Probing non-nucleonic degrees of freedom in nuclei at colliders

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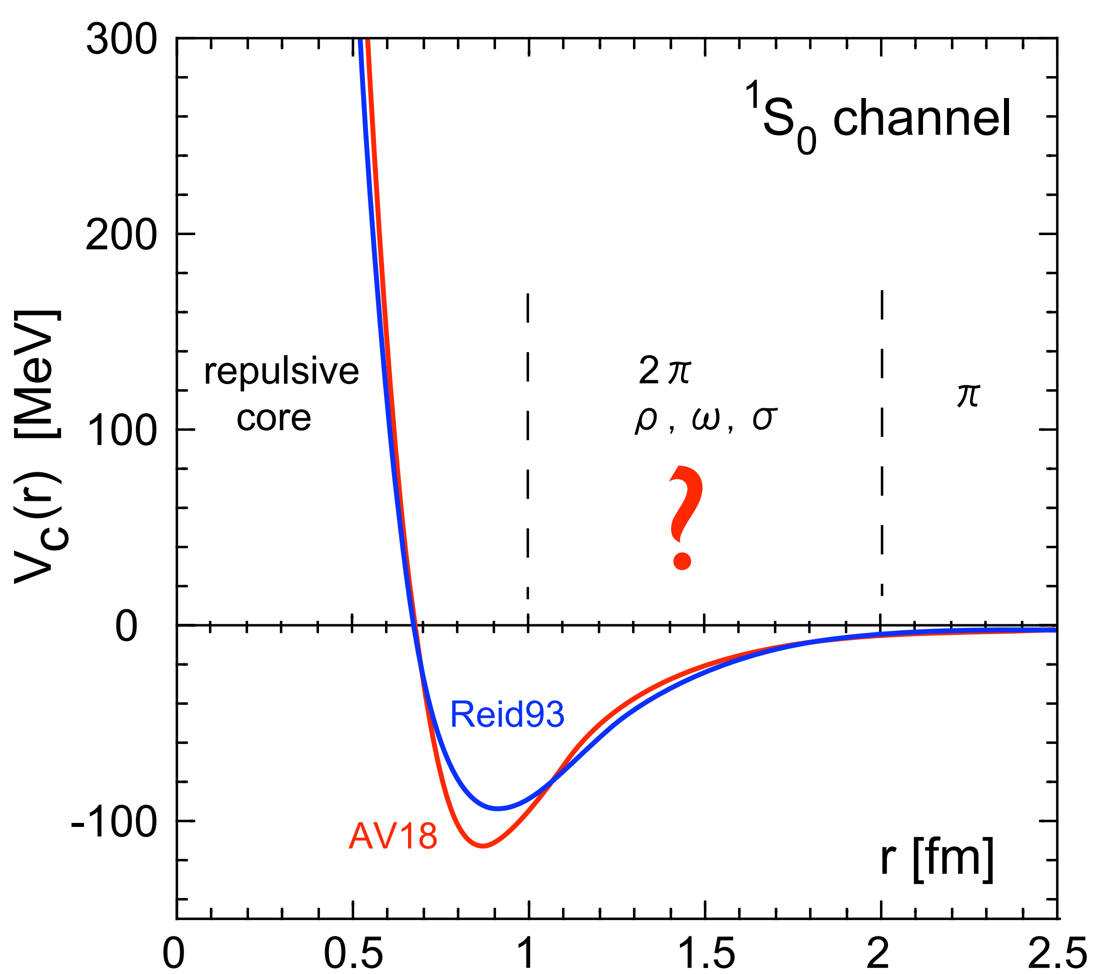
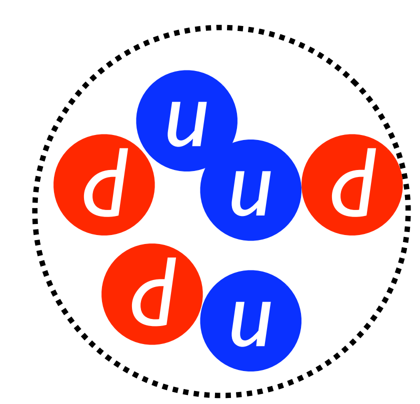
Where are quarks in nuclei?

Before QCD - paradox - strength of meson nucleon interaction increases with virtuality in the meson-nucleon field theoretical models: *zero charge (Landau) pole is present at rather small virtualities. No trace of this effect in NN and πN interactions. Even without the zero charge pole - interaction is very strong - why nucleus is not a meson soup?*



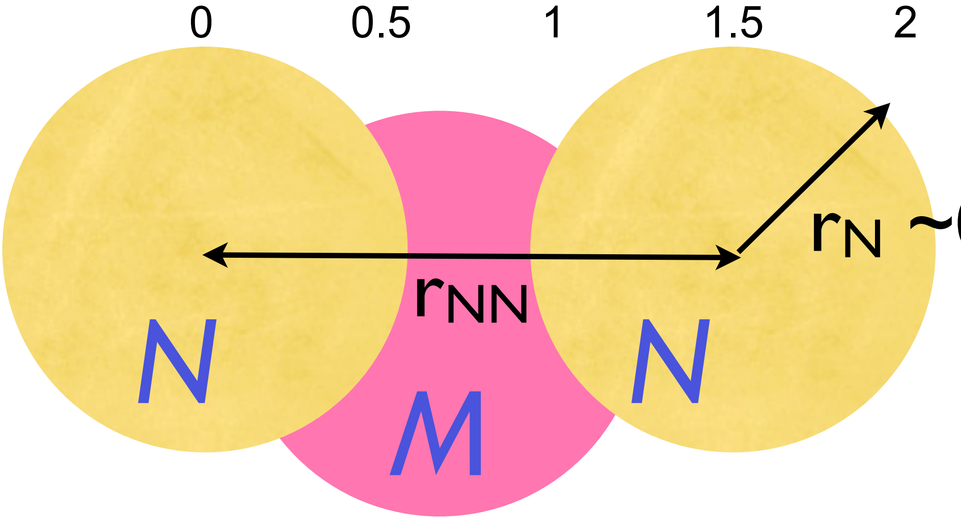
Perhaps a quark soup for r_{NN} < 1.2 fm?



quark kneading (FS75)

↓

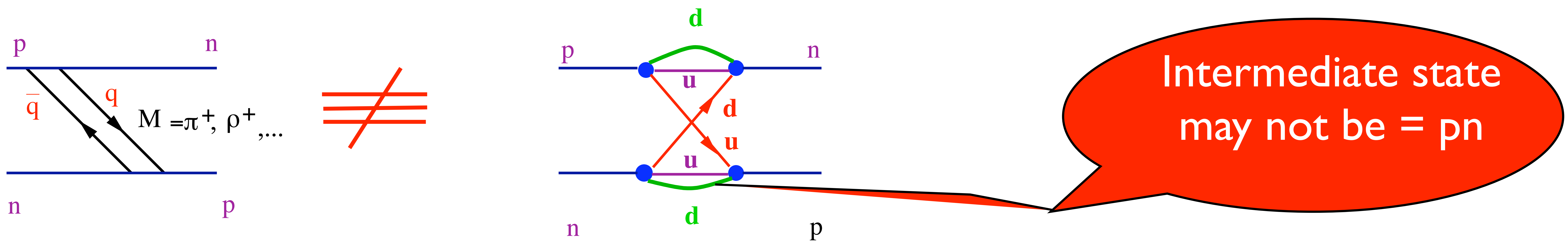
became popular under name
six quark bags



r_N ~0.6 fm for valence quarks

For r_{NN}< 1.5 fm difficult to exchange a meson - easy (?)to exchange quarks

- Microscopic origin of intermediate and short-range nuclear forces
  - do nucleons exchange mesons or quarks/gluons? Duality?



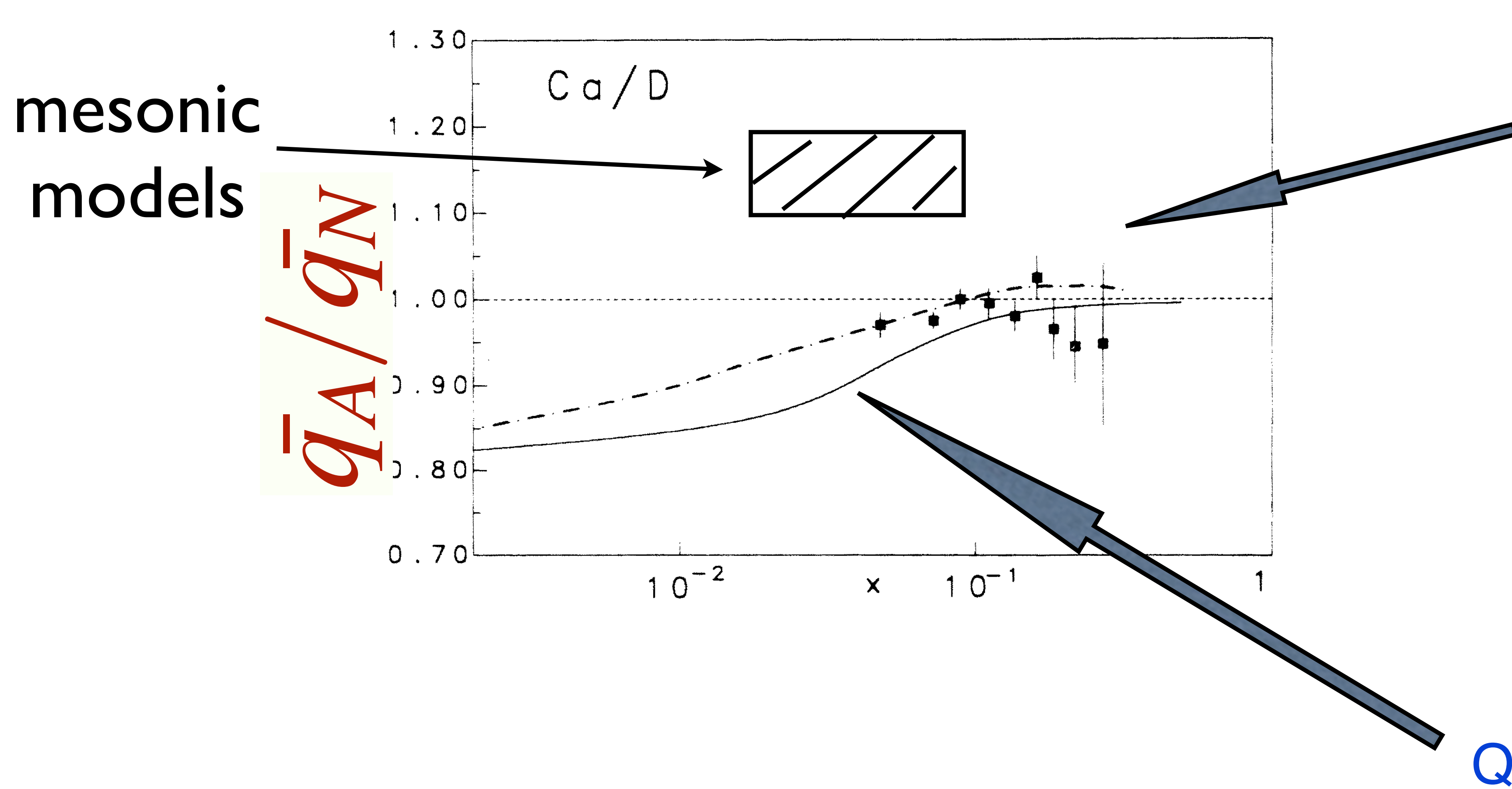
Meson Exchange — extra antiquarks in nuclei

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

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

Drell-Yan experiments: $\bar{q}_A/\bar{q}_N \sim 0.97$



Q^2 = 15 GeV^2

Q^2 = 2 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

In QCD a hidden parameter (FS 75-81) : in NN interactions: direct pion production is suppressed for a wide range of energies due to chiral properties of the NN interactions:

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

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

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

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

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

For I=1 channel where single Δ can be produced $k_N \approx 550\, MeV$

Correspondence argument: wave function - continuum ⇒ Small parameter for inelastic effects in the deuteron/nucleus WF, while relativistic effects are already significant since $v/c \sim 1$

☝ - *Correspondence argument is not applicable for the cases when the probe interacts with rare configurations in the bound nucleons due to the presence of an additional scale: nucleon form factors at* $Q^2 \geq 1$ *GeV*^{2}*, EMC effect,...*

Logic of quantum mechanics does not map easily to the language of virtual particles - transformational vacuum pairs. At the same time language of QM does not match space-time development of high energy processes which are usually light-cone dominated.

collider

⇒ Relativistic (light-cone) treatment of the nucleus (FS76) - price of switching from nonrelativistic to light-cone quantum mechanics is not very high: in broad kinematic range a smooth connection with nonrelativistic description of nuclei (more complicated structure of the scattering amplitude). Still needs tests for moderate momentum transfers ~ 2 GeV^2

Large violations of the LC many nucleon approximation for LC fractions α ($0 < \alpha < A$); $\alpha = A p_N / p_A$

collider frame

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

transition to new regime for NN correlations

$$\alpha_{I=0} \sim 1.65$$ (p_N backward in the nucleus rest frame ~ 0.5 GeV/c)

$$\alpha_{I=1} \sim 1.5$$ (p_N backward ~ 0.4 GeV/c)

Catch: *for A ≥ 4, three N SRC dominate for* *$\alpha \geq 1.5$ ➜ A=2, 3 are crucial*

General consideration - for small nucleon momenta deformation of of nucleon in the nucleus should be proportional to its off-shellness $(p_A - p_{(A-1)^*})^2 - m_N^2$

We first observed in the PLC model of the EMC effect

G.Miller's talk

Natural picture:

- Low momenta - nucleons are far from each other - main effect is deformations of individual nucleons - small correlation between deformation of nearby nucleons
- Increase of momenta - off shellness becomes large enough for significant excitation of baryon resonances
- Internal momenta very large ~ 1 GeV/c -- nucleons strongly overlap - quark language becomes preferable

→ *Looking for small effects for small nucleon momenta*

Looking for large effects in the extreme kinematics

What did we learn so far?

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

☛ Possible enhancement of non-nucleonic effects for spin observables

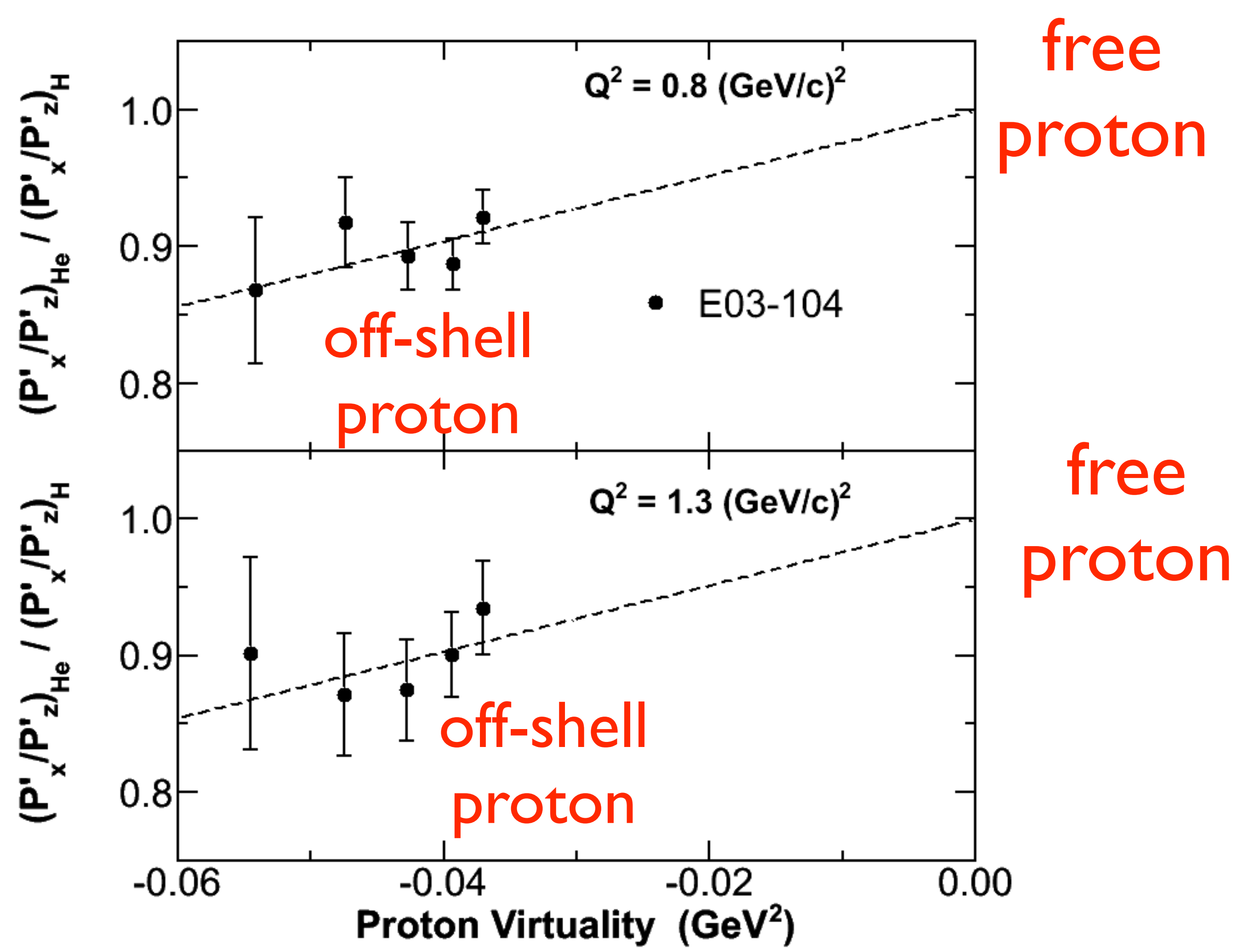
A=3 system - Bjorken sum rule is satisfied only with n.n.d. Guzey, F&S - 96

☛ 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 $A=40$. ⇒ mesonic degrees of freedom play small role in nuclei

☛ Wave function of bound nucleon is different from a free one
--- G_E/G_M Jlab S.Strauch data on $e\,^4He \to ep\,^3H$

effect virtuality of the struck nucleon *confirms our predictions & indicates that large n.n.d. effects are much larger at average / large nucleon momenta*



☛ High momentum nucleons are present in nuclei - mostly pn short-range correlations (SRC)

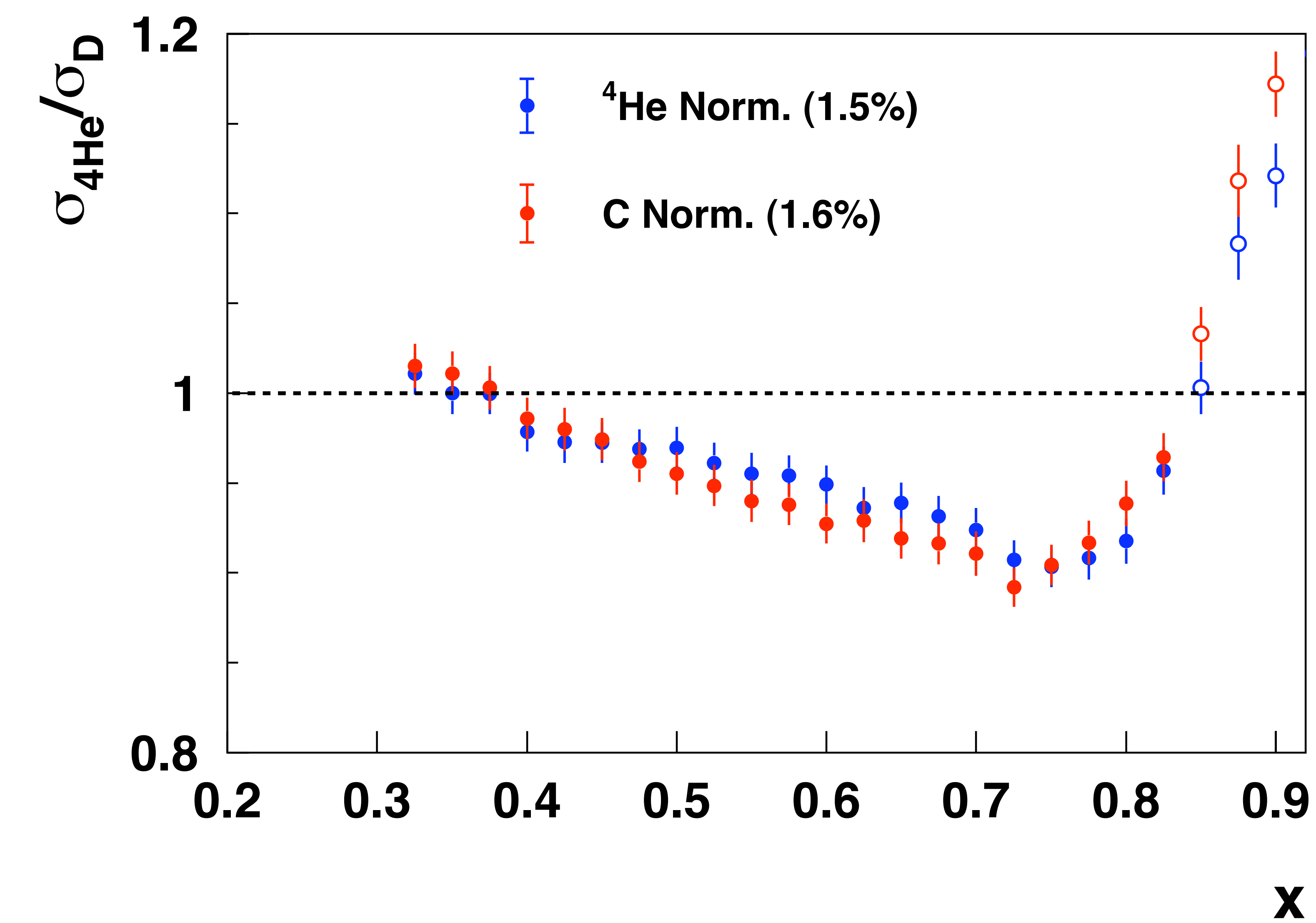
Scaling of the ratios of (e,e') cross sections → SRC have the same structure in light and heavy nuclei (main difference is probability) - true for 2N and 3N correlations.

Consistency of the inclusive and exclusive data ➠ even in SRC n.n.d. are a correction < 20%.

☛ Properties of light nuclei are well described by Schrodinger with vacuum NN potential + small correction on NNN

➠ EMC effect for light nuclei should be due to the local properties of nuclei - polarization of nucleons in NN interaction

Consistent with Jlab data indicate that EMC effect for ^{4}He and ^{12}C practically the same. In line with off-shellnesses of nucleons in ^{4}He being pretty close to that in ^{12}C (Ciofi et al)



General strategy

☛ *Study nuclear pdfs - gluons, valence and sea quarks for a wide range of A.*

- If no EMC effect crossover of $R_i(A) = p_A(x,Q^2)/p_N(x,Q^2)$ to $R_i > 1$ is at $x_i = \frac{2}{n_i + 1}$ $\quad x_g \sim 1/3$, $\quad x_{\bar{q}} \sim 1/4$
- Quantify x ~ 0.1 enhancement for valence quarks; check x~0.1 behavior of gluons

☛ *Semiinclusive, exclusive studies with the lightest nuclei to minimize f.s.i. effects*

No benefit in experiments with heavier nuclei

Strategies for probing types of Non-nucleonic degrees of freedom

Bound Nucleon deformations

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
$e+{}^2H \to e+N+X$; $e+{}^3He \to e+pN+X$

tagged structure functions FS85

Suppression of small size configurations mechanism - gives a reasonable magnitude of the effect at x ~ 0.6

Suppression of tagged F_{2N}

$$\frac{F_{2N\ bound}(x,Q^2)}{F_{2N\ free}(x,Q^2)} - 1 \propto \delta(p, E_{exc}) = \left(1 - \frac{p_{int}^2 - m^2}{2\Delta E}\right)^{-2}$$

- Different interaction in S and D wave → different deformation? Tensor polarized ^{2}H
- Different interaction for I=0 and I=1 → different deformation for pn and pp channels for ^{3}He ?
- Gluon tagging? Rates too low?

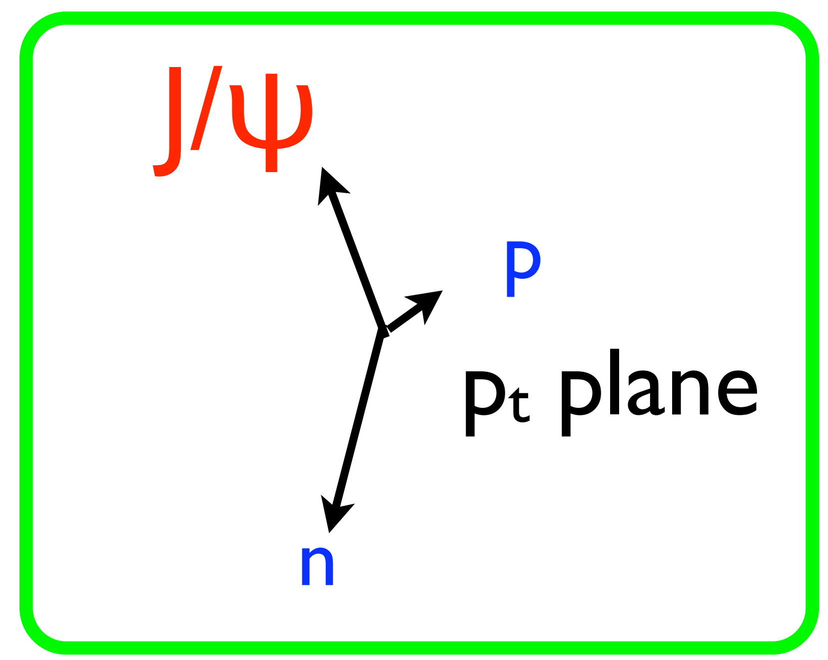
Can one tag protons and neutrons well enough? - S.White talk

How big is f.s.i. of the fragments of the hit nucleon with would be spectator?

Tagging for 3N SRC - $e + {}^3\vec{H} \rightarrow e + pp(pn) + X$

- *Is the transverse size of bound nucleon quark/ gluon distribution in bound nucleons modified?*

$\gamma +^2 H \rightarrow J/\psi + p + n$ at -t > 0. 3 GeV^2 in the spectator kinematics



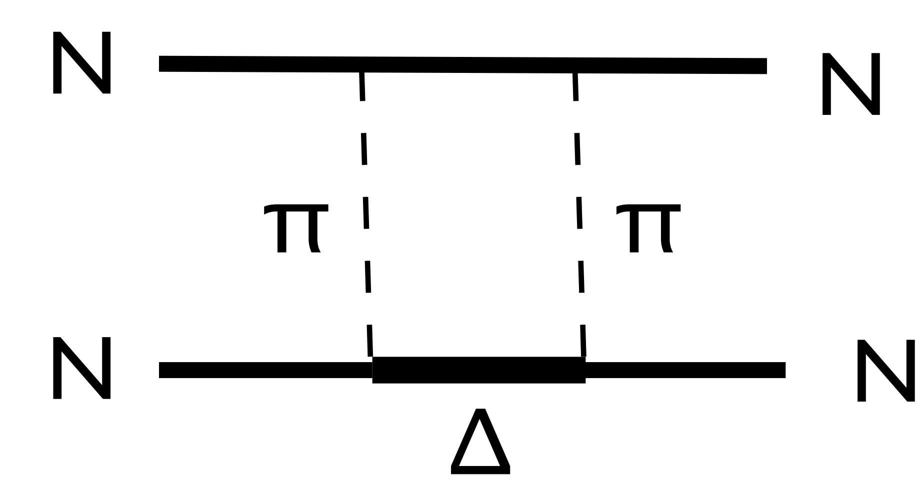
If t distribution is broader - swelling of gluon field in bound nucleons

Hadronic degrees of freedom - Δ's,...

The BNL and Jlab data indicate that 2N correlations dominate for $600 > k_N > 300$ MeV/c

Can one expect some Δ's in nuclei?

Meson exchange models: Attraction in NN at medium distance (1.2 fm) is due to two pion exchange



One can also generate Δ like clusters due to quark exchange potential

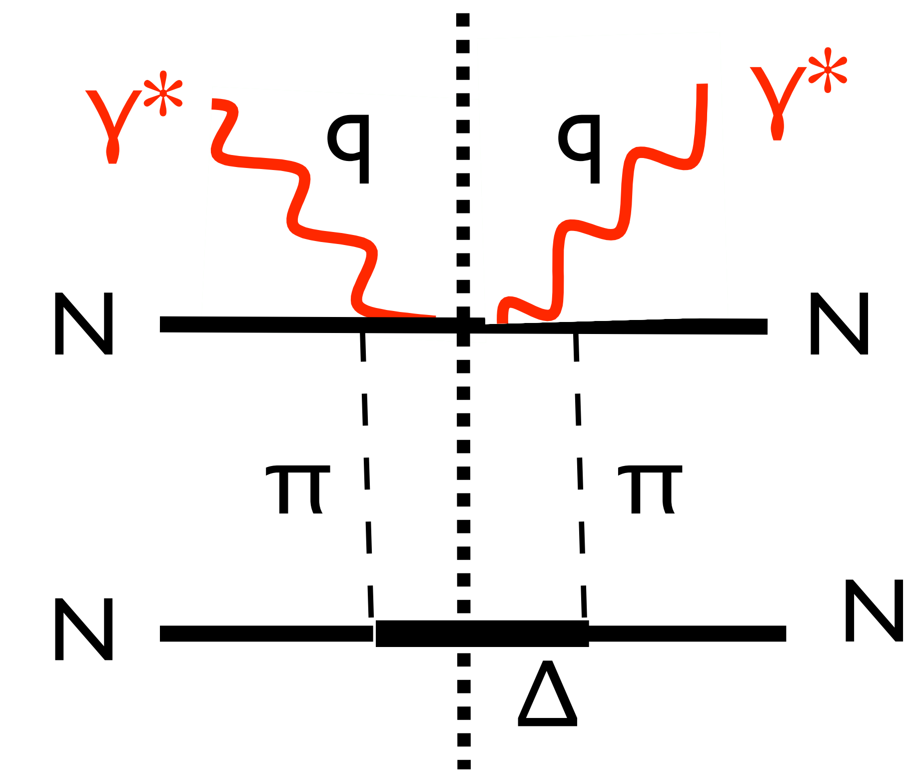
Often hidden in the potential. Probably OK for calculation of the energy binding, energy levels. However wrong for high Q^2 probes.

Explicit calculations of B.Wiringa (92 unpublished): ~1/2 of high momentum component is due to ΔN correlations, significant also ΔΔ . Tricky part - match with observables - momentum of Δ in the wf and final 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



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

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

$$\frac{\sigma(e+A\to\Delta^0+X)}{\sigma(e+A\to\Delta^{++}+X)}=0.93\pm0.2\pm0.3 \qquad \frac{\sigma(e+A\to\Delta^{++}+X)}{\sigma(e+A\to p+X)}=(4.5\pm0.6\pm1.5)\cdot10^{-2}$$

for the same light cone fraction. Doable with data mining with CLAS but energy is too low to study x distribution with Δ tag.

At collider one needs to consider reaction with production of Δ with $\alpha_\Delta > 1$ like

$$e +^2 H \to e + \Delta^{++} + X$$

$$e +^2 H \to e + \Delta^{++} + \, leading \, \pi^{\pm} + X$$

measurement of pions tests whether γ^* scattered off d - quarks

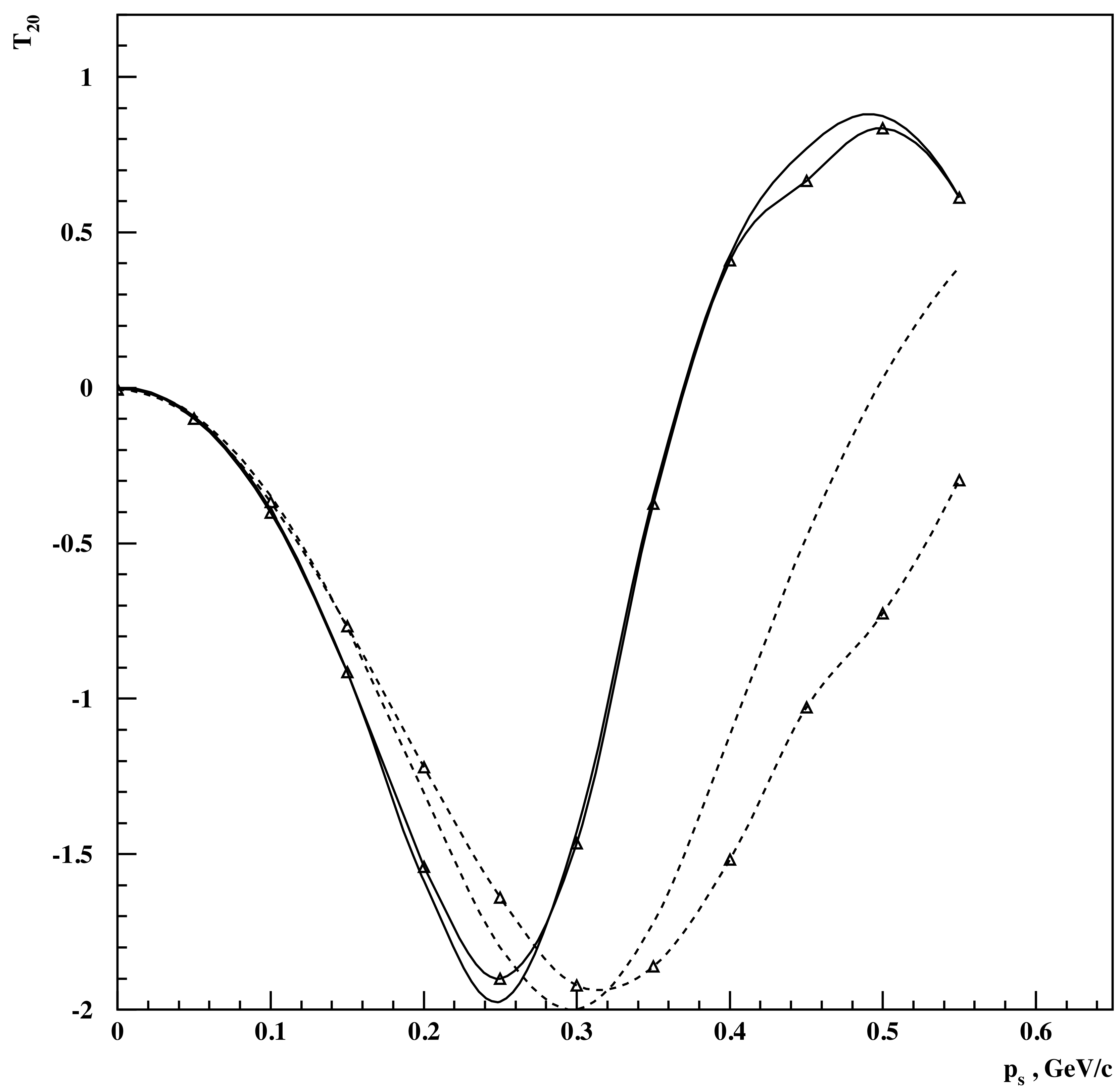
Tests possible to exclude rescattering mechanism: $\pi N \to \Delta$ FS90

For the deuteron one can reach sensitivity better than 0.1 % for $\Delta\Delta$ especially with quark tagging *(FS 80-90)*

Brief list of the directions of study:

- Decisive tests to discriminate between LC and virtual nucleon relativistic models of the deuteron:

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



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.

Similar effect for DIS

$$e + {}^2\vec{H} \rightarrow e + N + X$$

x -dependence of T_{20} ---way to look for difference of the EMC effect for S and D wave.

Extreme cases

- Comparison of F_{2A} for x > 1.2 in DIS with convolution with measured light cone nucleon density. Is suppression observed at x~ 0.6 is grossly amplified?

- Spectators for x > 1.2 - typical $\alpha \sim 0.5$

  are they nucleons? isobars, N's?*

- $\alpha_N > 1.5$ for ^2H Do nucleons still dominate?

  Does $F_{^2H}(x \to 2) \propto (2-x)^{10}\, for\, x > 1.4?$

Does LC density matrix of nucleons in the deuteron changes behavior from

$$\rho^N_{^2H}(\alpha, p_t \sim 0) \propto (2-\alpha)^3\, to\, (2-\alpha)^6$$???

Collider at W ~ 20 - 40 GeV (per nucleon) with a proper detector would be a powerful tool to study parton structure of correlations based on the current studies and studies to be performed at Jlab and hopefully at other medium energy experiments / facilities.

Main advantage - *ability to study nuclear fragment final states in correlation with production of the forward particles.*

Challenge: *studies of A-dependences - 5 - 10% effects*

Connection to the spin program: *experiments with the lightest nuclei - done in parallel with the neutron pdf program.*