Nuclear PDFs, Small x, Color Transparency

.

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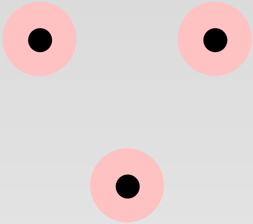
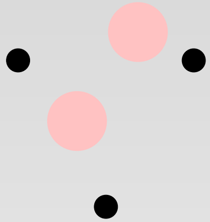
- Weak gluon shadowing: gluons overlap in longitudinal direction, but not in transverse plane.
- Weak CGC and Cronin effect with gluons.
- Diffractive CGC

Two scales of hadronic structure

Gluons do not propagate far from the source.
Light-cone snapshot of the proton:





B.K., A.Schäfer, A.Tarasov(1999):
the valence quarks carry small size gluon clouds, $r_0 = 0.3$ fm.

Shuryak & Zakhed (2004):
gluonic spots of small size, $r_0 = 0.3$ fm are floating in the proton.

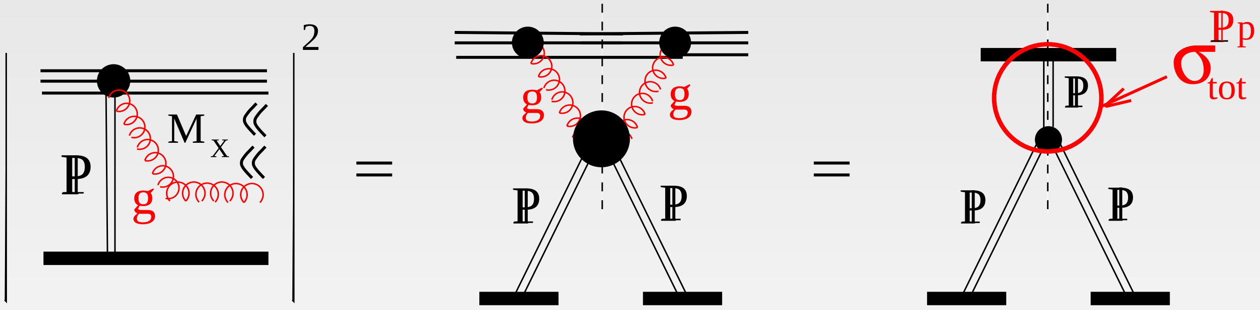
Do we have evidence for the two-scale structure in data?
Only soft processes are appropriate, hard reactions have too high resolution.

Evidences for two scales

- Gluon radiation must be suppressed by an order of magnitude (Color Transparency).

In soft inelastic collisions gluons are indistinguishable.

Diffraction offers a unique way to single out gluon radiation. Only radiation of a vector particle can provide the large mass tail, $d\sigma_{sd}/dM^2 \propto 1/M^2$.



One expects $\sigma_{tot}^{\mathbb{P}p} \sim$ 50 mb.

However, data lead to $\sigma_{tot}^{\mathbb{P}p}$ ~2 mb !!!

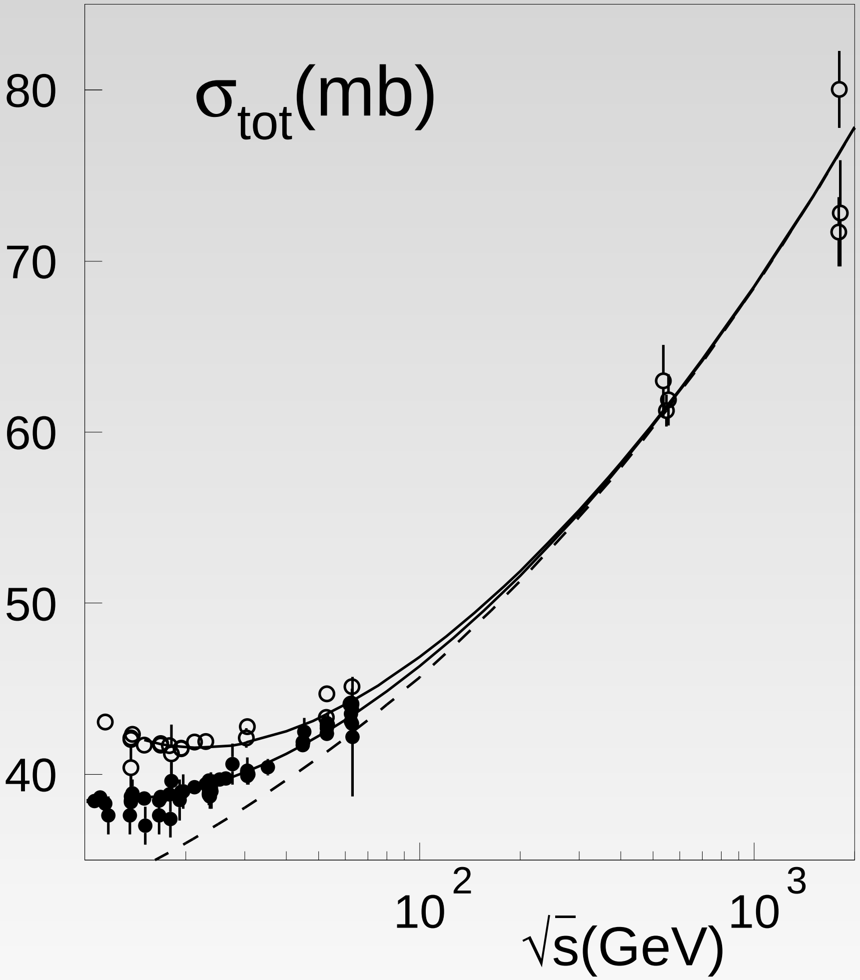
Evidences for two scales

- As far as gluon radiation is suppressed, hadronic cross sections should rise slowly with energy. Indeed, the observed energy dependence of the total pp cross section is well described [B.K., I.Potashnikova, E.Predazzi, B.Povh (2000)]

$$\sigma_{tot} = \sigma_0 + \sigma_1 \left(\frac{s}{s_0}\right)^{\Delta},$$

$$\Delta = \frac{4\alpha_s}{3\pi} = 0.17$$

$$\sigma_1 = \frac{27}{4} C\, r_0^2$$



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Evidences for two scales

- One should also expect a slow Gribov diffusion, i.e small $\alpha'_{I\!\!P}$. Indeed,

$$\alpha'_{I\!\!P} = \frac{1}{2}\,\frac{dB_{el}}{d\ln(s/s_0)} = \frac{\alpha_s}{3\pi}\,r_0^2 = 0.1\,\mathrm{GeV}^{-2}\,.$$

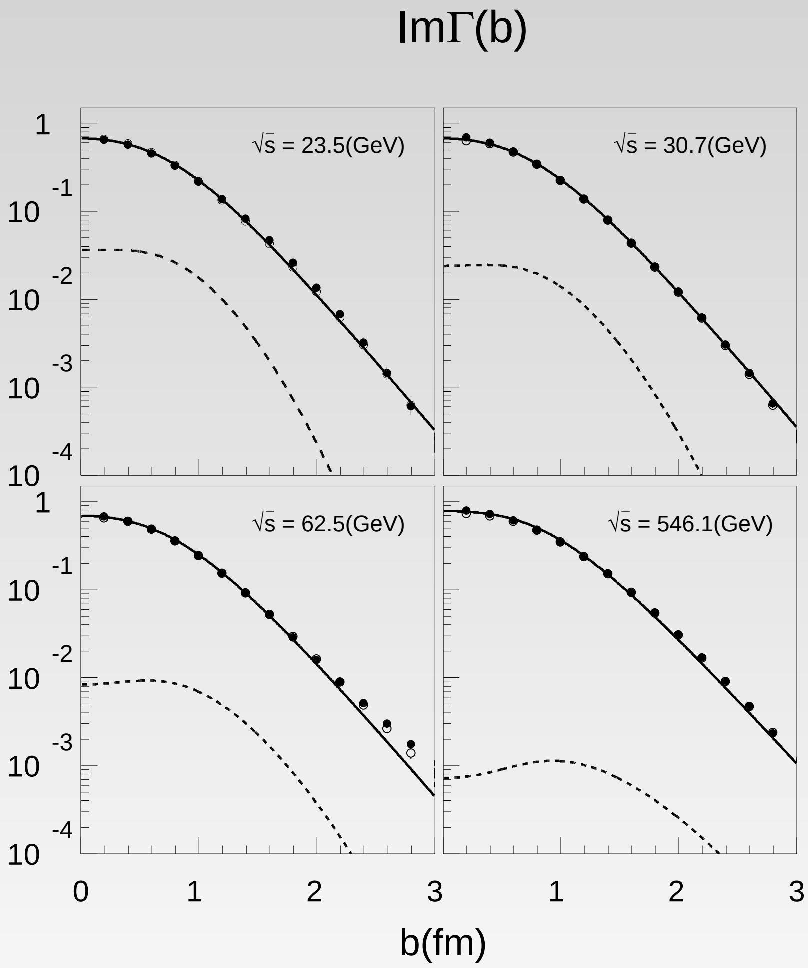
This prediction is well confirmed by ZEUS measurement in photoproduction of J/Ψ:

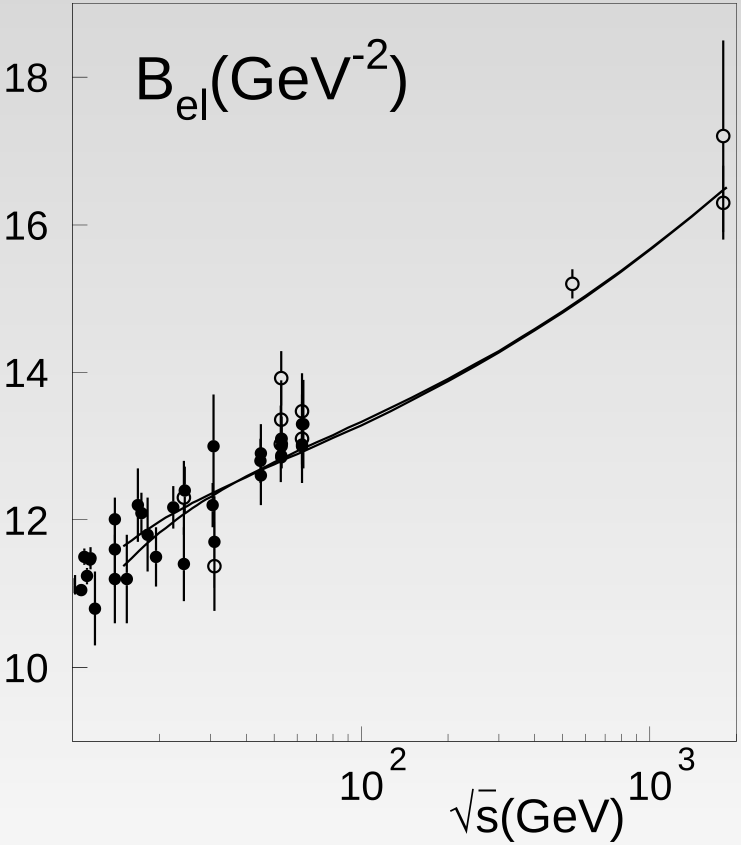
$$\alpha'_{I\!\!P} = 0.115 \pm 0.018\,\mathrm{GeV}^{-2}$$

Why data for pp elastic scattering show a much larger value of $\alpha'_{I\!\!P}$?

Unitarity saturation in pp collisions

Onset of the Froissart regime leads to a considerable rise of $\alpha'_{\mathbb{P}}$





$$\alpha'_{\mathbb{P}} \approx 0.1\,\mathrm{GeV}^{-2} \text{ , but } \alpha'_{eff} \approx 0.25\,\mathrm{GeV}^{-2}$$

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Evidences for two scales

- Seagull effect needs a high intrinsic transverse momentum of proton constituents $\langle \boldsymbol{k_T} \rangle \sim \mathbf{0.5 - 1}\,\mathrm{GeV}$.

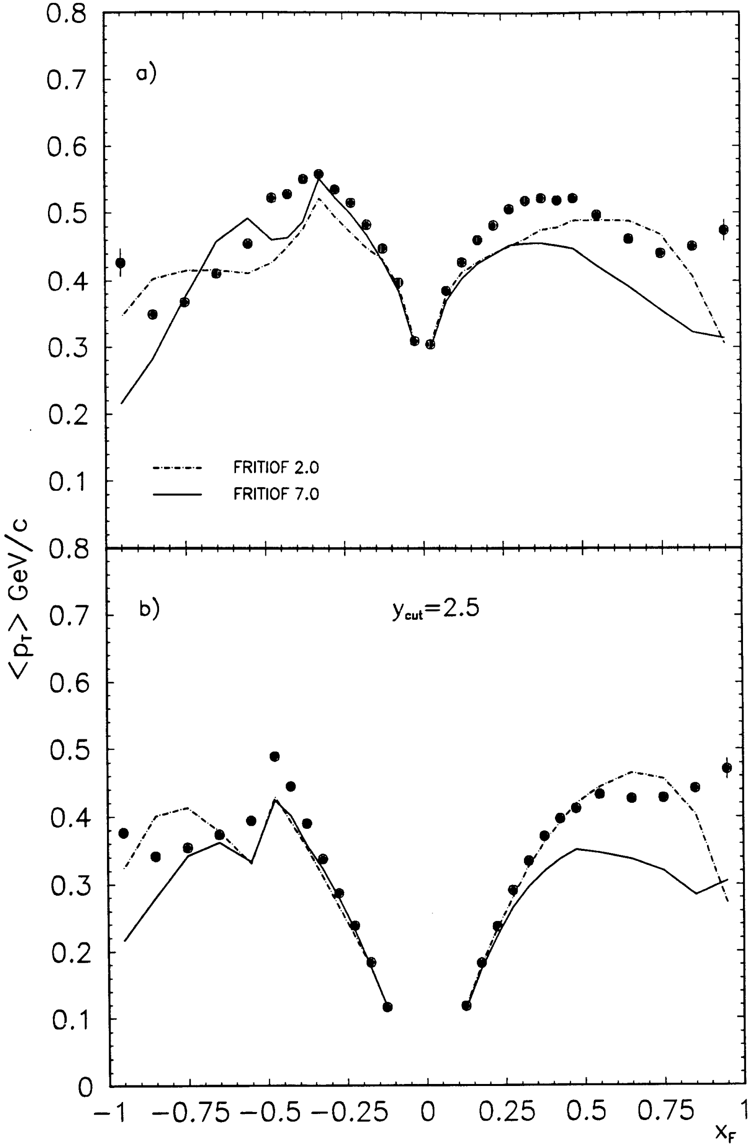

Fig.2

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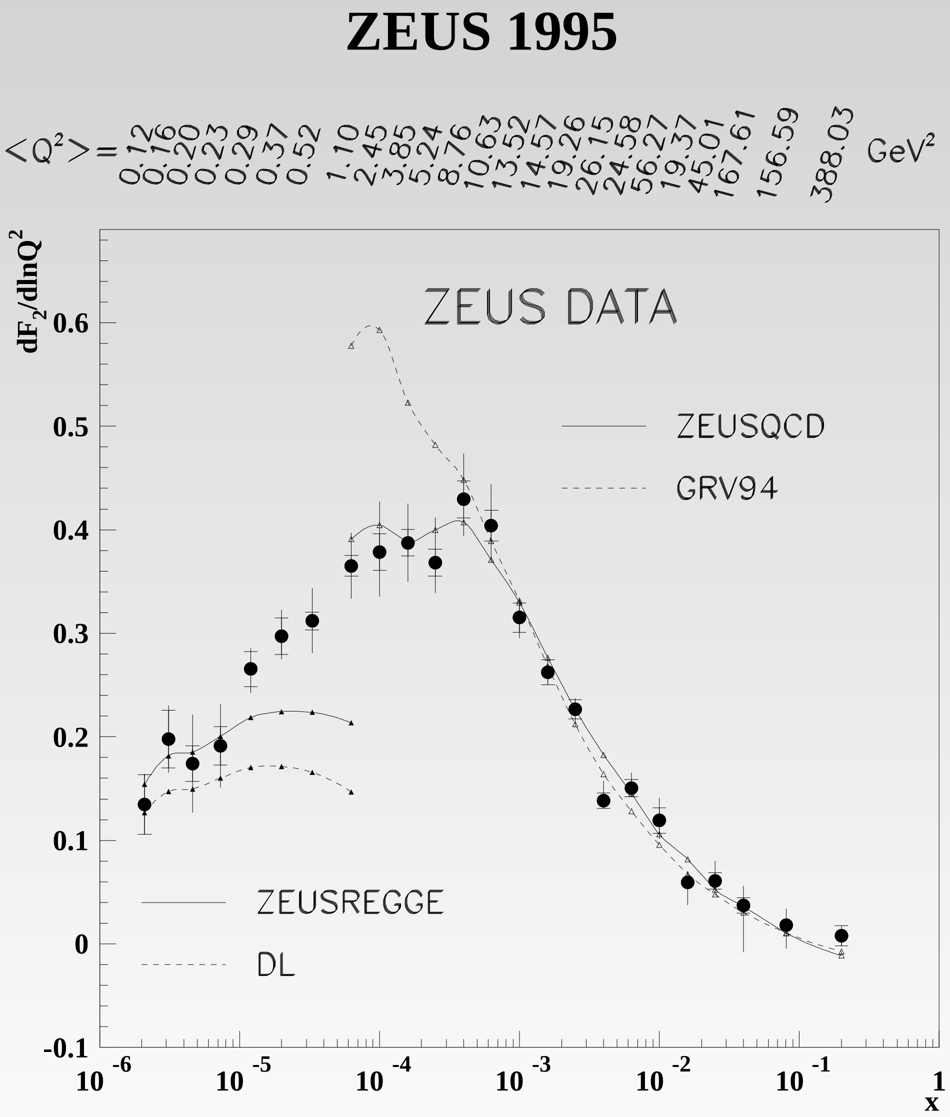
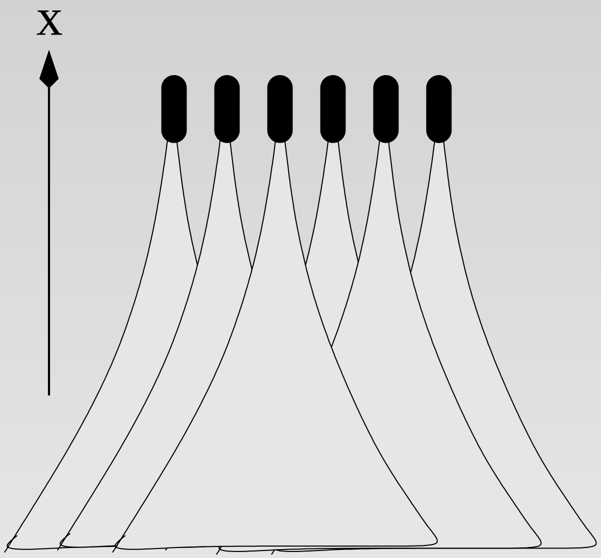
Evidences for two scales

- As far as gluons are located within small spots, it is difficult to resolve them at low scale, $Q^2 < 4/r_0^2$, while no changes happen at higher Q^2. This is confirmed by data from ZEUS.



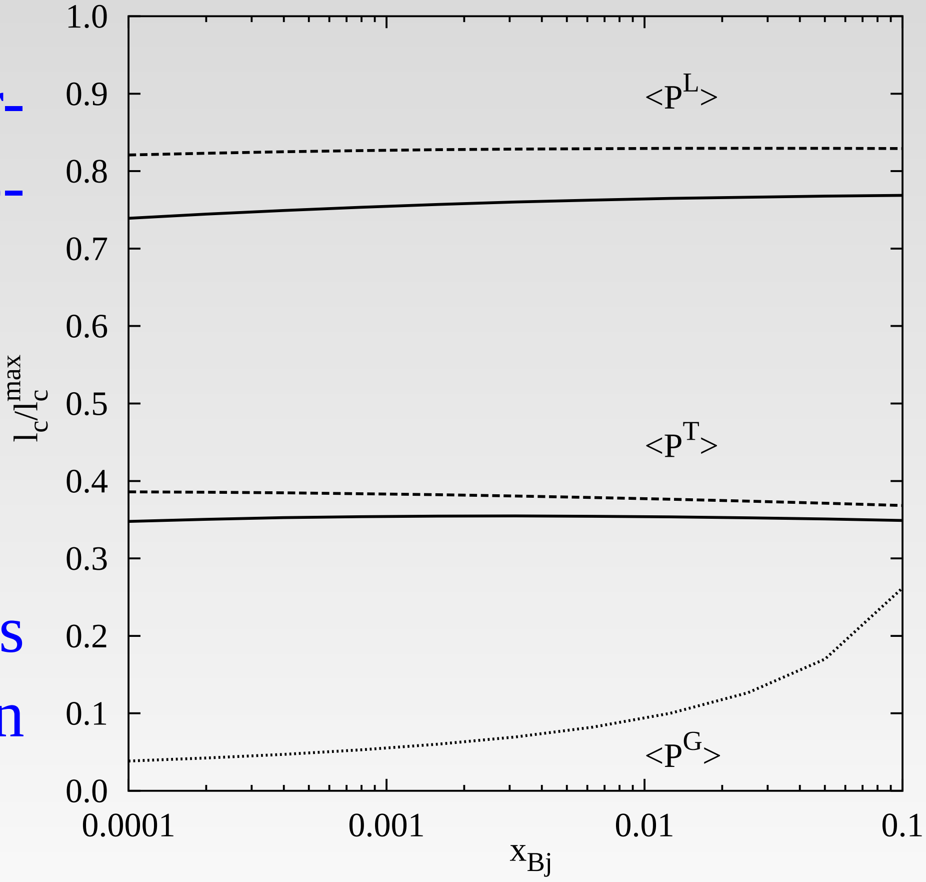
Shadowing



A Lorentz-boosted nucleus looks like a pancake, as well as the bound nucleons. So the nucleons are still well separated. However, parton at small $x < (m_N R_A)^{-1}$ are less contracted and overlap in the longitudinal directions. Then they can fuse reducing parton density at small x. This is how shadowing looks like in the infinite momentum frame [O.Kancheli (1973)].

Shadowing

The same phenomenon in the rest frame of the nucleus looks like coherent multiple interactions of the projectile fluctuations. These interactions shadow each other similar to the usual Glauber shadowing.



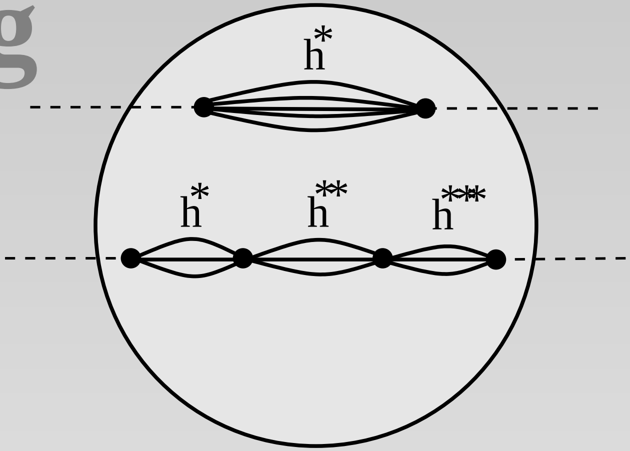
The parameter controlling coherence is the fluctuation lifetime (coherence time),

$$t_c = P\, t_{max} = \frac{P}{x\, m_N}$$

The factor P is different for quarks and gluons and also depends on photon polarization

[B.K., J.Raufeisen, A.Tarasov(2000)]

Onset of shadowing



- **Shadowing vs diffraction:**

Gribov's picture

The projectile hadron or a current produce diffractive chains via multiple interactions.

Each diffractive transition provides longitudinal a momentum transfer, $q_{ij} = (m_j^2 - m_i^2)/2E$, and corresponding phase shifts. At low energy oscillations terminate shadowing, at high energy shadowing may saturate.

(!) However, the absorptive cross sections are not known, as well as diffractive amplitudes between different excites states. Difficult to progress without *ad hoc* assumptions.

- One should switch to eigenstates which have no off-diagonal diffractive excitations. In QCD the eigenstates are dipoles which interact with certain cross sections.

Frozen dipoles

- If $t_c \gg R_A$ the dipole size is "frozen", i.e. it does not fluctuate during propagation though the nucleus. Quark shadowing [B.K., L.Lapidus, A.Zamolodchikov(1981)]

$$\left.\frac{q_A(x)}{Aq_N(x)}\right|_{x\ll1} = \frac{2}{\langle\sigma_{\bar{q}q}(r)\rangle}\int d^2b\left[1-\left\langle e^{-\frac{1}{2}\sigma_{\bar{q}q}(r)T_A(b)}\right\rangle\right]$$

For lead in the soft limit, $q_A/Aq_N = 0.35$

- **Gluon shadowing: Back-of-the-envelope estimate.**

$$\left.\frac{G_A(x)}{AG_N(x)}\right|_{x\ll1} = \frac{2}{\langle\sigma_{GG}(r)\rangle}\int d^2b\left[1-\left\langle e^{-\frac{1}{2}\sigma_{GG}(r)T_A(b)}\right\rangle\right]$$

$$= \;1-\frac{3C}{8}\,r_0^2\,\rho_A R_A+\frac{C^2}{10}\,r_0^4\,\rho_A^2\,R_A^2-\ldots\approx 0.74$$

Gluon shadowing is much weaker because $\sigma_{I\!Pp} \ll \sigma_{\pi p}$.

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Weak gluon shadowing

Even if small-x gluons overlap in the longitudinal direction, they can miss each other in transverse plane, if they are located within small spots. Indeed, for a heavy nucleus (lead) the mean number of gluonic spots overlapping with a given one is,

$$\langle n\rangle = \frac{3\pi}{4}\, r_0^2\, \langle T_A\rangle = \pi\, r_0^2\, \rho_A\, R_A = 0.3$$

Thus, the gluonic spots hardly overlap in transverse plane. Although their size rises with $1/x$, but very slowly, as $\ln(1/x)$, while the longitudinal overlap onsets linearly in $1/x$.

Such a small overlap is another explanation for the very weak gluon shadowing. It makes gluon saturation quite improbable within the currently accessible x-range.

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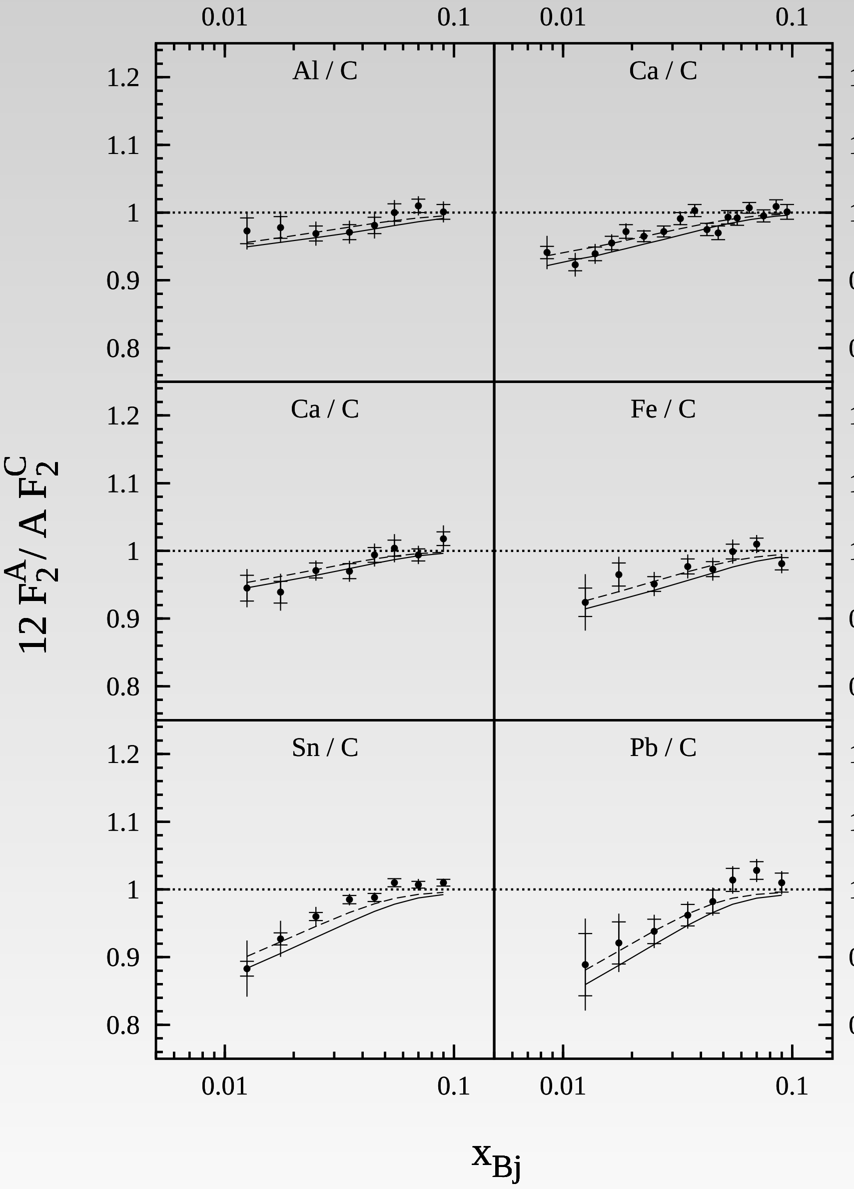
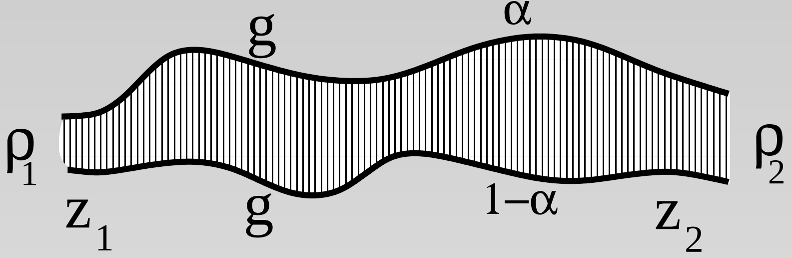
Onset of shadowing

The "frozen" approximation is not appropriate for gluons, a gluonic fluctuation always "breezes" propagating through the nucleus. The onset of quark shadowing is also controlled by fluctuating dipoles. This has always been a problem: either the fluctuation mass and phase shifts are known, but not the cross section, or one knows the cross sections (dipoles), but not the mass.

- The solution is the light-cone Green function method which includes both the transverse size of the dipole and motion of partons. [B.K., J.Raufeisen, A.Tarasov(1998)]



Gluon shadowing



$$
\begin{aligned}
& i\frac{d}{dz_2}G_{gg}(z_1,\vec{\rho}_1;z_2,\vec{\rho}_2) \\
= \quad & \left[-\frac{\Delta_\rho}{2\,p\,\alpha\,(1-\alpha)}+V_{gg}(z_2,\vec{\rho},\alpha)\right]G_{gg}(z_1,\vec{\rho}_1;z_2,\vec{\rho}_2)
\end{aligned}
$$

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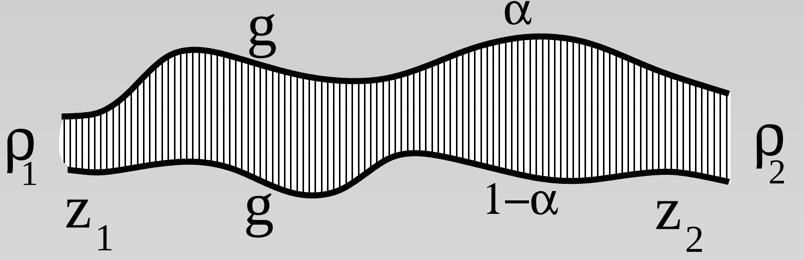
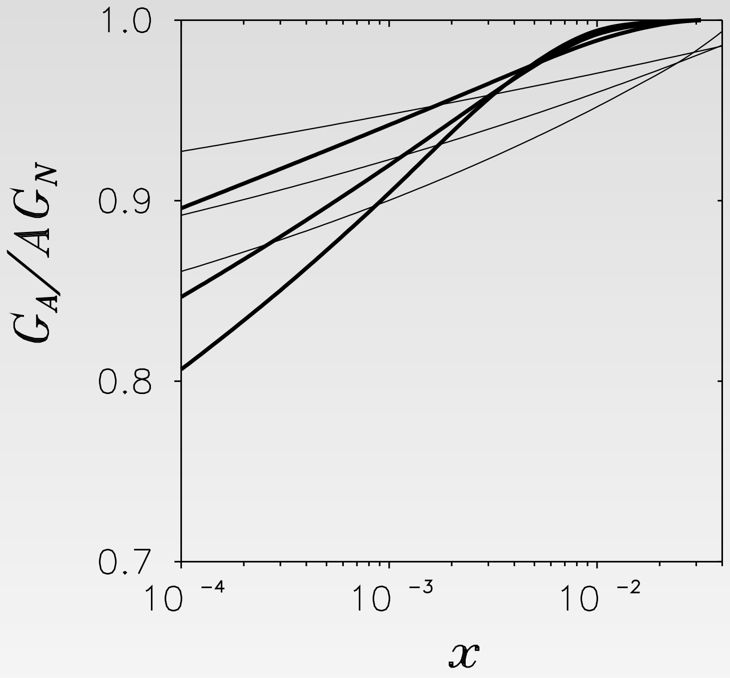
Gluon shadowing



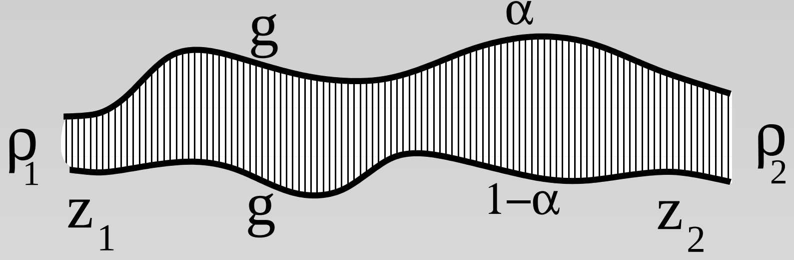
$$i\frac{d}{dz_2}G_{gg}(z_1,\vec{\rho}_1;z_2,\vec{\rho}_2) = \left[-\frac{\Delta_\rho}{2\,p\,\alpha\,(1-\alpha)} + V_{gg}(z_2,\vec{\rho},\alpha)\right]G_{gg}(z_1,\vec{\rho}_1;z_2,\vec{\rho}_2)$$



Predictions for C, Fe and Pb

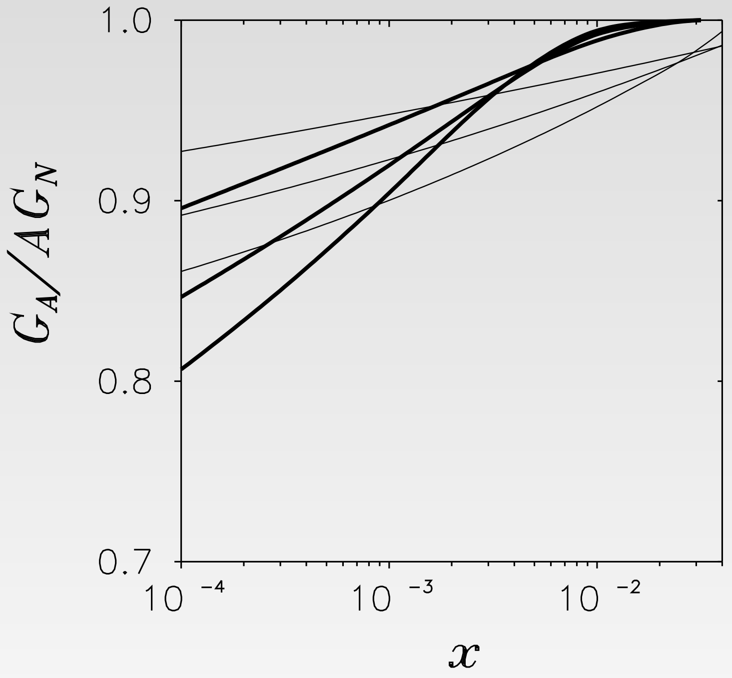
B.K., A.Schäfer, A.Tarasov(1999)

Gluon shadowing



$$i\frac{d}{dz_2}G_{gg}(z_1,\vec{\rho}_1;z_2,\vec{\rho}_2)$$

$$= \quad \left[-\frac{\Delta_\rho}{2\,p\,\alpha\,(1-\alpha)} + V_{gg}(z_2,\vec{\rho},\alpha)\right] G_{gg}(z_1,\vec{\rho}_1;z_2,\vec{\rho}_2)$$



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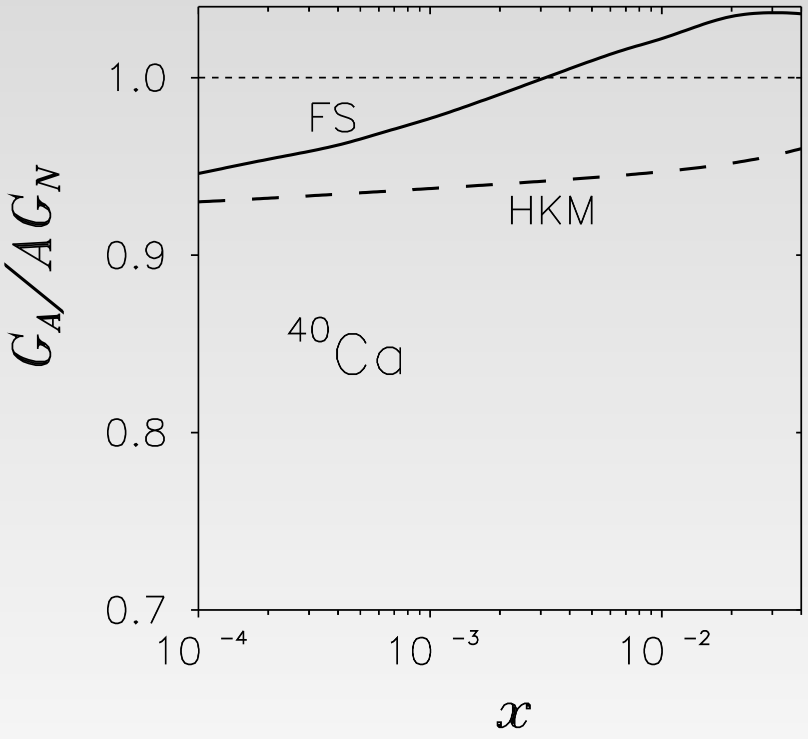

NLO analysis

D. de Florian & R. Sassot(2004)

Gluon shadowing

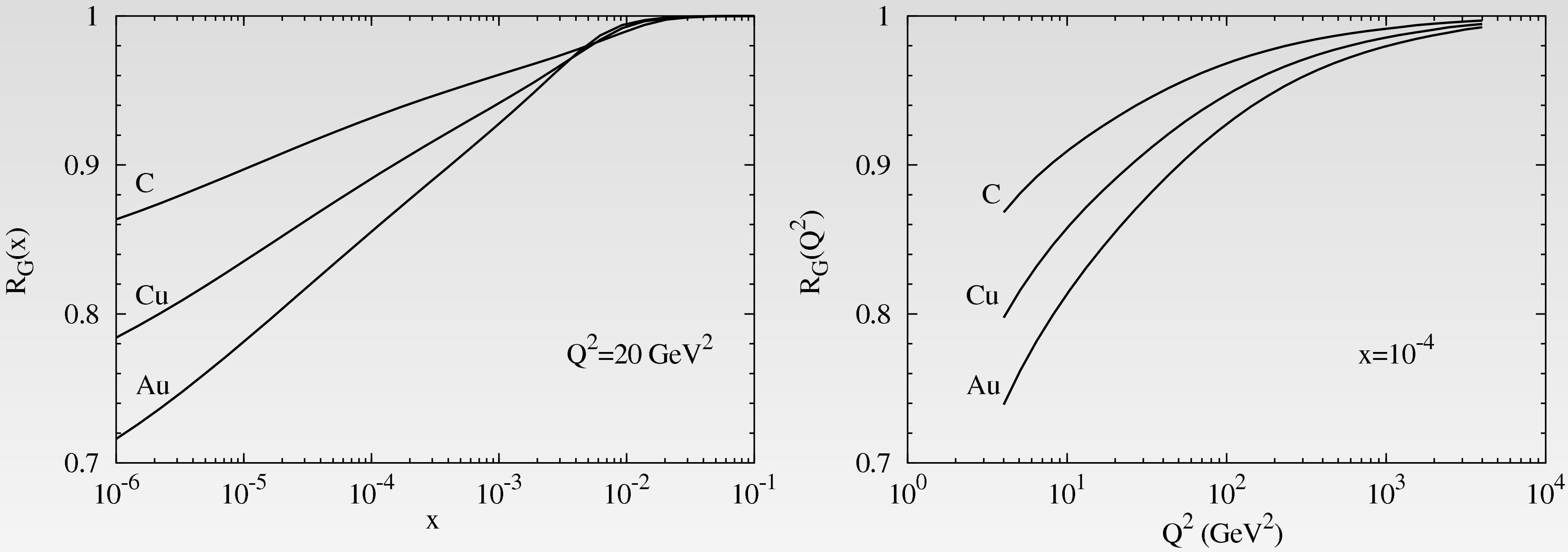

Figure 6: *The x- and Q^2-dependence of gluon shadowing for carbon, copper and gold. The x-dependence is shown for $Q^2 = 20\ GeV^2$, while the figure on the right is calculated for $x = 10^{-4}$.*

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Gluon shadowing

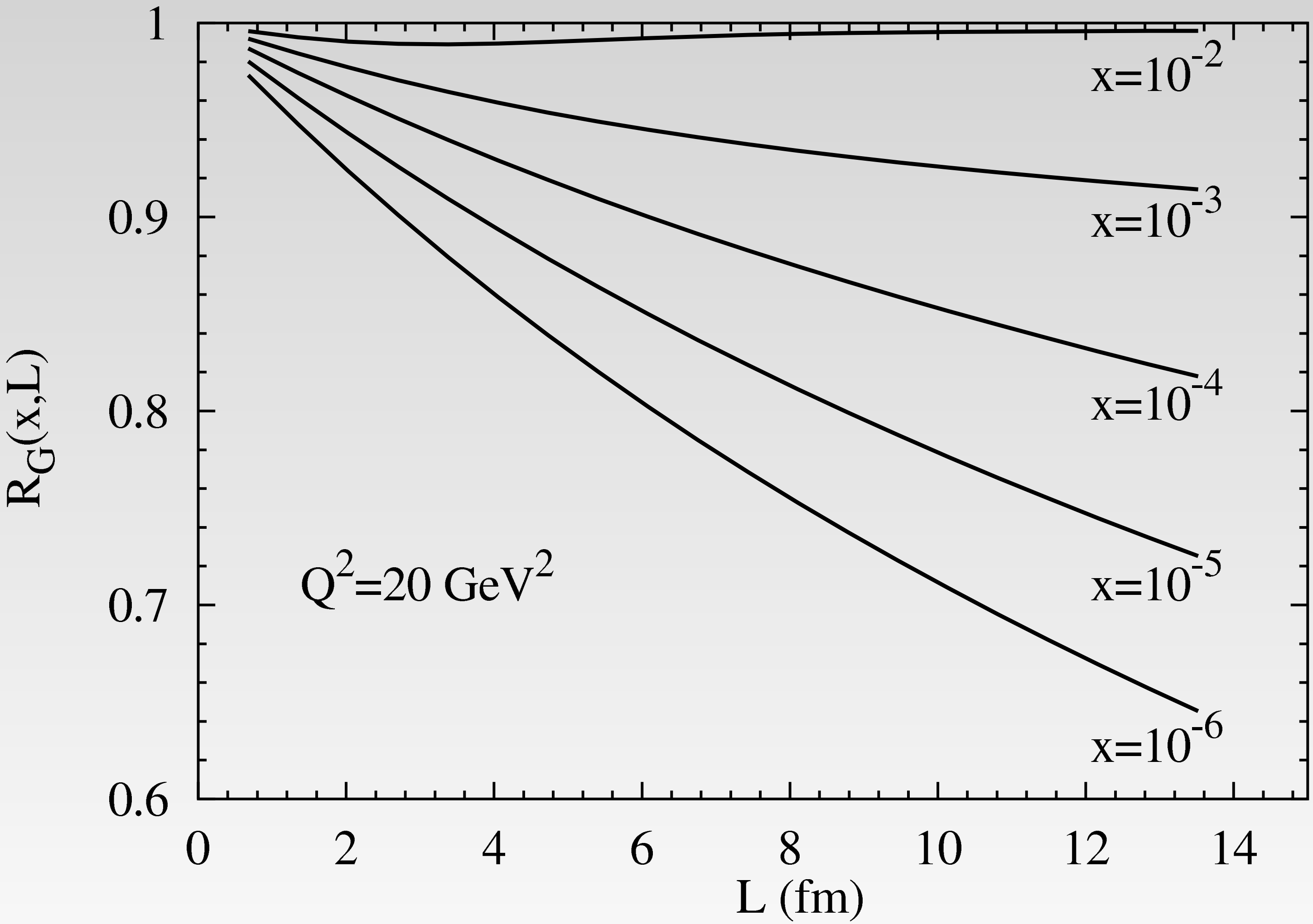
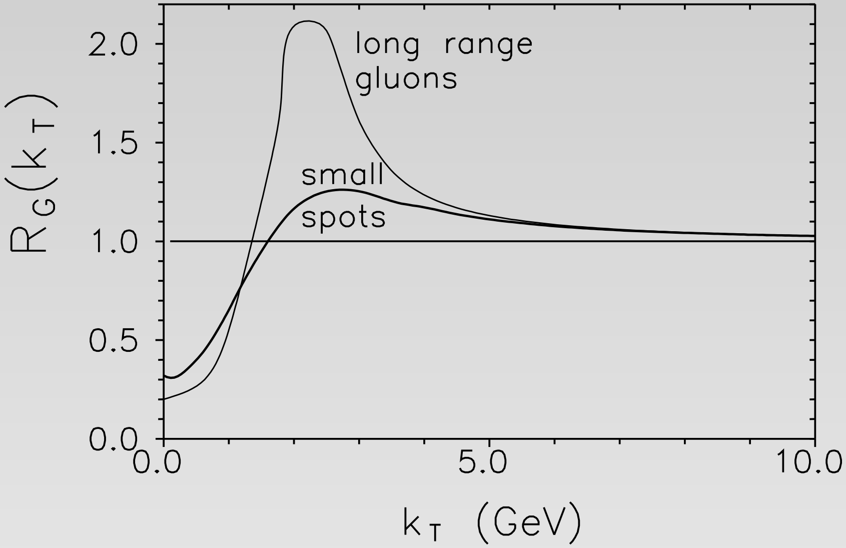


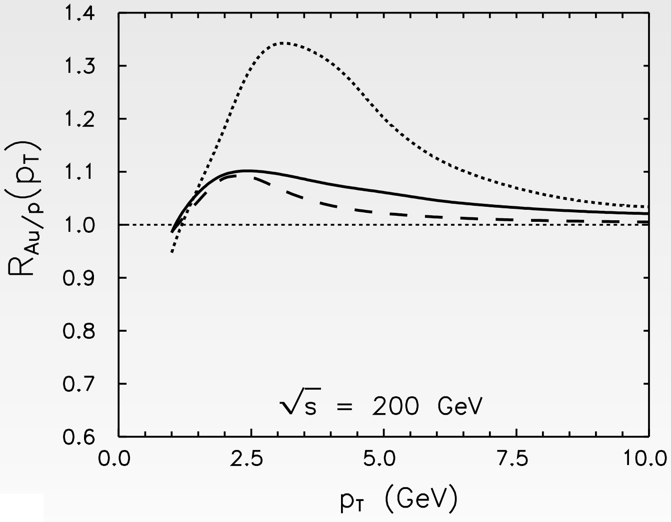
Figure 5: *Gluon shadowing vs. the length of the nuclear medium* $L = 2\sqrt{R_A^2 - b^2}$, *where* b *is the impact parameter and* R_A *the nuclear radius. All curves are for* $Q^2 = 20\ GeV^2$ *but for different values of* x.

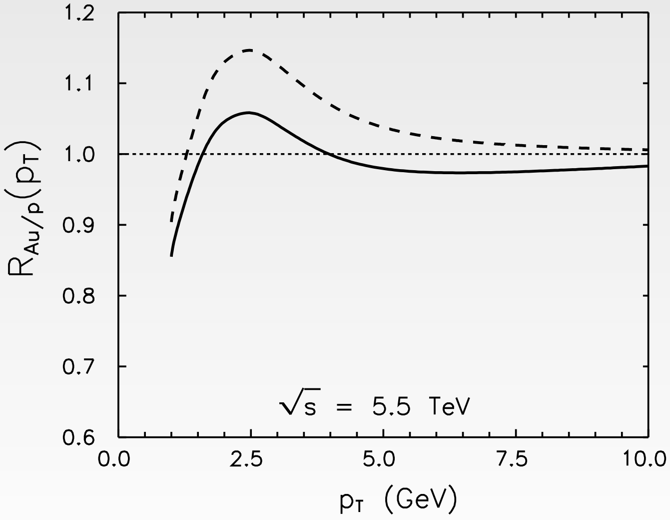
Color Glass Condensate

If gluons do not overlap in transverse plane, they do not interact, and not only gluon shadowing, but also CGC is considerably reduced.



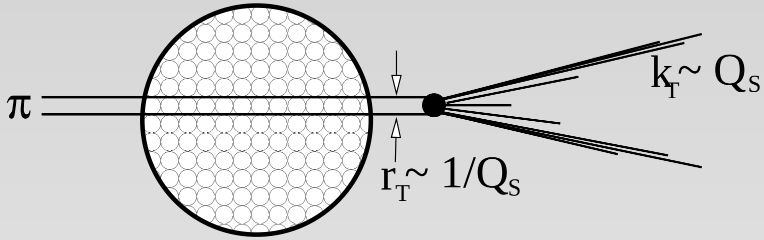
A weak Cronin effect predicted for RHIC (confirmed) & LHC.





Diffractive CGC

First theoretical observation of CGC:



G.Bertsch, S.Brodsky,
A.Goldhaber, J.Gunion(1981)

Dipoles propagating through the nucleus experience color filtering: nuclear matter is more transparent for small size dipoles having larger intrinsic momenta. The mean transverse momenta of quarks/jets rise $\propto R_A$. This is a direct measurement of the saturation scale which is expected to be

$$Q_s^2 \approx 0.1\,\mathrm{GeV}^2\,A^{1/3} \approx 0.6\,\mathrm{GeV}^2 \qquad \text{(for heavy nuclei)}$$

This is substantially larger than on a proton target. For gluon jets the saturation scale Q_s^2 should be doubled.

One may expect observation of real mini-jets at LHC.

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Summary

- There is growing theoretical and experimental support for the existence of a non-perturbative scale smaller than the usual $1/\Lambda_{QCD} \sim 1\,\mathrm{fm}$, and which is related to the gluonic degrees of freedom.

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Summary

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- In spite of a sufficient longitudinal overlap of gluons at small x, they hardly overlap in impact parameters. This leads to a substantial reduction of magnitude of nuclear shadowing and CGC for gluons. This expectation is well confirmed by the NLO analysis of DIS data on nuclei and RHIC data for Cronin effect.

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- In spite of a sufficient longitudinal overlap of gluons at small x, they hardly overlap in impact parameters. This leads to a substantial reduction of magnitude of nuclear shadowing and CGC for gluons. This expectation is well confirmed by the NLO analysis of DIS data on nuclei and RHIC data for Cronin effect.
- Theoretical tools for calculation of shadowing effects in nuclear PDFs are well developed. The light-cone dipole description allows to calculate shadowing in wide ranges of x and Q^2.

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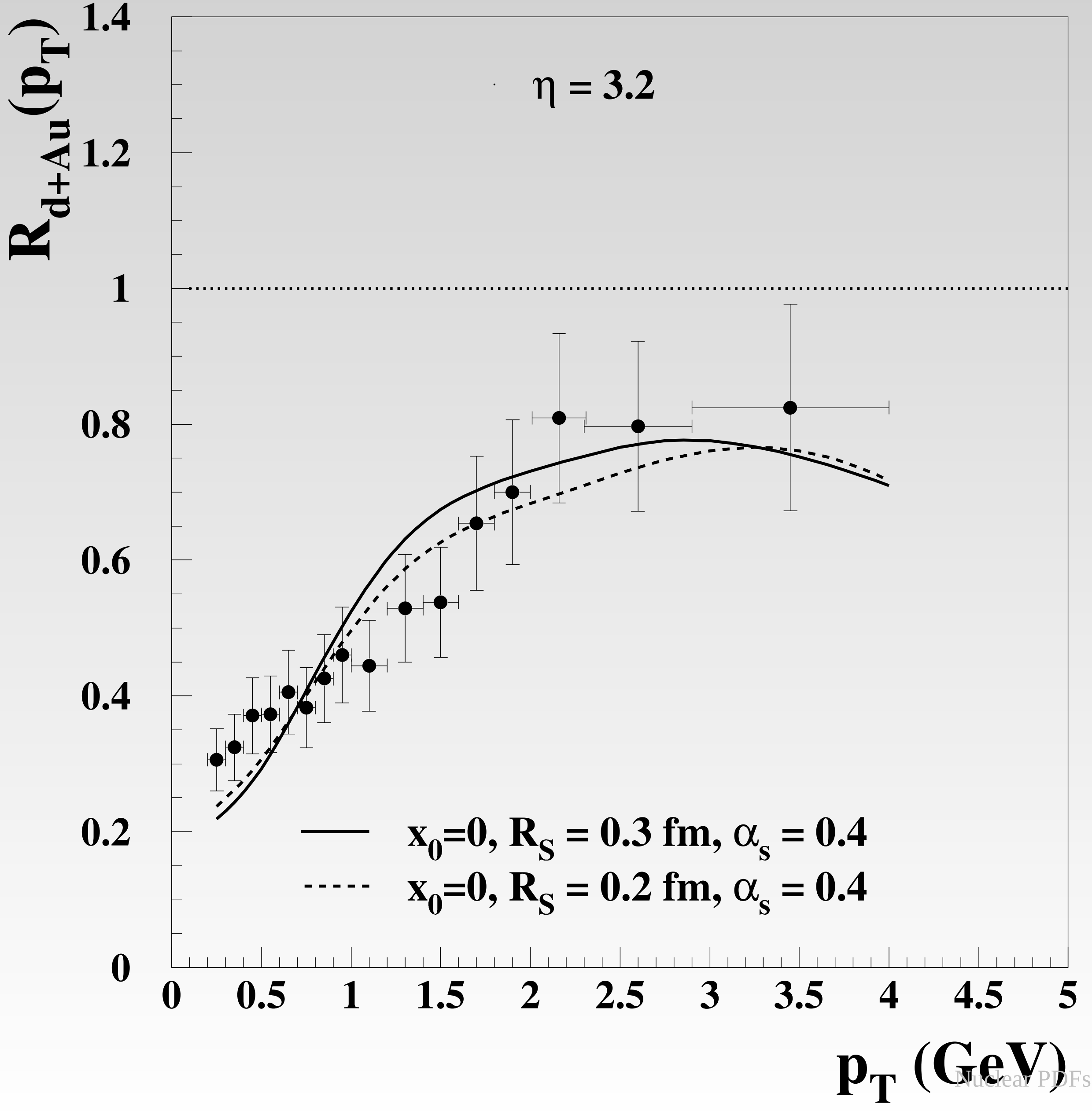
Forward rapidities



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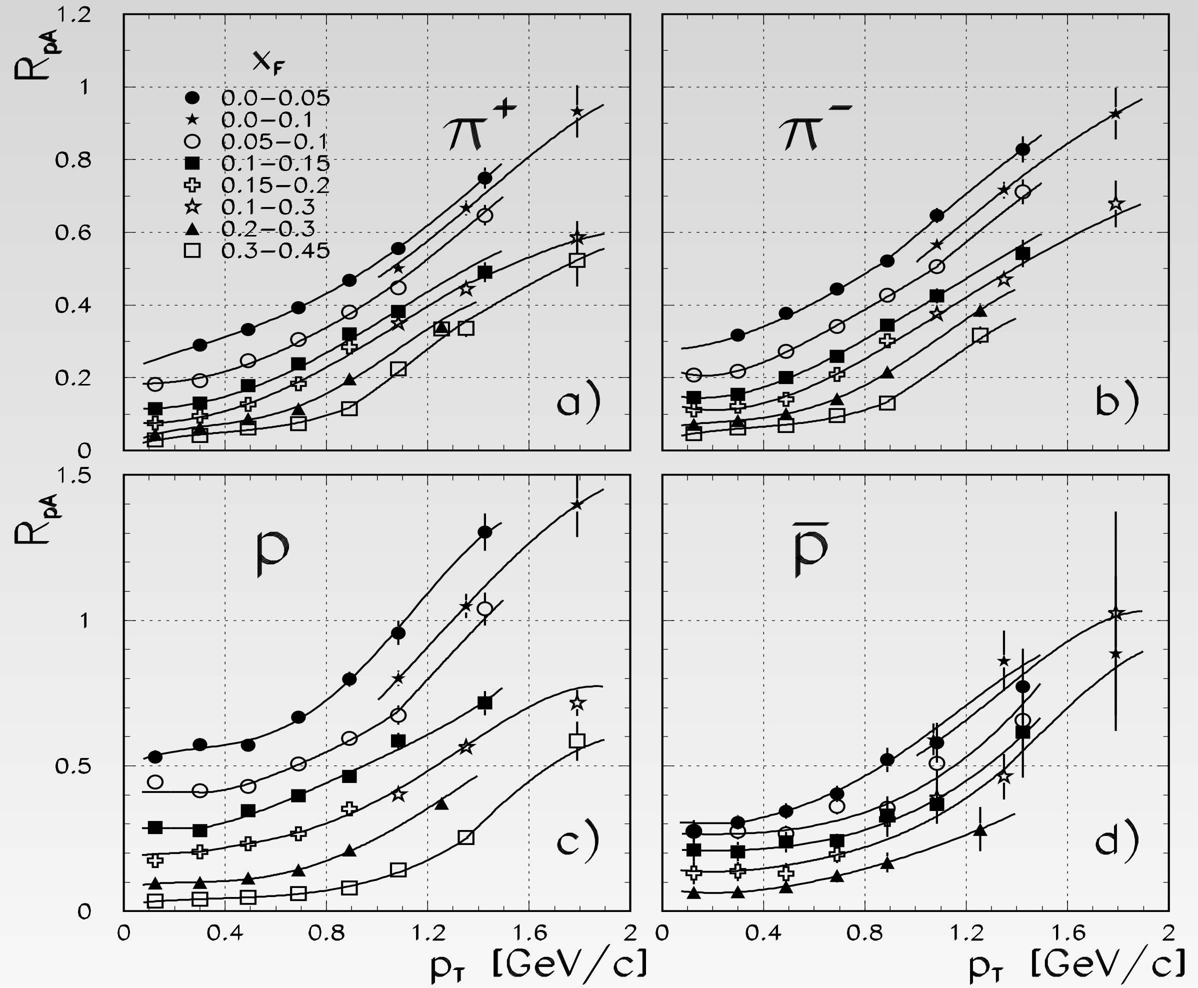

Figure 6.6: Nuclear modification factor R_{pA}, in different x_F intervals, for a) π^+'s, b) π^-'s, c) p's and d) $\bar{p}$'s produced in central p+Pb collisions at 158 GeV. Note: lines are drawn to guide the eye; errors are statistical only.