Particle production and final state effects in nuclear collisions

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Abstract. We discuss various features of multi-particle production in high-energy nuclear collisions within the IP-Glasma model. We demonstrate that for some observables in heavy-ion collisions the effects of final state interactions governed by fluid-dynamics are essential. In smaller systems, like proton-lead collisions, the same model fails to describe the azimuthal anisotropy of produced particles. This failure can be due to neglected initial state correlations or the lack of a detailed description of the fluctuating spatial structure of the proton at high energies, or both.

1. Introduction

For the physical interpretation of observables in heavy-ion, proton/deuteron-heavy-ion and (high-multiplicity) proton+proton collisions, it is essential to develop a sophisticated description of the multi-particle production mechanism and event-by-event fluctuations. In the high energy limit the color-glass-condensate (CGC) framework \cite{1} is the proper effective theory of quantum chromodynamics (QCD) that provides such description.

One particular implementation of the color-glass condensate picture is the IP-Glasma model \cite{2, 3}. It combines the IP-Sat dipole model \cite{4, 5, 6} with the classical dynamics of gluon fields created in the collision \cite{7, 8, 9}. One of its advantages over more fundamental approaches is its ability to model the spatial distribution, or impact parameter dependence, of hadrons and nuclei. With parameters of the initial lumpy gluon distributions constrained by inclusive and diffractive DIS data from e+\textit{p} scattering at HERA, the IP-Glasma model correctly describes the bulk features of various systems over a wide range of energies \cite{10}.

After briefly introducing the IP-Glasma model and the employed relativistic fluid dynamic simulation MUSIC in Section 2, we highlight various important features of the model that manifest in observables in different collision systems and compare to the well known Monte-Carlo (MC) Glauber model. These range from the correct description of the event-by-event distributions of flow coefficients \textit{v}_n in heavy-ion collisions (Section 3), to the correlation of multiplicity and geometry in ultra-central collisions of deformed nuclei (Section 4) to the prediction of relative system sizes in \textit{p}+\textit{p}, \textit{p}+\textit{A}, and heavy-ion collisions (Section 5). We close by discussing
shortcomings of the model that become prominent in p+A collisions where the predicted $v_n$ coefficients are significantly smaller than the experimental data (Section 6).

2. IP-Glasma + MUSIC

The IP-Glasma model relates the deeply inelastic scattering (DIS) constrained nuclear dipole cross-sections to the initial classical dynamics of highly occupied gluon Glasma fields after the nuclear collision. Given an initial distribution of color charges in the high energy nuclear wave-functions, the IP-Glasma framework computes the strong early time multiple scattering of gluon fields by event-by-event solutions of Yang-Mills equations. It is more general and accurate relative to “$k_T$-factorization” models often used in the small $x$ literature, especially for the soft dynamics that characterizes hydrodynamic flow, because it does not assume at least one nucleus to be dilute and non-linear effects in the interactions of strong gluon fields are taken into account.

The IP-Glasma model naturally includes the effect of several sources of quantum fluctuations: fluctuating distributions of nucleons in the nuclear wave-functions and intrinsic fluctuations of the color charge distribution. This, combined with Lorentz contraction, results in lumpy transverse projections of the gluon field configurations that vary event to event. The scale of this lumpiness is given on average by the nuclear saturation scale $Q_s$ which corresponds to distance scales smaller than the nucleon size [6].

A detailed description of the IP-Glasma model can be found in [2, 3, 10]. For the results shown in this work, the same model parameters as in [10] were used.

The IP-Glasma model provides the gluon fields’ energy-momentum tensor $T_{\mu\nu}$ at every transverse position and at a given time after the collision, from which the energy density $\varepsilon$ and flow velocities $u_{\mu}$ are extracted via the relation $u_{\mu}T^{\mu\nu} = \varepsilon u^\nu$. This provides the initial conditions for fluid dynamic simulations. In the results presented below, the viscous part of the energy momentum tensor is set to zero at the initial time of the fluid dynamic simulation. This is done because the gluon field $T^{\mu\nu}$ is very anisotropic (the longitudinal pressure is approximately zero) and without a mechanism for isotropization, which possibly could be provided by fluctuation triggered instabilities in 3+1 dimensional classical statistical simulations [11, 12], we assume instant isotropization (and thermalization) at the time of switching to fluid dynamics.

We employ the viscous relativistic fluid dynamic simulation MUSIC [13, 14, 15], which is a 3+1 dimensional simulation. However, because the initial conditions from the IP-Glasma model are boost-invariant it is used in its 2+1 dimensional mode.

3. Event-by-event flow distributions in heavy-ion collisions

Flow harmonics $v_n$ are defined via the Fourier decomposition of the azimuthal particle distribution

$$dN/d\phi \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n - \phi_n)$$

where $\phi_n$ represents the phase (event plane) of the $n^{th}$-order harmonic.

Their event-by-event distributions in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV have been measured by the ATLAS collaboration [16]. Comparisons of the experimental data to event-by-event fluid dynamic calculations have demonstrated that only IP-Glasma initial conditions can describe the distributions over the entire centrality range [17, 18, 19]. In Fig. 1 we present the maximally peripheral bins reported by the ATLAS collaboration for distributions of $v_2$, $v_3$, and $v_4$. In addition to the scaled $v_n$ distributions we show scaled eccentricity $\varepsilon_n$ distributions determined from the initial energy density distribution in the transverse plane. They show fairly good agreement with the $v_n$ distributions, in particular for $n = 3$. However, differences appear in the large $v_n$-tails for $n = 2$ and $n = 4$. This observation underlines the importance of final state fluid dynamic evolution and its non-linearities that allow a coupling of different $n$ components.
The results indicate that the fluctuations relevant for event-by-event fluctuations of flow harmonics are very well reproduced in the IP-Glasma model. These are both multiplicity fluctuations that enter via centrality selection, and geometry fluctuations. The former are more strongly affected by color charge fluctuations than the latter. The length scales of the color charge fluctuations are short (of order $1/Q_s$) and are thus not very important for geometric fluctuations probed by $v_2$, $v_3$ or $v_4$. Higher harmonics would be needed to resolve such length scales, but viscous effects dampen them strongly.

4. Multiplicity-geometry correlations in collisions of deformed nuclei

Ultra-central collisions of deformed nuclei such as uranium allow to study the mechanism of particle production via correlations of the multiplicity and the geometry [20]. In particular, after selecting very central events based on the number of spectator neutrons in the forward (and backward) direction, one can correlate the measured $v_2$ with the multiplicity.

A simple two-component Glauber model [21] predicts for collisions of two prolate $^{238}$U nuclei that the eccentricity of the interaction region decreases with increasing multiplicity for very central events. This is due to the contribution of the number of collisions $N_{coll}$ to the multiplicity in this model. If the uranium nuclei collide with their elongated direction aligned with the beam line (so called tip-tip collisions) the number of collisions is larger than if they collide with the shorter direction aligned with the beam line (side-side or body-body collisions). At the same time, tip-tip collisions produce an almost perfectly round interaction region, while body-body collisions generate larger eccentricities on average because of the deformation. For collisions of

Figure 1. Event-by-event distributions of $v_n$ in peripheral collisions. Shown are comparisons of the IP-Glasma+MUSIC calculations (of $v_n$ and $\varepsilon_n$) to experimental data from the ATLAS collaboration [16].
Correlation between the multiplicity (scaled by the mean multiplicity in the given bin) and the eccentricity of the interaction region in the transverse plane. In the IP-Glasma model a weak anti-correlation is found for both U+U and Au+Au collisions, while in the two component MC-Glauber model a stronger anti-correlation is found for U+U collisions and a positive correlation for Au+Au collisions. Figure from [22].

In the IP-Glasma model there is no explicit dependence of the multiplicity on $N_{\text{part}}$ and $N_{\text{coll}}$. There is, however, a weak logarithmic dependence on the orientation of deformed nuclei that is related to the relevant scale $Q_s$ and the running of the strong coupling constant. In [22] it was shown that this leads to a weaker anti-correlation of $\varepsilon_2$ and multiplicity in U+U collisions, and to a very weak anti-correlation (as opposed to a positive correlation) in Au+Au collisions. We demonstrate this in Fig. 2.

5. System sizes in various collision systems

Another interesting aspect, in particular when interpreting various experimental observations as emerging from final state collective dynamics, is the study of the system size in different collision systems. We define the initial size of the system $r_{\text{max}}$ as the (angle-averaged) radius where the energy density reaches a minimal threshold $\varepsilon_{\text{min}}$. The choice of $\varepsilon_{\text{min}}$ only affects the overall normalization of $r_{\text{max}}$; it does not affect the dependence of $r_{\text{max}}$ on the number of charged particles $N_{\text{ch}}$ [23].

In this way we can study within the IP-Glasma model how the system size depends on the collision system for a given multiplicity. We compare $r_{\text{max}}$ (for $\varepsilon_{\text{min}} = \Lambda_{\text{QCD}}^2 = (0.2 \text{ GeV})^4$) as a function of the third root of the charged particle multiplicity in p+p, p+Pb, and Pb+Pb collisions in Fig. 3. The lower end of the band is the initial size, the upper end the maximal size during fluid dynamic evolution. We find that initial sizes at a given multiplicity in p+p and p+Pb collisions are similar, while Pb+Pb collisions are initially larger. When applying fluid
dynamics, this leads to a more violent expansion of the smaller (higher energy-density) system, as can be seen when comparing the width of the band of p+Pb and Pb+Pb collisions at e.g. $\langle N_{ch} \rangle^{1/3} = 4$.

6. Hints towards complex geometries in high-multiplicity p+A collisions

In [19] it was established that the IP-Glasma+music model does a good job in describing experimental data from heavy-ion collisions out to fairly peripheral centrality bins. One can then ask how the model does in describing data from p+A collisions that produce similar multiplicities. Fig. 4 shows the multiplicity dependence of $v_2$ and $v_3$ in peripheral Pb+Pb collisions and (high-multiplicity) p+Pb collisions with comparable multiplicity. While the agreement with experimental data from the CMS collaboration [24] is fairly good in the Pb+Pb case, for p+Pb collisions, however, $v_2$ is significantly under-predicted. $v_3$ agrees for the lower multiplicity studied, but has a rather flat multiplicity dependence and underestimates the experimental data largely at the higher multiplicities.

The reason for this disagreement can be two-fold [19]. On the one hand, we are neglecting all initial state correlations that lead to a $v_2$ [25, 26, 27, 28, 29] and when including fluctuations should also produce odd harmonics. On the other hand, the description of the proton in the IP-Glasma model is somewhat over-simplified. The proton shape is approximated by a sphere, and any deviations from that are due to the small scale color charge fluctuations. The interaction region in p+Pb collisions is dominated by the shape of the smaller projectile, i.e., the proton. This leads to initial geometries in p+Pb collisions that have very small eccentricities and thus lead to small $v_n$ coefficients via fluid dynamic expansion. If there is indeed a significant contribution to $v_n$ coefficients in p+Pb collisions from collective effects, this indicates that the shape of the proton fluctuates significantly more than assumed in the IP-Glasma model. One could envision a description where the small $x$ gluon distributions are still concentrated around large $x$ valence quark positions, which would lead to much larger eccentricities and fluctuations.
In this case p+Pb collisions could be used to determine the shape and fluctuations of gluon distributions in the proton at high energies.

7. Conclusions
We have presented various important features of the IP-Glasma+MUSIC model, including the correct description of event-by-event flow harmonics in heavy-ion collisions, the prediction of geometry-multiplicity correlations in ultra-central collisions of deformed nuclei, and the multiplicity dependence of the system size in various collision systems. We have further demonstrated that within the IP-Glasma model, the measured azimuthal anisotropy of produced particles in p+Pb collisions is not well reproduced. We argue that this may be due to missing initial state correlations or the lack of a detailed enough description of the fluctuating gluon distribution in the proton. These details are most likely irrelevant for (not too peripheral) heavy-ion collisions, because initial state correlations can easily be destroyed by the strong final state interactions, and the fluctuations of nucleon positions dominate the geometry. The detailed sub-structure of each nucleon is much less important than in a p+A or p+p collision.

An improved description of the proton’s spatial structure is highly desirable to determine the origin of the large azimuthal anisotropies measured in p+A (and d+A) collisions.

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