Signatures of gluon saturation in high energy scattering

Wessels, E.

2009

document version
Publisher's PDF, also known as Version of record

citation for published version (APA)
Wessels, E. (2009). *Signatures of gluon saturation in high energy scattering*.

Summary

In high energy scattering off a hadron, the scattered particle probes gluons in the hadron that have a longitudinal momentum fraction x, which decreases as the centre of mass energy becomes larger. As x becomes smaller, the gluon density rises quickly. At very small values of x, the gluon density is expected to saturate in order to preserve unitarity. The physical picture behind this gluon saturation is that the gluon density increases so fast that the gluons start to overlap within the hadron with a probability of the order of unity, so that interactions among the gluons prevent the fast rise to continue.

Deep inelastic scattering at such small values of x can be described in the dipole formalism [1]. The virtual photon fluctuates into a quark-antiquark pair, i.e. a colour dipole, that subsequently scatters off the proton. The scattering of the dipole off the proton is given by the so-called dipole scattering amplitude $N(r_\perp, x)$, in which $r_\perp$ is the transverse size of the dipole. In the dipole picture, gluon saturation implies that the linear BFKL equation [2–4], which describes the evolution of the dipole scattering amplitude at small x, is expected to be supplanted by a non-linear evolution equation, such as the BK equation [5–8]. These equations are discussed in chapters 4 and 5.

An important consequence of saturation is geometric scaling [9], which means that the dipole amplitude becomes a function of a single parameter, $r_\perp Q_s(x)$, where $Q_s(x)$ is the so-called saturation scale. The total cross section of deep inelastic scattering then becomes a function of the single parameter $Q^2/Q_s^2(x)$, where Q^2 is the photon virtuality. This scaling behaviour of the cross section has been observed experimentally for values of x below 0.01 [10–12]. Here, we address the question whether geometric scaling is also visible in deuteron-gold collision data taken at the Relativistic Heavy Ion Collider (RHIC). Geometric scaling of the dipole amplitude, unlike in DIS, does not lead to a scaling property of the hadron production cross section in nucleon-nucleus collisions, since the dipole amplitude is convolved with parton distribution functions of the nucleon. Hence, one has to study the scaling properties of such data using specific models.

In the usual perturbative picture of nucleon-nucleus (and d-Au) scattering, a parton from the nucleon scatters off a parton from the nucleus. At very high energies however, when the gluon density in the nucleus becomes large enough, the nucleus can be described as a so-called colour glass condensate [13–16]. This formalism is discussed in chapter 3. Instead of scattering off a single gluon at small x, the incoming parton scatters off an effective colour field, the non-abelian analogue Weizsäcker-Williams field in electrodynamics, the sources of which are the partons of the nucleus at large x. In the

McLerran-Venugopalan (MV) model [13–15, 17], the distribution of these sources is assumed to be Gaussian, and an analytic result can be obtained for the amplitude, N_F, of a quark scattering off the nucleus. The amplitude N_F turns out to be equal to (minus) the Fourier transform of the dipole amplitude N that is used to describe deep inelastic scattering at small x. While the dipole amplitude that corresponds to the MV model shows saturation, it does not incorporate evolution in x. Hence, it cannot be used to investigate geometric scaling.

In principle, one can try to find a dipole amplitude that incorporates x evolution by solving the BK equation. However, presently no analytic solutions are known. Still, one can derive a couple of properties of the solution by considering the BFKL equation in the presence of a saturation boundary condition as an approximation to the BK equation [9], which is discussed in chapter 4. Alternatively, one can approximate the BK equation by expanding its kernel χ. This leads to the so-called travelling wave approximation [18, 19], which is discussed in chapter 5. Both approaches lead to the following two expectations for the dipole amplitude at $r_\perp \leq Q_s(x)$. Firstly, at asymptotically small x, the dipole amplitude becomes geometrically scaling. Secondly, in the kinematic region $1 < \ln 1/r_\perp^2 Q_s^2 \ll \bar{\alpha}_s \chi'(\gamma_s) \ln 1/x$, where $\gamma_s = 0.628$, the amplitude shows approximate geometric scaling, and can be written as $N(r_\perp, x) = (r_\perp^2 Q_s(x)^2)^\gamma$. Here, $\gamma = \gamma_s + \Delta\gamma$ with $\Delta\gamma \sim \ln(1/r_\perp^2 Q_s^2)/Y$, so that the exponent γ rises logarithmically with $1/r_\perp$ and violates geometric scaling at finite values of $Y = \ln 1/x$. The exponent γ is often referred to as the anomalous dimension.

In the absence of analytic solutions of the BK equation, phenomenological models for the dipole amplitude, which share some properties of the MV model, have been constructed, both for the description of small-x DIS data and d-Au collision data. A number of such models that incorporate to some extent the expectations from BFKL/BK evolution are discussed in chapter 6. We focus on the Dumitru-Hayashigaki-Jalilian-Marian (DHJ) model [20], which incorporates both the logarithmic rise and the scaling violations in the anomalous dimension γ. We study in chapter 7 whether these properties are actually consistent with numerical solutions of the BK equation. To do so, we employ the code of Ref. [21] to generate the numerical solutions, and combine them with the DHJ expression for the dipole amplitude to obtain a numerical result for the anomalous dimension γ. From this analysis we recover some expected properties of the anomalous dimension, the most important difference being its behaviour at the saturation scale. Instead of $\gamma(r_\perp = 1/Q_s) = 0.628$, we find that $\gamma(r_\perp = 1/Q_s)$ is in general a function of x, which approaches a value of 0.44 in the limit of $x \to 0$.

In chapter 8, we investigate whether the small-x properties of the anomalous dimension that are incorporated in the DHJ model are necessary to describe the RHIC data on hadron production in d-Au collisions. While the DHJ model is able to describe the forward data, i.e. at hadron rapidities of more than 2, it turns out that the same data can also be described by a new model whose anomalous dimension has neither the logarithmic rise, nor the scaling violations that are expected from small-x evolution. In fact, this exactly geometrically scaling model is able to describe the data at all rapidities. Where the DHJ model deviates from the data, the probed values of x in the gold nucleus become larger than 0.01, so that one cannot expect to find small-x effects in the first place. Since at rapidities of 2 and larger both models work, the data are not restrictive enough to discern the exact properties of the anomalous dimension. Hence, we conclude that while the RHIC data turn out to be compatible with geometric scaling, no signatures of small-x evolution are found. Further, we show that at the new Large Hadron Collider (LHC), the DHJ model and the geometrically scaling model are clearly distinguishable at small x, due to the much higher energies. Hence, the LHC will provide a first test of the expected small-x properties of the anomalous dimension of phenomenological dipole models.

Another observable that is sensitive to saturation is the transverse polarization of Λ hyperons that are produced in high energy nucleon-nucleus collisions. As discussed in chapter 9, due to the odd dependence on transverse momentum of the polarized fragmentation functions that are used in the description of this observable [22–24], the polarization is sensitive to the derivative of the dipole scattering amplitude with respect to transverse momentum. In Ref. [25] it was shown that in the MV model this derivative, and hence Λ polarization, peaks around the saturation scale. Extending this analysis, in chapter 9 we find that also using more realistic models that include x-evolution, the polarization displays a peak at transverse momenta that are proportional to the saturation scale. We show that the x dependence of the saturation scale can in principle be reconstructed from the running of the peak position with x_F. Even though this result is to some extent model dependent, the appearance of the peak and its relation to the saturation scale are expected to be generic for dipole models that incorporate saturation. We show that the peak in the polarization is expected to show up at transverse momenta above 1 GeV for LHC kinematics. Hence, the polarization of Λ particles offers a unique way of directly probing the saturation scale in nucleon-nucleus collisions.

In conclusion, the small-x inspired properties of existing phenomenological dipole models are neither completely compatible with the BK equation, nor with presently available RHIC data. We have proposed a model that is compatible with both the RHIC and DIS data, but does not have the small-x properties of previous models—in particular it does not incorporate a logarithmic rise of the anomalous dimension or violations of geometric scaling. Rather, it is exactly geometrically scaling like the DIS data. Hence, neither the scaling violations nor the logarithmic rise that are expected from small-x evolution can be established using present data. We have shown that this may be different at LHC. The transverse momentum distribution of produced hadrons is sensitive to the rise of the anomalous dimension, so that by measuring the slope of this distribution it will be possible to distinguish the logarithmic rise expected from small-x evolution and the faster rise of the new model that follows from the RHIC data. Further, we have shown how the polarization of Λ hyperons provides a direct probe of the saturation scale, so that a measurement of this polarization may, especially at LHC, offer the possibility of probing the x dependence of the saturation scale in nucleon-nucleus collisions.

Bibliography

[1] A. H. Mueller and B. Patel, *Single and double BFKL pomeron exchange and a dipole picture of high-energy hard processes*, Nucl. Phys. **B425**, 471 (1994), hep-ph/9403256

[2] V. S. Fadin, E. A. Kuraev and L. N. Lipatov, *On the Pomeranchuk Singularity in Asymptotically Free Theories*, Phys. Lett. **B60**, 50 (1975)

[3] E. A. Kuraev, L. N. Lipatov and V. S. Fadin, *The Pomeranchuk Singularity in Nonabelian Gauge Theories*, Sov. Phys. JETP **45**, 199 (1977)

[4] I. I. Balitsky and L. N. Lipatov, *The Pomeranchuk Singularity in Quantum Chromodynamics*, Sov. J. Nucl. Phys. **28**, 822 (1978)

[5] I. Balitsky, *Operator expansion for high-energy scattering*, Nucl. Phys. **B463**, 99 (1996), hep-ph/9509348

[6] I. Balitsky, *Factorization for high-energy scattering*, Phys. Rev. Lett. **81**, 2024 (1998), hep-ph/9807434

[7] I. Balitsky, *Factorization and high-energy effective action*, Phys. Rev. **D60**, 014020 (1999), hep-ph/9812311

[8] Y. V. Kovchegov, *Small-x* F_2 *structure function of a nucleus including multiple pomeron exchanges*, Phys. Rev. **D60**, 034008 (1999), hep-ph/9901281

[9] E. Iancu, K. Itakura and L. McLerran, *Geometric scaling above the saturation scale*, Nucl. Phys. **A708**, 327 (2002), hep-ph/0203137

[10] K. J. Golec-Biernat and M. Wüsthoff, *Saturation effects in deep inelastic scattering at low* Q^2 *and its implications on diffraction*, Phys. Rev. **D59**, 014017 (1999), hep-ph/9807513

[11] A. M. Stasto, K. J. Golec-Biernat and J. Kwiecinski, *Geometric scaling for the total* $\gamma * p$ *cross-section in the low x region*, Phys. Rev. Lett. **86**, 596 (2001), hep-ph/0007192

[12] F. Gelis, R. B. Peschanski, G. Soyez and L. Schoeffel, *Systematics of geometric scaling*, Phys. Lett. **B647**, 376 (2007), hep-ph/0610435

[13] L. D. McLerran and R. Venugopalan, *Computing quark and gluon distribution functions for very large nuclei*, Phys. Rev. **D49**, 2233 (1994), hep-ph/9309289

[14] L. D. McLerran and R. Venugopalan, *Gluon distribution functions for very large nuclei at small transverse momentum*, Phys. Rev. **D49**, 3352 (1994), hep-ph/9311205

[15] L. D. McLerran and R. Venugopalan, *Green's functions in the color field of a large nucleus*, Phys. Rev. **D50**, 2225 (1994), hep-ph/9402335

[16] A. Dumitru, A. Hayashigaki and J. Jalilian-Marian, *The color glass condensate and hadron production in the forward region*, Nucl. Phys. **A765**, 464 (2006), hep-ph/0506308

[17] Y. V. Kovchegov, *Non-Abelian Weizsaecker-Williams field and a two- dimensional effective color charge density for a very large nucleus*, Phys. Rev. **D54**, 5463 (1996), hep-ph/9605446

[18] S. Munier and R. B. Peschanski, *Geometric scaling as traveling waves*, Phys. Rev. Lett. **91**, 232001 (2003), hep-ph/0309177

[19] S. Munier and R. B. Peschanski, *Traveling wave fronts and the transition to saturation*, Phys. Rev. **D69**, 034008 (2004), hep-ph/0310357

[20] A. Dumitru, A. Hayashigaki and J. Jalilian-Marian, *Geometric scaling violations in the central rapidity region of d + Au collisions at RHIC*, Nucl. Phys. **A770**, 57 (2006), hep-ph/0512129

[21] R. Enberg, *BKsolver: numerical solution of the Balitsky-Kovchegov nonlinear integro-differential equation*, http://www.isv.uu.se/~enberg/BK/

[22] P. J. Mulders and R. D. Tangerman, *The complete tree-level result up to order 1/Q for polarized deep-inelastic leptoproduction*, Nucl. Phys. **B461**, 197 (1996), hep-ph/9510301

[23] M. Anselmino, D. Boer, U. D'Alesio and F. Murgia, *Lambda polarization from unpolarized quark fragmentation*, Phys. Rev. **D63**, 054029 (2001), hep-ph/0008186

[24] M. Anselmino, D. Boer, U. D'Alesio and F. Murgia, *Transverse Lambda polarization in semi-inclusive DIS*, Phys. Rev. **D65**, 114014 (2002), hep-ph/0109186

[25] D. Boer and A. Dumitru, *Polarized hyperons from p A scattering in the gluon saturation regime*, Phys. Lett. **B556**, 33 (2003), hep-ph/0212260