Directions for color and chiral transparency studies

Mark Strikman, PSU

Topics to be covered

Introduction - QCD factorization and Discovery of high energy CT

Search for CT at intermediate energies - bane of space -time evolution

Future directions for Jlab at 6 and 12 GeV

Based on studies together principally with Farrar, Frankfurt, Miller, Sargsian, Zhalov

Jlab SRC workshop Oct.26, 2007

Color transparency phenomenon plays several different roles:

- ✠ probe of the high energy dynamics of strong interaction
- ✠ probe of minimal small size components of the hadrons

at intermediate energies also a unique probe of the space time evolution of wave packages

Important for probing SRC as we need to take into account FSIs

Important for determining in what range of Q one can probe GPDs in exclusive processes - generalized CT = QCD factorization

CT at intermediate energies requires *three conditions*: small configurations, small cross section and suppression of expansion

CT at high energies requires *two conditions*: small configurations, small cross section. However the small cross section condition is more difficult to satisfy (large gluon density at small x)

Warning - at low energies where gluons play relatively small role, small dipole cross section does not go to zero:

$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff})d^2\left[x_N G_N(x,Q^2_{eff}) + 2/3 x_N S_N(x_N,Q^2_{eff})\right]$$

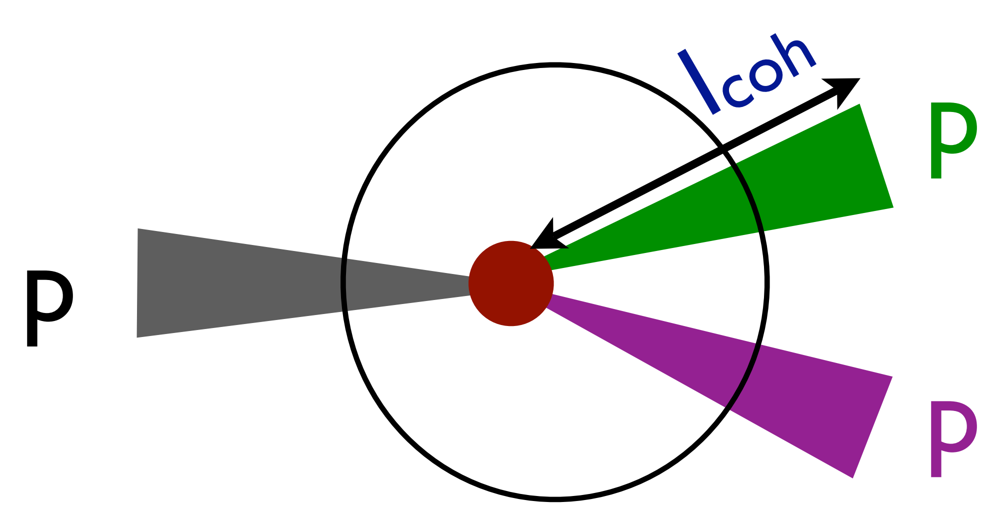
where S is sea quark distribution for quarks making up the dipole

Main challenge: |qqq> (|q$\bar{q}$>) is not an eigenstate of the QCD Hamiltonian. So even if we find an elementary process in which interaction is dominated by small size configurations - they are not frozen. They evolve with time - expand after interaction to average configurations and contract before interaction from average configurations (FFLS88)

$$|\Psi_{PLC}(t)\rangle = \Sigma_{i=1}^{\infty} a_i \exp(iE_it)\,|\Psi_i\rangle = \exp(iE_1t)\Sigma_{i=1}^{\infty} a_i \exp\left(\frac{i(m_i^2 - m_1^2)t}{2P}\right)|\Psi_i\rangle\,;$$

$$\sigma^{PLC}(Z) = (\sigma_{hard} + \frac{Z}{l_c}[\sigma - \sigma_{hard}])\theta(l_c - Z) + \sigma\theta(Z - l_c)\,.$$

Quantum Diffusion model of expansion



pA→ pp (A-1) at large t and intermediate energies

l_{coh}~ 0.3 fm p_N[GeV]

actually incoherence length

MC at RHIC assume much larger l_{coh}

Note - one can use multihadron basis with build in CT (Miller and Jennings) or diffusion model - numerical results for σ^{PLC} are very similar.

Discovery of high energy CT

$\Longrightarrow$ **Need to trigger on small size configurations at high energies.**

Two ideas:

$\diamond$ Select special final states: diffraction of pion into two high transverse momentum jets - an analog of the positronium inelastic diffraction. Qualitatively - from the uncertainty relation $d \sim 1/p_t(jet)$

$\diamond\diamond$ Select a small initial state - diffraction of longitudinally polarized virtual photon into mesons. Employs the decrease of the transverse separation between q and $\bar{q}$ in the wave function of γ_L^*, $d \propto 1/Q$.

QCD factorization is valid with proofs based on the CT property of QCD

- dijets - pQCD analysis - Frankfurt, Miller, MS 93; elaborated arguments related to factorization 2003 - FNAL experiment of D.Ashery confirmed our predictions

- vector meson production at high energies - theory works well for HERA energies

> - Presence of small size $q\bar{q}$ Fock componentss in light mesons is unambigously established
> - At transverse separations $d \leq 0.3$ fm pQCD reasonably describes "small $q\bar{q}$ - dipole"- nucleon interaction for $10^{-4} < x < 10^{-2}$
> - Color transparency is established for the interaction of small dipoles with nucleons and with nuclei (for $x \sim 10^{-2}$)

CT is easier to probe for mesons than for baryons as only two quarks have to come close

Intermediate energies

Main issues

- ☛ At what Q^2 / t particular processes select PLC - for example interplay of end point and LT contributions in the e.m. form factors,....

- ☛ If the PLC is formed - how long it remains smaller than average configuration

Studies of FS & Miller and Jennings

$l_{coh} = (0.3 \div 0.4 \text{ fm}) \, p_h$ [GeV] actually length of incoherence

and about the same for pions and nucleons due to similarity of the Regge slopes for meson and baryon trajectories

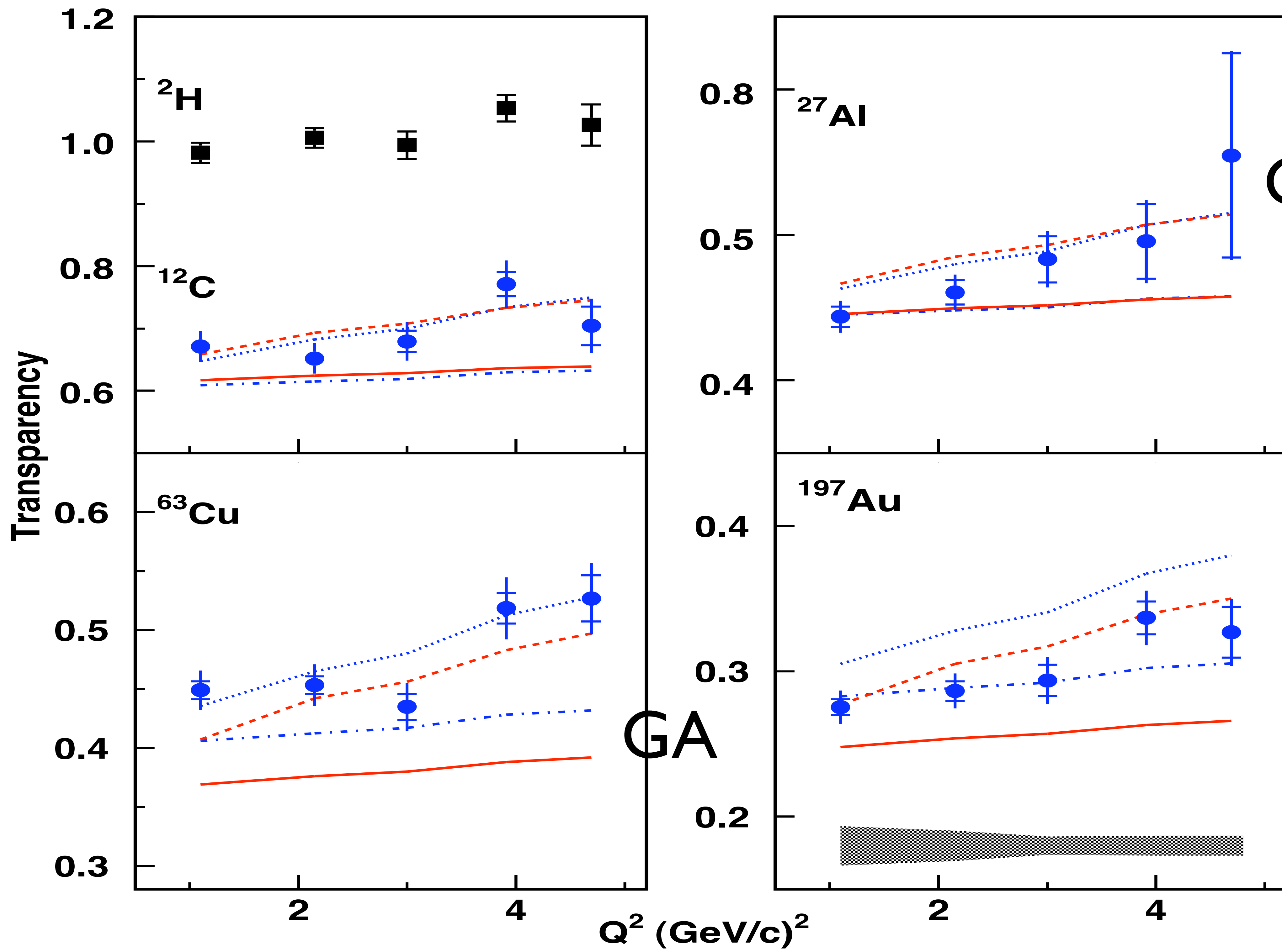
In dijet production $p_t \sim 1$ GeV/c corresponding to $Q^2 \sim 4\, p_t^2 \sim 4\,GeV^2$ seemed to be enough to squeeze the system (though not yet to reach asymptotic in z distribution)

Hence pion production: $\gamma^* + A \to \pi A^*$, seems promising to look for an early onset of CT.

MS and Gerry Miller - tried to sell this process at the CT workshop at Jlab in 95

Published calculations together with Larson last year with $l_{coh} = 0.2 \text{ -- } 0.4$ fm p_π [GeV]

Note - pion production in exclusive processes is due to quark exchange in t-channel, the same is true for rho-meson production at Jlab energies. Squeezing at large energies seems to start at rather small Q. In case of Jlab - support from early decrease of the t-slope.



GA= Glauber approximation

GA+ CT

Solid and Dashed - Larson Miller, MS

Dot-Dashed and Dotted - Ghent group: W. Cosyn and J. Ryckebusch

$$T = \frac{A_{\text{eff}}}{A} = \frac{1}{A}\int d^3r\rho(r)\exp\left[-\int_z^{\infty} dz'\sigma_{\text{eff}}(z'-z,p_\pi)\rho(r')\right].$$

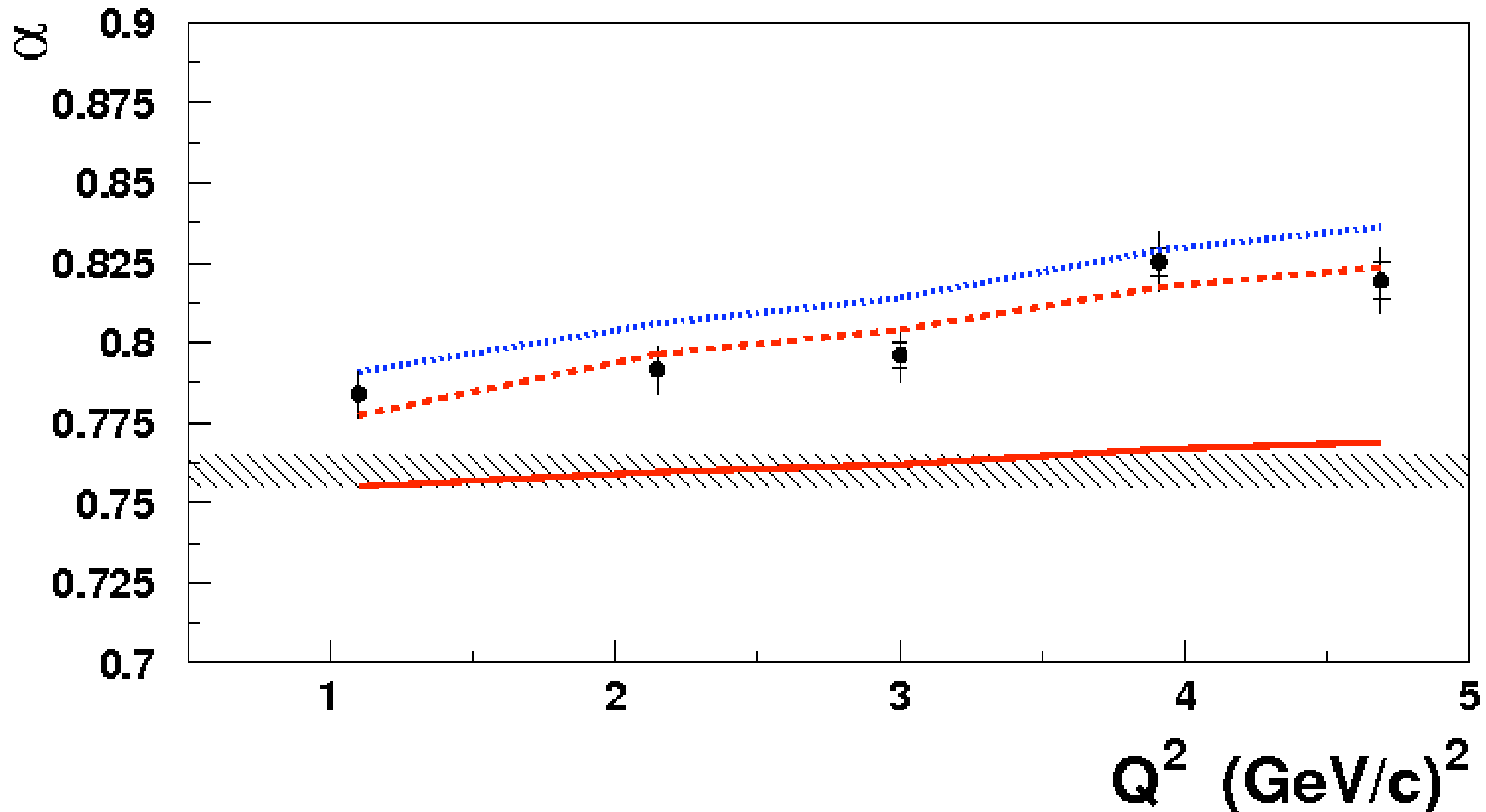


FIG. 3: The parameter α (from $\mathrm{T} = \mathrm{A}^{\alpha-1}$) is shown vs Q^2. The inner error bars are the statistical uncertainty and the outer error bars are the quadrature sum of statistical and systematic and model uncertainties. The hatched band is the value of α extracted from pion-nucleus scattering data [23]. The solid, dashed, and dotted lines are α obtained from fitting the A dependence of the theoretical calculations, Glauber, Glauber+CT [20], and Glauber+SRC+CT [21] respectively.

LMS

CR

VM CT studies

☺ CT is observed for $\gamma + A \to J/\psi + A$ at FNAL (Sokoloff et al)

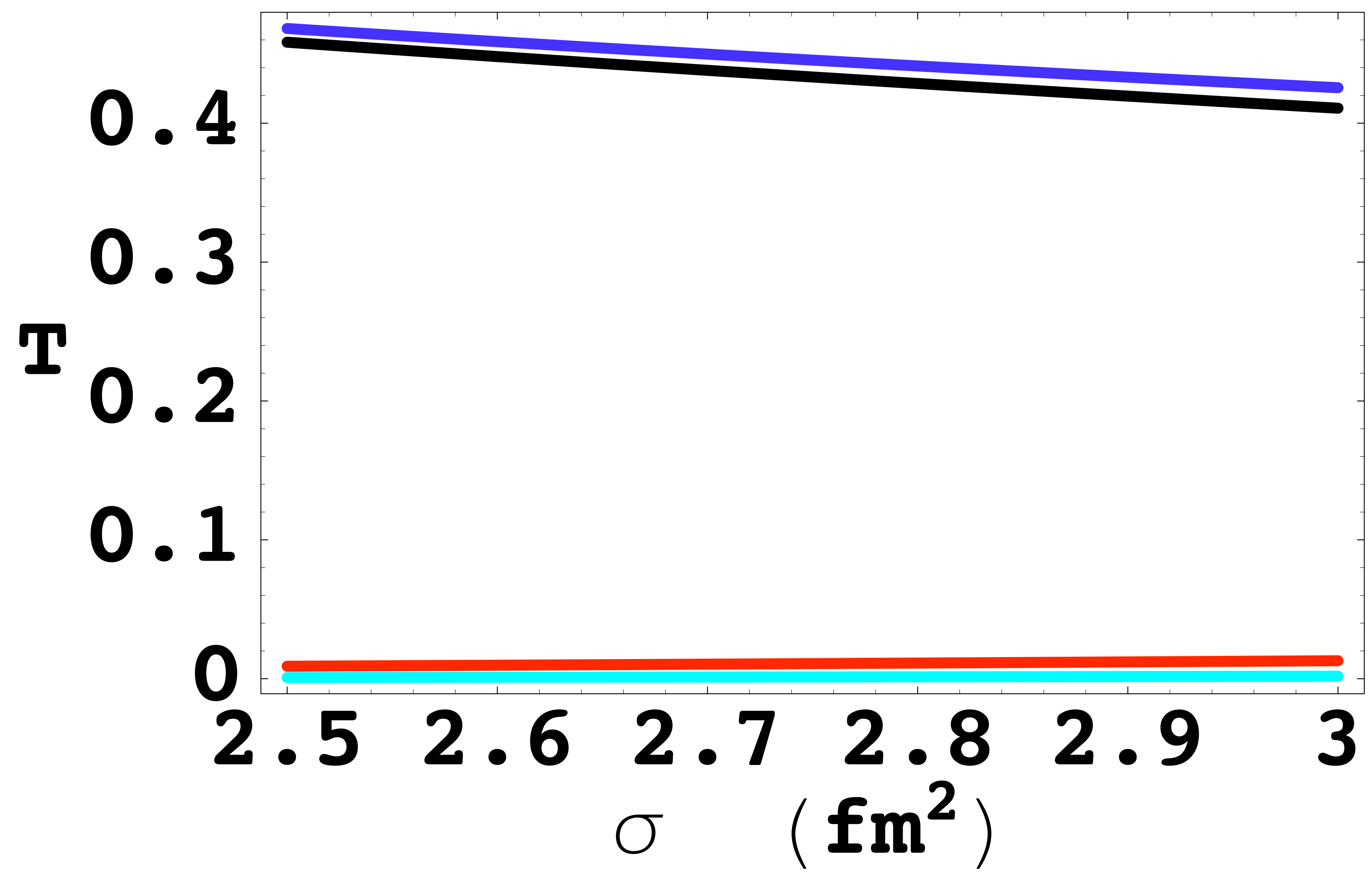
◆ ρ -meson production at high energies - inconclusive - some evidence in incoherent scattering - E665, HERMES - missing energy is significant - hadrons can be produced - in principle a different type of process.

Complication: ρ has large width. Decay length $\sim p_\rho/\Gamma m_\rho$ less or comparable to the radius of iron for $p_\rho <$ 2GeV/c. Two pions are absorbed with cross section > 60 mb for these energies - effect disappears at large p_ρ and mimics CT pattern. Jlab experiment has applied a correction - we (Frankfurt, Miller, MS 07) find a different expression - but numerical difference is not large.

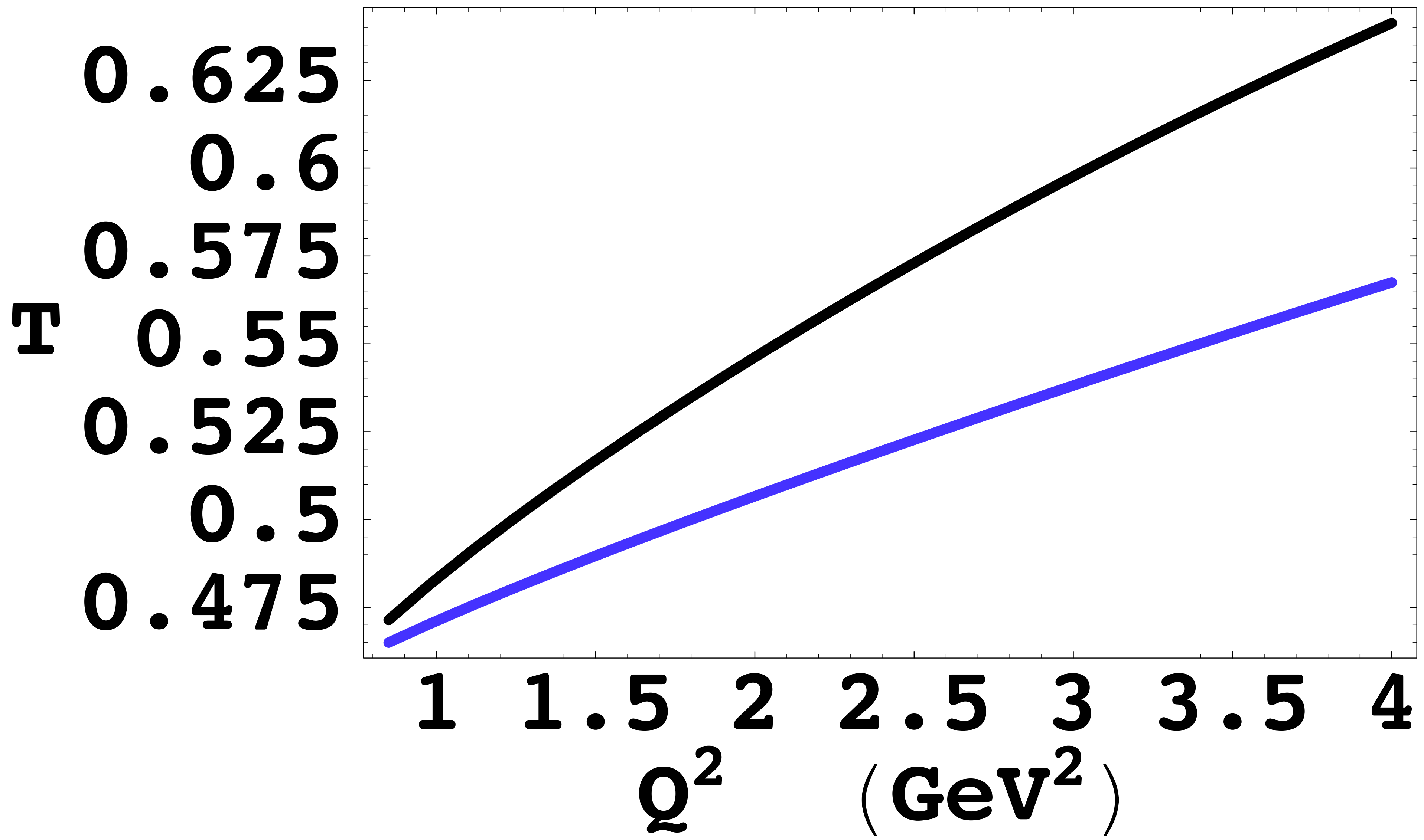
In the Jlab ρ experiment upper limit on the excitation energy is imposed. Hence several processes can contribute - production of ρ without extra elastic rescatterings - T_0, one elastic rescattering T_1,... There are also interference terms which are strongly suppressed at the t-range of the experiment.

$$T_0 = \int d^2b \int_{-\infty}^{\infty} dz \; \rho(b,z) \left(1 - \sigma_{\rm tot} T(b,z)\right)^{A-1} .$$

$$T_1 = (A-1)\frac{1}{\pi(B_1+B_2)} \exp\left(\frac{B_1^2}{B_1+B_2} q^2\right) \frac{\sigma_{\rm tot}^2}{16\pi}(1+\alpha^2) \int d^2b \int_{-\infty}^{\infty} dz \rho(b,z) T(b,z) \left(1 - \sigma_{\rm tot} T(b,z)\right)^{A-2} .$$



Glauber calculations. Transparency vs. σ_{tot}. The black curve represents T_0 , the red curve T_1 , and the cyan curve T_2 . The sum $T_0 + T_1 + T_2$ is shown in the blue curve. The forward limit, no momentum transfer is used. Effect of T_1 + T_2 remains small for the t-range of the experiment.



Color transparency using T_0 with $\sigma_{\mathrm{tot}} = 25$ mb.

We use the same inputs for the quantum diffusion model as for the pion case. Magnitude of the effect seems to agree with preliminary Jlab data.

Black and blue curves are for two different settings of the experiment corresponding to $l_c = \frac{\nu}{(m_\rho^2 + Q^2)} = 0.85 fm$ and *l_c=0.45 fm*.

Small l_c corresponds to distances over which quark-antiquark pair is produced. So one treat the problem as production of a pair in one point with further expansion over the distance l_{coh}

Directions for future studies at Jlab

Until condition $l_{coh} \geq l_{inter} = 1/\sigma\rho_A$ is met

CT should remain small (independent of whether it exists at all)

Promising situation for Jlab at 11 GeV for meson production - many channels to compare dynamics of different GPDs and mesons

For nucleon $l_{inter} \sim 2fm \Longrightarrow Q^2 \geq 13GeV^2$

12 GeV upgrade (e,e'p) experiment can reach at least Q^2=15 GeV^2

One needs further studies at intermediate Q^2 since the current situation is rather contradictory. 10 - 20% are not excluded - problem uncertainties in quenching.

K.Garrow et al 02

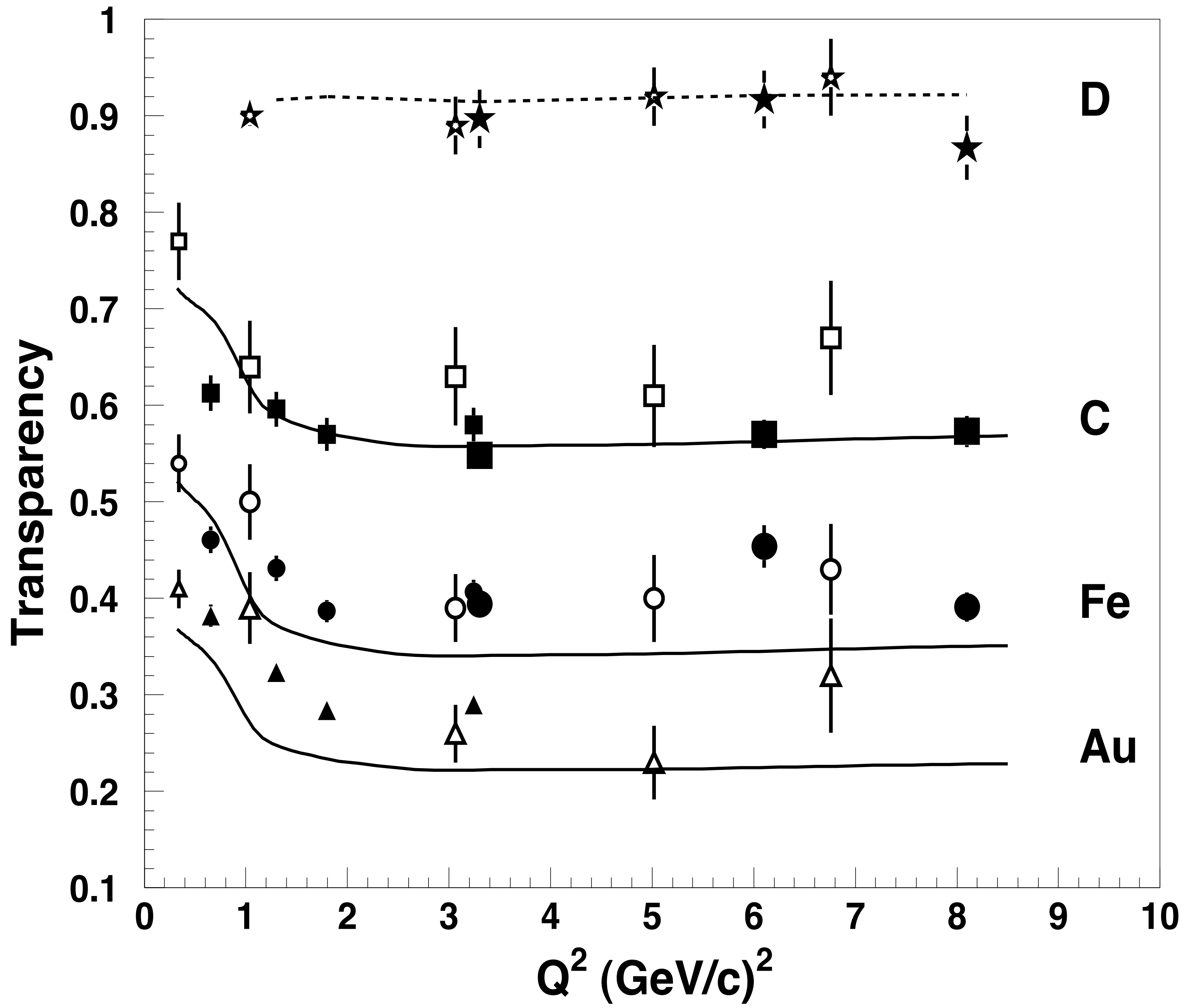
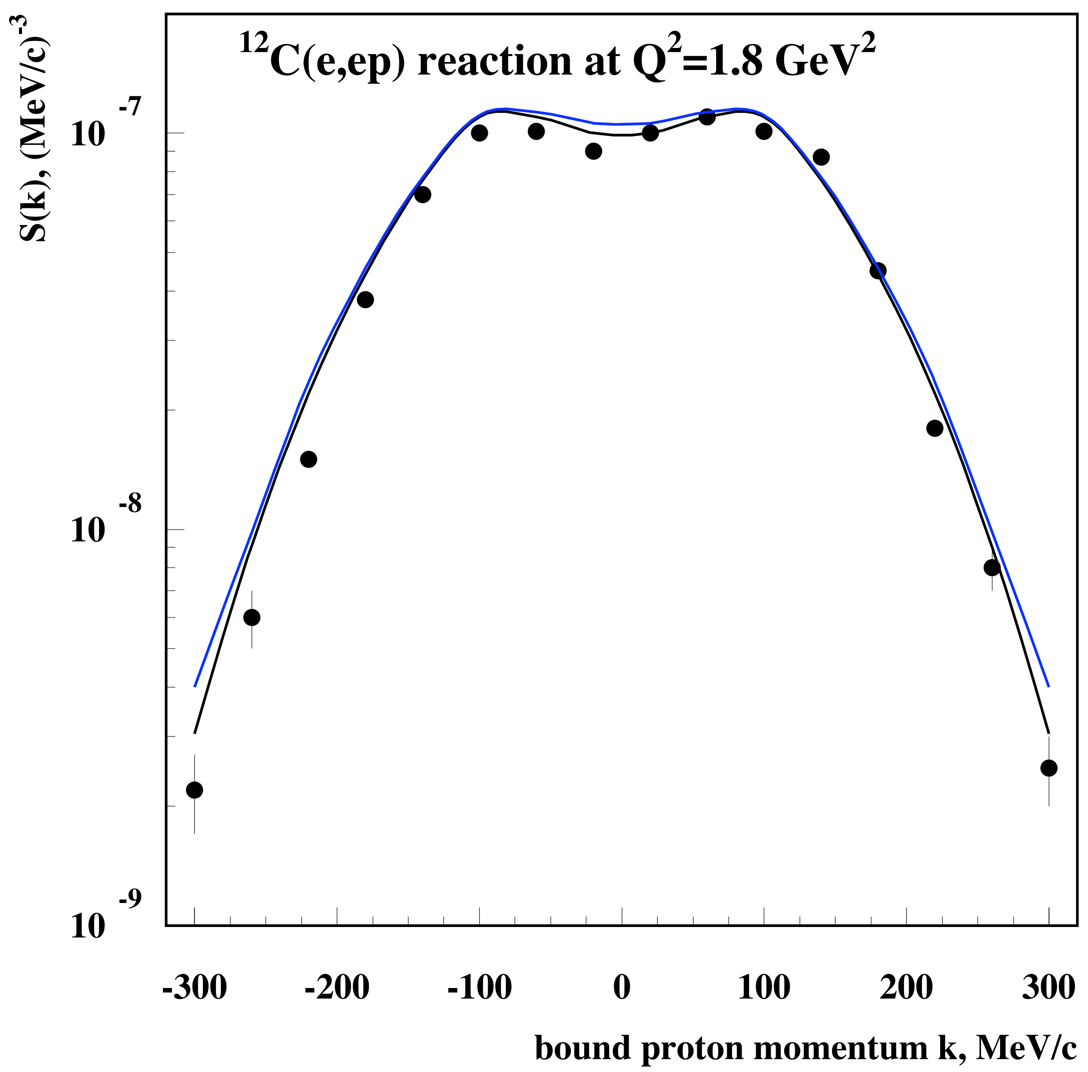


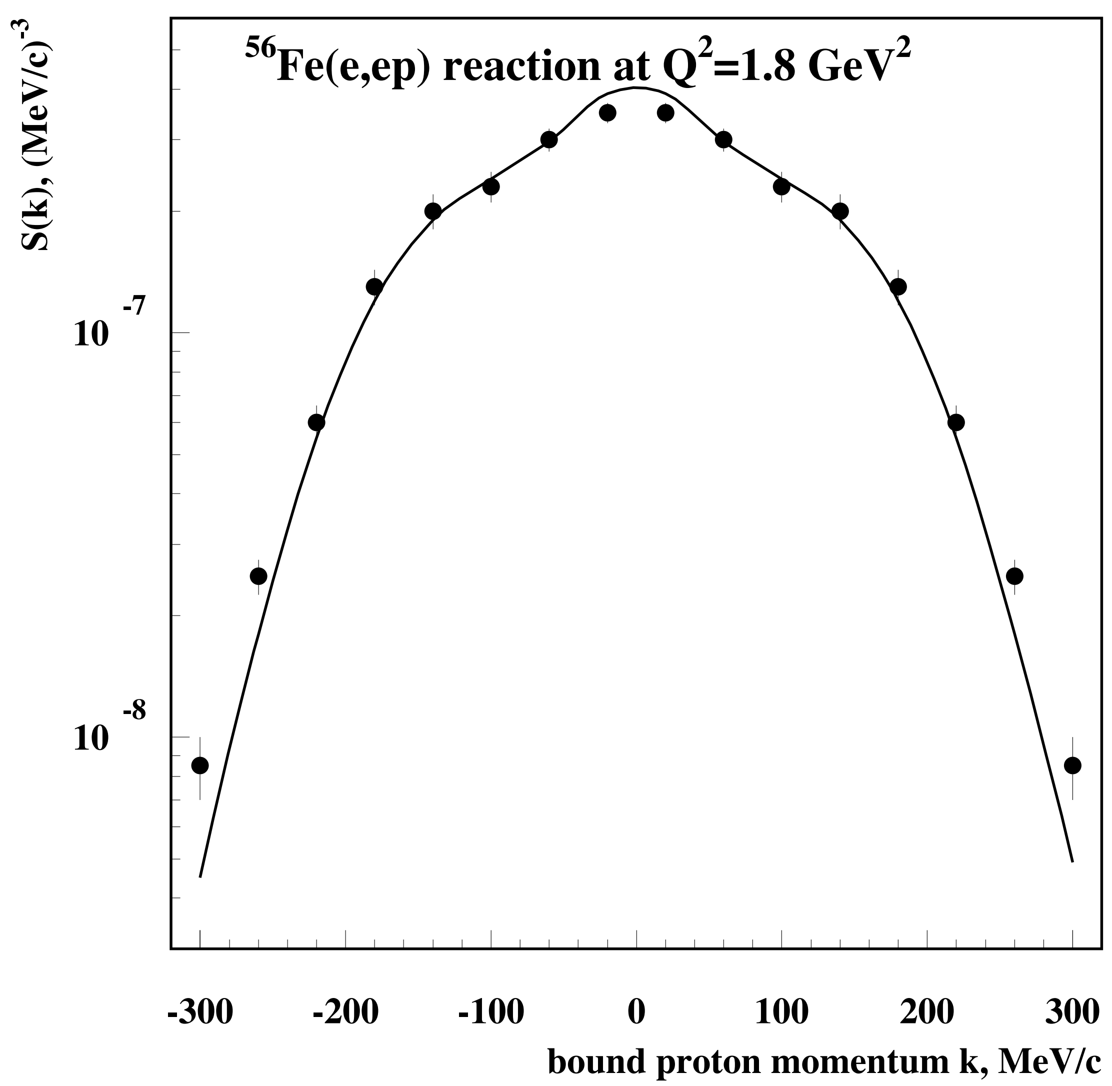
FIG. 3. Transparency for (e,e′p) quasielastic scattering from D (stars), C (squares), Fe (circles), and Au (triangles). Data from the present work are the large solid stars, squares, and circles, respectively. Previous JLab data (small solid squares, circles, and triangles) are from Ref. [16]. Previous SLAC data (large open symbols) are from Ref. [8,9]. Previous Bates data (small open symbols) at the lowest Q^2 on C, Ni, and Ta targets, respectively, are from Ref. [25]. The errors shown include statistical and systematic (± 2.3%) uncertainties, but do not include model-dependent systematic uncertainties on the simulations. The solid curves shown from $0.2 < Q^2 < 8.5$ (GeV/c)^2 are Glauber calculations from Ref. [26]. In the case of D, the dashed curve is a Glauber calculation from Ref. [27].

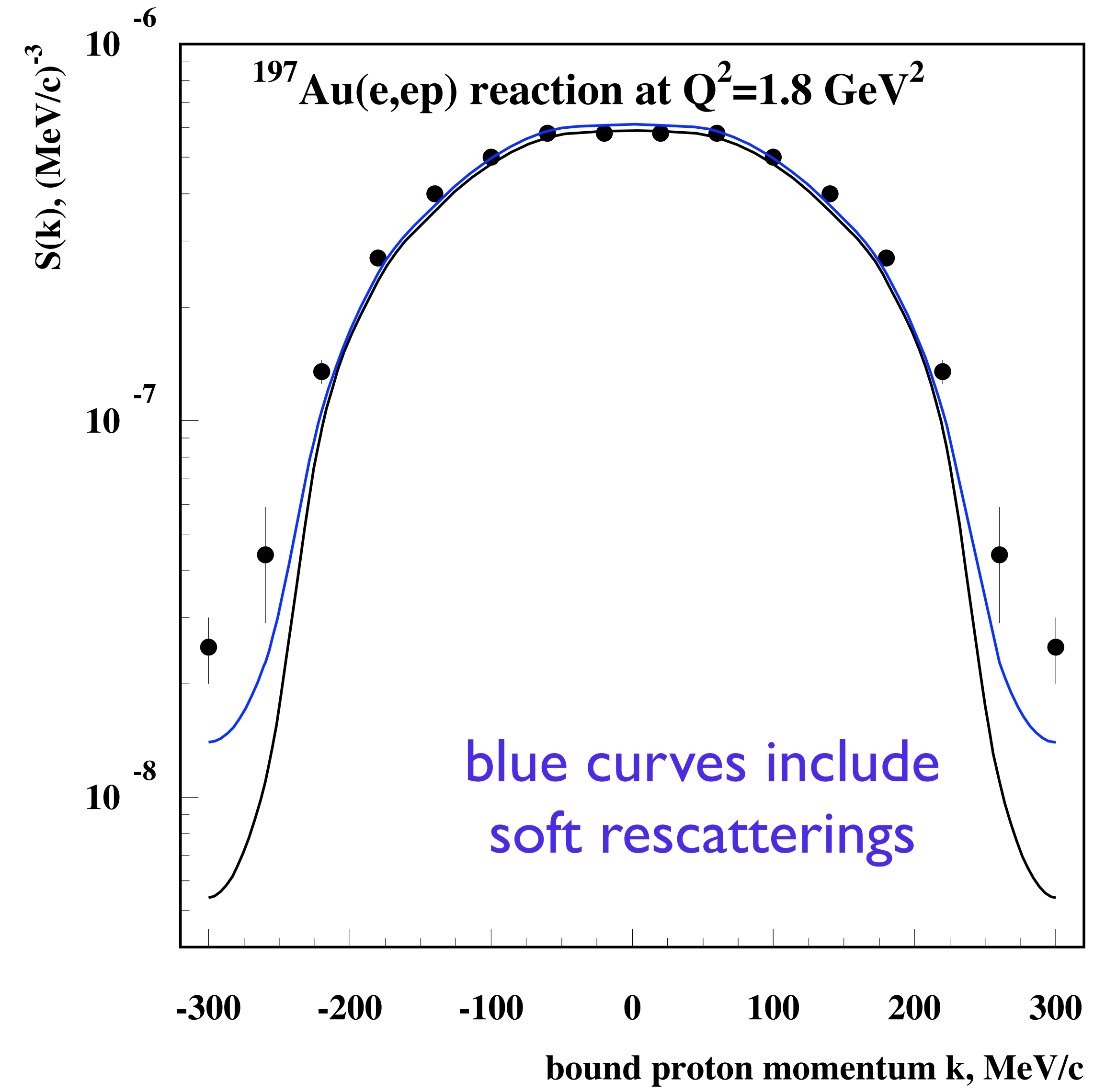
[26] H. Gao, V.R. Pandharipande, and S.C. Pieper (private communication); V.R. Pandharipande and S.C. Pieper, Phys. Rev. C **45**, 791 (1992).

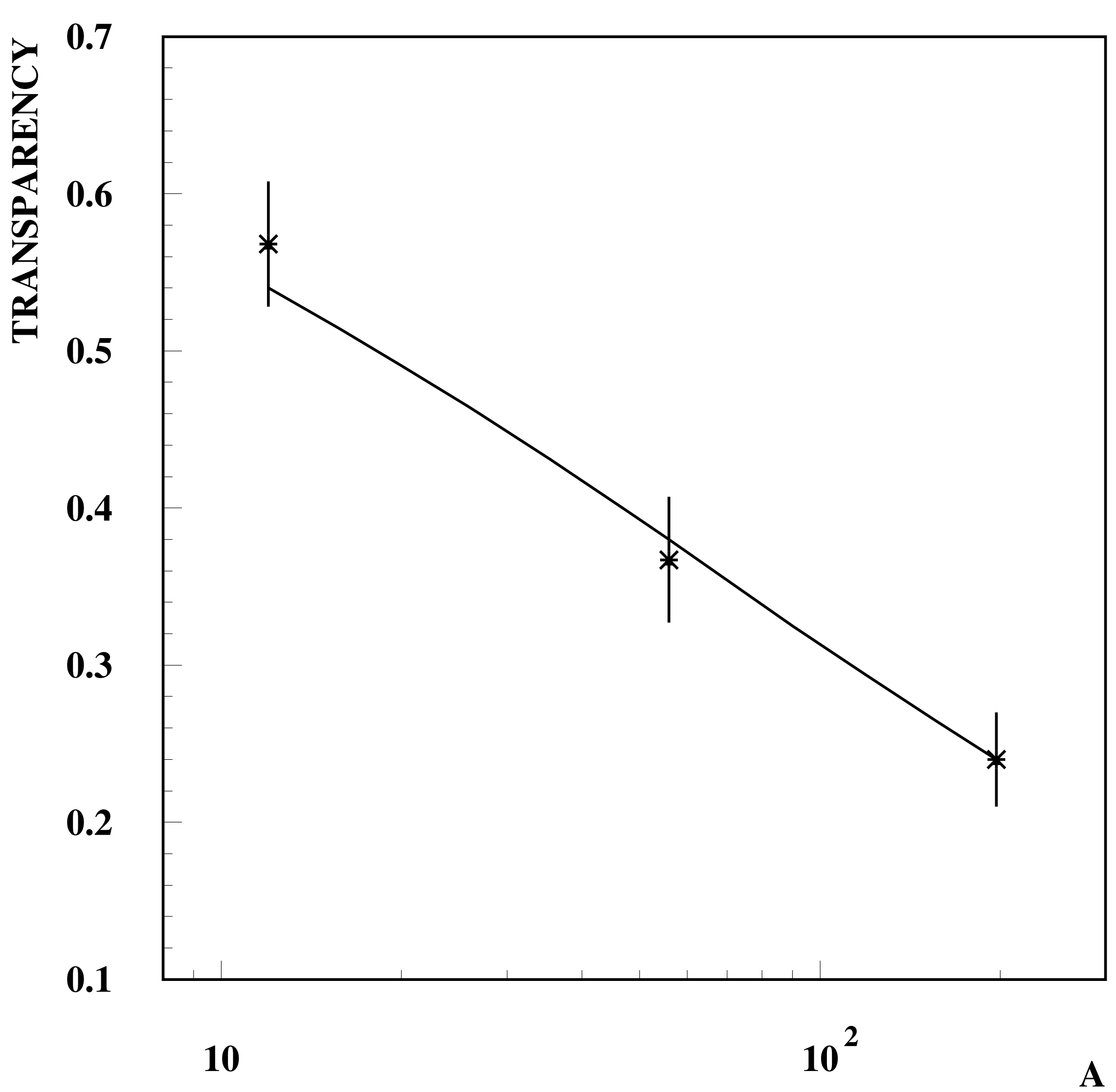
Discrepancy with Glauber calculation is typically 30% for heavy nuclei???

Glauber model (Frankfurt, Strikman, Zhalov) : very small suppression at large Q^2 : Q> 0.9









Comparison of transparency calculated using HFS spectral function with the data. No room for large quenching, though 10-15% effect does not contradict to the data.

Small quenching is consistent with a small strength at large excitation energies for the momentum range of the NE-18 experiment (R. Milner - private communication)

Need data on (e,e'p) for small k and large E_r and Q^2 ~ 2 GeV^2

Alternative possibility - 10-15% transparency effect

Chiral transparency - pion cloud contribution becomes negligible in the nucleon form factor at Q^2 > 1 GeV^2 ➠ at large Q charge exchange processes should be suppressed (LF& H.Lee, GM, MS, MS- 97). Difficult to observe for e,e'p processes as effect of pions is relatively small.

Alternative - use charge exchange processes. In FLMSS - considered 3He target. - not very practical process $e^3He \to e\, n\, n\, \Delta^{++}$

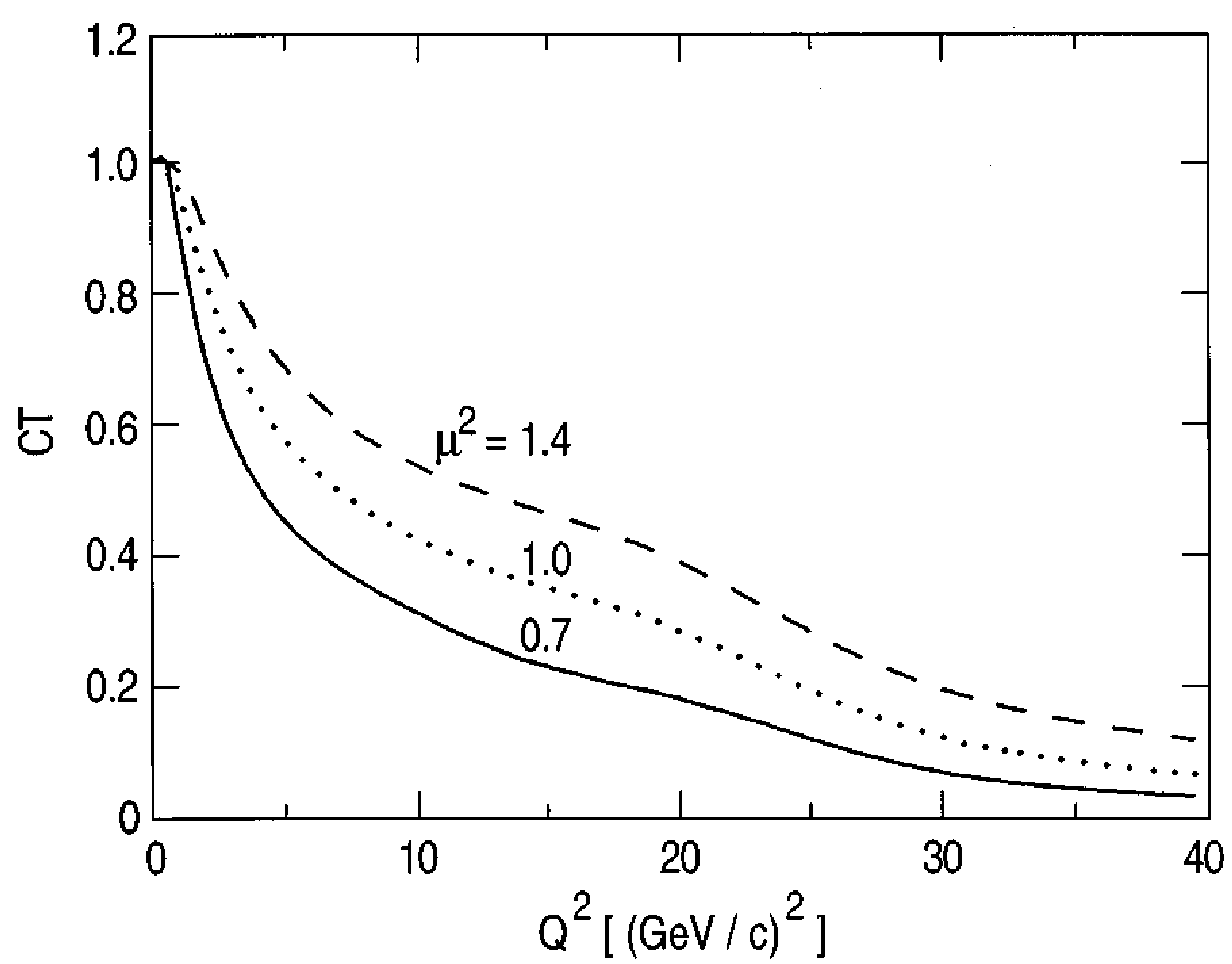


FIG. 1. Chiral transparency ratio CT of Eq. (29). The transverse momentum of the neutron is 0.3 GeV/c. Harmonic oscillator wave functions are used with $b=1$ fm. The parameter μ^2, which determines the value of l_c, is varied.

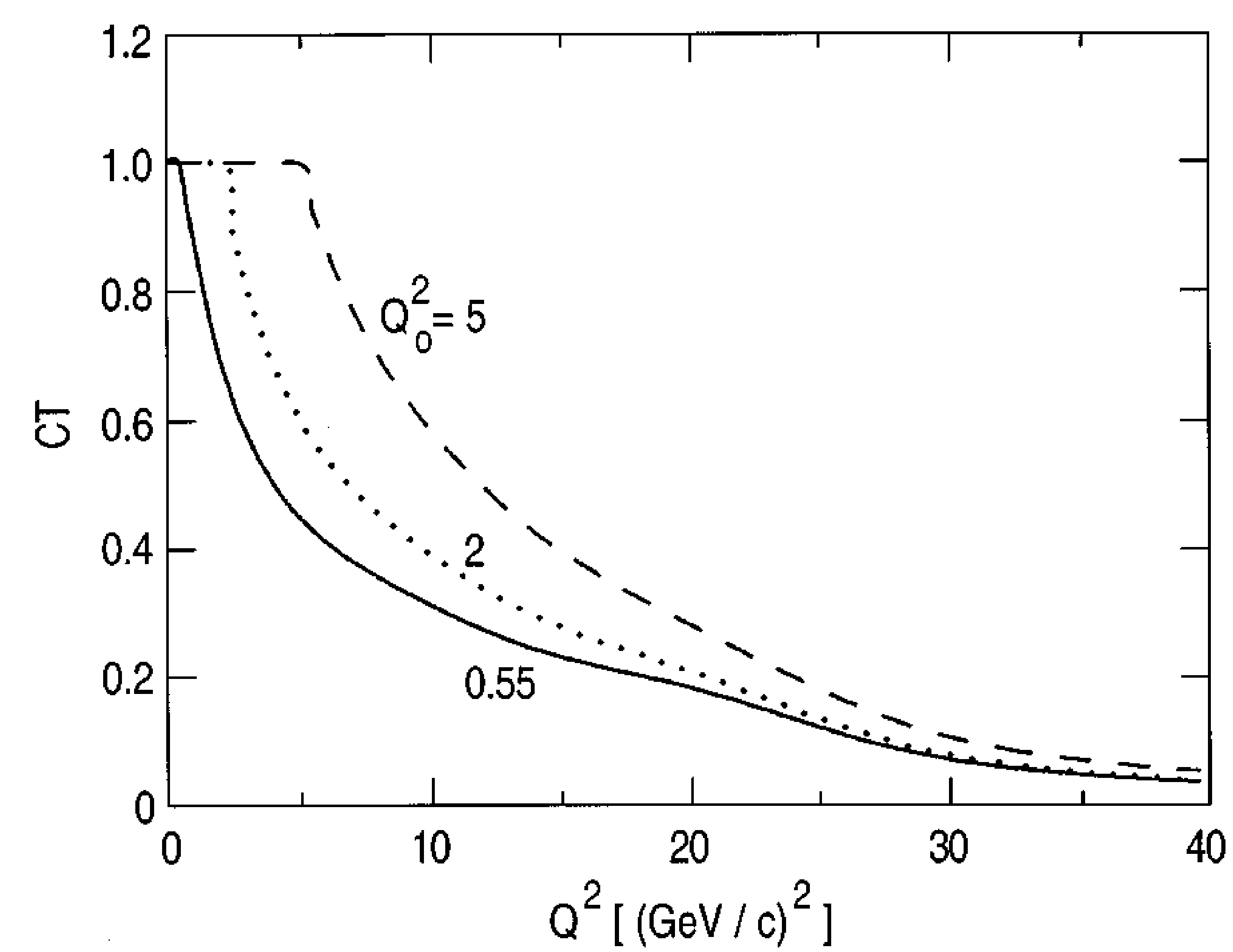
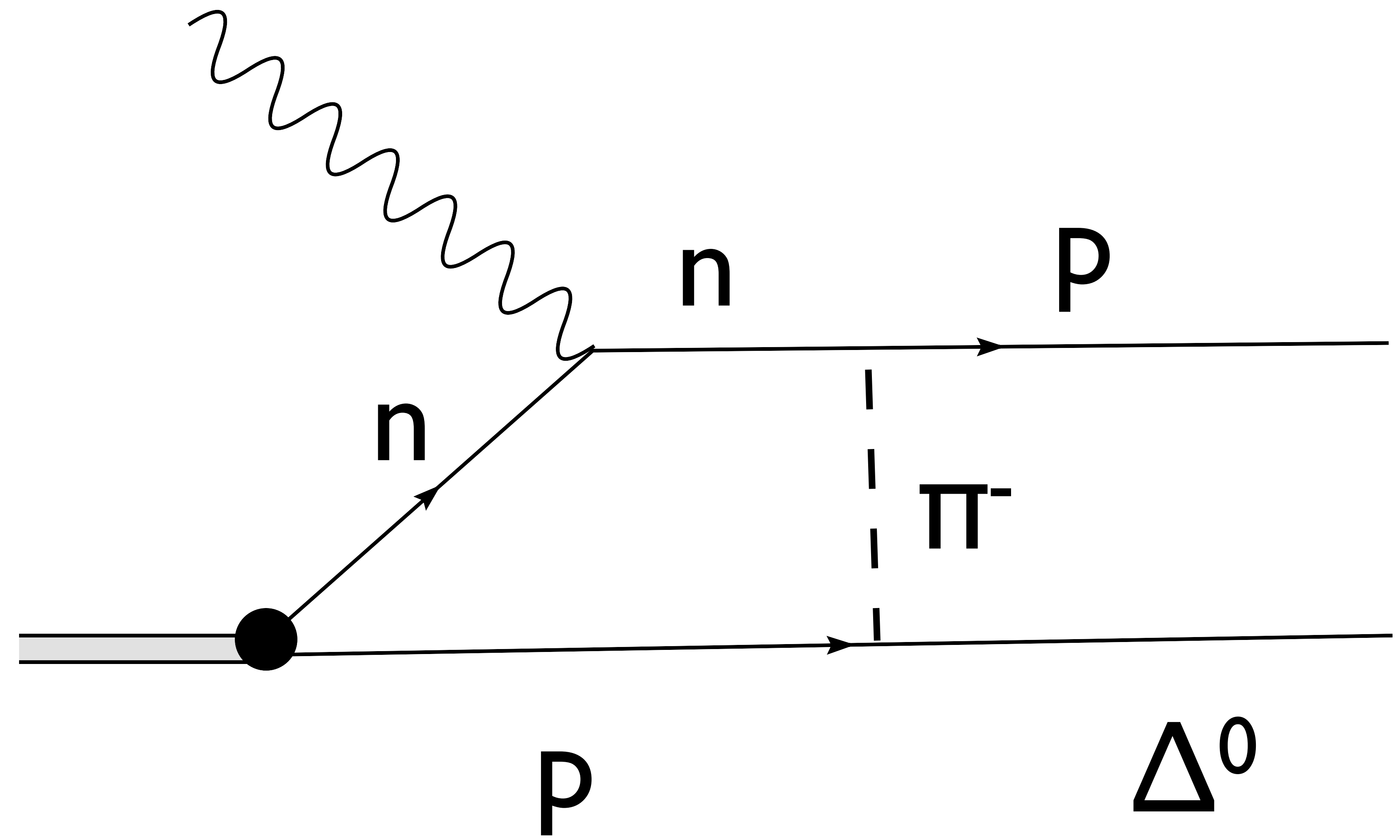


FIG. 2. Chiral transparency ratio CT of Eq. (29). The transverse momentum of the neutron is 0.3 GeV/c. Harmonic oscillator wave functions are used with $b=1$ fm. The parameter Q_0^2, which determines the value of κ, of Eq. (11) is varied.

Much more practical



Charge exchange drops with s as s^{-2} - chiral transparency - a faster drop + effect is larger for $\alpha_\Delta > 1$ where nucleons are closer. Change of distribution over $\alpha_\Delta > 1$ with increase of Q. CLAS should have more than enough data to study this process. One can also do detailed studies in parallel with $eD \to epn$ studies via missing mass.

☛ Large angle $\gamma + N \to \pi + N$ in nuclei. Quark Counting rules with point-like photon imply a change of A-dependence already in the region where expansion effects are large - because in this regime photon penetrates to any point in the nucleus

☺ A-dependence of virtual compton scattering - at what Q transition of vector dominance to CT. HERMES data are consistent with Guzey and MS prediction based on CT and closure - but accuracy of the data is moderate.

Conclusions

High energy CT is well established

LHC:

- Search for proton dissociation into three jets (TOTEM-CMS)
- Investigation of color opacity in ultraperipheral collisions

Jlab - 12 GeV l_{coh} large enough to suppress expansion effects

- Decisive test of CT for meson production
- Will allow to learn whether nucleon f.f. at $Q^2 \sim 10$ -15 GeV^2 are dominated by PLC or mean field configurations

J-PARC, GSI Interesting programs possible complementary to Jlab