Small Gluonic Spots in the Nucleon:
Searching for Signatures in Data

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Abstract. Nuclear shadowing and color glass condensate are possible only at sufficiently small $x$ where parton clouds of different nucleons overlap in the longitudinal direction. Another condition vital for these effects, an overlap of partons in impact parameters, is not easy to fulfill for gluons which are located within small spots, as follows from the observed weakness of diffractive gluon radiation (smallness of the triple-Pomeron coupling). The predicted weakness of the leading twist gluon shadowing has been confirmed recently by data for $J/\Psi$ production and Cronin effect in $d-Au$ collisions at RHIC. Smallness of gluonic spots also leads to a rather low value of $\alpha'_p$, the slope of the Pomeron trajectory, confirmed by ZEUS data on elastic photoproduction of $J/\Psi$. At the same time, saturation of unitarity for central $pp$ collisions leads to a substantial increase of $\alpha'_p$ in good agreement with elastic $pp$ data.

One of the most intriguing observations in soft hadronic collisions is the smallness of the cross section of diffractive gluon radiation usually expressed in terms of so called triple-Pomeron coupling, or the Pomeron-proton total cross section. The dependence of the cross section of the process $pp \rightarrow pX$ on the effective mass $M_X$ unambiguously identifies the gluon radiation. Only partons with spin one can provide $1/M_X^2$ behavior, while quarks lead to $1/M_X^3$. To see that this diffractive excitation channel is indeed weak, one can compare the measured Pomeron-proton cross section, $\sigma_{tot}^{Pp} \approx 2$ mb, with the expected $\sim 50$ mb corresponding to a meson-proton cross section enlarged by the Casimir factor $9/4$, since the Pomeron is expected to be a gluonic system. This estimate assumes that the gluon dipole has a mean size of a meson, and the smallness of the observed cross section signals that the gluonic system is much smaller. Adjusting the mean gluon separation to data one arrives at rather small transverse distance $r_0 = 0.3$ fm$^1$. This goes well along with earlier observations of a small gluon correlation radius on the lattice and the small instanton radius. Small gluonic spots in the proton were also considered in the recent analysis$^2$.

Of course, the spatial distribution of gluons in the proton is a fundamental issue and should affect many observables. Some of manifestation of this phenomenon in recent data from RHIC and HERA are considered below.

Gluon shadowing (saturation, color glass condensate).

Gluons at small $x$ are less contracted in the longitudinal direction than their sources. Therefore, at $x \lesssim 1/(m_x R_A)$ gluons originated from different nucleons can
overlap and fuse leading to a phenomenon known as shadowing. However, this is not a sufficient condition for shadowing, the gluons must overlap in impact parameters as well. Apparently, smallness of the gluonic spots in the proton should substantially reduce their transverse overlap. The mean number of gluons overlapping with a given gluon in a nucleus can be estimated as,

$$\langle n_G \rangle \sim \pi r_0^2 N \rho_A R_A,$$

where $N_G$ is the mean number of gluons in a proton. According to estimates in [3] the mean number of gluons $N_G \approx 2$ at the energy of RHIC, and we arrive at a rather small number of overlaps, $\langle n_G \rangle \sim 0.5$, quite far from what is needed for saturation. Such a weak overlap also results in a weak gluon shadowing. Predictions for $x$- and $Q^2$-dependences of nuclear shadowing can be found in [1].

Note that gluon shadowing at low $Q^2$ corresponds to the triple-Pomeron part of the inelastic Gribov’s shadowing, and can be calculated directly via diffraction cross section without any knowledge of the spatial distribution of gluons in the proton. This shadowing turns out to be quite weak [1] and according to the dipole approach, the effect may only decrease with $Q^2$. On the other hand, similar calculations [4], but with the triple-Pomeron part extracted from low statistics diffractive data at HERA may lead to a very strong gluon shadowing.

So far we discussed the nuclear modification of gluon density, while the transverse momentum distribution is also modified, the phenomenon which nowadays is known as color class condensate [5]. Overlapping gluons in nuclei are pushed to higher transverse momenta, and apparently this effect should be also diminished if gluons are located within small spots. In order to demonstrate this, we calculated the ratio of the $k_T$ distributions of gluons radiated by a quark colliding with a heavy nucleus ($A=200$) and a proton. Both, the numerator and denominator are calculated using the light-cone dipole formalism [6, 7] with the light-cone quark-gluon wave function [1],

$$\Psi_{qG}(\vec{r}) = \frac{2}{\pi} \sqrt{\frac{\alpha_s}{3}} \frac{\vec{e} \cdot \vec{r}}{r^2} \exp \left[ -\frac{r^2}{2r_0^2} \right],$$

where $r_0$ is the parameter of the light-cone potential. We consider two possibilities, $r_0 = 0.3$ fm corresponding to small gluonic spots, and $r_0 = 1$ fm corresponding to a long-range propagation of gluons. The results depicted in Fig. 1 show how the magnitude of the Cronin effect is sensitive to the spatial distribution of gluons in the proton. More realistic calculations including initial state parton distributions and fragmentation functions were done in [8]. Recent data for pion production in the PHENIX experiment [9] confirmed the predicted weak Cronin enhancement (see also [10]) which is another confirmation for the spot structure of the proton.

**Nuclear suppression of $J/\Psi$ at RHIC.**

The data for $J/\Psi$ production in $d-Au$ collisions released by the PHENIX collaboration [11] provides probably the first direct access to gluon shadowing. The whole nuclear suppression which also includes the higher twist part related to the $\bar{c}c$ size [12], turns out to be quite weak in accordance with the prediction in [1], thus
confirming the idea of small gluonic spots. These data deserve few comments:
(i) The current nuclear-to-proton ratios must be diminished by about 20% due to the Gribov’s and diffractive corrections missed in the analysis (see details in [10]). The central-to-peripheral ratio is subject to even larger Gribov’s corrections which are concentrated mainly on the periphery of the collision [10].
(ii) Values of $x_2$ assigned to the data points in [9] must be increased. They should be related to the effective mass of the produced $\bar{c}c$ pair which is heavier than $J/\Psi$.
(iii) Comparison of the PHENIX and E866 data demonstrate a dramatic violation of QCD factorization which is the basis for any current model of $J/\Psi$ production. Although the above corrections bring the RHIC data closer to E866, nevertheless a strong breakdown of the $x_2$ scaling still remains. The reason lies in factorization breakdown towards the kinematic bound of inclusive reactions [13]. This is the case for the minimal $x_2$ explored in the E866 experiment. In fact, there is no room for gluon shadowing in the E866 data (on the contrary to the conclusions in [12]), and the strong suppression observed at large $x_F$ has a different origin [13].
(iv) The prediction of a very weak leading twist gluon shadowing in [1] is rather reliable, since is dictated by diffractive data. At the same time, a large higher twist correction to gluon shadowing was predicted for $\chi_2$ production in [12]. This prediction is rather model dependent, since is based on the potential model for gluon interaction. Unfortunately, no data for $\chi_2$ production at RHIC are available so far, while the available data [11] for $J/\Psi$ cannot be used to test this expectation.

Energy dependence of the elastic slope in $J/\Psi$ photoproduction.

Another manifestation of small gluonic spots in the proton is a rather slow Gribov’s diffusion which is responsible for the observed energy dependence of the elastic slopes. Indeed, the mean square radius of a spot is proportional to the product of $r_0^2$ and the mean number of gluons in the spot. Correspondingly, it was predicted in [3] that the

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Ratio of $k_T$- distributions of gluons radiated in quark-nucleus ($A=200$) and quark-nucleon collisions. The thick and thin curves correspond to $r_0 = 0.3 \text{ fm}$ and $1 \text{ fm}$ respectively (see the text).}
\end{figure}
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effective slope of the Pomeron trajectory reads,
\[ \alpha'_{IP} = r_0^2 \frac{\alpha_s}{3\pi} \ln \left( \frac{s}{s_0} \right). \]  
(3)

Different estimates of the running coupling \( \alpha_s \) at the soft scale of the order of \( 1/r_0^2 \sim 0.4 \text{ GeV}^2 \) converge at the value \( \alpha_s \approx 0.4 \) \[3\]. With this value the Pomeron slope predicted in [3] is rather small, \( \alpha'_{IP} \approx 0.1 \text{ GeV}^{-2} \). At first glance, this is in contradiction with the value \( \alpha'_{IP} \approx 0.25 \text{ GeV}^{-2} \) known from phenomenology of soft hadronic collisions. However, a direct comparison with the energy dependent slope \( B_{pp}(s) \) of elastic \( pp \) cross section demonstrates excellent agreement [3]. This is because the effective slope and \( \alpha'_{IP} \) are substantially increased due to the effects of unitarity saturation. Indeed, the \( pp \) elastic amplitude Fourier transformed to impact parameters nearly saturates unitarity for central collisions where it is nearly independent of energy. All the observed rise of the total cross section comes from peripheral collisions. This leads to a fast growth of the interaction radius with energy.

At the same time, one expects almost no unitarity effects for hadronic species having smaller cross sections, for instance \( J/\Psi \)-proton elastic collisions. In this case the elastic amplitude is about order of magnitude smaller than in \( pp \), and the unitarity corrections are negligible. Therefore, the observed value of \( \alpha'_{IP} \) should be close to the bare value Eq. (3). Indeed, the recent measurements at HERA [14], have revealed a rather small value of \( \alpha'_{IP} = 0.116 \pm 0.026 \text{ GeV}^{-2} \) in a good accord with the prediction Eq. (3) made in [3]. This is another manifestation of small gluonic spots in the proton.

Summarizing, new data carrying the signatures of the small gluonic spot structure of the proton have become available recently. This includes the weak gluon shadowing correction seeing in PHENIX data on \( J/\Psi \) production, a weak color glass condensate seeing in the Cronin effect for pions, and the effective slope of the Pomeron trajectory in elastic photoproduction of \( J/\Psi \) which is twice as small as in elastic \( pp \) scattering.

References