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Color fluctuation effects in proton–nucleus collisions

M. Alvioli [a,b], M. Strikman [c,*]

[a] ECT*, European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Strada delle Tabarelle 286, I-38123 Villazzano (TN), Italy
[b] CNR IRPI, via Madonna Alta 126, 06128 Perugia, Italy
[c] 104 Davey Lab, The Pennsylvania State University, University Park, PA 16803, USA

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ABSTRACT

Color fluctuations in hadron–hadron collisions are responsible for the presence of inelastic diffraction and lead to distinctive differences between the Gribov picture of high energy scattering and the low energy Glauber picture. We find that color fluctuations give a larger contribution to the fluctuations of the number of wounded nucleons than the fluctuations of the number of nucleons at a given impact parameter. The two contributions for the impact parameter averaged fluctuations are comparable. As a result, standard procedures for selecting peripheral (central) collisions lead to selection of configurations in the projectile which interact with smaller (larger) than average strength. We suggest that studies of pA collisions with a hard trigger may allow to observe effects of color fluctuations.

1. Introduction

Currently most of the experimental studies as well as modeling of the nucleus–nucleus (proton–nucleus) collisions involve using the Glauber model. Namely, the number of involved nucleons is calculated probabilistically assuming that each Nucleon–Nucleon (NN) inelastic collision is determined by the value of σ_{in}^{NN} at the collision energy.

However, the dominance of large longitudinal distances in high energy scattering [1] changes qualitatively the pattern of multiple interactions. Indeed, in the Glauber approximation high energy interactions of the projectile with a target occur via consecutive rescatterings of the projectile off the constituents of the target. The projectile during the interactions is on mass shell — one takes the residues in the propagators of the projectile. This approximation contradicts the QCD based space–time evolution of high energy processes dominated by particles production. The projectile interacts with the target in frozen configurations since the life time of the configurations becomes much larger than the size of the target. Hence there is no time for a frozen configuration in the projectile to combine back into the projectile during the time of the order R_T, the radius of the target. As a result the amplitudes described by Glauber model diagrams die out at large energies $\propto 1/s$ (a formal proof which is based on the analytic properties of the Feynman diagrams was given in [2,3]).

In the Glauber model the number of interacting nucleons is calculated probabilistically assuming that the probability of individual NN inelastic collisions is determined by the value of σ_{in}^{NN} at the collision energy. Fluctuations of the number of wounded nucleons at a given impact parameter are generated solely by fluctuations of the positions of nucleons in the nucleus and (in some models) due to peripheral collisions of nucleons, where the interaction is gray and hence the chance to interact differs from one or zero. Hard collisions are treated as binary collisions, which is equivalent to taking the diagonal generalized parton densities of nuclei, $f_A(x,Q^2,b)$, proportional to the impact factor $T(b)$:

$$F_A\big(x,Q^2,b\big)=f_N\big(x,Q^2\big)T(b), \tag{1}$$

where $T(b)$ is normalized as $\int d\boldsymbol{b}\,T(b)=A$. A nuclear shadowing correction is introduced for $x\leqslant 0.01$.

The high energy theory of soft interactions with nuclei was developed by Gribov [4] who expressed the shadowing contribution to the cross section of hadron–nucleus (hA) interactions through the contribution of non-planar diagrams. The Gribov–Glauber theory, in difference from the low energy Glauber theory, requires taking into account that a particular quark–gluon configuration of the projectile is frozen during the collision and that it may interact with different strength as compared to the average strength. This leads to fluctuations of the number of collisions which are significantly larger than in the Glauber model. The fluctuations of the strength of the interaction are related to the ratio of inelastic and elastic diffraction in NN scattering at $t=0$. Relevance of fluctuations of the strength was first pointed out in [5,6] but these effects were never analyzed in detail before.

Another effect contributing to fluctuations of observables in hA collisions is fluctuations of the gluon density which can originate both from the fluctuations of the nucleon configurations and from

* Corresponding author.
E-mail address: strikman@phys.psu.edu (M. Strikman).

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the fluctuations of the gluon densities in the individual nucleons. We will consider this effect elsewhere.

The Letter is organized as follows. In Section 2 we summarize the necessary information about fluctuations of the strength of NN interaction. In Section 3 we use the Gribov–Glauber model in the optical approximation to obtain analytic results for the strength of fluctuations of the number of wounded nucleons and relative contributions to these fluctuations of the fluctuations of the strength of the interaction and of geometry of collisions. In Section 4 we develop a full Monte Carlo (MC) model in which the geometry of projectile–target nucleon interaction is accounted for, and the strength of the interaction fluctuates on an event-by-event basis. The results for the change of the distribution over the number of collisions and for the dependence of the average strength of the interaction on impact parameter are presented. Possibilities for observing color fluctuation effects in collisions with hard triggers are outlined.

2. Color fluctuation effects in proton–nucleus collisions

2.1. Gribov inelastic shadowing

It was demonstrated by Gribov [4] that the nuclear shadowing contribution to the total cross section of the hadron–deuteron scattering can be expressed through the diffraction cross section at $t=0$. Operationally this amounts to the replacement in the Glauber formulæ of the elastic hN cross section at $t\sim 0$ by the sum of elastic and diffractive cross section at $t=0$, leading to an enhancement of the multinucleon interactions. For heavier nuclei the Gribov formulæ involve the coupling of the projectile to $N>2$ vacuum exchanges which has to be modeled.

The contribution of the double scattering to the total hadron–nucleon (hN) cross section is enhanced by a factor $1+\omega_\sigma$, where

$$\omega_\sigma = \frac{d\sigma(hN\to XN)}{dt} \Big/ \frac{d\sigma(hN\to hN)}{dt}\bigg|_{t=0}. \tag{2}$$

The relation between the double scattering cross section and the total diffraction cross section can be naturally understood in the Good and Walker formalism [7], which provided the effective realization of the Feinberg–Pomeranchuk picture [8] of the inelastic diffraction. In this formalism one introduces eigenstates of the scattering matrix diagonal in σ; see Ref. [9] for a review. Configurations with different σ_i scatter without interference off two target nucleons contributing in the case of scattering of two nucleons with strength $\propto\sigma_i^2$ to the shadowing of the total cross section. This is the same quantity as in the expression for the total cross section of hadron–nucleon diffraction at $t=0$. This interpretation of the Gribov result for the shadowing correction to the total cross section was first given by Kopeliovich and Lapidus [10].

2.2. Distribution over the strength of interaction

The fluctuations of strength of interaction arise naturally in QCD where the strength of interaction depends on the volume occupied by color. In particular, the presence of some small configurations leads to fluctuations interacting with a small cross section. So we will refer to these fluctuations as color fluctuations.

In order to describe the effect of color fluctuations for a variety of processes it is convenient to introduce the notion of distribution over the strength of interaction, $P_h(\sigma_{tot})$ — the probability for an incoming hadron to interact with total cross section σ_{tot}. The distribution $P_h(\sigma_{tot})$ satisfies two normalization sum rules:

$$\int d\sigma_{tot}\, P_h(\sigma_{tot}) = 1, \qquad \int d\sigma_{tot}\,\sigma_{tot} P_h(\sigma_{tot}) = \sigma_{tot}^{hN}, \tag{3}$$

and the Miettinen–Pumplin relation [11]

$$\int d\sigma_{tot}\left[\sigma_{tot}^2/\left(\sigma_{tot}^{hN}\right)^2 - 1\right] P_h(\sigma_{tot}) = \omega_\sigma, \tag{4}$$

where σ_{tot}^{hN} is the free cross section. Experimentally, ω_σ first grows with energy then starts dropping at energies $\sqrt{s}\geqslant 100$ GeV. There are no direct measurements at the RHIC energy of 200 GeV, but an overall analysis indicates that it is of the order 0.25. The first LHC data seem to indicate that inelastic diffraction still constitutes a large fraction of the cross section — it is comparable to the elastic cross section, suggesting $\omega_\sigma\sim 0.2$ at those energies. It is difficult at the moment to ascribe error bars to these numbers. However, it is expected that the values of ω_σ corresponding to the LHC energies will be soon measured with a good precision.

It is worth emphasizing here that these seemingly small values of ω_σ correspond to very large fluctuations of the interaction strength. For example, if we consider a simple two component model (equivalent to the quasi-eikonal approximation), in which two components are present in the projectile wave function with equal probability and interact with strengths $\sigma_{tot}^{(1)}$ and $\sigma_{tot}^{(2)}$:

$$\sigma_{tot}^{(1)} = \sigma_{tot}^{hN}(1-\sqrt{\omega}), \qquad \sigma_{tot}^{(2)} = \sigma_{tot}^{hN}(1+\sqrt{\omega}). \tag{5}$$

Thus for $\omega_\sigma = 0.25$, we have $\sigma_{tot}^{(1)}/\sigma_{tot}^{hN} = 0.5$, $\sigma_{tot}^{(2)}/\sigma_{tot}^{hN} = 1.5$ and hence $\sigma_{tot}^{(1)}/\sigma_{tot}^{(2)} = 3$.

3. Gribov–Glauber model predictions for fluctuations in the optical approximation

In order to illustrate the effects of the color fluctuations and their interplay with the fluctuations of the local nuclear density we first consider the optical approximation of the Glauber model where the radius of the NN interaction is neglected as compared to the distance between the nucleons.

Within this model the total inelastic hadron–nucleus cross section σ_{in}^{hA} can be written as follows:

$$\sigma_{in}^{hA} = \int d\boldsymbol{b}\left(1-\left[1-x(b)\right]^A\right) = \sum_{N=1}^{A}\frac{(-1)^{N+1}A!}{(A-N)!N!}\int d\boldsymbol{b}\, x(b)^N, \tag{6}$$

where $x(b)=\sigma_{in}^{hN}T(b)/A$ and normalization $\int d\boldsymbol{b}\, T(b) = A$.

Note that in Eq. (6) nucleon–nucleon correlations in the nuclear wave function are neglected as well as the finite radius of the hadron–nucleon interaction; an implementation of correlations in the optical limit in the Gribov–Glauber formalism can be found in Refs. [12,13] and in Ref. [14] within the MC approach and will not be discussed here. Eq. (6) can be rewritten as a sum of positive cross sections [15] as follows:

$$\sigma_{in}^{hA} = \sum_{N=1}^{A}\sigma_N, \quad \sigma_N = \frac{A!}{(A-N)!N!}\int d\boldsymbol{b}\, x(b)^N\left[1-x(b)\right]^{A-N}, \tag{7}$$

where σ_N denotes the cross section of the physical process in which N nucleons have been involved in inelastic interactions with the projectile. Using Eq. (7), the average number of interactions $\langle N\rangle$ can be expressed as

$$\langle N\rangle = \sum_{N=1}^{A} N\sigma_N \Big/ \sum_{N=1}^{A}\sigma_N = \frac{\sigma_{in}^{hN}}{\sigma_{in}^{hA}}\int d\boldsymbol{b}\, T(b) = \frac{A\sigma_{in}^{hN}}{\sigma_{in}^{hA}}, \tag{8}$$

which coincides with the naive estimate of shadowing as being equal to the number of nucleons shadowed in a typical hA inelastic collision.