Space-Time Characteristics of Nuclear Hadronization

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A program of measurements to experimentally characterize multi-variable **hadronization length scales** and **transverse momentum broadening**. These measurements will elucidate the nature of real-time color field restoration through gluon emission, and clarify the role of partonic multiple scattering within the nuclear medium. The program relies on the large acceptance and multi-particle reconstruction capabilities of $CLAS^{++}$ in Hall B, the MAD in Hall A, and the SHMS in Hall C, with an 11 GeV electron beam.

Topics Addressed by Hadronization Studies

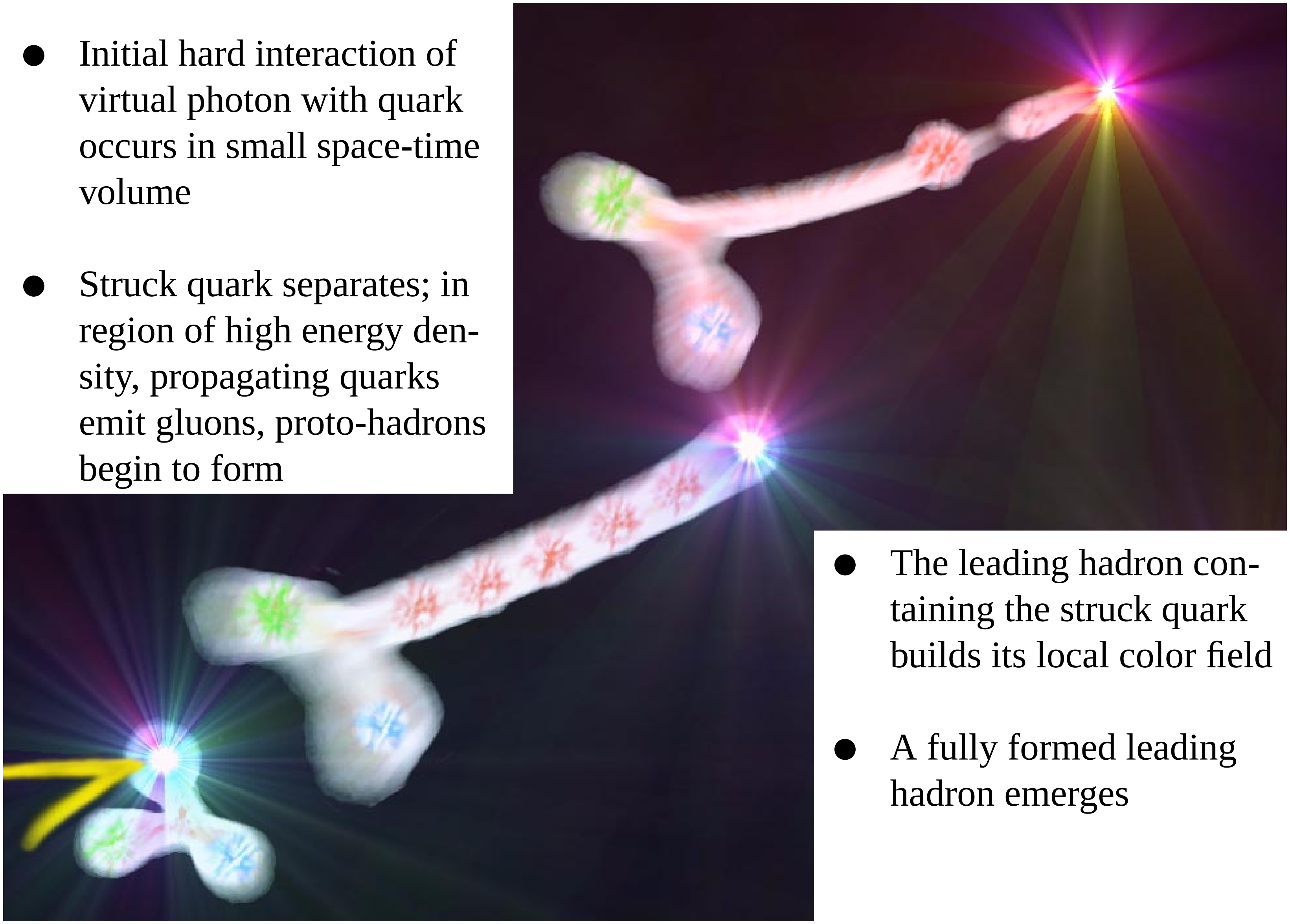
- The fundamental process of gluon emission
  - ➥ The rate and momentum spectrum of gluon emission is closely connected to the experimental observables
  - ➥ Produces a substantial partonic energy loss (dE/dx) which may exhibit exotic in-medium coherence effects
  - ➥ The connection between gluon emission and hadron formation
- Color field restoration
  - ➥ Struck quark's color field is temporarily truncated, is restored in real time via hadron formation over distance scales of several fm.
  - ➥ Analog in QED is well-known and understood

➪➪ ***Experimental data addressing these topics are very limited***

Conceptual Pictures of Hadronization in Vacuum

- Initial hard interaction of virtual photon with quark occurs in small space-time volume

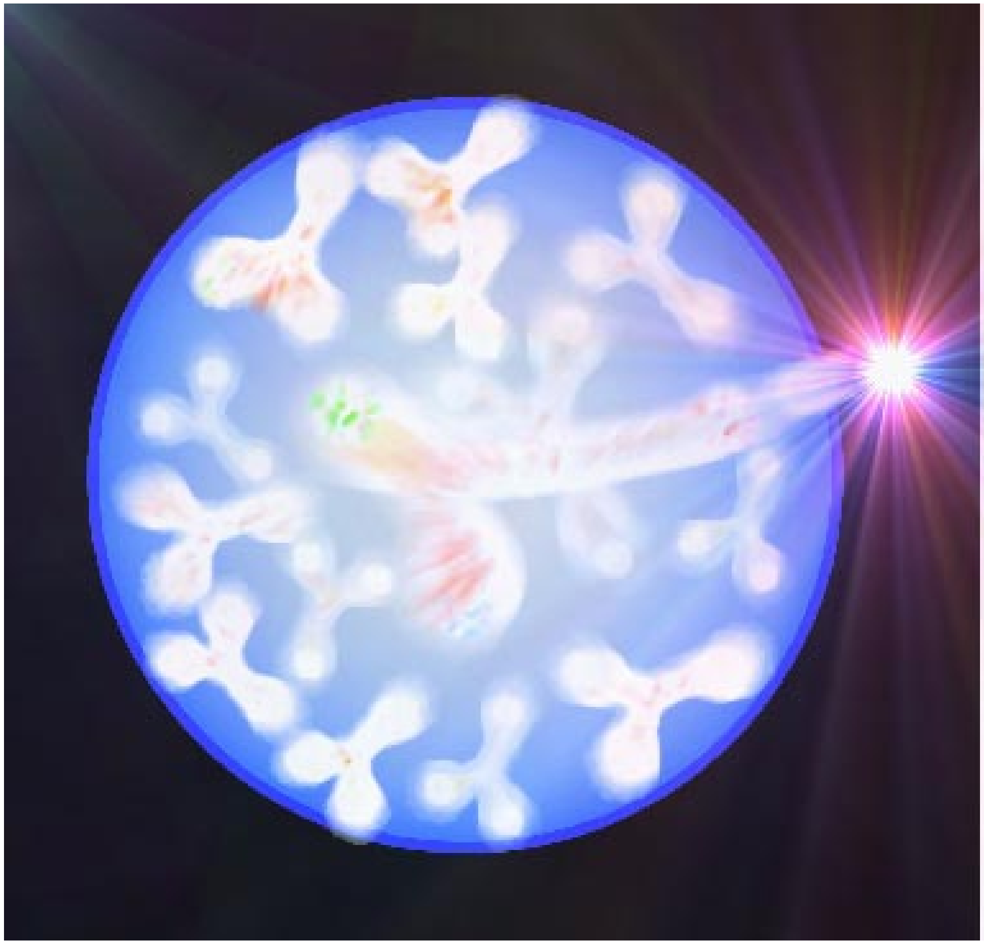
- Struck quark separates; in region of high energy density, propagating quarks emit gluons, proto-hadrons begin to form



- The leading hadron containing the struck quark builds its local color field

- A fully formed leading hadron emerges

Hadronization in the Nuclear Medium



Essentially the same process as in vacuum, with minor variations:

- While the propagating quark and its subsequent proto-hadron pass ‘transparently’ through the medium, the fully formed hadron interacts strongly
- The strongly interacting hadrons ‘disappear’ (shift to lower momentum/higher multiplicity/larger angles)
- The propagating quark multiple scatters through the medium

➪➪ ***The space-time interval required to form the hadron can be ‘measured’ using target nuclei of varying diameters***

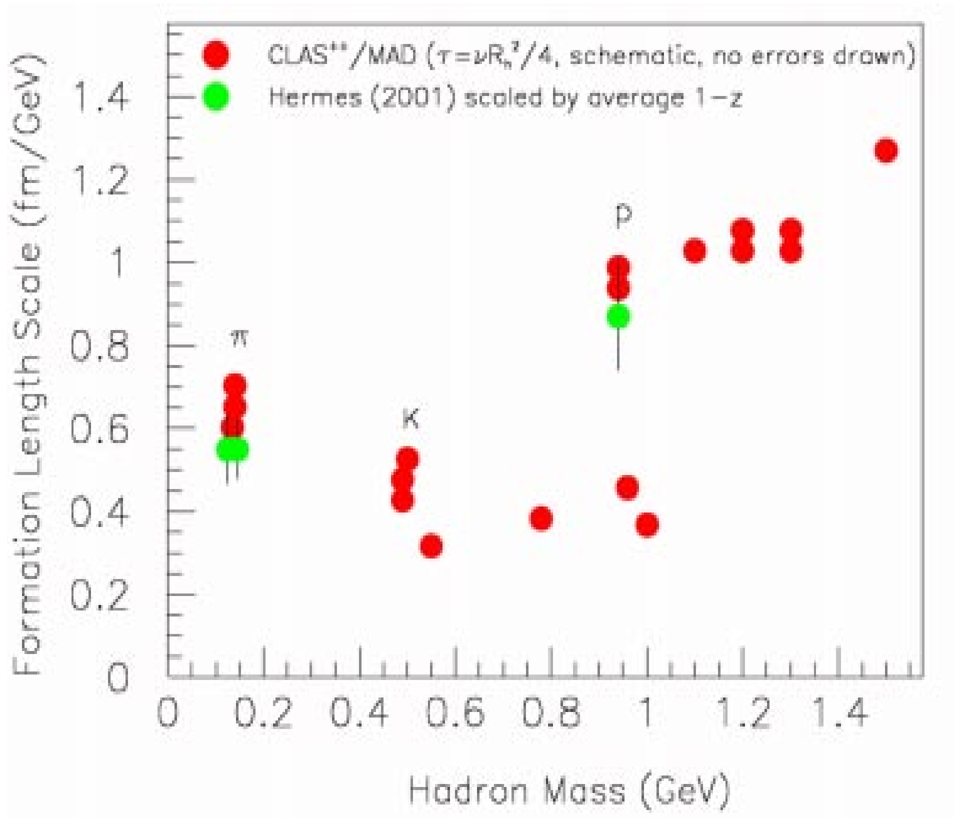
Observables and Kinematic Variables

- Virtual photon energy $\nu = E_e - E_{e'}$ assumed to be the initial energy of the struck quark, and the four-momentum transferred by the electron Q^2
- The fraction of the virtual photon's energy carried by the final hadron: $z = \frac{E_{hadron}}{\nu}$ and the momentum component of the hadron transverse to the virtual photon's direction: p_T
- Hadronic multiplicity ratio: the ratio of the number of hadrons produced in deep inelastic kinematics on nucleus A compared to deuterium, normalized to the number of DIS electrons (closely related to fragmentation function ratios):

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

Hadronic Formation Lengths

- Can make simplistic predictions of formation length. (Many have been made.)
- Can take radius R of hadron being formed, boost to lab frame, get $\tau \sim R^2 \nu$.
- HERMES nitrogen target analysis* for π^+, π^-, p, found good fit to data at Q^2~1-2 GeV^2 using $\tau = c_h(1-z)\nu$.

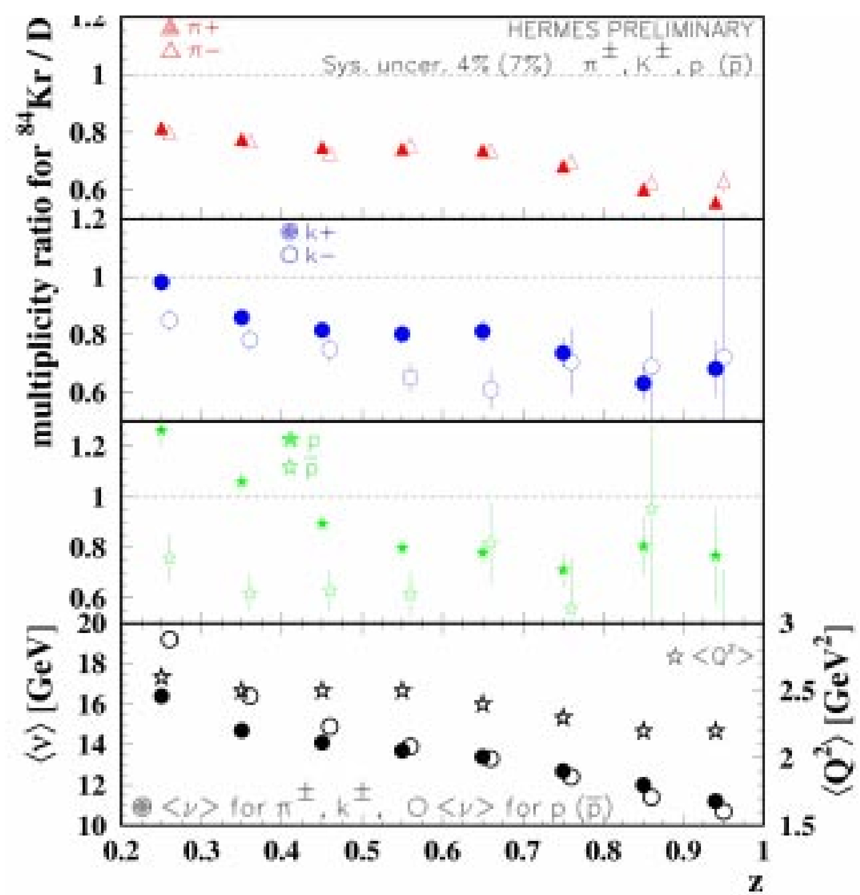


➪➪ JLAB data could add much more information to this picture by measuring many more hadrons and out to much higher Q^2.

*Hermes also has data for K^+, K^-, $\bar{p}$ for a krypton target for which formation length analyses have not yet been published.

Multi-Variable Formation Lengths

- Realistic formation lengths are functions of multiple variables (HERMES used ν, ***z***)

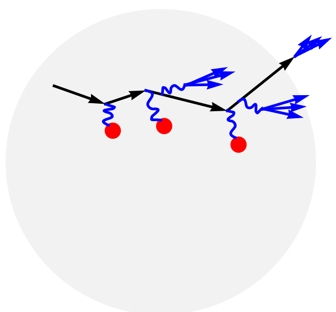


- At JLAB we can experimentally determine the dependencies on ***ν, z, Q^2, p_T, hadron mass, helicity, and quark flavor.***

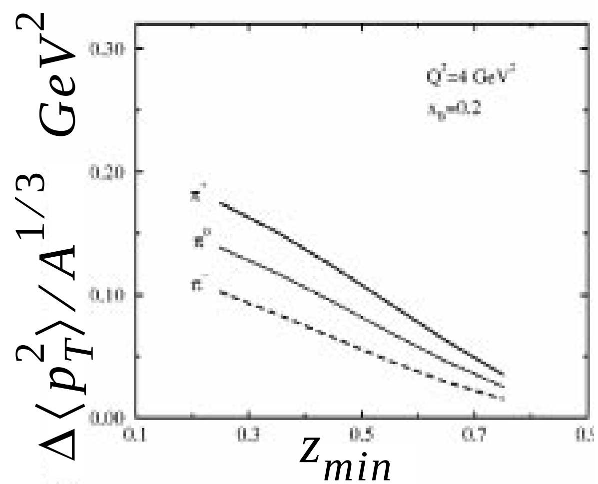
- Sophisticated theories predict more complex variable dependencies:
  - ➥ Gluon bremsstrahlung model
  - ➥ Twist-four pQCD model
  - ➥ Lattice

➪➪ Complete characterization of the multi-variable properties of the formation length is crucial for unambiguous interpretation.

Transverse Momentum Broadening



- Partons traversing the nuclear medium multiple scatter. This induces additional gluon radiation.
- The additional gluon radiation can be related to a quark energy loss (dE/dx) which has been estimated to be at the 1 GeV/fm scale in particular calculations.



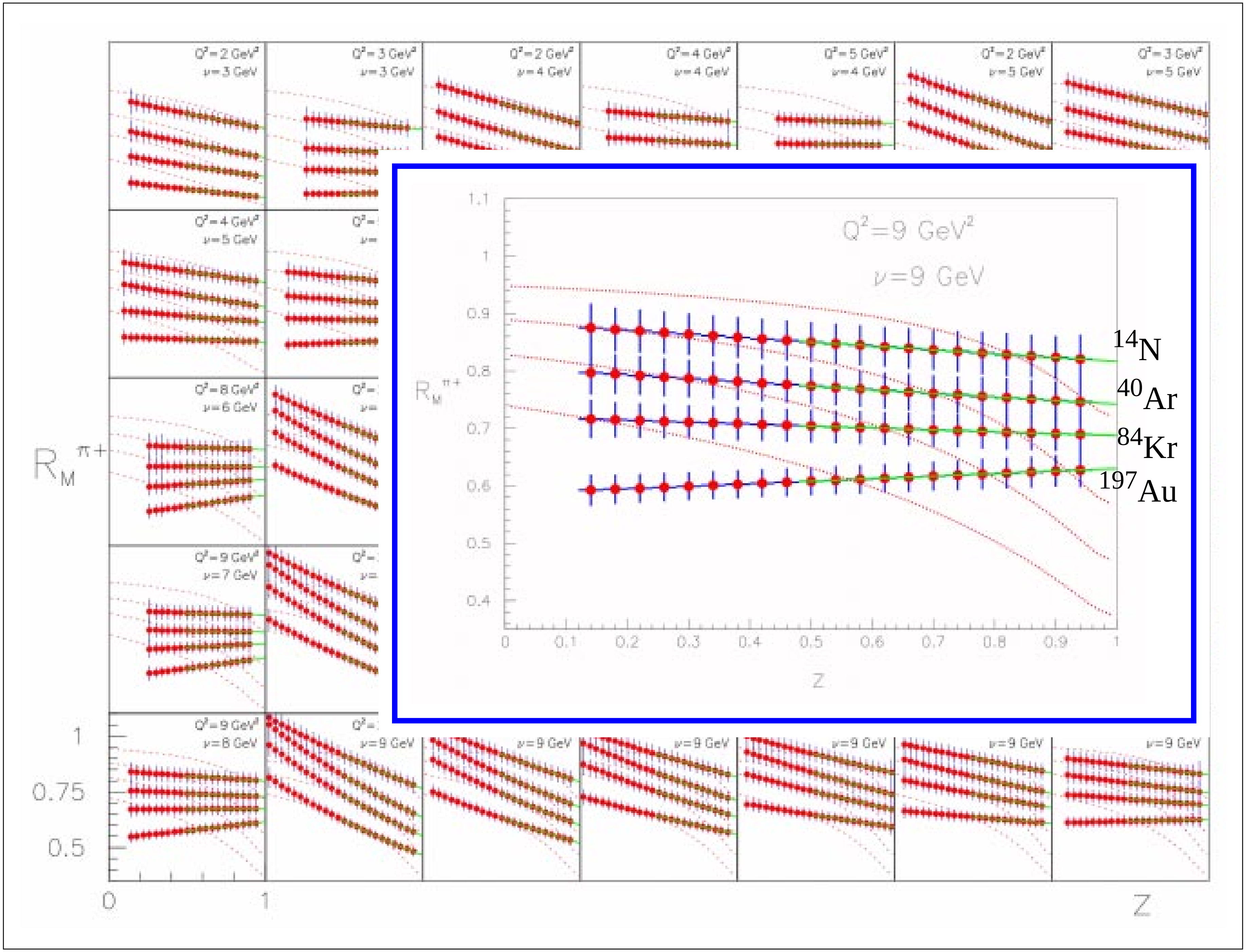
- The p_T distribution of the outgoing hadrons consequently broadens for larger nuclei, ~ $A^{1/3}$.
- Calculations indicate that a quark-gluon correlation function can be directly inferred from transverse momentum broadening (PRD 61 096003).

⇨⇨ ***CLAS^{++} can access this quantity for approximately 10 hadron species; the SHMS in Hall C can access it to the highest momenta and best resolution for several hadron species***

Measurement Method

- Measure semi-exclusive hadron production in DIS kinematics on five nuclear targets, e.g. ^{2}H, ^{14}N, ^{40}Ar, ^{84}Kr, ^{197}Au with 11 GeV electron beam.
- Identify the hadronic final state.
- Measure R_M^h and $\Delta\langle p_T^2\rangle$.
- For each hadron, divide the data into multi-dimensional bins in subsets of Q^2, ν or x, p_T, z, ϕ, A, etc. as statistics permit.
- The primary experimental results are the dependence of R_M^h and $\Delta\langle p_T^2\rangle$ on the above variables.
- Higher level analysis: will have to test factorization assumptions, test isolation of current fragmentation, understand radiative corrections, extract formation lengths for all hadrons in a unified framework.

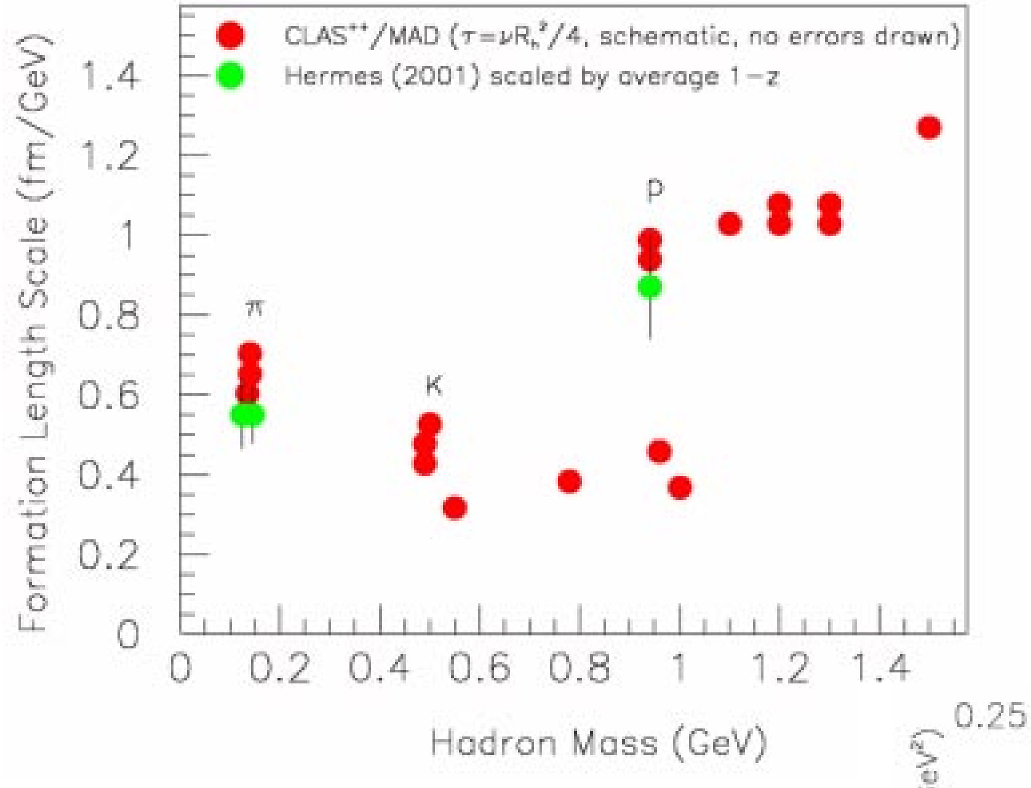
Examples of Experimental Data and Theoretical Predictions


Q^2=9 GeV^2
ν=9 GeV
$R_M^{\pi+}$
z
^{14}N
^{40}Ar
^{84}Kr
^{197}Au
Z

Accessible hadrons

- Select hadrons with $c\tau$ > nuclear diameter.
- The sum total of the experimental information consists of plots such as the preceding for each hadron in the table - a very large data set.
- Hadrons detected in charged particle channels can also be studied for transverse momentum broadening.
- Several possible analysis divisions into multiple experiments

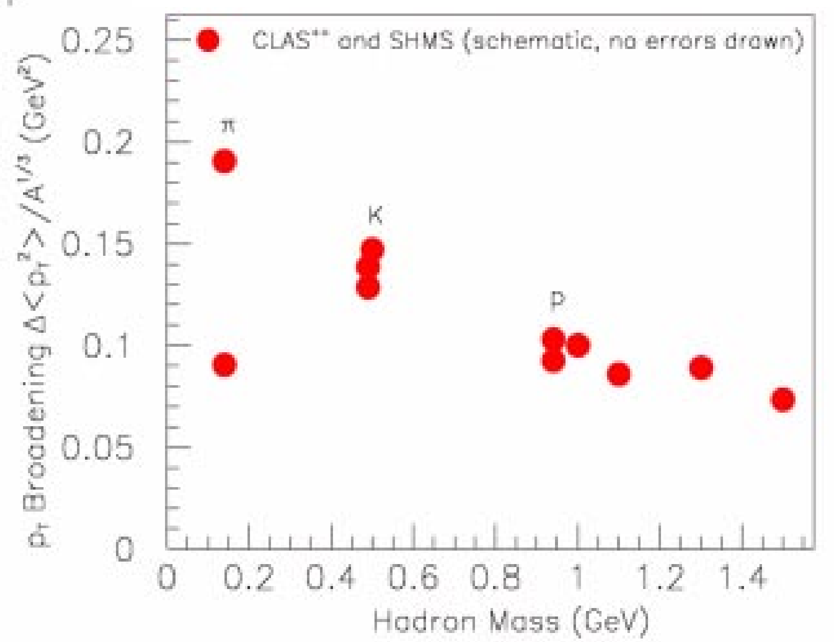
hadron	channel	number / 1000 DIS events
π^0	$\gamma\gamma$	**1100**
π^+	**direct**	**1000**
π^-	**direct**	**1000**
η	$\gamma\gamma$	**120**
ω	$\pi^+\pi^-\pi^0$	**170**
η'	$\pi^+\pi^-\eta$	**27**
ϕ	K^+K^-	**0.8**
K^+	**direct**	**75**
K^-	**direct**	**25**
K^0	$\pi^+\pi^-$	**42**
p	**direct**	**1100**
$\bar{p}$	**direct**	**3**
Λ	$p\pi^-$	**72**
$\Lambda(1520)$	$p\pi^-$	**-**
Σ^+	$p\pi^0$	**6**
Σ^0	$\Lambda\gamma$	**11**
Ξ^0	$\Lambda\pi^0$	**0.6**
Ξ^+	$\Lambda\pi^-$	**0.9**



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.



Scientific Goals: Summary

- Space-time description of the hadronization process - *color field restoration*
- The *fundamental process of gluon emission* and its connection to hadronization
- *Partonic energy loss* (dE/dx), and potential exotic in-medium coherence effects
- Quark-gluon correlations

Conclusions

- The capability for a new class of measurement:
  - ➥ physics of color field of hadrons in space-time domain
  - ➥ a bridge to understanding high-energy properties of nuclei
  - ➥ connects to investigations at several other major laboratories
- JLab at 12 GeV is an excellent place to carry out these measurements:
  - ➥ appropriate energy range
  - ➥ high luminosity ➟ can study lower-rate processes
  - ➥ solid target capability ➟ can use largest nuclei

➪➪ ***Outstanding opportunity to discover a wealth of new physics***