Black disc regime for hard processes in QCD and accompanying phenomena.

Leonid Frankfurt

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Introduction.

QCD as the theory of strong interactions has been established by comparing experimental data with the model independent predictions of QCD.

1. Cross sections of hard processes are well understood within the framework of QCD factorization theorems =QCD evolution equations .

2. The transparency of nuclei for the propagation of spatially small wave package of quarks and gluons observed at FNAL in the hard exclusive processes:
$\pi+A \rightarrow 2jets+A$; $\gamma+A \rightarrow \psi+A$ and at TJNF in the large t process:
$\gamma+A \rightarrow \pi+A$ demonstrated direct role of color in the wave functions of mesons .
This phenomenon is observable as the consequence of special QCD factorization theorem. (L.Frankfurt, J.Miller, M.Strikman, G.Baum, B.Blattel, H.Heiselberg 1991-1993) .

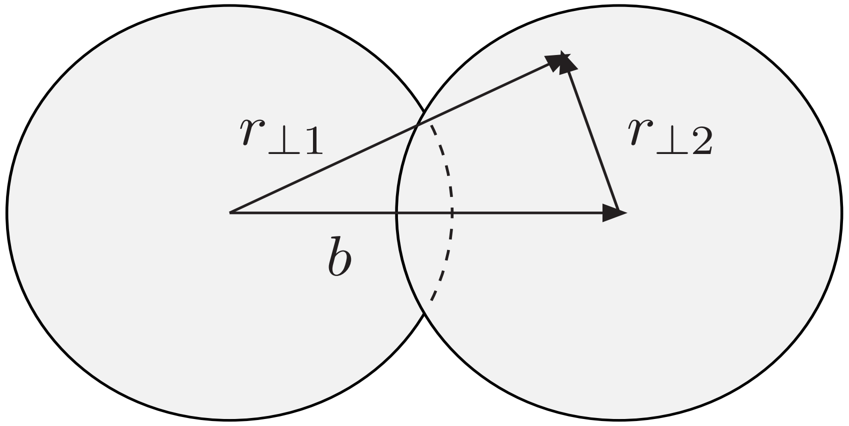
Distribution of color in a nucleus

No color flow at large internucleon distances. The average distance in the transverse plane between the centers of two nucleons is related to the slope of t dependence of the cross section of hard diffractive process , B_{diff}

$$\left\langle (r_{\perp 1} - r_{\perp 2})^2 \right\rangle = 4\, B_{\rm diff}\,. \sim 1\,\text{fm}$$

local reshuffling of color in the cylinder of radius $\sim \sqrt{2\, B_{\rm diff}} \approx 0.7$ fm

Compare to convolution of GPDs - given by the slope of DVCS. Experimentally $B_{DVCS} \approx B_{diff}$



Caution. At $Q^2 \geq -t >> Q^2_0$ Q^2 evolution strongly depends on t
B.Blok,L.Frankfurt and M.Strikman

Spatial distribution of color within the proton wf has been measured at HERA in the dependence of hard semiexclusive process on momentum transfer t in particular in $\gamma+p \to J/\psi+p$

$B=4 \pm 0.5\ \mathrm{GeV}^{-2}$

Information from GPDs

- fit to 2-gluon form factor from diffractive J/ψ production
  Frankfurt, Strikman, Weiss (FSW(2004)):

$$F_g(x,t,\mu) = \frac{1}{\left(1 - \underbrace{\frac{t}{m_g^2(x,\mu)}}\right)^2}$$

mass scale varies to take into account evolution/small-x

- In impact parameter space:

$$\mathcal{F}_g(x,\rho,\mu) = \frac{m_g^3(x,\mu)\rho}{4\pi} K_1(m_g(x,\mu)\rho)$$

The total cross section of DIS in QCD -puzzle.

E.Fermi proved within the nonrelativistic quantum mechanics applicability of impulse approximation for the total cross section of neutron scattering off molecule H_2 since momentum transfer to molecule significantly exceeds momentum of electron within molecule .

To generalize idea of E.Fermi to quantum field theory , to suppress vacuum fluctuations, to explain Bj scaling claimed by SLAC J.Bjorken and R.Feynman introduced the concept of light-cone wave function of a hadron (nucleus) and parton distributions within a hadron(nucleus). On the contrary Schrodinger wave functions of a hadron(nucleus) is ill defined for the bound state consisting from the relativistic constituents .

Parton model fundamentally contradicts to basics of QCD since QCD as a quantum field theory contains ultraviolet divergencies. Thus momentum transfer Q will be always smaller than momenta of constituents within bound state (a hadron,nucleus). Bj scaling means death of preQCD field theories.

Asymptotic freedom: D.Politzer, D.Gross, F.Wilczek

$$\alpha(Q^2)=c/\log(Q^2/\mathrm{Lambda}^2)$$

explained puzzle. It allowed to evaluate the contribution of large momenta of constituents which lead to the violation of Bj scaling and to demonstrate that effective parameter characterizing pQCD series is small :

$$\xi=N_c/(2\pi)^2 \int d^2k\, \alpha(k^2)/k^2$$

QCD evolution equation well describe numerous data on structure functions of DIS and amplitudes of hard diffractive processes. It is one of basic tools of high energy physics now.

At sufficiently small x effective parameter of pQCD series becomes large : $\eta=\xi \mathrm{Log}(x_0/x)$

Summing leading terms over η (D.Gross, F. Wilczek, Y. Dokshitzer) leads to structure functions of hadrons rapidly increasing with energy:

$$F_2(x,Q^2) \sim \exp \sqrt{(\xi \mathrm{Log}(x_0/x))}$$

As the consequence of energy -momentum conservation this formulae should be applicable within pQCD in a wide kinematical region of small x including x achieved at HERA. To some extent this is implemented in the resummation models.

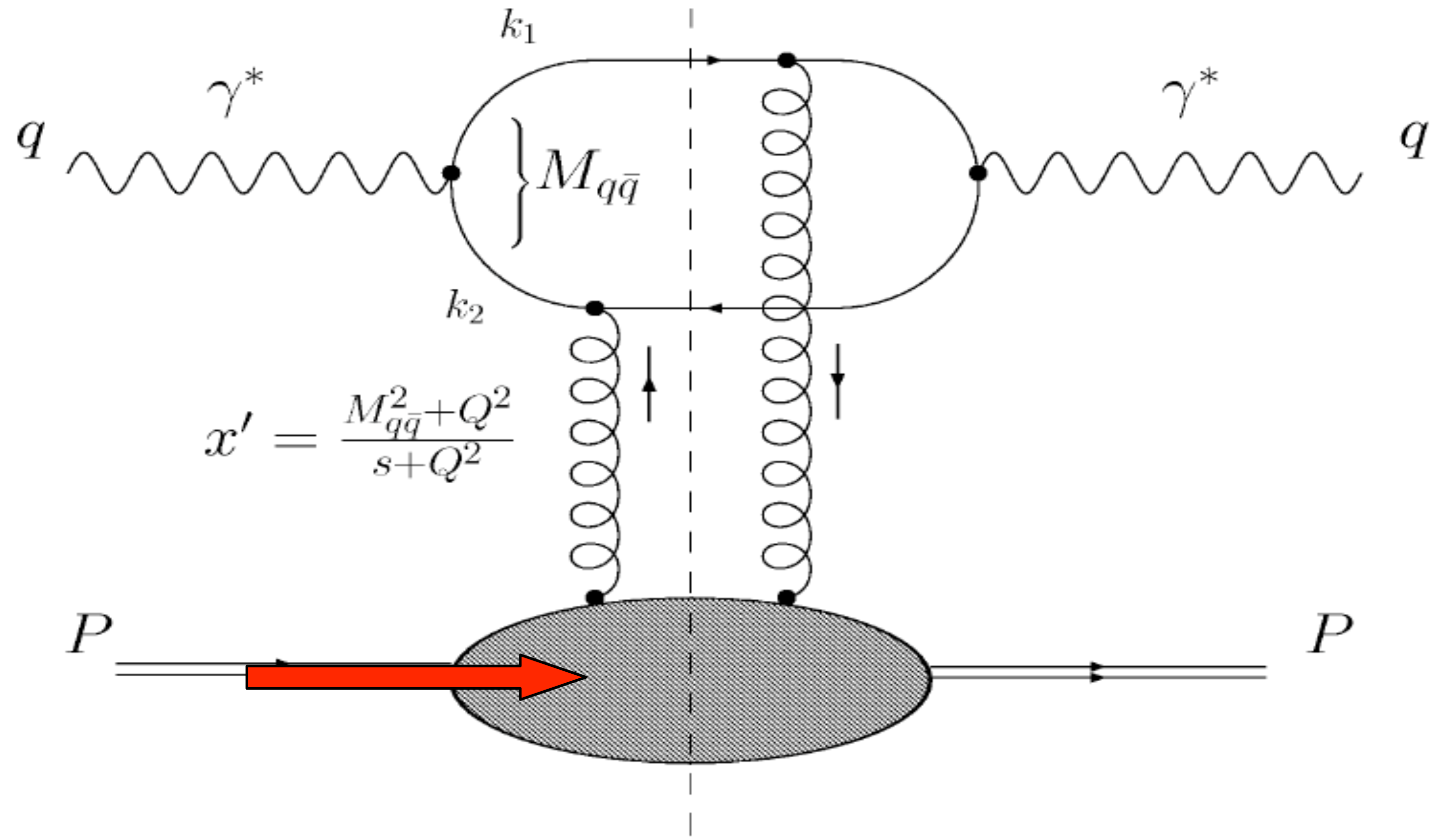
At sufficiently small x parameter η is not small anymore so the justification of Bj scaling based on asymptotic freedom becomes insufficient and the concept of parton distributions is not defined in this kinematics. New approaches are needed.

The aim of this talk is to visualize properties of black disc (BD) regime where pQCD fails but legitimate calculations are possible. Basic feature of BD regime is complete absorption of spatially small color neutral wave package by hadron (nucleus) medium which is analogue of Fraunhofer diffraction of light off black screen . Thus with increase of energies transparency of hadrons, nuclei for the propagation of spatially small color neutral wave package would disappear. Challenging questions: are the structure functions of hadrons, nuclei will rapidly increase with energy or this increase will slow down , what are the properties of new QCD regime and how to observe new QCD phenomena.

I will briefly outline also experimental indications for the onset of BD regime and explain evident advantages of nuclear target for the investigation of this new QCD regime.

Dipole Picture:

next 9 slides prepared by Ted Rogers



\+ others.

$$\sigma_{L/T}(x, Q^2) = \int_0 dz \int d^2\mathbf{d}\, \underbrace{|\psi_{L/T}(z,d)|^2}_{\text{Photon wavefunction}}\, \underbrace{\hat{\sigma}^{q\bar{q}}(d, x')}_{\text{X-section for q-qbar configuration.}}$$

$(\bar{Q}^2 = \lambda / d_{q\bar{q}}^2 \sim Q^2)$

$x' \approx x$

DGLAP limit:

$$\hat{\sigma}^{q\bar{q}}(d, x') \approx \hat{\sigma}^{q\bar{q}}_{pQCD}(d, x') = \frac{\pi^2}{3} d^2 \alpha_s(\bar{Q}^2) x' g_N(x', \bar{Q}^2)$$

CONSERVATION OF PROBABILITY IS EVIDENT AT FIXED IMPACT PARAMETER

- $$\Gamma(s,b) = \frac{1}{2is(2\pi)^2}\int d^2\mathbf{q}\, e^{i\mathbf{q}\cdot\mathbf{b}} F_{hN}(s,t), \qquad t \approx -\mathbf{q}^2$$

Profile Function

amplitude
for configuration h of size d.

- s-channel unitarity:

$$\begin{aligned}
\sigma_{tot} &= 2\int d^2\mathbf{b}\, \Re\Gamma(s,b), \\
\sigma_{el} &= \int d^2\mathbf{b}\, \left|\Gamma(s,b)\right|^2, \\
\sigma_{inel} &= \int d^2\mathbf{b}\, \underbrace{\left(2\Re\Gamma(s,b) - \left|\Gamma(s,b)\right|^2\right)}_{\Gamma^{inel}(s,b)}.
\end{aligned}$$

$\Gamma = 1/2 \rightarrow \Gamma^{inel} = 3/4$ nearly black

Information from DIS: GPDs

- The generalized gluon PDF and deep inelastic J/ψ production.

$$x f_g(x,t,\mu) = x f_g(x,\mu)\, F_g(x,t,\mu)$$

$$F_g(x,t=0,\mu) = 1$$

- Impact parameter space gluon distribution function.

$$\mathcal{F}_g(x,\rho,\mu) = \int d^2\mathbf{\Delta}\, \underbrace{F_g(x,t,\mu)}_{\text{2 gluon form factor}}\, e^{-i\mathbf{\Delta}\cdot\rho}, \qquad t = -\Delta^2$$

Describes transverse distribution of hard partons

"Black Disk Limit":

- At high energies amplitude is predominantly imaginary .

$$\Gamma(s,b) \leq 1$$

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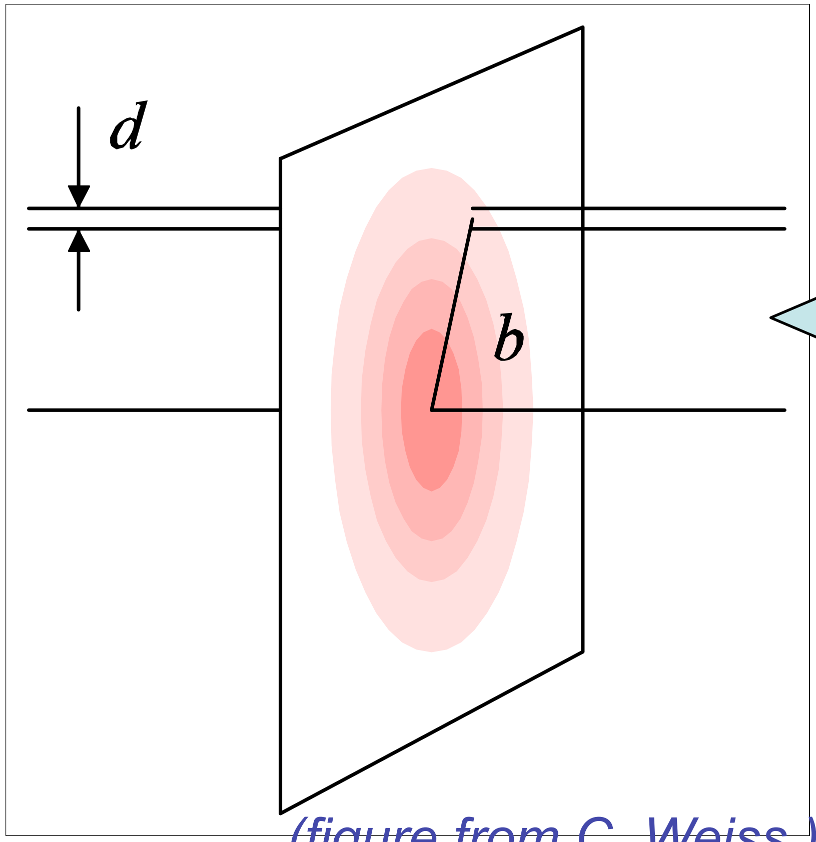
$$\Gamma(b < b_{max}, d) = 1$$

Black Disk Limit =complete absorption

$$\sigma_{el} = \sigma_{inel}.$$

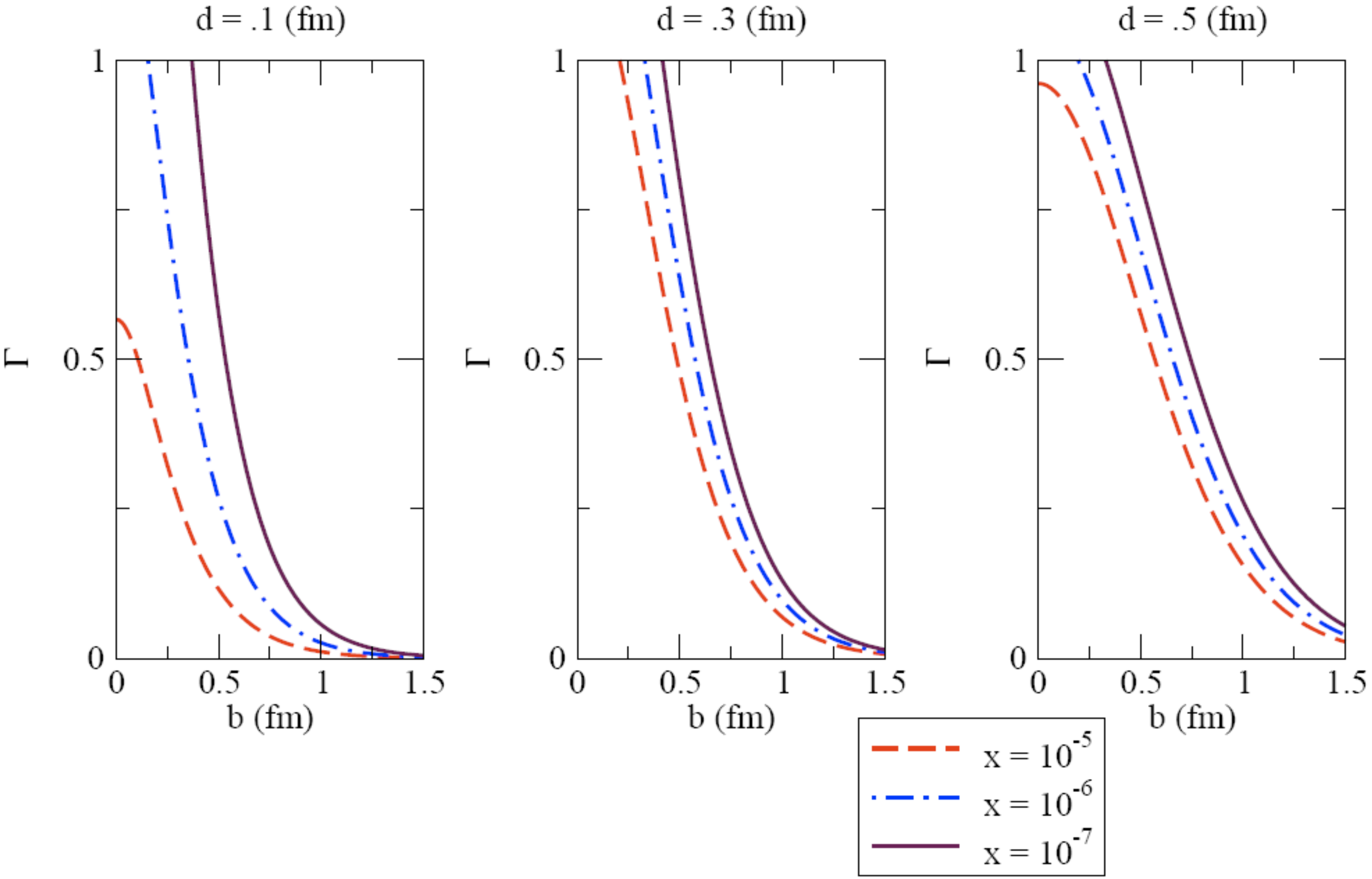


(figure from C. Weiss.)

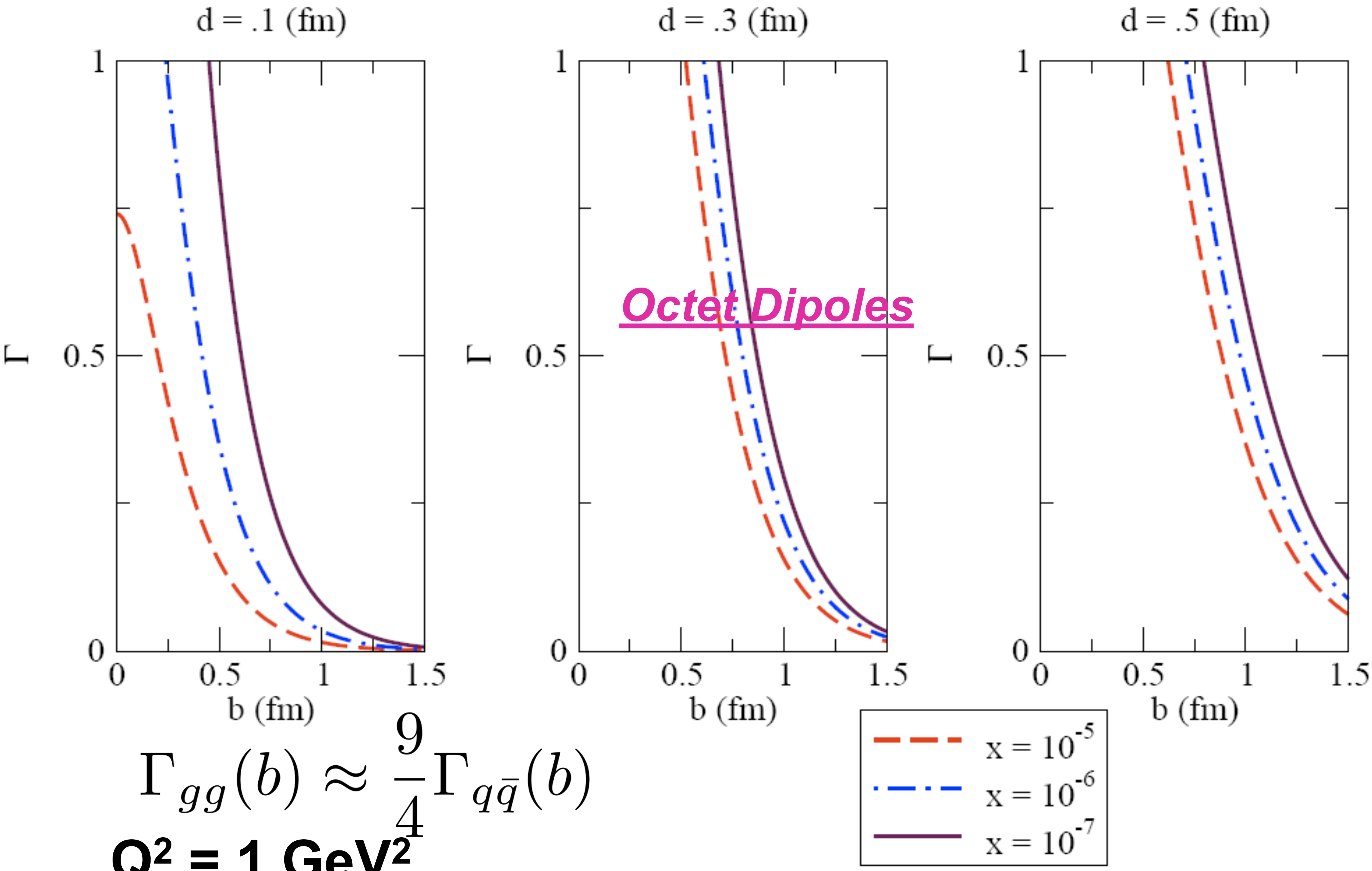
Central black region grows with decrease of x.

Cause increase with energy of cross sections of hard processes forever.

LHeC Kinematics

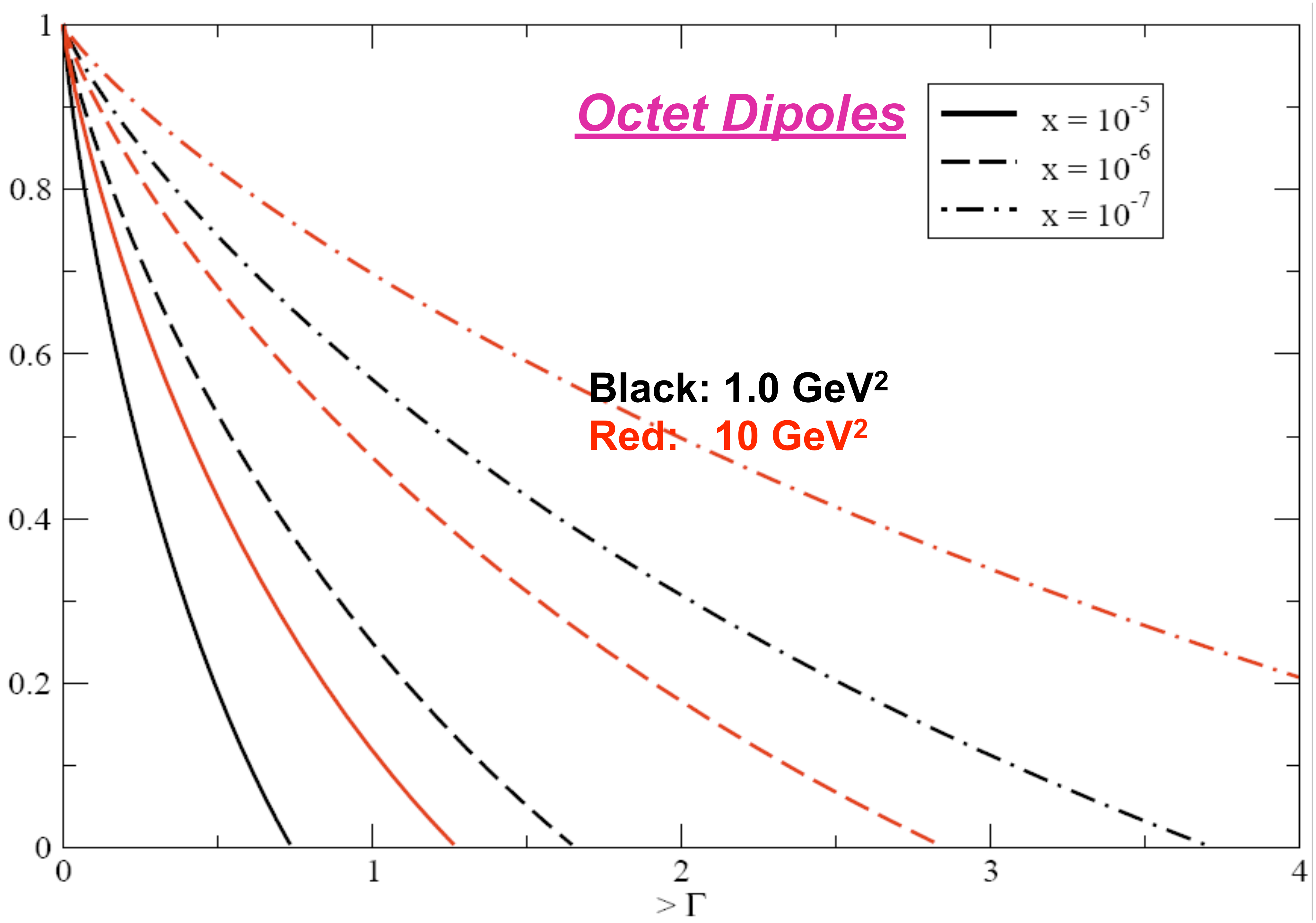


$Q^2 = 10\ GeV^2$



$$\Gamma_{gg}(b) \approx \frac{9}{4}\Gamma_{q\bar{q}}(b)$$

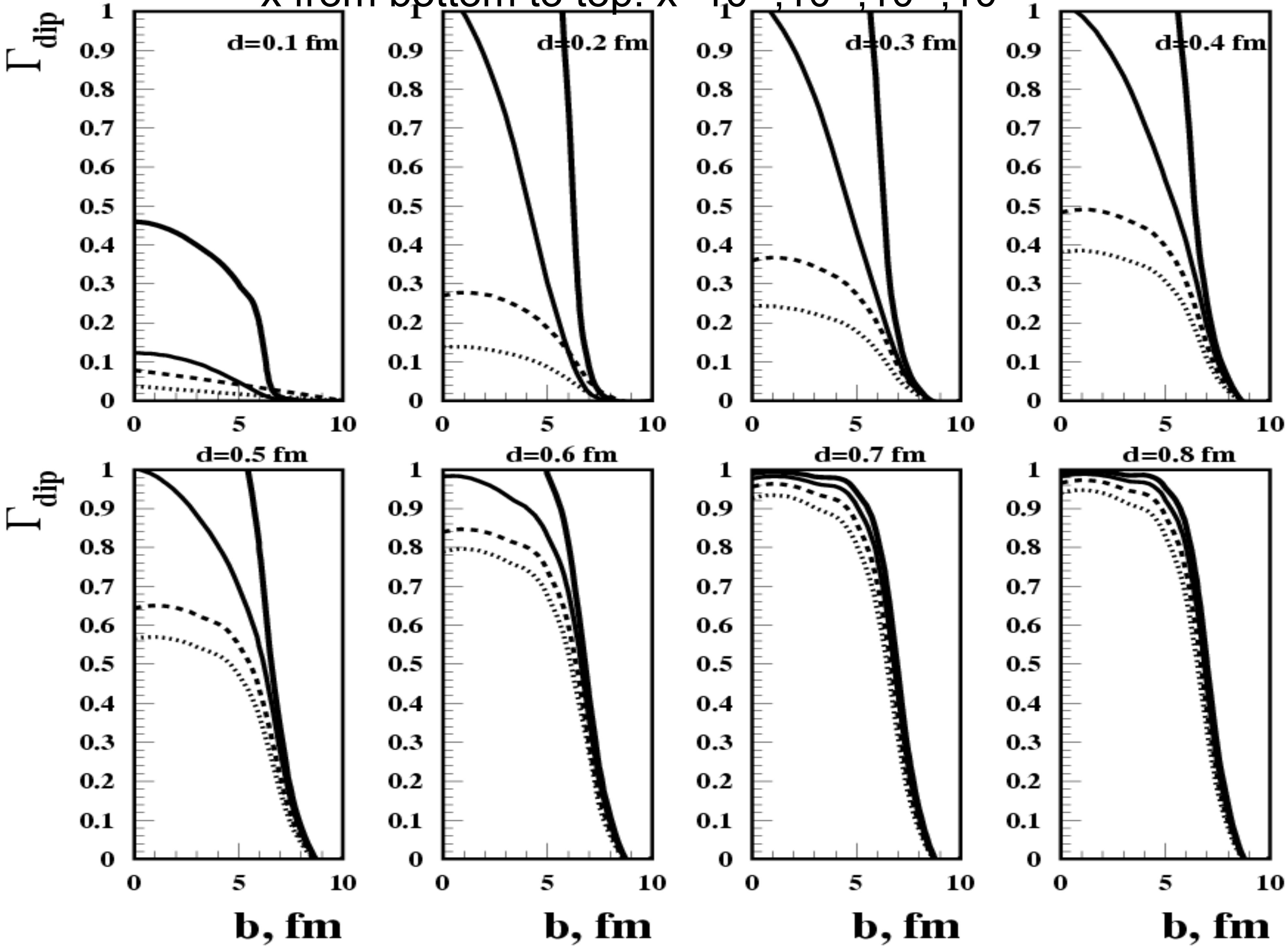
$Q^2 = 1$ GeV^2



Octet Dipoles
x = 10^-5
x = 10^-6
x = 10^-7
Black: 1.0 GeV²
Red: 10 GeV²
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
> Γ

^{208}Pb

x from bottom to top: x=10^{-2},10^{-3},10^{-4},10^{-5}



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- Effects of black disk are enhanced in eA collisions. Important advantage of nuclear target is almost uniform nuclear matter in impact parameter space-so BDR is achieved in a large region of space.

Signals of Proximity to black disk limit.

* **Total cross sections** Frankfurt, Guzey, McDermott, MS (FGMS-01)

$$F_{2A}(x,Q^2) = \frac{Q^2}{12\pi^3}\left(\sum_f e_f^2\right)(2\pi R_A^2)\,\ln\frac{x_0(Q^2)}{x},$$

(update to QCD of Gribov BD of 68)

where $x_0(Q^2)$ slowly decreases with increasing Q^2

The same prediction for DVCS amplitude at t=0.

Proton $\Gamma^{dp}(s,b) \propto \exp(-\mu b)$ for small dipole - p scattering

$$F_{2p}(x,Q^2) = \frac{Q^2}{12\pi^3}\left(\sum_f e_f^2\right)\sigma(dipole-p)\ln\frac{s}{s_0} \propto$$

$$\propto R_p^2 Q^2 \ln(1/x)(1+c(x)\ln^2(1/x))$$

✷ *Black-disk limit in hard diffractive scattering from heavy nuclei*

Gribov: non-diagonal transitions between diffractive eigenstates are forbidden in BDR

⇒ model independent predictions for diffraction in BDL FGMS
where $\sigma_{diff}=\sigma_{tot}/2$

Examples:

✷ $$\frac{dF_T^{\gamma_T^*\to X}(x,Q^2,M_X^2)}{dM_X^2 d\Omega_X} = \frac{\pi R_A^2}{12\pi^3}\frac{Q^2M_X^2}{(M_X^2+Q^2)^2}\frac{d\sigma(e^+e^-\to X)/d\Omega_X}{\sigma(e^+e^-\to\mu^+\mu^-)}.$$

``jetty" final states - mostly diffraction to quark - antiquark and quark-antiquark - gluon jet states. Dominant final state - two jets with distribution over $\cos\theta$ like in e^+e^- annihilation(three-jets events are also like in e^+e^- annihilation. A smooth transition from DGLAP - graduate increase of high pt component with decrease of x at fixed Q.

✷ *Vector meson exclusive and semiexclusive production*

- a fine probe of onset of BDR for interaction of small quark dipoles and dynamics of dipole media interaction. In BDR

$$\frac{d\sigma^{\gamma_T^*+A\to V+A}}{dt} = \frac{M_V^2}{Q^2}\frac{d\sigma^{\gamma_L^*+A\to V+A}}{dt} = \frac{(2\pi R_A^2)^2}{16\pi}\frac{3\Gamma_V M_V^3}{\alpha(M_V^2+Q^2)^2}\frac{4|J_1(\sqrt{-t}\,R_A)|^2}{-tR_A^2}$$

Gross violation of Collins and F.S. factorization theorem
- enhancement by a factor Q^4

Expectation: Transition from the CT regime without LT nuclear shadowing at x> 0.01 *(observed at FNAL)*:

$$\sigma_{elastic}(\gamma A \to J/\psi + A) \propto A^{4/3}, \sigma_{quasielastic}(\gamma A \to J/\psi + A') \propto A$$

$\Downarrow$ *LT shadowing*

$\Downarrow$ *BDR*

$$\sigma_{elastic}(\gamma A \to J/\psi + A) \propto A^{2/3}, \sigma_{quasielastic}(\gamma A \to J/\psi + A') \propto A^{1/3}$$

Change of A dependence by a factor ~$A^{2/3}$!!!

New QCD domain

Allows to determine σ_{tot}(“small dipole” - nucleus)

✷ *Inclusive production of leading hadrons*

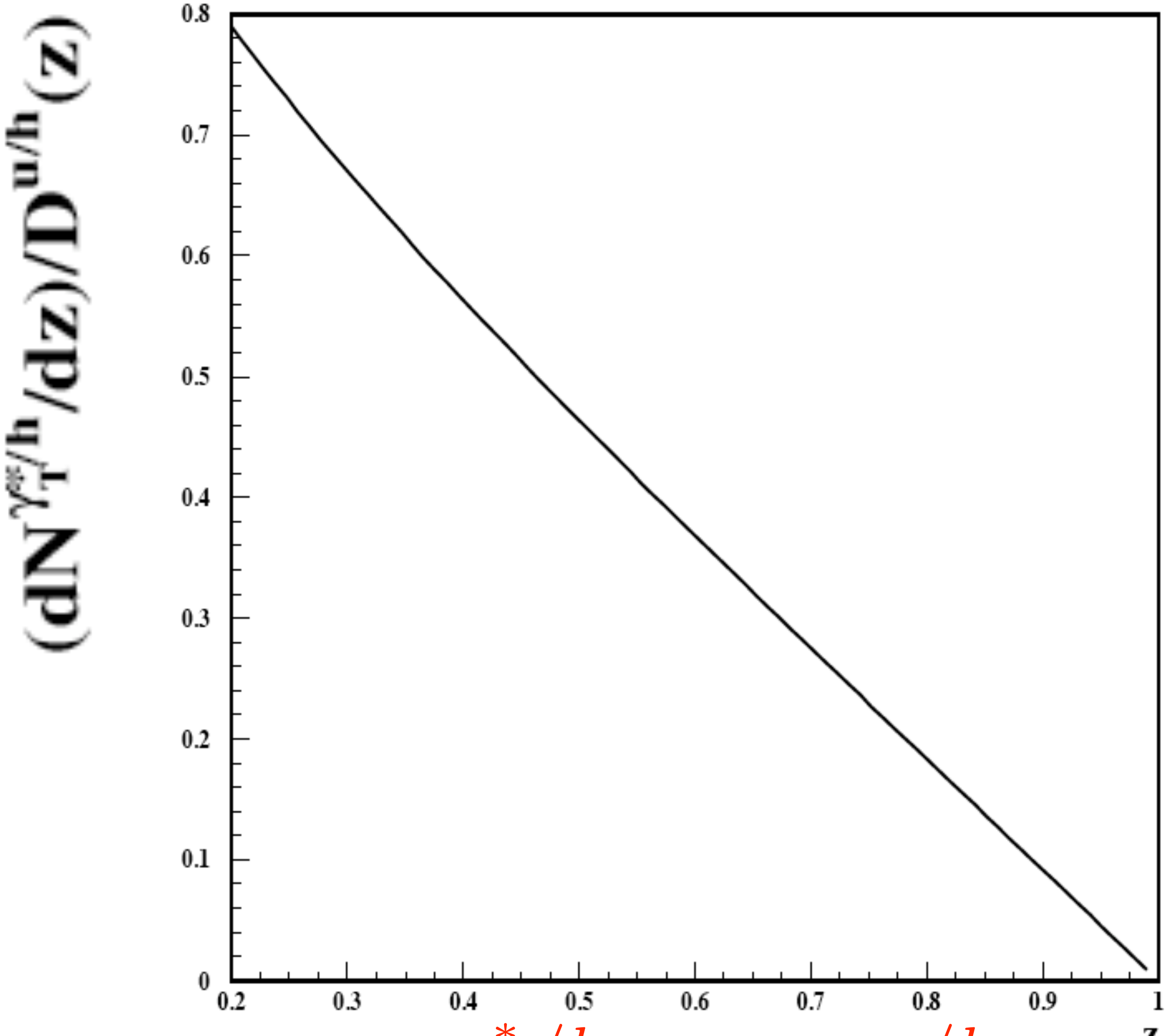
The mechanism of fragmentation in BDR: quark and antiquark with $p_t \propto Q$ and known z-distribution peaked at ~1/2 fragment independently since in this case overlap between showers is small (as long as LC fractions are large).

Hence to a first approximation

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

In BDR the leading particle spectrum in BBL is strongly suppressed. The inclusion of the $q\bar{q}g$ states in the virtual photon wave function (due to the QCD evolution) will further amplify the effect (post-selection). Related to the effect of fractional energy losses in BDR (FS03- 08) (consistent with BRAMHS, STAR data)

Perfect experimental observable. Study leading spectrum of hadrons as a function of neutron deposition in the forward calorimeter. DGLAP - no correlation. BDR - strong correlation. Also for the central impact parameters BDR onset is at substantially larger x. Cannot trigger on centrality in diffraction.



$$dN^{\gamma_T^*/h}/dz)/D^{u/h}(z,Q^2)$$

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

Hard processes with gaps - just one example: *Propagation of ultrafast small dipoles through nuclear media*

Study of energy dependence of inelastic dipole - nucleus interactions in large

$t=-(p_\gamma-p_V)^2$ process $(\gamma,\gamma^*)A$ ->Vector Meson + rapidity gap +X. For now analyzed real photon case which will be studied in the early HI run at LHC

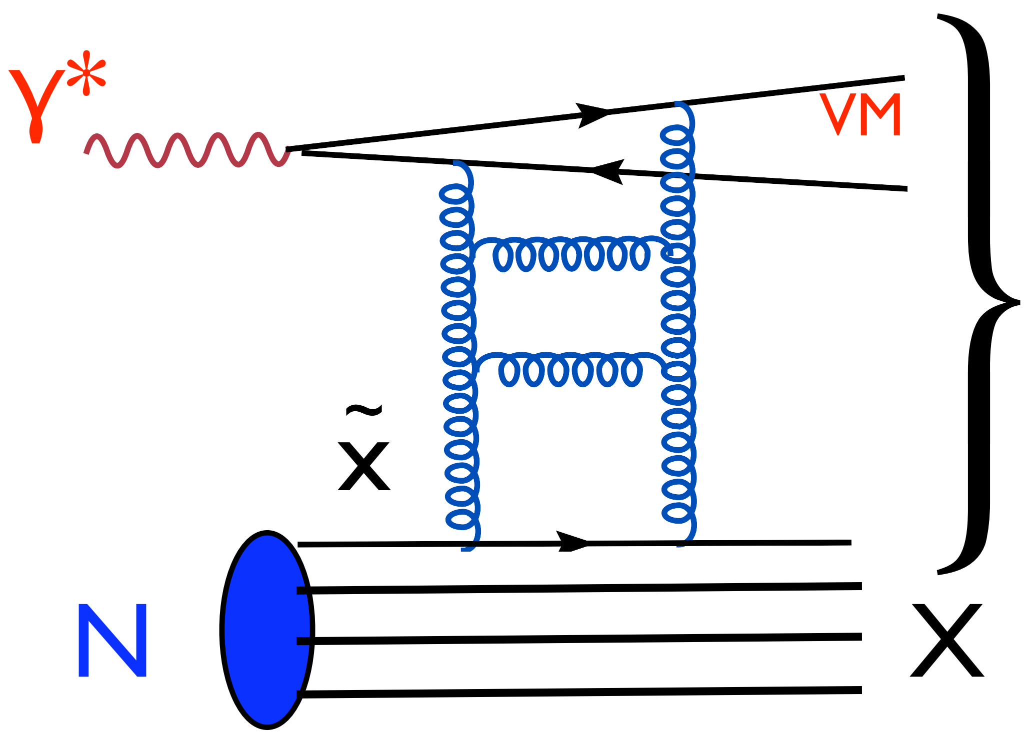
Fast track to observing the black disk regime of interaction with strong gluon fields   F& L & Zhalov - PRL June 09

elementary reaction scattering of projectile off a parton of the target at large t belongs to a class of reactions with hard white exchange in t-channel

FS 89, FS95,

Mueller & Tung 91

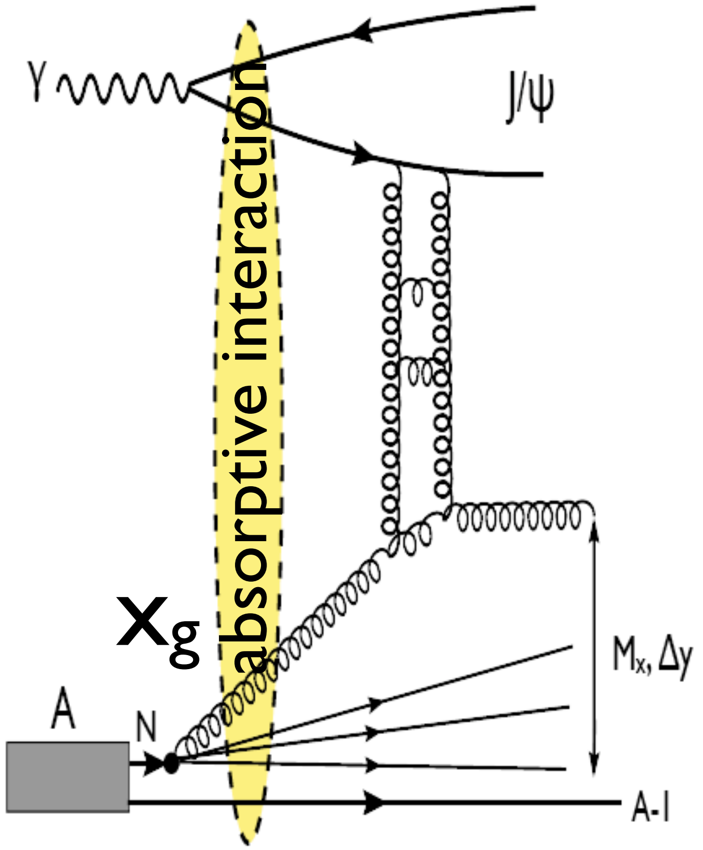
Forshaw & Ryskin 95



$$s' = \tilde{x} W^2_{\gamma p},$$

$$\tilde{x} = \frac{-t}{(M_X^2 - t)}$$

best way to measure of the strength of inelastic interactions of small dipole in the processes initiated by elastic small dipole - parton scattering. In HI via UPC feasible for at $[s']^{1/2}$=20 GeV - 100 GeV at the LHC



$\gamma + A \to J/\psi + gap + X$

$$s' = \tilde{x} W^2_{\gamma N}$$

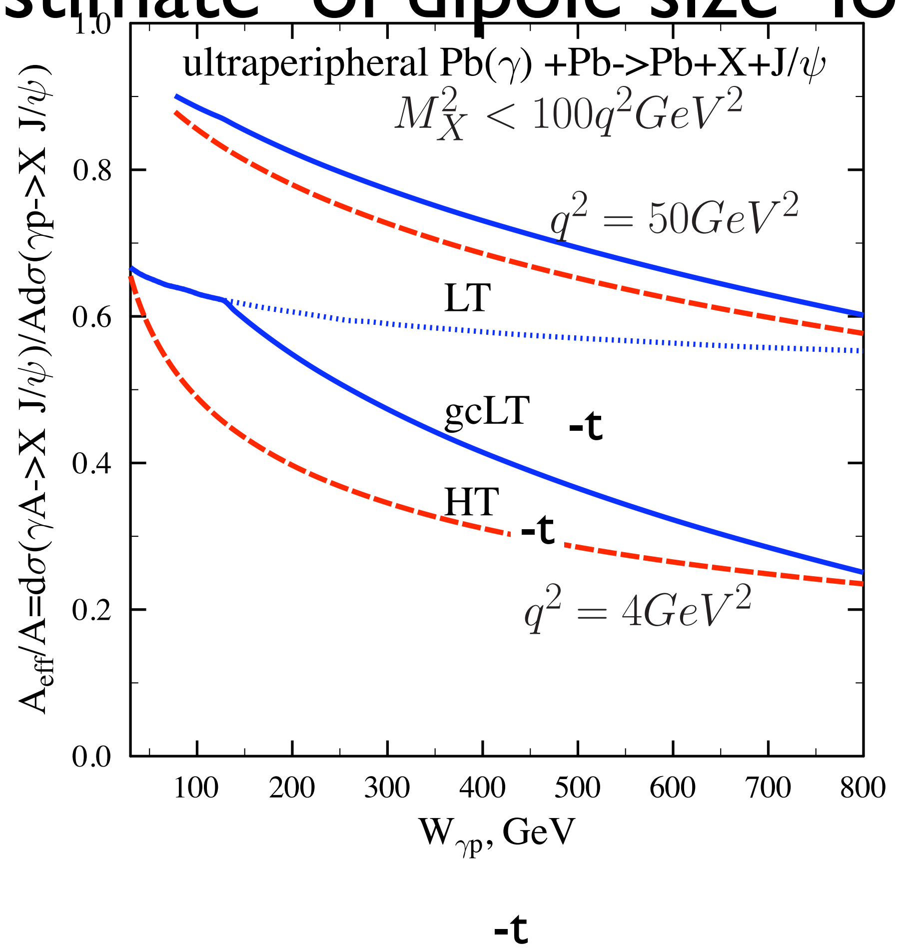
Complementary to coherent J/ψ.

- Tracks dipole though ~ 10 fm of nuclear matter
- Allows to measure dipole size as a function of q^2
- Can reach maximal W of LHeC

Estimate of dipole size for $q^2=0$

$$d^2(-t)/d^2(0) \approx (1 - t/4m_c^2)^{-1}$$

$$(d_0 = .25\text{fm}, m_c = 1.5\, GeV)$$

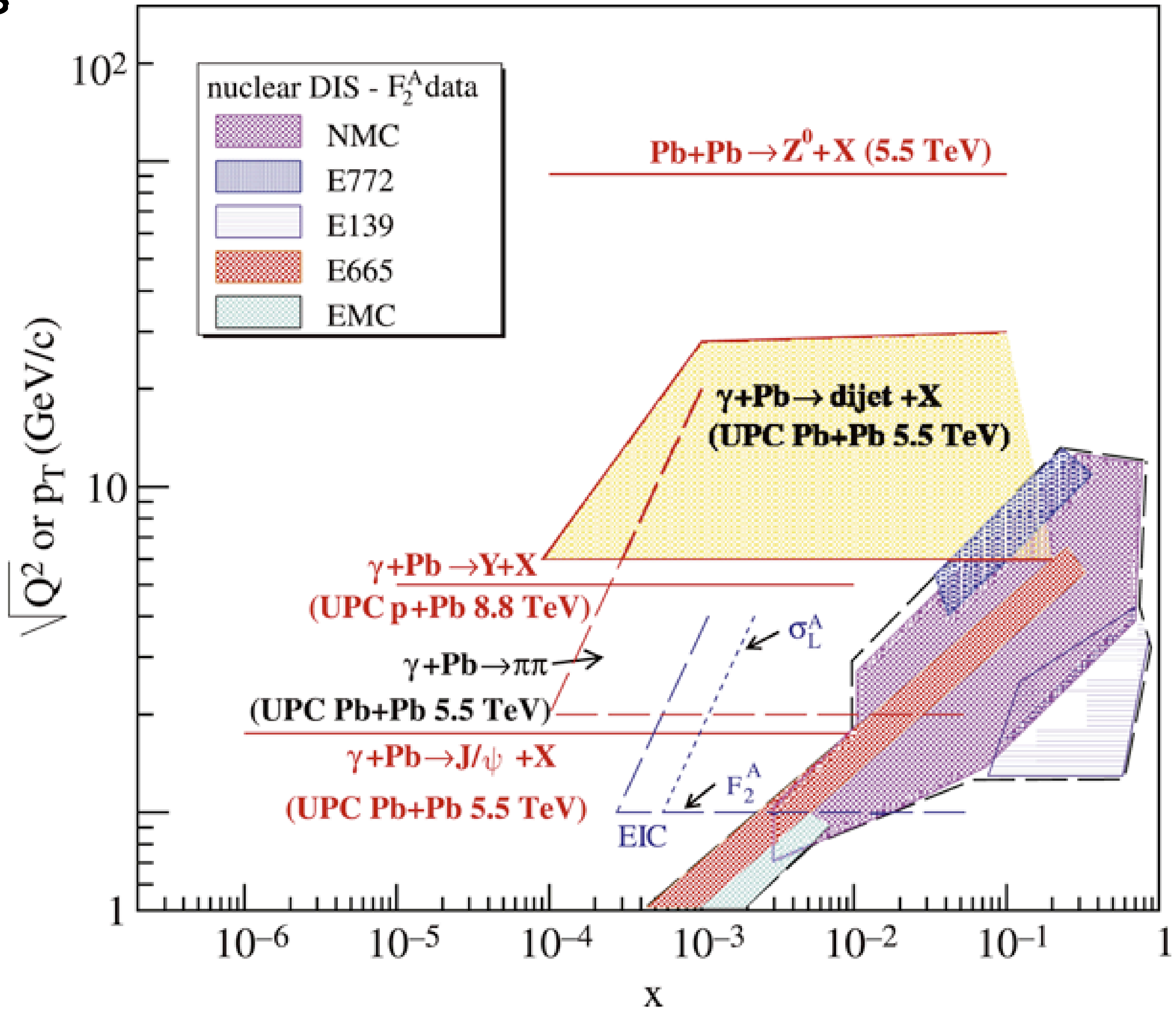


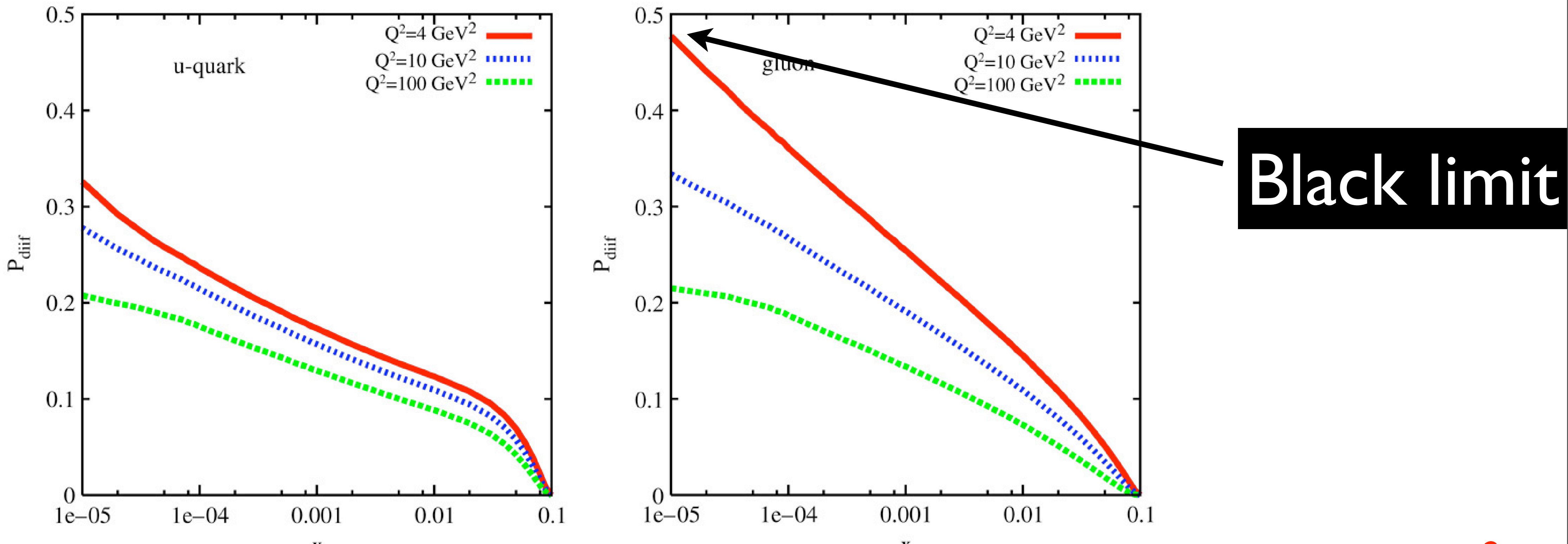
Significant absorption is expected in the leading twist and higher twist models of dipole interaction

CONCLUSIONS

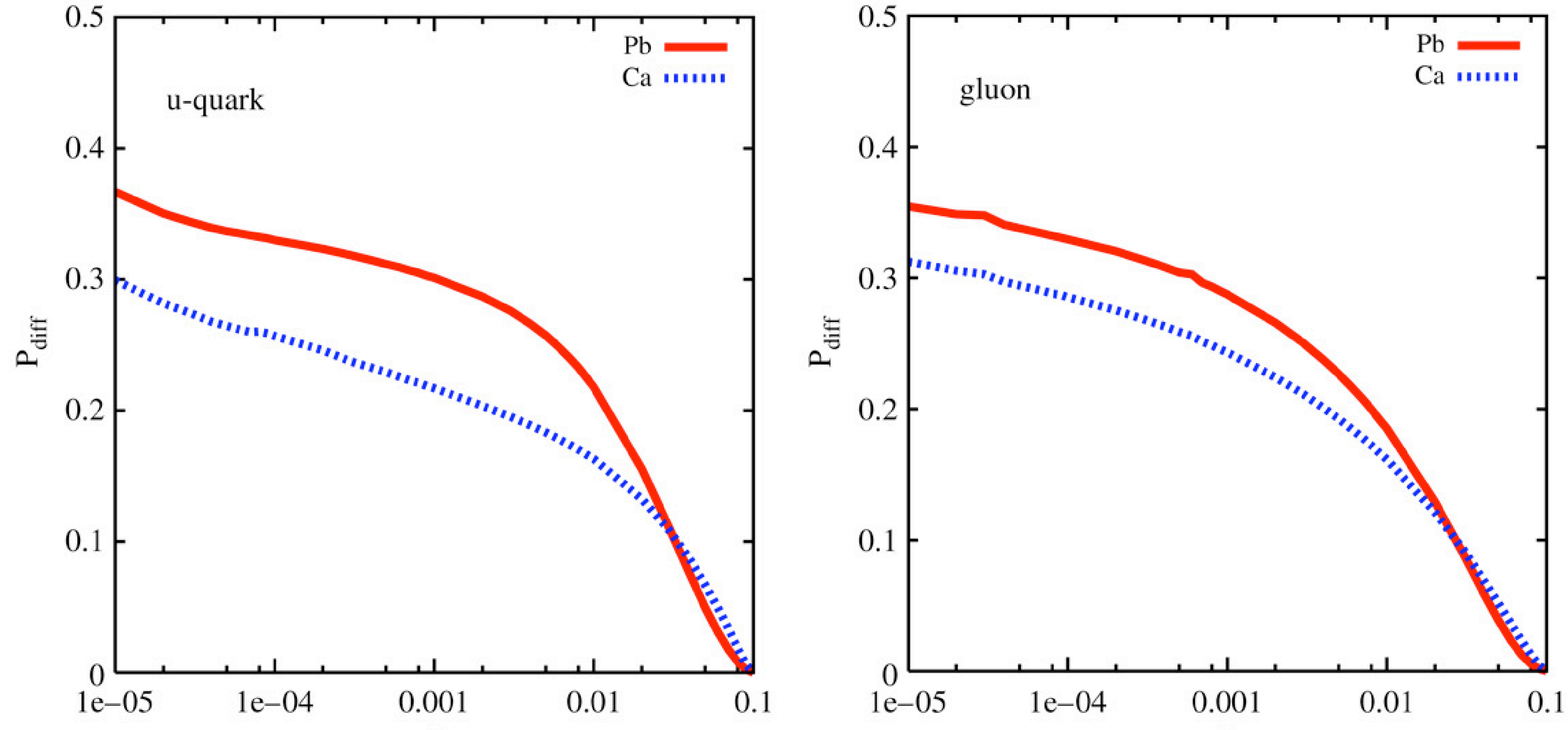
LHeC covers kinematics where large nuclear effects should be present both in the LT region, and in the regimes of transition to BDR and BDR.

First peek into this region will be due to UPC at LHC



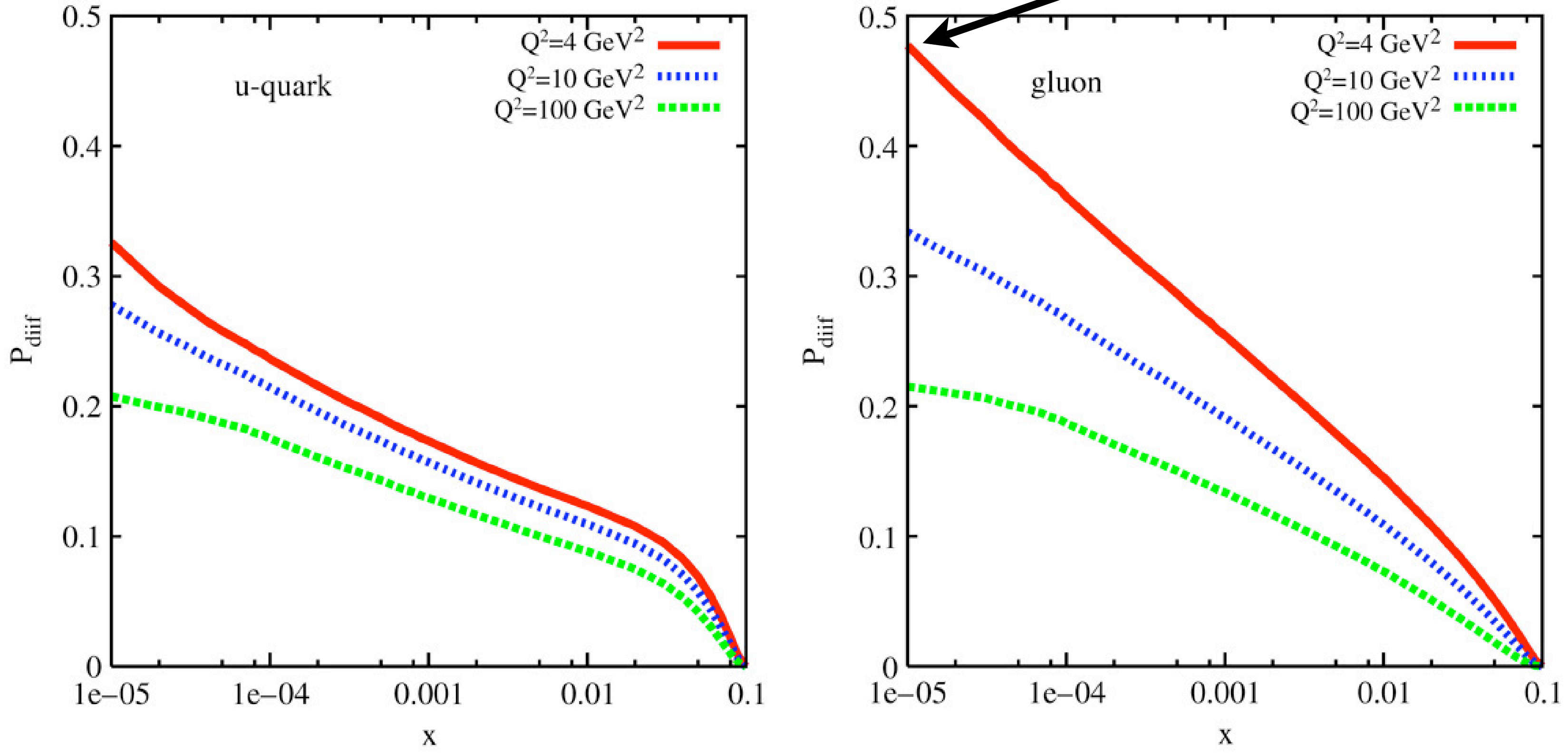


The probability of hard diffraction on the nucleon, $P_{j\ diff}$ as a function of x and Q^2 for u quarks (left) and gluons (right).



The probability of hard diffraction, $P_{j\ diff}$ as a function of x and Q^2 for u quarks (left) and gluons (right) for Q^2=4 GeV^2

Black limit



Evidence for onset of BDR at HERA for gluons at Q=2 GeV

The probability of hard diffraction on the nucleon, $P_{j\ diff}$ as a function of x and Q^2 for u quarks (left) and gluons (right) based on the current HERA data.

Guzey et al

Warning - curves for $x <$ few $\cdot 10^{-4}$ is extrapolation of the fits.

For gluon channel $B=7\ \mathrm{GeV}^{-2}$ leads to impact factor $\Gamma_{gg}(b=0, Q^2=4\ \mathrm{GeV}^2) \sim 1$ for $x \sim 10^{-3}$ $\Rightarrow$ new regime? increase of B?

Consistent with analysis of the exclusive processes at HERA