Open questions in nucleon fragmentation

Questions posed by HERA, how to address them before EIC and what can be studied at EIC.

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Mini-Workshop "Target Fragmentation Physics with EICSUNY, September 2020

Outline

* **Physics of validity of leading twist dynamics in target fragmentation**

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

* **Observables for EIC**

* ***Examples of observables necessary for studying short-range correlations at EIC***

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

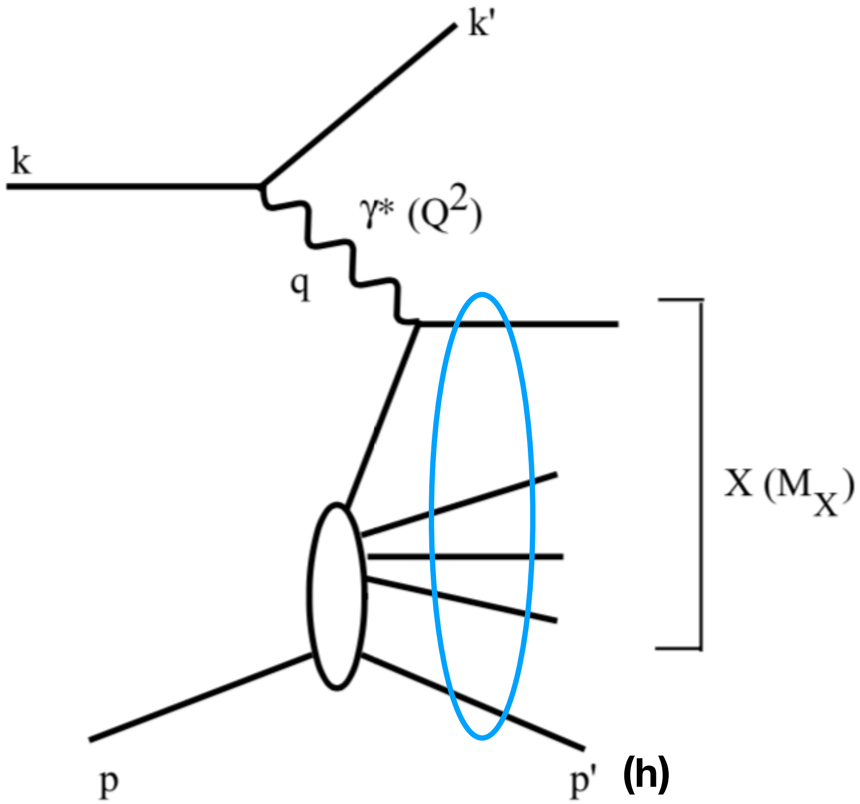
- **information about fragmentation necessary for optimizing SRC studies for example ΔΔ component of the deuteron**

- **Formation time of hadrons in the fragmentation region**

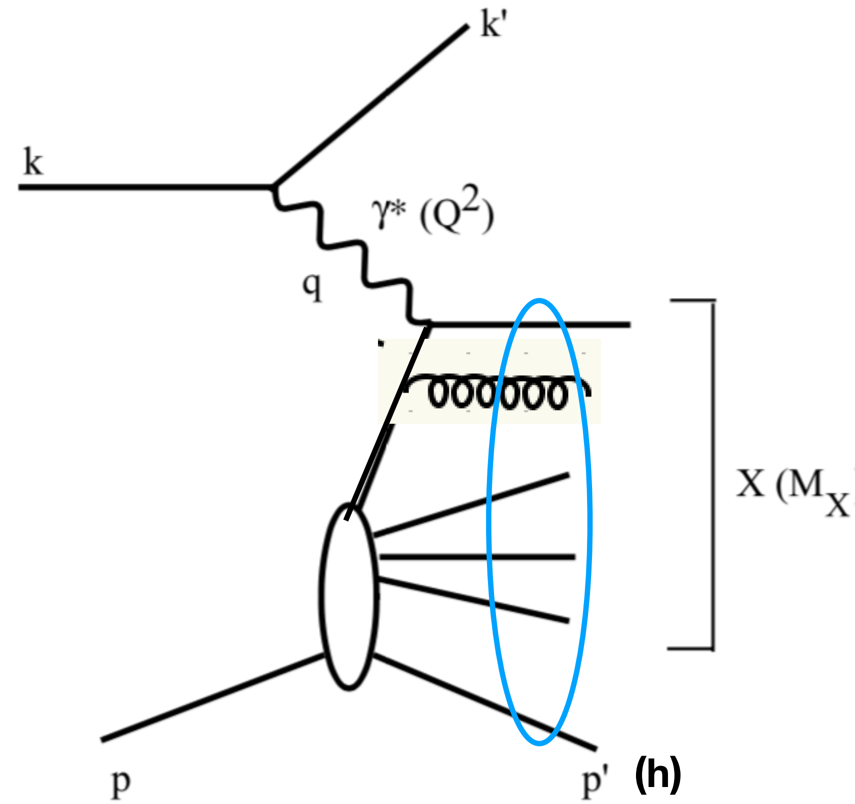
Note that many requirements to detector for studying fragmentation are similar to the ones for studying SRC

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 since overall interaction does not resolve qg which are located at transverse distance << 1/Q₀

one can define fracture (Trentadue &Veneziano) parton distributions

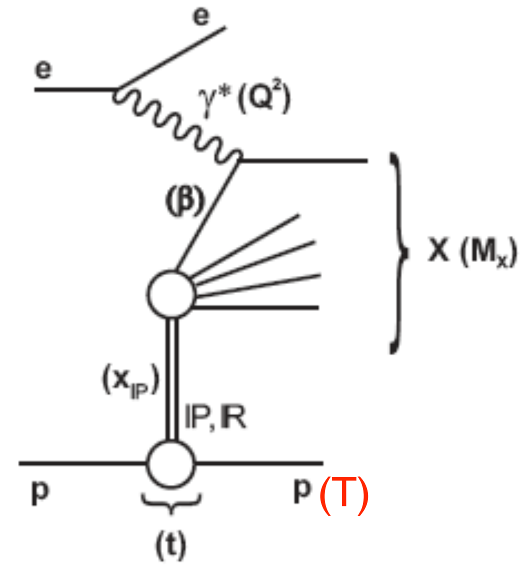
at collider

$$x_L = p_{Tag}/p_{init}$$

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

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

z= β= x_L/(1-x) ≤ 1



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

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

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

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

Theorem:

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

Comments:

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

small x regime: **expect: z= β distribution weakly depends on x.**

x ≥ 0.1 regime: ***expect strong dependence of z -distribution on x (will discuss later)***

Onset of factorization - Q_0^2 is determined by onset of color screening (not closure like in DIS) - studied only for small x. May depend on W, x. For large x rapidity interval between target and current regions is reduced - freezing of fsi maybe delayed.

Factorization theorem is applicable for any h - not only nucleons

h - meson is interesting but not studied (ZEUS π^0 ?)

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) .

$z = x_L/(1-x) < 1$ **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 (FS77):

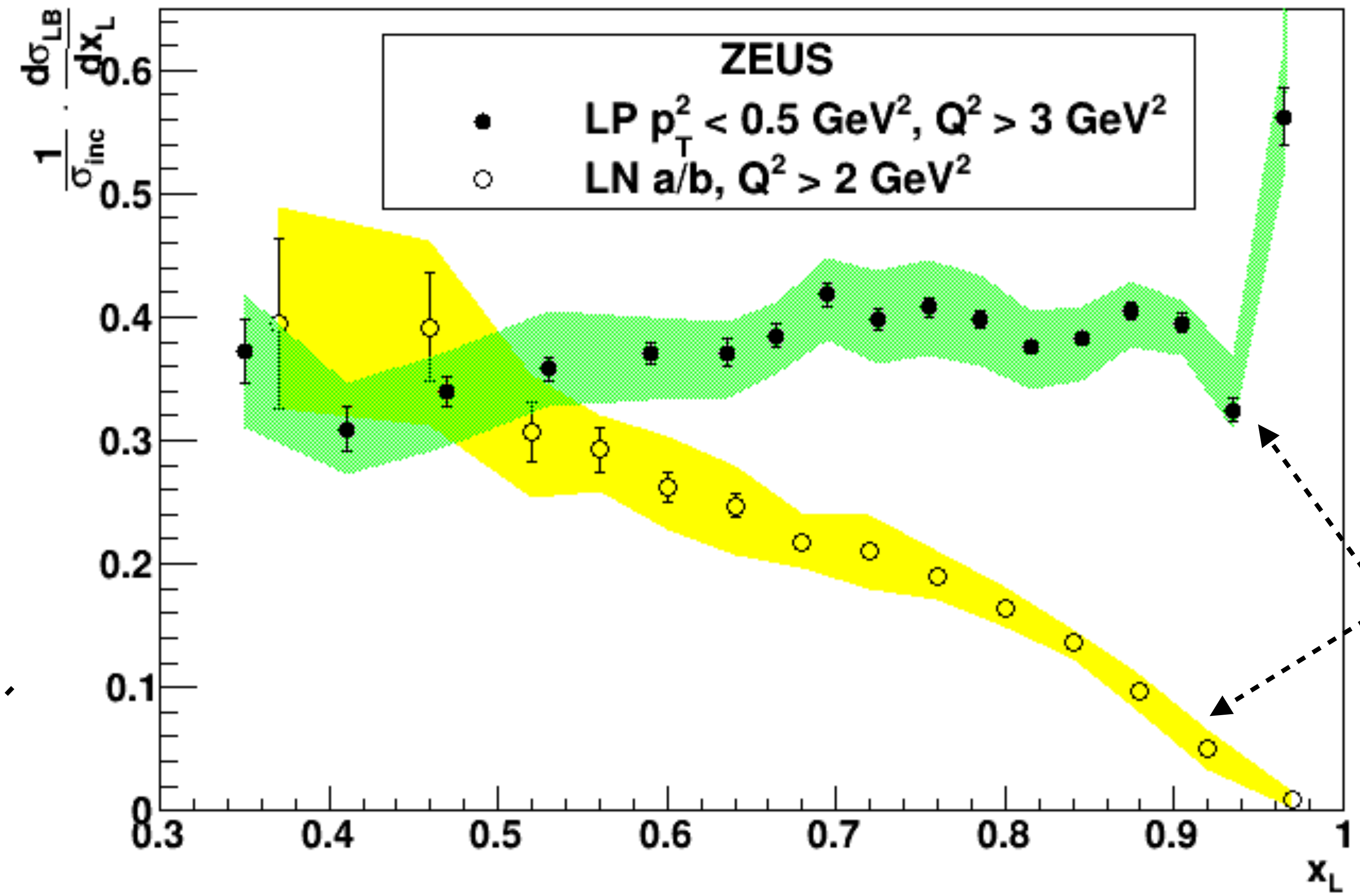
$$f_j(x,z) \propto (1-z)^{n(x)}$$

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

all 3 valence quarks are involved

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]

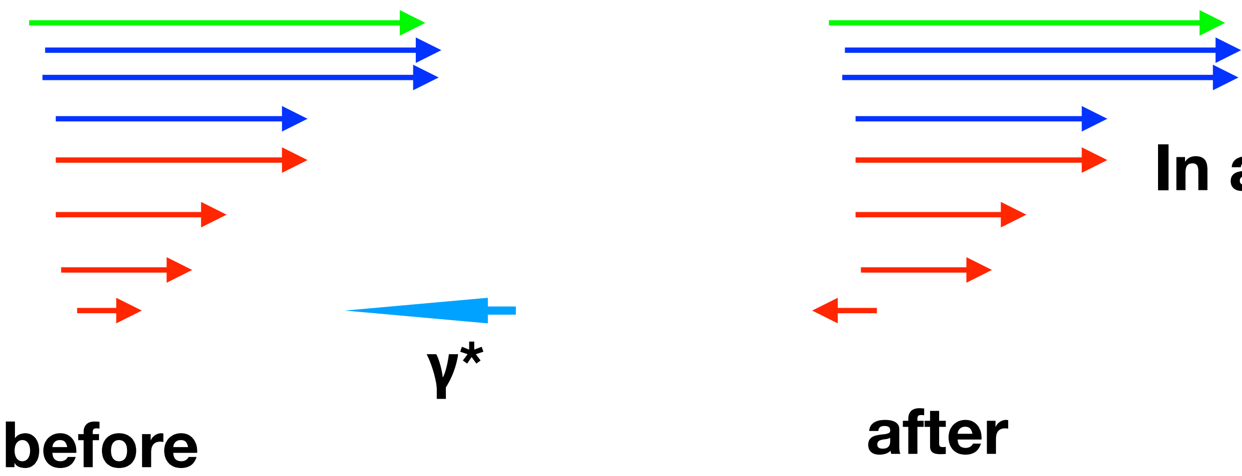
HERA studies missed a puzzle: where are baryons. Should be #baryons - # anti baryons = 1 per event. For small x and x_L > 0.3 only 0.46 baryons are observed (70% p, 30% n) (strange baryons not measured but likely 30% correction of neutrons

➜ 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

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 ahalysis:

leading protons x_L>0.5 — 3 valence quarks **mostly protons & few neutrons**

protons 0.5 >x_L>0.3(?) — 2 valence quarks

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

} comparable number of neutrons and protons

1/3 uu , 2/3 ud → 1/3 p +2/3(p/2 +n/2)➟ p/n ≈ 2 agreescwith data at x~ 0.6

OBSERVATIONS

if $x \ll (1-x_L)$, 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,

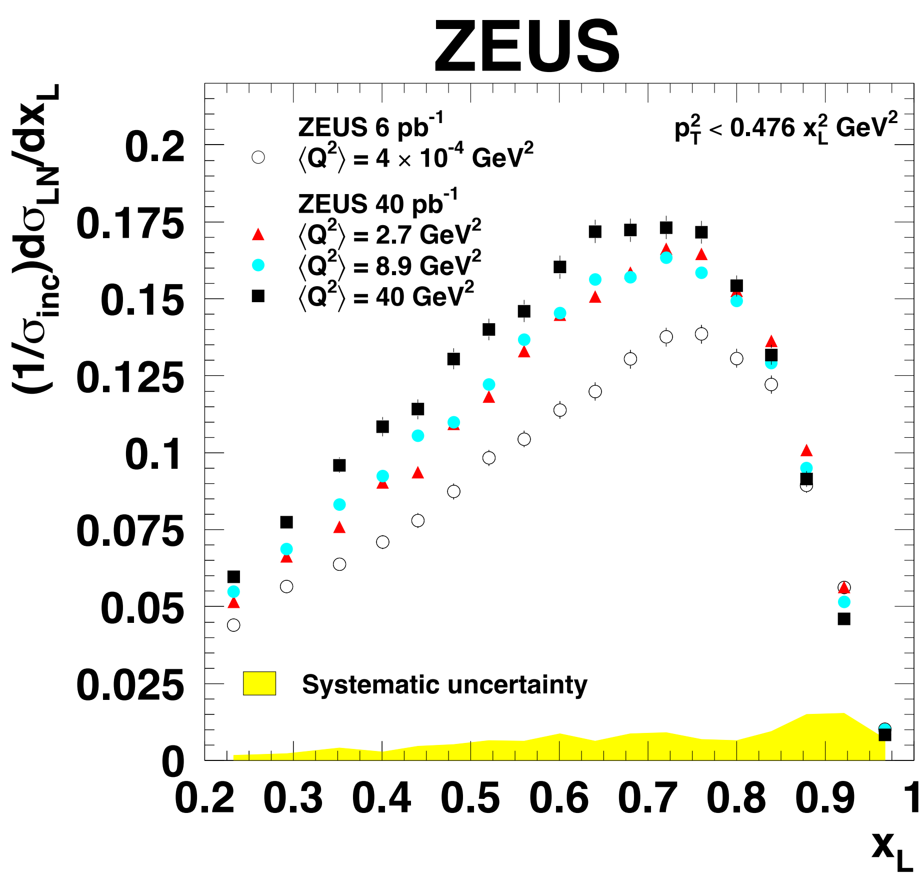
observed

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 , $n_h(y\sim0)$ and nucleon yield:

larger n_h —-smaller nucleon multiplicity at large x_L

significant reduction for $n_h \sim 2\langle n_h \rangle$



There were numerous attempts to extract from reaction

$ep \to en + X$ pion pdfs

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 $> 1/m_\pi$

Additional problem: Soft factorization leads to contributions to nucleon yield from all fragmentation processes. Simple example - data find the ratio of p and n yields of 2 or larger for $x_L > 0.6$, while in the pion model it is equal to 1/2 (same for ρ-exchange).

Pion model fits to the neutron data but don't address the question how mechanisms which contribute to proton production feed into neutron production (for example Δ-isobar decays - like $\Delta^+ \to p\pi^0$)

x -dependence of fragmentation

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

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

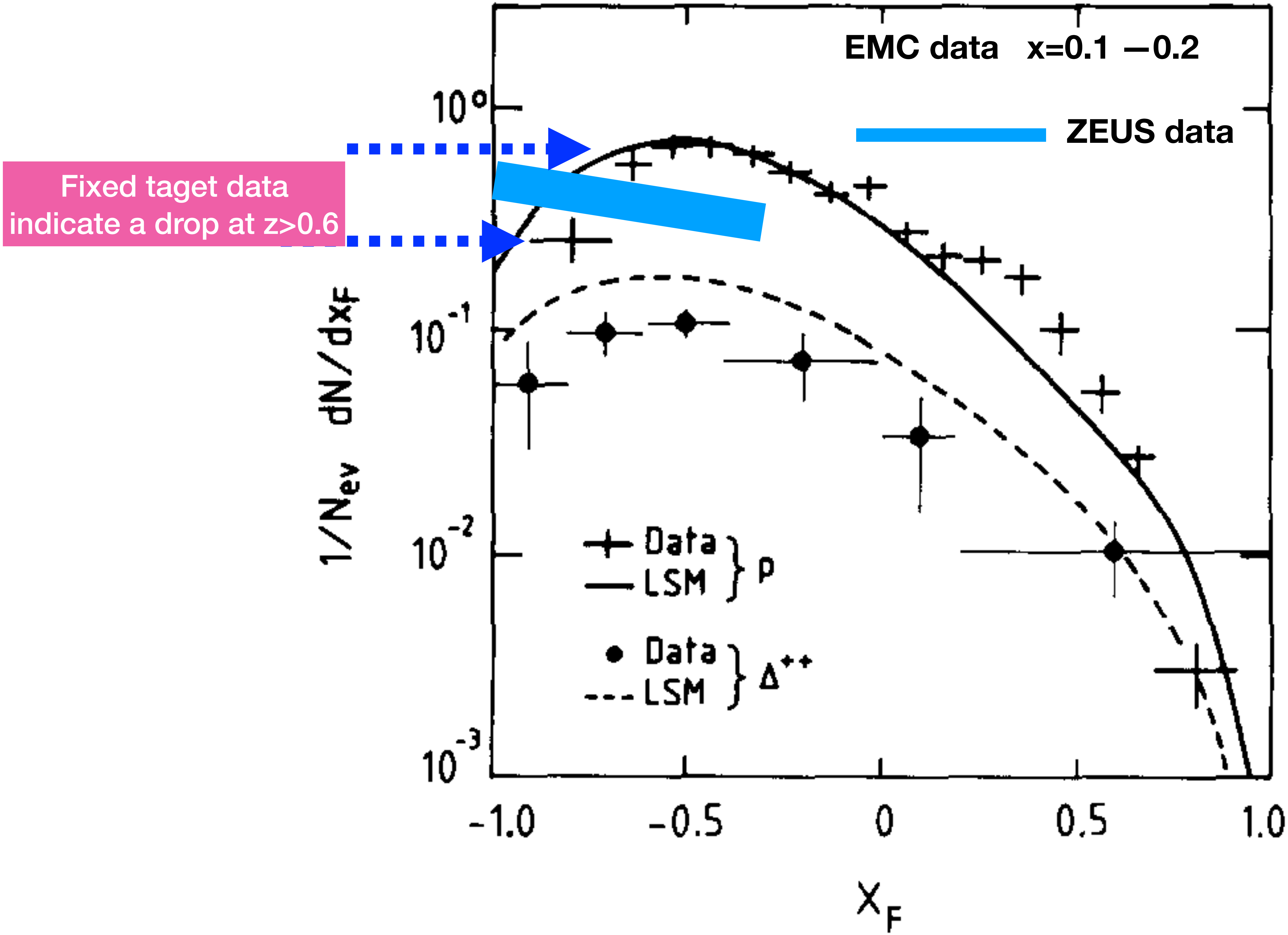
$$r(z) = \frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dz} \propto (1-z)^{n(x)}$$

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

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

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

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



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 separation of 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

HERA data mining?

- DIS data at $x > 0.1$?

- $\gamma p \to$ "dijet" + n + X

no data were plotted as a function of β for bins of x (of interacting gluon/ quark)

Hint of steeper drop with increase of β with increase of x

LHC ultraperipheral collisions

pA scattering with ion producing a photon

Already plenty of $\gamma p \to$ "dijet" + X data was ZDC working in this run? Future?

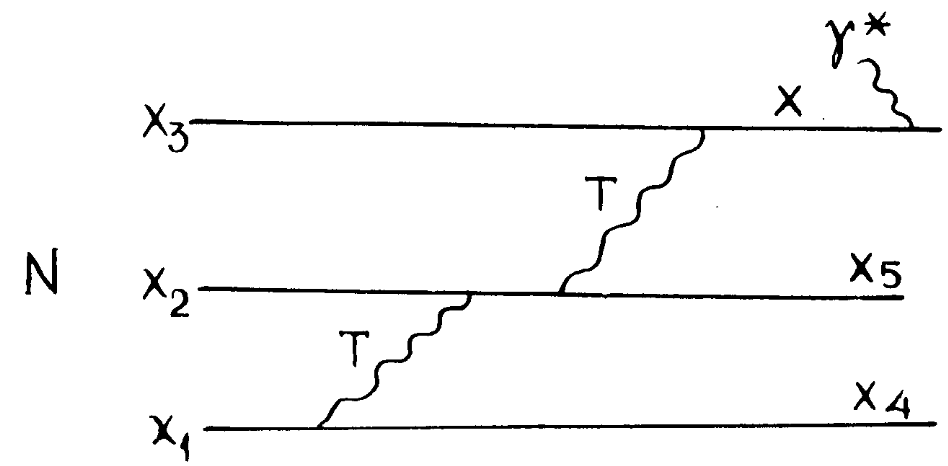
Daniel Takaki talk

Nucleus fragmentation in γA collisions (Alexei Larionov talk)

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 = +/- helicity proton can compare fragmentation of uu and ud with helicities 0 or 1.
- is ud→ p = ud→ n not guaranteed: $r_{p\to u} \stackrel{?}{=} r_{n\to d}$
- ☛ 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 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/conclusions

The discussed studies 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.

Question which maybe possible to answer in near future:

How fragmentation at large z and x>0.1 differs for removal of color octet and color triplet- first look using data mining at HERA and UPC at LHC

Data on fragmentation would serve as a 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

EXTRA

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

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

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

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%

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

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)* 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 $< 0.2\%$