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The ridge through colored glass

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Abstract

We briefly outline the role of gluon saturation, and the interplay between initial and final state effects, in generating the ridge observed in high multiplicity proton–proton and proton–nucleus collisions.

Keywords: Color glass condensate; Glasma; Quark–gluon plasma

1. Introduction: High multiplicity events and gluon saturation

The striking data on azimuthally collimated long range rapidity correlations in proton–nucleus ($\mathrm{p} + \mathrm{A}$) collisions presented at Quark Matter 2014 were one of the highlights of the conference. There is a strong viewpoint that these results present compelling evidence for collective flow of the produced matter, as opposed to being primarily an initial state effect. We shall examine this viewpoint closely, if briefly, in this note. We shall also recapitulate the pre-Quark Matter studies that argued that key features of the data can be understood as an initial state phenomenon. Since Quark Matter, several papers have appeared that have an initial state perspective. These too will be addressed within space constraints.

Regardless of whether collective flow drives the effect or not, the dynamics of the initial state holds the key to understanding the phenomenon. By this we mean specifically the quark and gluon configurations in the proton and the nucleus that are triggered in high multiplicity events, as well as the preequilibrium dynamics that may occur prior to the time when hydrodynamics may be relevant. Consider proton–proton ($\mathrm{p} + \mathrm{p}$) collisions where a small but distinct ridge is seen in high multiplicity events. The highest multiplicity events triggered corresponded

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to charged particle multiplicities $N_{\mathrm{ch.}} \geq 110$ particles in nearly 5 units of rapidity; these are rare, approximately one in a million events.

It is natural to ask what the spatial structure is of the quark–gluon configurations in the proton that generate such large numbers of hadrons. The guidance from the typical events studied in HERA inclusive deeply inelastic scattering (DIS) data is that the gluon momentum distribution behaves as $xdN/dx \propto 1/x^{\lambda(Q^2)}$. The $\lambda(Q^2)$ extracted from data has an interesting structure [1]; it is nearly constant with $\lambda(Q^2) \approx 0.08$ until $Q^2 = 1\ \mathrm{GeV}^2$, but rises subsequently approximately as $\ln(Q^2)$ with $\lambda(Q^2 = 10\ \mathrm{GeV}^2) \sim 0.25$. Working in a frame where the rapidity evolution of gluons from the beam rapidity down to $y = 0$ is in the wavefunction of one of the protons, one finds in the rapidity interval $0 \leq y \leq 2.4$ that $N(Q^2 = 2\ \mathrm{GeV}^2) \sim 6$–$7$ gluons. This is obtained by integrating the gluon distribution over the corresponding x range $(x_{\mathrm{min.}}, x_{\mathrm{max.}}) \equiv (2 \cdot 10^{-4}, 2.2 \cdot 10^{-3})$ with $\lambda(Q^2 = 2\ \mathrm{GeV}^2) = 0.14$. If all the gluons in the collision are released, one obtains about 13 gluons in nearly 5 units of rapidity, a far cry (assuming parton–hadron duality) from the > 110 hadrons measured in the high multiplicity $\mathrm{p}+\mathrm{p}$ events. To obtain numbers that are in the ball park, one must have the effective value of $\lambda(Q^2 = 2\ \mathrm{GeV}^2) \approx 0.4$, a very rapid rise of the gluon distribution indeed!

If there is a very rapid rise of the gluon distribution, when does the parton model picture of individual partons break down? A simple estimate is obtained if we assume that each of the $O(10^2)$ gluons is of radius $2/Q$, and one requires that they do not overlap. The only way to ensure this is to increase the gluon radius of the proton; for $N_{\mathrm{ch.}} \sim 100$, our estimate would give ~ 3 fm! The Hanbury-Brown–Twiss (HBT) radii (typically larger than the initial proton size) measured in $\mathrm{p}+\mathrm{p}$ collisions at the LHC, for comparable multiplicities are smaller than 2 Fermi [2]. If on the other hand one allows gluon modes with $k_\perp \leq Q_S$, where Q_S is the saturation scale, to be maximally occupied with occupancies $\sim 1/\alpha_S$, the gluon radius of the proton can be smaller. The number of produced gluons can be computed numerically in the CGC framework [3] and one obtains [4] $dN_g^{\mathrm{prot.}}/d\eta \approx \frac{1.1 C_F}{2\pi^2} \frac{S_\perp Q^2_{S,\mathrm{prot.}}}{\alpha_S}$. Here $C_F = 4/3$ and $S_\perp = \pi R^2_{\mathrm{prot.}}$; for $R_{\mathrm{prot.}} = 0.8$ fm and $\alpha_S = 0.3$, one obtains $dN_g^{\mathrm{prot.}}/d\eta \sim 110$ for $Q^2_{S,\mathrm{prot.}} = 2\ \mathrm{GeV}^2$.

There are several aspects of this back of the envelope estimate that are worthy of note. Firstly, at the price of a reasonable semi-hard scale, by allowing for occupancies $1/\alpha_S$, one is able to accommodate the high multiplicities generated in the proton–proton collisions without requiring proton radii inconsistent with HBT analyses. Secondly, the saturation scale of $Q^2_{S,\mathrm{prot.}} = 2\ \mathrm{GeV}^2$, while not apparently very large, is in fact quite large for a proton. To put this in context, saturation model fits to HERA inclusive and diffractive data give $Q_S^2 \sim 0.5\ \mathrm{GeV}^2$ at the center of the proton [5]. The additional factor of 4 in Q_S^2 obtained in rare, triggered LHC events is only otherwise attained in a multi-TeV center-of-mass $\mathrm{e}+\mathrm{p}$ DIS collision. Finally, the approximate boost invariance of two particle correlations arises naturally in the Color Glass Condensate (CGC) framework that describes the properties of saturated gluons.

These considerations suggest that regardless of whether initial state or final state dynamics dominates, the gluons responsible for this dynamics exist in high occupied states characterized by a semi-hard dynamical saturation scale. If one accepts this, it then follows immediately that the highly occupied modes with $k_T \ll Q_S$ must experience some sort of collective dynamics; the open question is whether this collective dynamics is best described by (nearly ideal) hydrodynamics. Conversely, the dynamics of modes with $k_T \geq Q_S$ is not collective dynamics, but is nevertheless non-trivial dynamics described by the CGC – at large k_T is should match on to perturbative QCD. We will next address what this initial state CGC dynamics is, and outline some of the open issues.