Leading twist nuclear shadowing, onset of black disk regime and post selection effect for the leading hadron production

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BNL glasma workshop, May 12, 2010

In collaboration with Dumitru, Frankfurt, Gerland, Guzey, Rogers, Vogelsang

Theory of leading twist nuclear shadowing

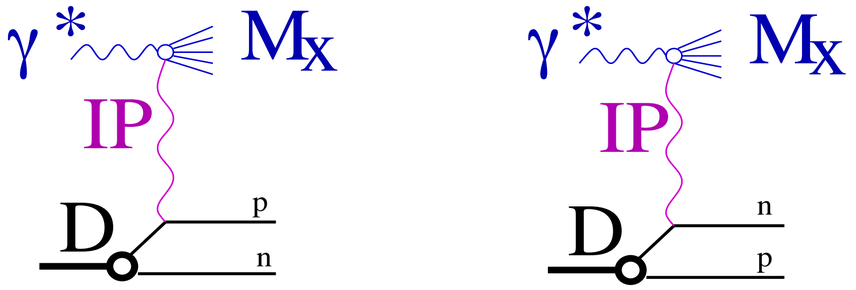
FS98; Guzey &FS 2002-2010

Gribov 69 Connection between nuclear shadowing and diffraction - nuclear rest frame

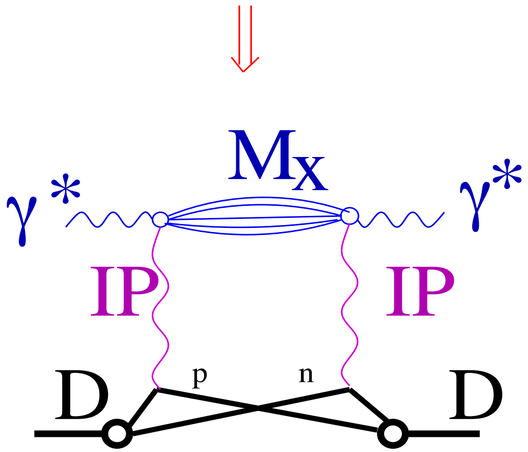
Qualitatively, the connection is due to a possibility of small momentum transfer to the nucleon at small x, where $-t_{min} = x^2 m_N^2 (1 + M_{dif}^2/Q^2)$

$$If\ \sqrt{-t} \leq \text{"average momentum in nucleon(nucleus)}$$

Deuteron example -amplitudes of diffractive scattering off proton and off neutron interfere



Valid both for LT and HT.
The only assumption D=p+n



Collins factorization theorem for diffraction 97

Diffractive cross sections induced by hard probes are expressed through diffractive parton densities $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$ *. Factorization confirmed at HERA in*

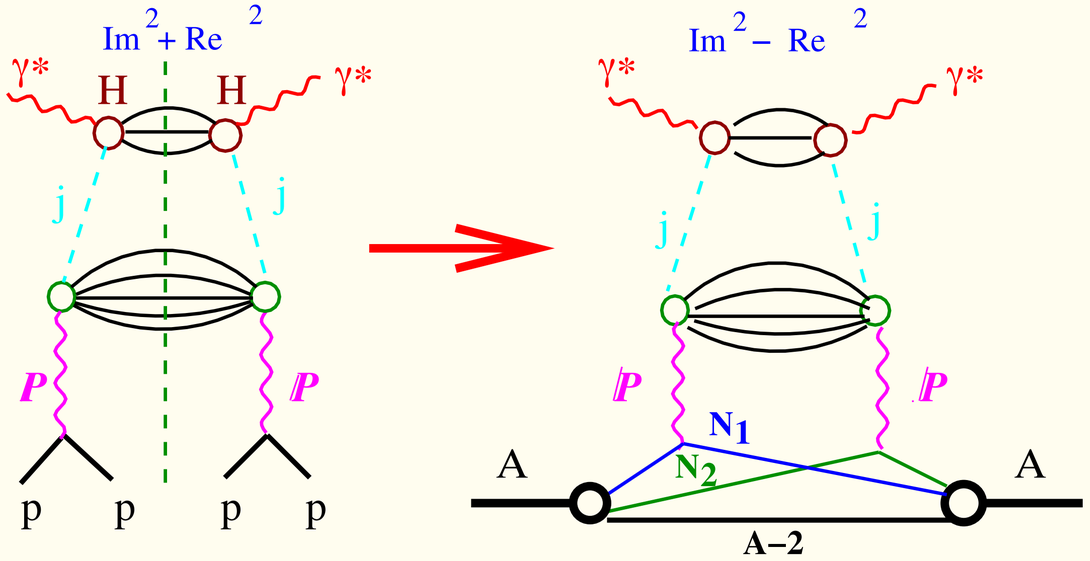
- Scaling violation for $F_3^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P})$
- Jet production in diffraction - gluon diffractive pdfs
- Charm production in diffraction - gluon diffractive pdfs

Experimental energy dependence very close to soft Pomeron:

$$\alpha_{I\!P}^{diff}(t \sim 0) = 1.11$$

Combining Gribov theory of shadowing and pQCD factorization theorem for diffraction in DIS allows to calculate LT shadowing for all parton densities (instead of calculating F_{2A} only)

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive pdf's $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$:



Hard diffraction

off parton "j"

Leading twist contribution

to the nuclear shadowing for

structure function $f_j(x,Q^2)$

Theorem: in the low thickness limit (or for x>0.005)

$$\mathrm{f}_{j/A}(x,Q^2)/A = f_{j/N}(x,Q^2) - \frac{1}{2+2\eta^2}\int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_x^{x_0} dx_{I\!P} \cdot$$

$$\cdot f^D_{j/N}\left(\beta, Q^2, x_{I\!P}, t\right)_{|k_t^2=0}\ \rho_A(b,z_1)\ \rho_A(b,z_2)\ \ \mathrm{Re}\left[(1-i\eta)^2 \exp(i x_{I\!P} m_N (z_1 - z_2))\right],$$

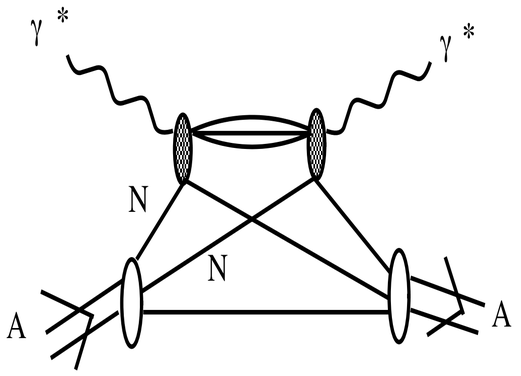
where $f_{j/A}(x,Q^2), f_{j/N}(x,Q^2)$ are nucleus(nucleon) pdf's,

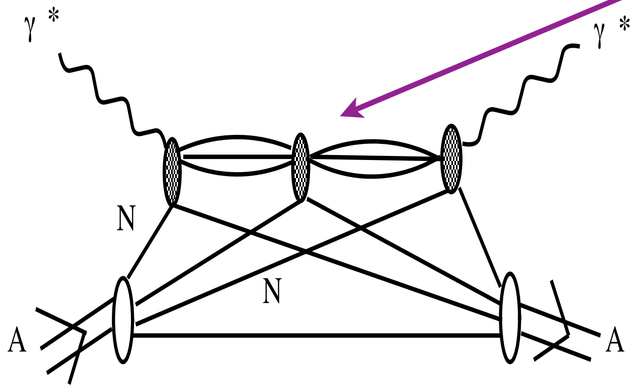
$\eta = ReA^{diff}/ImA^{diff} \approx 0.17,\ \rho_A(r)$ nuclear matter density.

$x_0(quarks) \sim 0.1,\ x_0(gluons) \sim 0.03$

Including higher order terms

Some sensitivity to the fluctuations of strength of interaction





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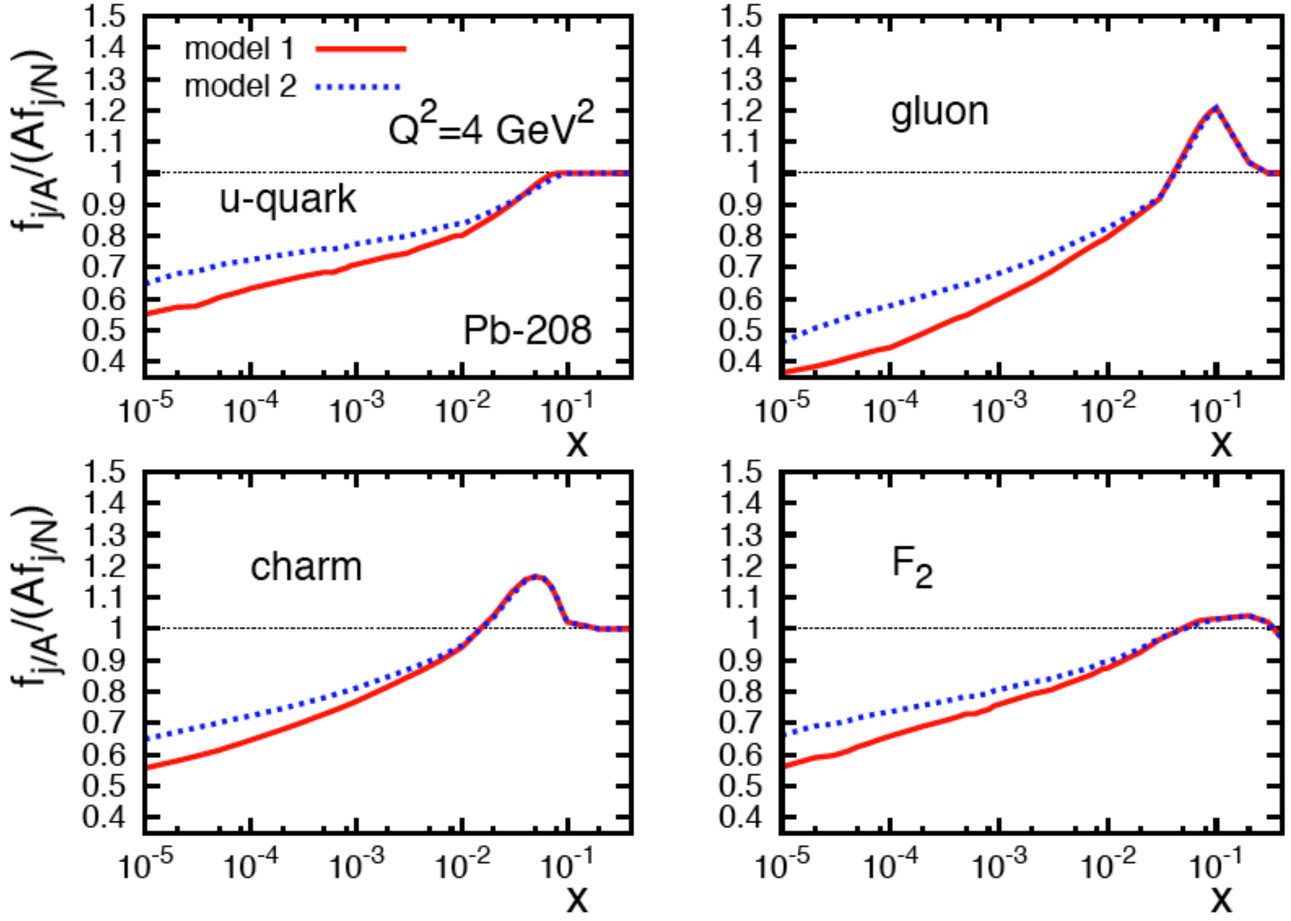
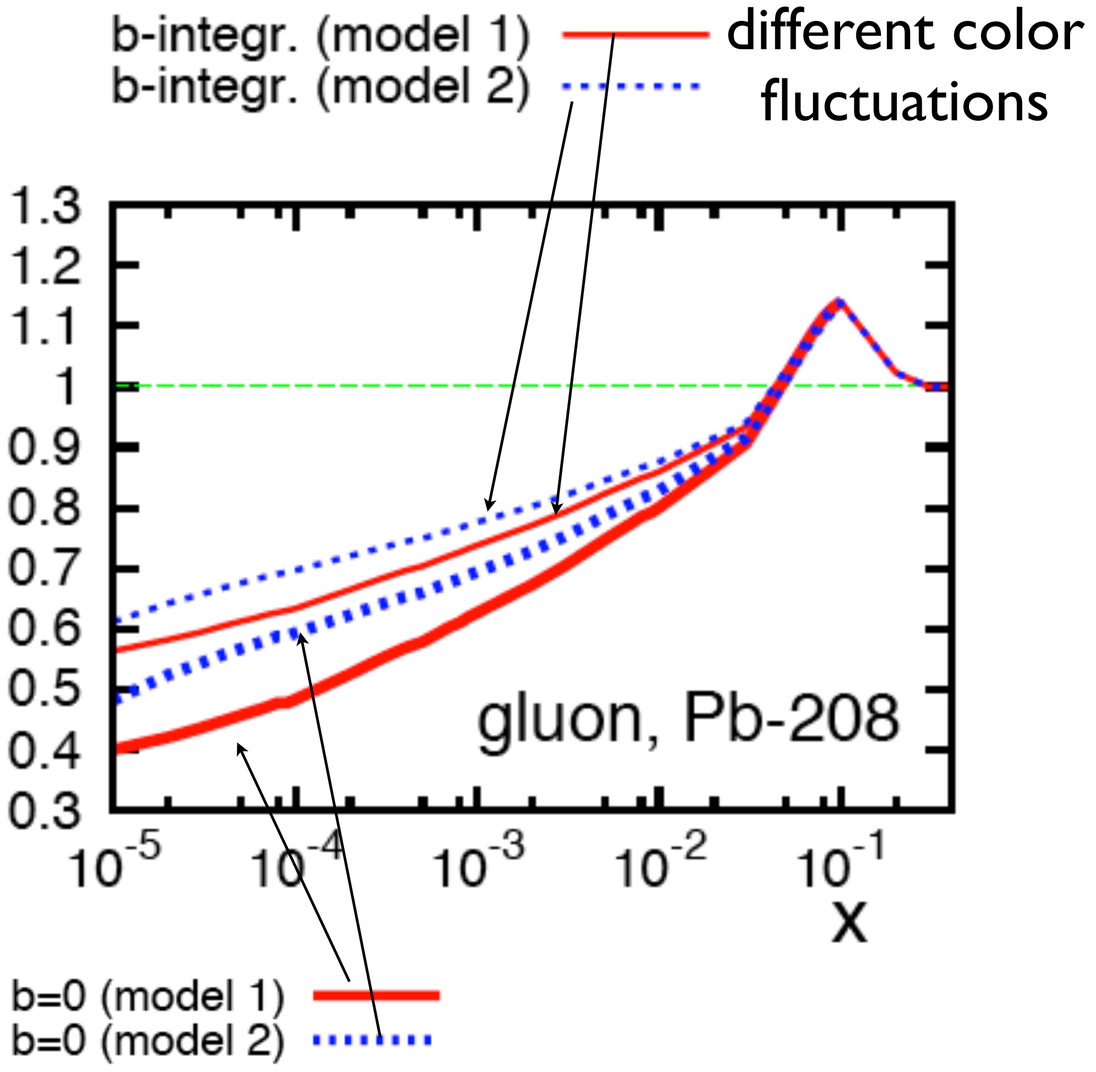




Predictions of the LT theory of nuclear shadowing for pdfs of Pb at Q^2= 4 GeV^2

Where non-linear regime sets in?

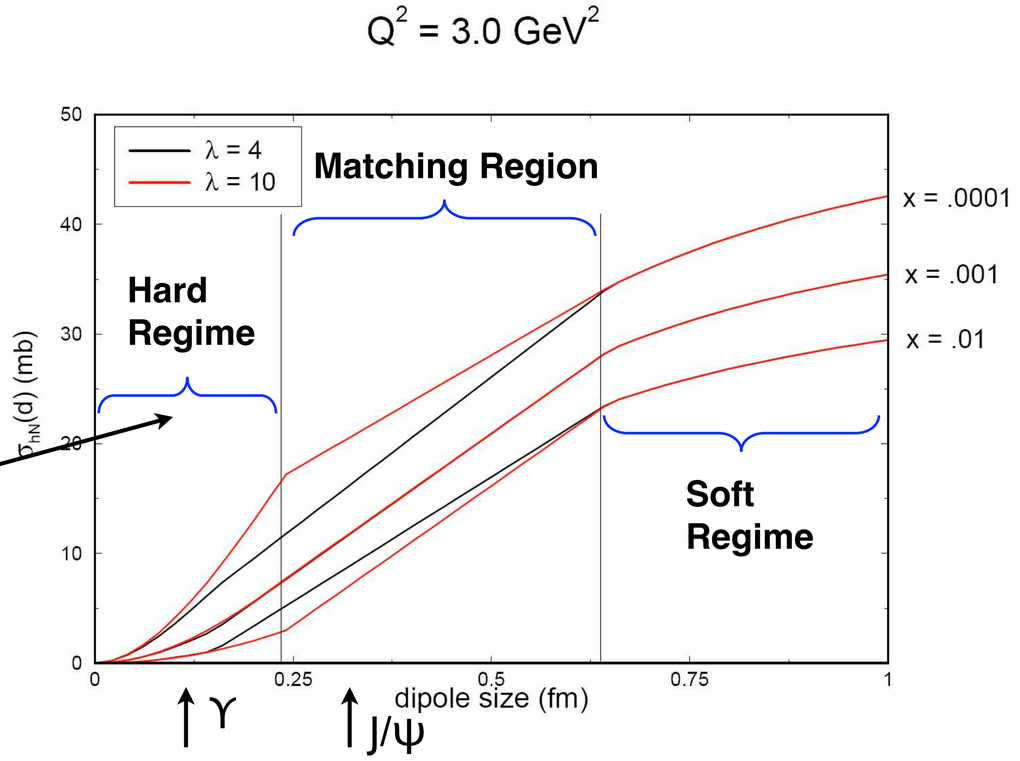
High energy color transparency is well established

At high energies weakness of interaction of point-like configurations with nucleons is routinely used for quantitative explanation of DIS phenomena at HERA. In particular *HERA data confirm increase of the cross sections of small dipoles predicted by pQCD*

studies of the "quark-antiquark dipole"(transverse size d) - nucleon cross section based pQCD and HERA data

$$\sigma_{inel} = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x.\lambda/d^2)$$

F^2 Casimir operator of color SU(3)



Frankfurt et al 2000-2001

Dipole approximation for DIS and vector meson production describes bulk of the HERA data. Challenge - limiting behavior of σ - onset of black disk regime (BDR) - addressed in a number of models

Impact parameter distribution in "h"(dipole)p interaction

Study of the elastic scattering allows to determine how the strength of the interaction depends on the impact parameter, b:

$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}e^{i\vec{q}\vec{b}}A_{hN}(s,t); \qquad ImA = s\sigma_{tot}F_{2g}(t,x)$$

Two gluon form factor determined from the HERA vector meson production data using the QCD factorization theorem + finite size corrections

$$\sigma_{tot} = 2\int d^2b\mathrm{Re}\Gamma(s,b)$$

$$\sigma_{el} = \int d^2b|\Gamma(s,b)|^2$$

$$\sigma_{inel} = \int d^2b(1-(1-\mathrm{Re}\Gamma(s,b))^2-[\mathrm{Im}\Gamma(s,b)]^2)$$

$$\Gamma(b<b_0) = \theta(b_0-b) \equiv \sigma_{inel} = \sigma_{el}$$

- black disk regime -BDR

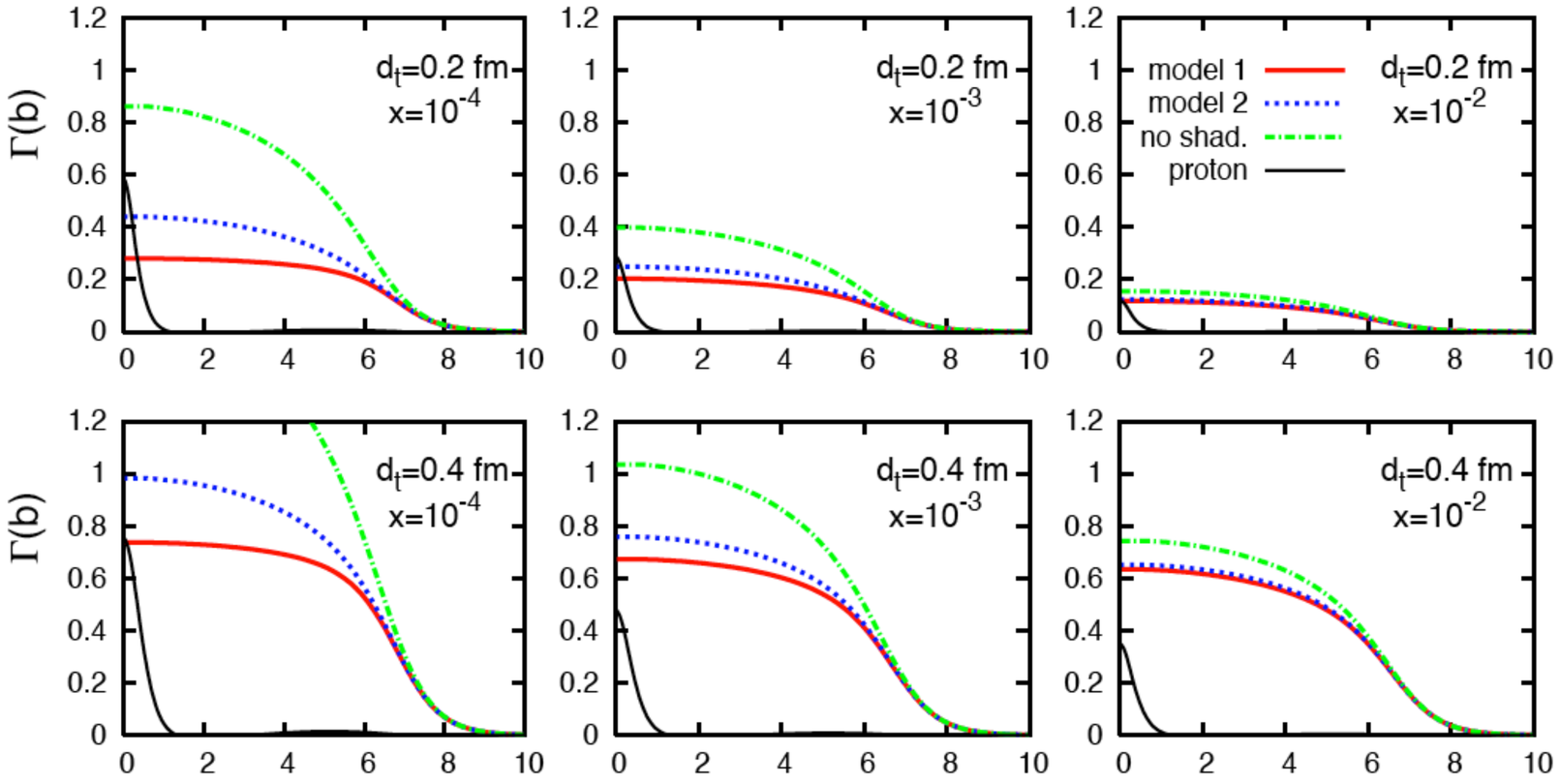
Allows a bit more refined analysis than Koepf , FS 96

$\sigma_{el}/\sigma_{inel} < 1$ was studied

Note that elastic unitarity: $\frac{1}{2}ImA = |A|^2 + \ldots$ allows $\Gamma(b) \leq 2$

Impact factor Γ(b) for quark - antiquark dipole p/Pb scattering

Update of Rogers et al 03



$$p_t \approx \frac{\pi}{d}$$

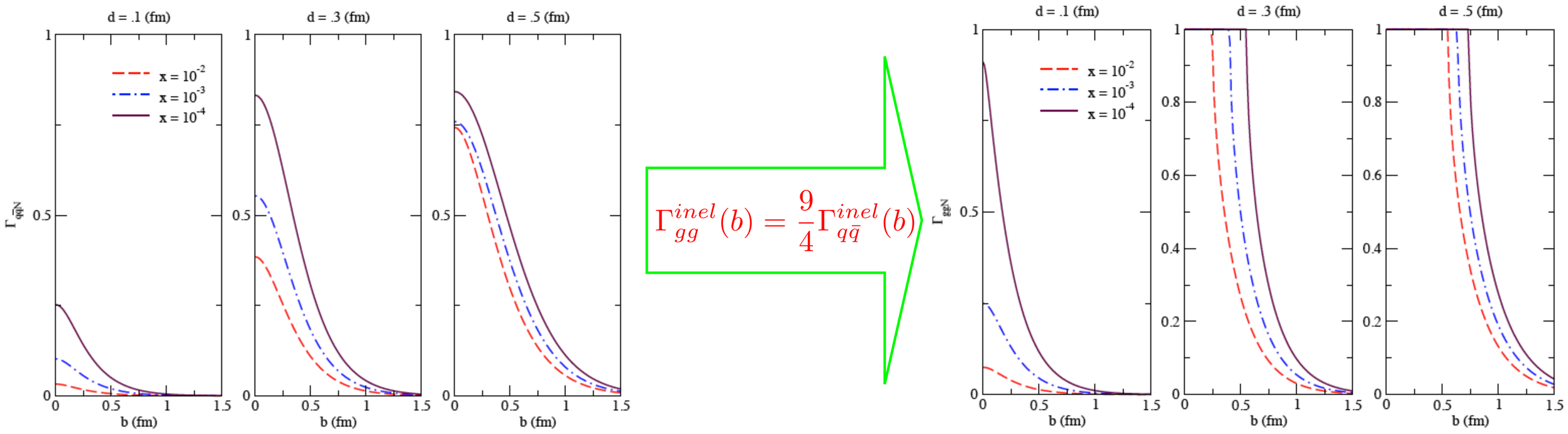
$$p_t \approx 1.5\, GeV/c$$

$$p_t \approx 0.75\, GeV/c$$

Probability of inelastic interaction is

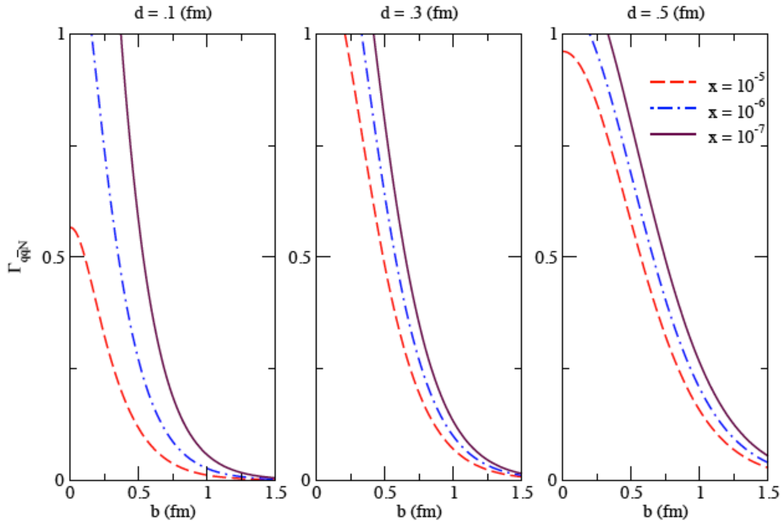
$P_{in}= |1-\Gamma(b)|^2$ → $P_{in}=3/4$ for $\Gamma(b)=1/2$

Gluon densities in nuclei and proton at b=0 are rather similar. However very few processes with proton are sensitive to b=0 not <b> while in nuclei it is trivial to select range of b with practically the same Γ(b).

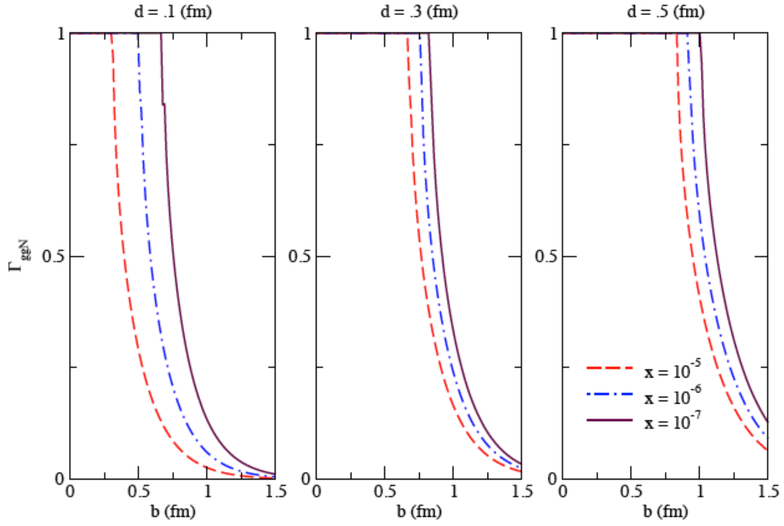


At HERA in quark channel range of b where interaction is close to BDR is small except for $Q^2 \sim 1$ GeV^2 .

For gluons BDR range is much larger $Q^2 \sim 4$ GeV^2 for $x=10^{-4}$?



(a)



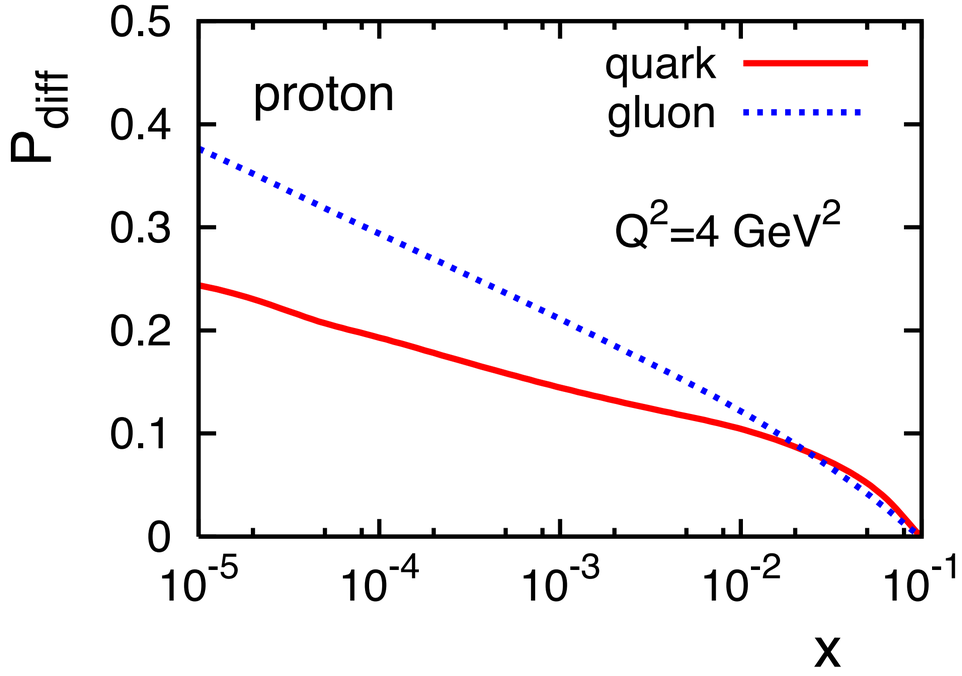
(b)

Much larger range in virtualities at the LHC energies. Estimate was made using double log approximation for parton densities, which works fine at HERa for inclusive cross sections (Forte's talk) and for energy dependence of rapidity gap events (Blok, FS 2010)

Test - diffraction in ep DIS at HERA

What is probability that if the parton j is removed, there will be a diffraction?

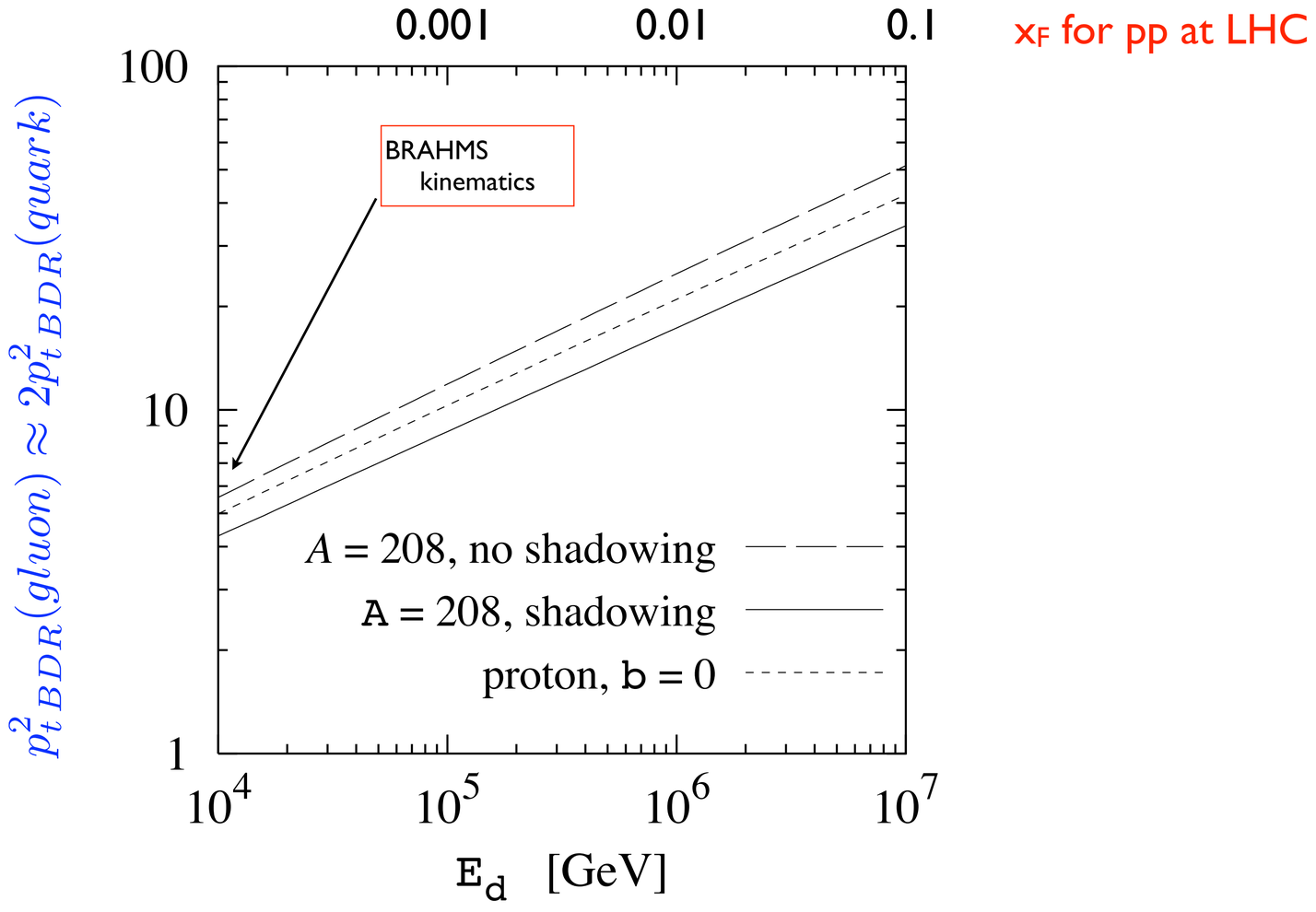
$$P^j_{\rm diff} = \frac{\int_x^{0.1} dx_{I\!P}\, \beta f_j^{D(3)}(\beta, Q^2, x_{I\!P})}{x f_j(x, Q^2)}$$



gg -N interaction seems close to BDR for Q^2~4 GeV^2, $x \leq 10^{-4}$

The probability of hard diffraction on the nucleon, $P_{j\ \rm diff}$ as a function of x for u quarks and gluons.

Onset of BDR for interaction of a small dipole - break down of LT pQCD approximation - natural definition of boundary: $\Gamma_{dip}(b) = 1/2$ - corresponds the probability for dipole to pass through the target at given b without interaction: $|1-\Gamma_{dip}(b)|^2 < 1/4$ ➠ $p_{t\,BDR} \sim \frac{\pi}{2d_{BDR}}$



Warning - estimate assumes $x^{-\omega}$ regime for all x- may overestimate $p_{t\,BDR}$ for parton energies (in nucleus rest frame) $E_d > 10^5$ GeV - better to use double log approximation

Post selection effect in BDR - effective energy losses

"Parton Propagation" for $p_t \leq p_t^{(BDR)}$

The simplest case example: *Inclusive production of leading hadrons in DIS for* $Q < 2p_t^{(BDR)}$

Guzey, McDermott, Frankfurt, MS 2000

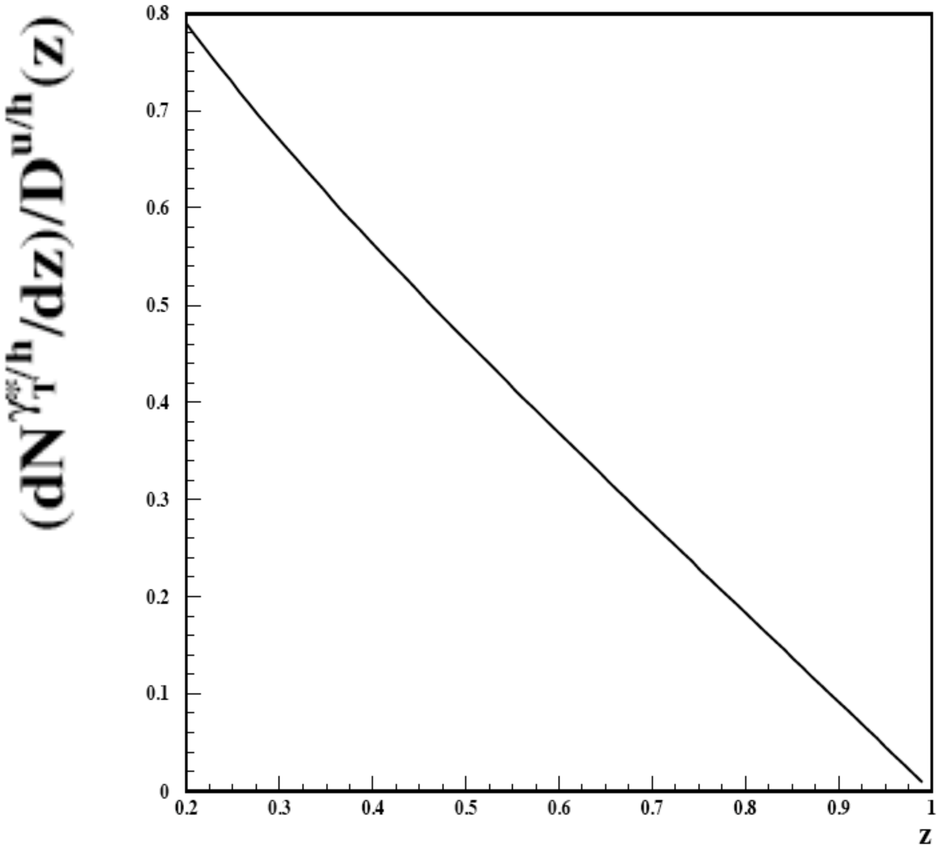
The mechanism of fragmentation in BDR: target selects quark and antiquark in the γ^* wave function with $p_t \propto Q_{BDR}$ and known z-distribution peaked at ~1/2

fragment independently since in this case overlap between showers is small (as long as LC fractions are large). Energy splits before the collision

Hence to a first approximation

$$\bar{D}^{\gamma_T^* \to h}(z) = 2\int_z^1 dy D_q^h(z/y)\frac{3}{4}(1+(2y-1)^2)$$

Gross scaling violation in BDR as compared to DGLAP. The leading particle spectrum in BDR is strongly suppressed. The inclusion of the $q\bar{q}g$ states in the virtual photon wave function (due to the QCD evolution) further amplifies the effect.



The total differential multiplicity normalized to the up quark fragmentation function as a function of z at Q^2=2 GeV^2.

Forward partons with p_t less than BDR scale should loose energy and p_t distribution should broaden

Suppression of the leading hadron production in pA scattering at large p_t comparable to the scale of Black disk regime at given energy (FS 01-06)

$\Rightarrow$

Natural explanation of the BRAHMS forward pion result at RHIC, and the forward - central STAR correlations data

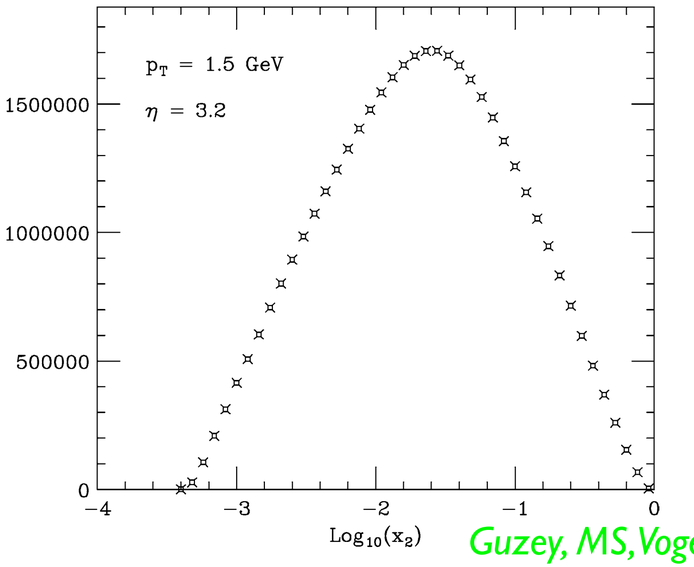
Our estimates indicate that

- quarks near BDR effectively loose in average ~ 10 --15 % of their energy via qg splitting
- gluons effectively loose large fraction of their energy since gg splitting is more symmetric in z

Post selection and forward pion production in DAu collisions at RHIC

☞ For pp - pQCD works both for forward inclusive pion spectra and for correlations (STAR)

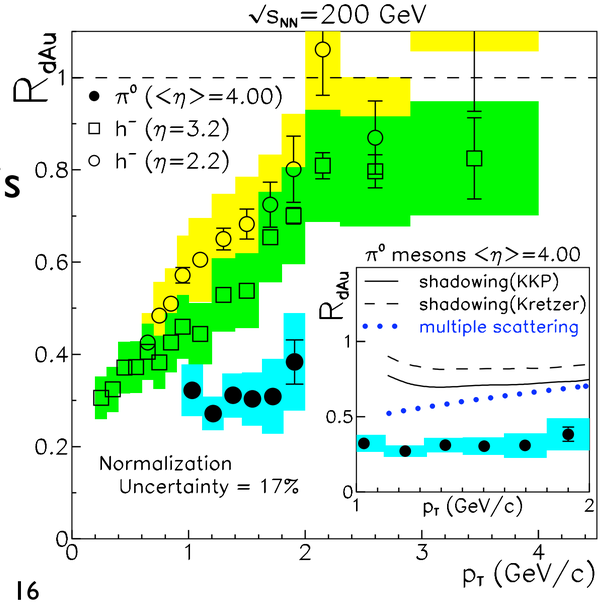
Tests that main contribution to forward pion production comes from quark scattering off gluons with <x> > 0.01 which are not screened in the case of scattering off nuclei



Guzey, MS, Vogelsang 04

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 $\eta = 3.2$.

☞ Suppression of the pion spectrum for fixed p_t increases increase of η_N. Dynamical suppression effect for η=3.2 is even larger than the BRHAMS ratio (by a factor of 1.5) due isospin effect.

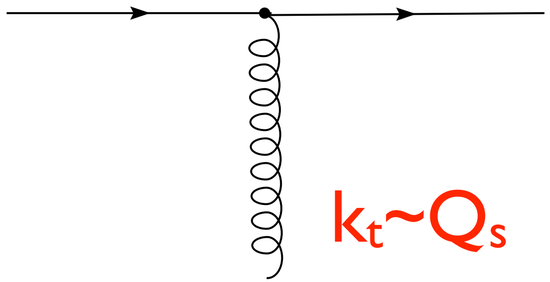


BRAHMS and STAR are consistent when the BRAHMS data are corrected for the isospin effect

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

Color Glass Condensate inspired model

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



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 minimal bias events, no recoil jets in the kinematics expected in pQCD.

⇒ dominant yield from central impact parameters

Energy losses in BDR regime - 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 decreasing with increase of k_t

⇒ 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% (1TeV in gold rest frame)

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 minimal 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 at QM 09

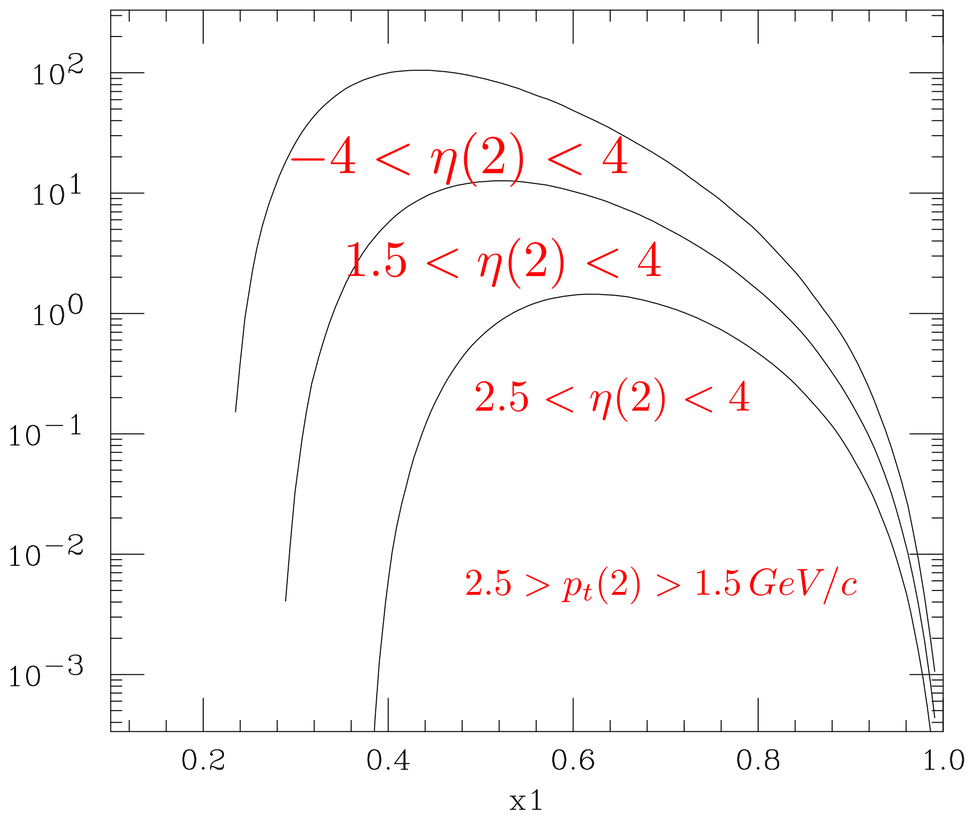
Independent of details - the observed effect is a strong evidence for breaking pQCD approximation in the kinematics sensitive to strong gluon field in nuclei

New forward forward pion data qualitatively consistent with increase of the suppression for this kinematics in 2 →2 scenario as the second jet is also in BDR. Stronger post selection effect - enhanced effective energy losses.

Relevant effects:

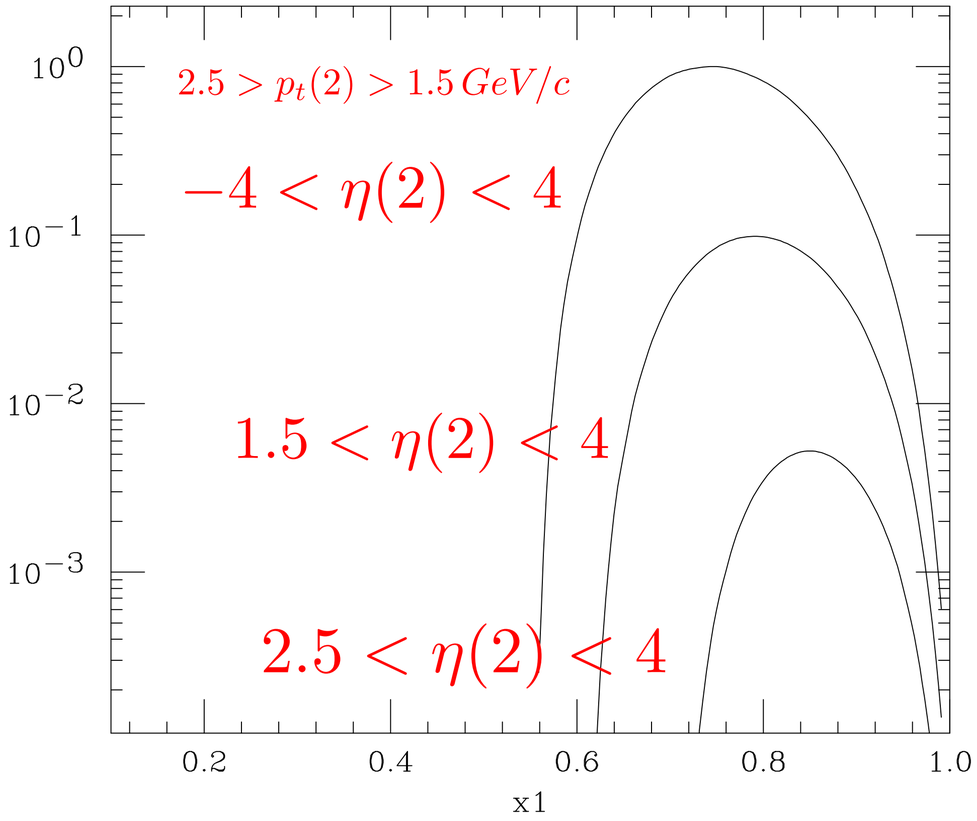
- second jet is mostly from gluons which have larger effective energy losses
- x_2 is in the region where gluon shadowing is a factor of 2 - a factor of two smaller relative contribution of forward- forward vs forward inclusive
- forward- forward events correspond to larger x_1 than forward triggers (next slide) - further enhancement of suppression due to fractional energy losses.

Trigger $2.9 < \eta < 3.2$
$p_t = 2.5\,GeV/c$



AVG1 = 4.828E-01 AVG2 = 5.575E-01 AVG3 = 6.436E-01

Trigger $3.8 < \eta < 4.0$
$p_t = 2.5\,GeV/c$

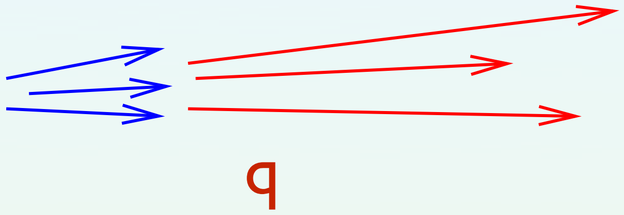


AVG1 = 7.540E-01 AVG2 = 7.965E-01 AVG3 = 8.519E-01

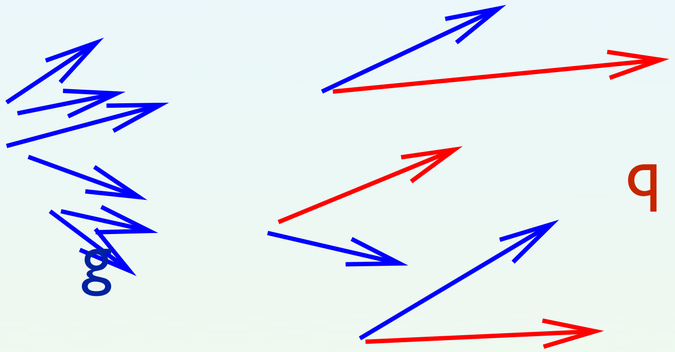
$\langle x_1 \rangle$ for different rapidity cuts

Overall - a distinctive feature of post-selection BDR mechanism is a strong increase of the strength of the suppression with increase of $\langle x_1 \rangle$. Bins in y are too large.

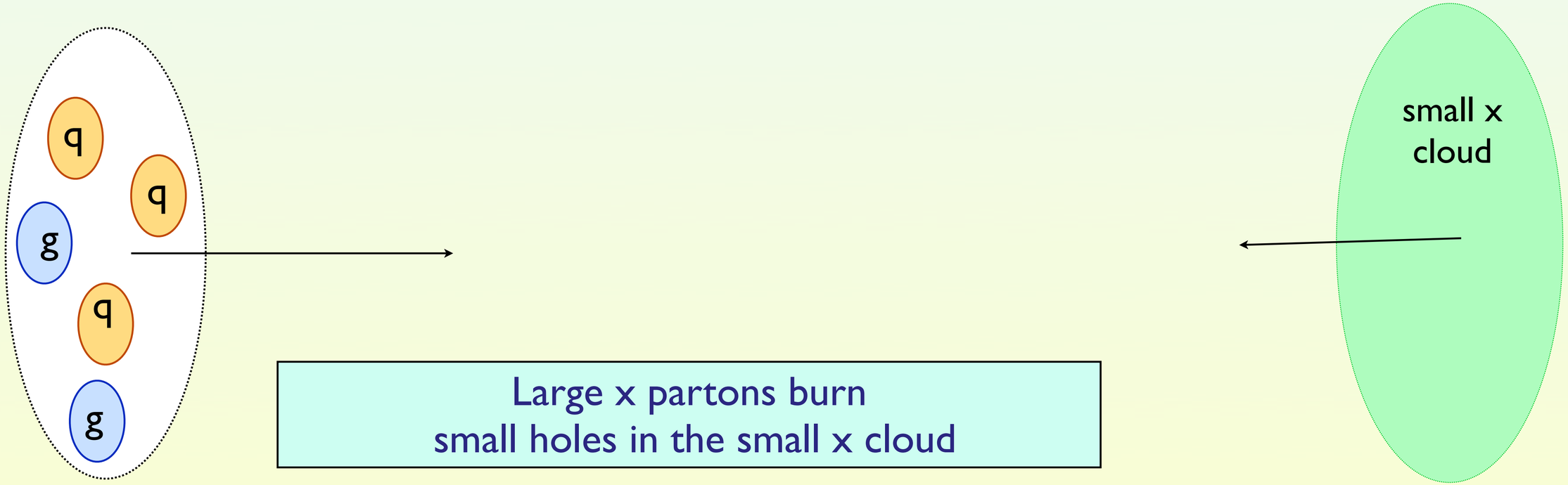
Leading hadron produciton in the central pA(pp) collisions



fast partons in a nucleon before collisions



fast partons in a nucleon after central collisions



Large x partons burn
small holes in the small x cloud

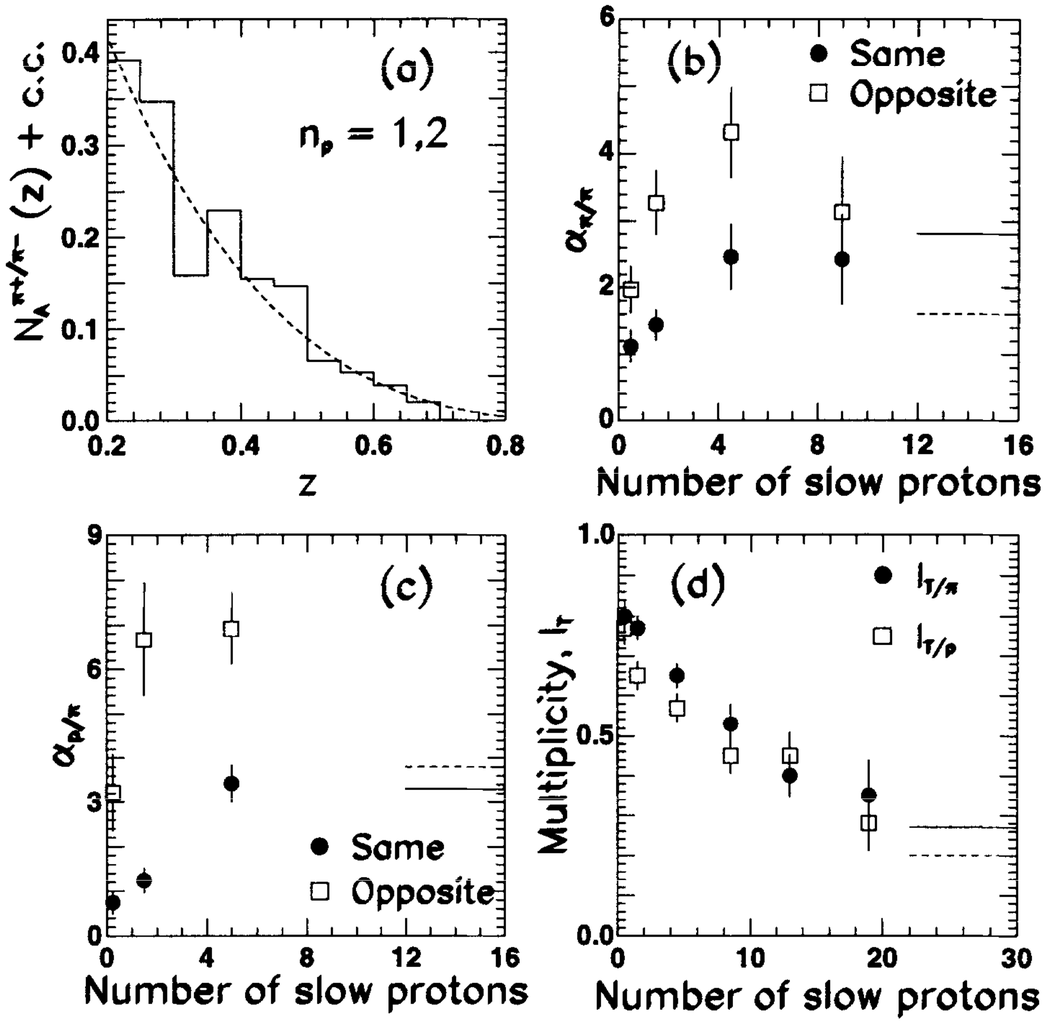
The leading particle spectrum will be strongly suppressed compared to minimal bias events since each parton fragments independently and splits into a couple of partons with comparable energies. The especially pronounced suppression for nucleons: for $z \geq 0.1$ the differential multiplicity of pions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

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

The limiting curve of leading particles from hadron-nucleus collisions at infinite A

A. Berera [a,1], M. Strikman [a], W.S. Toothacker [b], W.D. Walker [c], J.J. Whitmore [a]

Physics Letters B 403 (1997) 1–7



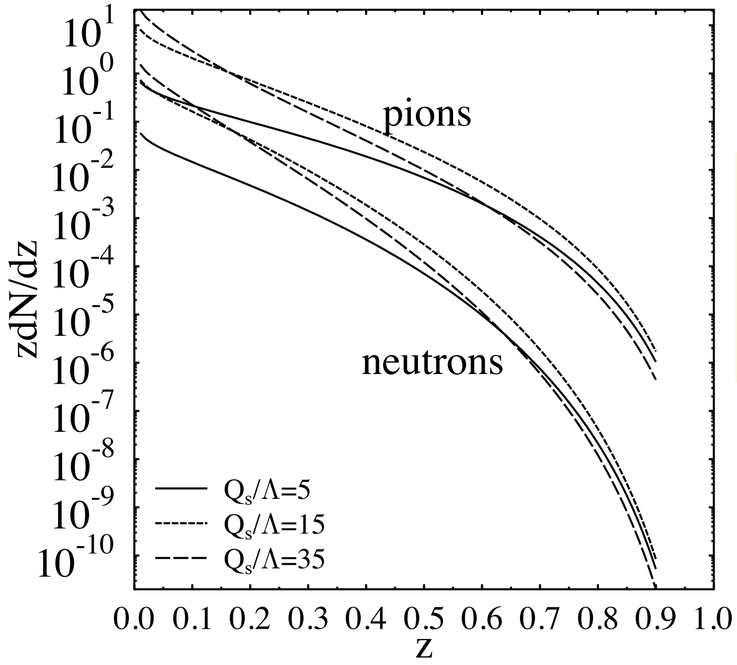
$$\frac{dN}{dz} \propto (1-z)^{\alpha}$$

Fig. 2. Experimental results for h–A collisions at 100 GeV/c: (a) Differential multiplicity for $\pi^- A \to \pi^+$ combined with $\pi^+ A \to \pi^-$ for events with $n_p = 1,2$ (n_p is the number of slow protons). The dashed curve is a fit to the form $(1-z)^{\alpha}$; (b) Leading exponent α for $\pi A \to \pi$, solid circles (open boxes) when the produced π has the same (opposite) charge to that of the beam projectile; the horizontal lines on the right are the theoretical limits from QGSM fragmentation functions to the same (dashed) and opposite (solid) charge leading particle; (c) Leading exponent α for $\pi A \to p(\bar{p})$, the horizontal lines on the right are the theoretical results from EMC fragmentation functions to like (dashed) and opposite (solid) charge leading particle; (d) The integrated multiplicity of hadrons with $z_m > 0.2$ for $\pi^{\pm}$ (solid circles) and proton (open boxes) beam projectiles as a function of n_p. The horizontal lines on the right of the figure are the theoretical asymptotic limits for π (dashed) and proton (solid) projectiles.

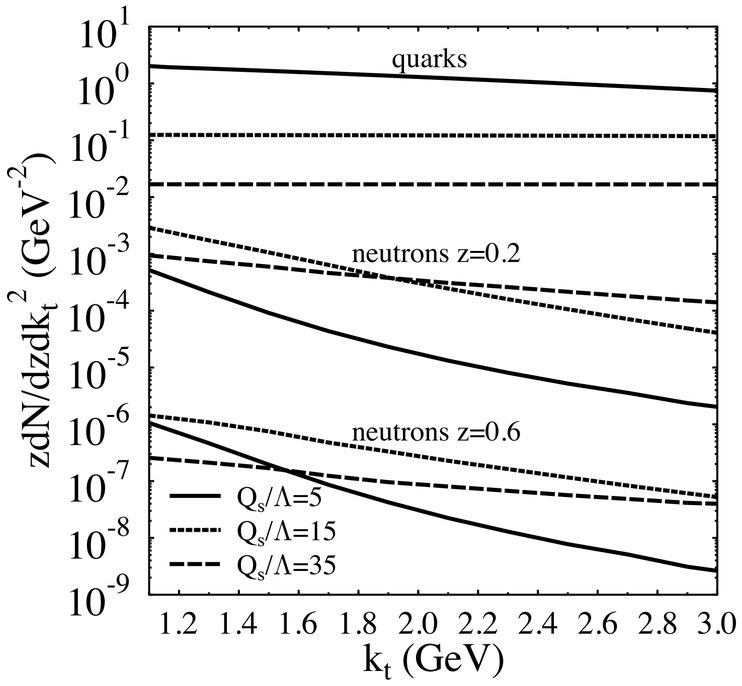
Simple model of p_t broadening - eikonal rescattering model with saturation (Boer, Dumitru 2003)

$$C(k_t) \sim \frac{1}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}} \exp\left(-\frac{\pi k_t^2}{Q_s^2 \log \frac{Q_s}{\Lambda_{QCD}}}\right).$$

Quark gets a transverse momentum of the order Q_s but does not loose significant energy. Use of the convolution formula for fixed transverse momentum of the produced hadron using $C(k_t)$ - Dumitru, Gerland, MS -PRL03



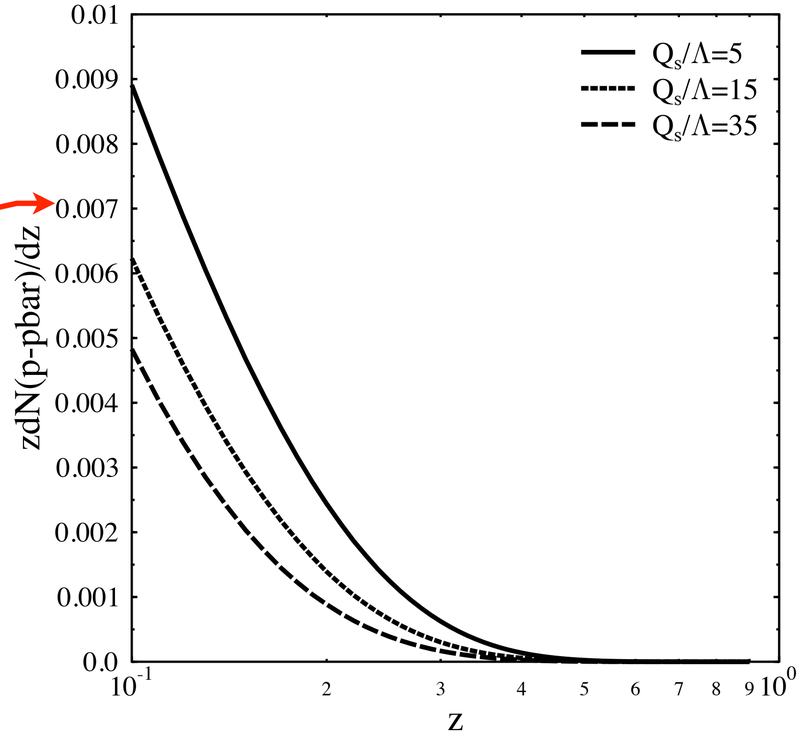
Steep fall with z, strong E_{inc} dependence



Weak p_t dependence, becomes weaker with increase if E_{inc}

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

Very few forward baryons!!!



Longitudinal distribution of net protons

Warning: Parton carrying a fraction y of the quark with given carries y p_t part of the quark's transverse momentum.

Condition for independent fragmentation y p_t > $1/r_N$ ~.3 - 0.5 GeV/c

➠ For RHIC independent fragmentation is probably safe for z > 0.2

Experimental situation is not clear - no data in the very forward region. Best hope - neutrons from ZDC

Conclusions

- QCD factorization theorems and use of unitarity allows to calculated nuclear pdfs with a small theoretical uncertainty.

- Post-selection leads to fractional energy losses in the black disk regime

- Consistent evidence from analysis of HERA data and leading pion production in d- Au presence of the BDR up to transverse momenta 1 -- 1.5 GeV/c at $x \sim 10^{-4}$

- Critical test - strong suppression of the leading baryon and meson spectra at $x_F > 0.3$ in d-Au