Resolving microscopic structure of nuclei at 12 GeV: short range correlations and the origin of the EMC effect

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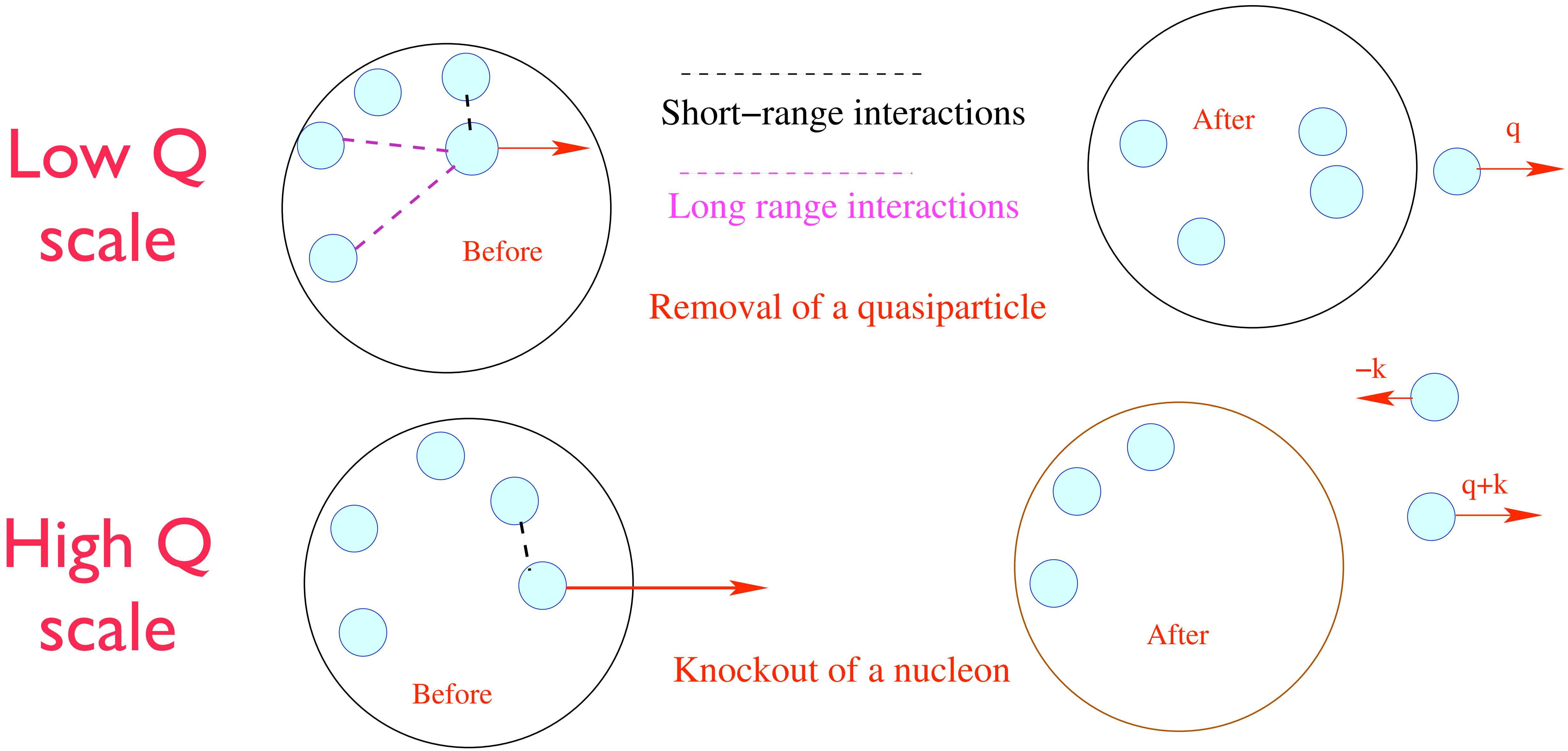
Based on the theoretical analyses performed together with

L.Frankfurt, C.Ciofi, M.Sargsian, M.Zhalov

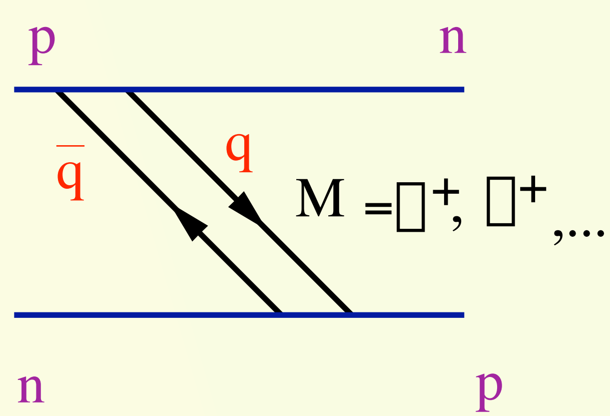
Workshop: The physics of nuclei with 12 GeV electrons. November 4, 2004

Experience of quantum field theory - interactions at different resolutions (momentum transfer) resolve different degrees of freedom - renormalization,.... No simple relation between relevant degrees of freedom at different scales.



Fundamental questions of microscopic quark-gluon structure of nuclei and nuclear forces

- Are nucleons good nuclear quasiparticles?
- Origin of intermediate and short-range nuclear forces: Do nucleons exchange mesons or quarks (gluons) ?



Meson Exchange

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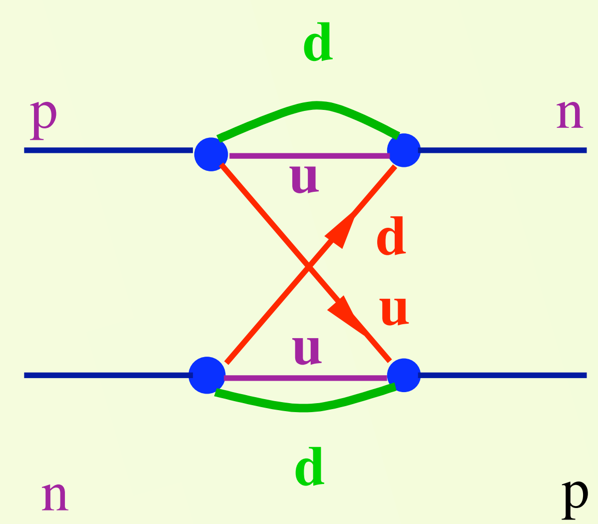
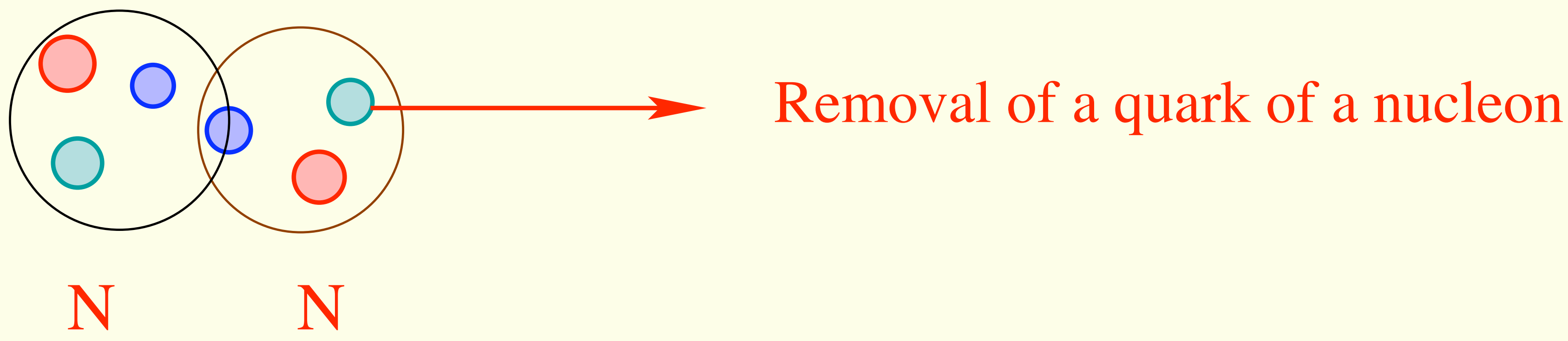
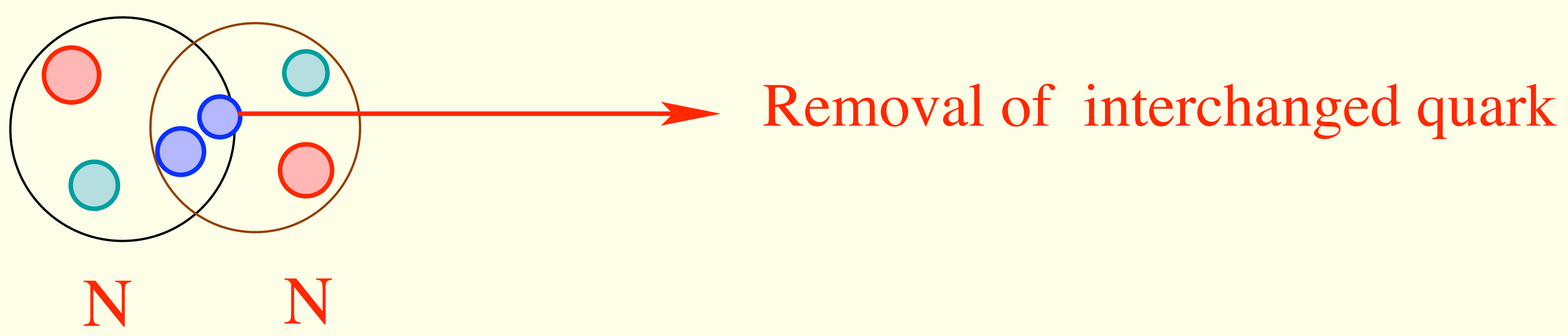


Quark interchange

Quark removal in the DIS kinematics





Three prong approach to the study of short-range correlations

Large Q, x>1
A(e,e') processes:
superfast quarks,
fast nucleons

$Q^2 \geq 2\ GeV^2$
$(e,e'N),(e,e'NN)$
Short-range nucleon cor.
bound N form fact.

Closure: can use all nuclei

Short-range few nucleon correlations in nuclei: quark-gluon & hadronic structure

Final state interactions: best to use A=2,3

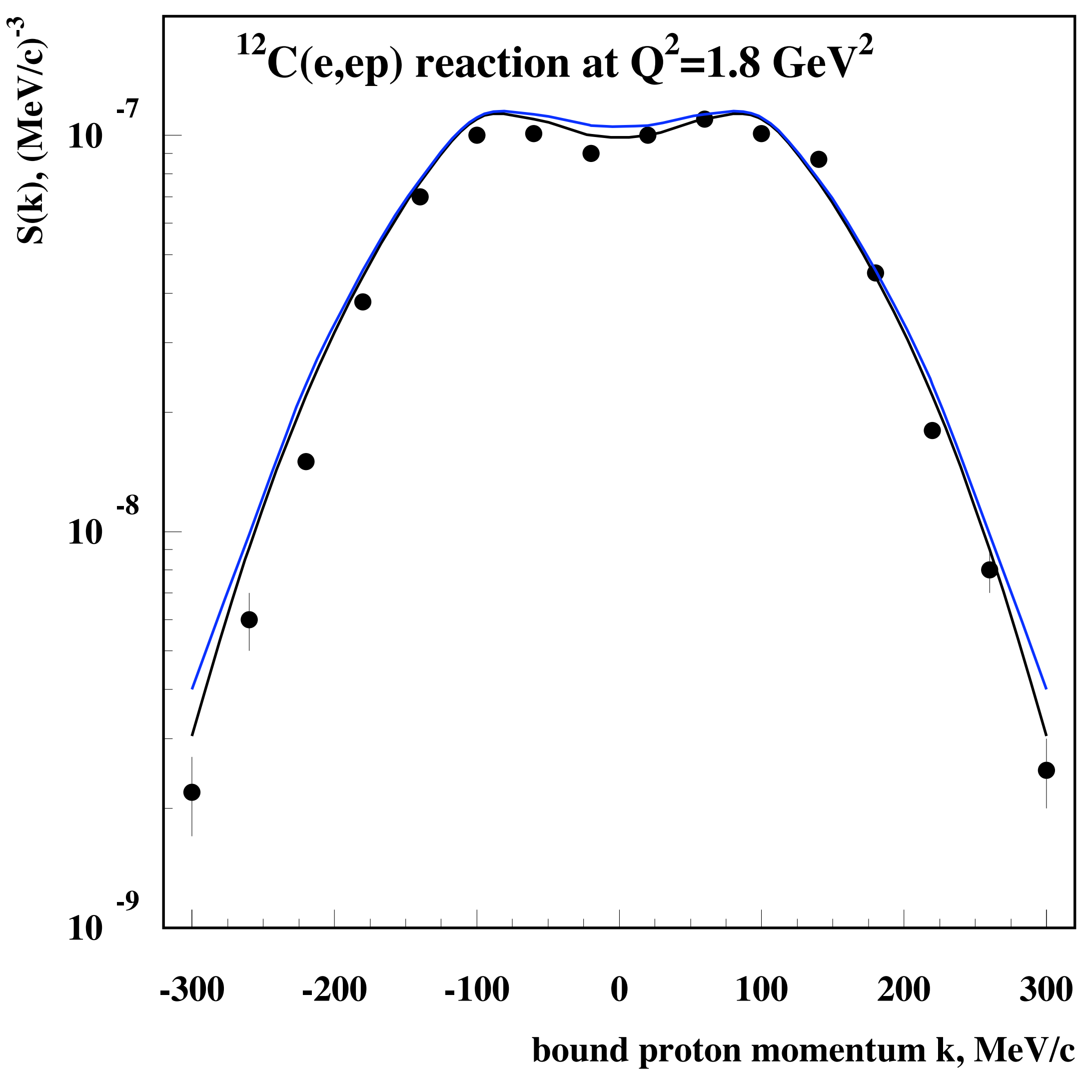
DIS processes
eA→e+backward N +X
Quark distribution in bound nucleon

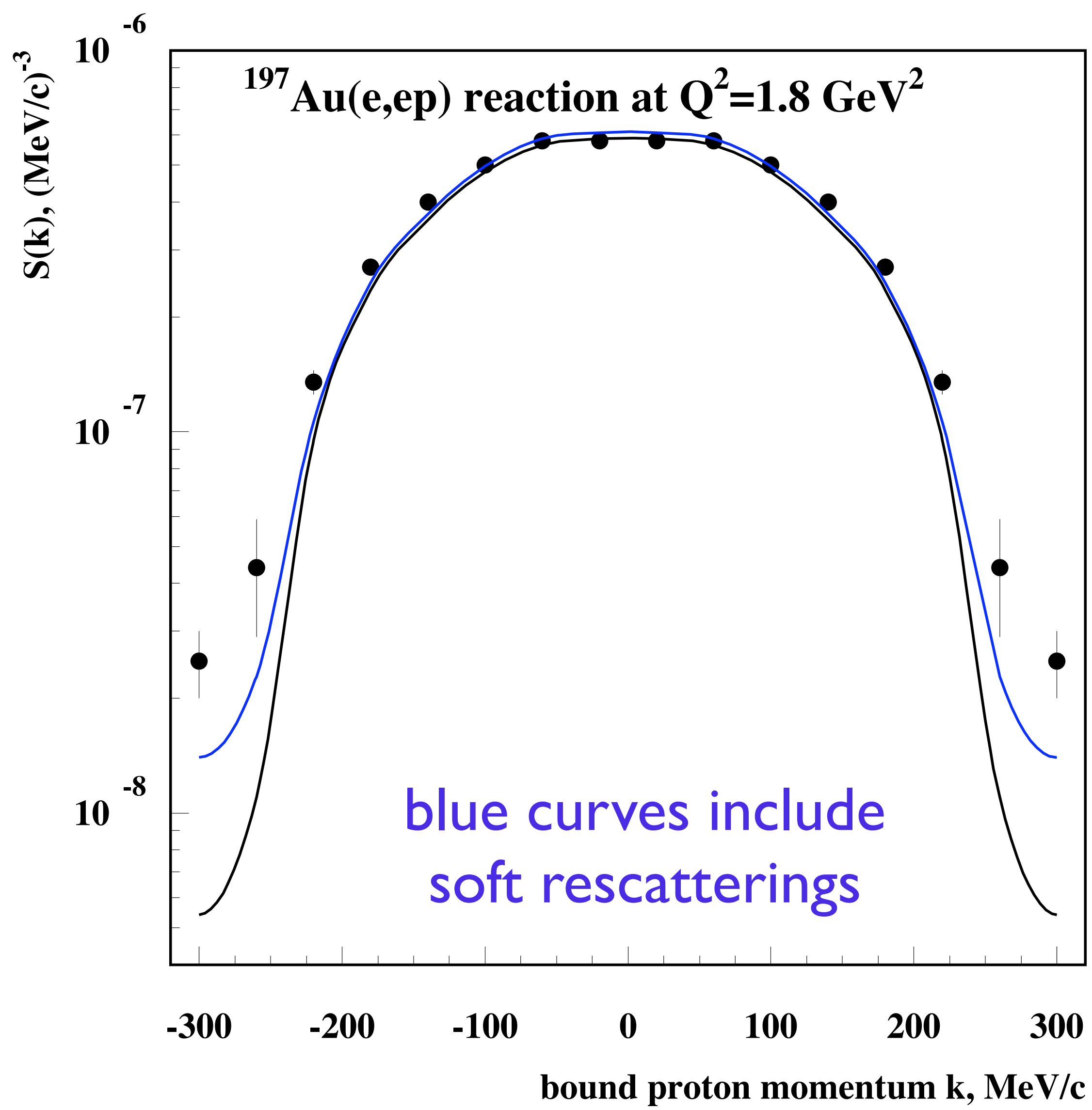
Before focusing on SRC, consider nucleons with momenta $< k_F$

Appear to be good quasiparticles - correct Q^2 dependence for $Q^2 \geq 2$ GeV^2 - data of JLab E91013 Collaboration

Open question: quenching, Q, - suppression as compared to realistic shell model

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





Expected theoretical accuracy of Glauber/eikonal for such Q^2 is better than ~5%

⇒ Q^2 dependence of quenching nucleon is a better quasiparticle at large Q^2

Opposite conclusion - Dickhoff et al suppression is independent of Q^2 : Q=0.7 .
Difference mainly due to use of the optical model on N-(A-1) interaction.

Explanation: Correlation move strength to large excitation energies.

In view of inherent uncertainties of interaction models which are at least 5%, it is hardly possible to measure directly quenching at large in Q^2 in a reliable way if it is $\leq 15\%$.

A much better way would be to perform measurements at $Q^2 = 2\ GeV^2$

for small nucleon momenta at high excitation energies. No reasons to expect similar high/low energy ratio as at low Q^2 if the change of the quenching is due to renormalization of interaction. Dickoff et al interpretation implies extra strength above shells:

$$\square(E_{A-1} > E_{shell})/\square(E_{A-1} < E_{shell}) \sim 0.4$$

Crucial for Color Transparency studies in A(e,e'p).

Short-range nucleon correlations (SRC)- considered to be an elusive feature of nuclear structure - Phys.Lett. rules of 1976 - reject claims to the opposite without review

Theorem: high momentum component of the nuclear wave function is not observable (Amado)

Theoretical analysis of F&S (75) : results from the medium energy studies of short-range correlations are inconclusive due to insufficient energy/momentum transfer leading to complicated structure of interaction (MEC,...), enhancement of the final state contributions.

Way out - use processes with large energy and momentum transfer:

$$q_0 \geq \ 500\ MeV \gg |V_{NN}^{SR}|,\ \vec{q} \geq 1\ GeV/c \gg 2\ k_F$$

Adjusting resolution scale allows to avoid Amado theorem.

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.

Our initial analysis (77-81) was based on analysis of the structure of the singularities of the many body Schrodinger eq, extension to relativistic case using light-cone (LC) formalism and analysis of the only process available at that time which could be due to SRC - production of fast backward nucleons and pions (+ deuteron form factor)

- Momentum dependence is weakly A-dependent since it it determined by singularities of the potential for $V_{NN} \quad \frac{1}{k^n} \; and \; \square(k) \quad \frac{V_{NN}}{k^2}$

- Average recoil energies are large and growing with momentum as $\langle E_{rec} \rangle \approx \frac{k^2}{2m_N}$

- Two-nucleon SRC dominate: 3N/2N ~ 20%. However kinematics exists where 3N dominate.

$$\int d^3k n_A(k) \square(k - k_F)_{|A\sim 200} \approx 0.25 \pm 0.05$$

- Light-cone density matrix, $\square_A^N(\square, p_\perp), \; A \geq \square \geq 0$ (α -light-cone fraction)

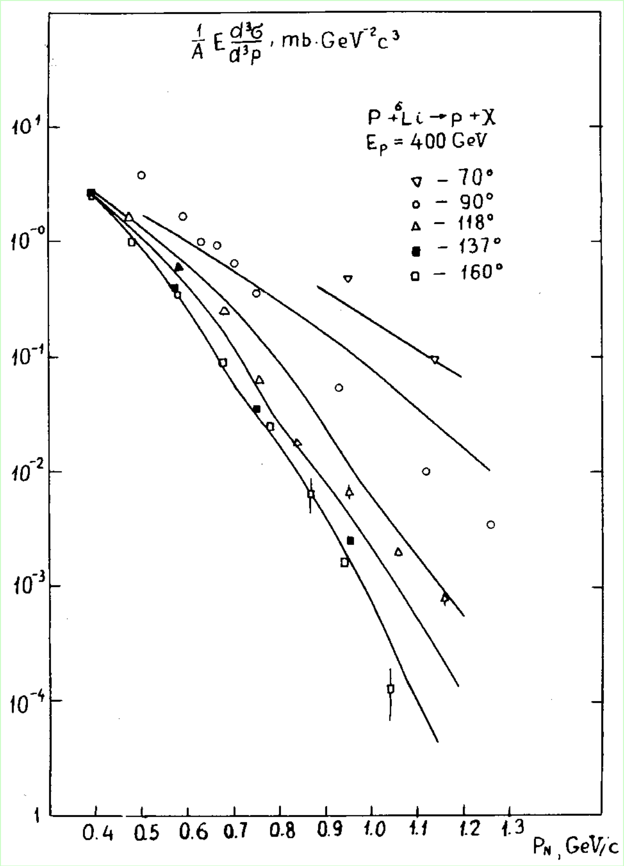
was found to be proportional to A=2 one

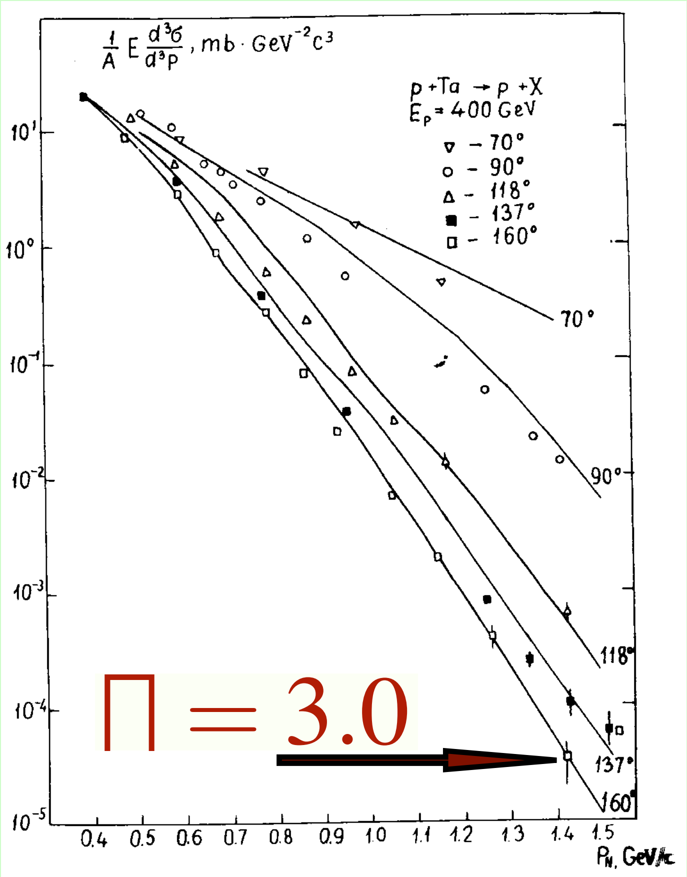
$$\square_A^N(\square, p_\perp) = a_2(A) \square_{^2H}^N(\square, p_t)_{|1.5 \geq \square \geq 1.25}$$

Two -nucleon SRC

$$\square_A^N(\square \geq 1.5, 0) \quad \exp(-7\square)$$

Three & Four nucleon SRC





Comparison of the FNC model with the 400 GeV data on the fast backward nucleon production.

The clean test of large value of SRC and dominance of two & three nucleon correlations is A(e,e') process at $x>1$, $Q^2>1$ GeV^2 due to *a possibility to use closure over the interactions with nucleons not belonging to FNC.*

Interplay of quasielastic (QE) and deep inelastic scattering:

$Q^2<5$ GeV^2 QE dominates - nucleon LC distribution is probed

$Q^2>10$ GeV^2 DIS dominates - superfast quark distribution is probed

QE: LC dominance on the level of elastic scattering off nucleons: the large Q^2 amplitude depends only on the LC fraction, α , carried by interacting nucleon - analog of the Bjorken x for a parton.

⇒ ***Possible to use closure in variables conjugated to*** α exactly as in DIS. Numerically OK

already for $Q^2>1.5$ GeV^2 (Day, Frankfurt, Sargsian, MS 93)

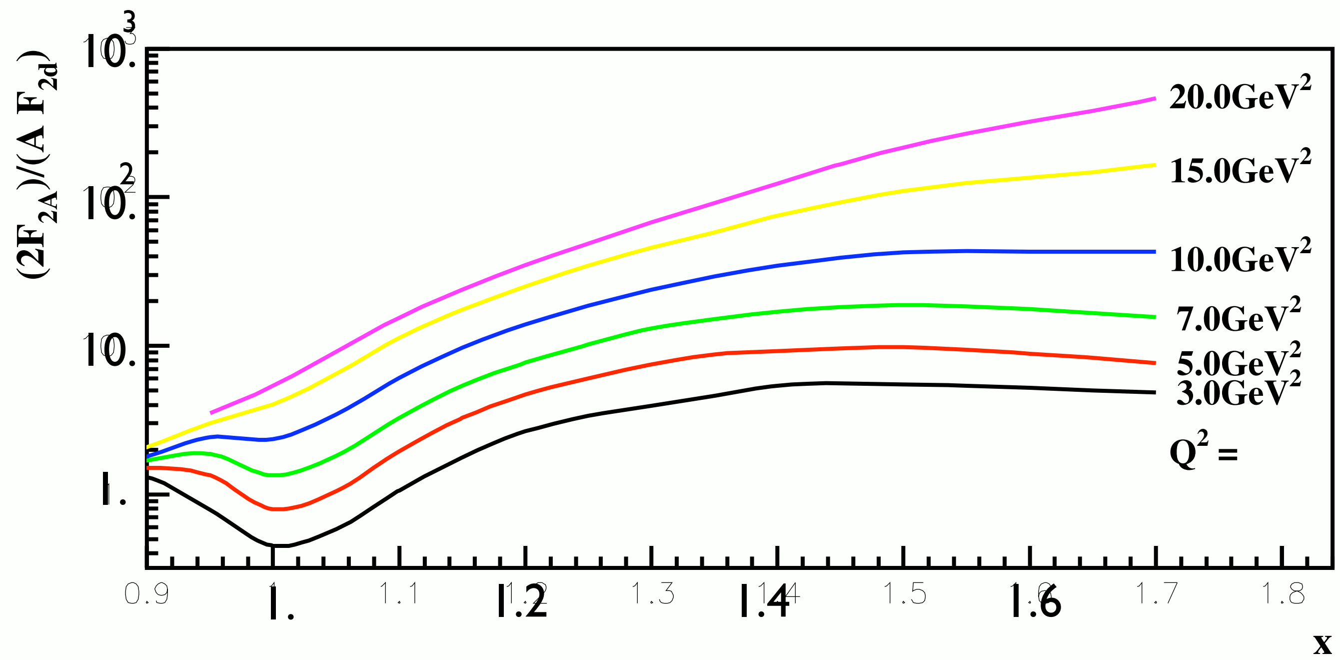
The cross section is expressed through the light-cone density matrix of the nucleus
LC density matrix integrated over $p_\perp : \int \rho_A^N(\alpha, p_\perp) d^2 p_\perp$

On the contrary, one cannot use closure in E_{mis} - no direct connection to nucleon density in QM.

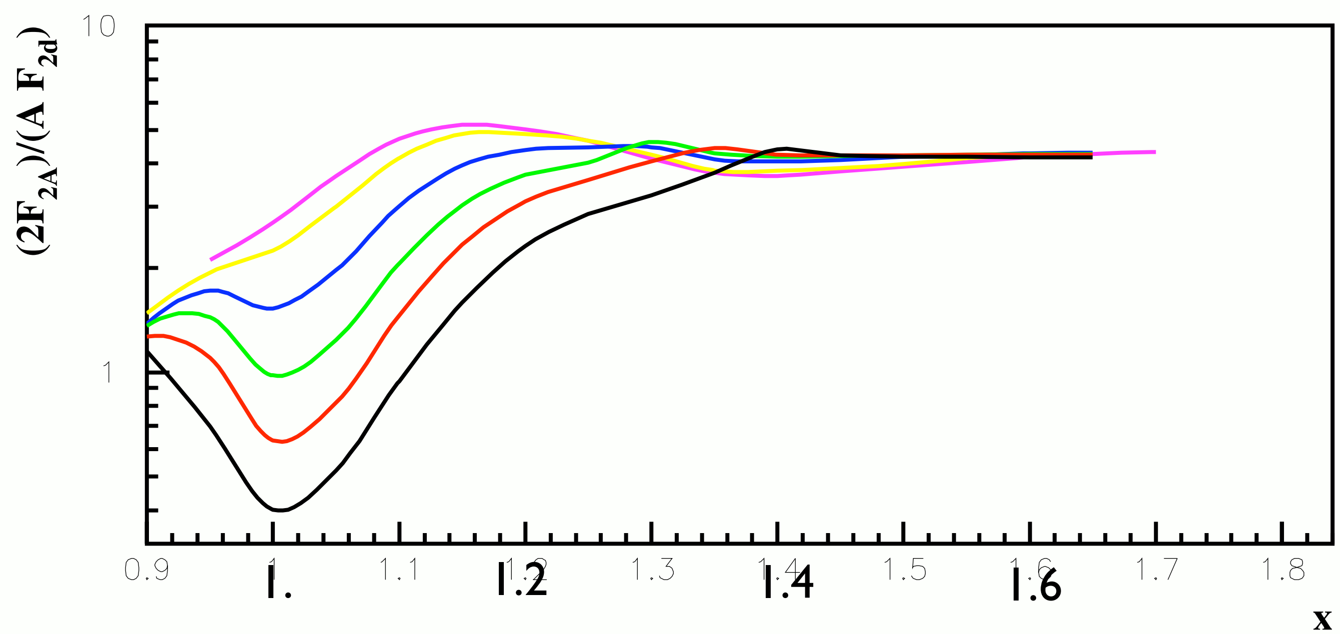
Scaling pattern for the ratios. In particular for x<2:

$$\frac{2}{A}\frac{\sigma_{eA\to e+X}(x,Q^2)}{\sigma_{e+{}^2H\to e+X}(x,Q^2)} = a_2(A) = const\ for\ Q^2 \geq 1.5 GeV^2, 1.3 \leq x \leq 1.8$$

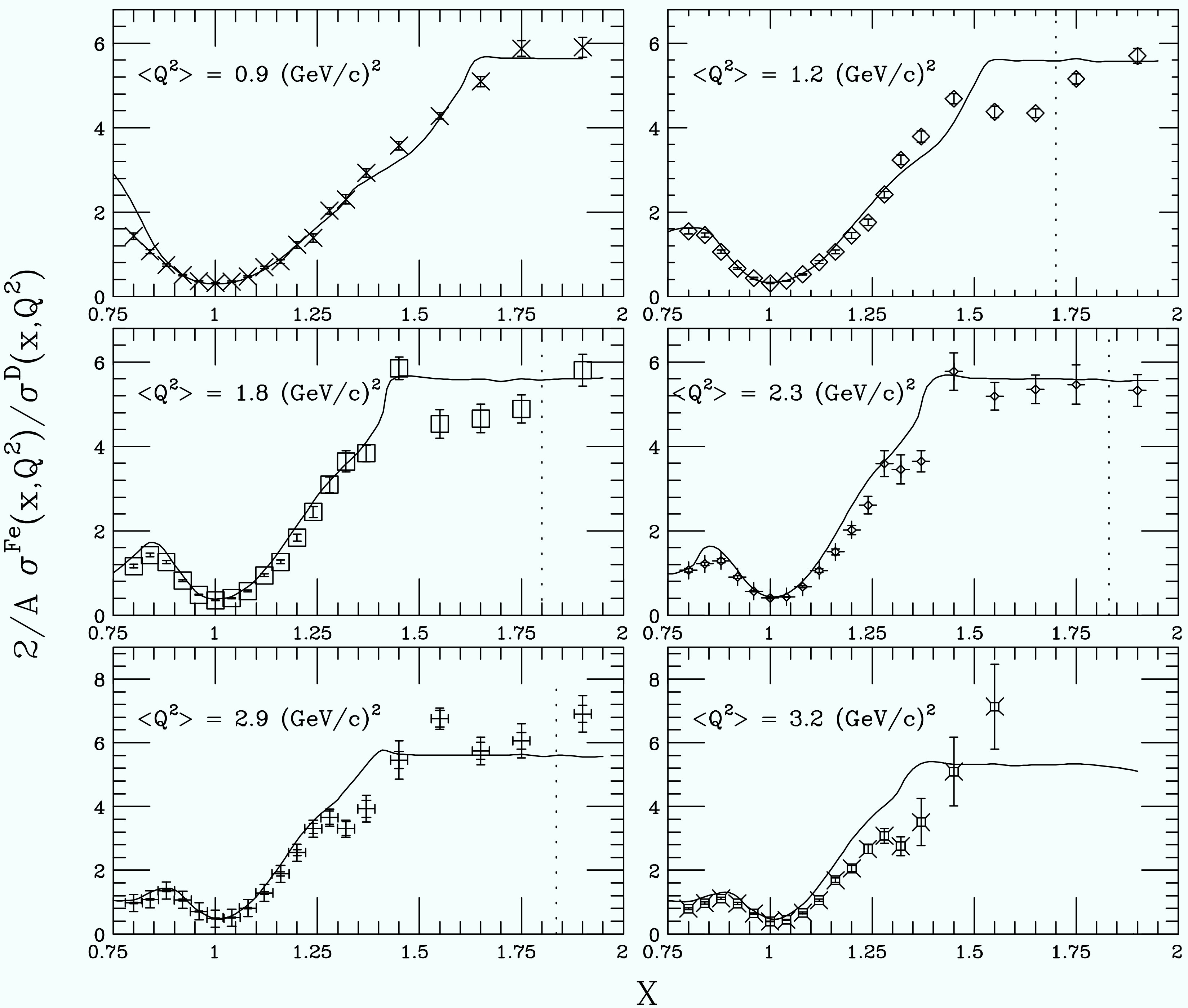
Q-dependence of the C/D ratio based on SRC model including quasielastic and DIS contributions



Few-nucleon correlation model

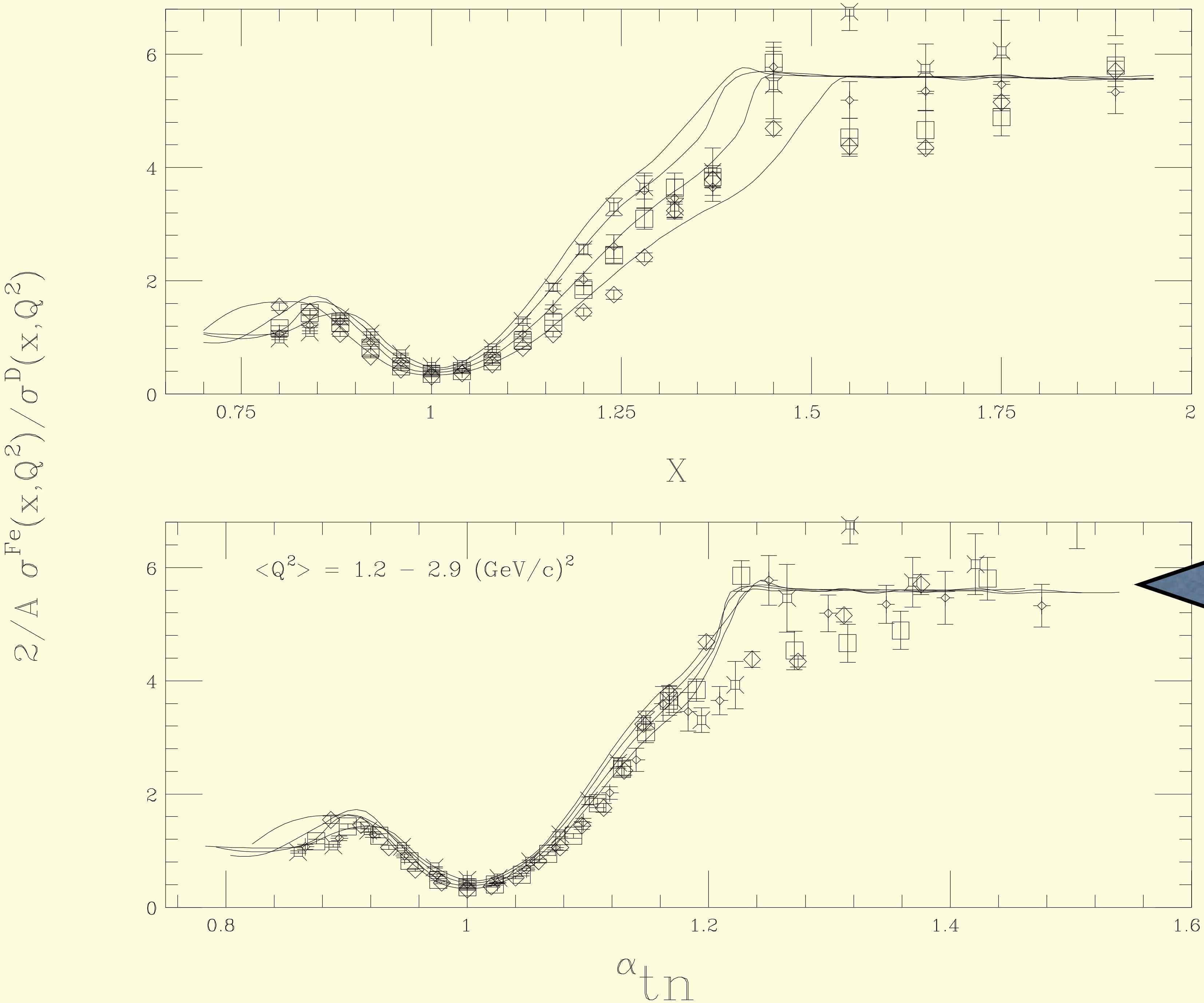


Two-nucleon correlation approximation



Day et al 93

Curves - two nucleon SRC model



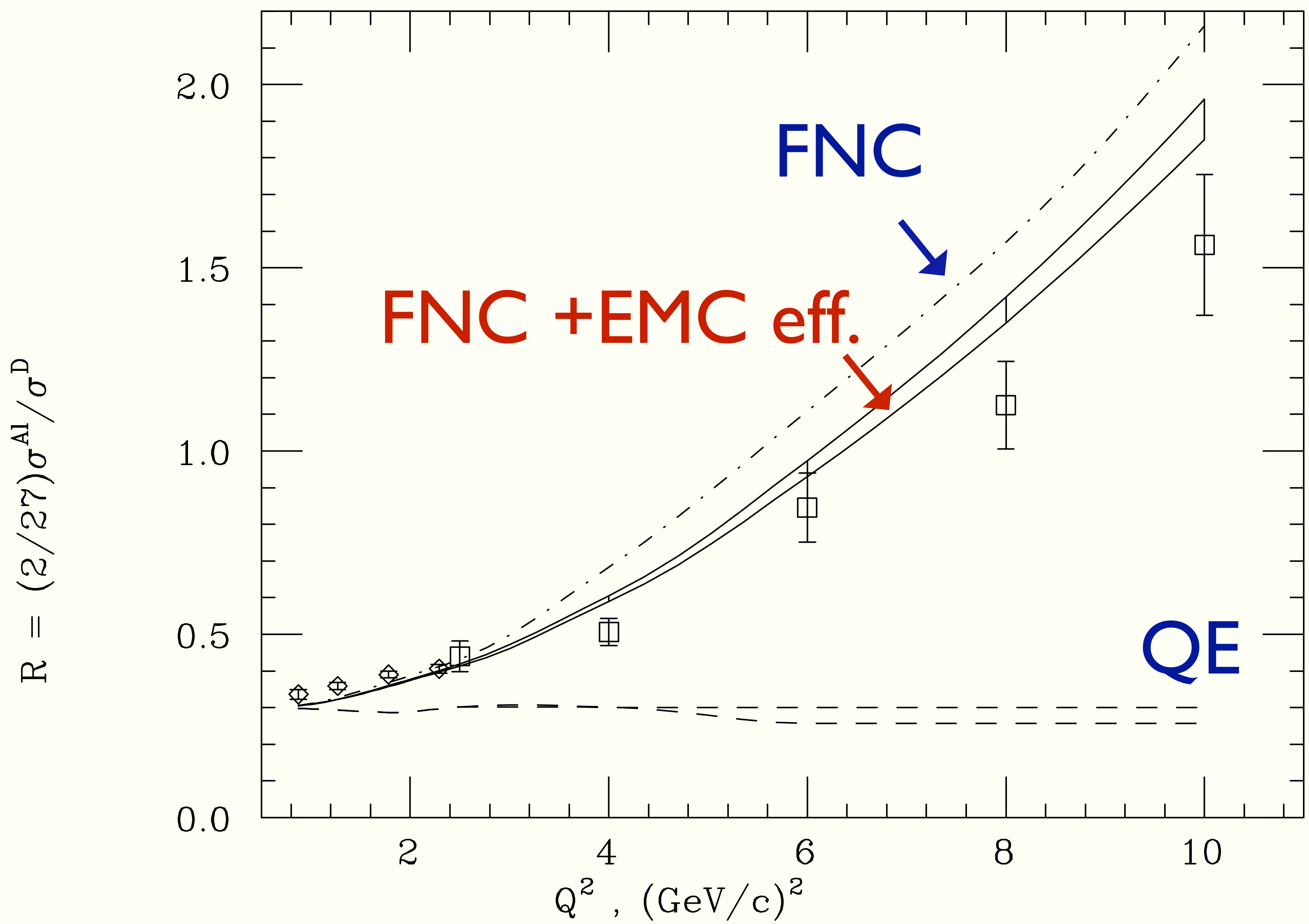
Note: dip at x=1 clearly shows that an easy onset of the Bj scaling in a Nachtmann type variable is impossible for x>0.8.

$$a_2(Fe) = 5.2 \pm 0.9$$

Consistent with our analysis of the fast backward hadron phenomena

Precocious scaling of the ratios in the light cone fraction α_{tn} calculated for two nucleon approximation. Curves are calculation in two nucleon correlation approximation.

The increase of the A/D ratio at x=1 with increase of Q^2 occurs because in the QE term $\alpha \sim x$ while for inelastic contribution which dominate at $Q^2 > 10\ GeV^2$, $\alpha \sim x + 0.5$.



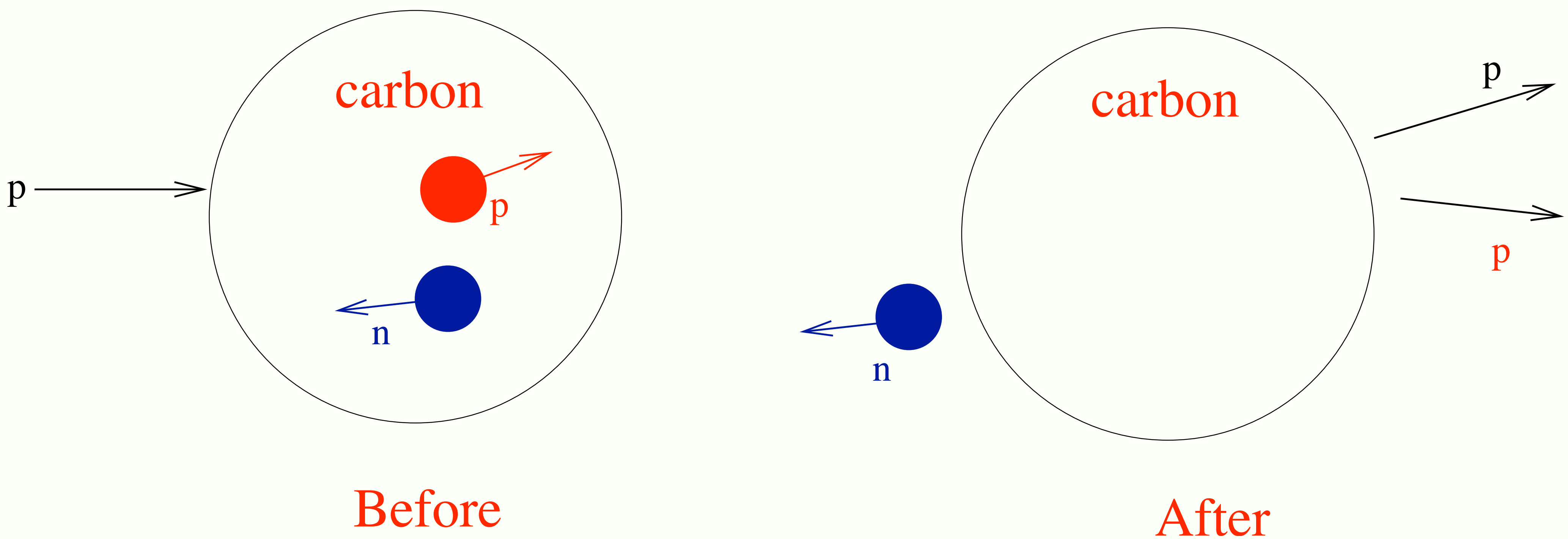
Data from SLAC

Progress in the last 10 years

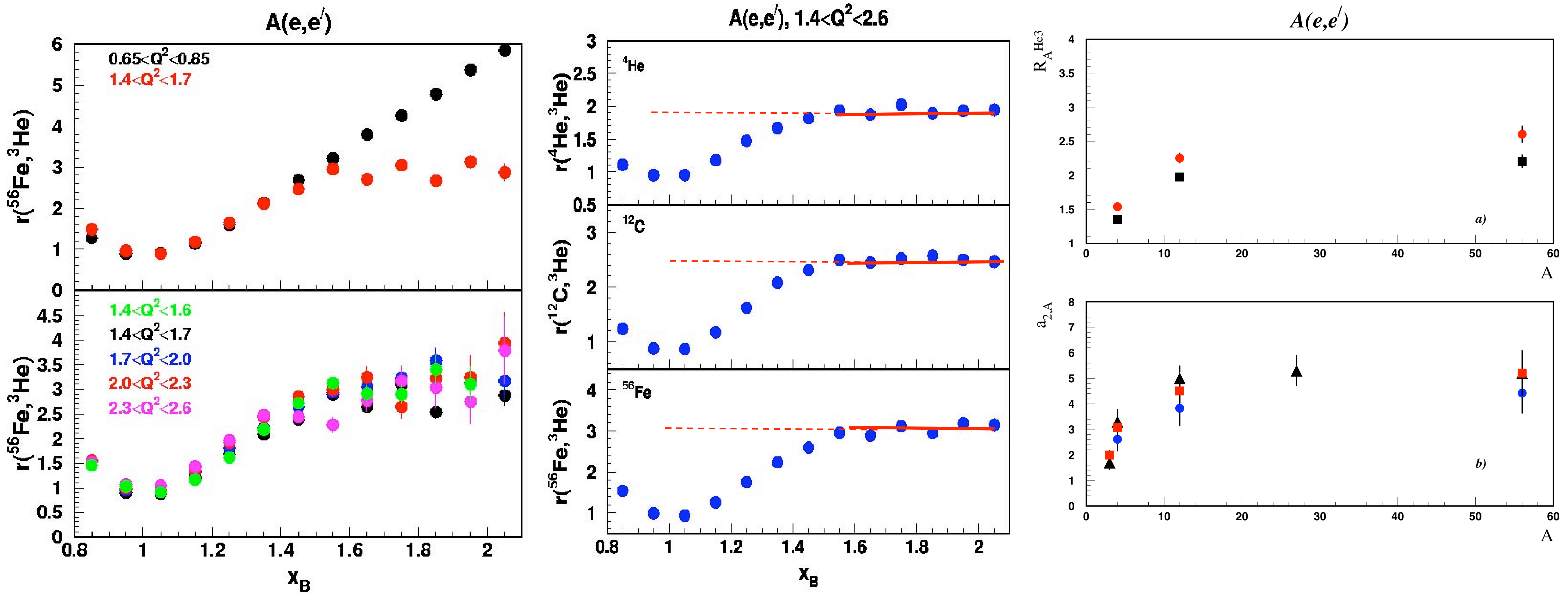
- (e,e') x>1 at Jlab
- (p,2p),(p,2pn) at BNL:

elementary process

large angle ~90° pp scattering



Jlab confirmed and extended results for the ratios of 93 - K.Egiyan talk



Qualitative change of x dependence
from low to high Q region:
flat regime sets for $Q^2 \geq 1.4$ GeV^2

Ratios of probabilities for 3-nucleon SRCs *(preliminary data)*

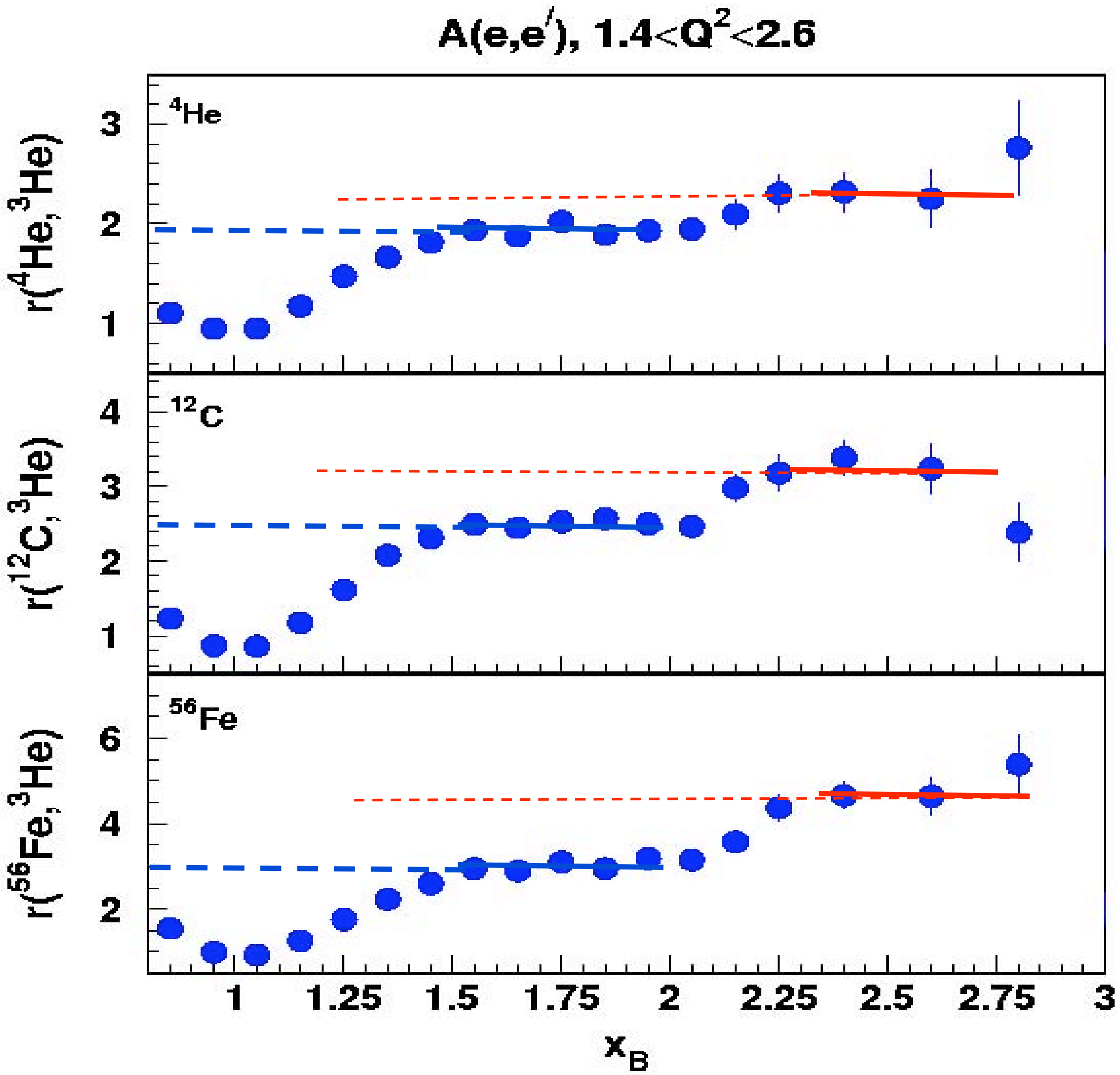
Scaling factors in $2.3 < x_B < 2.8$ interval are the ratios of probabilities of 3-nucleon SRC in nucleus A and ^{3}He:

$$\frac{a_{3N}(A)}{a_{3N}(^3He)} = \begin{matrix} 2.33 \pm 0.12 & ^4He \\ 3.18 \pm 0.14 & ^{12}C \\ 4.63 \pm 0.19 & ^{56}Fe \end{matrix}$$

The chance for a nucleon in ^{4}He, ^{12}C and ^{56}Fe to be involved in 3-nucleon SRC is 2.33, 3.18, and 4.63 times higher than in ^{3}He.

This is what we measured directly.

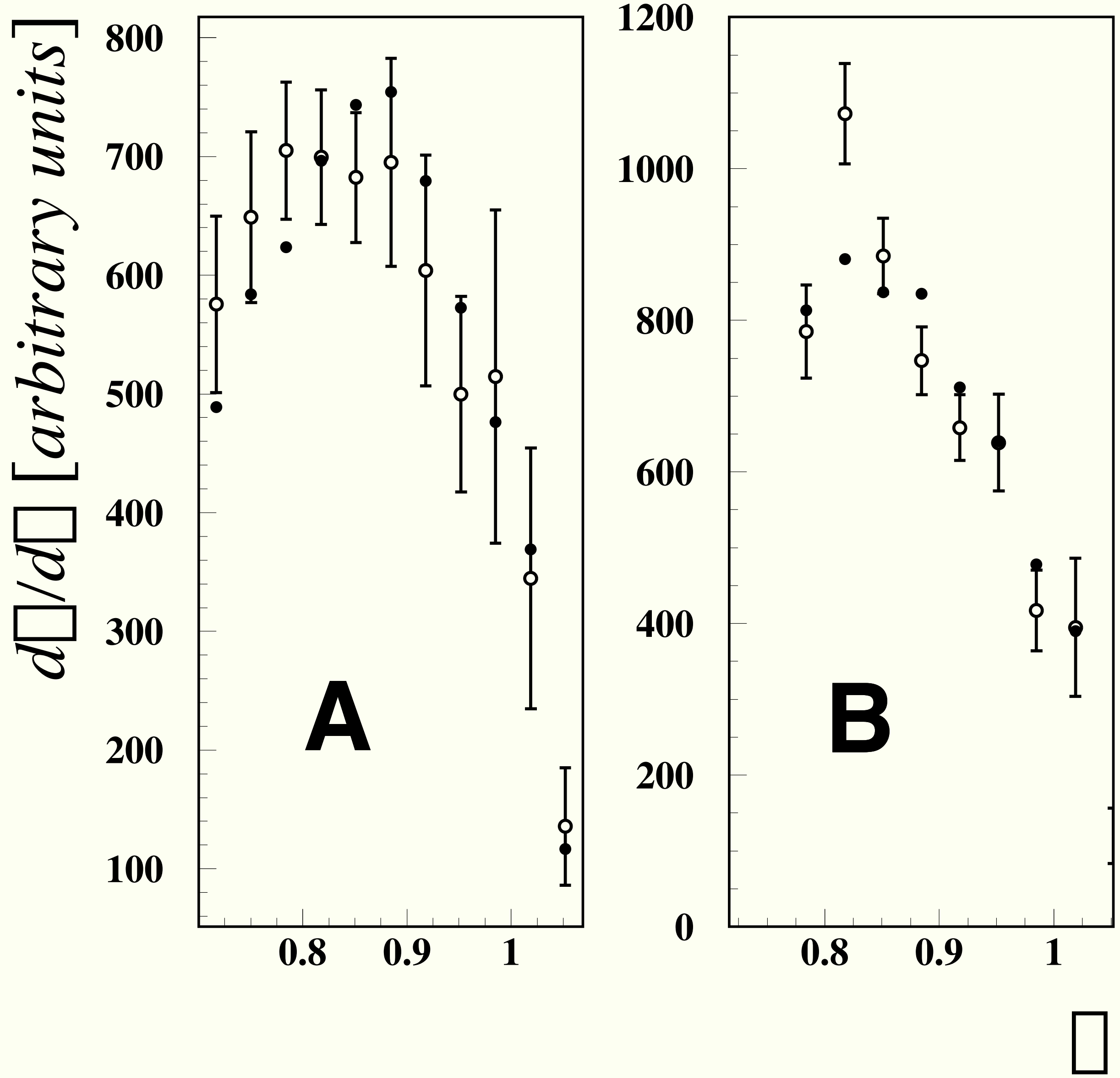
K.Egiyan talk



$a_{3N}(^{56}Fe)/a_{3N}(^{12}C)$

agrees well with our prediction of 81

BNL (p,2p) E850 for the first time measured LC density for $\alpha<1$ –
an important test of the self consistency

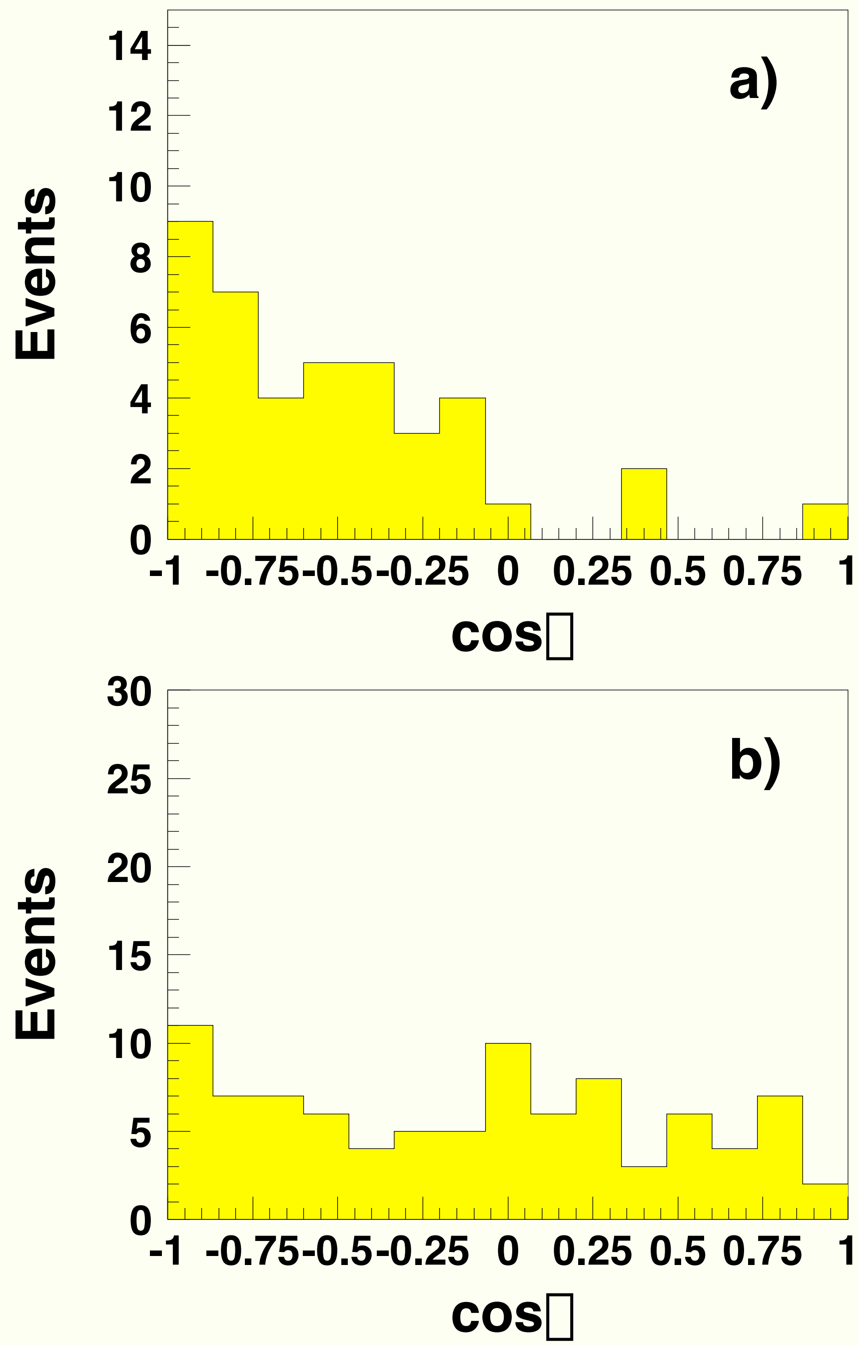


Yaron, Alster, Frankfurt, Piasetzky, Sargsian, Strikman
Phys.Rev.C66:024601,2002

A comparison between calculated α-distribution • and experimental data ○ at 5.9 GeV/c (A) and 7.5 GeV/c (B) for the hard process C(p,2p) studied by E850 at BNL.

E850

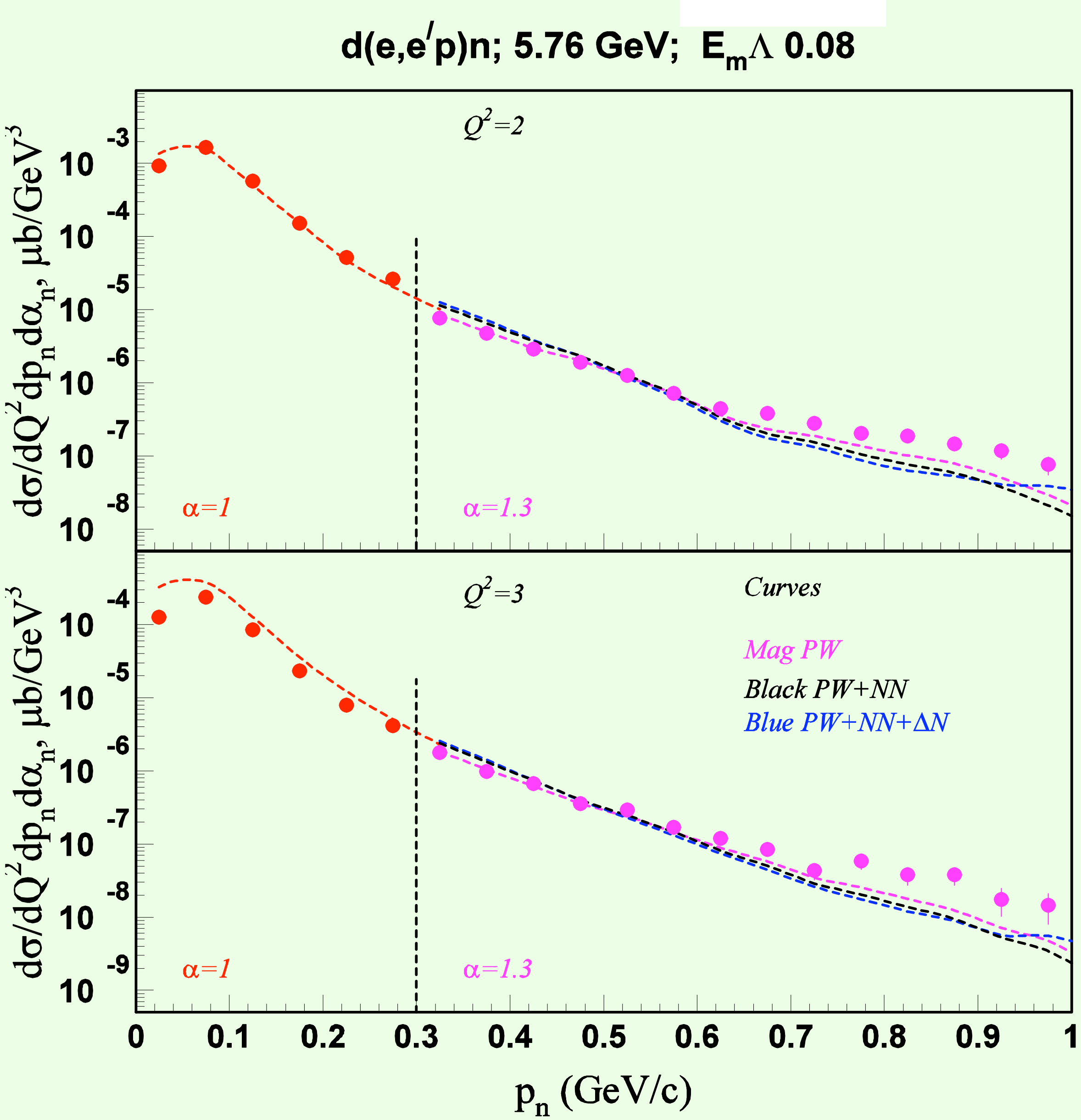
Phys.Rev.Lett.
90:042301,2003



Confirmed prediction of Farrar et al 88 that knock out of a fast forward moving proton should be predominantly accompanied by production of a fast backward neutron. Data are well reproduced by MC of Sargsian based two nucleon correlation approximation.

Plots of cos γ, where γ is the angle between p_n and p_f, for $^{12}C(p,2p+n)$ events. Panel (a) is for events with $p_n >$ 0.22 GeV/c, and panel (b) is for events with $p_n <$ 0.22 GeV/c; 0.22 GeV/c = k_F, the Fermi momentum for ^{12}C.

Matching between the inclusive processes where all configurations may contribute and knockout processes implies that *SRC are predominantly made of the nucleons at least up to momenta 500 MeV/c* (99% nucleons in the deuteron have smaller momenta). In particular the recent measurements at Jlab at large $\alpha>1.25$- reported in the K.Egiyan talk show a good agreement with the impulse approximation plus corrections for rescatterings which are small in this case.



Note: NN component of the six quark bag is small. Hence to produce a comparable number of backward nucleons one would need to renormalize probability of NN correlations from 25% upwards by a factor of 5 at least.

Future directions:

☛ Inclusive measurements

☝ Systematic studies of the absolute cross sections and the A-dependence at large x (up to x=3 at medium Q)

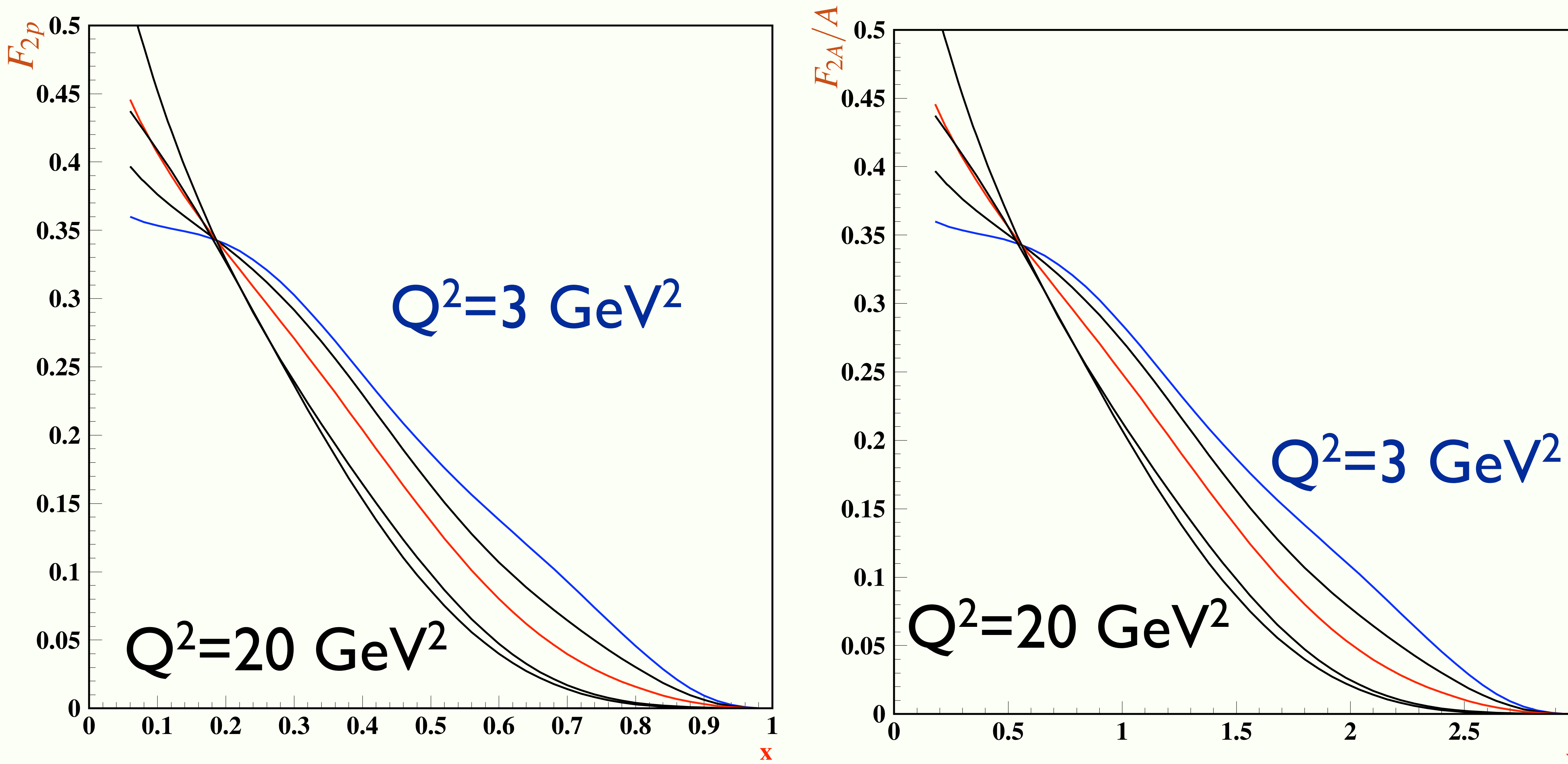
Transition to quark degrees of freedom - properties of the drops of the superdense nuclear matter.

12 GeV is obviously a huge gain for Q range

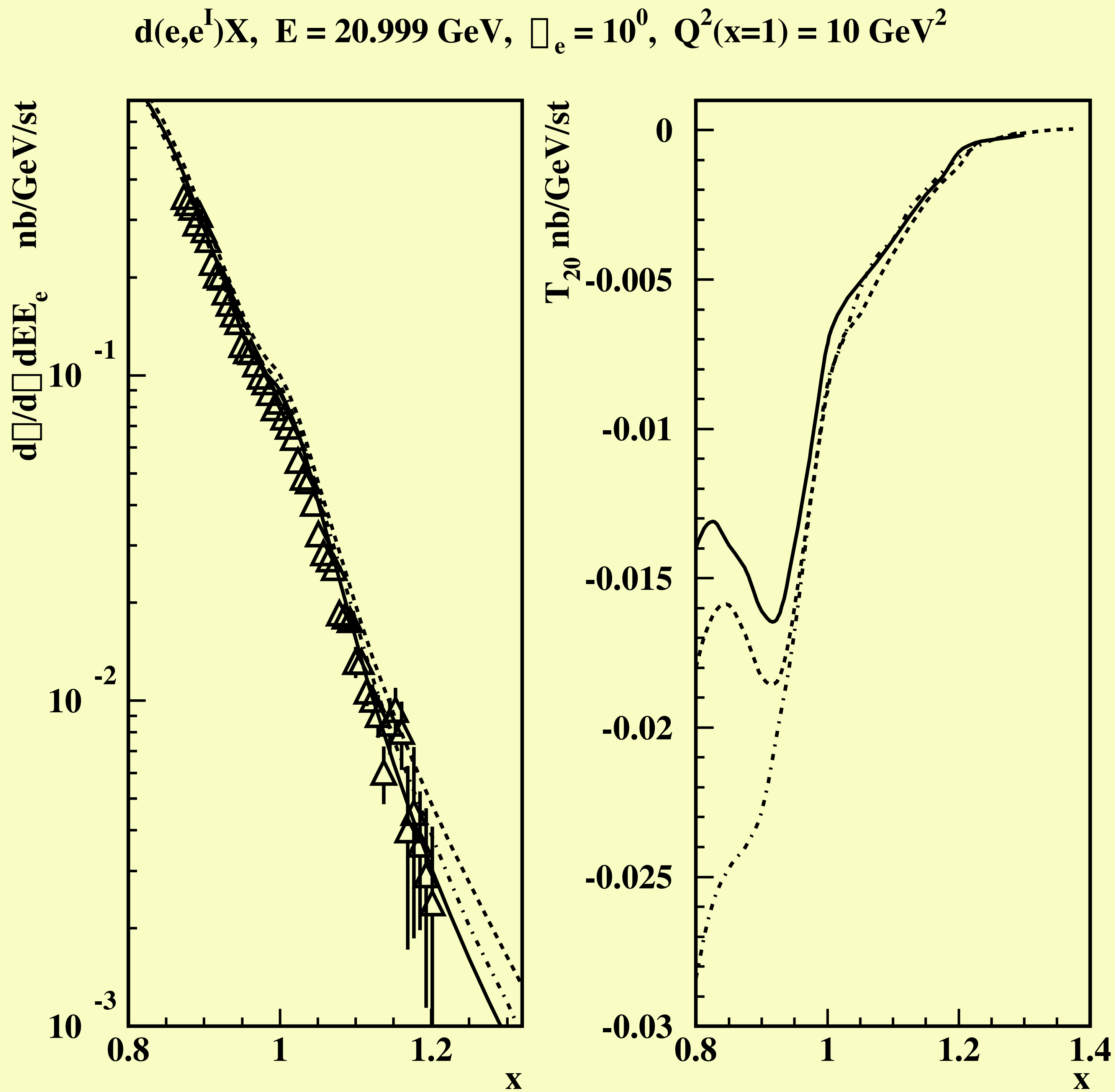
☝ Challenging problem - scattering off the tensor polarized deuteron

Issues: S-, D- wave separation, sensitivity to relativistic effects.

Scaling violation for large x



Q^2 ~ 20 GeV^2 *are necessary to reach scaling region and hence measure x>1 quark distribution in nuclei in a model independent way*

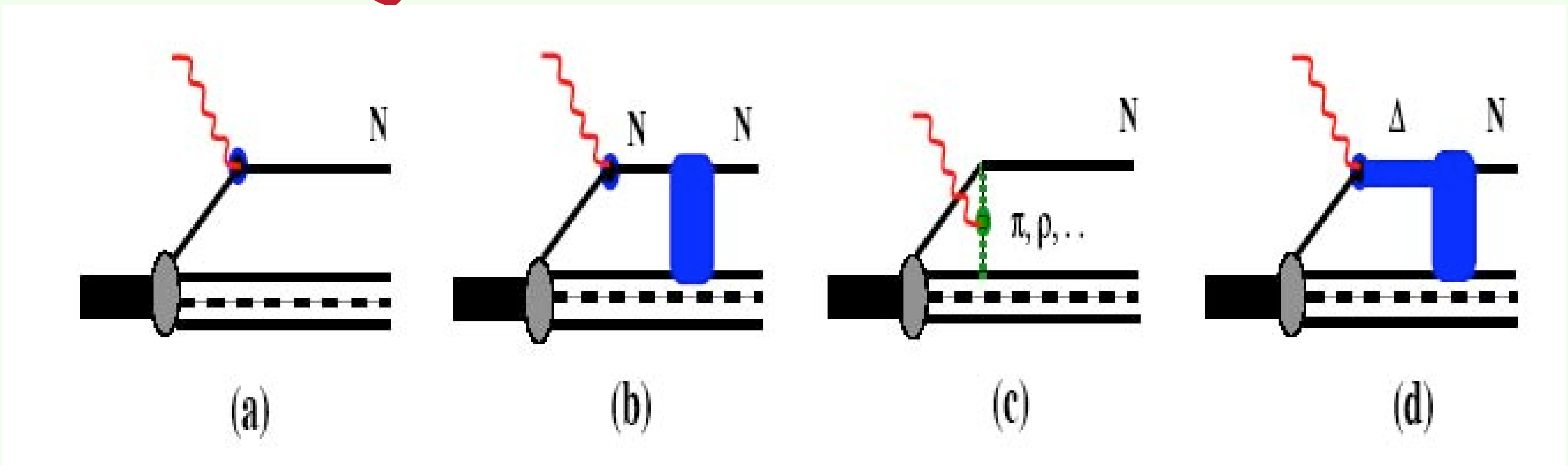


x dependence of the unpolarized and tensor polarized cross sections. Solid line - LC approach with PLC suppression, dashed - LC, and dashed-dotted - VN. Experimental data from Rock et al., Phys. Rev. Lett. 49 , 1139 (1982)

☛ High Q^2 A(e,e'N) processes

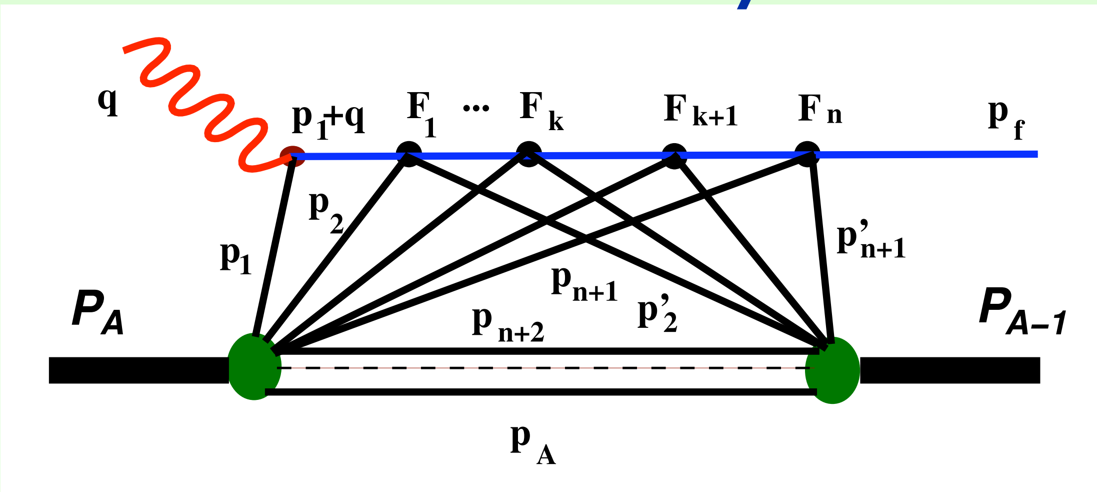
To derive analog of the eikonal approximation for high Q (e,e'N) processes one needs to account for two effects - different velocity of the initial virtual photon and the final nucleon and fixed momentum of the final nucleon as in the conventional Glauber approximation one integrates over all momenta of nucleons in the target.

Derivation is based on the analysis of the relevant Feynman diagrams. Great simplification for x>1 where only diagrams "b" are important for $Q^2 > 2$ GeV^2.



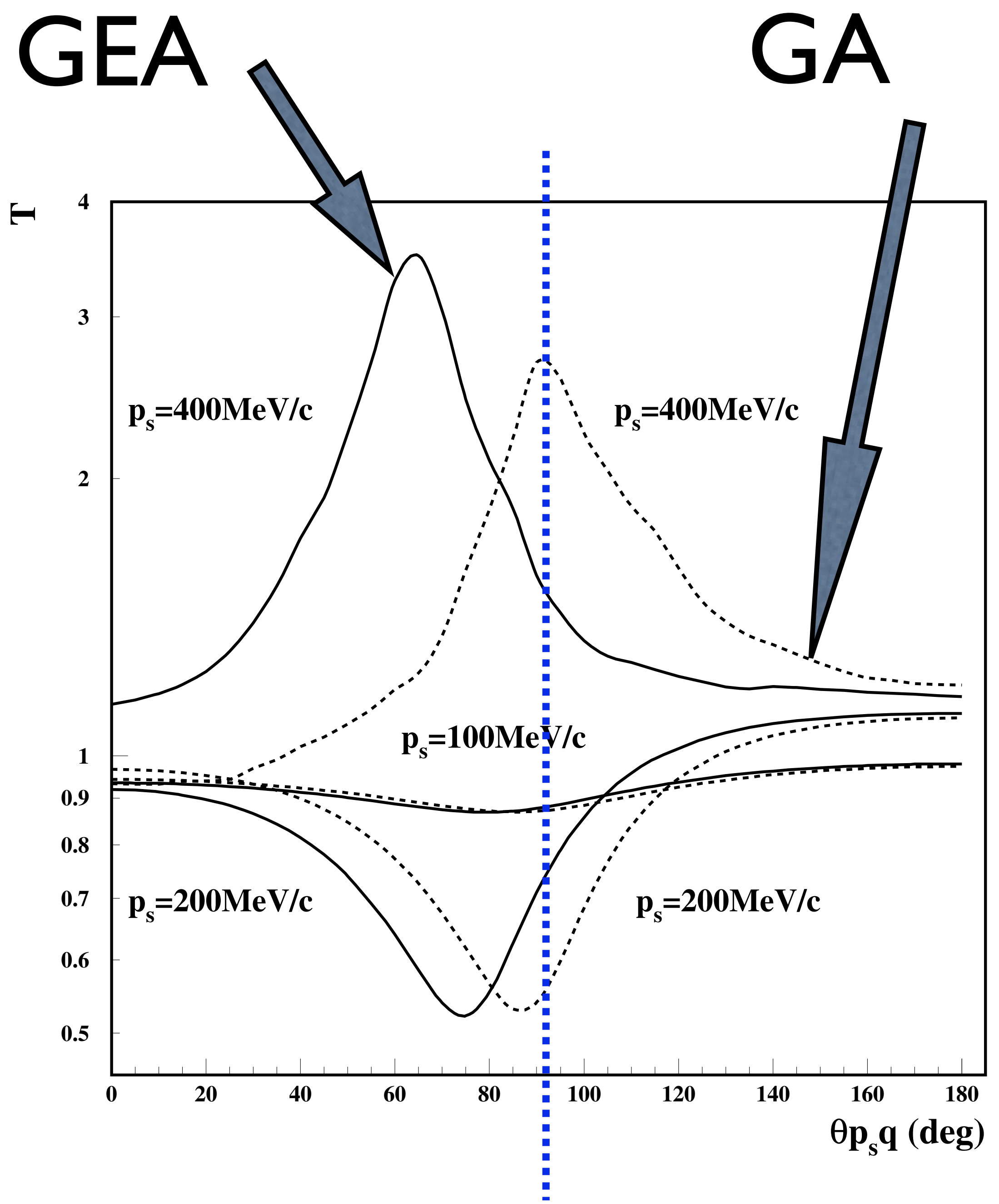
(d)/(a) at large Q^2 decreases as $1/Q^4$ due to energy dependence of the charge exchange with an additional suppression due to a faster decrease of $N \to \Delta$ transition with increase of Q^2

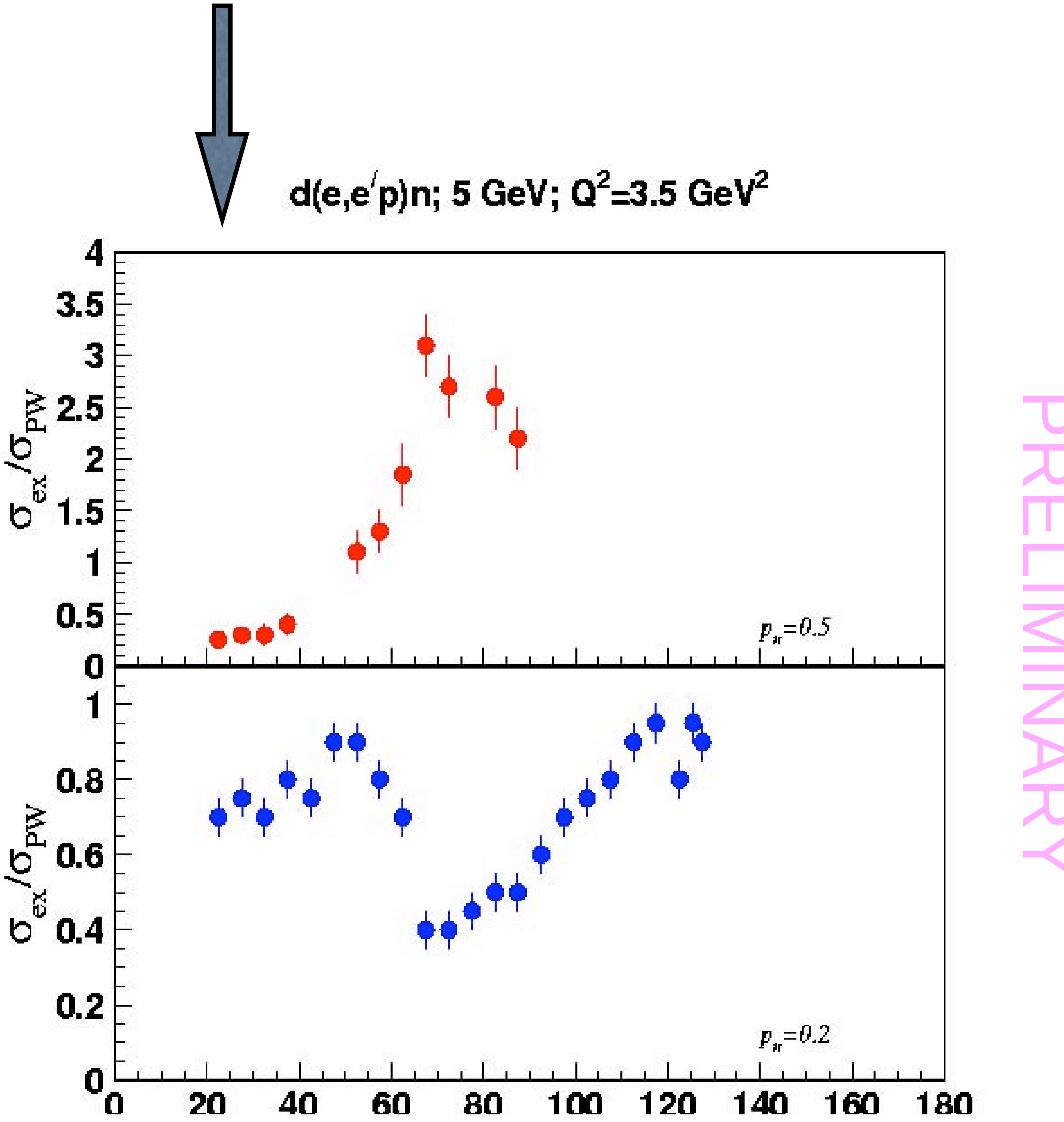
Relevant formulae derived from analysis of the Feynman diagrams



in series of papers of Frankfurt, Sargsian, MS 95-97 and reviewed in Sargsian 2001 - GEA - generalized eikonal approximation. Key difference/complication is the need to take into account longitudinal momentum transfer in the propagators (no time to describe the final answer in this talk). We expect that approximations which worked for (p,pN) at 1 GeV should work also for $Q^2 \sim 2$- 4 GeV^2

Recoil-Neutron Angular Distributions; Hall A Exp.

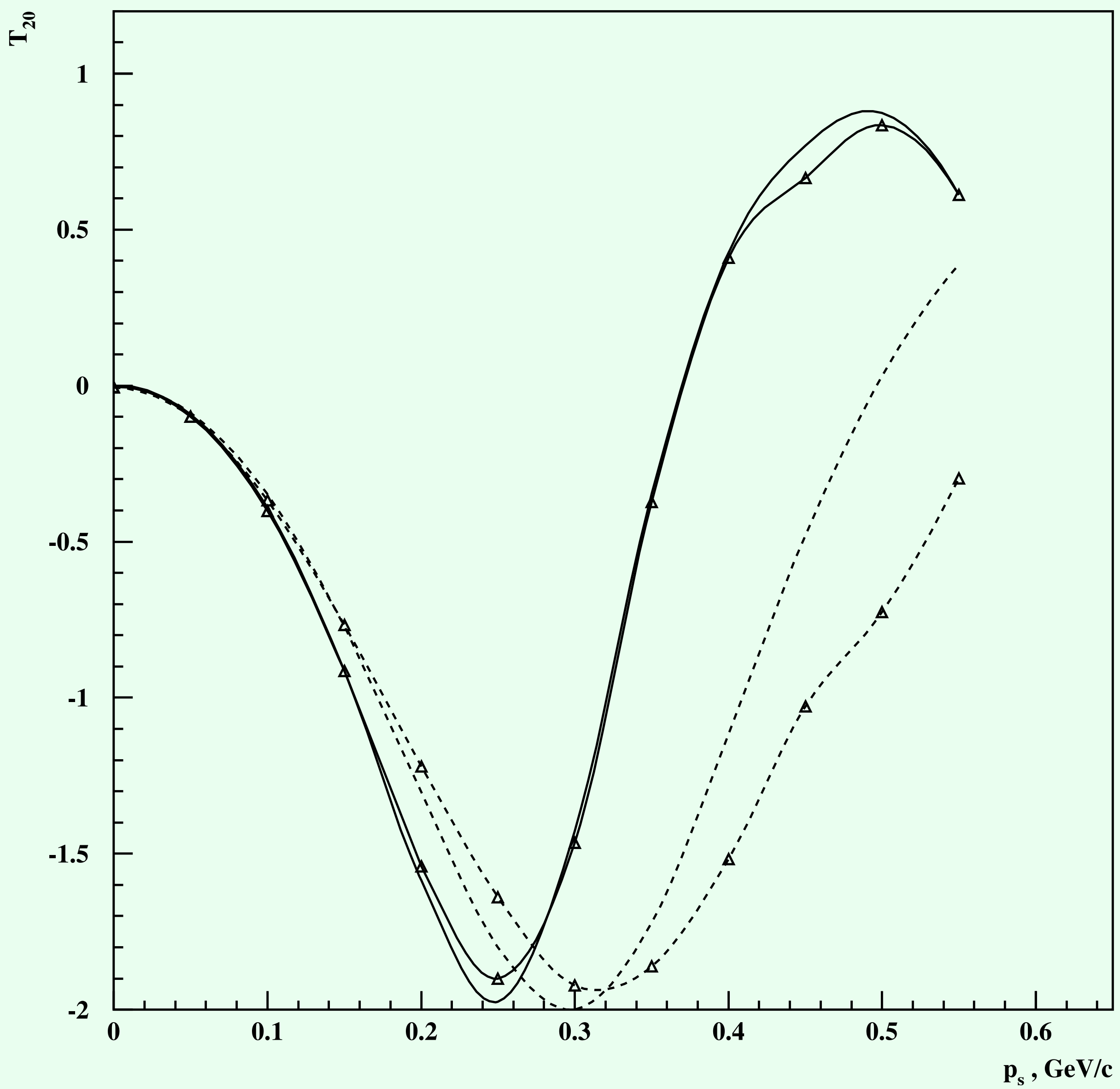




After further tests, checking parameters of Δ interaction (diagram d), it would be possible to use these processes in two distinct kinematics - minimal FSI to study SRC (small transverse momenta) and maximal FSI - looking for CT.

Brief list of the directions of study:

- Decisive test to discriminate between LC and virtual nucleon relativistic models of the deuteron: $e + {}^2\vec{H} \to e + p + n$



p_s dependence of the (e,e'p) tensor polarization (analog of T_{20} for the elastic form factor) at $\theta_s=180^0$. Solid and dashed lines are PWIA predictions of the LC and VN methods, respective marked curves include FSI.

☝

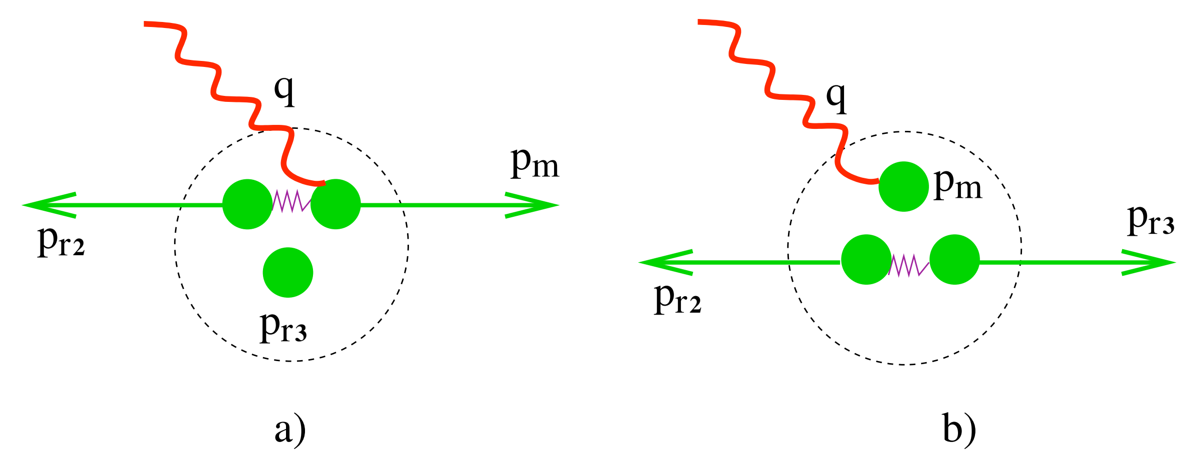
Use 3He(e,e'ppn)

reactions to study pn, pp and ppn correlations.

Remember:

structure (though not probability) of 2N and 3N correlations is very similar in A=3 and heavy nuclei

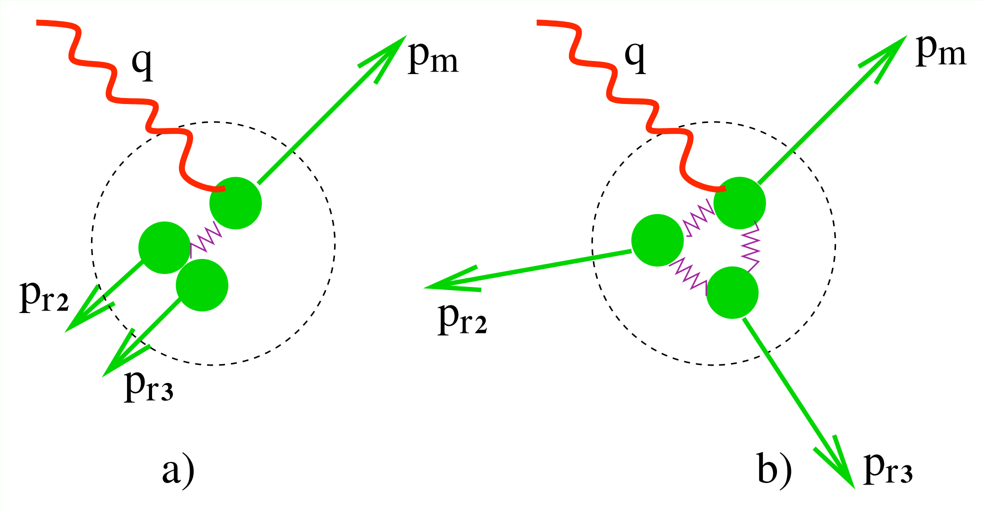
- 2N Correlations



-Type 2N-I correlations: $E_m^{(2N-I)} = \sqrt{m^2 + p_m^2} - m - T_{A-1}$

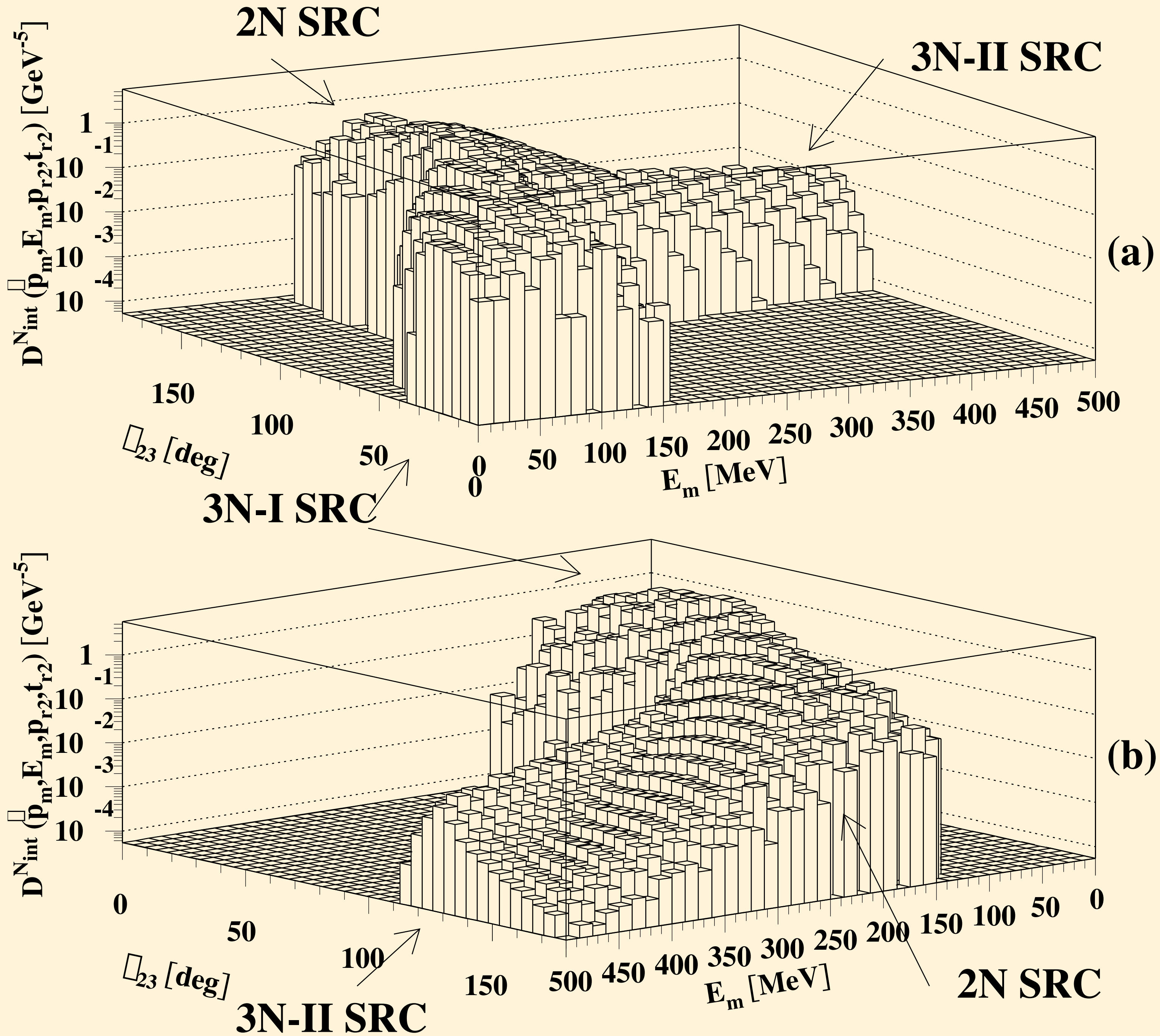
-Type 2N-II correlations: $E_m^{(2N-II)} = \sqrt{m^2 + p_{r2}^2} + \sqrt{m^2 + p_{r3}^2} - 2m$

- 3N Correlations

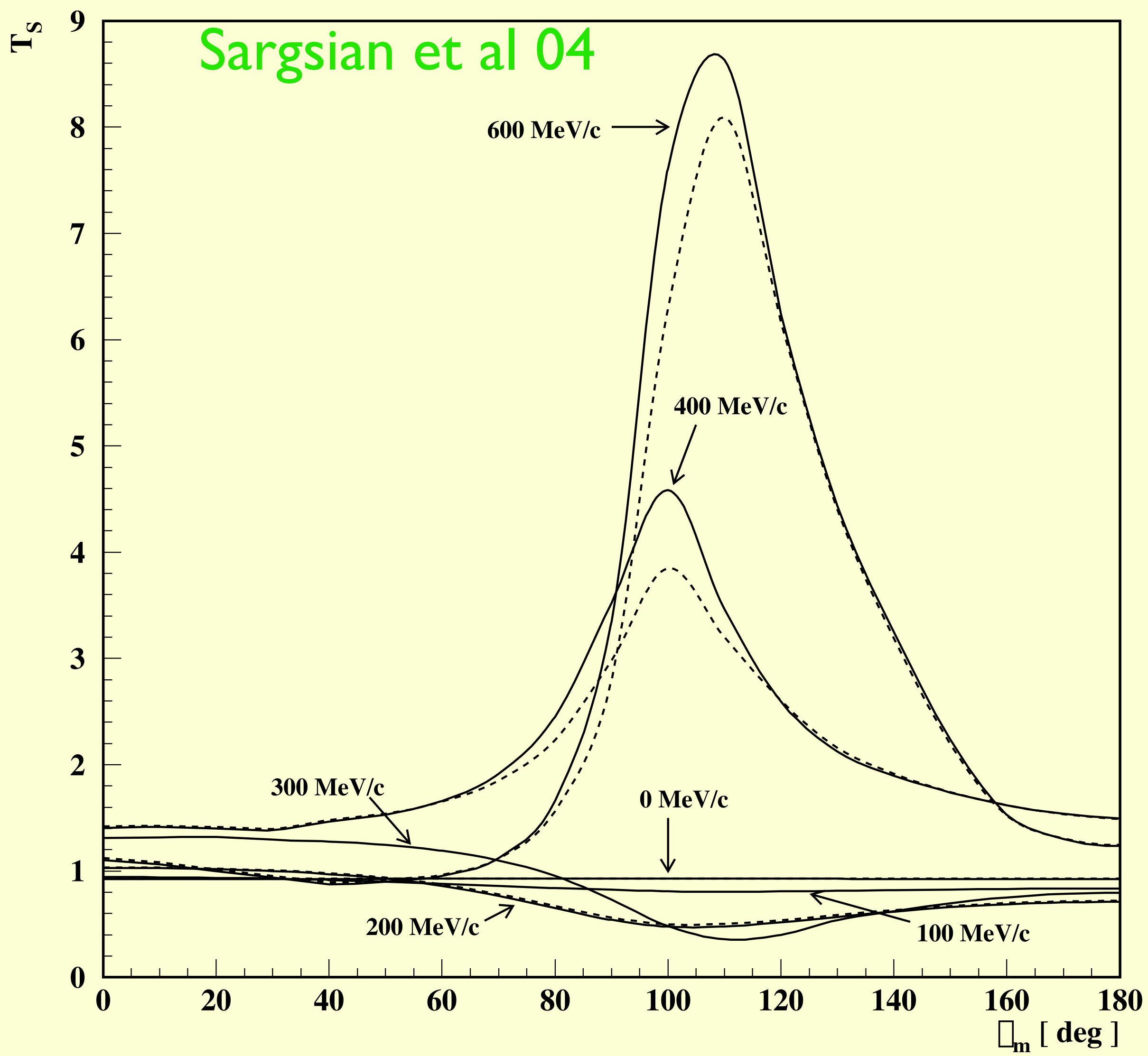


-Type 3N-I correlations: $E_m^{(2N-I)} \approx |\epsilon_A|$

-Type 3N-II correlations: $E_m^{(3N-II)} = 2\sqrt{m^2 + p_m^2} - 2m - T_{A-1}$



Dependence of the decay function of ^{3}He on the relative angle of the recoil pn pair and missing energy E_m for missing $p_m > 700$ MeV/c



Angular dependence of the transparency, T, for electron scattering off a proton in 3He at different values of missing momentum. The missing energy is chosen to enhance contribution of the scattering off pn pairs. Dashed lines include single and double rescatterings while solid lines include only single rescatterings.

Generally at large Q and large energy transfer it is possible to find kinematics (for small transverse momenta of the knocked out nucleon) where distortion effects are small and the decay function can be determined.

Searching/discovering baryonic nonnucleonic degrees of freedom in nuclei

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

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

Sufficiently large Q are necessary to suppress two step processes where Δ^{++} isobar is produced via charge exchange

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

Searching/discovering mesonic degrees of freedom in nuclei

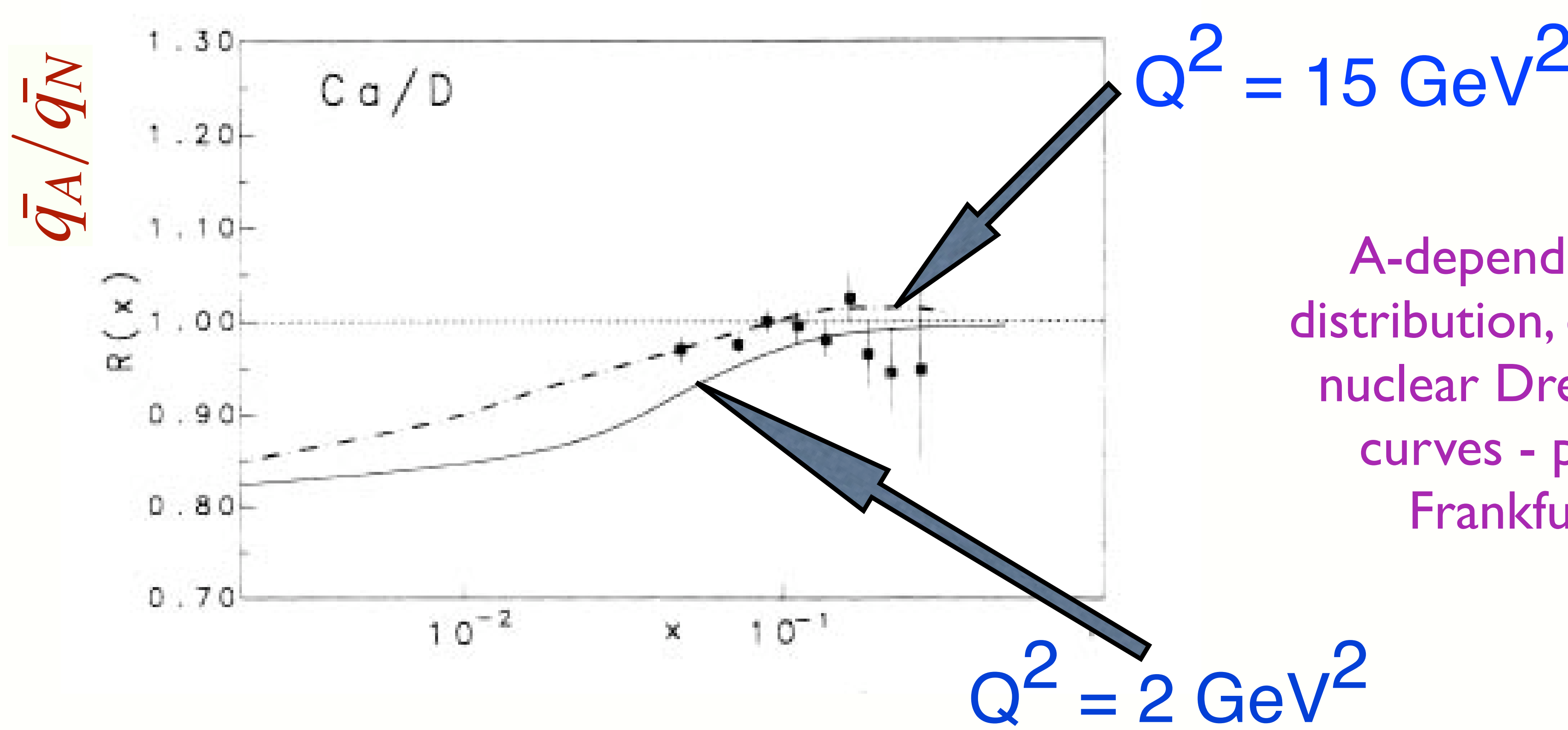
$e + {}^2H \rightarrow e + \ forward\ \square^{-}(along\ \vec{q}) + p(forward)\ + \ p(forward)$ FS 77

$p_N \sim 0.3 - 0.4\ GeV/c$

Origin of the EMC effect.

☛ The EMC effect at $0.7 \geq x \geq 0.4$ is ***unambiguous signature of the presence of nonnucleonic degrees of freedom in nuclei.*** *Claims to the opposite are due to the violation of baryon or energy-momentum conservation or both.*

☛ The lack of the enhancement of antiquarks - *a serious problem for the models where nucleus is described as a system of nucleons and mesons which predict* $\bar{q}_A/\bar{q}_N \sim 1.1\text{-}1.2$ for $x=0.1$ and $A=40$.



A-dependence of antiquark distribution, data are from FNAL nuclear Drell-Yan experiment, curves - pQCD analysis of Frankfurt, Liuti, MS 90

Gaining understanding of the EMC effect (extending current JLab studies)

- Is EMC effect the same for u- and d-quarks? *Use ^{3}He target and pion tagging of knocked out quarks.*

- 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 $e+D \to e+N+X$.

- Are baryonic non-nucleonic degrees of freedom present in nuclei?

  Mesonic models (like Argonne- Urbana potential) -few % Δ -isobars per nucleon (>30% for momenta > 300 MeV/c)

Study of $x_F \geq 0.5$ production of Δ− isobars in $e+D(A) \to e+\Delta+X$. For the deuteron one can reach sensitivity better than 0.1 % for $\Delta\Delta$ (FS 80)

Constrains on the explanation of the EMC effect include suppression of antiquarks, lack of significant modification of the nucleon form factor in a bound nucleon with small momenta.

→ Makes appealing idea that the observed effect is due to modification of the quark distribution in the nucleon with large momenta.

Dynamical model - color screening model of the EMC effect (FS 83-85)

Combination of two ideas:

(a) Quark configurations in a nucleon of a size << average size (PLC) should interact weaker than in average and their probability in nucleons is suppressed.

(b) Quarks in nucleon with $x>0.5$ belong to small size configurations (no pion field), large relative quark momenta.

Introducing in the wave function of the nucleus explicit dependence of the internal variables we find for weakly interacting configurations in the first order perturbation theory using closer we find

$$\tilde{\psi}_A(i) \approx \left(1 + \sum_{j \neq i} \frac{V_{ij}}{\Delta E}\right) \psi_A(i)$$

where $\Delta E \sim m_{N^*} - m_N \sim 600 - 800\ MeV$ average excitation energy in the energy denominator. Using equations of motion for Ψ_A the momentum dependence for the probability to find a bound nucleon with momentum p in a PLC was determined for the case of two nucleon correlations and mean field approximation. After including higher order terms we obtained for the deuteron:

$$\delta_D(p) = \left(1 + \frac{2\frac{p^2}{2m} - \epsilon_D}{\Delta E_D}\right)^{-2}$$

Accordingly $$\frac{F_{2A}(x,Q^2)}{F_{2N}(x,Q^2)} - 1 \quad \langle \Box(p) \rangle - 1 = \left\langle \frac{2\frac{p^2}{2m} - \Box_A}{\Box E_A} \right\rangle \quad \langle \Box(r) \rangle \;\; for\ A \geq 12$$

which describes well the A-dependence of the EMC effect for 0.7>x>0.4 (FS83) as well as the magnitude of the EMC effect.

Repeat the program for A=3 for a final state with a certain energy and momentum for the recoiling system FS & Ciofi et al .
Introduce formally virtuality of the interacting nucleon as

$$p_{int}^2 - m^2 = (m_A - p_{spect})^2 - m^2.$$

Find the expression which is valid both for A=2 and for A=3(both NN and deuteron recoil channels):

$$\Box(p, E_{exc}) = \left(1 - \frac{p_{int}^2 - m^2}{2\Box E}\right)^{-2}$$

Dependence we find for small virtualities

$$(1 - c(p_{int}^2 - m^2))$$

seems to be very general for the modification of the nucleon properties. Indeed, consider analytic continuation of the scattering amplitude to $p_{int}^2 - m^2 = 0$ .At this point modification should vanish. Quantum mechanical treatment automatically took this into account.

This generalization of initial formula allows a more accurate study of the A-dependence of the EMC effect and further emphasizes interest of the tagged structure functions where modification is expected to increase quadratically with tagged nucleon momentum. It is applicable for searches of the form factor modification in (e,e'N). If you observed effect at 100 MeV/c - go to 200 MeV/c and see whether the effect will increase by a factor of ~3-4.

Conclusions

Further studies at 6 GeV will allow to

☺ Produce a detailed structure of SRC on the level of nucleonic degrees of freedoms.
6 GeV was already a bonus as compared to 4 GeV stage.

☺ Establish quantitative understanding of the final state interactions at Q^2 range 2 - 4 GeV^2 relevant for studies of SRC.

Studies at 12 GeV will allow to

☺ Model independent determination of the spectrum of superfast quarks in nuclei - quark structure of drops of superdense nuclear matter.

☺ Establishing the origin of the non nucleonic degrees of freedom in nuclei.