Quest for nonnucleonic degrees of freedom in nuclei

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MIT SRC & EMC workshop, March 2019

Outline

What are nonnucleonic degrees of freedom responsible for the EMC effect

The Hunting of the Snark (Δ's)

EMC effect unambiguously demonstrates presence of the no nucleonic degrees of freedom in nuclei

Can account of Fermi motion describe the EMC effect?

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

light -cone nucleon density matrix A>α>0

Many nucleon approximation:

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

=0 in many nucl. approx.

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YES

If one violates baryon charge conservation or momentum conservation or both

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Generic models of the EMC effect

- extra pions - $\lambda_\pi \sim 6\%$ -for fitting Jlab and SLAC data ~ 6%

  For $F_{2N}(x) \propto (1-x)^n$ $\quad R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x}$

  + enhancement for x<0.1from scattering off nuclear pion field with $\alpha_\pi \sim 0.15$

- 6 quark configurations in nuclei with probability $P_{6q} \sim$ 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 $(1/A)F_{2A}(x,Q^2) = F_{2D}(x, Q^2\xi_A(Q^2))/2$

- Color screening model - small swelling - enhancement of deformation at large x due to suppression of small size configurations in bound nucleons with effect roughly $\propto k_{nucl}^2$ next few slides

Very few models of the EMC effect survive when constraints due to the observations of the SRC, no enhancement of antiquarks, etc are included - essentially one generic scenario - strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with most of the effect due to the SRCs.

Models with modification of rare configurations in bound nucleons addresses the paradox:

evidence that the EMC effect is due to SRC

VS

evidence that the SRCs are 90% nucleons

since these models require a small nonnucleonic component — few %

Price to pay — large modification of rare configurations responsible for F_2 at x> 0.5.

EMC effect for x=0.5 for Ca/(p+n) ~ 12% while probability of SRC ~20%.

Huge effect for scattering of SRC even if scattering off mean field gives 20 - 30%

Nucleon in quark configurations of a size << average size should interact much weaker than in average. Application of the variational principle indicates that probability of such configurations in bound nucleons should be suppressed (as it leads to stronger overall attraction) and effect should grow with virtuality of the nucleon.

We estimated the effect in the perturbation theory over the difference of the configuration dependent and average potentials

Relevant for the EMC effect if large x configurations in nucleon have smaller than average size (evidence from pA LHC experiments and PHENIX (RHIC) - will briefly discuss later.

Introducing in the wave function of the nucleus explicit dependence of the internal variables

$$\left[-\frac{1}{2m_{\rm N}}\sum_j \nabla_i^2 + \sum_{i,j}{}' V(R_{ij}, y_i, y_j) + \sum_i H_0(y_i)\right]\psi(y_i, R_{ij}) = E\psi(y_i, R_{ij}).$$

NR potential

$$U(R_{ij}) = \sum_{y_i, y_j, \tilde{y}_i, \tilde{y}_j} \langle \varphi_{\rm N}(y_i)\varphi_{\rm N}(y_j)|V(R_{ij}, y_i, y_j, \tilde{y}_i, \tilde{y}_j)|\varphi_{\rm N}(\tilde{y}_i)\varphi_{\rm N}(\tilde{y}_j)\rangle,$$

In the first order perturbation theory for V << U using closure we find

$$\delta = \left|\frac{\psi_0 + \delta\psi_0}{\psi_0}\right|^2 \simeq 1 + 2\sum_j{}' U(R_{ij})/\Delta E_A.$$

$\Delta E_A = m_{N^*} - m_N$

For average configurations in nucleon (V ≃ U) no deformations

modification of average properties of bound nucleons is < 2- 3 %

Momentum space

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

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

general case

$p_{int} = M_A - p_{A-1}$

effect ∝ virtuality

Dependence of the modification of bound nucleon pdf on virtuality is a generic effect — the discussed mechanism - explains why effect is large for large x and practically absent for x~ 0.2 (average configurations V(conf) ~ <V>)

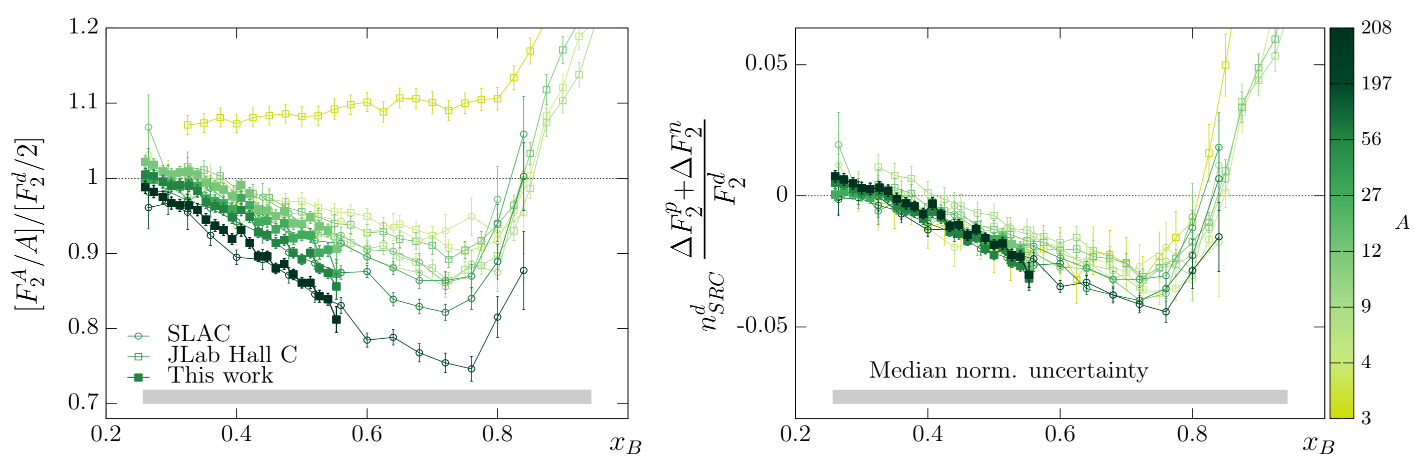
Model leads to universal shape and A-dependence of deviation of the EMC ratio from one

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

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

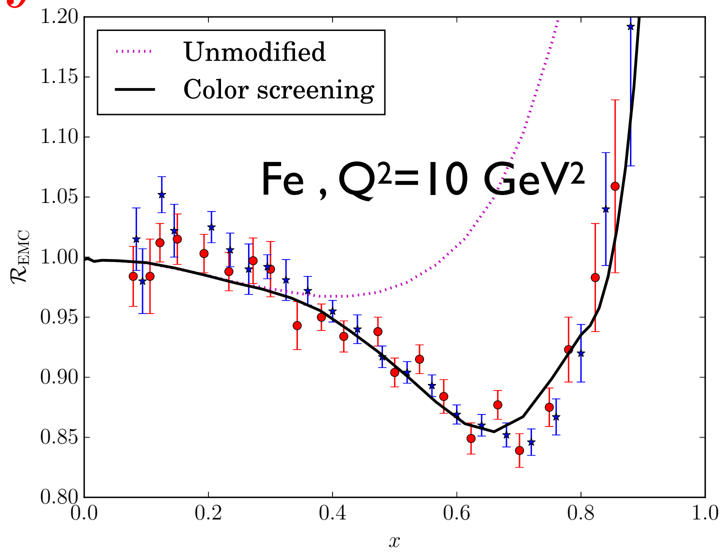
universality extend to x=0.8 where Fermi motion is important - another indication of dominance of SRCs as Fermi motion is dominated by SRC

Nature CLAS + MS



Assuming that suppression is small for x≤ 0.45, grow linearly between x=0.45 and 0.65 and equal to $\delta_A(k)$ at larger x gives a reasonable description of the data within the model with SRCs with

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

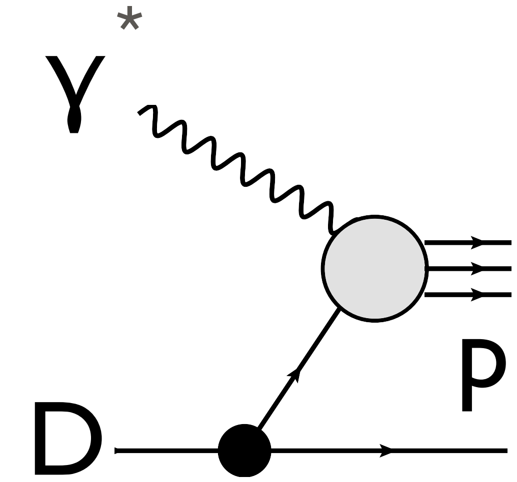


Freese, Sargsian, MS 14

Allows to predict x > 1 tail. Important already x=1 is interesting since it probes in this limit SRCs

$$\langle\alpha\rangle = x + 0.5$$

"Gold plated test" FS 83-85



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

Collider kinematics -- nucleons with $p_N > p_D/2$ - C.Weiss talk,
Jlab experiments -L.Weinstein's 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.

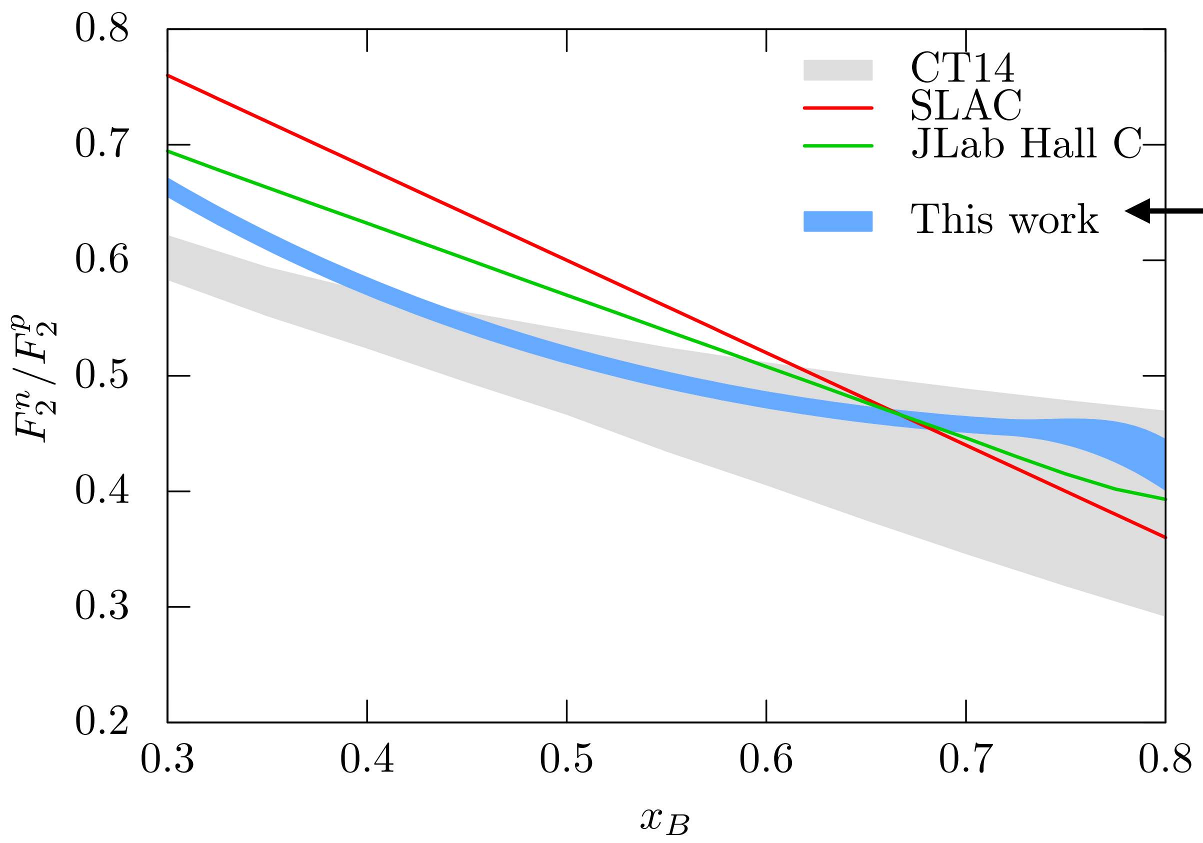
$$1 - F_{2N}^{bound}(x/\alpha, Q^2)/F_{2N}(x/\alpha, Q^2) = f(x/\alpha, Q^2)(m^2 - p_{int}^2)$$

Here α is the light cone fraction of interacting nucleon

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

Tagging combined with detection of forward pions for flavor separation

⟹ **Separate EMC effect for u and d quarks in the proton/neutron. Maybe rather different as d/u strongly changes with x**



correcting for the EMC effect based on pn src dominance

Tagging with polarized deuteron:

is the EMC effect the same for S and D waves? Different interactions in S and D wave —> different sensitivity to the size of configurations.

is the EMC effect the same for parallel and antiparallel helicities of quark and nucleon ?

Different EMC effect for

$$\lambda_u = \lambda_D/2 \qquad \lambda_d = \lambda_D/2$$

$$\lambda_u = -\lambda_D/2 \qquad \lambda_d = -\lambda_D/2$$

Topic for further exploration: pattern of f.s.i. - change of spectator rate, momentum distortions. Needs further studies (C.Weiss talk)

tagging for A>2 — can produce backward nucleon in a final state scattering off NN SRC.

example: neutrino experiment off Ne and 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

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

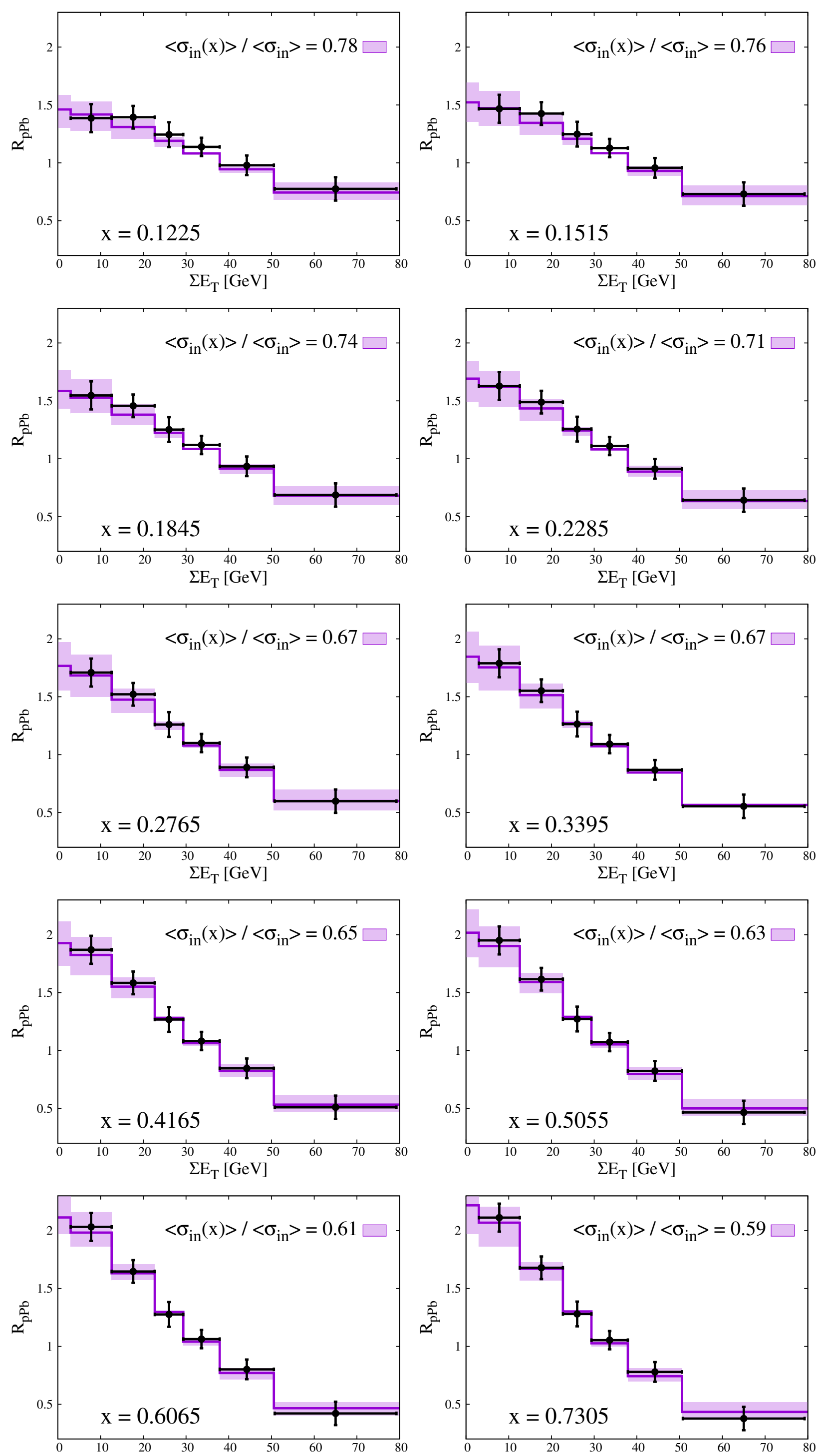
Here $<\sigma>$ is cross section averaged over φ and dΩ is the phase volume and the factor c characterizes non-spherical deformation.

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.

In QCD interaction depends on the size of hadron or configuration in the hadron

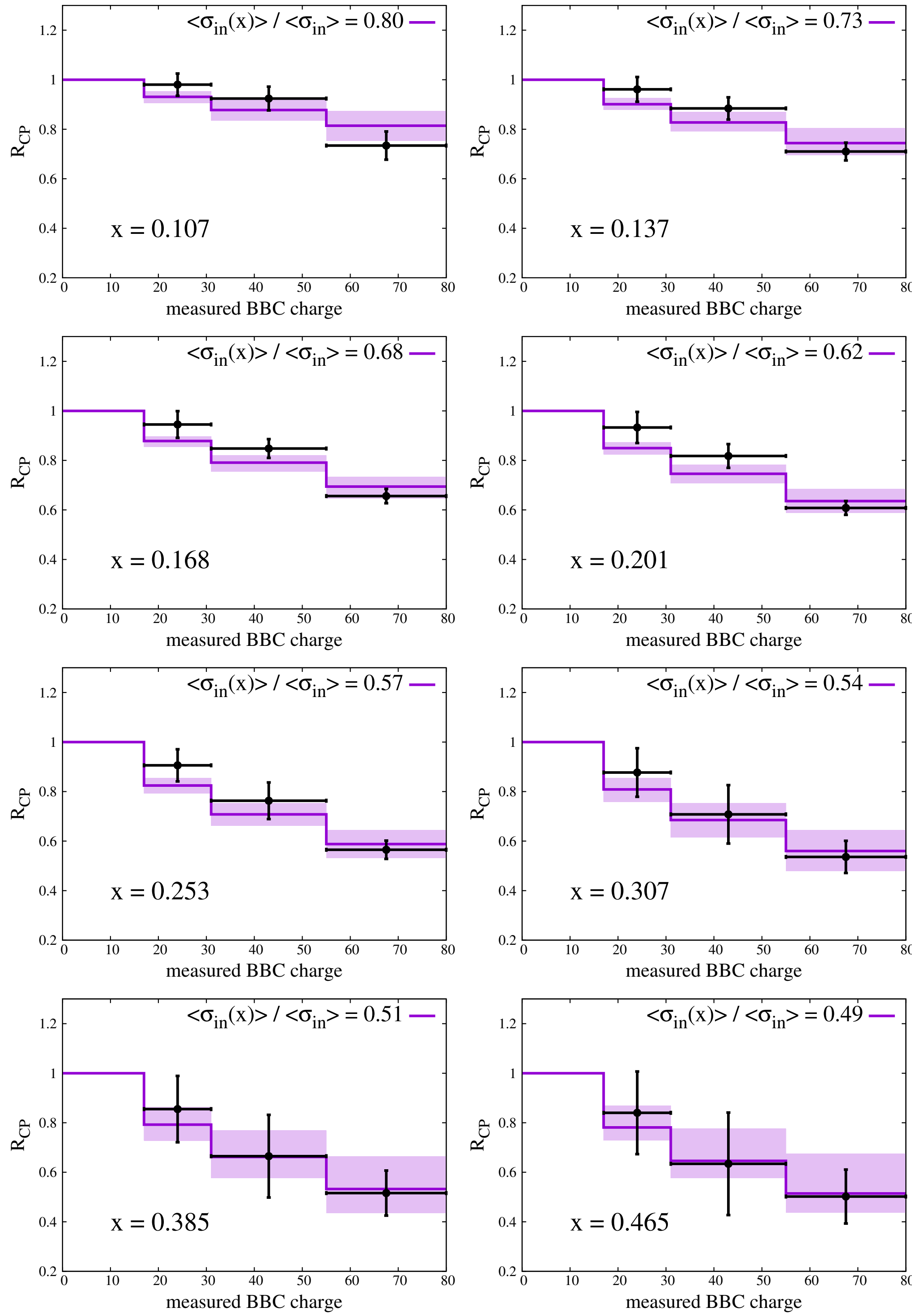
Expectation: Quarks in nucleon with $x>0.5$ --0.6 belong to small size configurations with strongly suppressed pion & gluon fields (while pion exchange is critical for SRC especially D-wave.). Test we suggested in 83 is to measure number of wounded nucleons, ν, in pA collisions for hard trigger with large x.

Prediction: . drop of ν, with increase of x. Observed at LHC and RHIC.



Deviations from Glauber model for production of dijets as a funciton of number of wounded nucleons, described in the color fluctuation model as due to decrease of $<\sigma_{eff}(x)>/\sigma_{in}$

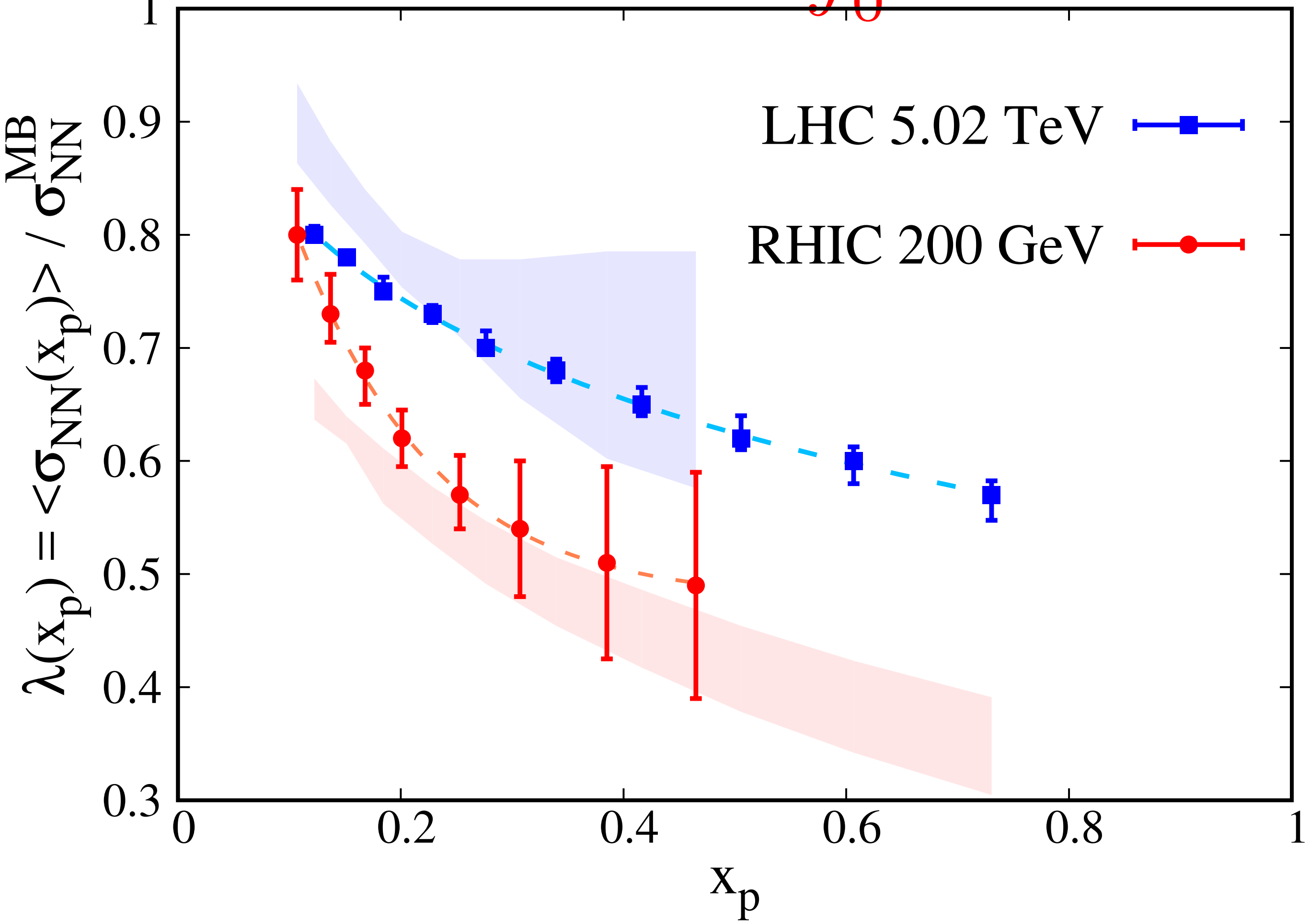
Data from pA ATLAS



Similar analysis with DAu RHIC jet production data at zero rapidity and high p_T.

Implicit eqn for relation of $\lambda(x_p, s_1)$ and $\lambda(x_p, s_2)$

$$\int_0^{\lambda(x_p;\sqrt{s_1})\sigma_{tot}(\sqrt{s_1})} d\sigma\, P_N(\sigma;\sqrt{s_1}) = \int_0^{\lambda(x_p;\sqrt{s_2})\sigma_{tot}(\sqrt{s_2})} d\sigma\, P_N(\sigma;\sqrt{s_2})$$



Highly nontrivial consistency check of interpretation of data at different energies and in different kinematics

suggests $\lambda(x_p=0.5$, low energy) ~1/4). Such a strong suppression results in the EMC effect of reasonable magnitude due to suppression of small size configurations in bound nucleons - - (Frankfurt & MS83) - discussion above.

HUNTING for Δ -isobars is nuclei

Intermediate states with Δ -isobars.

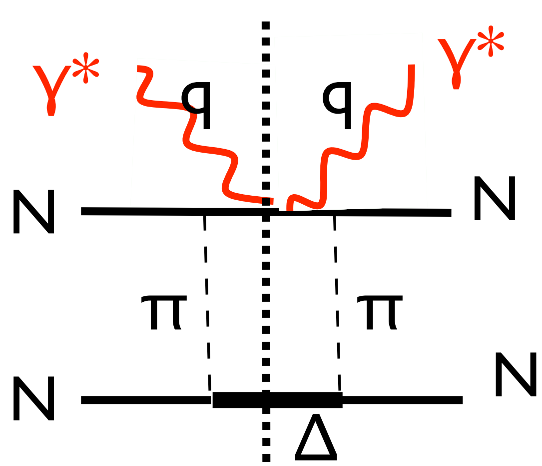
Often hidden in the potential. Probably OK for calculation of the energy binding, energy levels. However wrong for high Q^2 probes. role of Δ's -

Explicit calculations of B.Wiringa (1991) reported at Penn State -
~(1/3 —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 initial state

Large Δ admixture in high momentum component

⇓

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



I do not discuss N*'s but they may contribute as well

Generic feature: distribution of ***ΔΔ over relative momenta in the deuteron wave function is broad similar trend for ΔN***

$$\frac{1}{2E_\Delta - m_d} = \frac{1}{2\sqrt{m_\Delta^2 + k^2} - m_d}$$

Reason: the energy denominator in difference from NN state is practically constant up to k ~ ***$m_\Delta/2$***

The same in the light cone formalism

$$\left[\frac{m_\Delta^2 + k_t^2}{\alpha(2-\alpha)} - m_d^2\right]^{-1}$$

α/2 is the light-cone fraction carried by isoba

Since difference is large small sensitivity to change of α:

change of α from 1 to 1.3: α(2-α) --- 1 to 0.91

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 **much more important in I=1 (pp,nn) SRCs**

➡ Δ's **much broader distribution in momenta (α,k_t)**

Expectations during 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

appears to be 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 high fraction ?

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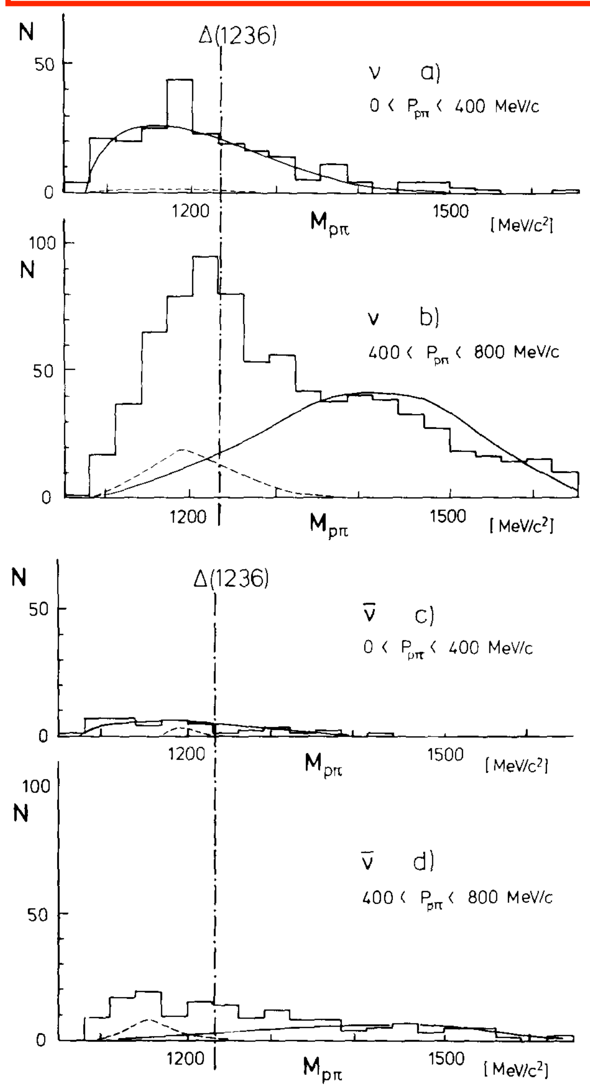
SEARCH FOR A Δ(1236)–Δ(1236) STRUCTURE OF THE DEUTERON

Based on the analysis of 15499 νD interactions
probability to find deuteron in Δ++Δ- state < 0.2% on 90% CL

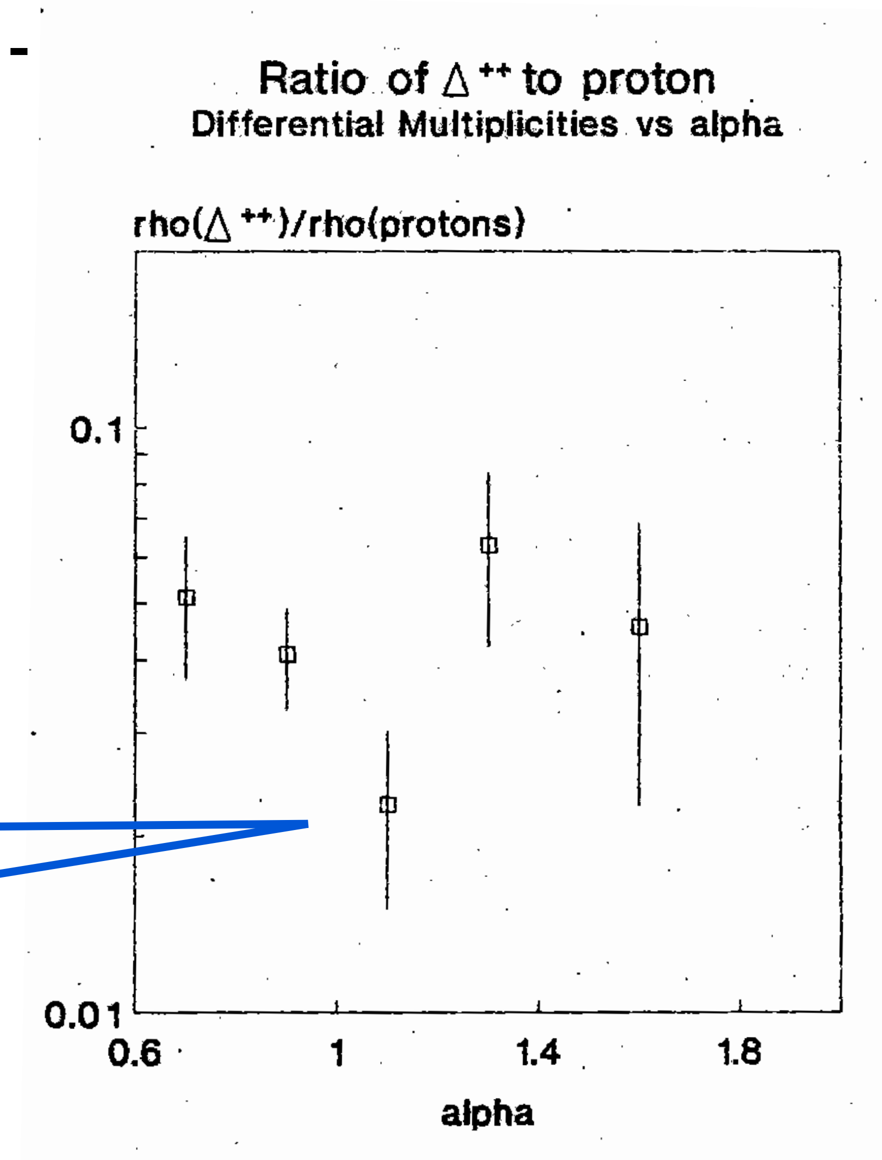


$$\frac{P_D(\Delta\Delta)}{P_D(SRC)} < 0.1$$

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 = Γ(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.

Possible evidence for Δ's in nuclei

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

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

expect R=1 for isosinglet nucleus

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

$$\Downarrow$$

$$\frac{P(\Delta)}{P_{SRC}(N)}\sim\ 0.1$$

suppression at α~1

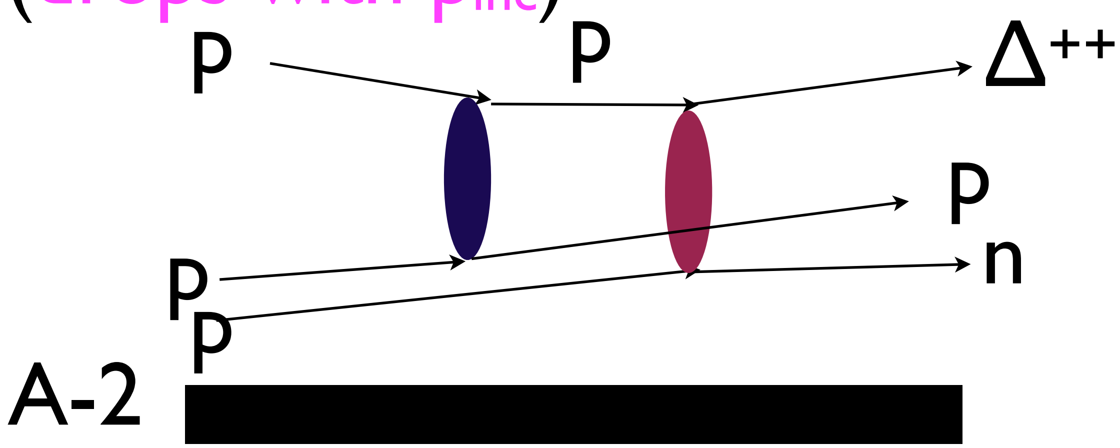
New data are necessary: many options in Jlab kinematics ? New Jlab experiments ?

Perfect kinematics for EIC in particular $\vec{e}+\vec{D}\to e+\Delta^{++}+X(or\ forward\,\pi^{\pm})$

☛ PROTON (ANTIPROTON) BEAMS CRITICAL FOR TESTING FACTORIZATION): LOOK FOR CHANNELS FORBIDDEN FOR SCATTERING OFF SINGLE NUCLEONS BUT ALLOWED FOR SCATTERING OFF EXOTICS: Δ'S 6Q... AT LARGE C.M. ANGLES

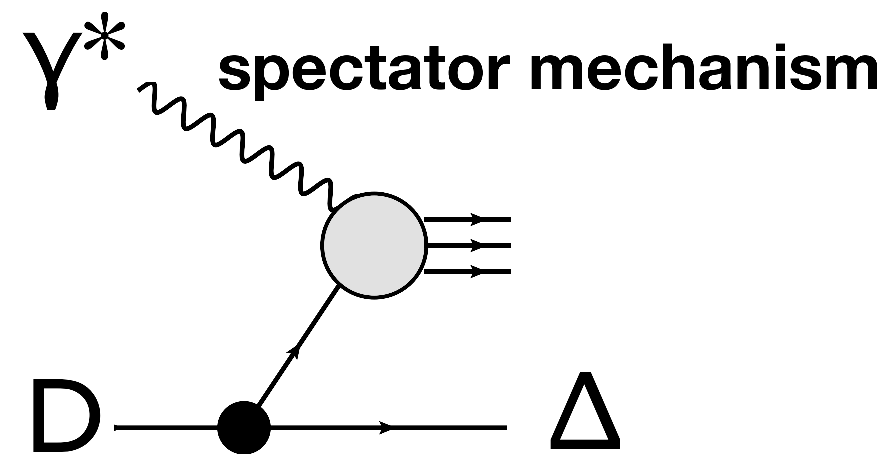
$$p + A \to \Delta^{++} + p + (A-1)$$

Background: two step process with charge exchange at the second step (drops with p_{inc})



Important tool for the analysis: $\alpha_\Delta < 1$ cut as the α_Δ distribution is broader than α_N distribution. Measuring the strength of charge exchange using $\alpha_\Delta = 1$ range

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 $e+{}^2H \to e+ \ forward\ \Delta^{++} + \ slow\ \Delta^-$

$\alpha=1$, $p_t=0$ corresponds to $p_3 \sim 300$ 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: πN→Δ FS90

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

Conclusions

Good hunting and don't forget the No.1 rule of duck hunting

— to go where the ducks are