Fundamental questions about QCD dynamics which can be probed in (very) forward kinematics:

Topic for white paper

- ✓ Nonlinear QCD dynamics in pp, pA, UPC
- ✓ Do minijets exist? Energy dependence and suppression mechanism
- ✓ Nucleon fragmentation - probe of multiparton structure, soft - hard interplay
- What is energy dependence small dipole - small dipole cross section (Perturbative Pomeron ?)
- Novel phenomena in pp diffraction with jets
- Color fluctuation phenomena in pp, pA , UPC

Propagation of partons through nuclear media

Combining pp, UPC and DIS

Propagation of color dipoles through nuclear media

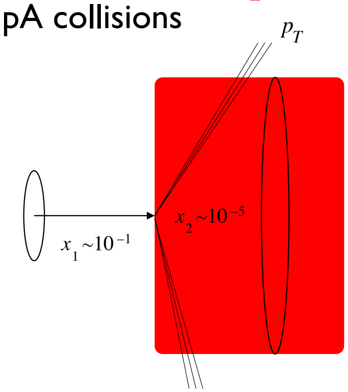
Mark Strikman, 2/9/2022, Snowmass meeting

Evidence for nonlinear QCD dynamics in the fragmentation region in pA scattering

- Black disk limit (limit of 100% absorption) / saturation effects due to the small x effects: in proton - proton/nucleus collisions a parton with given x_1 resolves partons in another nucleon down to $x_2 = 4p_\perp^2/x_1 s$

At LHC $x_1 = 0.1, p_\perp = 2GeV/c \longrightarrow x_{2min} = 10^{-6}$

Near GZK
In central pA collisions $x_1 = 0.1, p_\perp = 2GeV/c \longrightarrow x_{2min} = 10^{-9}$ **for CR protons**

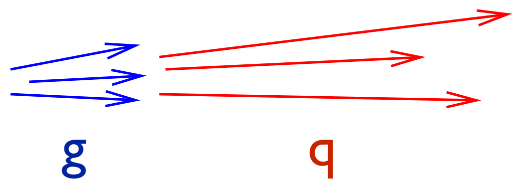


Black disk limit in central collisions: Leading partons in the proton, x_1, interact with a dense medium of small x_2 – gluons in the nucleus (shaded area), acquiring a significant transverse momentum, $p_\perp$ and loosing a finite fraction of its momentum

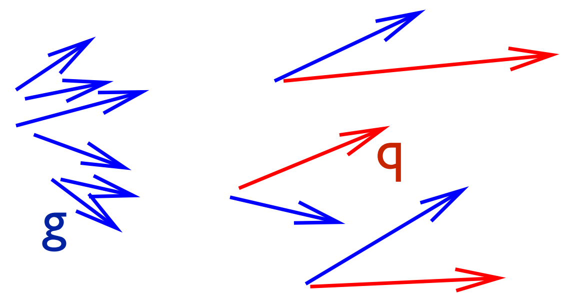
Larger x_1, larger the blackening.

Note, there is no isignificant gain in gluon density per unit area are between proton and Pb, but fluctuations of gluon density are much smaller in case of nuclei

Characteristics of the nucleon fragmentation in the central pA(pp) collisions

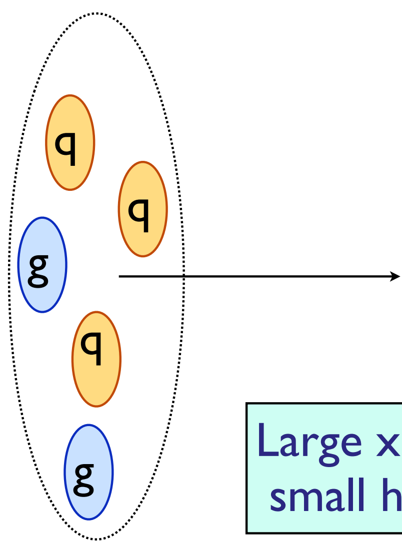


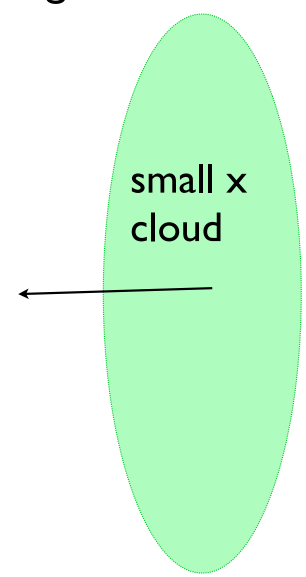
fast partons in a nucleon before collisions



fast partons in a nucleon after central collisions

Smaller light cone fractions & larger $p_\perp$

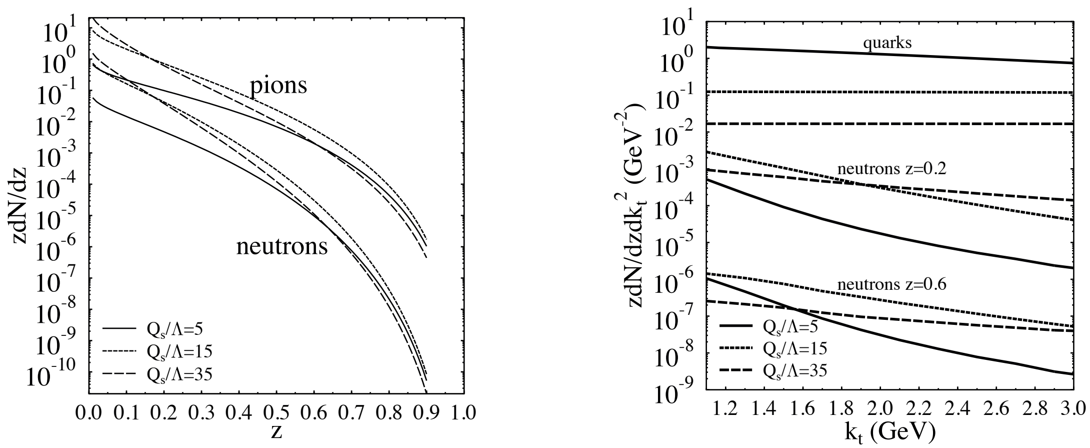




Large x partons burn
small holes in the small x cloud

The leading particle spectrum will be strongly suppressed compared to minimal bias events since each parton fragments independently and splits into a couple of partons with comparable energies. The suppression for nucleon production is especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions should exceed that of nucleons. This model neglects additional suppression due to finite fractional energy losses in BDL

$$\frac{1}{N}\left(\frac{dN}{dz}\right)^{pA\to h+X} = \sum_{a=q,g}\int dx\, x f_a(x, Q^2_{eff}) D_{h/a}(z/x, Q^2_{eff})$$



Longitudinal (integrated over p_t) and transverse distributions in Color Glass Condensate model for central pA collisions. (Dumitru, Gerland, MS -PRL03). Spectra for central pp - the same trends.

Generic features expected in all models in which interaction strength is comparable with the one black disk regime:

- ☛ Strong suppression of the large z spectra at low p_t

- ☛ Broadening of the transverse momentum distributions of leading hadrons at large z,

Both effects should become more and more pronounced with increase of collision energy and centrality of collision / increase of A.

LHCf / RHICf - inclusive measurements , could not remove contribution peripheral and ultraperipheral collisions (in pA UPC diffraction like events at LHC >> coherent diffractive events),

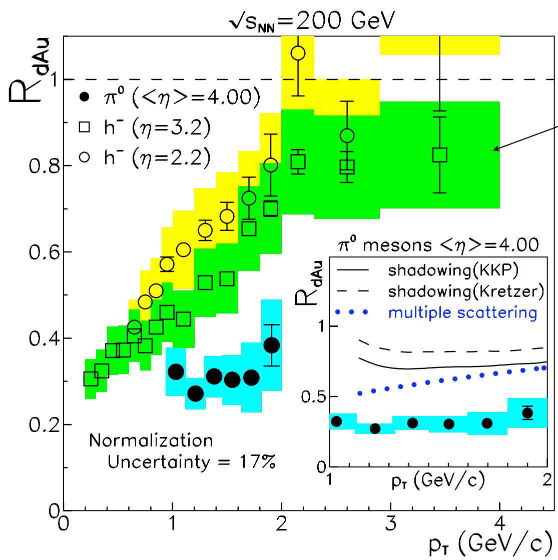
ALICE neutron production

Suppression can be even stronger as in BDR quarks and gluons loose significant fraction of their energy - 10 —15 %.

MS & Frankfurt

Obviously this prediction is qualitatively different from of DGLAP expectations

So far most detailed data are from RHIC dA run (no relevant results from pA run so far)



Significant nuclear suppression = $R_{dAu}/1.5$

BRAHMS and STAR are consistent when an isospin correction which reduces h^- ration measured by BRAHMS by a factor ~ 1.5 (Guzey, MS, Vogelsang 04 =GSV04) is introduced

STAR reached z~ 0.5 for $p_\perp$ ~ 3 GeV/c $x_g>0.01$

$$g_A(x=.01)/g_N(x=.01)\approx 1.$$

pQCD prediction of R_{dAu}(pQCD)=1.0 is grossly violated !!!

Summary of the challenge

☞ For pp - pQCD works both for inclusive pion spectra and for forward - central rapidity correlations

☞ Suppression of the pion spectrum for fixed pt increases with increase of y_N. Pion production is mostly from peripheral collisions

The key question what is the mechanism of the suppression of the dominant pQCD contribution - scattering off gluons with $x_A > 0.01$ where shadowing effects are very small.

two scenarios: CGC& post-selection

(a) CGC: leading pions from central collisions;

(b)post-selection - pions from peripheral collisions ← supported by soft multiplicity data

Independent of details -the observed effect is a strong evidence for breaking pQCD approximation. Natural suspicion is that this is due to effects of strong small x gluon fields in nuclei as the forward kinematics sensitive to small x effects.

Future: analysis of the A-dependence/centrality of pion production data at wide range of energies. Production of leading mesons in pp collisions with centrality trigger - like multijet production.

Independent of details -the observed effect is a strong evidence for breaking pQCD approximation certain kinematics for pA scattering. Natural suspicion is that this is due to effects of strong small x gluon fields in nuclei as the forward kinematics sensitive to small x effects.

Future: analysis of the A-dependence/centrality of pion production data at wide range of incident energies - effect for fixed x_h and $p_\perp$ increases with s.

Measure recoil minijet (fix range of x_g) . Production of leading mesons in pp collisions with centrality trigger.

UPC at LHC energies for x_h ~0.5 and fixed p_T $s_{\gamma N} \sim s_{NN}$(RHIC)

Large forward suppression in UPC /LHC

Looking for minijets at central rapidities

☛ **Do few GeV minijets exist on the level expected in pQQCD?**

hard (minijet) collisions with p_t ~ few GeV main source of σ_{inel} (pp)

HERWIG, Pythia

puzzle: Suppression factor grows rather rapidly with s

What is mechanism of energy dependence of the suppression of minijets in pp and pA scattering?

explanation (?) saturation - black disk regime - problem similar suppression in peripheral and central pp collisions & present for collisions at $x \sim 10^{-2}$ — 19^{-3}

Is the origin of suppression at y~0 reported by MC analyses the same as for forward rapidities?

Tools:

☛ long range correlations in rapidity sensitive to minijets:

M.Azarkin, P.Kotko, A.Siodmok and M.Strikman,``Studying minijets and MPI with rapidity correlations,''Eur. Phys. J. C 79 (2019) 180

Fix y, p_T of one hadron (minijet) at y ~ 2 — 4 and measure < p_T> for negative rapidities;

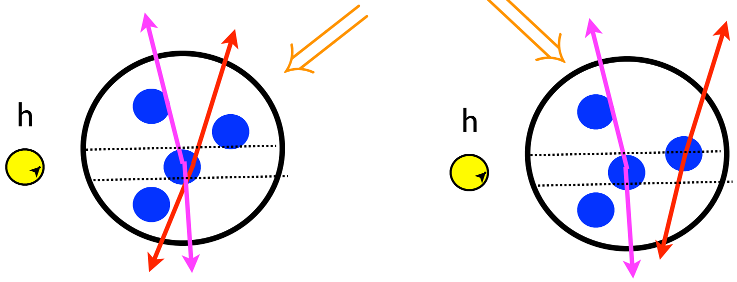
Soft dynamics Gaussian distribution in Δy,

Hard mechanism — power law.

☛ proton (photon) - nucleus scattering

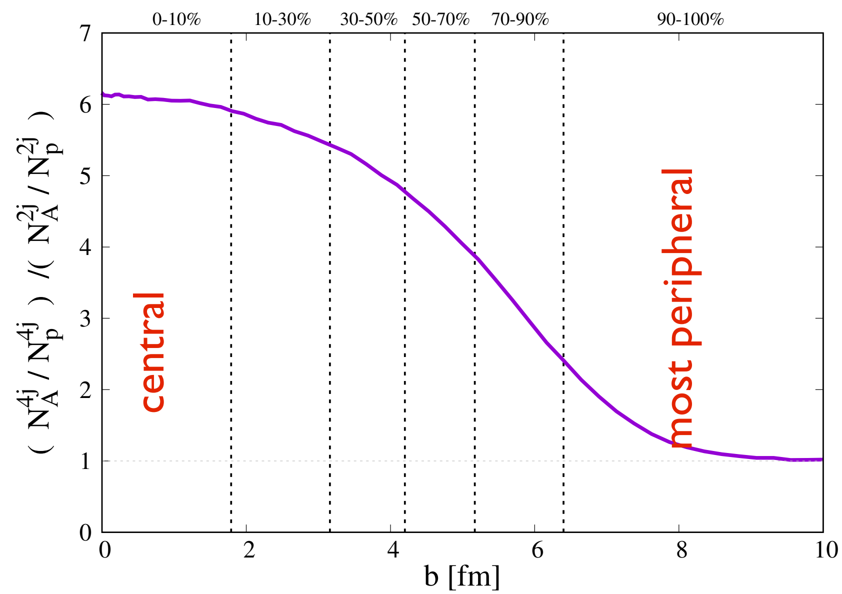
MS & Treleani 95 - PRL 2002

$$\sigma = \sigma_1 \cdot A + \sigma_2$$



Single scattering Double scattering

M.Alvioli, M.Azarkin, B.Blok and M.Strikman, ``Revealing minijet dynamics via centrality dependence of double parton interactions in proton–nucleus collisions,''Eur. Phys. J. C 79(2019) 482



DPS events/ SPS events as a function of b normalized to ratio at b> 6 fm

☛ c $\bar{c}$ production at small transverse momenta.

Open questions in nucleon fragmentation

Current knowledge is pretty limited; fixed target energies, HERA at x close to zero

Opportunities:

a) UPC - soft (minimum bias) regime

b) UPC - hard (dijet/ direct photon) regime

c) LHC minimum bias regime regime

d) LHC centrality regulated by presence of dijet, multiparton interactions, central (y~0) multiplicity,…

Potentially also data from HERA archive for larger x

Note: In collider kinematics detector at the sea kinematics
- reduced uncertainties in say comparison at different s in particular violation of the Feynman scalin'

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 $x_L=(1-x)$

$\beta=x/(1-x_N)$

Currently except for diffraction all data are for $x << 1- x_L$
integrals over x and β << 1.

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

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

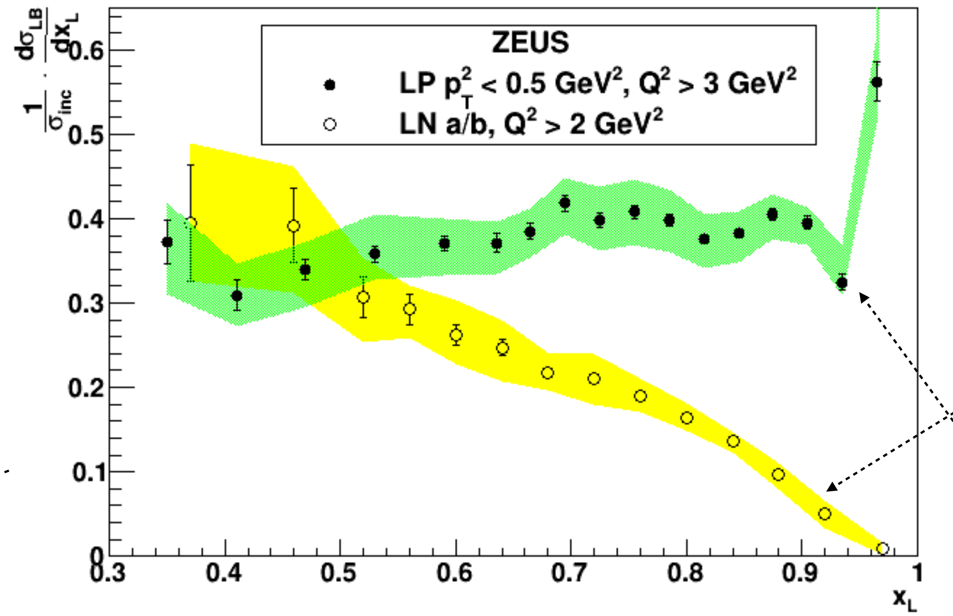
$$f_j(x,z) \propto (1-z)^{n(x)}$$

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



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]

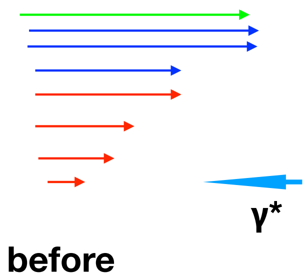
HERA studies missed a puzzle: where are baryons. Should be #baryons - # anti baryons = 1 per event. For small x and $x_L > 0.3$ only 0.46 baryons are observed (70% p, 30% n) (strange baryons not measured but likely 30% correction of neutrons

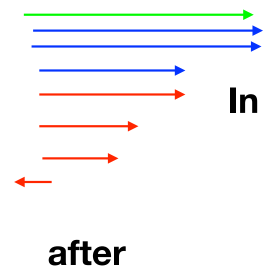
➜ A lot (50%) of baryons are produced below x_L =0.3

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 analysis:

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 agreed with 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,

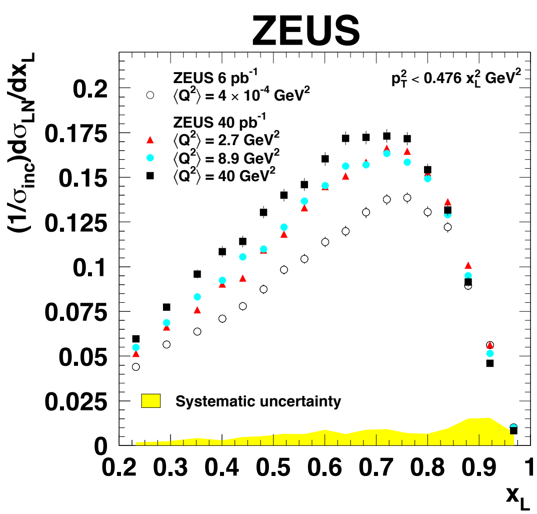
observed

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 $n_h \sim 2\langle n_h\rangle$



x -dependence of fragmentation

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

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

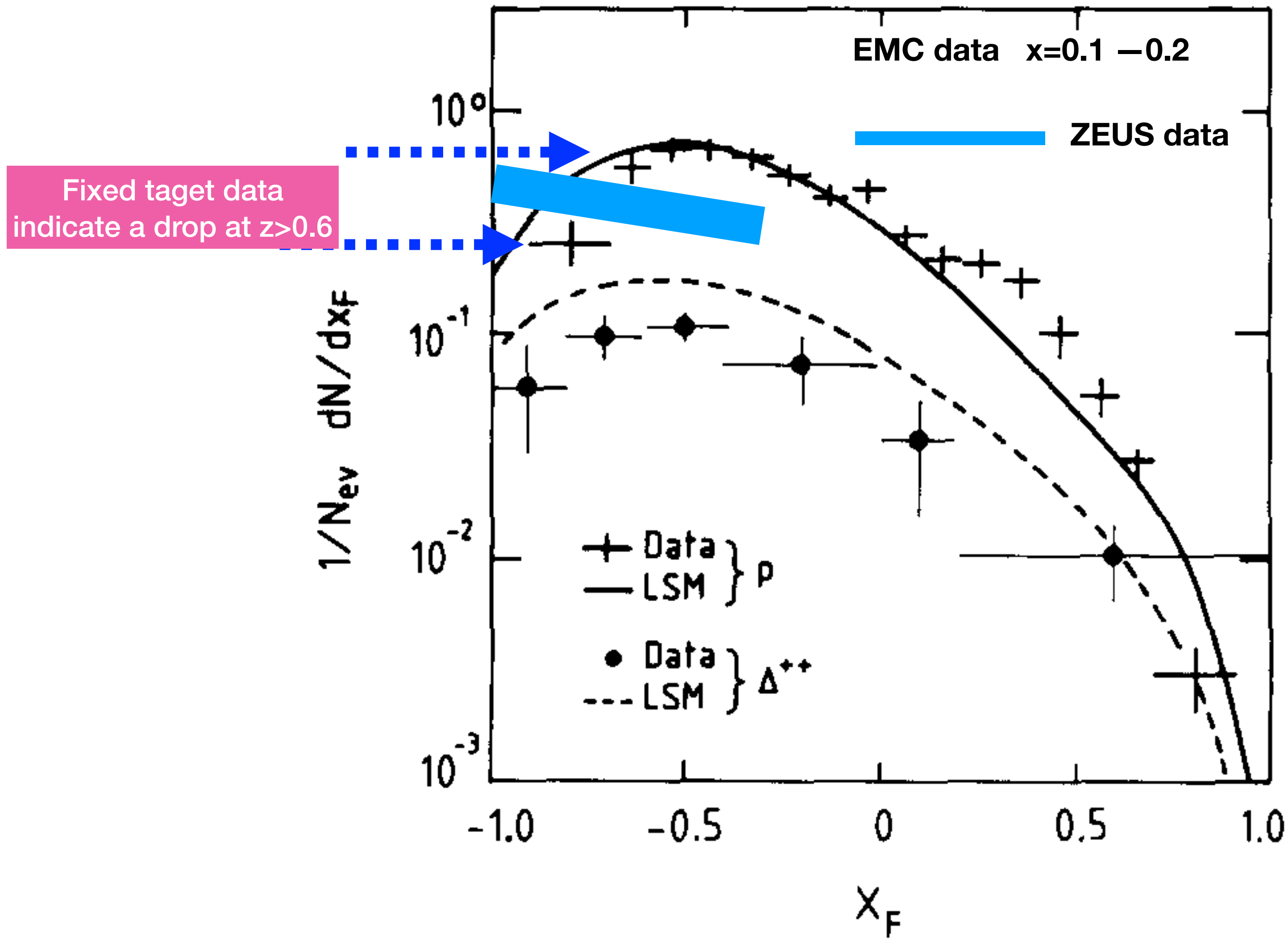
$$r(z) = \frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dz} \propto (1-z)^{n(x)}$$

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

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

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

Does Feynman scaling holds for and large x_{L}at super high energies?,

Increase of the impact parameters (Peripheral collisions) works to keep fragmentation the same

Blackening -at evere increasing range of impact parameters kills very forward production

Which contribution wins depends probably on mechanism of taming of minaret contribution.

CONCLUSIONS

There is a wide range of QCD phenomena in the very forward kinematics which could be explored in LHC in pp, pA& UPC collisions which may allow an unambiguous observation of nonlinear QCD effects, test multiparton structure of nucleons, dynamics of hadronization.

Some relevant data are already accumulated at LHC and preserved in the HERA archives.