SRC measurements: Opportunities and Challenges at EIC

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Outline

Nucleon fragmentation in DIS

Short range correlations nucleon resolution scale

Short range correlations quark - gluon resolution scale

"Physics and detector requirements at zero-degree of colliders"

Sept. 24, 2019, SUNY

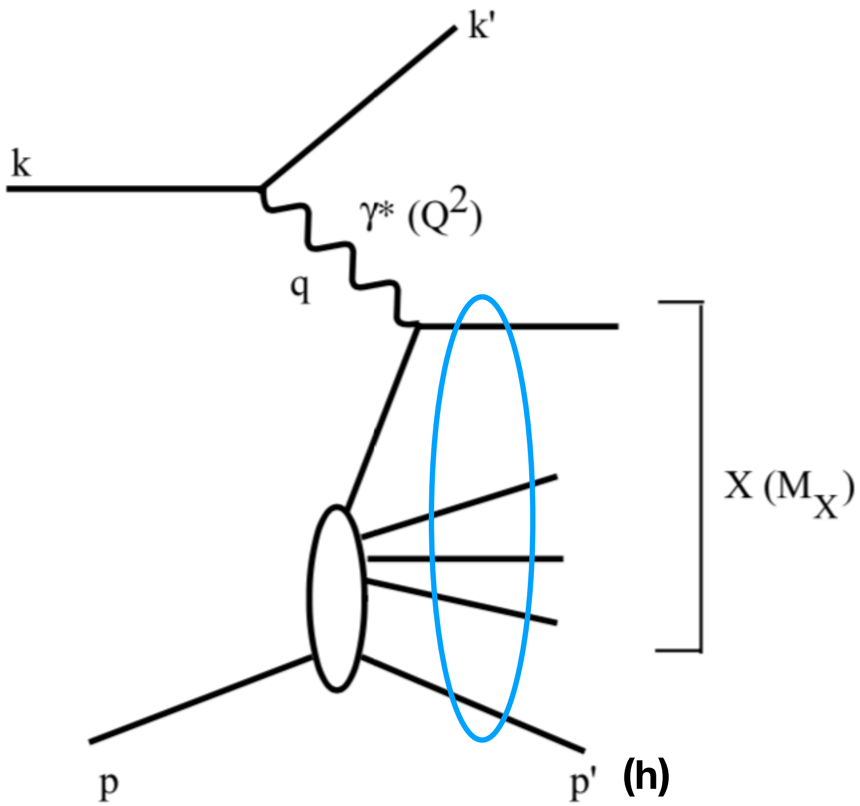
Before considering requirements for a detector to study SRCs at the EIC I will consider

Fragmentation in DIS off nucleons

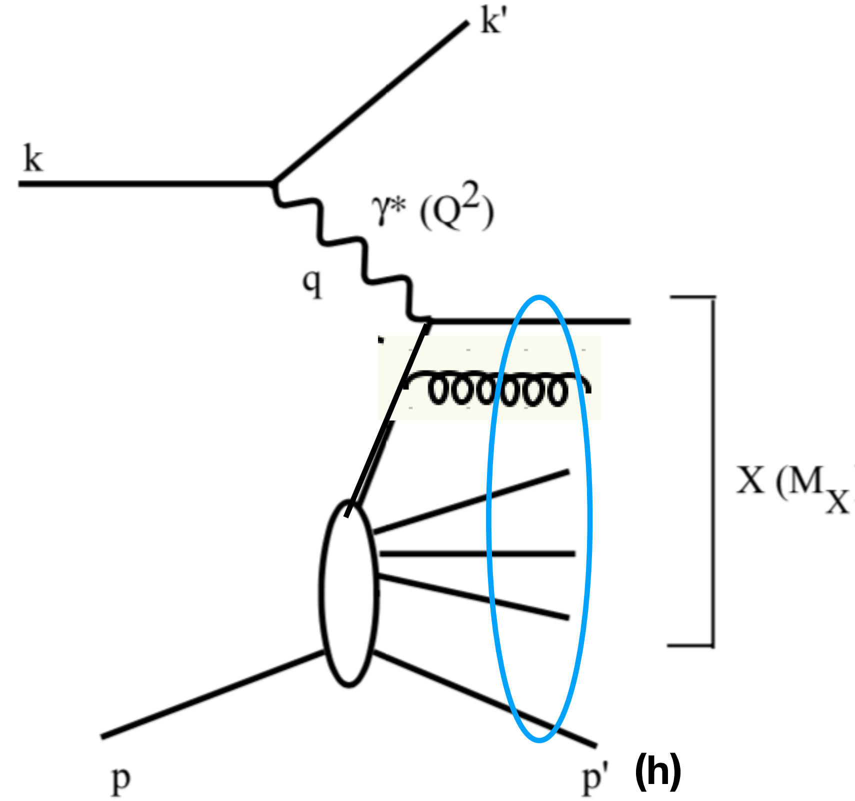
- **many requirements to detector are similar**
- **information about fragmentation necessary for optimizing SRC studies**
- **fragmentation is a probe of nucleon structure and QCD dynamics for which EIC can add a lot**

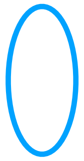
Collins factorization theorem: consider hard processes like

$$\gamma^* + T \to X + T(T'), \quad \gamma^* + T \to \ jet_1 \ + \ jet_2 + X + T(T')$$



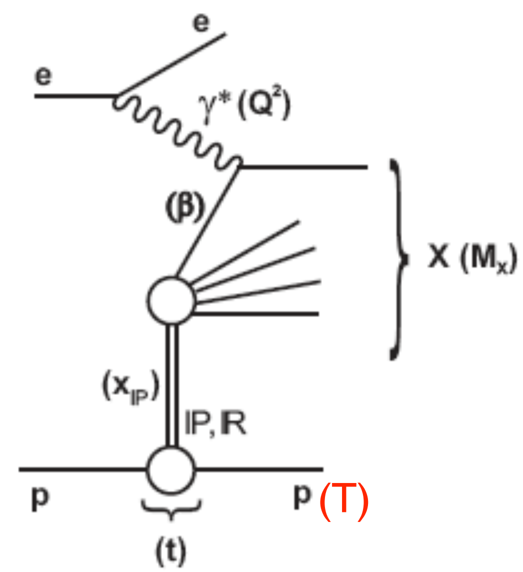
$$Q_0^2 \ \rightarrow Q^2$$



Interaction of partons which would form h h with the rest of partons:  *— does not change since overall interaction does not resolve qg which are located at transverse distance << 1/Q_0*

one can define fracture (Trentadue &Veneziano) parton distributions

$$\beta \equiv x/x_{I\!P} = Q^2/(Q^2 + M_X^2)$$



$$f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$$

$$x_{T_f} = 1 - x_{I\!P}$$

$$F_2(x, Q^2) = x \sum_{j=q,\bar{q},g} \int_x^1 \frac{dy}{y} C_j\left(\frac{x}{y}, Q^2\right) f_j(y, Q^2)$$

$$F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) = \beta \sum_{j=q,\bar{q},g} \int_\beta^1 \frac{dy}{y} C_j\left(\frac{\beta}{y}, Q^2\right) f_j^{D(4)}(y, Q^2, x_{\mathbb{P}}, t)$$

Theorem:

For fixed $x_{I\!P},\ t$ universal fracture pdf + the evolution is the same as for normal pdf's

Comment: $x_{I\!P}$ *is traditional notation - notions of Pomeron is not necessary in general factorization analysis*

Fracture pdfs are practically not explored except fragmentation in ep scattering in

$$p \to n, p \to p$$

Need high statistics as fj are functions of (x, β, Q^2, t) not not only β, Q^2, t like for quark fragmentation functions (Current fragmentation) .

Convenient quantity $x_L = p_h/p_p$ — light cone fraction of proton carried by h

$z = x_L/(1-x) < 1$ Maximal $x_L = (1-x)$

Currently except for diffraction all data are for $x \ll 1 - x_L$ integrals over x and $\beta \ll 1$.

Soft factorization: weak dependence on x for $z \ll 1$ and not very large Q^2

Strong dependence of leading (large z) baryon production on x:

$$f_j(x,z) \propto (1-z)^{n(x)}$$

$n(x < 0.01) = -1$ diffraction

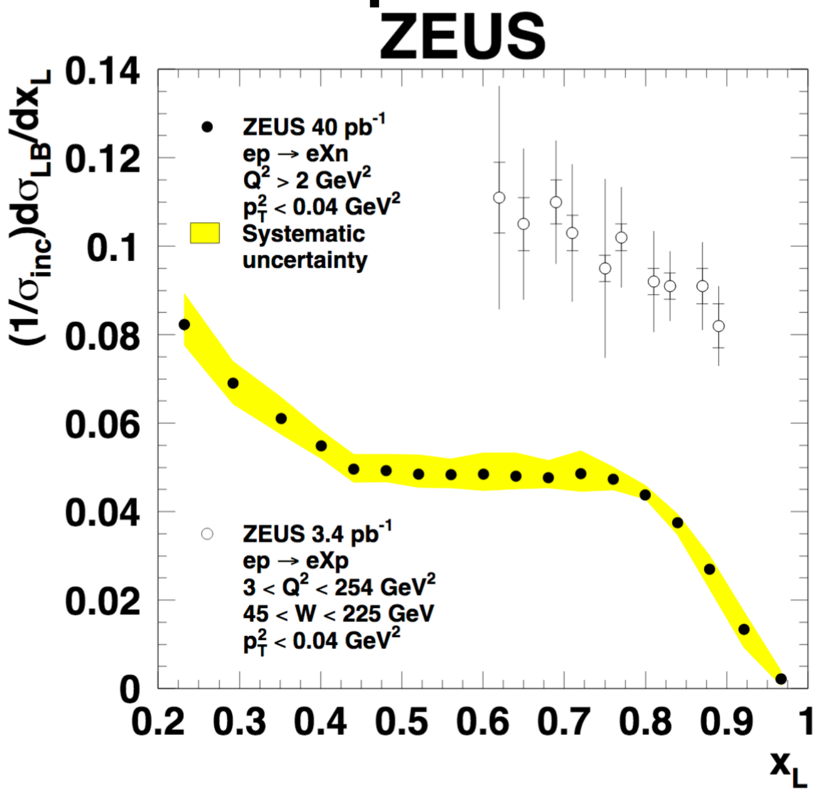
$n(x \sim 0.1) = 0$ onset of sea quarks

$n(x \sim 0.2) = 1$ valence quarks

$n(x \sim 0.5) = 2$? fragmentation of two quarks with large relative momenta

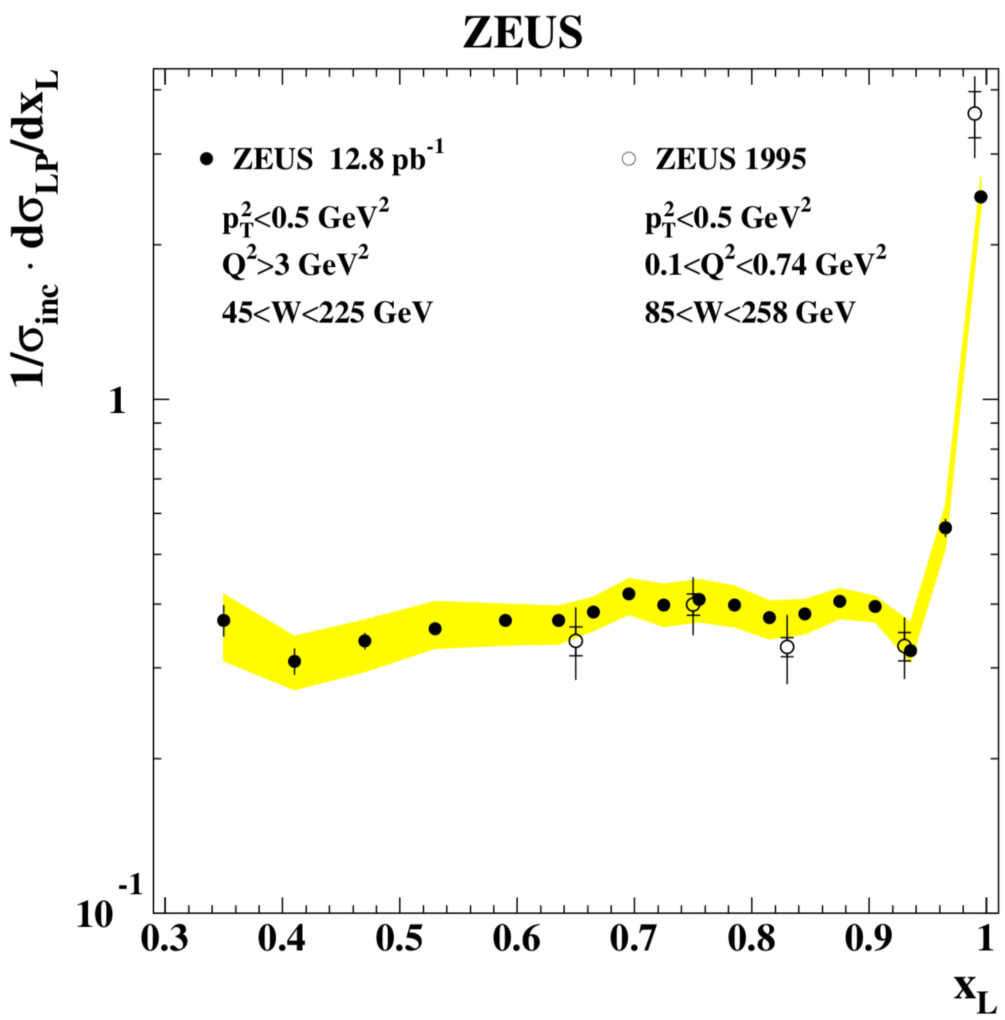
There were numerous attempts to extract from reaction $ep \to en + X$ pion pdfs

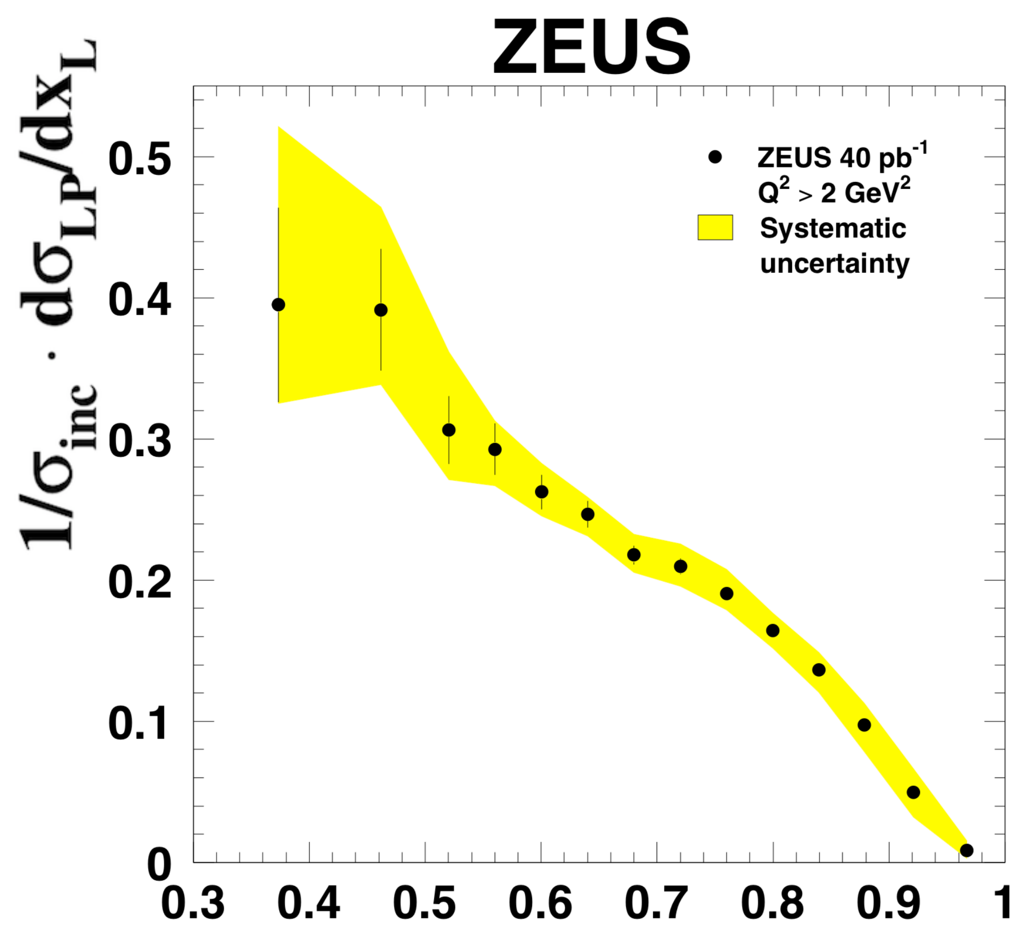
this contribution requires approaching the pion pole which is practically impossible. Soft factorization leads to contributions to nucleon yield from all fragmentation processes. Simple example - data report the ratio of p and n yields of 2, while in the pion model it is equal to 1/2.



Missed a puzzle: where are baryons. Should be #baryons - # anti baryons = 1 per event. For small x and x_L >0.3 only 0.4 is observed (70% p, 35% n)

➜ A lot of baryons produced below x_L =0.3


ZEUS
ZEUS 12.8 pb^{-1}
p_T^2<0.5 GeV^2
Q^2>3 GeV^2
45<W<225 GeV
ZEUS 1995
p_T^2<0.5 GeV^2
0.1<Q^2<0.74 GeV^2
85<W<258 GeV
$1/\sigma_{inc} \cdot d\sigma_{LP}/dx_L$
x_L


ZEUS
ZEUS 40 pb^{-1}
Q^2 > 2 GeV^2
Systematic uncertainty
$1/\sigma_{inc} \cdot d\sigma_{LP}/dx_L$

A sample of interesting channels

By using polarized ep scattering and detecting pions in the current fragmentation region we can do a flavor & helicity separation. Qualitatively new information about working of confinement and about baryon structure.

Removal of u (d) quark with helicity = +/i helicity proton can compare

fragmentation of uu and ud with helicities 0 or 1.

- is ud→ p = ud→ n

- how Δ isobar production / spin alignment depends on helicity of diquark

  longitudinal polarization of hyperons

- z-dependence of the meson production

- expect abundant production of baryon production for large x including rare/exotic baryons like 20-multiplet due to large angular momenta of spectator quarks (Feynman problem).

- meson production at large z: $(1-z)^n$, n -2 — 4?

- correlations of fragmentation and central multiplicity (easier at HERA)

Summary: from discussed studies we would get a precision knowledge of how a proton wave packet evolves when a parton with given x and flavor, helicity is removed from it.

Removal of color octet vs removal a triplet for large z, and x >0.1 -

green pastures

Reference point for fragmentation in pp scattering with a hard (e.g.) dijet trigger. Screening, Multiparton interactions.

Requirements to detector:

x_L range for protons down to 0.1, p_T range: $0 < p_T < 0.7$ GeV/c

Δ^{++}, Δ^0 **pions with x_L range from 0.3 to 0.1**

Λ hyperon ? **$c\tau$=7.98 cm**

Why studying SRC is important

- Best chance to observe new physics beyond many nucleon approximation - Δ's, quark - gluon degrees of freedom, etc

- Properties of drops of very dense nuclear matter ➜ Eq. of state for cores of neutron stars

Very different strength of pp and pn SRC, practical disappearance of the Fermi step for protons for ρ(neutron star) >ρ (nuclear matter)

- ~80% of kinetic energy of heavy nuclei is due to SRCs = powerhouse of nuclei

- Microscopic origin of intermediate and short-range nuclear forces

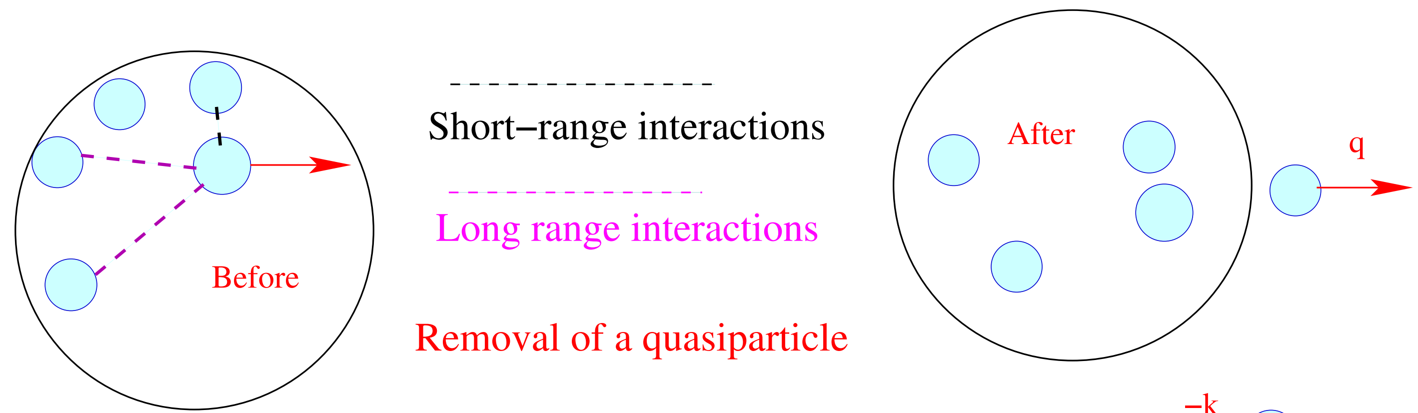
- Numerous applications

Modeling of νA quasielastic scattering

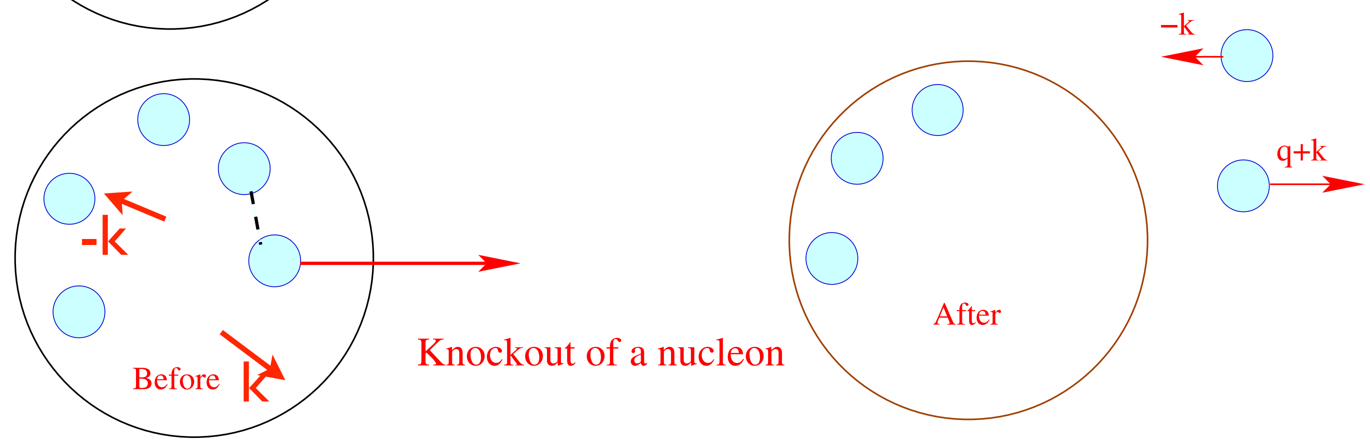
Neutron production in AA collisions at RHIC, LHC

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.

Low Q^2 scale



High Q^2 scale I



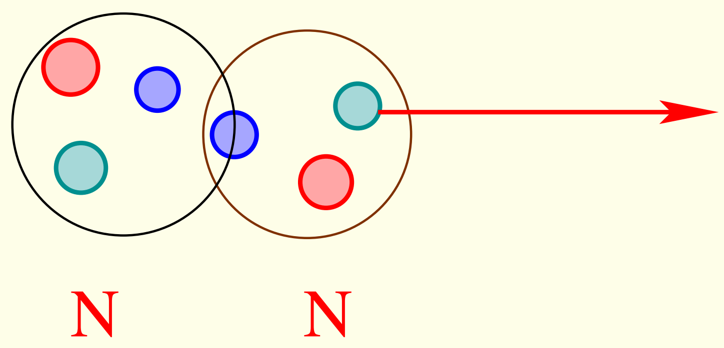
from short-range correlation
(SRC)

DIS limit — knockout of a quark (next slide)

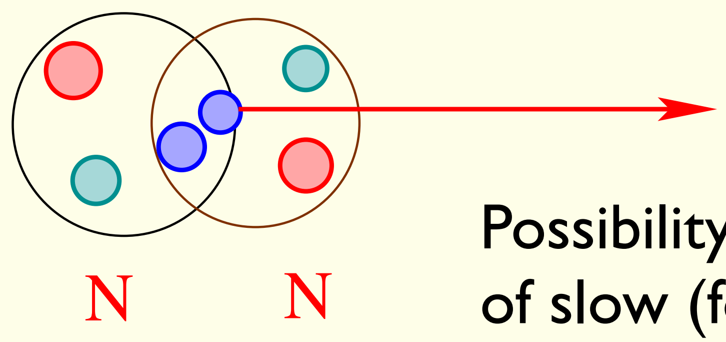
our informal definition: 2 N SRC = two nearby nucleons with momenta approximately back to back

SRC - understood generically as correlations in the two nucleon wave function at small r_1-r_2 for decades were considered an elusive property of nuclei

High Q^2 scale II Quark removal in the DIS kinematics



Removal of a quark of a nucleon



Removal of interchanged quark

Possibility of decay of the residual system with production of slow (for example backward in the nucleus rest frame) baryons like N*, Δ-isobar if color is not localized in one nucleon.

New effects if one would remove a valence gluon (EIC) ?

Due to the findings of the last few years at Jlab and BNL SRC are not anymore an elusive property of nuclei !!

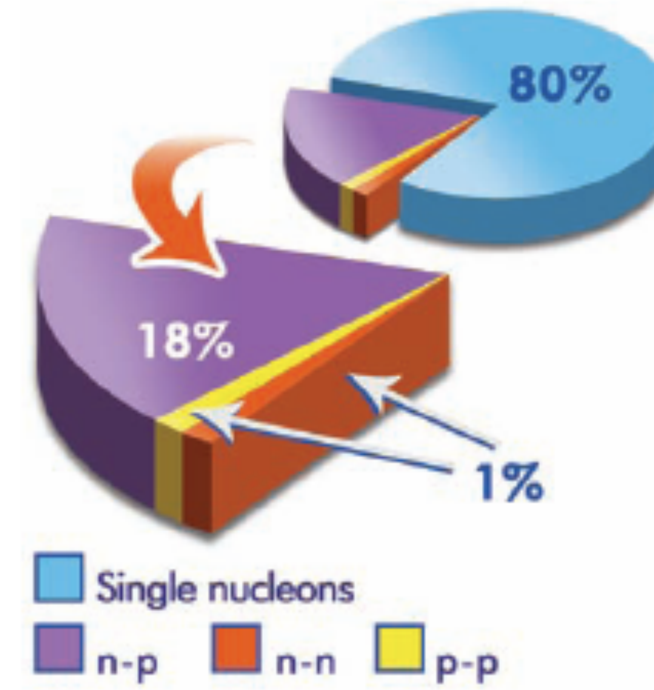
Summary of the findings

- Practically all nucleons with momenta k≥300 MeV 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 times larger than for pp correlation
  BNL + Jlab

- Probability for a nucleon to have momentum > 300 MeV/c in medium nuclei is ~20 — 25%
  BNL + Jlab 04 +SLAC 93

- In heavy nuclei protons have in average higher momenta than neutrons.



The average fraction of nucleons in the various initial-state configurations of ^{12}C.

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.

Different probes, different kinematics - the same pattern of very strong correlation - Universality is the answer to a question: "How to we know that (e,e'pN) is not due to meson exchange currents?"

Open questions which can be addressed using forward detector:

Precision measurements of 2N, tests of factorization

Kinematics - SRC via backward nucleons in lab frame in reaction

$\gamma^* + D \longrightarrow N + X$ = nucleons with $\alpha = 2p_N/p_D > 1.3$

Detector should be able to detect protons with moderate p_t up to all the way up to $\alpha=2$.

steep α dependence on nucleon spectrum: exp (-8α) challenge for using ZDC

Direct observation of 3N SRC : electron scattering with production of two backward nucleons $\alpha_1 \sim \alpha_2 > 1.3$ or one with $\alpha > 1.6$

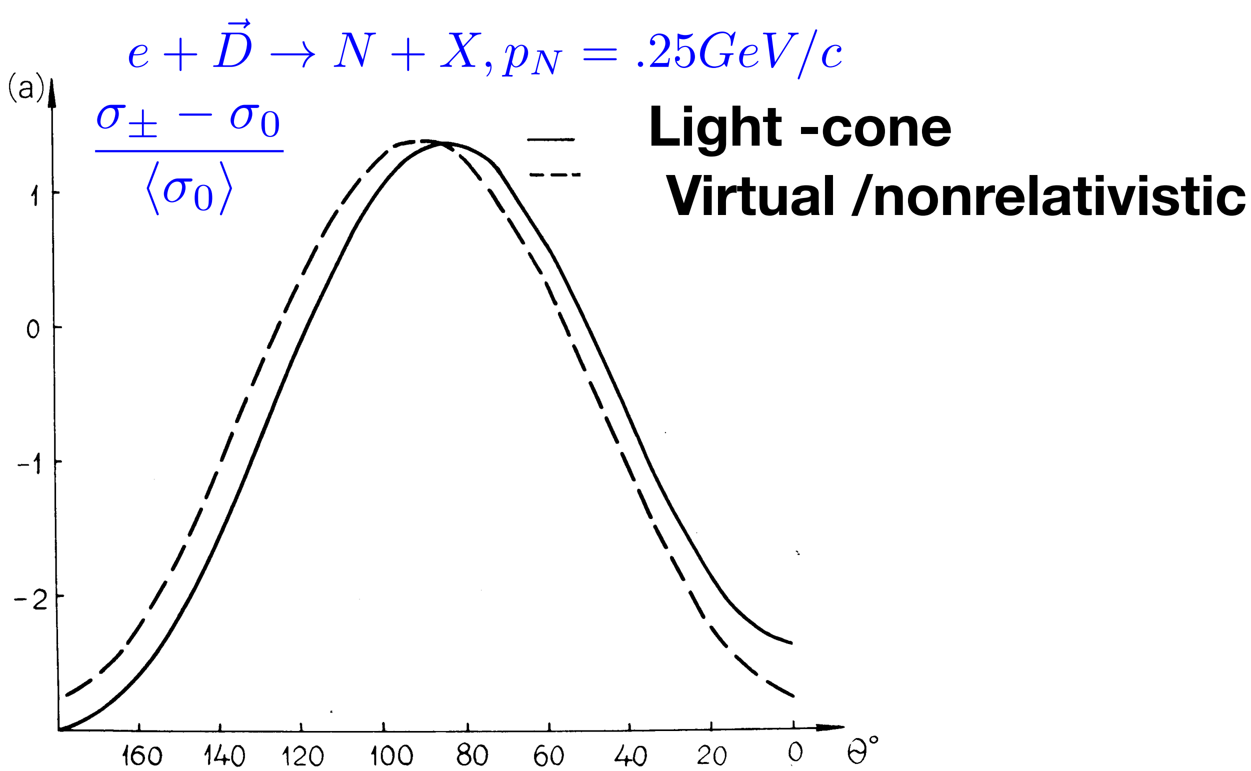
Testing origin of the EMC effect (tagged structure functions)

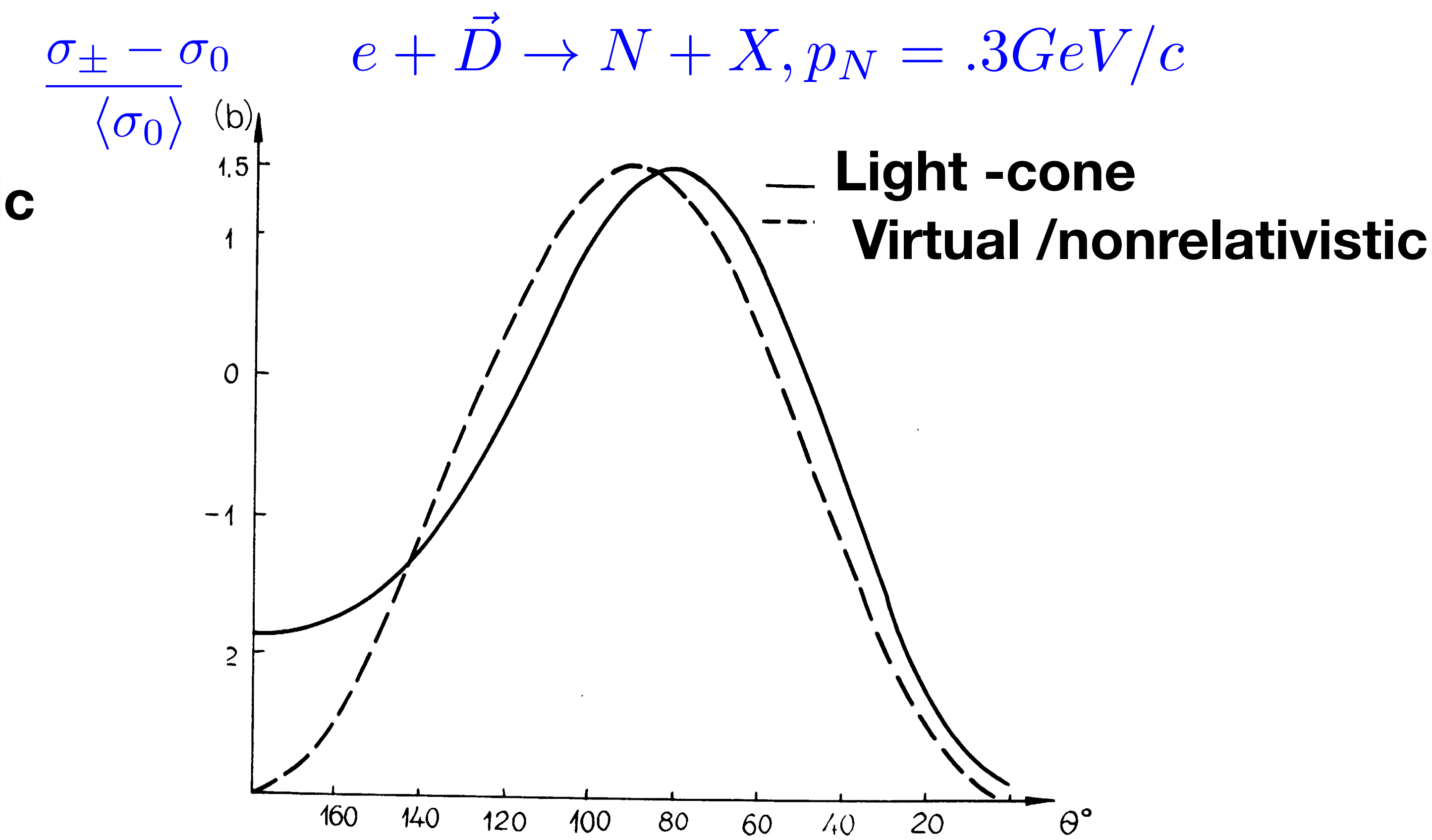
Discovery of non-nucleonic degrees of freedom in nuclei: Δ's ,..

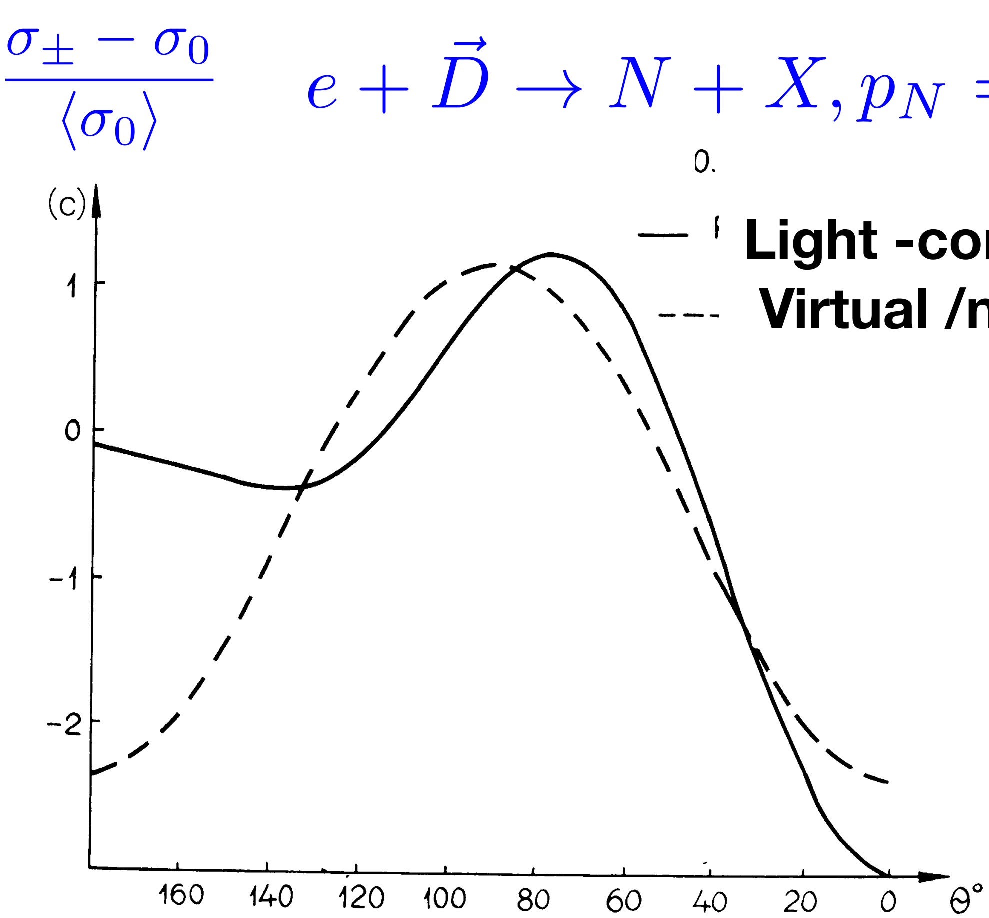
Comment:

use of A> 3 (4?) at EIC would not add much to study of SRC except in inclusive scattering due to universality of SRC and fsi

CRITICAL TEST OF THE RELATIVISTIC EFFECTS POLARIZED DEUTERON BEAMS







Factorization test: T_{20} should be universal - the same for various hard inclusive (x,Q) and exclusive processes

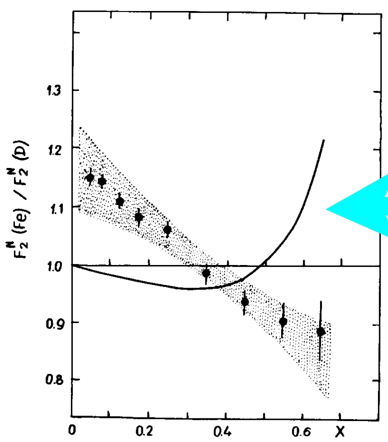
Mechanisms of violation of factorization: nonnucleonic degrees of freedom in D /EMC effect, fsi

EMC effect

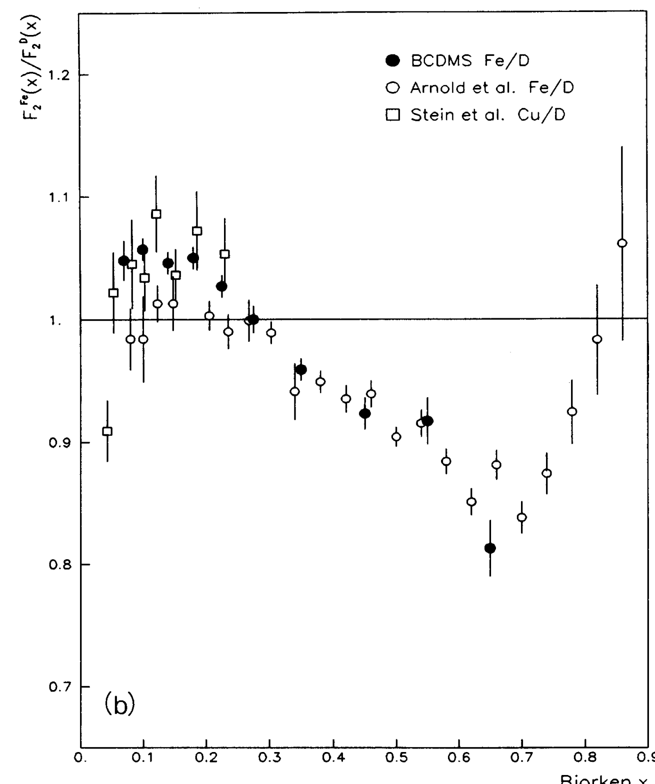
nucleus is a collection of quasifree nucleons

EMC effect: nuclear quark pdfs for 0.6> x >0.3

EMC ratio $R_A(x,Q^2) \equiv \frac{\sigma_A(x,Q^2)}{Z\sigma_p(x,Q^2)+N\sigma_n(x,Q^2)}$ =1



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



With few exceptions all EMC effect data are at rather low Q where higher twist effects are significant .No knowledge of nuclear effects for gluons at x>0.01.

One should not be surprised by presence of the effect but by its smallness for x<0.35 where bulk of quarks are, since distances between nucleons are comparable to the radii of nucleons.

Large effects for atoms in this limit.

models of the EMC effect at x >0.3

First explanations/models of the EMC effect (no qualitatively new models in 30 years)

- Pionic model: extra pions - $\lambda_\pi \sim 4\%$ -actually for fitting Jlab and SLAC data ~ 6% for A> 40

  + enhancement from scattering off pion field with $\alpha_\pi \sim 0.15$

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

  $$R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x}$$

  killed by data on Drell -Yan process

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

- *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 (color screening model) - small swelling - enhancement of deformation at large x due to suppression of small size configurations in bound nucleons + valence quark antishadowing with effect roughly $\propto k_{nucl}^2$

Dependence of the modification of bound nucleon pdf on virtuality is a generic effect — the color screening mechanism - explains why effect is large for large x and practically absent for x~ 0.2 (average configurations V(conf) ~ <V>). Large x ⇒ smaller size nucleon configurations ⇒weaker attraction ⇒suppression

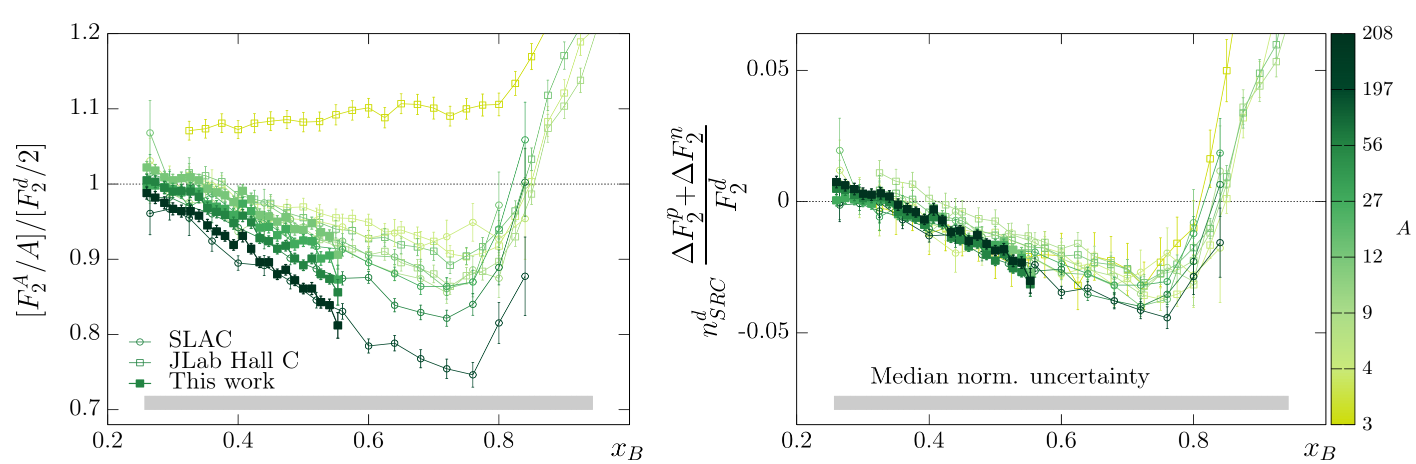
Model leads to universal x-shape and A-dependence of deviation of the EMC ratio from one, dominance of pn SRC in the EMC effect

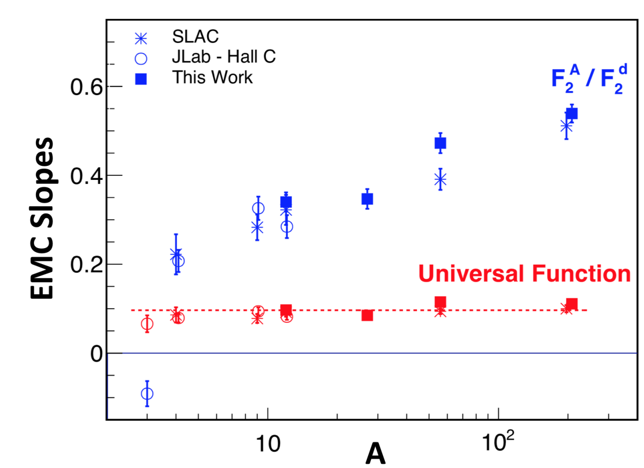
$$\sigma_{eA}(x,Q^2)/\sigma_{eD}(x,Q^2) - 1 = (a_2(A)-1)f(x,Q^2)$$

x >1.4, Q^2 > 2 GeV^2

relative probabilityy of NN (mostly pn) SRC in nucleus and deuteron

universality extend to x=0.8 where Fermi motion is important - another indication of dominance of SRCs as Fermi motion is dominated by SRC





Nature

Challenge: probability of SRC ~ 20% (90 % pn), while EMC effect is 10% . Large modifications in large x configurations in SRC. Some EMC effect for mean field

What are expectations for non-nucleonic degrees of freedom?

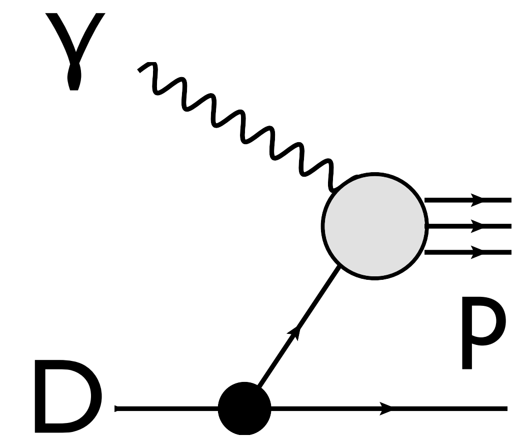
- Deformation of the bound nucleon wave function like for electrons in a molecule as compared to two independent atoms.

- Hadronic degrees of freedom - Δ-isobar - small probability but maybe important. Pions - very small effect but possible to study.

Let us first consider deformation effect (color screening model)

In QCD interaction depends on the size of hadron or configuration in the hadron
Quarks in nucleon with $x>0.5$ --0.6 belong to small size configurations with strongly suppressed pion & gluon fields (while pion exchange is critical for SRC especially D-wave.). Test we suggested in 83 is to measure number of wounded nucleons, ν, in pA collisions for hard trigger with large x.
Prediction: drop of ν, with increase of x. Observed at LHC and RHIC.

“Gold plated test” FS 83



Tagging of proton and neutron in e+D→e+ backward N +X (lab frame). Also 3He with neutron momentum very small in ^{3}He rest frame (ZDC) to study pp SRC

Collider kinematics -- nucleons with $p_N > p_D/2$ - C.Weiss talk,

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 for say 200 MeV/c - go to 400 MeV/c and see whether the effect would increase by a factor of ~3-4. (α between 1.3 and 1.5/

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

f is the same universal function as in EMC effect

Here α is the light cone fraction of interacting nucleon

$$\alpha_{spect} = 2 - \alpha = \frac{2E_N}{E_D}$$

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

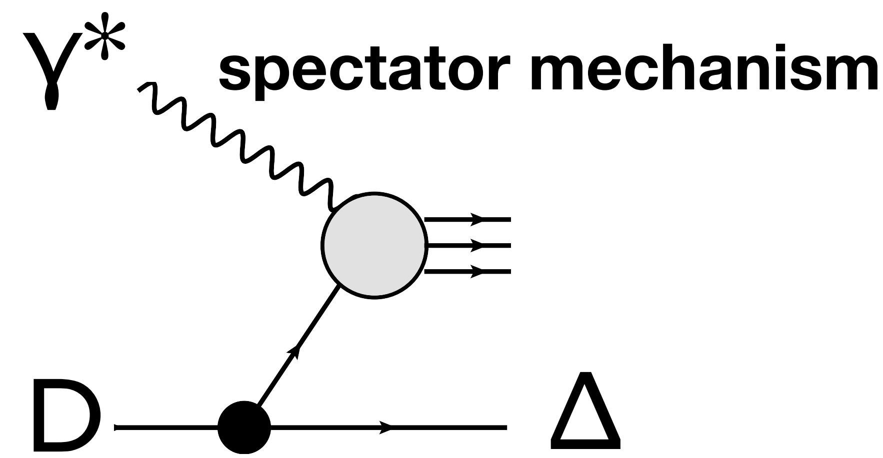
A priori the deformation of a bound nucleon can also depend on the angle φ between the momentum of the struck nucleon and the reaction axis as

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

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)*. In difference from 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.

Looking for Δ's, 6q.... in DIS



$$\sigma_{eD\to e\Delta+X} = \sigma_{e\Delta\to X}(x/(2-\alpha),Q^2)\frac{\psi^2_{\Delta,\Delta}(\alpha,p_t)}{2-\alpha}$$

$$\alpha_\Delta = \frac{\sqrt{m_\Delta^2+p^2}-p_3}{m_d/2}$$ p is target rest frame momentum of Δ isobar

Advantage σ(e Δ) can be estimated with a reasonable accuracy in difference from $e + {}^2H \to e + \; forward\ \Delta^{++} + \; slow\ \Delta^-$

α=1, p_t=0 corresponds to p_3 ~ 300 MeV/c forward - for good acceptance in Jlab kinematics necessary to detect slow protons and pions. forward nucleon and pion (in the deuteron fragmentation) at EIC (Easy (?)).

Competing mechanism - Δ's from nucleon fragmentation =direct mechanism

$$\left.\frac{\sigma^{lD/\Delta}}{dx\ dy\ \frac{d\alpha}{\alpha}\ d^2k_t}\right|_{direct} = \int \frac{d\beta}{\beta}\ d^2p_t\ \rho_D^N(\beta,p_t)\ \times \qquad (18)$$

$$\times\ \frac{d\sigma^{lN/\Delta}}{dx\ dy\ d\alpha/\alpha\ d^2k_t}\left(\beta E_l, x/\beta, y, Q^2, \frac{\alpha}{\beta - x}, k_t - \frac{\alpha}{\beta}\ p_t\right)$$

For scattering of stationary nucleon

$$\alpha_\Delta < 1 - x$$

Also there is strong suppression for production of slow Δ's - larger x stronger suppression

$$x_F = \frac{\alpha_\Delta}{1-x} \qquad \sigma_{eN\to e+\Delta+X} \propto (1-x_F)^n, n \geq 1$$

Numerical estimate for $P_{\Delta\Delta}$ =0.4%

$$\left.\frac{\sigma^{1D/\Delta}}{dx\, dy\, \frac{d\alpha}{\alpha}\, d^2k_t}\right|_{direct} \Bigg/ \left.\frac{\sigma^{1D/\Delta}}{dx\, dy\, \frac{d\alpha}{\alpha}\, d^2k_t}\right|_{spect} < 0.1$$

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)*

Δ-isobars are natural candidate for most important nonnucl. degrees of freedom

Large energy denominator for NN →NΔ transition ➡ Δ's **predominantly in SRCs**

Δ 's in 3He on 1% level from Bjorken sum rule for A=3 - Guzey &F&S 96

Expectations during the EMC effect rush

TABLE II. Pion excess and Δ fraction in nuclear matter (NM) and nuclei.

	$\langle \delta n^{\pi} \rangle / A$	$\langle n^{\Delta} \rangle / A$
NM, $k_F = 0.93$	0.08	0.03
NM, $k_F = 1.13$	0.12	0.04
NM, $k_F = 1.33$	0.18	0.06
^{2}H	0.024	0.005
^{3}He	0.05	0.02
^{4}He	0.09	0.04
^{27}Al	0.11	0.04
^{56}Fe	0.12	0.04
^{208}Pb	0.14	0.05

ruled out by Drell - Yan data

Friman, Pandharipande, WIringa 1983

$$\frac{P(\Delta)}{P_{SRC}(N)} \sim \frac{0.04}{0.2} \sim 0.2$$

Too large ?

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

is confirmed by neutrino study of Δ-isobar production off D

Best limit on the probability of $\Delta^{++}\Delta^{-}$ component
in the deuteron $< 0.2\%$. (however details of procedure are not available)

Side remark: Polarized deuteron extra bonus: $\Delta^{++}\Delta^{-}$ mostly in D-wave -- hence large spin effects

Conclusions

Studying quark - gluon structure of SRCs is doable at EIC

prime kinematics is $x > 0.1 — 0.2$

at small $x < 0.1$ longitudinal distances become large ~ $1/2m_N x$ and much larger than R_{cor} ~ 1.2 fm and contribution of SRCs is usually suppressed.

Several other processes which could be used involve hard diffraction with J/ψ production - no time to discuss

Issues for proton fragmentation and studies of SRCs are pretty similar

acceptance in the forward direction

counting rates, optimal energies, resolution

polarized deuteron beam

Complications/distortions due to the f.s.i.

Use of complementary reactions (Jlab, EIC) - tests of factorization are very important

Note: f.s.i. can be studied now using UPC data at LHC

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

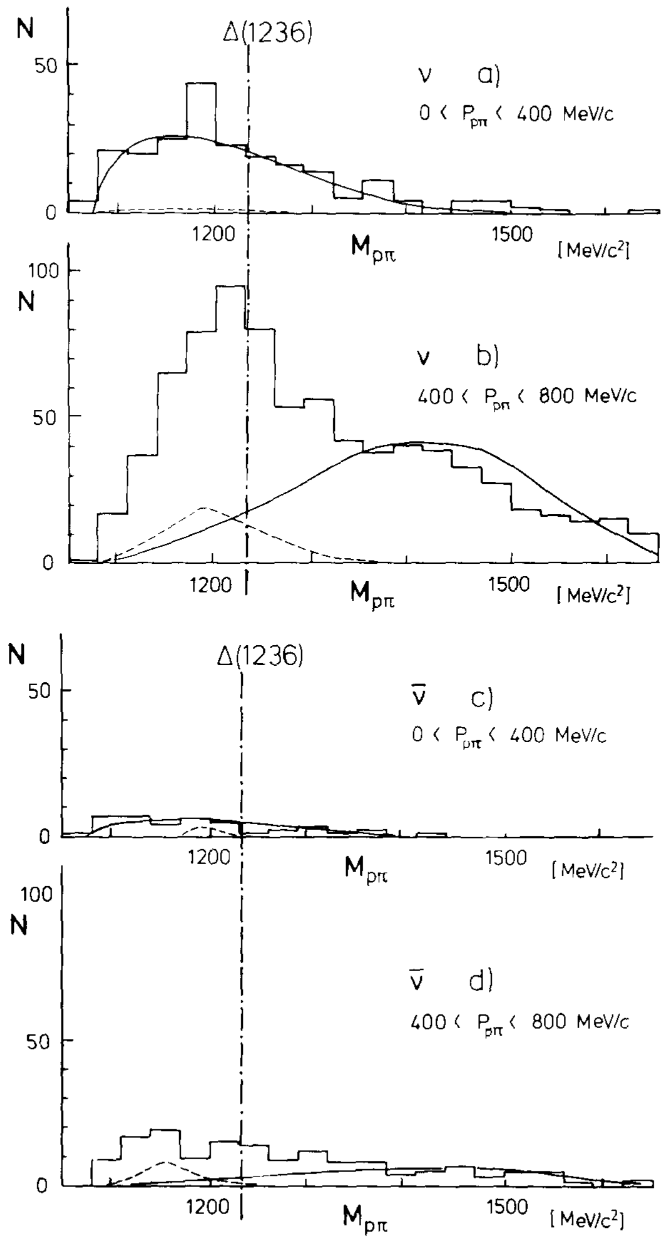
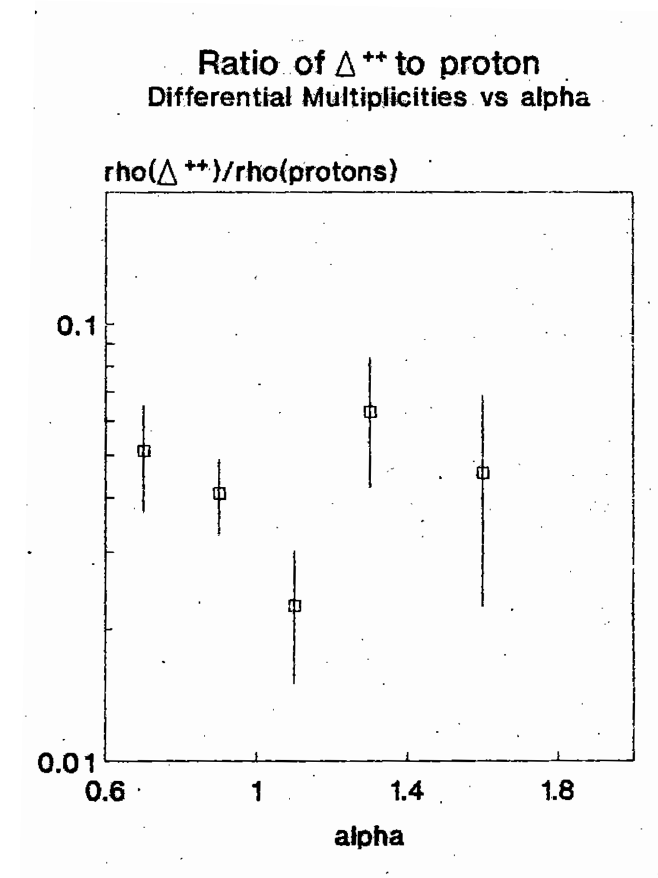


Fig. 1. Effective mass distributions of $p\pi^+$ combinations for ν (top) and $\bar{\nu}$ (bottom) interactions. The distributions are presented for two intervals of the combined $p\pi^+$ momentum: 0–400 and 400–800 MeV/c. The chosen bin size is 30 MeV/c^2 = $\Gamma(1235)/4$. The solid lines show the 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.



$$\frac{\sigma(e + A \to \Delta^0 + X)}{\sigma(e + A \to \Delta^{++} + X)} = 0.93 \pm 0.2 \pm 0.3$$

$$\frac{\sigma(e + A \to \Delta^{++} + X)}{\sigma(e + A \to p + X)} = (4.5 \pm 0.6 \pm 1.5) \cdot 10^{-2}$$

❄ Bjorken sum rule for A=3

One needs to include Δ's in the A=3 system on the level of 1% to remove the discrepancy with 3N model (Guzey, FS 94)

Perfect kinematics for EIC studies - Δ's along nucleus