Quark Propagation and Fundamental Processes in QCD

- Hadronization
- Quark-gluon dynamics
- Model approaches
- Connections to HERMES, LHC/RHIC, and Fermilab
- JLab experiments – present and future

Will Brooks, November 2004

Quark Propagation and Fundamental Processes in QCD

Hadronization

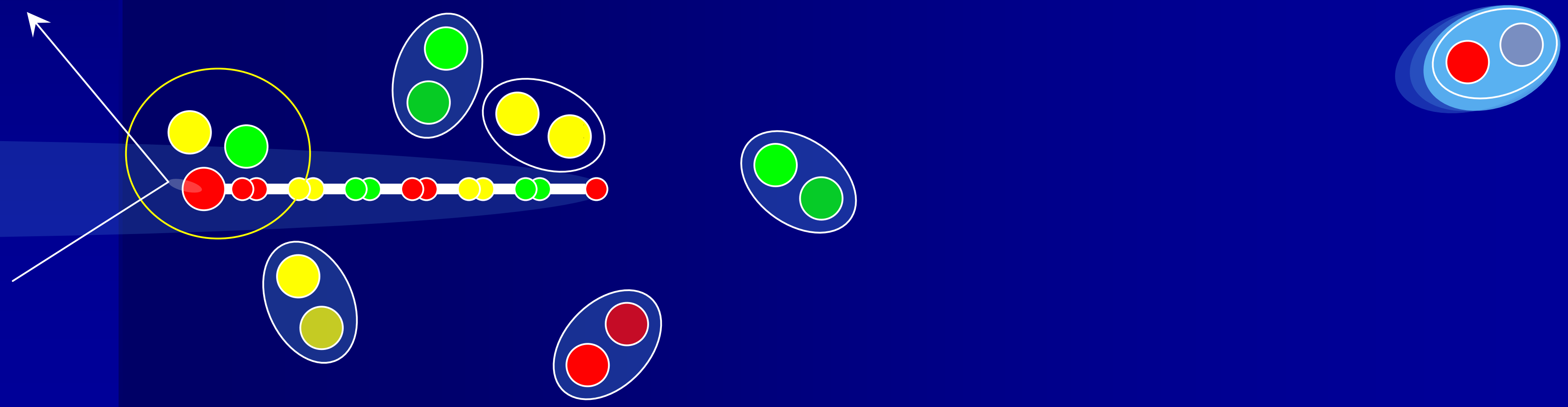
- The transformation of energetic quark in color field into hadron(s)
- Time dependence of restoration of hadron's local color field

Quark-gluon dynamics

- Partonic energy loss via gluon emission
- Quark-gluon correlations

Fascination with Hadronization

- Hadronization is at the heart of the most fascinating feature of QCD: *confinement*



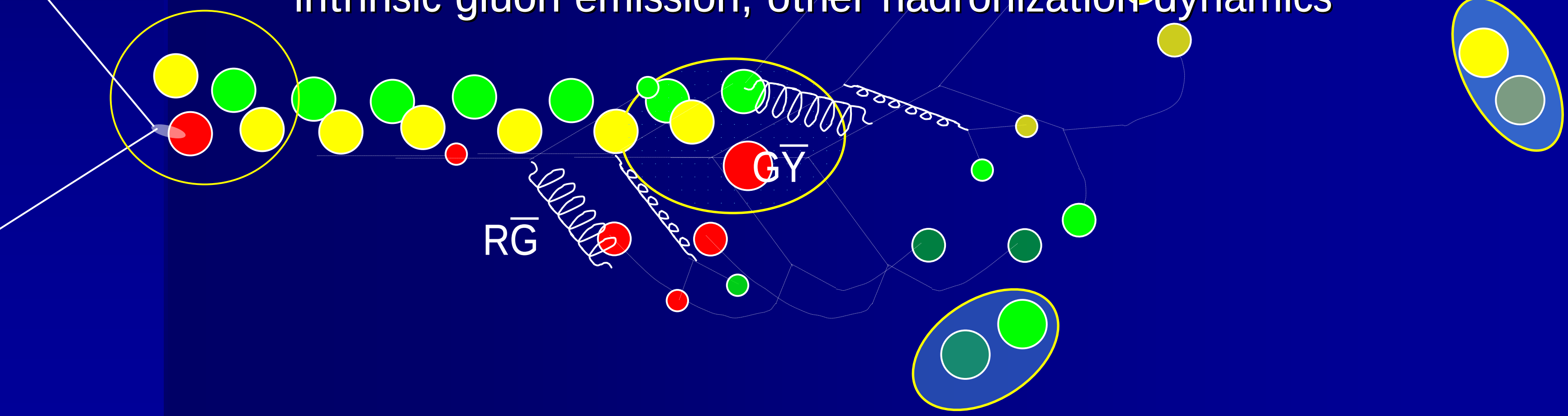
Fascination with Hadronization

ν energy transferred by the electron (initial energy of struck quark)

Q^2 four-momentum transferred by the electron (initial size of struck quark)

z_h $= E_{hadron}/\nu$, fraction of struck quark energy carried by hadron; $0<z_h<1$

p_T quark/hadron momentum transverse to virtual photon direction; results from initial quark transverse momentum, multiple scattering in-medium, intrinsic gluon emission, other hadronization dynamics



Target Frame DIS Kinematics

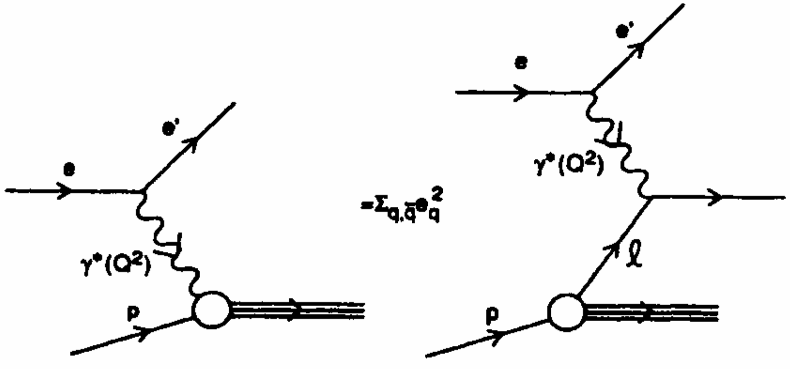
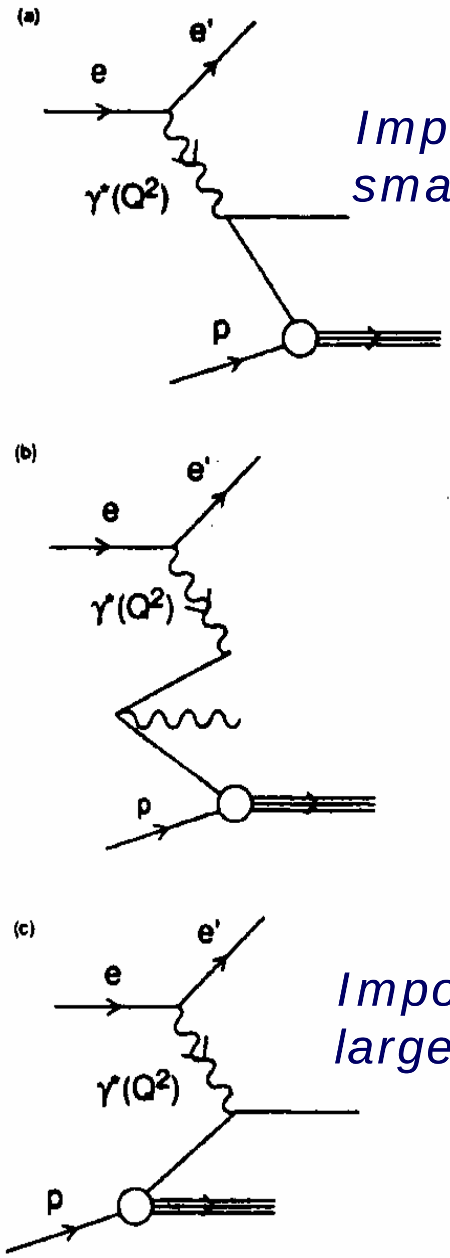


FIG. 1. DIS in the infinite-momentum frame.

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



Important at small x

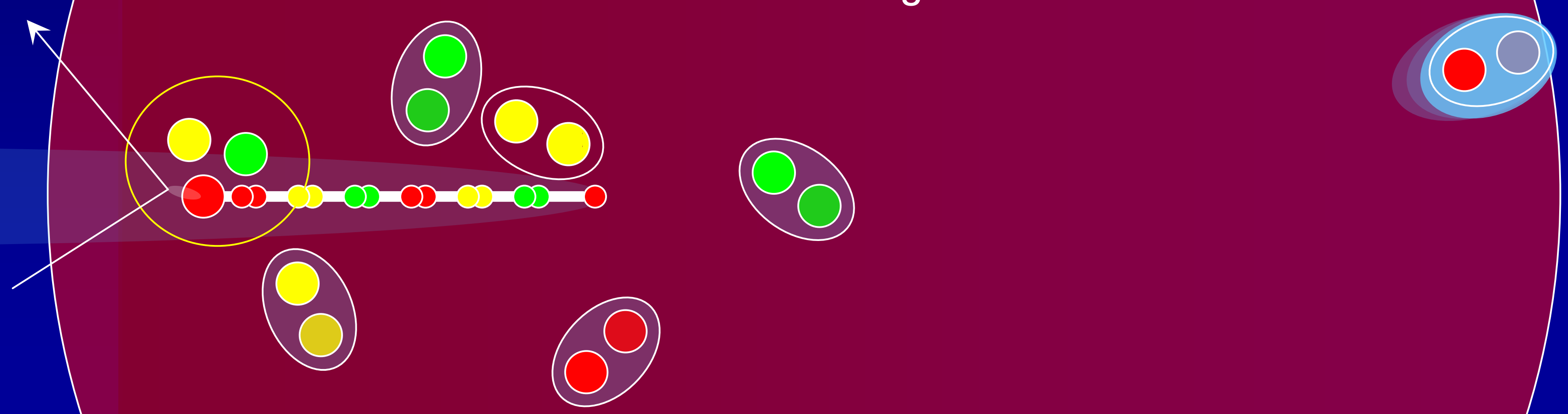
Important at large x

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

Nuclear Deep Inelastic Scattering

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

Initial focus on properties of leading hadron; correlations with subleading and soft protons is also interesting

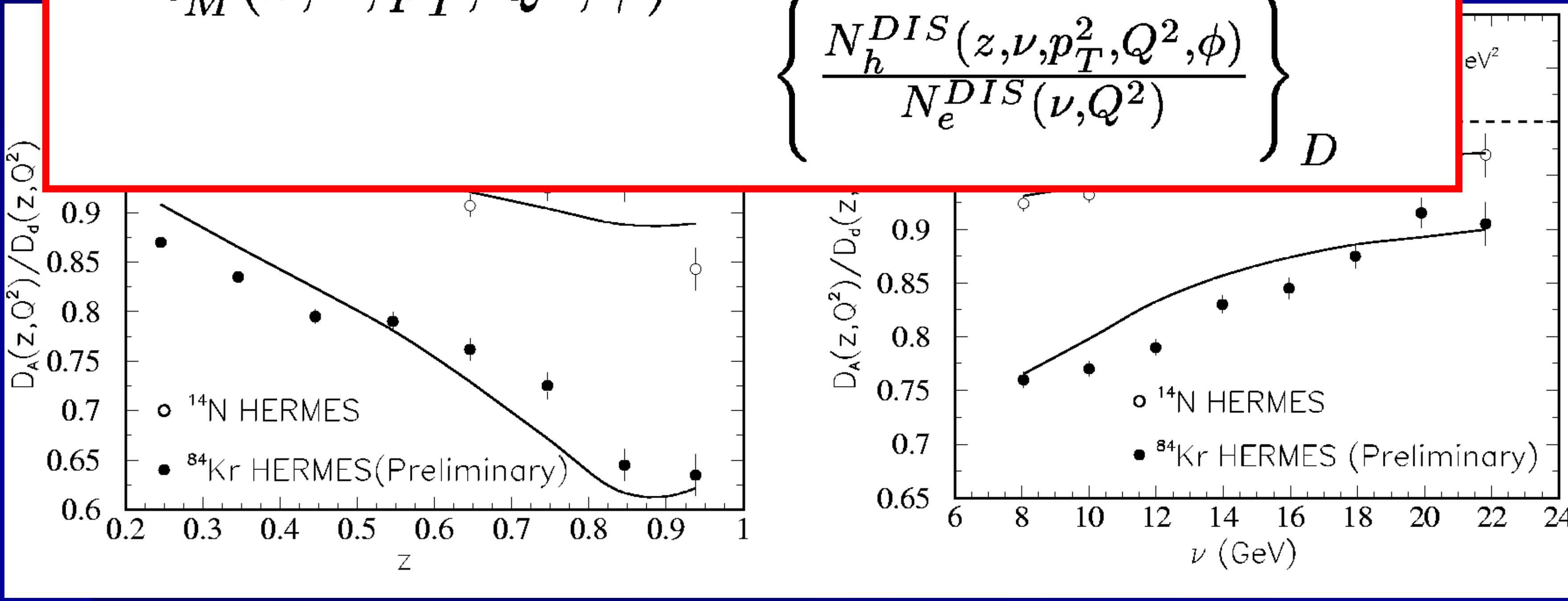


$$R^h_M(z,\nu) = \frac{\left\{\dfrac{N_h(z,\nu)}{N_e^{DIS}(\nu)}\right\}_A}{\left\{N_h(z,\nu) \right.}$$

Observables

Hadronic multiplicity ratio

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



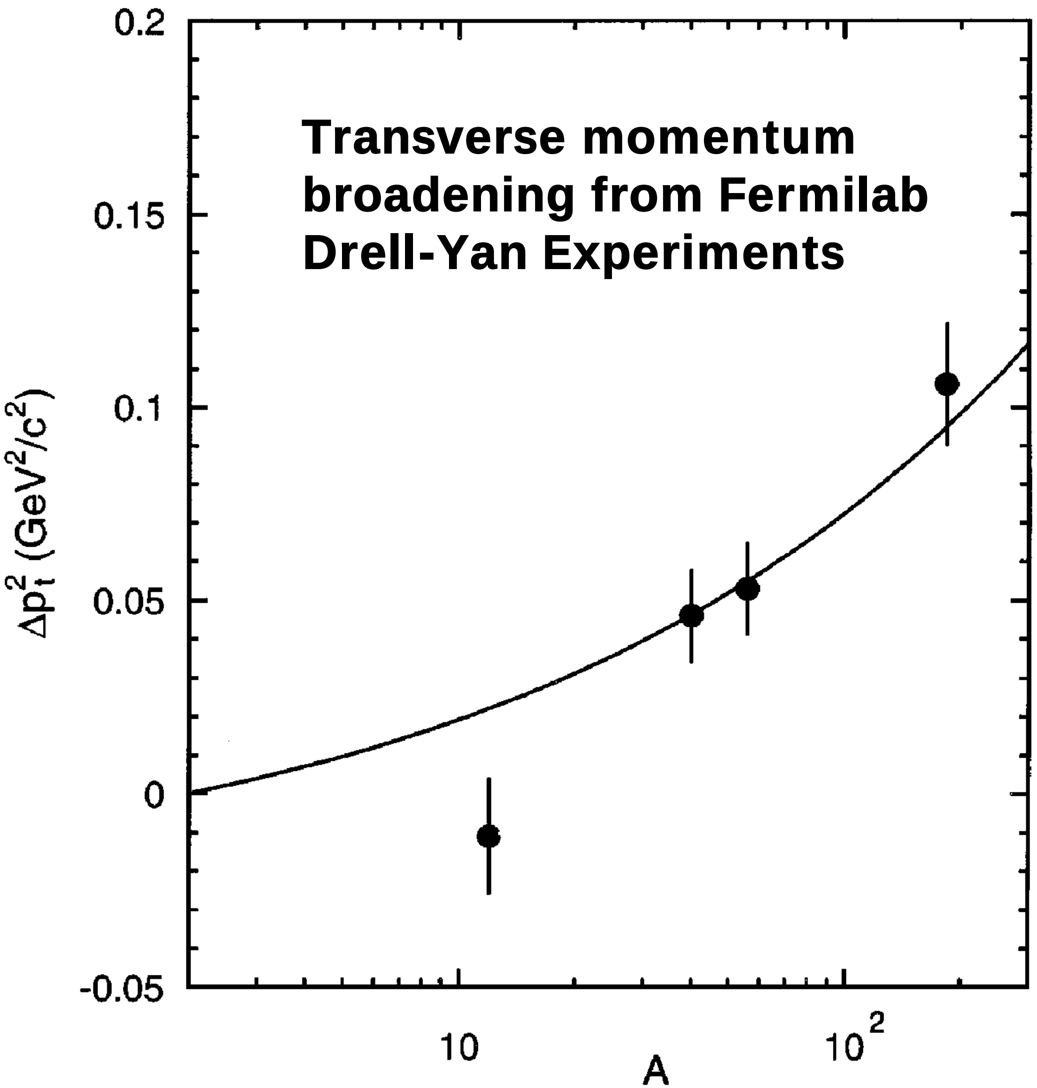
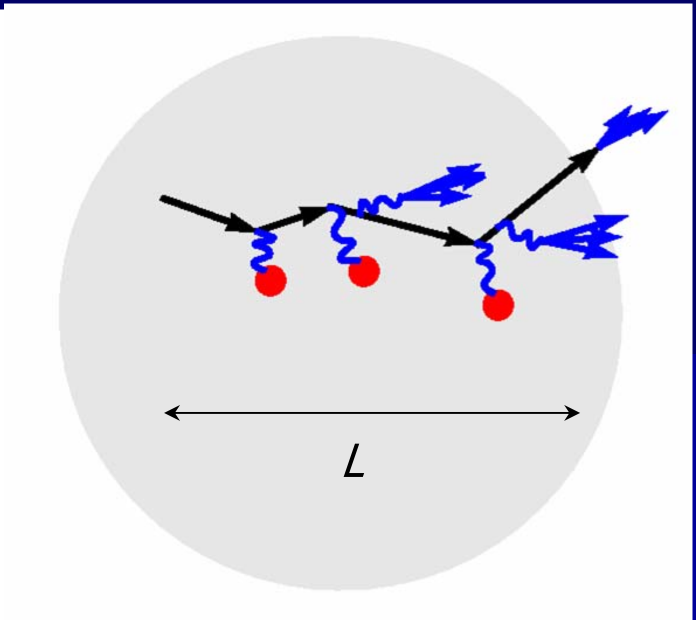


Figure 15 $\Delta\langle p_t^2\rangle \equiv \langle p_t^2\rangle(A) - \langle p_t^2\rangle(^2H)$ versus A for the DY process from E772 (123; PL McGaughey, JM Moss, JC Peng, unpublished data). Solid curve corresponds to $0.027((A/2)^{1/3} - 1)$.



as L^2 (!) – QCD LPM effect

nected to transverse

ervable):

L

dx may be of measurable

function (Guo and Qiu,

- Energy loss is proportional to the *gluon density* of the medium

Recent Model Approaches: Semi-Inclusive DIS on Nuclei

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

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 Coupled-Channel Transport (Mosel, F

- Initial state from P
- Detailed final state

coupled-channel BUU transport model

- Tested extensively against many other

reactions with lep

probes

Rescaling models (Accardia, Pirner,

nfinement of nucleon

λ_0)

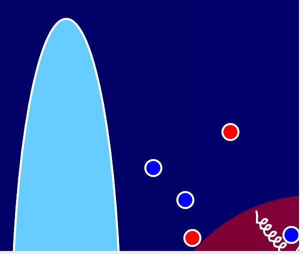
- => PDF's and frag. fcns. modified

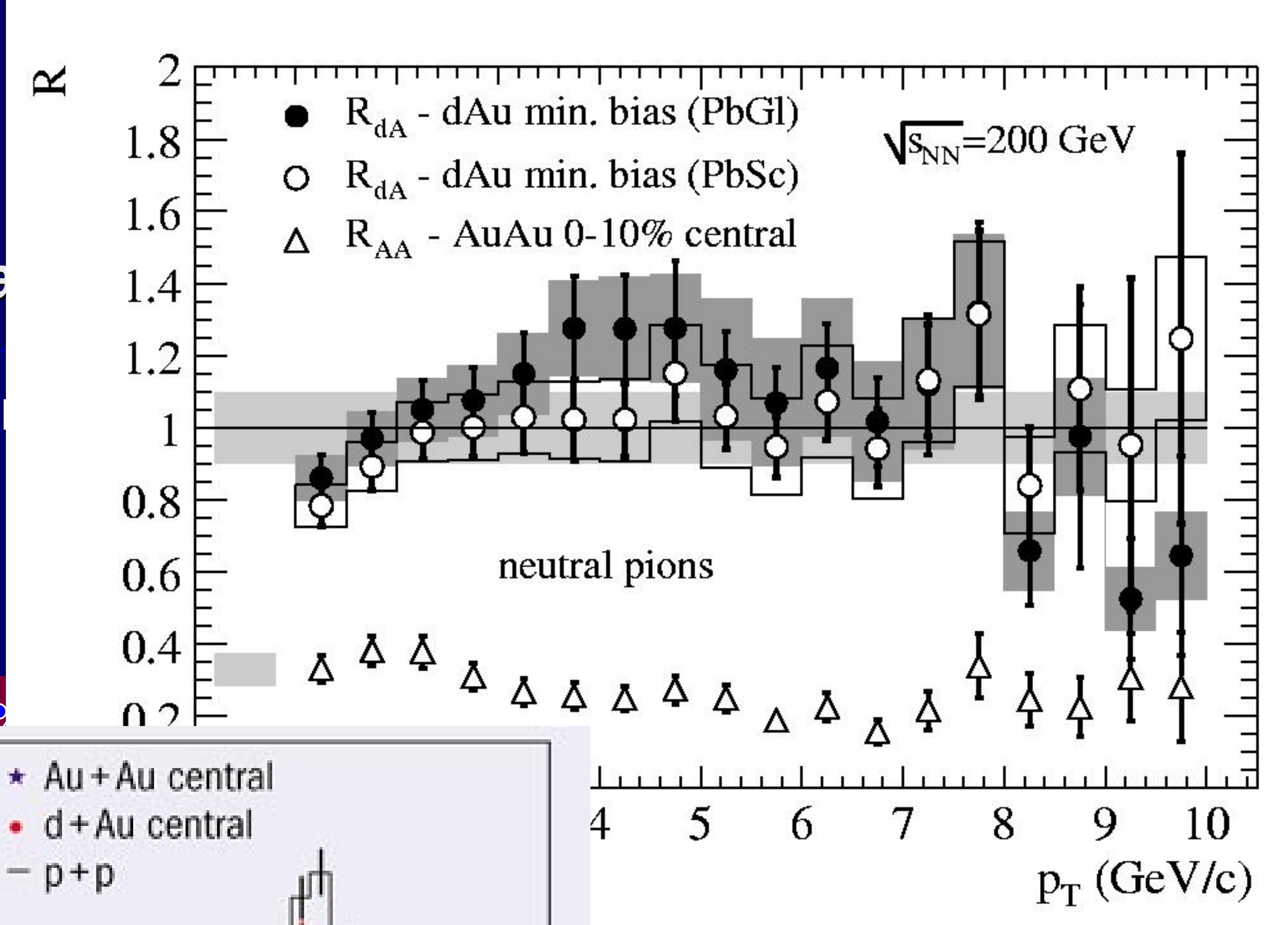
The models vary in sophistication, but all can describe the HERMES data!

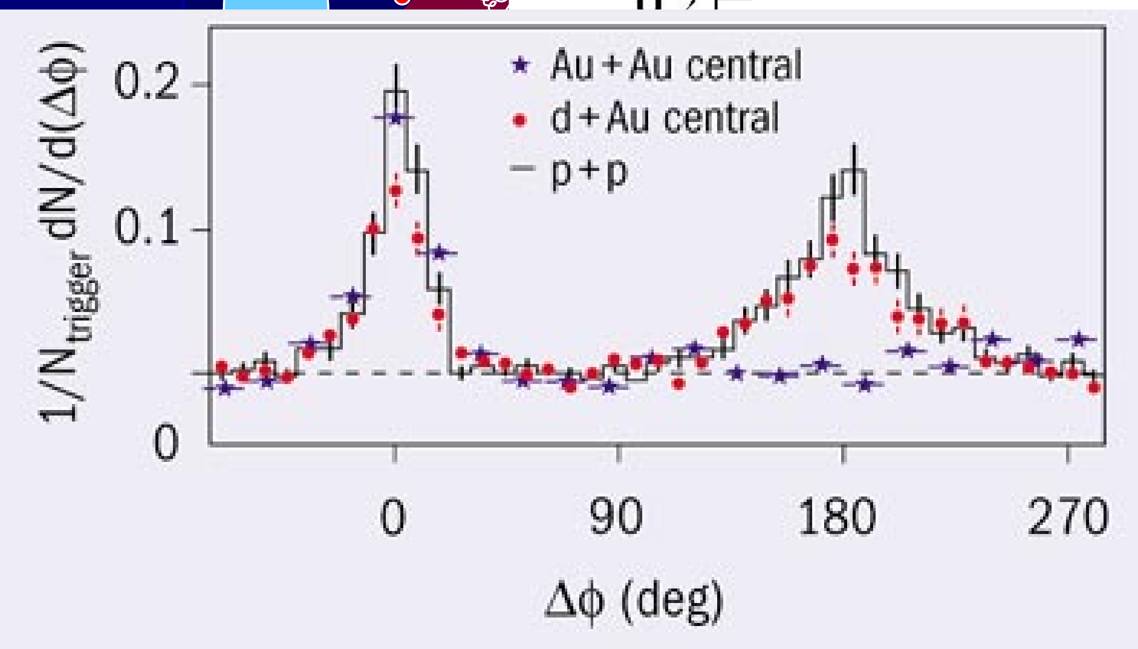
Differentiate among models: extend measurements to more variables and observables

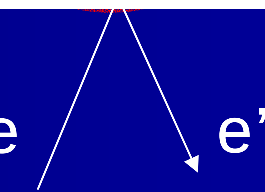
Releva

Relativistic I









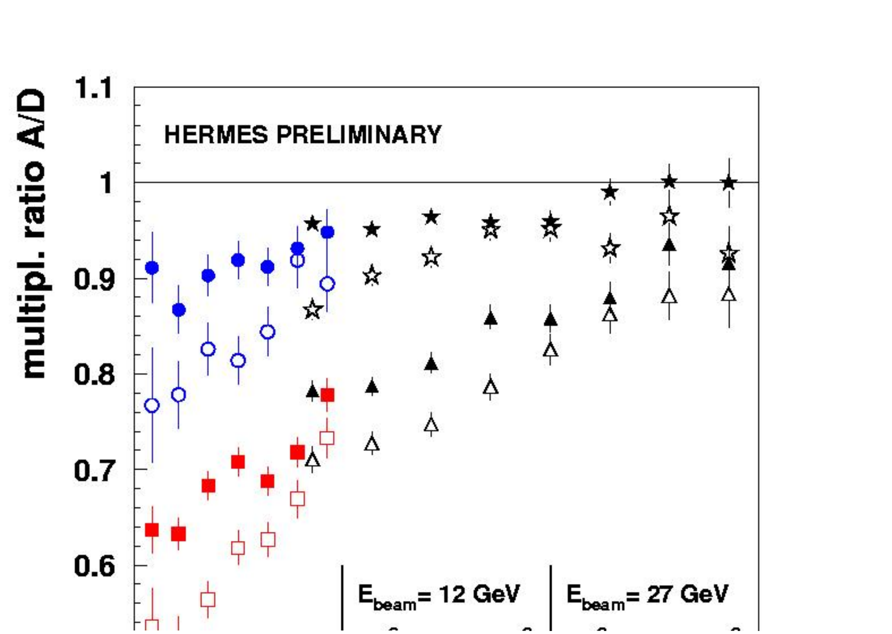
tial quark energy is known

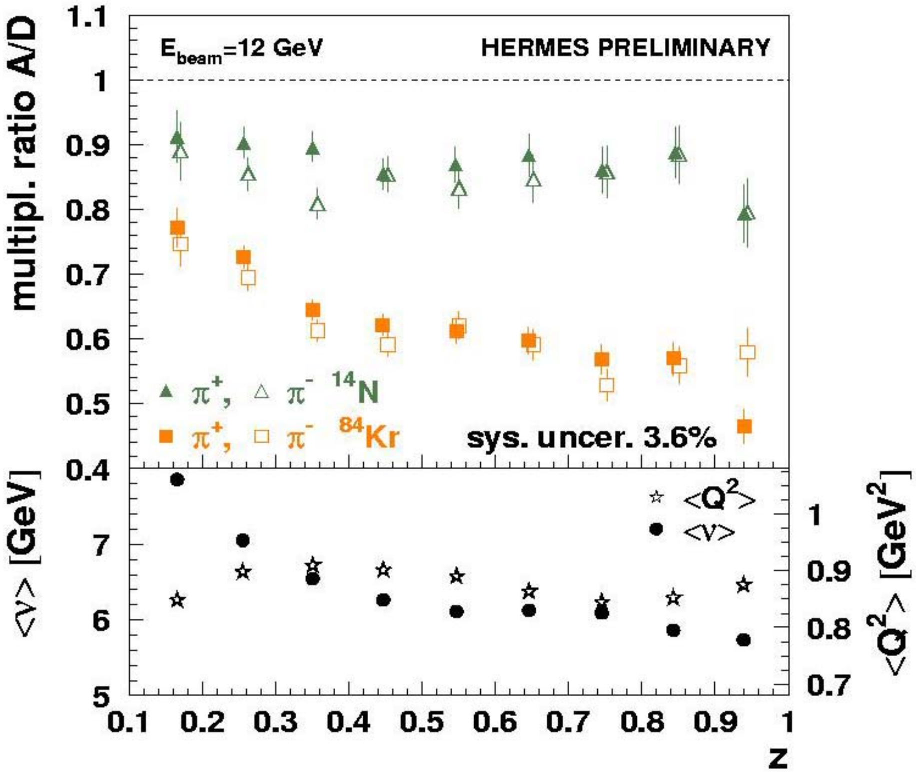
operties of medium are known

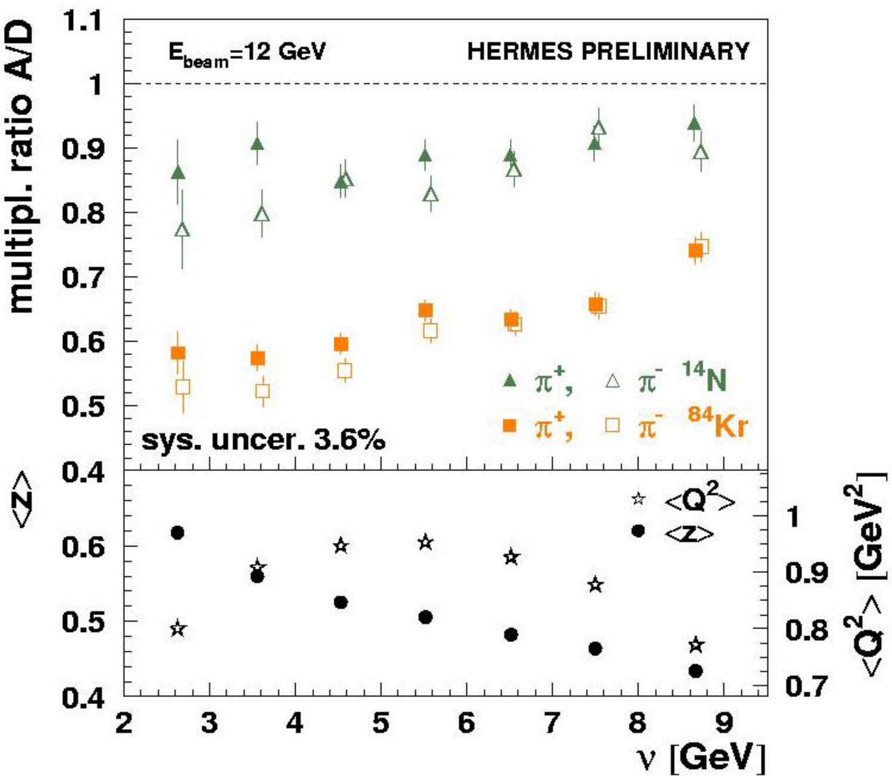
HERME

Summary of

- Mostly 27 G



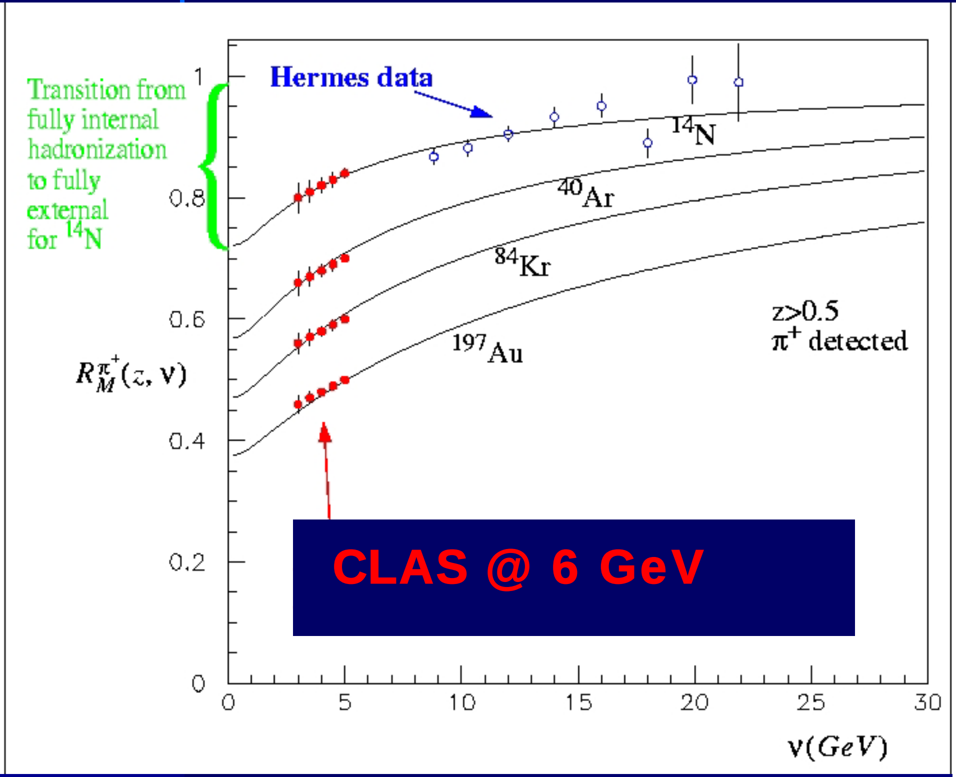


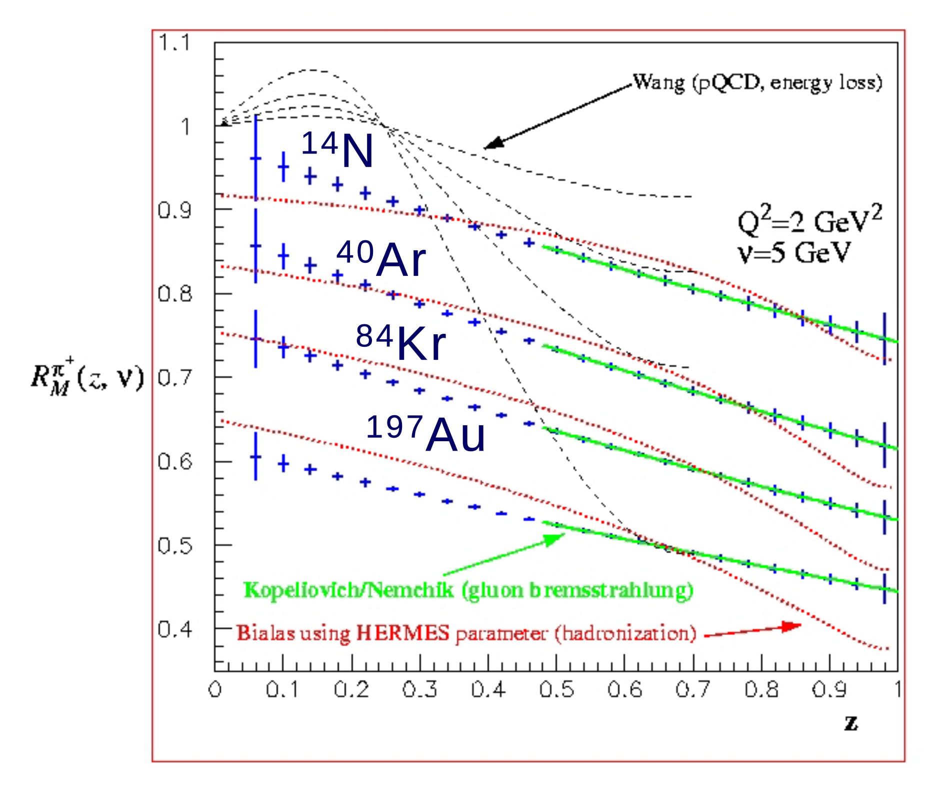


Jefferson Lab Experiments: Next 7 Years

- E02-104 (Brooks, CLAS EG2) in Hall B
  - Took part of data in January-February this year
  - Hadronization, transverse momentum broadening surveyed over a wide kinematic range
- E04-002 (Chen, Norum, Wang) in Hall A
  - Hadronization in narrow kinematic bins with good particle ID for charged K and π
  - Waiting to get on the schedule
- Interest in Hall C (Ent, Gaskell, Keppel, Kinney)
  - Transverse momentum broadening in narrow kinematic bins with good particle ID for charged K and π
  - Proposal under discussion

Sample of Anticipated 6 GeV Data





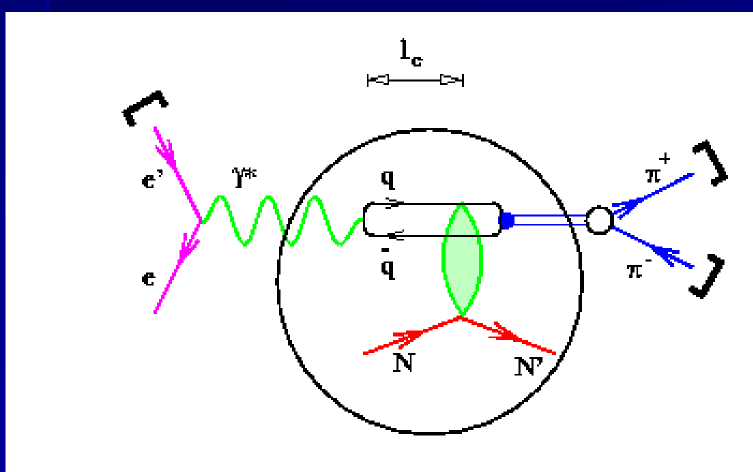
CLAS EG2

Physics Focus

Search for Color Transparency

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

Compare absorption in deuterium, carbon, aluminum, and iron

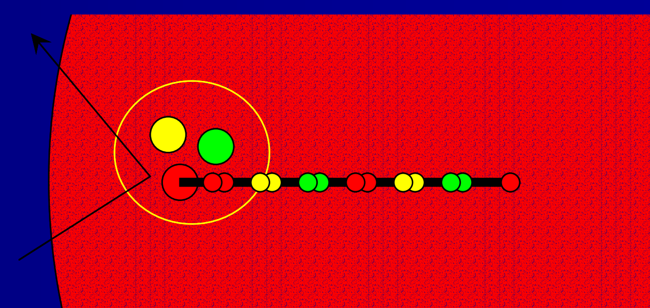


E02-110

Quark Propagation through Nuclei

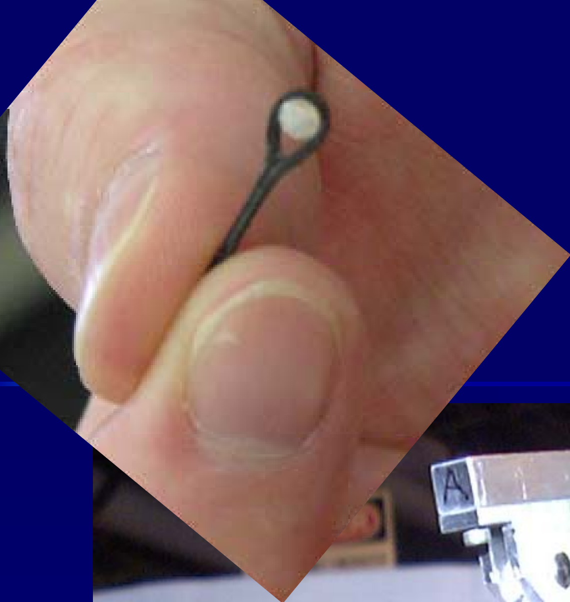
Measure attenuation and transverse momentum broadening of hadrons (π, K) in DIS kinematics

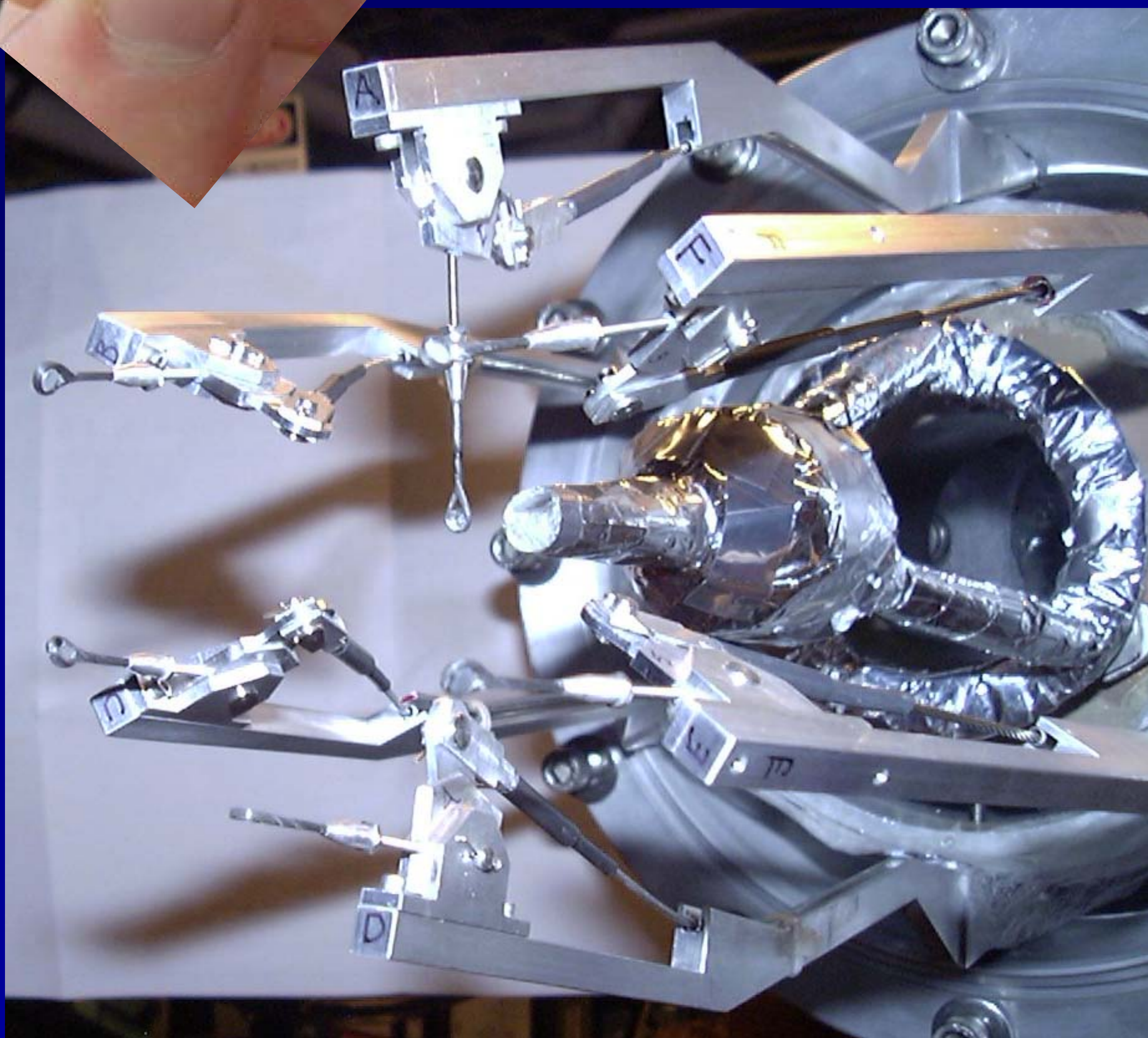
Compare absorption in deuterium, carbon, iron, tin, and lead



E02-104

CLAS EG2
Targets





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

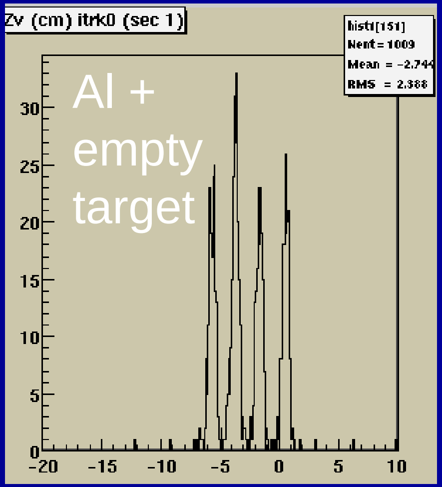
  -Carbon

  -Aluminum (2 thicknesses)

  -Iron

  -Tin

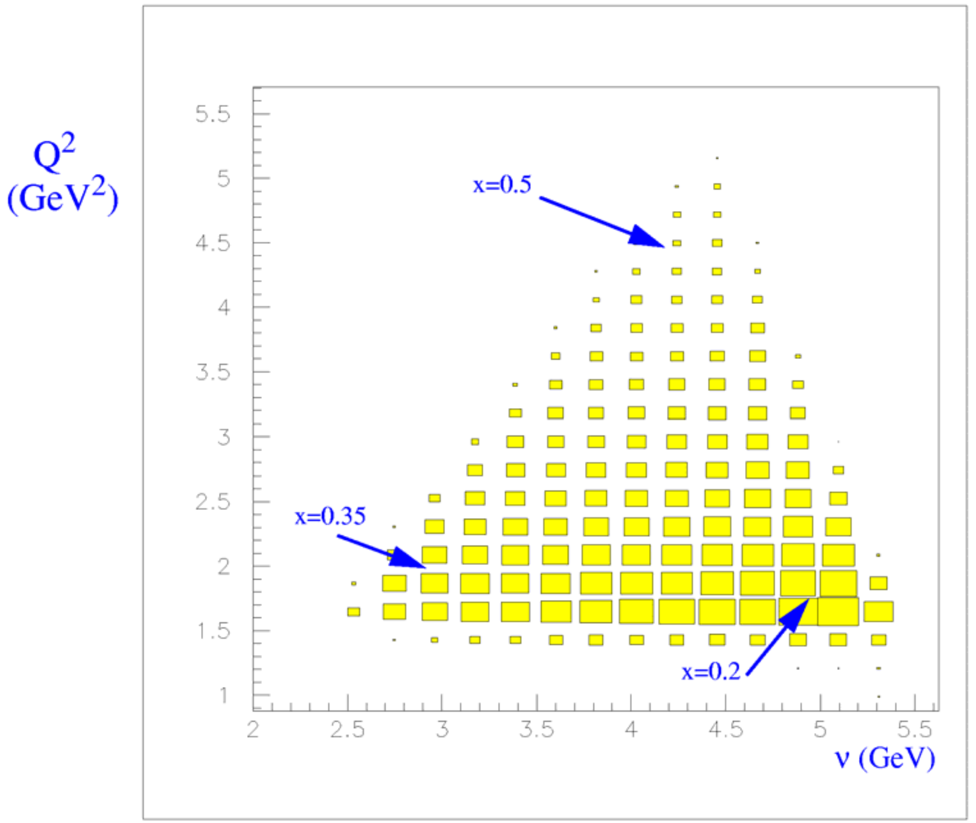
  -Lead



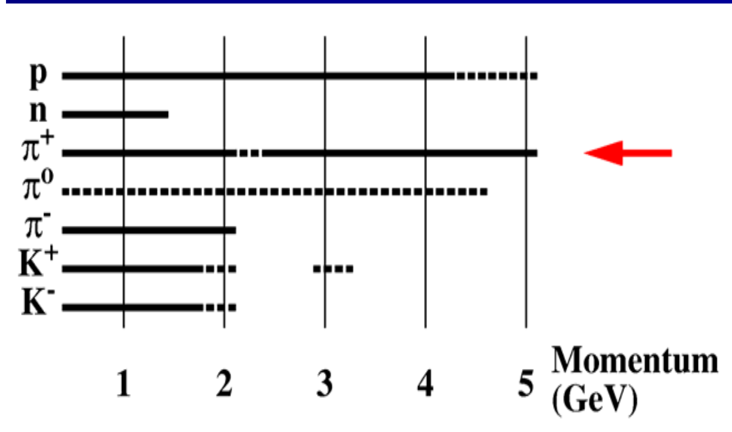
CLAS EG2
Running Conditions

- Beam energies: 4 GeV (7 day) and 5 GeV (50 days)
- Luminosity: 1.9-2.0 E34 (D+Fe), 1.3 E34 (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)
  - Anticipate ~1 billion (D+C, 5 GeV)
- Primary challenges:
  - Beam current stability
  - Beam profile
  - DAQ stability (December 2003 – January 2004)
  - DC gas (summer 2003) and temperature (December 2003)

CLAS Kinematic Coverage and Particle Identification at 6 GeV

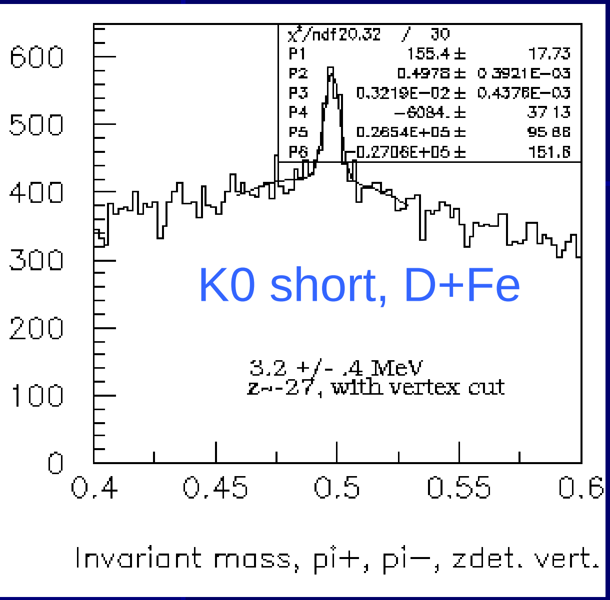


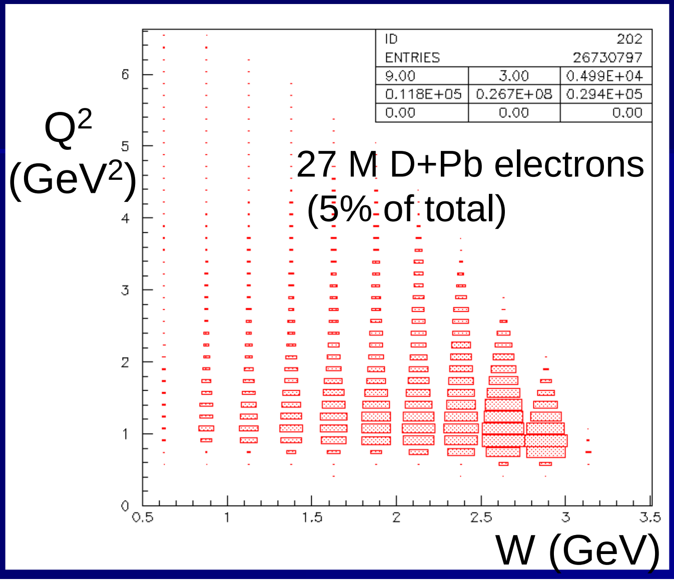
Directly identified particles

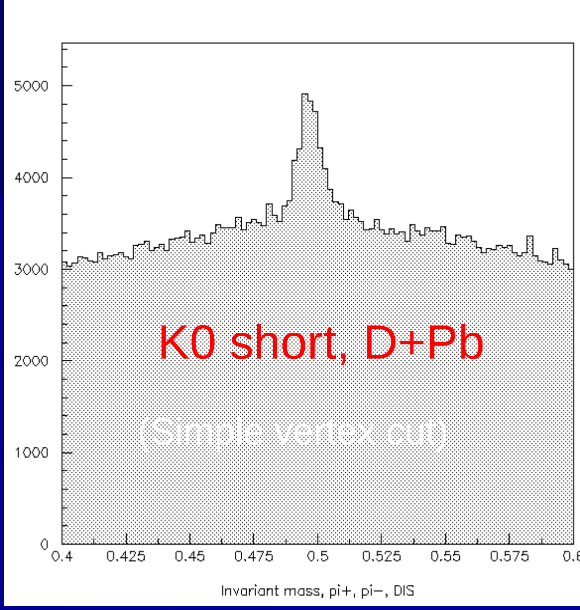


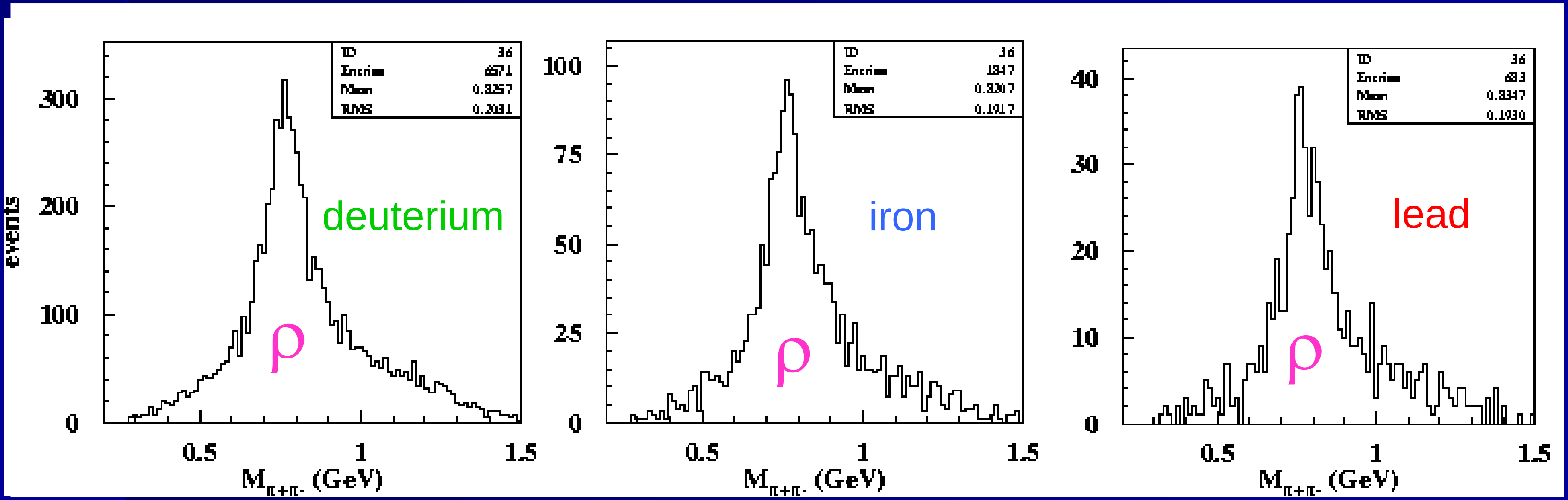
CLAS EG2

Online Physics Results







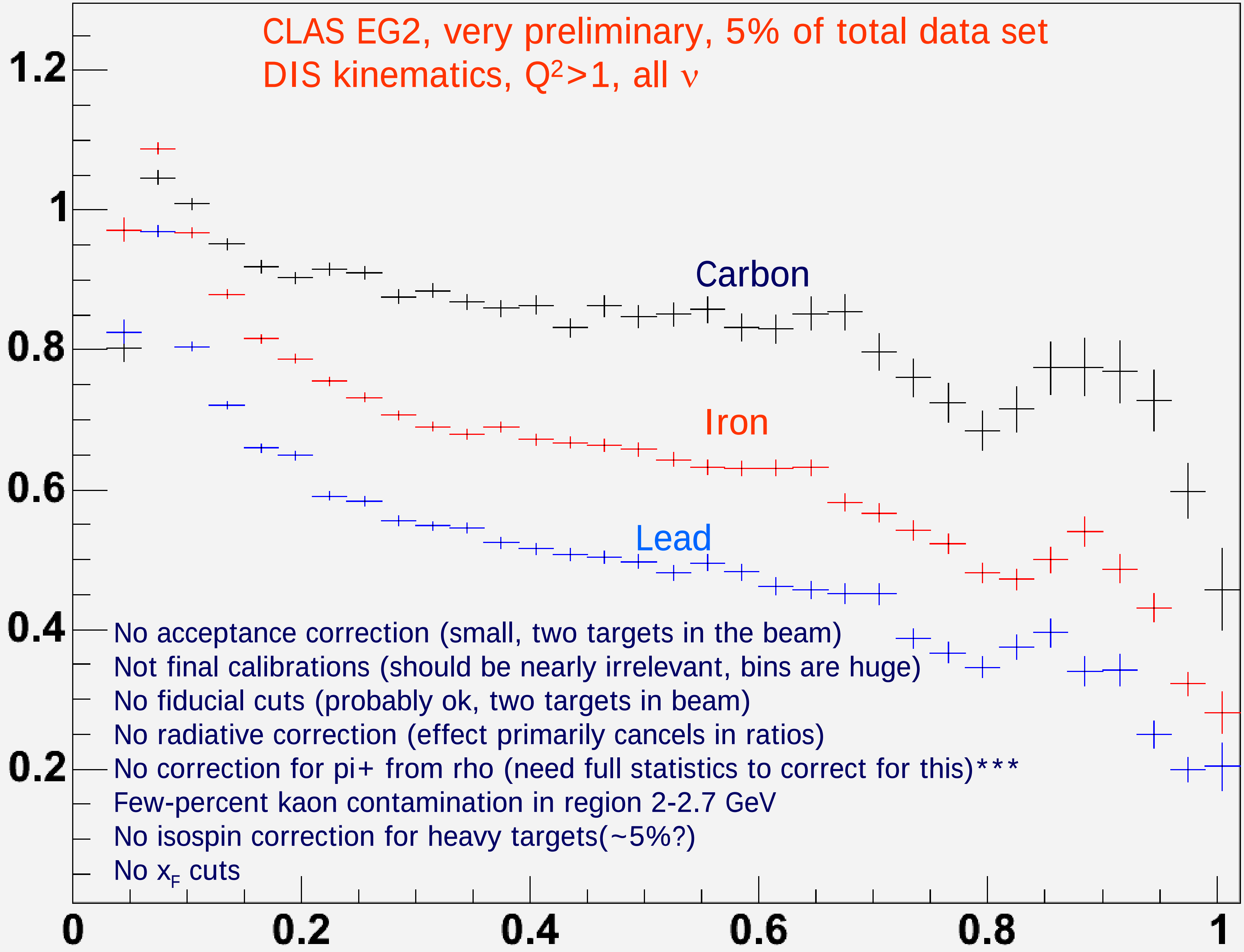


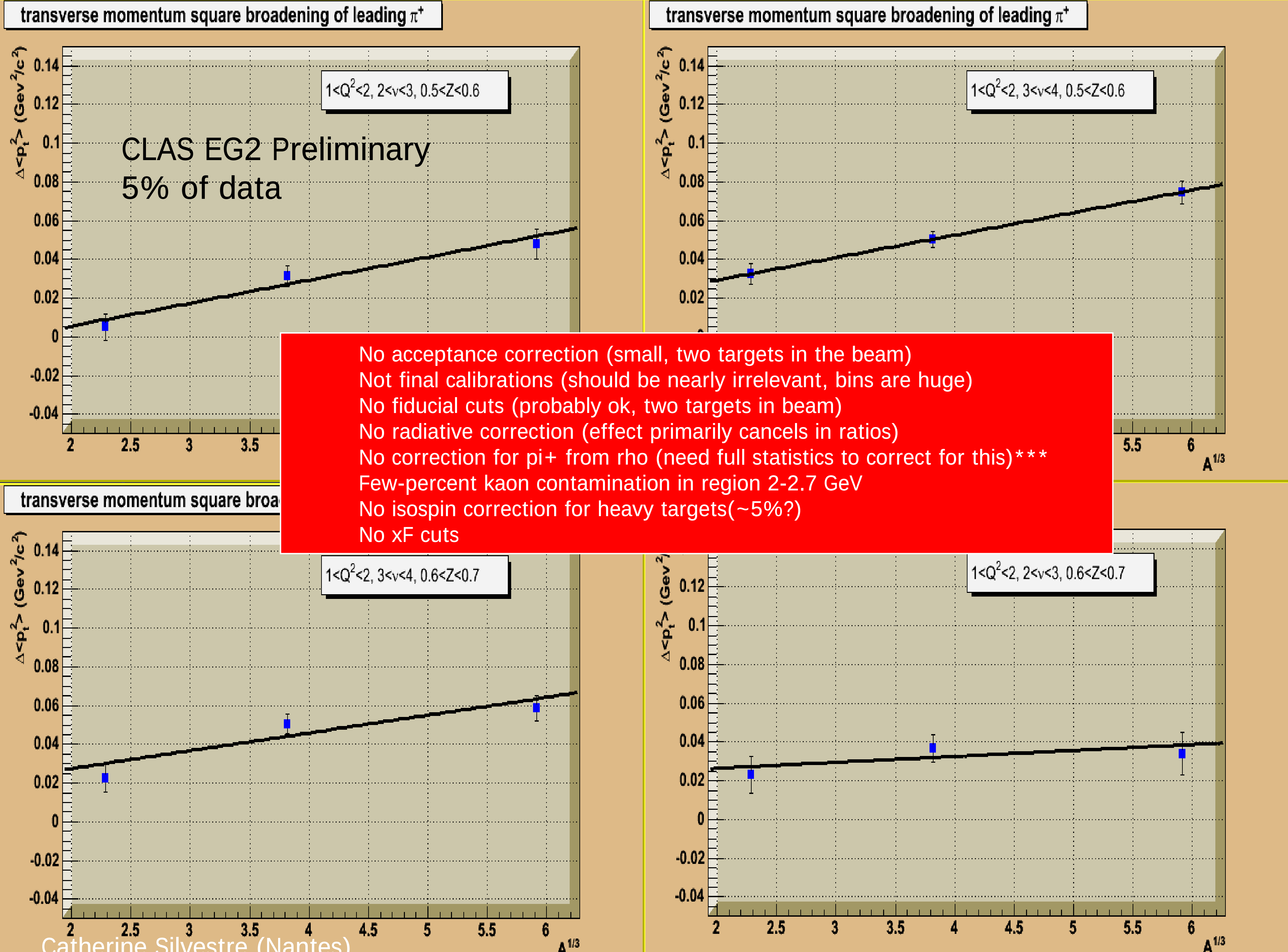
Preliminary Results from EG2

- Based on 5% of data with preliminary calibrations
- Disclaimers and caveats:
  - 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 rho contribution of pi+ (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

Multiplicity ratio for pion+:

Hayk Hakobyan, Yerevan State U.





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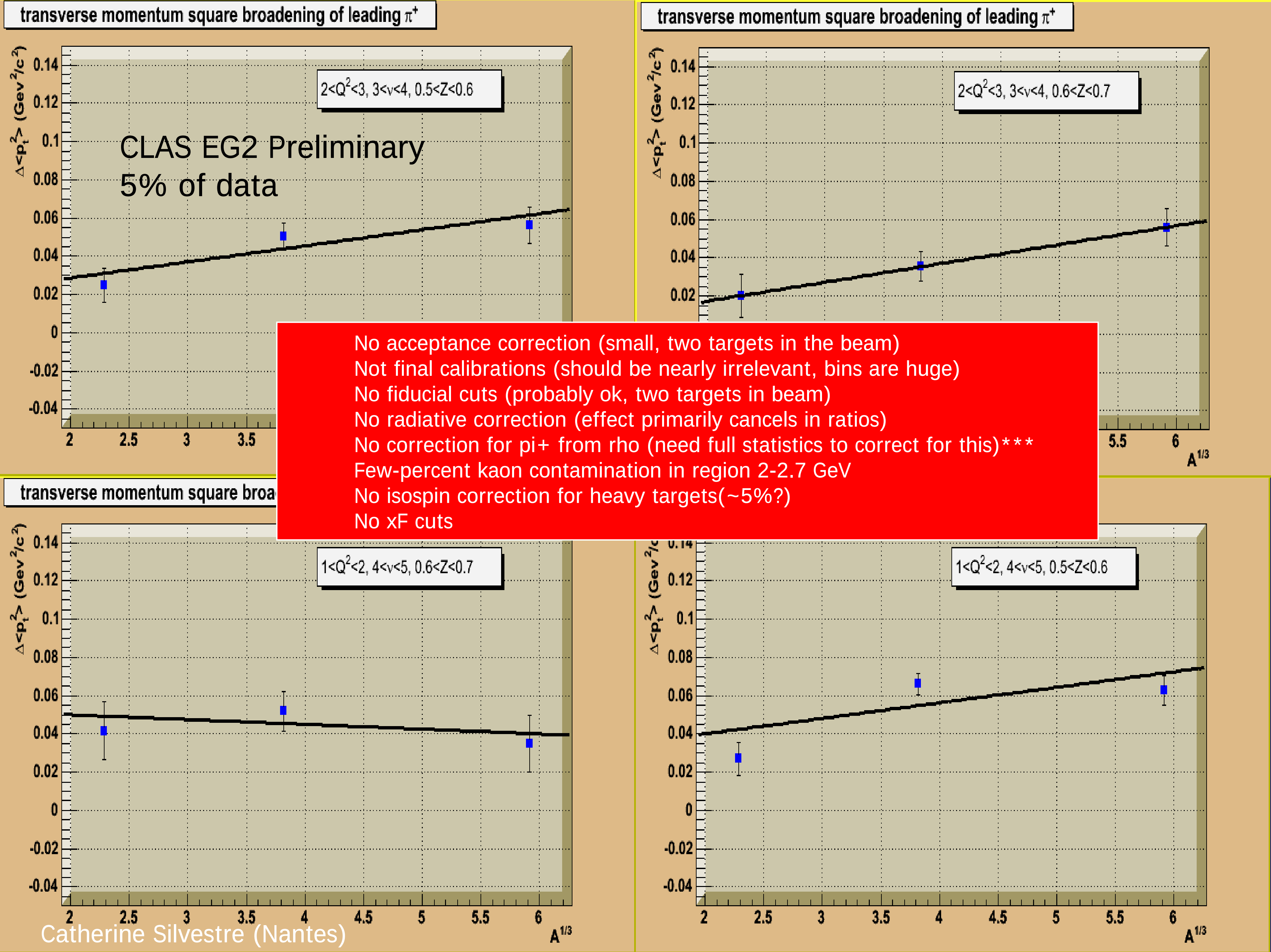
Catherine Silvestre (Nantes)



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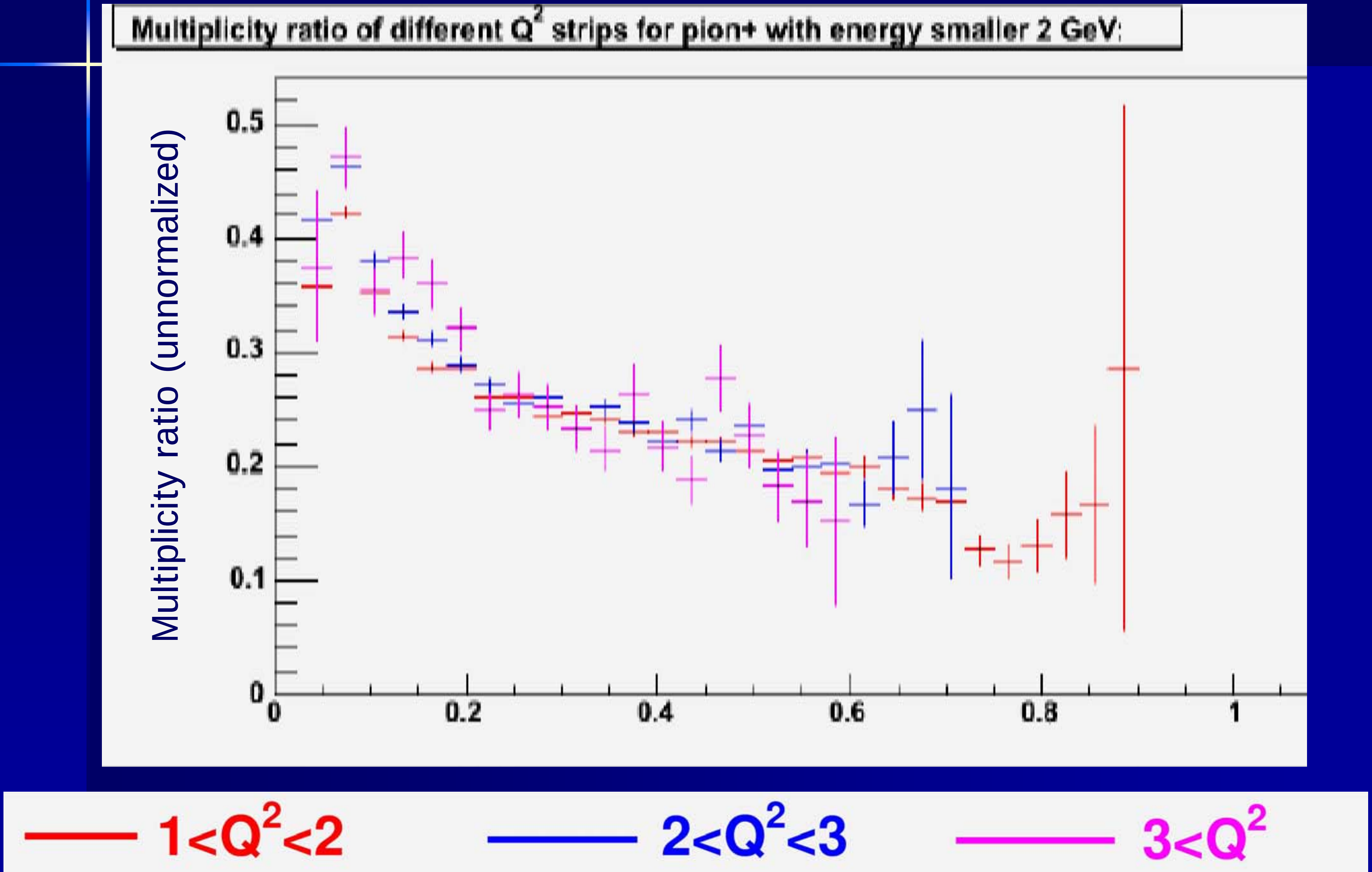
Catherine Silvestre (Nantes)

No clear Q^2 dependence seen



12 GeV Anticipated Data

Examples of Experimental Data and Theoretical Predictions

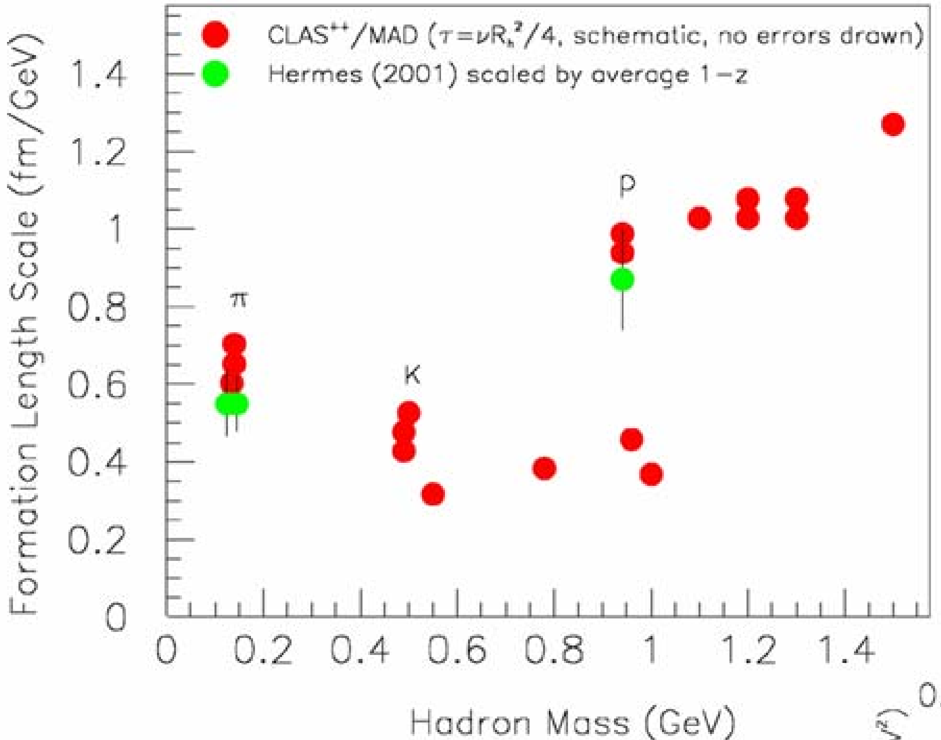
Bins in yellow are accessible at 6 GeV

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

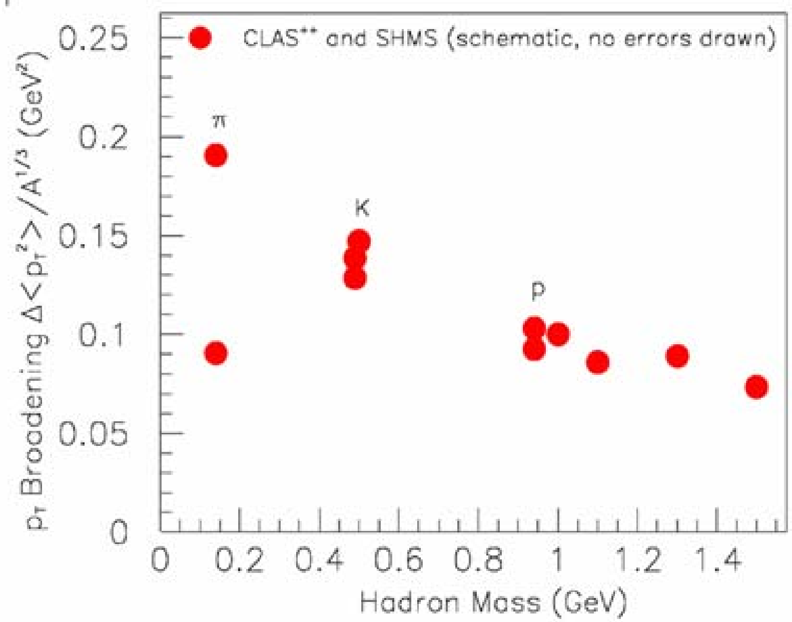
12 GeV Anticipated Data

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.



Conclusions

- The birth of a new class of experiments
- Exciting opportunity to gain new insight into two fundamental QCD processes – hadronization and gluon bremsstrahlung
- The Next Seven Years – new data from all three halls will break new ground
- 12 GeV experiments will be even better

Potential issues

- How much of attenuation is explained by soft gluon radiation?
- Extent to which factorization applies
- Resonances in the residual system
- Distinguish target from current fragmentation?