Directions for probing QCD in and with nuclei

Mark Strikman, Penn State

Outline

In : short-range correlations and non-nucleonic degrees of freedom

With: color and chiral transparency phenomena

Hall C workshop, August 4, 2008 Jlab

QCD in nuclei

Last three years - a qualitative progress in the study of SRC based on the analysis of the high momentum transfer (e,e') Jlab data, (p,2pn) BNL data and (e,e'pp) & (e,e'pn) Jlab data. SRC are not anymore an elusive property of nuclei !!

Summary of the theoretical analysis of the experimental findings

practically all of which were predicted well before the data were obtained

More than ~90% all nucleons with momenta k≥300 MeV/c belong to two nucleon SRC correlations — BNL + Jlab +SLAC

Probability for a given proton with momenta 600> k > 300 MeV/c to belong to **pn** correlation is 18±5 times larger than for **pp** correlation — BNL + Jlab

} Piasetzky talk

Probability for a nucleon to have momentum > 300 MeV/c in medium nuclei is ~25% — BNL + Jlab 04 +SLAC 93

Probability of non-nucleonic components within SRC is small - < 20% - 2N SRC mostly build of two nucleons not 6q, ΔΔ,... — BNL + Jlab +SLAC

Three nucleon SRC are present in nuclei with a significant probability — Jlab 05

60% of the kinetic energy of nucleons for A> 50 is due to SRC >> than in EFT

The findings confirm our predictions based on the study of the structure of SRC in nuclei (77-93), add new information about isotopic structure of SRC. In particular this confirms our interpretation of the fast backward hadron emission observed in the 70's-80's as to due to SRC and allows to use information from these experiments for planning new experiments which would allow unambiguous interpretation.

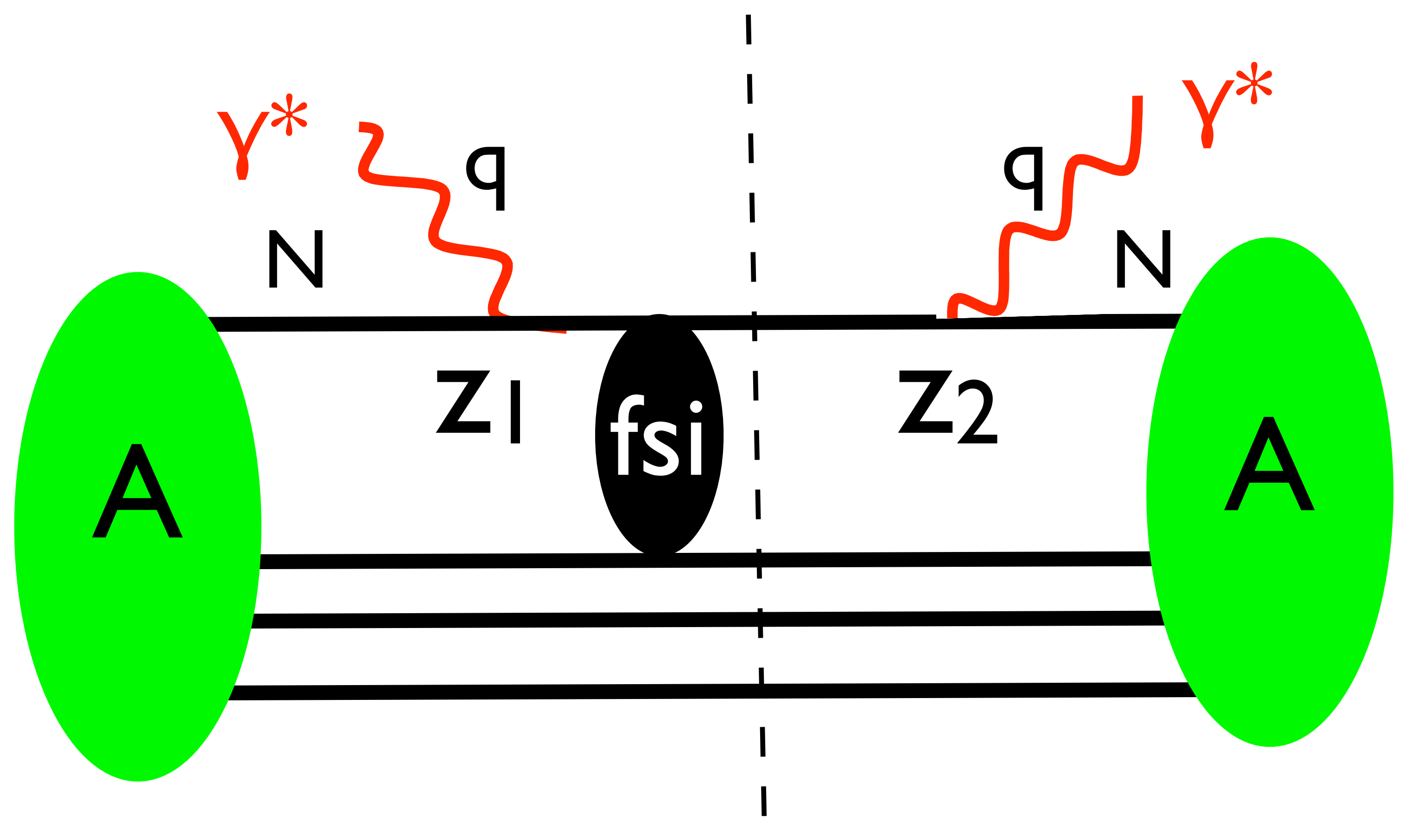
The recent progress in studies of SRC confirms that hard processes are well suited for study of microscopic nuclear structure.

What are possible strategies for further discoveries?

How to reconcile findings about SRCs with the EMC effect and suppression of antiquarks in nuclei? Really to explain the EMC effect it is absolutely necessary to have nonnucleonic degrees of freedom in nuclei - naively higher the density larger deviations are from NN picture.

Progress in the studies of SRC at high momentum due to two concepts

- Closure approximation for A(e,e') at $x=Q^2/2q_0m_N > 1$, $Q^2 > 1.5$ GeV^2 up to fsi in the SRC



$z_1 - z_1 < 1.2$ fm ➠ only fsi within SRC

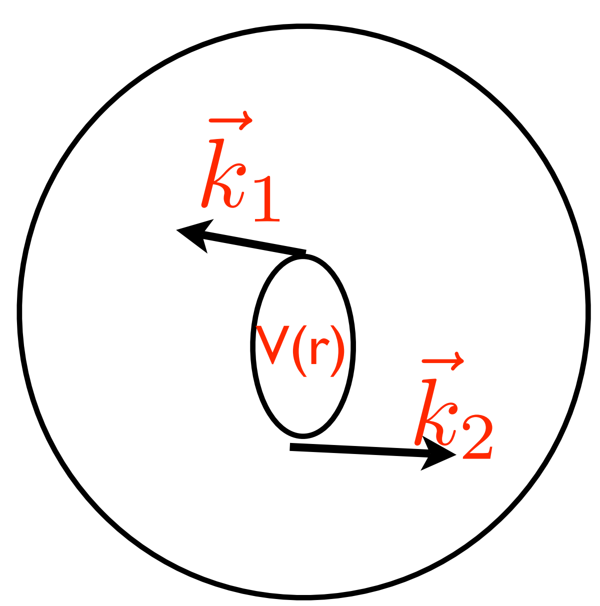
Corrections could be calculated for large Q using generalized eikonal approximation (GEA). For interactions of knocked out nucleon with slow nucleons they are less than few % -   LF & Misak Sargsian & MS (08)

Local fsi (within a SRC) are not small but they are the same for different nuclei and cancel in the ratios of the cross sections for the same x > 1

Hard exclusive processes where a nucleon of SRC is removed instantaneously

probe another quantity sensitive to SRC - nuclear decay function (FS 77-88) - probability to emit a nucleon with momentum k_2 after removal of a fast nucleon with momentum k_1, leading to a state with excitation energy E_r (nonrelativistic formulation)

$$D_A(k_2, k_1, E_r) = |\langle \phi_{A-1}(k_2, ...)\, | \delta(H_{A-1} - E_r) a(k_1) |\, \psi_A \rangle|^2$$

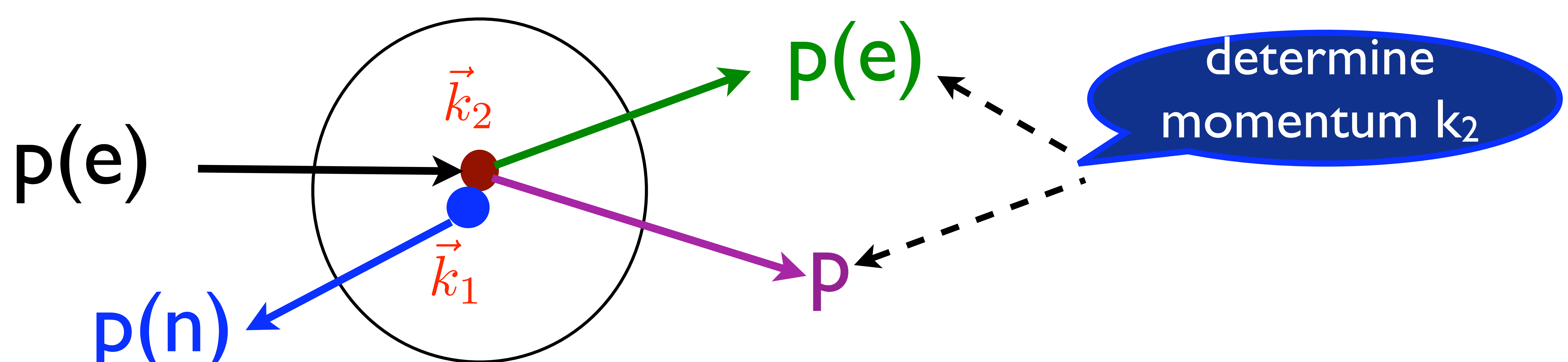


$\vec{k}_1 + \vec{k}_2 \approx 0$

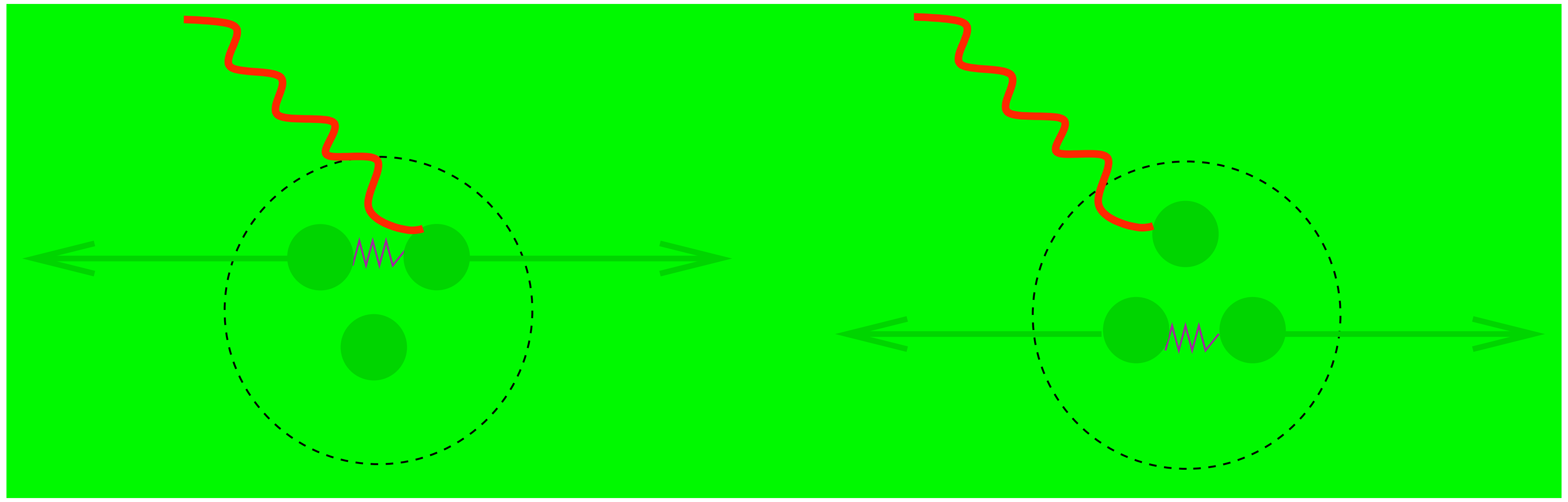
$k_1 > k_F$

General principle (LF&MS77): to release a nucleon of a SRC - necessary to remove nucleons from the same correlation - perform a work against potential $V_{12}(r)$

Operational definition of the SRC: nucleon belongs to SRC if its instantaneous removal from the nucleus leads to emission of one or two nucleons which balance its momentum: includes not only repulsive core but also tensor force interactions.



For 2N SRC can model decay function as decay of a NN pair moving in mean field (like for spectral function in Ciofi & Simula, LF&MS 01) Piasetzky et al 06

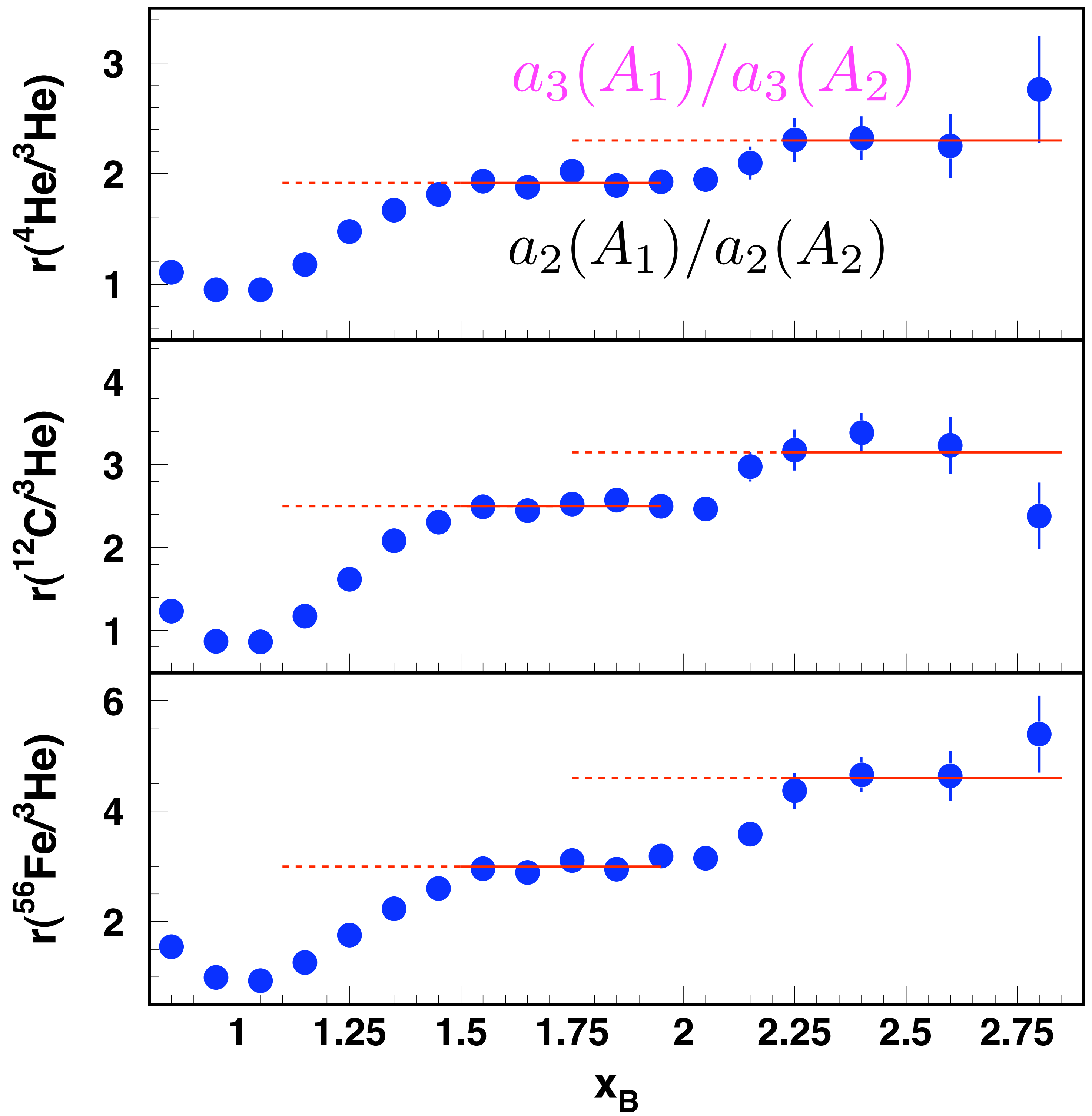


Studies of the spectral and decay function of ^{3}He reveal both 2N and 3N SRCs Sargsian et al 2004

Note that in the decay one needs to take into account recoil effects - naturally accounted for when using relativistic light-cone decay functions: conservation of LC fractions

Problem - no methods so far to calculate decay functions for A >4. However the decay function and another interesting characteristics of the nuclear structure - two nucleon momentum distributions in the nuclei (Schiavilla et al 07, Alvioli et al 08) is close to decay function for $k_1+k_2=0$, $k_1>>k_F$. *Further studies of connection for the case* $|k_1+k_2|>$ 50 - 100 MeV/c are necessary.

Scaling of ratios - evidence for universal nucleonic SRC



Ratio of the cross sections of (e,e')scattering off a ^{56}Fe (^{12}C,^{4}He) and ^{3}He per nucleon

Jlab data from Hall B.

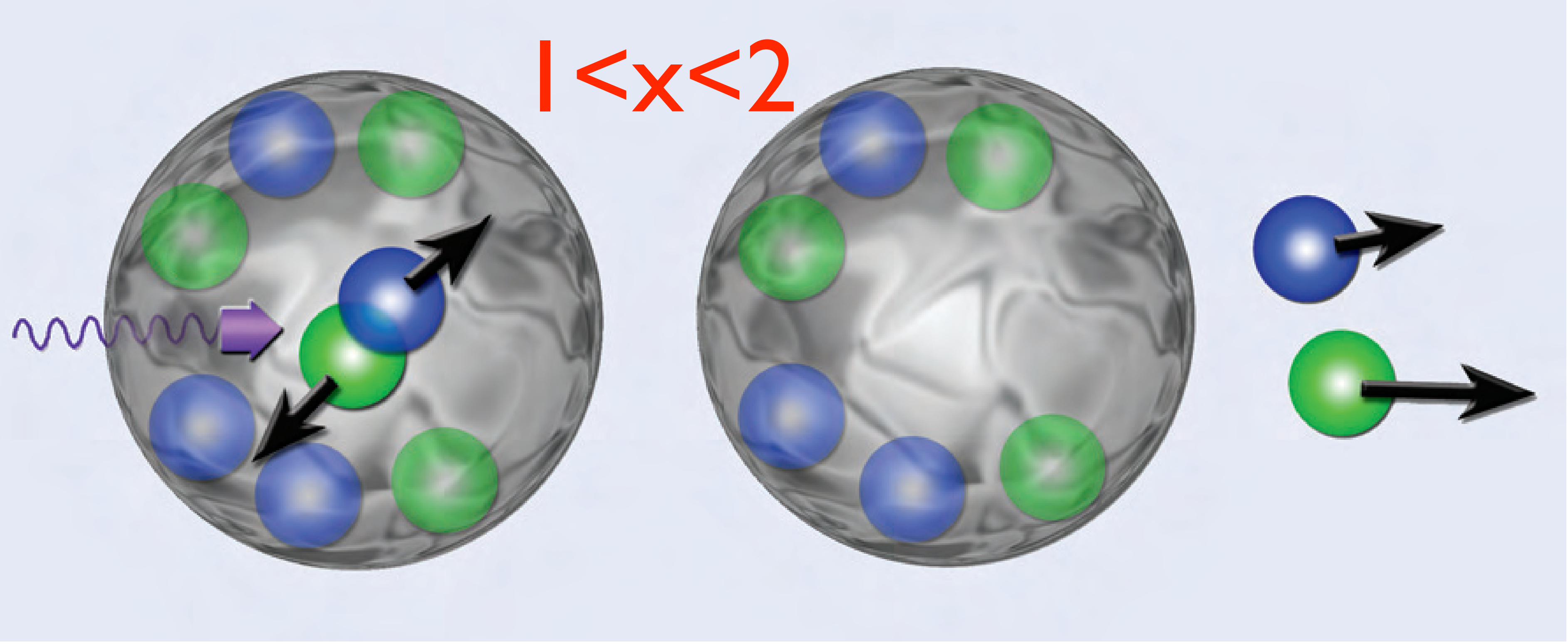
$Q^2 > 1.5$ GeV^2

confirm our 1980 prediction of scaling for the ratios due to SRC

Fe/C ratios for x~1.75, x~2.5 agree within experimental errors with our prediction - density based estimate:

$$r_2 = (A_1/A_2)^{0.15}$$

$$r_3 = (A_1/A_2)^{0.22}$$



Before absorption of the photon

After absorption

The best evidence for presence of 3N SRC. One probes here interaction at internucleon distances <1.2 fm corresponding to local matter densities $\geq 5\rho_0$ which is comparable to those in the cores of neutron stars!!!

Two nucleon correlations - probability relative to "pn" in deuteron

Day, L.Frankfurt, Sargsian, MS, 93

$$a_2(^3\text{He}) = 1.7(0.3) \ ,$$
$$a_2(^4\text{He}) = 3.3(0.5) \ ,$$
$$a_2(^{12}\text{C}) = 5.0(0.5) \ ,$$
$$a_2(^{27}\text{Al}) = 5.3(0.6) \ ,$$
$$a_2(^{56}\text{Fe}) = 5.2(0.9) \ ,$$
$$a_2(^{197}\text{Au}) = 4.8(0.7) \ ,$$

Significant uncertainties in absolute scale

	$a_2(A/^3\text{He})$	$a_{2N}(A)(\%)$	$a_3(A/^3\text{He})$	$a_{3N}(A)(\%)$
^3He	1	$8.0 \pm 0.0 \pm 1.6$	1	$0.18 \pm 0.00 \pm 0.06$
^4He	$1.96 \pm 0.01 \pm 0.03$	$15.6 \pm 0.1 \pm 3.2$	$2.33 \pm 0.12 \pm 0.04$	$0.42 \pm 0.02 \pm 0.14$
^{12}C	$2.51 \pm 0.01 \pm 0.15$	$20.0 \pm 0.1 \pm 4.4$	$3.18 \pm 0.14 \pm 0.19$	$0.56 \pm 0.03 \pm 0.21$
^{56}Fe	$3.00 \pm 0.01 \pm 0.18$	$24.0 \pm 0.1 \pm 5.3$	$4.63 \pm 0.19 \pm 0.27$	$0.83 \pm 0.03 \pm 0.27$

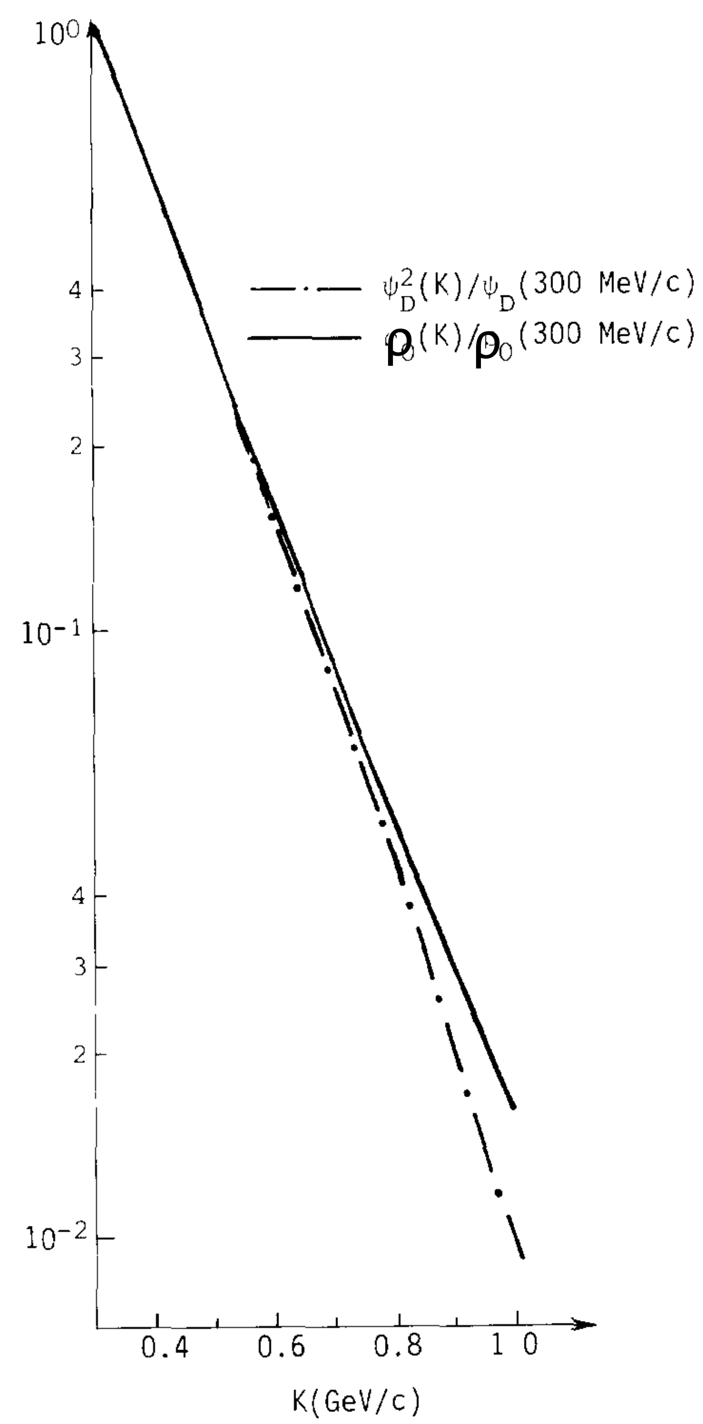
K.Egiyan, et al 2005

Amazingly good agreement between two analyses for a_2 (A)

Compare also to the analysis of EVA data on (p,2p) - a_2(C) ~ 5

Yaron et al 02

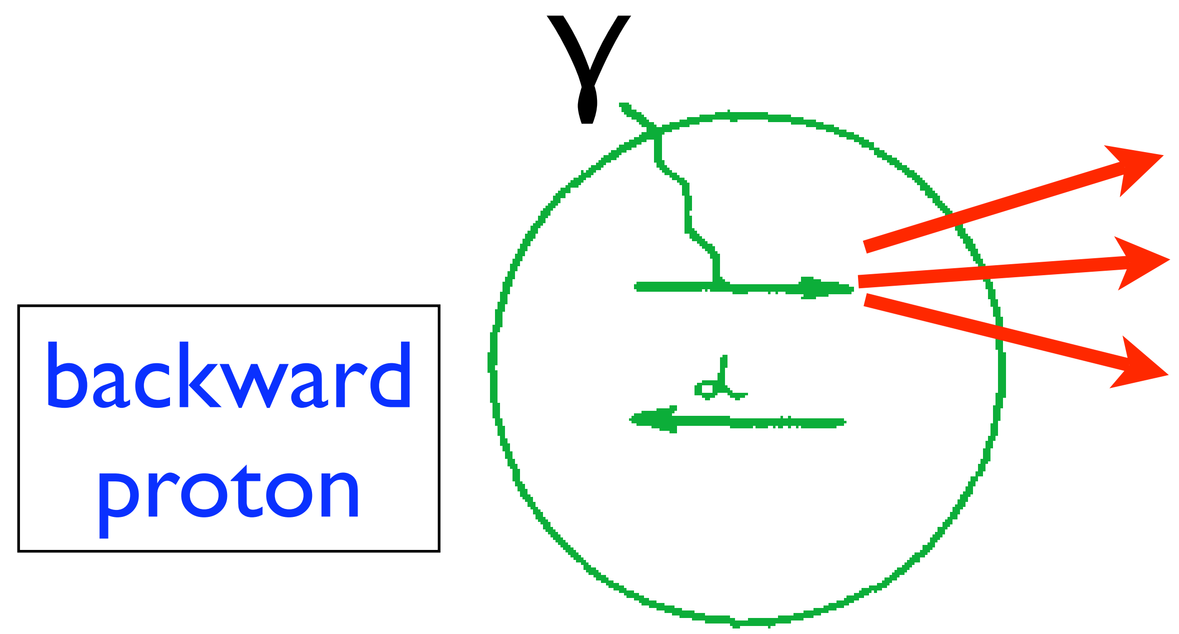
We extracted two nucleon correlation function from analysis of $\gamma(p)\ {}^{12}C \rightarrow p+X$ processes



Hamada-Johnston WF

Extracted from the data assuming dominance of 2N SRC

From Phys.Lett 1977



Momentum distribution normalized to its value at 300 MeV/c.

We also estimated from these data $a_2(^{12}C) = 4 \div 5$

☛ Backward direction is very good for looking for decay of SRCs

Further 2N correlation studies

- Detailed studies of (e,e') at 1<x <2. Onset of scaling of ratios. Reaching Q where it is violated. Isotopic effects (Ca, ^{3}H/^{3}He)

- Processes with detection of nucleons. Need more phase space to be able to find kinematics with min between nucleons of the 2N SRC.

Easier to do with proton beams or higher energy electron beams - In this respect BNL (p,2pn) experiment ($-t= 5$ GeV^2) had a better kinematics than Jlab (e,e'pp/pn) experiment ($Q^2= 2$ GeV^2)

Further studies are necessary, preferably using both leptonic and hadronic projectiles:

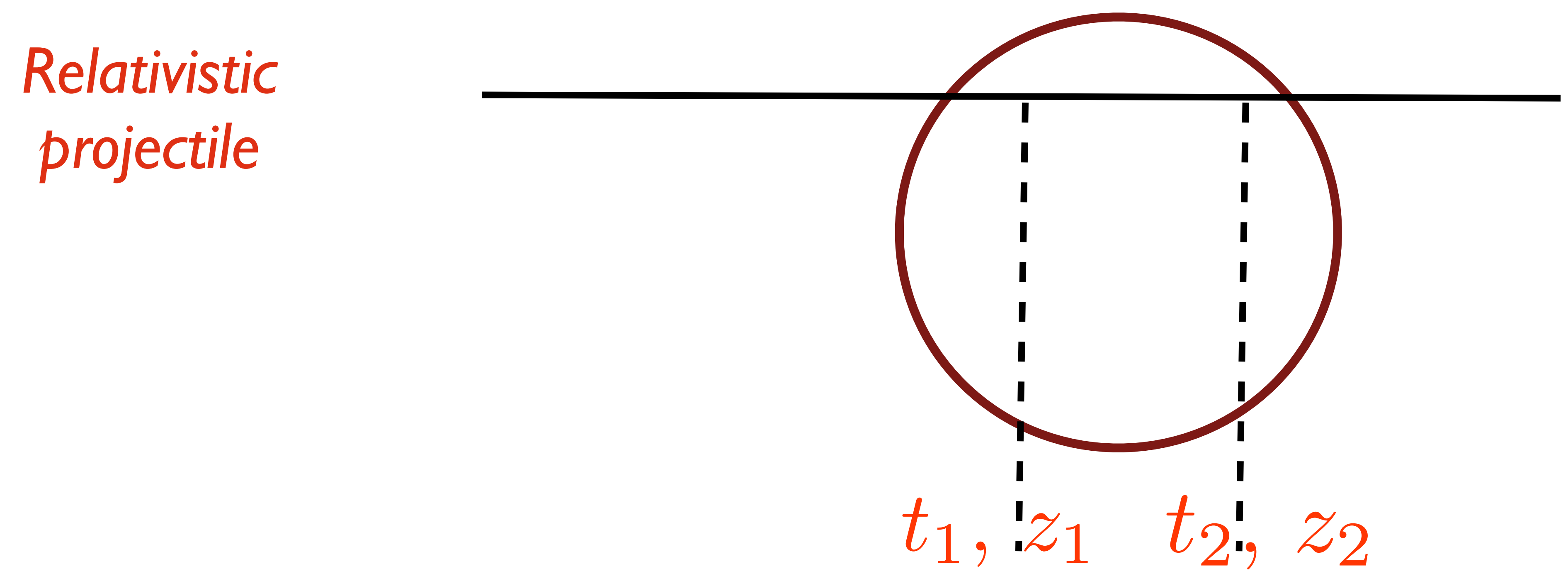
factorization tests for 2N SRC - removal of a nucleon at different Q and by different probes - are necessary to demonstrate that ***decay function is universal*** *(first step consistency of BNL and Jlab data)*

Studies of forward - backward correlations for a range of light nuclei ^{3}He/^{4}He(e,e')pp/pn at Jlab at Q^2=2 ÷4 GeV^2 and at proton facilities (J-PARC, GSI) with (anti)protons of energies starting at 6 GeV. A-dependence of the pp/pn ratio, its dependence on momentum of hit nucleon. Need statistics > 100 times higher than EVA and Jlab07. Gross reduction of errors on pp/pn. Important to cover region of momenta $k_F < k < 300$ MeV/c to explore transition from mean field to SRC.

What about large angle photon induced processes at large t:
$\gamma A \to \pi^- p$ + backward N + (A-2)

- What is the optimal way to include relativistic effects in particular minimal ones due transformation vacuum pairs? High energy process develops along the light cone (LC).

$\Rightarrow$



$$t_1 - z_1 = t_2 - z_2$$

Similar to the perturbative QCD the amplitudes of the processes are expressed through LC wave functions

<u>*Best probe*</u>

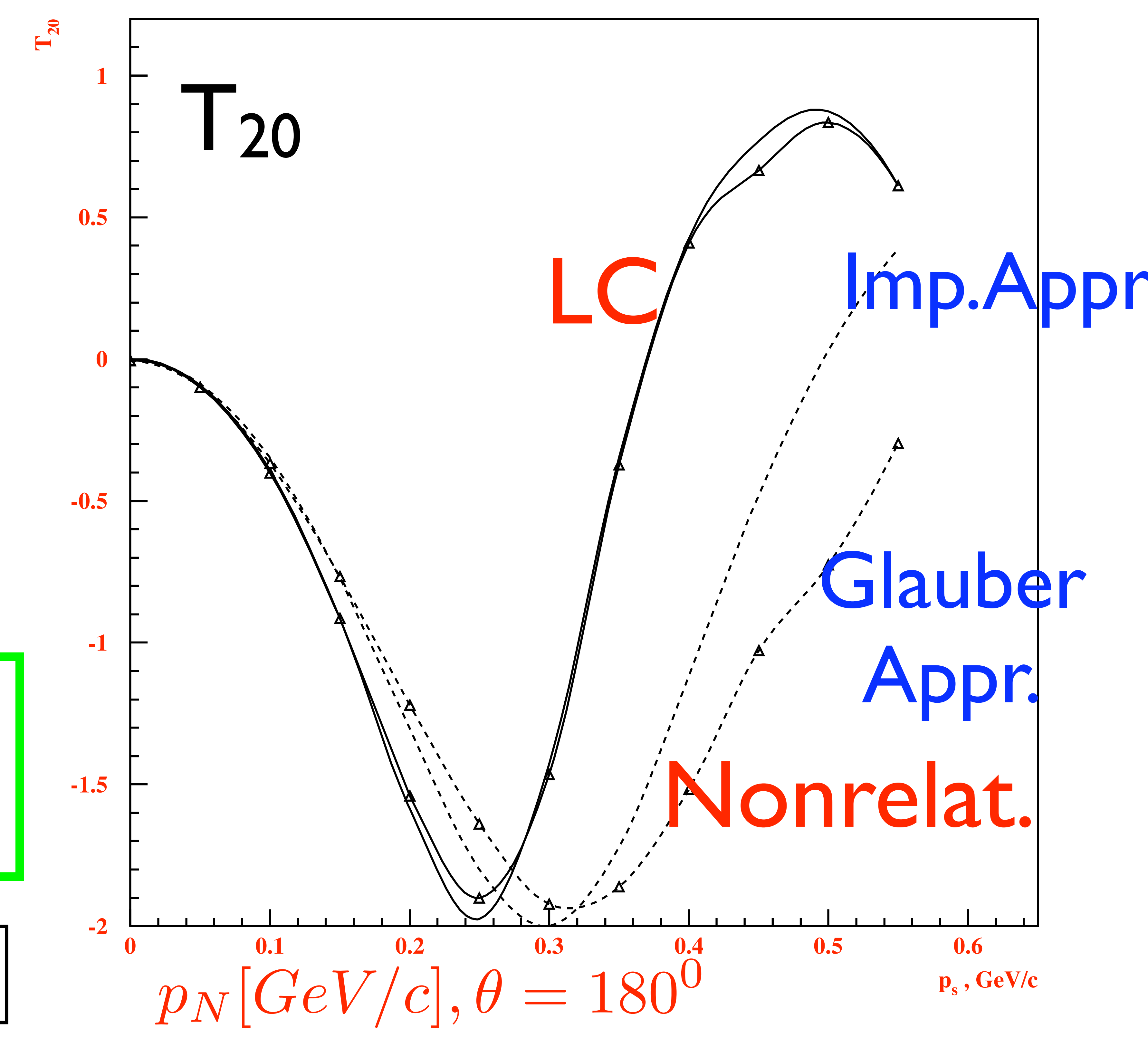
Measurement of S/D ratio in ^2H as a function of the nucleon momentum in

$e +^2 \vec{H} \rightarrow e + p + n$ at $Q^2 \sim 2$ GeV^2

- large relativistic effects FS78

(a) T_{20} for tensor D polarization
(b) Proton polarization for vector D polarization

Measured in NIKHEF for Q^2 =.21 GeV^2 Passchier et al 2002



- How EMC effect depends on the virtuality/off-energy-shellness of the nucleon?

  Is dependence the same for u- and d- quarks?

Tagging of proton and neutron in e+D→e+ backward N +X.

Expectation: Deviation of F_{2N}(bound) from F_{2N} should grow with virtuality of the interacting nucleon: $p_{int}^2 - m^2 = (m_A - p_{spect})^2 - m^2.$

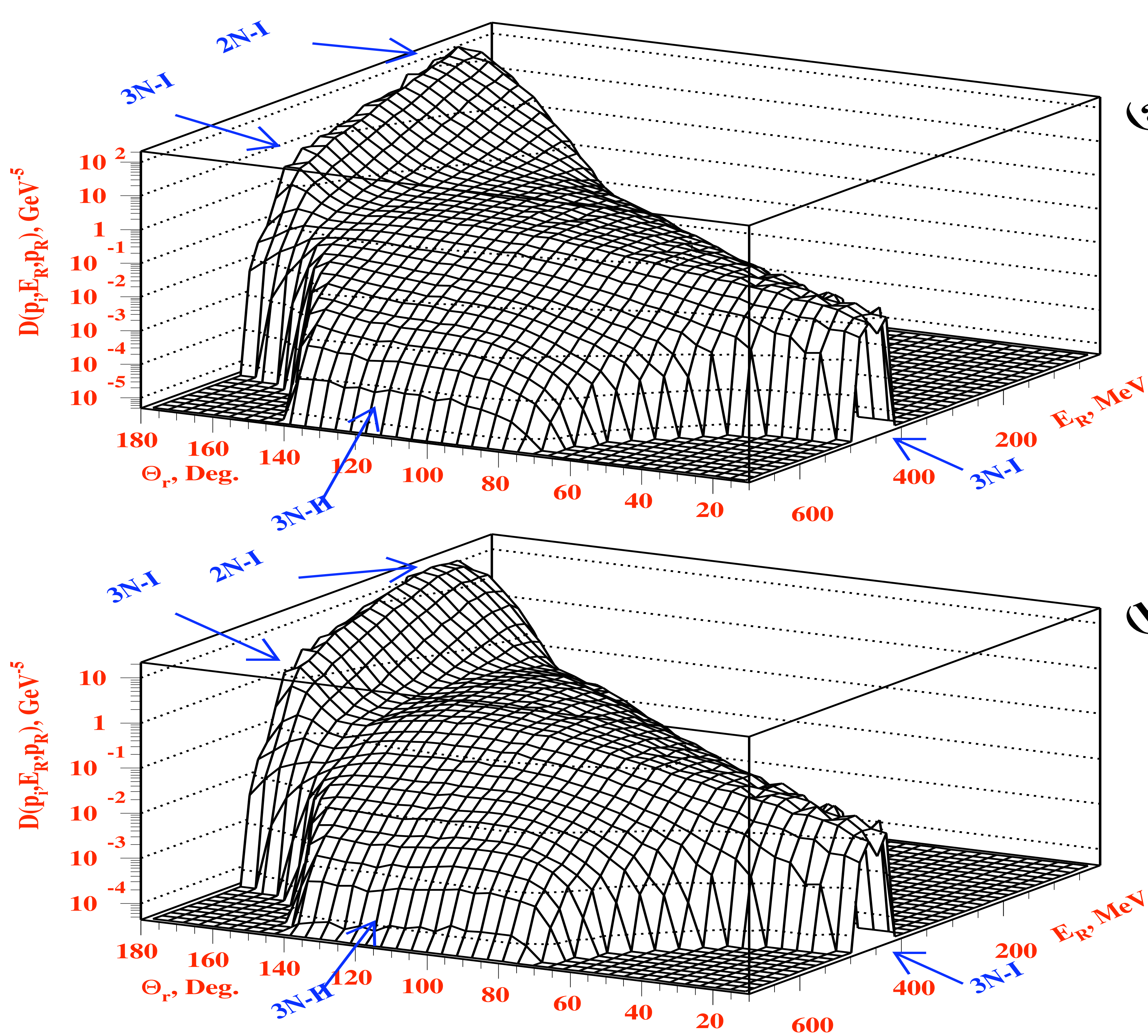
linearly for small virtualities as now observed for G_{Ep}/G_{Mp} at Jlab.

$$\frac{F_{2A}(x,Q^2)}{F_{2N}(x,Q^2)} - 1 \propto (p_{int}^2 - m_N^2)/\Delta E m_N$$

Further 3N correlation studies

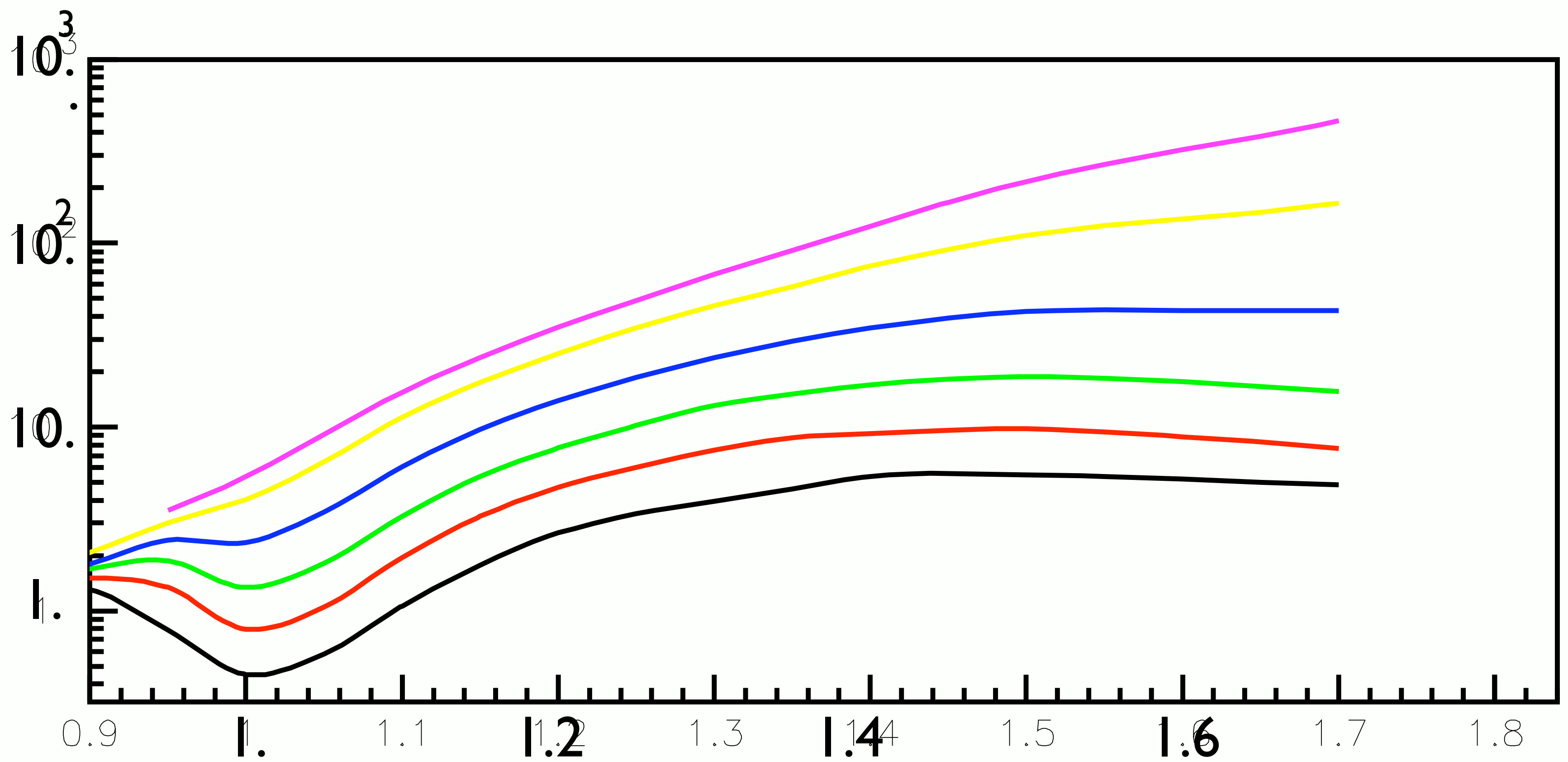
Evidence for 3N SRC

- Analysis of the production of fast backward nucleons in the kinematics forbidden for scattering off the deuteron
- Scaling of the ratios of (e,e’) cross sections for 3> x >2
- Calculation of the light-cone wave functions of nuclei
- 3N SRC can be seen in the structure of decay of 3He (Sarsgian et al).

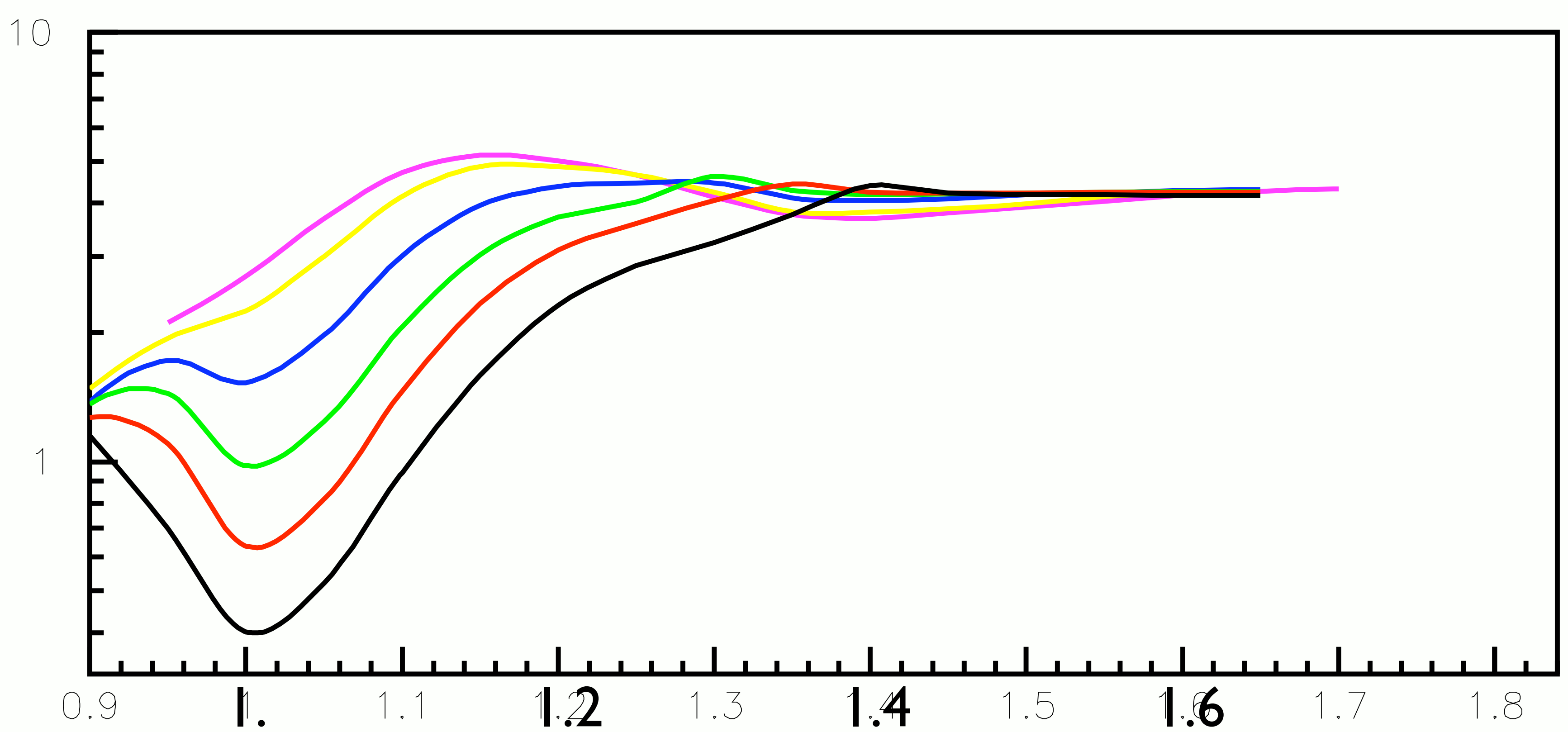


Dependence of the decay function on residual nuclei energy, E_R and relative angle of struck proton and recoil nucleon, Θ_r. Figure (a) neutron is recoiling against proton, (b) proton is recoiling against proton. Initial momentum of struck nucleon as well as recoil nucleon momenta is restricted to $p_i, p_r \geq 400$MeV/c.

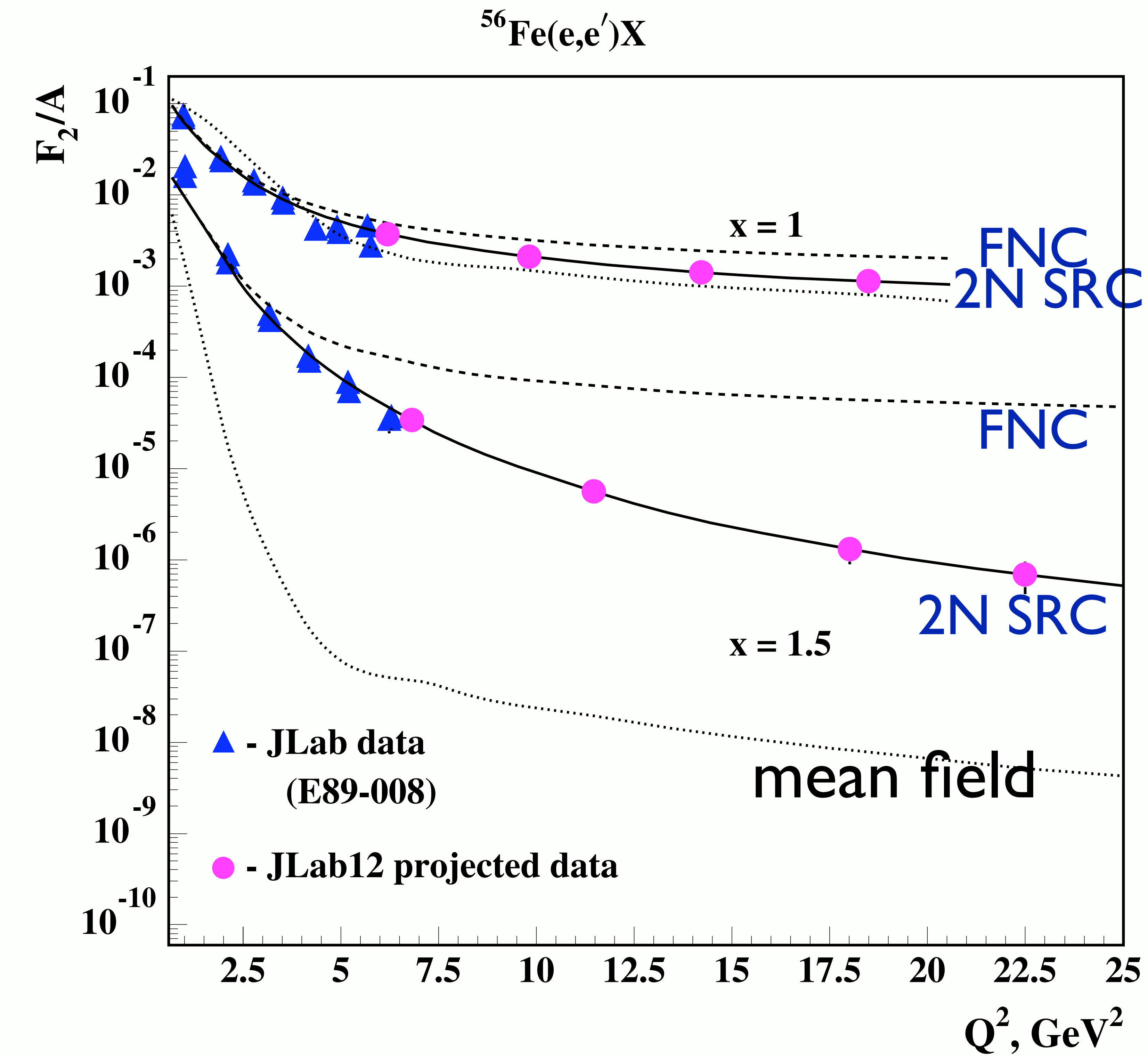
Q²-dependence of the C/D ratio based on SRC model including quasielastic and DIS contributions



Few-nucleon correlation model



Two-nucleon correlation approximation



Mapping structure of 3N SRC from
e A→ e "forward N"+ "backward N" + "backward N" + A-3

Use as a guide correlations in p A→ p (backward) + p (backward) +X measured by Bayukov et al 86

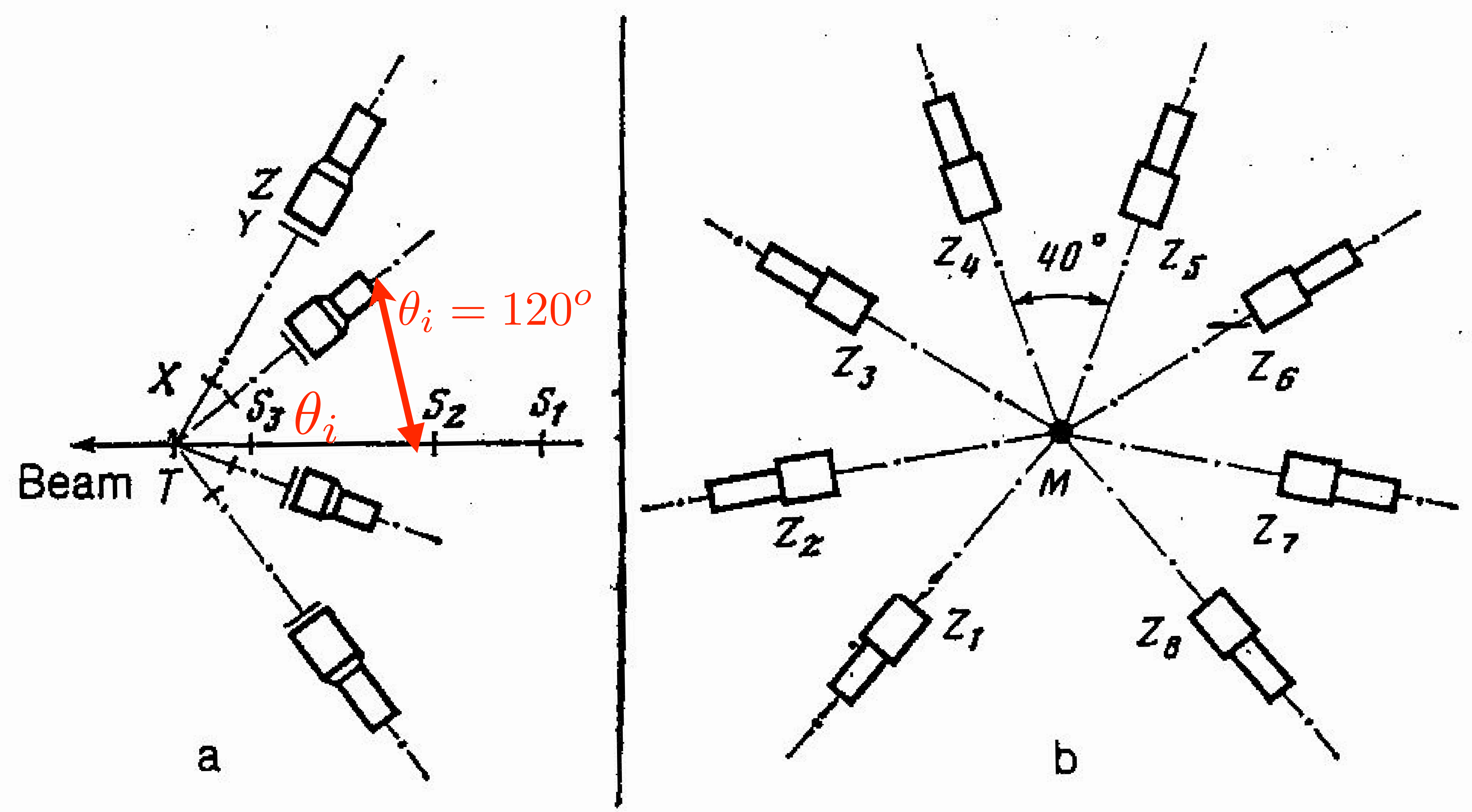
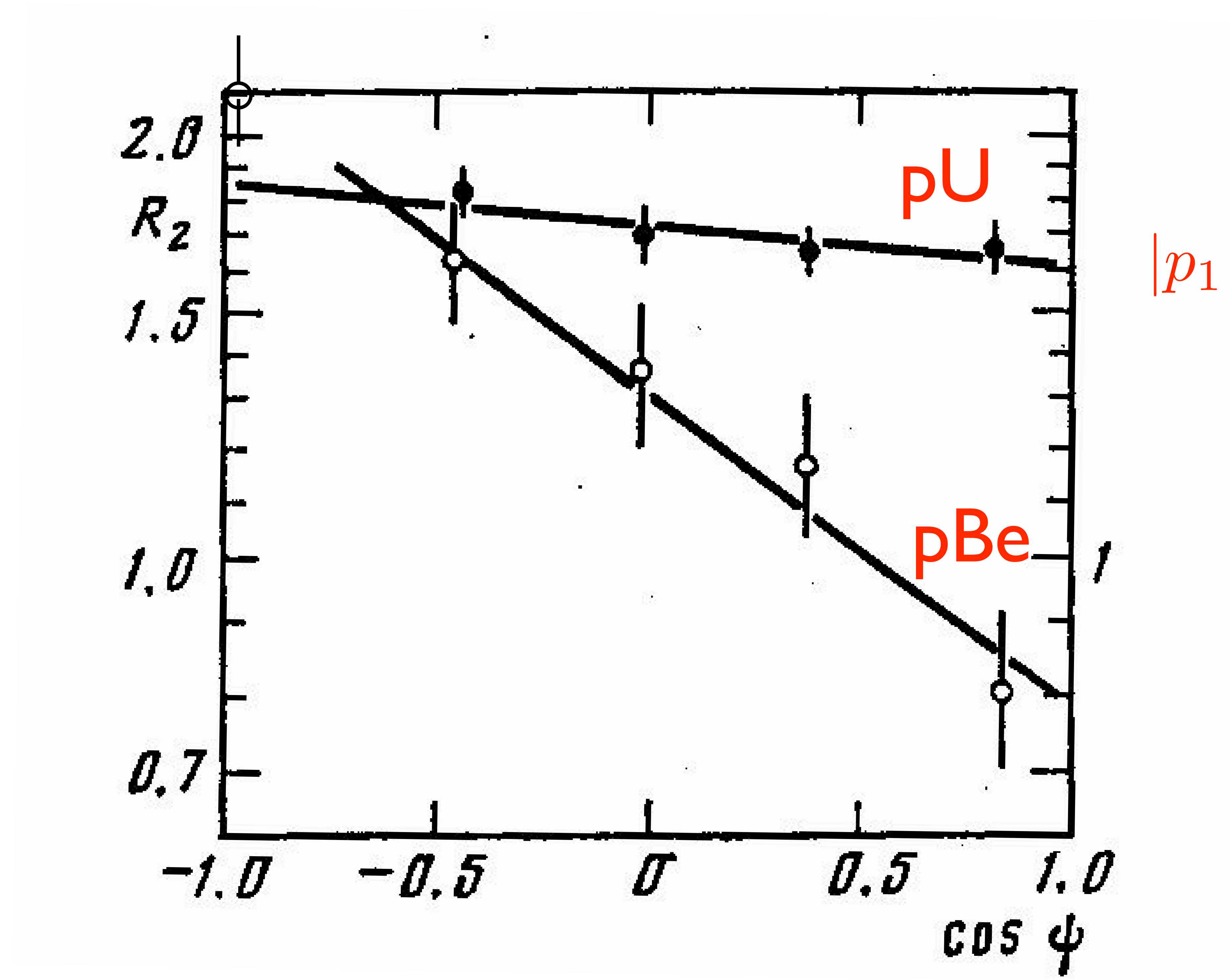


FIG. 1. Diagram of apparatus. (a)—Side view, (b)—view along the beam direction. Only the Z counters are shown.

$$R_2 = \frac{1}{\sigma_{pA}^{in}} \frac{d\sigma(p+A \to pp+X)/d^3p_1 d^3p_2}{d\sigma(p+A \to p+X)/d^3p_1 d\sigma(p+A \to p+X)/d^3p_2}$$

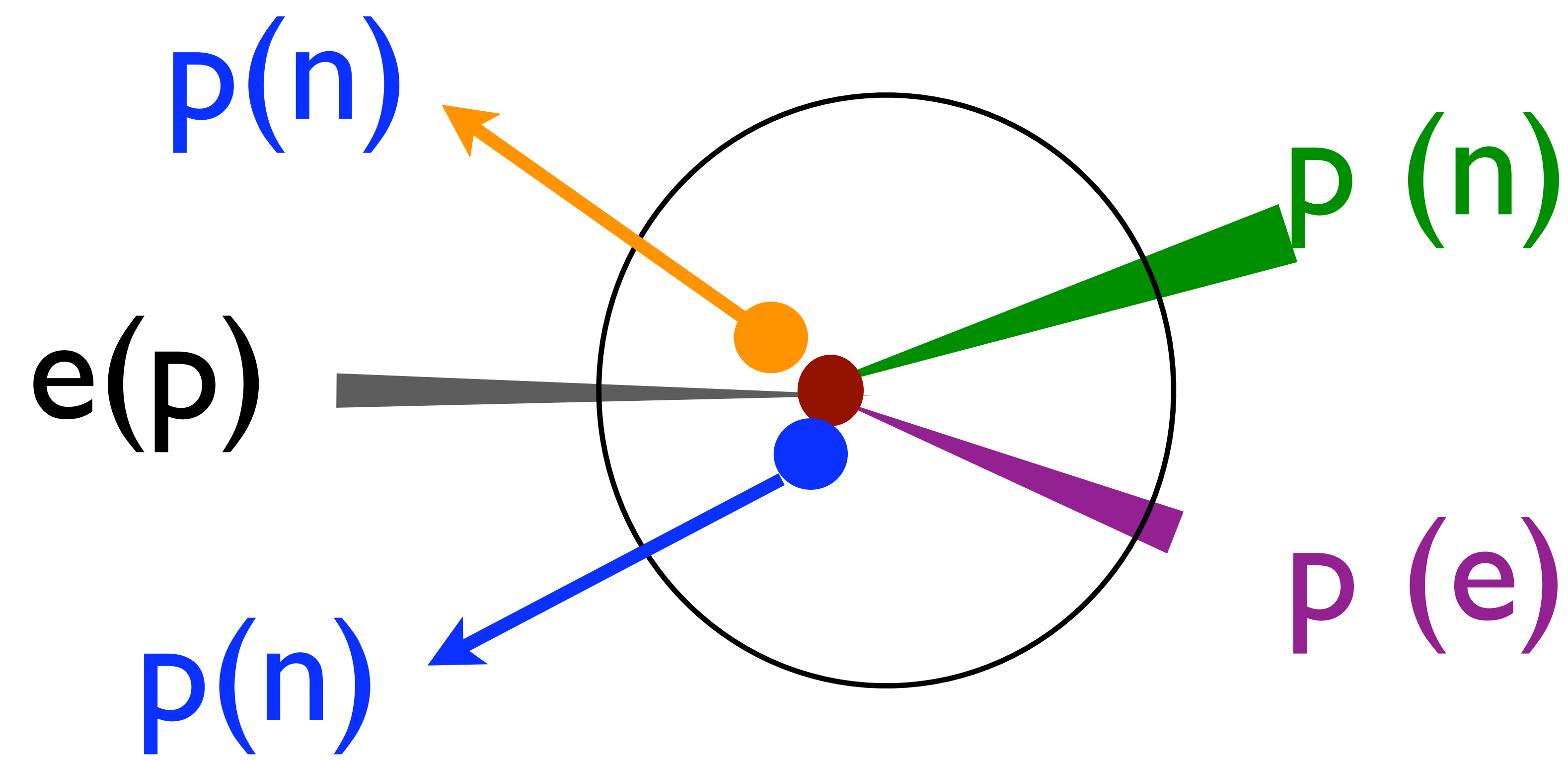


$|p_1| = |p_2| \approx 500 MeV/c$

Curves is experimental fit.

We can reasonably reproduce the pattern of ψ dependence of R_2

Study 3N correlations in A(e,e' p +2 backward nucleons) &A(p,p' p +2 backward nucleons).
Reminder: for the neutron star dynamics mostly isotriplet nn, nnn,.. SRC are relevant.



Start with ^{3}He, followed by ^{4}He, C.

$$\alpha = A\frac{E_N - p_N^{(3)}}{E_A - p_A^{(3)}}$$

light-cone fraction

Expectations:

(a) $\alpha_{1\,Back.Nucl} + \alpha_{2\,Back.Nucl}\alpha_{1\,Forw.Nucl} \approx 3$

(b) ppn ~ nnp >> nnn, ppp

(c) e+A → e+ 2N +X stronger angular dependence and larger $R_2(\psi=-180°)$ than in pA.

Quest for non-nucleonic degrees of freedom

Up to what momenta description of NN correlations in terms of nucleonic degrees of freedom maybe justified?

Decomposition over hadronic states could be useless if too many states are involved in the Fock representation

$$|D\rangle = |NN\rangle + |NN\pi\rangle + |\Delta\Delta\rangle + |NN\pi\pi\rangle + ...$$

We can use the information on NN interactions at energies below few GeV and the chiral dynamics combined with the following general quantum mechanical principle - *relative magnitude of different components in the wave function should be similar to that in the NN scattering at the energy corresponding to off-shellness of the component.*

Important simplification is due to the structure of the final states in NN interactions: direct pion production is suppressed for a wide range of energies due to chiral properties of the NN interactions:

$$\frac{\sigma(\mathrm{NN} \to \mathrm{NN}\pi)}{\sigma(\mathrm{NN} \to \mathrm{NN})} \simeq \frac{k_\pi^2}{16\pi^2 F_\pi^2}, \quad F_\pi = 94 \ \mathrm{MeV}$$

⇒ Main inelasticity for NN scattering for $T_p \leq 1$ GeV is single Δ-isobar production which is forbidden in the deuteron channel.

|Δ Δ> threshold is $k_N = \sqrt{m_\Delta^2 - m_N^2} \approx 800\, MeV/c$!!!

Small parameter for inelastic effects in the deuteron WF, while relativistic effects are already significant as v/c ~1

For the nuclei where single Δ can be produced $k_N \approx 550\, MeV/c$

⇒ Best to look for admixture at large backward momenta ($\alpha_\Delta > 1$)

To summarize: pn and pp correlations are predominantly build of nucleons 10--20 % (?) accuracy. Little room for exotic components (6q, Δ-isobars) should be corrections even in SRC where energy scale is larger and internucleon distances are < 1.2 fm. Still because of suppression of pion fields, *looking for exotic baryonic degrees of freedom most promising.*

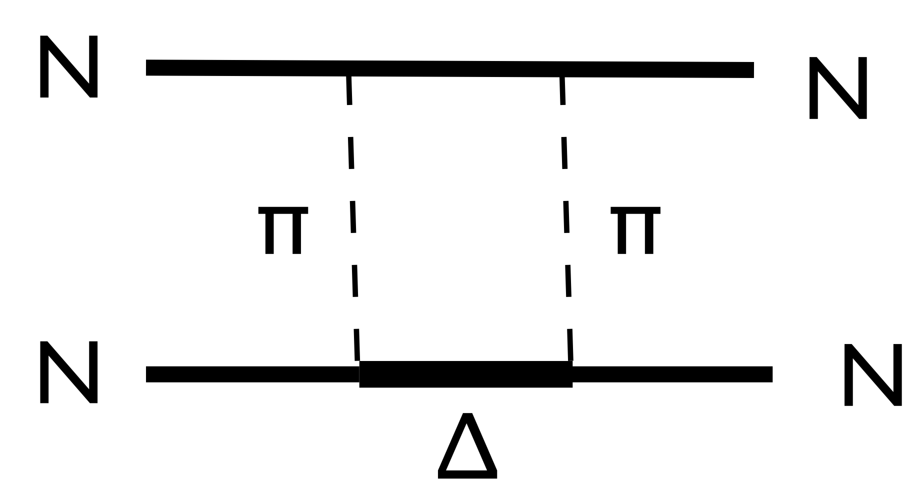
Non-nucleonic degrees of freedom

The reviewed data seem to indicate that 2N correlations dominate for

$600 > k_N > 300$ MeV/c

What about Δ's in nuclei?

Attraction in NN at medium distance (1 fm) is due to two pion exchange



Reminder - quark exchanges also should generate Δ's

Intermediate states with Δ -isobars.

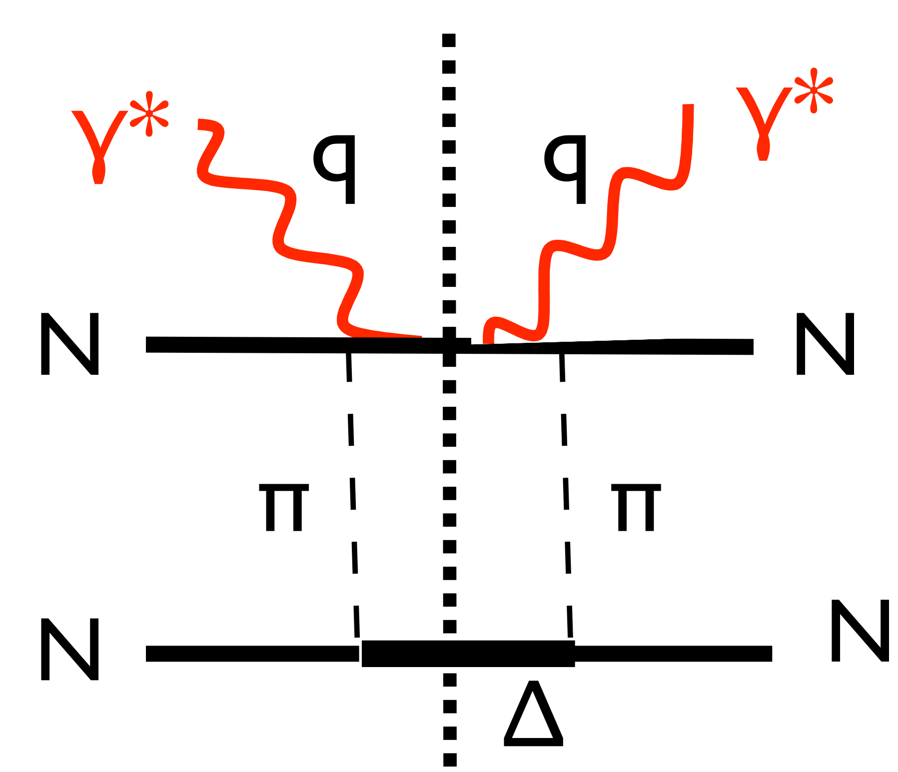
Often hidden in the potential. Probably OK for calculation of the energy binding, energy levels. However wrong for high Q^2 probes.

Explicit calculations of B.Wiringa - ~1/2 high momentum component is due to ΔN correlations, significant also ΔΔ . Tricky part - match with observables - momentum of Δ in the wf and initial state

Large Δ admixture in high momentum component

⇓

- ☛ Suppression of NN correlations in kinematics of BNL experiment
- ☛ Presence of large E_R tail (~ 300 MeV) in the spectral function



Looking for non-nucleonic degrees of freedom (a sample of processes)

electron beams

isobars, N*'s $\alpha_\Delta > 1$

for x> 0.1 very strong suppression of two step mechanisms (FS80)

Confirmed by neutrino study of Δ-isobar production off deuteron

Best limit on probability of $\Delta^{++}\Delta^{-}$ component in the deuteron < 0.2%

An analysis has been made of 15 400 ν–d interactions in order to find a $\Delta^{++}(1236)$–$\Delta^{-}(1236)$ structure of the deuteron. An upper limit of 0.2% at 90% CL is set to the probability of finding the deuteron in such a state.

SEARCH FOR A Δ(1236)–Δ(1236) STRUCTURE OF THE DEUTERON

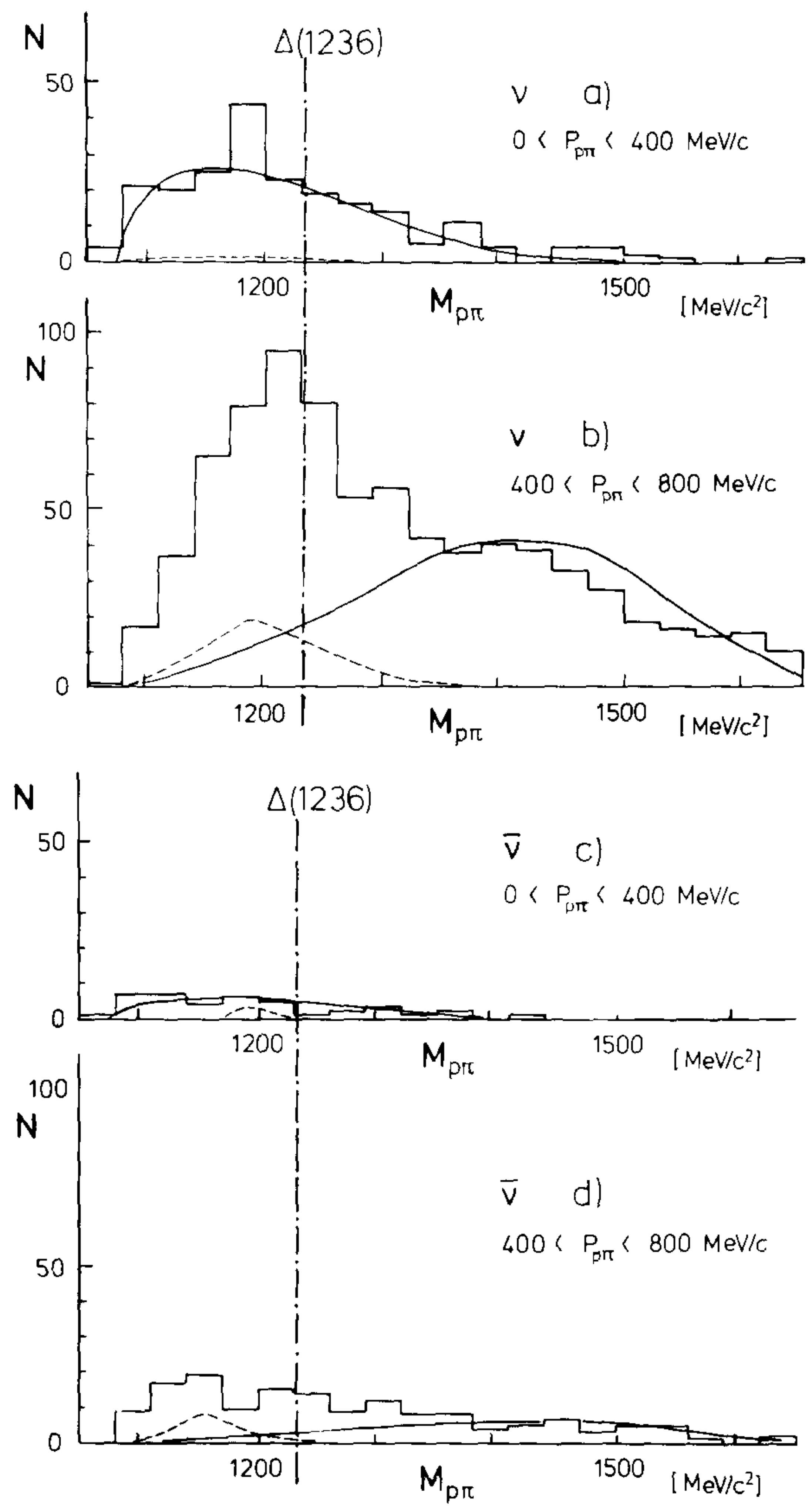


Fig. 1. Effective mass distributions of $p\pi^+$ combinations for ν (top) and $\bar{\nu}$ (bottom) interactions. The distributions are presented for two intervals of the combined $p\pi^+$ momentum: 0–400 and 400–800 MeV/c. The chosen bin size is 30 MeV/c^2 = $\Gamma(1235)/4$. The solid lines show the calculated background of combinations of a pion with a spectator proton. The dotted lines show prompt $p\pi^+$ production as obtained from $\nu/\bar{\nu}$–hydrogen data.

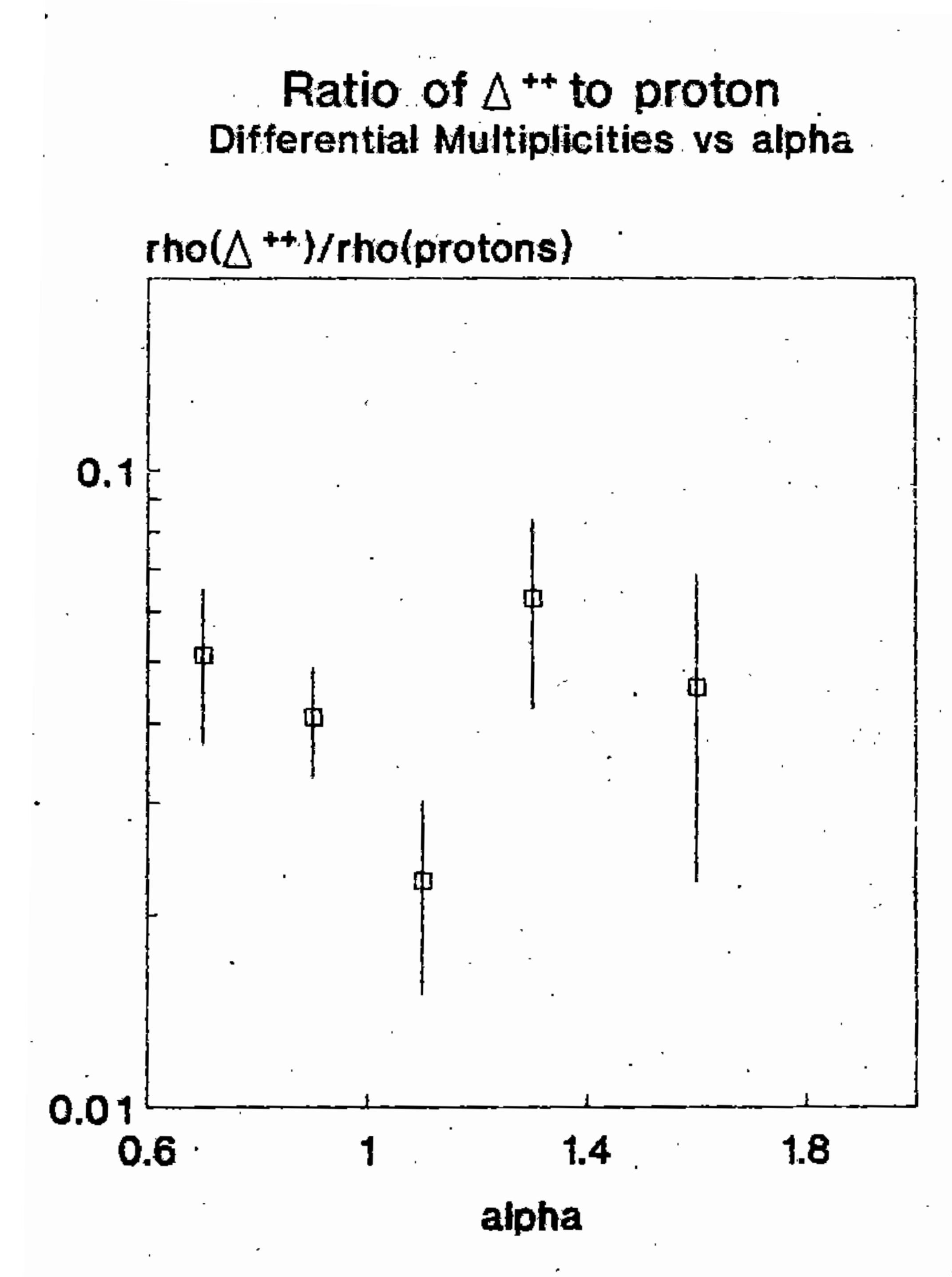
Is there a positive evidence for Δ's in nuclei?

Indications from DESY AGRUS data (1990) on electron - air scattering at E_e=5 GeV (Degtyarenko et al).

Measured Δ^{++}/p, Δ^0/p for the same light cone fraction alpha.

$$\frac{\sigma(e+A\rightarrow\Delta^0+X)}{\sigma(e+A\rightarrow\Delta^{++}+X)}=0.93\pm0.2\pm0.3$$

$$\frac{\sigma(e+A\rightarrow\Delta^{++}+X)}{\sigma(e+A\rightarrow p+X)}=(4.5\pm0.6\pm1.5)\cdot10^{-2}$$



It seems that there are data in the CLAS archive to do this much better.

Even better job can be done at 11 GeV using different various setups

☞ *Searching/discovering baryonic nonnucleonic degrees of freedom in nuclei*

(a) Knockout of Δ^{++} isobar in $e+{}^2H \rightarrow e+ \ forward\ \Delta^{++} + \ slow\ \Delta^{-}$

$$e+{}^3He \rightarrow e+ \ forward\ \Delta^{++} + \ slow\ nn$$

Sufficiently large Q are necessary to suppress two step processes where Δ^{++} isobar is produced via charge exchange. Can regulate by selecting different x - rescatterings are centered at x=1.

(b) Looking for slow (spectator) Δ's in exclusive processes with ^{3}He

Another possibility for 12 GeV, study of x_F *≥0.5 production of Δ− isobars (slow* Δ's in rest frame) *in* e+*D(A)*→e+ Δ +X. *For the deuteron one can reach sensitivity better than 0.1 % for* ΔΔ especially with quark tagging *(FS 80-89)*

(c) $e+{}^2H \rightarrow e+ \ forward\ N + \ slow\ N^*$

(d) Measure G_E/G_M as a function of nucleon momentum for SRC in deuteron, extending current ^{4}He measurements to k > 400 MeV/c

QCD with nuclei

Color transparency (CT) phenomenon plays a dual role:

- 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
relevant for interpretation of RHIC AA data

Basic tool of CT: suppression of interaction of small size color singlet configurations.

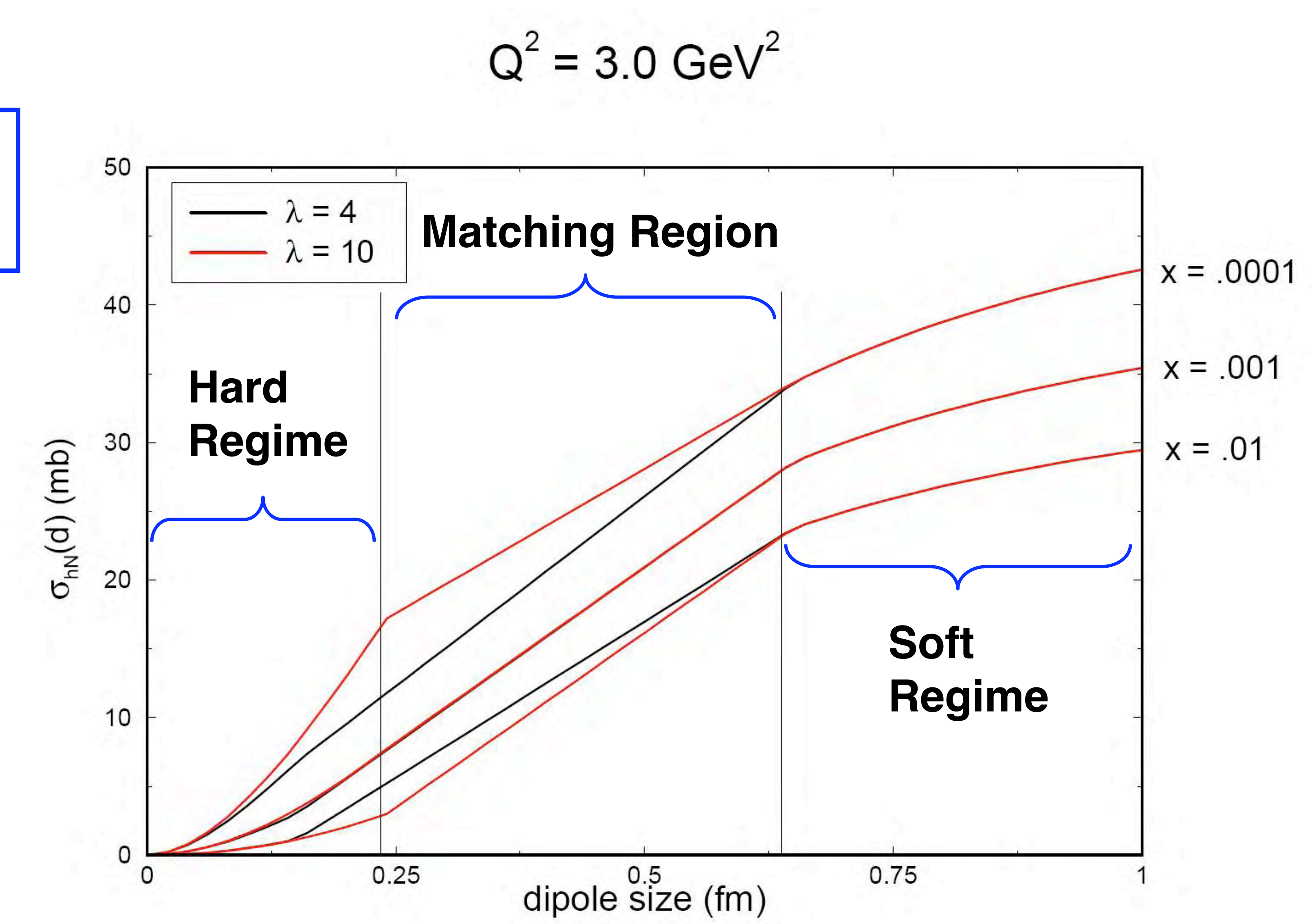
For a dipole of transverse size d:

$\sigma = cd^2$ *in the lowest order in* α_s *(two gluon exchange F.Low 75)*

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

$$\left. +2/3 x_N S_N(x_N, Q^2_{eff})\right]$$

Maybe important at Jlab energies



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

(Baym et al 93, FS&Miller 2000)

ABC of CT: squeeze and freeze

Squeezing: *(a) high energy CT*

✳ Select special final states: diffraction of pion into two high p_t jets: $d_{q\bar{q}} \sim 1/p_t$

✳ Select a small initial state: γ^*_L - $d_{q\bar{q}} \sim 1/Q$ in $\gamma^*_L + N \rightarrow M + B$

QCD factorization is valid for these processes with the proof based on the CT property of QCD

(b) Intermediate energy CT

* Nucleon form factor
* γ^*_L (γ^*_T ?)+ $N \rightarrow M + B$
* Large angle (t/s = const) two body processes: $a + b \rightarrow c + d$

Freezing: ***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)

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

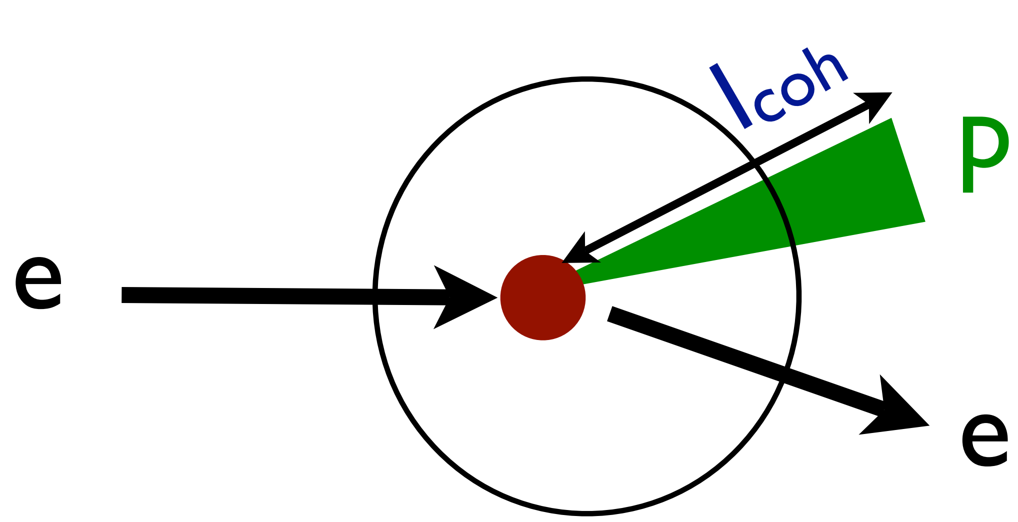
$$\sigma^{PLC}(Z) = (\sigma_{hard} + \frac{Z}{l_c}[\sigma - \sigma_{hard}])\theta(l_c - Z) + \sigma\theta(Z - l_c)\,.$$

Quantum Diffusion model of expansion

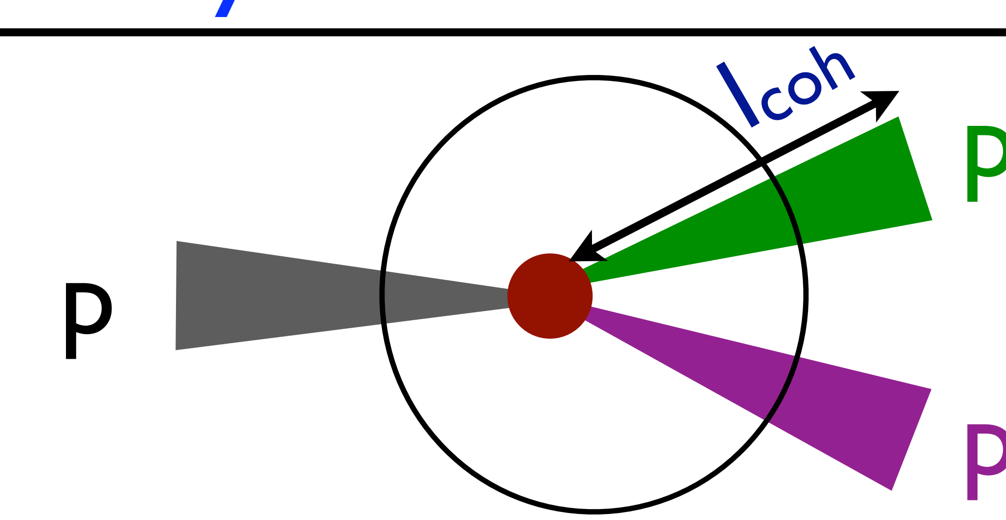
$l_{coh} \sim (0.3- 0.4)$ fm p_N[GeV]

actually incoherence length

MC at RHIC assume much larger l_{coh}



eA→ ep (A-1) at large Q



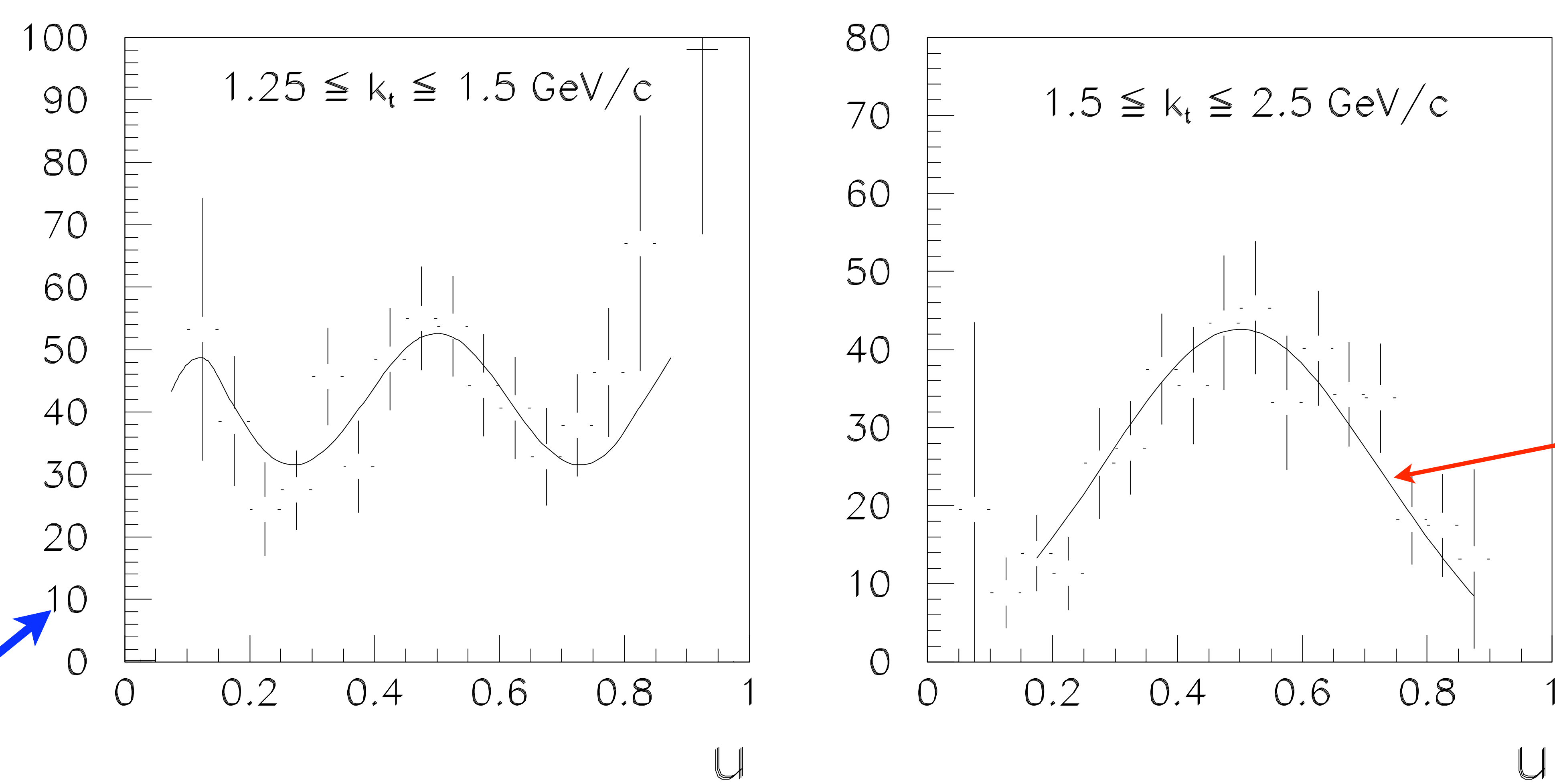
pA→ pp (A-1) at large t and intermediate energies

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

High energy color transparency is well established

At high energies weakness of interaction of point-like configurations with nucleons - is routinely used for explanation of DIS phenomena at HERA.

First experimental observation of high energy CT for pion interaction (Ashery 2000): $\pi + A \to$"jet"+"jet" $+A$. Confirmed predictions of pQCD (Frankfurt ,Miller, MS93) for *A-dependence, distribution over energy fraction, u carried by one jet, dependence on p_t(jet), etc*



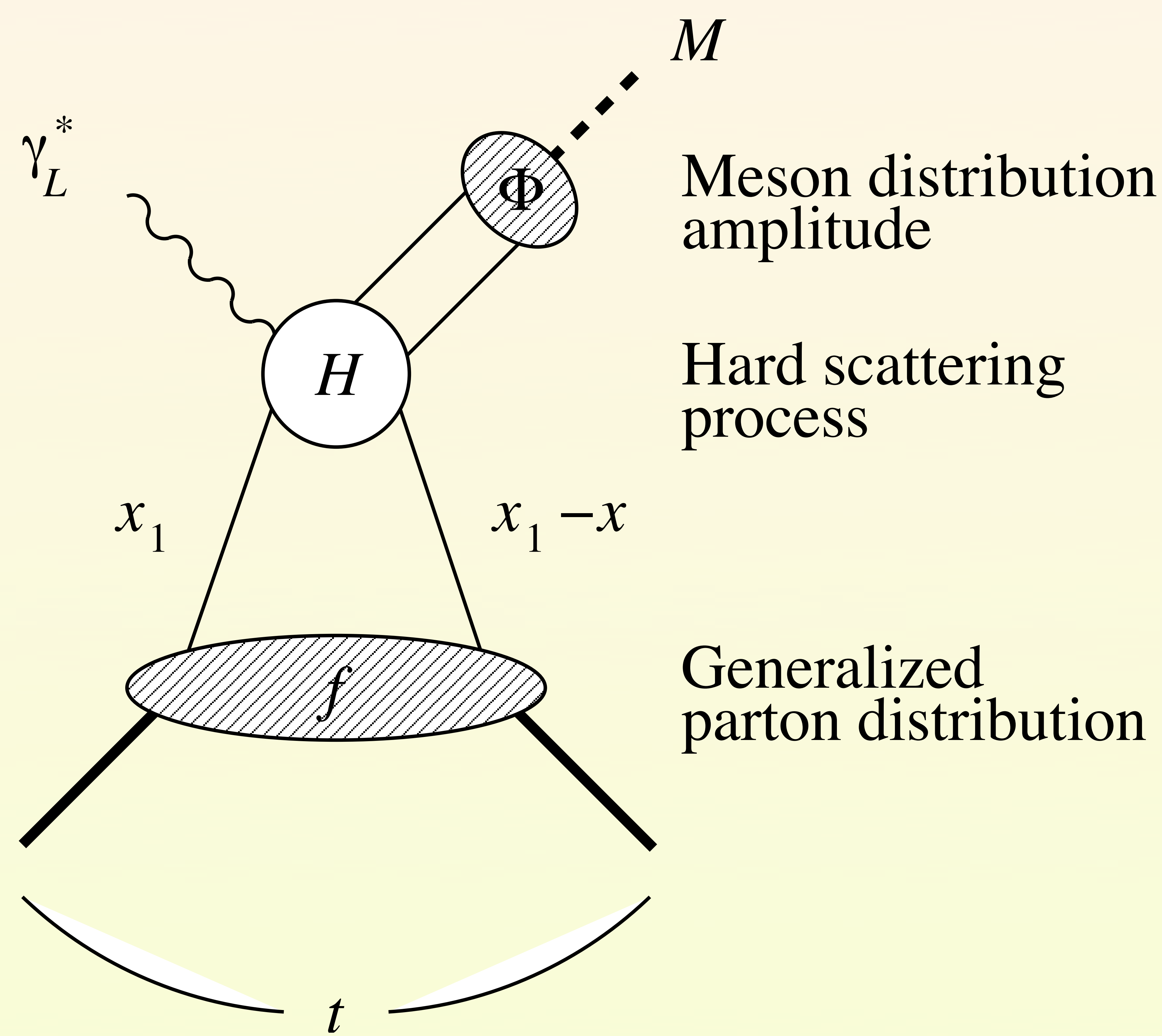
prediction

(π wave funct)^2

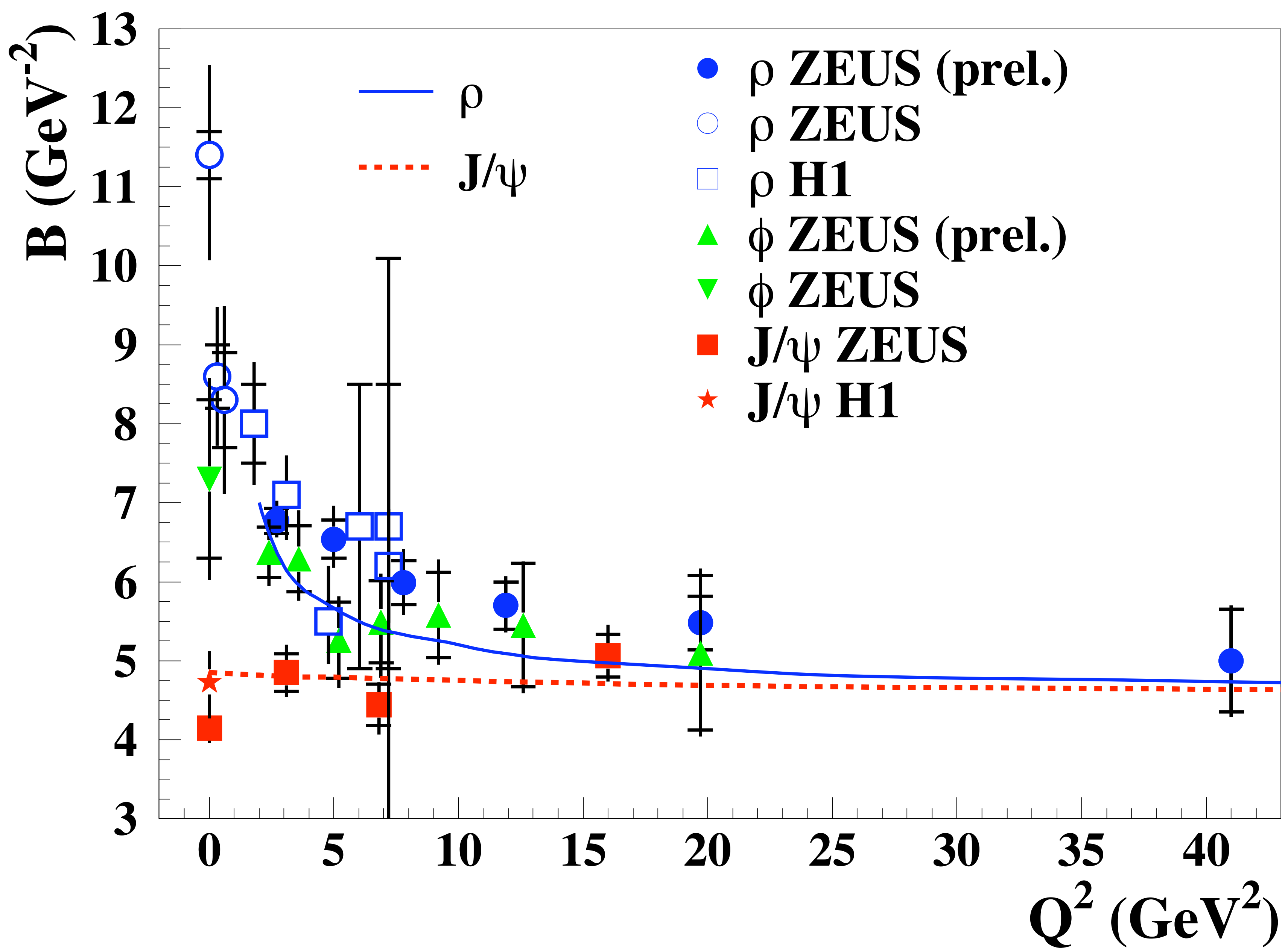
Squeezing occurs already before the leading term (1-z)z dominates!!!

$$Q^2(\pi\ f.f.) \sim 4k_t^2(jet)$$
$$\Downarrow$$
strong squeezing in π form factor for Q^2=6 GeV^2

QCD factorization theorem for DIS exclusive meson processes (Brodsky,Frankfurt, Gunion,Mueller, MS 94 - vector mesons,small x; general case Collins, Frankfurt, MS 97). The prove is based (as for dijet production) on the CT property of QCD not on closure like the factorization theorem for inclusive DIS.



Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite transverse size effects explain key elements of high Q^2 data.



$$\frac{B(Q^2)-B_{2g}}{B(Q^2=0)-B_{2g}} \sim \frac{R^2(dipole)}{R_\rho^2}$$

Convergence of the t-slopes, B ($\frac{d\sigma}{dt}=A\exp(Bt)$), of ρ-meson electroproduction to the slope of J/psi photo(electro)production - **direct proof of squeezing**

$$\frac{R^2(dipole)(Q^2\geq 3GeV^2)}{R_\rho^2} \leq 1/2$$

- 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 $x \sim 10^{-2}$)

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, exclusive meson production.

☛ $l_{coh} = (0.3 \div 0.4 \text{ fm}) \, p_h$ [GeV] ➔ p_h=6 GeV corresponds $l_{coh} = 2$ fm $\sim 1/\sigma_{NN}\rho_0$

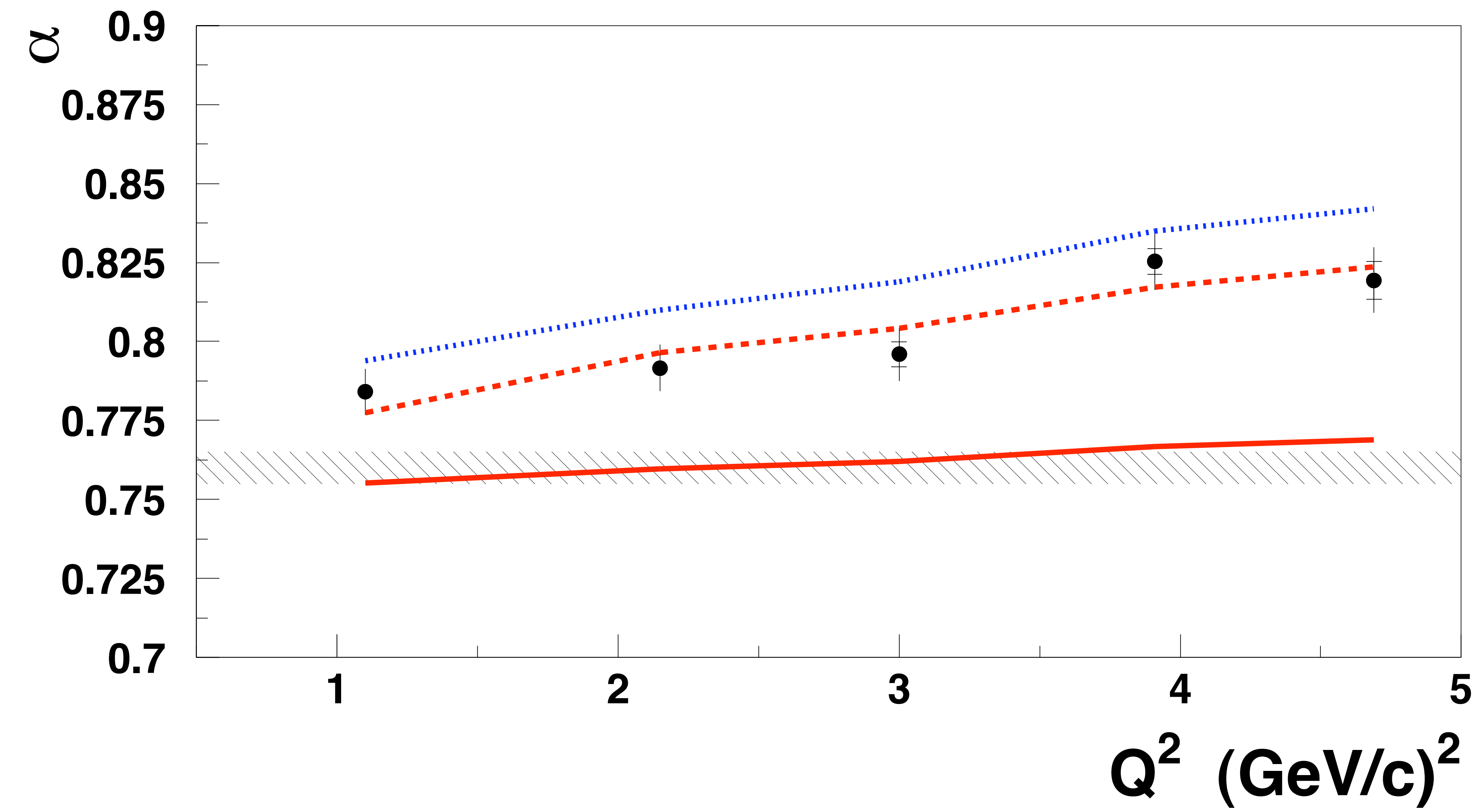
need high energies to see large CT effect even if squeezing is effective at lower energies

Experimental situation

- Energy dependence of transparency in (p,2p) is observed for energies corresponding to $l_{coh} \geq$ 2 fm. Such dependence is impossible without freezing. But not clear whether effect is CT or something else? Needs independent study.

- $\gamma^* + A \to \pi A^*$ evidence for increase of transparency with Q - Dutta's talk

Note that elementary reaction for Jlab kinematics is dominated by ERBL term so γ^* N interaction is local. γ^* does not transform to $q\bar{q}$ distance $1/m_N x$ before nucleon



VM production

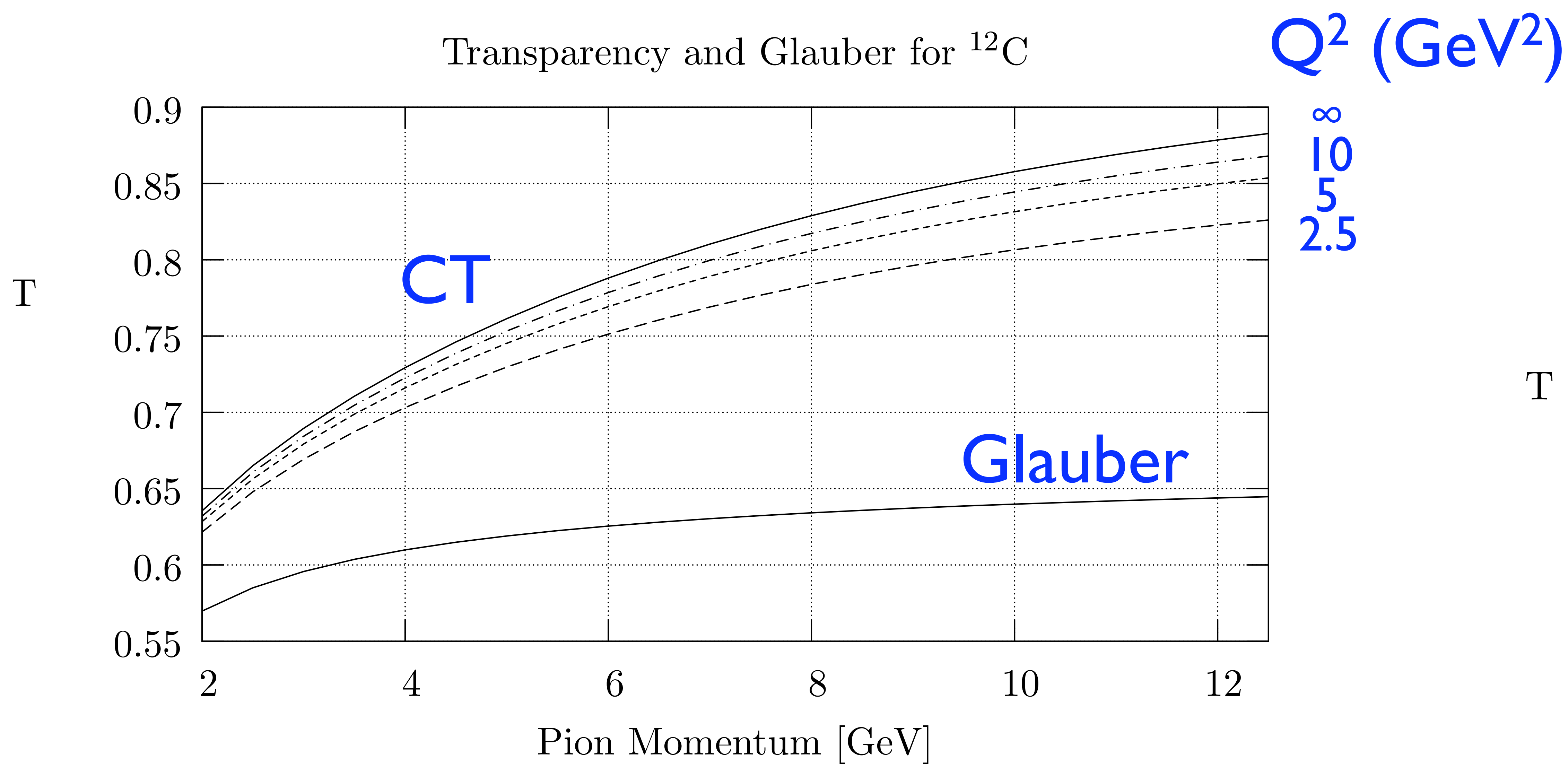
- CT is observed for $\gamma + A \to J/\psi + A$ at FNAL (Sokoloff et al)

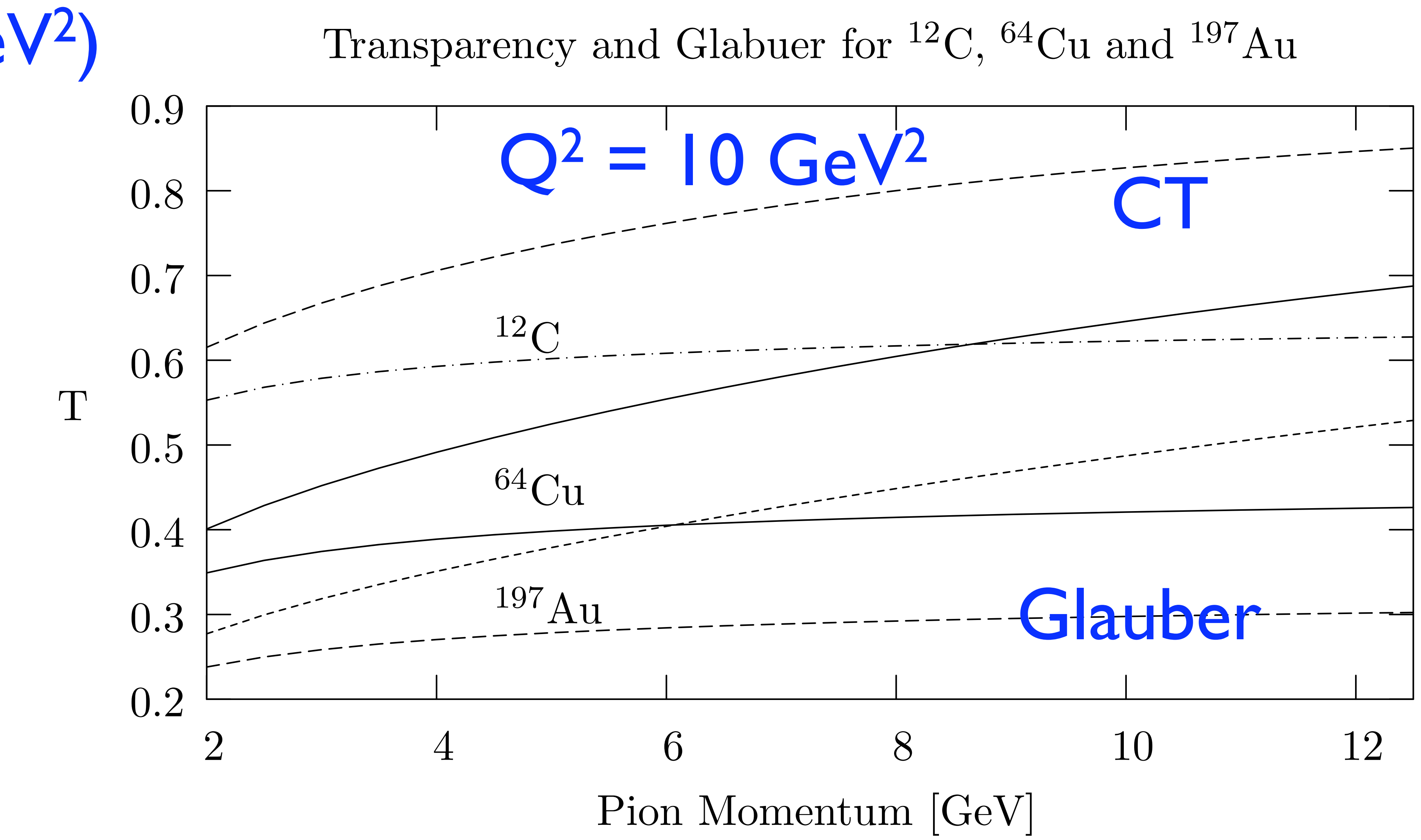
- ρ -meson production at high energies - inconclusive - some evidence in incoherent scattering - E665, HERMES - missing energy is significant - hadrons can be produced - in principle a different type of process.

Jlab energies - 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 experimental data have a sufficiently tight cut on missing energy - they are still analyzed.

Future directions for meson CT studies

Gain in energy of a factor of two even for the same Q^2 should greatly improve freezing and hence amplify the effect





Diffusion model predictions (Larson, Miller, MS 06)

For large l_{coh} the CT effect is larger for heavy nuclei. Larger sensitivity to expansion than to degree of squeezing as soon as it is large enough.

Study of CT for meson production is a key component of justifying using meson production in at Jlab 12 for the GPD studies. If there is no squeezing - no chance to use even ratios of the cross sections or polarizations

Resonance / continuum A-dependence

For small l_{coh} final state is produced inside the nucleus. Compare say

$$T(\gamma^* + A \to \pi^+\pi^-(nonresonance) + A^*) \text{ vs } T(\gamma^* + A \to \pi^+(\rho) + A^*)$$

Expect that for moderate l_{coh} (*opacity regime*) resonances / background enhanced!!!

Revealing mechanism of two body processes like $\gamma(\gamma^*) + N \rightarrow \gamma(\pi) + N$

Question: at what t the processes become hard?

Two levels: (*a) transition from VDM photon to point-like photon at* $t=t_0$

(b) squeezing of the produced hadrons

(a) A rather fast change of A-dependence from $A^{1/3}$ to $A^{2/3}$

(b) A relatively slow change of A-dependence

G.Miller and MS

low transverse momentum transfer $|-t|$

$$T_{\rm Low}(A) = \int d^2b \int_{-\infty}^{\infty} dz \rho(b,z) e^{-\sigma_{\rho N}\int_{-\infty}^{z} dz' \rho(b,z')} e^{-(\sigma_{\pi N}+\sigma_{NN})\int_z^{\infty} dz' \rho(b,z')}$$

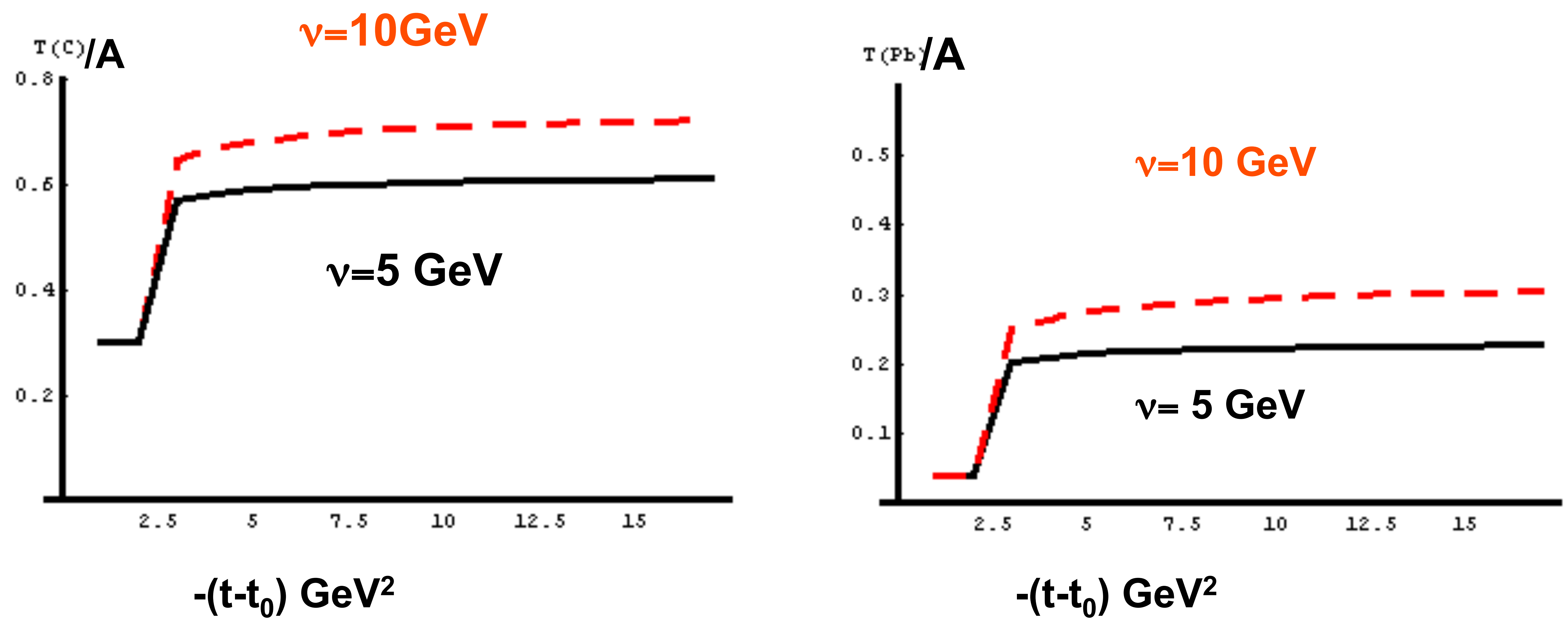
$$T_{\rm Low}(A) \propto A^{1/3}$$

High transverse momentum transfer $|-t|$

$$T_{\rm High}(A) = \int d^2b \int_{-\infty}^{\infty} dz \rho(b,z) 1 e^{-(\sigma_{\pi N}+\sigma_{NN})\int_z^{\infty} dz' \rho(b,z')}$$

$$T_{\rm High}(A) \propto A^{2/3}$$

$\gamma N \rightarrow \pi N$ Transparency vs. A, ν



Interesting to study also as a function of Q.

(Virtual) Compton scattering - screening for low Q low t as for pion - nucleus interaction. At what Q/t does transition occurs from hadronic to quark degrees of freedom?

Dynamics of the nucleon form factor

Until condition is met

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

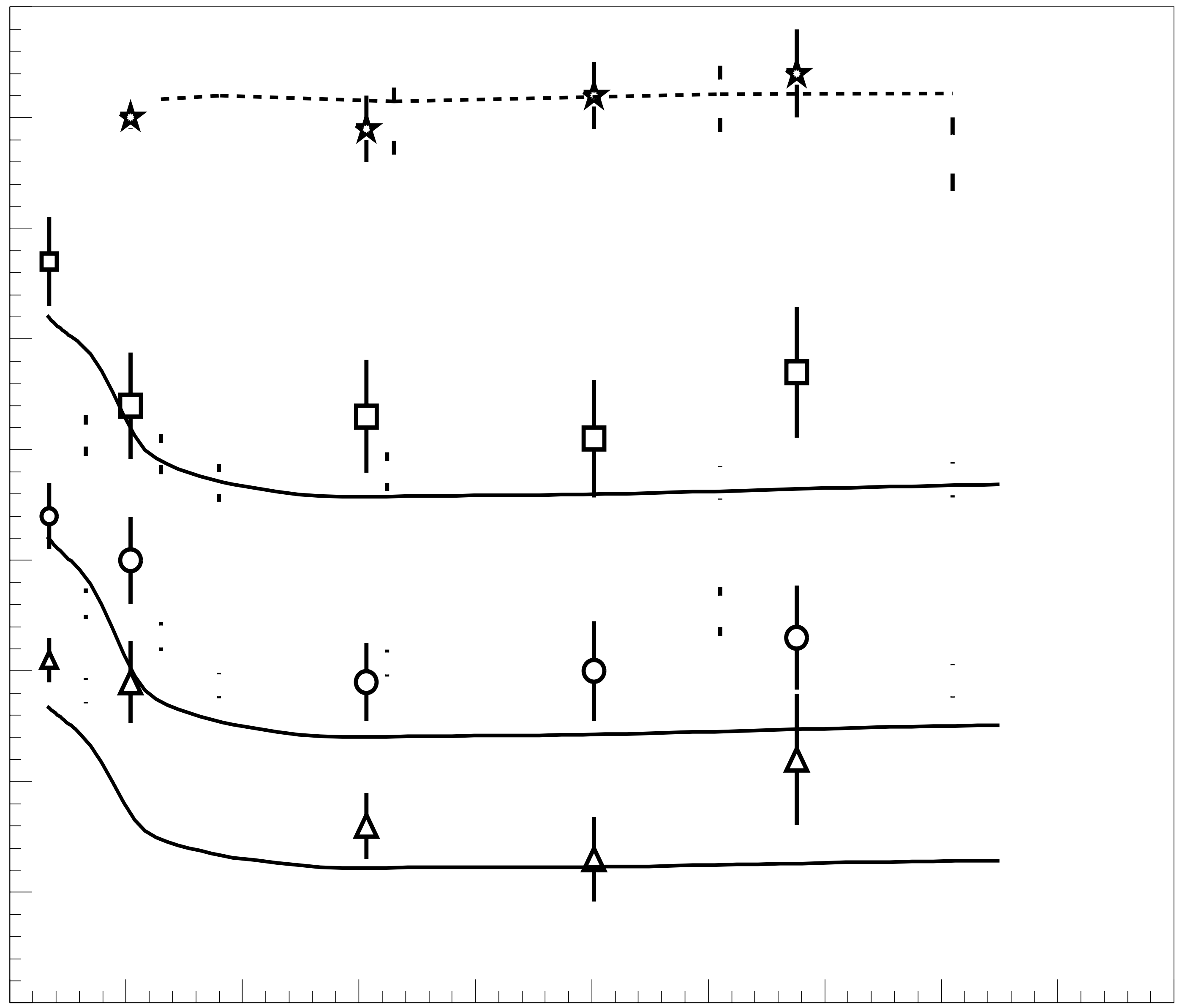
CT should remain small (independent of whether squeezing exists at all)

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

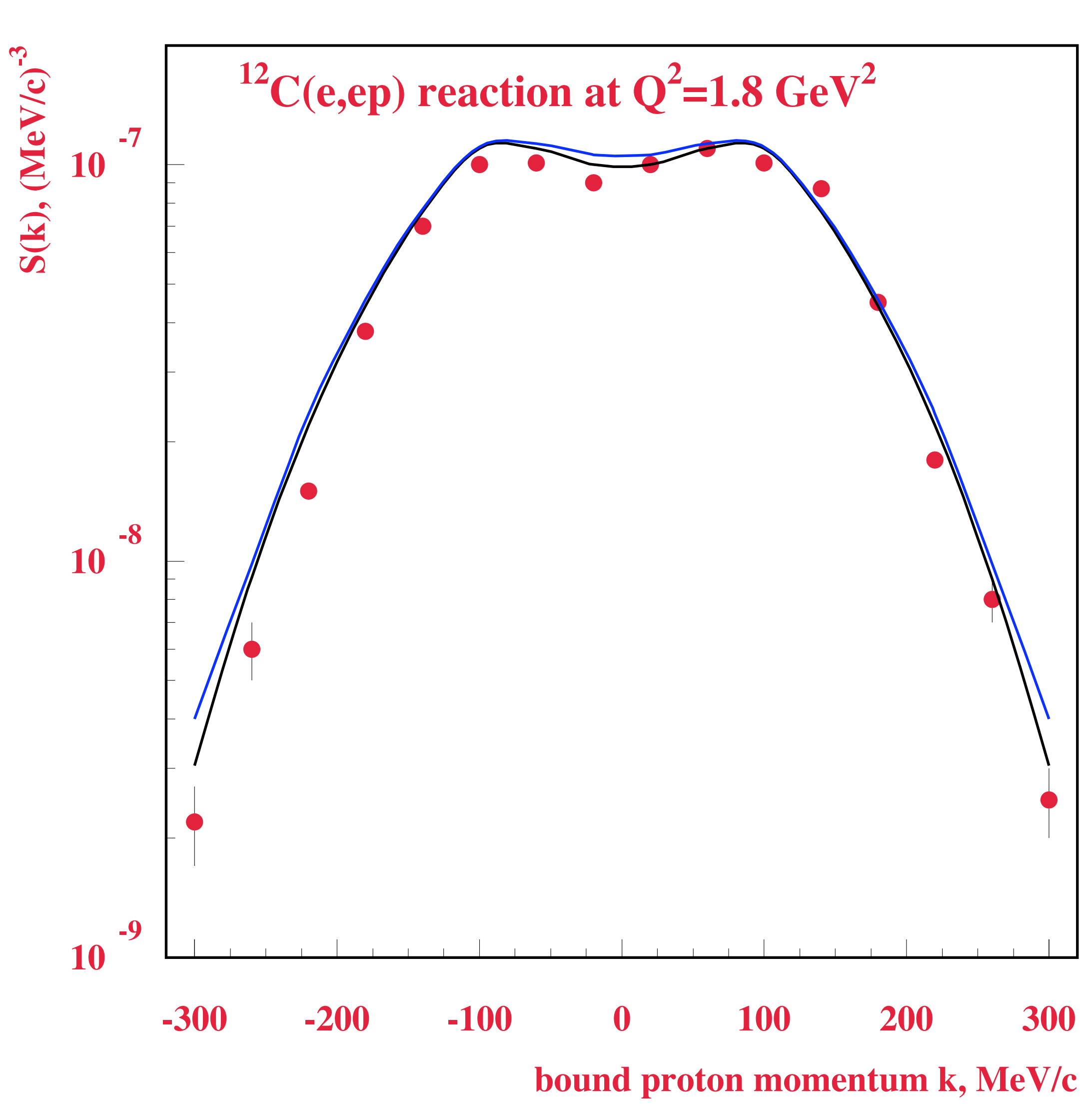
K.Garrow et al 02

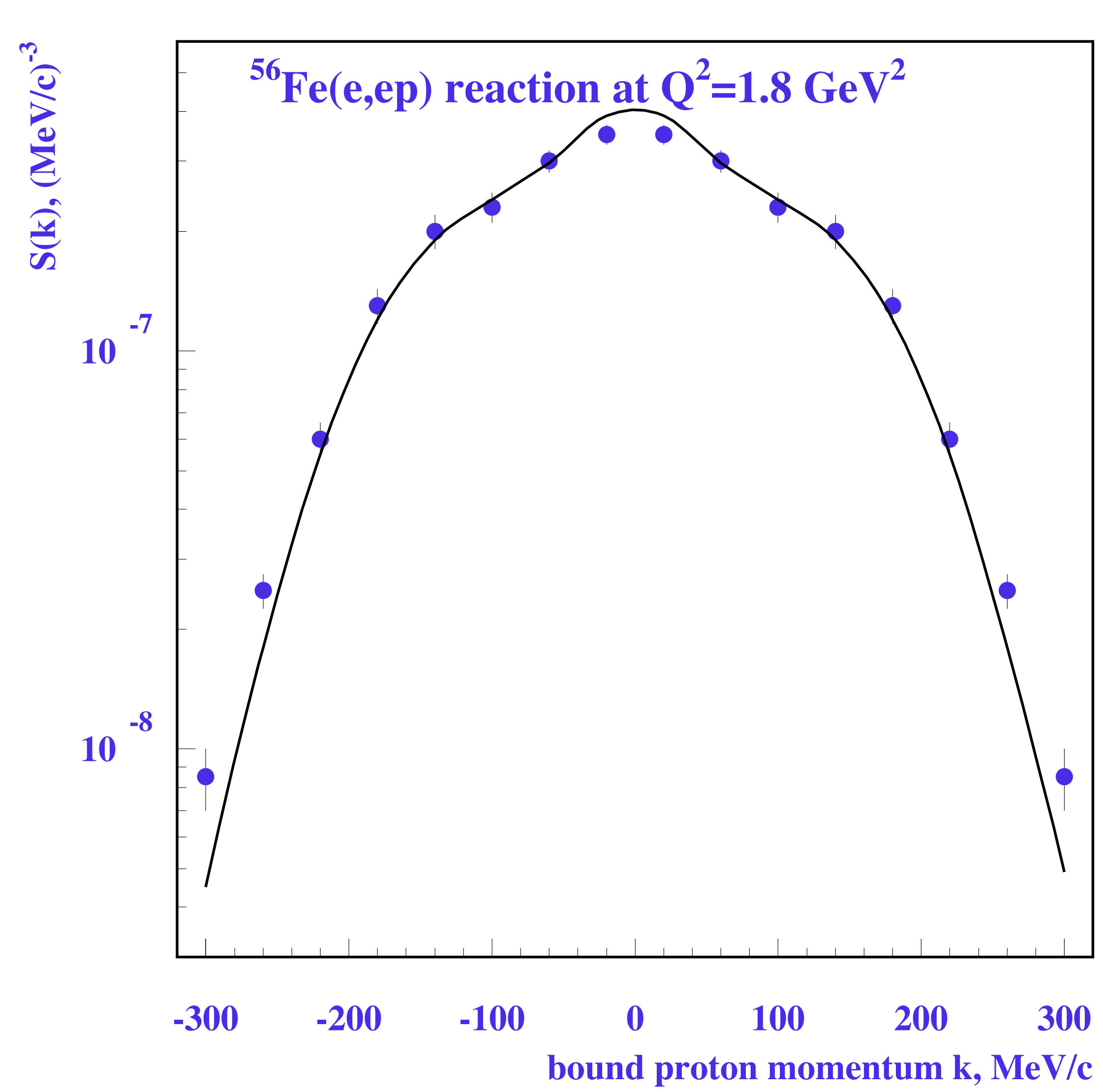


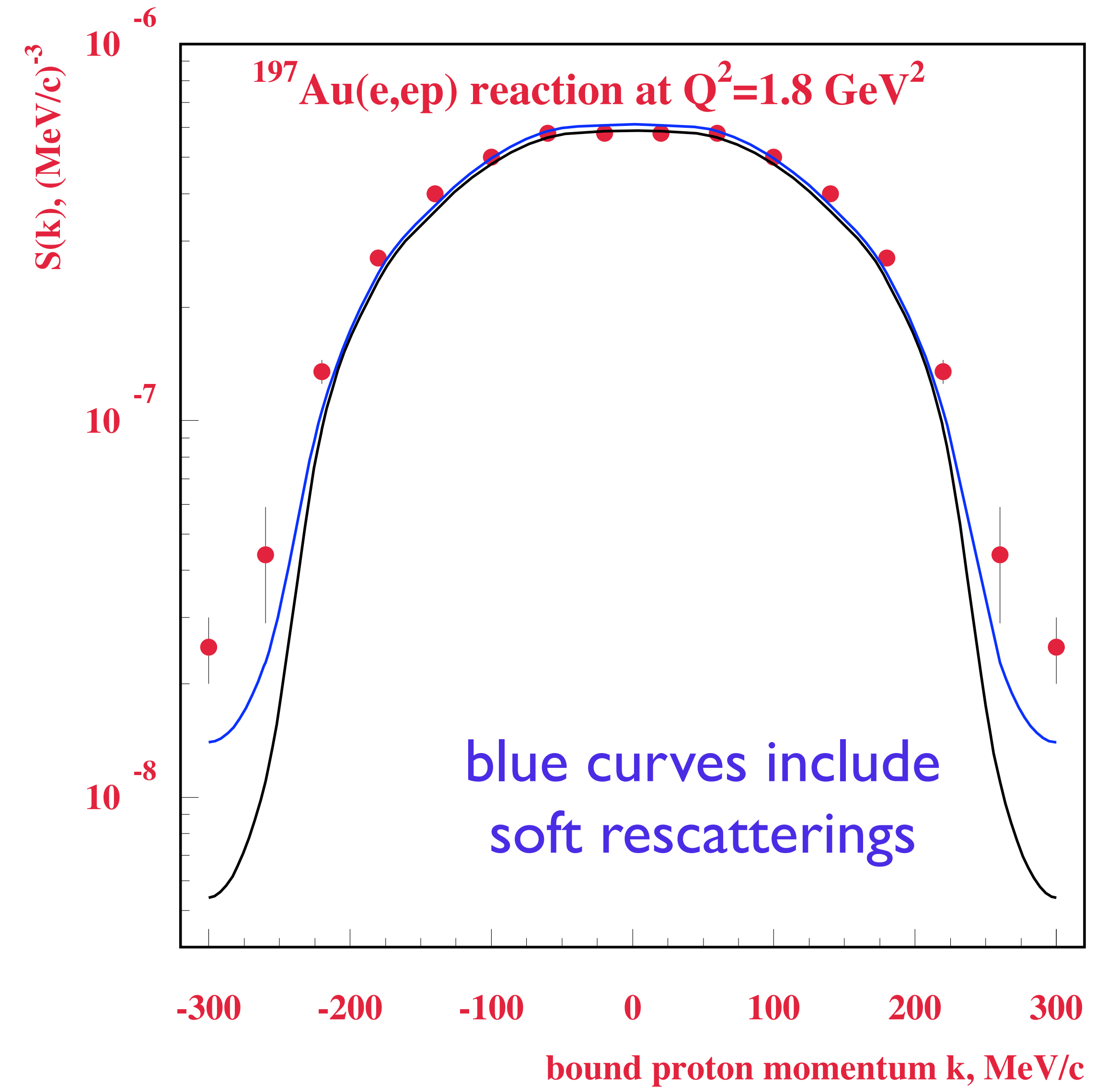
[26] H. Gao, V.R. Pandharipande, and S.C. Pieper (private communication); V.R. Pandharipande and S.C. Pieper, Phys. Rev. C **45**, 791 (1992).

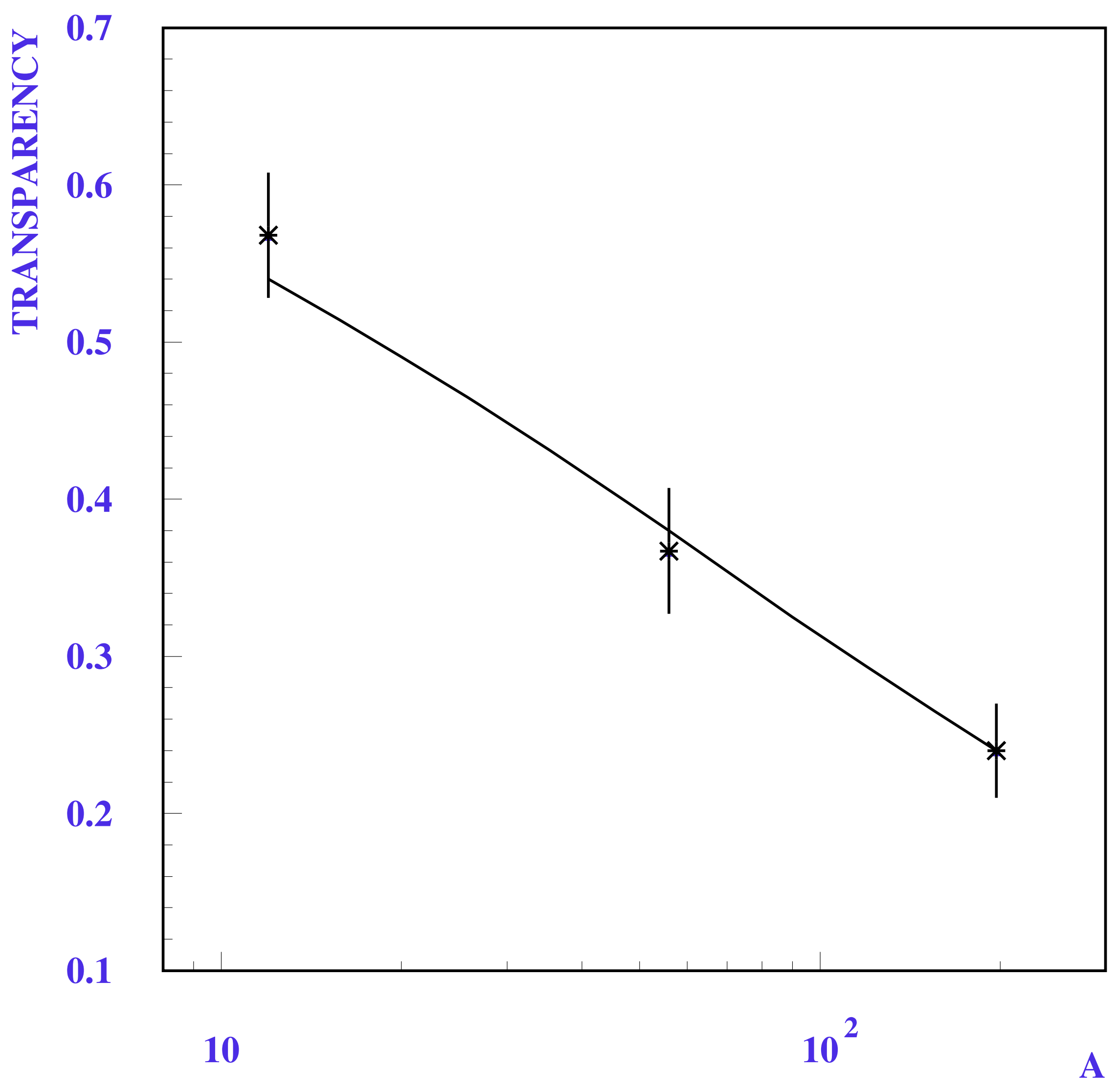
Discrepancy with Glauber calculation is typically 30% for heavy nuclei???

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)

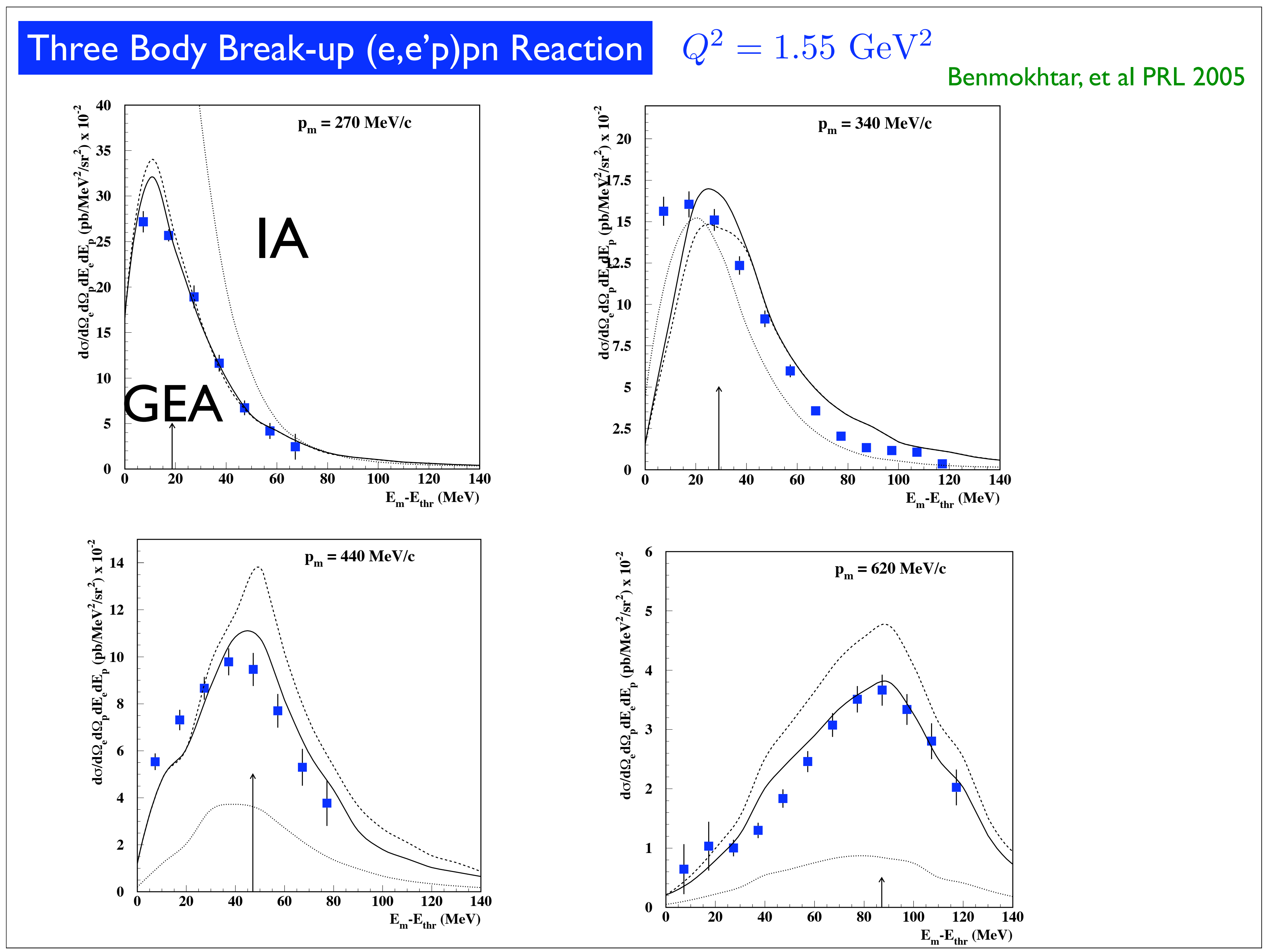
Need data on (e,e'p) for small k and large E_r and Q^2 ~ 2 GeV^2

Alternative possibility - 10-15% chiral transparency effect

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 Schiavilla et al and Perugia group

Since distances in the rescatterings are < 2 fm, freezing condition is by far less demanding. Rather easy to select the proper channel like $e^2H \rightarrow epn$ using just two high energy spectrometers. Issue - chose kinematics were contribution of Δ-isobar intermediate states is small.

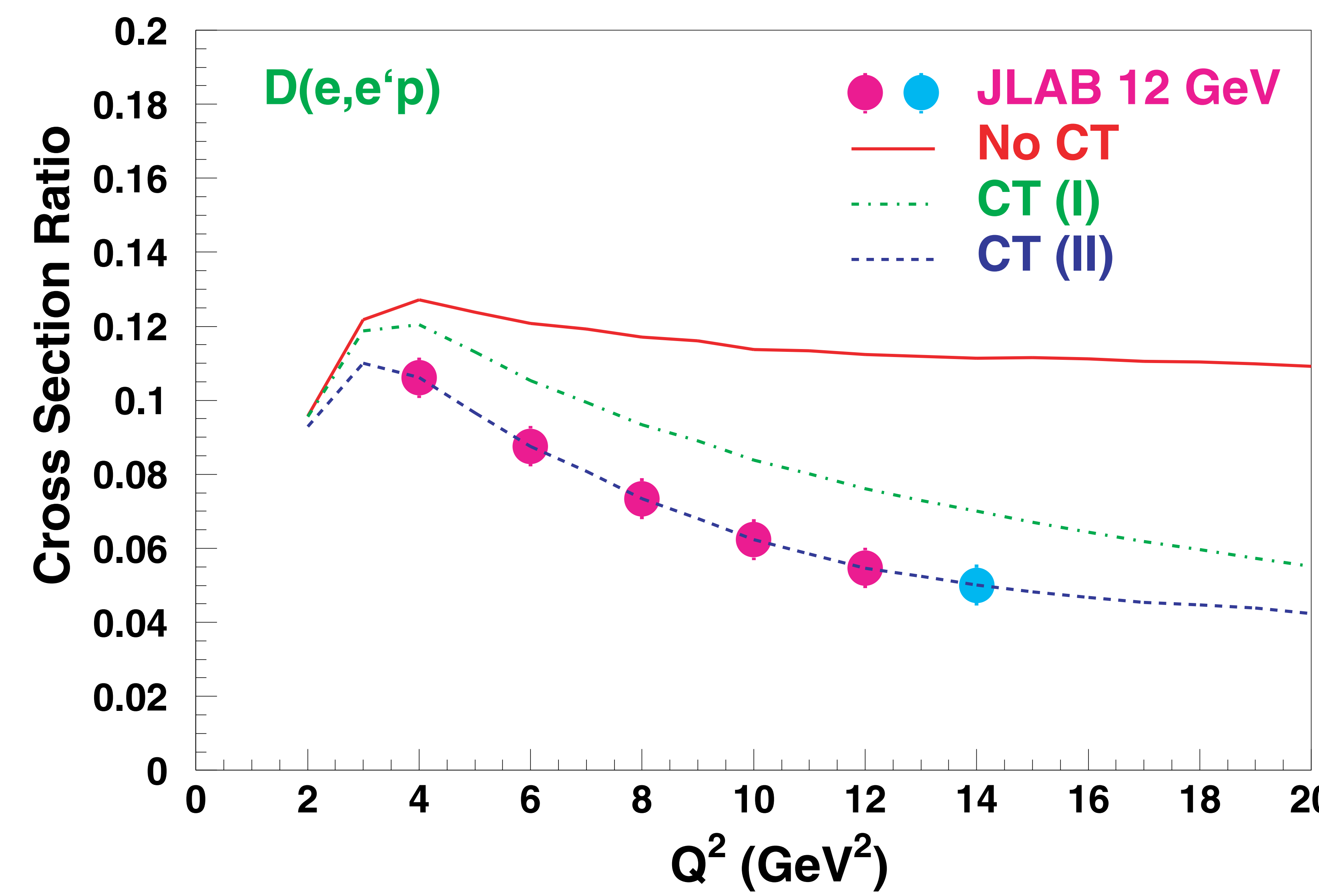
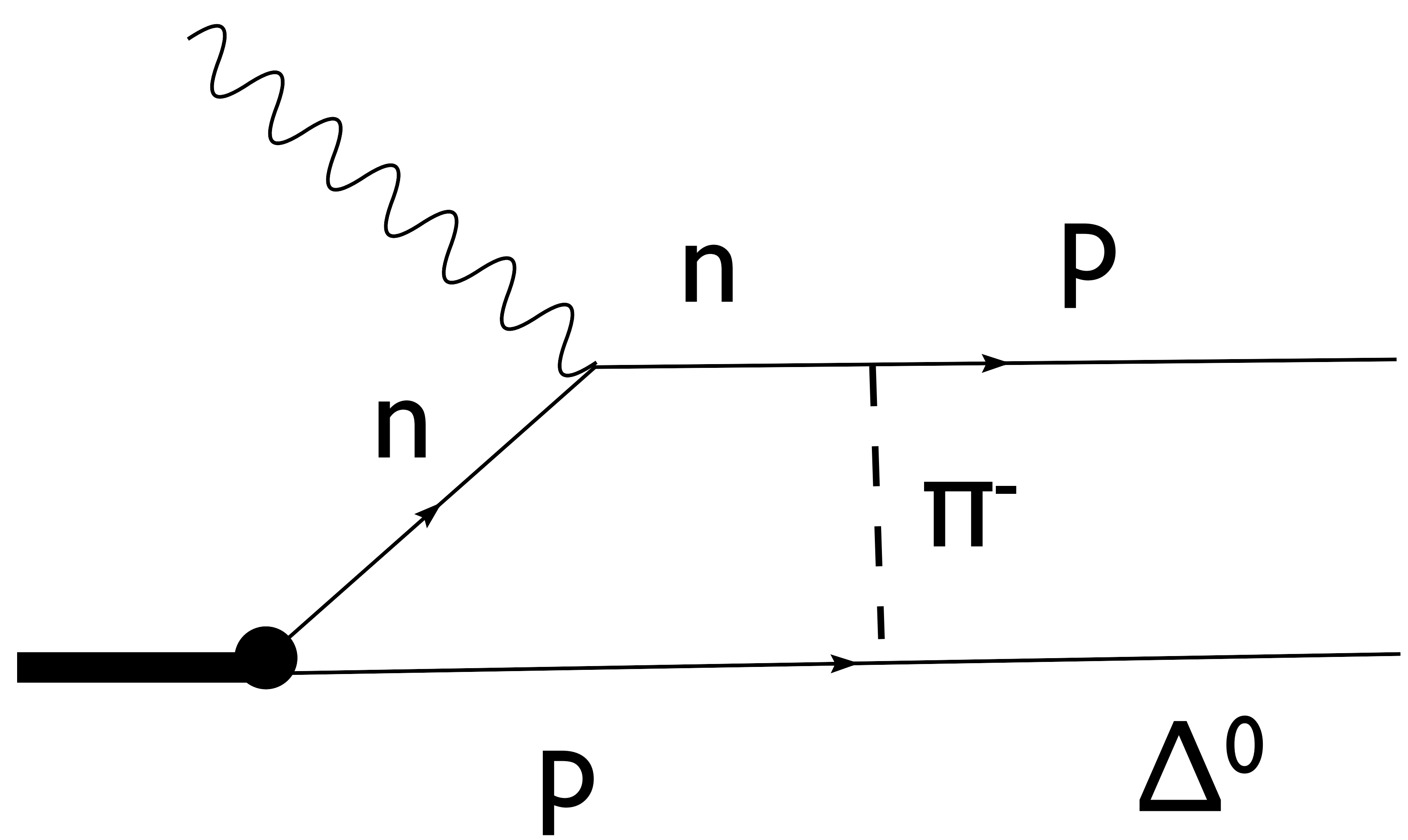


Figure 15. The ratio of the cross section at 400 MeV/c missing momentum to the cross section at 200 MeV/c as a function of Q^2. The solid line corresponds to the GEA prediction. The dashed and dash-dotted lines represent the quantum diffusion model of CT with $\Delta M^2 = 0.7$ and 1.1 GeV^2, respectively. The drop with Q^2 in the colour transparency models comes from a reduction in the rescattering of the struck nucleon, which is the dominant source of events with $p_m > k_F$.

As nucleon is a more complex system than mesons it is natural before looking for color transparency search for effects of "Chiral transparency" - pion cloud contribution becomes negligible in the nucleon form factor at $Q^2 > 1$ GeV^2

Example I: at large Q charge exchange processes should be suppressed (LF& H.Lee, Miller, Sargsian, MS- 97).



Example II: Chiral dynamics in production of pions near threshold

Large Q reaction γ^* N → Nπ for $M_{N\pi} - M_N - M_\pi < M_\pi$

Cross section is related to nucleon f.f. using chiral rotation and explains the SLAC data

Pobylitsa, Polyakov, MS 2001

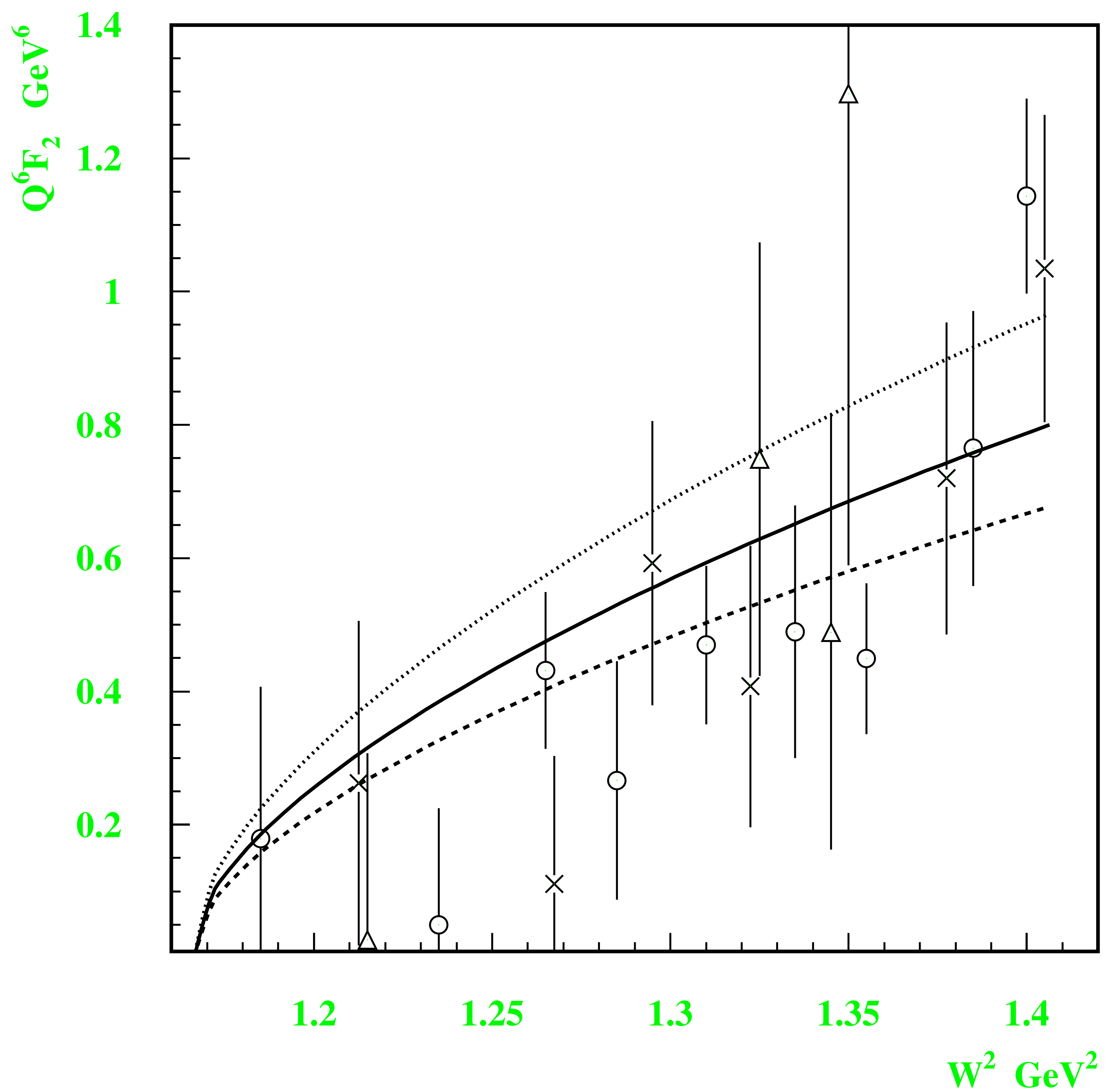


FIG. 2. Values of $F_2^p(W, Q^2)$ scaled by Q^6 as a function of W^2. The data of the E136 experiment are at average Q^2 values of 9.4, 11.8 (×), 15.5, 19.2 (○), 23, 26, and 31 (△) GeV^2. The theoretical predictions of the hSPT (18) at Q^2 = 10, 20, 30 GeV^2 are given by dotted, solid, and dashed lines respectively.

Physical picture: γ^* hits 3q configuration which later emits a pion. Time scale is likely to correspond to $l_{coh} > l_{coh}$(form factor) as only pion cloud is removed from nucleon.

- At $Q^2 \sim$ 5-7 GeV^2 the system which propagates through nucleus interacts with $\sigma \sim$ 40 mb not $\sigma = \sigma_{NN} + \sigma_{\pi N} \sim$ 70 - 80 mb

⇒ Large chiral transparency effect

Conclusions

Impressive experimental progress of the last three years -

Discovery of strong short range correlations in nuclei with strong dominance of I=0 SRC

- proves validity of strategy of use of high momentum transfer processes
- provides solid basis for further discoveries & more precise studies

A number of theoretical challenges including a) calculation of the decay functions, b) isotopic effects for SRC, c) isobars, d) relativistic effects, e) studies of FSI dynamics - optimizing for signal of SRC, understanding the role of CT effects (GEA - good starting point - need more tests of isobar FSIs)

Evidence for onset of CT in exclusive meson production - good news for GPD studies

Several experiments are under way/ been planned for 12 GeV will allow to probe many QCD aspects of large momentum transfer processes, need more coherence in the program & complementary studies using hadron beams.