A 2+1D Monte Carlo generator for jets in heavy ion collisions

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Abstract. At the Large Hadron Collider (LHC) in Geneva, Switzerland and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in the United States, it is widely believed that a new state of matter, the Quark-Gluon Plasma (QGP), is routinely created by colliding the nuclei of heavy elements such as gold or lead at nearly the speed of light. In head-on collisions between heavy nucleii, it is not uncommon to create tens of thousands of particles and the patterns they produce in the detectors can be very complex. In order to connect theoretical predictions to experimental measurements, it is useful to create a computer algorithm which uses Monte Carlo techniques to simulate the collisions. Such 'Monte Carlo Generators (MCG)' may be programmed to contain much of the known physics, but the development of MCG's in heavy ion physics has been hampered by the complexity of the interplay between different physics effects. Heavy-ion MCG's have, therefore, often been forced to make simplifying assumptions. JEWEL is one such an MCG, attempting to focus primarily on the physics of highly energetic particles that traverse the QGP. We present an extension of JEWEL which allows JEWEL to consider a dynamical background which evolves in time and has no symmetry in the plain transverse to the beam direction. We also show preliminary results from a variety of analyses.

1. Introduction

The standard model of Cosmology presents a largely consistent theory of the evolution of the universe, but relies almost entirely on deductions made from the observation of light at different wavelengths [1]. The evolution of our universe is therefore only traceable by astrophysical means in so far as photons are able to escape the early stages of the evolution and travel to our detectors, placing a limit on how far into the universe's history observational astronomers can see. However, until about a microsecond after the big bang, the universe was entirely opaque to photons [2], so that this epoch of the universe's evolution must be studied differently [2].

One such method is to attempt to recreate the extraordinarily hot and dense conditions that prevailed by colliding the nuclei of heavy atoms such as lead or gold at ultra-relativistic energies. In doing so, it is now widely believed that colossal colliders, the largest of which is the Large Hadron Collider (LHC) in at CERN in Switzerland, create a new state of matter by bringing the nucleons within the nucleii of these atoms to temperatures and pressures that are reminiscent of the early universe [3]. This new state of matter is called the quark-gluon plasma (QGP) because the degrees of freedom are no longer those of nucleonic matter, but rather those of the constituent particles of protons and neutrons, known within the standard model of particle physics as quarks and gluons.

The QGP that is created in nucleus-nucleus (also referred to as "AA") collisions, is very short lived [4], with a life-span on the order of 1 fm/c in natural units (or 10^{-28} s). For this reason, studying the QGP relies on the study of constituents of the QGP and probes of the QGP that are created along with the QGP in the collision. Such studies require a detailed theoretical understanding of the properties and evolution of the QGP, as well as the various decay products and their signatures in the detectors that are placed around the point at which the collision occurs. One important probe of the QGP is the manner in which a hard parton (a quark or a gluon) that is created at the same time as the quarks and gluons that make up the QGP, but which has an energy at least an order of magnitude or two higher than the average QGP constituent, traverses and interacts with the lower energy partons within the QGP. Such "hard partons" will lose energy as they interact with the QGP via the strong nuclear force, eventually arriving at the detector with less energy than expected [5], and depositing a characteristic collimated spray of particles in the detector, known as a "jet".

2. Monte Carlo generators and JEWEL

The paradigm within which the properties of a jet in the presence of a QGP are studied is cognisant of the fact that the evolution of the jet has a number of different stages [6]: first, the hard parton is produced via a hard scattering process which may be computed directly via quantum chromo-dynamics (QCD); second, even in the absence of a QGP, it is known that the hard parton will radiate energy according to well-understood evolution equations; the presence of the QGP medium will also induce additional radiation, the modelling of which has a rich literature; finally, the hard quark or gluon does not appear in the detector as a free quark or gluon, but rather as hadrons, and one must therefore also consider the manner in which the quark or gluon hadronizes and produces a variety of decay products that eventually leave a signature in the detector.

In addition to the complicated, multi-scale problem that is the production and evolution of the jet, the entire heavy ion collision is itself a multi-scale problem involving a number of different stages that are studied individually [7, 8]: initially, the two heavily Lorentz contracted nucleii approach each other, each with its own individual distribution of partons that are all highly boosted, presenting a considerable challenge to the determination even of the initial state of the collision. Once one has modeled the initial distribution of the deposited energy, one is faced with a system that is very far out of equilibrium, the out of equilibrium evolution of which needs to be understood in order to provide a realistic initial condition for the equilibrated evolution of the QGP. The QGP itself (within which the jet will propagate as described above) now evolves in a manner which is well described by viscous hydrodynamics before finally expanding and cooling sufficiently for hadronization to set in.

It is clear that the physics of a heavy ion collision is rich and varied, but in order to

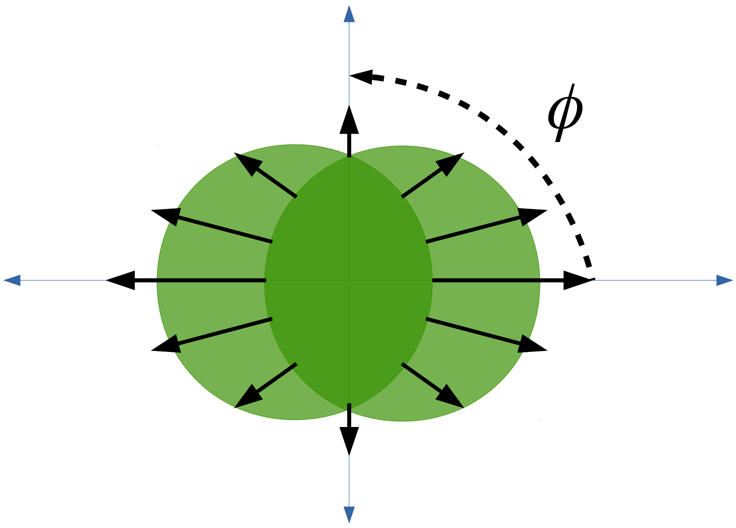

Figure 1. The overlap region of two nuclei as seen in the plane transverse to the beam and the azimuthal angle ϕ as measured in the event plane. Black arrows indicate the emmission of high-momentum particles in plane ($\phi \sim 0, \pi$) and lower-momentum particles out-of-plane ($\phi \sim \frac{\pi}{2}, \frac{3\pi}{2}$. (Drawn by author))

extract meaningful information regarding the QGP from the manner in which a jet is modified, it is necessary to collect all of the information and produce theoretical predictions that are sophisticated enough to involve the major components of the jet and QGP evolution, but may also be easily compared to data. This problem is ideally suited to a Monte Carlo generator. Monte Carlo generators use random number generators to simulate a heavy ion collision and may encode a variety of different physics effects without the need for fully inclusive first principles analytical calculations. Monte Carlo generators have been used extensively in the particle physics community [8], but the complexity of heavy ion collisions has, until recently, hampered the development of a dedicated heavy ion Monte Carlo. JEWEL (Jet Evolution With Energy Loss) is a Monte Carlo generator specifically designed to study the evolution of a jet in a heavy ion collision [9, 10, 11, 12].

JEWEL is a sophisticated generator with many features, the details of which are not important for the present discussion. The reader is referred to the current manual [13] and references therein for further discussions. In essence, JEWEL uses a Glauber distribution for the colliding nucleii to determine the kinematics of a straight forward $2 \to 2$ QCD scattering process for the production of the jet. JEWEL then evolves the jet using the DGLAP evolution equations along with additional $2 \to 2$ scatterings to model the energy loss by sampling a model for the medium, before passing the evolved jet constituents to a modified version of PYTHIA (a widely used generator that has the ability to model the hadronization of partons in order to create a realistic sample of events). JEWEL is freely available for download and ships with two medium options: vacuum jet evolution and jet evolution with a simple classical gas model for the medium which is radially symmetric in the plane transverse to the beam.

3. Generalizing JEWEL

Although a radially symmetric medium is not a bad approximation for head-on collisions, the experimental reality is that the vast majority of collisions are slightly off-center, resulting in an initially almond shaped spatial distribution of the energy density [14]. There is also ample evidence for rich physics related to the evolution of such an asymmetric QGP [15] and it is therefore important to incorporate, within JEWEL, the ability to consider a background medium which contains non-trivial information in at least one temporal direction and two spatial directions (the evolution of the medium in the direction of the beam is, on the time scales considered in a heavy-ion collision, well approximated by a simple scaling mechanism called Bjorken scaling).

We have generalized JEWEL to include the ability to sample a 2+1D background medium when evolving a jet and are in the process of producing Monte Carlo data that will illustrate its usefulness. One possibility for further study is to investigate the path-length dependence of the energy loss of a hard parton by considering the angular distribution of jets given a particular orientation of the almond-shaped background medium. This situation is depicted in fig. 1. If the energy loss does indeed depend heavily on the distance traveled through the medium (as is expected from a number of perturbative QCD calculations), then it is likely that jets emitted out-of-plane (along the long direction of the almond) will be "quenched" with respect to jets emitted in-plane (along the short direction). One would perform such an analysis event-by-event, but combine the results from many events in order to obtain an emission spectrum. Due to the steeply falling spectrum of jets, such quenching will be visible as a modulation of the number of jets with a particular p_T as a function of the azimuthal angle ϕ. This analysis is does not require a control event in which there is not QGP with which to compare, which is a major hurdle in understanding jet quenching in small colliding systems.

The generalization of JEWEL presented here is based on an existing JEWEL routine that is not yet publicly available and which was used to investigate the effects of including a hydrodynamic profile for the medium in JEWEL [16, 17]. The routine allows JEWEL to read in the temperature and velocity profile of time-snapshots in the hydrodynamical evolution of the background and sample this data in order to construct appropriate four-momenta for the scattering centers. However, the existing routine is only able to read in radially symmetric data.

In order to create the possibility to read in data that is azimuthally asymmetric, a number of changes were made to the existing hydrodynamic medium routine. These changes include, but were not limited to, allowing the dynamical allocation of memory, rewriting the read-in routines so as to allow for a variety of differently formatted hydrodynamical data, and expanding two-dimensional (τ, r) interpolation to three-dimensional (τ, x, y) interpolation. No substantial changes were made to the main JEWEL program.

4. Conclusions

We have presented an argument for studying the quenching of highly energetic partons that traverse the QGP as well as described the need for dedicated Monte Carlo generators that model jet quenching. We have presented a need to generalize a commonly used jet Monte Carlo, JEWEL, in order to include the use of azimuthally asymmetric hydrodynamic profiles for the modeling of the background that the jet interacts with. We have, lastly, briefly described the changes made to an existing, radially symmetric, hydrodynamic routine for JEWEL and an example of a useful analysis that may be done with the data produced with the new routine.

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