The Initial Stages of Colliding Nuclei and Hadrons

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Abstract. The final day of the Hot Quarks 2016 conference was focused on the discussions of the initial stages of colliding nuclei and hadrons. In this conference proceedings we give a brief overview of a few selective topics discussed at the conference that include latest developments in the theoretical description of the initial state towards understanding a number of recent experimental results from RHIC and LHC.

1. Introduction

In the standard model of heavy ion collisions, by "initial stages", one commonly refers to two Lorentz contracted sheets of saturated partonic matter that collide to form an ensemble of highly occupied gluon fields. This initial stage undergoes a pre-equilibrium evolution and eventually evolves to a phase describable by viscous hydrodynamics. Many aspects of the standard model of heavy collisions have been verified by a number of experimental observations. One powerful observable in this context is the two-dimensional (2D) di-hadron correlation function (per-trigger-particle associated yield distribution) expressed in terms of relative pseudo-rapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$) of the emitted particles as shown in the left panel of Fig.1. Such correlations include two major components, the di-jet and the ridge. The short range di-jet correlations give rise to a narrow near-side peak at ($\Delta\eta = 0, \Delta\phi = 0$) but can extend over the entire $\Delta\eta$ range on the away side ($\Delta\phi \sim \pi$) whereas the long-range ridge-like correlations can persist up to large $\Delta\eta$ on both near and away sides.

The production of back-to-back di-jets are constrained by momentum conservation and the strength of such correlations gets diminished when going from peripheral to central events [1]. Such observation is a consequence of the well-known scenario of jet-quenching, a key signature to support the formation of a strongly correlated Quark Gluon Plasma (sQGP) in A+A collisions. On the other hand, the strength of the long range ridge-like correlations are often characterized by the Fourier coefficients $V_{\Delta n}$ obtained after the harmonic decomposition of the correlation functions integrated over $\Delta\eta$. These two particle $V_{\Delta n}$ coefficients can be related to single-particle azimuthal anisotropy harmonics v_n, a possible source of which is the hydrodynamic expansion of the medium in response to initial spatial anisotropy that is nearly boost-invariant, once again consistent with the scenario of sQGP formation in A+A collisions.

For years collisions of small systems such as p+p and p+A have been providing baselines for measurements in A+A collisions. Such consensus has been strongly challenged by a number of striking recent measurements that resemble features commonly observed in A+A collisions. As shown in Fig.1, the long range ridge like structure seen in peripheral Pb+Pb collisions also appears in the high multiplicity events in p+p and p+Pb collisions for hadrons with $1 < p_T < 3$ GeV.
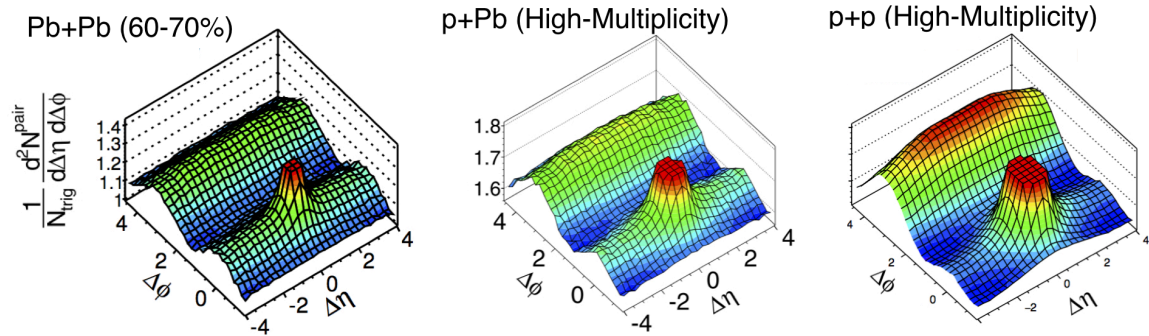
Figure 1. Di-hadron correlations in relative pseudo-rapidity and azimuthal angle in peripheral Pb+Pb and high multiplicity p+Pb and p+p collisions [1–3].

2. Initial state correlations

By looking at Fig. 1 a natural question arises : does the same underlying mechanism drive these long-range correlations in all collision systems ? From causality arguments it is known that any form of correlation that spans over a wide range of rapidity must originate at the early stages of collisions [4]. This makes long-range di-hadron correlations an initial state driven phenomenon for any collision systems. However what short of initial state correlations dominate the experimental observations could be a matter of debate. In recent years, two possible sources of initial state correlations have been identified : 1) intrinsic momentum space correlations of partons that survive the process of hadronization, 2) position space correlations (geometric) of partons that are converted to momentum space correlations by the final state interactions. In principle both should contribute to the observed experimental correlations although their relative contribution will depend on the collision system.

In a scenario like A+A collisions where the system size and the number of produced initial partons is large, the mean free path of a typical semi-hard parton ($\sim$ GeV) is expected to be much smaller than the system size. Therefore, the initial-state momentum space correlations between such partons may be destroyed due to the phenomenon of quenching. This is a natural consequence for a system approaching thermalization and undergoing hydrodynamic evolution in the subsequent phase [5,6]. As a result of which the azimuthal correlations of final hadrons particularly at small transverse momentum in A+A collisions will be dominated by hydrodynamic response to the initial state geometry caused by the position space correlations of initial partons.

In the collisions of small systems, however, the scenario is different as the number of initial (semi-) hard partons is small. In a typical low multiplicity event of small collision systems, the dominant correlation will be due to initial state momentum space correlations of back-to-back jets that escape the interaction region without loosing a fraction of their energy by interacting with the other soft partons produced in the collision. Going to relatively higher multiplicity events, additional multi-parton processes will start to contribute to such momentum space correlations as a consequence of gluon saturation. Going to even higher multiplicity events, interaction among the produced particles will lead to dilution of initial state correlations. Eventually in the limit of very high multiplicity, when all semi-hard partons are quenched, a complete loss of momentum space correlations will be accompanied by formation of a thermalized medium and one will recover the picture of A+A collisions. Therefore, for a fixed size system there may be a critical density of partons leading to a cross over from a regime dominated by initial-sate dynamics to one dominated by final state interaction such as hydrodynamic expansion (see Ref [7] for a detailed discussion). So far a first-principles description of a given system over
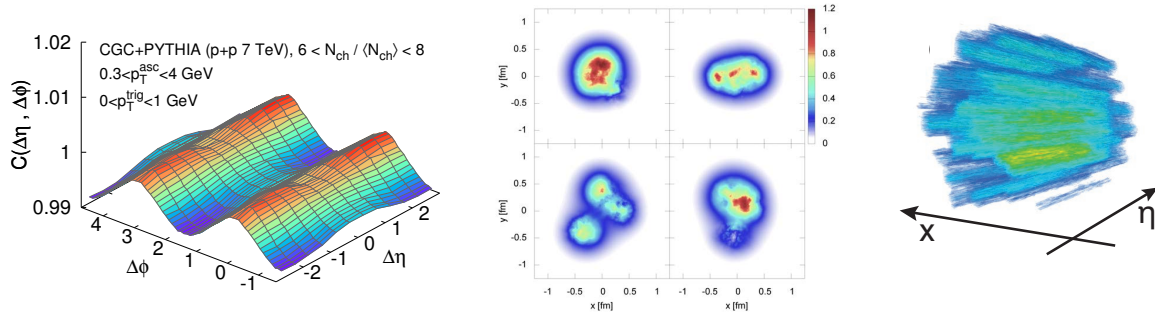
Figure 2. (left) Ridge-like structure of the di-hadron correlations obtained in CGC-PYTHIA (CGC-Lund) framework [10]. (Center) Distribution of gluon density around valance quarks inside a proton constrained by HERA data [11]. (Right) Distribution of initial energy density obtained from the 3D-Glasma initial conditions [12].

the entire regime of parton densities in a single framework is not feasible. Current theoretical studies of the initial state therefore mainly focus in a regime where either 1) final state effects can be neglected, e.g. to describe the systematics of di-hadron correlations in small collision systems or 2) the initial state momentum space correlations can be neglected, e.g. to describe the initial conditions for fluid-dynamic simulations in A+A collisions. We will discuss these approaches in the rest of the proceedings.

3. Angular correlations in the collisions of small systems

The interesting observations in small collision systems such as p+p are made in high multiplicity events. It is therefore necessary to understand how such events originate in the first place. This would require an understanding of multi-particle productions in QCD at high energies ($\sqrt{s} \to \infty, x \to 0$). At such energies the occupation number of gluons below the saturation momentum $k_\perp < Q_S$ in the hadron wave functions becomes large ($O(1/\alpha_S)$) as a consequence of gluon saturation. In the collisions of two such hadrons, the weak coupling description of particle production at high energies is best captured in the framework of Color-Glass-Condensate (CGC). In this framework the origin of high-multiplicity events is a consequence of initial state fluctuations that lead to rare configurations of the parton distribution in the colliding hadrons and the mechanism of correlated n-particle production in CGC [8, 9]. The same underlying mechanism is also responsible for azimuthally collimated two particle production.

The angular collimation in CGC can be attributed to the details of the wave functions of the colliding hadrons that lead to enhancement in the probability of finding two gluons with similar quantum numbers and transverse momentum close to the saturation scale Q_S. Such angular collimation extends over a long range in rapidity due to the boost-invariant nature of the classical gluon fields that dominate the hadronic wave function. Such fields lead to rapidity independent gluon production over an interval of $\Delta y \lesssim 1/\alpha_s$ that can generate ridge like structure. The systematics of such correlations in CGC have been analyzed under different approximation schemes e.g. the glasma-graph contribution to two gluon production, Bose-enhancement of two idential momentum partons in the projectile, spatial density variations of partons, local anisotropy of color-domains in the target, multiple interactions of the classical fields [4, 13–23], etc. For a recent review on this we refer the reader to Ref [24].

The different sources of fluctuations and the mechanisms of multi-particle production that lead to initial partonic correlations within the framework of CGC discussed above are well incorporated in the phenomenological approach of the IP-Glasma model [25]. In this model one can compute the momentum space distributions of gluons dN_g/dyd^2k_t after collisions

that contain the information of $n-$particle correlations. Averaged over many events, these lead to quantities of experimental interests like two-particle azimuthal correlation functions, multiplicity distributions, etc. However such correlations exist at the parton and in order to make comparisons to experimental data, a realistic hadronization scheme is required. The recent major progress in this direction has been the development of CGC-PYTHIA (CGC-Lund) model [10] which combines the event-by-event distribution dN_g/dyd^2k_t from IP-Glasma and the Lund string fragmentation of PYTHIA. CGC-PYTHIA naturally produces the probability distribution of multiplicity $P(N_{ch})$ for charged hadrons that is consistent with the experimental distributions. The tails of such distributions are populated by high multiplicity events ($N_{ch} > 6 \times \langle N_{ch} \rangle$) for which one can calculate the 2D di-hadron correlation function as shown in Fig.2 (left). One can clearly see the long-range[1] ridge like structure as seen in the experiment (Fig.1). In addition, the CGC-PYTHIA model, purely from initial state dynamics, can also reproduce the mass ordering of average transverse momentum $\langle p_T \rangle_p > \langle p_T \rangle_K > \langle p_T \rangle_\pi$ and elliptic flow coefficients $v_2(\pi) > v_2(K) > v_2(p)$ at $p_T \lesssim 3$ GeV that are often regarded as signatures of collectivity driven by hydrodynamics [10].

4. Initial state geometry, fluctuations in heavy ion collisions

Significant amount of research in recent years has been focused on the development of fluctuating initial conditions for A+A collisions. The commonly used Monte-Carlo models of A+A collisions can be classified into many categories e.g. 1) the models purely based on collision geometries such as different implementations of MC-Glauber, 2) models that combine collision geometry with string-fragmentations such as NeXus [26], EPOS [27], UrQMD [28] and AMPT [29] 3) models that include gluon saturation such as DIPSY [30], MC-KLN [31, 32], MC-rcBK [33] and IP-Glasma [25]. These models provide the distributions of initial energy, entropy density, flow etc. that can be matched to hydrodynamic simulations under certain approximations [34]. Due to a large number of unknown parameters involved in the hydrodynamic simulations, in principle it is difficult to directly constrain these models from the measurements in A+A collisions. However recently a few techniques and observables have been identified. For example the studies in Ref. [35] have demonstrated that, in the regime where non-linearities from hydrodynamics are negligible, the correlation between v_3 and v_2 can directly constrain the correlation of ε_3 and ε_2. Such studies have largely excluded different models expect DIPSY, IP-Glasma and MC-Glauber with binary collision scaling. Among other observables, the probability distributions of flow harmonics $P(v_n)$ measured by the ATLAS collaboration [36] have been found to be largely insensitive to the hydrodynamic evolution, particularly the effects of viscosity [37] and therefore can be directly compared to the corresponding initial state eccentricity distributions $P(\varepsilon_n)$. Both MC-KLN and MC-Glauber models have failed to describe $P(v_n)$ data and are therefore been largely constrained at LHC energies. In addition, recently the STAR collaboration [38] has measured the correlation of v_2 with multiplicity N_{ch} from RHIC in ultra-central Au+Au and deformed U+U collisions. Such measurements indicate that models of initial conditions with binary collision scaling of multiplicity such as the two-component Glauber model can not describe the trend seen in data. A good description to such data can be obtained from IP-Glasma model which indicates that color-coherence play important role in the particle production at RHIC [39].

In this context, there have been three major recent developments for Glauber-like models of initial conditions that include, TRENTO [40], Quark-Glauber [41, 42] and Shadowed Glauber [43]. These improvements to Glauber initial conditions modify the two-component model that relate collision geometry to multiplicity or energy density by including additional coherence and lead to a successful description of ultra-central U+U data at RHIC. Recently a p-QCD based model of initial conditions "EKRT" has been developed [37] that includes NLO

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[1] The experimental distribution of the di-hadron correlations also includes the di-jet peak which is not present in the current implementation of CGC-PYTHIA.

cross section of mini-jet production using nuclear PDF, geometry of A+A collisions and an implementation of gluons saturation. EKRT combined with viscous hydrodynamic simulations successfully describes a large number of data including v_n, $P(v_n)$ at RHIC and LHC.

The IP-Glasma is the only model of initial conditions that naturally includes sub-nucleonic fluctuations of initial energy densities. However importance of additional sources of sub-nucleonic fluctuations in the IP-Glasma model was realized while analyzing p+A collisions [44]. In the original implementation of IP-Glasma the proton shape was assumed to be round. A recent modification to the IP-Glasma model includes eccentric shape of protons with gluon density distributed around three valence quarks as shown in Fig. 2(center). Such shape has been constrained by incoherent diffractive $e + p$ data of HERA [11] and will be important for studying light-heavy ion collisions at RHIC and LHC.

Over the past years most of the models of initial conditions have assumed boost-invarince and have not included the full three dimensional (3D) fluctuating structure of the initial energy density. Although such assumptions are somewhat acceptable for observables at mid-rapidity at the LHC and top RHIC energy, at lower energies it is essential to incorporate the longitudinal dependence of initial energy density to perform a full 3+1 dimensional hydrodynamic simulations. Such calculations have been performed by initializing the hydrodynamic simulations with inputs from UrQMD [28], AMPT [29] and EPOS [45] initial conditions. Recently, the inclusion of longitudinal structure in Glauber like initial conditions was performed in the 3D-Glauber model introduced in Ref [46] by combining the LeXus model [47] of scattering with the geometry of heavy ion collisions. 3D-Glauber provides both energy density and net-baryon density needed to perform full 3D+1 hydrodynamic simulations for the Beam Energy Scan (BES) program at RHIC. Many CGC models of initial conditions based on k_T-factorization can provide full 3D initial energy density. In case of the IP-Glasma model, in the original implementation, boost-invariance was assumed. Recently the rapidity dependence of the initial energy density has been included in the IP-Glasma model (Fig.2(right)) by incorporating the JIMWLK evolution of the classical fields in rapidity and this new implementation is referred to as the 3D-Glasma model [12]. Among other models of initial conditions that can provide rapidity dependent initial conditions are the strong coupling based Holographic initial conditions that include the numerical relativity solutions to AdS/CFT to match with hydrodynamic simulations [48, 49]. In such models the transverse geometry is needed to be introduced separately, using a MC-Glauber implementation. Such initial conditions can also be generalized to lower energies.

It must be noted that in most cases the current state of hydrodynamic modeling of A+A collisions comes with a big caveat of directly matching of different models of initial conditions under the assumption of instant thermalization or isotropization. For example, in the weak coupling approach, the initial state consisting of highly occupied gluons $f \sim \mathcal{O}(\frac{1}{\alpha_S}) \gg 1$ is far from being isotropic. However a recent work [5] demonstrates that one can use an effective kinetic theory (EKT) description of QCD to such initial distribution after a subsequent pre-equilibrium evolution when the occupation number becomes $f \ll \mathcal{O}(\frac{1}{\alpha_S})$. The EKT description can then lead the system towards isotropization that can be smoothly matched to a hydrodynamical description when the occupancies are $f \sim \mathcal{O}(1)$ [5].

5. Conclusion

The study of the initial state is a continuously progressing field of research and a large number of exciting new developments have improved our understanding of the structures of colliding hadrons and nuclei. Recent measurements in small systems have provided many challenges towards understanding of the interplay between initial and final state effects in different collisions systems. A comprehensive simulation of heavy ion collisions by smoothly matching initial conditions to fluid-dynamic simulations is very close to reality with recent progress in the understanding of thermalization.

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