Proton structure fluctuations: constraints from HERA and applications to $p + A$ collisions

Heikki Mäntysaari, Björn Schenke, Chun Shen, Prithwish Tribedy

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

We constrain proton structure fluctuations at small-x by comparing with the HERA diffractive vector meson production data, and find that large geometric fluctuations in the proton wave function are needed. Hydrodynamical simulations of proton-nucleus collisions including the fluctuating proton structure are found to be compatible with the momentum anisotropies measured at the LHC.

Keywords: diffraction, fluctuations, CGC, Color Glass Condensate, proton-nucleus collisions

1. Introduction

One of the striking findings of the proton-nucleus collisions at the LHC has been the presence of strong collective phenomena in high multiplicity events. These signals, particularly long range rapidity correlations with distinct anisotropies in the azimuthal direction, are very similar to those that have been traditionally interpreted as evidence for the creation of an almost perfect fluid in ultrarelativistic heavy ion collisions (for a review of recent collectivity measurements, see Ref. [1]). This has raised a natural question whether the high-multiplicity proton-nucleus, and even proton-proton collisions, can be described using the same relativistic hydrodynamic framework that has been successful in describing a vast variety of LHC and RHIC heavy ion data (see e.g. Ref [2]).

In hydrodynamical simulations the initial state geometric anisotropies are converted into momentum space correlations and are observed e.g. as an elliptic (v_2) and triangular flow (v_3). Thus, in order to model proton-nucleus collisions using relativistic hydrodynamics, a detailed knowledge of the initial state geometry is crucial. In particular, the event-by-event fluctuations of the (on average round) proton are needed to model the initial state. Without large eccentricities in the initial state it is difficult to explain the large flow harmonics observed at the LHC [3].

One possibility to constrain the proton structure fluctuations is given by diffractive deep inelastic scattering measured at the HERA electron-proton collider. Unlike other DIS observables, diffractive scattering processes are sensitive to the transverse geometry of the target. The actual process we have in mind here is exclusive vector meson production (in this work J/Ψ). These processes can be divided into two categories. In *coherent diffraction*, where the target hadron remains in the same quantum state, the transverse momentum spectra of the produced vector mesons are directly related to the average density profile of the
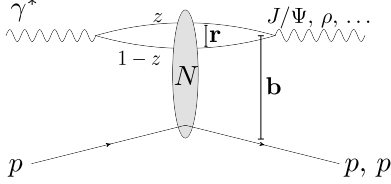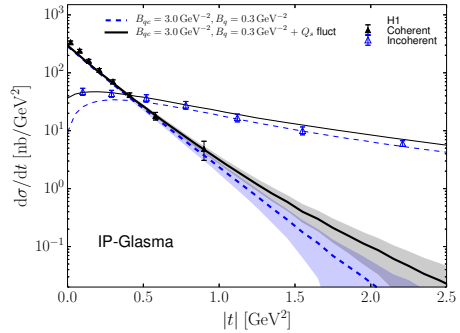
Fig. 1. Diffractive vector meson production in dipole picture.

Fig. 2. Coherent and incoherent diffractive J/Ψ production compared with the H1 data [12].

target [4, 5]. On the other hand, in *incoherent diffraction*, where the target breaks up but there is still no net color charge exchanged between the vector meson and the target, the cross section is proportional to the *amount of fluctuations* in the target wave function [4, 6, 7].

In this work, we constrain the proton shape fluctuations using HERA diffractive J/Ψ production data, and use the obtained fluctuating protons as an input for hydrodynamical simulations of proton-nucleus collisions at the LHC energy $\sqrt{s_{NN}} = 5.02$ TeV. The diffractive calculations are published in Refs. [8, 9] and the hydrodynamical simulations in Ref. [10].

2. Theoretical framework: IP-Glasma

Coherent vector meson production data from HERA has been described well by dipole model calculations (see e.g. [11]), assuming a Gaussian density profile for the proton, $T_p(\mathbf{b}) = \frac{1}{2\pi B}e^{-\mathbf{b}^2/(2B)}$, with $B = 4$ GeV^{-2}. We include event-by-event fluctuations by assuming a constituent quark inspired picture, where the small-x gluons are located around the three valence quarks. We sample the locations of these *hot spots* in the transverse plane from a Gaussian distribution that has a width B_{qc}. The density profile of each of these hot spots is then assumed to be Gaussian with different width B_q. This corresponds to the replacement $T_p(\mathbf{b}) \to \frac{1}{3} \sum_{i=1}^{3} T_q(\mathbf{b} - \mathbf{b}_i)$ with $T_q(\mathbf{b}) = \frac{1}{2\pi B_q}e^{-\mathbf{b}^2/(2B_q)}$. This replacement is performed in the impact parameter dependent saturation model (IPsat) fitted to inclusive HERA data [11]. In addition, we include saturation scale (Q_s) fluctuations as described in Ref. [9]. From the IPsat model, we can then calculate the saturation scale Q_s at each point in the transverse plane, and relate it to the color charge density. After solving the Yang-Mills equations we obtain the Wilons lines at each point in the transverse plane. From the Wilson lines, it is possible to evaluate the dipole-proton amplitude which is a necessary ingredient to calculations of diffractive cross sections as discussed below. The Wilson lines also include all the information about the initial state when we use hydrodynamical simulations to describe proton-nucleus collisions. For more details, the reader is referred to Refs. [8, 9, 10] and references therein.

The scattering amplitude for diffractive vector meson production can be written as [5]

$$\mathcal{A}_{T,L}^{\gamma^* p \to V p}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) = 2i \int d^2\mathbf{r} \int d^2\mathbf{b} \int \frac{dz}{4\pi} (\Psi^* \Psi_V)_{T,L}(Q^2, \mathbf{r}, z) e^{-i[\mathbf{b}-(1-z)\mathbf{r}]\cdot\mathbf{\Delta}} N(\mathbf{b}, \mathbf{r}, x_{\mathbb{P}}). \quad (1)$$

Here Q^2 is the virtuality of the photon, $\mathbf{b}$ impact parameter, $\mathbf{r}$ size of the quark-antiquark dipole and z longitudinal momenum fraction of the photon carried by the quark. The transverse momentum of the vector meson $\mathbf{\Delta} \approx \sqrt{|t|}$ is the Fourier conjugate to $\mathbf{b} - (1 - z)\mathbf{r}$. This scattering probes the gluon distribution of the target at longitudinal momentum fraction $x_{\mathbb{P}}$. The dipole-proton amplitude N is obtained as a trace of Wilson lines at positions $\mathbf{b}+\mathbf{r}/2$ and $\mathbf{b}-\mathbf{r}/2$. The interpretation of Eq. 1 is straightforward: first, the incoming virtual