EIC as ultimate tool for studying nucleon multiparton structure via nucleon fragmentation

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Outline

✱   **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*

probably will have no time to discuss
- some examples in C.Weiss talk

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 are similar

Collins factorization theorem: consider hard processes like

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

$$Q_0^2 \to Q^2$$
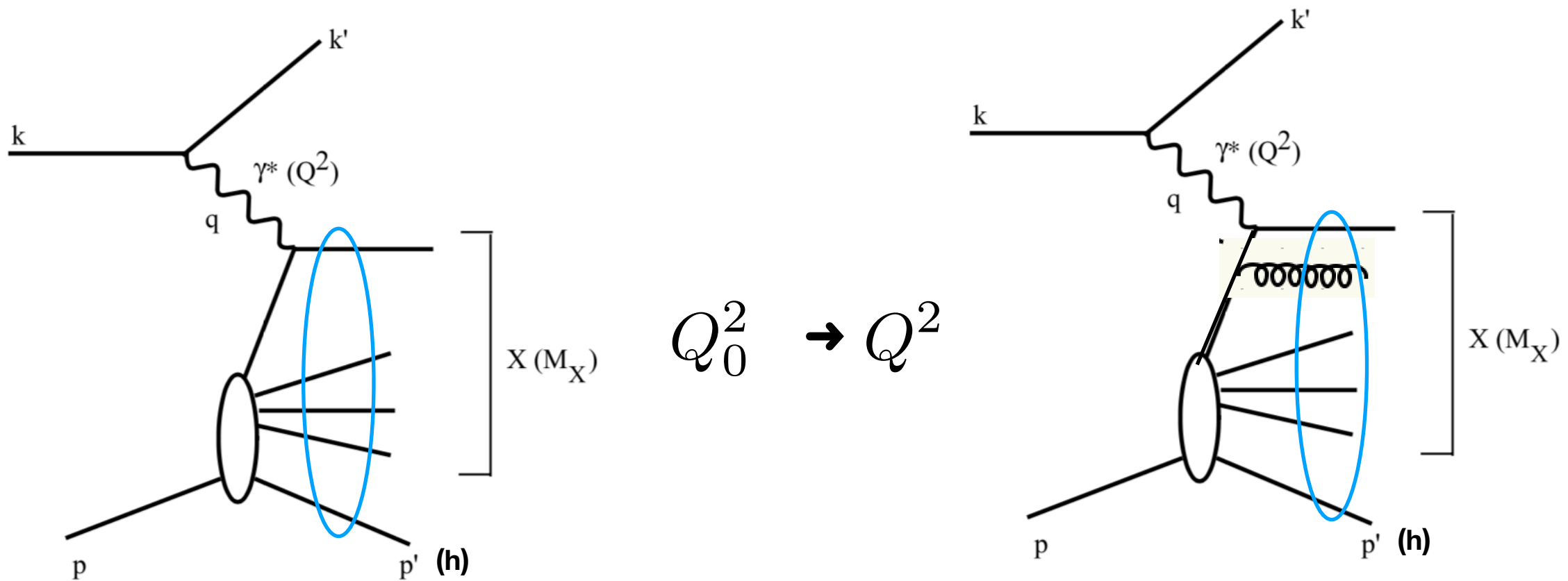
Interaction of partons which would form h h with the rest of partons: ⬭ *— does not change since overall interaction does not resolve qg which are located at transverse distance << $1/Q_0$*
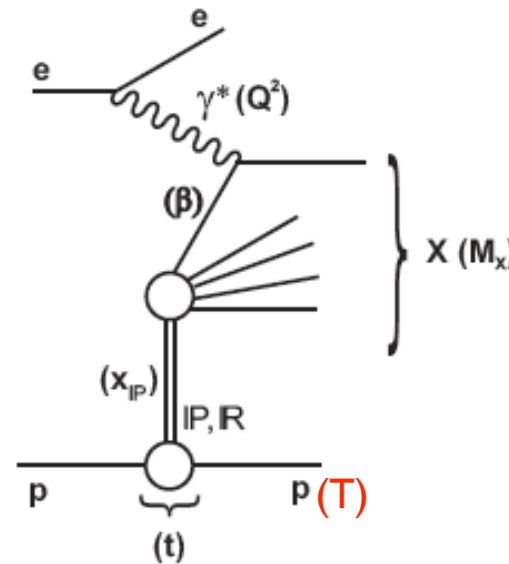
one can define fracture (Trentadue & Veneziano) parton distributions

at collider

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

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

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

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

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

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

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

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 - notion of Pomeron is not necessary in the general factorization analysis*

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

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

Need high statistics as fj 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 $x \ll 1 - x_L$ 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 ~0.1) =0? 1?   **onset of sea quark dominance**

n(x ~0.2) =1   **valence quarks**

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

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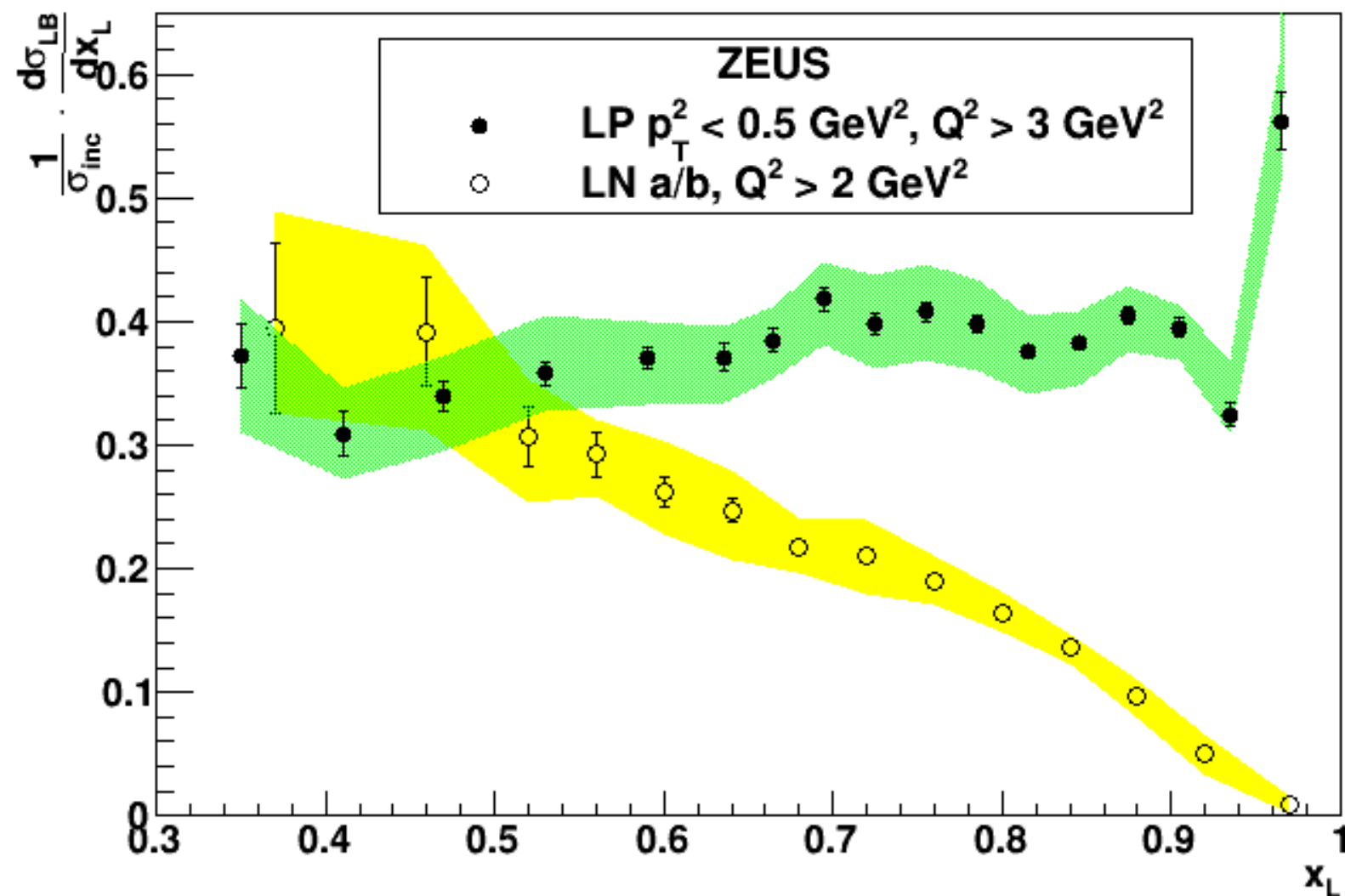
plot prepared
by W. Schmidke

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

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

γ*

before

after

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

protons 0.5 >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

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,
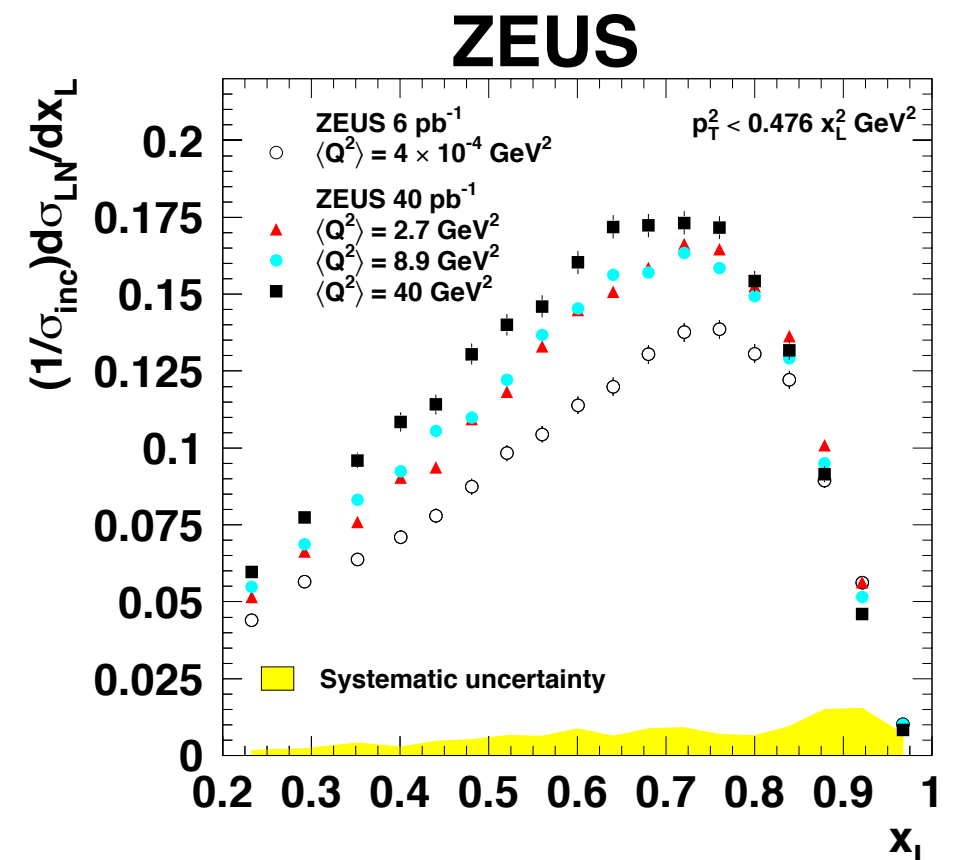
observed

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

larger n_h —-smaller nucleon multiplicity at large x_L

significant reduction for $n_h \sim 2<n_h>$

There were numerous attempts to extract from reaction

$$ep \rightarrow en + X \quad \text{pion pdfs}$$

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$_\pi$

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.

x -dependence of fragmentation

For sea quark knock out up to x~0.1 —- approximate matching to HERA:
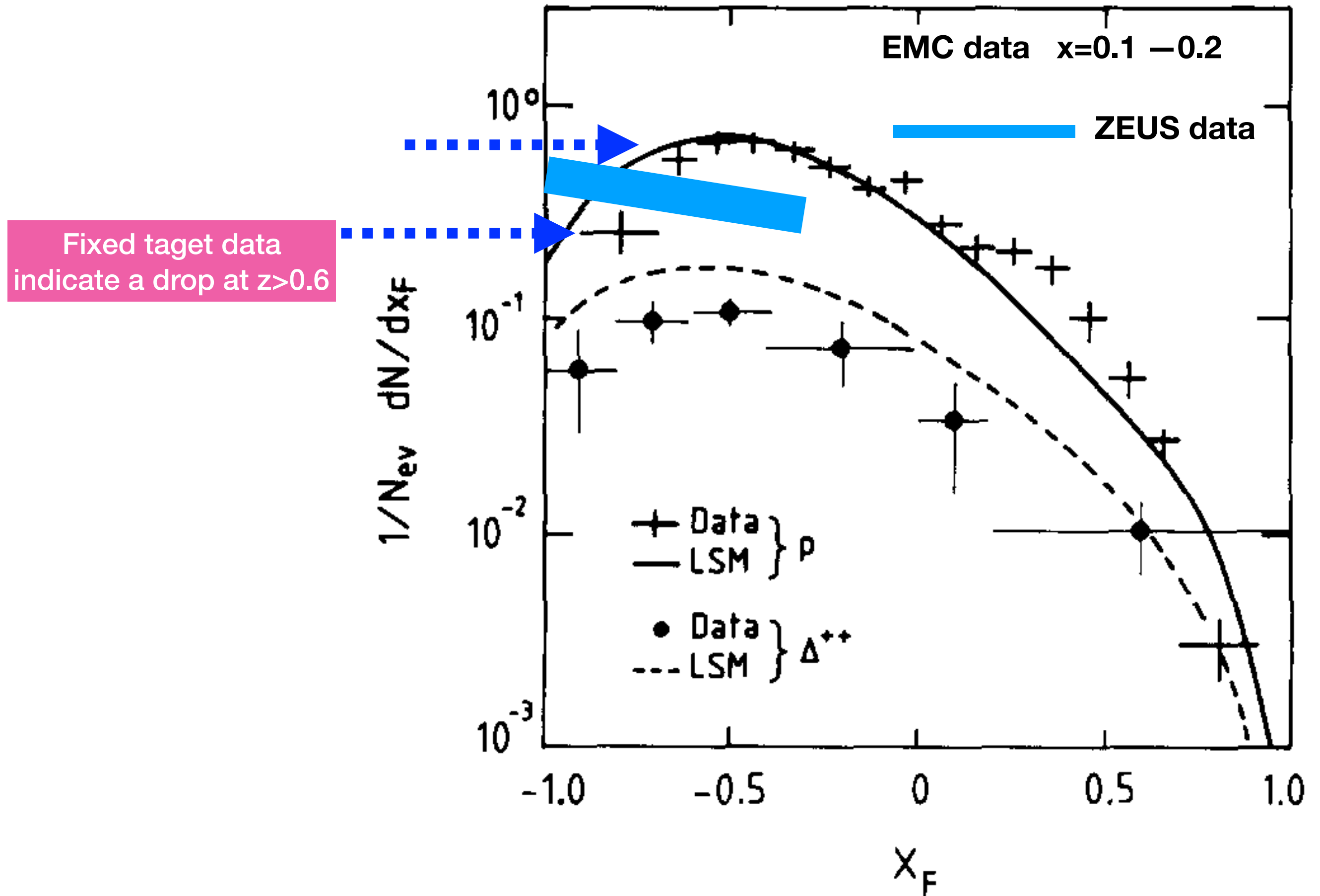
$$z = x_L/(1-x) < 1 \qquad\qquad r(z) = \frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dz} \propto (1-z)^{n(x)}$$

$n_{p \to p}(x < 10^{-2}) \sim 0$ $\qquad\qquad\qquad$ $n_{p \to n}(x < 10^{-2}) \sim 1$

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

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

EMC data   x=0.1 −0.2

ZEUS data

Fixed taget data
indicate a drop at z>0.6

$1/N_{ev}$ dN/dx_F

10^0

10^{-1}

10^{-2}

10^{-3}

$+$ Data $\}$ p
— LSM

● Data $\}$ Δ^{++}
--- LSM

-1.0   -0.5   0   0.5   1.0

X_F

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 Δ⁰

	$\langle n_{tot} \rangle$	$\langle n_F \rangle$	$\langle n_B \rangle$
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
Δ⁰	<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 ÷ 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**
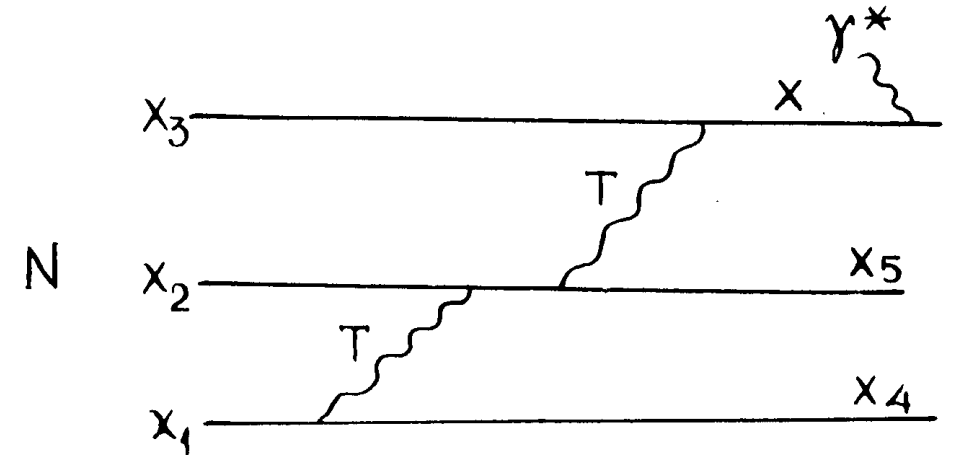
✳ **Analysis of centrality leading jets in pA at LHC: (Alvioli et al)**

area factor of 4 smaller than average

⇒ **larger transverse momenta of spectators**

⇒ **enhanced probability of independent fragmentation of the spectator quarks**

$$r(z) = \frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dz} \propto (1-z)^{n(x)} \qquad \text{n(x > 0.5) ≥ 2}$$

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 = +/i helicity proton can compare
fragmentation of uu and ud with helicities 0 or 1.

▶ is ud→ p = ud→ n   not guaranteed: $r_{p\to u} \overset{?}{=} r_{n\to d}$

▶   ☞   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: 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 ?   cτ=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 $\Delta\,\Delta$ admixture in the deuteron in eD scattering

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

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 $p_3 \sim 300$ MeV/c forward in lab

Competing mechanism - Δ's from nucleons=direct mechanism

$$\frac{\sigma^{1D/\Delta}}{dx\ dy\ \frac{d\alpha}{\alpha}\ d^2k_t}\Bigg|_{direct} = \int \frac{d\beta}{\beta}\ d^2p_t\ \rho^N_D(\beta, p_t)\ x$$

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

(18)

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For scattering of stationary nucleon

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

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

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

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

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

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%

$$\frac{\sigma_{\pm} - \sigma_0}{\langle \sigma_0 \rangle} \quad \textbf{for} \quad e\vec{D} \rightarrow e + p + X$$

competition: spectator vs direct mechanism of nucleon production.

Background is small for x ~0.2. FS80. However used a simple guess for nucleon fragmentation. Would be nice to do datelining of hERA data and UPC pA processes.

Spectator mechanism predictions for scattering off tensor polarized deuteron

$\frac{\sigma_{\pm} - \sigma_0}{\langle \sigma_0 \rangle}$ — Light -cone Virtual N

pN=250 MeV/c

pN=300 MeV/c

pN=350 MeV/c

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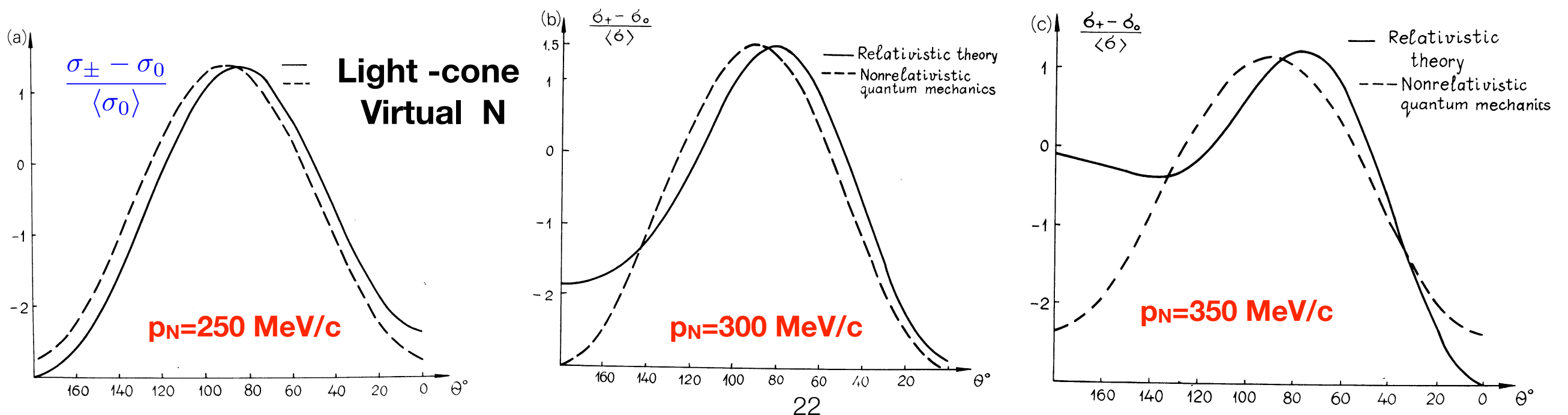
**Puzzle in nuclear fragmentation: a factor > 2 fewer
slow neutrons are produced in the DIS process**

μ +Pb → μ + n +X   **E665, 1995**

than according to cascade models

Zhalov, Tverskoi, MS 96 - confirmed by Larionov &MS 2019

**Option 1:Pythia not modeling well wrong model of fragmentation
(not very likely such a gross effect)**

**Option 2: novel coherence effect - perhaps related to ability off DIS in
which a small x parton is removed to break effectively a nucleon**