Hadron attenuation and medium effects in photoproduction: QCD in the spacetime domain

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OUTLINE

- Physical picture and physics focus
- Experimental considerations in Hall D
- Recent related studies
- Conclusion

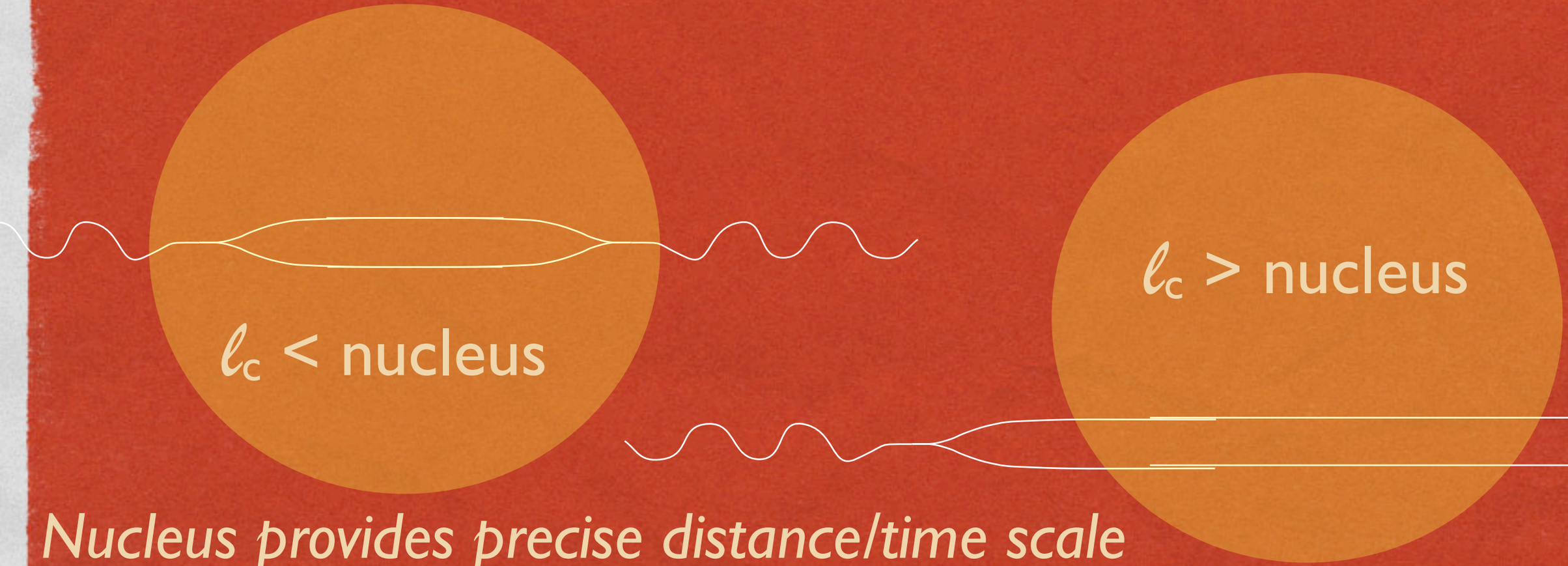
SPACETIME QCD

- QCD not well explored in spacetime domain
- Nuclei provide precise distance/time measure
- Existing program for CLAS/CLAS12 extracts lifetime of deconfined light quarks (production time), color field restoration time (hadron formation time)
- Hall D diffraction measurements provide new, unique information on *spacetime development of prehadrons*

PHYSICAL PICTURE AND PHYSICS FOCUS

Vacuum process:

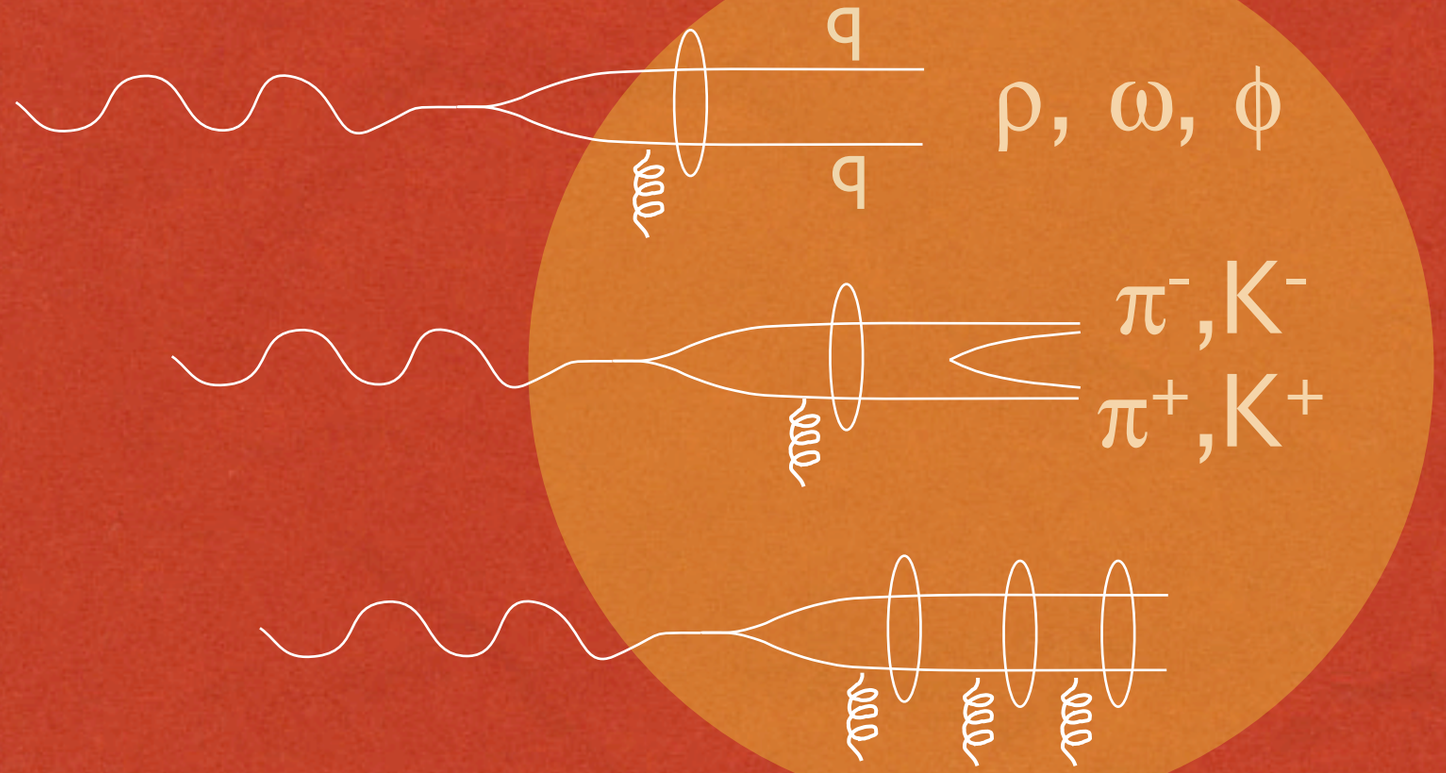
Lifetime of fluctuation: coherence length $\ell_c = 2E_\gamma/M^2_{qq}$



Nucleus provides precise distance/time scale

PHYSICAL PICTURE AND PHYSICS FOCUS

Processes in-medium:



Color-neutral
2-gluon exchange

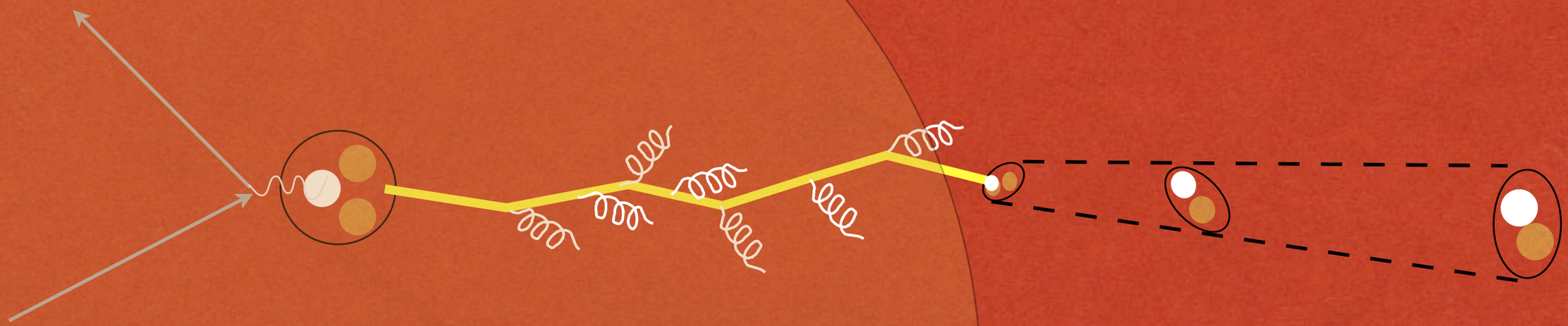
In-medium **broadening of (transverse) momentum**
(ρ, ω, ϕ, π, K)

Nucleus not excited: coherent

Nucleus excited/breaks up: incoherent

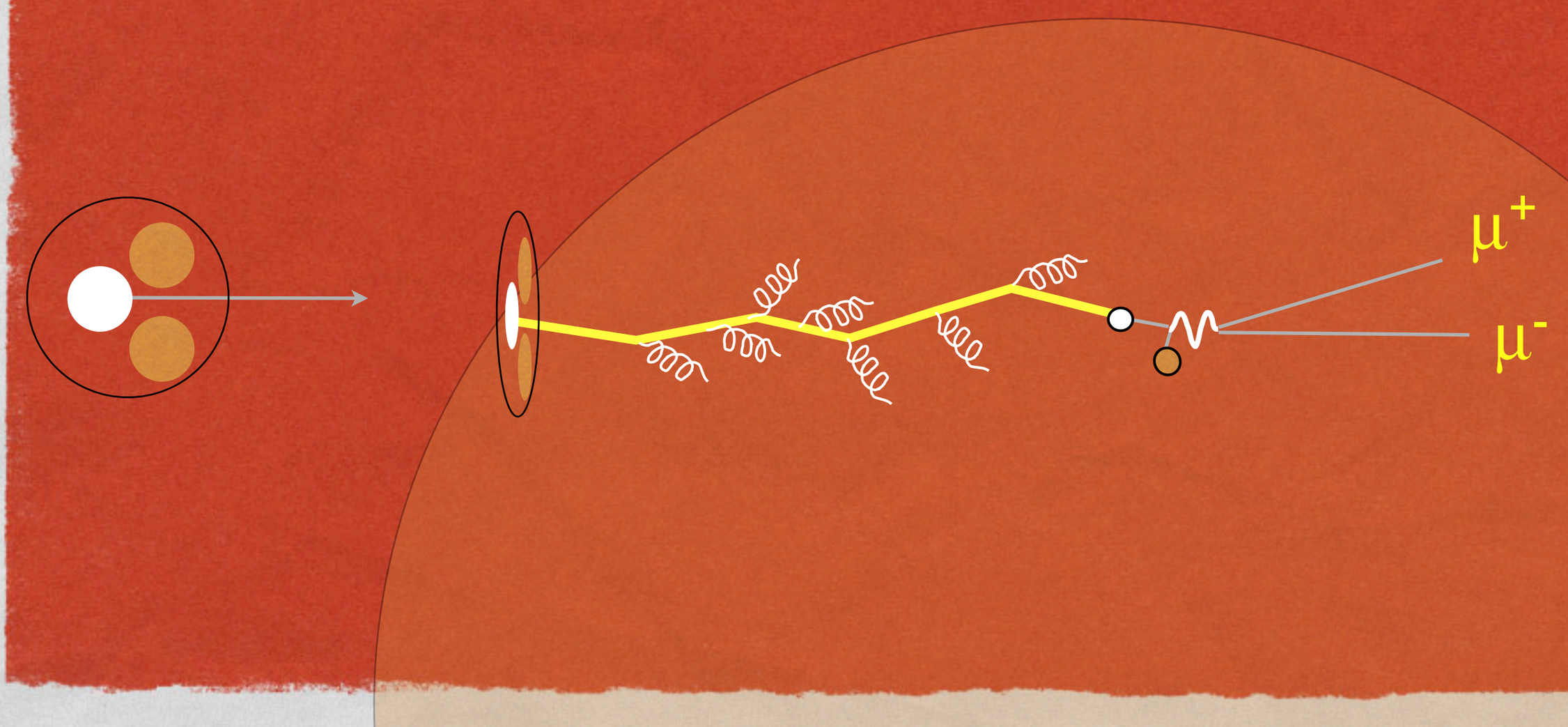
COMPARE TO DIS AND DRELL-YAN:

Partonic multiple scattering: medium-stimulated gluon emission, broadened p_T

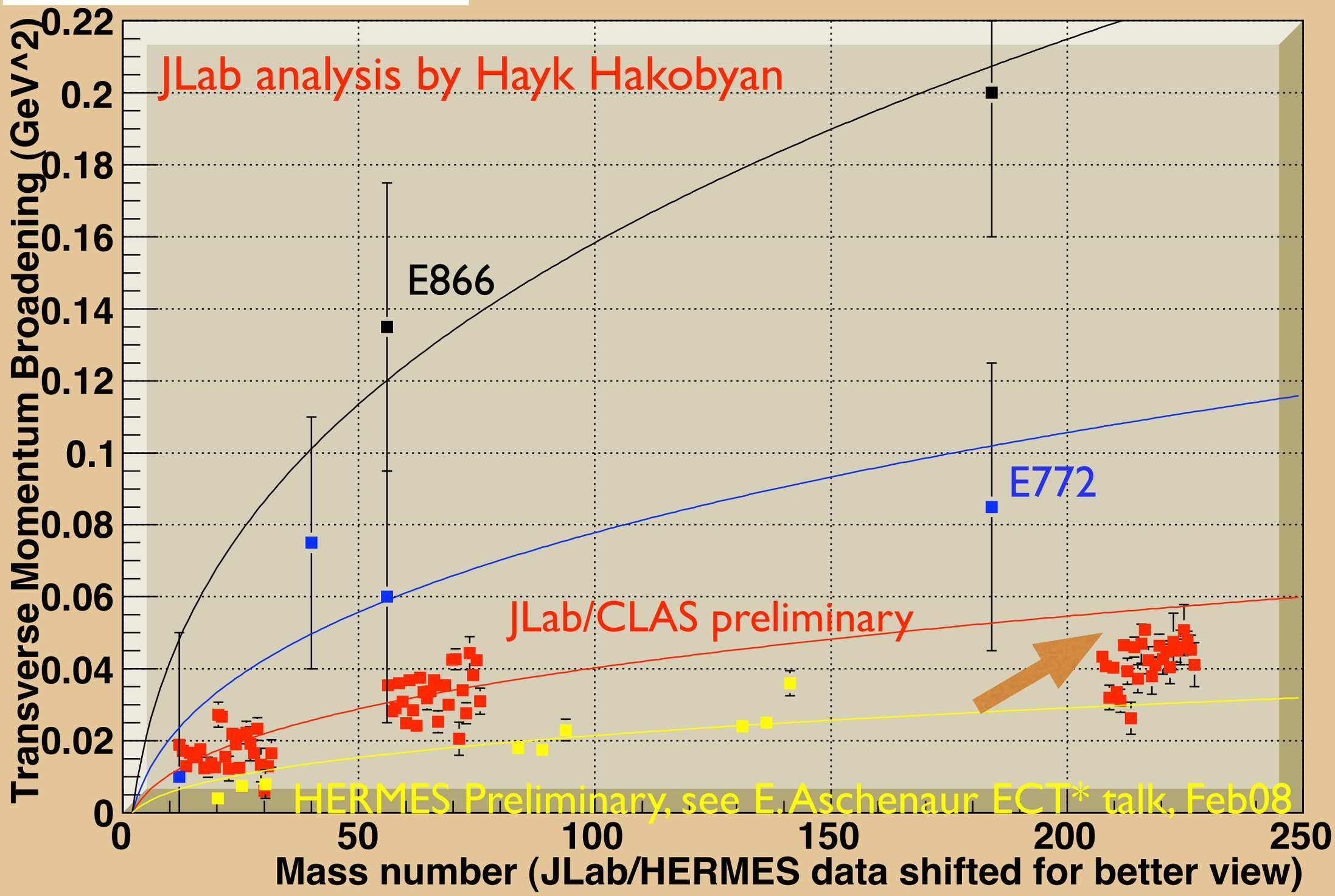


MEDIUM - DRELL-YAN

e.g., 800 GeV protons - no in-medium hadronization - have p_T broadening



$$\Delta\langle p_T^2\rangle = D\left[(A/2)^{1/3} - 1\right]$$



JLab data saturate, allows extraction of production time τ_p

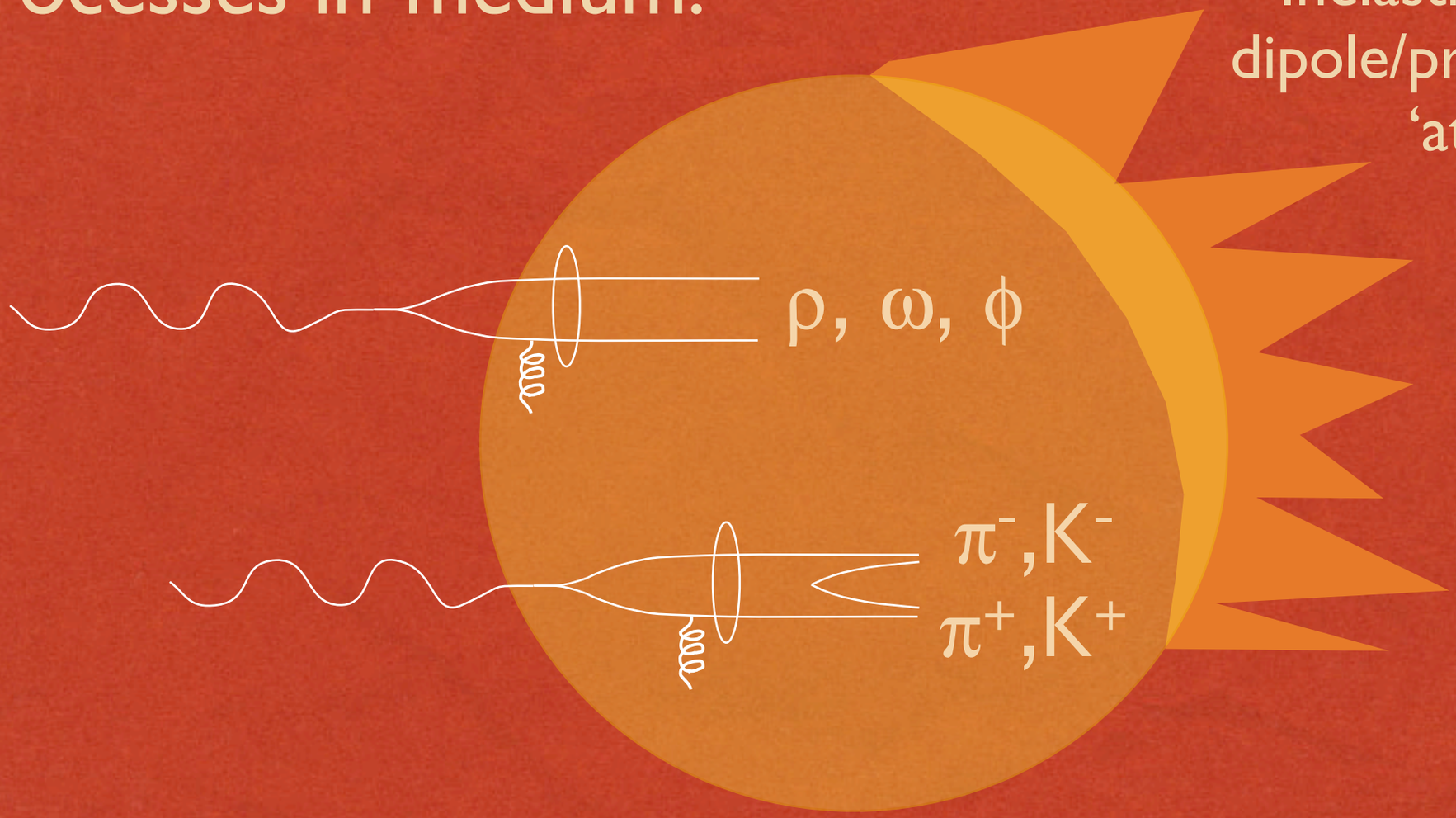
TRANSVERSE MOMENTUM BROADENING

- For a *propagating colored quark*:
  - elastic scattering of quark
  - medium-stimulated radiative gluon emission
    - related to jet quenching at RHIC/LHC
    - no direct experimental measurement yet
- For a *propagating color-neutral dipole*:
  - elastic scattering of dipole

PHYSICAL PICTURE AND PHYSICS FOCUS

Processes in-medium:

Inelastic interaction of dipole/prehadron/meson - ‘attenuation’

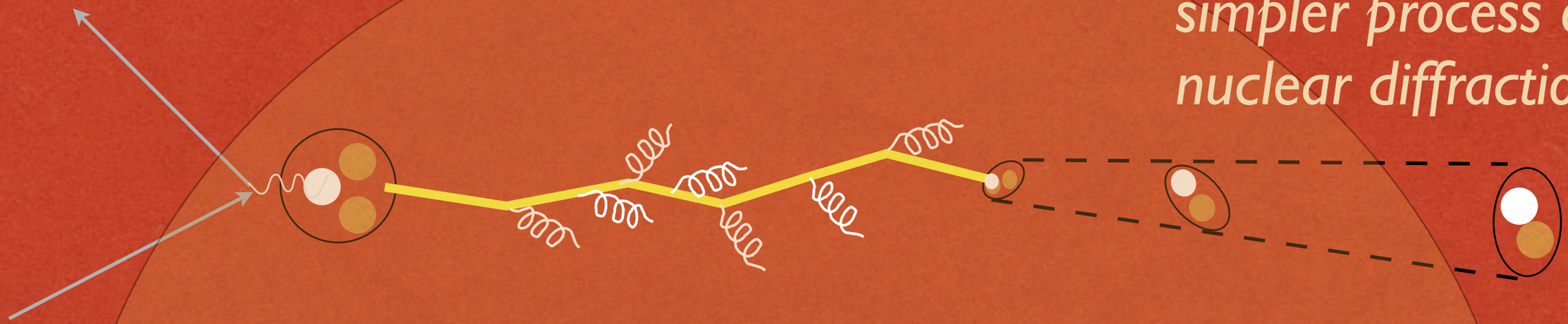


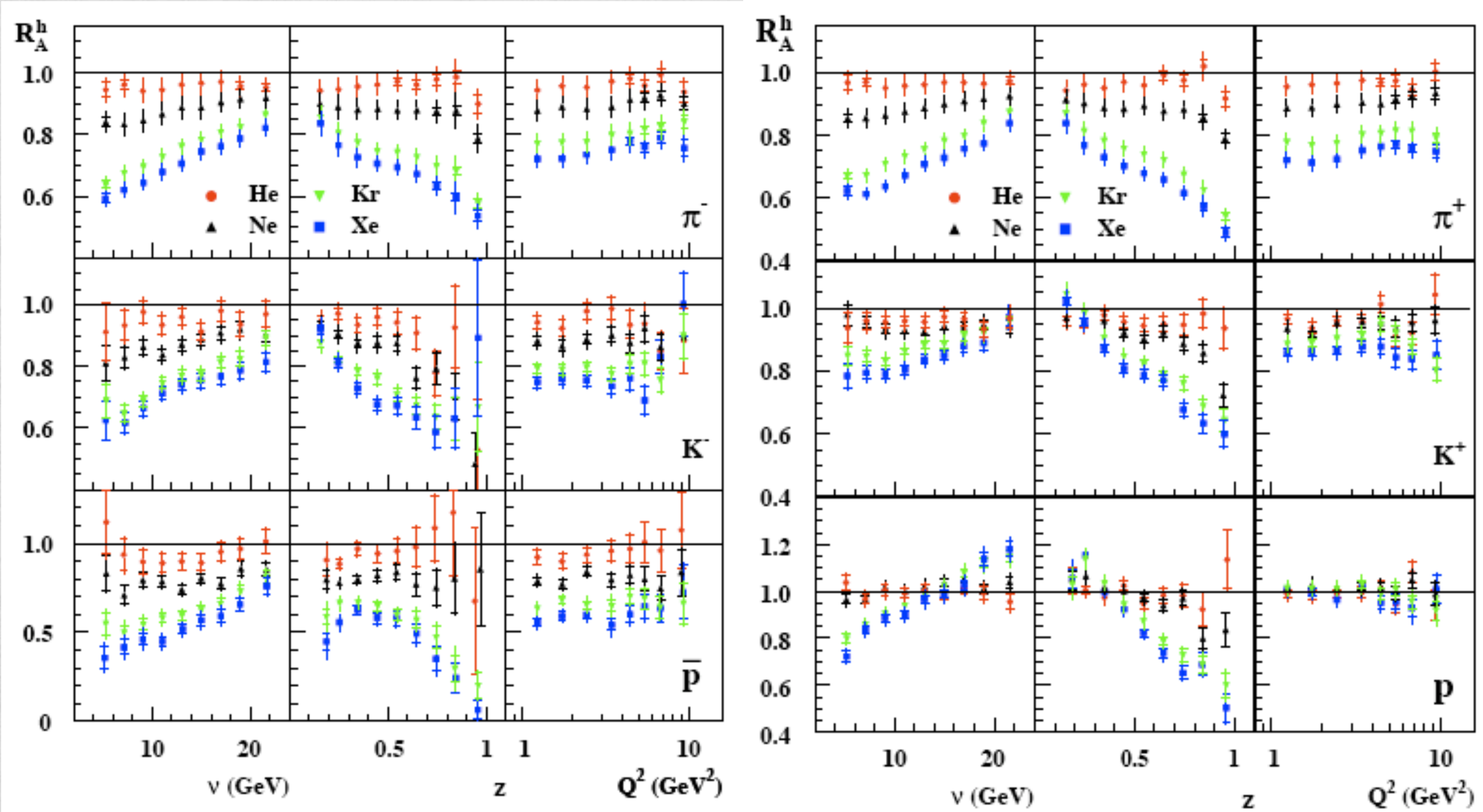
Nucleus excited/breaks up: incoherent

MEDIUM - DIS

When hadronization occurs *inside* the medium, also have *prehadron/hadron interaction*

This phase of the interaction is comparable to the simpler process of nuclear diffraction

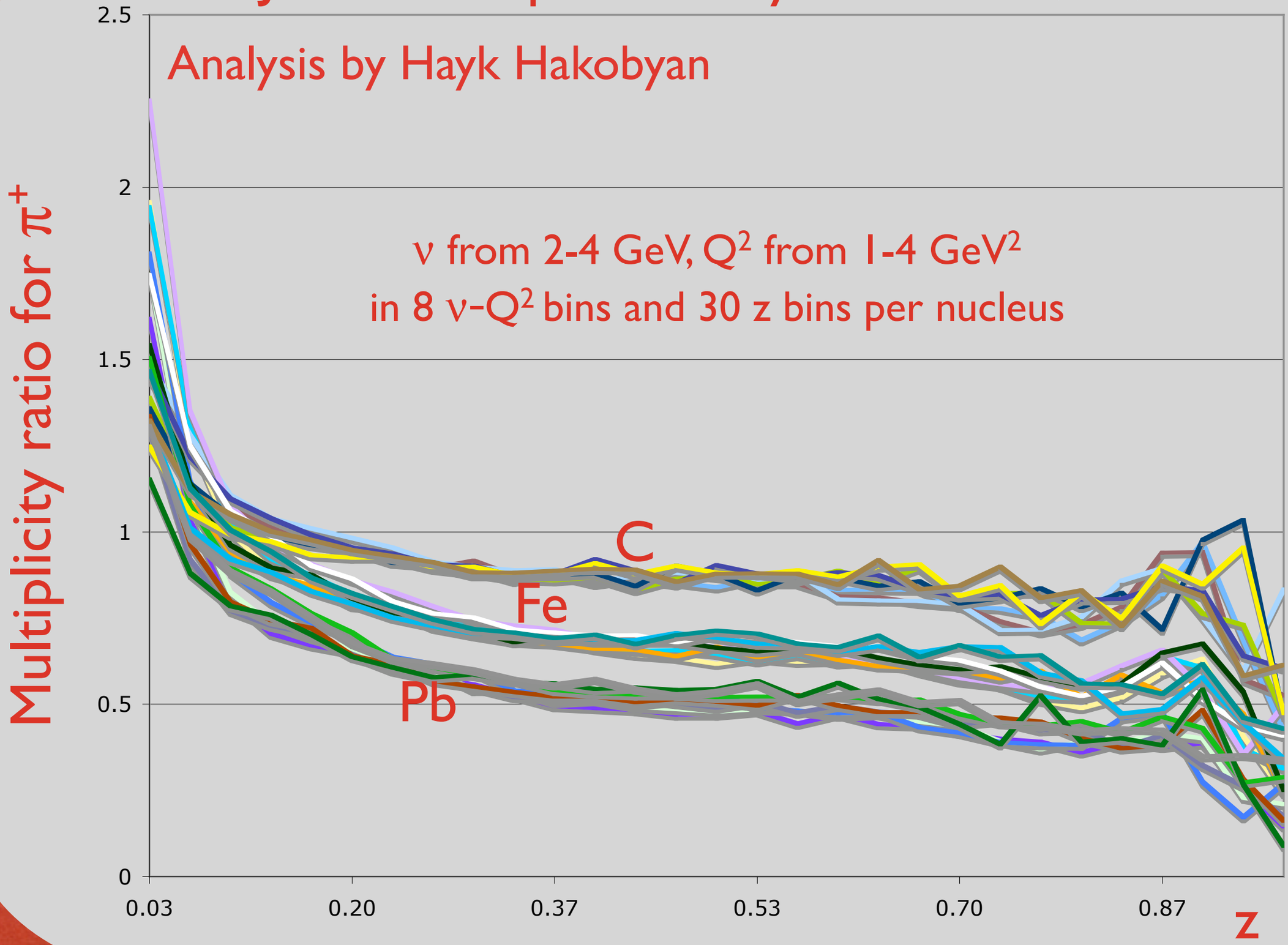




HERMES hadron attenuation data for He, Ne, Kr, Xe: π^{+-}, K^{+-}, p, antiproton

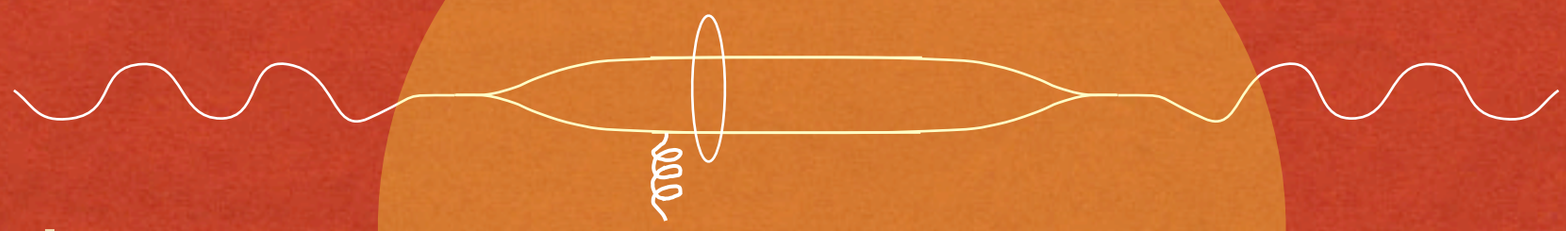
The data thus far do not cleanly distinguish between the two mechanisms - radiative gluons or prehadron interaction - new information on prehadron interactions could be crucial

JLab/CLAS preliminary data for C, Fe, Pb



PHYSICAL PICTURE AND PHYSICS FOCUS

Compton process:



Sensitive to the new generalized gluon density distribution (unintegrated)

For Hall D, could supplement FCAL with a new small calorimeter: <3 degrees, high resolution, downstream

PHYSICAL PICTURE AND PHYSICS FOCUS - SUMMARY

- Important complementarity with DIS/DY studies
  - Simpler mechanisms:
    - can isolate dipole elastic broadening
  - Can study prehadron/hadron attenuation
    - vector mesons, pions, kaons
    - without radiative energy loss complications
    - Compare to DIS (pA?)

PHYSICAL PICTURE AND PHYSICS FOCUS - SUMMARY

"Wish List"	Coherent	Incoherent
p_T broadening	ρ, ω, ϕ	ρ, ω, ϕ
	$\pi\pi$, KK	$\pi\pi$, KK
Hadron attenuation	ρ, ω, ϕ	ρ, ω, ϕ
	$\pi\pi$, KK	$\pi\pi$, KK

Issues:

- PID for forward, highest energy mesons
- Experimental resolution - p_T, missing energy, t, for identifying coherent events
- Prefer fully instrumented tagging hodoscope

Measure: dependence on A, E_γ; E_{h1}, E_{h2}

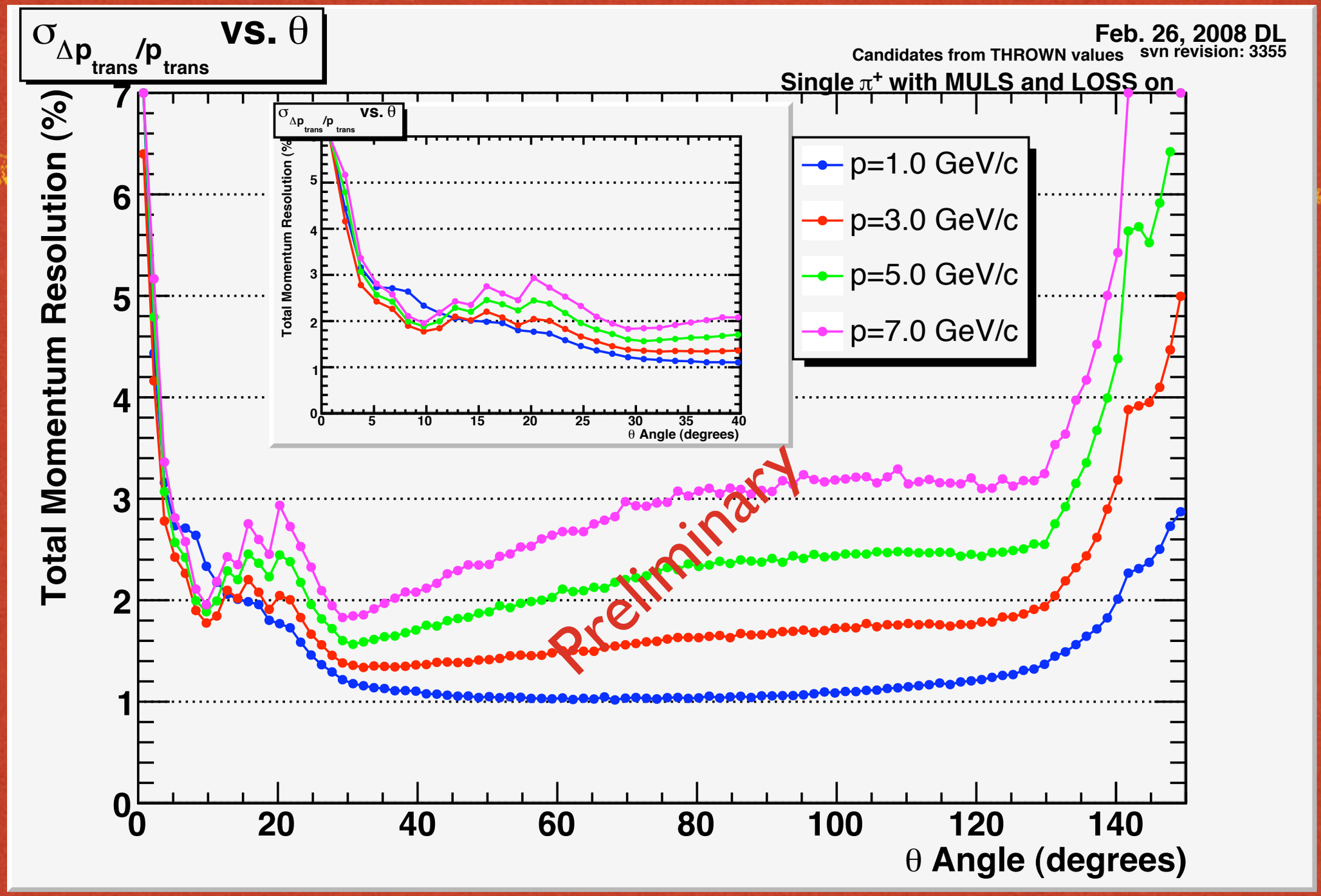
EXPERIMENTAL ISSUES - RESOLUTION

- Distinguish between coherent and incoherent events via t, p_T, missing energy

- Ideal world: ~1 MeV resolution to distinguish nuclear-excited states from ground state. Reality: 40-100 MeV.

- HERMES
  - coherent: $|t'|<0.045$ GeV^2 N, $|t'|<0.4$ GeV^2 H
  - incoherent: $0.09<|t'|<0.4$ GeV^2
  - δE_{miss} ~0.25 GeV, $\delta t'$ ~ 0.008 GeV^2

CHARGED PARTICLE RESOLUTION



- 5-10 degrees, 2 - 5 GeV x 2 particles, σ ~ 40-100 MeV
- <5 degrees, 2-3 times worse

EXPERIMENTAL ISSUES - RESOLUTION

- Will need significant corrections from simulation to account for resolutions; but good statistics will help
- Fermi smearing an irreducible component anyway
- Veto of additional charged and neutral particles will also be valuable for identification of coherent events

EXPERIMENTAL ISSUES: NUCLEAR TARGETS

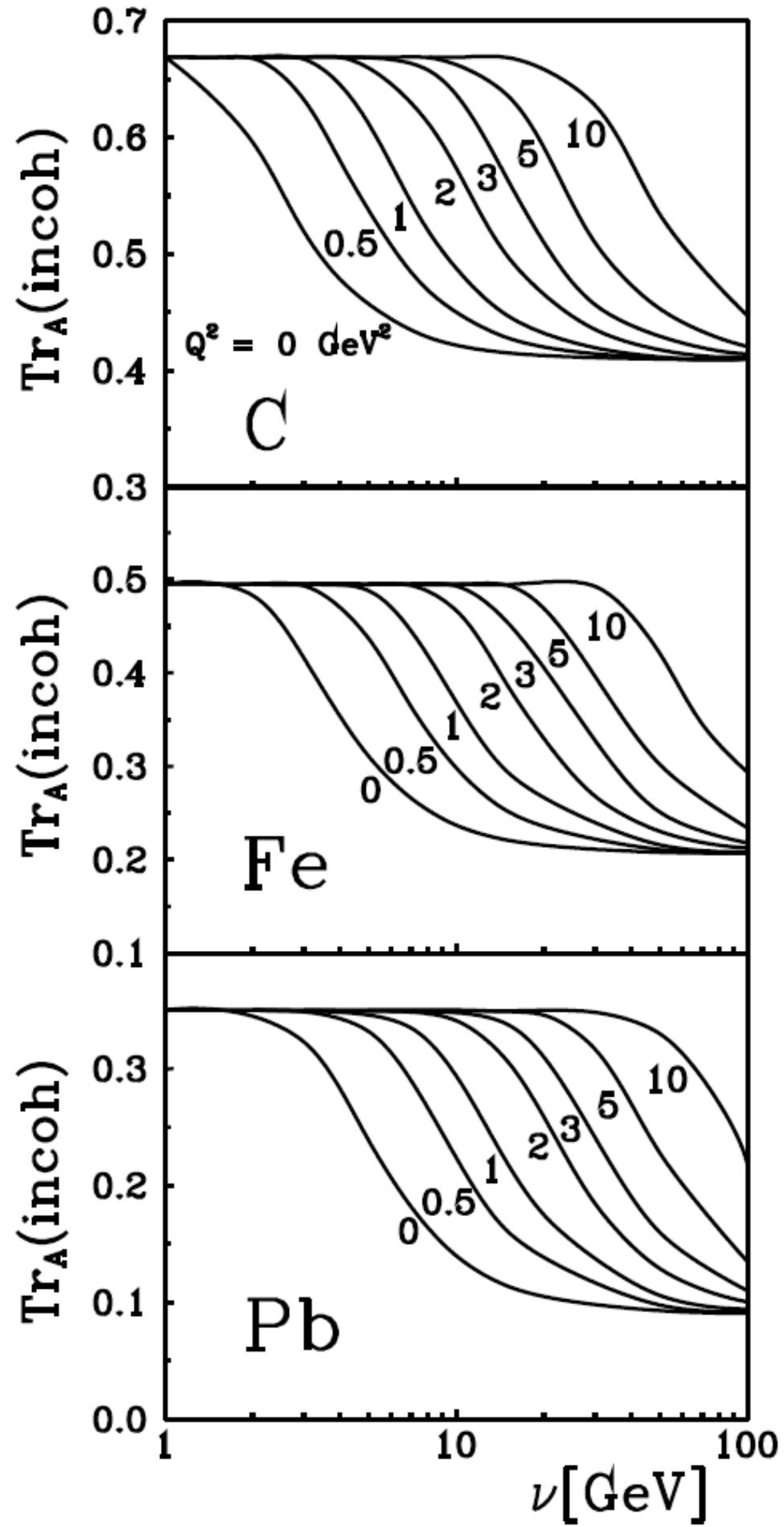
- X-ray hits in drift chambers
  - Probably no issue - CLAS experience - target self-shields, can also do additional shielding
- Neutron hits in calorimeters
  - Probably no issue - CLAS experience, but should check GDR for low-energy neutrons
  - TOF rejection will reduce
- e^+e^- pairs from low-energy photons
  - Primary issue - need to make targets thin to compensate - likely to be the **luminosity limit**

RHO AND PHI MESONS IN NUCLEI, GLAUBER THEORY

Glauber Multiple Scattering Theory for the Photoproduction of Vector Mesons off Nuclei and the Role of the Coherence Length

Huefner, Kopeliovich, Nemchik arXiv:nucl-th/9605007

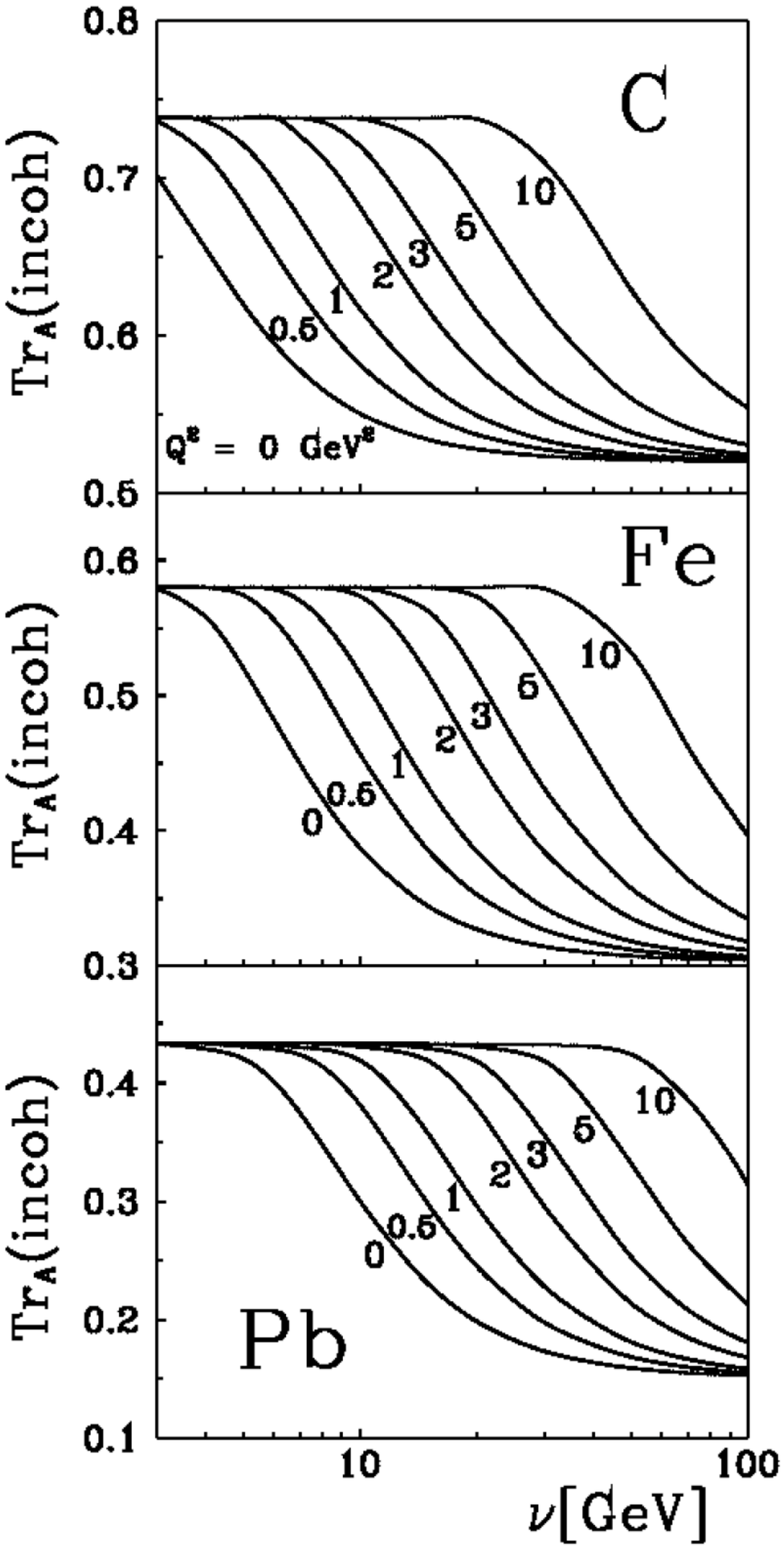
The integrated cross section for the incoherent photoproduction of vector mesons on nuclei $\gamma^* A \to VX$, $X \neq A$, is calculated within Glauber theory and as a function of the photon energy. The inverse of the longitudinal momentum transfer is called coherence length l_c and depends on the virtuality and the energy of the photon. Nuclear transmission factors strongly depend on l_c/R_A (R_A is the nuclear radius) and this effect may interfere with the search for color transparency effects.



Nuclear attenuation of ρ mesons ~A in Glauber theory, *incoherent*

Low and high coherence length limits correspond to meson formation *in* the medium and *before entering* the medium

$$Tr^{\gamma V}(q_L, A) = \frac{\sigma_{inc}(\gamma A \to V X; q_L)}{A\ \sigma(\gamma N \to V N)}$$

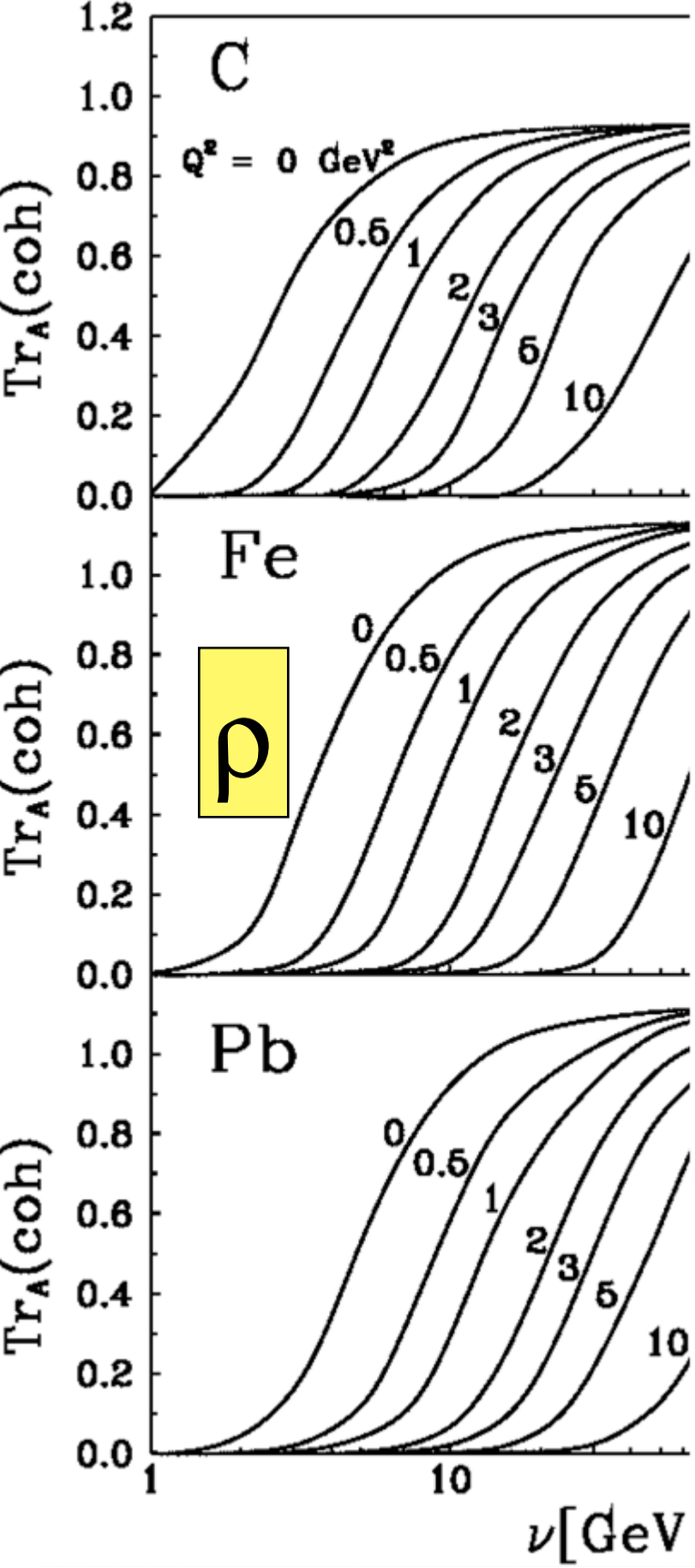


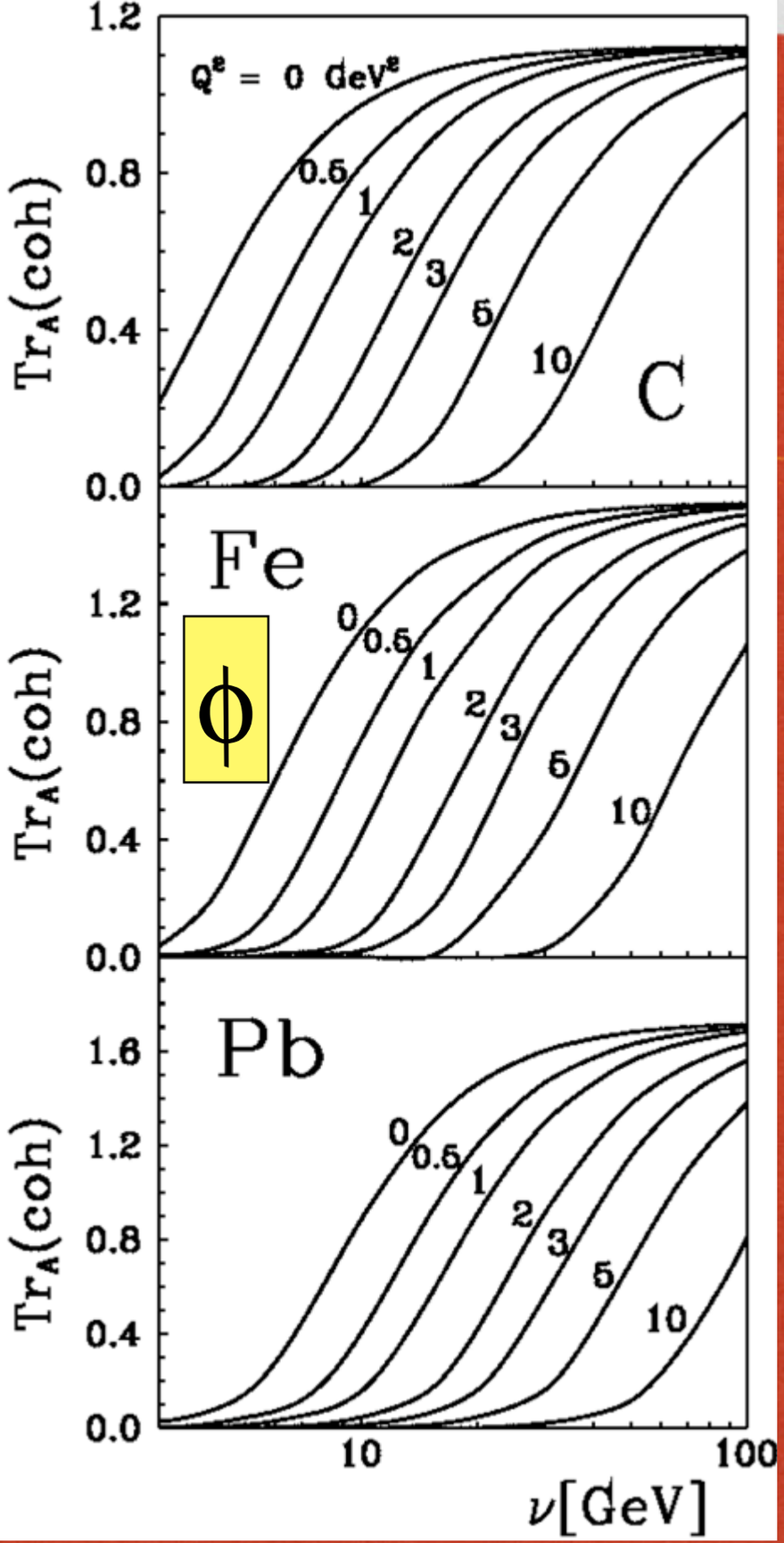
Nuclear attenuation of ϕ mesons, Glauber, *incoherent*

Less attenuation than for ρ, somewhat different functional form

$$Tr^{\gamma V}(q_L, A) = \frac{\sigma_{inc}(\gamma A \to V X; q_L)}{A\,\sigma(\gamma N \to V N)}$$

Kopeliovich and Nemchik, arXiv:nucl-th/9511018

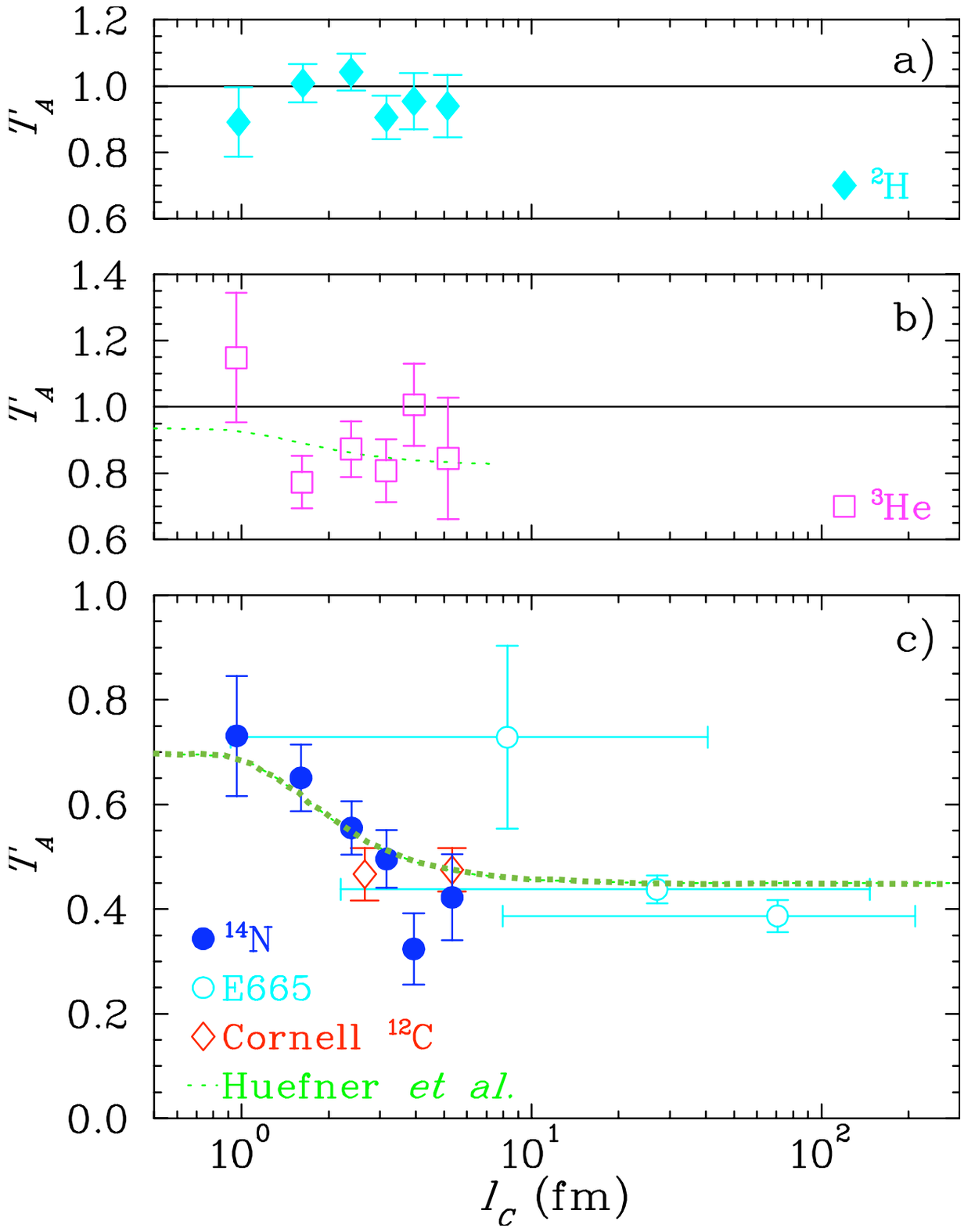




Coherent ρ and ϕ production, Glauber

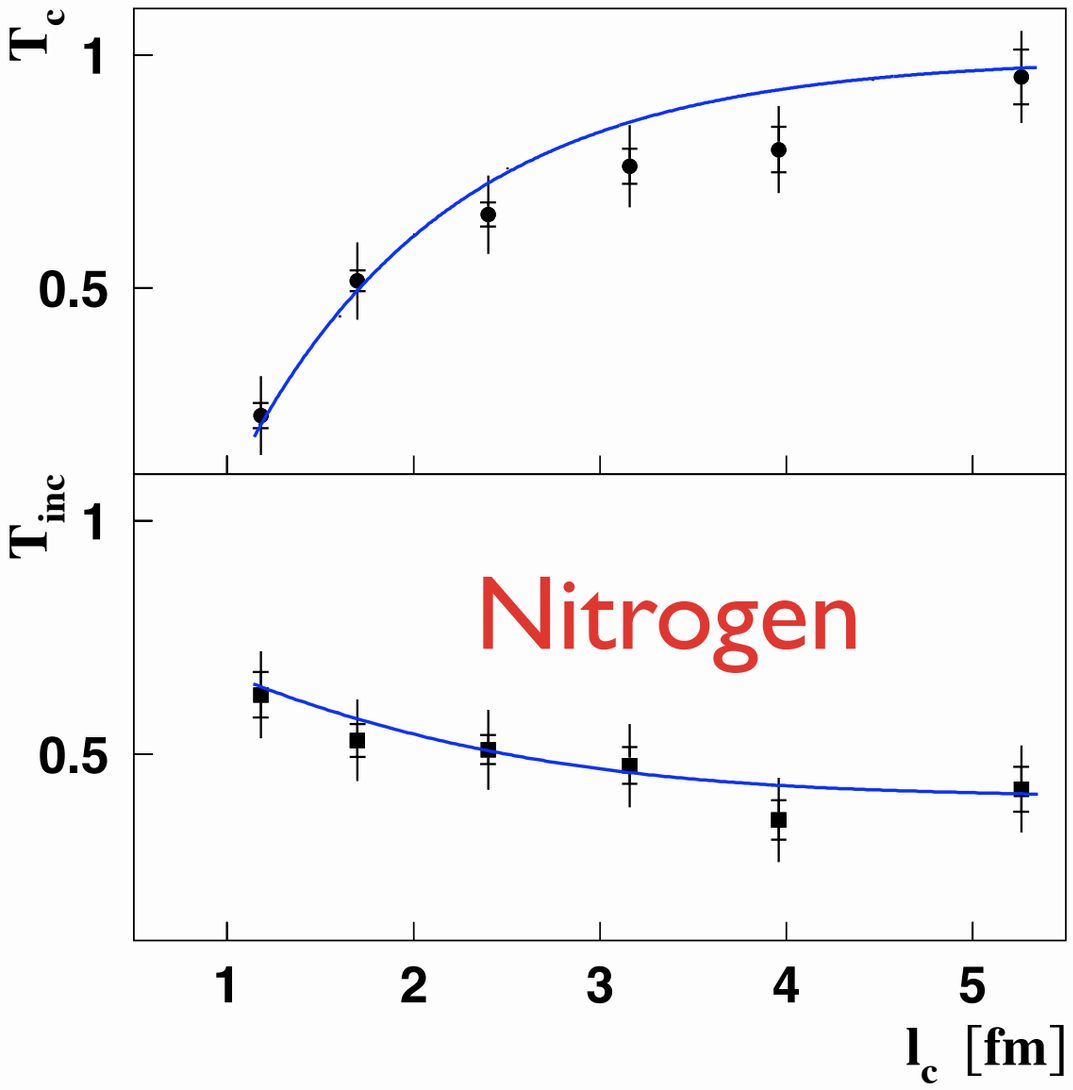
Qualitatively different from incoherent production

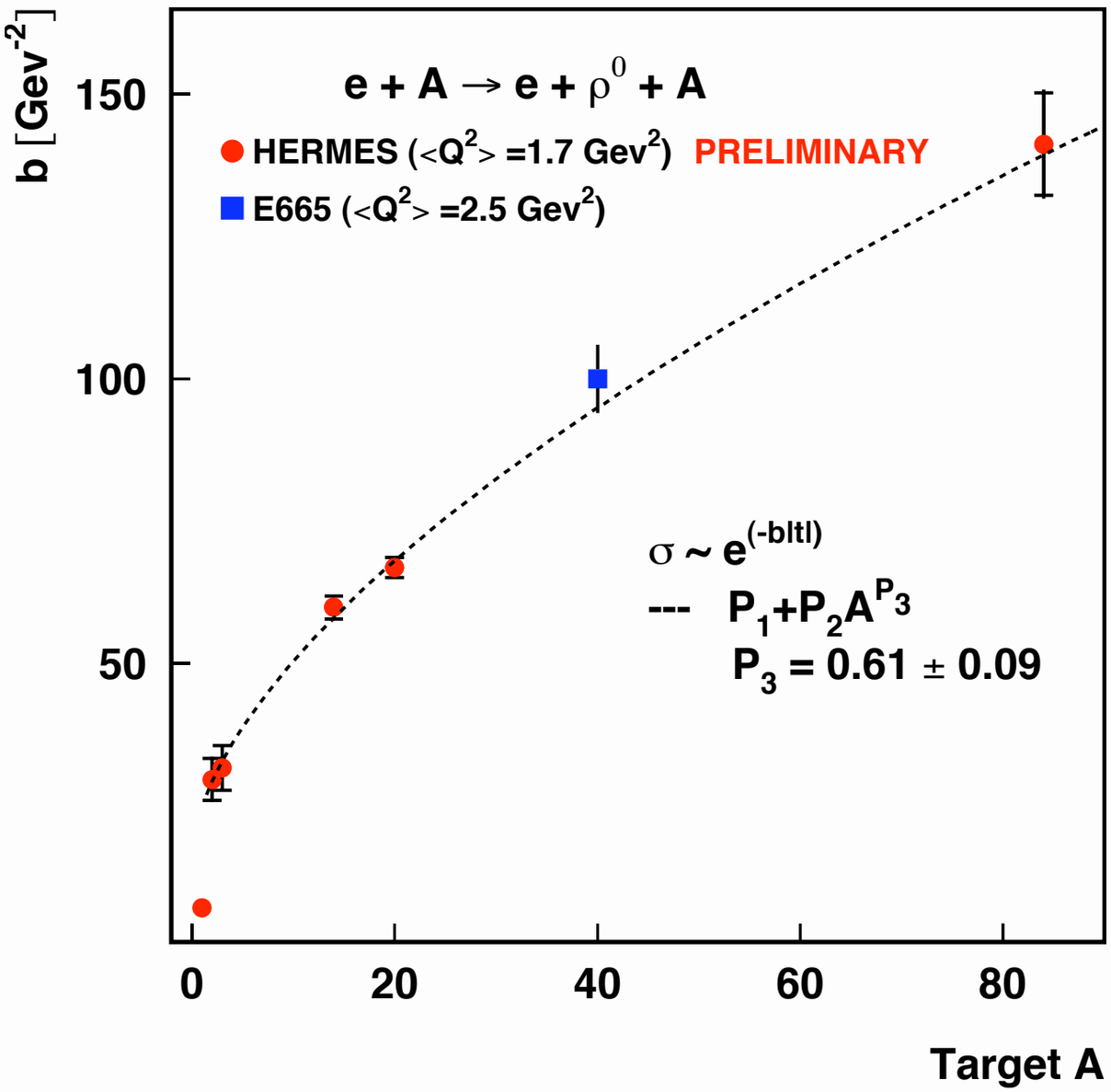
Kopeliovich and Nemchik, arXiv:nucl-th/9511018



HERMES data for incoherent ρ electroproduction vs. coherence length, ^{2}H, ^{3}He, N

Dotted curve is prediction from Huefner, Kopeliovich, Nemchik, 1996





HERMES ρ results for nuclei

PHI MESONS IN NUCLEI, COUPLED CHANNELS

ϕ-meson photoproduction from nuclei

A. Sibirtsev[1], H.-W. Hammer[1], U.-G. Meißner[1,2] and A.W. Thomas[3]

Eur.Phys.J. A29 (2006) 209-220; arXiv:nucl-th/0606044

Abstract. We study coherent and incoherent ϕ-meson photoproduction from nuclei. The available data are analyzed in terms of single and coupled channel photoproduction. It is found that the data on coherent photoproduction can be well reproduced within a single channel optical model and show only little room for $\omega - \phi$ mixing. These data indicate a normal distortion of the ϕ-meson in nuclei, which is compatible with the results obtained through the vector meson dominance model. The data on incoherent ϕ-meson photoproduction show an anomalous A-dependence resulting in a very strong ϕ-meson distortion. These data can be explained by a coupled channel effect through the dominant contribution from the $\omega \rightarrow \phi$ or $\pi \rightarrow \phi$ transition or, more speculative, through the excitation of a cryptoexotic B_ϕ-baryon.

ϕ-N cross sections, energy dependence

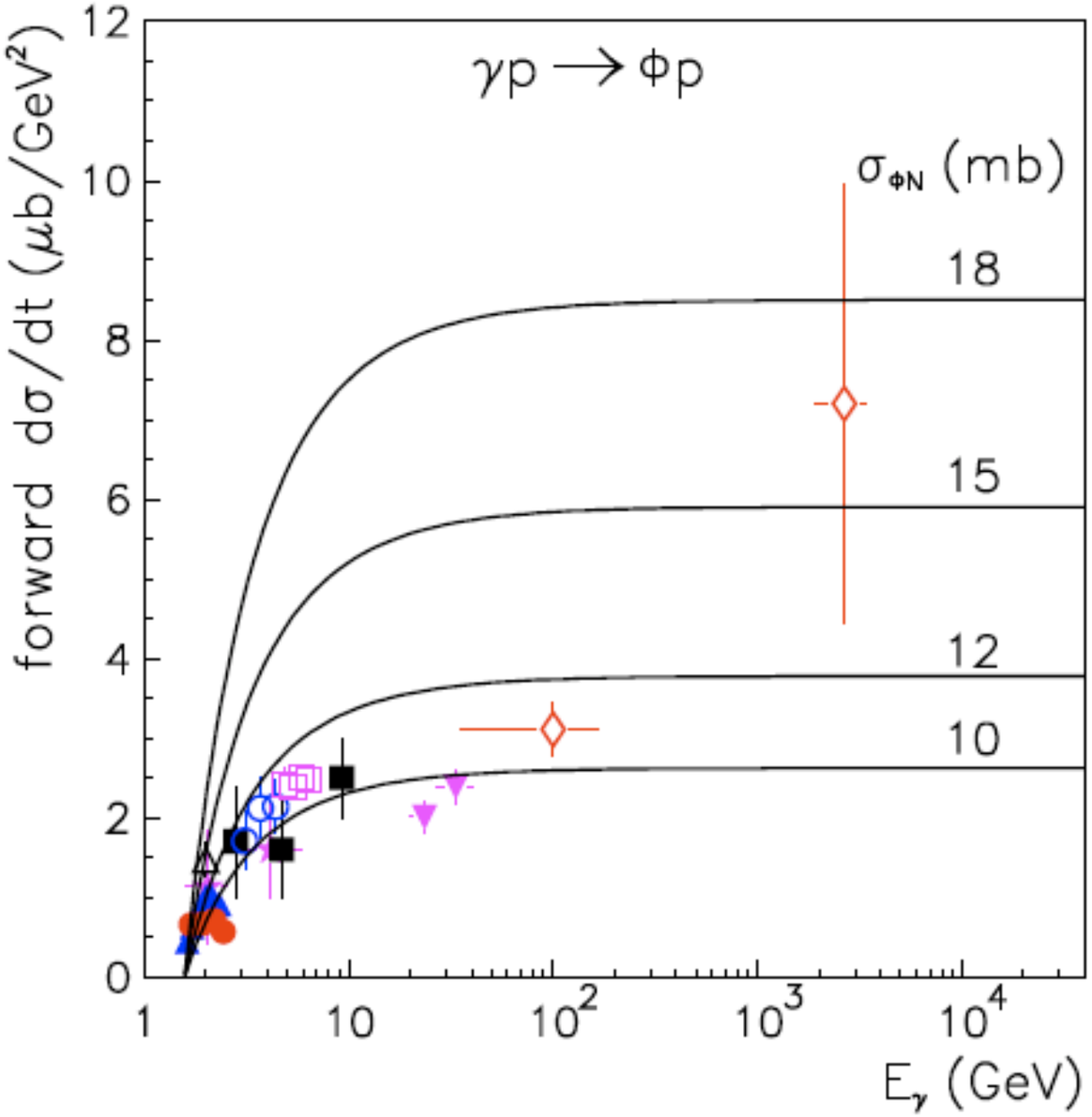


Fig. 1. The forward $\gamma p \rightarrow \phi p$ differential cross section as a function of photon energy. The data are taken from Refs.[32,33,34,35,36,37,38, 39,40,41]. The lines show the calculations using Eq.(7) with α_ϕ=0 and for different values of $\sigma_{\phi N}$.

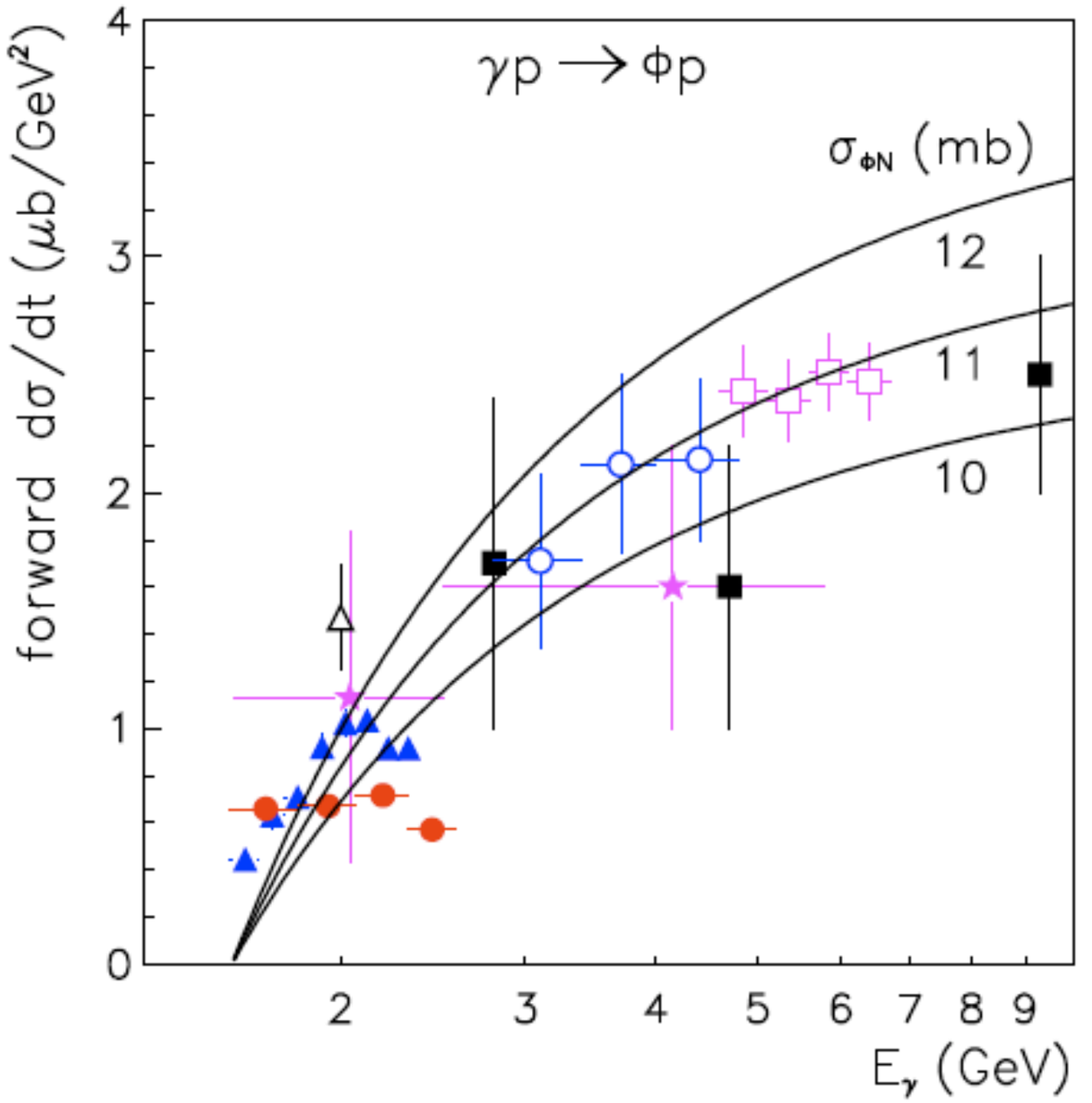


Fig. 2. Same as in Fig.1 for a low photon energy scale. The solid circles show the results collected by SAPHIR [40], while the solid triangles are the measurements from SPRING-8 [41].

Hall D could fill in E_γ<10 GeV with precision, consistent dataset

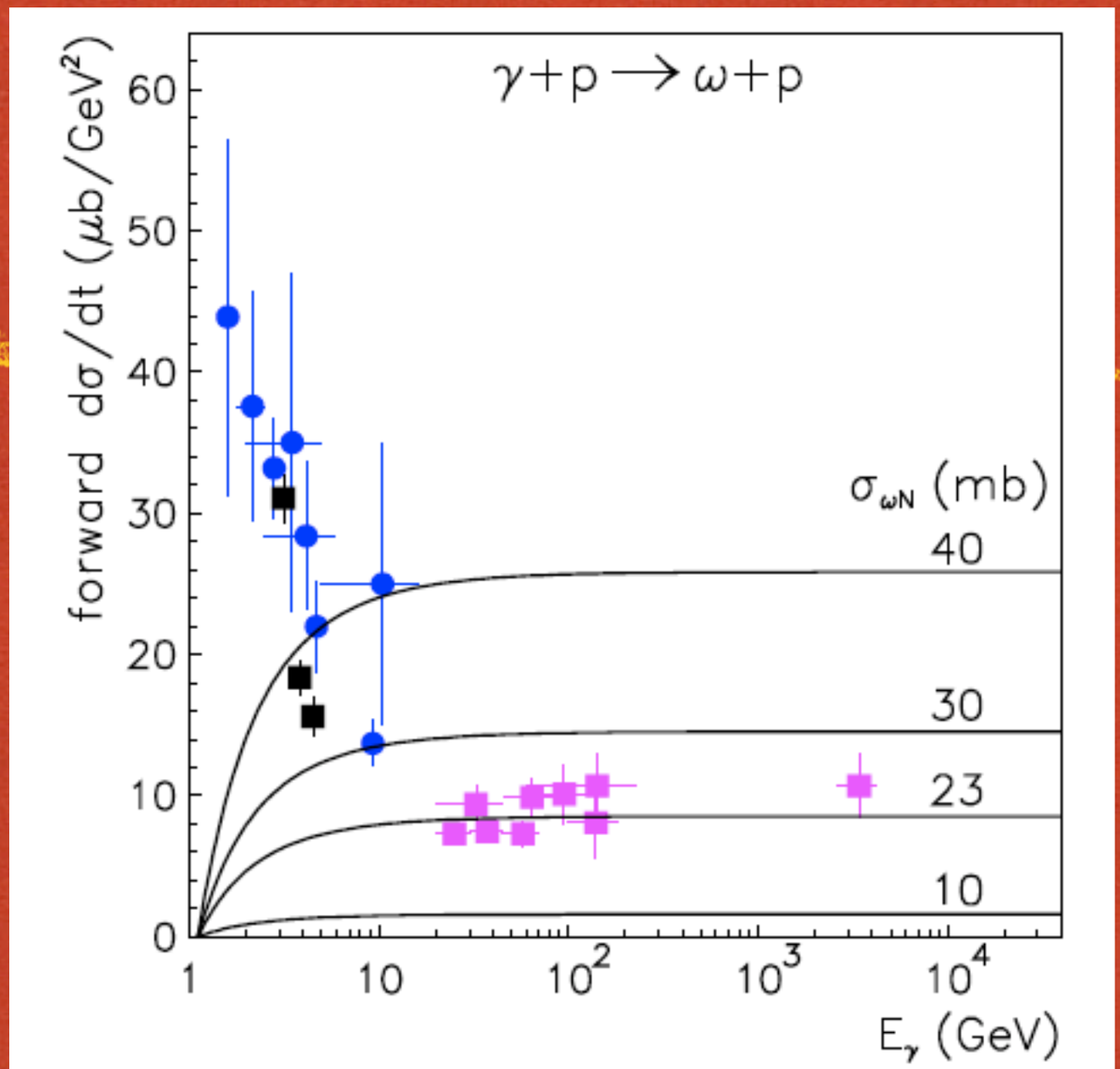


Fig. 3. The forward $\gamma p \rightarrow \omega p$ differential cross section as a function of photon energy. The data are collected in Ref.[29]. The lines show the calculations based on Eq. (7) with α_ω=0 and for different values of $\sigma_{\omega N}$.

Data for ω, E_γ<10 GeV, could benefit from improvement...

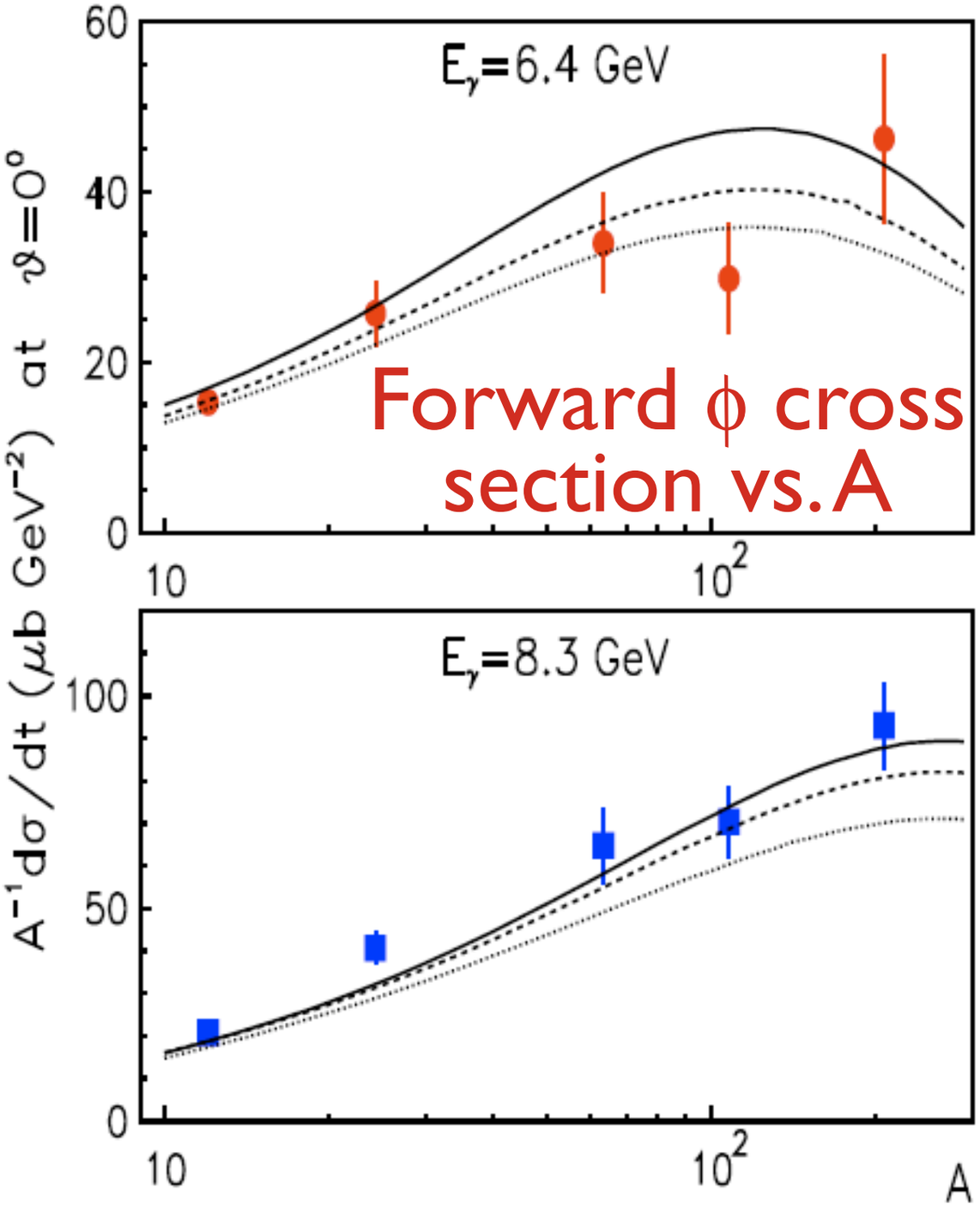


Fig. 8. The forward $\gamma A \rightarrow \phi A$ differential cross section as a function of the mass number. The symbols show the data collected at Cornell [22] at photon energies 6.4 (circles) and 8.3 GeV (squares). The lines are the coupled channel scattering calculations by Eq.(21) with the total ϕN cross section of 11 mb and the ωN cross section of 23 mb and for the transition Σ=0 (solid), 0.3 (dashed) and 0.5 mb (dotted). Both experimental results and calculations are divided by A. The normalization of the calculations is fixed by VDM as explained in the text.

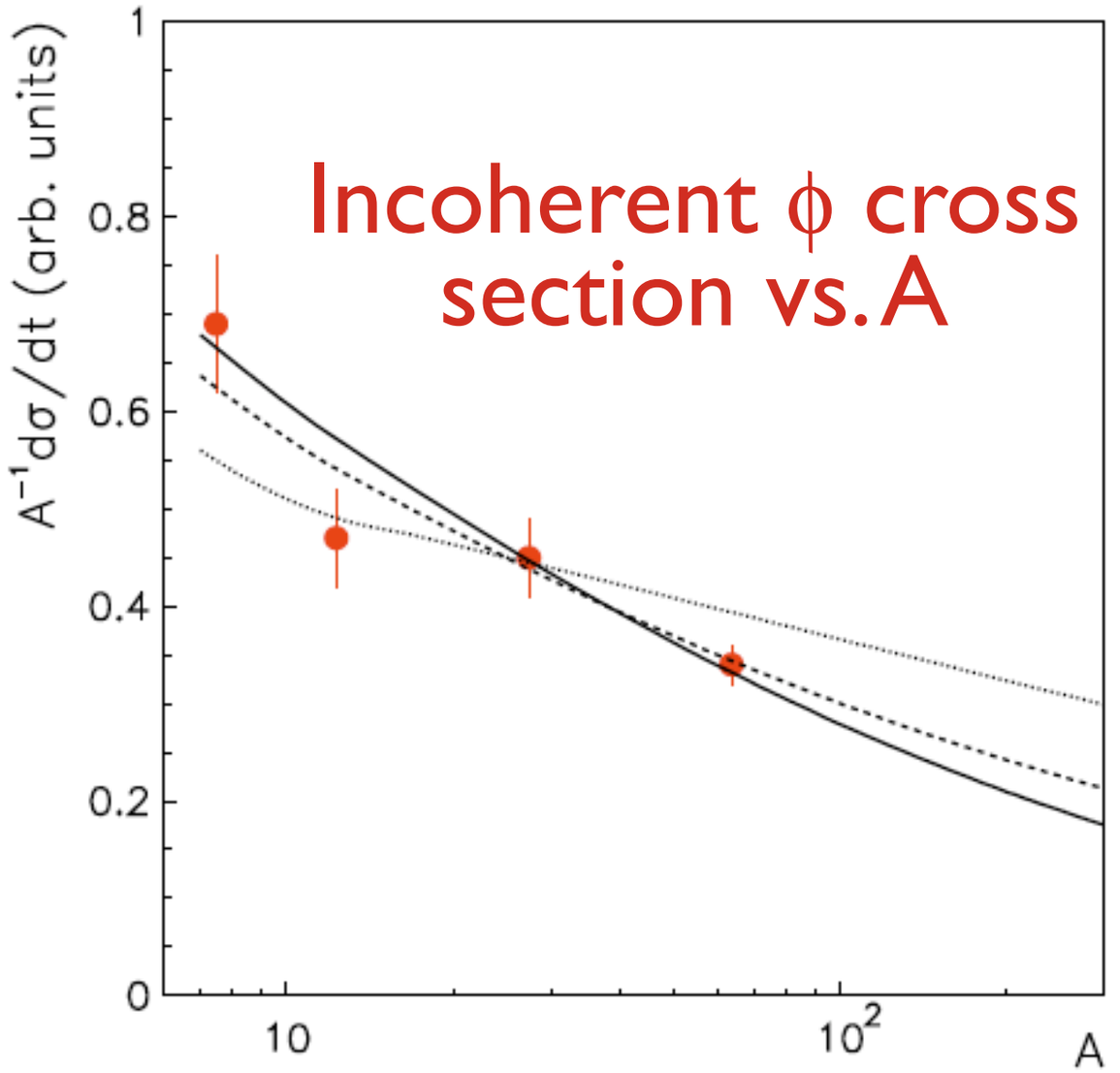


Fig. 9. The incoherent ϕ-meson photoproduction cross section as a function of the mass number. The circles show the data collected at SPRING-8 [20]. The solid line is the coupled channel scattering calculations by Eq.(25) with the total ϕN cross section of 11 mb and the ωN cross section of 23 mb, while the dashed line is result obtained with $\sigma_{\phi N}$=11 mb and $\sigma_{\omega N}$=30 mb. The dotted line is the single channel results for $\sigma_{\phi N}$=11 mb. Both experimental results and calculations are divided by A. The normalization of the calculations is fixed at the Al target.

CONCLUSIONS

- High-statistics program of diffraction measurements on nuclei possible in Hall D
- Substantial new information on space-time QCD, excellent complement to Hall B program
- Diffractive Compton process: particularly sensitive to new Generalized Gluon Distributions

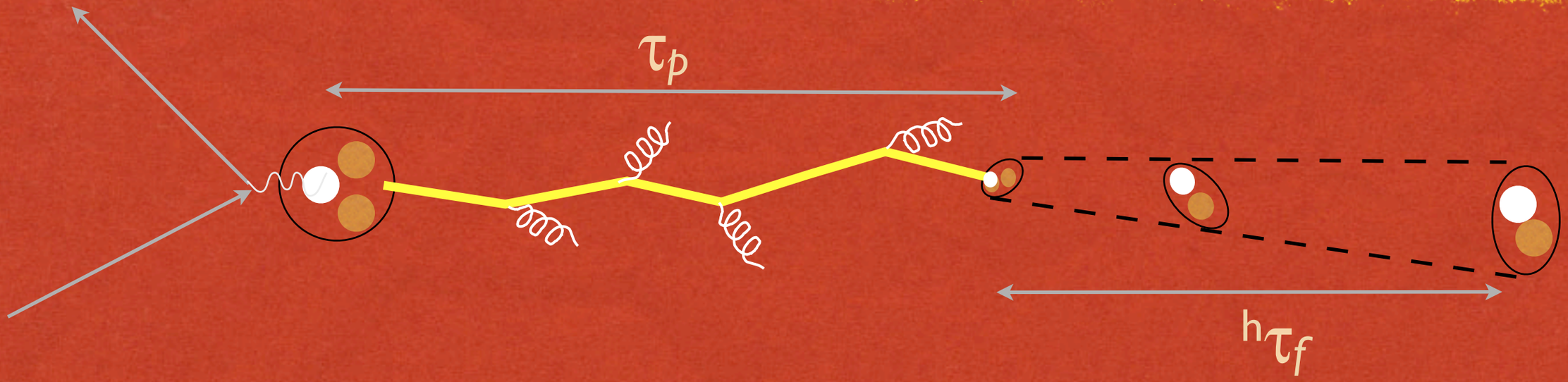
ADDITIONAL SLIDES

The ρ^0 production sample was extracted from events with exactly three tracks: a scattered positron and two oppositely charged hadrons, as described in detail in Ref. [20]. Events with π^0 mesons were excluded by disregarding events with an untracked cluster in the calorimeter. Evaluated for each event were the Bjorken scaling variable $x = Q^2/2m_p\nu$, with m_p the mass of the proton, the squared four-momentum transfer to the target $t' = t - t_0$, with t_0 its minimum value, and the photon-nucleon invariant mass squared $W^2 = m_p^2 + 2m_p\nu - Q^2$. The kinematic coverage in ν, x and W is $5 < \nu < 24$ GeV, $0.01 < x < 0.35$ and $3 < W < 6.5$ GeV, with mean values of 13.3 GeV, 0.07 and 4.9 GeV, respectively.

The exclusive ρ^0 production signal was extracted in the kinematic region $-2 < \Delta E < 0.6$ GeV and $0.6 < M_{\pi\pi} < 1$ GeV, where $\Delta E = \nu - E_\rho + \frac{t}{2m_p}$ is the exclusivity variable [20, 23] with E_ρ the energy of the produced ρ^0 meson, and $M_{\pi\pi}$ the invariant mass of the detected hadron pair, assuming that they were pions. In the analysis of nuclear transparency for coherent production, the exclusive ρ^0 mesons have been selected with $|t'| < 0.045$ GeV^2 for nitrogen and $|t'| < 0.4$ GeV^2 for hydrogen, while in the analysis for incoherent production the t' restriction was $0.09 < |t'| < 0.4$ GeV^2 for both data samples. The resolution of ΔE is about 0.25 GeV [23], and the t' resolution is about 0.008 GeV^2. It has been shown [20] that the

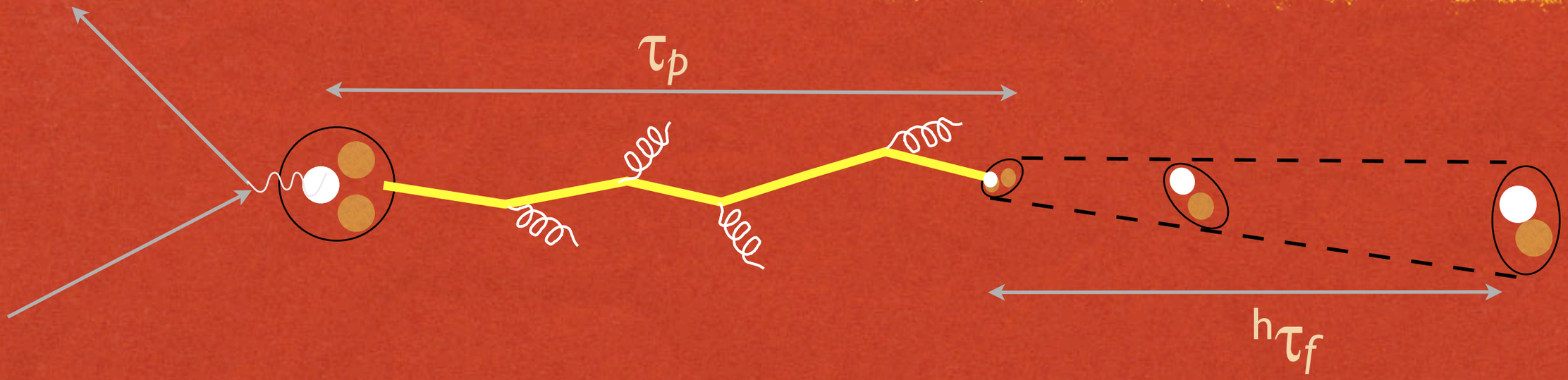
HERMES rho analysis procedure 2003 paper

PHYSICAL PICTURE - VACUUM



- ***production time*** τ_p is time required to form color singlet pre-hadron; 'lifetime of deconfined quark'; universal(?)
- ***formation time*** $^h\tau_f$ is time required to form full-sized hadron

PRODUCTION TIME EXTRACTION



- ***production time*** τ_p is time required to form color singlet pre-hadron; 'lifetime of deconfined quark'

- ***Postulate***:

  - pT broadening (δp^2_T) only accumulates during production time phase

  - ***Saturation of δp^2_T vs. A signals end of production time phase - enables extraction of*** τ_p