Space-time Properties of Hadronization:

insights from semi-inclusive DIS on nuclei

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Outline

- Introduction
- Transverse momentum broadening and quark energy loss in nuclei
- Hadron formation lengths
- Other opportunities with existing data

Main Physics Focus

QCD in the space-time domain:

- 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 *transverse momentum broadening* that arises due to partonic elastic scattering and medium-stimulated gluon emission

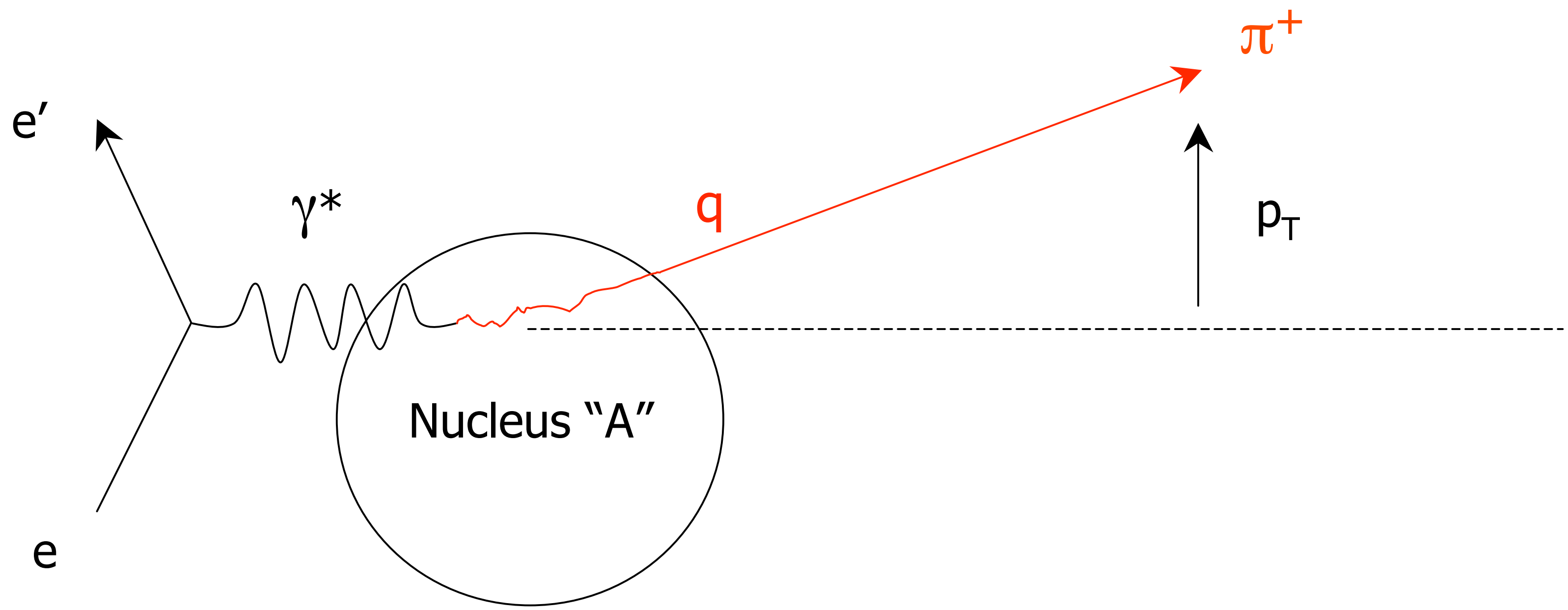
- How long does it take to form the full color field of a hadron?
  - The formation time τ_f^h measures this
  - Measure τ_f^h via *hadron attenuation in nuclei* together with the understanding of the production time τ_p

“How long can a light quark remain deconfined?”

p_T Broadening, Production Time, and Quark Energy Loss

Definitions

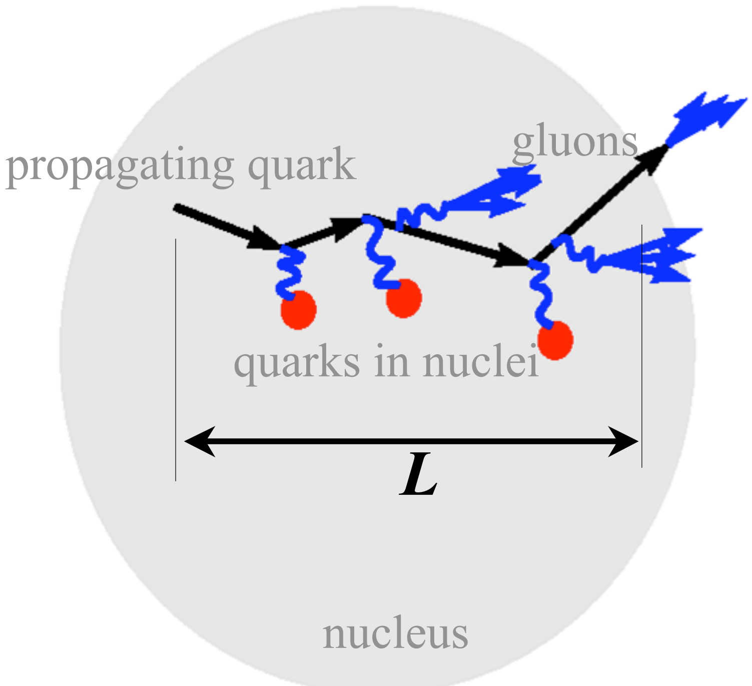
$$p_T\ broadening:\quad \Delta p_T^2 \equiv \left\langle p_T^2 \right\rangle_A^{DIS} - \left\langle p_T^2 \right\rangle_D^{DIS}$$



Production time: lifetime of deconfined quark, e.g., $\tau_p \approx \dfrac{\nu(1-z)}{c\dfrac{dE}{dx}}$

p_T Broadening and Quark Energy Loss

- Quarks lose energy by *gluon emission* as they propagate
  - In vacuum
  - Even more within a medium



- This energy loss is manifested by Δp_T^2
- Δp_T^2 is a signature of the *production time* τ_p

- $\Delta E \sim L$ dominates in QED
- $\Delta E \sim L^2$ dominates in QCD?

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

Medium-stimulated loss calculation by BDMPS

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

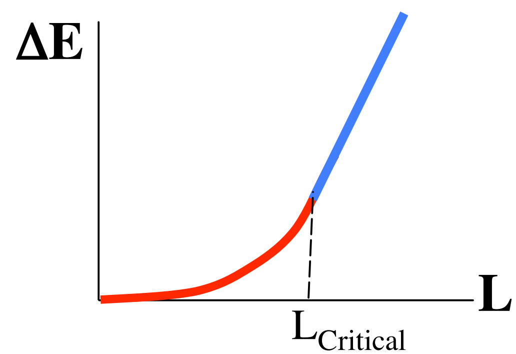
Three regions: if mean free path is λ, and medium length is L, then →

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

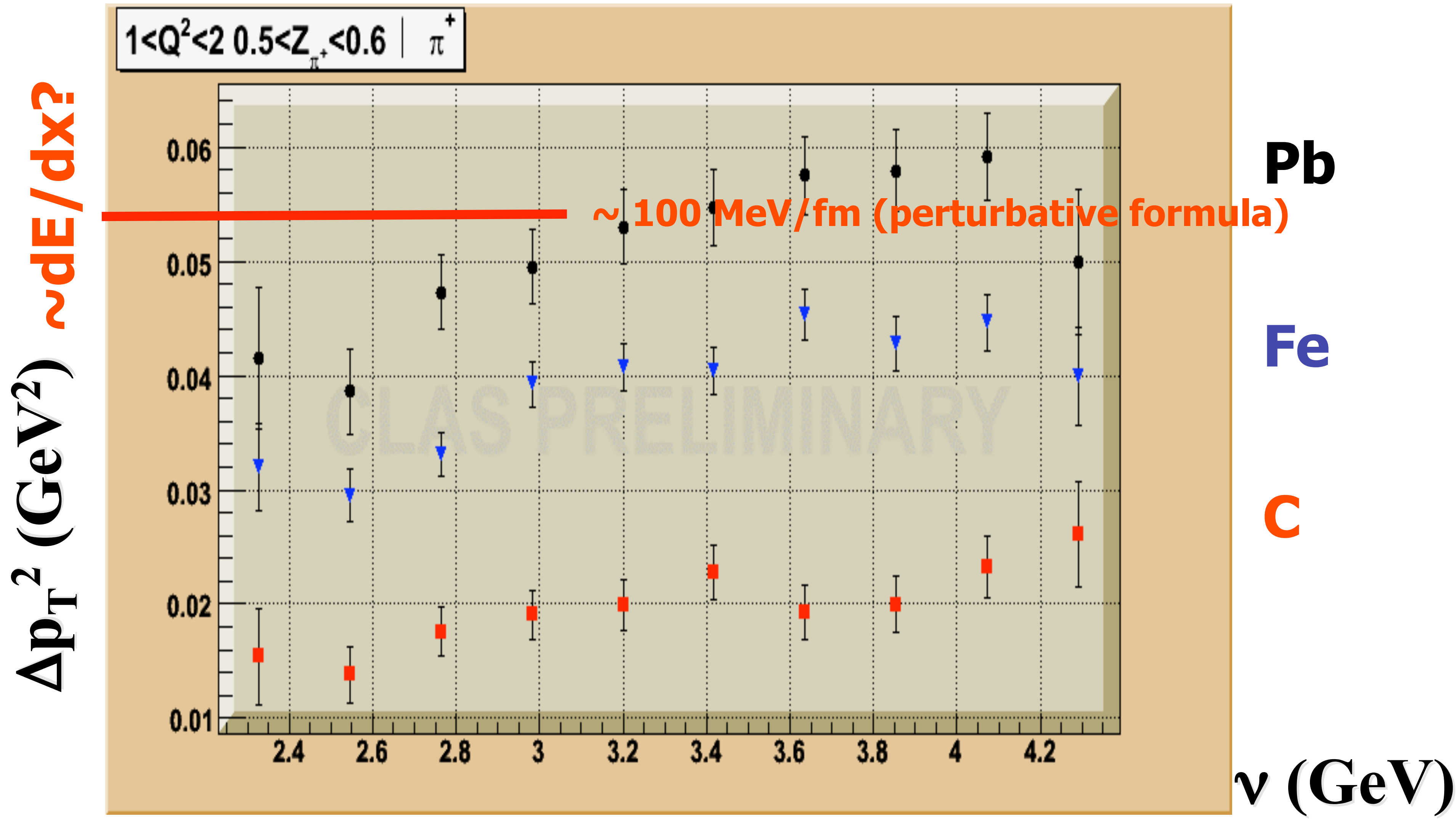
Two conditions emerge:

$$-\frac{dE}{dx} \propto L \qquad L < L_{Critical}$$

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

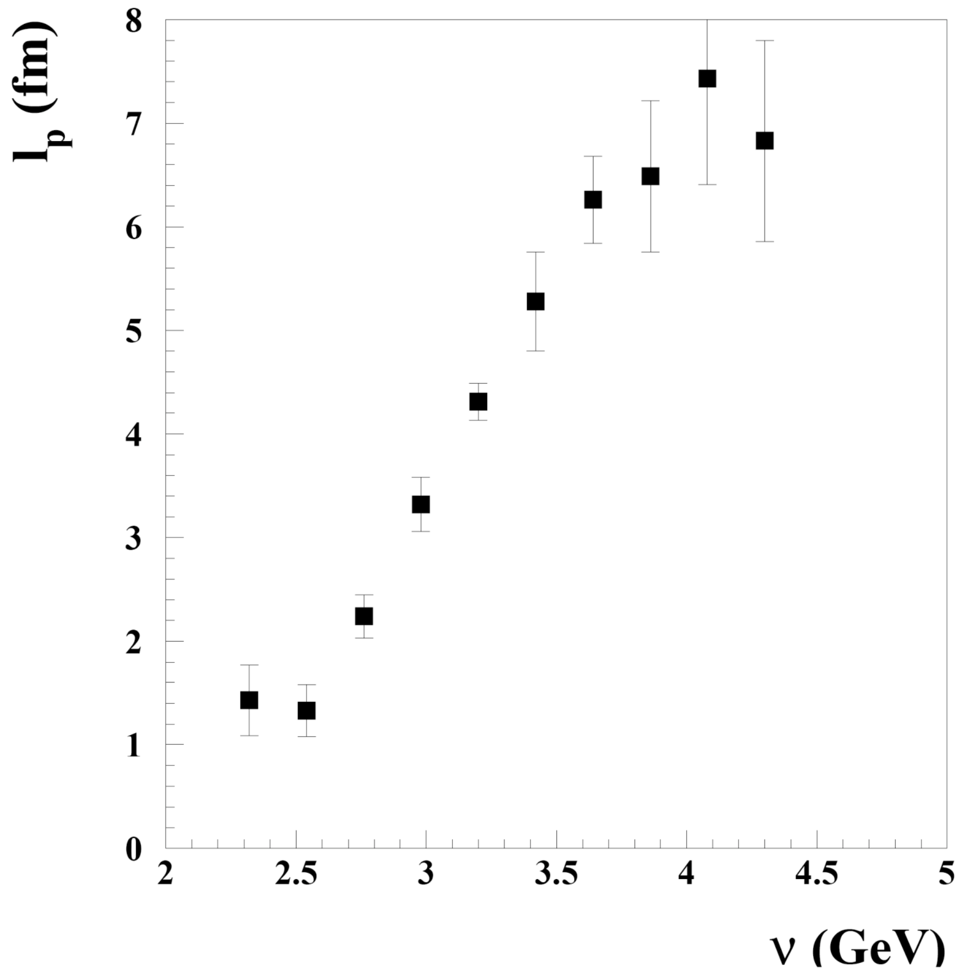


Δp_T^2 vs. ν for Carbon, Iron, and Lead

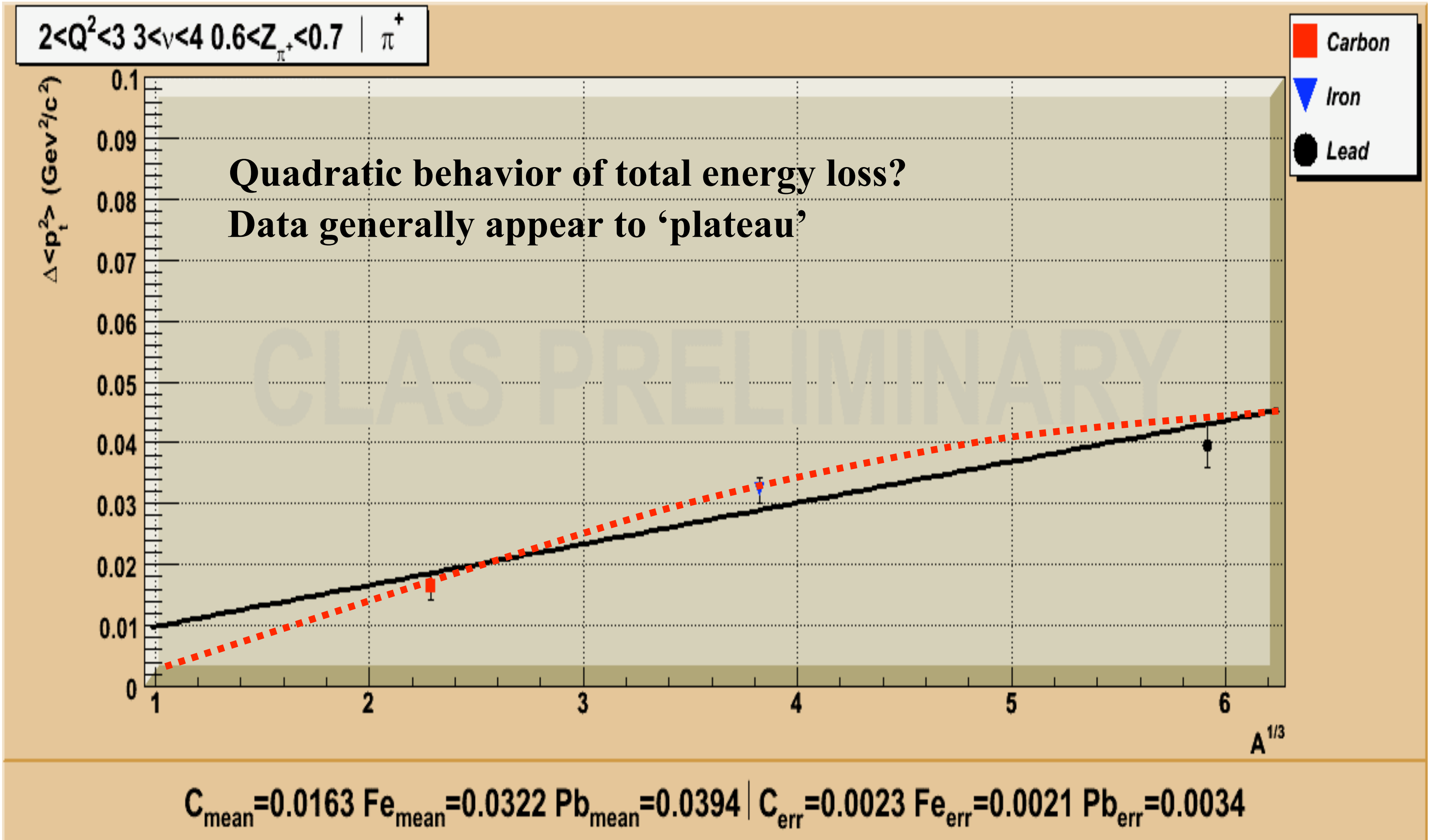


Production length from JLab/CLAS 5 GeV data

(Kopeliovich, Nemchik, Schmidt, hep-ph/0608044)



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



Only statistical errors shown

pT Broadening - Summary

What we have learned

- Precise, multivariable measurements of Δp_T^2 are feasible
- Quark energy loss can be estimated:
  - Data consistent with the novel $\Delta E \sim L^2$ 'LPM' behavior
  - ~100 MeV/fm for Pb at few GeV, perturbative formula
  - Can do a direct measurement?
- Deconfined quark lifetime can be estimated, ~ 5 fm @ few GeV
- Much more theoretical work needed for quantitative results

Outstanding questions

- Is the physical picture accurate?
  - Transition to $\Delta E \sim L^*E^{1/2}$ behavior at higher ν? **JLAB12/EIC**
  - Can asymptotic behavior $\Delta E \rightarrow 0$ be observed, $\nu \rightarrow \infty$? **EIC**
  - Hadronic corrections under control? Consistent with DY? **E906**
- Plateauing behavior due to short τ_p or energy loss transition? **JLAB12**
- Quantitative connection: jet quenching at RHIC/LHC? **THEORY**

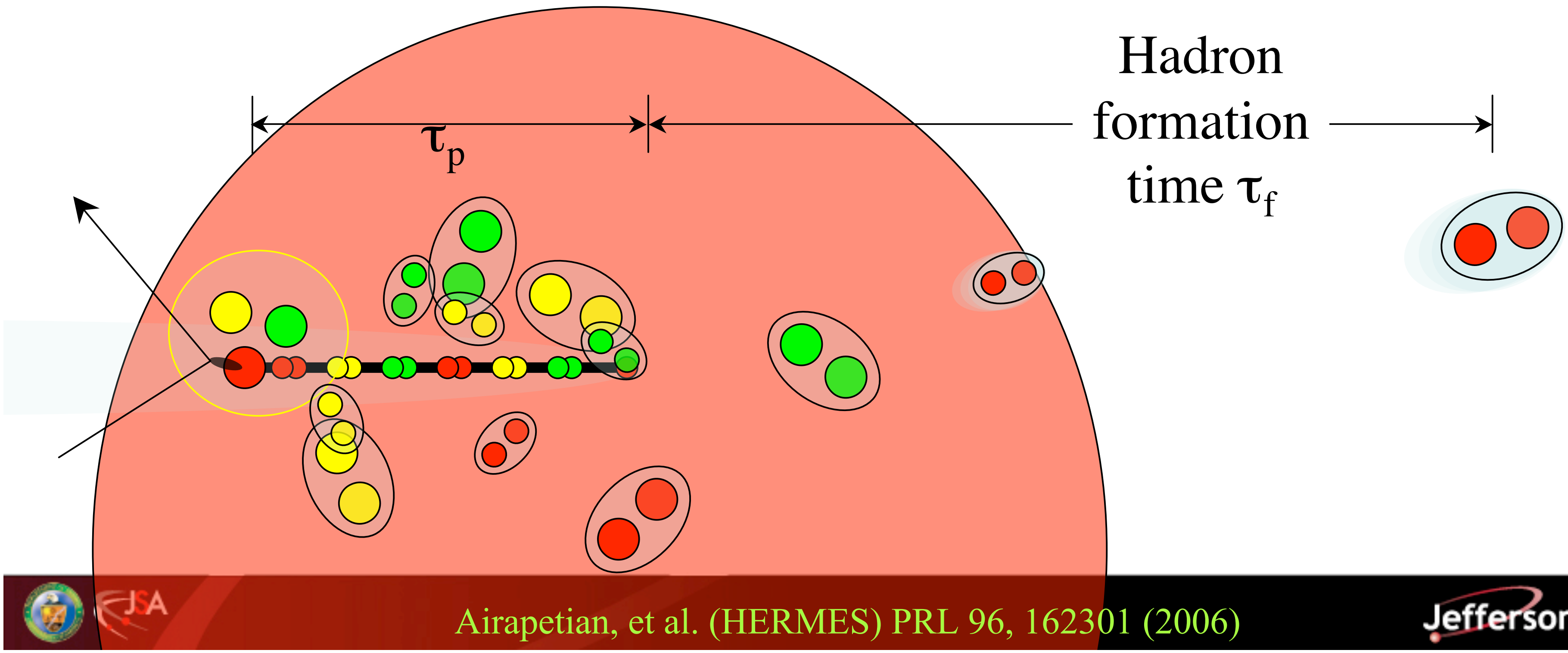
"How long does it take to form the full color field of a hadron?"

Hadron Attenuation

Definitions

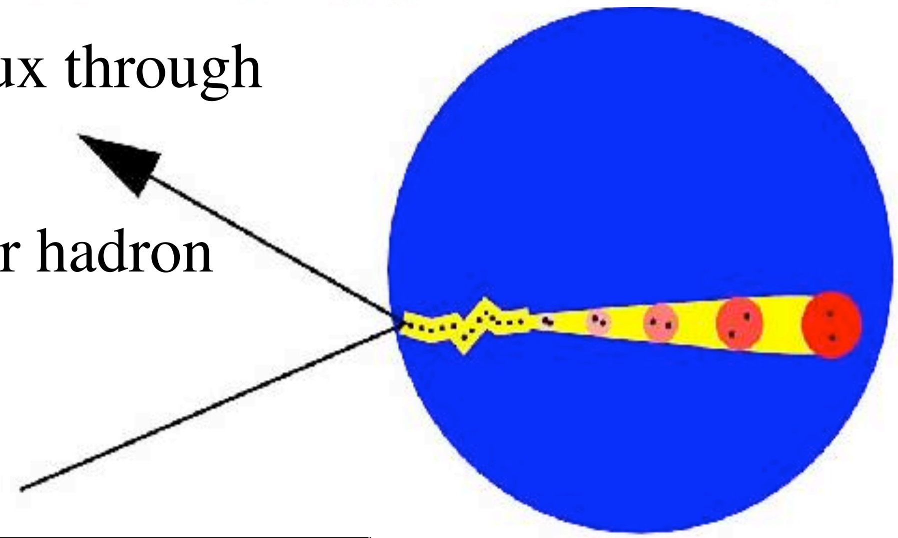
Hadronic multiplicity ratio

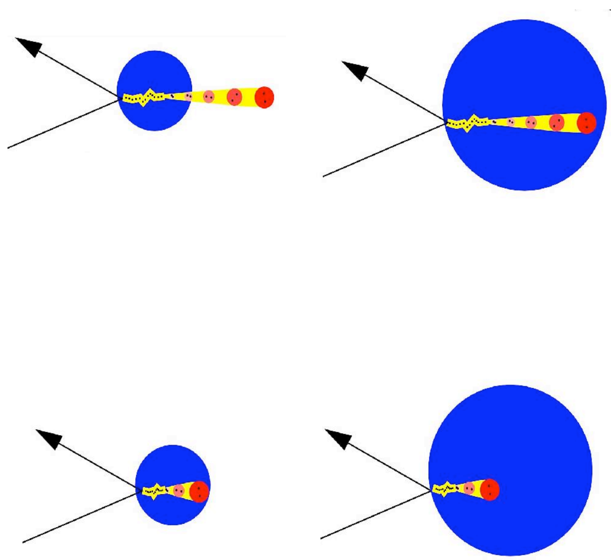
$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_A}{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_D}$$



Hadron Attenuation – Physics Picture

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

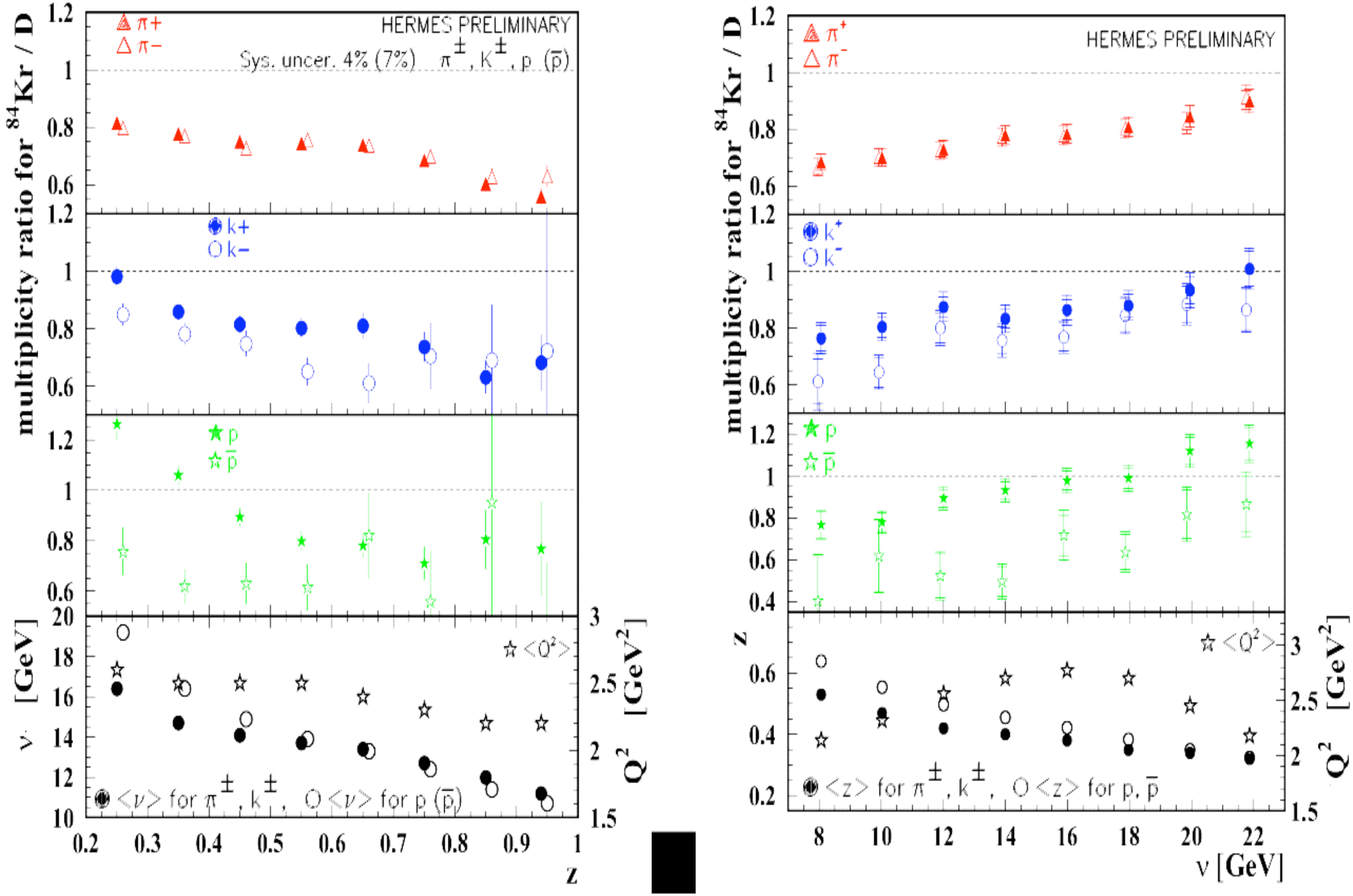




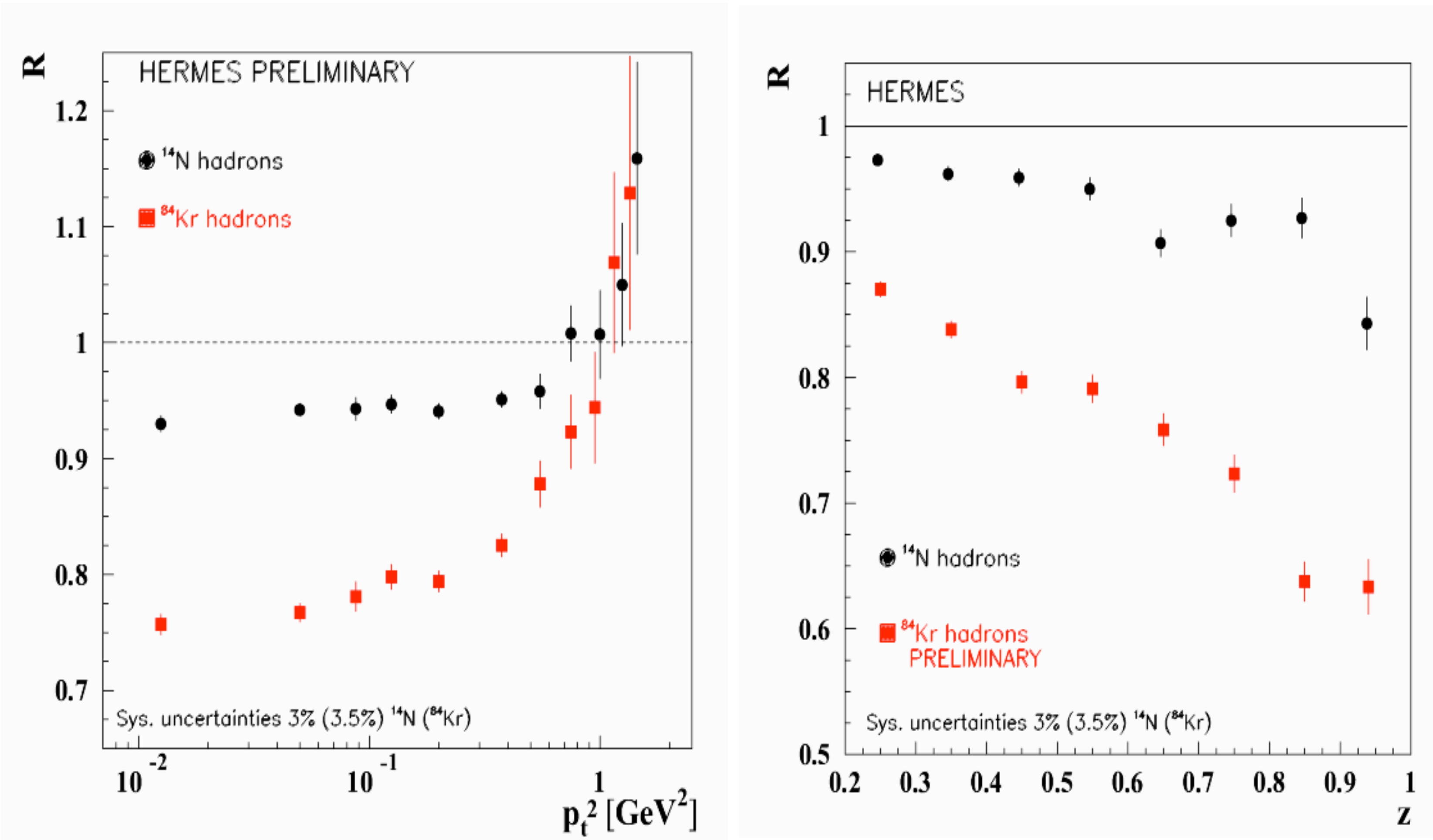
z_h~0.5, larger ν, less attenuation

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

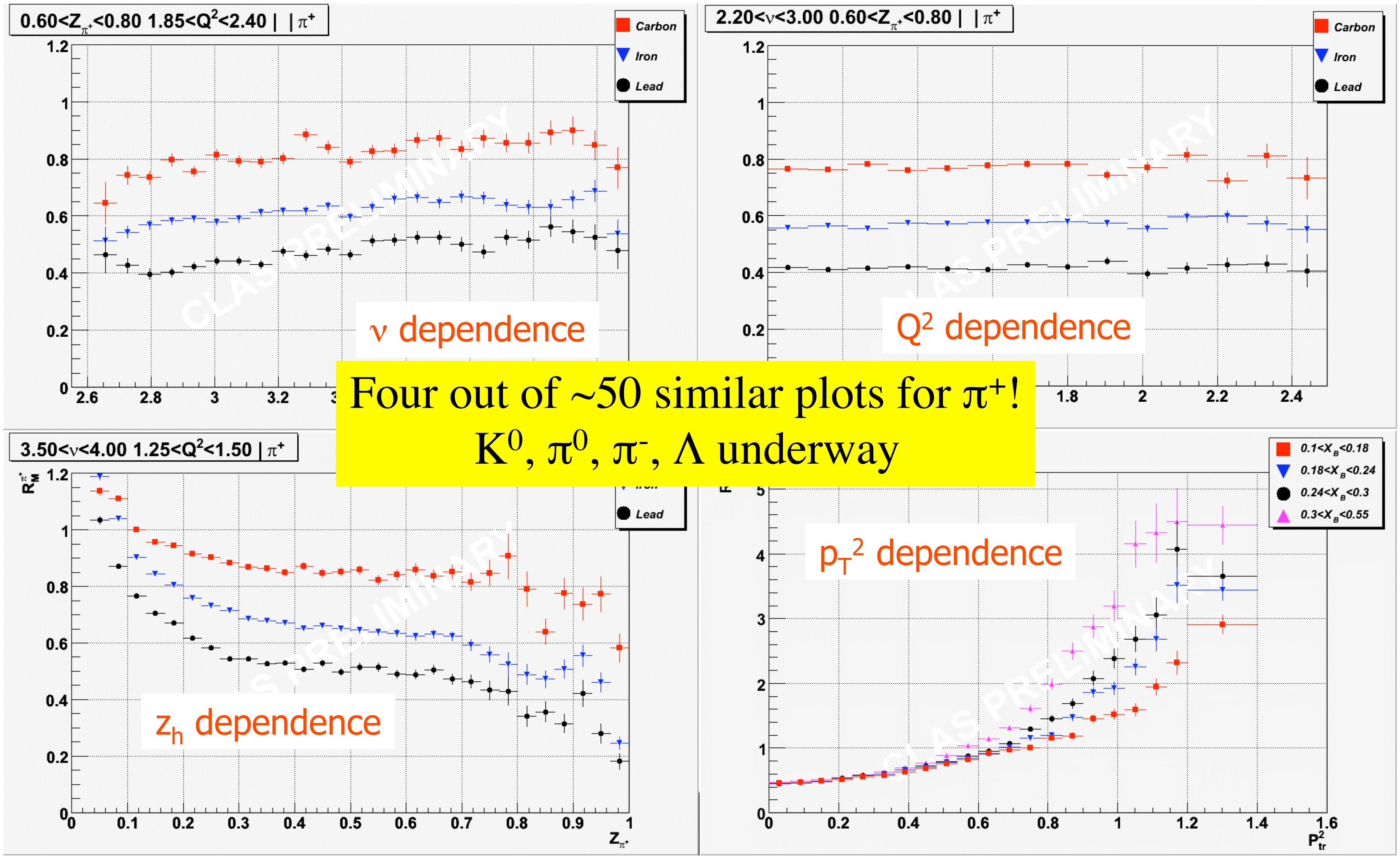
HERMES Data – Kr for p, K, π



Hermes Data – Dependence on p_T and A



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

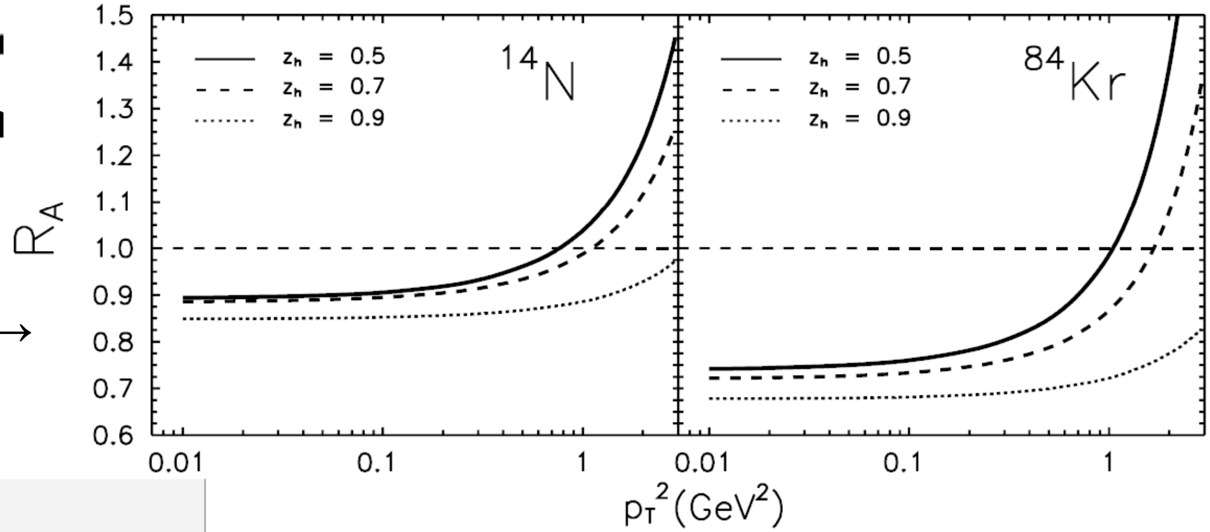


Four out of ~50 similar plots for π^+!
K^0, π^0, π^-, Λ underway

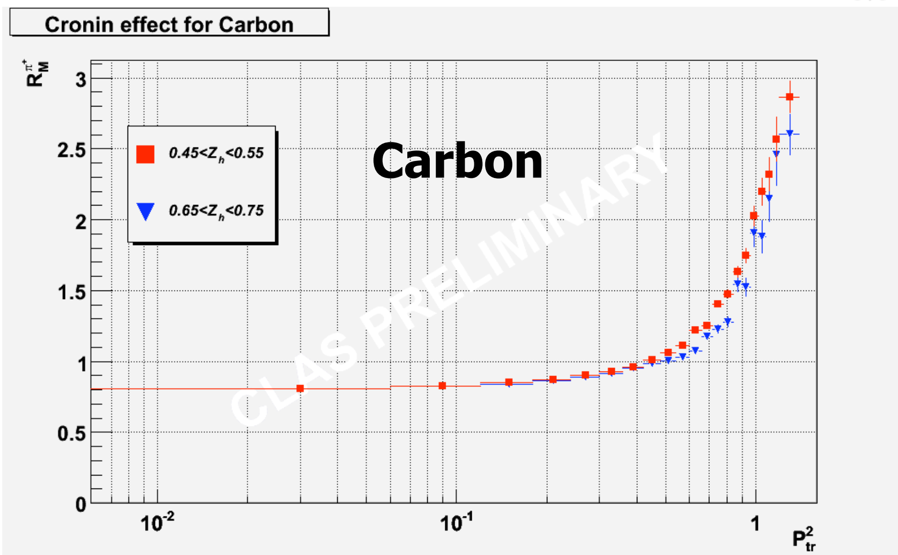
Cronin Effect
Dependence on z_h

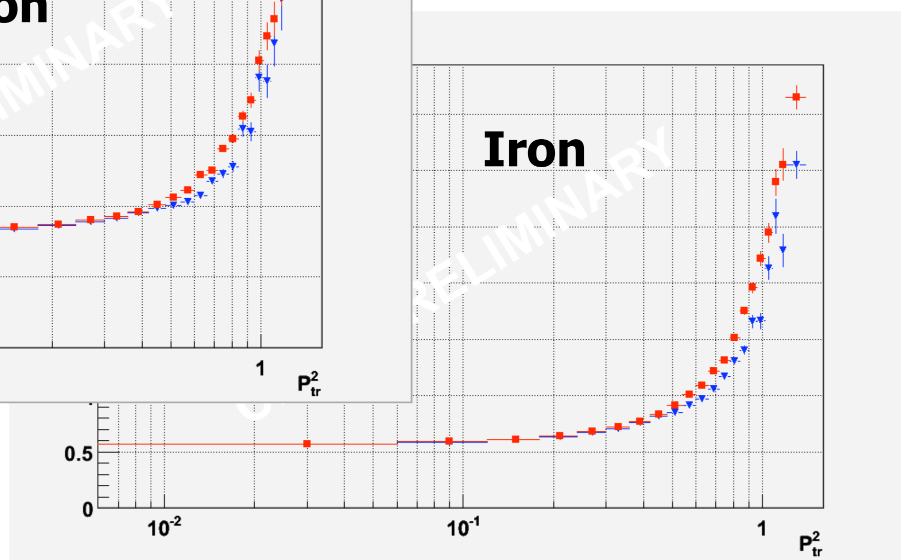
B.Z. Kopeliovich et al. / Nuclear Physics A 740 (2004) 211–245

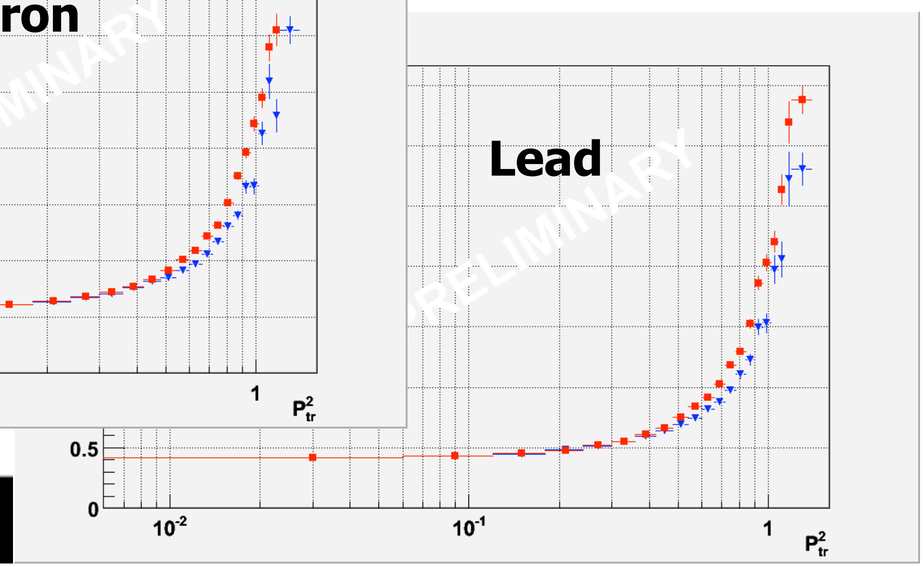
Theoretical *prediction* →



Probes reaction mechanism







CLAS preliminary data
z=0.5 and 0.7

Accessible Hadrons (12 GeV)

12 GeV Anticipated Data

Examples of Experimental Data and Theoretical Predictions

π^+

Bins in yellow accessible at 5 GeV

Hadron Attenuation - Summary

What we have learned

- Hadronic multiplicity ratios depend strongly on hadron species, are universally suppressed at high z
- Main ingredients: prehadron cross sections, gluon radiation, formation lengths; possible exotic effects
- Verified EMC observation: Cronin-like phenomenon in lepto-nuclear scattering; new dependence on A, Q^2, x, z observed

Outstanding questions

- Energy loss or pre-hadron interaction? **THEORY JLAB12**
- How do hadrons form? Optimal method to extract formation lengths? **THEORY JLAB12**

Conclusions

- *Fundamental space-time processes in QCD* finally becoming experimentally accessible
- **Parton propagation, hadron formation**
- **Plenty of exciting opportunities for the future!**

- **NB: can also use this data for inclusive, semi-inclusive EMC, HBT, ……..**

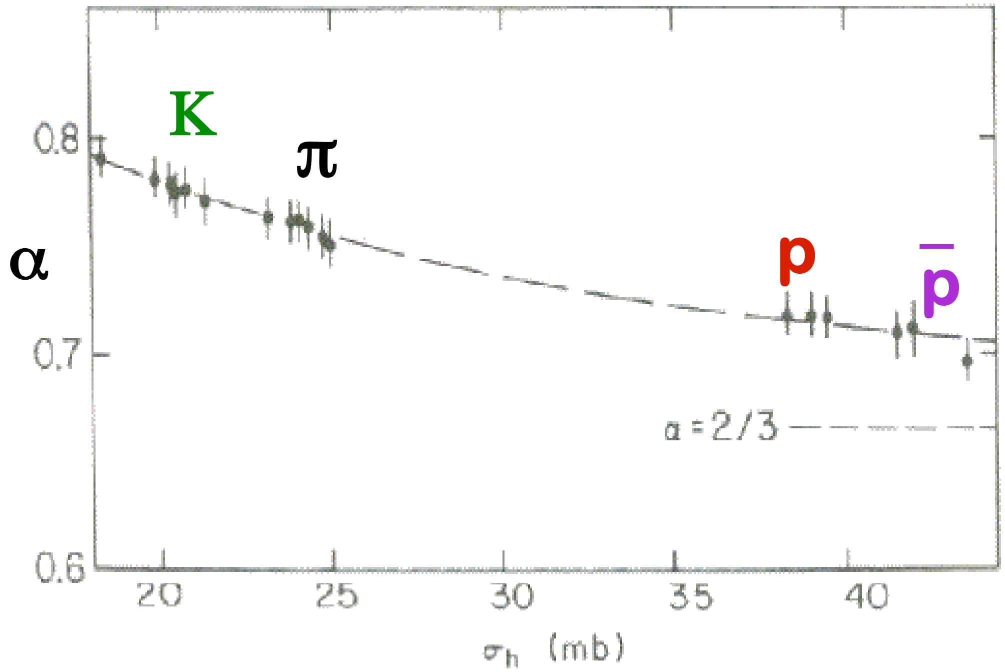
Backup Slides

Kinematics for p_T Broadening

Choose kinematics favoring propagating quark in-medium:

- z (=E_h/ν) > 0.5 – enhance probability of struck quark
- z << 1.0 and ν/m_h >> 1 – maximize production length to ensure $c\tau_p$ >> nuclear size
- z, x such that nucleon factorization holds, to suppress target fragmentation influence
- $x > 0.1$ to avoid quark pair production

Hadron-Nucleus Absorption Cross Sections



Hadron–nucleus absorption cross section

Fit to $\sigma(A) = \sigma_0 A^{\alpha}$

Hadron momentum
60, 200, 280 GeV/c

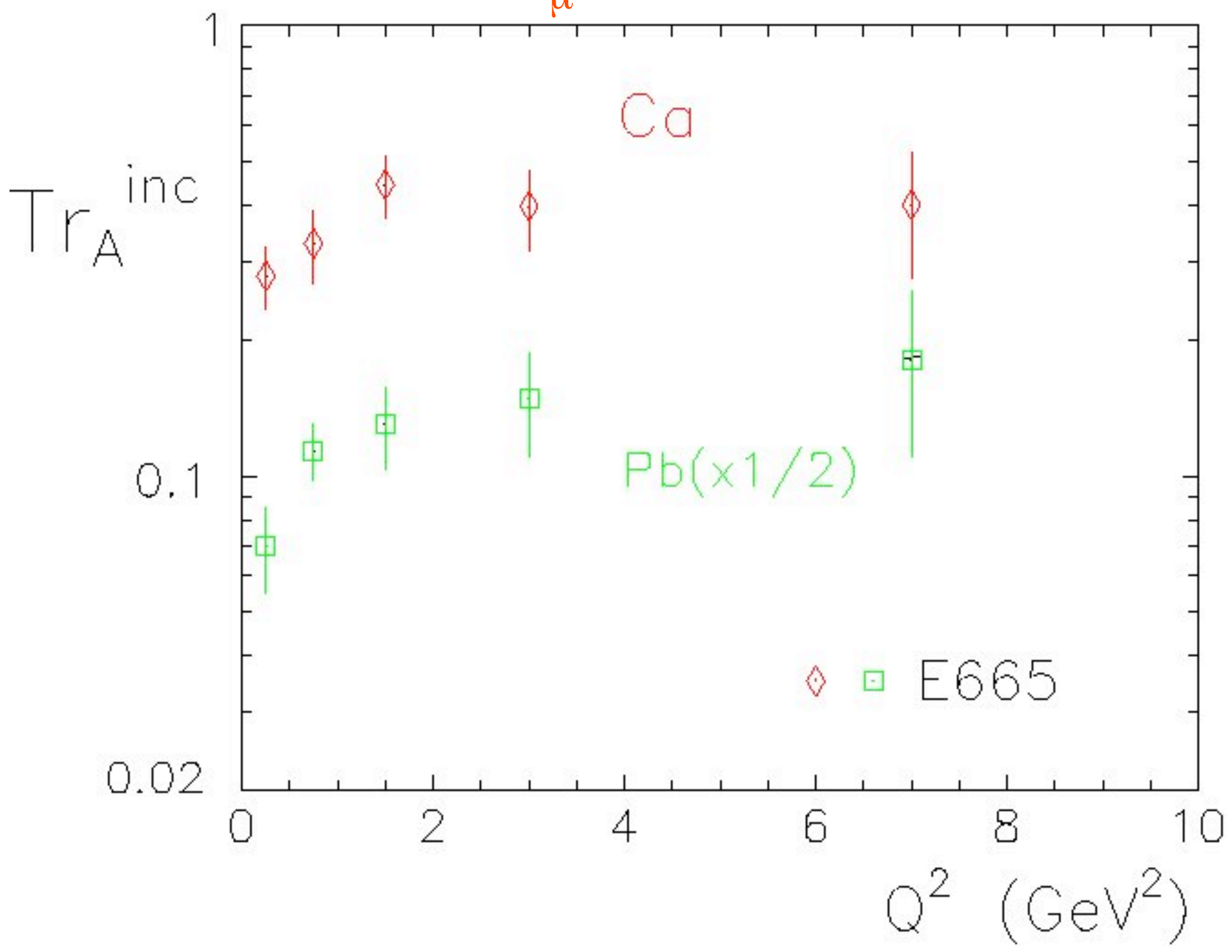
$\alpha < 1$ interpreted as due to the strongly interacting nature of the probe

Experimentally $\alpha =$ 0.72 – 0.78, for p, K, π

A. S. Carroll *et al.* Phys. Lett 80B 319 (1979)

FNAL E665 experiment

$E_\mu = 470$ GeV

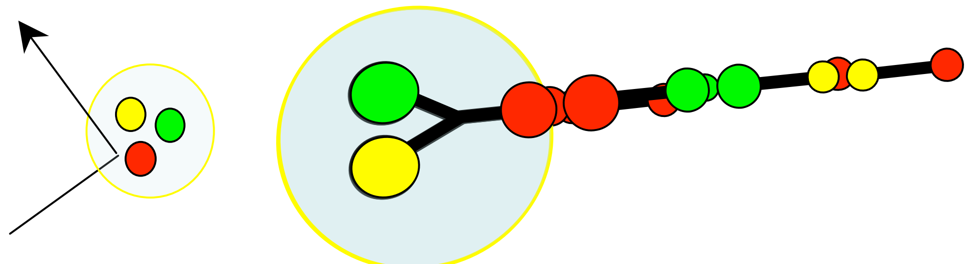


Adams et al. PRL74 (1995) 1525

deconfined?

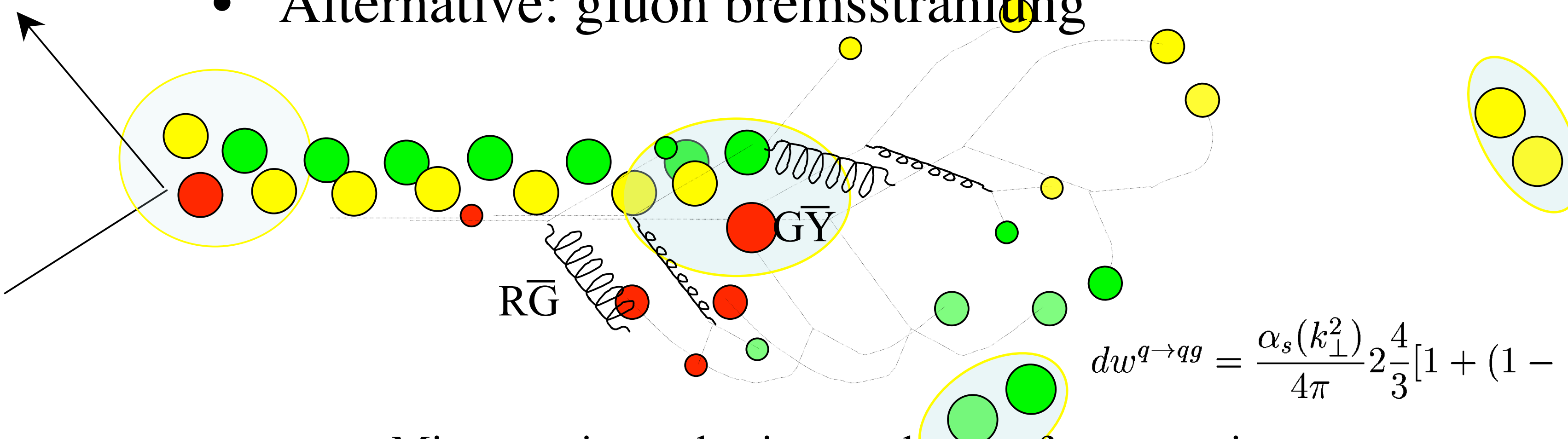
Physical picture, DIS

- Ubiquitous sketch of hadronization process: string model



$$W = \frac{\kappa}{2\pi^3}\exp\left(-\frac{\pi m_q^2}{2\kappa}\right)$$

- Alternative: gluon bremsstrahlung



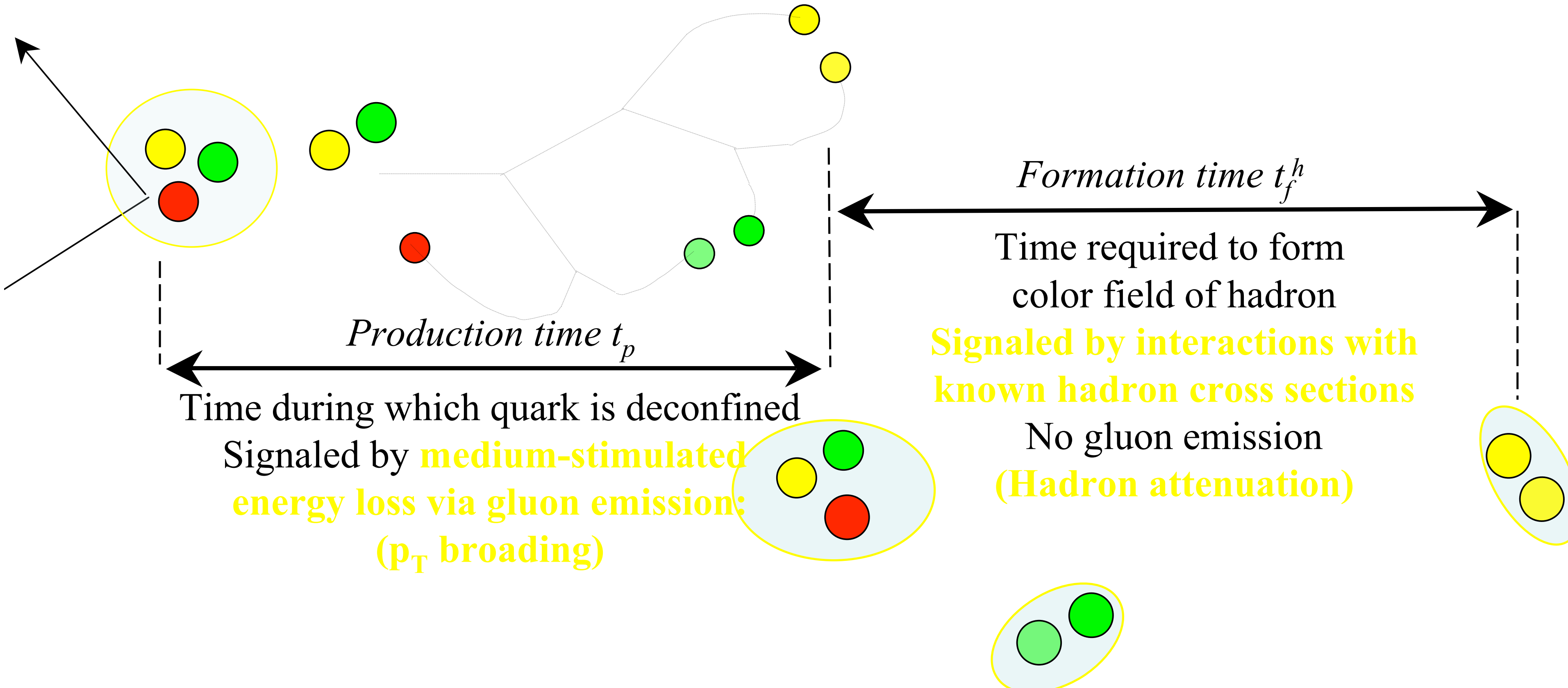
$$dw^{q\to qg} = \frac{\alpha_s(k_\perp^2)}{4\pi}2\frac{4}{3}\left[1+\left(1-\frac{k}{E}\right)^2\right]\frac{dk}{k}$$ [redacted]

Microscopic mechanism not known from experiment

deconfined?

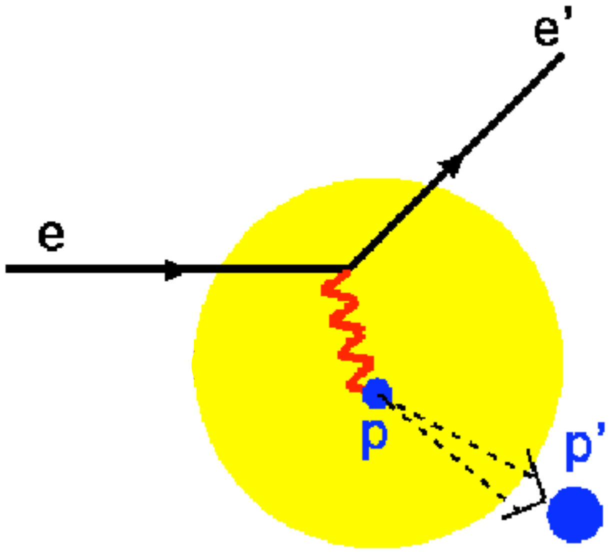
Characteristic time scales

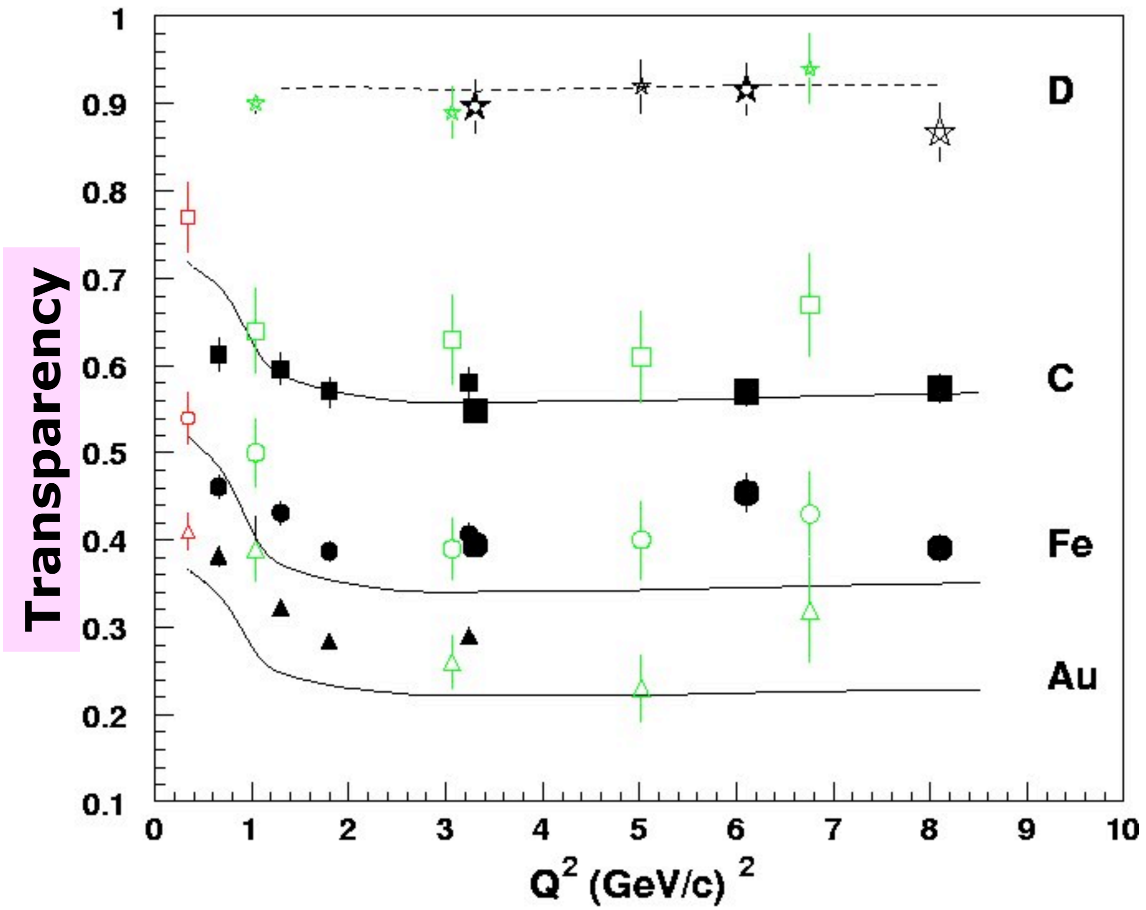
- Two distinct dynamical stages, each with characteristic time scale:



These time scales are essentially unknown experimentally

Quasi-free A(e,e'p) : No evidence for CT



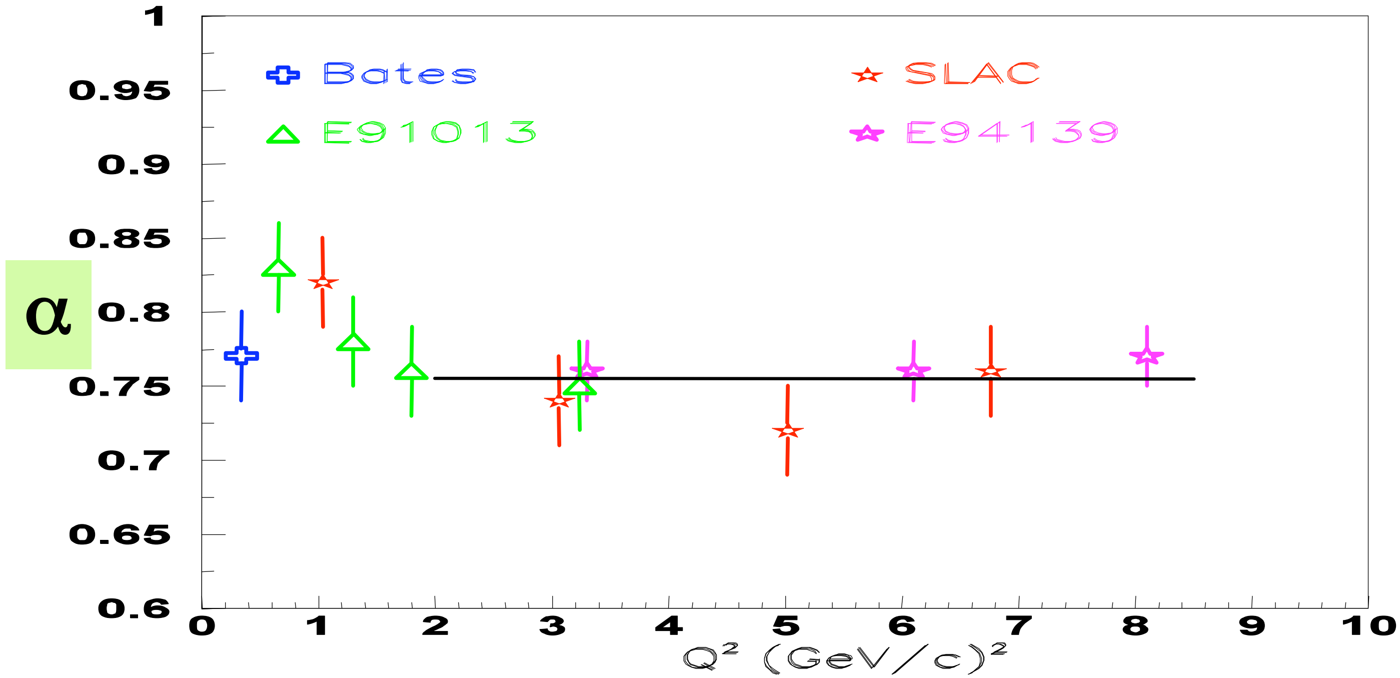


Conventional nuclear physics calculation by Pandharipande et al.
gives adequate description

JLab data **SLAC data** **Bates data**

A(e,e'p) Results -- A Dependence

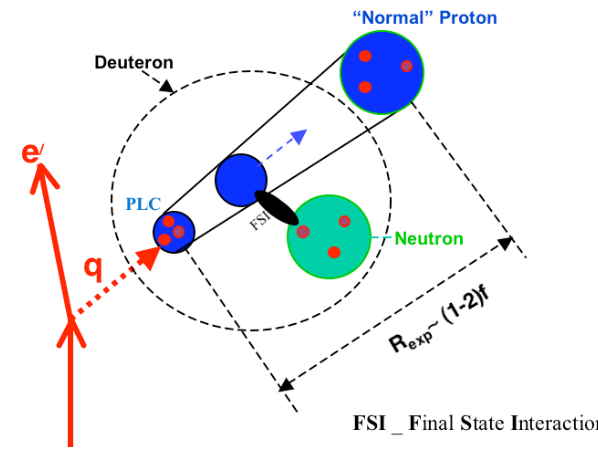
Fit to $\sigma = \sigma_0 A^{\alpha}$



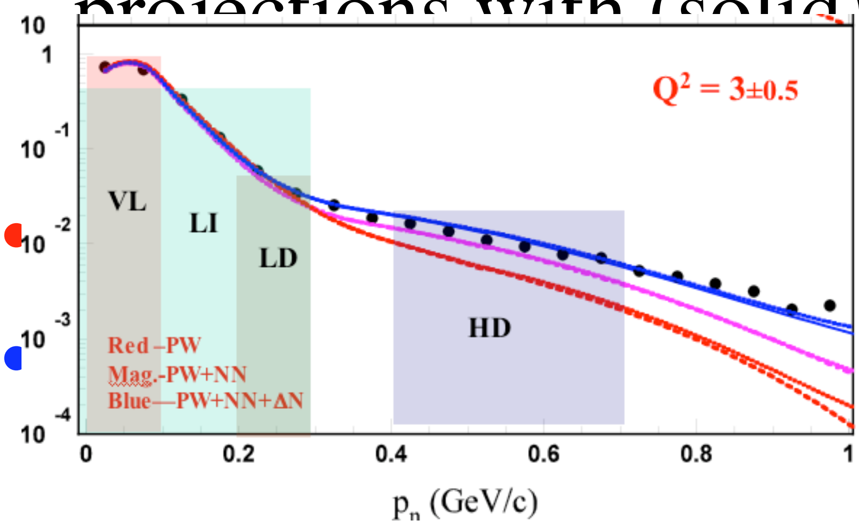
for $Q^2 > 2$ $(GeV/c)^2$ **α = constant = 0.75**

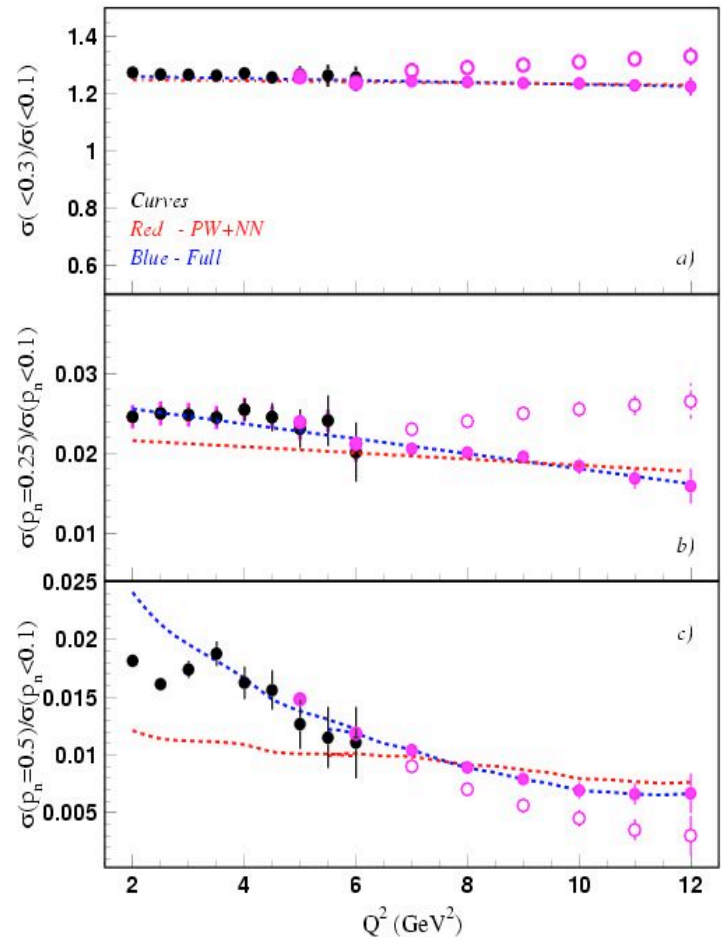
Close to proton-nucleus total cross section data!

Color Transparency in D

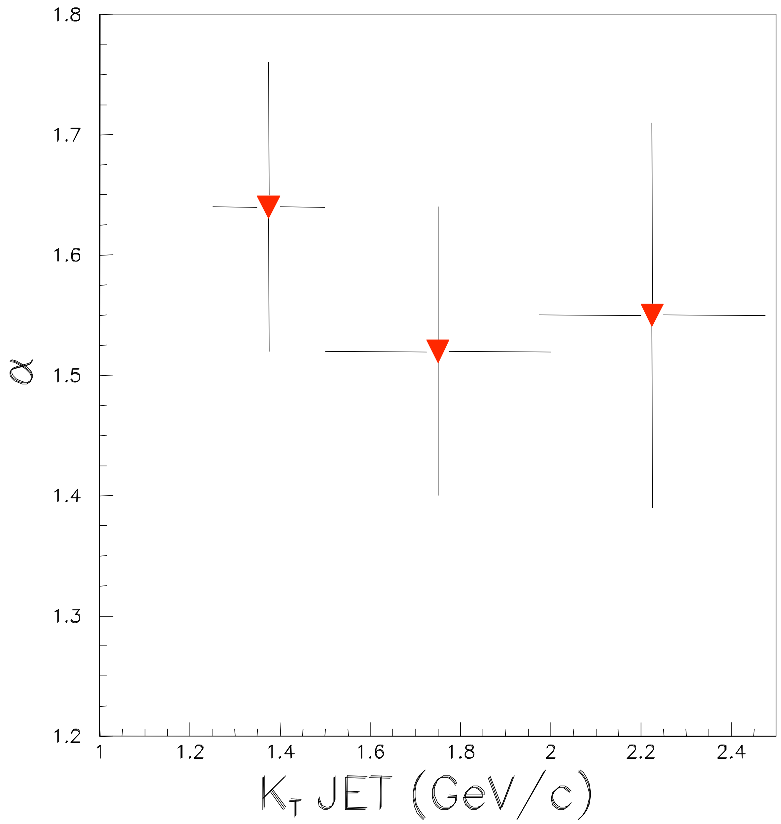


- Experimental ratios: σ(<0.3)/σ(0.1), σ(0.25)/σ(0.1) and σ(0.5)/σ(0.1)
- Black points: 6 GeV CLAS data already taken
- Magenta points: 11 GeV projections with (solid) and





A(π^-,di-jet) Fermilab E791 Data



Coherent π^- diffractive dissociation with 500 GeV/c pions on Pt and C.

Fit to $\sigma = \sigma_0 A^{\alpha}$

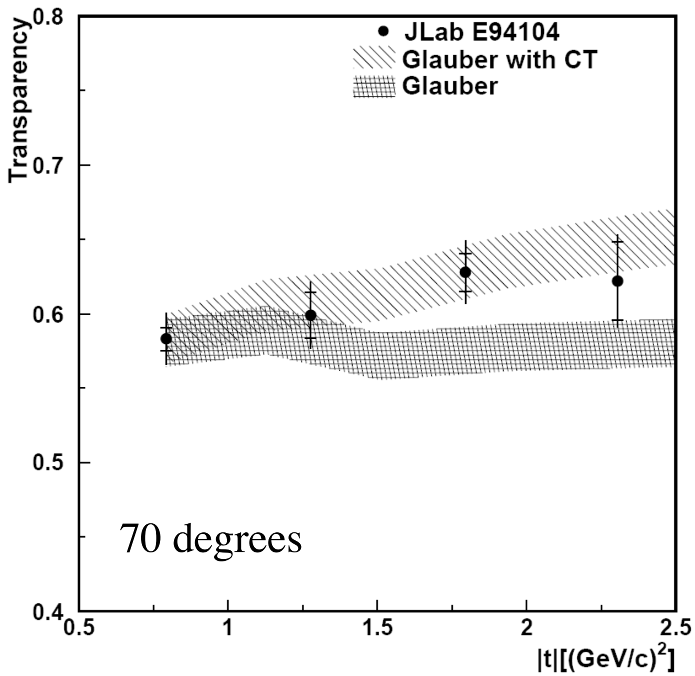
α >> 0.76, π-nucleus total cross-section

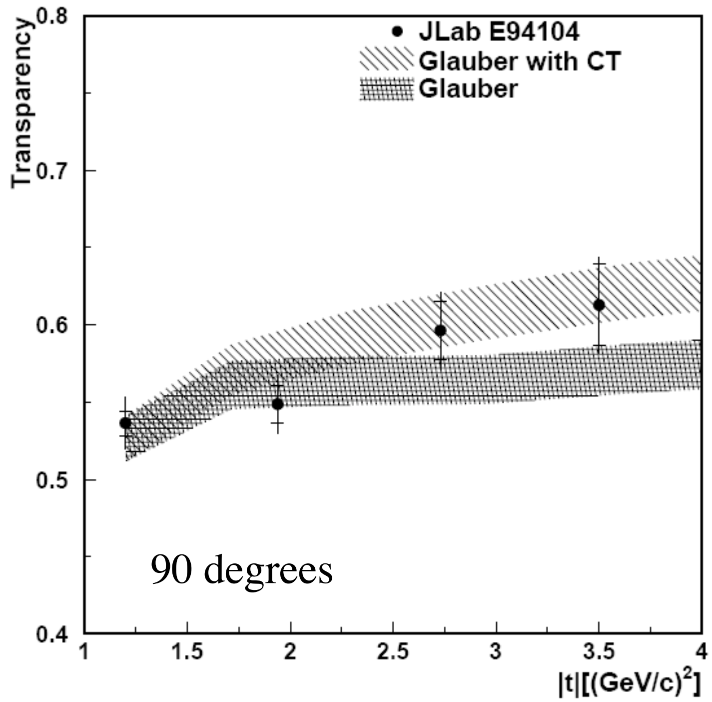
Aitala et al., PRL 86 4773 (2001)

Brodsky, Mueller, Phys. Lett. B206 685 (1988)

Frankfurt, Miller, Strikman, Nucl. Phys. A555, 752 (1993)

Pion Electroproduction

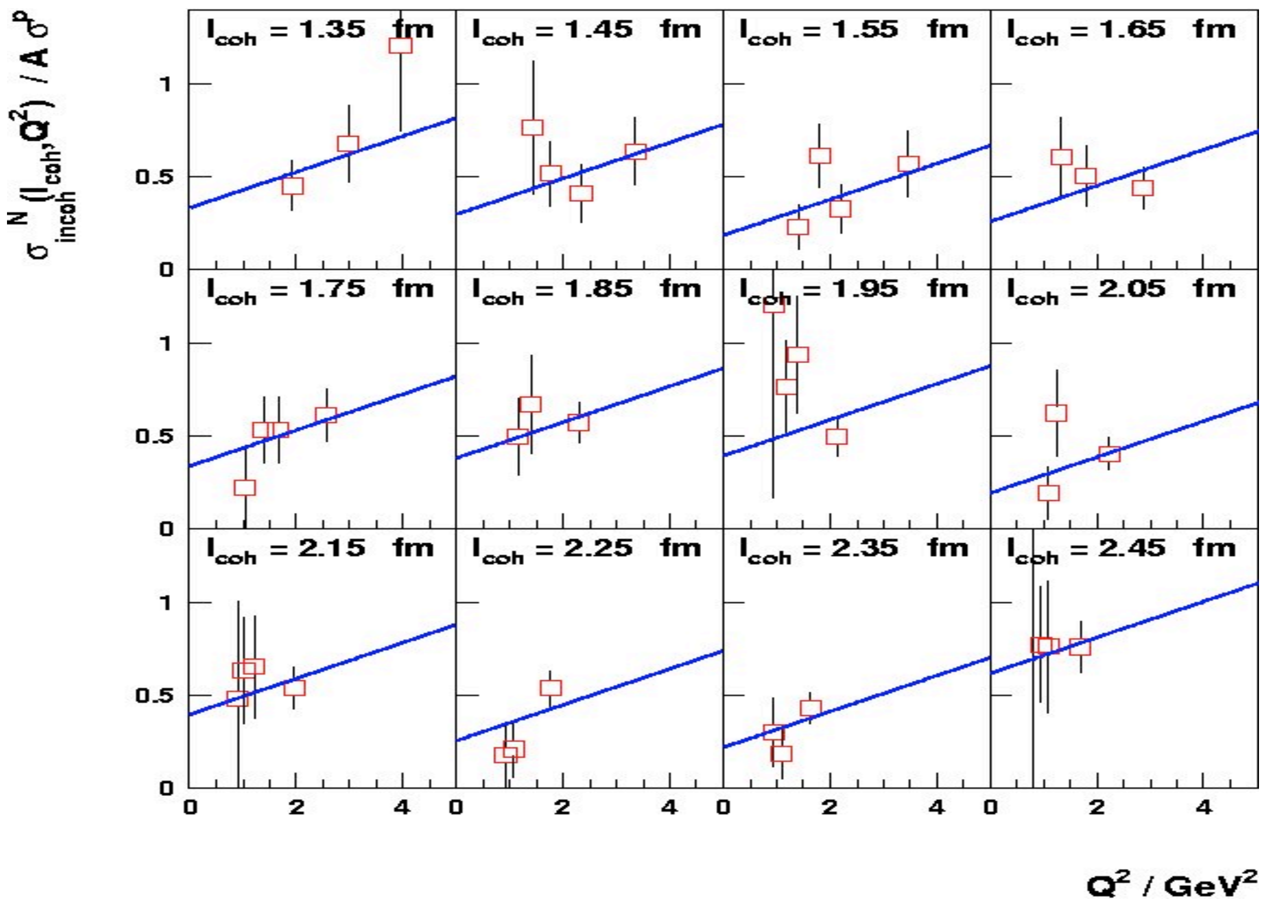


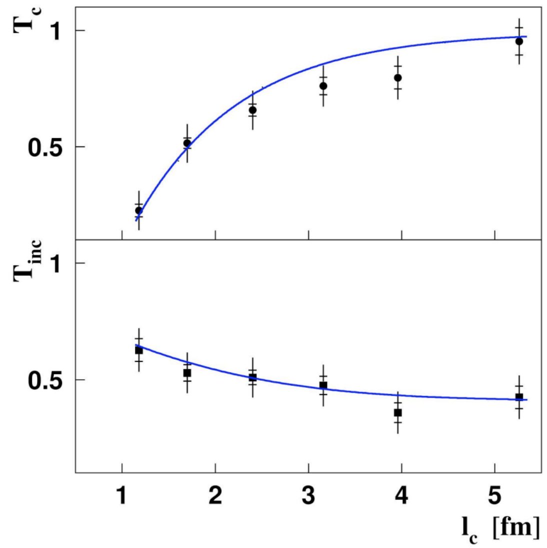


ρ^0 Electroproduction at Fixed Coherence Length

HERMES Nitrogen data : $T_A = P_0 + P_2 Q^2$

$P2 = (0.097 \pm 0.048_{stat} \pm 0.008_{syst})\ GeV^{-2}$





Airepetian et al. (HERMES Coll.) Phys. Rev. Lett. 90 (2003) 052501

'A' Dependence of Transparency

[illegible] = $\frac{\text{[illegible]}}{\text{[illegible]}}$

Usually $\sigma(A) = \sigma_0 \; A^{\alpha}$

$\therefore$ T = $A^{\alpha-1}$

α

from fit of
T(A) = $A^{\alpha-1}$ at fixed Q^2