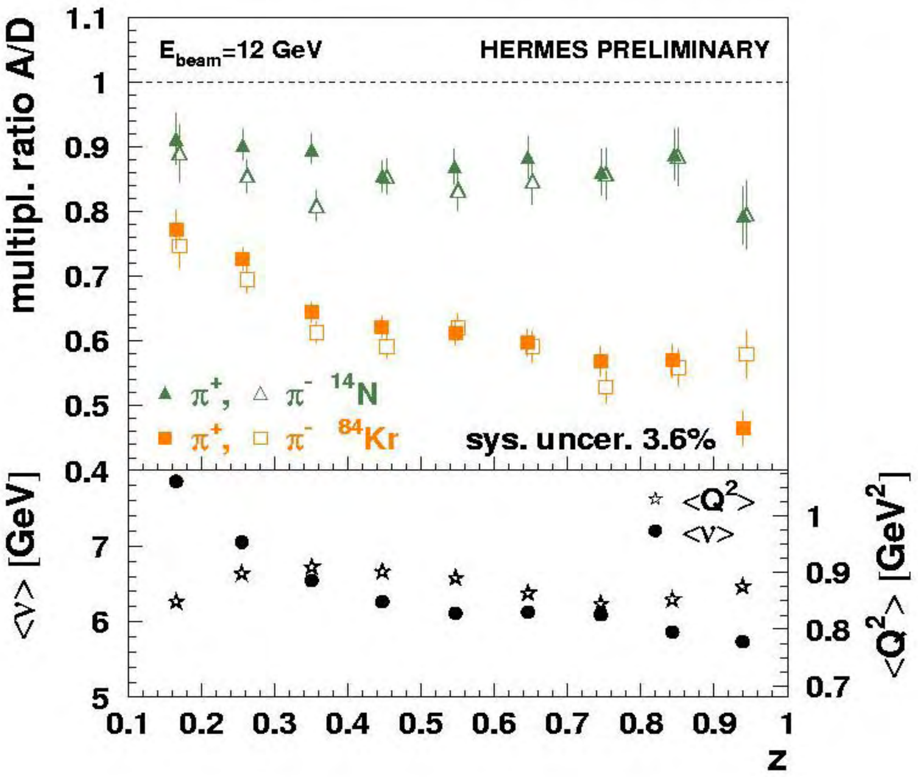
τ = 6.3 fm ~ radius Pb

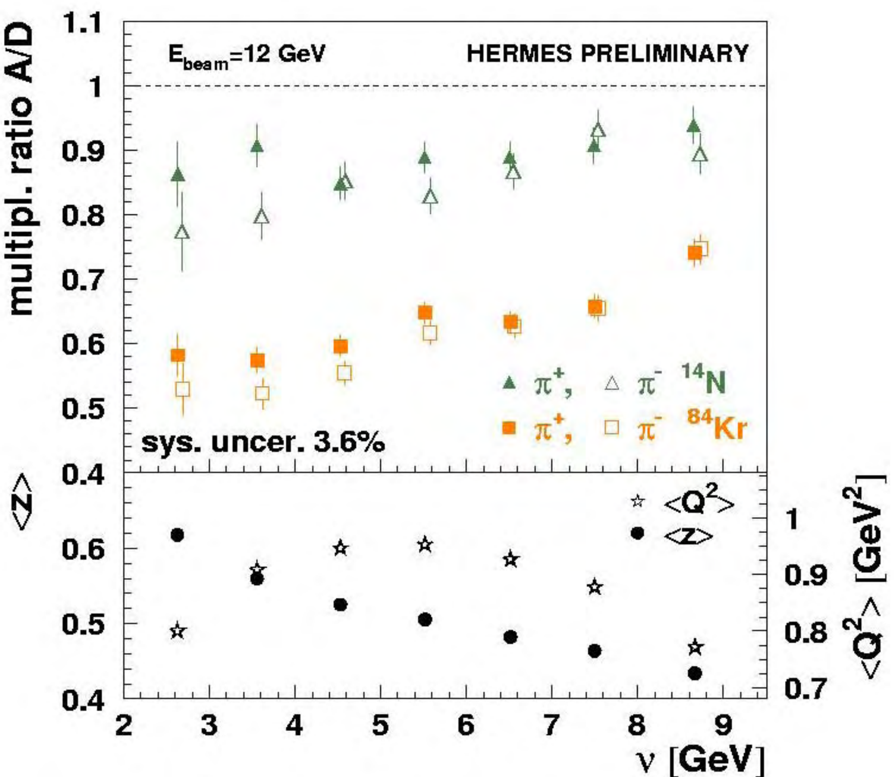
HERMES dat

Summary of

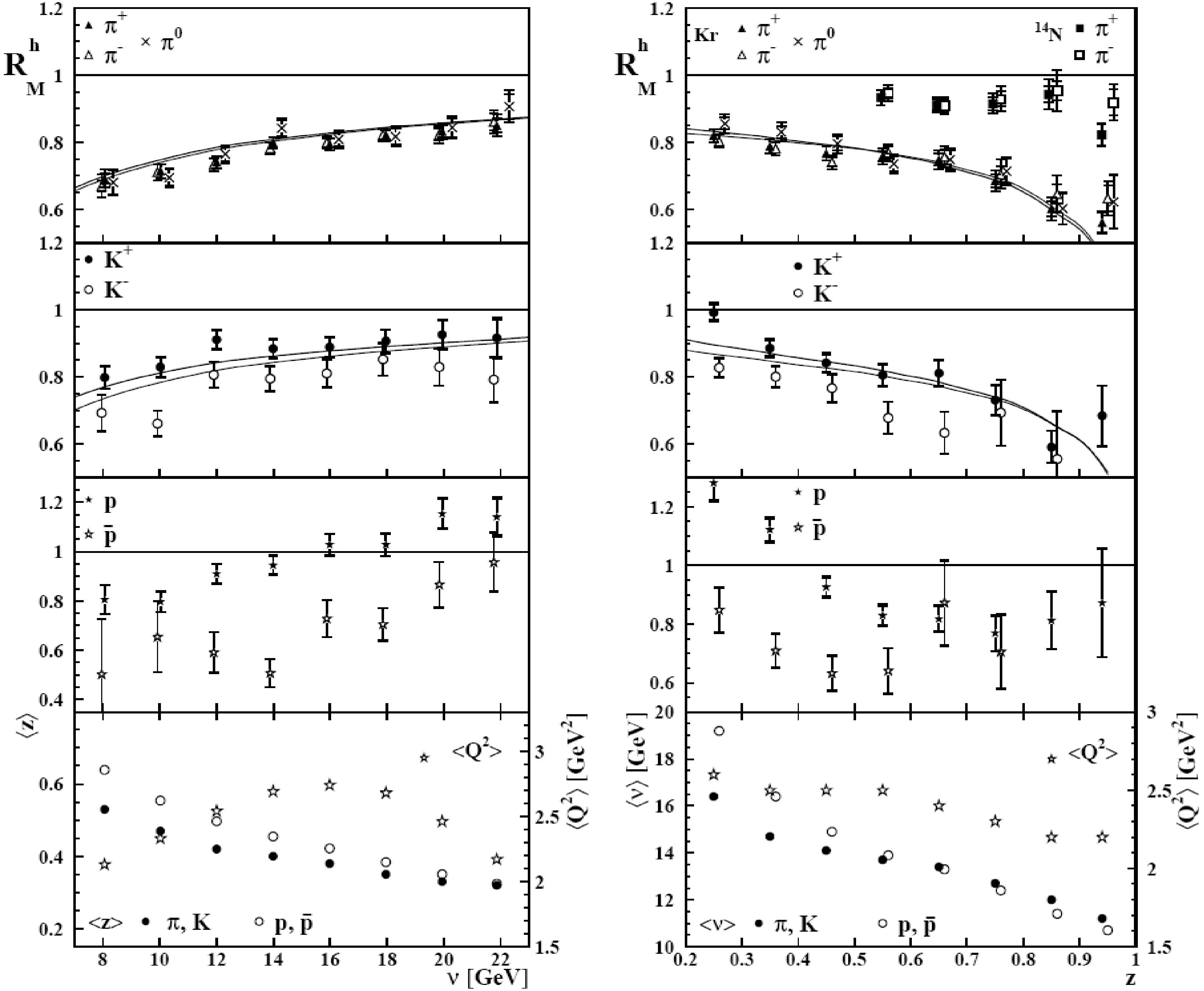
- Mostly 27 G





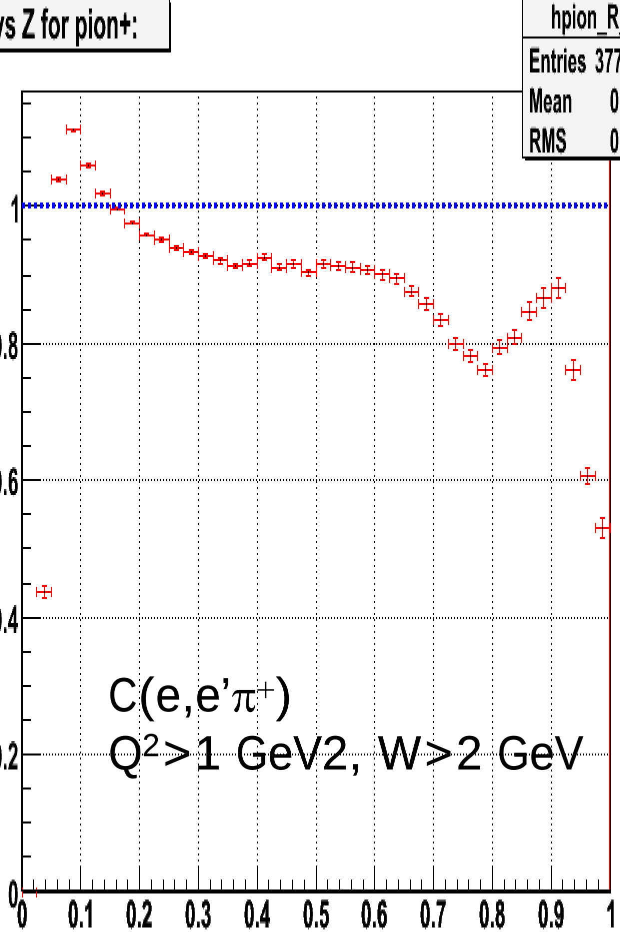


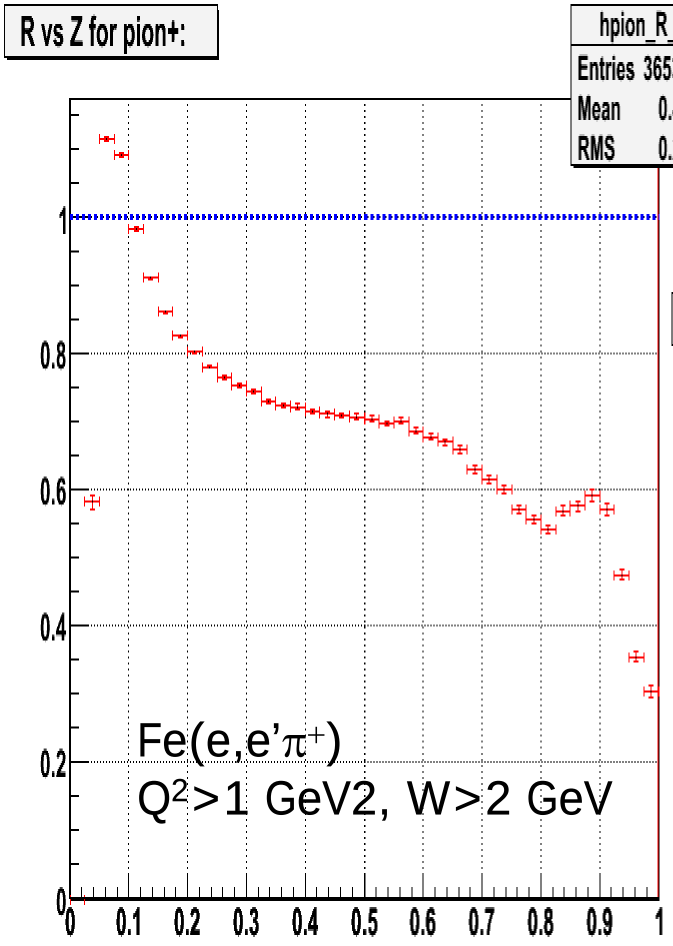
Hermes 27 GeV Data

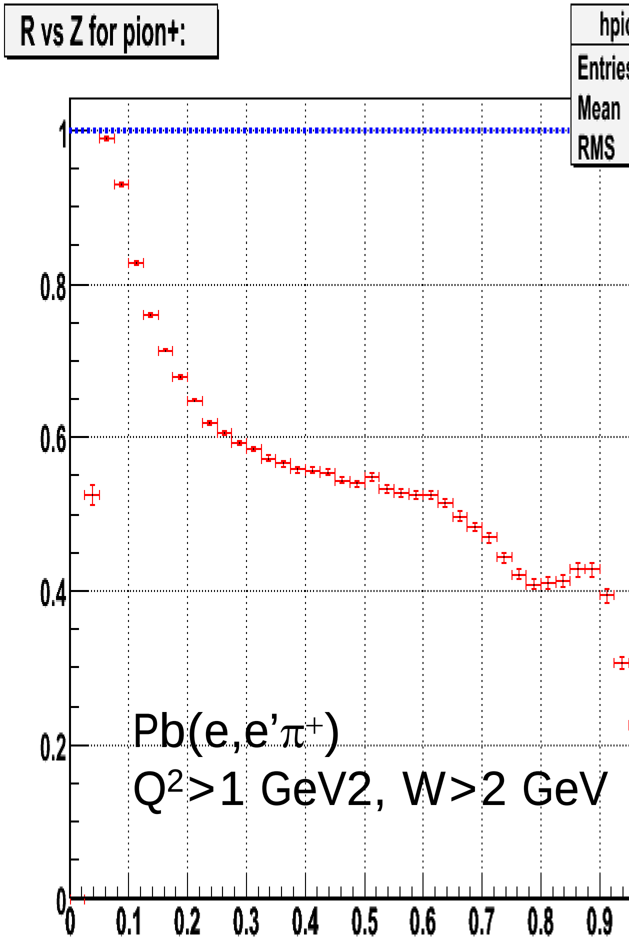


CLAS 5 GeV Data: Hadronic Multiplicity Ratio vs. Z

Preliminary
CLAS/JLab data
Hayk Hakobyan

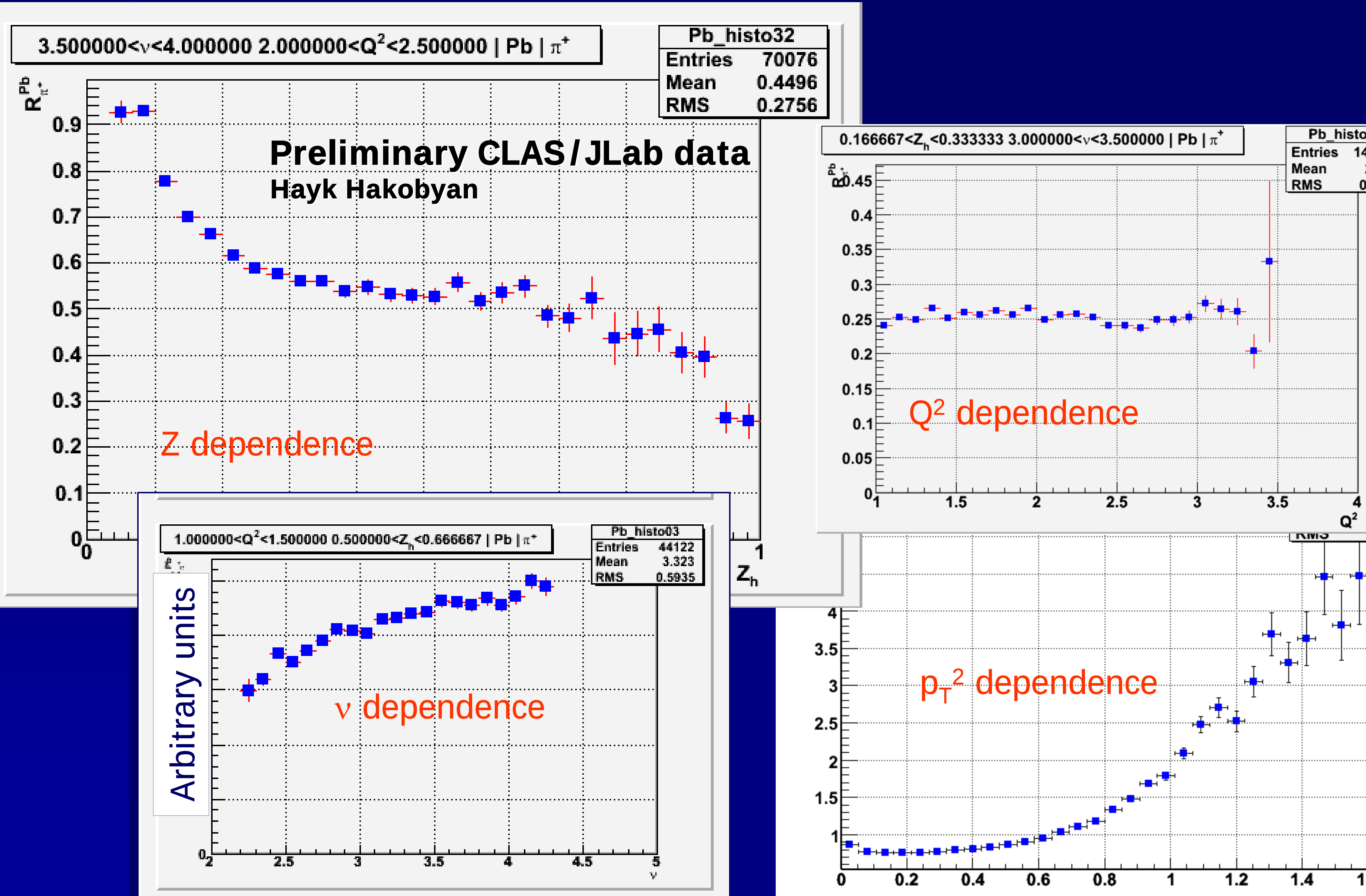






Statistical accuracy permits binning into ν, p_T, and Q^2 in addition to z and A

Examples of multi-variable slices of CLAS 5 GeV data (dozens of such plots exist for C, Fe, Pb)



Preliminary CLAS / JLab data

Hayk Hakobyan

Z dependence

Q^2 dependence

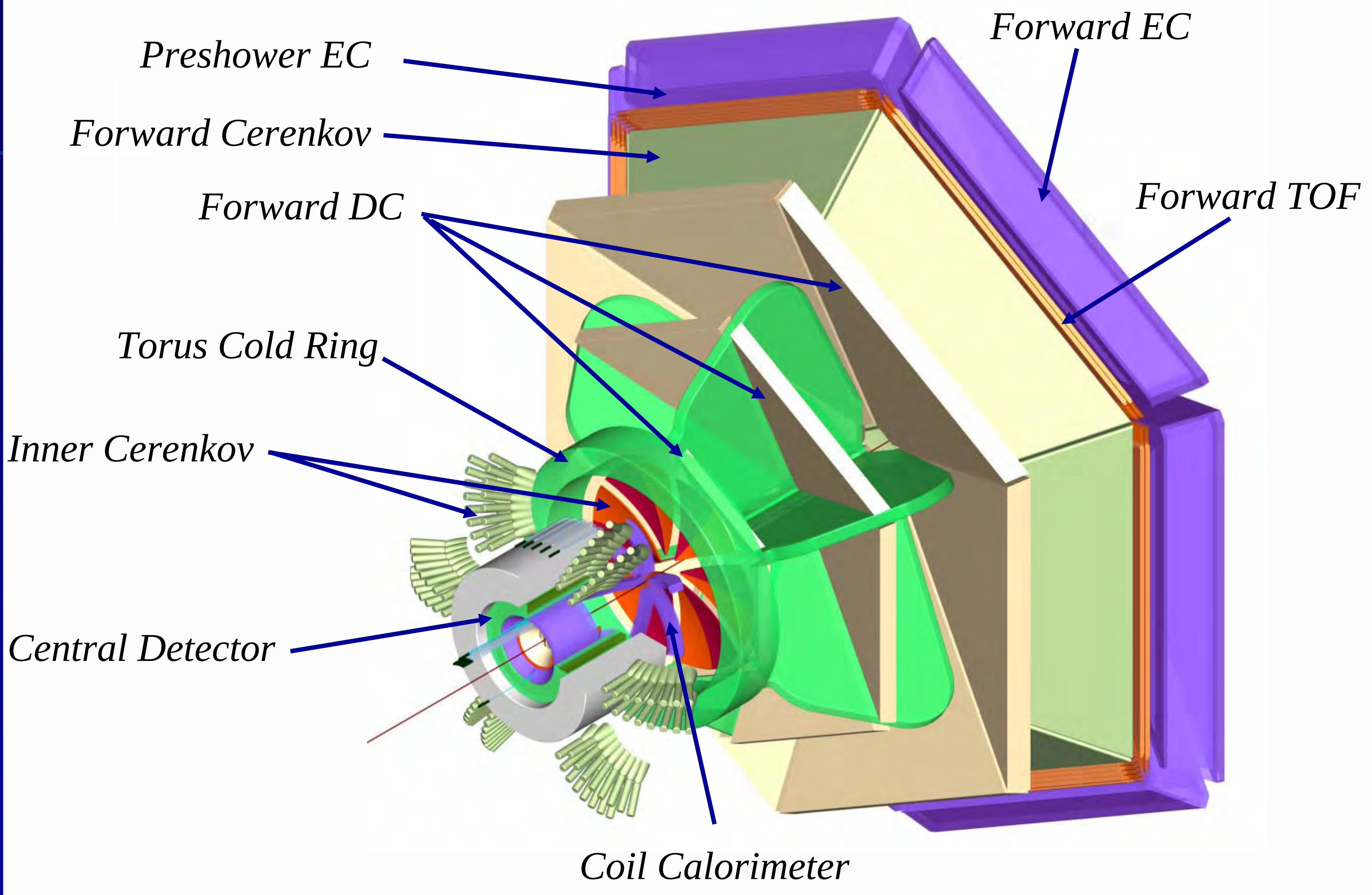
Arbitrary units

ν dependence

p_T^2 dependence

CLAS12

(a few years from now)

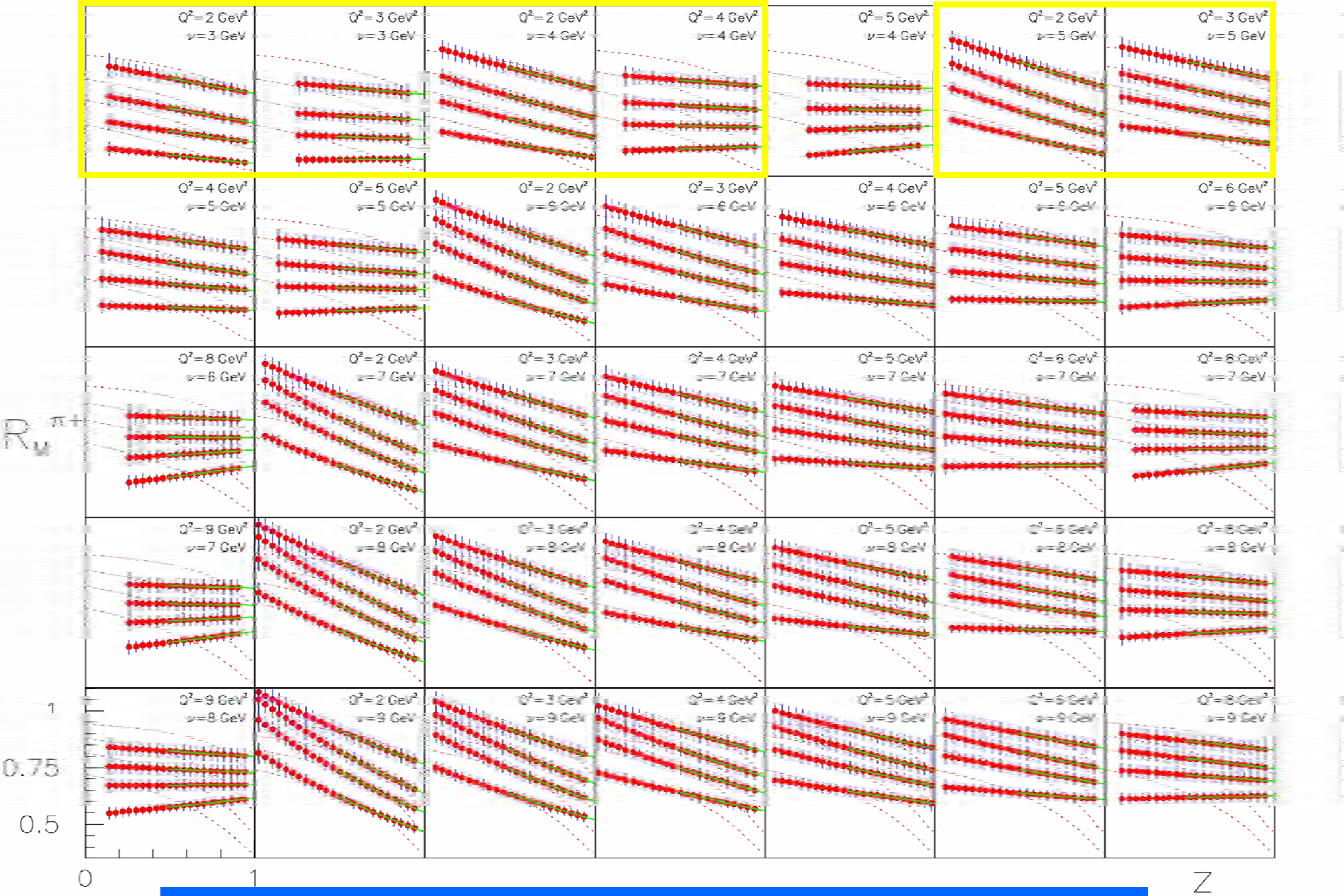


Accessible Hadrons (12 GeV)

hadron	$c\tau$	mass (GeV)	flavor content	detection channel	production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	$u\bar{d}$	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	170
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\eta$	27
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	K^+K^-	0.8
K^+	3.7 m	0.49	$u\bar{s}$	direct	75
K^-	3.7 m	0.49	$\bar{u}s$	direct	25
K^0	27 mm	0.50	$d\bar{s}$	$\pi^+\pi^-$	42
p	stable	0.94	ud	direct	1100
$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$	direct	3
Λ	79 mm	1.1	uds	$p\pi^-$	72
$\Lambda(1520)$	13 fm	1.5	uds	$p\pi^-$	-
Σ^+	24 mm	1.2	us	$p\pi^0$	6
Σ^0	22 pm	1.2	uds	$\Lambda\gamma$	11
Ξ^0	87 mm	1.3	us	$\Lambda\pi^0$	0.6
Ξ^-	49 mm	1.3	ds	$\Lambda\pi^-$	0.9

12 GeV Anticipated Data

Examples of Experimental Data and Theoretical Predictions



Bins in yellow are accessible at 6 GeV

Sample of Models

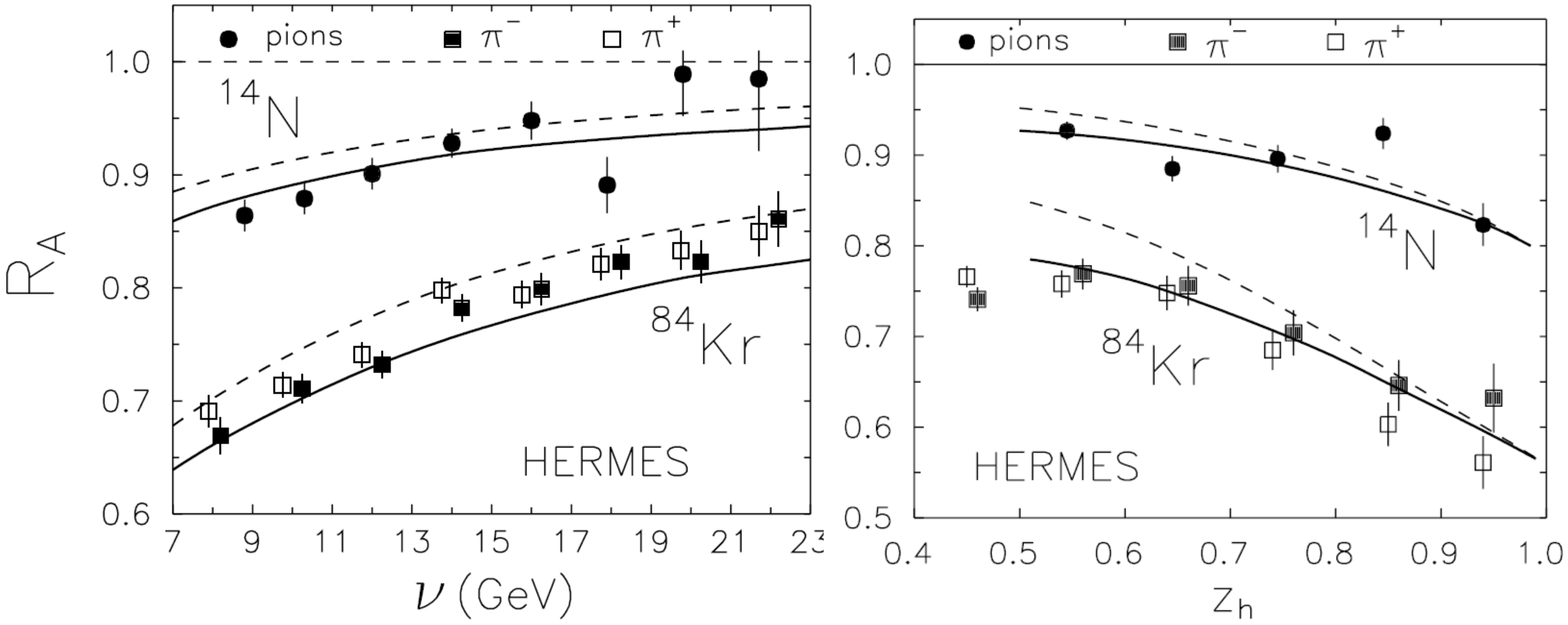
- Gluon bremsstrahlung model
  - Gluon radiation + hadronization model
- Twist-4 pQCD model
  - Medium-induced gluon radiation only
- Rescaling models
  - Gluon emission, partial deconfinement, nuclear absorption
- PYTHIA-BUU coupled channel model
  - Fundamental interaction + coupled channel nuclear final state interaction

Gluon Bremsstrahlung Model

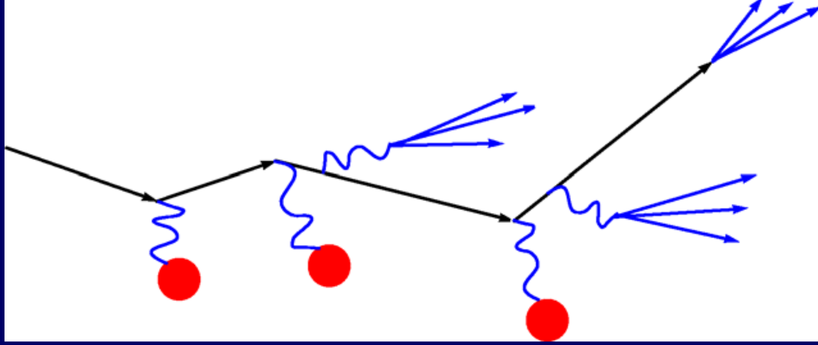
- Authors B. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki
- Time and energy dependent model for energy loss by gluon emission coupled to a hadron formation scheme
- Gluon emission:
  - Two time constants
  - Q^2 dependence
- Hadron formation:
  - Color dipole cross section
  - Struck quark and nearest antiquark projected to hadronic wave function

Gluon Bremsstrahlung Model and HERMES Data

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



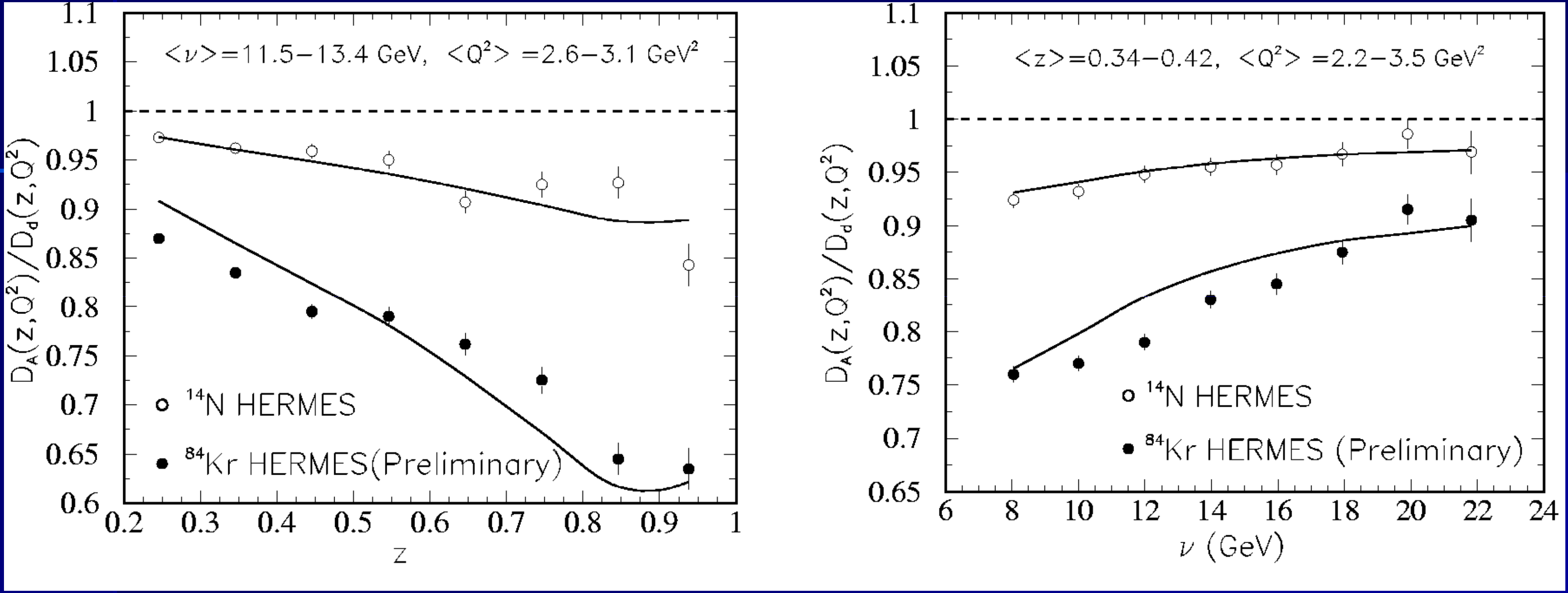
Twist-4 pQCD Model



- 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



$$\frac{d\sigma^h_{\rm DIS}}{d\vec{p}_{e'}\,dz_h} = \frac{1}{E'}\,\frac{\alpha^2_{\rm EM}}{2\pi s}\,\frac{1}{Q^4}\,L_{\mu\nu}\,\frac{dW^{\mu\nu}}{dz_h}$$

$$\frac{dW^{\mu\nu}}{dz_h} = \sum_q \int dx\, f_q^A(x,Q^2)\, H^{(0)}_{\mu\nu}\, \widetilde{D}_{q\to h}(z_h,Q^2).$$

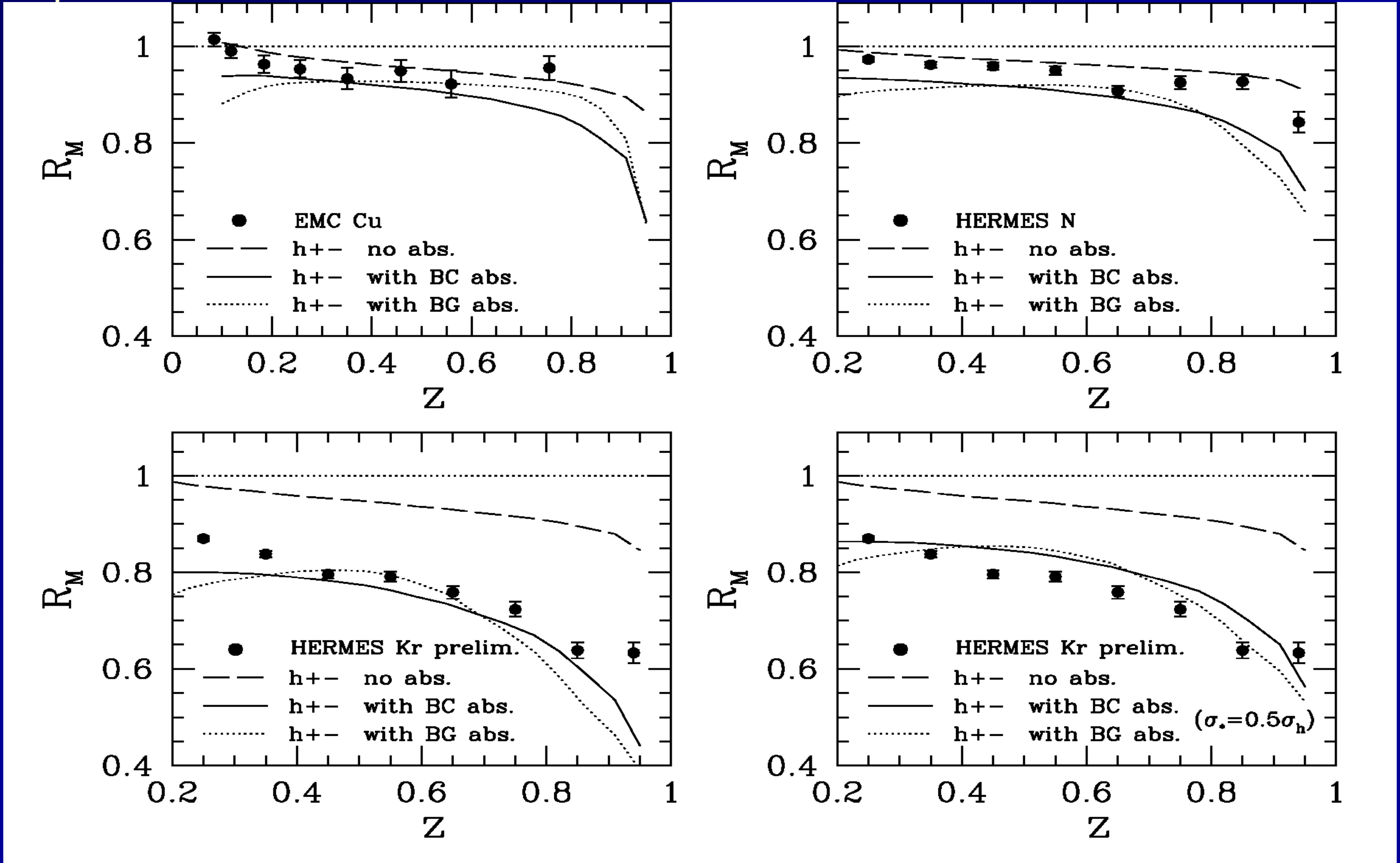
$$\widetilde{D}_{q\to h}(z_h,Q^2) \equiv D_{q\to h}(z_h,Q^2) + \Delta D_{q\to h}(z_h,Q^2)$$

$$\Delta D_{q\to h}(z_h,Q^2) = \int_0^{Q^2} \frac{dp_T^2}{p_T^2}\,\frac{\alpha_s}{2\pi} \int_{z_h}^1 \frac{dz}{z} \times \left[\Delta\gamma_{q\to qg} D_{q\to h}(z_h/z) + \Delta\gamma_{q\to gq} D_{g\to h}(z_h/z)\right]$$

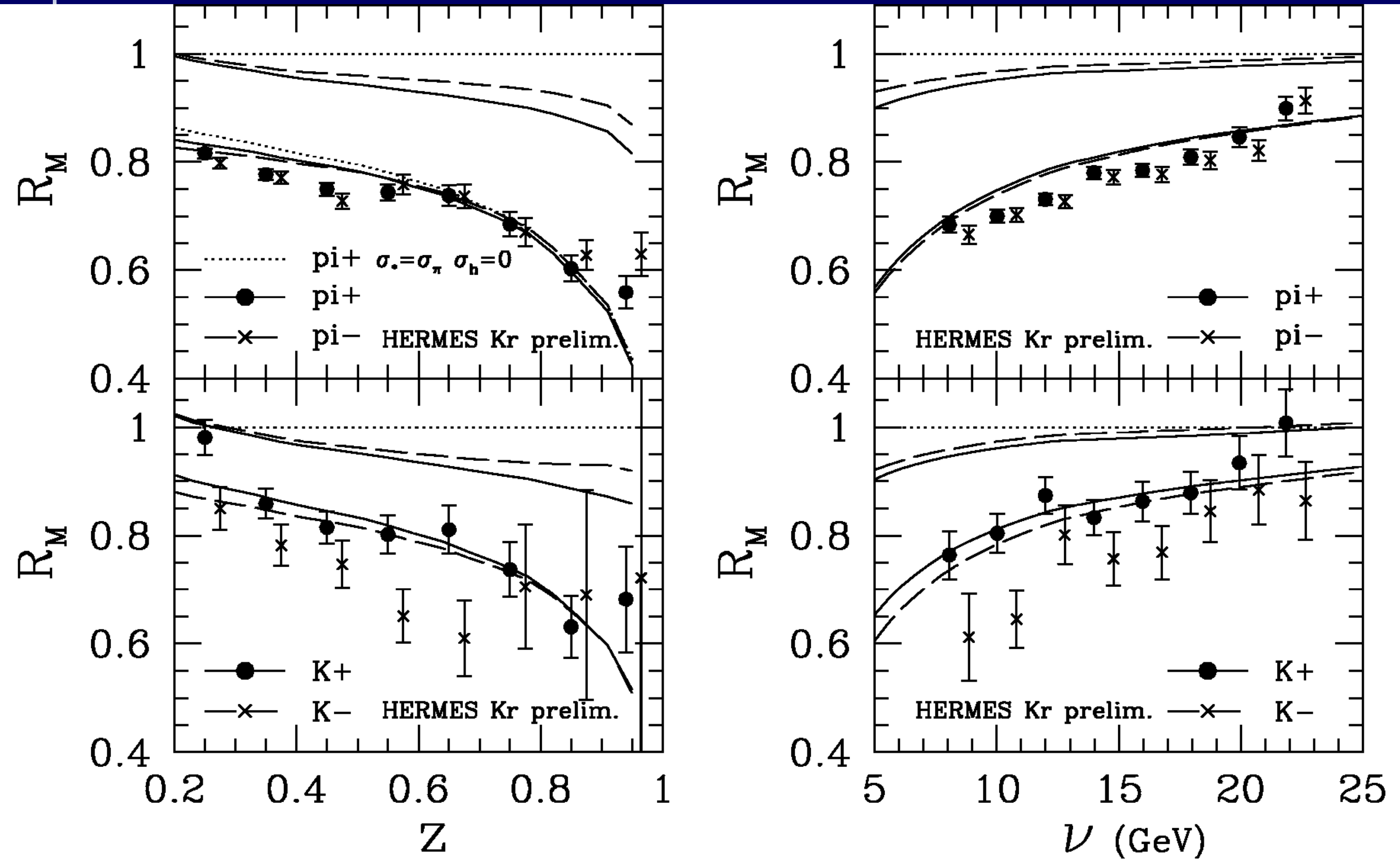
Rescaling Models

- 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 reinteraction and absorption

Rescaling Model, EMC/HERMES Data



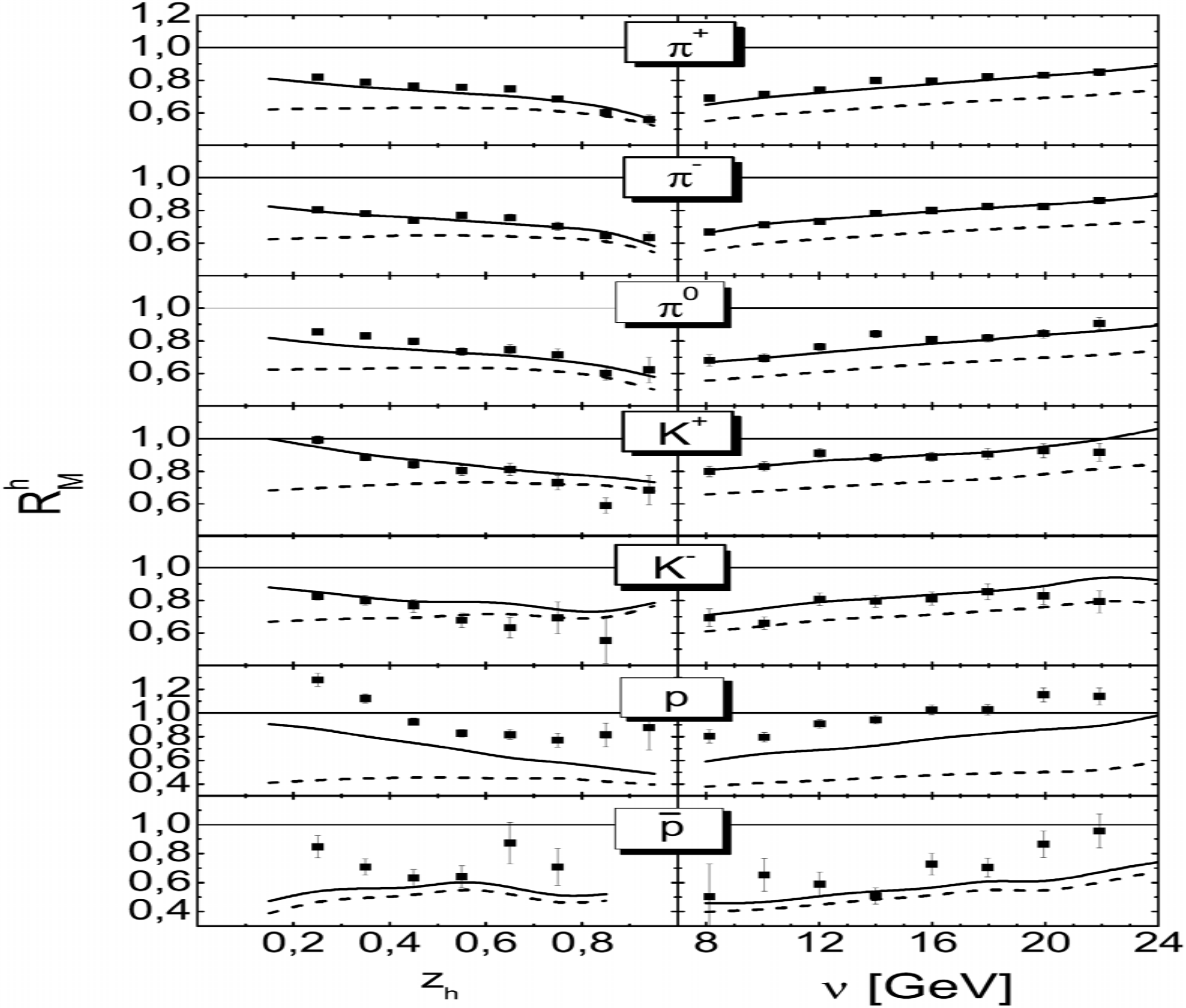
Rescaling Model, HERMES Flavor-separated Kr Data



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



Impact of Models – Summary

- ~4-6 modern models currently on the market:
  - Varying degrees of sophistication
  - All can fit the published data using different assumptions
- → Need more data:
  - Hermes heavy target data, flavor-separated hadrons, high energies
  - CLAS lower-energy, high statistics, wide range of targets, wide range of final states
- Need lattice calculations (~5-10 years away)

Conclusions

- Understanding how confinement acts in forming hadronic systems is a fundamental question in QCD
  - Using the nucleus as analyzer offers a wealth of new information
  - Hadron production/formation lengths, quark energy loss the main focus

- Connections (the theme of this workshop!)
  - Jet quenching at RHIC
  - Drell-Yan at Fermilab
  - Neutrino-nucleus interactions

Drell-Yan: 800 GeV protons on a variety of nuclear targets (McGaughey, Moss, Peng, Ann. Rev. Nucl. Part. Sci. 49, 271 (1999)

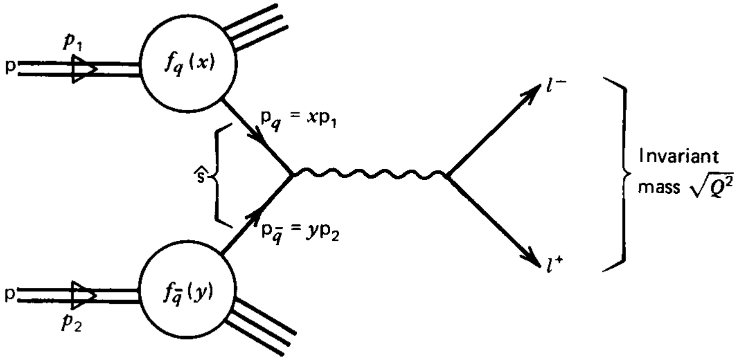


Fig. 11.14 The Drell–Yan process, pp → $l^- l^+$X.

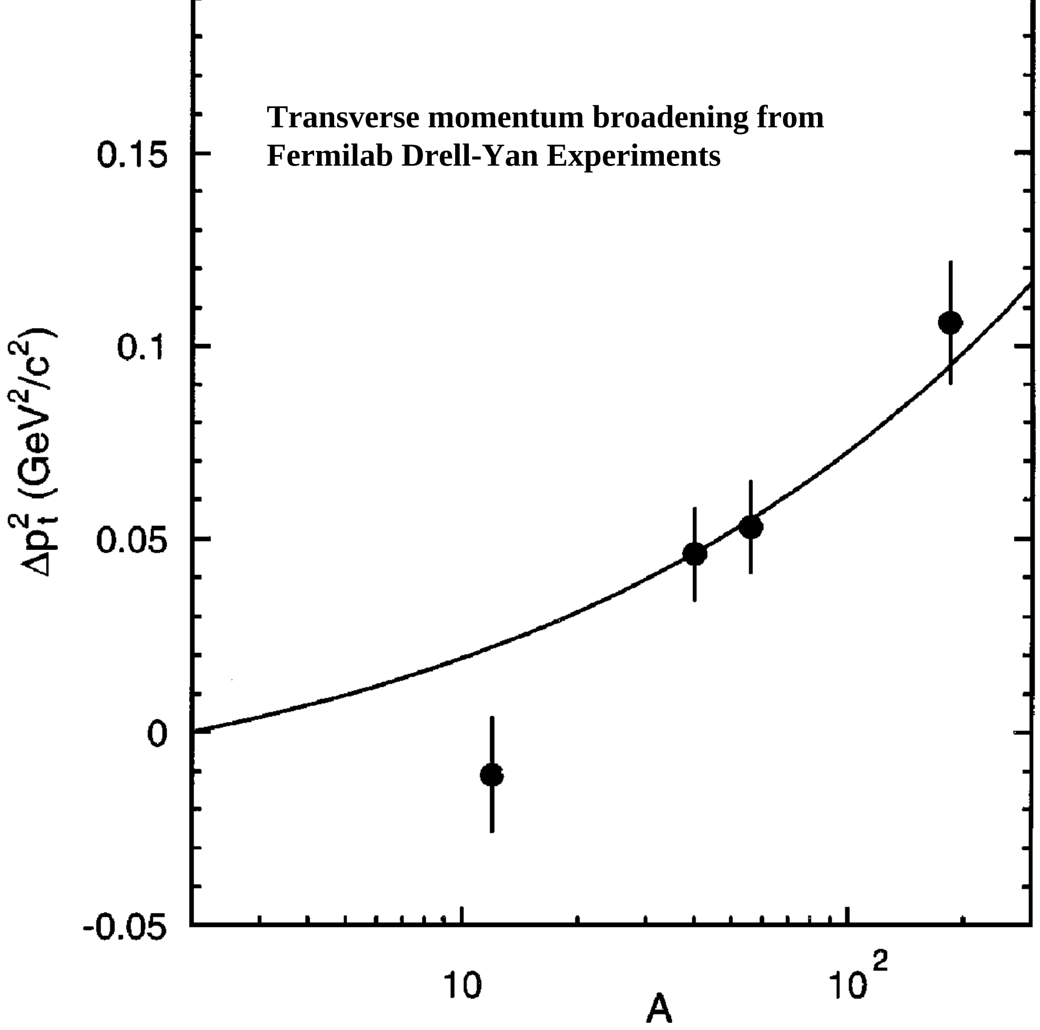
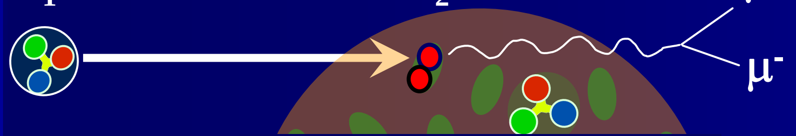

Transverse momentum broadening from Fermilab Drell-Yan Experiments

Figure 15 $\boxed{\Delta\langle p_t^2\rangle \equiv \langle p_t^2\rangle(A) - \langle p_t^2\rangle(^2H)}$ versus A for the DY process from E772 (123; PL McGaughey, JM Moss, JC Peng, unpublished data). Solid curve corresponds to $0.027((A/2)^{1/3} - 1)$.

Incident quark, x_1

Target anti-quark, x_2

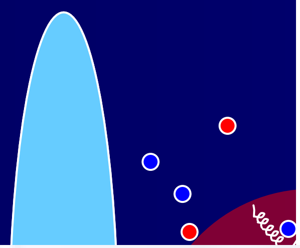


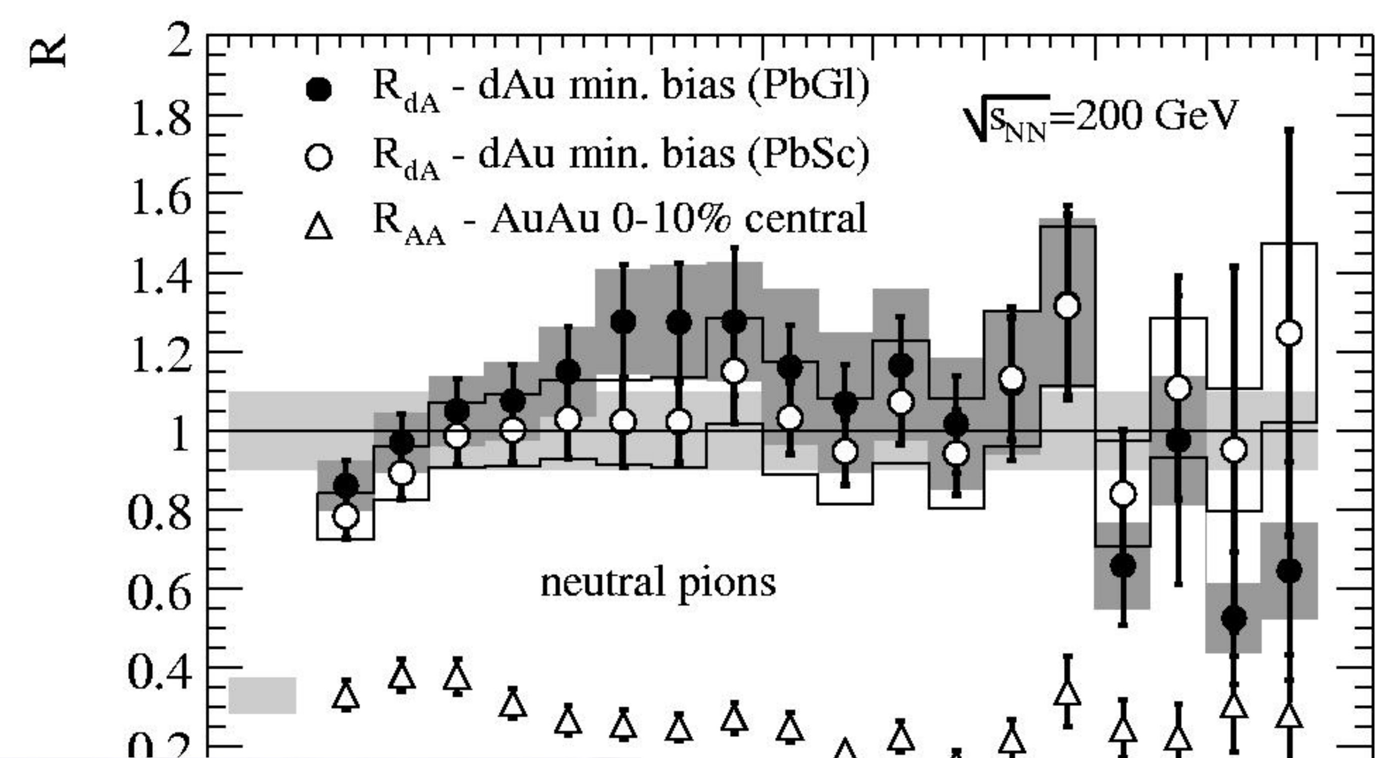
Connection to Relativistic Heavy Ion Physics

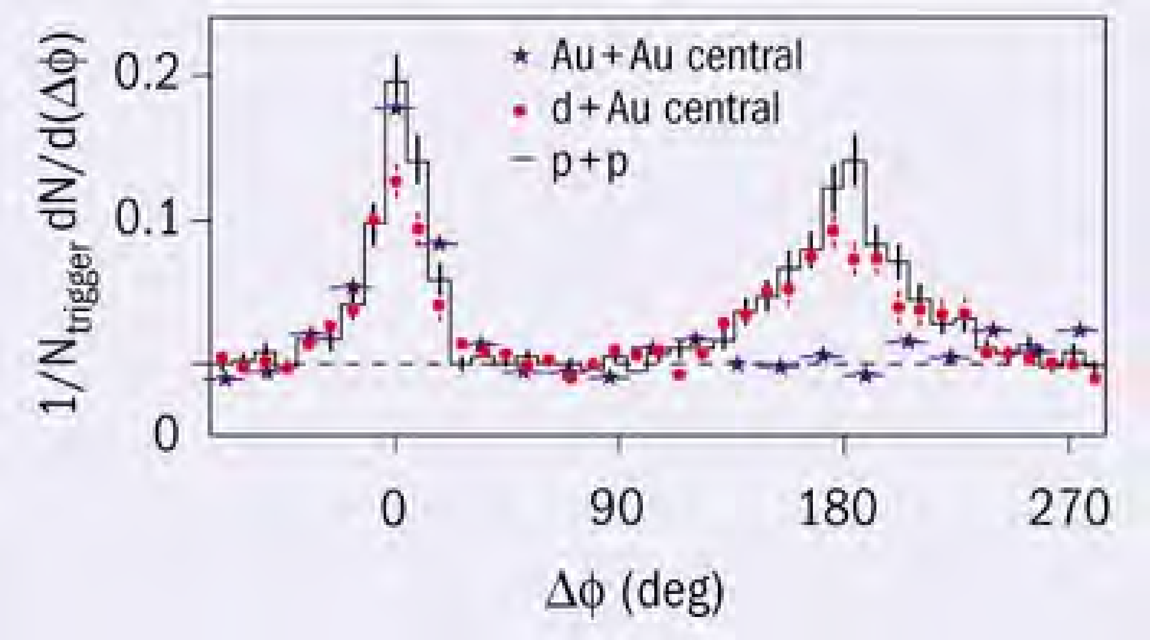
- One proposed signature of the Quark Gluon Plasma is jet quenching: the suppression of high p_T jets
- Jet quenching caused by radiative energy loss would be an indication of high partonic density, e.g., QGP
- Hadron formation might give an alternative explanation for jet quenching
- Nuclear DIS is closely related to propagation of partons in AA collisions
- p_T (A-A) $\approx$ ν (DIS). Relevant energies are ~few GeV

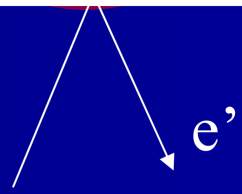
Releva

Relativistic



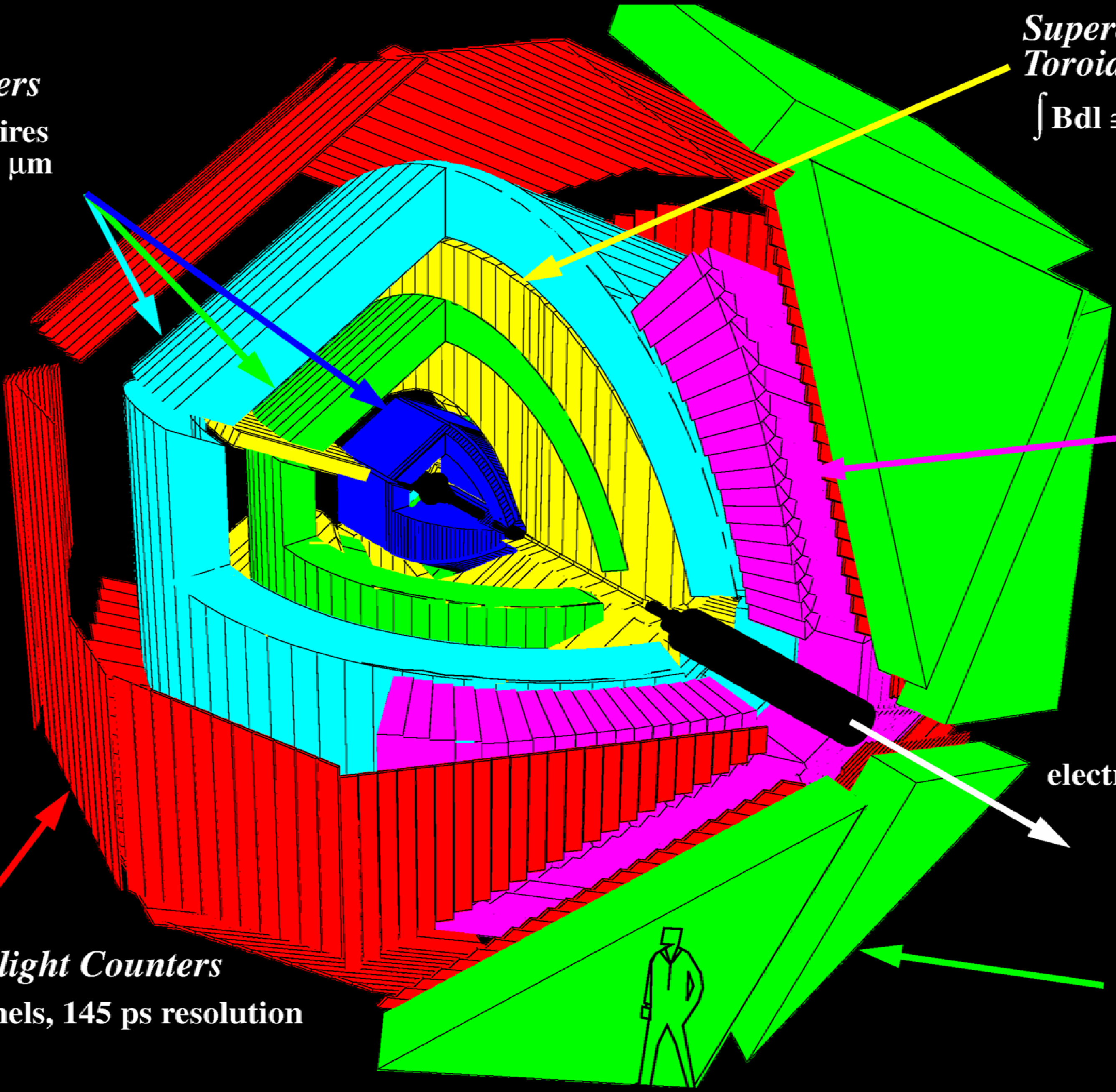






Initial quark energy is known
Properties of medium are known

CLAS – the CEBAF Large Acceptance Spectrometer



Drift Chambers

35,000 wires

$\sigma_R = 350\ \mu m$

Superconducting Toroidal Magnet

$\int Bdl \cong 1.7$ T-m

Cerenkov Counters

216 channels

99.5% efficient

over 50 m^2 area

electron beam direction

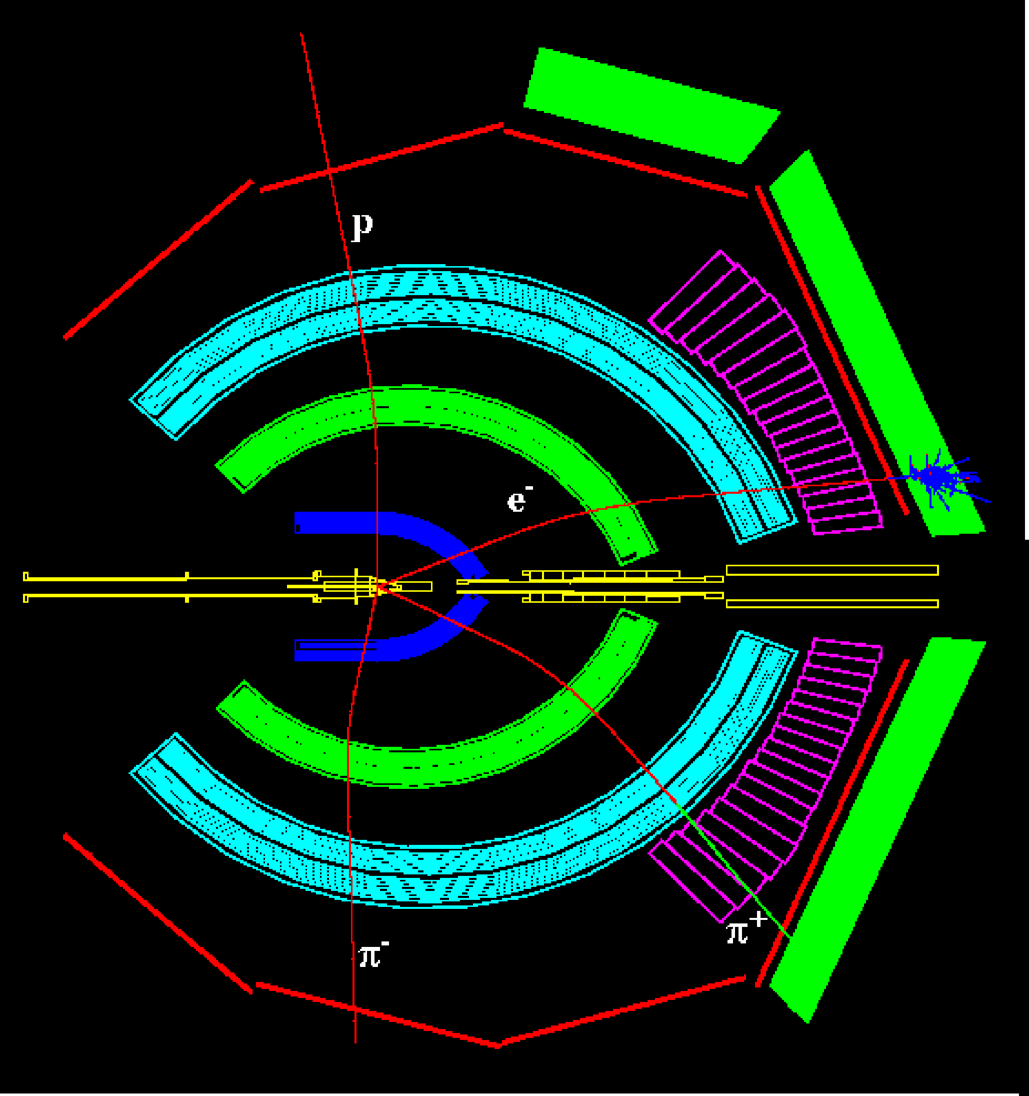
Electromagnetic Shower Calorimeters

1700+ channels

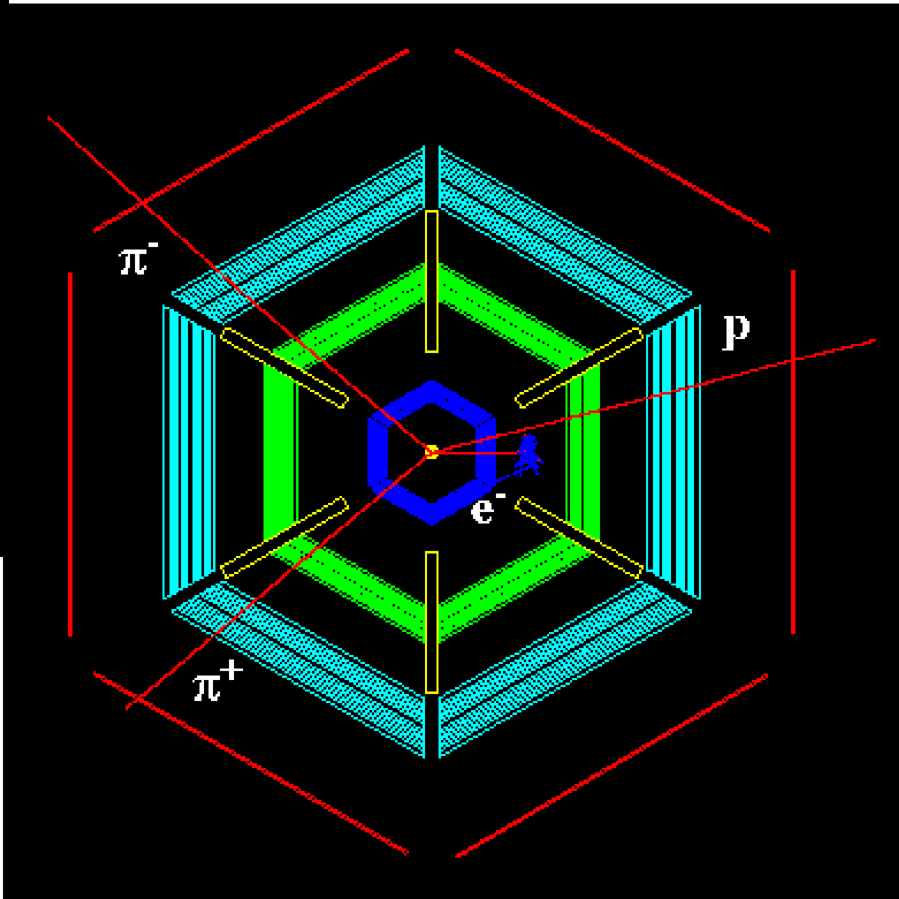
$\sigma/E = 10\%/E^{0.5}$

Time of Flight Counters

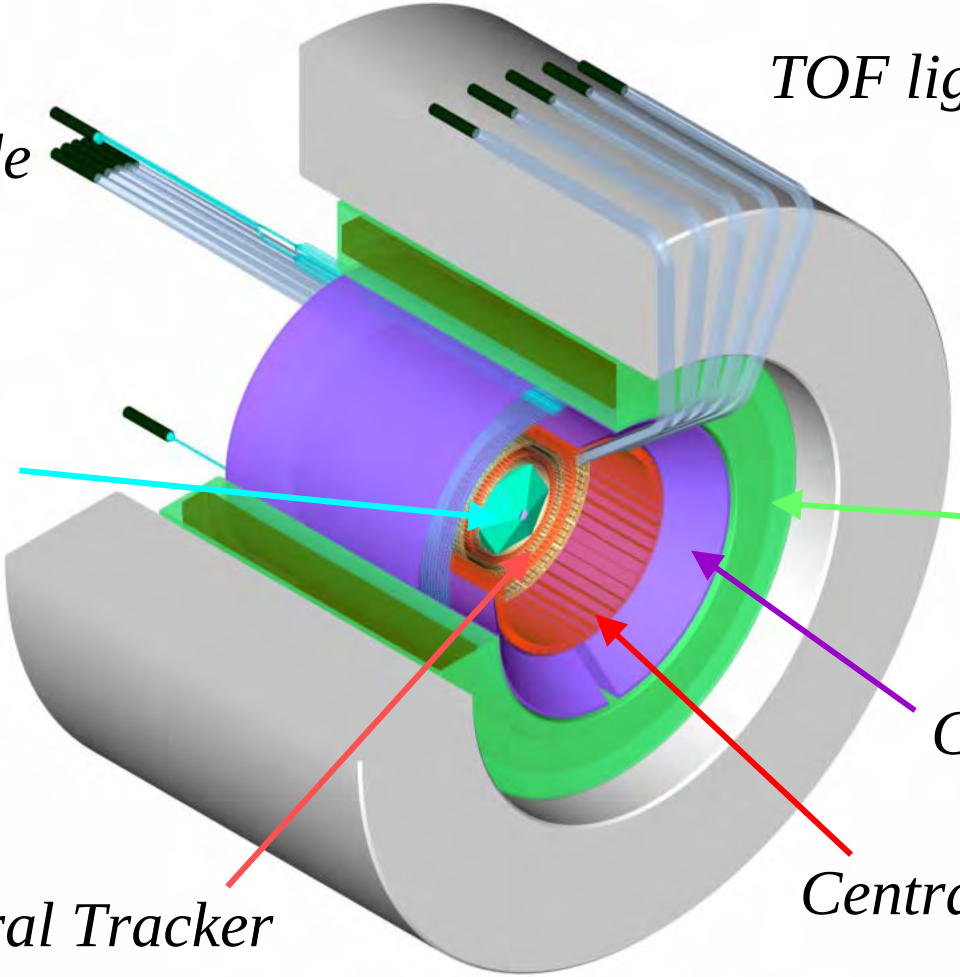
500+ channels, 145 ps resolution



- Charged particle angles 8° - 144°
- Neutral particle angles 8° - 70°
- Momentum resolution ~0.5% (charged)
- Angular resolution ~0.5 mr (charged)
- Identification of p, π^+/π^-, K^+/K^-, e^-/e^+



The CLAS12 Central Detector



TOF lightguide

TOF light guide

Flux return

Microstrip

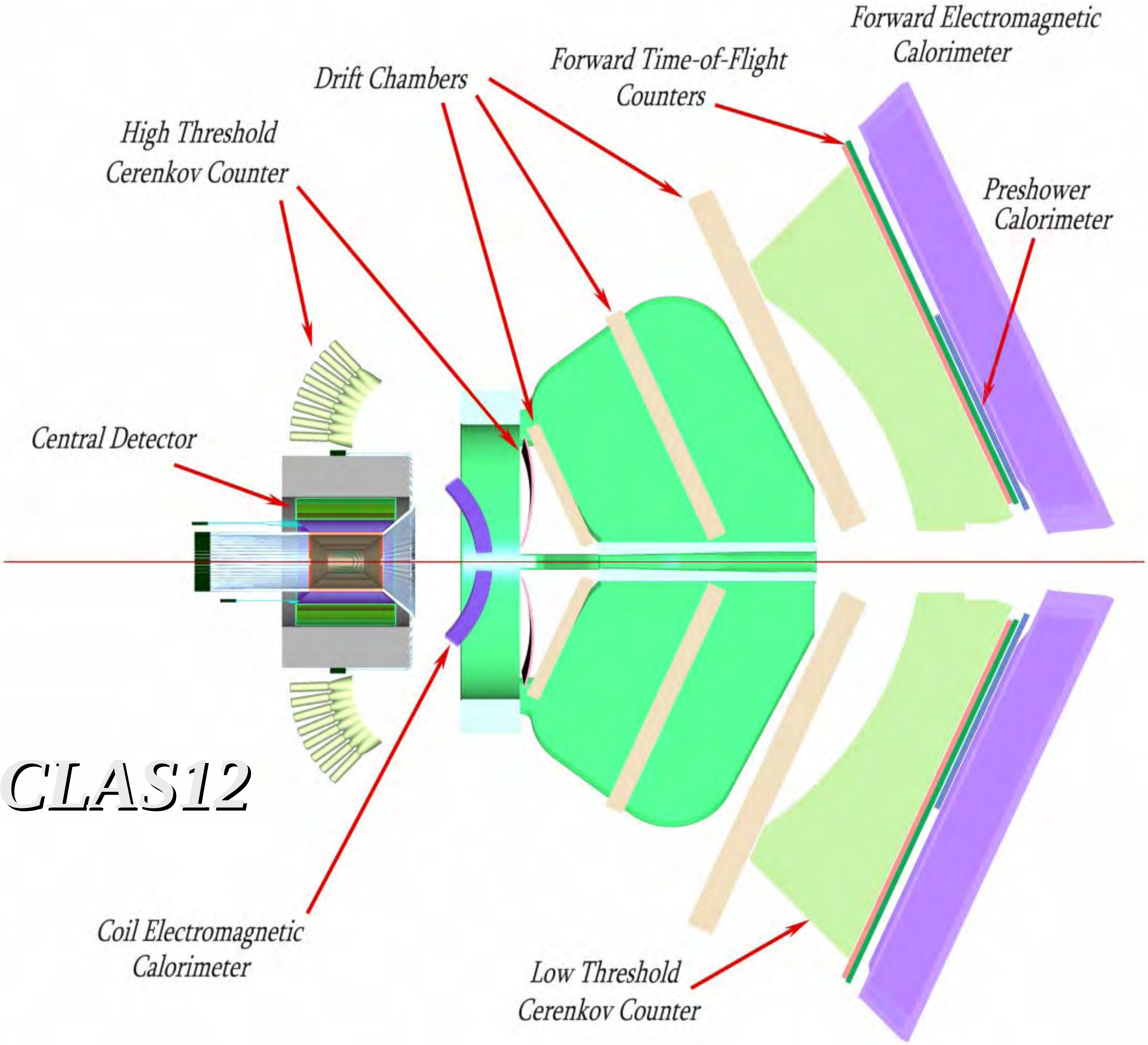
Superconducting solenoid coil (Bmax = 5T)

Central EC

Central TOF

Central Tracker

CLAS12


Forward Electromagnetic Calorimeter
Forward Time-of-Flight Counters
Drift Chambers
High Threshold Cerenkov Counter
Preshower Calorimeter
Central Detector
Coil Electromagnetic Calorimeter
Low Threshold Cerenkov Counter

Nuclear Quark/Hadron Propagation

Experimental Method in CLAS

- Use a range of targets, light to heavy
- DIS kinematics + measure hadrons
- Single electron trigger
- Nuclear medium modifies fragmentation functions and p_T distributions
- 5 GeV beam: $Q^2 \leq 4$ GeV^2, $\nu \leq 4.5$ GeV
- 11 GeV beam: $Q^2 \leq 9$ GeV^2, $\nu \leq 9$ GeV
- Measure $\pi^{+,-,0}$, η, ω, η', ϕ, $K^{+,-,0}$, p, Λ, $\Sigma^{+,0}$, $\Xi^{0,-}$

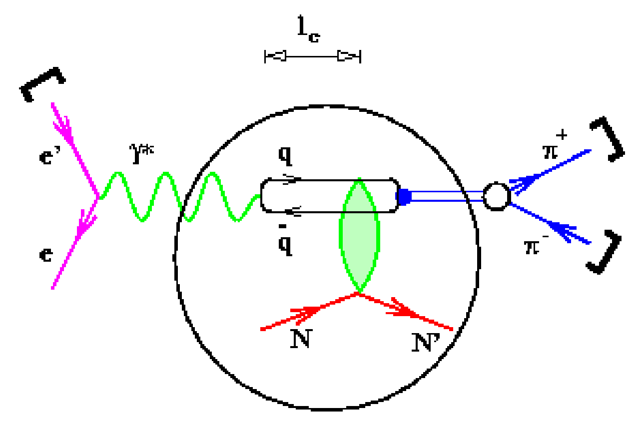
CLAS EG2

Physics Focus

Search for Color Transparency

Measure rho absorption vs. Q^2 at fixed coherence length

Compare absorption in deuterium, carbon, aluminum, and iron



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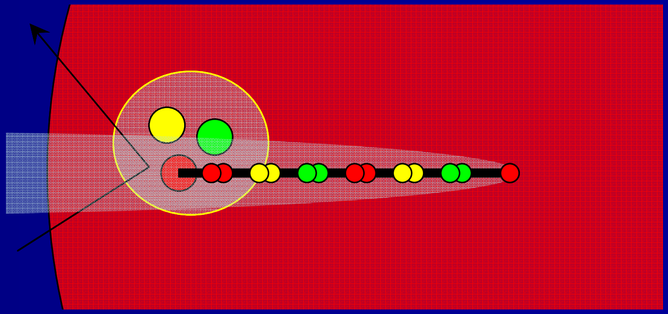
Quark Propagation through Nuclei

Measure attenuation and transverse momentum broadening of hadrons (π, K) in DIS kinematics

Compare absorption in deuterium, carbon, iron, tin, and lead



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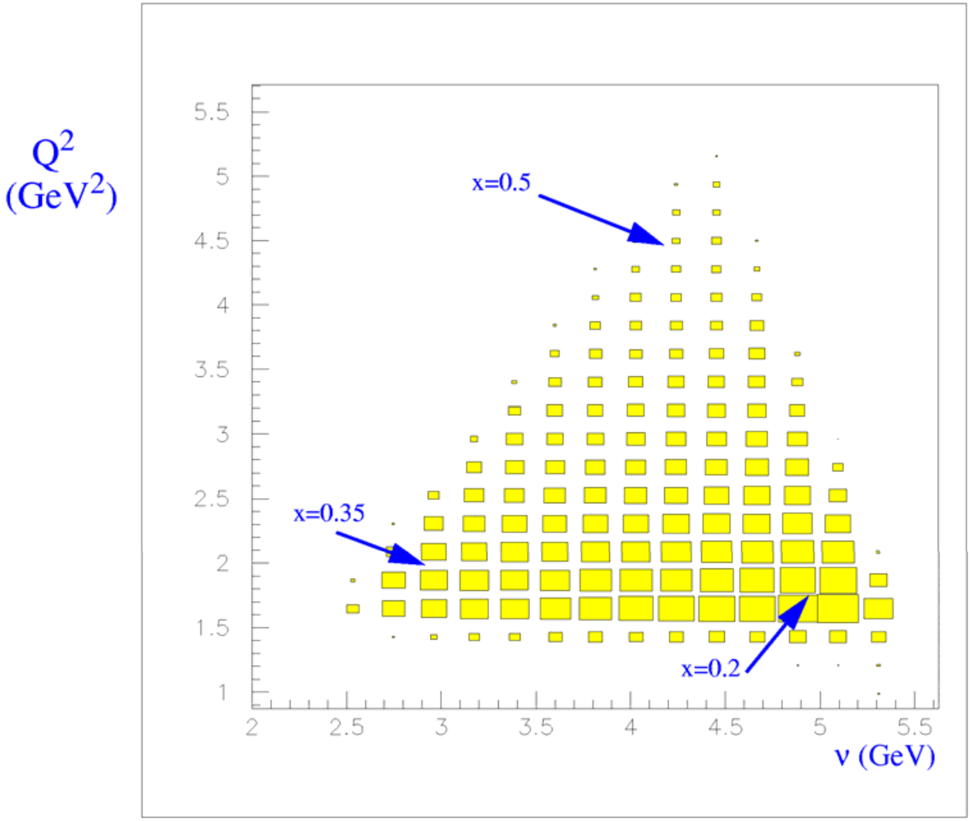
CLAS EG2

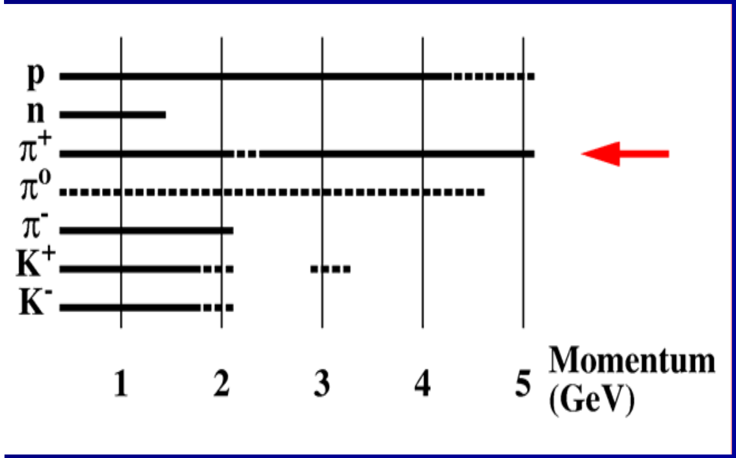
Running Conditions

- Beam energies: 4 GeV (7 days) and 5 GeV (50 days)
- Luminosity: 1.9-2.0 x 10^{34} (D+Fe), 1.3 x 10^{34} (D+Pb)
- Data taking:
  - DC occupancy < 3%,
  - deadtime 7% (D+Pb) and 14% (D+Fe)
- Number of triggers:
  - 0.6 billion (D+Fe, 4 GeV)
  - 2 billion (D+Fe, 5 GeV)
  - 1.5 billion (D+Pb, 5 GeV)
  - 1 billion (D+C, 5 GeV)

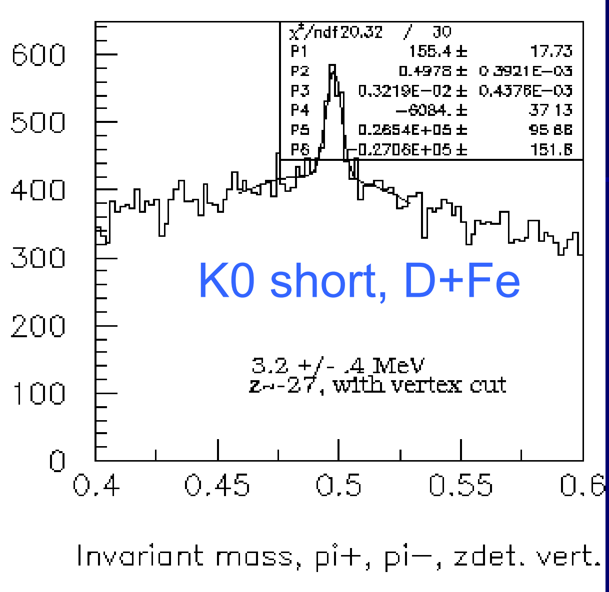
CLAS Kinematic Coverage and Particle Identification at 6 GeV



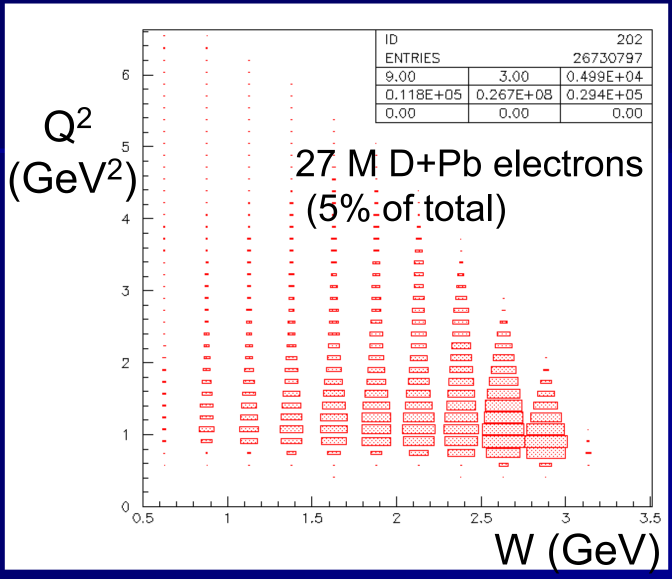
Directly identified particles

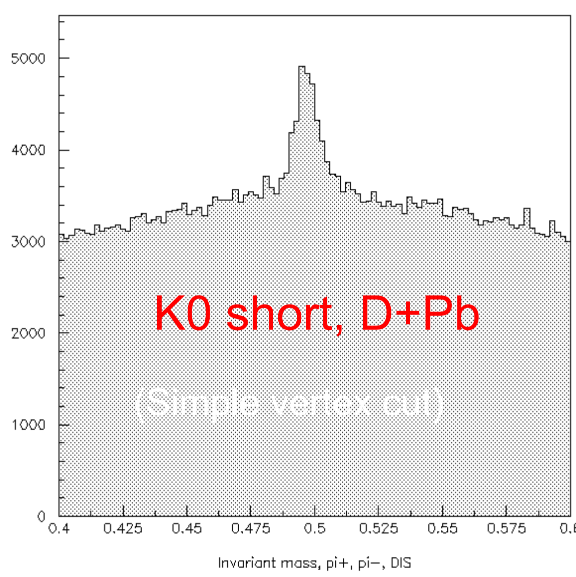


CLAS EG2
Online Physics Results

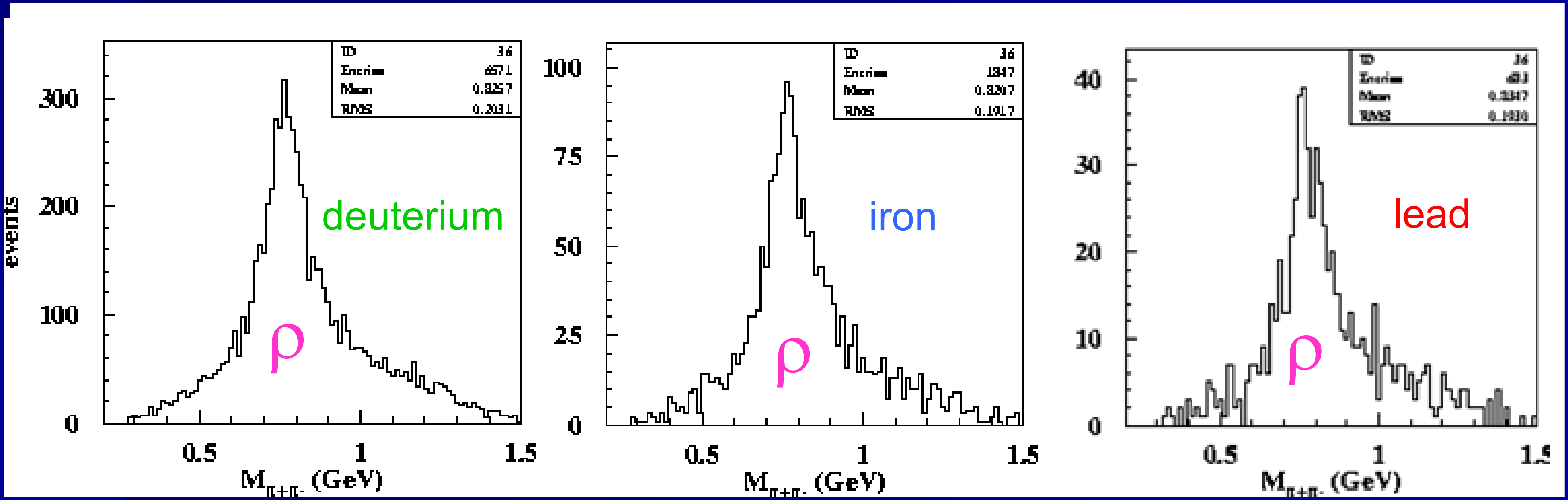

K0 short, D+Fe

3.2 +/- .4 MeV
z~-27, with vertex cut


27 M D+Pb electrons
(5% of total)


K0 short, D+Pb

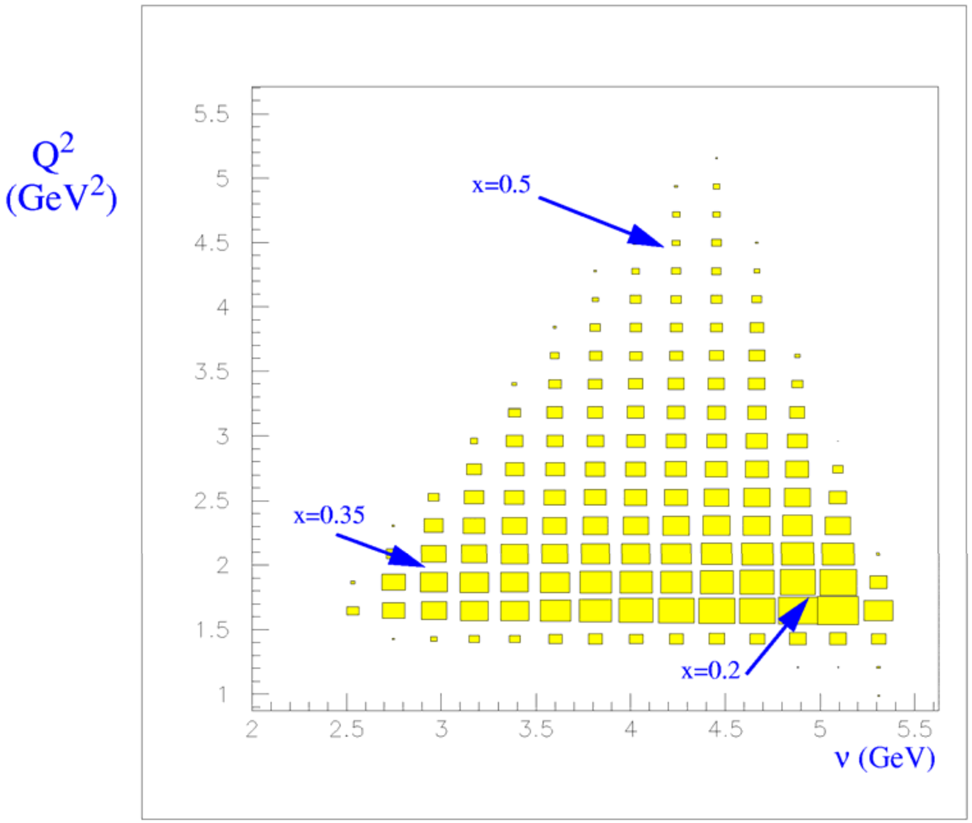
(Simple vertex cut)


deuterium

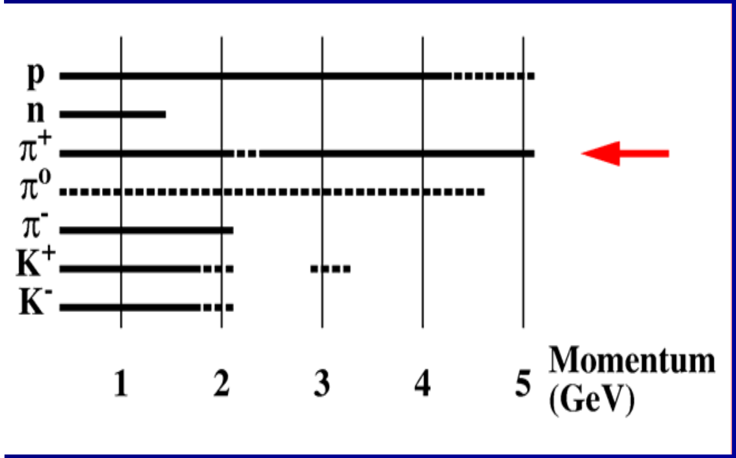
iron

lead

CLAS Kinematic Coverage and Particle Identification at 6 GeV

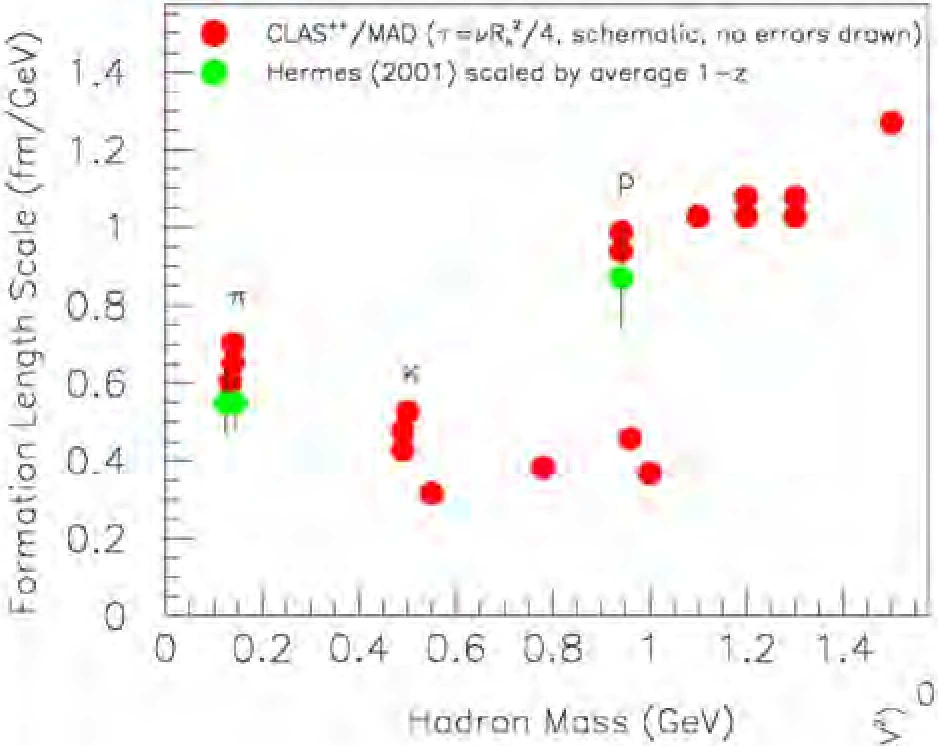


Directly identified particles



12 GeV Anticipated Data

Schematic Examples of Analysis Results



- Formation lengths for a wide variety of hadrons using data from CLAS^{++} and MAD.

- Transverse momentum broadening for a number of hadrons using data from CLAS^{++} and SHMS, for a particular Q^2, ν.