Jet Hadronization via Recombination of Parton Showers in Vacuum and in Medium

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Abstract

We have studied the hadronization of jet parton showers based on the quark recombination model. This is achieved by letting gluons at the end of the perturbative shower evolution undergo a non-perturbative splitting into quark and antiquark pairs, then applying a Monte-Carlo version of instantaneous quark recombination, and finally subjecting remnant quarks (those which have not found a recombination partner) to Lund string fragmentation. When applied to parton showers from the PYTHIA Monte Carlo generator, the final hadron spectra from our calculation compare quite well to PYTHIA jets that have been hadronized with the default Lund string fragmentation. Modeling the quark gluon plasma produced in heavy ion collisions by a blast wave model, we have further studied medium effects on the hadronization of jet shower partons by also including their recombination with the thermal partons from the quark gluon plasma. We find that the latter leads to a significant enhancement of intermediate transverse momentum pions and protons at both RHIC and LHC. Our results thus suggest that medium modification of jet fragmentation provides a plausible explanation for the enhanced production of intermediate transverse momentum hadrons observed in experiments.

Keywords: Quantum Chromodynamics, Quark Gluon Plasma, Hadronization

Jets in quantum chromodynamics (QCD) have a long history as tools to test QCD itself, electroweak theory, and physics beyond the standard model. Recent developments both in theory and experiment have also made jets into promising probes in heavy ion physics. Jets embedded in quark gluon plasma (QGP) created in high energy nuclear collisions suffer from jet quenching. Details of the jet-medium interaction encode important aspects of QGP at various scales. To make better connections between theory and experiment several groups around the world are currently developing event-by-event jet shower Monte Carlo (MC) simulations. Those shower MCs are reasonably controlled as long as the shower is in the perturbative domain, typically determined by the virtuality of partons $Q$, or the temperature $T$ of the surrounding medium. As $Q$ reaches a lower cutoff, usually around 1 GeV, and the temperature reaches the critical temperature $T_c$ perturbative methods have to be discarded. This leaves the hadronization of partons in jet showers unaccounted for.

Non-perturbative models like the Lund string fragmentation model used in PYTHIA or the cluster hadronization model used in HERWIG have been used to describe the transition from partons to hadrons in jets in the vacuum, e.g. in $e^+ e^-$ or $p + p$ collisions. On the other hand, there is strong evidence in A+A collisions, that recombination of partons from jets with partons in the surrounding medium can create hadrons. The instantaneous quark recombination model has been applied both to the recombination between thermal partons, and for recombination between thermal partons and leading jet partons. The instantaneous recombination model has been successfully deployed for a variety of observables at intermediate momenta ($\sim 2-6$ GeV/c) in heavy ion collisions. Clearly, the possibility that quarks in jet showers pick
up partons from the thermal medium to form hadrons, as they pass through the $T = T_c$ hypersurface in the collision, needs to be accounted for. Such a mechanism involves the exchange of momentum, energy and flavor quantum numbers of the jet shower with the medium, thus influencing a number of jet and high-$p_T$ hadron observables. It needs to be studied theoretically, and in light of available experimental jet reconstruction techniques.

Here we report on our effort within the JET collaboration to develop a hadronization module for jet shower MCs that incorporates quark recombination effects for jets in a medium but also reproduces hadronization of jets in the vacuum. This will be accomplished by a hybrid approach using recombination and string fragmentation. The idea that quarks in a jet shower could hadronize by recombination has earlier been discussed in [9]. Let us start by considering a perturbative jet shower in the vacuum. All partons have been evolved in [9]. Let us start by considering a perturbative jet shower in terms of their momentum fraction $z$. The total momentum before and after the decay is shown in (after gluon decays) as a function of distances $\Delta r$ and $\Delta k$ in position and momentum space. Those distances are measured for each pair in its common rest frame at the time the later parton is created. We can see that the distribution peaks at around $\Delta r \approx 0.5$ fm and $\Delta k \approx 0.4$ GeV. Thus many quarks in the shower could in fact find another parton in rather close proximity. On the other hand, long tails exist in the distribution which indicate the existence of “lonely quarks” which are unlikely to find a recombination partner.

We can now proceed to calculate the recombination probability for all pairs (and triplets) in a shower, and use MC techniques to pick recombining mesons (and baryons). To first approximation one can use spherical wells as hadron Wigner functions as in [3]. A more realistic approach postulates an harmonic oscillator approximation for quark bound states. The Wigner function of the $n$th excited state ($n = 0$ corresponds to the ground state) of a 1-D harmonic oscillator of frequency $\omega$ is well known to be (11)

$$W_n(u) = 2(-1)^n L_n \left( \frac{4u}{\hbar \omega} \right) e^{-2u/\hbar \omega},$$

where $u = \frac{\hbar \omega}{2} \sqrt{\frac{\sigma^2 + \sigma^2 k^2}{\omega}}$, $\sigma \equiv \left( \frac{\hbar \omega}{m} \right)^{1/2}$, and the $L_n$ are

![Figure 1: Distribution $dN/dz$ of partons in 100 GeV PYTHIA quark showers before (top panel) and after (bottom panel) decay of gluons.](image-url)
Laguerre polynomials. The Wigner function of a single quark in this bound state has to be smeared by at least the minimal quantum mechanical uncertainty to yield a positive Wigner function. With Gaussian wave packets of width $\delta = \sigma / \sqrt{2}$ (a choice made for simplicity [10]) we obtain for the $n^{th}$ state a probability

$$\psi_n = \left( \frac{\mu}{\hbar \omega} \right)^n \frac{1}{n!} e^{-\mu^2 / \hbar \omega}$$  (3)

The construction of states for the 3-D case are then straightforward [10]. We fix the width parameters $\sigma$ for the stable hadrons $\pi$, $K$ and $N$ by using measured charge radii. We allow recombination into excited states which are currently given by the excited harmonic oscillator spectrum, with a subsequent decay into stable hadrons.

When we recombine mesons and baryons in jet showers as described we find that a large fraction of small-$z$ partons indeed finds a recombination partner, while at larger $z$ the success of recombination drops rapidly, see Fig. 3. These remnant partons have propagated far away in phase space from other quarks. In reality, instead of facing the QCD vacuum they would rather be forced to connect to another color charge via a QCD string. Hence we reintroduce strings between remnant partons. We use PYTHIA 6 string fragmentation routines to calculate the hadrons from this remnant string fragmentation. This completes the brief overview of our hadronization module. All partons in the system have been converted into hadrons.

Fig. 4 shows hadron spectra from our recombination-fragmentation hybrid model applied to 100 GeV PYTHIA parton showers, compared to the same parton showers hadronized directly with string fragmentation in PYTHIA. We see that the distribution of pions, kaons, nucleons and $\Lambda$s as a function of momentum fraction $z$ generally coincide rather well with the results of pure string fragmentation. Fig. 5 shows the same for the distribution of momenta transverse to the jet axis. We conclude that our hybrid hadronization model which replaces string fragmentation by quark recombination for partons close together in phase space is well suited to describe fragmentation of jets in the vacuum. In the near future we plan to test the module directly with data in $e^+ e^-$ and $p + p$ collisions.

Why would one want to replace a successful hadronization model like string fragmentation by quark recombination? The answer is that implementing medium effects is rather straightforward in recombination models. In addition to considering the recombination probabilities of quarks and antiquarks in a jet shower one also samples the thermal partons from a blastwave or from the $T = T_c$ hypersurface of a fluid dynamic simulation, and allows pairs and triplets between thermal partons and shower partons as well. For individual jets the details of the location relative to the hypersurface is very important and the relative importance of shower-thermal and shower-shower recombination depends on this geometry. Note that in a typical situation (a jet originating a few fm inside the $T = T_c$ hypersurface) the bulk of the jet shower partons are created inside the QGP. Thus they have to propagate through the medium to the hadronization hypersurface, or are absorbed by the medium, processes which will have to be carefully simulated in shower MCs. However, the leading part of the jet typically emerges from the hyper-
surface, i.e. these partons are born outside of the QGP. Using a blast wave model we find that overall shower-thermal recombination (for baryons the mixed terms, shower-shower-thermal and shower-thermal-thermal, exist) in most situations becomes more important than shower-shower recombination and leads to a noticeable enhancement of pion and proton production at intermediate hadron $p_T$. The increase in shower-thermal recombination gives rise to phenomena like the proton/pion enhancement observed in experiment. In the near future the in-medium realization of our hadronization module will be combined with realistic in-medium jet shower MCs to study these effects in detail.

In summary, we have developed a hybrid hadronization model which employs quark recombination of shower partons and uses string fragmentation to hadronize remnant quarks. We find that our model can reproduce the spectra of pure string fragmentation in the vacuum rather well. The introduction of medium partons is rather straight forward and gives rise to hadrons from shower-thermal recombination. In collaboration with groups developing in-medium jet shower MCs simulations we will apply our hadronization model to the phenomenology of jets and high-$p_T$ hadrons in heavy ion collisions in the near future.

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