Fragmentation as a probe of hadron structure and onset of nonlinear QCD regime

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2/10/2022, Fragmentation workshop

Nucleon fragmentation - probe of multiparton structure, soft - hard interplay

Nonlinear QCD dynamics in pp, pA, UPC in the fragmentation

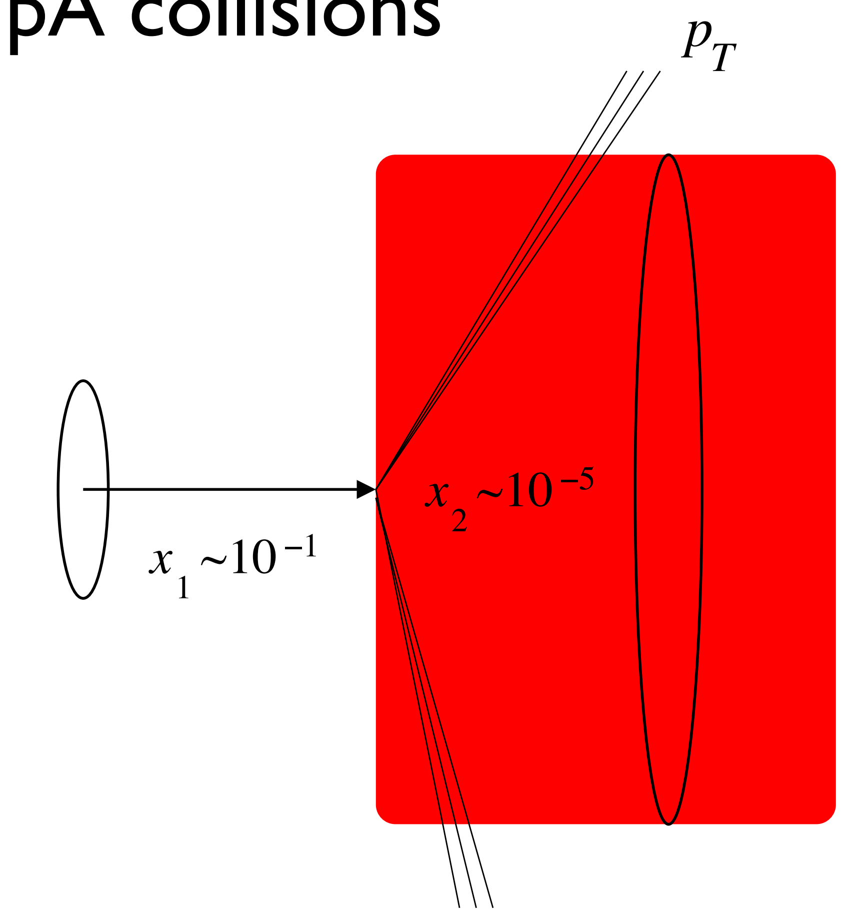
Steps to make ZDC effective diagnostic tool of p(Gamma) A dynamics

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

At LHC $x_1 = 0.1, p_\perp = 2GeV/c \longrightarrow x_{2min} = 10^{-6}$ $x_2 = 4p_\perp^2/x_1 s$

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



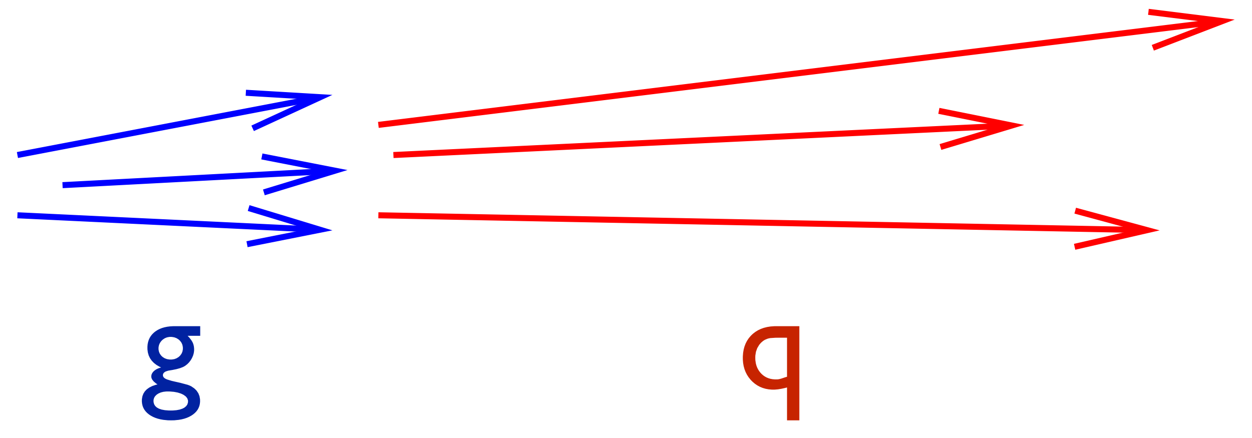
Black disk limit in central collisions: Leading partons in the proton, x_1, interact with a dense medium of small x_2 – gluons in the nucleus (shaded area)(actually integral over x_2), acquiring a significant transverse momentum, $p_\perp$ and loosing a finite fraction of its momentum

Larger x_1, stronger the blackening.

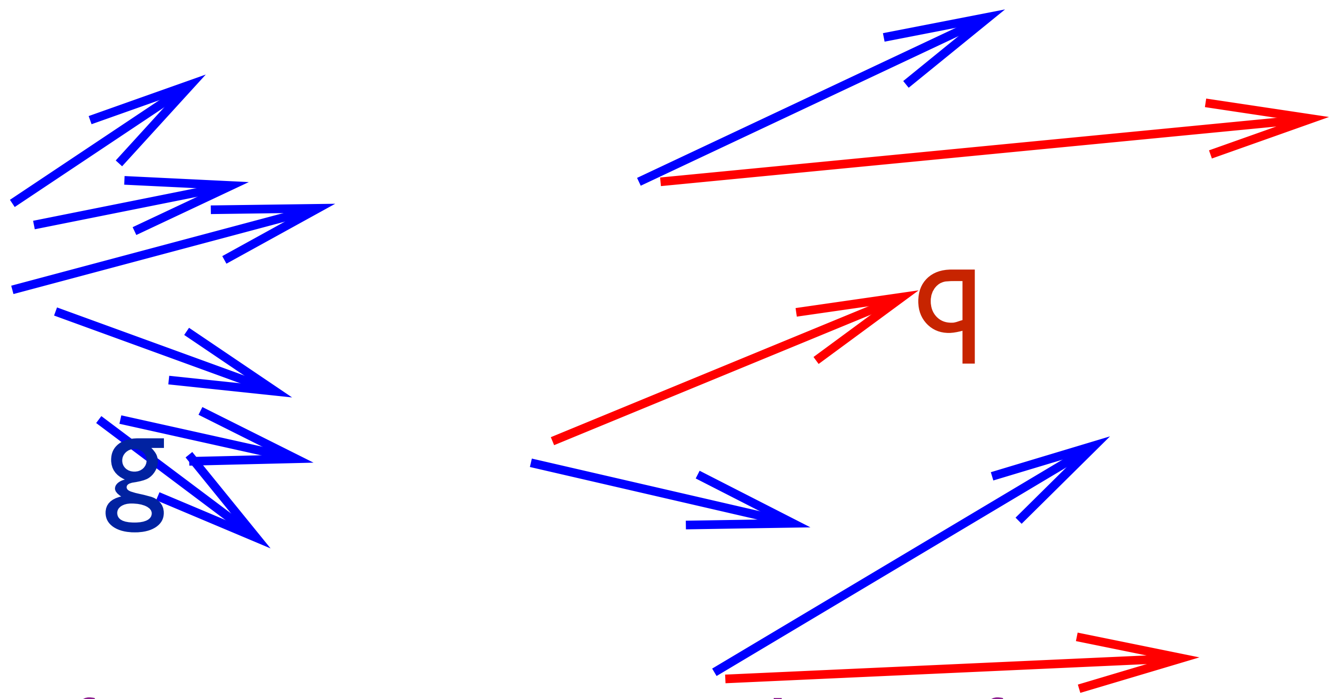
Note, there is no significant gain in gluon density per unit area between proton and Pb targets but fluctuations of gluon density are much smaller in case of nuclei

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

γ p/A case more involved due to strong photon fluctuations Guzey's talk

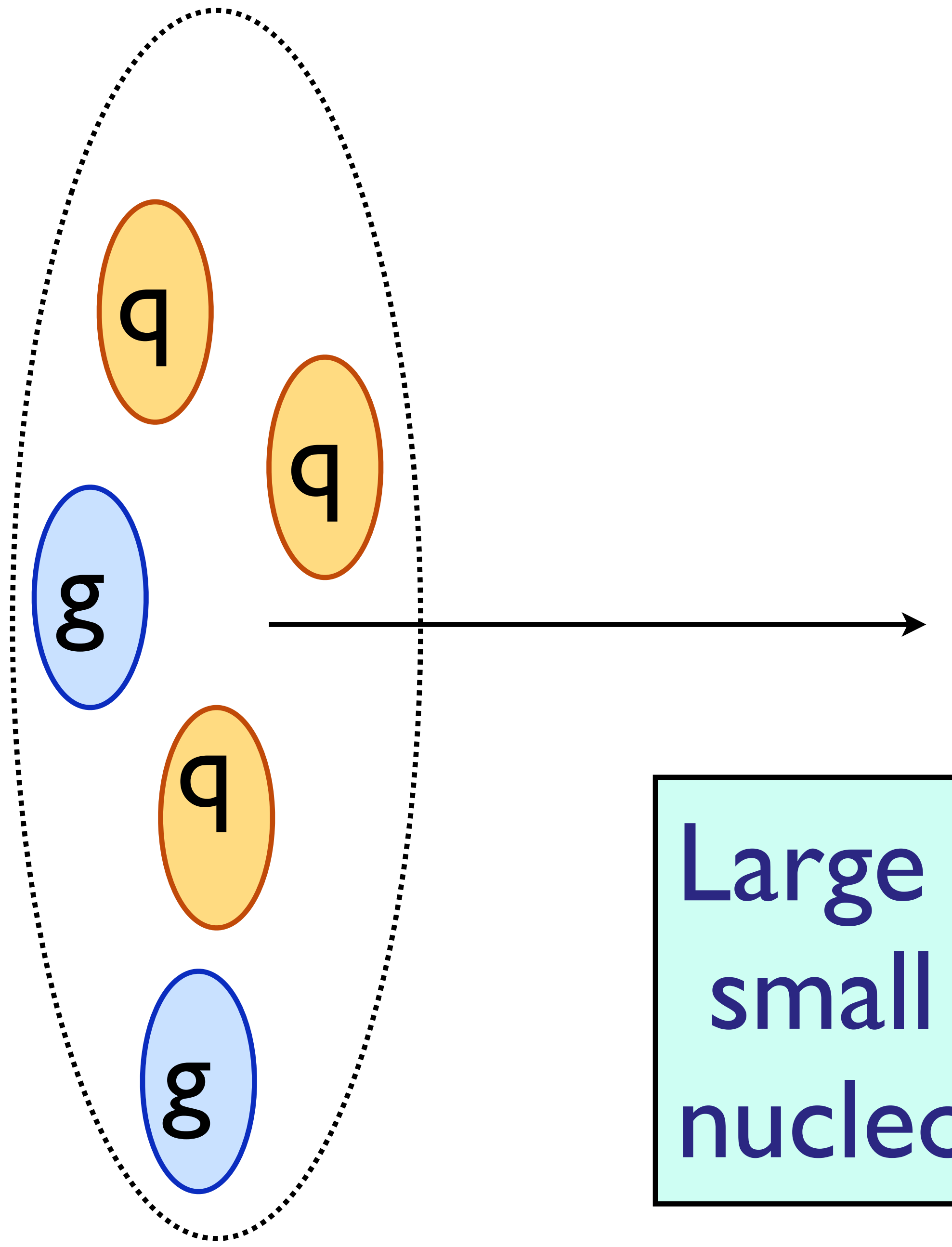


fast partons in a nucleon before collisions

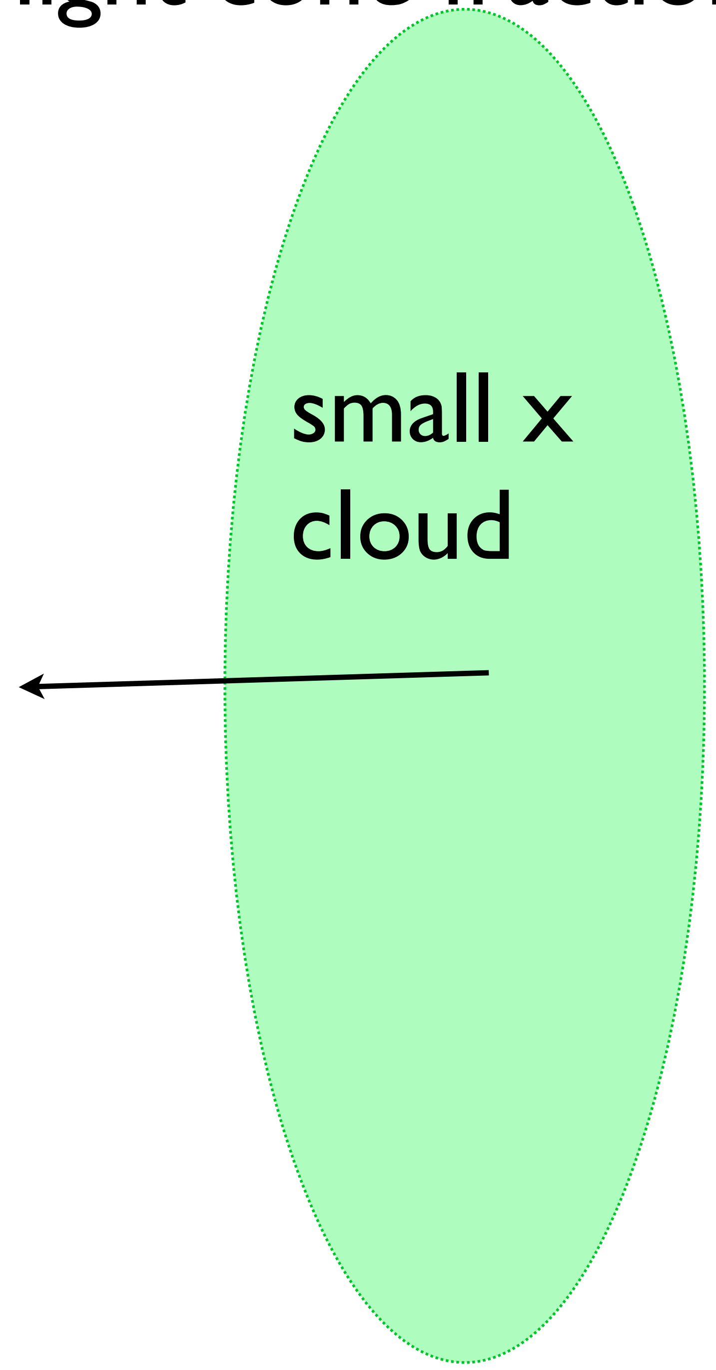


fast partons in a nucleon after central collisions

Smaller light cone fractions & larger $p_\perp$

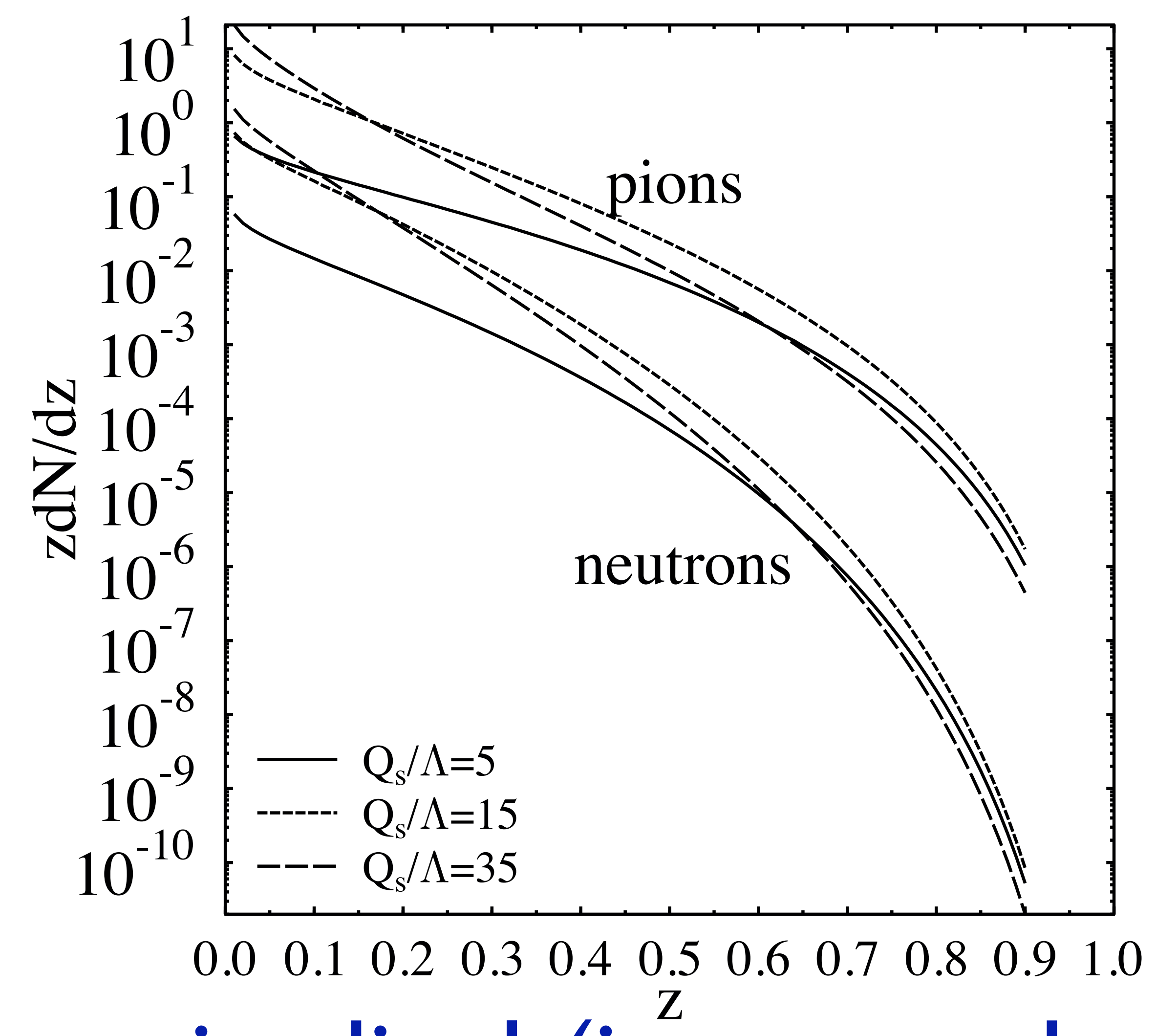


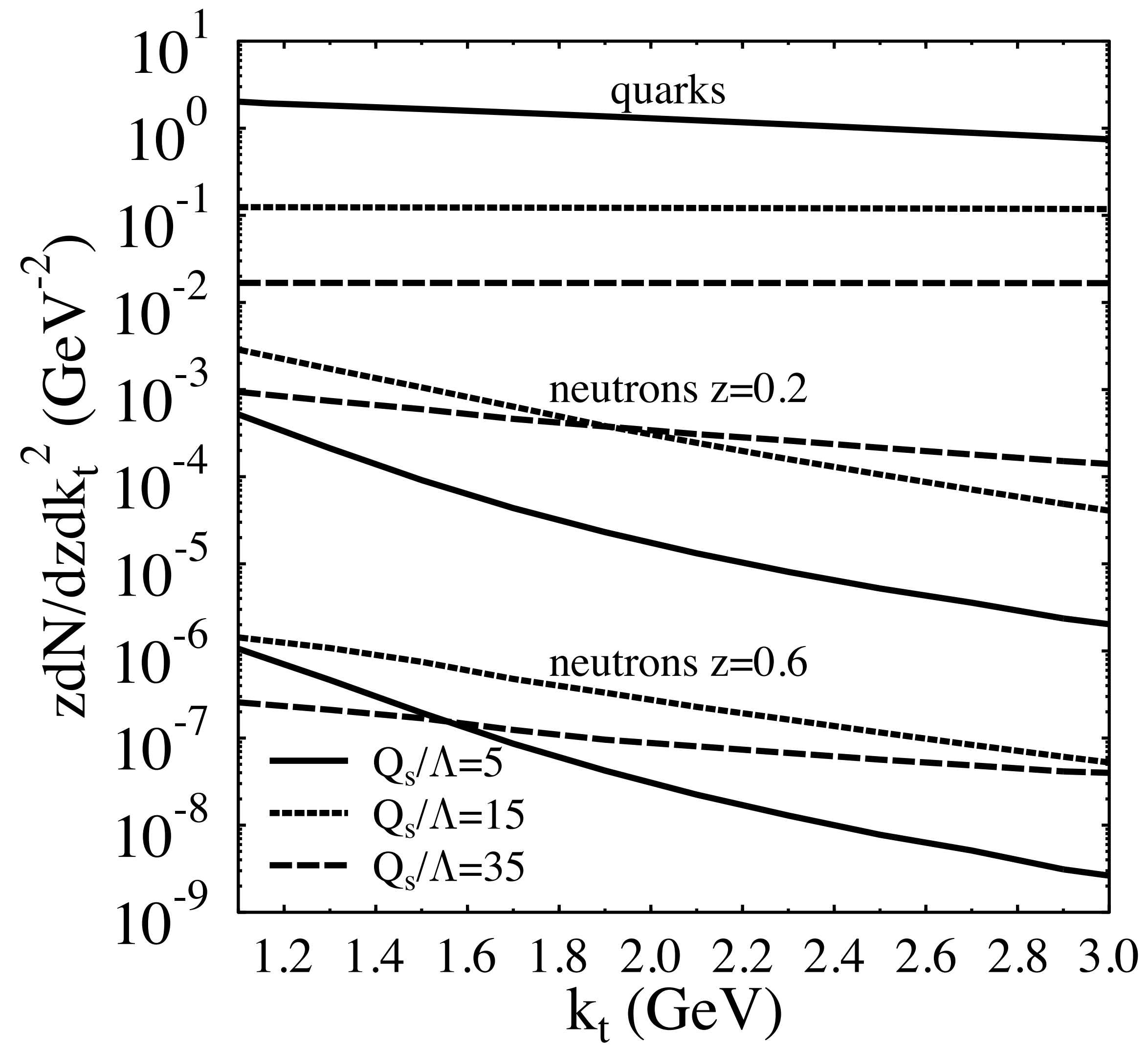
Large x partons of nucleon "1"burn small holes in the small x cloud of nucleon "2"(nucleus) and vice versa



The leading particle spectrum will be strongly suppressed compared to minimum 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 .A fragmenting parton receives x'/x fraction of the transverse momentum received by a pparton while propagating through the gluon field. Hence for smallish z merging becomes possible.

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





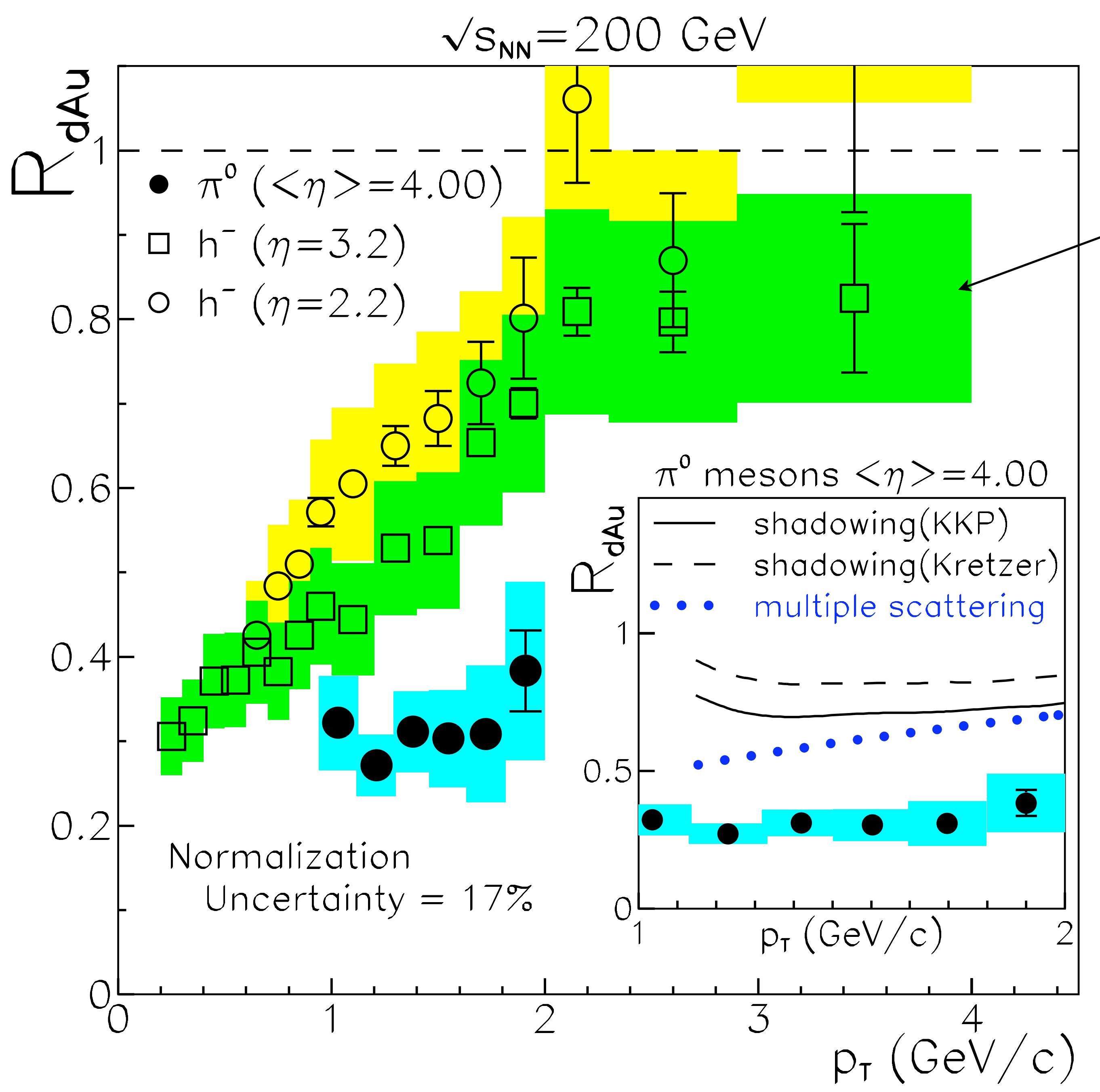
Longitudinal (integrated over p_t) and transverse distributions in Color Glass Condensate model for central pA collisions. (Dumitru, Gerland, MS -PRL03). Spectra for central pp - the same trends. Review of different approaches in A.Dumitru talk)

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 !!!

Suppression of the forward nucleon spectrum in pA is observed at LHC - Chiara Oppedisano’s talk

However rapidity dependence of suppression was not reported so far. Plus analysis used pseudorapidity variable which may result in a contribution of rather soft nucleons with small transverse momenta to a very forward kinematics.

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

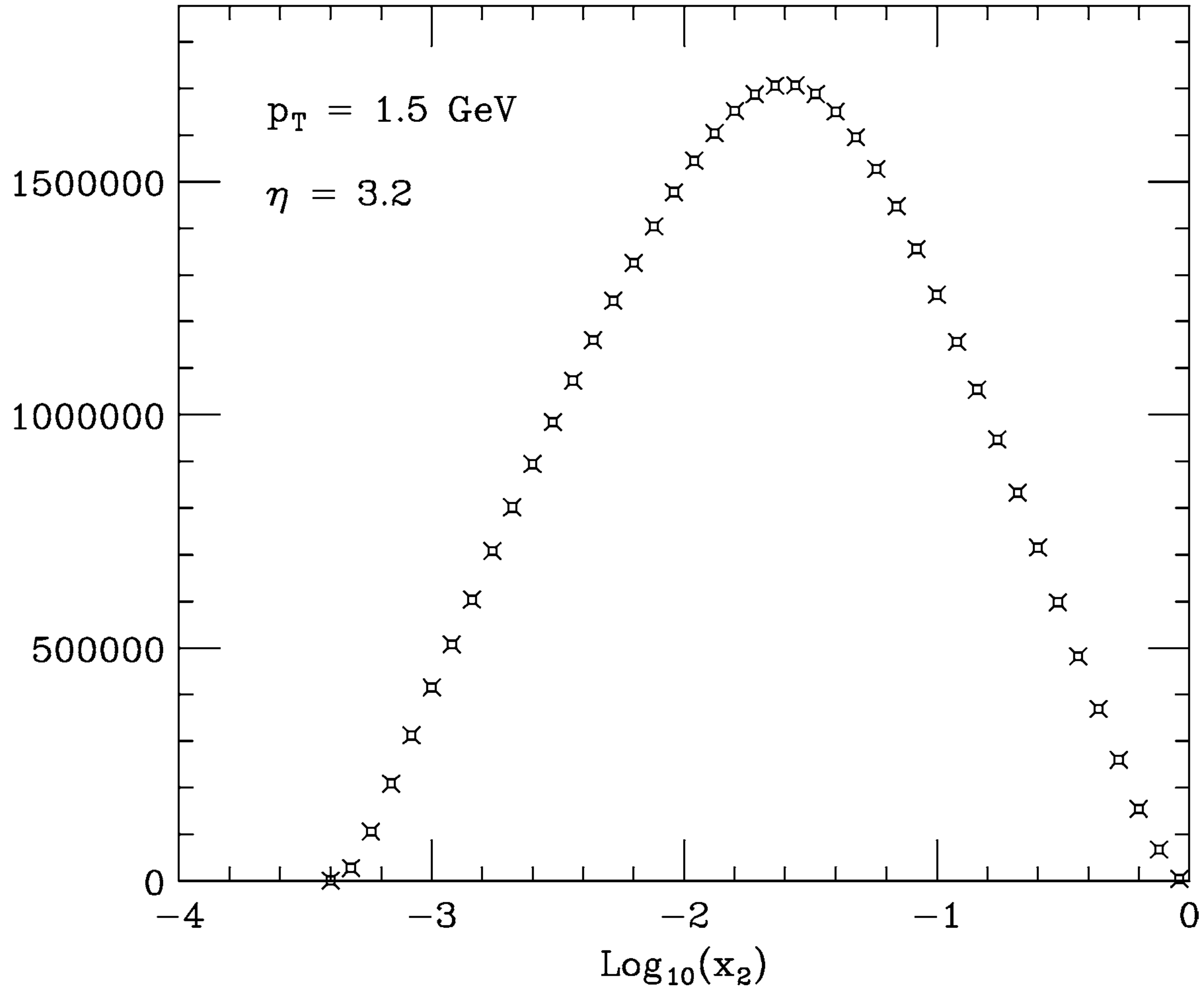


Fig. 1. Distribution in $\log_{10}(x_2)$ of the NLO invariant cross section $E\, d^3\sigma/dp^3$ at $\sqrt{s} = 200$ GeV, $p_T = 1.5$ GeV and $\eta = 3.2$.

Guzey, MS,Vogelsang 04

CGC motivated calculations with an accurate treatment of energy conservation found similar shape (very small contribution of small x)

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 p_t increases with increase of y_N. Analysis of the data indicates that pion production mostly originates 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.

Independent of details -the observed effect is a strong evidence for breaking pQCD approximation. Natural suspicion (since effect is present for Pb but not pp) is that this is due to effects of strong small x gluon fields in nuclei as the forward kinematics sensitive to small x effects.

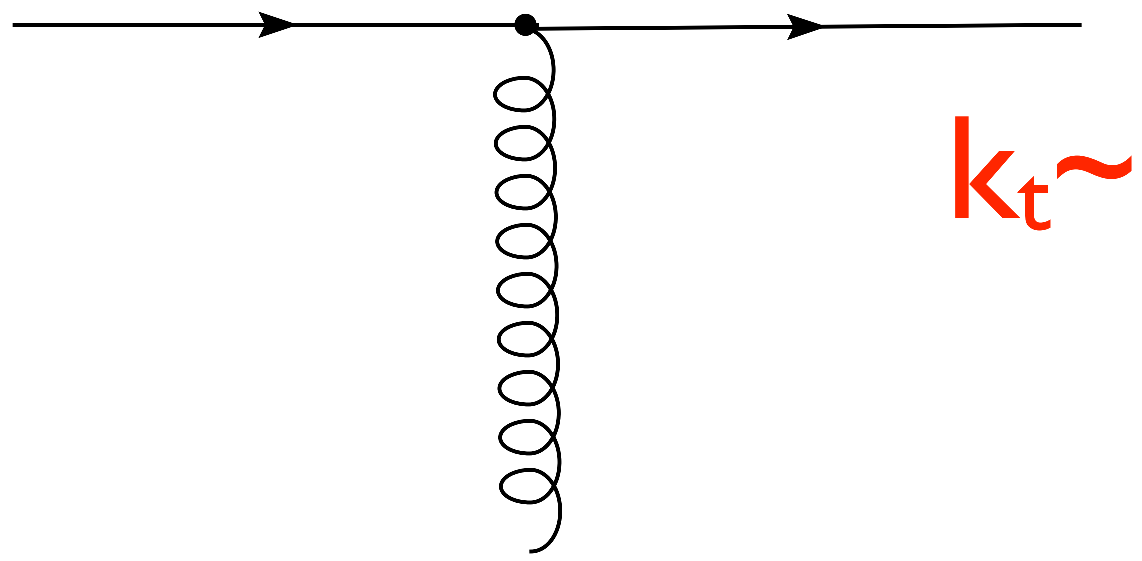
Two possible explanations both based on presence of high gluon field effects

(a) CGC: leading pions from central collisions;

(b)post-selection - pions from peripheral collisions

Color Glass Condensate model

Assumes that the process is dominated both for a nucleus and nucleon target by the scattering of partons with minimum x allowed by the kinematics: $x \sim 10^{-4}$ in a $2 \to 1$ process.



$k_t \sim Q_s$

Two effects - (i) density is smaller than for the incoherent sum of participant nucleons by a factor N_{part}, (ii) enhancement due to increase of k_t of the small x parton: $k_t \sim Q_s$. → Overall dependence on N_{part} is $(N_{part})^{0.5}$, collisions with high p_t trigger are more central than the minimum bias events, no recoil jets in the kinematics expected in pQCD.

⇒ dominant yield from central impact parameters

Energy losses in black disk regime (BDR) - usually only finite energy losses discussed (BDMPS) - hence a rather small effect for partons with energies 10^4 GeV in the second nucleus rest frame. Not true in BDR - post selection - energy splits before the collision - effectively 10- 15 % energy losses.

⇒ dominant yield from peripheral impact parameters

To use information about central rapidities in a detailed way we used the relevant information from dAu BRAHMS analysis. Results are not sensitive to details.

We confirm that pion production is strongly dominated by peripheral collisions, and that there is no significant suppression of dijet mechanism for forward -central correlation.

For central impact parameters suppression is by a factor > 5, which requires energy losses of >10%

Since the second jet has much smaller longitudinal momentum than the jet leading to the forward pion production it propagates in a much more pQCD like regime with much smaller energy losses, and hence does not affect the rate of correlation. If the energy losses were fractional but energy independent this would not be the case.

Test of our interpretation- ratio, R, of soft pion multiplicity at y ~0 with π^0 trigger and in minimum bias events.

In CGC scenario R ~ 1.3

In BDR energy loss scenario we calculated R ~ 0.5

STAR - R ~0.5 Gregory Rakness - private communication

Further confirmation - forward -central correlation data reported by STAR and PHENIX

Forward pion data from DAu collisions qualitatively consistent with increase of the suppression for this kinematics as the second jet is also in BDR. Stronger post selection effect - enhanced effective energy losses. However far the A-dependence of pion production in pA scattering at RHIC was not reported. So it is difficult to interpret the data where two pions are produced with similar longitudinal momenta - suppression is higher than in single pion case but to get a reliable interpretation one needs models which reproduce suppression for a single pion production.

Independent of details - strong evidence for breaking pQCD approximation in the kinematics sensitive to strong gluon field in nuclei

Future: analysis of the A-dependence/centrality of pion production data at wide range of incident energies - effect for fixed x_h and $p_\perp$ should increase with increases with s. (Suppression at LHC >> than at RHIC)

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 meson suppression in UPC /LHC

Open questions in nucleon fragmentation

Dual role: detector of multiparton nucleon structure and when inbeddded in nuclei a microvertex detector of low energy activity in the interactions with nuclei

DGLAP factorization, talks later today & talks reviewing the data

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

Guzey's talk -removal of a gluon from a nucleon

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 scaling

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 $\beta << 1$.

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):

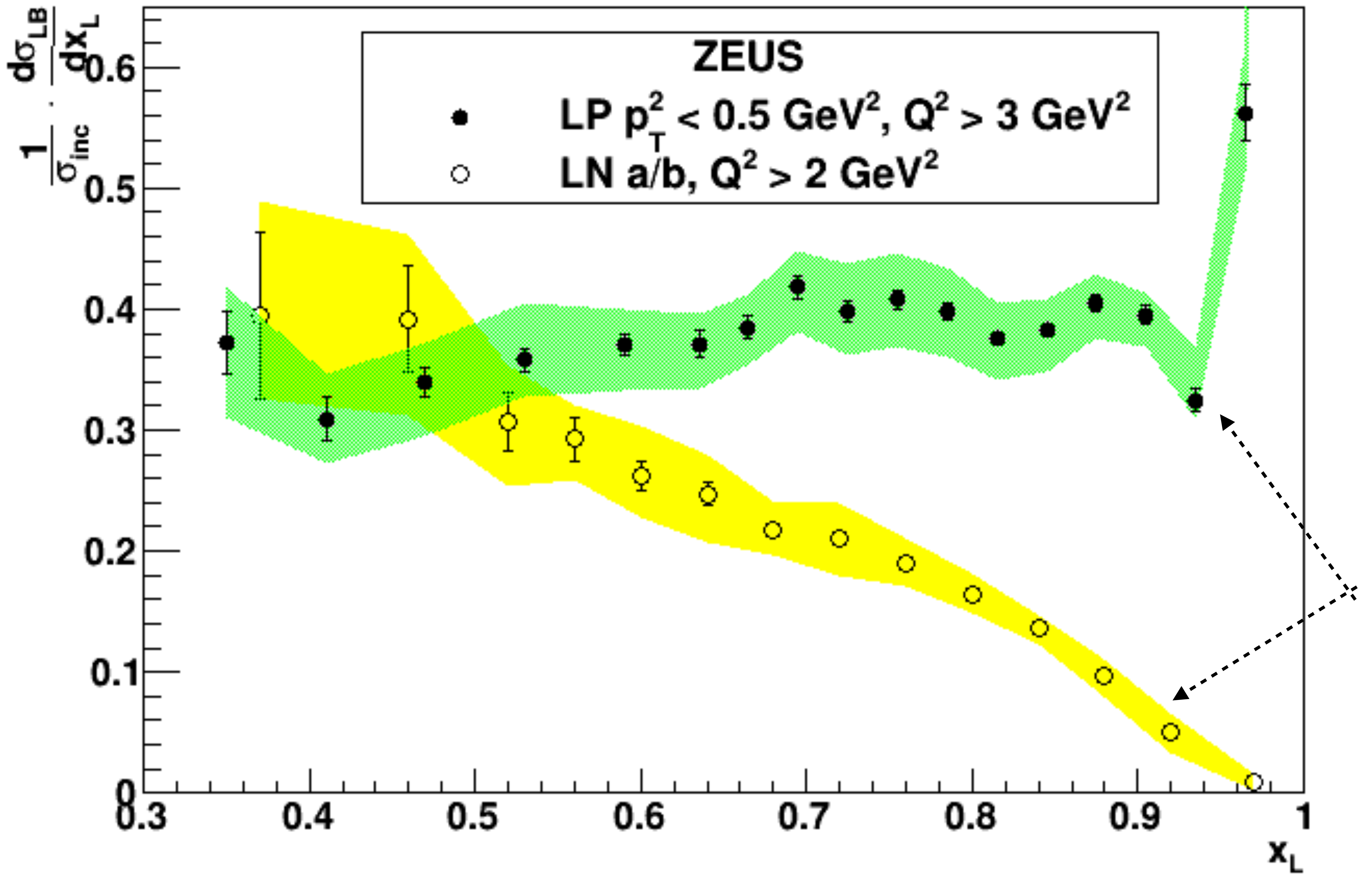
$$f_j(x,z) \propto (1-z)^{n(x)}$$

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

$n(x \sim 0.1) =0? 1?$ 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]

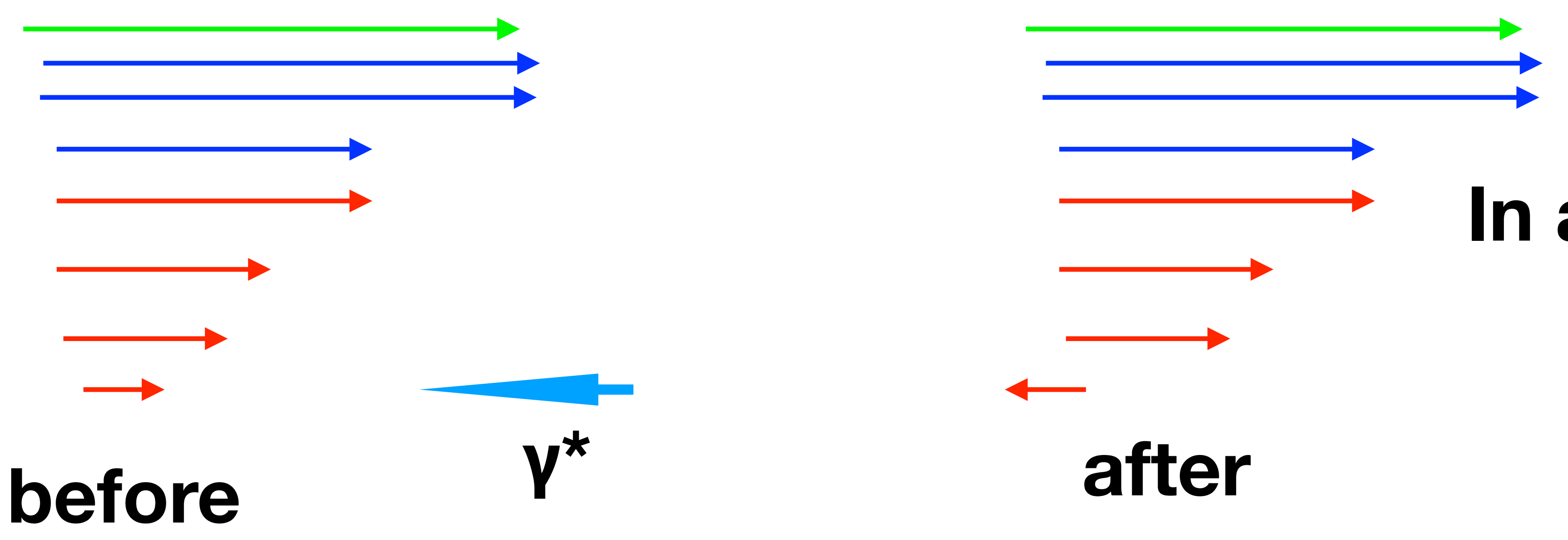
HERA studies missed a puzzle: where are baryons. Should be #baryons - # anti baryons = 1 per event. For small x and x_L > 0.3 only 0.46 baryons are observed (70% p, 30% n) (strange baryons not measured but likely 30% correction of neutrons

➜ 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 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

Does a removal of small x gluon leads to the same decay as removal of quark? HERA has relevant data - could not find them. Recollection the data are consistent with soft factorization

EXPERIMENTAL OBSERVATIONS

Expect that for $x << (1-x_L)$, nucleon multiplicity for removal of (anti)quark or a gluo are the same.

Soft factorization

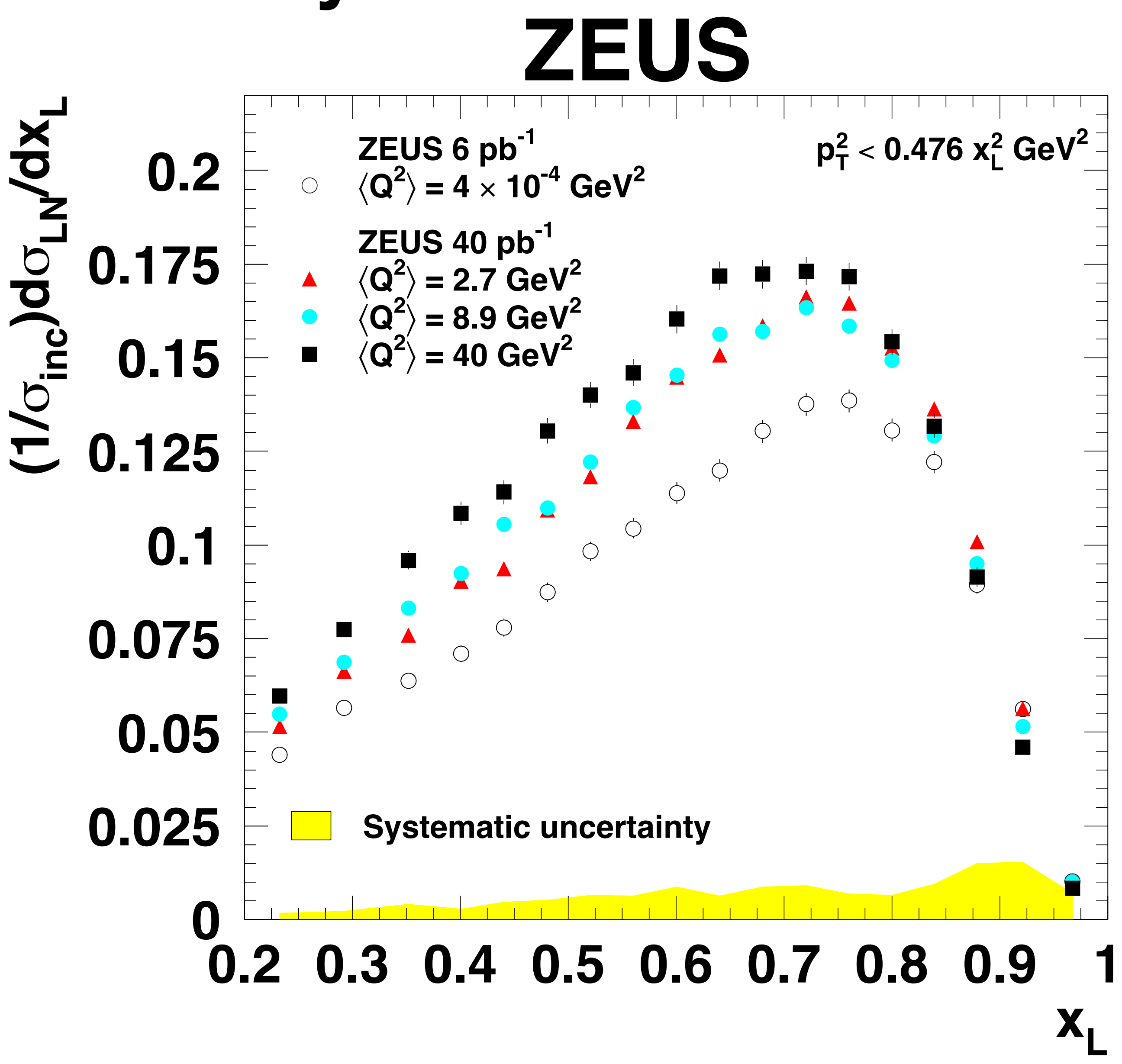
Does a removal of small x gluon leads to the same decay as removal of quark? HERA has relevant data - could not find them. Recollection is that the data are consistent with soft factorization.

Not trivial - color octet vs color triplet

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:

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

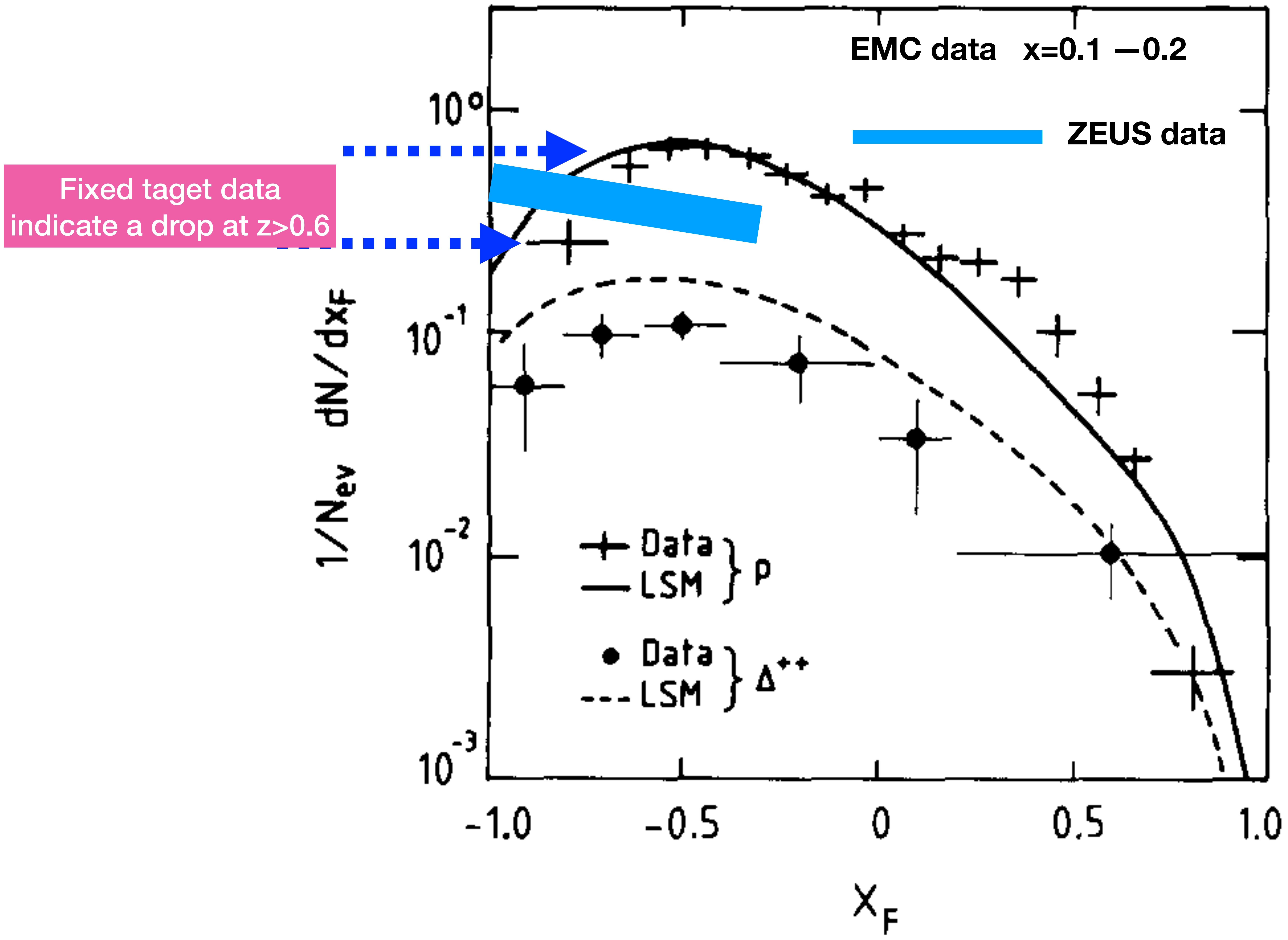
$$r(z) = \frac{1}{\sigma_{inc}} \frac{d\sigma_{LN}}{dz} \propto (1-z)^{n(x)}$$

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

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

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 in pp scattering (Peripheral collisions) works to keep fragmentation rate the same

Blackening at small impact parameters increasing range of b kills very forward production

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

Measurements for large x_F of neutron production s a function of $W_{\gamma p}$, minimum bias, events with dijets (direct photon) charm,...comparison with pp.

Need additional tools for study of interaction in the nucleus fragmentation region.

Neutrons in ZDC. Mechanism of production — models described on Friday by Larionov & FLUKA

Starting point: quasi elastic $\gamma A \to J/\psi + N + (A-1)$

Neutron multiplicity as a function of p_t of J/psi

Including nucleon dissociation significant growth at p_t~ 0.5 GeV/c.

Probably possible to separate elastic and quasi elastic channels as a function of t.

Diet production in the direct photon kinematics and comparing to FNAL muon - nucleus data. Reported a suppressed neutron production - require long formation time - Larionov 's talk.

In soft regime number of neutrons is proportional to the number of wounded nucleons , hence prediction

$$\frac{N_n(\gamma Pb)}{N_n(\gamma Pb \to dijet + X for x > 0.01} \sim \frac{A\sigma\gamma p)}{\sigma(\gamma Pb)} \sim 3$$

Applications to pA, AA collisions

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.