

MARTINI — MONTE CARLO SIMULATION OF JET EVOLUTION*

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We present the Modular Algorithm for Relativistic Treatment of heavy IoN Interactions (MARTINI), an event generator for the hard and penetrating probes in high energy nucleus–nucleus collisions. The simulation consists of a time evolution model for the soft background, such as hydrodynamics, PYTHIA 8.1 to generate and hadronize the hard partons after the medium evolution, which is based on the McGill-AMY formalism and includes both radiative and elastic processes. MARTINI allows for the generation of full event configurations in the high p_T region. We present results for the neutral pion and photon nuclear modification factor in Au+Au collisions at RHIC.

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1. Introduction

High transverse momentum jets in heavy-ion collisions provide information on the produced hot quark–gluon plasma (QGP). To extract this information from experimental data, it is important to develop a good theoretical understanding of the particle production, the interactions of hard partons with the medium, the medium evolution, and the process of hadronization.

In the Modular Algorithm for Relativistic Treatment of heavy IoN Interactions (MARTINI) we incorporate all these aspects into a Monte Carlo framework, to create a most efficient connection between theory and experiment. The creation of particles is taken care of by a slightly modified version of PYTHIA 8.1 that takes into account isospin effects. Initial vacuum showering is also done by PYTHIA. MARTINI handles the subsequent medium evolution by sampling transition rates computed using thermal field

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theory. Both radiative [1–3] and elastic [4] processes are included. The transition rates depend on the thermal background, and information on the temperature, flow and QGP fraction is read in from external sources, like hydrodynamic simulation data. Finally, the evolved partons hadronize using PYTHIA’s Lund model routines.

In this work we present results on neutral pion and photon production and compare to experimental data.

2. The simulation

At the core of MARTINI lies the McGill-AMY formalism for jet evolution in a dynamical thermal medium. This evolution is governed by a set of coupled Fokker–Planck type rate equations of the form

$$\frac{dP(p)}{dt} = \int_{-\infty}^{\infty} dk \left(P(p+k) \frac{d\Gamma(p+k, k)}{dk} - P(p) \frac{d\Gamma(p, k)}{dk} \right), \quad (1)$$

where $d\Gamma(p, k)/dk$ is the transition rate for processes where partons of energy p lose energy k .

In the AMY finite temperature field theory approach, radiative transition rates can be calculated by means of integral equations [3], which correctly reproduce both the Bethe–Heitler and the LPM results in their respective limits [5]. We include transition rates for the processes $g \rightarrow gg$, $q(\bar{q}) \rightarrow q(\bar{q})g$, and $g \rightarrow q\bar{q}$. Furthermore, we include elastic processes employing the transition rates computed in [4], and gluon–quark and quark–gluon conversion due to Compton and annihilation processes, as well as the QED processes of photon radiation $q \rightarrow q\gamma$ and jet-photon conversion.

In MARTINI, we solve Eq. (1) using Monte Carlo methods, keeping track of each individual parton, rather than the probability distributions P . This way we obtain information on the full microscopic event configuration in the high momentum regime, including correlations, which allows for a very detailed analysis and offers a direct interface between theory and experiment. The average over a large number of events will correspond to the solution found by solving Eq. (1) for the probability distribution. Fig. 1 demonstrates this for a $T = 300$ MeV QGP brick of length $L = 1$ fm. Here, we show the final quark distribution after a quark of initial energy $E_i = 10$ GeV passed through the brick, comparing a direct solution of Eq. (1) (see *e.g.* [4]) and the result obtained after 10^5 MARTINI runs, for only elastic and both radiative and elastic processes.

In a full heavy-ion event, the number of individual nucleon–nucleon collisions that produce partons with a certain minimal transverse momentum p_T^{\min} is determined from the total inelastic cross-section, provided by

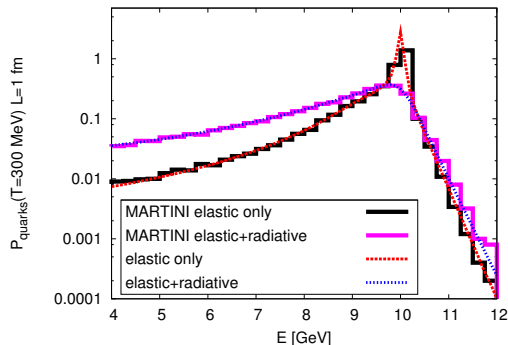


Fig. 1. Quark distribution after passing through a brick of length 1 fm with temperature 300 MeV. Comparing direct solutions of Eq. (1) (dashed) to the MARTINI results. The initial quark energy was 10 GeV. See main text for details.

PYTHIA. The initial transverse positions of these collisions are determined by the initial jet density distribution $\mathcal{P}_{AB}(b, \mathbf{r}_\perp)$, which is determined by the nuclear thickness and overlap functions. The initial parton distribution functions can be selected with the help of the Les Houches Accord PDF Interface (LHAPDF) [6]. We assume isospin symmetry and include nuclear effects on the parton distribution functions using the EKS98 [7] or EPS08 [8] parametrization, by user choice.

The soft medium is described by hydrodynamics or other models, which provide information on the system's local temperature and flow velocity. Before the hydrodynamic evolution begins ($\tau < \tau_0$), the partons shower as in vacuum. At this point, the AMY formalism does not include interference between vacuum and medium radiation. So, we have explored two different implementations of the transition from vacuum to medium evolution. One is to include the complete vacuum shower, which is motivated by there being no apparent reason why the vacuum splittings should end immediately once the medium has formed. Since most of the vacuum shower occurs before the medium has formed, this is a reasonable approximation. The other is to stop the vacuum evolution at the virtuality scale $Q_{\min} = \sqrt{p_T/\tau_0}$, determined by the time τ_0 at which the medium evolution begins. Using the latter method requires an about 10% larger α_s to describe the pion R_{AA} (see below).

During the medium evolution, individual partons move through the background according to their velocity. Probabilities to undergo an interaction are determined in the local fluid cell rest frame using the transition rates and the local temperature. If a process occurs, we sample the radiated or transferred energy from the transition rate of that process. In case of an elastic process, we also sample the transferred transverse momentum, while for radiative processes we assume collinear emission.

Radiated partons are also further evolved if their momentum is above a certain threshold $p_{\min} \simeq 2\text{--}3\text{ GeV}$. The overall evolution of a parton stops once its energy in a fluid cell's rest frame falls below the limit of $4T$, where T is the local temperature. For partons that stay above that threshold, the evolution ends once they enter the hadronic phase of the background medium. In the mixed phase, processes occur only for the QGP fraction. When all partons have left the QGP phase, hadronization is performed by PYTHIA, to which the complete information on all final partons is passed. Because PYTHIA uses the Lund string fragmentation model [9, 10], it is essential to keep track of all color strings during the in-medium evolution. For more information on the simulation please refer to Ref. [11].

The concept of MARTINI is modular, such that we can turn on and off different processes independently, and use different hydrodynamic or other data inputs.

3. Results for one-body observables

In Fig. 2 we present the results for the neutral pion nuclear modification factor, defined by

$$R_{AA} = \frac{1}{N_{\text{coll}}(b)} \frac{dN_{AA}(b)/d^2p_T dy}{dN_{pp}/d^2p_T dy}, \quad (2)$$

in Au+Au collisions at RHIC measured at mid-rapidity in two different centrality classes (0–10%) and (20–30%), employing the corresponding average impact parameters, 2.4 fm and 7.5 fm. Au+Au calculations take into account

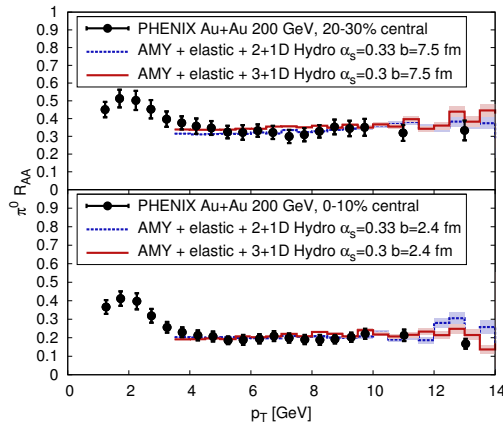


Fig. 2. The neutral pion nuclear modification factor for mid-central (upper panel) and central (lower panel) collisions at RHIC with $\sqrt{s} = 200\text{ GeV}$. MARTINI results ($b = 2.4\text{ fm}$ and $b = 7.5\text{ fm}$) using 3+1 [15] (solid) and 2+1 [12–14] (dashed) dimensional hydro evolution compared to PHENIX data from [16].

both radiative and elastic processes in the medium described by either the 2+1 dimensional hydrodynamics of [12–14] or the 3+1 dimensional hydrodynamics of [15], using a coupling constant $\alpha_s = 0.33$ or $\alpha_s = 0.3$, respectively. α_s was adjusted to describe the experimental measurement of the neutral pion nuclear modification factor R_{AA} in most central collisions. The same value of α_s is used in all following calculations. We find very good agreement with the data for both centrality classes.

We also studied photon production within MARTINI. Apart from direct photons and those produced in the PYTHIA showers, MARTINI includes jet-medium photons from photon radiation and jet-photon conversion. Fig. 3 shows R_{AA}^γ as a function of p_T for most central Au+Au collisions ($b = 2.4$ fm) at RHIC compared with 0–10% central PHENIX data. The presented result includes all the vacuum final state radiation and is hence an upper limit for R_{AA}^γ . Including interference between medium and vacuum radiation is a future task.

For more detailed results please refer to [11].

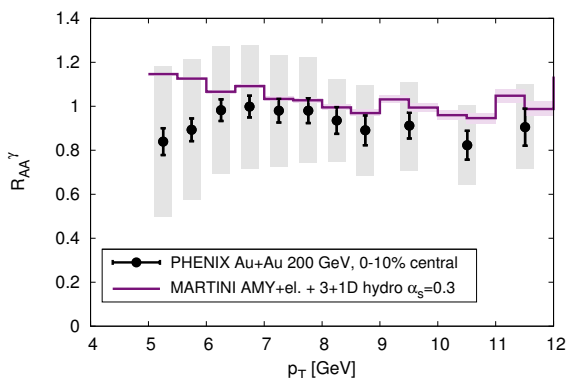


Fig. 3. Photon nuclear modification factor for central collisions at $\sqrt{s} = 200$ GeV. MARTINI results compared to data from [17]. See main text for details.

4. Conclusions and outlook

We presented first results obtained with the newly developed Modular Algorithm for Relativistic Treatment of heavy IoN Interactions (MARTINI). This hybrid approach describes the soft background medium using hydrodynamics or other medium models and simulates the hard event microscopically, using PYTHIA 8.1 to generate individual hard nucleon–nucleon collisions. Hard partons are evolved through the medium using the McGill-AMY evolution scheme including radiative and elastic processes. On the parton level, we found the same result as a direct solution of the Fokker–Planck type rate equations for the brick problem. Fragmentation is performed employing PYTHIA 8.1 which uses the Lund string fragmentation model. Apart

from parameters in PYTHIA which were fixed by matching the neutral pion and photon spectra in $p + p$ collisions to experimental data, α_s is the only free parameter. Employing the 3+1 dimensional hydrodynamic evolution from [15], it was set to $\alpha_s = 0.3$ (and 0.33 for the 2+1 dimensional hydro) to match the neutral pion R_{AA} measurement for central collisions. Using the same value for all other calculations (there was no additional freedom in any of the calculations), we were able to describe the neutral pion R_{AA} in mid-central collisions as well as the photon R_{AA} in the regarded p_T range.

We showed that MARTINI can reproduce one-body observables in good agreement with the data. The next step will be to explore its full potential by studying many-body observables and correlations. Another future task is the implementation of heavy quark evolution.

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