Color transparency: 33 years and still running

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Topics to be covered

Discovery of high energy CT and search for disappearance of CT at LHC

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

Future directions for Jlab studies

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

Exclusive reactions, Jlab May 22, 07

Color transparency phenomenon plays a dual role:

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

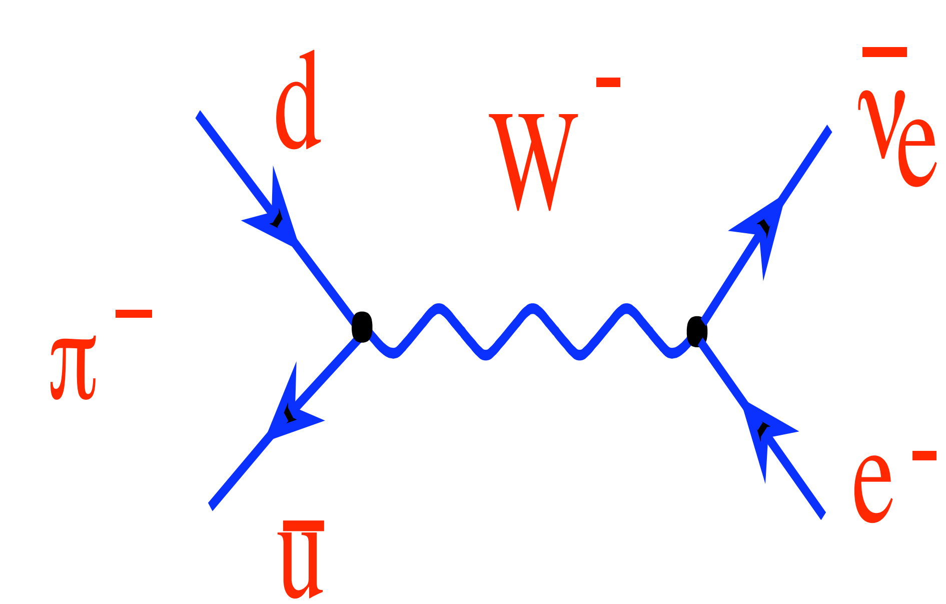
at intermediate energies also a unique probe of the space time evolution of wave packages - relevant for interpretation of RHIC AA data

Sample of high energy questions

- What is the origin of the total cross sections of hadron-hadron interactions? Are they always a weak function of energy? Can hadron collapse to a small configuration and interact with much smaller cross section than the average one - color transparency. If so, would this effect disappear at very high energies - color opacity.

- Can one measure the wave functions of hadrons? Can a high energy hadron exist is a configuration with no gluon field if looked at by a high resolution probe?

How can the process of decay happen like $\pi^- \to W^- \to \mu\bar{\nu}_\mu$, $\rho \to e^+e^-$, where q and $\bar{q}$ have to come very close together **and leave no gluon field behind.**



Beginning of CT - discovery of ***narrow*** J/ψ - November 04 and observation of small cross section for its photoproduction which within VDM corresponded to

$$\sigma_{tot}^{VDM}(J/\psi N) \sim 1\,mb$$

Note this number is actually underestimates genuine J/ψ-N cross section due to production of J/ψ in small size configurations FS85

$$\sigma_{tot}(J/\psi N) \sim 4\,mb$$

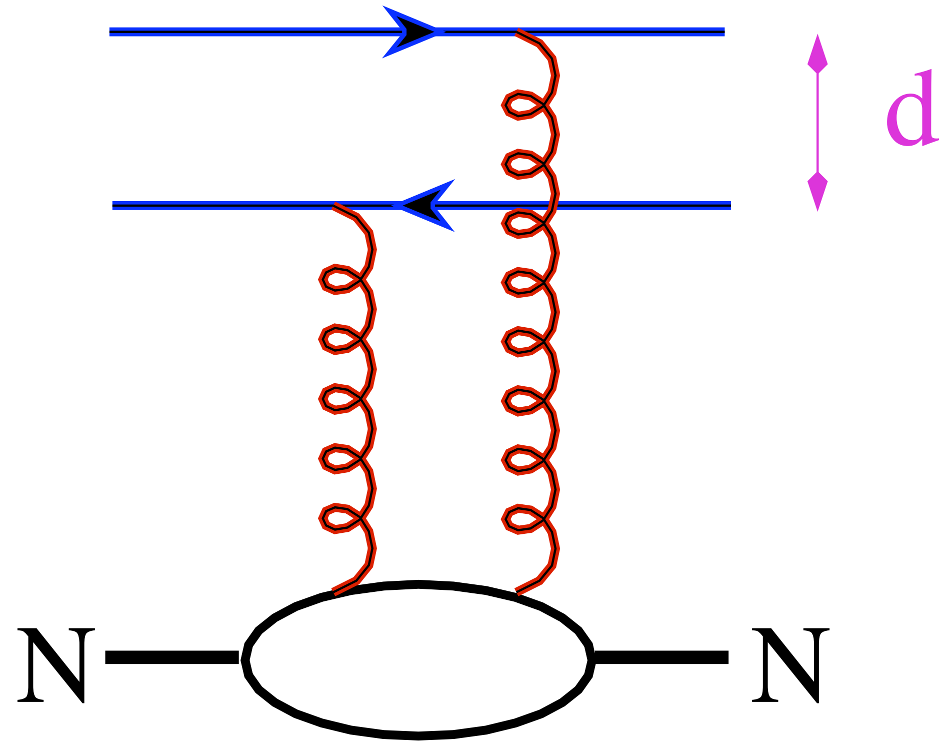
Future studies of A-dependence of J/ψ photoproduction at 12 GeV

Winter of 74-75 - numerous discussions between Leonya Frankfurt and Volodya Gribov - on implications for strong interactions - no single scale, weak interactions of small hadrons. Gribov asked how this property could hold at high energy even if the system is small over long time it will emit a ladder and due to diffusion interact as a normal hadron

[F.E. Low](#) **A Model of the Bare Pomeron Phys.Rev.D12:163-173,1975**.

Two-gluon exchange model

Clear statement that in the limit of small object interaction is proportional to square of its radius - recast of well known property of QED

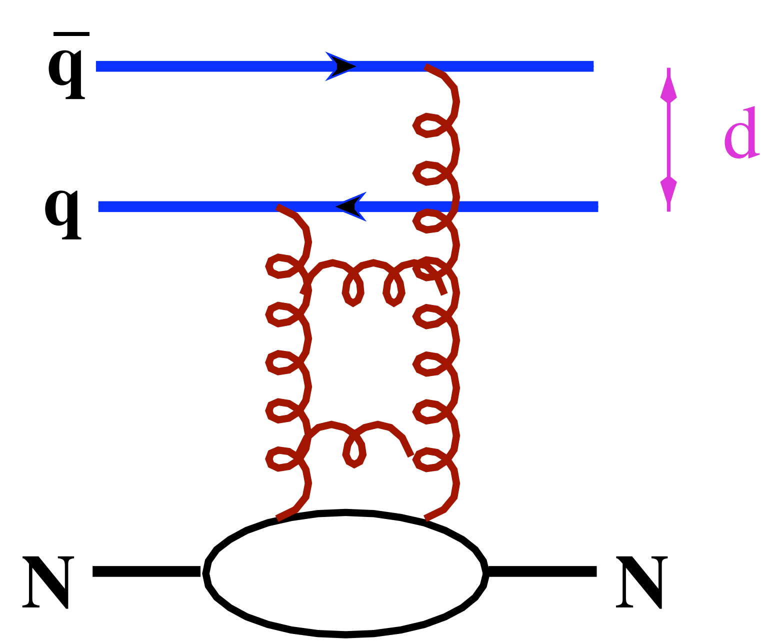


Two gluon exchange model

F.Low & S.Nussinov 75

$\sigma = C\, b^2$ (F.Low 75)

C does not depent on E_{inc}

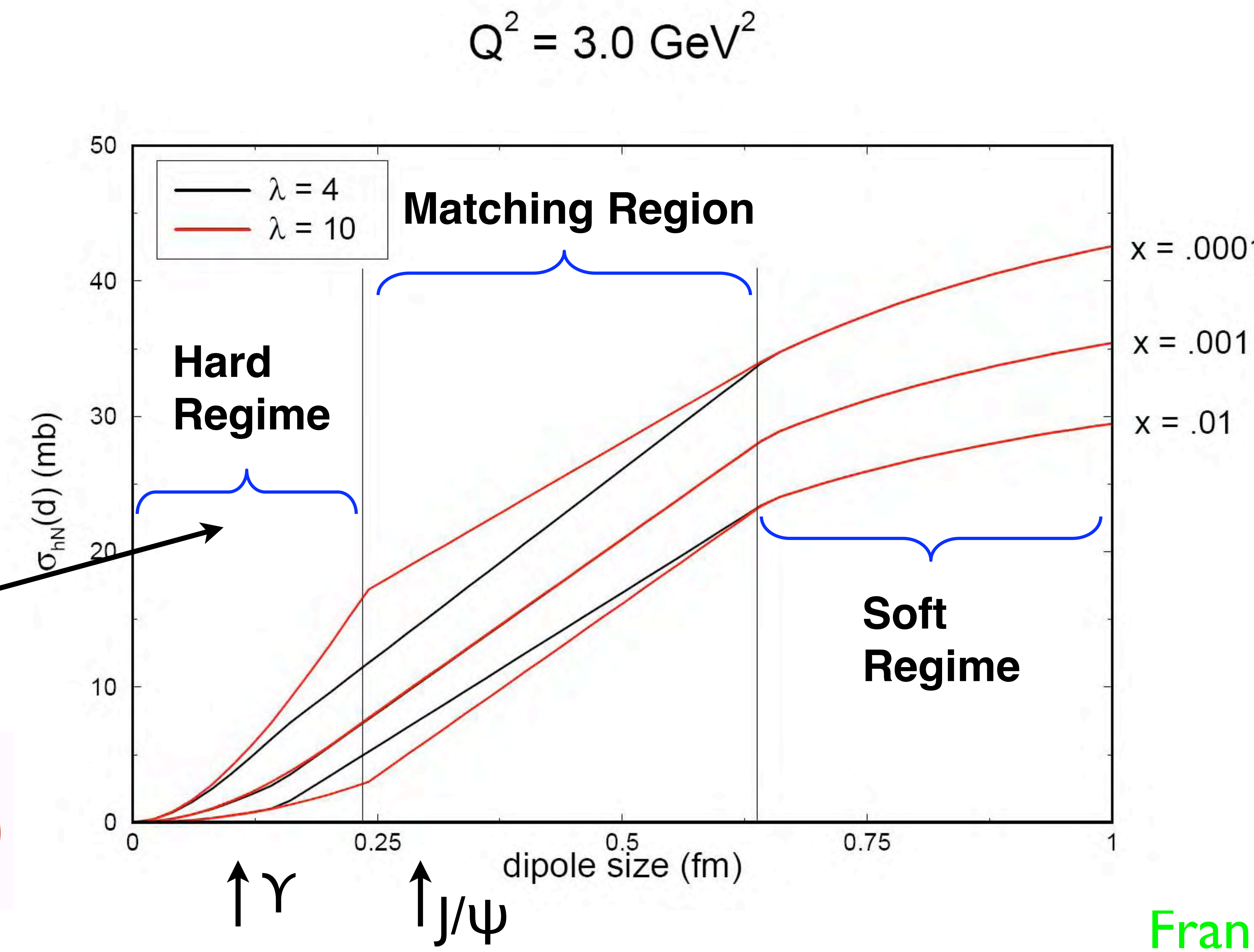


pQCD in the leading log d approximation **(Baym, Blattel,FS, 93)**

$$\sigma^{inel}_{q\bar{q}N}(d,E_{inc}) = \frac{\pi^2}{3} d^2 \alpha_s\left(\frac{\lambda}{d^2}\right) \text{ x } G_N\left(x,\frac{\lambda}{d^2}\right)$$

Qualitative difference from QED: cross section rapidly increases with energy - a fingerprint of small size dipole interaction in a wide energy range ($\lambda(x = 10^{-3}, Q^2 = 10\ GeV^2 \approx 9$). Leads to emergence of an exciting new physics of high densities in the perturbative regime at very high energies. Also, qualitatively different from soft physics: $\sigma_{tot}(soft) \propto s^{0.1}, \sigma_{tot}^{dipole-N}(d = .3fm) \propto s^{0.2}, \sigma_{tot}^{dipole-N}(d = .1fm) \propto s^{0.4}$.

studies of the "quark-antiquark dipole"(transverse size d) - nucleon cross section based pQCD and HERA data



$$\sigma_{inel} = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x.\lambda/d^2)$$

F^2 Casimir operator of color SU(3)

Frankfurt et al 2000-2001

Dipole approximation for DIS and vector meson production describes bulk of the HERA data.
Challenge for the future - limiting behavior of σ - onset of black disk regime - addressed in a number of models [Affirmative answer to Gribov's question]

New idea - use CT property of interaction of small color singlet configurations to probe dynamics of hard exclusive processes - namely large angle hadron- hadron scattering

A.Mueller & S. Brodsky 82

Expectation:

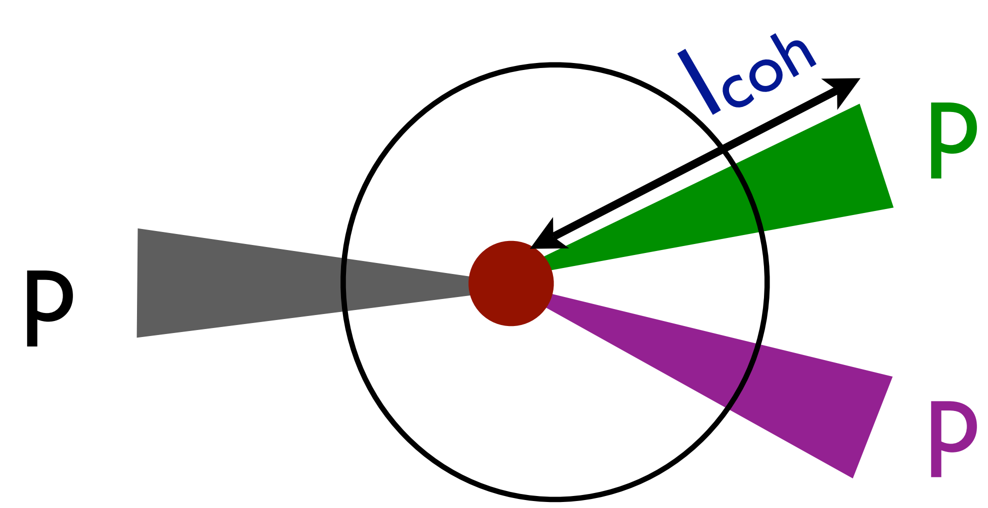
$$\frac{d\sigma(h+A\to h+p+(A-1))}{dt} = Z\frac{d\sigma(h+p\to h+p)}{dt}$$

Main challenge: |qqq> 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)

$$|\Psi_{PLC}(t)\rangle = \Sigma_{i=1}^{\infty} a_i \exp(iE_i t)\,|\Psi_i\rangle = \exp(iE_1 t)\Sigma_{i=1}^{\infty} a_i \exp\left(\frac{i(m_i^2 - m_1^2)t}{2P}\right)|\Psi_i\rangle\,.$$

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

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.

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

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 proof based on the CT property of QCD - see C.Weiss talk

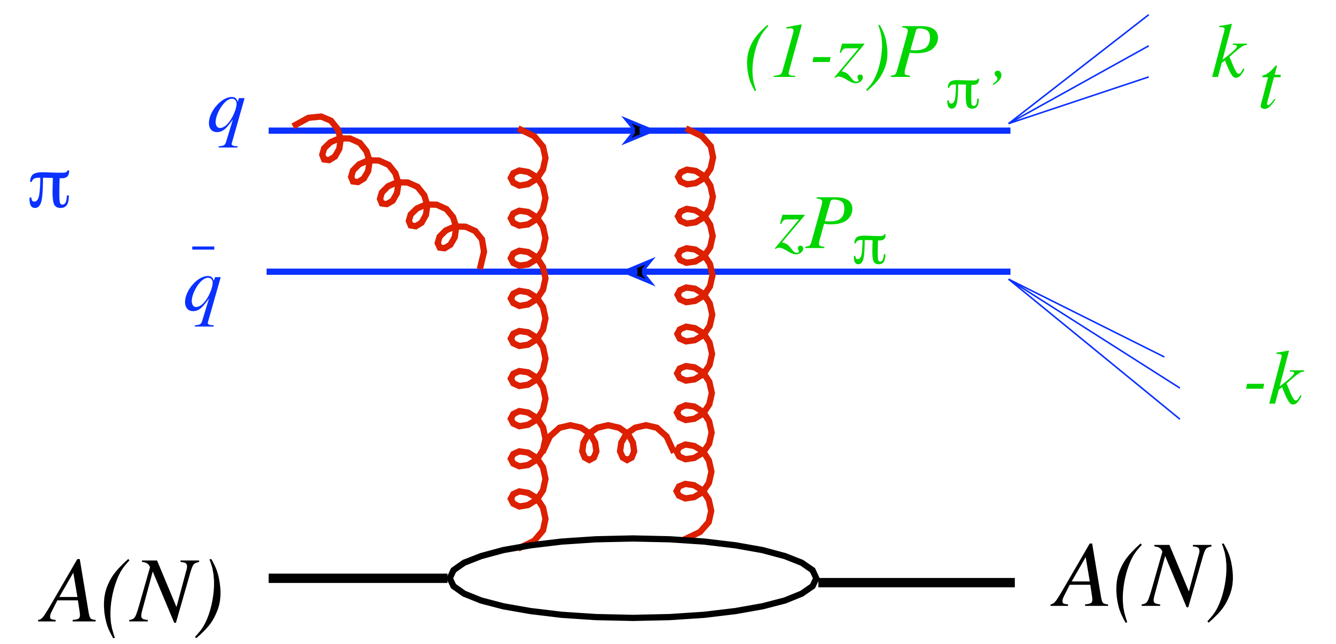
$$\pi + N(A) \rightarrow \text{“}2\ high\ p_t\ jets'' + N(A)$$

Mechanism:

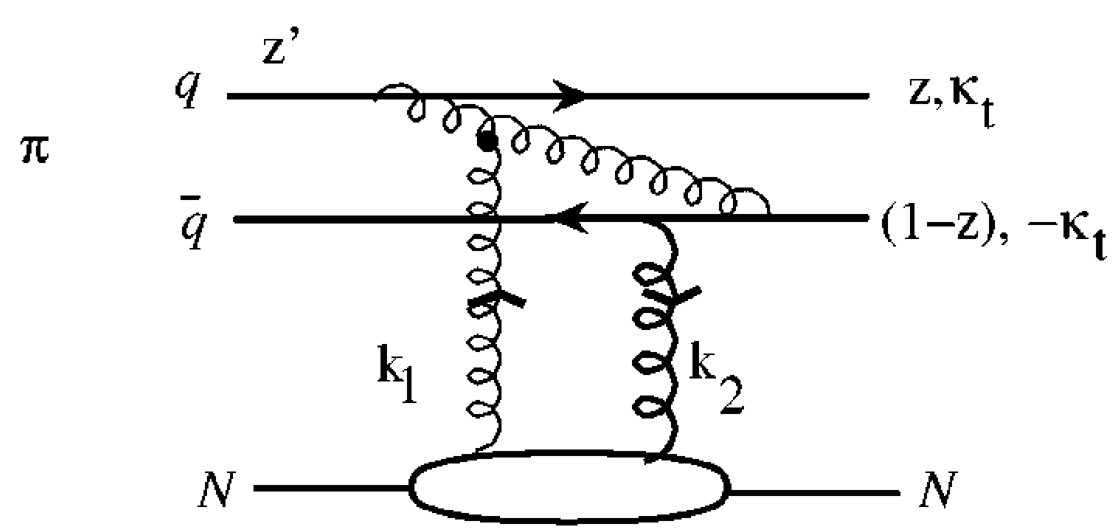
Pion approaches the target in a frozen small size $q\bar{q}$ configuration and scatters elastically via interaction with $G_{target}(x, Q^2)$.

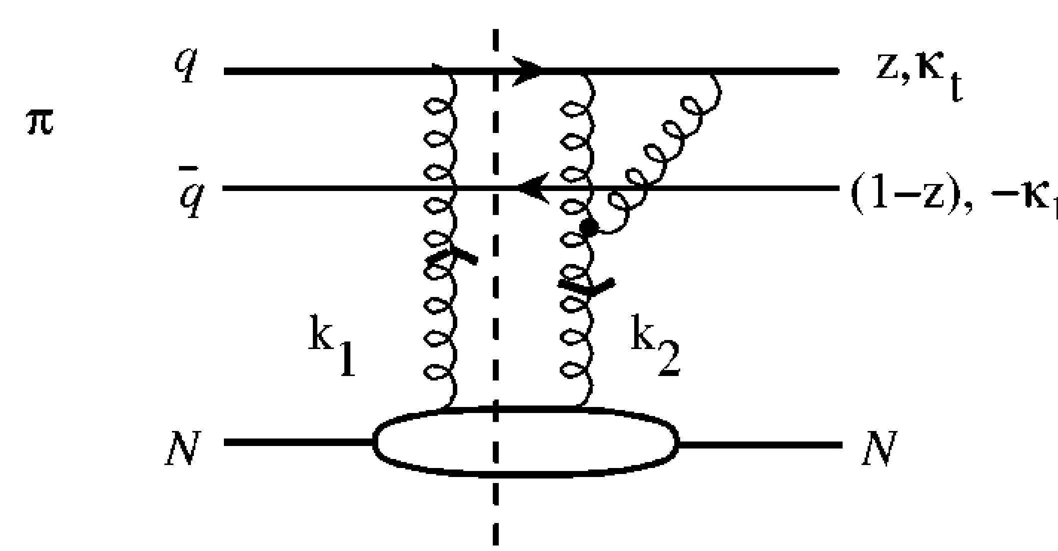
- First attempt of the theoretical analysis of πN process - Randa 80 - power law dependence of p_t of the jet (wrong power)
- First attempt of the theoretical analysis of πA process - Brodsky et al 81 - exponential suppression of p_t spectra, weak A dependence ($A^{1/3}$)
- pQCD analysis - Frankfurt, Miller, MS 93; elaborated arguments related to factorization 2003

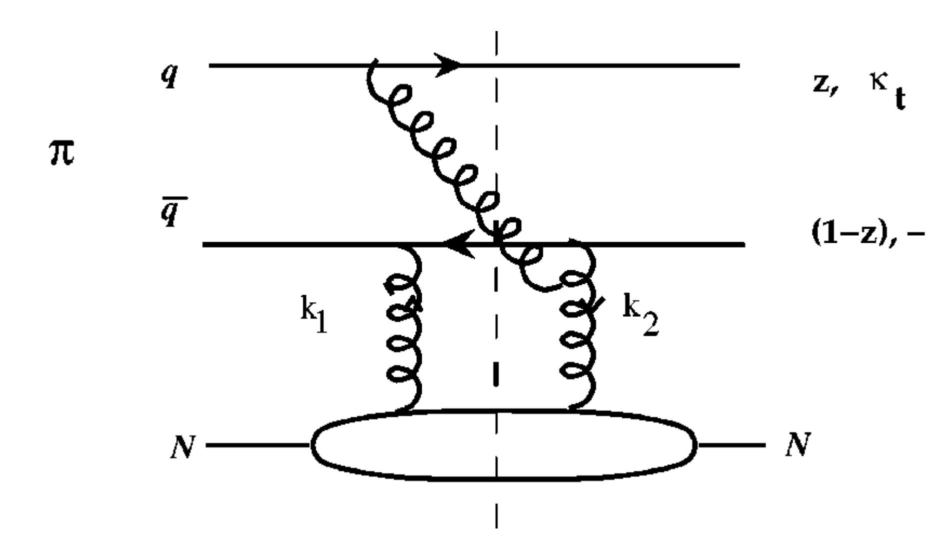
Dominant diagram

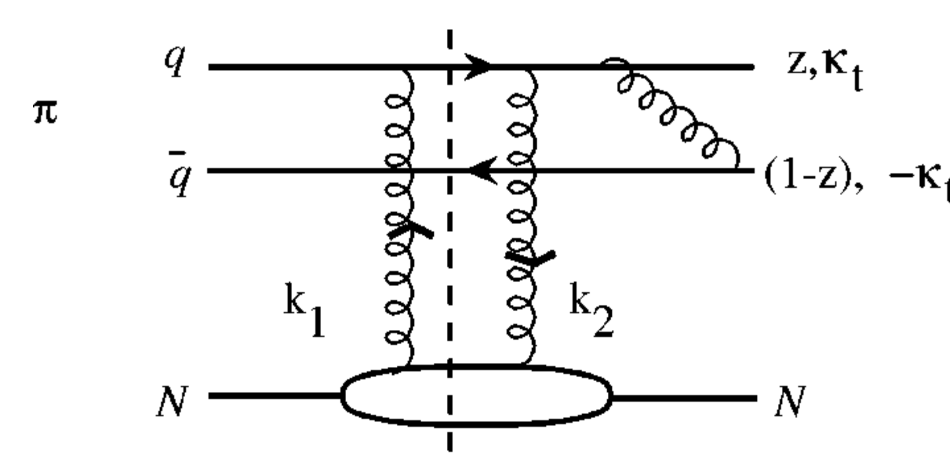


Examples of the Suppressed diagrams









A slightly simplified final answer is

$$A(\pi + N \to 2\,jets + N)(z, p_t, t=0) \propto$$

$$\int d^2 d \psi_\pi^{q\bar{q}} \sigma_{q\bar{q}-N(A)}(d,s)\exp(ip_t d)$$

$$d = r_t^q - r_t^{\bar{q}},$$

$\psi_\pi^{q\bar{q}}(z,d) \propto z(1-z)_{d\to 0}$ is the quark-antiquark Fock component of the meson light cone wave function

Plane wave in the final state - faster onset of scaling than for VM production

$\Longrightarrow$ A-dependence: $A^{4/3}\left[\frac{G_A(x,k_t^2)}{AG_N(x,k_t^2)}\right]^2$, where $x = M^2_{dijet}/s$. $(A^{4/3} = A^2/R_A^2)$

$\Longrightarrow$ $\frac{d\sigma(z)}{dz} \propto \phi_\pi^2(z) \approx z^2(1-z)^2$ where $z = E_{jet_1}/E_\pi$.

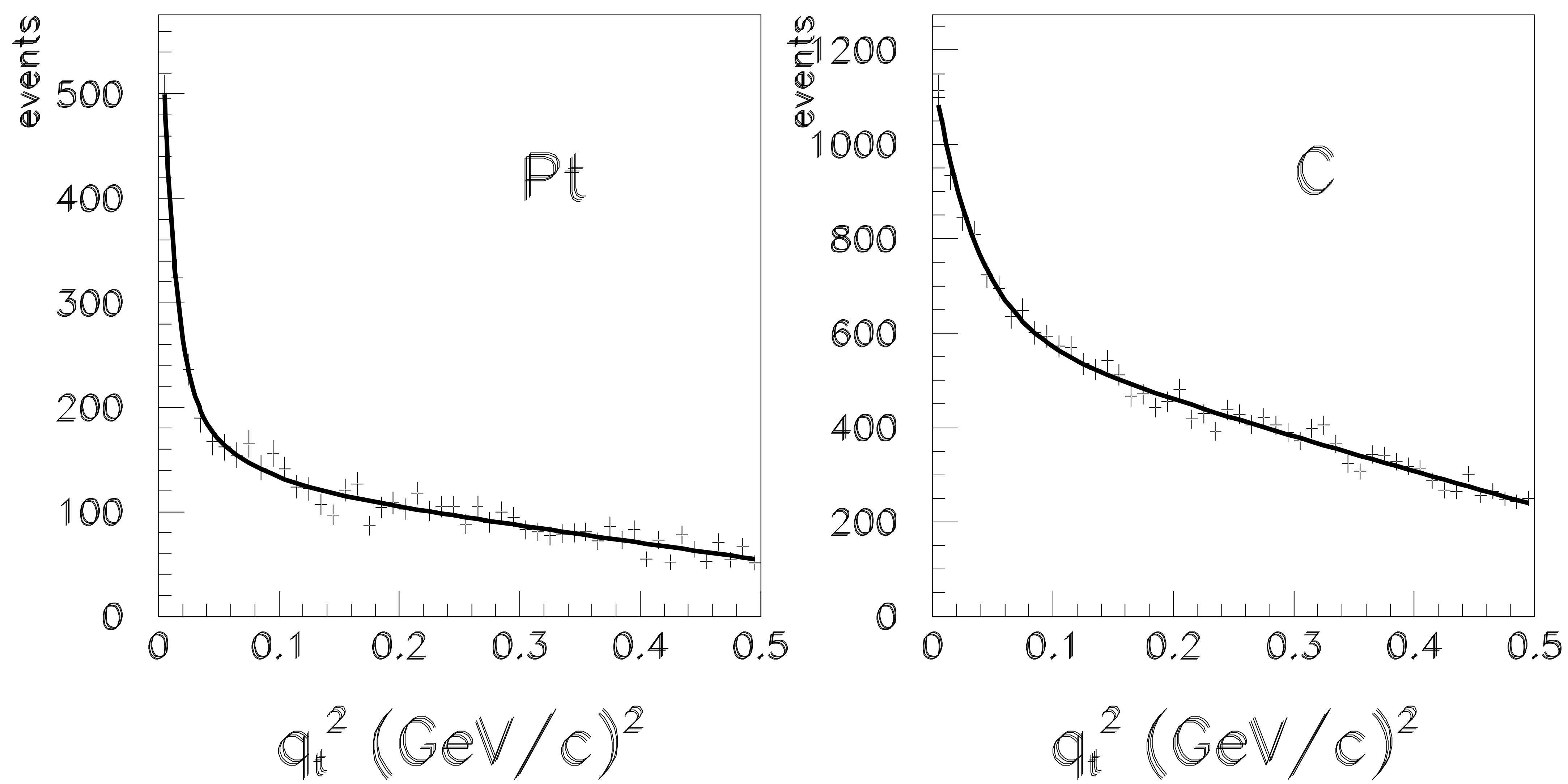
$\Longrightarrow$ k_t dependence: $\frac{d\sigma}{d^2k_t} \propto \frac{1}{k_t^n}, n \approx 8$ for $x \sim 0.02$

$\Longrightarrow$ Absolute cross section is also predicted

What is the naive expectation for the A-dependence of pion dissociation for heavy nuclei? Pion scatters off a black absorptive target. So at impact parameters $b < R_A$ interaction is purely inelastic, while at $b > R_A$ no interaction. Hence $\sigma_{inel} = \pi R_A^2$. How large is σ_{el}? Remember the Babinet's principle from electrodynamics: scattering off a screen and the complementary hole are equivalent. Hence $\sigma_{el} = \pi R_A^2$, while inelastic diffraction occurs only due to the scattering off the edge and hence $\propto A^{1/3}$

The E-791 (FNAL) data $E^{\pi}_{inc} = 500 GeV$ (D.Ashery et al, PRL 2000)

♡ Coherent peak is well resolved:



Number of events as a function of q_t^2, where $q_t = \Sigma_i p_t^i$ for the cut $\Sigma p_z \geq 0.9 p_\pi$.

♡♡ Observed A-dependence $A^{1.61\pm0.08}$ $[C \to Pt]$

FMS prediction $A^{1.54}$ $[C \to Pt]$ for large k_t & extra small enhancement for intermediate k_t.

For soft diffraction the Pt/C ratio is ~ 7 times smaller!!

(An early prediction Bertsch, Brodsky, Goldhaber, Gunion 81

$\sigma(A) \propto A^{1/3}$)

In soft diffraction color fluctuations are also important leading to

$$\sigma_{soft\ diffr}(\pi + A \to X + A) \propto A^{.7}$$

Miller Frankfurt &S, 93

Recent analysis of D.Ashery (05)

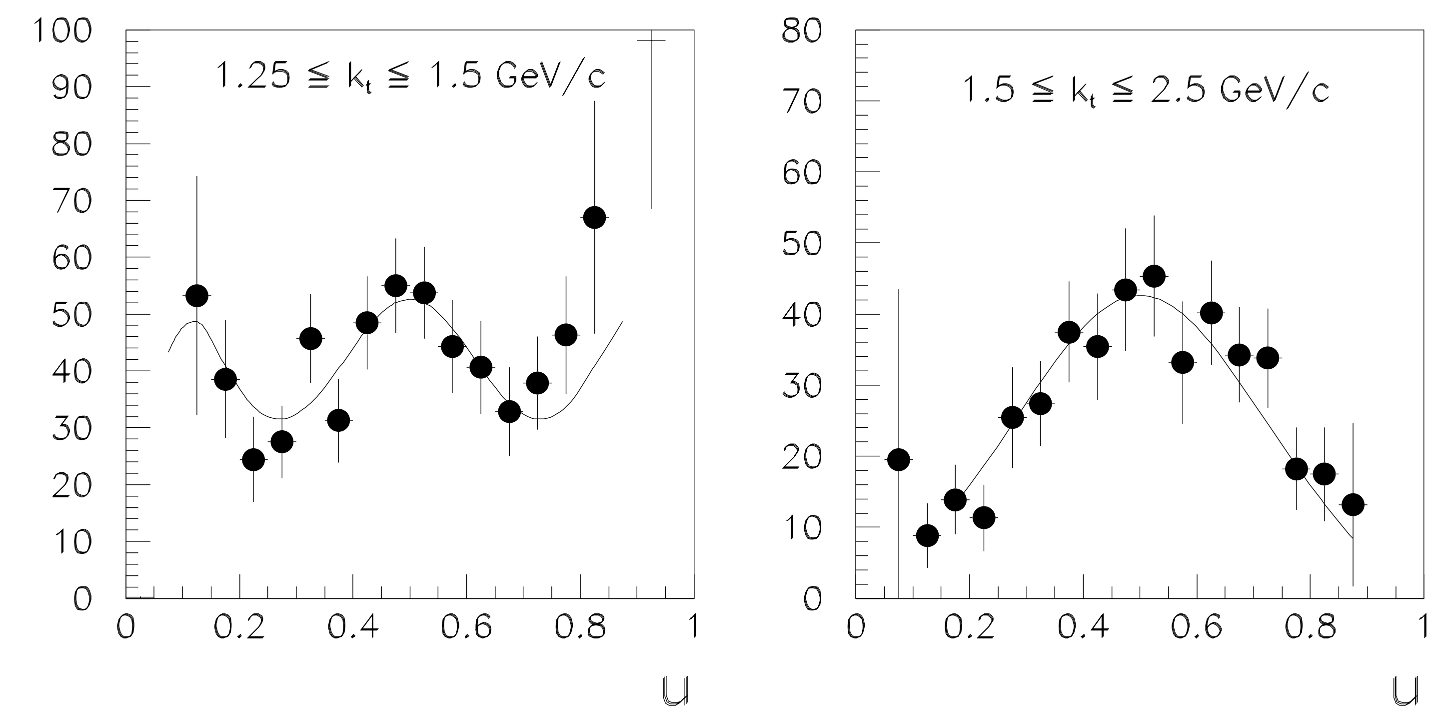
Fit to Gegenbauer Polynomials

Generate Acceptance-Corrected Momentum distributions

Assume $\frac{d\sigma}{du} \propto \phi_\pi^2(u, Q^2)$ **in both** $k_\perp$ **regions**

Fit distributions to:

$$\frac{d\sigma}{du} \propto \phi_\pi^2(u, Q^2) = 36u^2(1-u)^2 \left(1.0 + a_2 C_2^{3/2}(2u-1) + a_4 C_4^{3/2}(2u-1)\right)^2$$

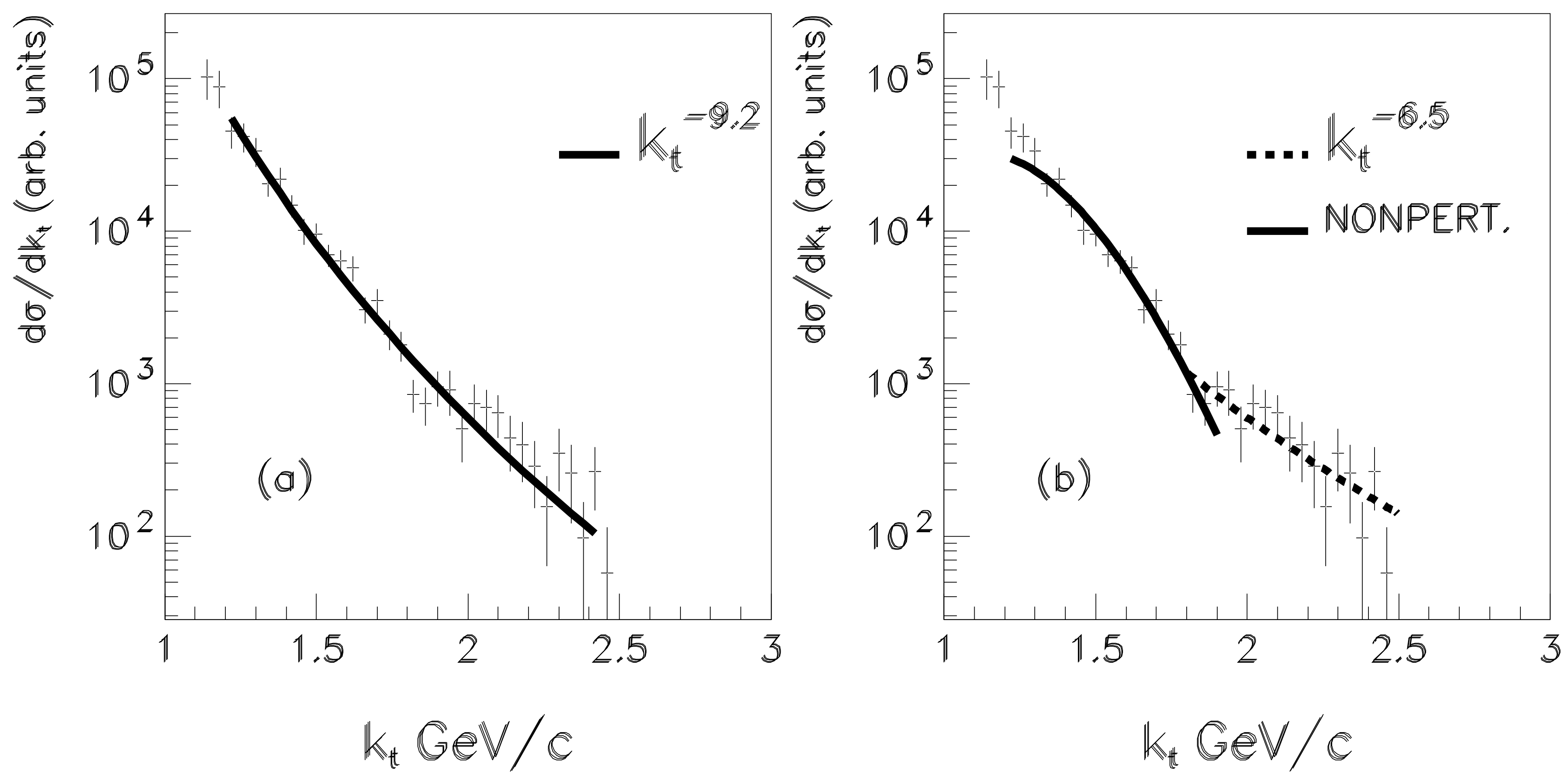


For high k_t : $a_2 = a_4 = 0 \rightarrow$ **Asymptotic**

For low k_t : $a_2 = 0.30 \pm 0.05, \quad a_4 = (0.5 \pm 0.1) \cdot 10^{-2} \rightarrow$ **Transition**

Squeezing occurs already before the leading term (1-z)z dominates!!!

♡♡♡♡ k_t^{-n} *dependence of* $d\sigma/dk_t^2 \propto 1/k_t^{7.5}$ *for* $k_t \geq 1.7 GeV/c$ *close to the QCD prediction -* $n \sim 8.0$ *for the kinematics of E971*



or higher terms in Gegenbauer expansion???

Combined with a success of dipole /QCD factorization picture for VM production at high energies (reviewed by C.Weiss)

- Presence of small size $q\bar{q}$ Fock components in light mesons is unambiguously established
- At transverse separations d ≤ 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 small dipole interaction with nucleons, nuclei (for $x \sim 10^{-2}$)

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

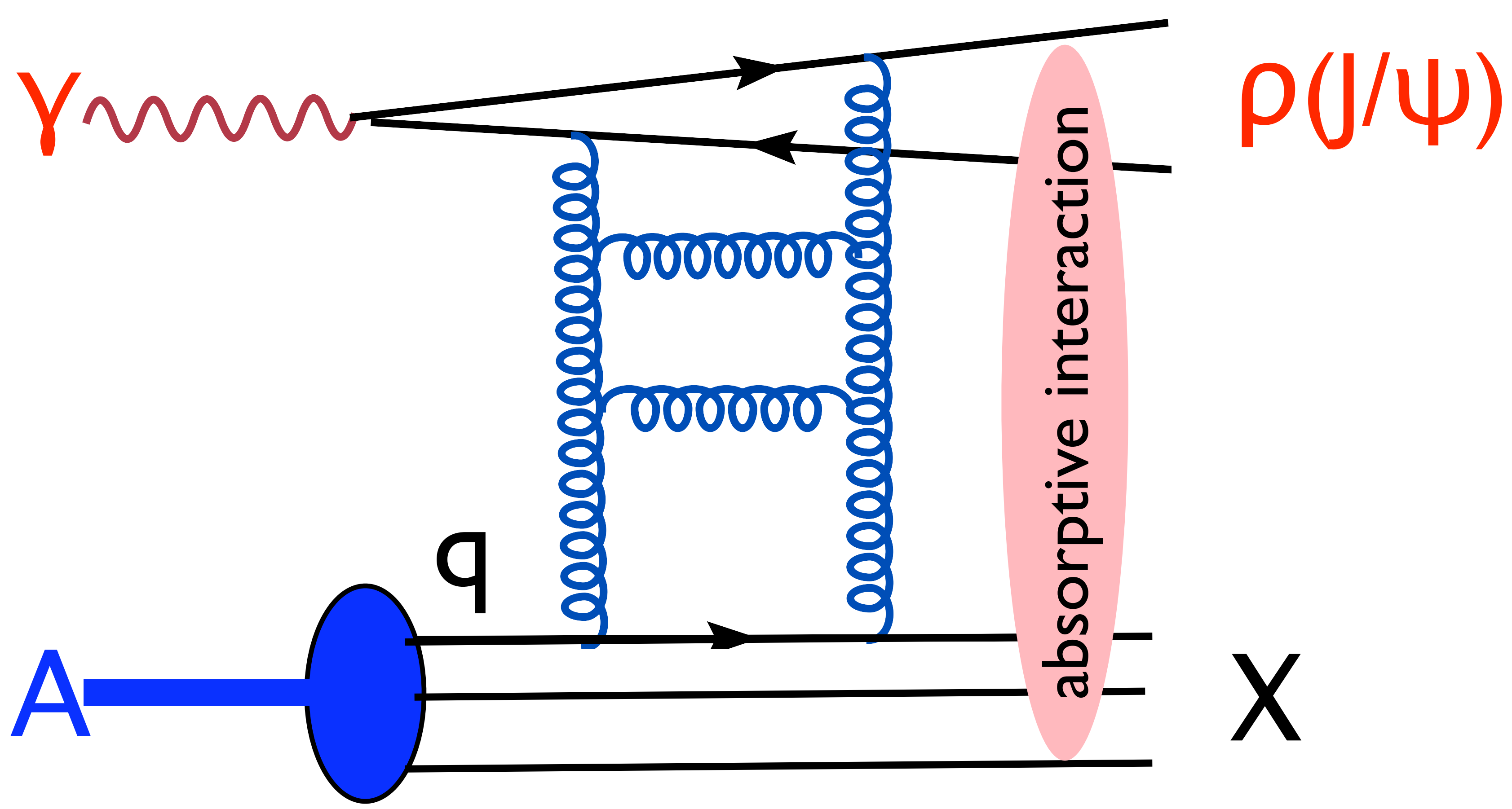
Meson is not as much of a rope (camel) as a baryon and can be easier put through a needle

Future high energy CT studies at LHC - ultraperipheral heavy ion collisions (UPC) - UPC group is to release report in few days.

- $\gamma + A \to \rho(J/\psi) + gap + X$ FS & Zhalov 06

measure of the strength of inelastic interactions of small dipole in the processes initiated by BFKL elastic $q\bar{q}$ - parton scattering at W=30 GeV - 1 TeV - interplay of color transparency and color opacity

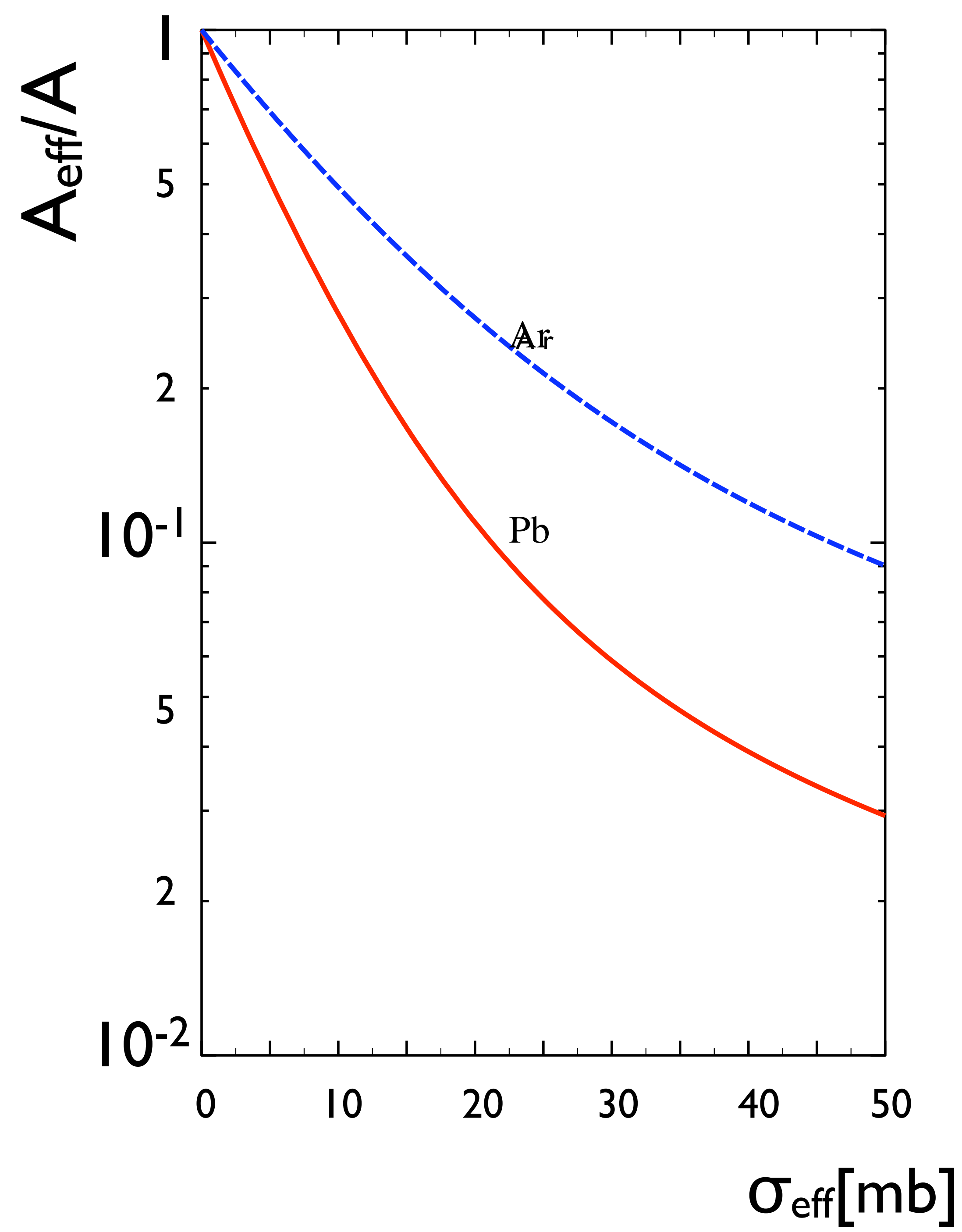
at virtuality ~ m_q^2 -t



Advantages:

trigger on hadron production in a rapidity interval close to one of the nuclei - much easier than single VM production trigger

no ambiguity which of the nuclei emitted photon - Large W are possible



Strong sensitivity of A_{eff}/A to the strength of inelastic $q\bar{q}$-N interactions

Predict:

- A_{eff}/A should increase with t at fixed W
- A_{eff}/A should decrease with increase of W at fixed t - onset of black disk regime

Complementary to quasielastic process - no small x partons in the nucleus are involved on the trigger level

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,....

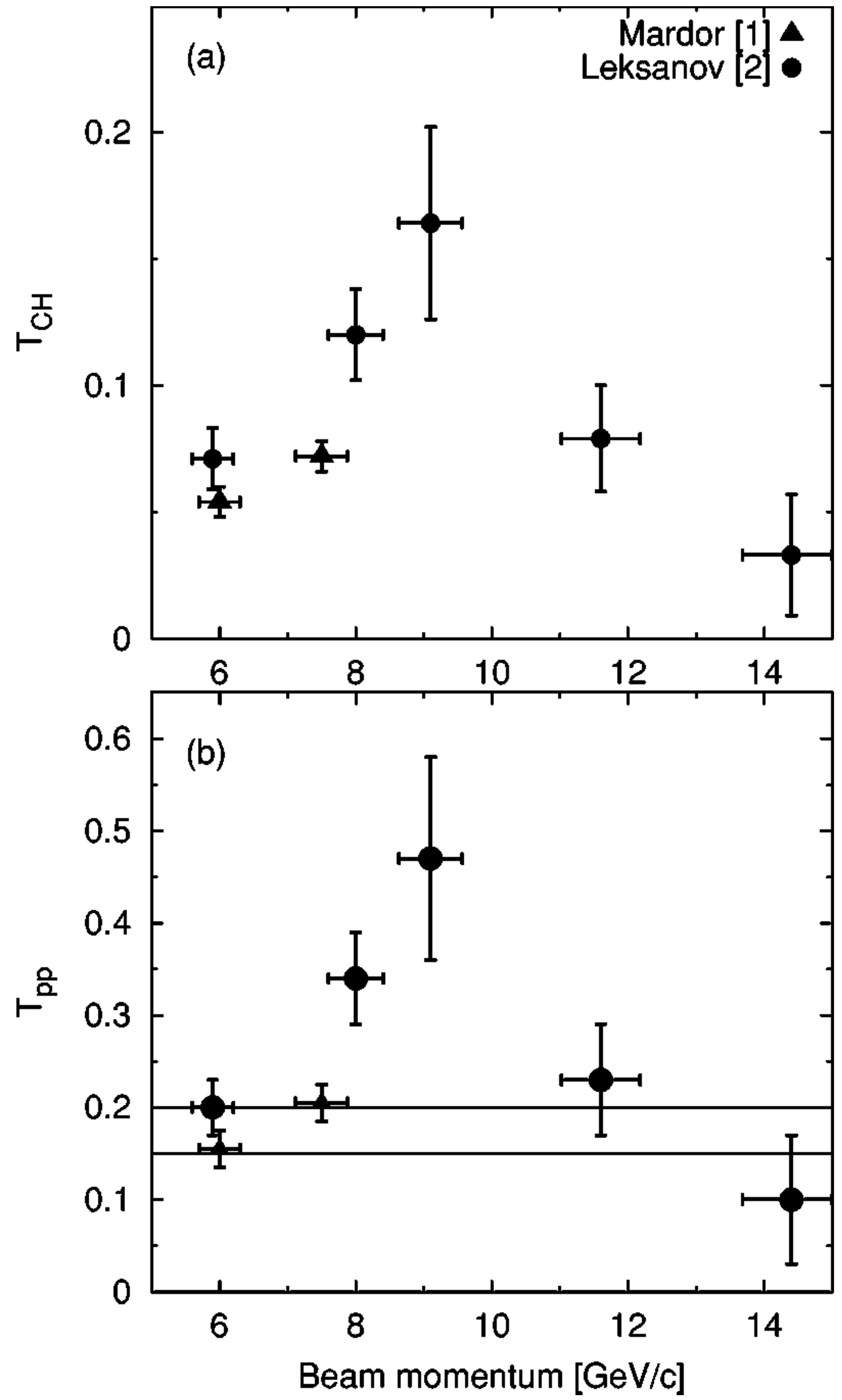
☛ If the PLC is formed - how long it remains smaller than average configuration

Studies of FS & Miller and Jennings

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

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

Long story of the studies of p+A



The final data from EVA BNL experiment

FIG. 11. (a) (top frame) The nuclear transparency ratio T_{CH} as a function of beam momentum. (b) (bottom frame) The nuclear transparency T_{pp} as a function of the incident beam momentum. The events in these plots are selected using the cuts of Eq. (9), and a restriction on the polar angles as described in the text. The errors shown here are statistical errors, which dominate for these measurements.

- Eikonal approximation calculation with proper normalization of the wave function (Frankfurt, Zhalov, MS) agrees well the 5.9 GeV data.

- Significant effect for p= 9 GeV where l_{coh}= 2.7 fm.

$\Rightarrow$ 10 GeV is sufficient to suppress rather significantly expansion effects. Hence one can use energies above ~10 GeV to study other aspects of the dynamics

- Glauber level transparency for 11.5 -14.2 GeV a problem for all models as $24\ GeV^2 \leq s' \leq 30\ GeV^2$ since it is too broad for a resonance of for interference of quark exchange and Landshoff mechanisms

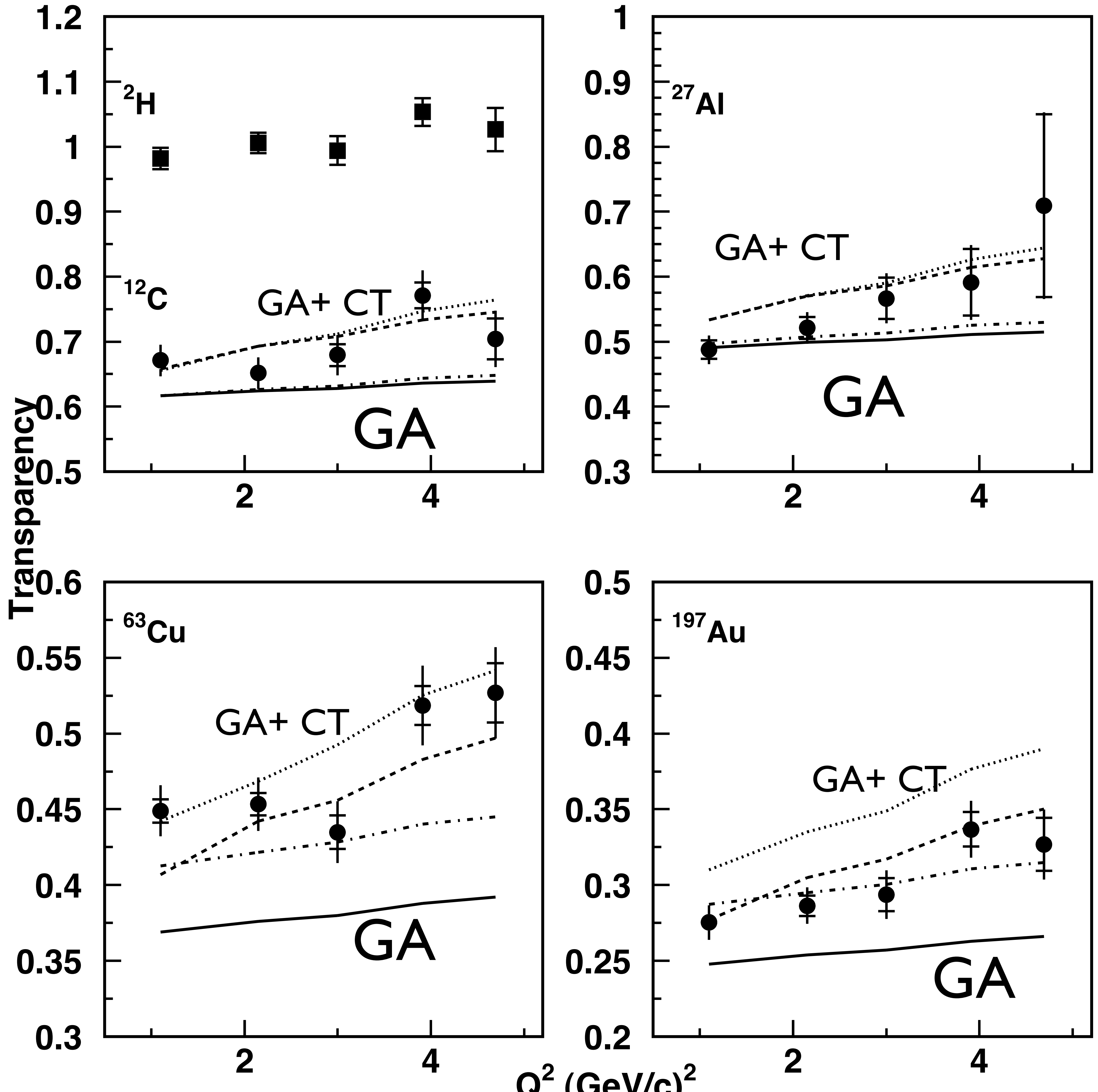
In dijet production $p_t \sim 1$ GeV/c corresponding to $Q^2 \sim 4\, p_t^2 \sim 4\,\mathrm{GeV}^2$ seemed to be enough to squeeze the system (though not yet to reach asymptotic in z distribution

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 at CT workshop here in 95

Published calculations last year with $l_{coh} = 0.3$ fm p_π [GeV]

Jlab data to be released soon - kindly provided by D.Dutta



GA= Glauber approximation

GA+ CT

Solid and Dashed - Larson Miller, MS

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

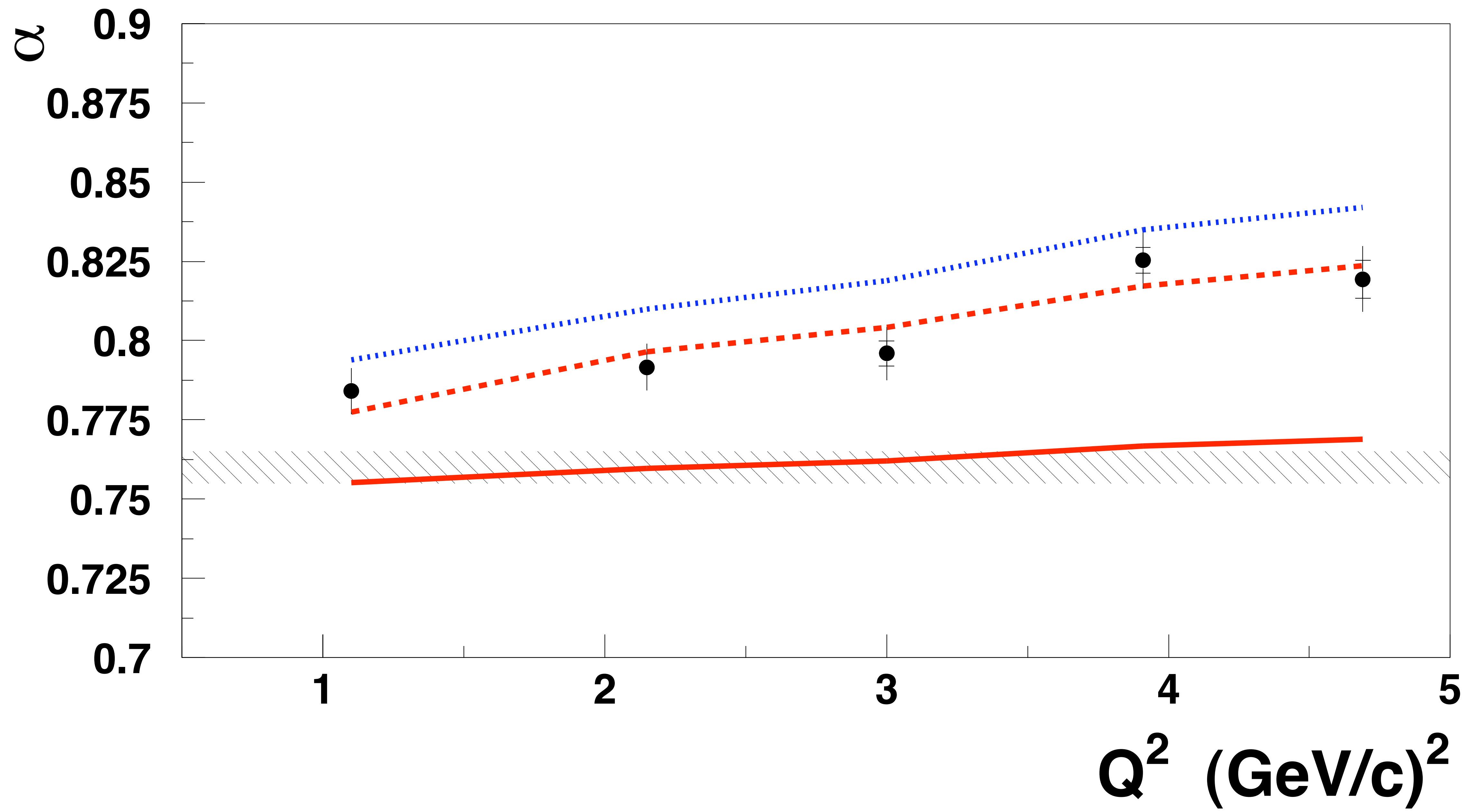


FIG. 3: The parameter α is shown vs Q^2. The inner error bars are the statistical uncertainty and the outer error bars are the quadrature sum of statistical and systematic and model uncertainties. The hatched line is the value of α extracted from pion-nucleus scattering data [31]. The solid, dashed, and dotted lines are α obtained from fitting the A dependence of the theoretical calculations, Glauber, Glauber +CT [26, 27], LMS and Glauber+SRC+CT [28, 29] respectively.

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.

◆ Jlab experiment - next talk. Two comments:

a) 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.

b) Transparency of lower Q is very low - comparable to that for (e,e'p) where $\sigma \sim$ 40 mb

Further theoretical studies are necessary to estimate quantitatively the role of this effect for the Jlab kinematics. I wish I am wrong - the t-slope data reported Guidal do suggest squeezing of the rho wave function.

Directions for future studies at Jlab

Until condition is met

$$l_{coh} \geq l_{inter} = 1/\sigma\rho_A$$

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

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

K.Garrow et al 02

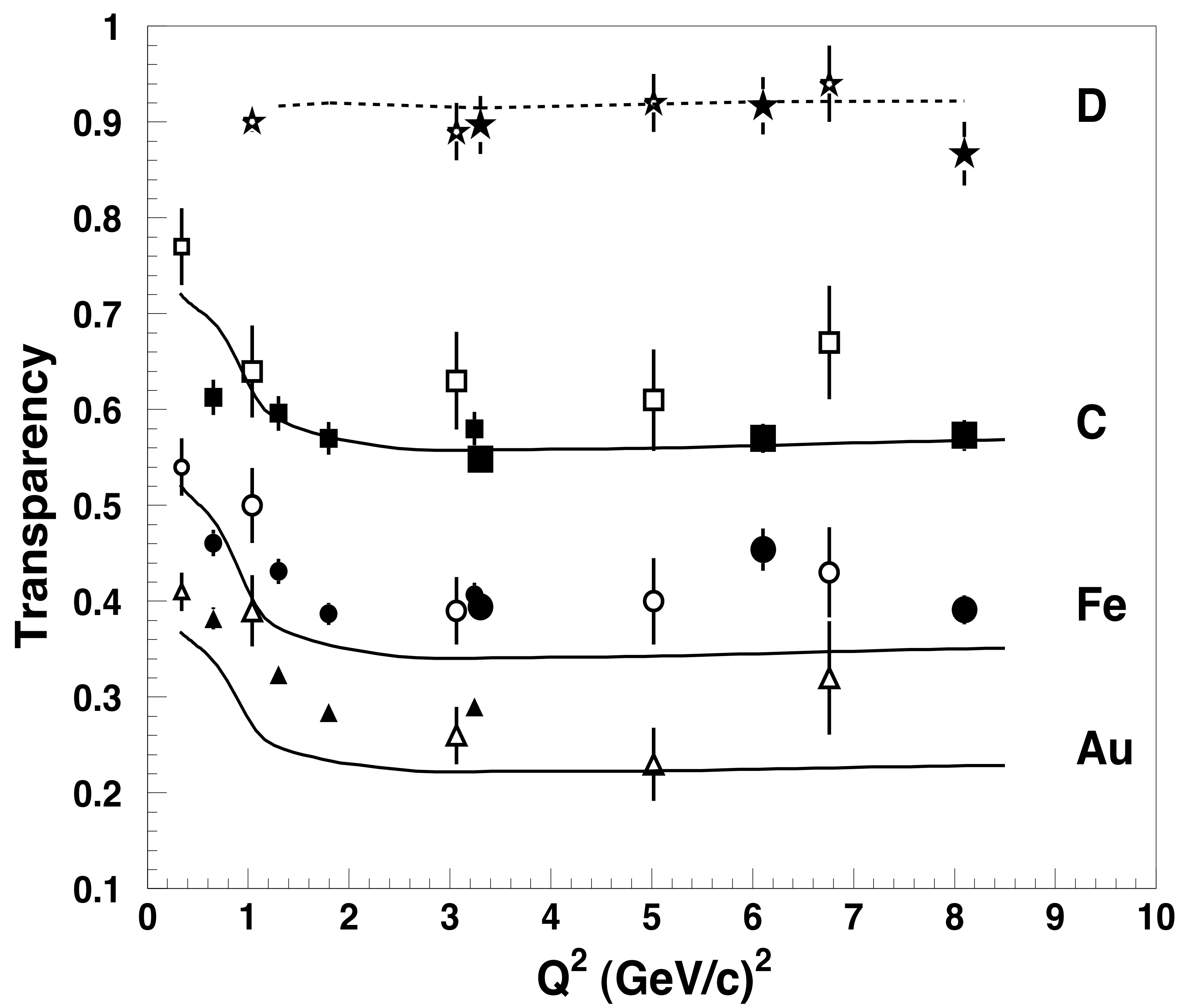
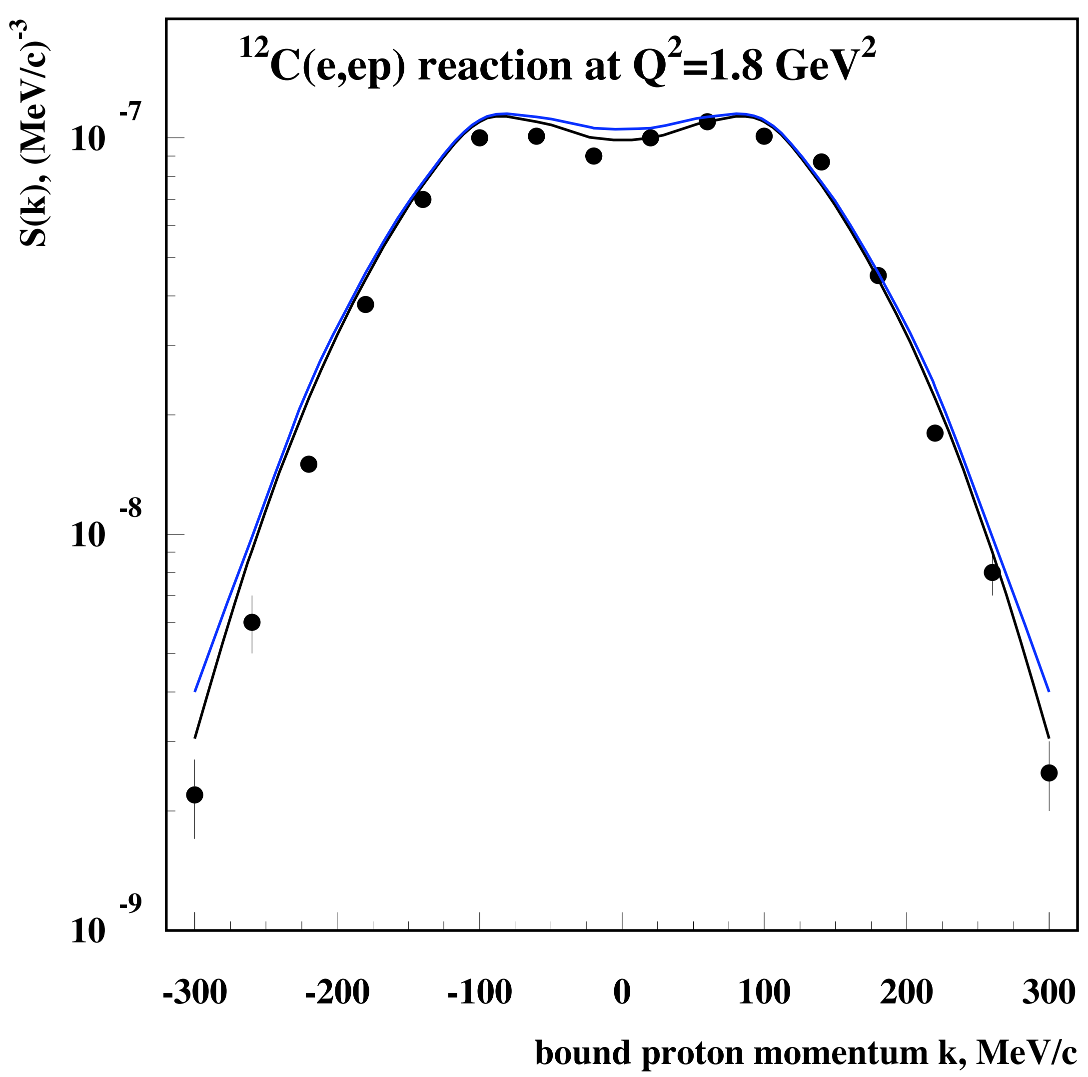


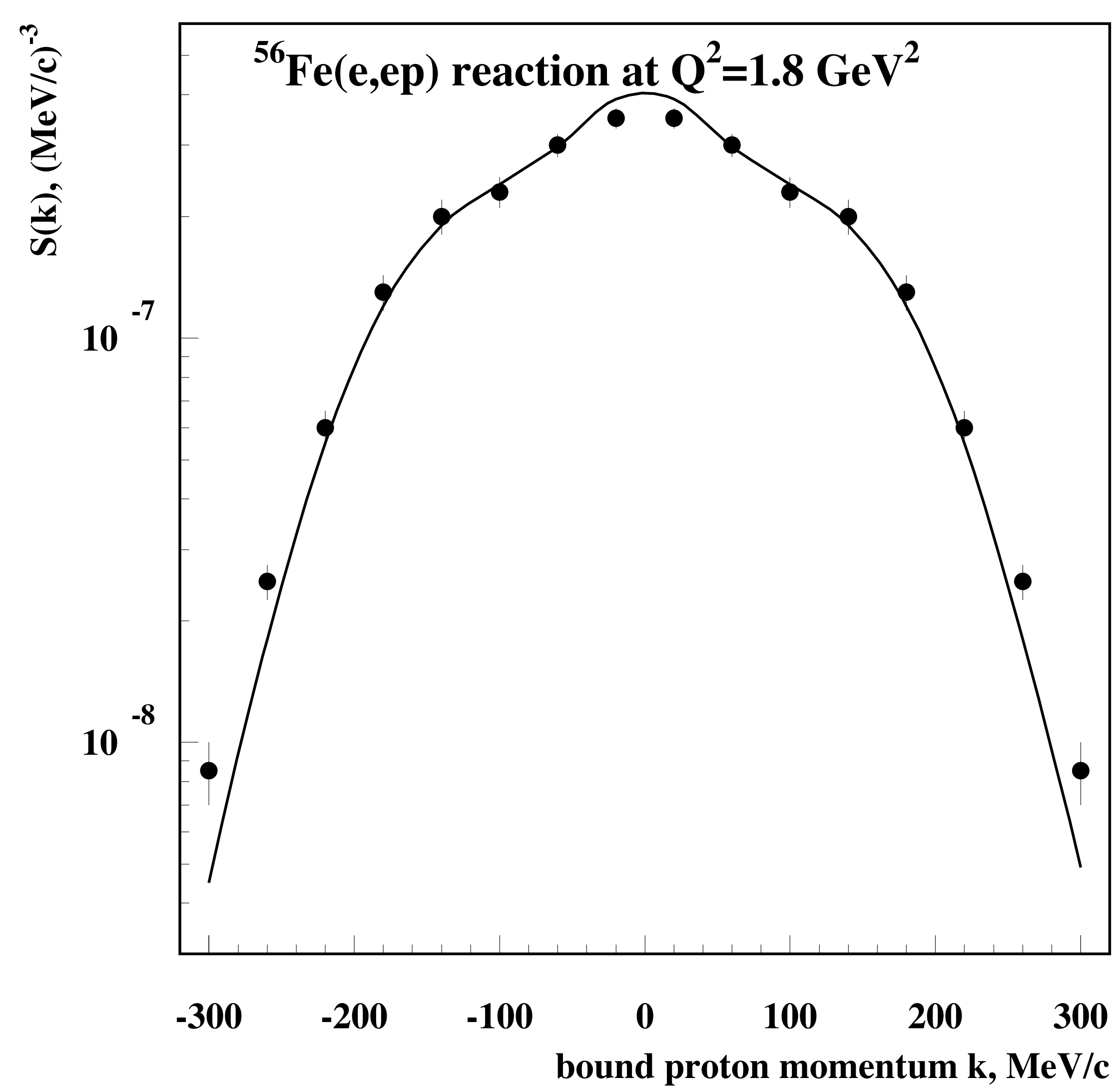
FIG. 3. Transparency for (e,e′p) quasielastic scattering from D (stars), C (squares), Fe (circles), and Au (triangles). Data from the present work are the large solid stars, squares, and circles, respectively. Previous JLab data (small solid squares, circles, and triangles) are from Ref. [16]. Previous 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].

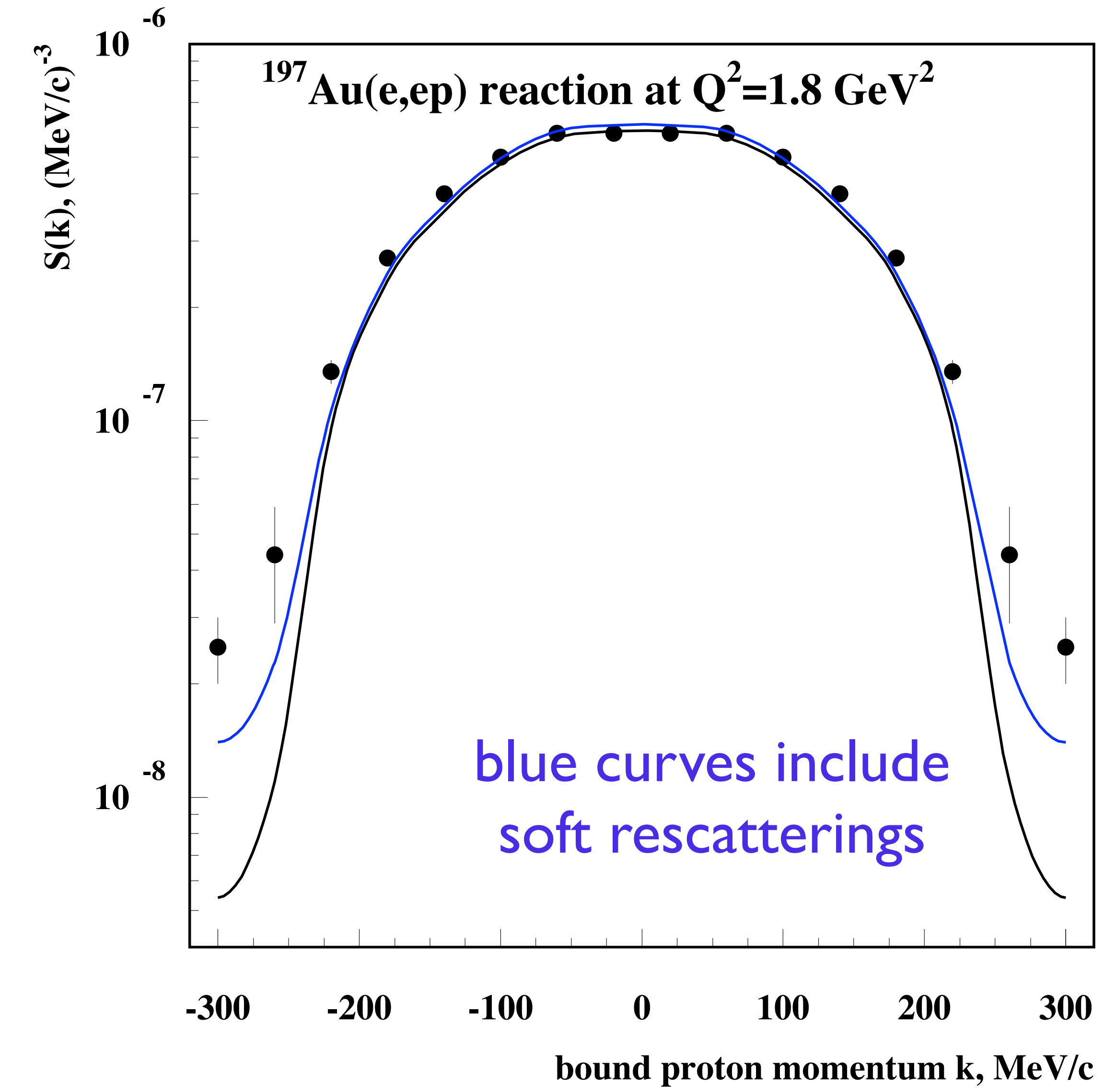
[26] H. Gao, V.R. Pandharipande, and S.C. Pieper (private communication); V.R. Pandharipande and S.C. Pieper, Phys. Rev. C **45**, 791 (1992).

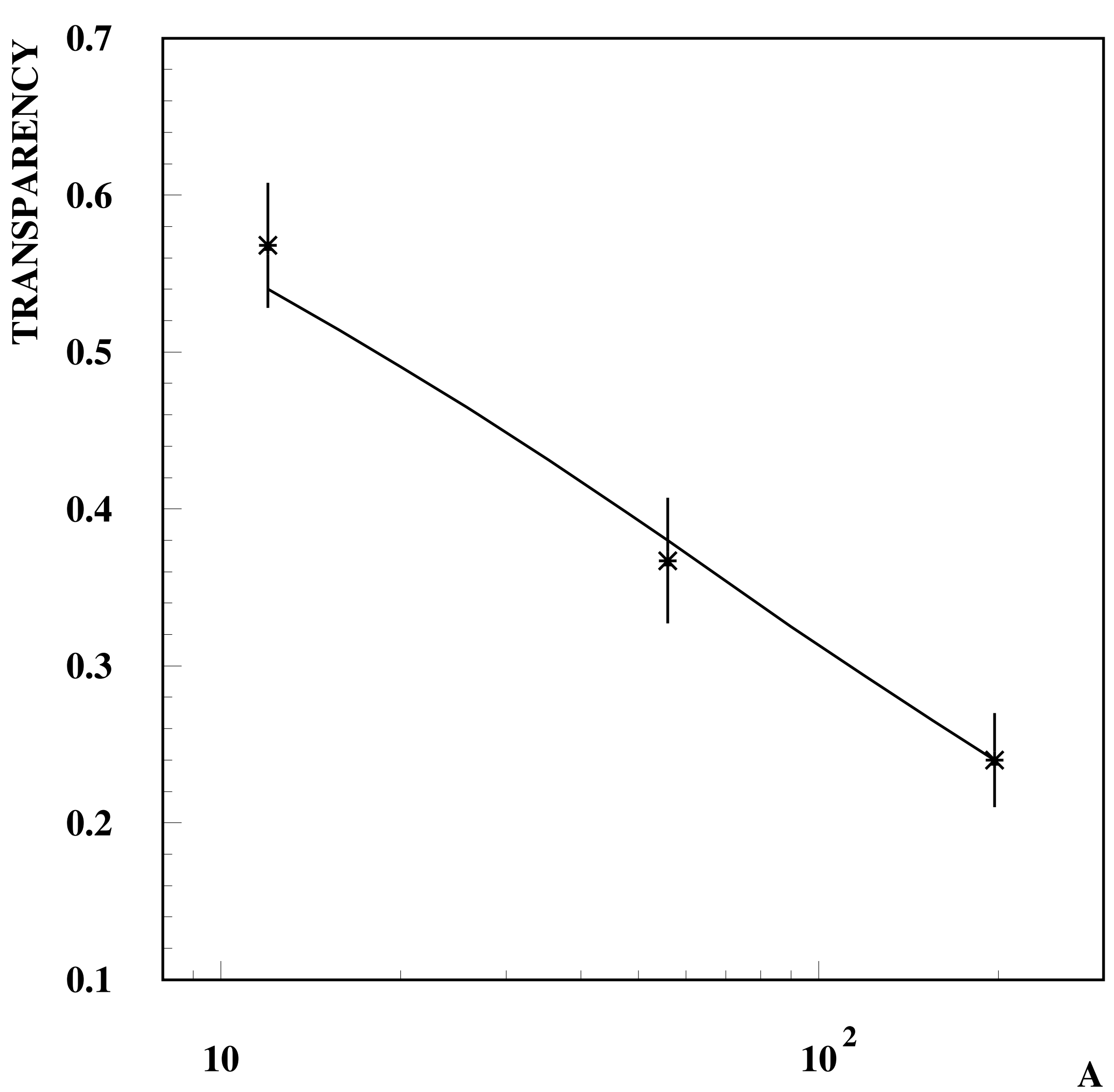
Discrepancy with Glauber calculation is typically 30% for heavy nuclei???

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









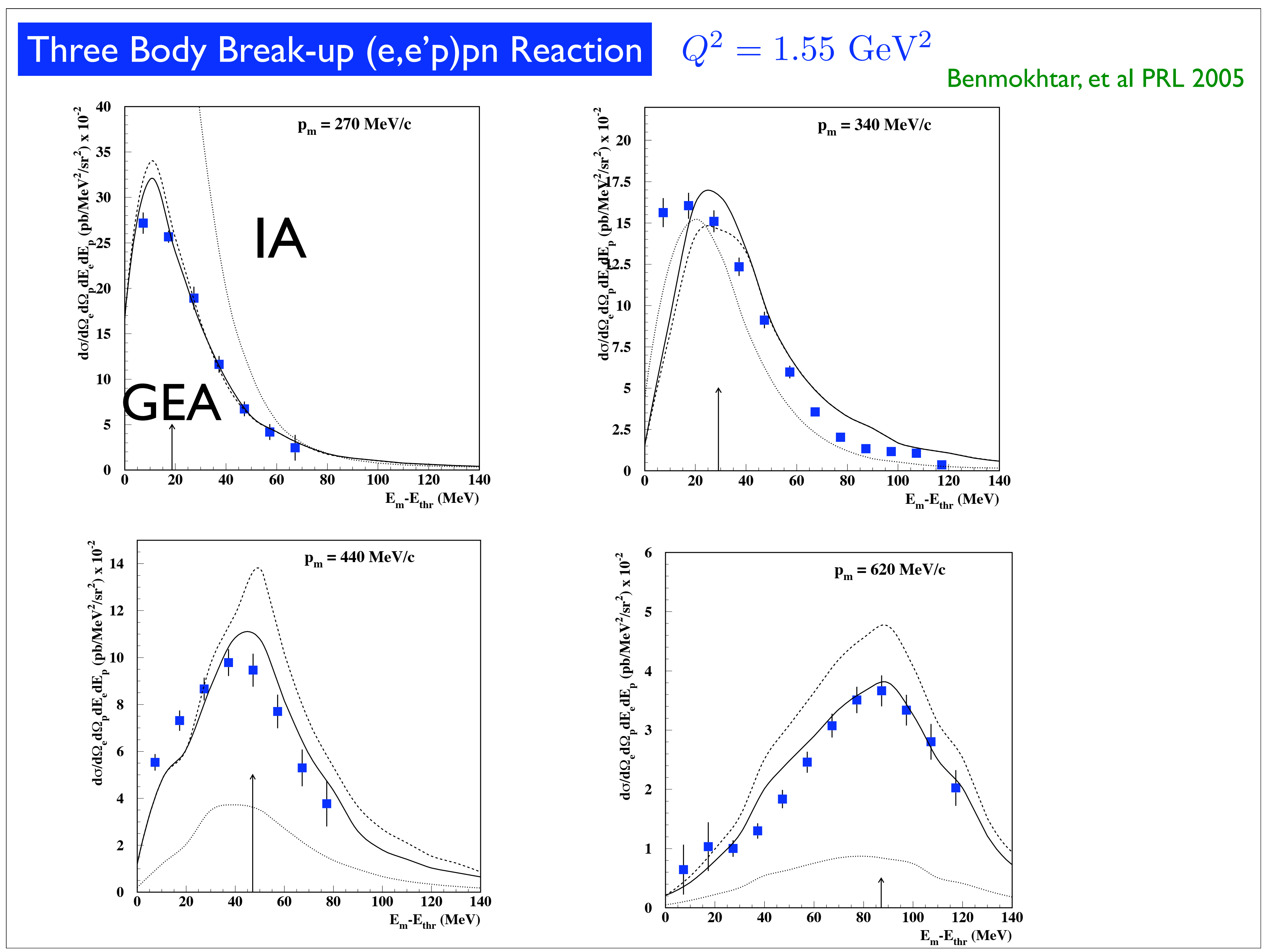
Comparison of transparency calculated using HFS spectral function with the data. No room for large quenching, though 10-15% effect does not contradict to the data.

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)

Complementary strategy - use processes where multiple rescatterings dominate in light nuclei (^{2}H,^{3}He)

Egiyan, Frankfurt, Miller, Sargsian, MS 94-95

Why: small distances - suppression of expansion, high power of σ_{eff}

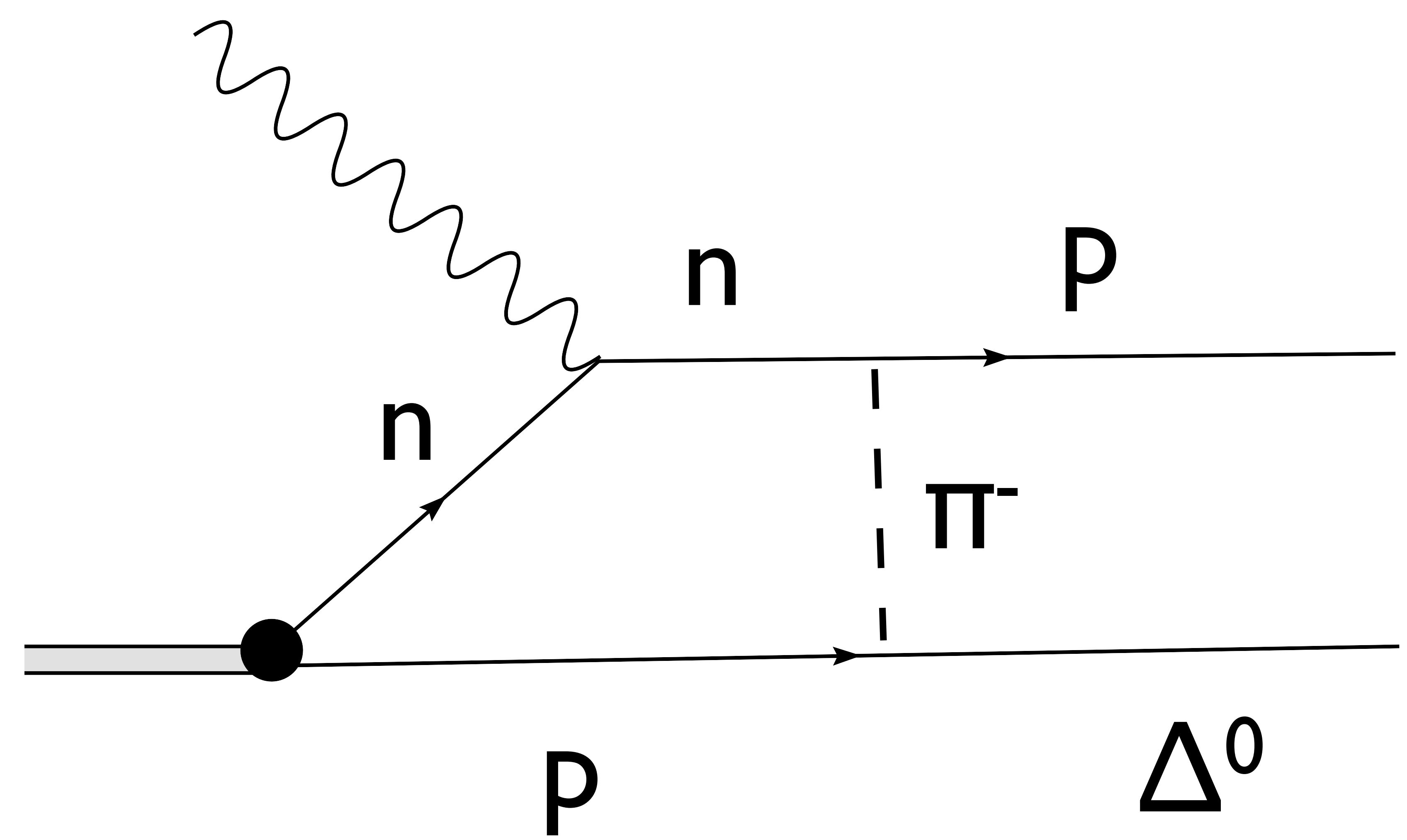


Calculation by Sargsian in GEA. Very similar results from Perugia group

Benchmark project - compare different codes for the same input

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).

Example:



☛ 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