Studying nucleon multiparton structure via nucleon fragmentation

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Outline

* Going beyond single parton characteristics

Strategy similar to one used now to probe short range correlations in nuclei: observe correlations through decay of the system after removal of a constituent

Physics of validity of leading twist dynamics in target fragmentation

* *What is known experimentally about nucleon fragmentation in hard processes*

* Observables for EIC

* *Few examples of nuclear observables*

Nucleon Fragmentation in DIS

WHY'S

- fragmentation is a probe of multiparton nucleon structure and QCD dynamics for which EIC can add a lot
  QCD Q^2 evolution is simple - clear advantage as compared to TMD's

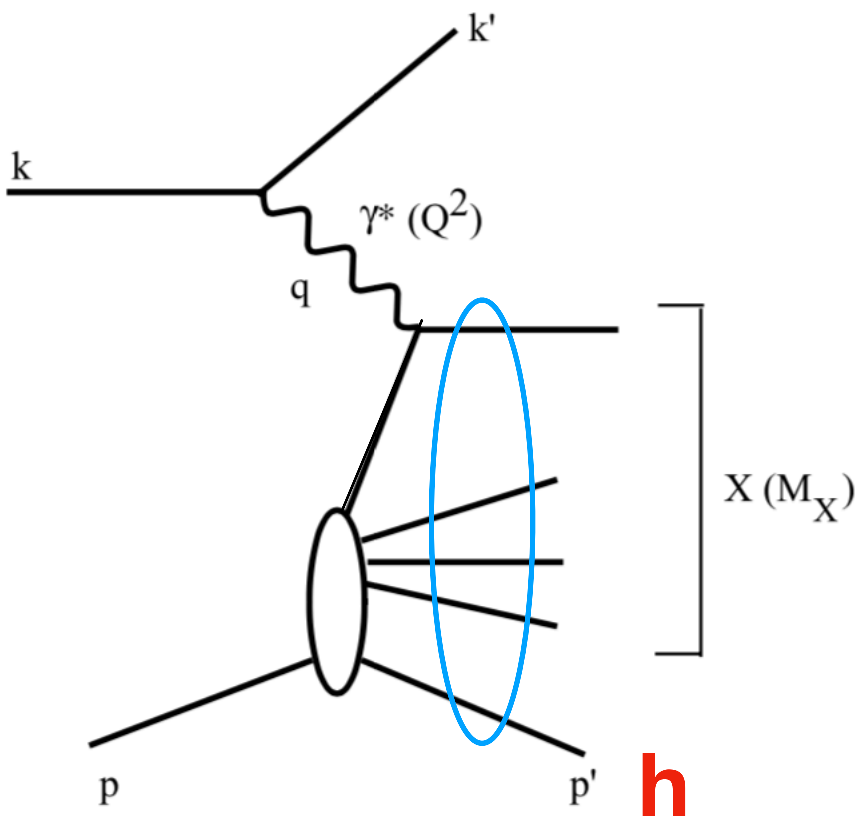
- information about fragmentation is necessary for optimizing studies of SRC - tagging, EMC effect, ΔΔ component of the deuteron

- Formation time of hadrons in eA scattering in nuclear fragmentation region

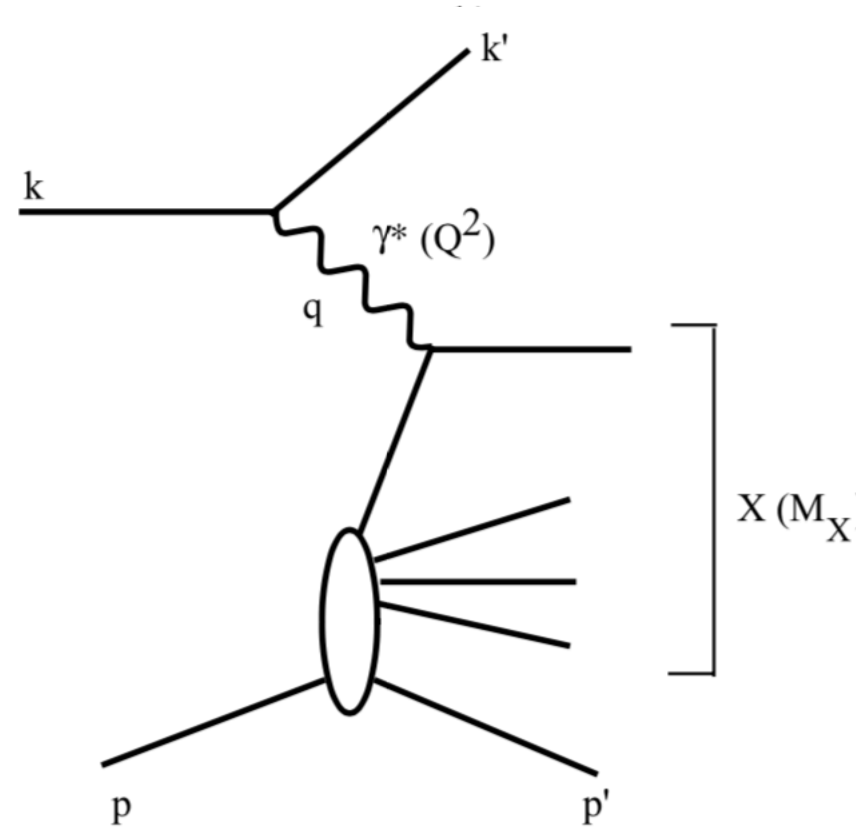
Note that many requirements to detector for studying fragmentation are similar to the ones for studying of short range correlations

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 with the rest of partons: — does not change with Q^2 since overall interaction does not resolve qg which are located at transverse distance $<< 1/Q_0$

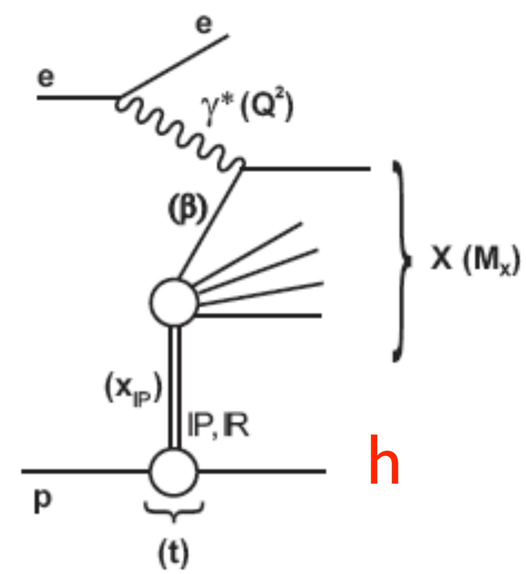
one can define fracture (Trentadue &Veneziano) parton distributions

at collider

$$x_L = p_h/p_{in} \quad x_L \le 1 - x$$

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

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



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

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

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

Theorem:

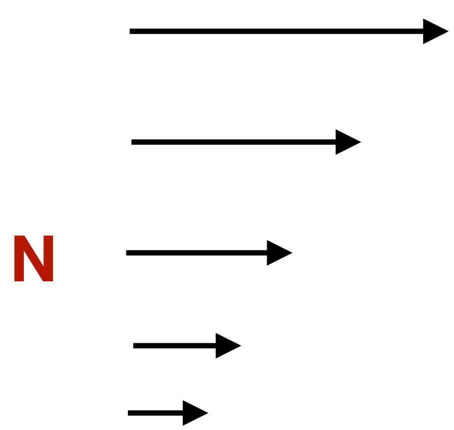
For fixed $x_{I\!P},\ t$ universal fracture pdf (same in different hard processes, but a priori depending on $x_{I\!P},\ t$)+ the evolution is the same as for normal pdf's

Comment: $x_{I\!P}$ *is traditional notation due to focus on diffraction - notion of Pomeron is not necessary in the general factorization analysis*

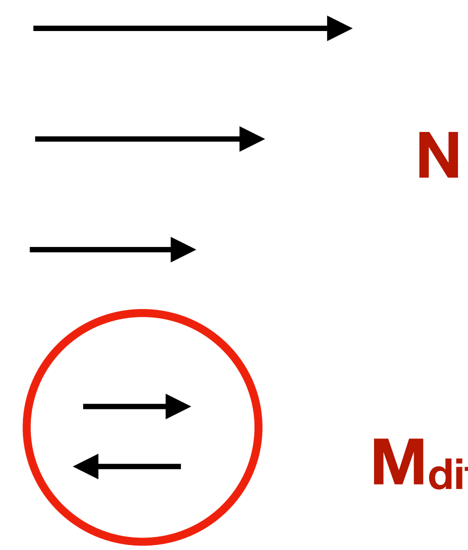
$x_{I\!P}$ **< 0.01 for diffraction but kinematically restricted to < 1**

Example: diffraction and nucleon structure

Consider Breit frame $q=(0, -2xp_N)$



nucleon before
absorption of virtual photon



nucleon and diffractive mass after
absorption of virtual photon

small x parton has a significant probability to have a nearby parton/partons with which it can form a white cluster

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

$$e + p \to e + p + X, e + p \to e + n + X$$

Need high statistics as f_j are functions of (x,β,Q^2,t) 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 $x << 1- z$ integrals over x and $\beta << 1$.

Soft factorization: for $x << 1$, we expect z, t-distribution to depend weakly on x at not very large Q^2

Strong dependence of leading (large z) baryon production on x (FS77):

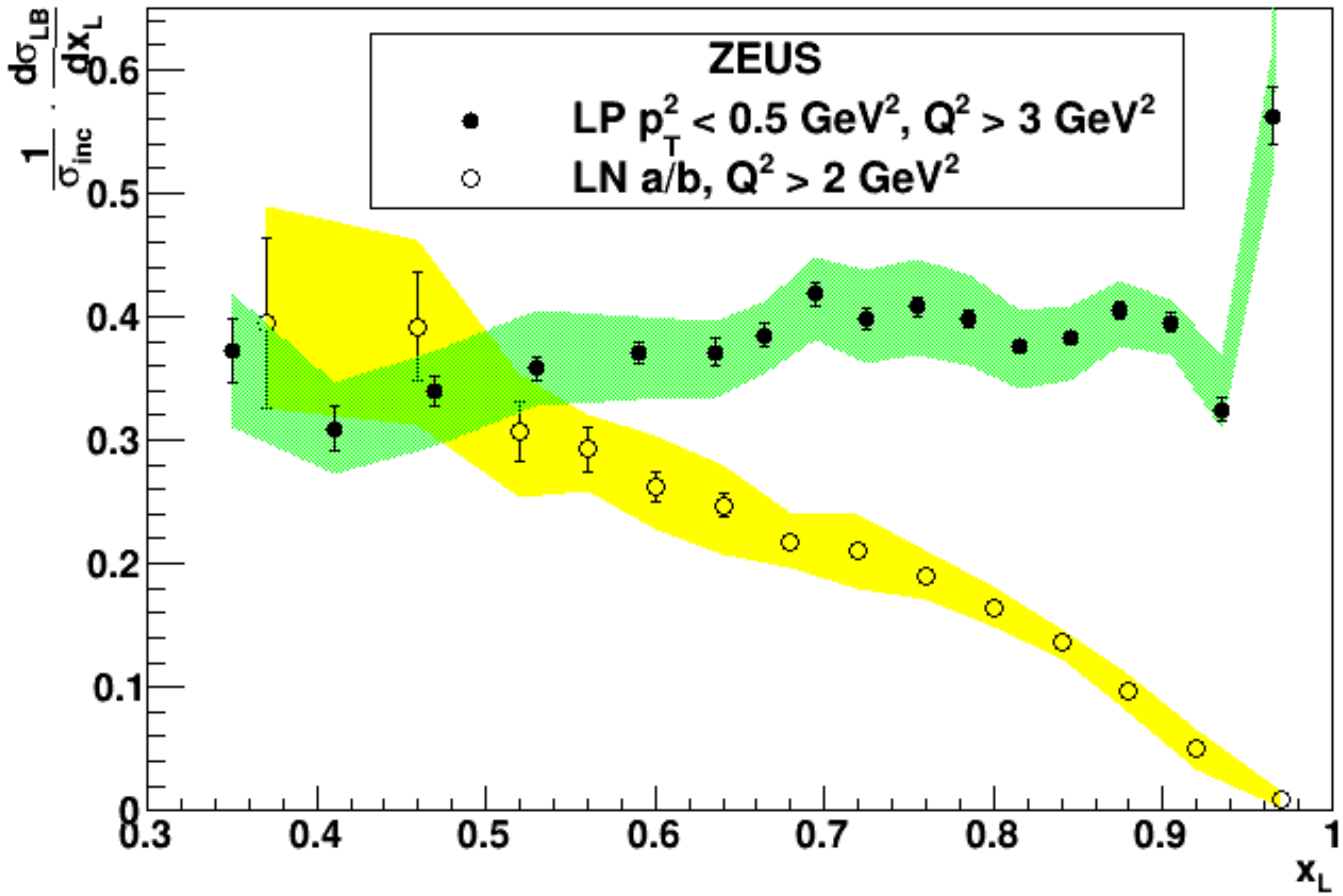
$$f_j(x,z) \propto (1-z)^{n(x)}$$

$n(x < 0.01) = -1$ **diffraction + flat (n=0) at smaller xL**

$n(x \sim 0.1) = 0? 1?$ **onset of sea quark dominance**

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

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



plot prepared
by W. Schmidke

r_LP = 0.299 +/- 0.003 (stat.) +0.008 -0.007 (syst.) [not shown in the paper]
r_LN = 0.159 +/- 0.008 (stat.) +0.019 -0.006 (syst.) [as shown in the paper]

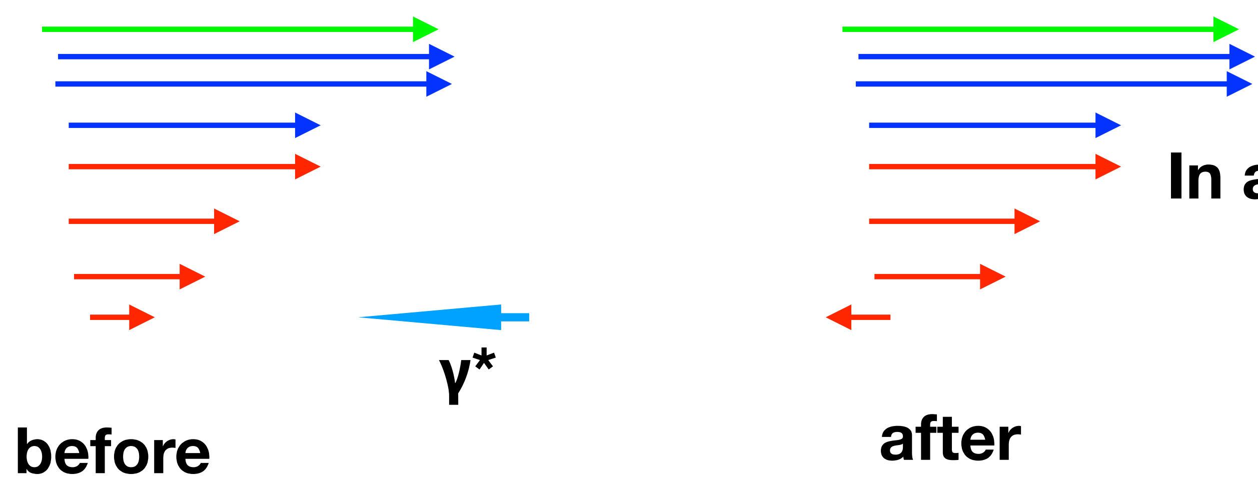
HERA studies missed a puzzle: where are baryons. Should be
#baryons - # anti baryons = 1 per event.
For small x and x_L > 0.3 only 0.46 baryons are observed (70% p, 30% n) (strange baryons not measured but likely 30% correction of neutrons

→ A lot (50%) of baryons are produced below x_L =0.3

In nucleus rest frame these baryons have large longitudinal momenta, p_L

For example for x_L =0.2, p_L~3 GeV. Are they formed inside nucleus?

x_{Bj} for these data is ~10^{-3}. It is highly nontrivial that a removal of a wee parton leads to a break up with large energy losses - nucleon seems to be pretty fragile



In average leading baryon carries only~1/3 of total momentum

long range correlations in color?

high degree of coherence of small x partons with leading partons

Emerging picture (small x) from my analysis:

leading protons $x_L>0.7$ — 3 valence quarks

protons $0.7 > x_L > 0.3$(?) — 2 valence quarks

protons $0.3 > x_L > 0.1$(?) — 1 valence quark

mostly protons & few neutrons

} comparable number of neutrons and protons

EXPECTATIONS &OBSERVATIONS

if x << (1-x_L), nucleon multiplicity for removal of (anti)quark or a gluon are the same.

Soft factorization

Hence no dependence of the x_L distribution on W,

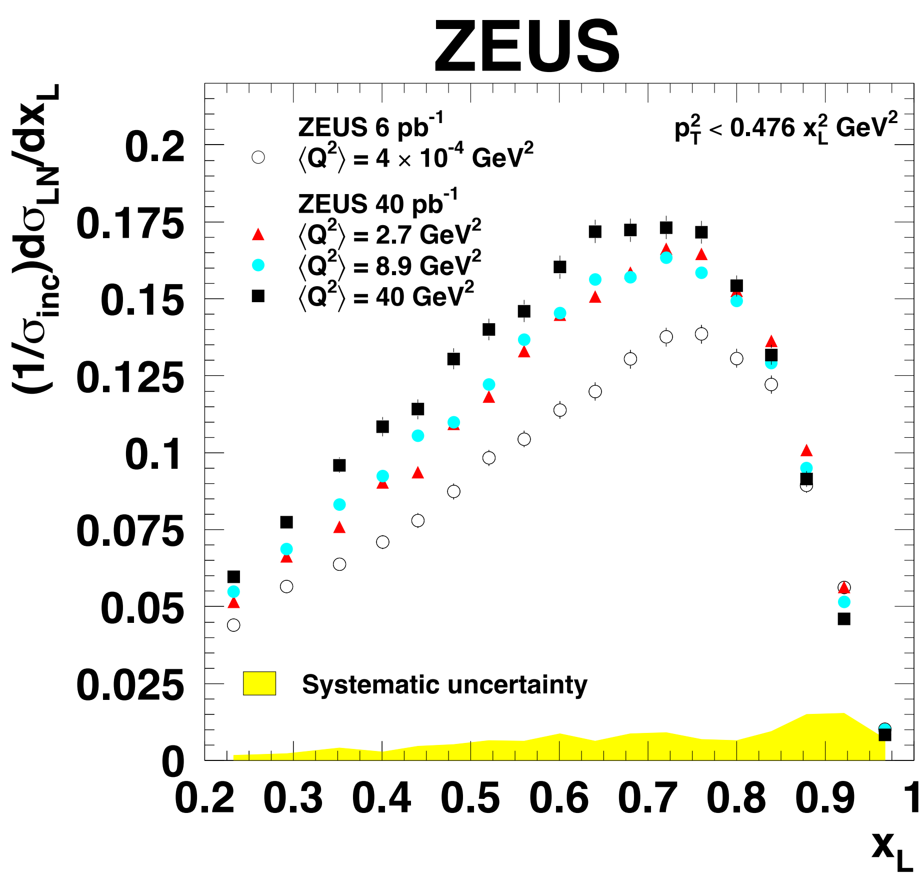
observed

Transition from photoproduction to DIS:
disappearance of shadowing - reduction of nucleon yield at Q^2=0.

In Gribov - Regge theory presence of shadowing implies presence of
a correlation between central rapidity multiplicity , n_h(y~0) and nucleon yield:

larger n_h --smaller nucleon multiplicity at large x_L

significant reduction for n_h ~2<n_h>



There were numerous attempts to extract pion pdfs from reaction

$$ep \to en + X$$

this contribution requires approaching the pion pole which is very difficult:

$$t = -\frac{1}{x_L}(m_N^2(1-x_L)^2 + p_t^2) \qquad x_L \geq 1 - m_\pi/m_N \sim 0.85, p_t \leq m_\pi$$

Space time interpretation - pion is well defined if its distance from the nucleon core is $> 1/m_\pi$

Soft factorization leads to contributions to neutron production in all fragmentation processes

Simple example -

data: p/n > 2 for $x_L > 0.6$ (natural for fragmentation)

Reggeon model: pion exchange: n/p = 1/2; need P' -exchange, ω-exchange p/n >> 1

Warning: Regge exchange (triple reggeon limit) makes sense only for large rapidity intervals corresponds to $1-x_L < 0.1$

For fragmentation observed : p/n > 2 for x_L ~ 0.6 is natural

If collective fragmentation of two valence quarks dominates at large z

uu —> p >> uu—> n, ud —-> 1/2 p + 1/2 n

Probability that uu , du diquark fragments is: 1/3 uu + 2/3 ud

Hence

$$\frac{p}{n} = \frac{\frac{1}{3} + \frac{2}{3} \cdot \frac{1}{2}}{\frac{2}{3} \cdot \frac{1}{2}} = 2$$

agrees with the HERA data for x ~ 0.5

x -dependence of fragmentation

For sea quark knock out up to x~0.1 —- approximate matching to HERA:

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

$$r(z) = \frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dz} \propto (1-z)^{n(x)}$$

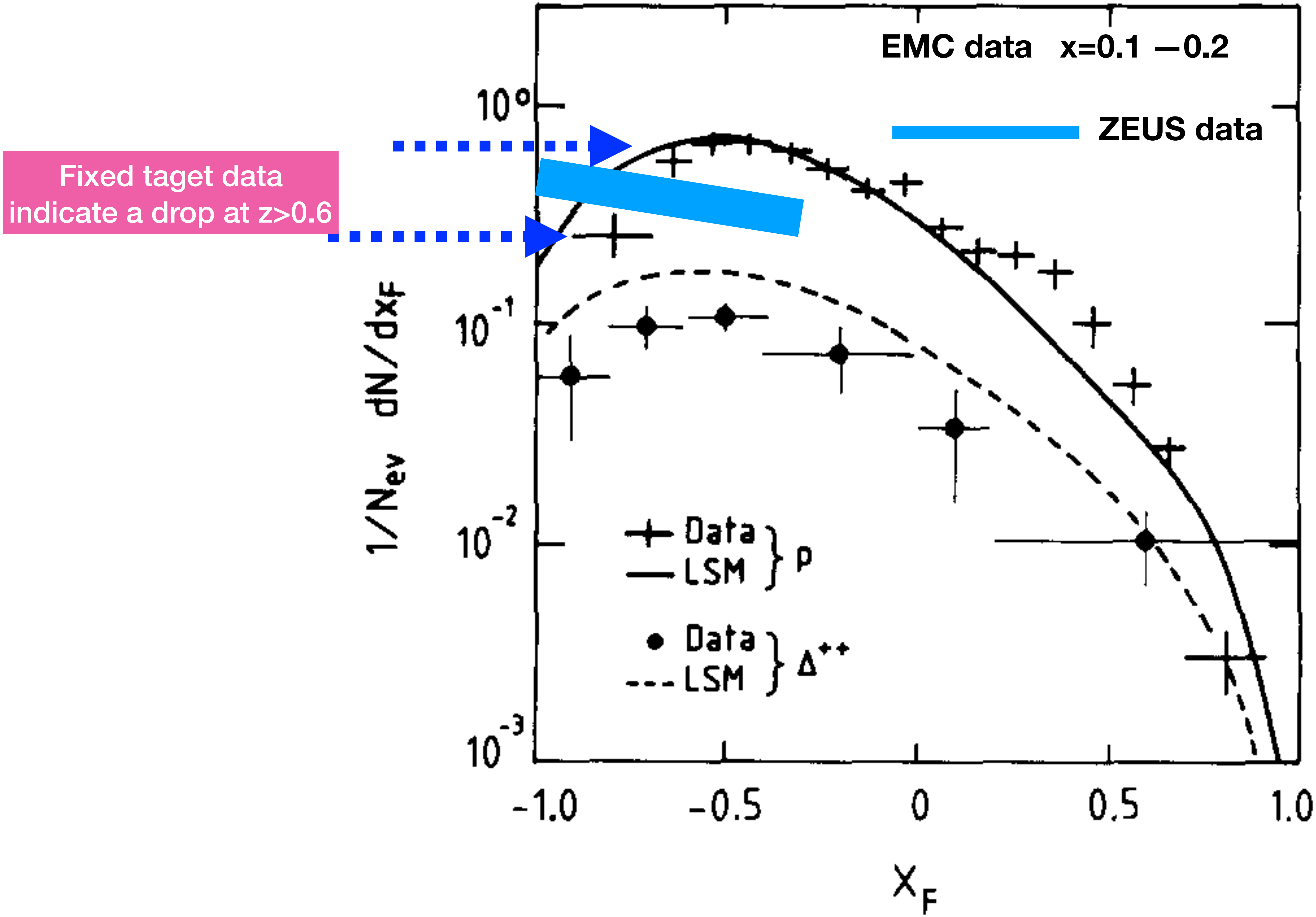
$n_{p\to p}(x \sim 10^{-2}) \sim 0$

$n_{p\to n}(x < 10^{-2}) \sim -1$

Based on our interpretation of p→n as fragmentation of two valence quarks we expect

$$r_{p\to n}(z, x < 0.01) \propto r_{p\to p}(z, x = 0.2)$$

qualitatively consistent with the EMC data since in the EMC kinematics u-quark is knocked out and ud fragments



W is not large enough to separate fragmentation and central regions for x_F> - 0.3 (?)

Measured total $\langle n_{tot} \rangle$, forward $\langle n_f \rangle$, and backward $\langle n_b \rangle$ average multiplicity of p (including those from Δ decays), Δ^{++}, and Δ^0

	$\langle n_{tot} \rangle$	$\langle n_F \rangle$	$\langle n_B \rangle$
p	0.62 ± 0.01	0.10 ± 0.01	0.52 ± 0.01
Δ^{++}	0.10 ± 0.02	0.02 ± 0.01	0.08 ± 0.02
Δ^0	< 0.18		

Significant $\langle n_F \rangle$: at high energies central rapidity range with equal number of baryons and anti baryons. For moderate z and moderate W (fixed target energies) no sufficient separation of current and target fragmentation regions. Significant Δ^{++} production in the proton fragmentation region for $\langle x \rangle \sim 0.1 \div 0.2$:

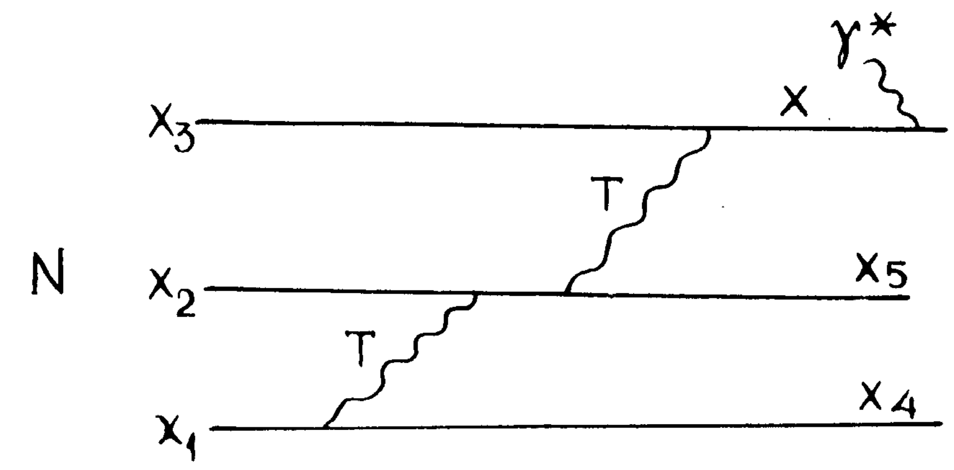
Δ^{++}/p (direct) $= 1/3 \div 1/5$

pretty large since mostly it is ud fragmentation since d-quark is hit in 10% of interactions

Novel fragmentation pattern at x> 0.5

Expectation: nucleon in large x configurations is smaller than in average.

* In pQCD diagrams corresponding to x → 1 limit are dominated by configurations in which two spectator quarks carry very different light-cone fractions and rather large transverse momenta



* Analysis of centrality leading jets in pA at LHC: (Alvioli et al)

area factor of 4 smaller than average

⇒ larger transverse momenta of spectators

⇒ enhanced probability of independent fragmentation of the spectator quarks

$$r(z) = \frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dz} \propto (1-z)^{n(x)}$$

n(x > 0.5) ≥ 2

Tools available at EIC for obtaining qualitatively new information about dynamics of nucleon fragmentation, working of confinement and probing correlations in nucleons

- **Double tagging: detecting pions, kaon, charm, dijet in the current fragmentation region to separate processes where u, d, gluon, was involved in hard interaction.**
- **Polarized ep scattering: comparison of fragmentation for parallel an antiparallel felicities of quark and nucleon**
- **Polarization/ spin alignment of produced baryons**
- **Comparison of proton and neutron fragmentation in polarized electron - polarized deuteron scattering**

A sample of interesting channels

- Removal of u (d) quark with helicity = /opposite to helicity proton can compare fragmentation of uu and ud with helicities 0 or 1.

- is ud→ p = ud→ n not guaranteed:

  I=0,S=0 diquarks?

  - different proportion of I=0 and I=1
  - Violation of SU(6) - large for large x

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

  longitudinal polarization of hyperons:

- octet baryons/ decuplet baryons - rate and x dependence

- z-dependence of the meson production

- expect abundant 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.

Green pasture: Removal of color octet (dijet production) vs removal a triplet for large z, and x >0.1 -

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

neutrons similar requirements or use D beams with tagged protons to select scattering off neutrons

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

Λ hyperon ? $c\tau = 7.98$ cm

Few applications for scattering off nuclei

Looking for non-nucleonic degrees of freedom (a sample of processes)

Coherence in production of hadrons in the nucleus fragmentation region

Looking for Δ Δ admixture in the deuteron in eD scattering

$$\sigma(e^2H \to e + \Delta + X) = \sigma(x' = \frac{x}{(2-\alpha)}, Q^2)\frac{\Psi^2_{\Delta\Delta}(\alpha, k_t)}{(2-\alpha)}$$

spectator mechanism

$$\alpha_\Delta = \frac{p_\Delta}{p_D/2}$$

$$\alpha_\Delta = \frac{\sqrt{m_\Delta^2 + p^2} - p_3}{m_d/2}$$

EIC frame

Rest frame ,p is Δ momentum

$\alpha=1$, $p_t=0$ corresponds to p_3 ~ 300 MeV/c forward in lab

Competing mechanism - Δ's from nucleons=direct mechanism

$$\left.\frac{\sigma^{1D/\Delta}}{dx\, dy\, \frac{d\alpha}{\alpha}\, d^2k_t}\right|_{direct} = \int \frac{d\beta}{\beta}\, d^2p_t\, \rho_D^N(\beta, p_t) \times \tag{18}$$

$$\times \frac{d\sigma^{1N/\Delta}}{dx\, dy\, d\alpha/\alpha\, d^2k_t} {}_{2l}\!\left(\beta E_1, x/\beta, y, Q^2, \frac{\alpha}{\beta - x}, k_t - \frac{\alpha}{\beta} p_t\right)$$

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%

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

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

For the deuteron one can reach sensitivity better than 0.1 % for ΔΔ especially with quark tagging *(FS 80-90)* for $x > 0.1$ very strong suppression of two step mechanisms (FS80)

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

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