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Long range correlations in high multiplicity hadron collisions: Building bridges with ridges

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ABSTRACT

We discuss the physics of the ridge – azimuthally collimated long range rapidity correlations – in high multiplicity proton–proton and proton–nucleus collisions. We outline some of the theoretical discussions in the literature that address the systematics of these ridge correlations.

1. Introduction

Quantum Chromodynamics (QCD) was established to be the right theory of the strong interaction shortly after the discovery of asymptotic freedom. In the 40 years since, the predictions of perturbative QCD have become so precise that they are used as background for new physics beyond the standard model. Nevertheless, if compared to Quantum Electrodynamics (QED) as a benchmark, there is a long way to go. In QED, simple questions about how electrons and photons interact with media are well understood; more generally, the collective properties of QED form a major part of what we call condensed matter physics. In QCD, we are a long way away from this level of understanding. Even formulating the right experiments to address questions, for example, about how quarks and gluons scatter off an extended strongly interacting medium, is challenging.

Prof. Wit Busza has been in the forefront of performing high energy scattering experiments that seek to address the elementary yet profound questions that bring into sharp relief our limitations in understanding nature's strong interaction. He realized early on that colliding protons at high energies of light and heavy nuclei are interesting in their own right [1]. They provide important insight into the multiple scattering of partons in a QCD medium, the energy loss and "stopping" of fast partons in-media [2], and tackle the important question of how partons hadronize in and out of media. In

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several cases, the data pointed to intriguingly simple scaling patterns, which are still not completely understood [3].

With the advent of the Relativistic Heavy Ion Collider (RHIC), Wit Busza lead the PHOBOS experiment to efficiently produce first results from RHIC [4]. Proton–nucleus (or in this case deuteron–nucleus) collisions came to be seen primarily as a benchmark for patterns in nucleus–nucleus collisions. There were however results obtained in deuteron–gold collisions of strong shadowing effects in forward single inclusive hadron production [5] and in "forward–forward" dihadron correlations [6]. Both of these effects were *predicted* to arise as a result of gluon saturation in nuclei [7,8].

Proton–nucleus collisions at the LHC, with previously unimaginable center-of-mass energies of $\sqrt{s} = 5020$ GeV/nucleon, have breathed fresh life into the subject. They have made transparent Wit Busza's view that these collisions are not merely a benchmark for interesting physics but are profoundly interesting in themselves in what they may offer of a deeper understanding of dynamics in QCD. In the rest of this talk, I will focus on the remarkable ridge phenomenon in high multiplicity proton–proton and proton–nucleus collisions. These are two particle correlations that are long range in their relative pseudorapidity separation and collimated in relative azimuthal angle. They were first discovered at RHIC in $A + A$ collisions [9]; in particular, the PHOBOS experiment demonstrated correlations over 4 units in relative rapidity [10]. At the LHC, the CMS heavy ion group, including several former PHOBOS members, have performed seminal work in uncovering such correlations in smaller sized systems. Recent reviews of the ridge effect can be found in [11–14].

2. Initial state effects and the ridge

In a series of three recent papers with Kevin Dusling [15–17], we argued that the ridge data on two particle correlations in high multiplicity proton–proton and proton–nucleus collisions from the CMS collaboration [18,19] provided strong evidence for gluon saturation and the Color Glass Condensate (CGC) effective field theory (EFT) [20].

Typically in perturbative QCD the only two parton correlation that one obtains is the back-to-back $\Delta\Phi \sim \pi$ correlation from the di-jet graph; this explains why none of the event generators saw the ridge collimation at $\Delta\Phi \sim 0$. In the CGC effective theory, the nearside $\Delta\Phi \sim 0$ collimation is obtained from connected two gluon production QCD graphs called "Glasma graphs". They are QCD interference graphs. In conventional perturbative QCD computations, these graphs are ignored for good reason. Their contribution at high p_T and in peripheral collisions is negligibly small.

However, most remarkably, the high occupancy of gluons (for transverse momenta $k_\perp \leq Q_S$, where Q_S is the saturation scale) in rare high multiplicity proton–proton events enhances such graphs by α_S^{-8}. This corresponds to a strikingly large enhancement of $\sim 10^5$ for typical values of the probed QCD fine structure constant α_S! Thus in the power counting of the EFT, gluon saturation ensures that Glasma graphs provide a significant additional contribution in high multiplicity events to "di-jet" QCD graphs.

The importance of Glasma graphs was first discussed in [21] and the formalism developed in [22,23]. It was first postulated as an explanation of the high multiplicity CMS proton–proton ridge in [24], and a quantitative description of the nearside collimated yield obtained in [25].

The di-jet contribution that is long range in rapidity is described in the CGC EFT by BFKL dynamics [26,27]. We showed in [17] that BFKL dynamics does well in describing the wayside spectra in high multiplicity proton–proton collisions. The description is significantly better than PYTHIA-8 [18], and $2 \to 4$ QCD graphs in the Quasi-Multi-Regge-Kinematics (QMRK) [28,29]. Both of these approaches overestimate the wayside yield especially at larger momenta.

Strictly speaking, the BFKL "impact factors" are replaced by the gluon unintegrated distributions obtained from solutions of the running coupling Balitsky–Kovchegov equation [30,31]. The latter encodes saturation effects in small x evolution. It is important to note that the corresponding di-jet contributions are then also enhanced $O(\alpha_S^{-4})$ by gluon saturation in high multiplicity hadron collisions. Without this saturation generated enhancement, the di-jet per trigger yield would not agree with the data. Subsequently we showed for the same parameter set as in proton–proton collisions, a good description is obtained for proton–nucleus collisions within the uncertainties of