Hadronic observables in p+p and d+Au collisions at RHIC using CGC+PYTHIA

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Abstract

The IP-Glasma model of CGC combined with the Lund model of PYTHIA provides a very successful description of hadron production from gluon dominated non-equilibrium matter in various small collision systems. This new CGC+PYTHIA framework, naturally reproduces several characteristic features of the hadronic observables such as the mass ordering of $v_2(p_T)$ and $\langle p_T \rangle$, often ascribed to collectivity driven by hydrodynamics at the LHC \cite{1}. In this contribution we extend our work to provide a systematic comparison of particle spectra and multiplicity distributions in p+p and d+Au collisions at the RHIC.

Keywords:

1. Introduction

The measurements of bulk hadronic observables in small collision systems at the RHIC and the LHC are of prime importance because they provide direct access to the underlying dynamics of multi-particle production in QCD. However, the theoretical description of such observables is challenging because of the dominance of soft non-perturbative processes. The two major challenges are the systematic treatment of the soft multi-parton production and a consistent treatment of the hadronization of soft partons. Although the former is well addressed by the Color Glass Condensate (CGC) effective theory over a wide range of kinematics, an \textit{ab initio} QCD based treatment of the latter is still missing. Effective approaches have been developed over the years towards a consistent treatment of hadronization \cite{2,3,4}. In the phenomenology of A+A collisions, the problem of hadronization is addressed by fluid-dynamic evolution followed by a Cooper-Frye prescription \cite{5}. Applying such a macroscopic approach across systems of all sizes is however challenging \cite{6}. The conventional microscopic description of small collision systems such as p+p, on the other hand, implements an effective hadronization model based on the Lund-string fragmentation \cite{4}. Such descriptions are implemented in Monte-Carlo event generators like PYTHIA \cite{7}. However, the underlying framework for multi-particle production in PYTHIA fails to describe several observations in high multiplicity events \cite{8}. Computations based on the CGC approach, on the other hand, explain the origin of
such events as a basic feature of rare highly occupied gluon states, as well as provide both qualitative and quantitative description of the most recent observations in such events [9, 10]. The only shortcoming over the years in this approach has been that the data-model comparisons are either done at the level of gluon distributions or by employing fragmentation functions[1], though the latter are applicable at higher $p_T$.

In [1] an approach was developed by combining the IP-Glasma model of CGC and the Monte-Carlo Lund-string fragmentation of PYTHIA. This new CGC+PYTHIA framework successfully describes bulk observations in p+p collisions like multiplicity distributions $P(n)$ and mean transverse momentum $\langle p_T \rangle$ of the identified particles. Most importantly, this model naturally describes the systematics of rare high multiplicity events that has recently generated a lot of interest. Observations such as the growth of the identified particles. Most importantly, this model naturally describes the systematics of rare high multiplicity events that has recently generated a lot of interest. Observations such as the growth of $\langle p_T \rangle$ with charged particle multiplicity $N_{ch}$, its mass ordering $\langle p_T \rangle_{p/p} > \langle p_T \rangle_{K^+} > \langle p_T \rangle_{\pi^0}$, the appearance of long-range di-hadron correlations and mass ordering of the elliptic anisotropy coefficient $v_2[2]$ are often attributed to signatures of collectivity driven by hydrodynamics. The CGC+PYTHIA framework successfully describes such observations without requiring strong final state interactions.

In this contribution, we employ the CGC+PYTHIA framework and focus on a few basic observables such as multiplicity distributions and transverse momentum spectra in 200 GeV p+p and d+Au collisions.

2. The CGC+PYTHIA framework

The details of the CGC+PYTHIA framework are described in [1]. In this framework, we estimate the event-by-event distribution of gluons $dN_g/dk_T dy$ from numerical solutions of the classical Yang-Mills equations as implemented in the IP-Glasma model [4]. The IP-Glasma lattice parameters in our computations are as follows: we use transverse lattices of size $N = 400$ and spacing $a = 0.04$ fm; we employ an infrared regulator of mass $m = 0.2$ GeV. We choose the ratio of the saturation scale to the parameter controlling the width of the color charge fluctuations to be $Q_s/g_s^2 \mu = 0.7$ and the width of the fluctuations of saturation scale $\sigma(\log(Q_s)) = 0.5$. Other details of the lattice setup are similar to the most recent IP-Glasma computation performed in [15]. We integrate the distribution $dN_g/dk_T dy$ to estimate the total number of gluons $N_g$ within the transverse momentum $0 < k_T < k_T^{\text{max}}$ and rapidity $-y^{\text{beam}} < y < y^{\text{beam}}$, where the beam rapidity at $\sqrt{s} = 200$ GeV is $y^{\text{beam}} = 5.36$. We then sample $N_g$ gluons to construct PYTHIA strings and feed them into the Monte-Carlo implementation of the Lund string fragmentation routine in PYTHIA (version 8.235) [7].

The Lund symmetric fragmentation function implemented in PYTHIA is given by

$$f(z, m_T) = \frac{1}{z} (1 - z)^a \exp \left( -\frac{b m_T^2}{z} \right),$$

where the parameters $a, b, m_T$ are constrained by global data – further tuning of the parameters $a$ and $b$ are allowed within the ranges of $0 \leq a \leq 2.0$ and $0.2 \leq b \leq 2.0$, which we will do below to estimate part of our systematic uncertainties.

\[1\] Very recently CGC+NRQCD formalism has been used for the hadronization of $J/\psi$ [11] in high multiplicity p+p/A collisions.
Fig. 2. (color online) Transverse momentum spectra of identified particles obtained from the CGC+PYTHIA framework (shown by bands) in 200 GeV p+p and d+Au collisions compared to the STAR data (shown by symbols).

3. Results

In Fig[1] we present the probability distribution of the scaled inclusive charged hadron multiplicity $P(N_{ch}/\langle N_{ch}\rangle)$ at midrapidity in p+p and d+Au collisions compared to STAR [12] and UA5 data [13]. We find a nice agreement over the entire range of available data, slightly better than a previous CGC computation that does not include fragmentation [16]. It is widely known that $P(N_{ch}/\langle N_{ch}\rangle)$ is intrinsically composed of multiple negative binomial distributions. To the best of our knowledge, CGC is the only available framework models like PYTHIA generate convolution of Poisson distributions for charged hadron multiplicity [8].

We now turn to more differential measurements. In Fig[2] we present the identified particle spectra for the two systems and compare them to the available data from STAR [12]. We present our results as shaded bands which already incorporate the systematic uncertainties in our calculations. These uncertainties include the variation of the evolution time for the Yang-Mills phase in the range of $\tau = 0.4 - 0.6$ fm, the variation of the Lund string fragmentation parameters $a$ and $b$ within the range allowed by PYTHIA and the variation of $k_{T}^{max}$ within a range of $8 - 15$ GeV. Within the uncertainties shown here, CGC+PYTHIA seems to provide a reasonable description of the identified particle spectra at RHIC.

In Fig[3] we show the invariant cross section at mid-rapidity for $n^0$ within the pseudorapidity window of $|\eta| < 0.3$ defined as $\sigma \times 1/(2\pi p_T)dN/dp_Tdy$. We use $\sigma$ to be the inelastic cross section in p+p collisions $\sigma_{inel} = 42$ mb and the total geometric cross section in d+Au collisions $\sigma_{geo} = 2180$ mb estimated by the MC-Glauber model calculations in [17]. Once again we show CGC+PYTHIA calculations as bands that include different aforementioned sources of systematic uncertainties. Within the uncertainties the calculations agree well with the PHENIX data from [18].

4. Summary

In this contribution, we extend our previous work using the newly developed CGC+PYTHIA framework to p+p and d+Au collisions at RHIC. A first data-model comparison of the bulk hadronic observables such as the probability distribution of inclusive charged hadron multiplicity, the identified particle spectra, and invariant cross section of neutral pions looks promising. There are now several new results from the small system scan at RHIC. One particularly striking observation is the hierarchy of $v_2(p_T)$ in $p/d/He – Au$ collisions [19]. Recent computations based on the CGC successfully describes such observations from initial state dynamics alone [16]. A similar hierarchy of $R_{p/d/He−Au}$ observed at RHIC [20] also demands a first principles explanation. A future extension of our work will focus on more complex observables for the small collision systems scan at RHIC. In addition to further exploration of small systems at RHIC and LHC, CGC+PYTHIA is also a promising framework for the phenomenology studies at a future EIC.

It is worth noting that many theoretical uncertainties, that we discuss later, are mitigated by taking the ratio $N_{ch}/\langle N_{ch}\rangle$. 

\[2\]
Fig. 3. (color online) Transverse momentum dependence of the invariant cross section for \( \pi^0 \) in 200 GeV \( p+p \) and \( d+Au \) collisions compared to the PHENIX data from [13].

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