

Hadron Formation Lengths: QCD Confinement in Forming Systems

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Workshop on Intersections of Nuclear Physics with Neutrinos and Electrons

May 5, 2006

Main Focus

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

“How do hadrons form, and how long does it take?”

- Quark energy loss and multiple scattering
 - 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”

Numerous other studies: correlations, associated photons

Steps: How Does Confinement Assemble Hadrons?

Step 1: Isolate correct interaction mechanisms - physical picture

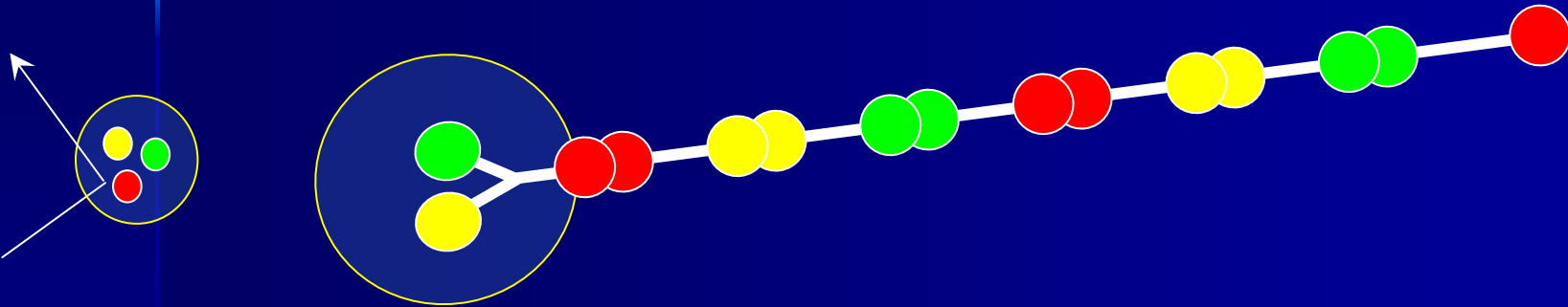
- Models
- Lattice studies require technical development, not happening soon
- Multi-hadron, multi-variable studies needed

Step 2: Extract characteristic parameters and functional dependencies

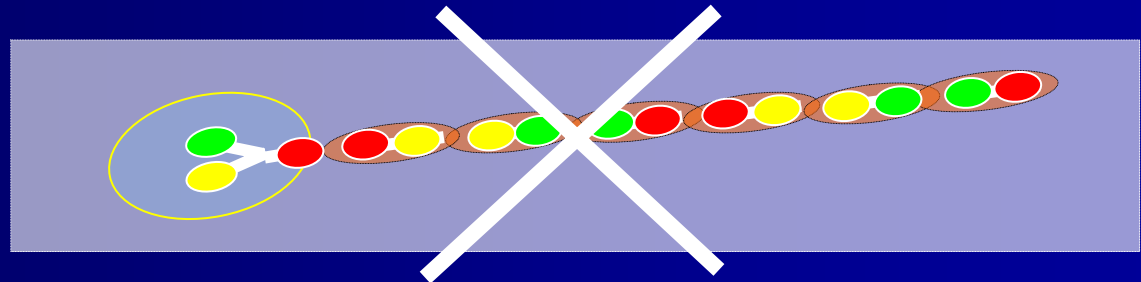
- Length scales
- Flavor dependence, size dependence
- Energy loss
- Correlation functions

Interaction mechanisms

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



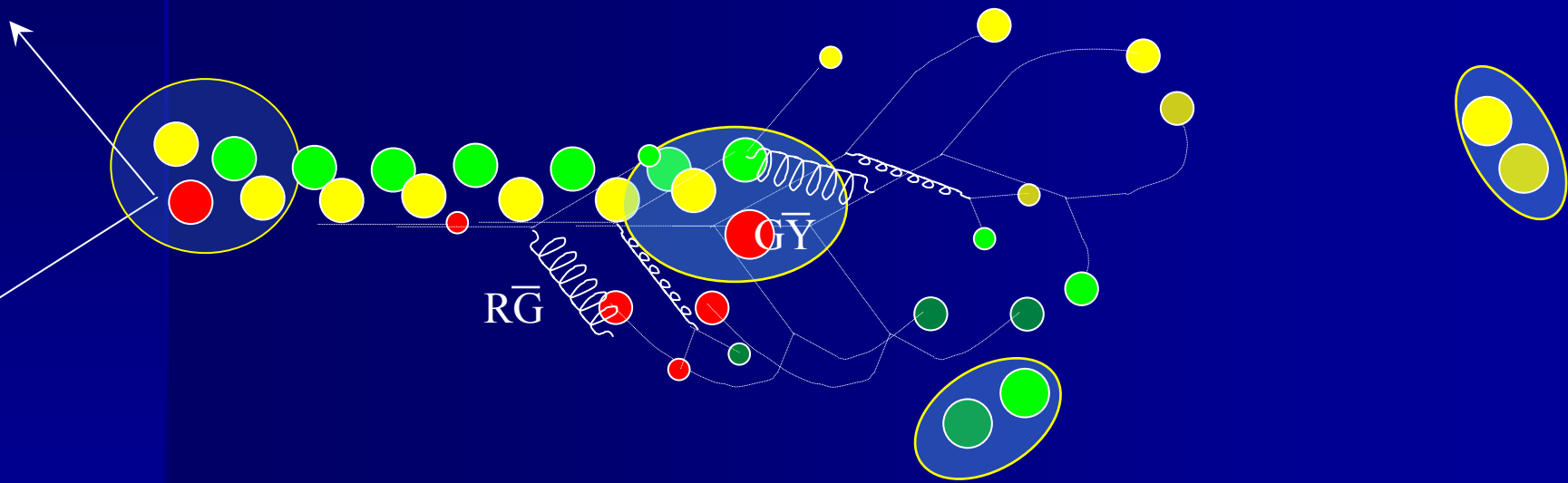
- Confinement process isn't finished yet, these are *colored* pairs:



- 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”:

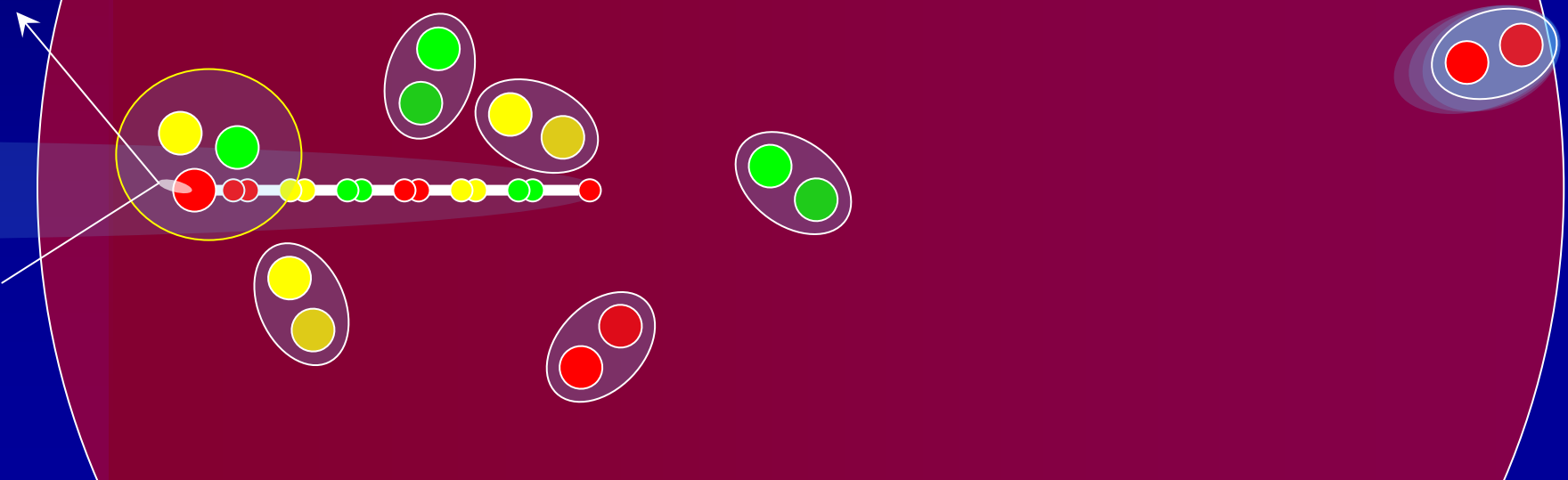


All hadron color explicitly resolved in this picture

Experimentally, it is completely unknown what the dominant mechanism is

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



Hadron formation lengths: 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:

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

If take, e.g., the pion mass, radius 0.66 fm, $E = 4$ GeV, then $t_f \sim 20$ fm.

- Slightly more sophisticated, if gluon emission time dominates

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

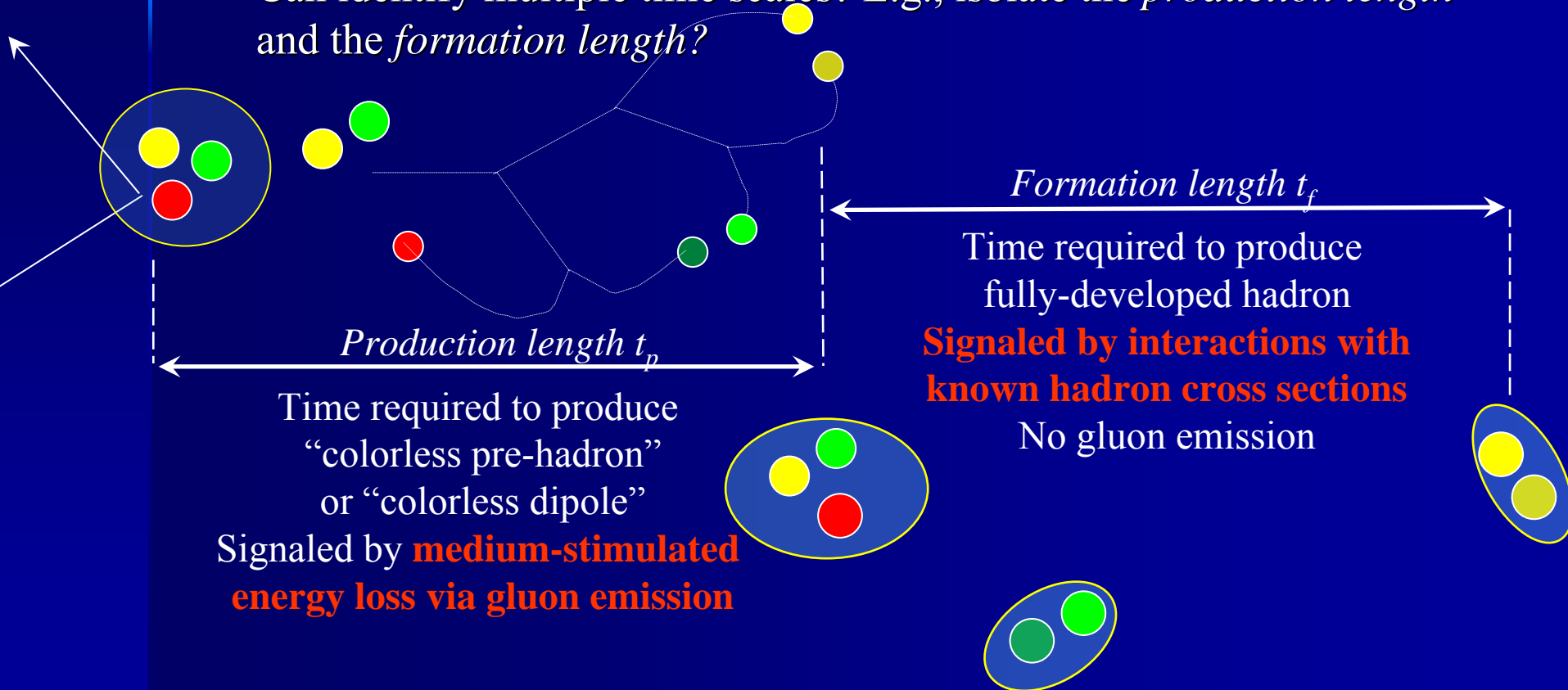
If take, e.g., pion mass, $z = E_{\text{hadron}}/v = 0.5$, $E_h = 4$ GeV, then $t_f \sim 13$ fm



Well-matched to nuclear dimensions!

Time scales for hadron formation

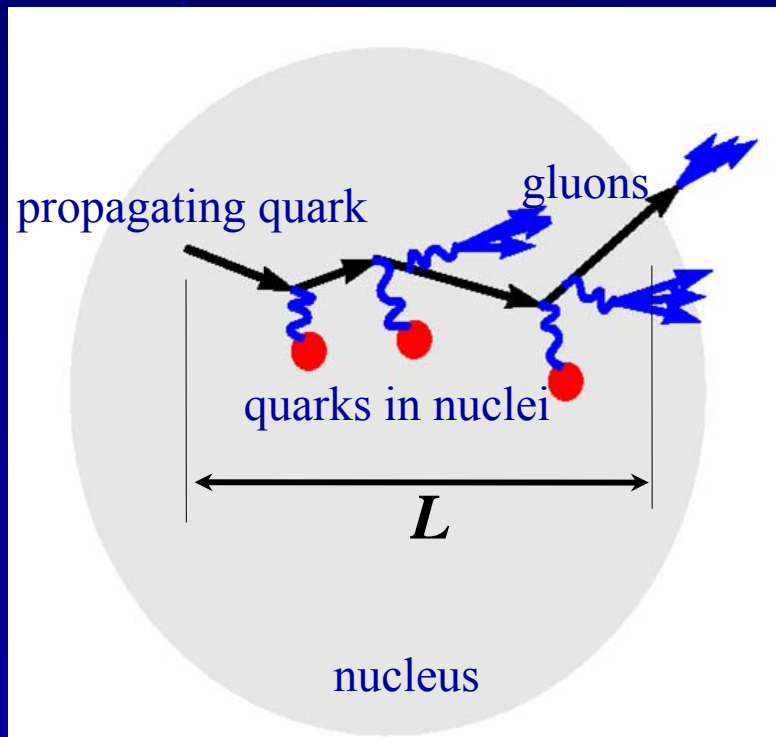
- Can identify multiple time scales? E.g., isolate the *production length* and the *formation length*?



It is essentially unknown what these time scales are

Experimental Studies: Propagation of Quarks

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



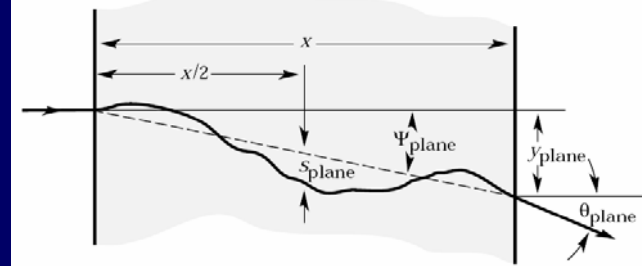
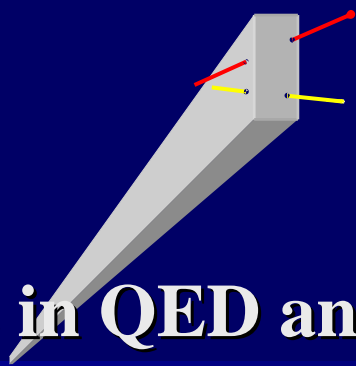
$$dE/dx \approx \frac{\alpha_s}{\pi} N_c \langle p_T^2 \rangle_L$$

Medium-stimulated loss
Calculation by BDMPS

This can be directly measured on a series of nuclei

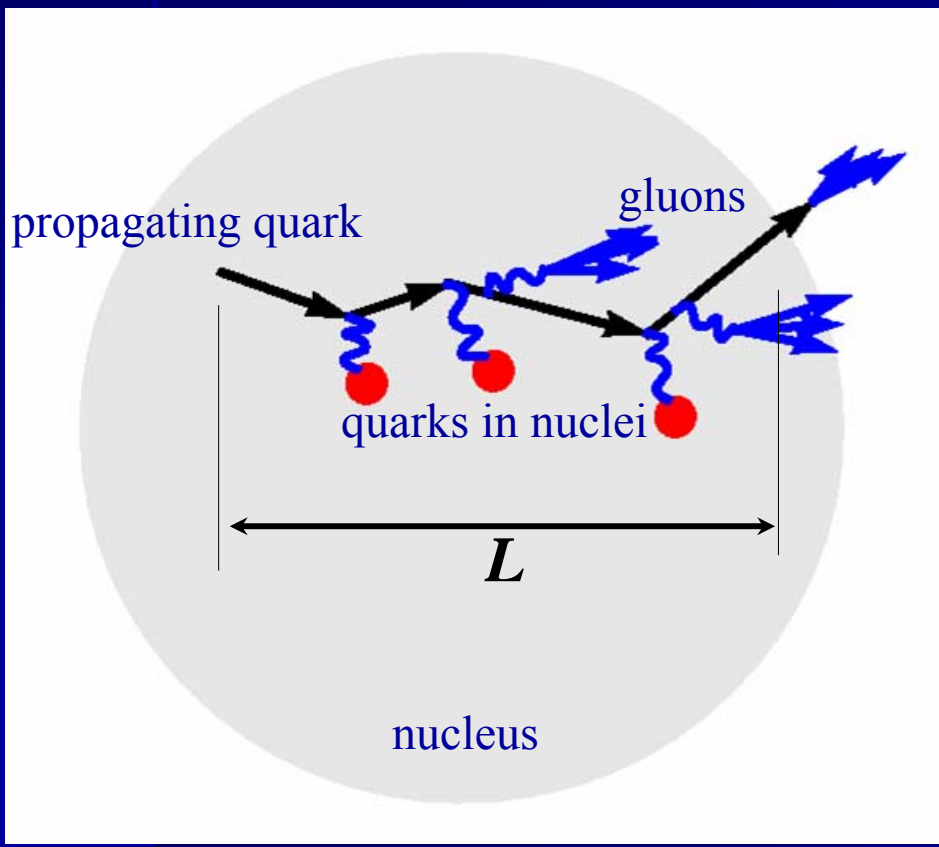
Signature of *production length* t_p

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:

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

QCD analog of LPM effect

Experiments Addressing the Same Topics

- Experimental avenues
 - Semi-inclusive deep inelastic scattering on nuclei
 - 1970's CERN EMC $eA \rightarrow e'Xh$, energy transfer ~ 35 -145 GeV
 - 2000's HERA HERMES $e^+A \rightarrow e^+Xh$, 12 and 26 GeV beam
 - 2000's Jefferson Lab CLAS, $eA \rightarrow e'Xh$, 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 $AA \rightarrow$ everything, 200 GeV/u colliding beams

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

Links

- Workshop Home
- Circular
- Program
- Travel

Click to download poster



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 (Valparaiso), D. Treleani (Trieste), B. Van Overmeire (Ghent), I. Vitev (Los Alamos), K. Wang (Charlottesville), K. Zapp (Heidelberg), B.-W. Zhang (Wuhan)

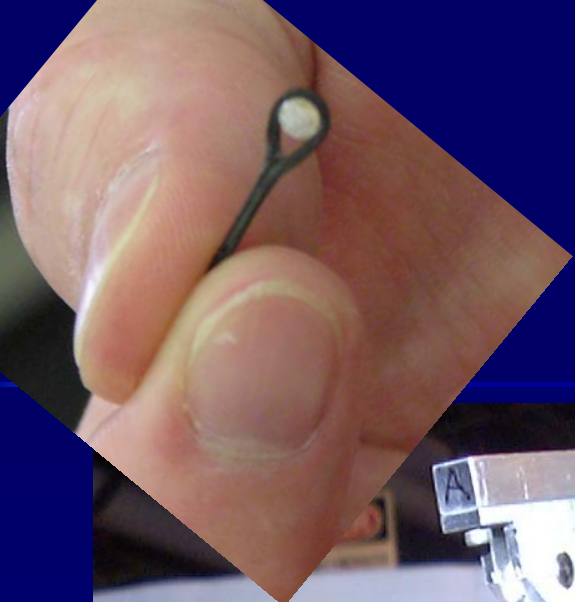
Sponsors



<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:

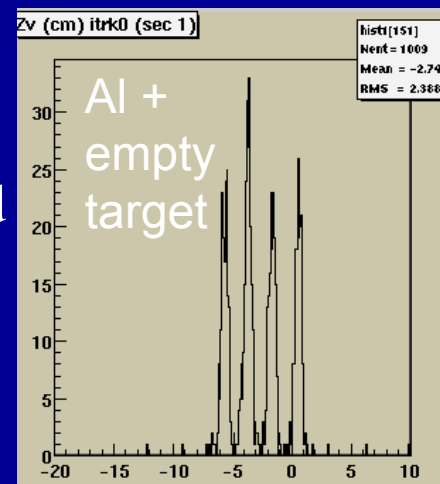
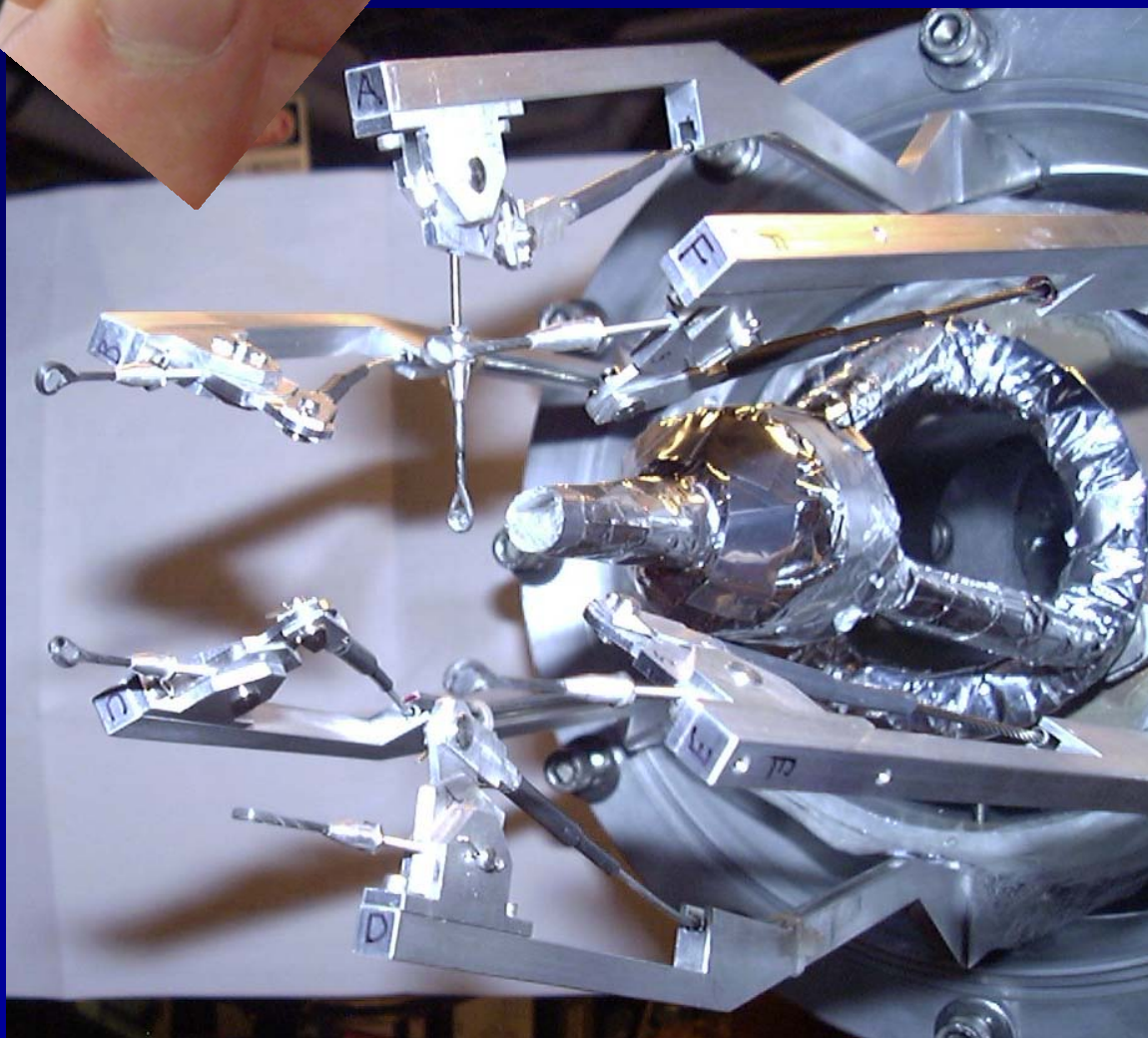
- Carbon

- Aluminum (2 thicknesses)

- Iron

- Tin

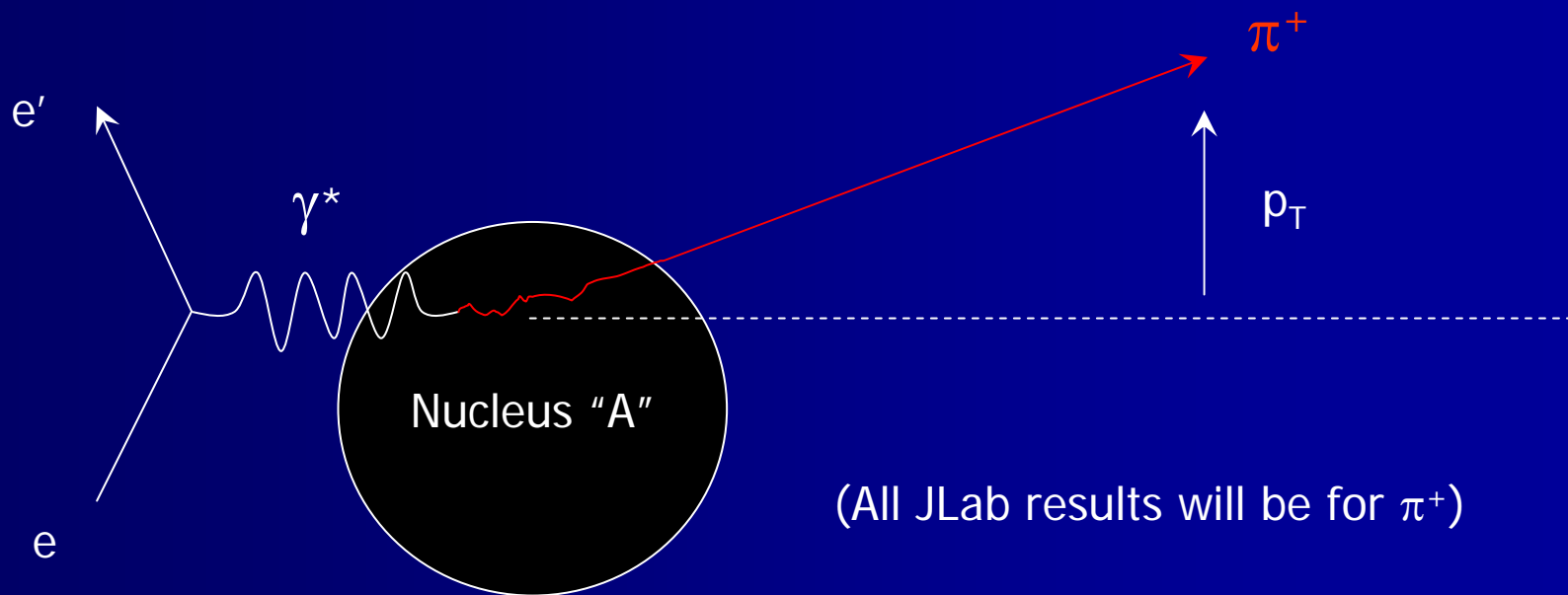
- Lead



Observable Number 1 – “ p_T Broadening”

Definition of “Transverse Momentum Broadening”

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

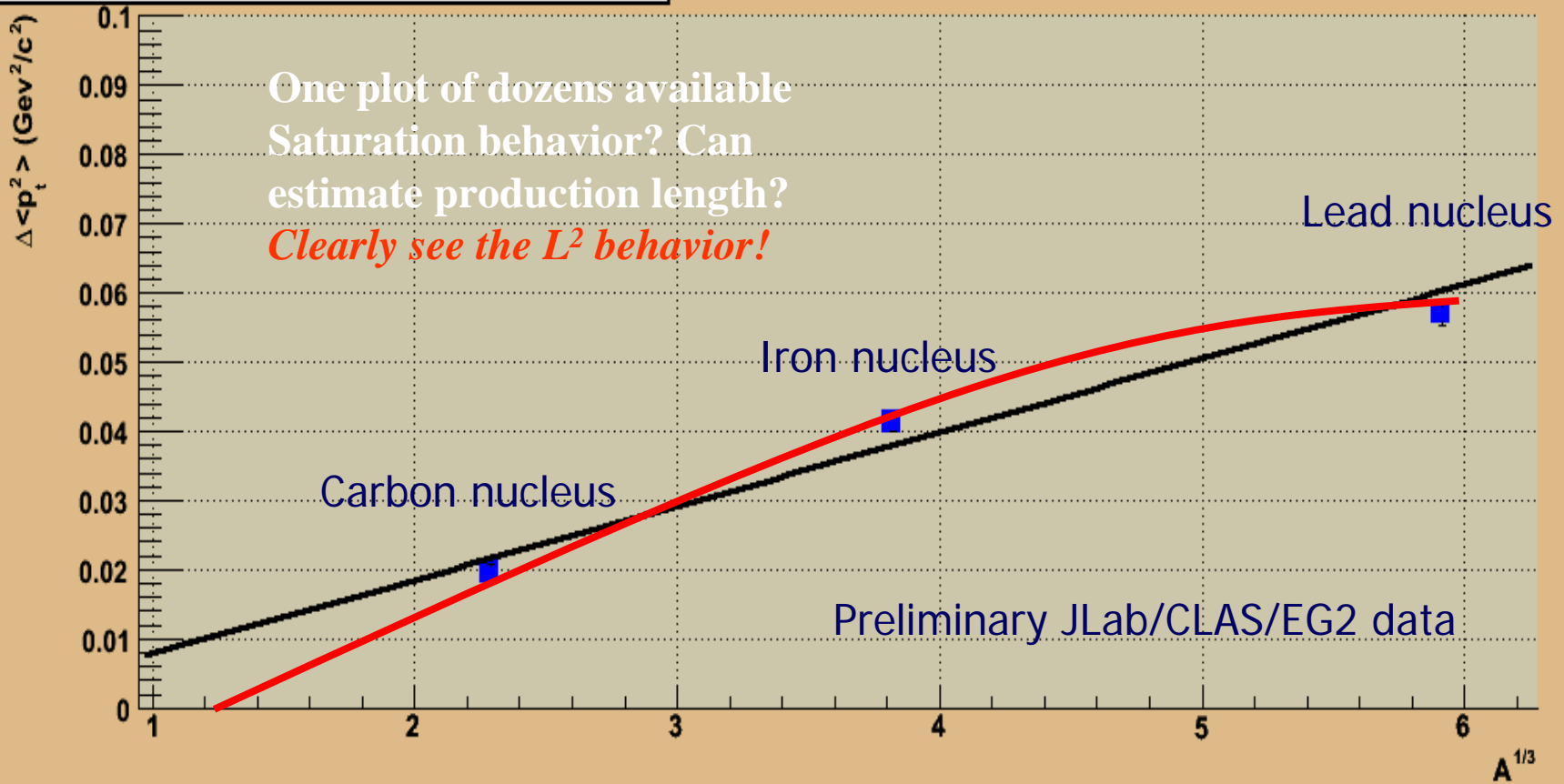


(All JLab results will be for π^+)

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

- Transverse momentum broadening vs. nuclear radius is \sim linear

$1 < Q^2 < 2$ $3 < \nu < 4$ $0.500000 < Z_{\pi^+} < 0.600000$ | π^+



Medium-Induced Quark Energy Loss

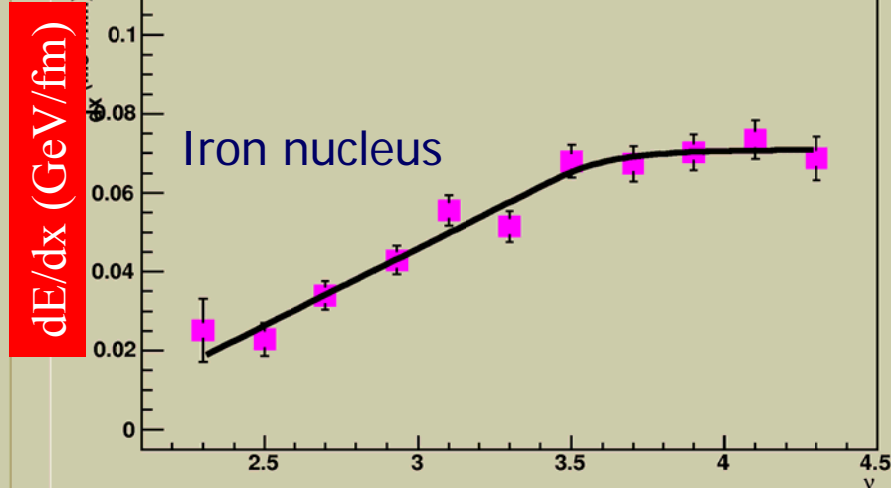
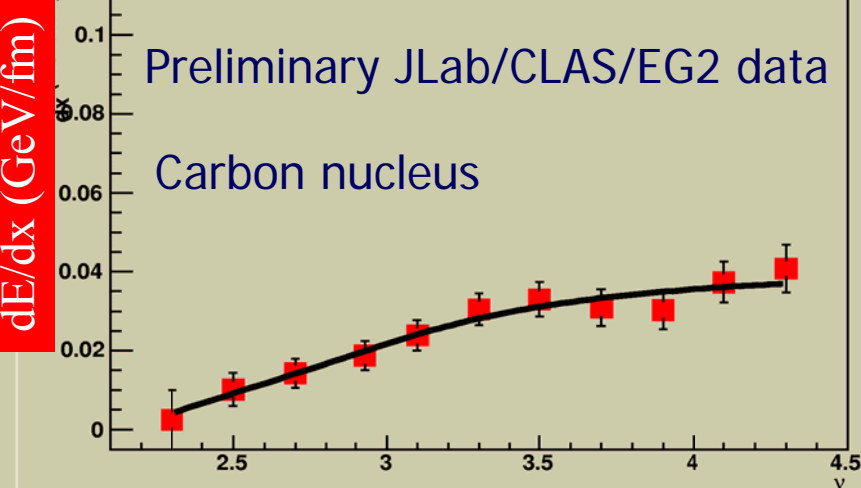
assuming perturbative formula

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

$1 < Q^2 < 2 \quad 0.5 < Z_{\pi^+} < 0.6 \quad \pi^+ \quad C$

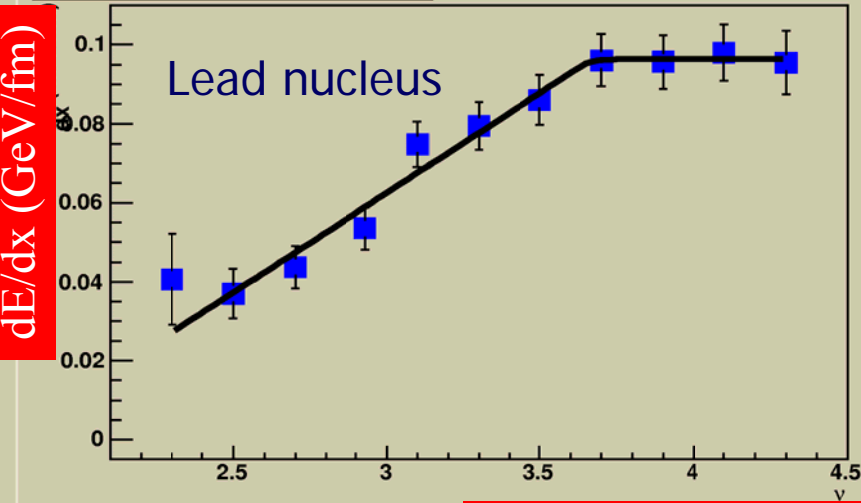
(Dozens of plots like this)

$1 < Q^2 < 2 \quad 0.5 < Z_{\pi^+} < 0.6 \quad \pi^+ \quad Fe$



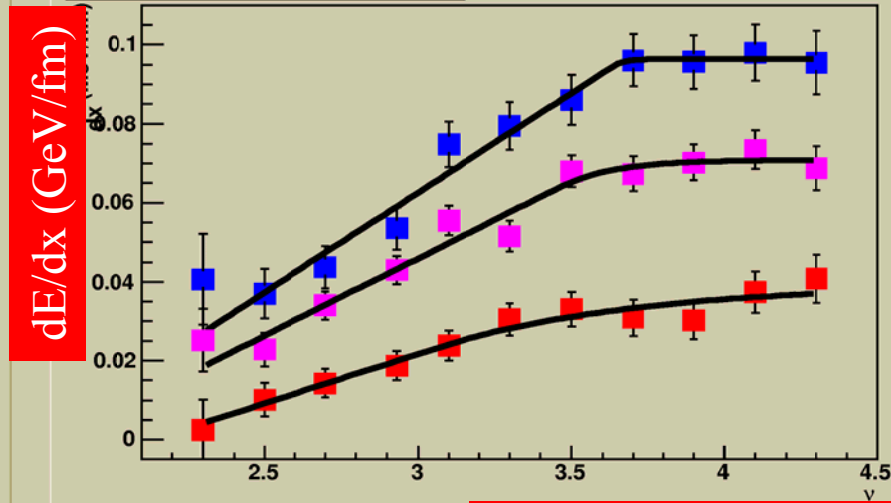
$1 < Q^2 < 2 \quad 0.5 < Z_{\pi^+} < 0.6 \quad \pi^+ \quad Pb$

Struck quark energy (GeV)



$1 < Q^2 < 2 \quad 0.5 < Z_{\pi^+} < 0.6 \quad \pi^+$

Struck quark energy (GeV)



Struck quark energy (GeV)

Struck quark energy (GeV)

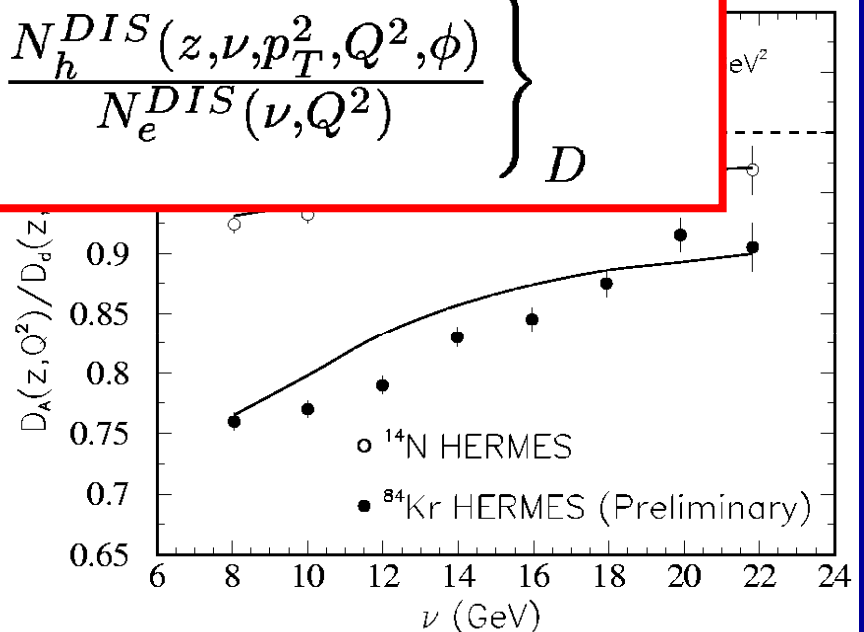
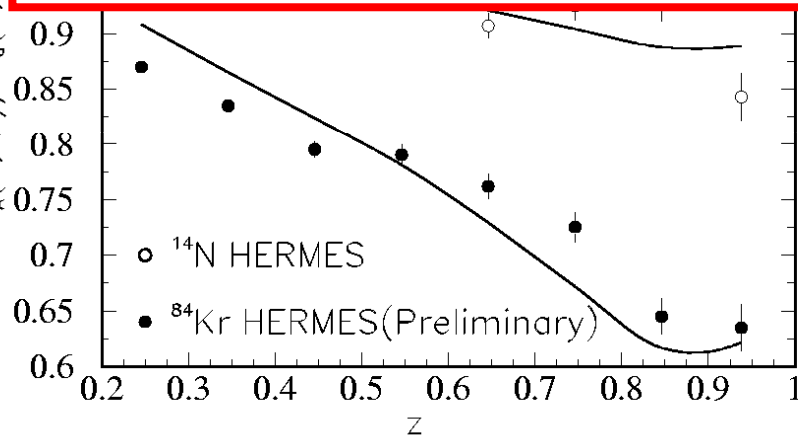
Observable Number 2 – Hadronic Multiplicity Ratio

Hadronic multiplicity ratio

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

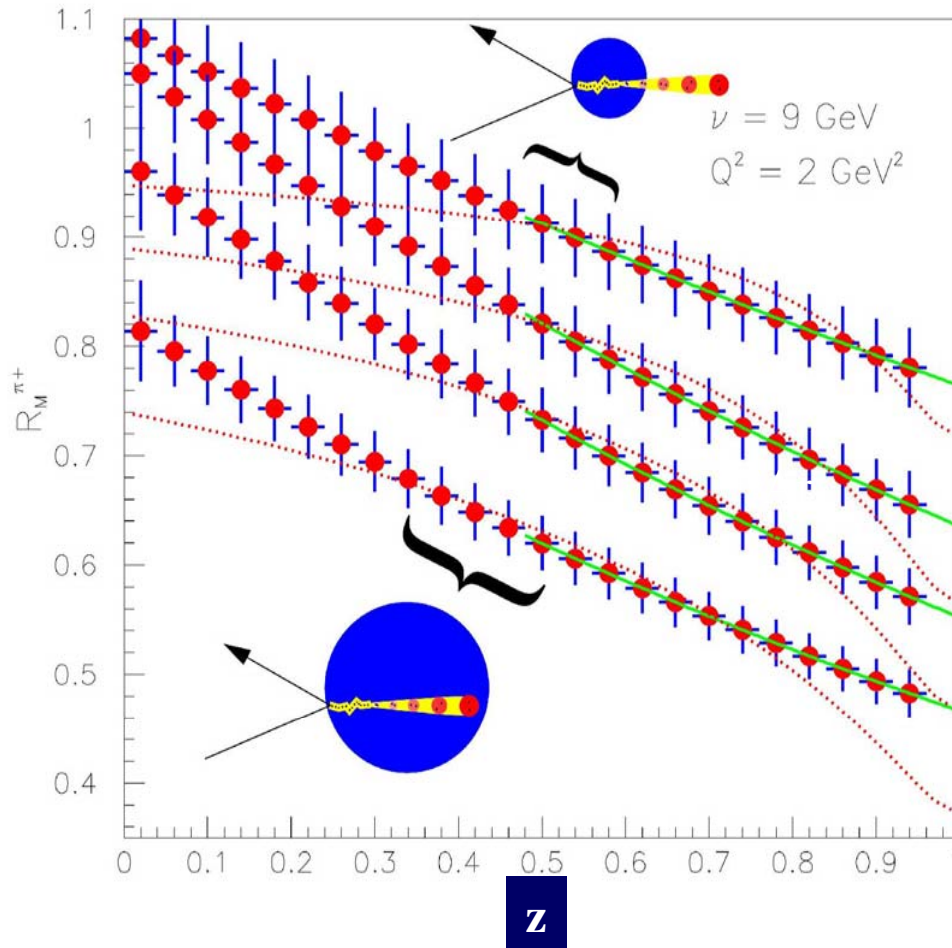
$$\left\{ \frac{N_h}{N} \right\}$$

$$\left\{ \frac{N}{N} \right\}$$

$$\left\{ \frac{N}{N} \right\}$$


Interpretation of Hadronic Multiplicity Ratio

(concrete example in hadronization picture, for 4 nuclei)



HERMES parameterization
for pion formation length:

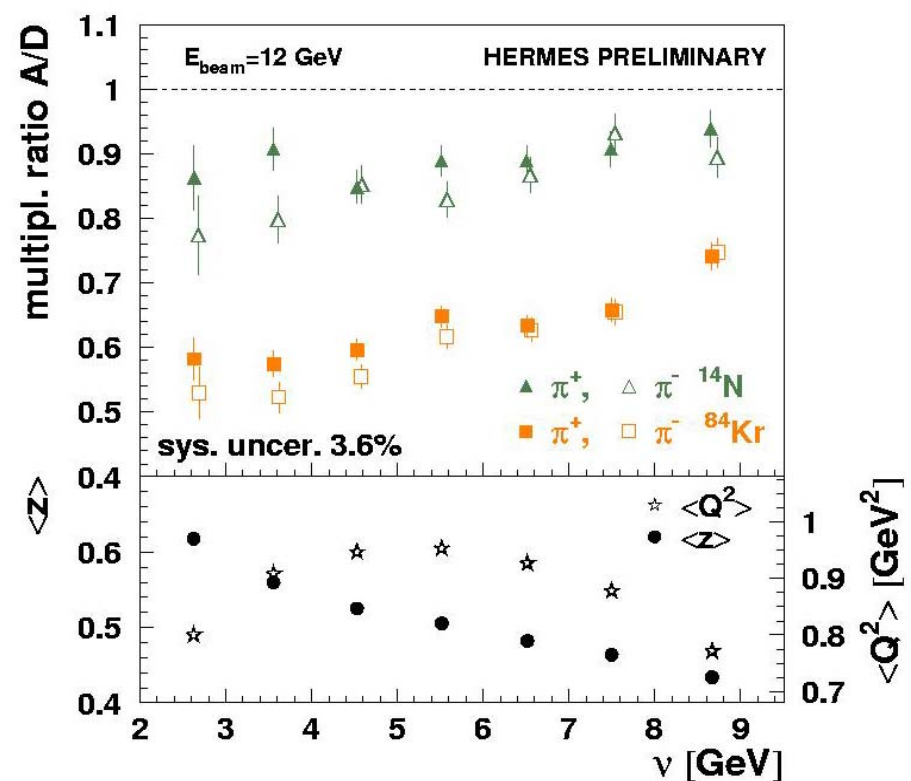
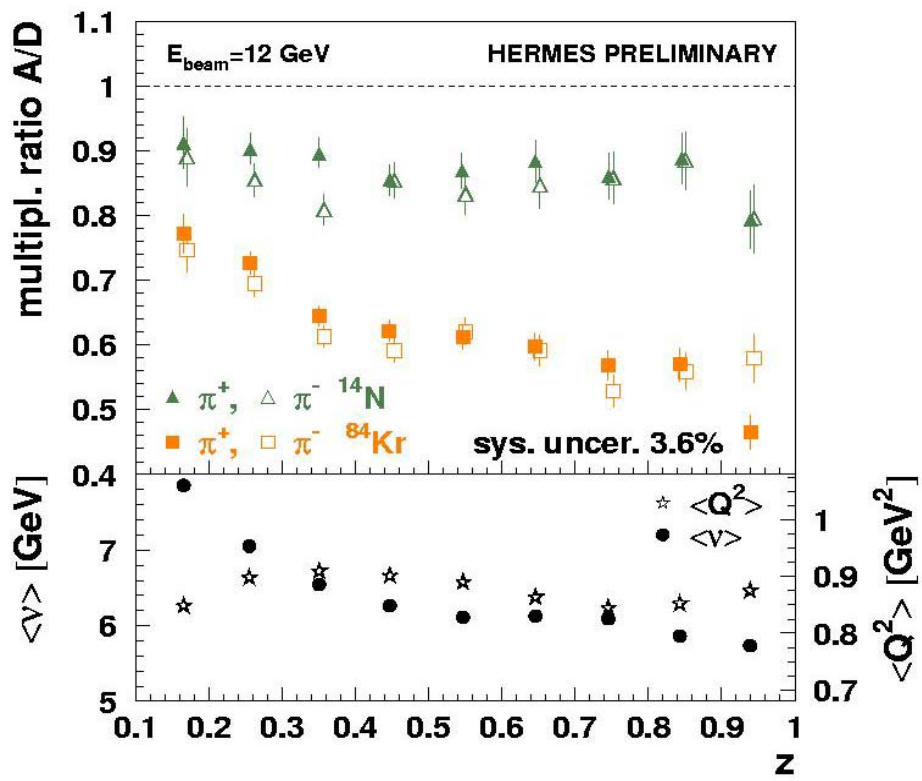
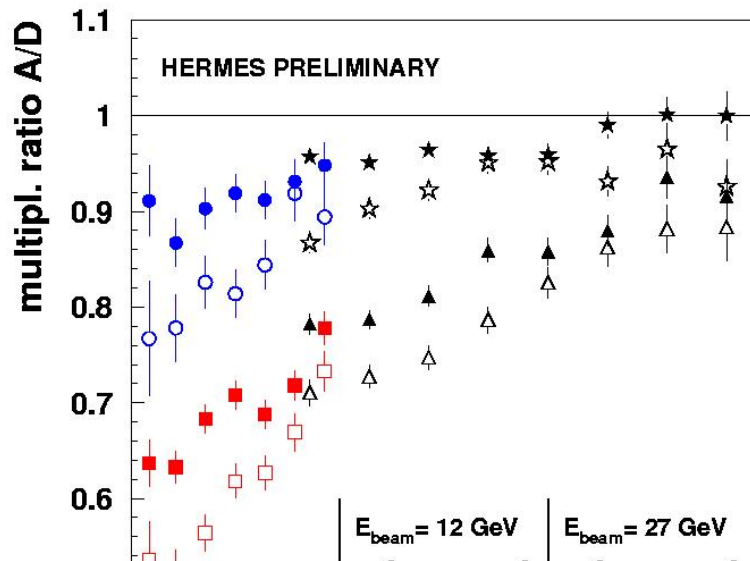
$$\tau = 1.4 \cdot \nu \cdot (1 - z) \text{ fm}$$

Example: $z = 0.5$, $\nu = 9 \text{ GeV}$,
 $\tau = 6.3 \text{ fm} \sim \text{radius Pb}$

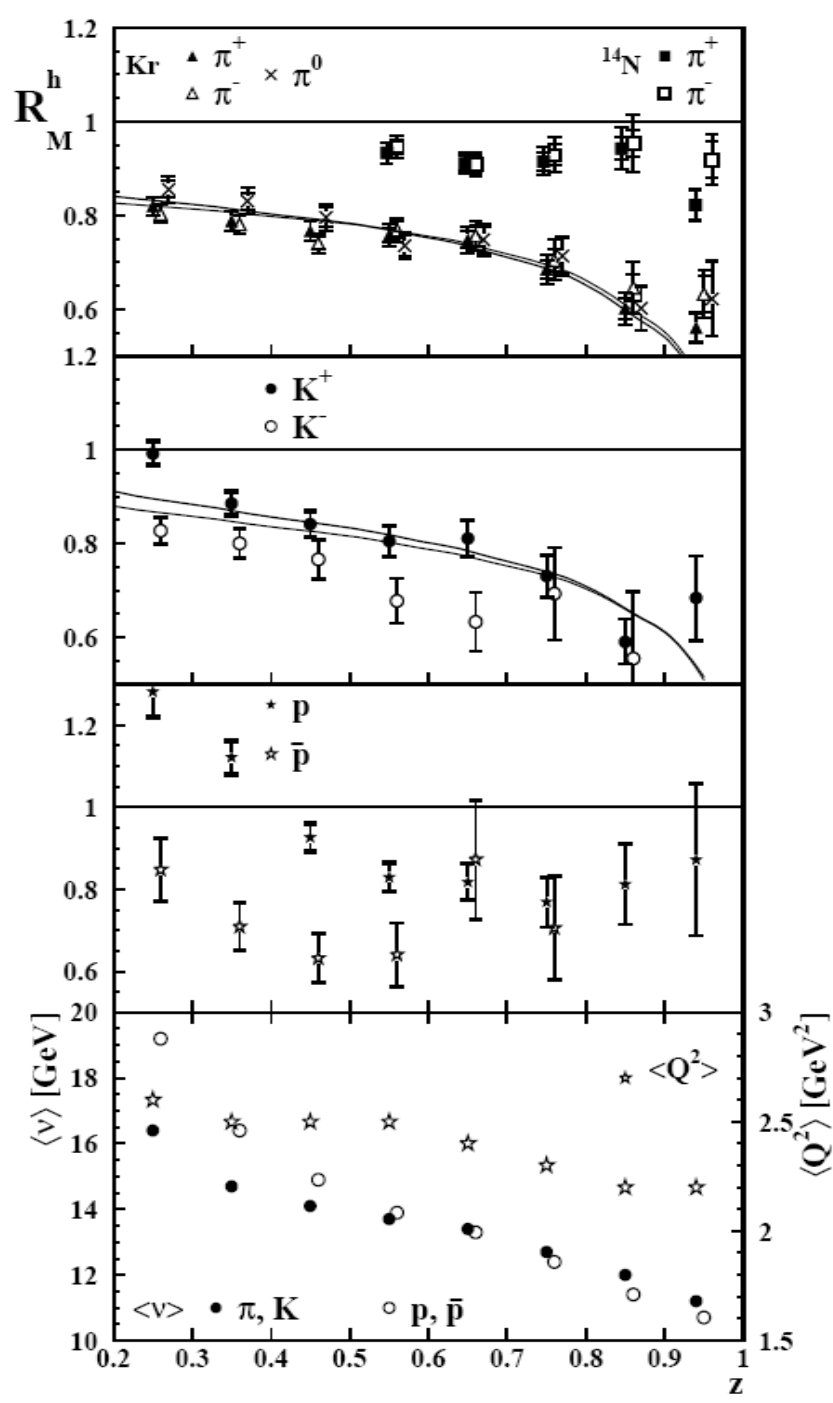
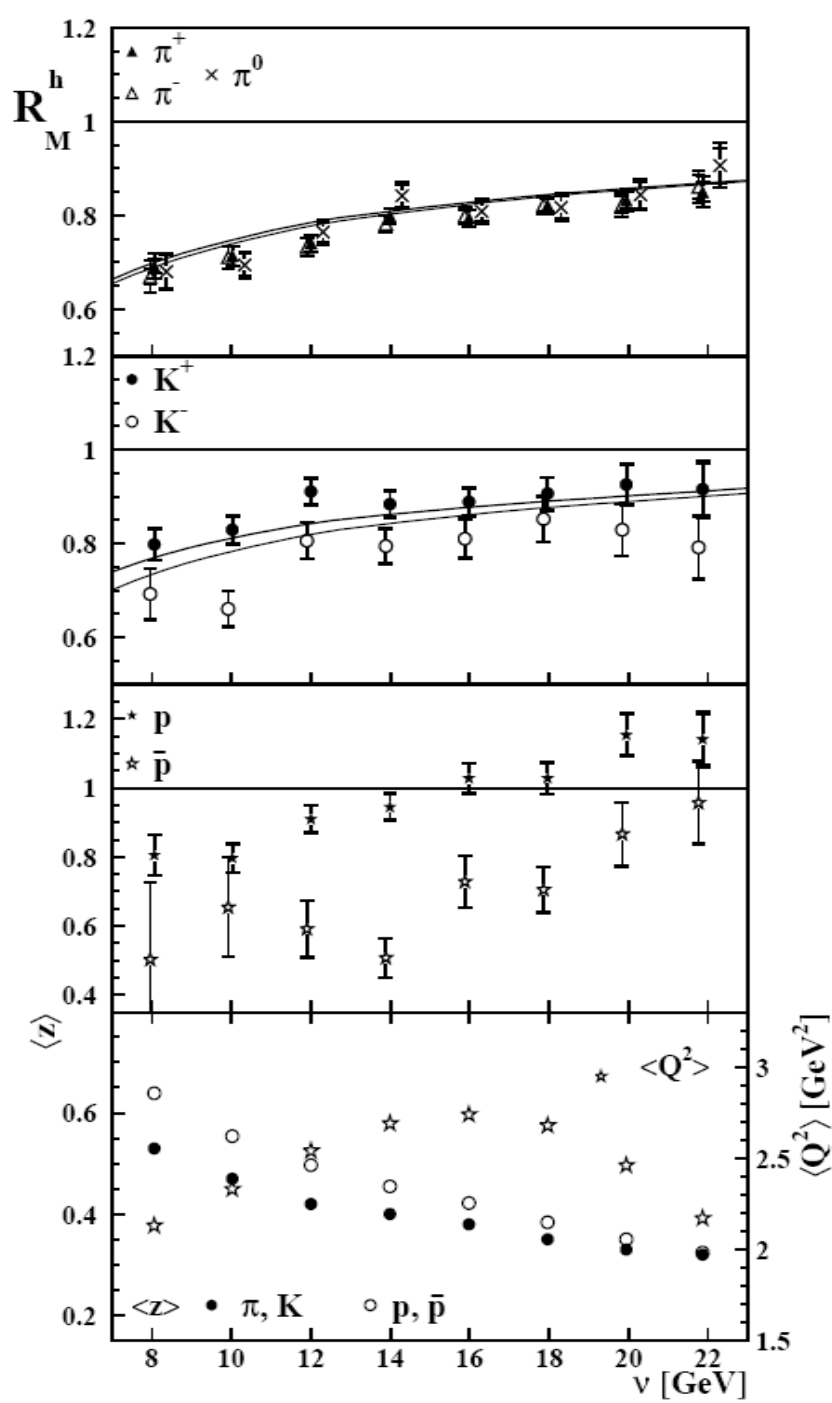
HERMES data

Summary of

- Mostly 27 Ge

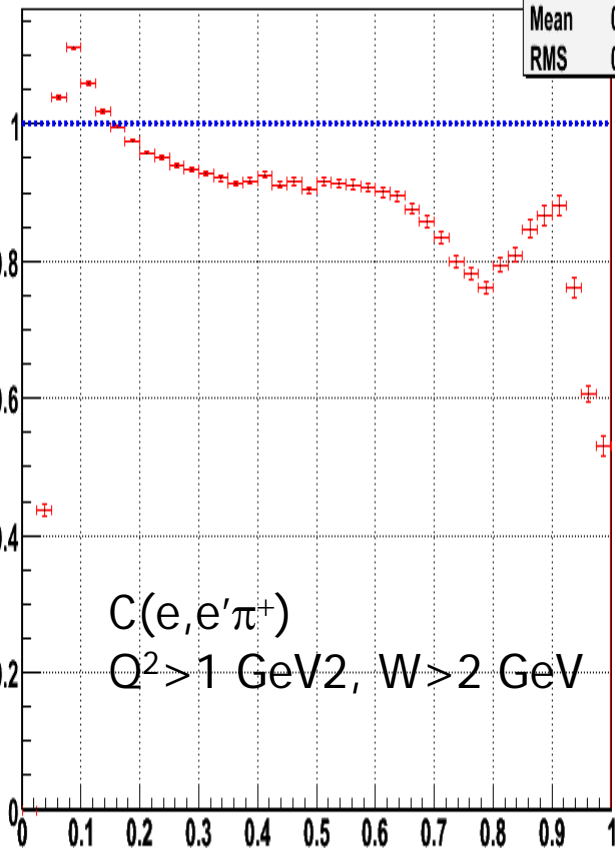


Hermes 27 GeV Data



vs Z for pion+:

Entries	3778710
Mean	0.4907
RMS	0.2743

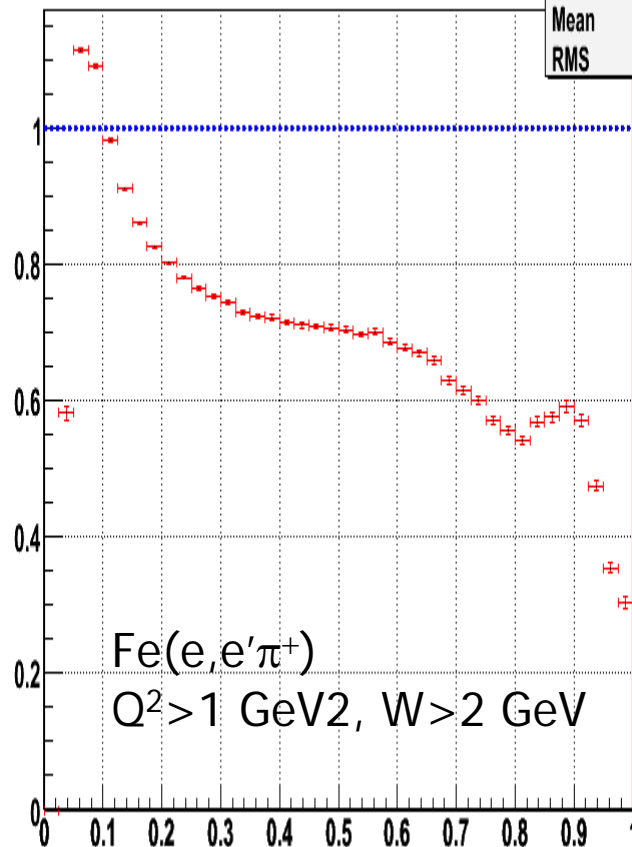


CLAS 5 GeV Data: Hadronic Multiplicity Ratio vs. Z

Preliminary
 CLAS/JLab data
 Hayk Hakobyan

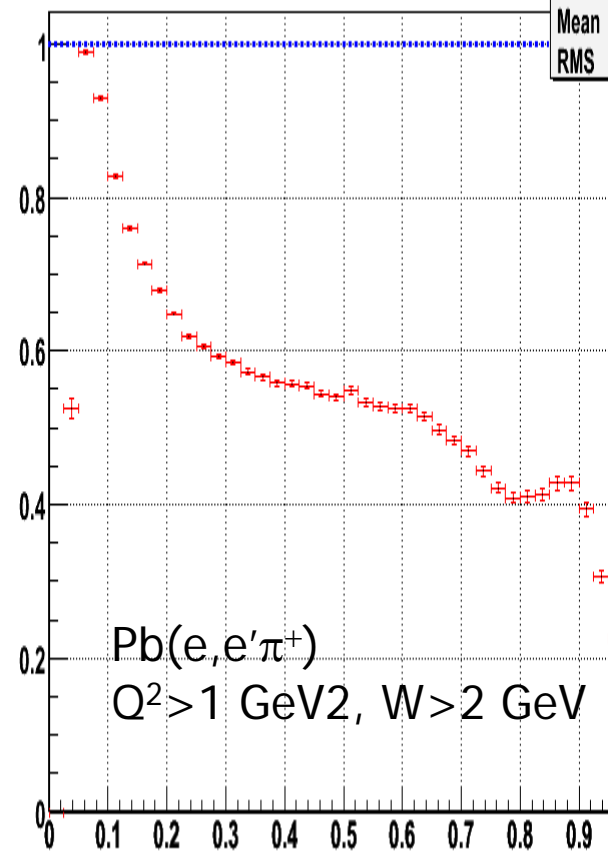
R vs Z for pion+:

Entries	3653606
Mean	0.4572
RMS	0.2743



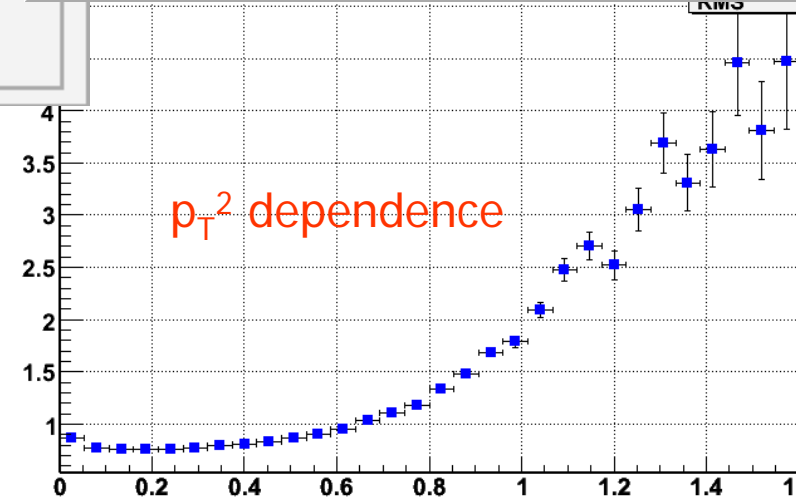
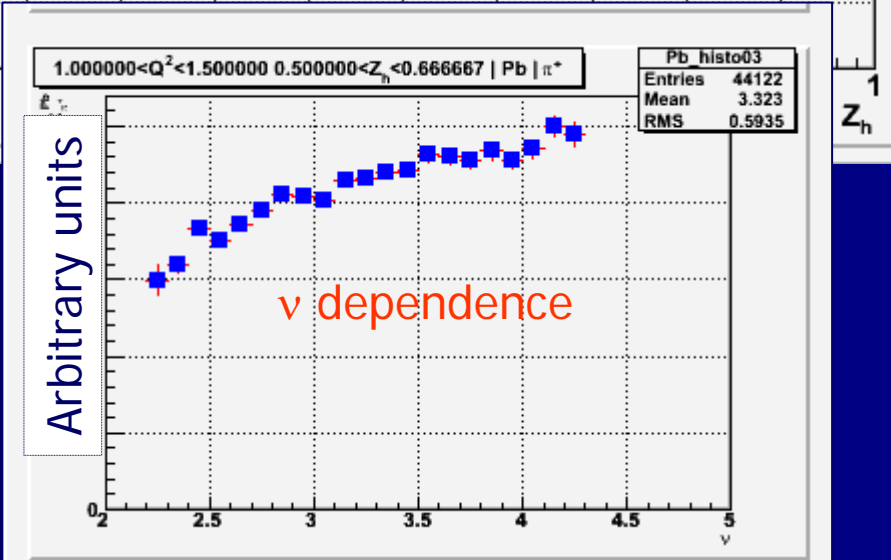
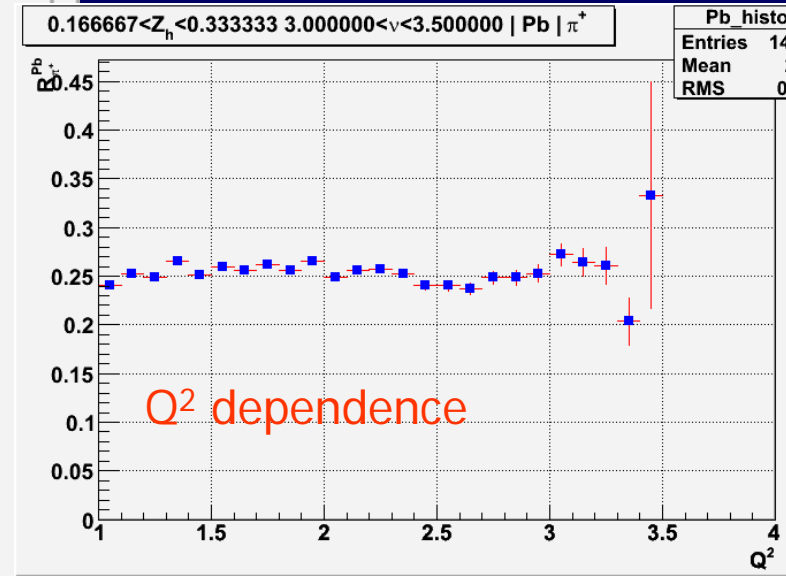
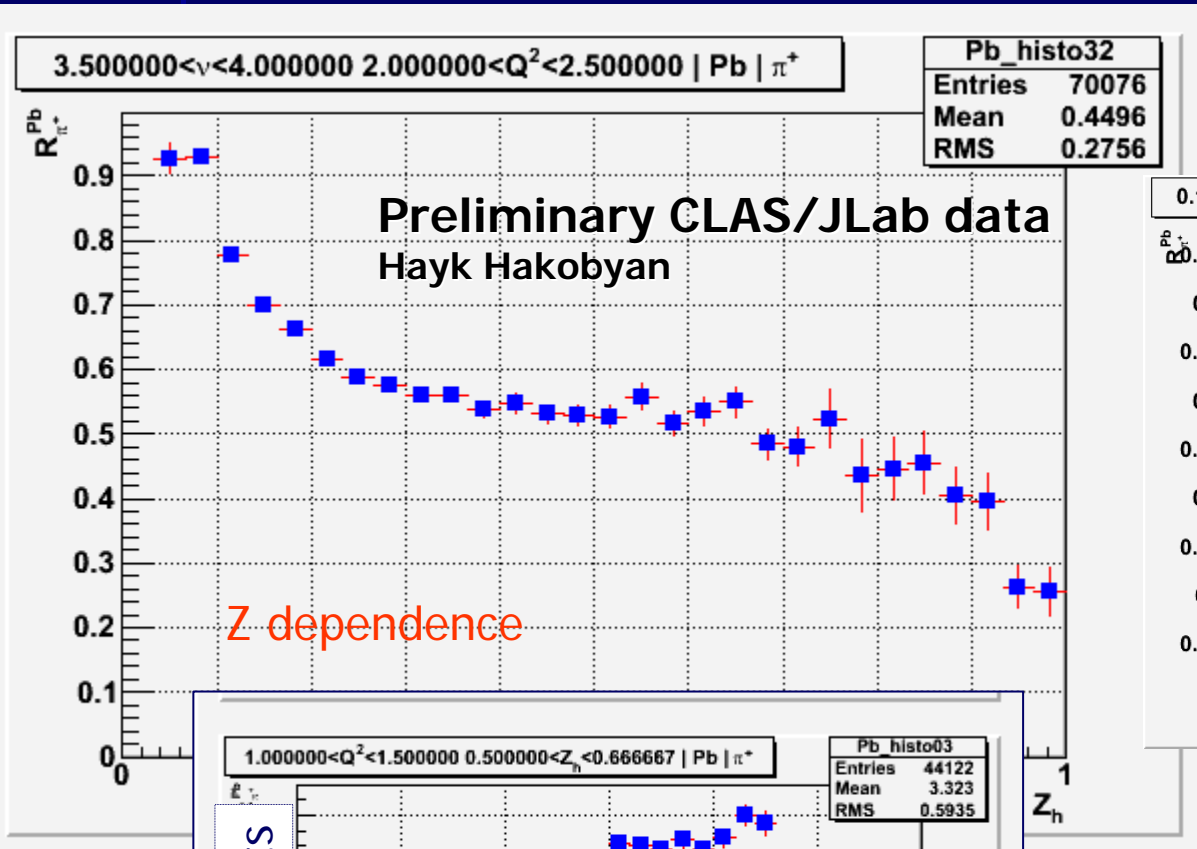
R vs Z for pion+:

Entries	
Mean	
RMS	



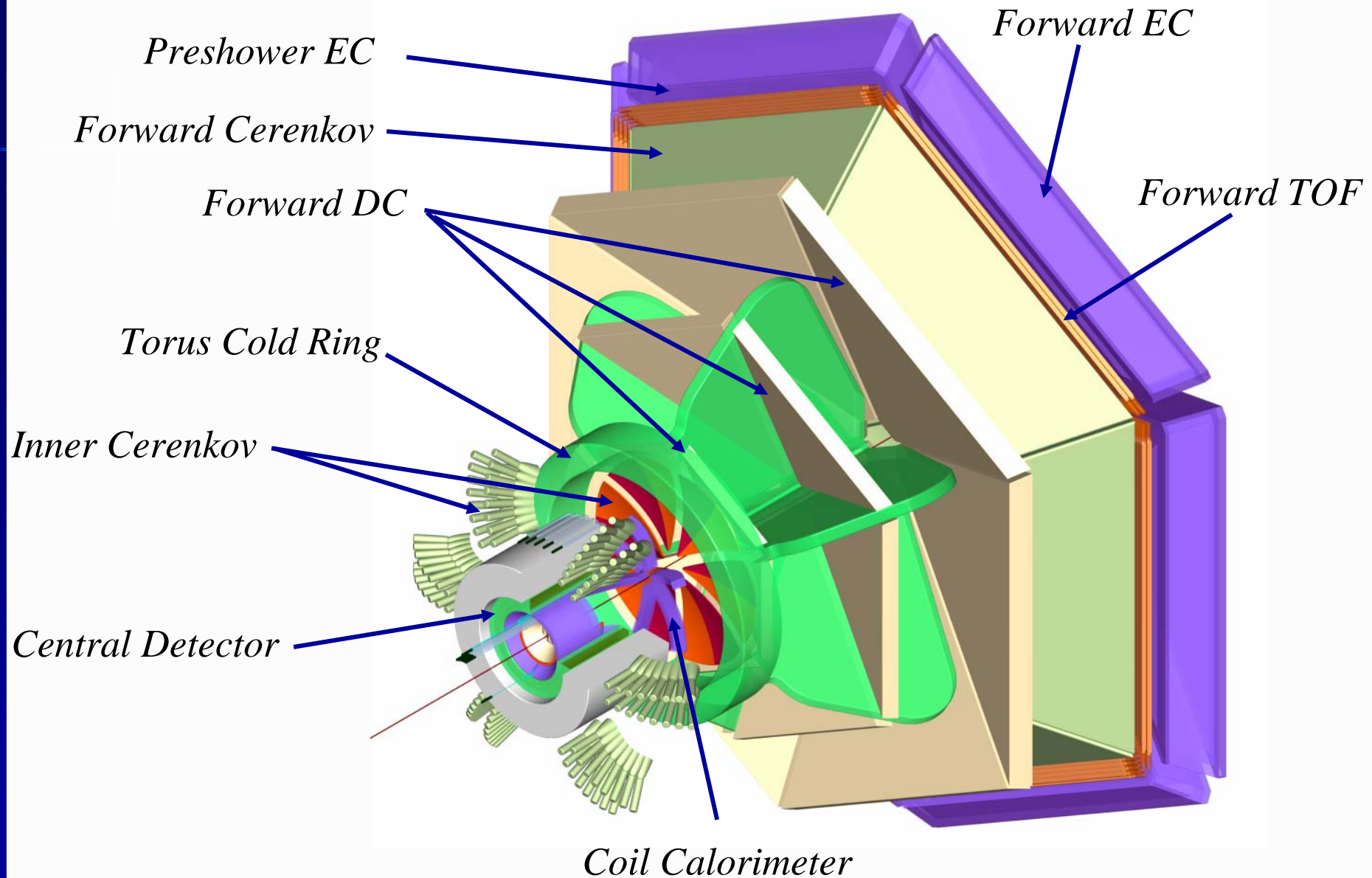
Statistical accuracy
 permits binning into ν ,
 p_T , and Q^2 in addition
 to z and A

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



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	$u\bar{d}$	direct	1100
\bar{p}	stable	0.94	$\bar{u}d$	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

Examples of Experimental Data and Theoretical Predictions



Bins in yellow are accessible at 6 GeV

Sample of Models

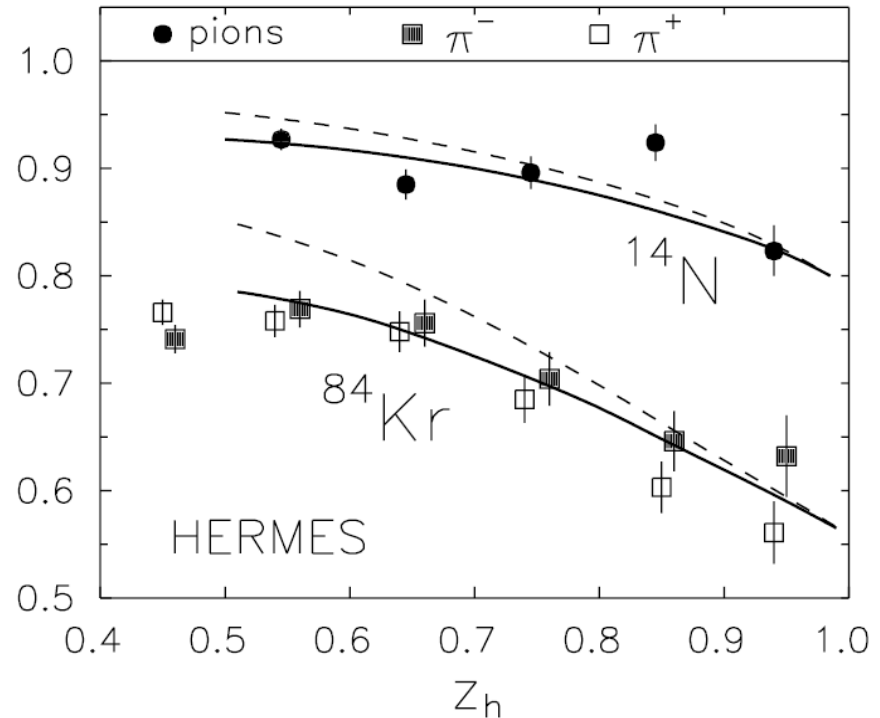
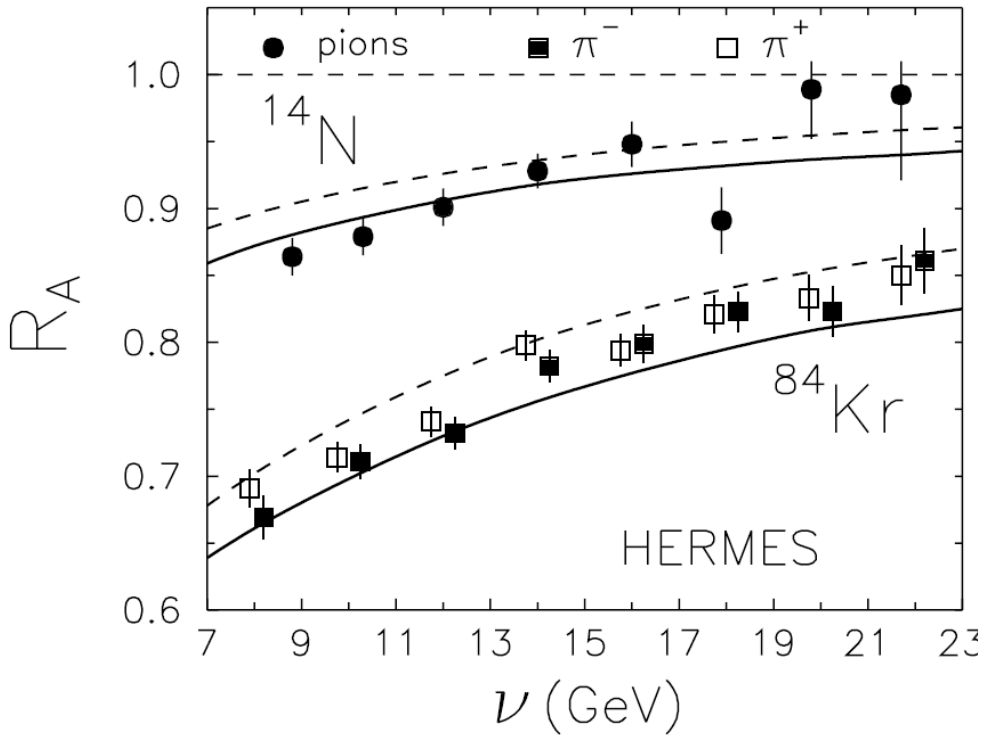
- Gluon bremsstrahlung model
 - Gluon radiation + hadronization model
- Twist-4 pQCD model
 - Medium-induced gluon radiation only
- Rescaling models
 - Gluon emission, partial deconfinement, nuclear absorption
- PYTHIA-BUU coupled channel model
 - Fundamental interaction + coupled channel nuclear final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

Gluon Bremsstrahlung Model

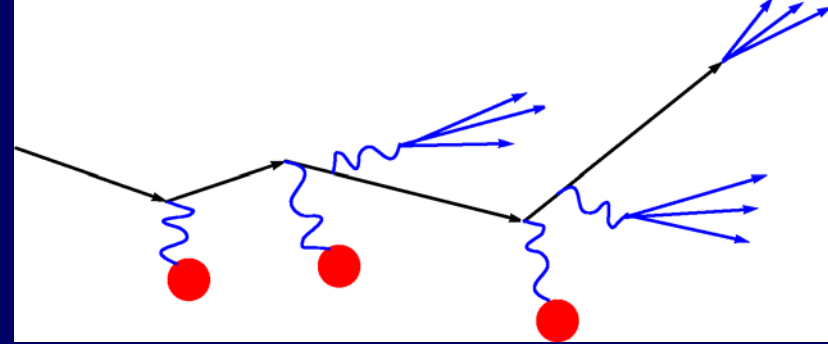
- Authors B. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki
- Time and energy dependent model for energy loss by gluon emission coupled to a hadron formation scheme
- Gluon emission:
 - Two time constants
 - Q^2 dependence
- Hadron formation:
 - Color dipole cross section
 - Struck quark and nearest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

Glueon Bremsstrahlung Model and HERMES Data

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



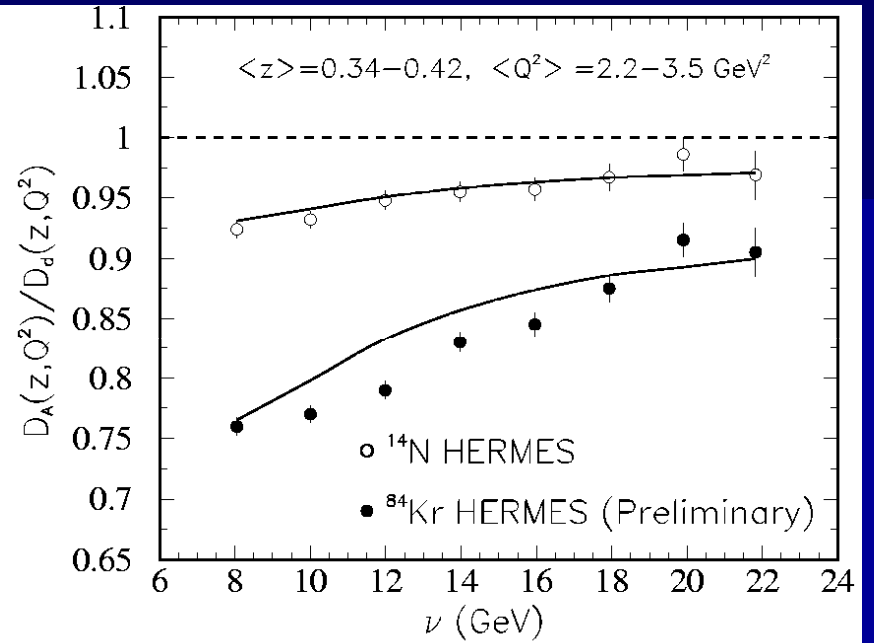
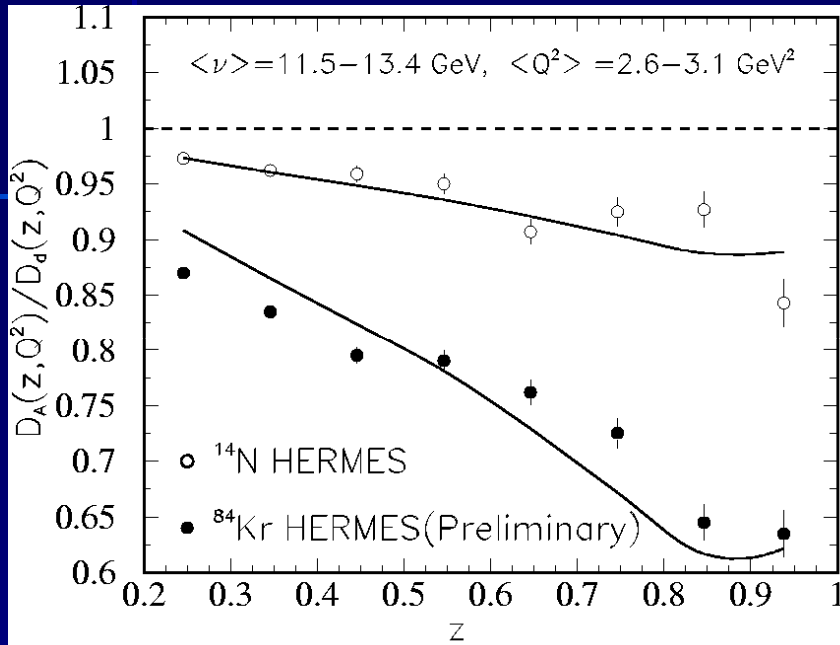
Twist-4 pQCD Model



- 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



$$\frac{d\sigma_{\text{DIS}}^h}{d\vec{p}_{e'} dz_h} = \frac{1}{E'} \frac{\alpha_{\text{EM}}^2}{2\pi s} \frac{1}{Q^4} L_{\mu\nu} \frac{dW^{\mu\nu}}{dz_h}$$

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

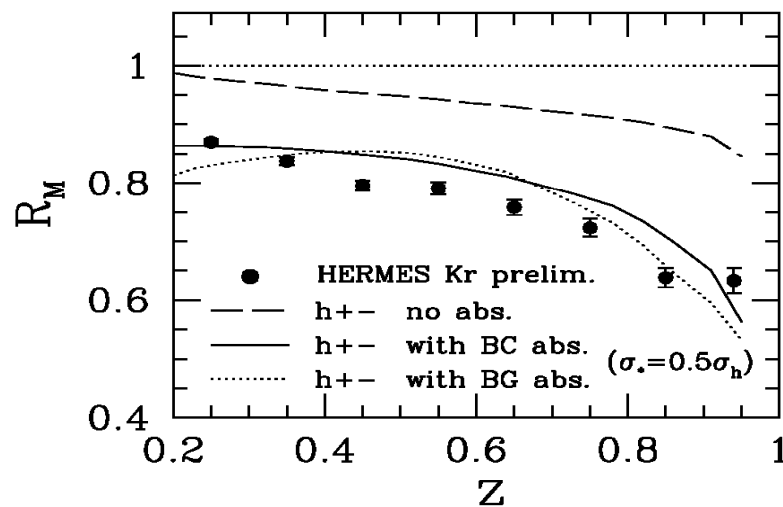
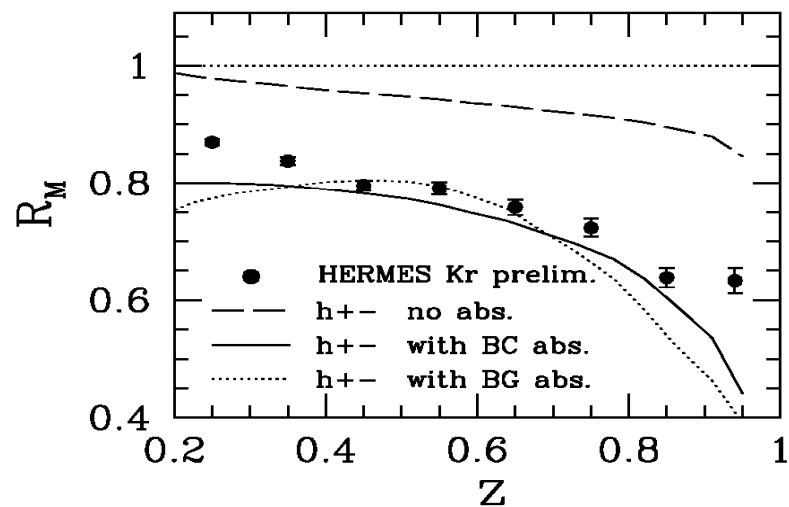
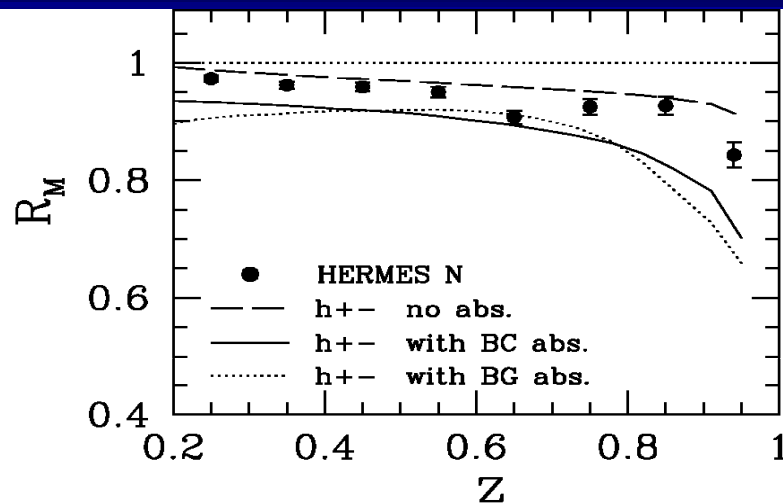
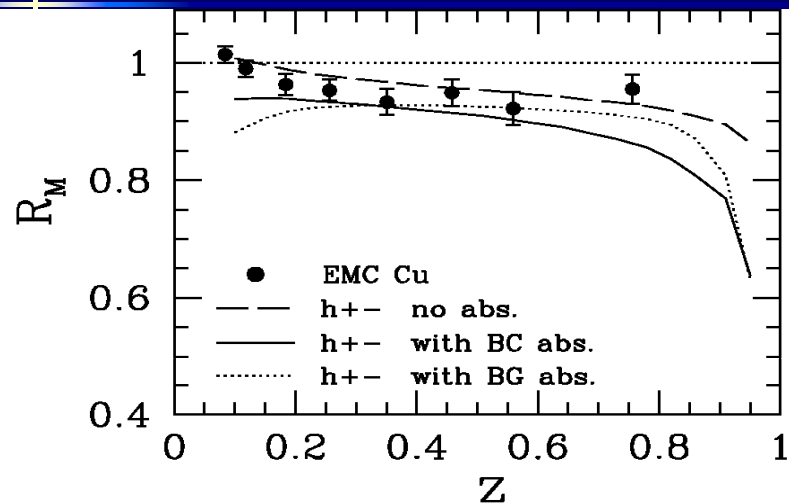
$$\widetilde{D}_{q \rightarrow h}(z_h, Q^2) \equiv D_{q \rightarrow h}(z_h, Q^2) + \Delta D_{q \rightarrow h}(z_h, Q^2)$$

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

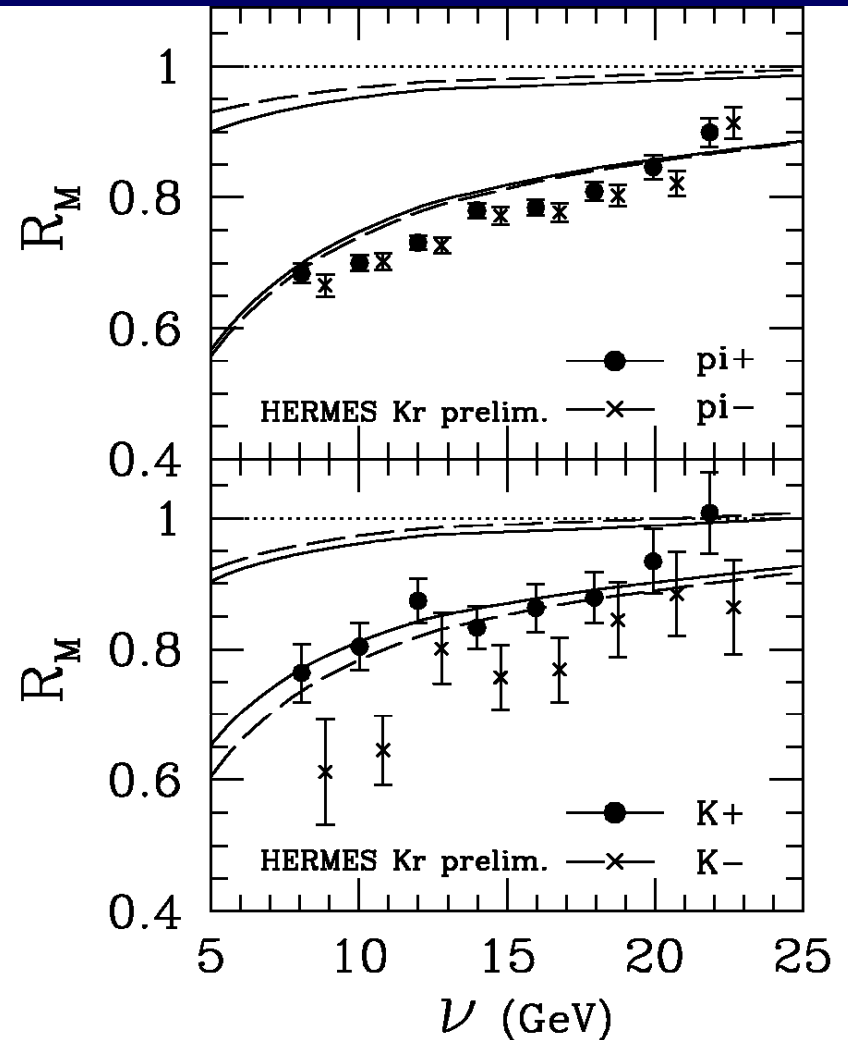
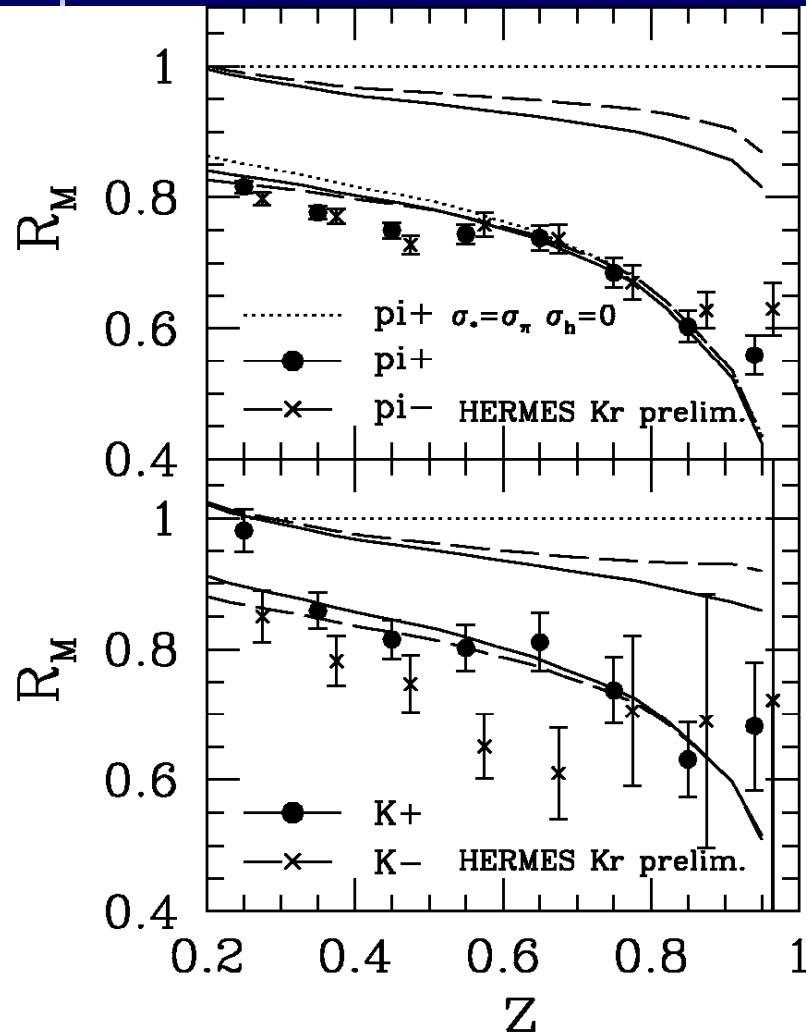
Rescaling Models

- 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



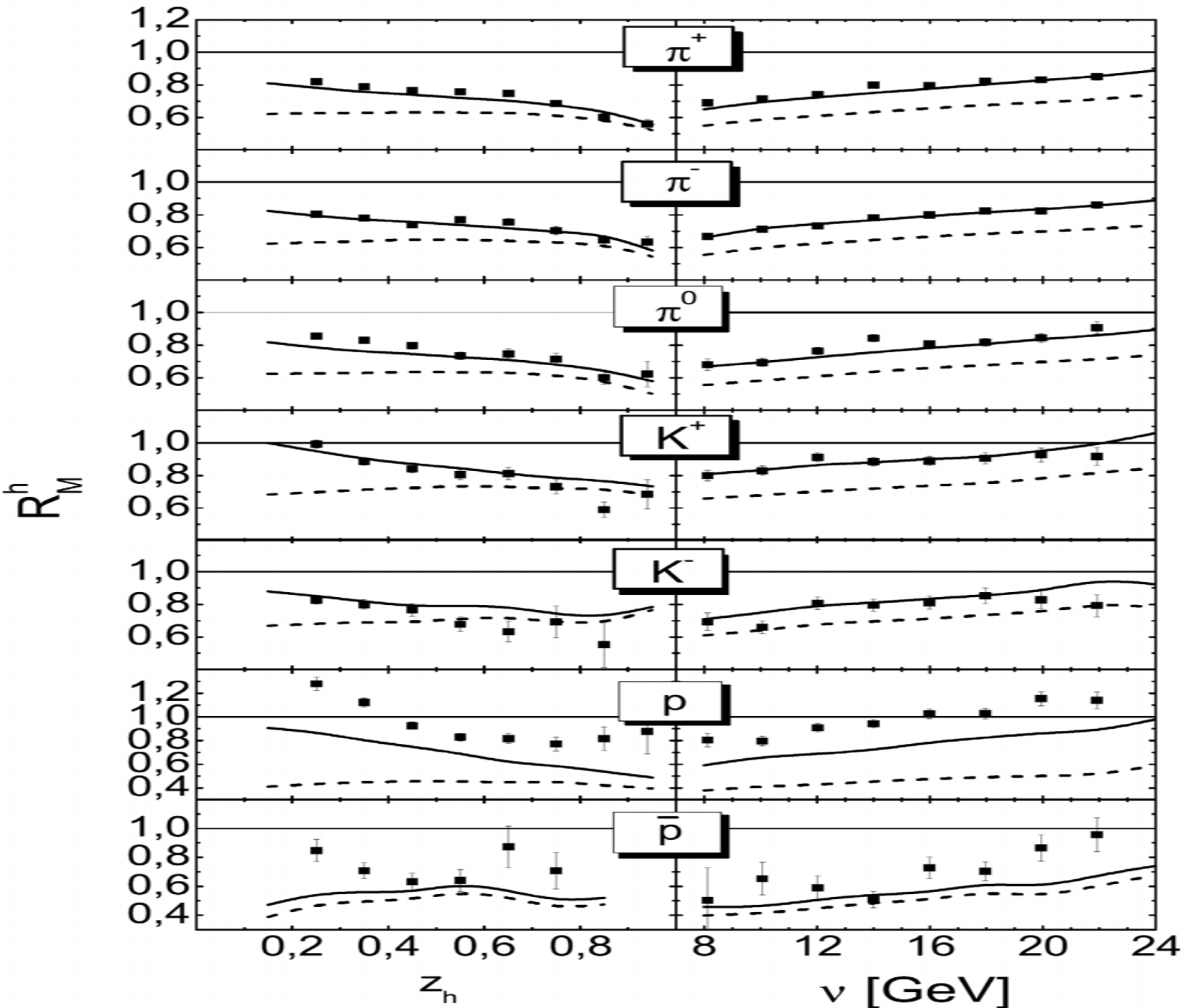
Rescaling Model, HERMES Flavor-separated Kr Data



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

- Other important connections
 - Jet quenching at RHIC
 - Drell-Yan at Fermilab
 - Neutrino-nucleus interactions

- Understanding these very large ‘hadron attenuation’ effects at a detailed level is crucial for the physics of this workshop!
 - Hermes data gave first glimpse
 - Massive dataset from CLAS becoming available
 - 12 GeV: the definitive program

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

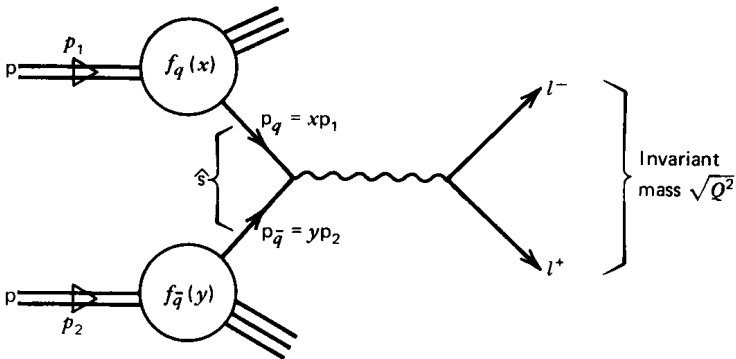


Fig. 11.14 The Drell-Yan process, $pp \rightarrow l^- l^+ X$.

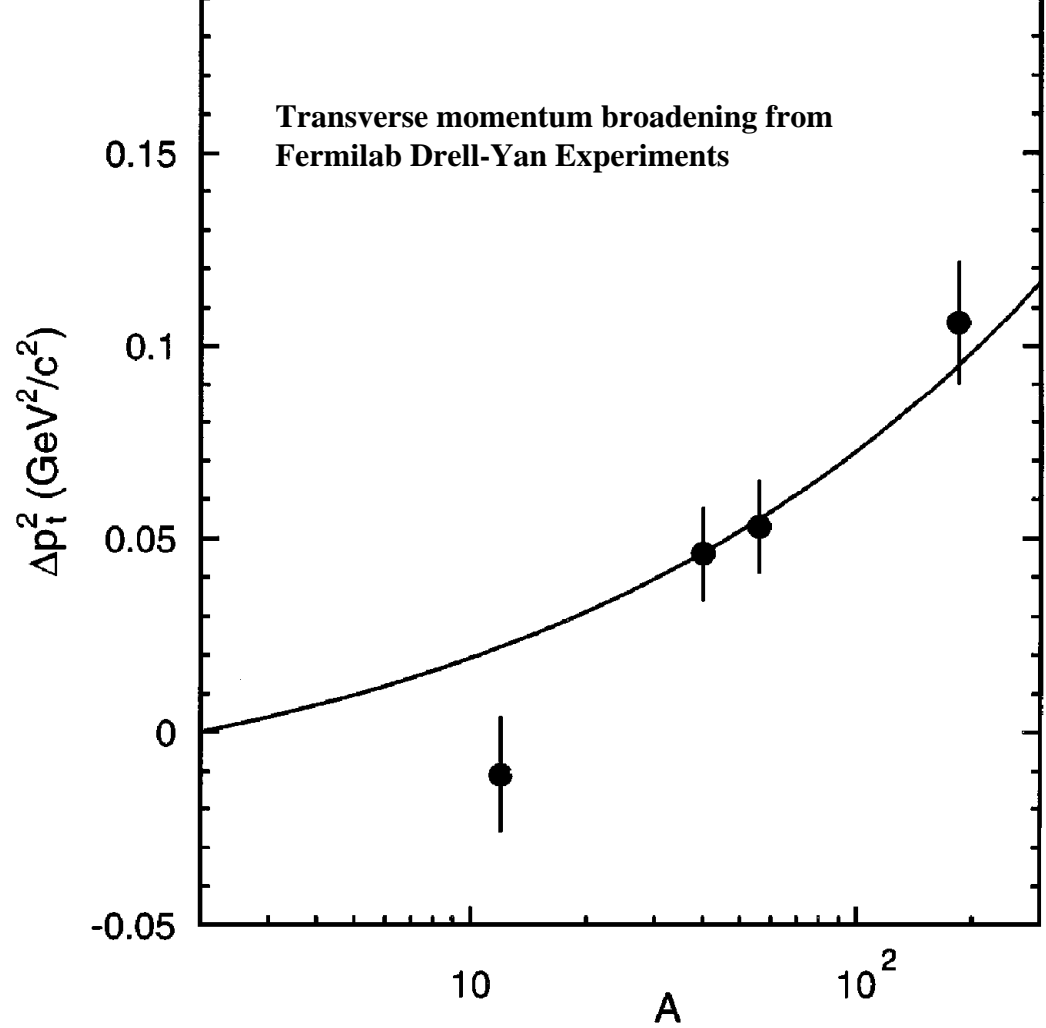
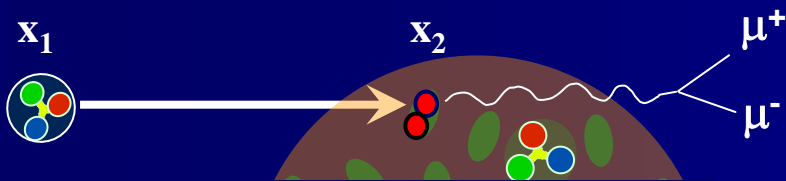


Figure 15 $\Delta \langle p_t^2 \rangle \equiv \langle p_t^2 \rangle(A) - \langle p_t^2 \rangle(^2H)$ versus A for the DY process from E772 (123; PL McGaughey, JM Moss, JC Peng, unpublished data). Solid curve corresponds to $0.027((A/2)^{1/3} - 1)$.

Incident quark, x_1

Target anti-quark, x_2

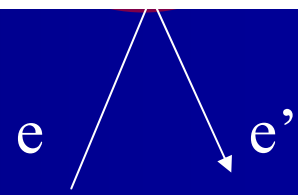
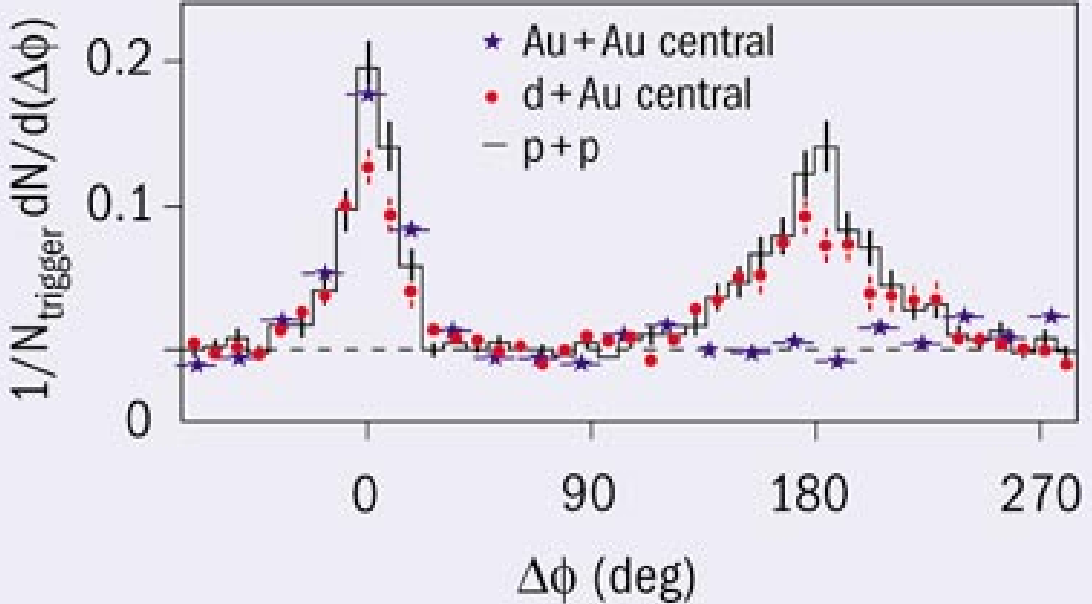
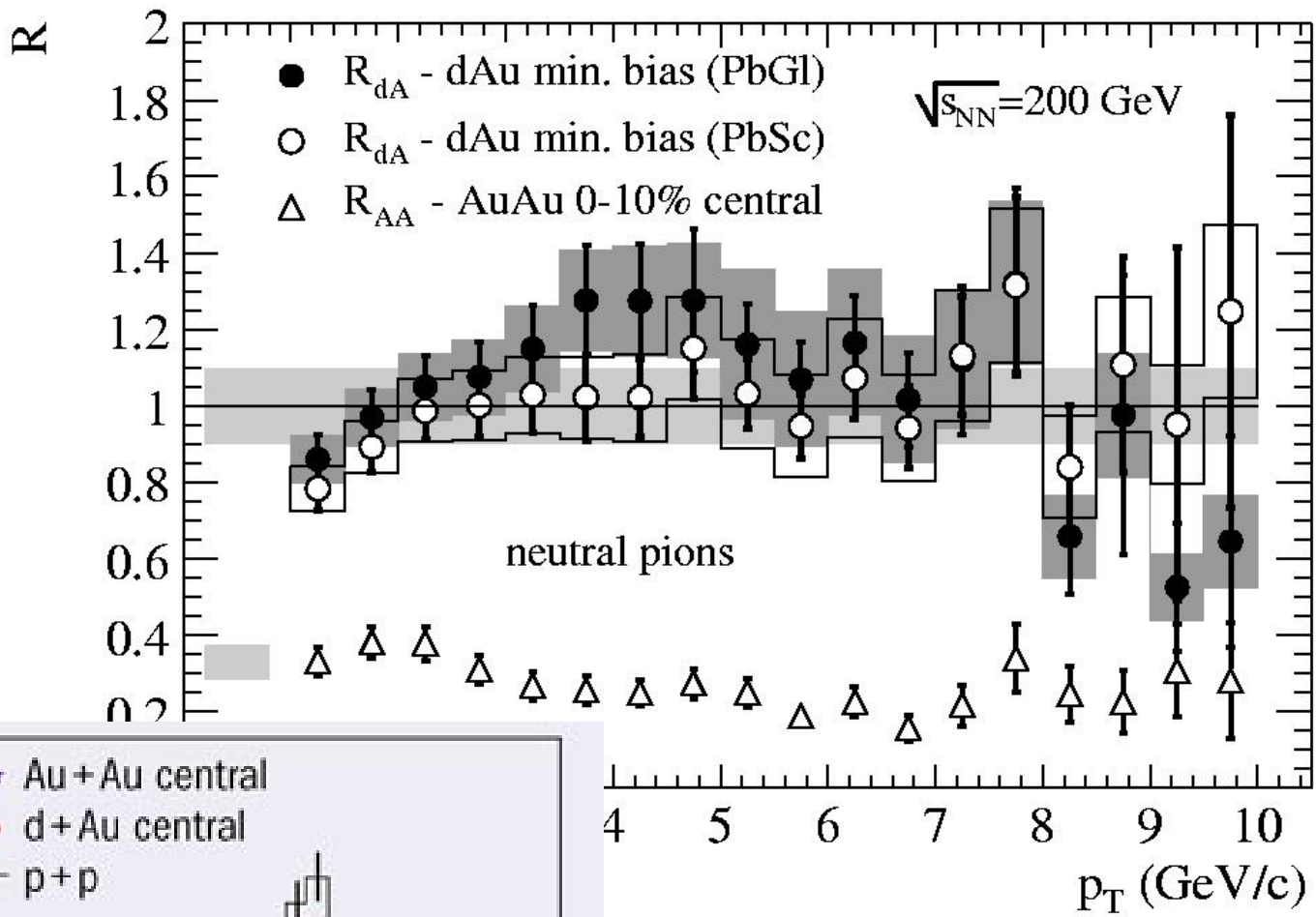
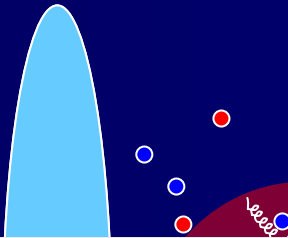


Connection to Relativistic Heavy Ion Physics

- 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 \sim few GeV

Releva

Relativistic



Initial quark energy is known
Properties of medium are known

Recent Model Approaches: Semi-Inclusive DIS on Nuclei

*The essential reaction mechanism has not been isolated:
Hadron forms *inside* nucleus or *outside*?*

Gluon Bremsstrahlung (Kopeliovich)

- Gluon radiation of colored quark
- Formation of color singlet pre-hadron
- Color transparency modulates pre-hadron (color dipole) attenuation
- Hadron attenuates in medium

Twist-4 pQCD Model (Wang)

- Medium-induced gluon radiation modifies fragmentation function
- *No* hadronization
- Non-abelian LPM effect predicted
- Can extrapolate to predict jet quenching in RHI collisions

Recent Model Approaches: Semi-Inclusive DIS on Nuclei

Semi-Classical Transport (Mosel, Falter)

- Initial state from Pythia
- Detailed final state in
- coupled-channel BUU

Stationary String Model (Akopov)

logical FSI
particles

The models vary in
sophistication, but all can
describe the HERMES data!

pQCD In-Medium (Arleo)

- Medium-modified
- Transport coefficient
- from Drell-Yan

Rescaling Models (Accardia, Pirner)

ment of nucleon in
fns. modified

Differentiate among models: extend
measurements to more variables and
observables

Gluon Bremsstrahlung Model

- Authors: B. Kopeliovich, J. Nemchik, E. Predazzi

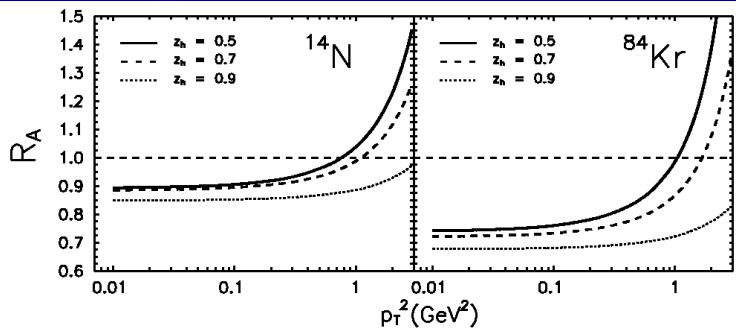


Fig. 13. p_T -dependence of nucleus-to-nucleon ratios binned in z_h for hadroproduction in DIS on nitrogen (left) and krypton (right).

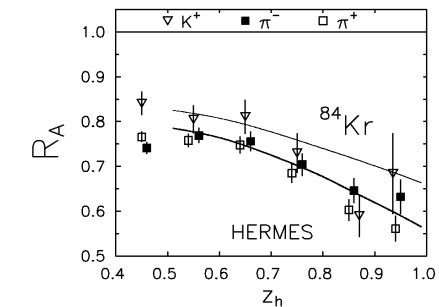
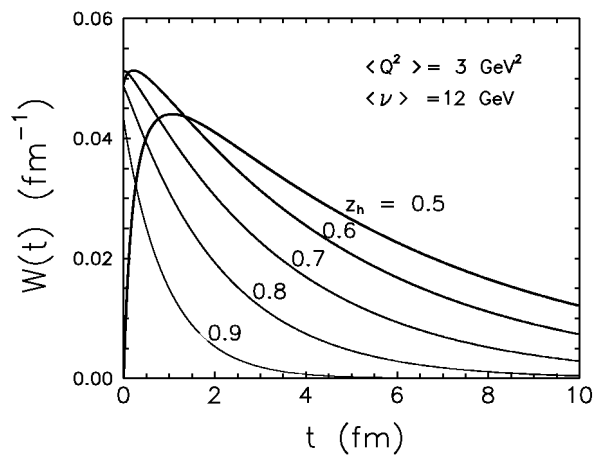


Fig. 11. Nuclear ratios for pions (thick curve) and positive kaons (thin curve) as function of z_h predicted by our model in comparison with HERMES data.

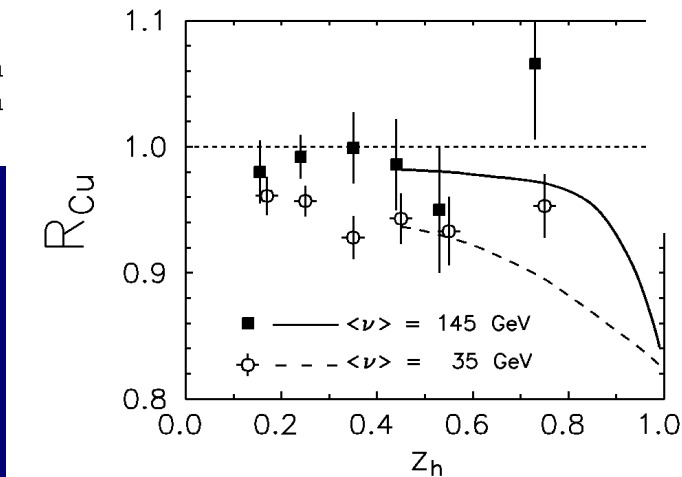
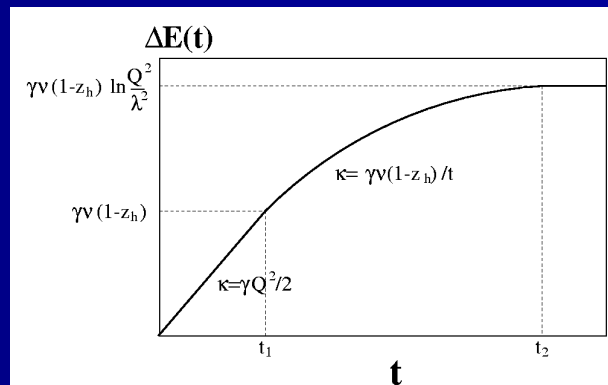
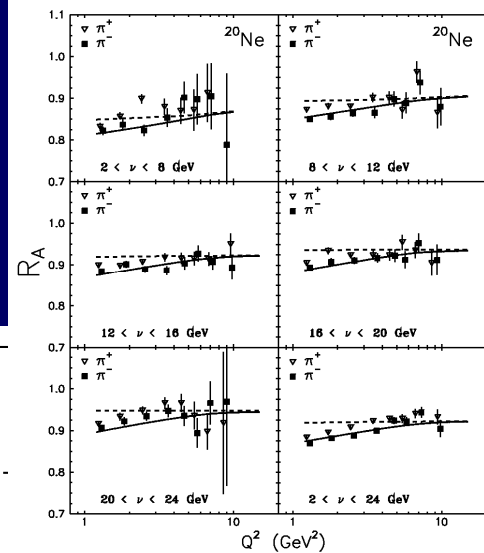
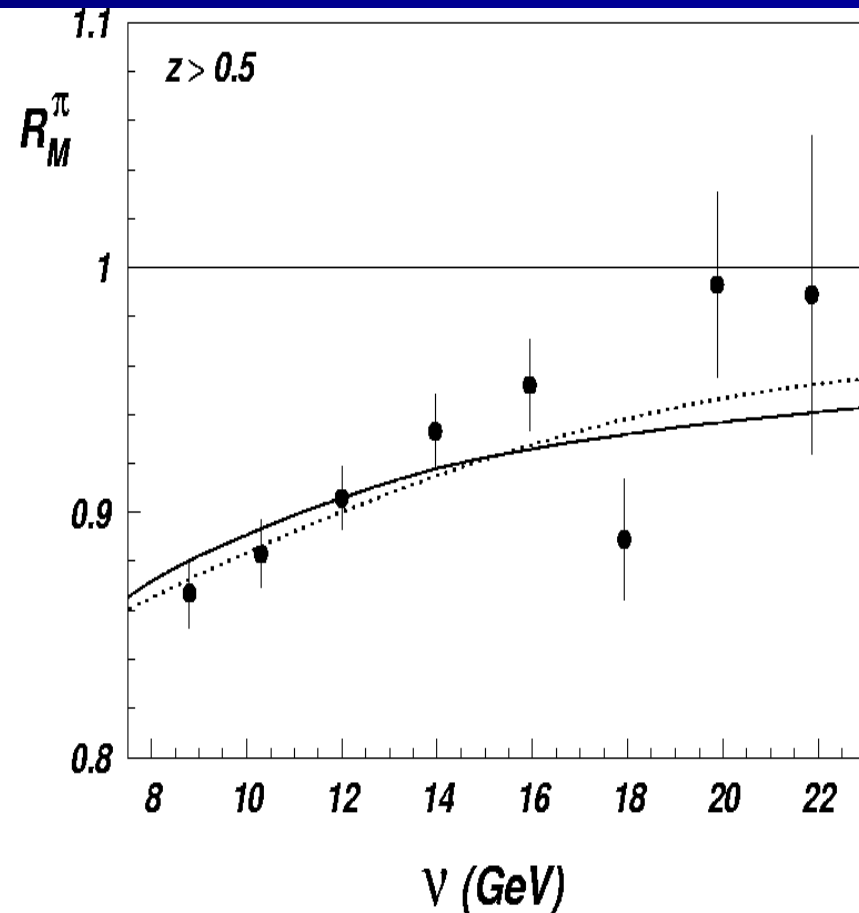
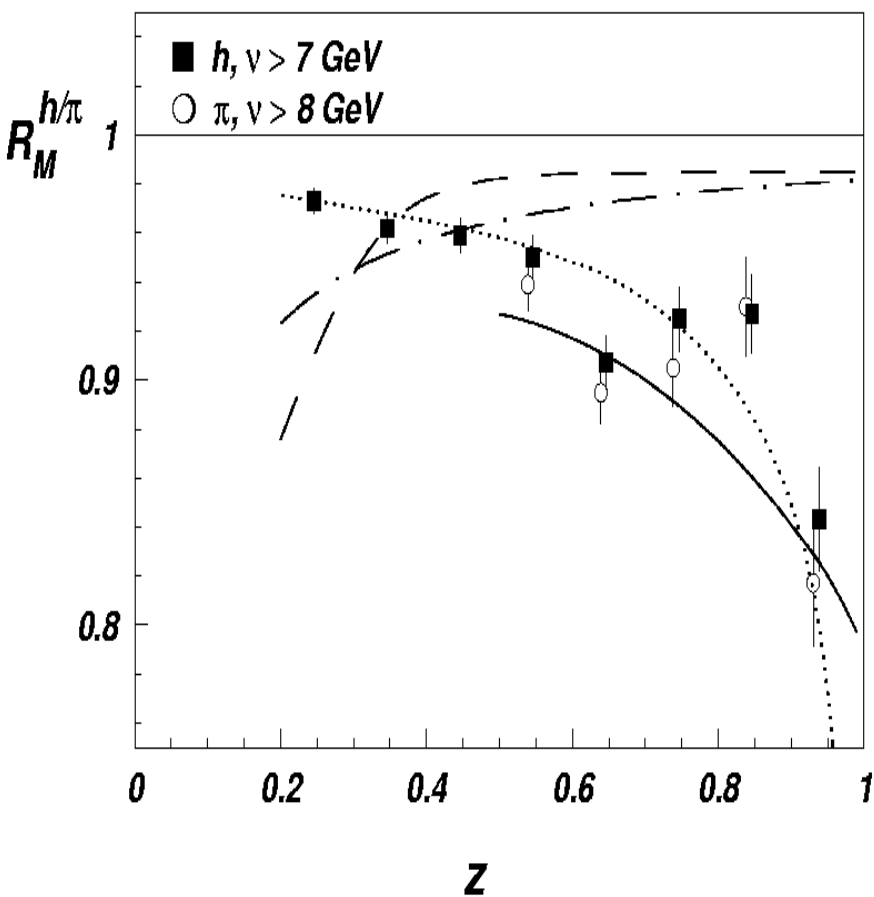


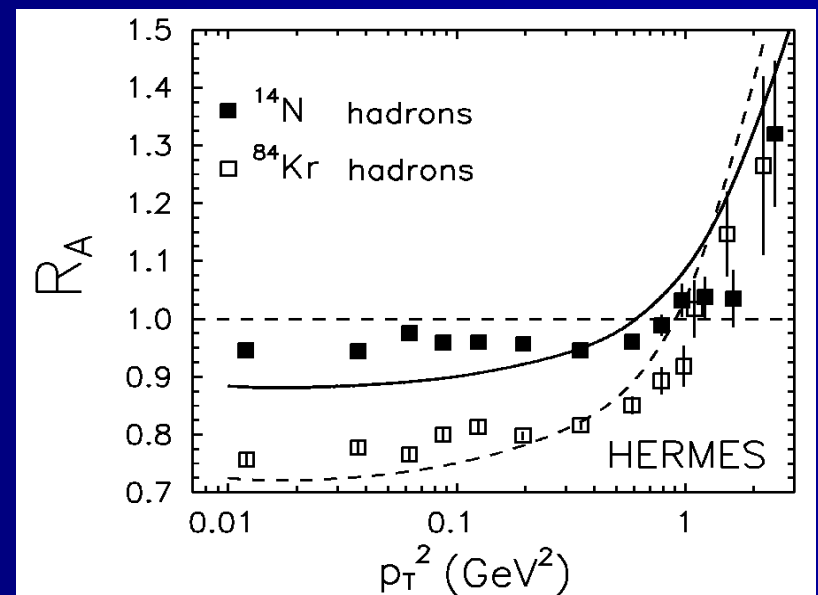
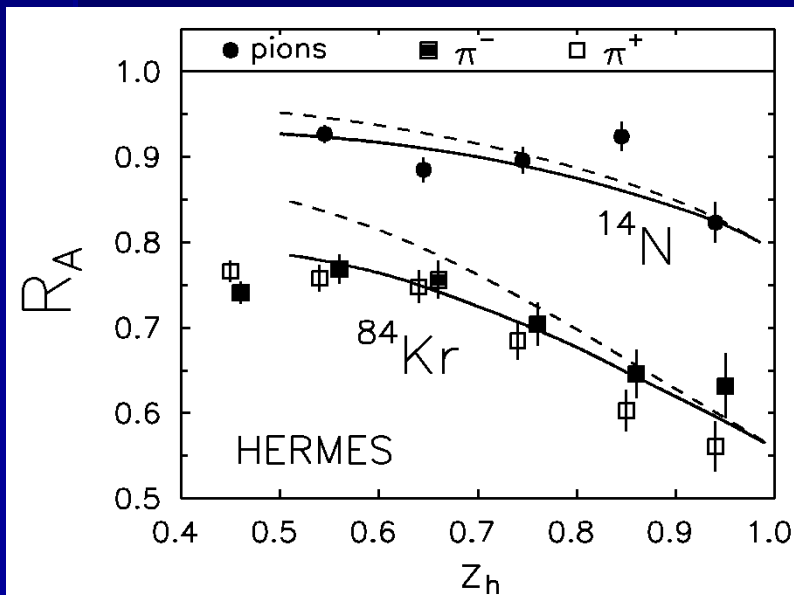
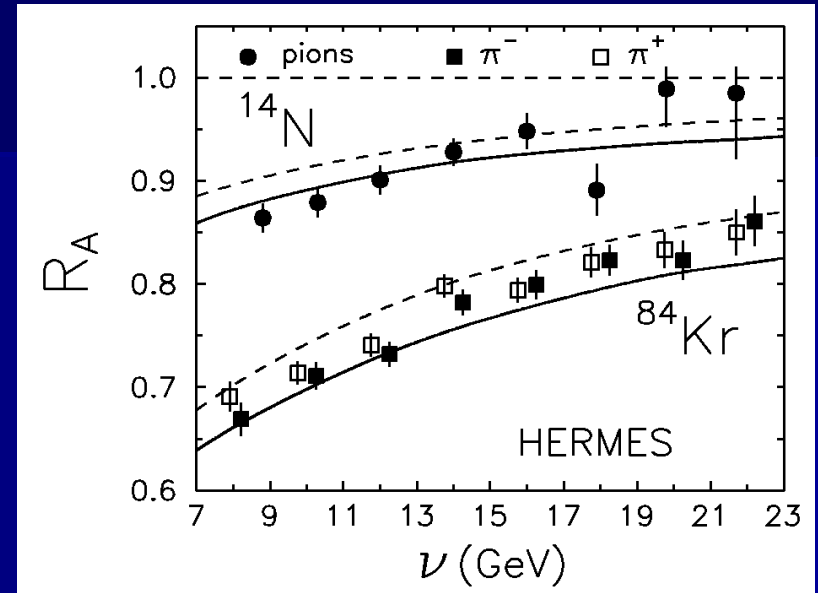
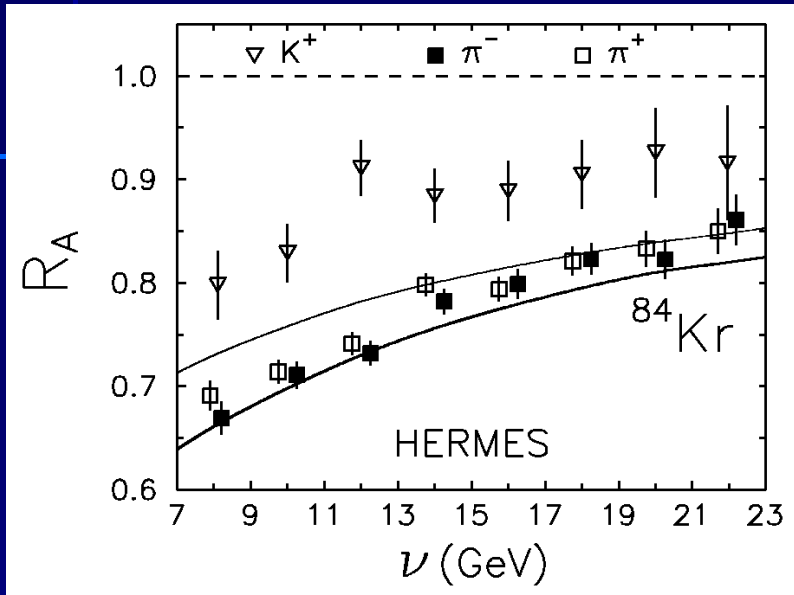
Fig. 6. Comparison of the model calculations for the z_h -dependence of nuclear suppression R_{Cu} (5) at the energy $\langle \nu \rangle = 35$ GeV (dashed curve) and $\langle \nu \rangle = 145$ GeV (solid curve) with the EMC data [42,44]. Calculations are done at $Q^2 = 11$ GeV².



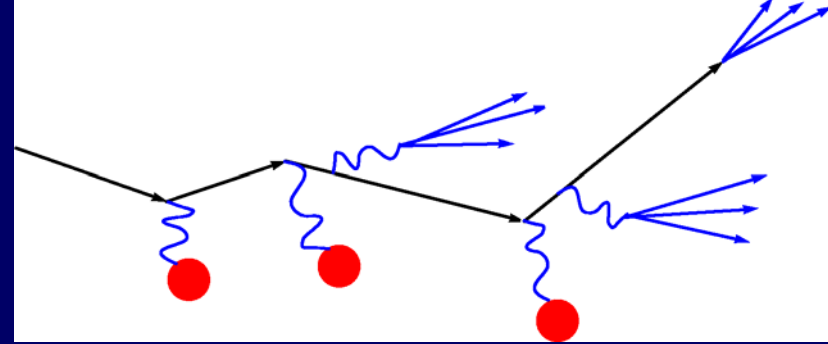
Gluon Bremsstrahlung Model (prediction of 1996) and HERMES Nitrogen Data



Gluon Bremsstrahlung Model and Hermes Data

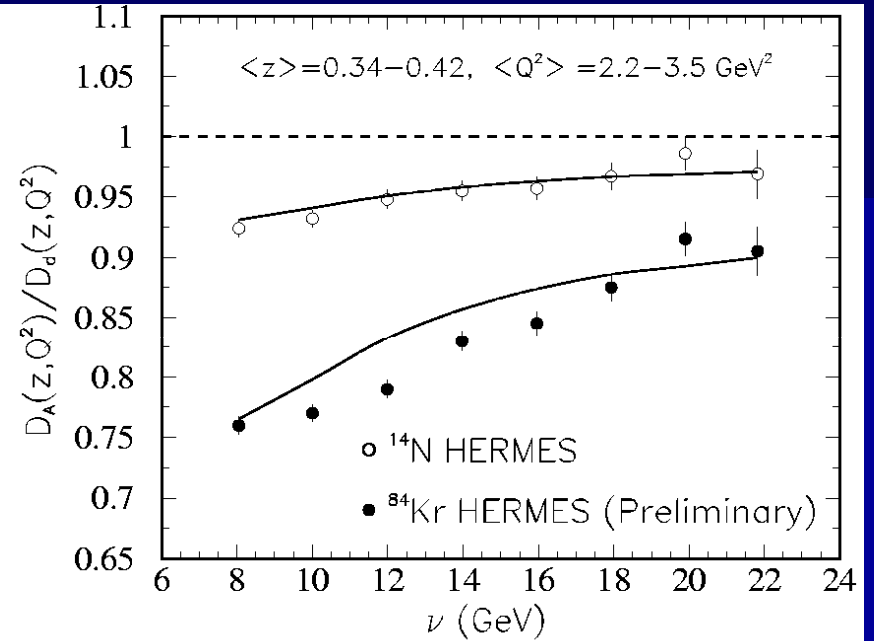
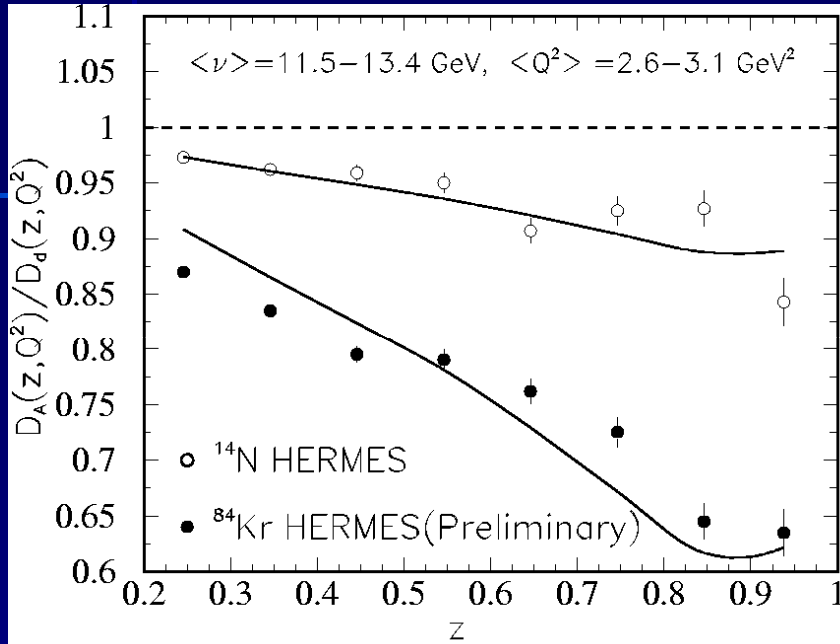


Twist-4 pQCD Model



- 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

Twist-4 pQCD Model



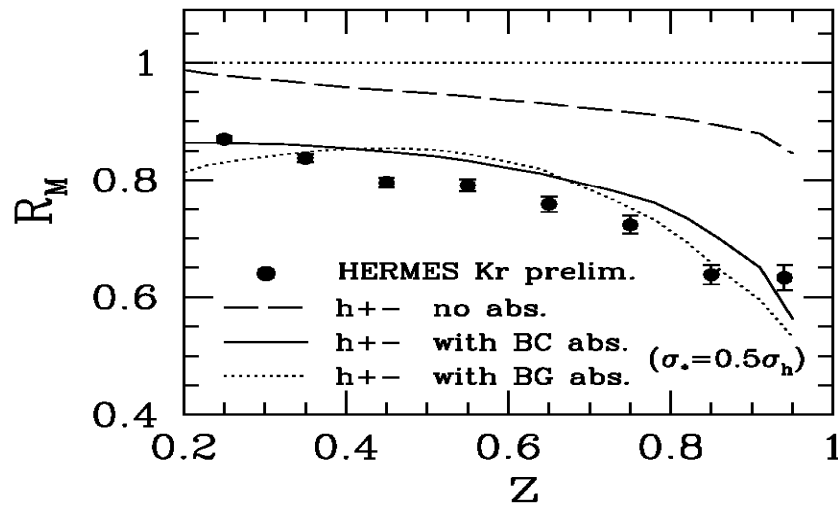
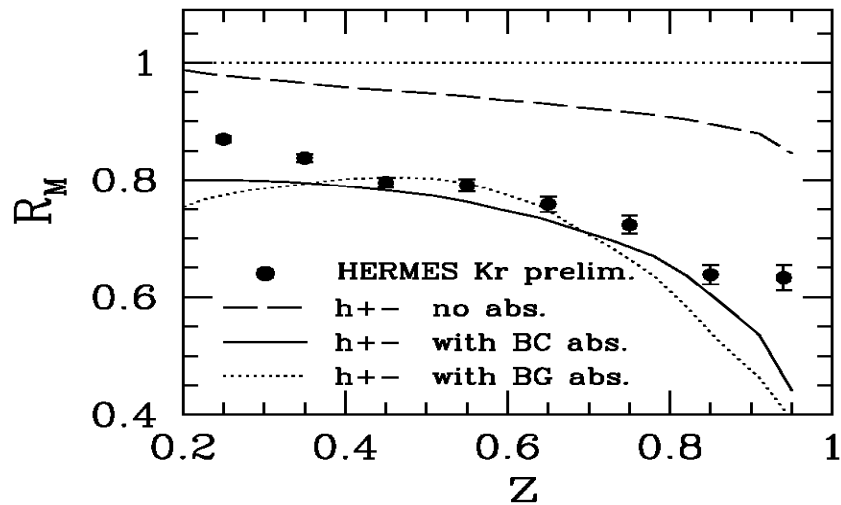
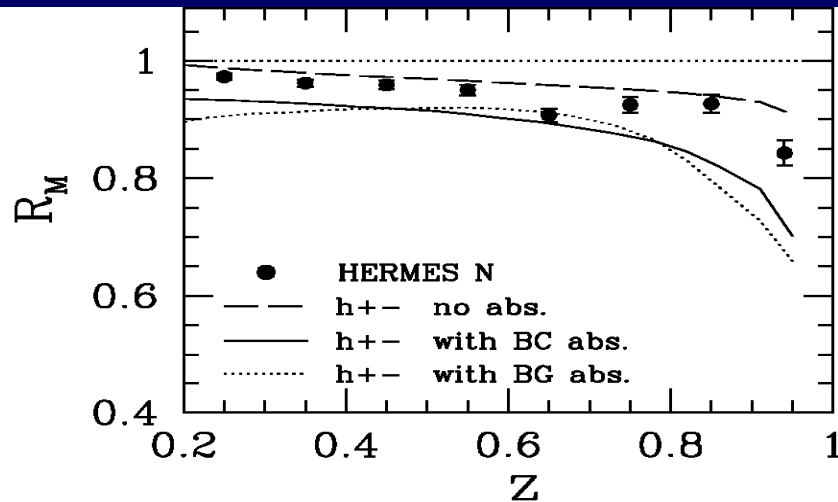
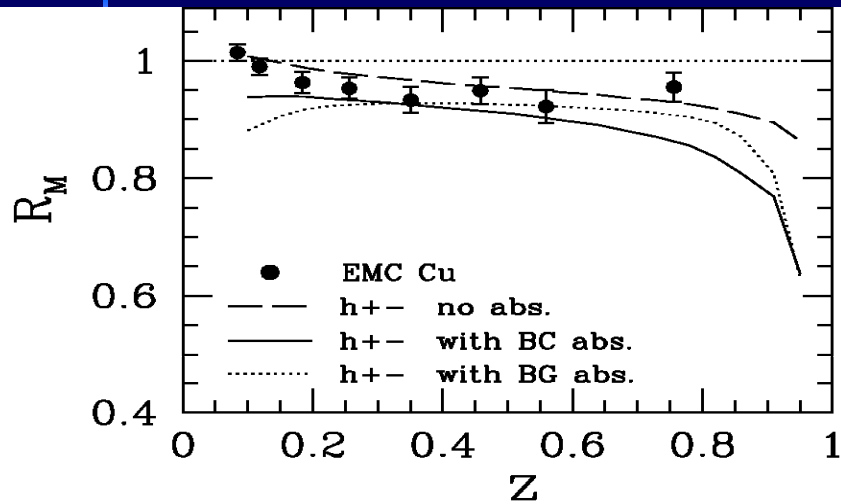
$$\frac{d\sigma_{\text{DIS}}^h}{d\vec{p}_{e'} dz_h} = \frac{1}{E'} \frac{\alpha_{\text{EM}}^2}{2\pi s} \frac{1}{Q^4} L_{\mu\nu} \frac{dW^{\mu\nu}}{dz_h}$$

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

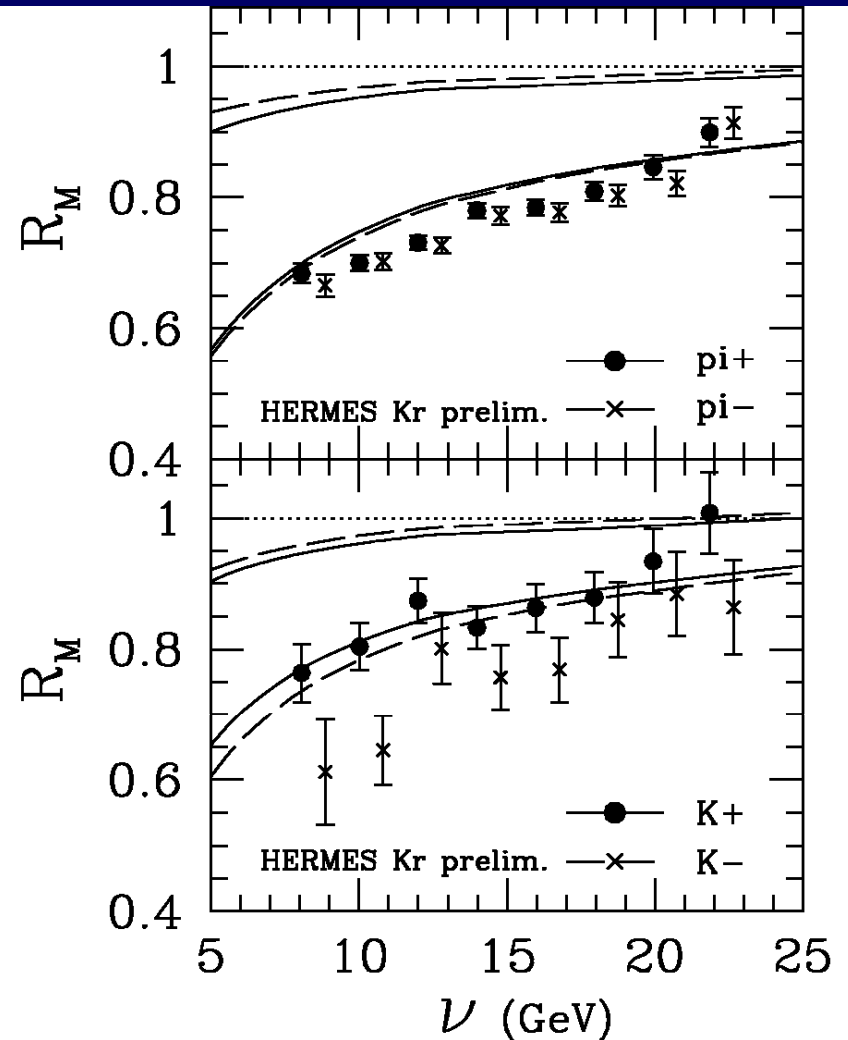
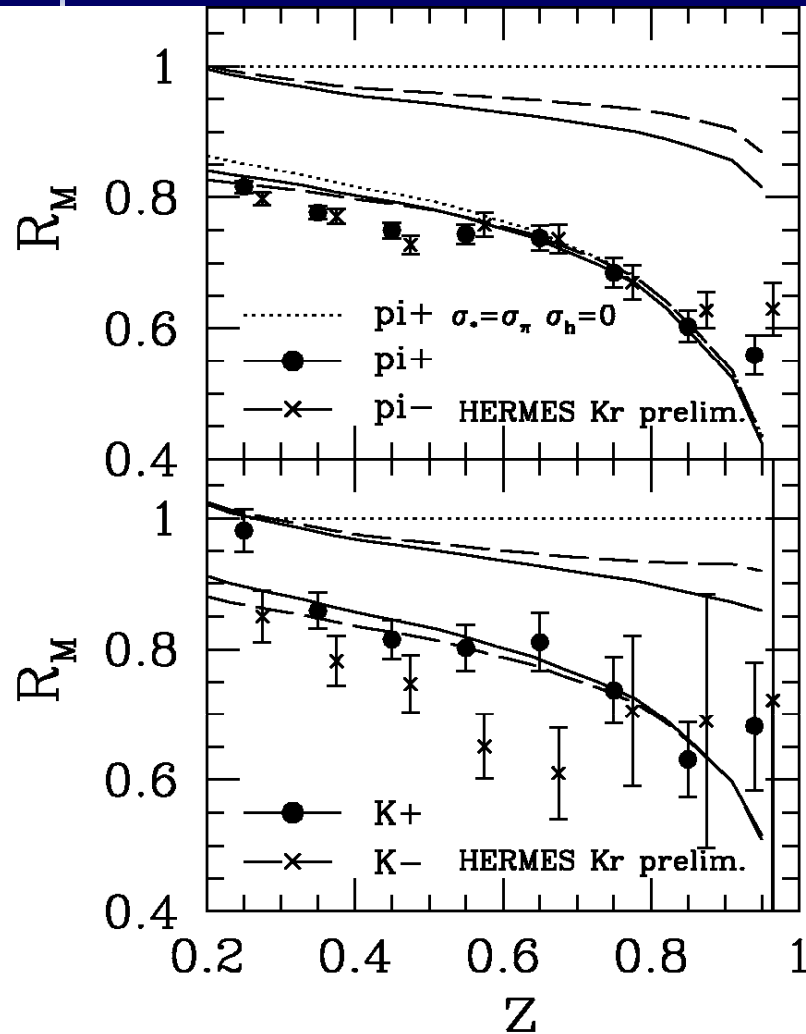
$$\widetilde{D}_{q \rightarrow h}(z_h, Q^2) \equiv D_{q \rightarrow h}(z_h, Q^2) + \Delta D_{q \rightarrow h}(z_h, Q^2)$$

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

Rescaling Model, EMC/HERMES Data



Rescaling Model, HERMES Flavor-separated Kr Data



Impact of Models – Summary

- ~4-6 modern models currently on the market:
 - Varying degrees of sophistication
 - All can fit the published data reasonably well 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 high standards for theory!
- Need lattice calculations (~5+ years away)

Jlab, CLAS, and CLAS12

- CW electron accelerators allow breakthrough measurements
 - High average luminosity from 100% duty factor
 - Excellent beam characteristics
- Second and third generation measurements of this kind will come from CLAS/CLAS12
 - Luminosity $\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ now, 10^{35} later
 - Large acceptance allows study of two-particle correlations
 - CLAS12 will be a superb instrument for these studies (11 GeV, good PID, high luminosity)

CLAS – the CEBAF Large Acceptance Spectrometer

Drift Chambers

35,000 wires
 $\sigma_R = 350 \mu\text{m}$

Superconducting Toroidal Magnet

$$\int Bdl \cong 1.7 \text{ T}\cdot\text{m}$$

Cerenkov Counters

216 channels
99.5% efficient
over 50 m^2 area

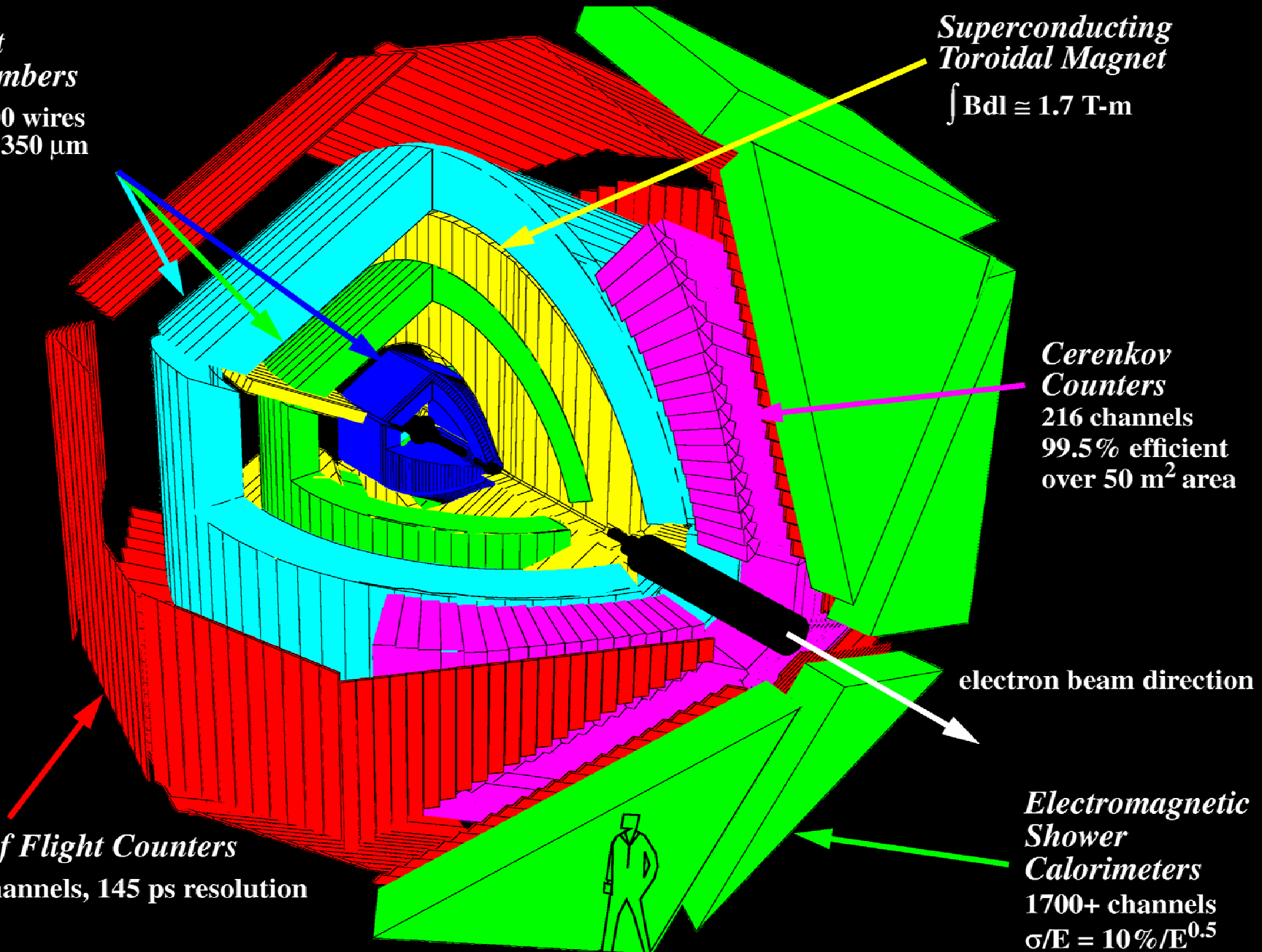
electron beam direction

Electromagnetic Shower Calorimeters

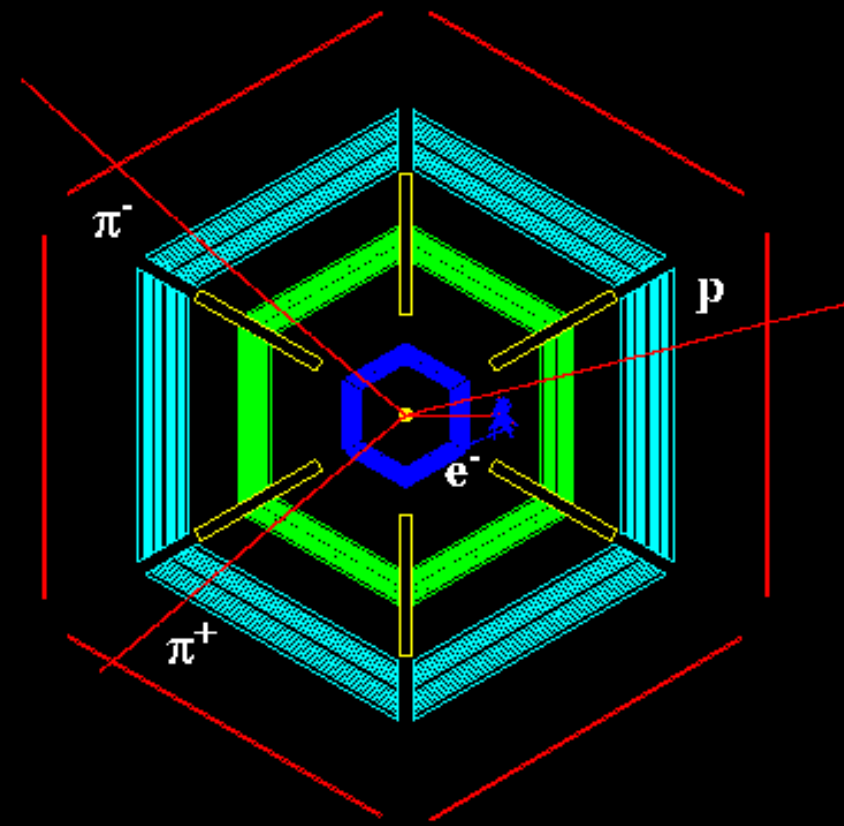
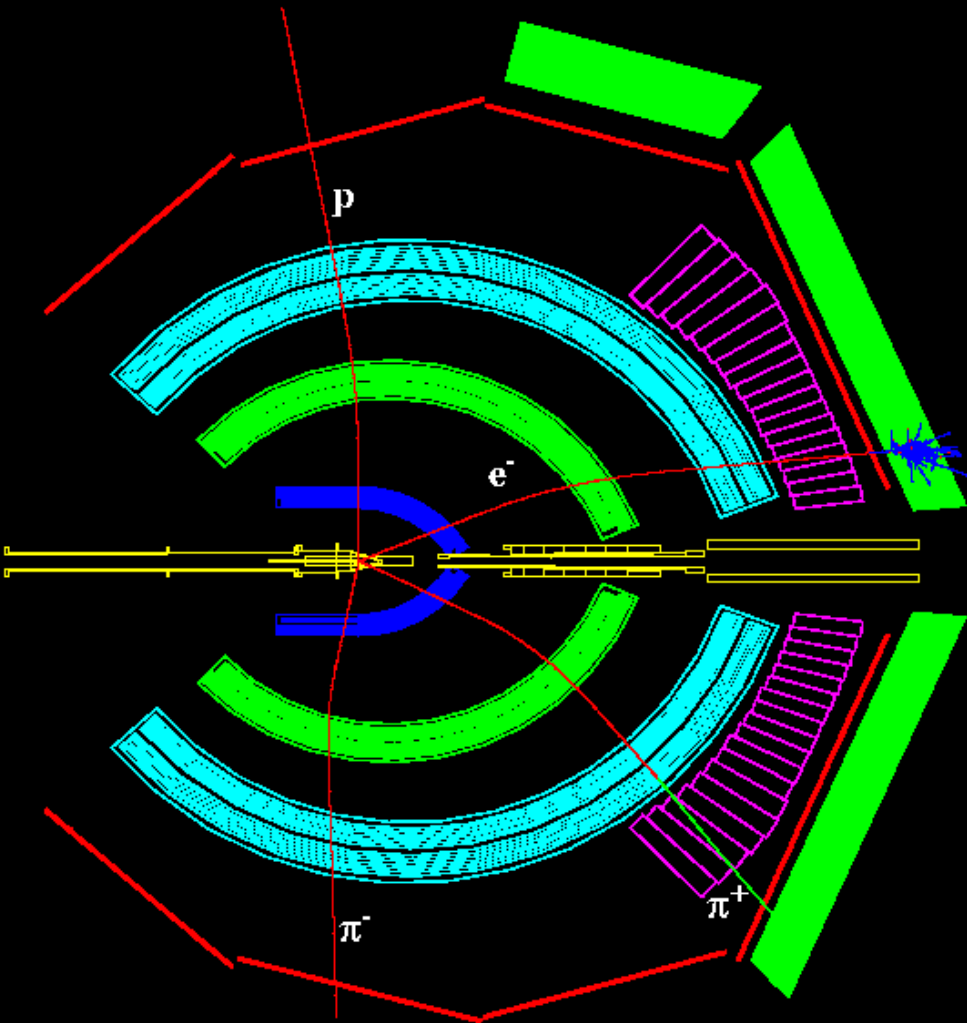
1700+ channels
 $\sigma/E = 10\%/E^{0.5}$

Time of Flight Counters

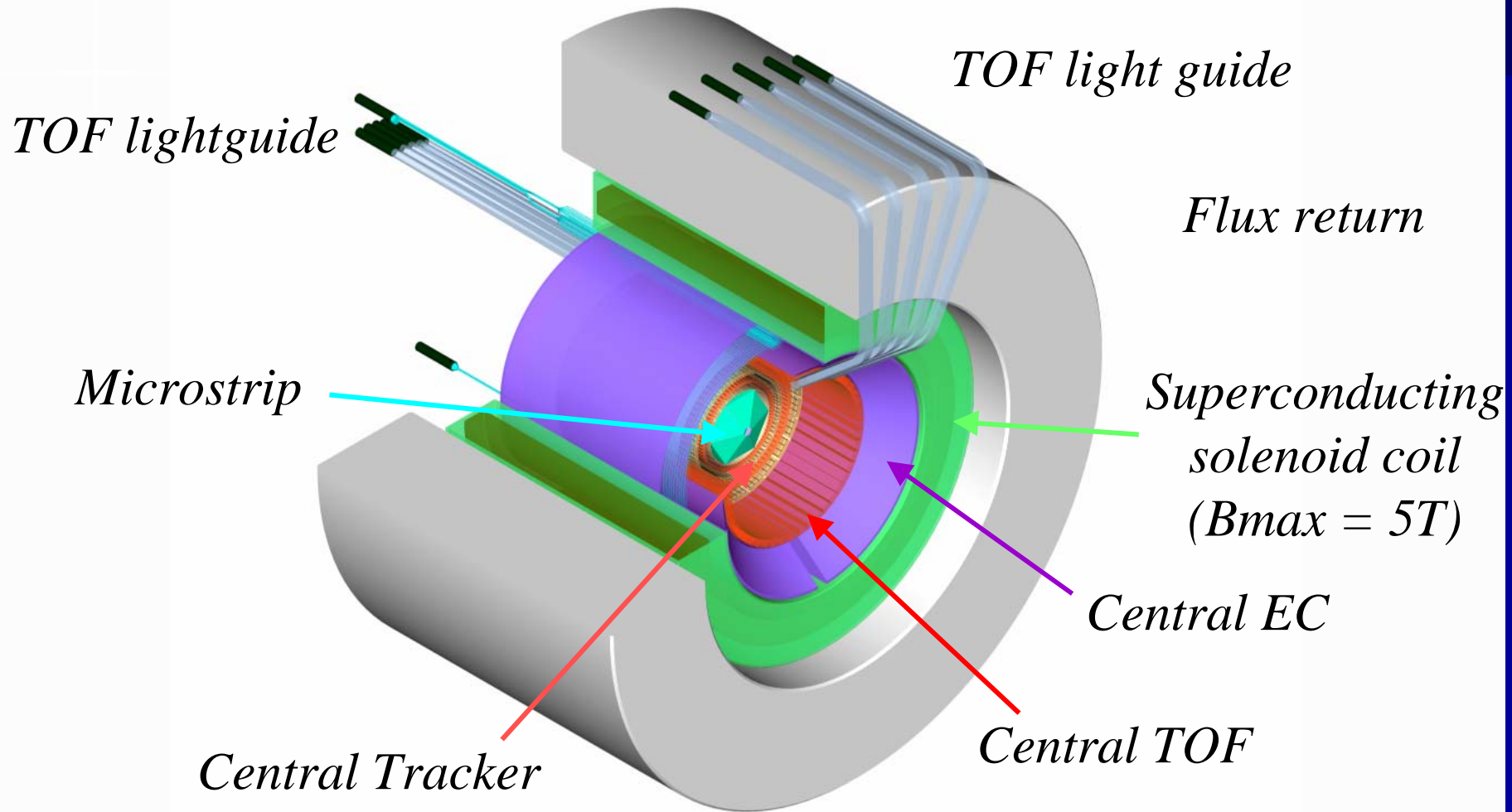
500+ channels, 145 ps resolution

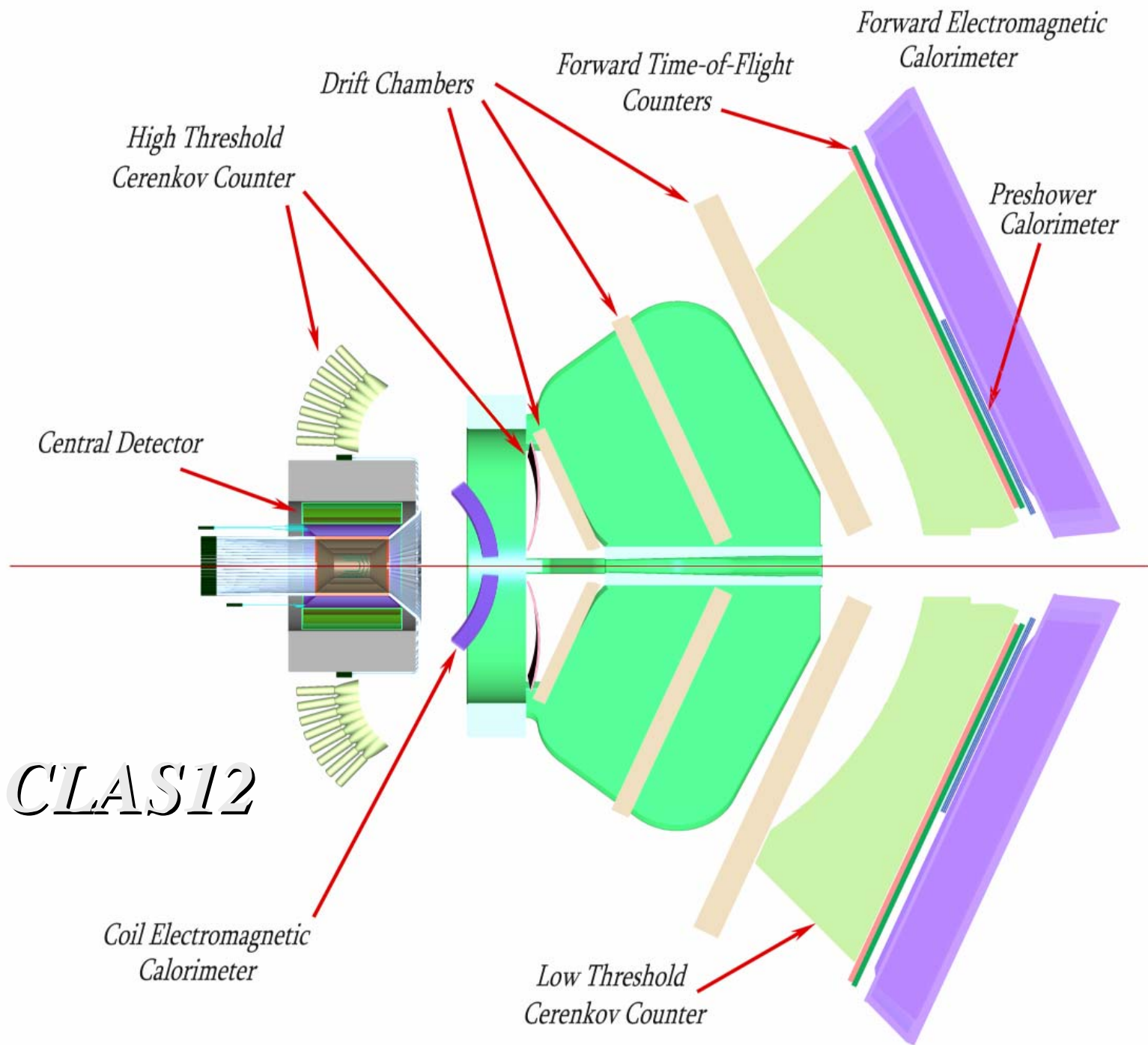


- Charged particle angles $8^\circ - 144^\circ$
- Neutral particle angles $8^\circ - 70^\circ$
- Momentum resolution $\sim 0.5\%$ (charged)
- Angular resolution ~ 0.5 mr (charged)
- Identification of p , π^+/π^- , K^+/K^- , e^-/e^+



The CLAS12 Central Detector





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: $Q^2 \leq 4 \text{ GeV}^2$, $\nu \leq 4.5 \text{ GeV}$
- 11 GeV beam: $Q^2 \leq 9 \text{ GeV}^2$, $\nu \leq 9 \text{ GeV}$
- Measure $\pi^{+,-,0}$, η , ω , η' , ϕ , $K^{+,-,0}$, p , Λ , $\Sigma^{+,0}$, $\Xi^{0,-}$

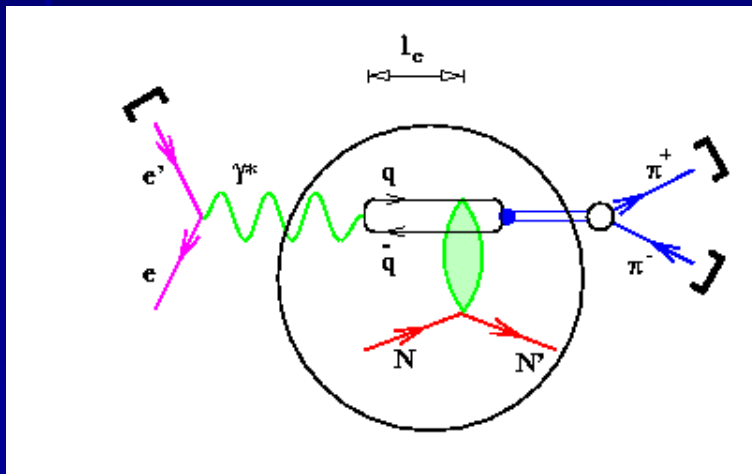
CLAS EG2

Physics Focus

Search for Color Transparency

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

Compare absorption in deuterium, carbon, aluminum, and iron

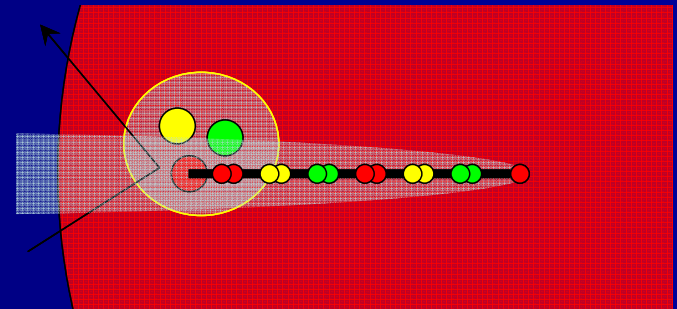


E02-110

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



E02-104

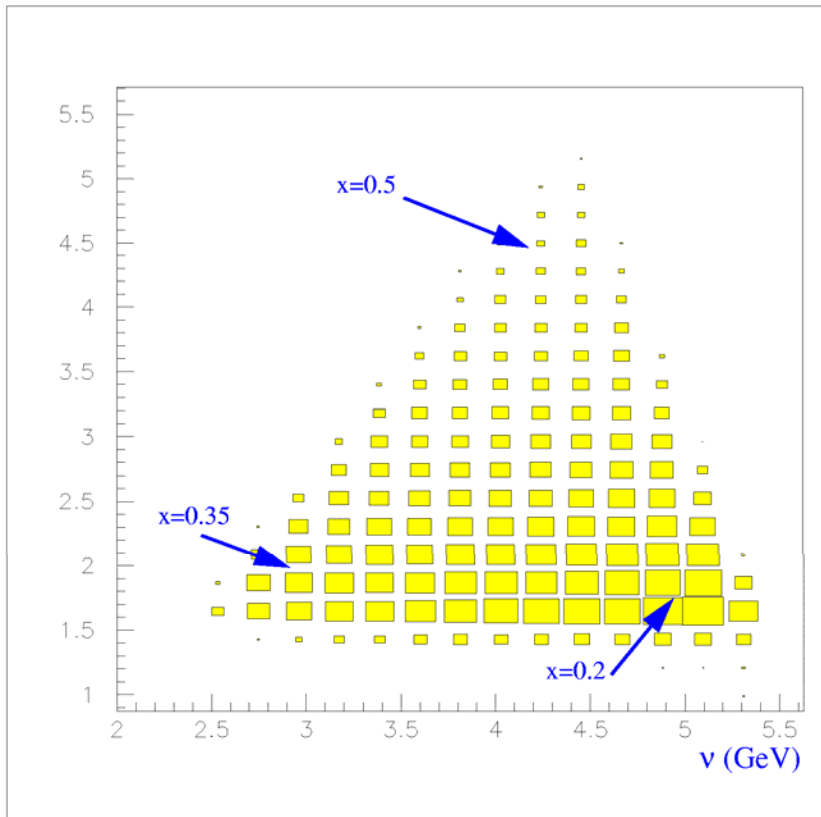
CLAS EG2

Running Conditions

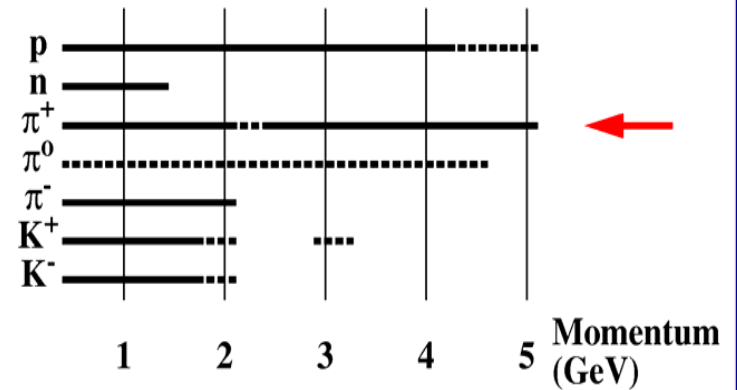
- Beam energies: 4 GeV (7 days) and 5 GeV (50 days)
- Luminosity: $1.9\text{-}2.0 \times 10^{34}$ (D+Fe), 1.3×10^{34} (D+Pb)
- Data taking:
 - DC occupancy $< 3\%$,
 - deadtime 7% (D+Pb) and 14% (D+Fe)
- Number of triggers:
 - 0.6 billion (D+Fe, 4 GeV)
 - 2 billion (D+Fe, 5 GeV)
 - 1.5 billion (D+Pb,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

CLAS Kinematic Coverage and Particle Identification at 6 GeV

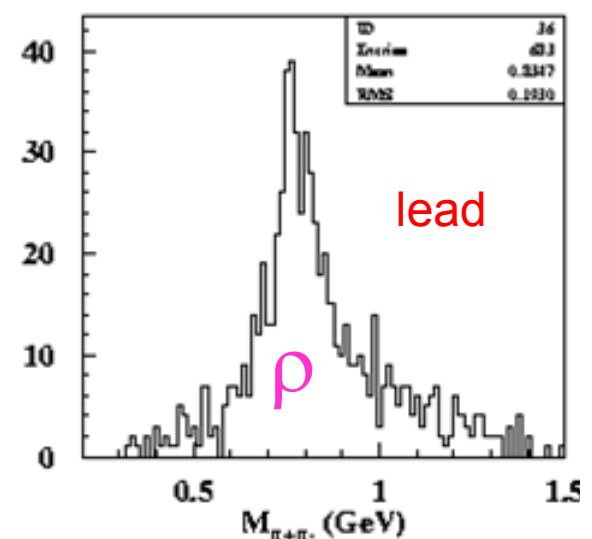
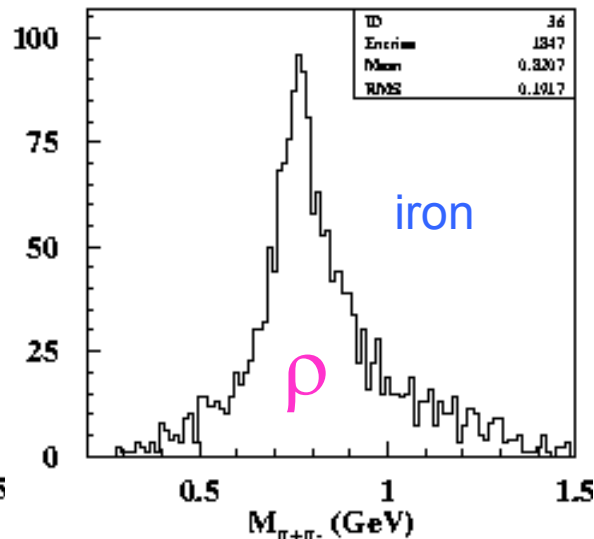
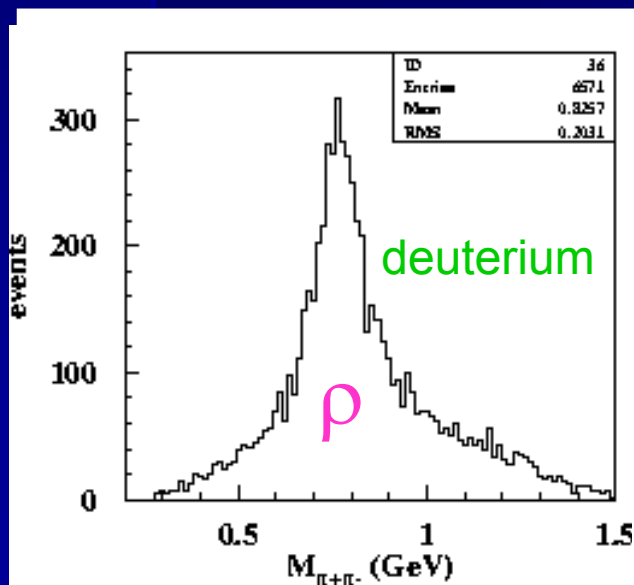
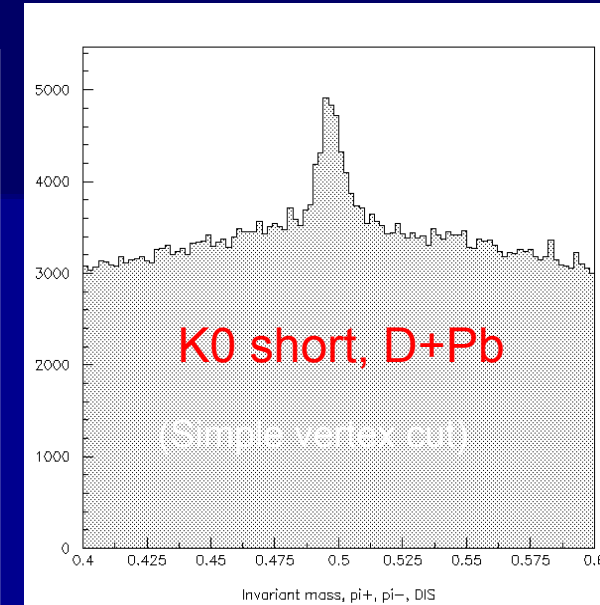
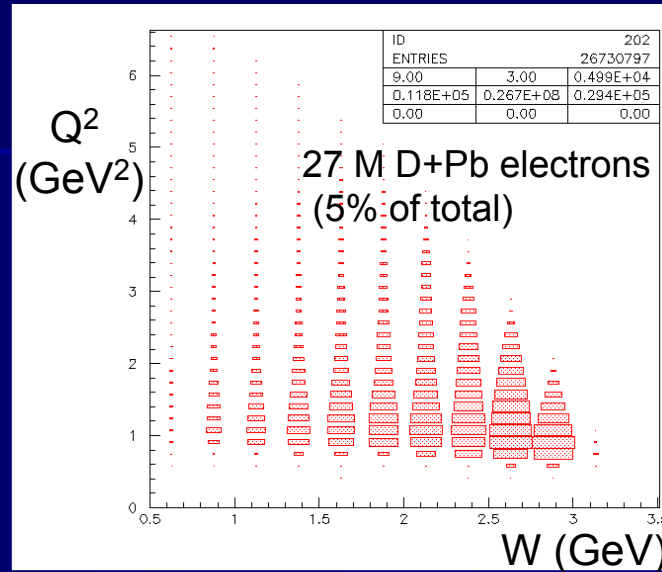
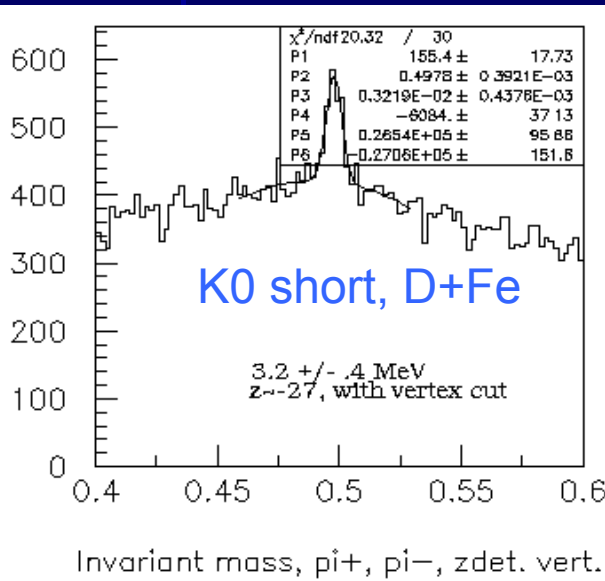
Q^2
(GeV²)



Directly identified particles

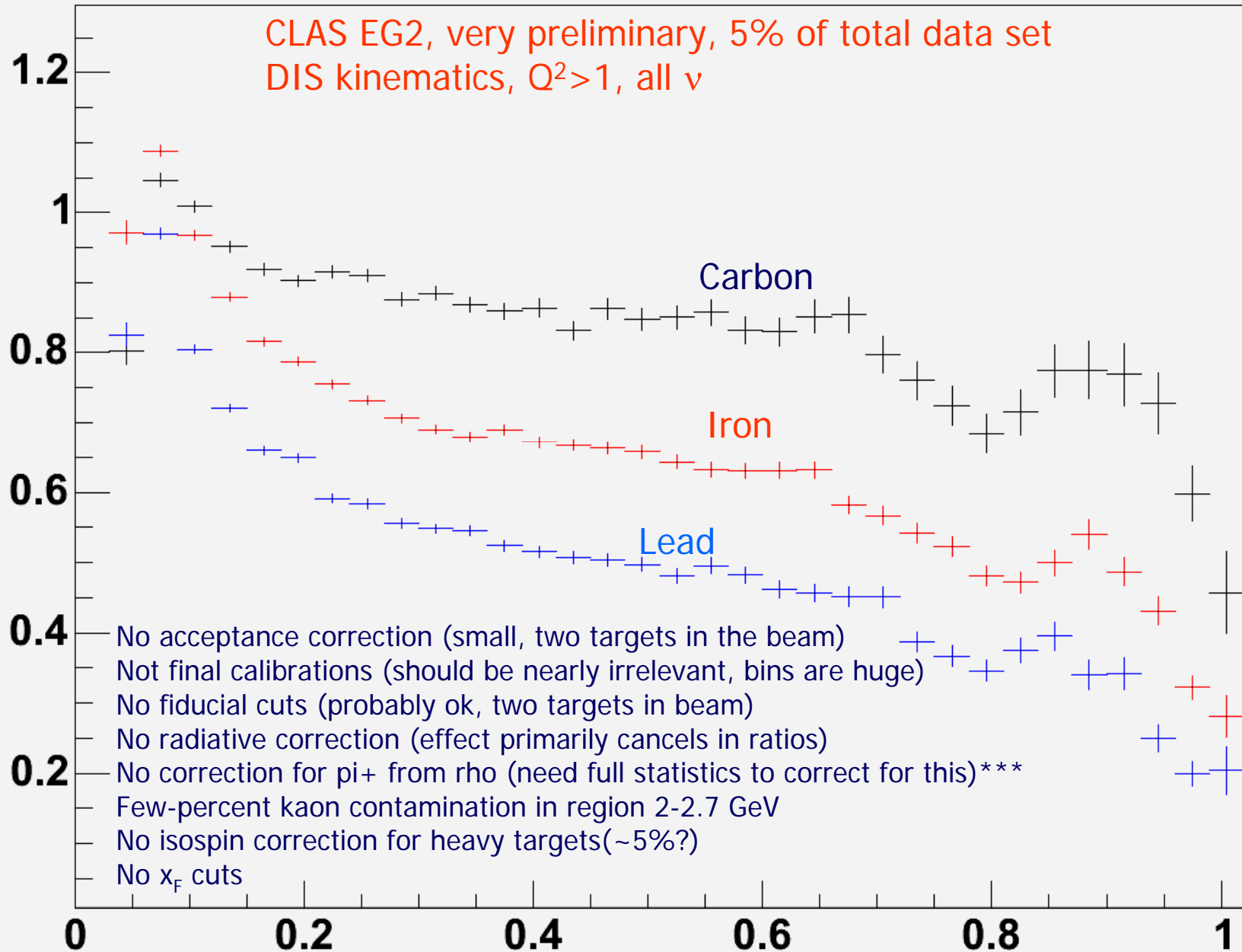


CLAS EG2 Online Physics Results

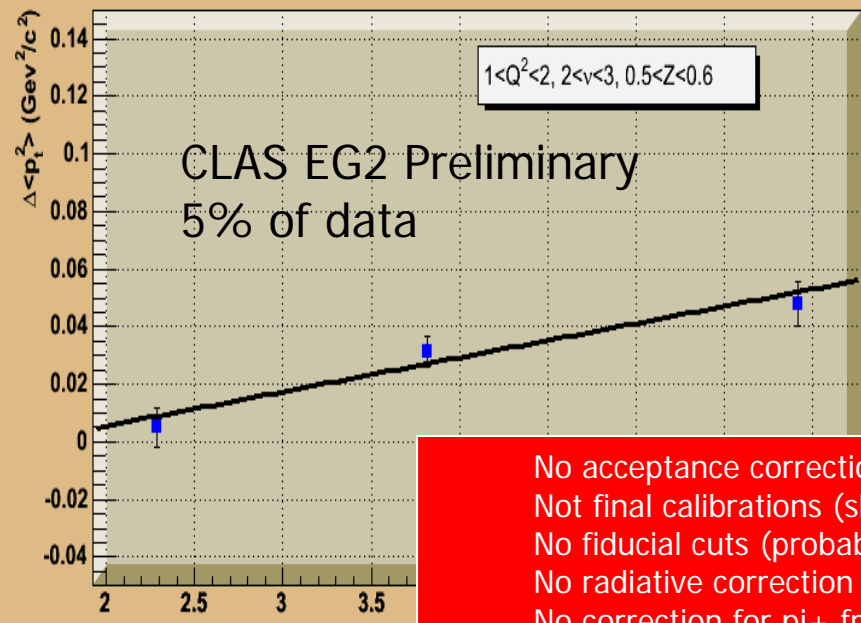


Multiplicity ratio for pion+:

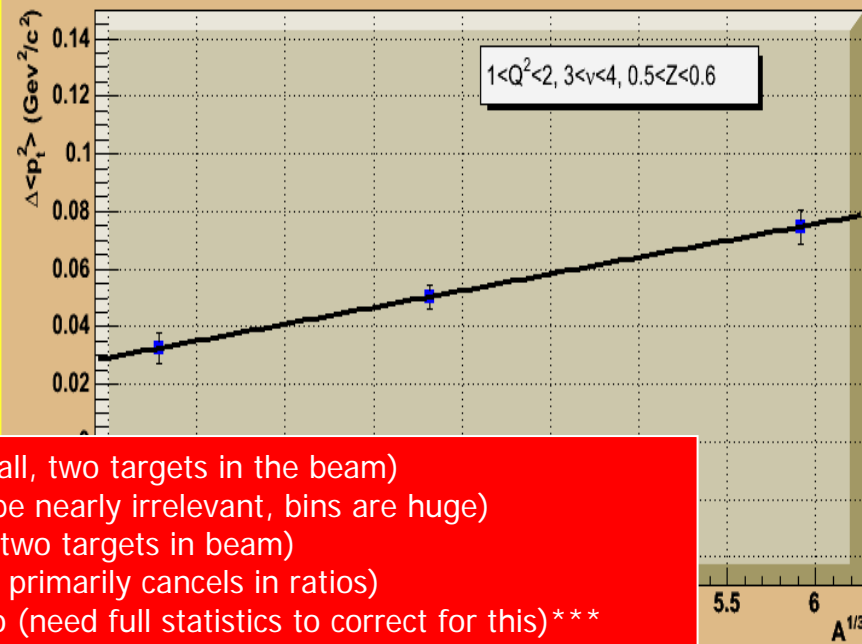
Hayk Hakobyan, Yerevan State U.



transverse momentum square broadening of leading π^+

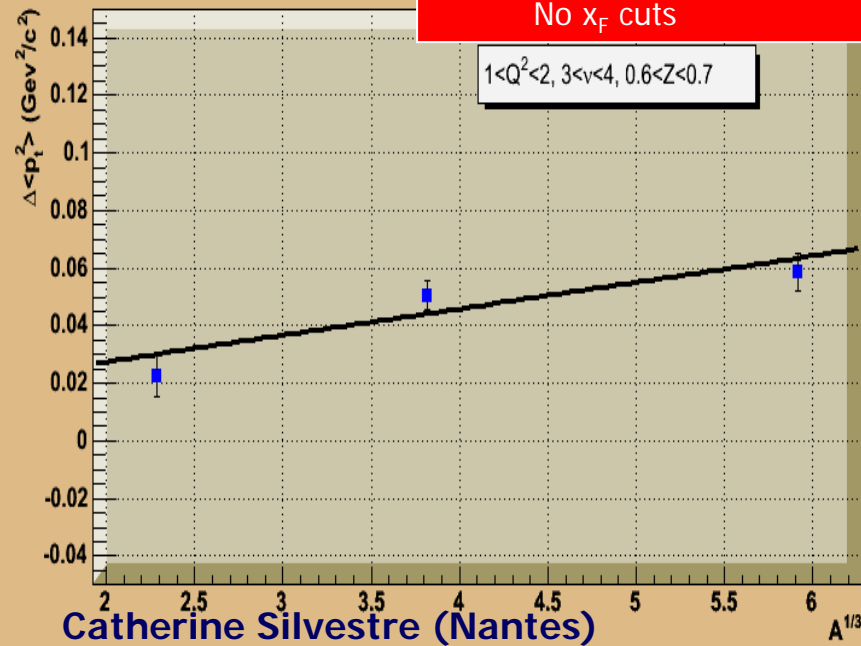


transverse momentum square broadening of leading π^+

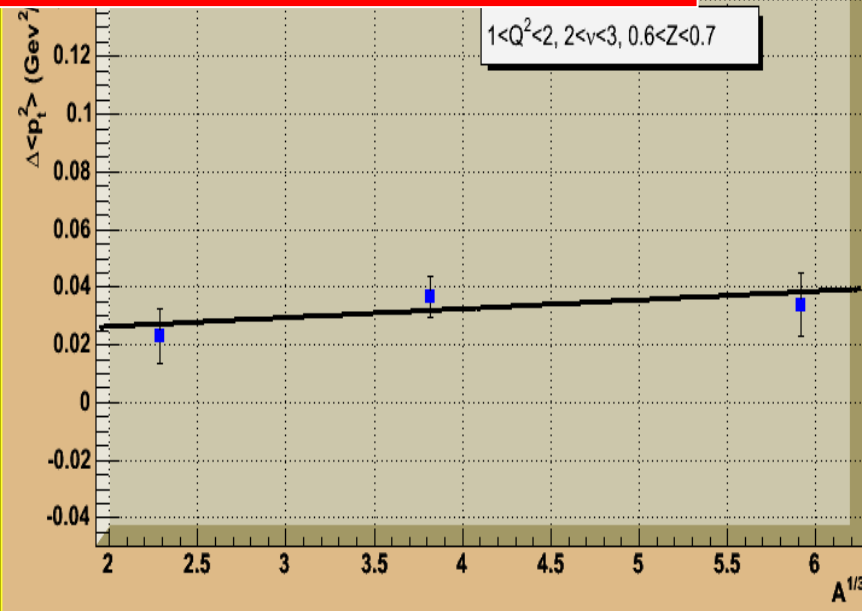


No acceptance correction (small, two targets in the beam)
 Not final calibrations (should be nearly irrelevant, bins are huge)
 No fiducial cuts (probably ok, two targets in beam)
 No radiative correction (effect primarily cancels in ratios)
 No correction for π^+ from ρ (need full statistics to correct for this)***
 Few-percent kaon contamination in region 2-2.7 GeV
 No isospin correction for heavy targets (~5%?)
 No x_F cuts

transverse momentum square broadening of leading π^+

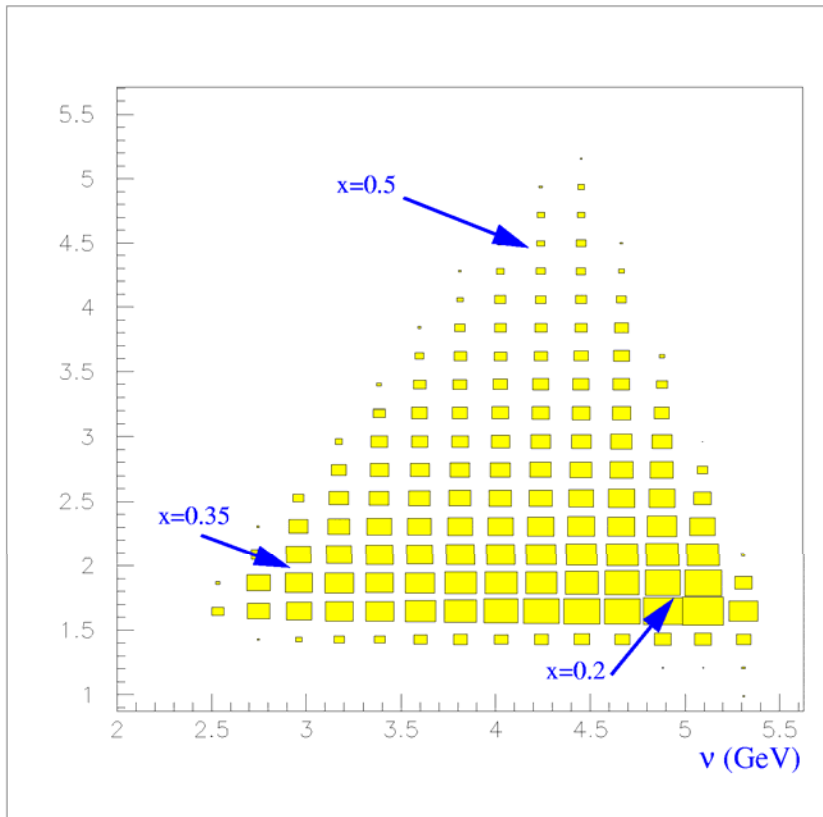


transverse momentum square broadening of leading π^+

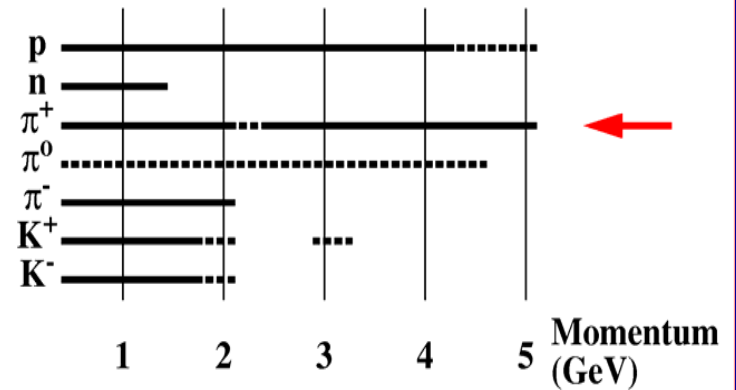


CLAS Kinematic Coverage and Particle Identification at 6 GeV

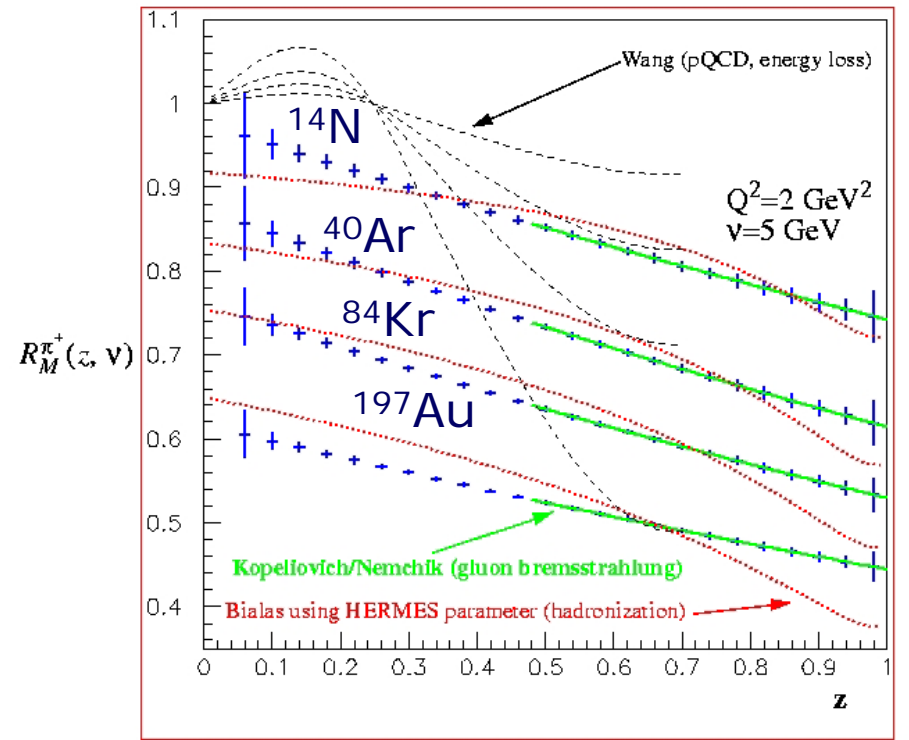
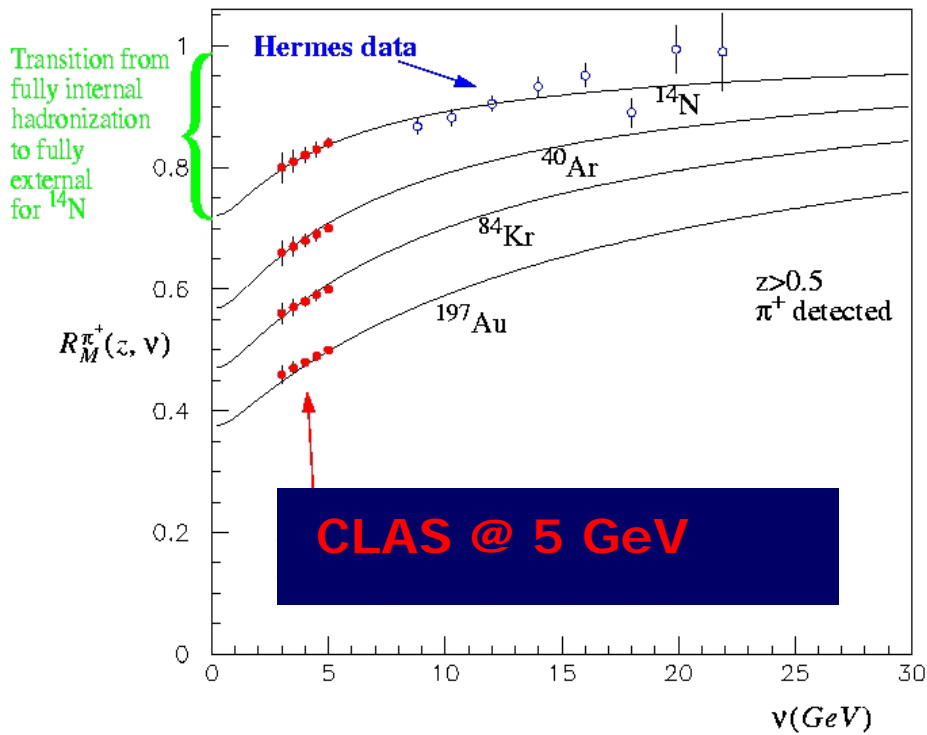
Q^2
(GeV²)

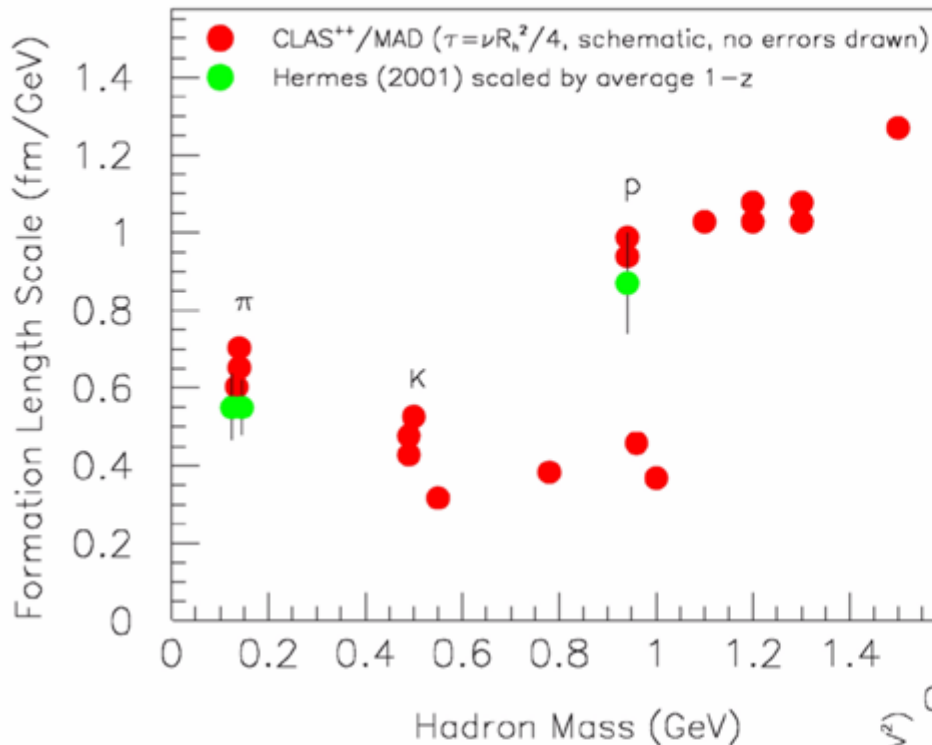


Directly identified particles



Sample of Anticipated 6 GeV Data



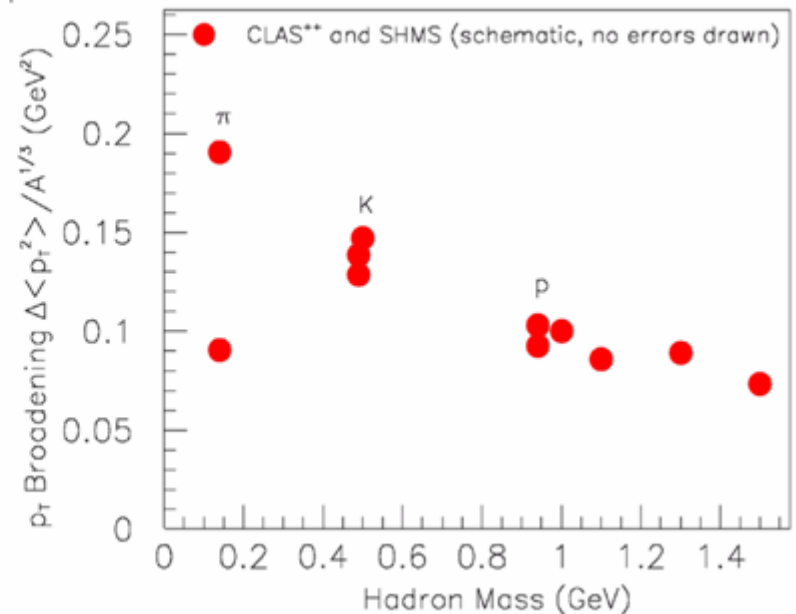


Schematic Examples of Analysis Results

- 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 .



Complications

- Where can pQCD be used? factorization
- Target/current fragmentation
- Resonances in final states

Benefits of CLAS/Jlab

- High luminosity and duty factor
 - Can access lower-rate reactions, higher p_T , higher Q^2
 - Can study multivariable dependence
- Large acceptance for multiple hadrons
 - Access to many hadrons through decay channels
 - Correlate final-state particles with leading hadron ('grey tracks')
 - Can test fragmentation model