RHIC Physics with the Parton Cascade Model

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Abstract. We present an analysis of the net-baryon number rapidity distribution and of direct photon emission in the framework of the Parton Cascade Model.

Collisions of heavy nuclei at relativistic energies are expected to lead to the formation of a deconfined phase of strongly interacting nuclear matter, often referred to as a Quark-Gluon-Plasma (QGP). Evidences for several of the signatures for the formation of this novel state of matter have recently been reported by experiments conducted at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory [1]. Many aspects of the experimental data indicate that an equilibrated state of hot and dense matter is formed in the collisions of Au nuclei at RHIC. However, it has not yet been well established how quickly this thermalized state is formed and which mechanisms are responsible for the rapid equilibration. It is thus of particular interest to identify processes that can give information about the pre-equilibrium dynamics in these collisions. In our contribution we focus on two such probes of the early phase at RHIC: direct photons and the distribution of net baryon number.

The parton cascade model [2] (PCM) provides a suitable framework for the study of the formation of a hot and dense partonic phase, starting from clouds of valence quarks, sea quarks, and gluons which populate the nuclei. The PCM was devised as a description of the early, pre-equilibrium phase of a nucleus-nucleus collision at high energy. The current implementation [3] does not include a description of the hadronization of the partonic matter and of the subsequent scattering among hadrons. These late-stage processes, however, are not expected to significantly alter the distribution of net baryon number with respect to rapidity, since the net baryon number is locally conserved and baryon diffusion in a hadronic gas can be shown to be slow [4].

The PCM assumes that the state of the dense partonic system can be characterized by a set of one-body distribution functions $F_i(x^\mu, p^\alpha)$, where $i$ denotes the flavor index.
(i = g, u, \bar{u}, d, \bar{d}, \ldots) and \( x^\mu, p^\alpha \) are coordinates in the eight-dimensional phase space. The partons are assumed to be on their mass shell, except before their first interaction.

In our numerical implementation, the GRV-HO parametrization \([6]\) is used, and the parton distribution functions are sampled at an initialization scale \( Q_0^2 \) to create a discrete set of particles. Partons generally propagate on-shell and along straight-line trajectories between interactions. Before their first collision, all partons move with the beam (target) rapidity and do not have an “intrinsic” transverse momentum.

The time-evolution of the parton distribution is governed by a relativistic Boltzmann equation:

\[
p^\mu \frac{\partial}{\partial x^\mu} F_i(x, \vec{p}) = C_i[F]
\]

where the collision term \( C_i \) is a nonlinear functional of the phase-space distribution function. The calculations discussed below include all lowest-order QCD scattering processes between massless quarks and gluons. A low momentum transfer cut-off \( p_T^{\text{min}} \) is needed to regularize the infrared divergence of the perturbative parton-parton cross sections. Additionally, we include the branchings \( q \to qg, q \to q\gamma, g \to gg \) and \( g \to q\bar{q} \). The soft and collinear singularities in the showers are avoided by terminating the branchings when the virtuality of the time-like partons drops below \( \mu_0 = 1 \) GeV. The results to be discussed below have been obtained using the VNI/BMS \([3]\) implementation of the PCM.

The left panel of Figure 1 shows the PCM prediction for the net baryon rapidity distributions for \( \sqrt{s_{NN}} = 200 \) GeV. Solid circles in Fig. 1 denote a calculation in which the PCM has been restricted to primary-primary parton scatterings, and therefore reflects a calculation in which each parton is allowed to scatter only once. Already one hard collision is sufficient to deposit a net surplus of quarks into the mid-rapidity region, resulting in a net baryon density at \( y_{cm} = 0.50 \) at 200 GeV. For comparison, the net baryon number distribution for each colliding nucleus, scaled by a factor 0.4 from the distribution shown in Fig. 1, is shown as a dotted line. This initial state rapidity distribution can be calculated from the parton structure functions by relating the longitudinal momentum of the partons \( p_z \) to the rapidity variable \( y = Y + \ln x + \ln(M/Q_s) \), where \( Y \) is the rapidity of the fast moving nucleon, \( M \) is the nucleon mass, and \( Q_s \) denotes the typical transverse momentum scale.

The remarkable similarity between the scaled initial state rapidity distribution and the PCM calculation involving primary-primary scattering demonstrates that the net baryon number distribution produced by first parton-parton collisions is predetermined by the initial parton structure of the nuclei. The factor 0.4 is the average “liberation factor” \( c \) for partons in the PCM for the selected parameters.

The squares represent a calculation with full parton-parton rescattering. Allowing for multiple parton collisions increases the net baryon density at mid-rapidity roughly by 75%, filling up the dip around mid-rapidity. This trend continues when parton fragmentation is included (diamonds): the net baryon density increases to nearly 17. The rapidity change of a quark in each subsequent collision after its liberation in the
first hard scattering yields an average rapidity shift of roughly 0.65 units per collision. The band around mid-rapidity denotes the range of experimental estimates for the net-baryon density at mid-rapidity [9, 10].

The right frame of Figure 1 shows the net baryon density at mid-rapidity as a function of the momentum cut-off $p_{T}^{\text{min}}$. The observed power law dependence of the net baryon density as a function of $Q_{0}$ stems from the properties of the pQCD cross sections in the PCM. The absence of a saturation at small values of $Q_{0}$ indicates that not all valence quarks are “liberated” in the range of cut-off values considered here. Indeed, we find that the liberation factor for quarks in the nuclear parton distributions varies from about 0.7 for $x > 0.1$ to about 0.2 for $x \approx 0.01$.

Overall we find that the valence quark distribution in the nucleon, combined with these multiple scattering effects, can explain the net baryon excess observed in Au+Au collisions at RHIC in the central rapidity region [11].

Figure 2 shows the photon production processes included in the PCM (left) as well as the transverse momentum distribution (right) of direct photons calculated in the PCM. The solid curve gives a pQCD prediction for prompt photon production, due to Compton and annihilation processes. The accuracy of the PCM implementation is confirmed by the quantitative agreement between this calculation and our results (shown as circles), when an eikonal approximation is used to treat all the collisions in the cascade. We note that a substantial enhancement of the high energy photons is caused by the multiple scattering of partons (triangles). Fragmentation processes lead to an even stronger enhancement in the production of photons. Firstly, there is production of photons from the fragmentation off the scattered quarks. Secondly, and more importantly, the fragmentation leads to a rapid multiplication of partons and enhanced multiple scatterings. The resulting calculation is denoted by the diamonds in figure 2. In summary, we find that multiple scattering of partons leads to a substantial
production of high energy photons, which rises further when parton multiplication due to final state radiation is included \cite{12}. The photon yield is found to scale as $N_{\text{part}}^{4/3}$ and is directly proportional to the number of hard parton-parton collisions in the system, providing valuable information on the pre-equilibrium reaction dynamics of the system.

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