Light Cone Nuclear Physics and SRC/EMC Effects

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Outline

Part I : SRC -few nucleon approximation

- Emergence of light cone dominance at high energies
- Properties of the light cone density matrix and SRCs
- Deuteron - LC - nonrelativistic correspondence
  Polarized deuteron

Part II: EMC effect 30 years after

- First theoretical ideas
- From “Every Model Cool” to facing tough constrains
- Shift of emphasize on large x and SRC; can pA at LHC help

Consensus of the 70's: it is hopeless to look for SRC experimentally

NO GO theorem: high momentum component of the nuclear wave function is not observable (Amado 78)

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 (meson exchange currents,...), enhancement of the final state contributions.

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

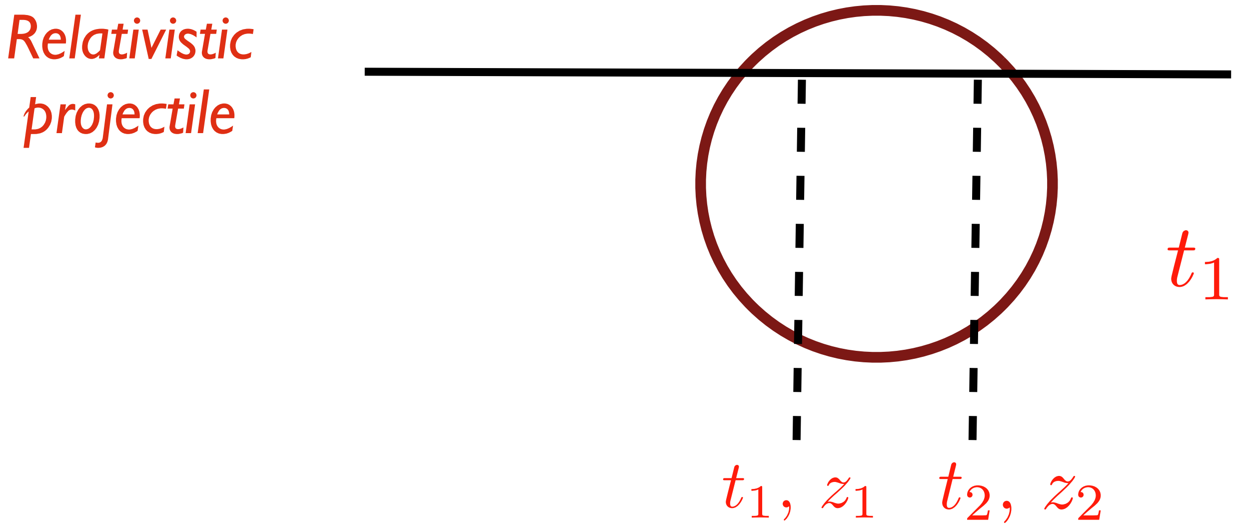
$$q_0 \geq 1GeV \gg |V_{NN}^{SR}|, \vec{q} \geq 1GeV/c \gg 2\ k_F$$

Adjusting resolution scale as a function of the probed nucleon momentum allows to avoid Amado theorem. Standard trick in QCD.

Actually it is now a standard trick in atomic (10 eV vs 1000 eV) and solid state physics (0.2 eV vs 30 eV) scales.

$\Rightarrow$ Need to treat the processes in the relativistic domain. The price to pay is a need to treat the nucleus wave function using light-cone quantization - - One cannot use (at least in a simple way) nonrelativistic description of nuclei.

⇒ High energy process develops along the light cone.

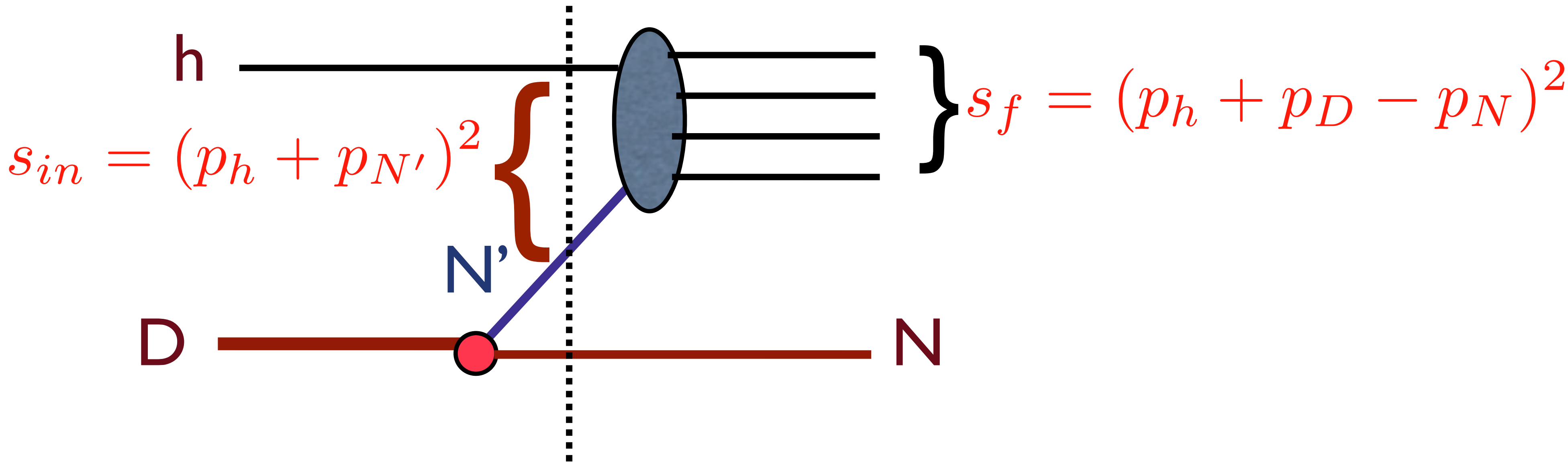


$$t_1 - z_1 = t_2 - z_2$$

Similar to the perturbative QCD the amplitudes of the processes are expressed through the wave functions on the light cone. *Note: in general no benefit for using LC for low energy processes.*

LC quantization is uniquely selected in high energy processes if one tries to express cross section through elementary amplitudes near energy shell.

Consider the break up of the deuteron in the impulse approximation:
h+D→X+N, for $E_h \to \infty$



In quantum mechanical treatment energy in the D→NN vertex is not conserved. As a result

$$\Delta \equiv (s_{in} - s_f) \to 2\,E_h(2\sqrt{m_N^2 + p_N^2} - m_D)_{\,|\,E_h \to \infty}$$

is infinite at high energies. Amplitude is far off energy shell.

In case of LC quantization along reaction axis

$$\begin{aligned}\Delta &= (p_{\rm NN}+p_{\rm h})^2-(p_{\rm D}+p_{\rm h})^2 = M_{\rm NN}^2-M_{\rm D}^2+(p_{\rm h})_+(p_{\rm NN}-p_{\rm D})_- + (p_{\rm h})_-(p_{\rm NN}-p_{\rm D})_+\\ &= M_{\rm NN}^2-M_{\rm D}^2+\frac{1}{2}(m_{\rm h}^2/E_{\rm h})(M_{\rm NN}^2/M_{\rm D}-M_{\rm D}) \simeq M_{\rm NN}^2-M_{\rm D}^2\end{aligned}$$

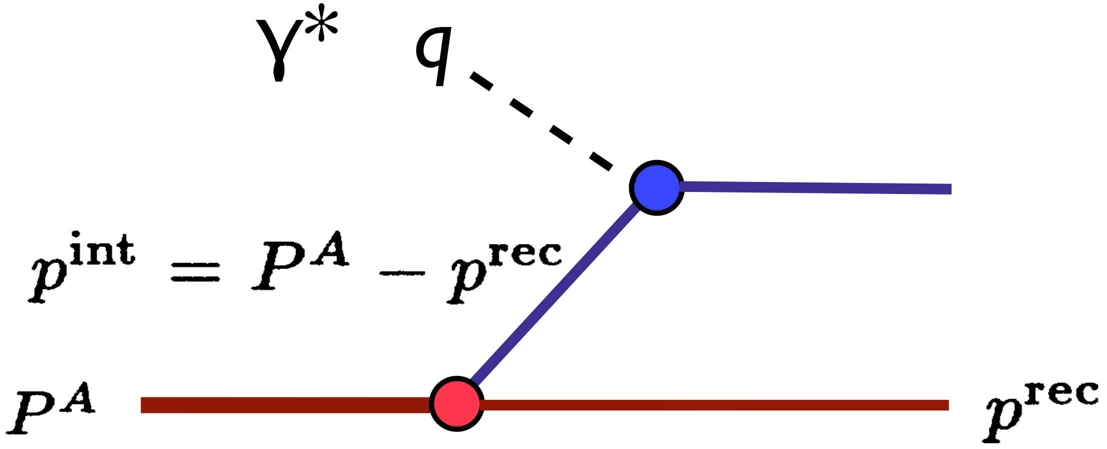
Here M^2_{NN} is invariant mass squared of the two nucleon system

Δ is finite and hence amplitude is close to the mass shell

Requirement of finite Δ uniquely fixes quantization axis for the high energy limit to be according to LC prescription

Onset of LC dominance in (e,e')

Consider example of high Q^2 (e,e') process at fixed large x >1 in the many nucleon approximation for the nucleus



The on-shell condition for the produced nucleon

$$(p^{\rm int} + q)^2 = m^2$$

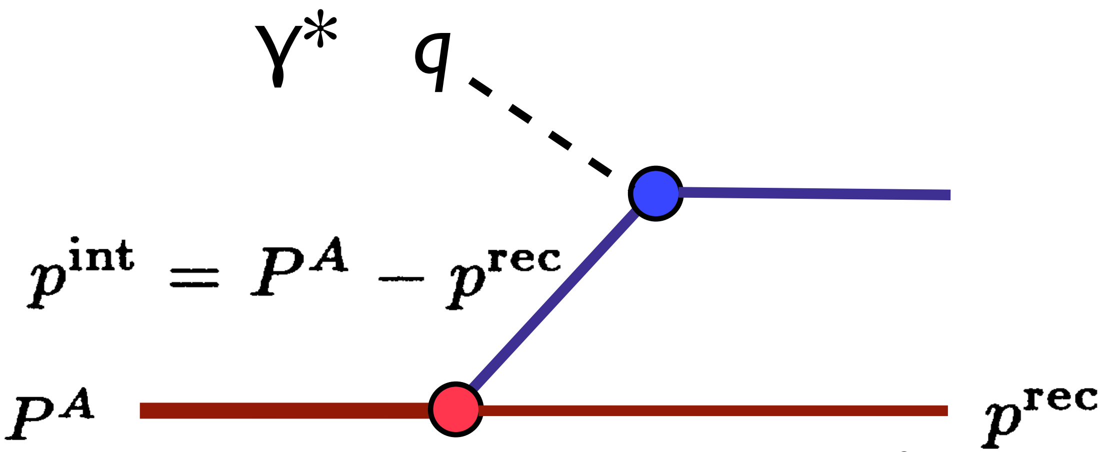
LC variables:

$$q_{\pm} = q_0 \pm q_3;$$

for any vector $a_\mu = (a_+, a_-, a_t)$,

$$\alpha \equiv \frac{Ap_-^{\rm int}}{P_-^A},\ p_t \equiv p_t^{\rm int} = -p_t^{\rm rec}$$

$$\tilde{m}^2 = (P^A - p^{rec})_+ (P^A - p^{rec})_- - (P^A - p^{rec})_t^2$$



Substituting

$$P_+^A = M_A^2 / P_-^A,$$

$$p_+^{\rm rec} = \frac{(m^{\rm rec})^2 + p_t^2}{(1-\alpha/A)P^+A_-},$$

and

$$\left(P^A - p^{\rm rec}\right)_- = \frac{\alpha}{A} P_-^A,$$

we obtain

$$\tilde{m}^2 = \left(M_A^2 - \frac{(m^{\rm rec})^2 + p_t^2}{(A-\alpha)/A} \right) \frac{\alpha}{A} - p_t^2,$$

where $m^{\rm rec}$ is the mass of the recoiling (A–1) nucleus.

$$\tilde{m}^2 + q_+ p_-^{\text{int}} + q_- p_+^{\text{int}} + q^2$$

$$= \tilde{m}^2 + q_+ \frac{M_A}{A}\alpha + q_- \left(\frac{\tilde{m}^2 + p_t^2}{\alpha(M_A/A)} \right) + q^2 = m^2$$

Use the nucleus rest frame

$$P_+^A = P_-^A = M_A.$$

$$\Rightarrow \quad \frac{\partial \alpha}{\partial \tilde{m}^2} = -\left(\frac{1 + (q_-/\alpha)(M_A/A)}{(q_+ M^A/A) - [q_-(\tilde{m}^2 + p_t^2)]/\alpha^2 M_A/A} \right)$$

$\longrightarrow$ 0 for large Q, fixed x, $\propto 1/q_+$

$\Rightarrow$ In high energy limit the cross section depends only on the spectral function integrated over all variables but α - light-cone dominance, in particular no depend on the mass of the recoil system. Relevant quantity light-cone nucleon density matrix.

$$\Rightarrow \quad \frac{\sigma_{eA}(x, Q^2)}{\sigma_{eD}(x, Q^2)} = \frac{\rho_A(\alpha_{tn})}{\rho_D(\alpha_{tn})}$$

For intermediate Q^2 corrections can be treated by taking an average value of recoil mass. The two nucleon approximation for p_-^{rec} is

$$p_-^{rec} = m_{(A-2)^*} + \frac{m^2 + p_t^2}{m(2-\alpha)} \qquad (*)$$

with Fermi motion of the pair leading to a spread of distribution over p_-^{rec} is but not to a significant change of $\langle p_-^{rec} \rangle$.

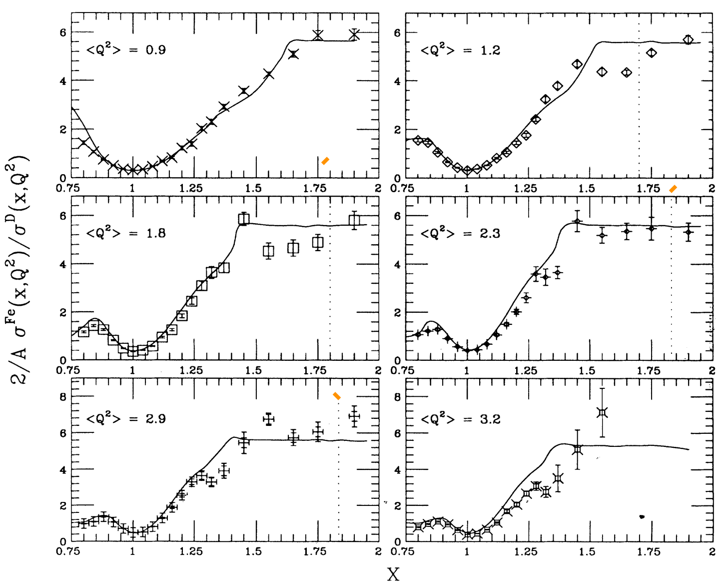
$\Rightarrow$ "super"scaling of the (e,e') ratios in $\alpha_{t.n.}$ - α calculated using (*).

At $\alpha \gtrsim 1.5$ (*) three nucleon correlations start to reduce p_-^{rec} as compared to (*). The (e,e') A/D ratios should start increasing at these α.

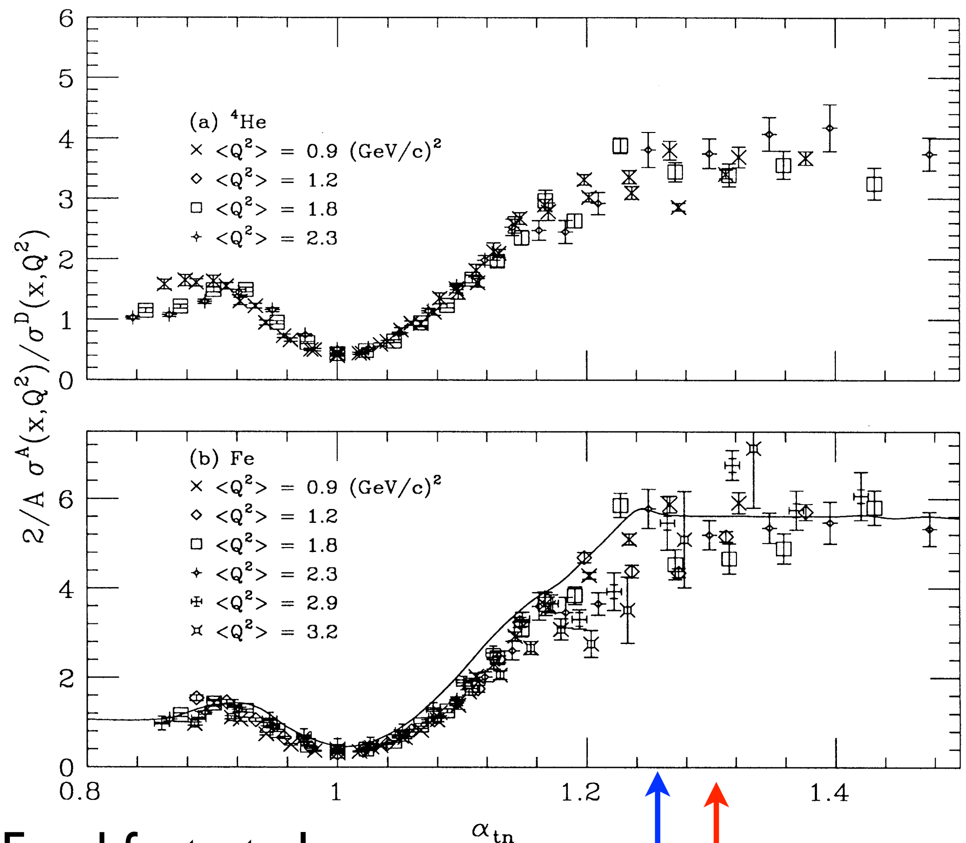
Warning: FSI is small in (e,e') for interaction of struck nucleon with nucleons not belonging to SRC. However different local FSI in two and three nucleon correlations may not cancel in the ratios.

$W - M_D \leq 50\, MeV$

$$\frac{\sigma_{A_1}(x,Q^2)}{\sigma_{A_2}(x,Q^2)} = \frac{\int \rho_{A_1}(\alpha_{tn},p_t)d^2p_t}{\int \rho_{A_2}(\alpha_{tn},p_t)d^2p_t} = \frac{a_2(A_1)}{a_2(A_2)}\Big|_{1.6>\alpha\geq 1.3}$$



Masses of NN system produced in the process are small - strong suppression of isobar, 6q degrees of freedom.



Frankfurt et al, 93

k_{min}=0.3 GeV

k_{min}=0.25 GeV

Right momenta for onset of scaling !!!

The local FSI interaction, up to a factor of 2, cancels in the ratio of σ's

High energy processes are dominated by interactions near LC- ➜ cross sections are simply expressed through LC wave functions

$$\rho^{\mathrm{p}}_{\mathrm{A}}(\alpha,k_\perp) = \int \psi^2(\alpha_1\ldots\alpha_A,k_{1\perp}\ldots k_{A\perp})\prod_{i=1}^{A}\frac{\mathrm{d}\alpha_i}{\alpha_i}\mathrm{d}^2k_{i\perp}\delta\left(1-\frac{\sum\alpha_i}{A}\right)$$

$$\times\ \delta\left(\sum_{i=1}^{A}k_{i\perp}\right)\sum_{i=1}^{Z}\alpha_i\delta(\alpha-\alpha_i)\delta(k_{i\perp}-k_\perp).$$

Single nucleon light cone density matrix

$$\int_0^A \rho^{\mathrm{N}}_{\mathrm{A}}(\alpha,k_\perp)\frac{\mathrm{d}\alpha}{\alpha}\mathrm{d}^2k_\perp = A$$

$$\int_0^A \alpha\rho^{\mathrm{N}}_{\mathrm{A}}(\alpha,k_\perp)\frac{\mathrm{d}\alpha}{\alpha}\mathrm{d}^2k_\perp = \int_0^A \rho^{\mathrm{N}}_{\mathrm{A}}(\alpha,k_\perp)\frac{\mathrm{d}\alpha}{\alpha}\mathrm{d}^2k_\perp\frac{\sum\alpha_i}{A} = A.$$

Example

$$F_{2A}(x,Q^2) = \sum_{\mathrm{N=p,n}}\int F_{2\mathrm{N}}(x/\alpha,Q^2)\rho^{\mathrm{N}}_{A}(\alpha,k_{\mathrm{t}})\frac{\mathrm{d}\alpha}{\alpha}\mathrm{d}^2k_{\mathrm{t}}.$$

If one uses a rest frame approaches - one needs to use a spectral function

$$P_A(k,E) = \langle \psi_A | a^+_{\mathrm{N}}(k) \delta(E + E_{\mathrm{R}} - E_{\mathrm{fX}}) a_{\mathrm{N}}(k) | \psi_A \rangle,$$

Information contained in n(k) is not sufficient/ of limited value

$$n_A(k) = \int_0^\infty P_A(k,E)\mathrm{d}E.$$

No correspondence between asymptotic of $n(k \to \infty)$ and $\rho_A^N(\alpha \to A)$

Some resemblance between structure of diagrams for high momentum dependence of various contributions to the spectral function P(k,E) and $\rho(\alpha, p_t)$.

LC spectral function - removal of a nucleon with given α, p_t with a distribution over recoil "+" component: $S(\alpha, p_t, p^+_{rec})$

$\int S(\alpha, p_t, p^+_{rec}) dp^+_{rec} = \rho_A^N(\alpha, p_t)$ similar to $\int S(k, E_{rec}) dE_{rec} = n_A^N(k)$

BUT

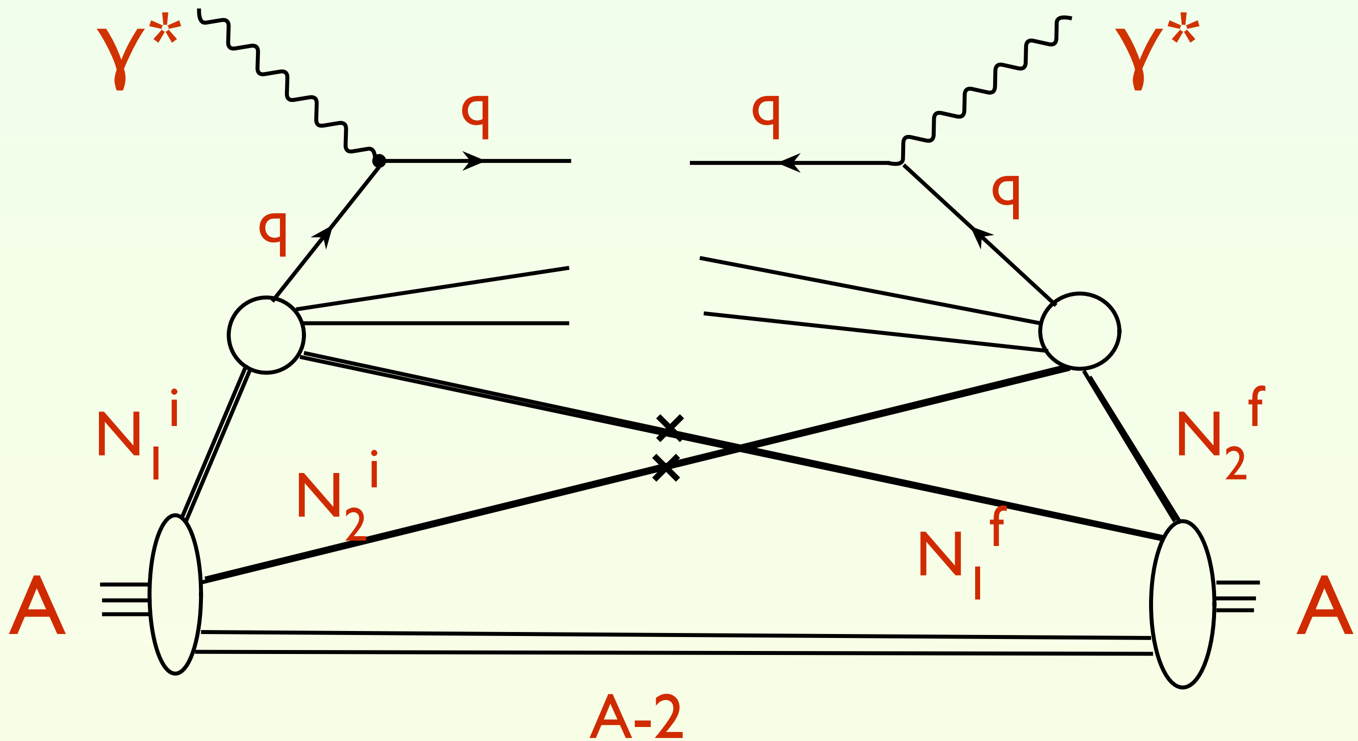
$\rho_A^N(\alpha, p_t)$ is a physical observable while $n_A^N(k)$ is not

Similarly the LC decay function $D(\alpha, p_t, \beta, r_t, p^+_{rec})$ has recoil effects build in (nonlinear relation between internal and observed momenta) - problem for using nonrel. decay function. *Reminder - decay function parametrically differs from double momentum distribution (even different A-dependence)*

Question: If one needs to introduce LC wave functions - why not switch directly to quarks & gluons? Parton densities are anyway defined on LC. Too many degrees of freedom, difficult to take into account overlapping integrals. For some cases one can demonstrate that impulse approximation (plus rescattering corrections) in terms of hadronic degrees of freedom is justified.

To illustrate this point let us consider whether / in what situations we trust impulse approximation form for the amplitude in the hadronic basis for the nucleus wave function (for simplicity we consider DIS where on quark level impulse approximation is fine)

Consider interference between scattering off two different nucleons



Introduce nucleon light-cone fractions, α. Free nucleon α=1, $\alpha_f \le 1 - x$

For nucleus to have significant overlap of |in> and <out| states

$$\alpha_{N_1^f} \le \alpha_{N_1^i} - x \sim 1, \ \alpha_{N_2^i} \le \alpha_{N_2^f} - x \sim 1$$

Interference is very strongly suppressed for x >0.2 - would require very large momenta in the nucleus WF

Additional suppression because of the suppression of large

$z \equiv x_F = \frac{\alpha}{1-x}$ for $x \geq 0.1$

$$\frac{d\sigma(z)}{dz/z}_{|z\to 1} \propto (1-z)^{n(x)}, \; n(x \geq 0.2) \sim 1, \; n(0.02 < x < 0.1) \sim 0, \; n(x < 0.01) \sim -1.$$

FS77

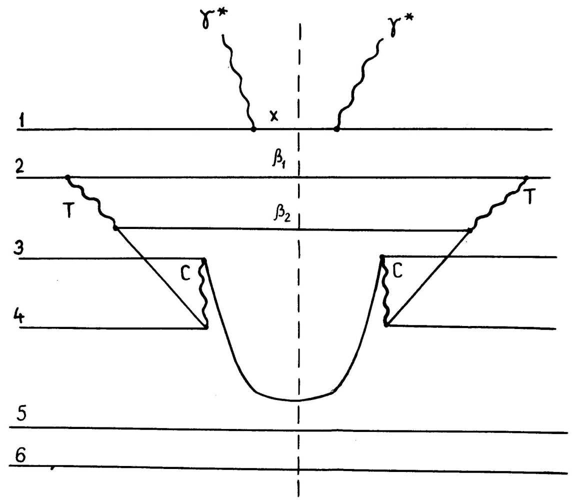
$\Longrightarrow$ Interference is small for x> 0.1 and impossible for x>0.3.

More subtle situation for pion fields.

$\Longrightarrow$ Large interference for x< 0.01 leading to large leading twist shadowing. How big is HT shadowing is an open question. Issue of duality.

Structure of the light cone density matrix.

In principle one can start from calculating many body LC wave function based on many body bound state equation (involves three body potential to keep rotational invariance satisfied). We use cluster expansion and analog of quark counting rules.



The dominant QCD diagram for the process $\ell + \mathrm{D} \to \ell' + \mathrm{N} + \mathrm{X}$

at fixed $x \sim \frac{1}{3}$ and $\alpha \to 2 - X$ in the 6q model of the deuteron

$$\rho_{\mathrm{D}}^{\mathrm{N}}(\alpha, k_\perp = 0) \sim (2-\alpha)^3 \quad \text{at } 1.5 < \alpha < 1.8.$$

FS79

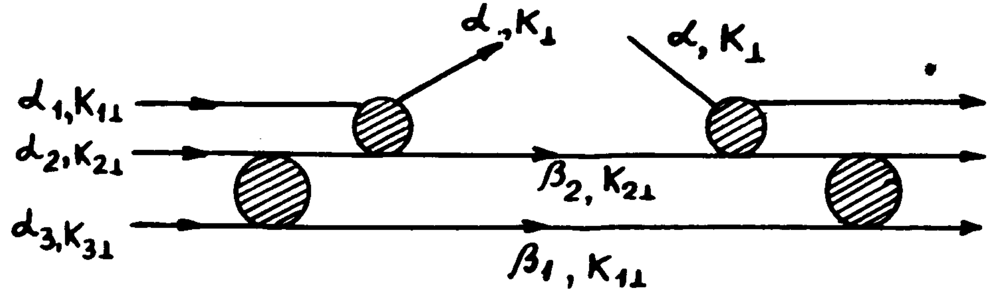


FIG. 2.8: A typical diagram for the three-nucleon correlation.

$$\rho_3(\alpha, k_\perp = 0) = \int \frac{\mathrm{d}\beta_1}{\beta_1}\mathrm{d}^2 k_{1\perp}\frac{\mathrm{d}\beta_2}{\beta_2}\mathrm{d}^2 k_{2\perp}\delta(\beta_1+\beta_2+\alpha-3) \times \delta(k_{1\perp}+k_{2\perp}+k_\perp)\psi^2(2-\beta_1, k_{1\perp})\psi^2\left(\left(2-\frac{2\beta_2}{\alpha}\right), k_{2\perp}\right).$$

Assuming that $\psi^2(2-\beta_1, k_\perp)_{\beta_1\to 0} \sim (2-\beta_1)^{n+1} f(k_\perp^2)$ we obtain

$$\rho_3(\alpha, k_\perp = 0) \sim (3-\alpha)^{2n+1}.$$

$$\rho_j(\alpha, k_\perp = 0) \sim (j-\alpha)^{n(j-1)+j-2}$$

$$\rho_A^N(\alpha, k_\perp = 0) = \sum_{j=2}^{A} a_j C j \left(1-\frac{\alpha-1}{j-1}\right)^{n(j-1)+j-2}$$

$$\rho_A^j(\alpha, k_\perp) \propto (1 - \frac{\alpha - 1}{j - 1})^{n(j-1)+j-2}$$

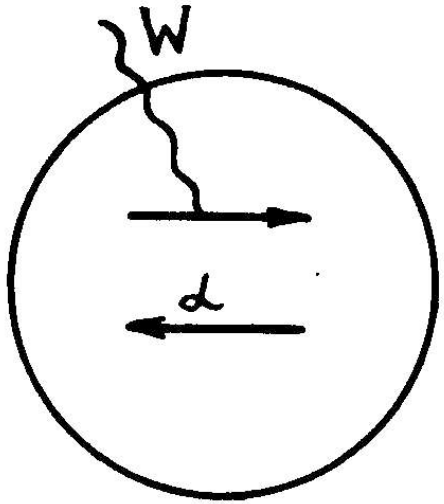
a remarkable property for n~ 3

$$\rho_A^{(3)}(\alpha, k_\perp)/\rho_A^{(2)}(\alpha, k_\perp) \approx const$$

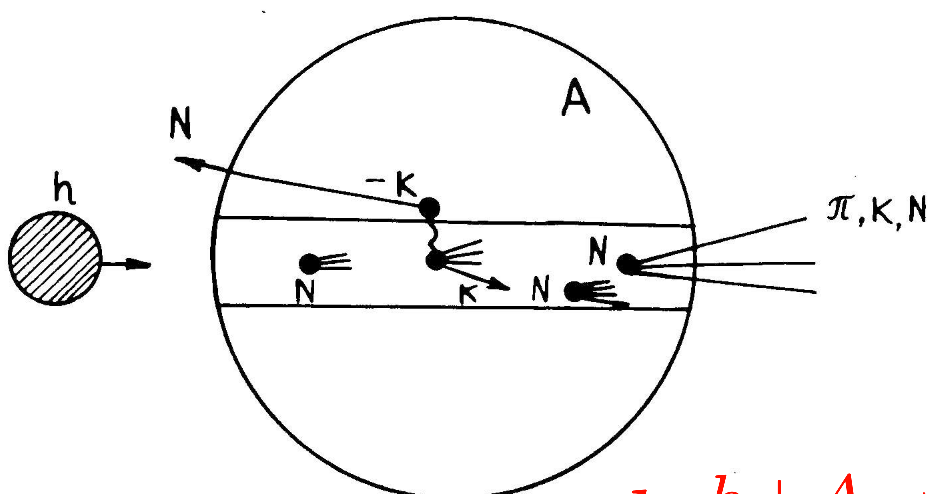
with accuracy 10% for $1.3 \leqq \alpha < 1.6$

and increasing rapidly for $\alpha \geq 1.6$

hence j> 2 SRCs contribute significantly to ρ^N_A already at $\alpha \geq 1.3$ but don't lead a strong dependence of ρ^N_A / ρ^N_D for $\alpha \leqq 1.6$. However the recoil "+" component is *in average* smaller for j> 2 but the distribution could be broader than for j=2. May impact scaling of the ratios at x> 1.



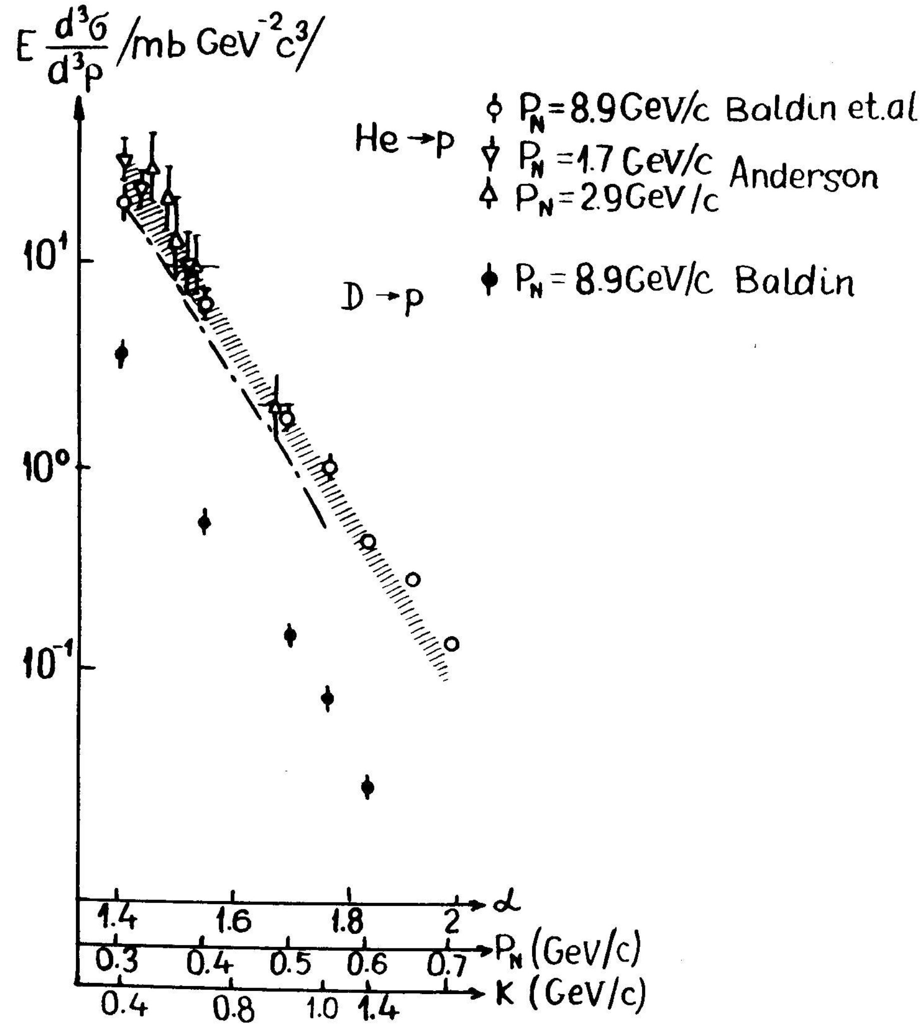
Production of a fast backward nucleon in the W* scattering from the two-nucleon correlation spectator mechanism.

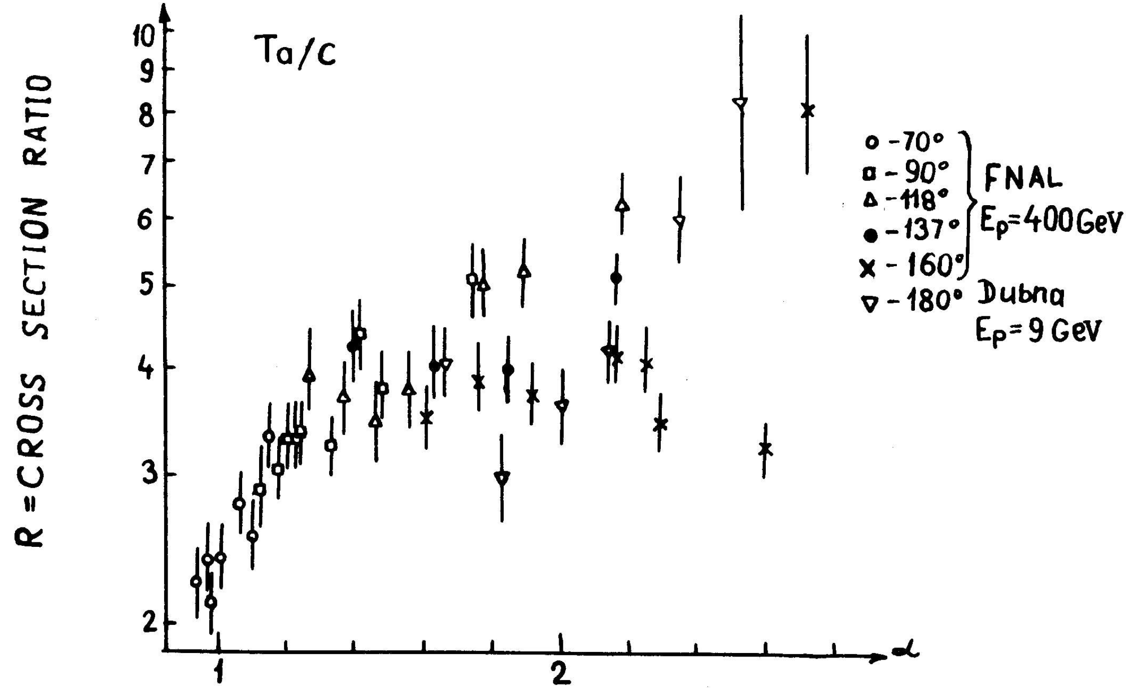


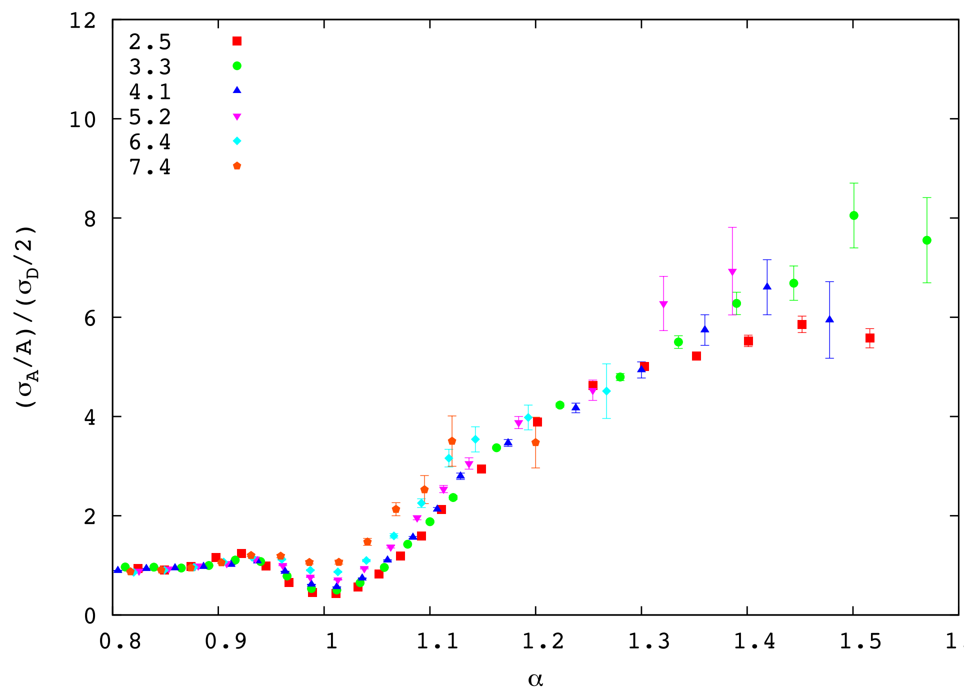
Production of a fast backward nucleon in the pA scattering

$$G_h^{A/N}(\alpha, p_t) \equiv \frac{d\sigma^{h+A\to N+X}}{\frac{d\alpha d^2 p_t}{\alpha}} = \kappa_h A \sigma_{in}^{hN} \rho_A^N(\alpha, p_t)$$

where factor κ_h accounts for local screening effects

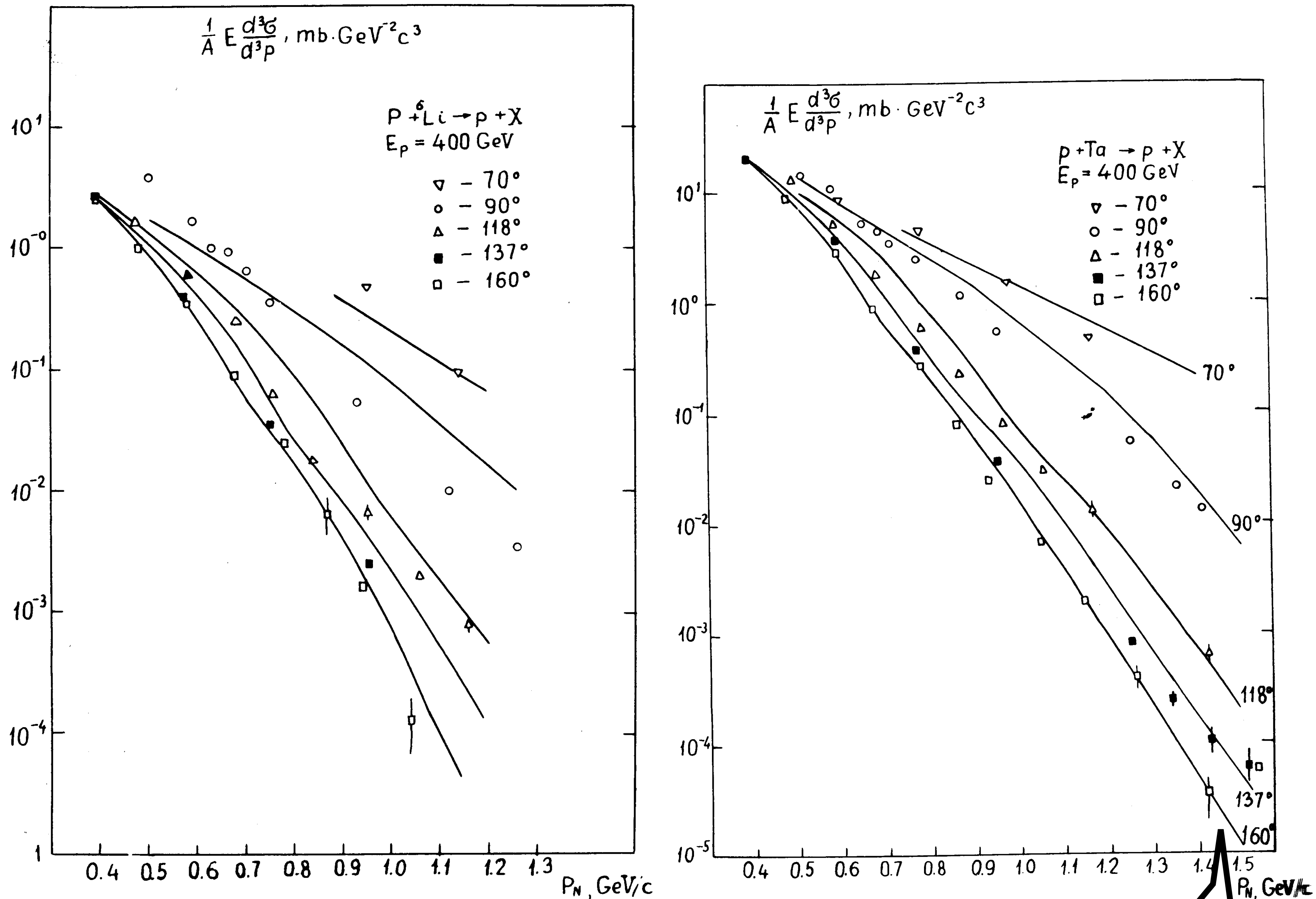






4He/ D similarity breaks around α ~ 1.6

From N.Fomin thesis



(a) (b)

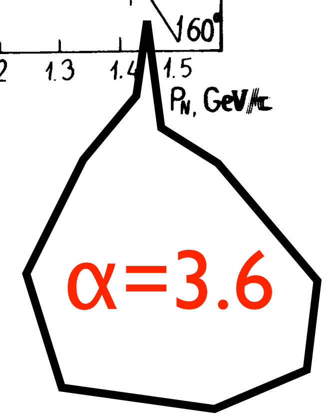
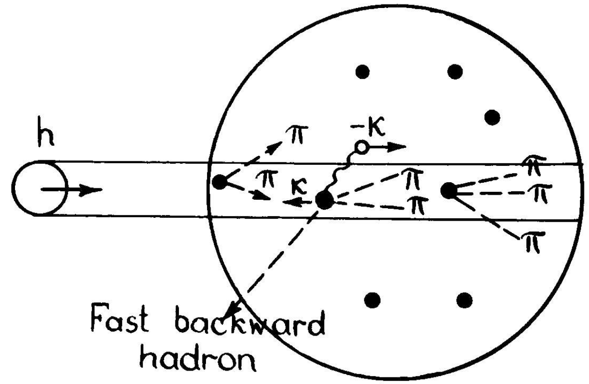
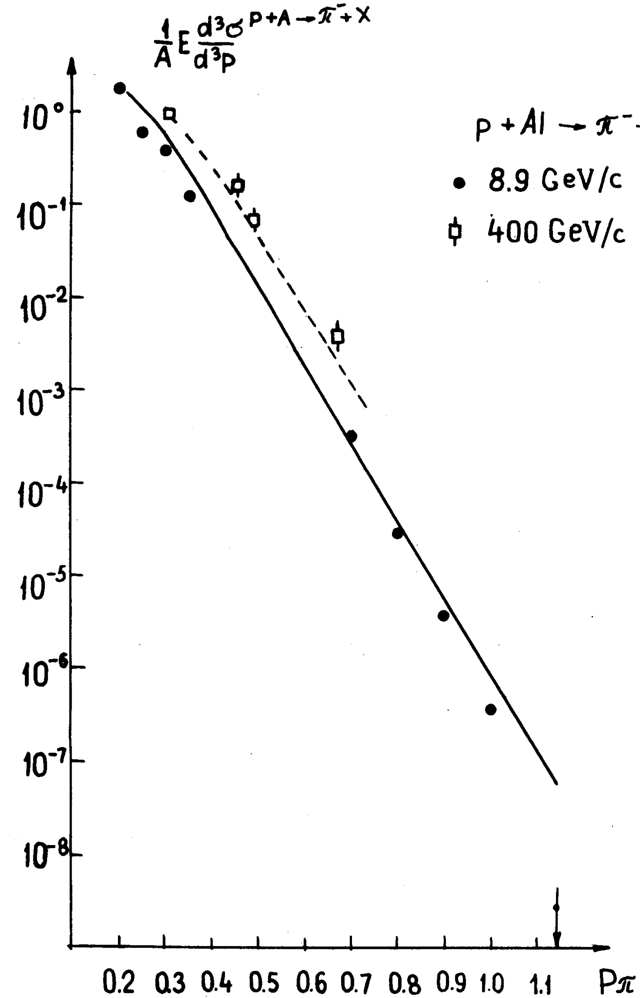


FIG. 8.4: Comparison of the FNC model with the 400 GeV data [35, 36].



$$G_{\rm h}^{\rm A/b}(\alpha, p_\perp) = \sum_{\rm N=p,n} \int \rho_{\rm A}^{\rm N}(x, k_\perp) G_{\rm h}^{\rm N/b}\left(\alpha/x, p_\perp - \frac{\alpha}{x} k_\perp\right) \frac{{\rm d}x}{x} {\rm d}^2 k_\perp.$$



Comparison of the FNC model predictions with the fast backward pion yields at E= 9 GeV and E= 400 GeV

Now we focus on the LC dynamics for two body case - more technical discussion

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

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

Problem - we cannot use a guiding principle experience of the models of NN interactions based on the meson theory of nuclear forces - *such models have a Landau pole close to mass shell and hence generate a lot of multi meson configurations*. (On phenomenological level - problem with lack of enhancement of antiquarks in nuclei)

Instead, 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 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:

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

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

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

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 $k_N \approx 550\, MeV$

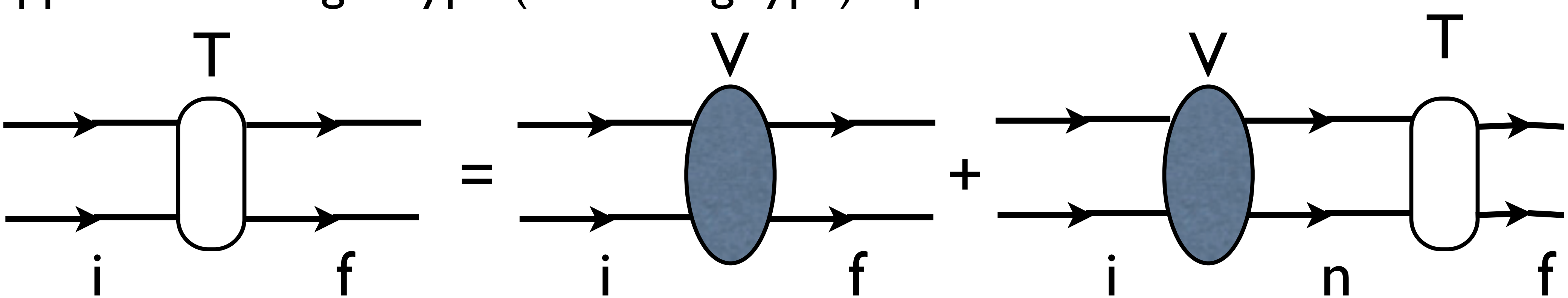
Warning: Correspondence argument (WF <--> continuum) is not applicable for the cases when the probe interacts with rare configurations (EMC effect?) in the bound nucleons due to the presence of an additional scale

Light-cone Quantum mechanics of two nucleon system

Due to the presence of a small parameter (inelasticity of NN interactions) it makes sense to consider two nucleon approximation for the LC wave function of the deuteron.

Key point is presence of the unique matching between nonrelativistic and LC wave functions in this approximation. Proof is rather involved.

First step: include interactions which do not have two nucleon intermediate states into kernel V (like in nonrel. QM) to build a Lippman-Schwinger type (Weinberg type) equation.



The LC "energy denominator" is $1/(p_{n_+} - p_{f_+})$

Using explicit expression for the propagator in terms of the LC variables and using corresponding expressions for the two-body phase volume on LC we obtain:

$$T(\alpha_i, k_{it}, \alpha_f, k_{ft}) = V(\alpha_i, k_{it}, \alpha_f, k_{ft}) + \int V(\alpha_i, k_{it}, \alpha', k'_t) \frac{d\alpha'}{4\alpha'(1-\alpha')} \frac{d^2 k'_t}{(2\pi)^3}$$

$$\times \frac{T(\alpha', k'_t, \alpha_f, k_{ft})}{[(m^2 + k'^2_t)/\alpha'(1-\alpha') - (m^2 + k^2_{ft})/\alpha_f(1-\alpha_f)]/2}$$

Second step: Impose condition that master equation should lead to the Lorentz invariance of the on-energy-shell amplitude of NN scattering

Introduce three- vector $\vec{k} = (k_3, k_t)$ with

$$\alpha = \frac{\sqrt{m^2 + k^2} + k_3}{\sqrt{m^2 + k^2}}$$

Invariant mass of two nucleon system is $M_{NN}^2 = 4\frac{m^2 + k_t^2}{\alpha(2-\alpha)} = 4m^2 + 4k^2$

$$\begin{aligned} T(k_{\rm i}, k_{\rm f}, k_{\rm i3}, k_{\rm f3}) &= V(k_{\rm i}, k_{\rm f}, k_{\rm i3}, k_{\rm f3}) \\ &+ \int V(k_{\rm i}, k', k_{\rm i3}, k'_3) \frac{{\rm d}^3 k'}{\sqrt{k'^2 + m^2}} \frac{1}{4(2\pi)^3} \frac{T(k', k_{\rm f}, k'_3, k_{\rm f3})}{k'^2 - k_{\rm f}^2}. \end{aligned}$$

We also derived LC Eqs for N-nucleon bound state (1991)

On-mass-shell $$T(k, k_3, k_{\rm f}, k_{\rm f3}) = T(k^2, k_{\rm f}^2, kk_{\rm f})$$

$$V(k, k_3, k_{\rm f}, k_{\rm f3}) = V(k^2, k_{\rm f}^2, kk_{\rm f})$$

For rotational invariance of T it is sufficient that the same relation is satisfied for V off-mass-shell. The proof that this condition is also necessary is much more complicated (FS + Mankievich 91) . At the same time it is obvious that it would be very difficult to satisfy the highly nonlinear equation for the on-shell amplitude if this condition were violated.

The proof uses methods of complex angular momentum plane and assumption that the amplitude is decreases sufficiently fast with momentum transfer (actually rather slow decrease was sufficient).

$$T(k,k_{\mathrm{f}}) = V(k,k_{\mathrm{f}}) + \int V(k,k') \frac{\mathrm{d}^3 k'}{4\sqrt{k'^2+m^2}} \, \frac{1}{k'^2 - k_{\mathrm{f}}^2} \, \frac{1}{(2\pi)^3} \, T(k',k_{\mathrm{f}})$$

Very similar structure for the equation for the scattering amplitude in NR QM and for LC. If a NR potential leads to a good description of phase shifts the same is true for its LC analog. Hence *simple approximate relation for LC and NR two nucleon wave function*

Spin zero /unpolarized case

Relation between LC and NR wf.

$$\int \Psi^2_{NN}\left(\frac{m^2+k_t^2}{\alpha(2-\alpha)}\right)\frac{d\alpha d^2k_t}{\alpha(2-\alpha)} = 1 \qquad \int \phi^2(k)d^3k = 1$$

$$\Psi^2_{NN}\left(\frac{m^2+k_t^2}{\alpha(2-\alpha)}\right) = \frac{\phi^2(k)}{\sqrt{(m^2+k^2)}}$$

Similarly for the spin 1 case we have two invariant vertices as in NR theory:

$$\psi^{\rm D}_\mu \varepsilon^{\rm D}_\mu = \bar{U}(p_1)\{\gamma_\mu \Gamma_1(M^2_{\rm NN}) + (p_1-p_2)_\mu \Gamma_2(M^2_{\rm NN})\}U(-p_2)\varepsilon^D_\mu.$$

hence there is a simple connection to the S- and D- wave NR WF of D

For two body system in two nucleon approximation

the biggest difference between NR and virtual nucleon approximation and LC is in the relation of the wave function and the scattering amplitude

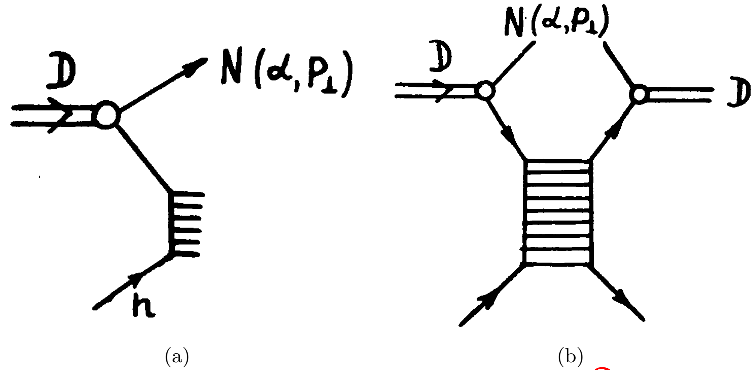
Let us illustrate this for the high energy deuteron break up $h + D \to X + N$ in the impulse approximation with nucleon been in the deuteron fragmentation region - spectator contribution.

For any particle, b, in the final state in the target fragmentation region the light cone fractions are conserved under longitudinal boosts

$$\alpha_{\mathrm{b}}/2 = (E_{\mathrm{b}} + p_{\mathrm{b}Z})/(E_{\mathrm{D}} + p_{\mathrm{D}Z})$$

Hence in the rest frame

$$2 > \alpha_{\mathrm{b}} \equiv \left(\sqrt{m_{\mathrm{b}}^2 + p_{\mathrm{b}}^2} - p_{\mathrm{b}Z}\right)/M_{\mathrm{D}}$$

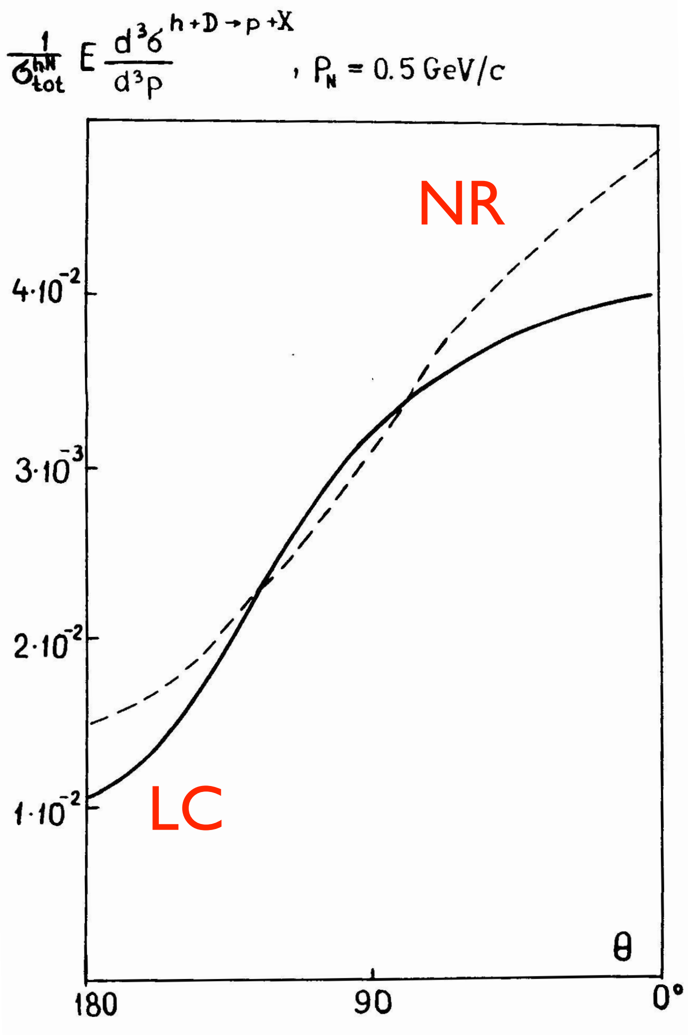


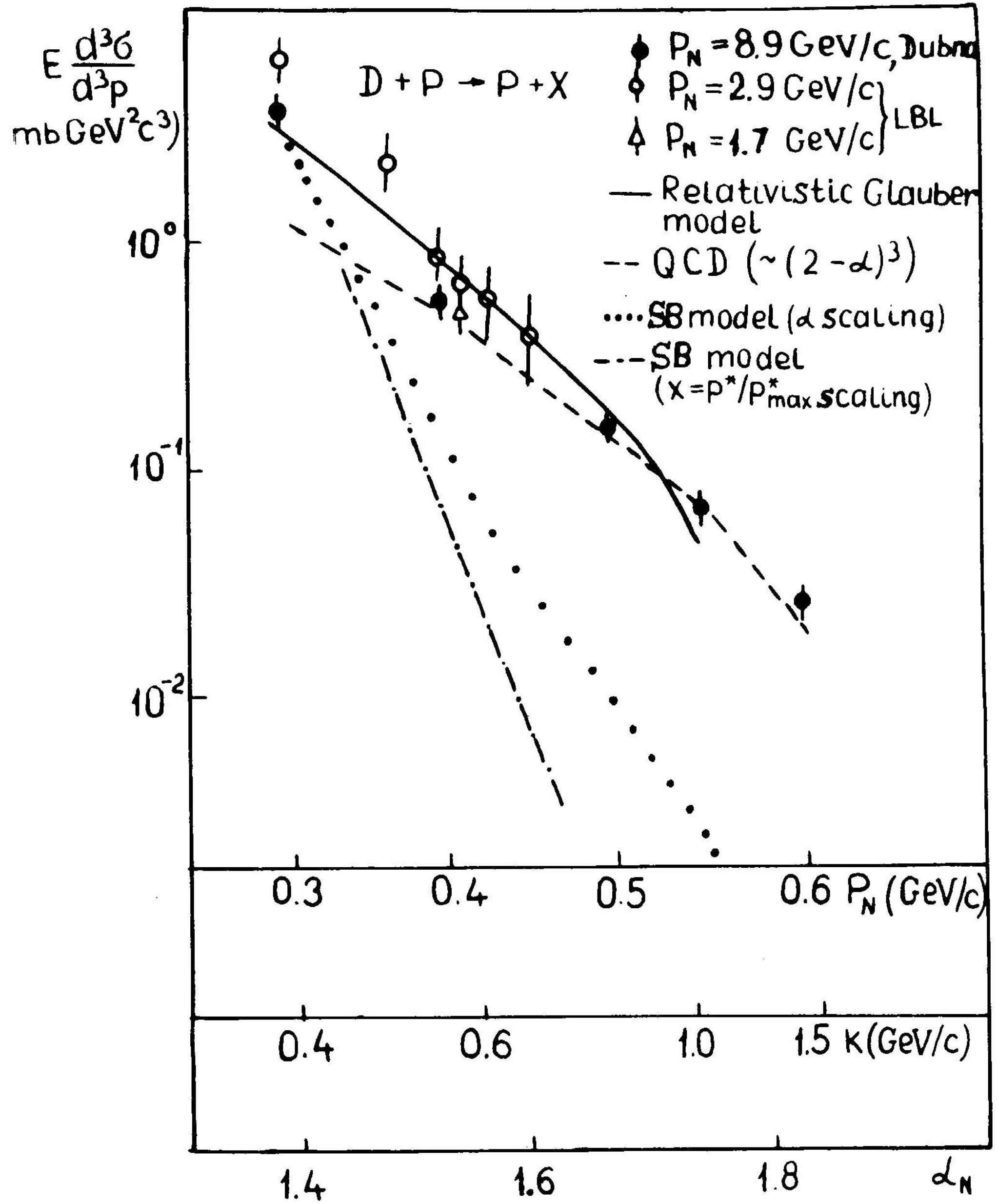
$$\frac{d\sigma^{D+h\to N+\cdots}}{(d\alpha/\alpha)d^2p_\perp}\Big|_{\text{LC imp.approx.}} = \sigma^{hN}_{inel.}[(2-\alpha)s_{NN}]\cdot\frac{[U^2(k)+W^2(k)]}{(2-\alpha)}\sqrt{k^2+m^2}$$

$$\frac{d\sigma^{D+h\to N+\cdots}}{(d\alpha/\alpha)d^2p_\perp}\Big|_{\text{NR imp.approx.}} = \sigma^{hN}_{inel.}[(2-\alpha)s_{NN}]\cdot(2-\alpha)[U^2(p)+W^2(p)]\sqrt{p^2+m^2}$$

LC nucleon: nonlinear relation between internal momentum k and observed momentum p (see next slide). Asymptotic behavior at $\alpha\to 2$ is determined by WF at $k\to\infty$. Similar to particle physics.

NR/Virtual nucleon: observed momentum is the same as in the WF, asymptotic at $\alpha\to 2, k_t=0$, is determined by WF at finite momentum 0.75 m, and has the same (2-α) dependence on α.





$$\alpha = (\sqrt{p^2 + m^2} - p_3)/(m_D/2)$$

$$\alpha = 1 - \frac{k_3}{\sqrt{k^2 + m^2}}$$

The best way to look for the difference between LC and NR/Virtual nucleon seems to be scattering off the polarized deuteron

$$\frac{\mathrm{d}\sigma(\mathrm{e}+\mathrm{D}_\Omega \to \mathrm{e}+\mathrm{N}+\mathrm{X})}{(\mathrm{d}\alpha/\alpha)\,\mathrm{d}^2 p_\mathrm{t}} \Bigg/ \frac{\mathrm{d}\sigma(\mathrm{e}+\mathrm{D} \to \mathrm{e}+\mathrm{N}+\mathrm{X})}{(\mathrm{d}\alpha/\alpha)\,\mathrm{d}^2 p_\mathrm{t}}$$

$$= 1 + \left(\frac{3k_i k_j}{k^2}\,\Omega_{ij} - 1\right) \frac{\frac{1}{2}w^2(k) + \sqrt{2}u(k)w(k)}{u^2(k)+w^2(k)} \equiv P(\Omega, k)$$

Ω is the spin density matrix of the deuteron, $\mathrm{Sp}\Omega = 1$

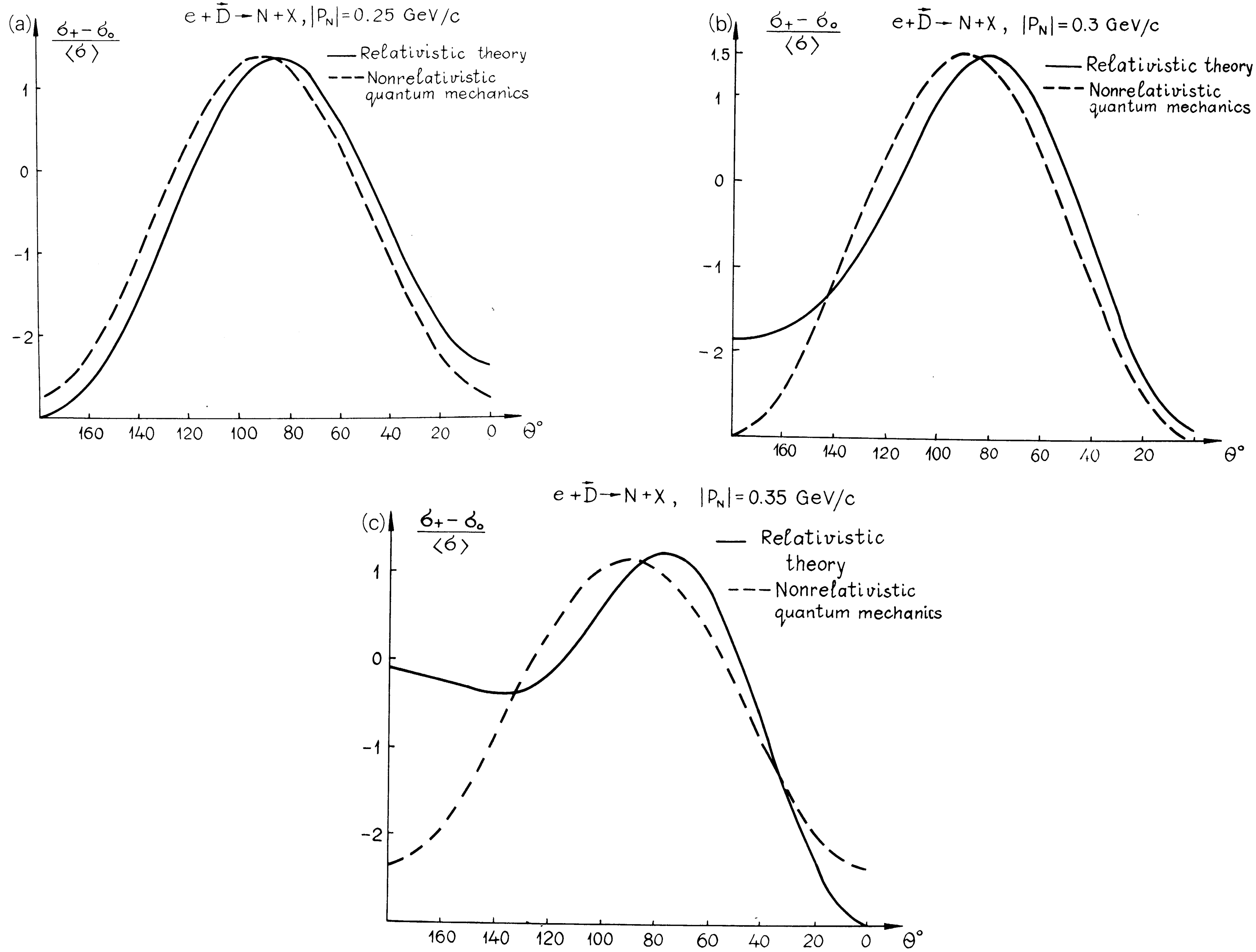
Consider

$$R = T_{20} = \left[\frac{1}{2}(\sigma_+ - \sigma_-) - \sigma_0\right] \Big/ \langle\sigma\rangle$$

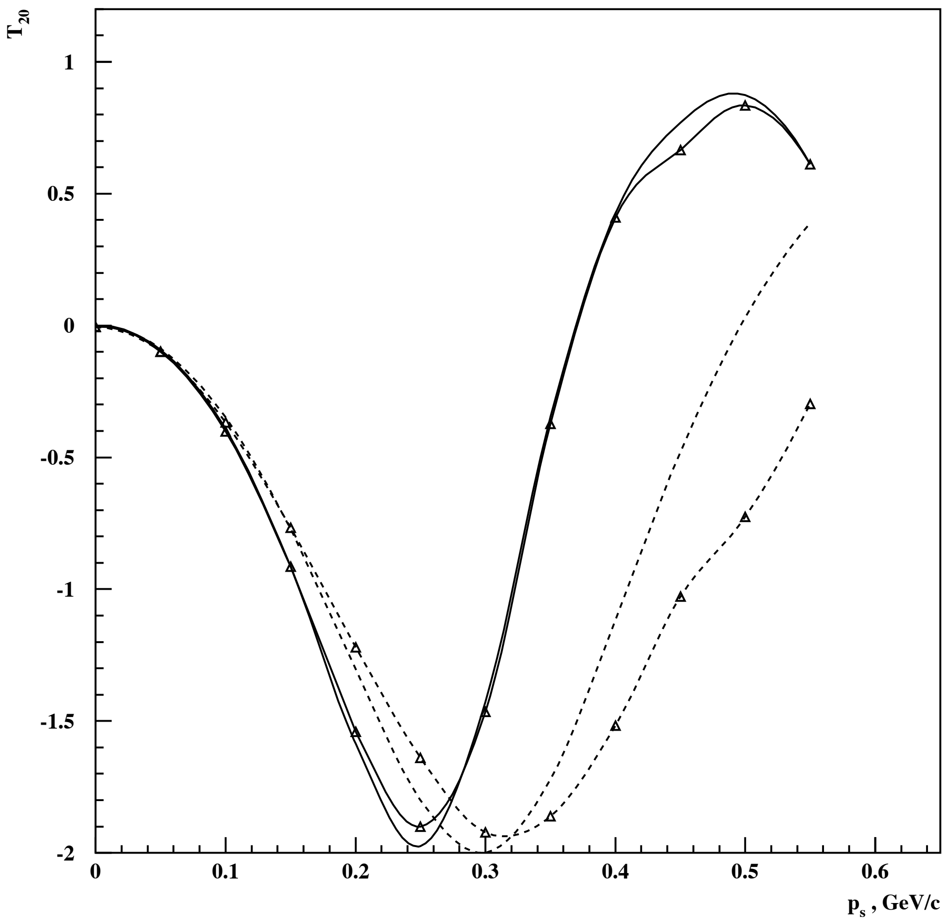
$$R^{lc}(p_\mathrm{s}) = \frac{3(k_\mathrm{t}^2/2 - k_z^2)}{k^2}\,\frac{u(k)w(k)\sqrt{2} + \frac{1}{2}w^2(k)}{u^2(k)+w^2(k)}$$

$$R^{\mathrm{nonrel}}(p_\mathrm{s}) = \frac{3(p_\mathrm{t}^2/2 - p_z^2)}{p^2}\,\frac{u(p)w(p)\sqrt{2} + \frac{1}{2}w^2(p)}{u^2(p)+w^2(p)}$$

trivial angular dependence for fixed p


(a)
$\frac{\sigma_+ - \sigma_0}{\langle\sigma\rangle}$
$e + \vec{D} \rightarrow N + X, |P_N| = 0.25$ GeV/c
— Relativistic theory
- - - Nonrelativistic quantum mechanics
1
0
-1
-2
160 140 120 100 80 60 40 20 0 θ°
(b)
$\frac{\sigma_+ - \sigma_0}{\langle\sigma\rangle}$
$e + \vec{D} \rightarrow N + X, |P_N| = 0.3$ GeV/c
— Relativistic theory
- - - Nonrelativistic quantum mechanics
1.5
1
0
-1
-2
160 140 120 100 80 60 40 20 θ°
$e + \vec{D} \rightarrow N + X, |P_N| = 0.35$ GeV/c
(c)
$\frac{\sigma_+ - \sigma_0}{\langle\sigma\rangle}$
— Relativistic theory
- - - Nonrelativistic quantum mechanics
1
0
-1
-2
160 140 120 100 80 60 40 20 0 θ°

Effect of FSI may differ on LC and NR - because of light cone fraction conservation



Sargsian and MS 96

p_s dependence of the(e,e'p) tensor polarization at ϑ=180°. Solid and dashed lines are PWIA predictions of the LC and VN methods, respectively. Marked curves include FSI.

Conclusions I

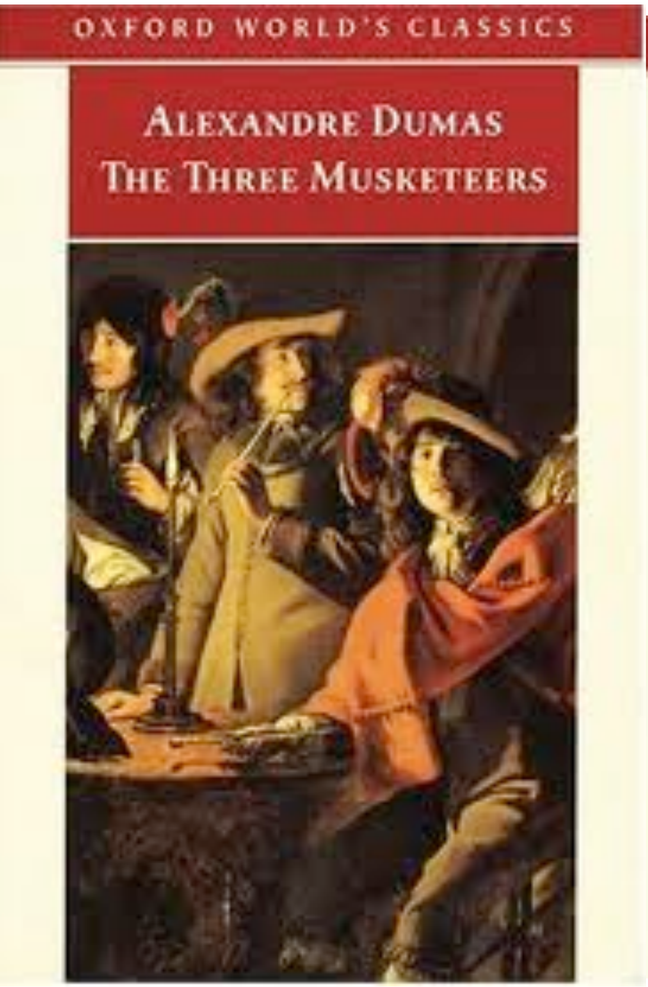
$\Rightarrow$ Light-cone approach allows to use a hidden parameter of medium energy NN interactions - small inelasticity.

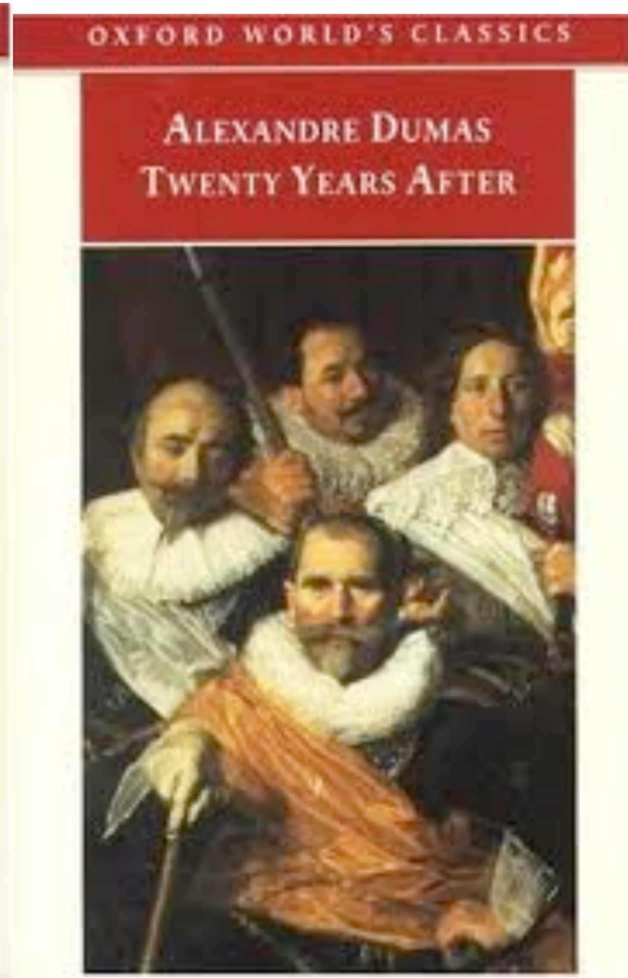
$\Rightarrow$ Several qualitative differences from virtual nucleon approximation

$\Rightarrow$ Allows to take into account space-time picture of high energy processes. Good current logic.

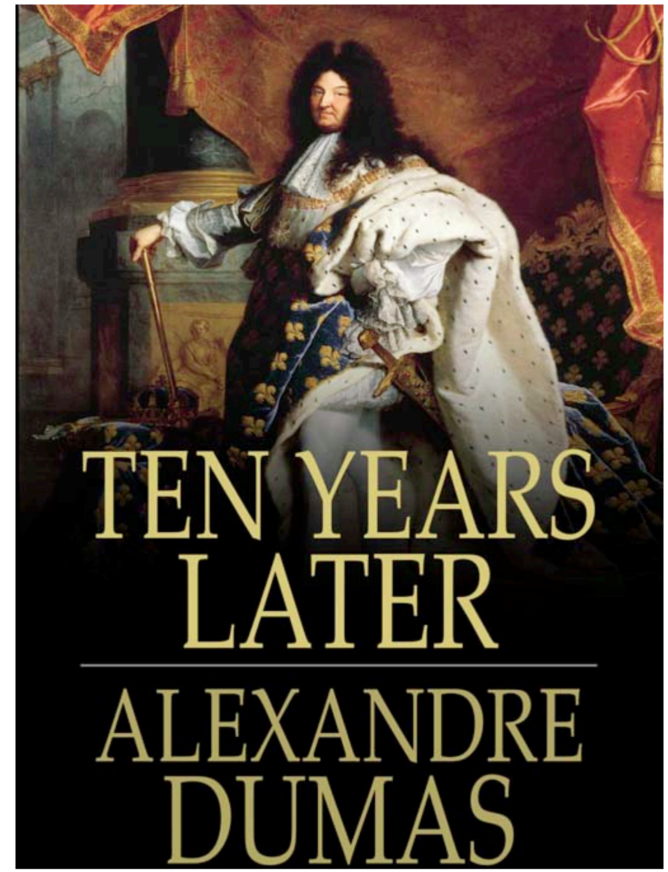
$\Rightarrow$ Need to develop approach combining LC and Glauber approach for high energy processes.

Part II: EMC Effect - 30 years after the discovery


OXFORD WORLD'S CLASSICS
ALEXANDRE DUMAS
THE THREE MUSKETEERS


OXFORD WORLD'S CLASSICS
ALEXANDRE DUMAS
TWENTY YEARS AFTER

+


TEN YEARS
LATER
ALEXANDRE
DUMAS

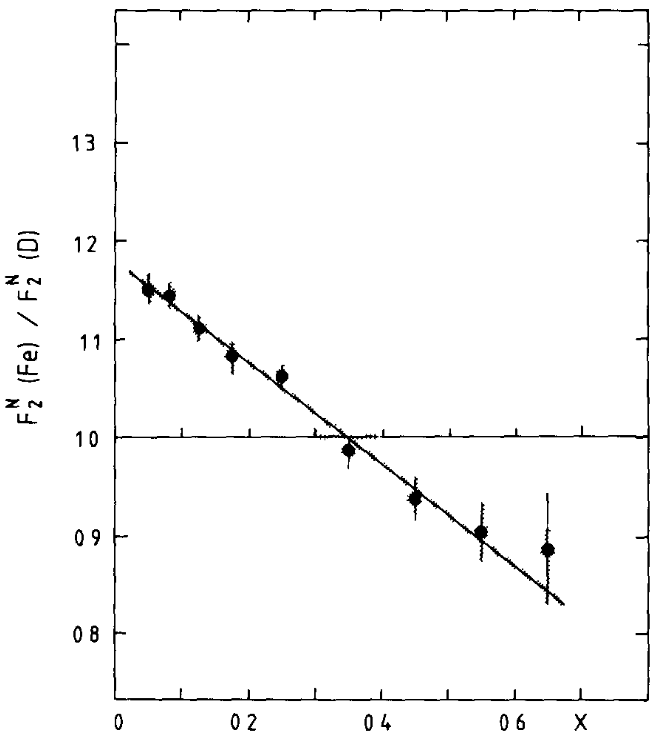
Volume 123B, number 3,4 PHYSICS LETTERS 31 March 1983

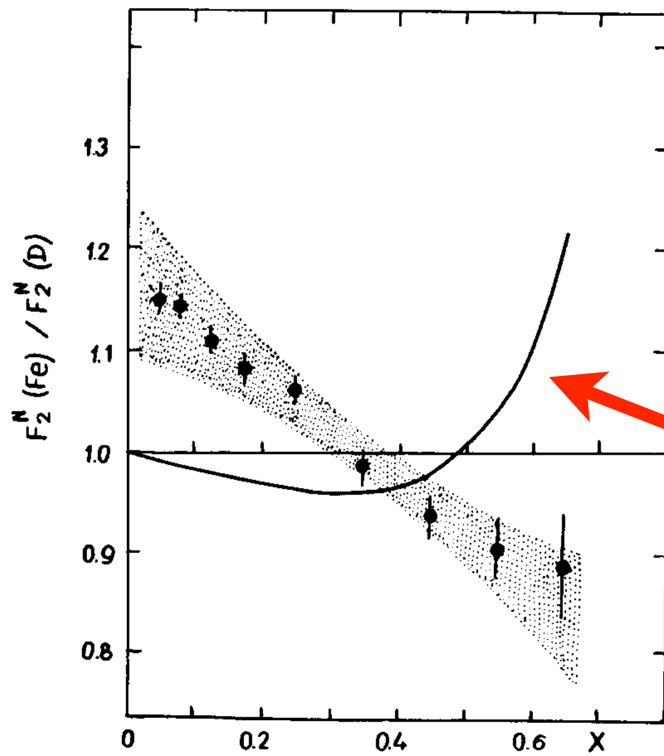
THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM

The European Muon Collaboration

First reported at the Rochester conference at Paris, 1982

Received 19 January 1983





Theoretical expectation under assumption that nucleus consists only of nucleons FS 81

How model dependent was the expectation?
EMC paper had many curves hence impression that curves could be moved easily.

Why the effect cannot be described in the approximation: nucleus = A nucleons?

P_A → = → $\alpha_1 P_A/A$, → $\alpha_2 P_A/A$, → $\alpha_3 P_A/A$

$\alpha_1 + \alpha_2 + \alpha_3 = 3$

If no Fermi motion: $\alpha_i = 1$

In this case probability to find a quark with momentum xP_A/A is

$$F_q^A(x) = A f_q^N(x)$$

⇒

$$R_A(x) \equiv F_q^A(x)/A f_q^N(x) = 1$$

Deviation of $R_A(x)$ from one is European Muon Collaboration (EMC) effect - 1983

early warning: EMC used different definition of x

Can account of Fermi motion describe the EMC effect?

YES

If one violates baryon charge conservation or momentum conservation or both

Many nucleon approximation:

$$F_{2A}(x,Q^2) = \int \rho_A^N(\alpha,p_t) F_{2N}(x/\alpha) \frac{d\alpha}{\alpha} d^2p_t$$

Light cone nuclear nucleon density (light cone projection of the nuclear spectral function - ≡probability to find a nucleon having momentum $\alpha P_A/A$

$$\int \rho_A^N(\alpha,p_t) \frac{d\alpha}{\alpha} d^2p_t = A$$

baryon charge sum rule

$$\frac{1}{A}\int \alpha \rho_A^N(\alpha,p_t) \frac{d\alpha}{\alpha} d^2p_t = 1 - \lambda_A$$

fraction of nucleus momentum NOT carried by nucleons

In nucleus rest frame $x = AQ^2/2m_A q_0$

Since spread in α due to Fermi motion is modest ⇒ do Taylor series expansion in (1- α): α= 1+ (α-1)

$$R_A(x,Q^2) = 1 - \frac{\lambda_A x F'_N(x,Q^2)}{F_N(x,Q^2)}$$

Fermi motion

$$+ \frac{x F'_{2N}(x,Q^2) + (x^2/2) F''_{2N}(x,Q^2)}{F_{2N}(x,Q^2)} \cdot \frac{2(T_A - T_{{}^2H})}{3m_N}$$

$$F_{2N} \propto (1-x)^n, n \approx 3$$

$$R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x} + \frac{xn\left[x(n+1)-2\right]}{(1-x)^2} \cdot \frac{(T_A - T_{{}^2H})}{3m_N}$$

small negative for x <0.5
> 0 and rapidly growing for x >0.5

EMC effect is unambiguous evidence for presence of non nucleonic degrees of freedom in nuclei. The question - what are they?

O.Nash: God in his wisdom made a fly
But he forget to tell us why

First explanations/models of the EMC effect

- Pionic model: extra pions - $\lambda_\pi \sim 4\%$ $\alpha_\pi \sim 0.15$

$$R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x}$$ + enhancement from scattering off pion field

- 6 quark configurations in nuclei with $P_{6q} \sim 20\text{-}30\%$

- *Nucleon swelling - radius of the nucleus is 20--15% larger in nuclei. Color is significantly delocalized in nuclei* Larger size → fewer fast quarks - possible mechanism: gluon radiation starting at lower Q^2

$$(1/A)F_{2A}(x,Q^2) = F_{2D}(x, Q^2\xi_A(Q^2))/2$$

- Mini delocalization - small swelling - enhancement of deformation at large x due to suppression of small size configurations in bound nucleons + valence quark antishadowing

Traditional nuclear physics strikes back:

EMC effect is just effect of nuclear binding : account for the nucleus excitation in the final state: $e + A \to e' + X + (A-1)^*$

First try: baryon charge violation because of the use of non relativistic normalization

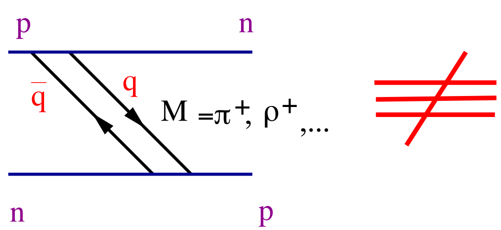
Second try: fix baryon charge ➔ violate momentum sum rule

Third try (not always done) fix momentum sum rule by adding mesons

⇓

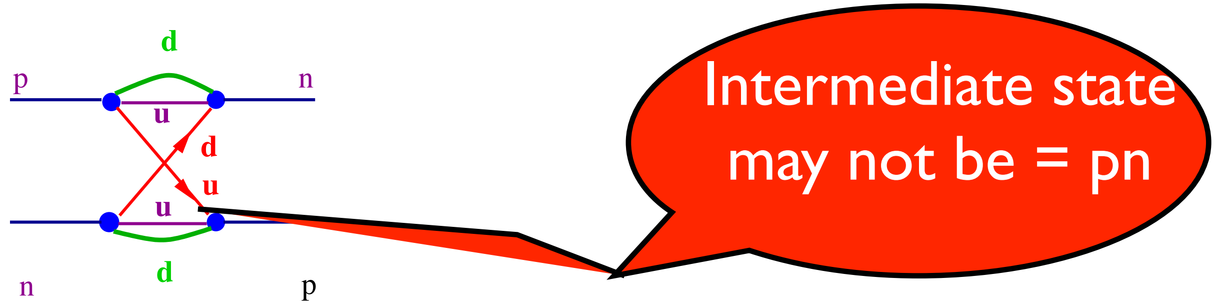
a version of the pion model

Pion model addresses a deep question - what is microscopic origin of intermediate and short-range nuclear forces - do nucleons exchange mesons or quarks/gluons? Duality?



Meson Exchange

extra antiquarks in nuclei



Quark interchange

no extra antiquarks

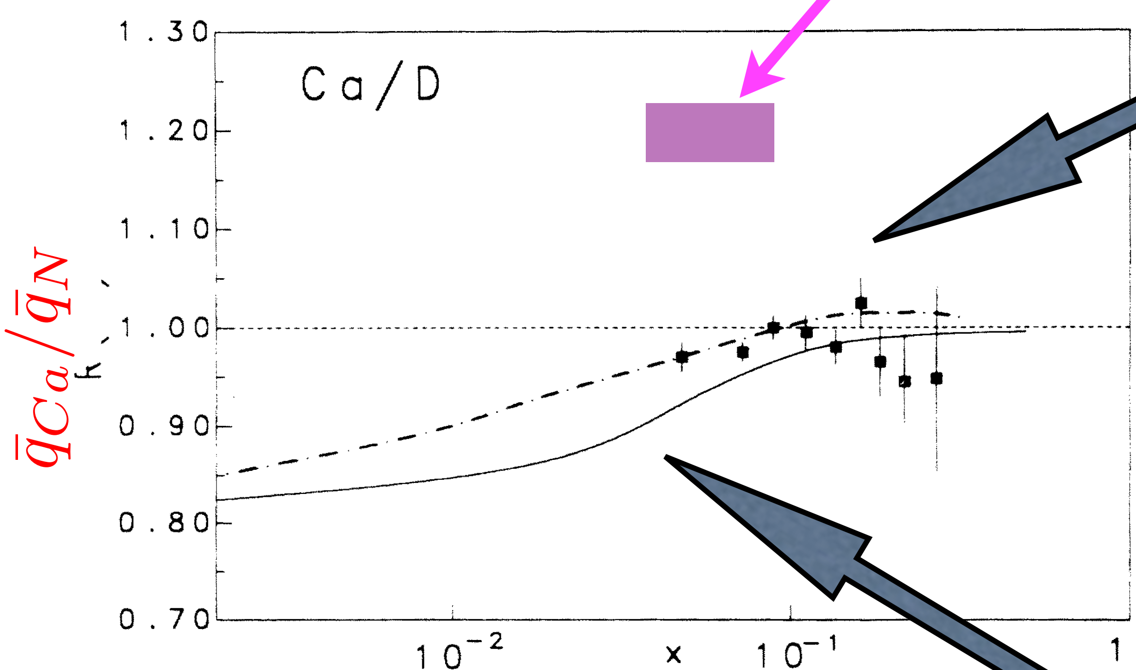
may correspond to a tower of meson exchanges with coherent phases - high energy example is Reggeon; pion exchange for low t special - due to small mass

Drell-Yan experiments (1989): $\bar{q}_{Ca}/\bar{q}_N \approx 0.97$

vs meson model expectation

$\bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2_{|\, x=0.05 \div 0.1}$

$Q^2 = 15$ GeV^2



A-dependence of antiquark distribution, data are from FNAL nuclear Drell-Yan experiment, curves - pQCD analysis of Frankfurt, Liuti, MS 90. Similar conclusions Eskola et al 93-07 analyses

$Q^2 = 2$ GeV^2

Five commandments

Honor baryon conservation law

Honor momentum conservation law

Thou shalt not introduce dynamic pions into nuclei

Thou shalt not introduce large deformations of low momentum nucleons

However large admixture of nonnucleonic degrees of freedom (20-- 30 %) strange but was not ruled out.

Qualitative change due to recent direct observation of short-range NN correlations at JLab and BNL

Honor existence of large predominantly nucleonic short-range correlations

enough for one tablet of law

Are SRC findings, lack of deformation of low momentum nucleon and lack of enhancement of antiquarks consistent with existence of the EMC effect?

Very few models of the EMC effect survive when all these constraints are included - essentially one scenario survives - strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with most of the effect due to the SRCs .

Let us characterize the effect as an averaged over nucleon momenta deformation of the bound nucleon pdf

First need to correct for two effects not related to nonnucleonic degrees of freedom

- In the fast frame (high energy processes) Coulomb photons are dynamical degree of freedom - implicit in the Fermi calculation of e.m interactions of fast particles. For large Z photons carry a significant fraction of the nucleus momentum -λ_γ ~.65 % for A=200

- Experimentalists used $x_p=Q^2/2m_p q_0$ instead of Bj's $x_A=AQ^2/2m_A q_0$

Correction for these two effects is

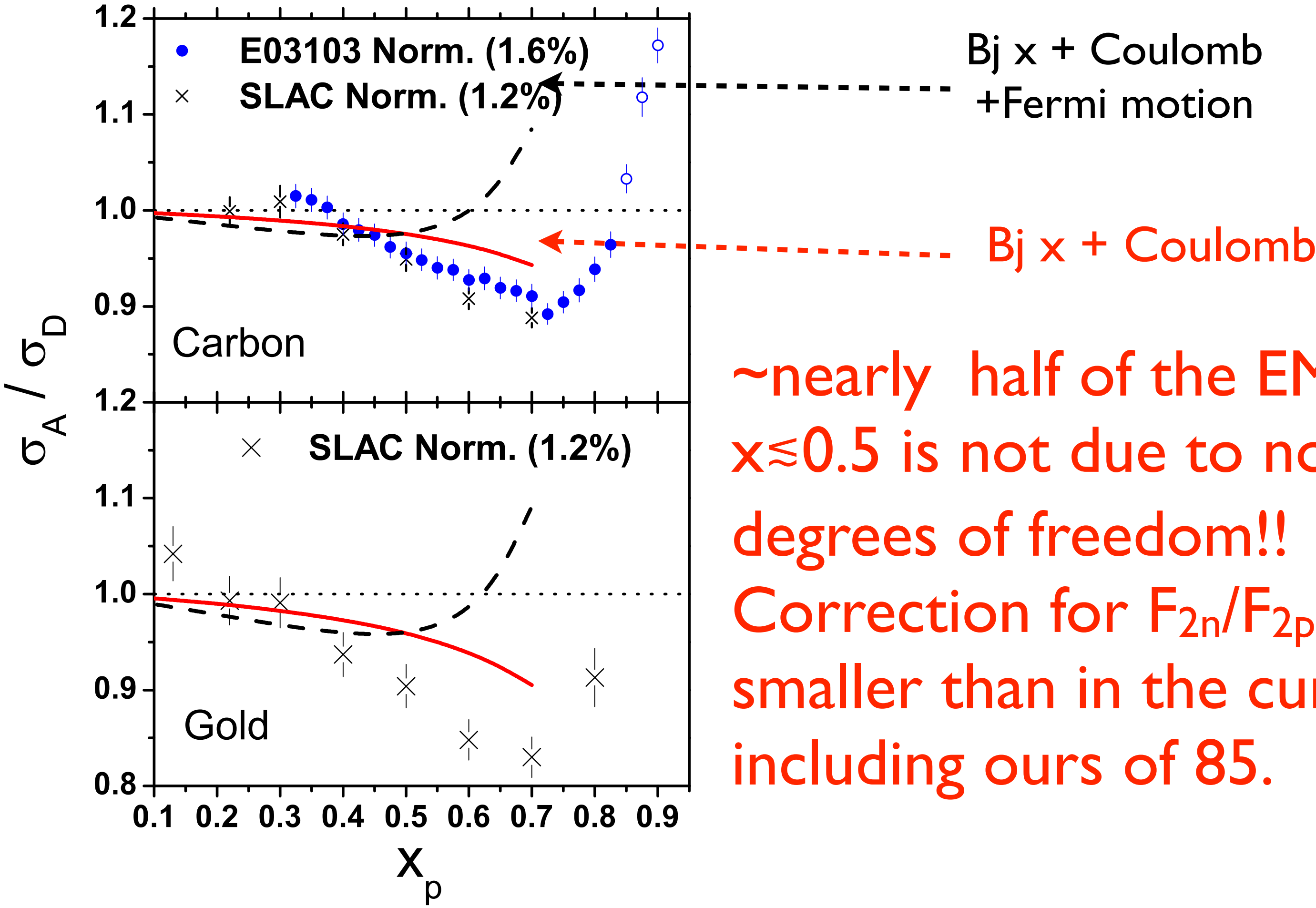
$$R(x_p) = f_A^j(x(1 + r_x + \lambda_\gamma))/f_N^j(x) \approx 1 - (r_x + \lambda_\gamma)n\frac{x}{1-x},$$

where

$$x_p/x = Am_p/m_A = (1 + (\epsilon_A - (m_n - m_p)N/A)/m_p) \equiv 1 + r_x,$$

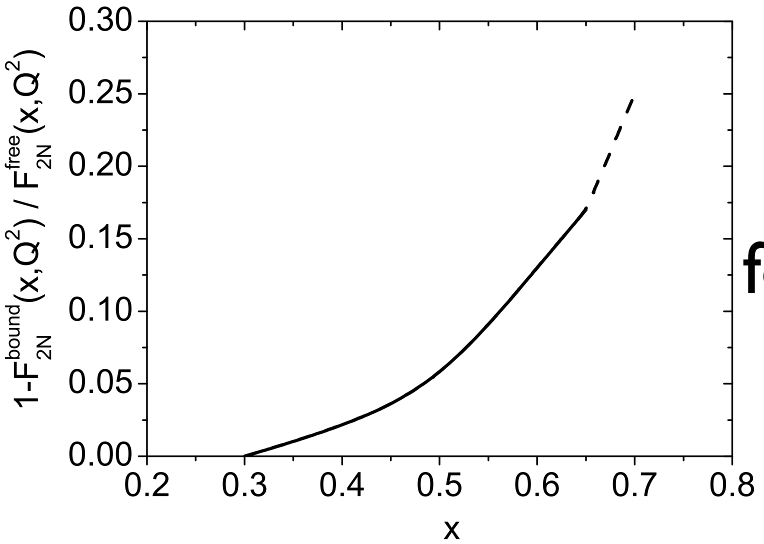
at the last step we took $f^j_N(x)$ $(1-x)^n$.

use of correct x is main effect for A< 40;
correct x and Coulomb are
approximately the same



~nearly half of the EMC effect at $x \lesssim 0.5$ is not due to nonnucleonic degrees of freedom!!
Correction for F_{2n}/F_{2p} is significantly smaller than in the current analyses including ours of 85.

Large hadronic effect only for x>0.5 - natural in the mini-delocalization / color screening model of F&S 83-85



for k~ 300 MeV/c

Estimate of the ratio of the bound and free nucleon structure functions in medium and heavy nuclei as a function of x

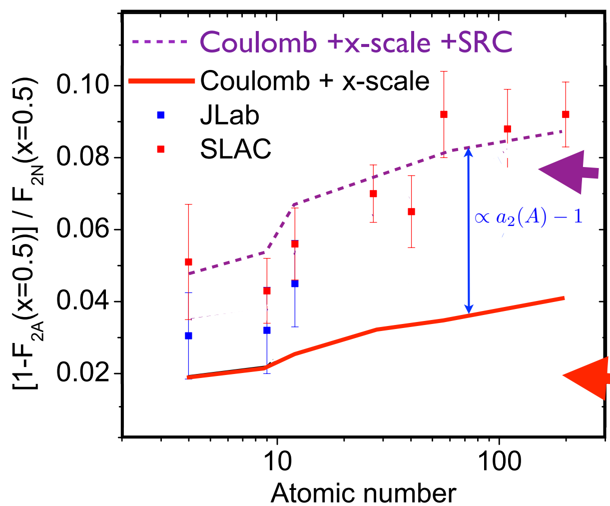
Theoretical expectation LF & MS85 hadronic effect

$\propto$ $\langle k^2 \rangle$ $\approx$ $\propto$ nucleon virtuality

accuracy ~ 20% $\propto$ $a_2(A)$

Contribution of nucleon modification to the EMC effect - weak function of A for A≥12

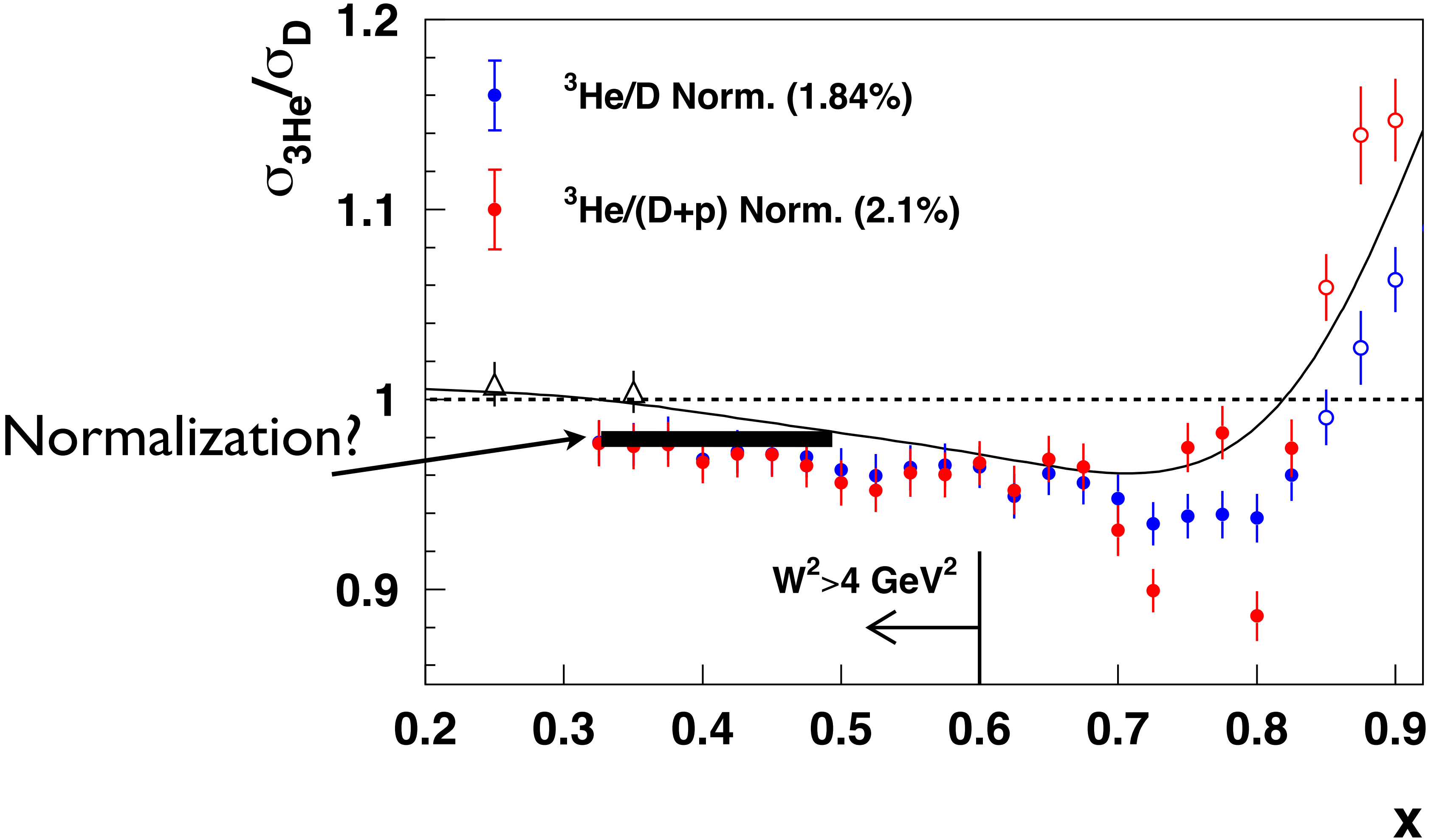
Example - magic point x=0.5 - no Fermi motion



Coulomb + x-scale + (hadronic EMC effect $\propto$ $a_2(A)$)

Coulomb + x-scale

^{3}He data not included - too large errors due to p/n ratio uncertainty.



From SRC expected effect is 0.01 for x=0.5 - within the errors

Probability for a quark to have x> 0.5, ~ 0.02

hadronic EMC effect at x ~ 0.5, 0.04

Probability of exotic component relevant for the large x EMC effect~ 2 10^{-3}

Nuclei are build of nucleons with accuracy ~ 99%, with large high momentum 2N SRC component (high density drops)

Note - G_E/G_M probes amplitude of deformation not probability - hence larger effects are possible for small momenta - at the same time the data are consistent with proportionality of the effect to the virtuality - check universality - deuteron !!!

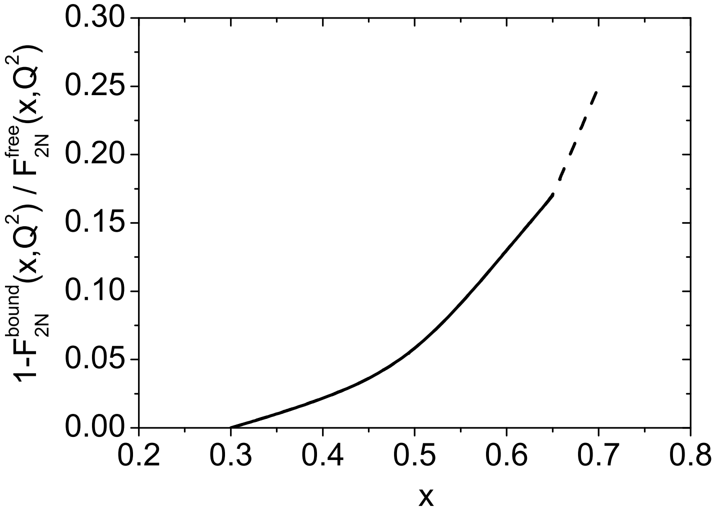
Dynamical model - color screening model of the EMC effect (FS 83-85)

Combination of two ideas:

(a) Quark configurations in a nucleon of a size << average size (PLC) should interact weaker than in average. Application of the variational principle indicates that probability of such configurations in nucleons is suppressed.

(b) Quarks in nucleon with x>0.5 --0.6 belong to small size configurations with strongly suppressed pion field - while pion field is critical for SRC especially D-wave.

Will be possible to test in the just completed pA LHC run will discuss in the end of the talk



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, $\delta_A(p)$ with momentum p in a PLC was determined for the case of two nucleon correlations and mean field approximation. In the lowest order

$$\delta_A(p) = 1 - 4(p^2/2m + \epsilon_A)/\Delta E_A$$

After including higher order terms we obtained for SRCs and for deuteron:

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

Accordingly $$\frac{F_{2A}(x,Q^2)}{F_{2N}(x,Q^2)} - 1 \propto \langle \delta(p) \rangle - 1 = -4 \left\langle \frac{\frac{\mathbf{p}^2}{2m} + \epsilon_A}{\Delta E_A} \right\rangle$$

which to the first approximation is proportional to $a_2(A)$, roughly proportional to $<\rho^2(r)>$. Accuracy is probably no better than 20%.

Repeat the program for A=3 for a final state with a certain energy and momentum for the recoiling system FS & Ciofi Kaptari 06.
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):

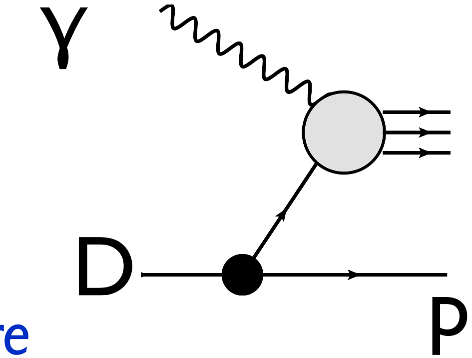
$$\delta(p, E_{exc}) = \left(1 - \frac{p_{int}^2 - m^2}{2\Delta E}\right)^{-2}$$

Dependence of suppression we find for small virtualities: $1-c(p^2_{int}-m^2)$

seems to be very general for the modification of the nucleon properties. Indeed, consider analytic continuation of the scattering amplitude to $p^2_{int} - m^2=0$. At this point modification should vanish. Our 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.

Tagging of proton and neutron in e+D→e+ backward N +X (FS 85).



interesting to measure 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 an effect is observed at say 100 MeV/c - go to 200 MeV/c and see whether the effect would increase by a factor of ~3-4.

$$1 - F_{2N}^{bound}(x/\alpha, Q^2)/F_{2N}(x/\alpha, Q^2) = f(x/\alpha, Q^2)(m^2 - p_{int}^2)$$

Here α is the light cone fraction of interacting nucleon

$$\alpha_{spect} = (2-\alpha) = (E_N - p_{3N})/(m_D/2)$$

However since overall genuine EMC effect is small for x ≲0.5 tagging for such x (x/α) is hardly practical below p= 400 MeV/c - however situation dramatically improves if x/α ≥0.6.

Optimistic possibility - EMC effect maybe missing some significant deformations which average out when integrated over the angles

A priori the deformation of a bound nucleon can also depend on the angle φ between the momentum of the struck nucleon and the reaction axis as

$$d\sigma/d\Omega/ < d\sigma/d\Omega >= 1 + c(p,q).$$

Here <σ> is cross section averaged over φ and dΩ is the phase volume and the factor c characterizes non-spherical deformation.

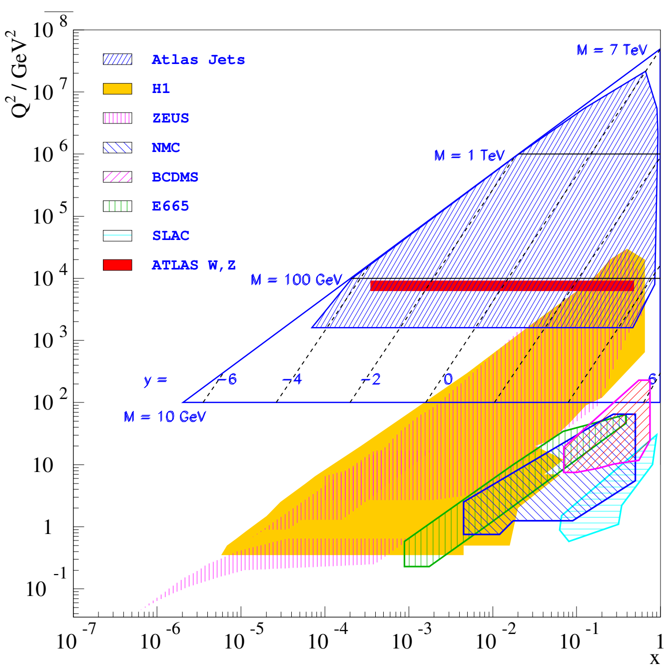
Such non-spherical polarization is well known in atomic physics *(discussion with H.Bethe)*.

Contrary to QED detailed calculations of this effect are not possible in QCD. However, a qualitatively similar deformation of the bound nucleons should arise in QCD. One may expect that the deformation of bound nucleon should be maximal in the direction of radius vector between two nucleons of SRC.

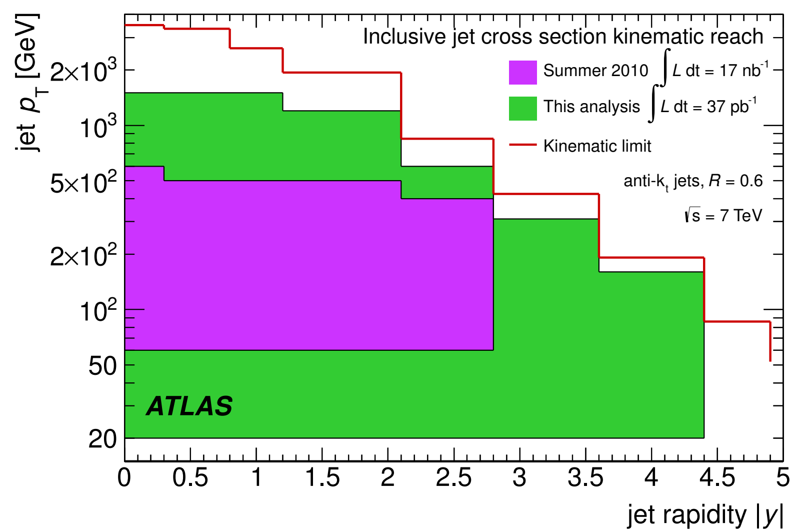
LHC - jets with large p_t - -- no nuclear shadowing effects

Inclusive jet/dijet cross section measurements

Using full 2010 dataset (**37 pb^{-1}**)
$\rightarrow$ probe perturbative QCD in new kinematic regime



$7 \cdot 10^{-5} < x < 0.9$
$Q^2 > 2 \cdot 10^7$ GeV^2



20 GeV$<p_T^{jet}<$1.5 TeV
70 GeV $< m_{12} <$ 5 TeV
$|y| <$4.4

C. Doglioni - 29/05/2012

The number of events in pA run > # events in 2010 pp run

A lot of high p_t , x_p> 0.6 pA events should have been collected in pA run!!!

Possible to measure the number of active nucleons as a function of x_p

Test of our interpretation of the EMC effect at large x --- a drop of the number of active nucleons at x> 0.5 - more "peripheral like" events

Conclusions II

Experiments at JLab achieved important progress in the quest for understanding quark-gluon structure of nuclei by bringing together studies of the EMC effect and SRCs

Possible explanations are very much constrained by

- $\bar{q}_A/\bar{q}_N \leq 1$
- bound nucleon at k< 200 MeV/c ≈ free nucleon
- presence of 20% universal 2N SRC build predominantly of nucleons which appear to give dominant contribution to the hadronic component of EMC effect

Need to explain why effect is small at x< 0.5 and rapidly grows at larger x

Mechanism of suppression of rare small size configurations in bound nucleons so far survives, main issue is whether x > 0.5 selects small size configurations.

Other possible mechanism of suppression of rare large x components in far off shell nucleons?