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

Rainer J. Fries, Kyongchol Han, Che Ming Ko

Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station TX 77845, USA

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 cut-off, 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 [1] or the cluster hadronization model used in HERWIG [2] 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 [3, 4, 5, 6, 7, 8] 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 (~ 2-6 GeV/c) in heavy ion collisions. Clearly, the possibility that quarks in jet showers pick

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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 carefully 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 to some small virtuality Q_0 of order 1 GeV. For test purposes we will use $e^+ + e^-$ showers produced by PYTHIA 6 [1]. The first step toward hadronization is a forced splitting of gluons into quark-antiquark pairs. This is done by simply decaying gluons isotropically in their rest frame into light quarks $u\bar{u}$, $d\bar{d}$ or $s\bar{s}$ using their remnant virtualities. The resulting distribution of partons in the jet shower in terms of their momentum fraction z of the total momentum before and after the decay is shown in Fig. 1.

The instantaneous recombination model projects quark states onto hadron states enforcing only momentum conservation. This can be conveniently expressed in terms of the Wigner functions of the quark-antiquark (3-quark) Wigner function and a meson (baryon) Wigner function [8]. In the case of mesons

$$\frac{dN_M}{d^3\mathbf{p}_M} = g_M \int d^3\mathbf{r}_1 d^3\mathbf{k}_1 d^3\mathbf{r}_2 d^3\mathbf{k}_2 f_q(\mathbf{r}_1,\mathbf{k}_1) f_{\bar{q}}(\mathbf{r}_2,\mathbf{k}_2) \times W_M(\Delta\mathbf{r},\Delta\mathbf{k})\delta^{(3)}(\mathbf{p}_M - \mathbf{k}_1 - \mathbf{k}_2), \quad (1)$$

where W_M is the meson Wigner function, $\Delta\mathbf{r}$ and $\Delta\mathbf{k}$ are the relative position and momentum of the partons, g_M is a statistical factor, and the quark-antiquark Wigner function has been factorized into single quark Wigner functions f. The latter is an approximation neglecting correlations in the parton system. A similar formula can be devised for baryons [8, 10].

It is clear that the rate of hadronization through recombination will depend on the density of partons in phase space, more precisely on the average distance in phase space relative to the width of the hadron Wigner function in phase space. Fig. 2 shows the distribution

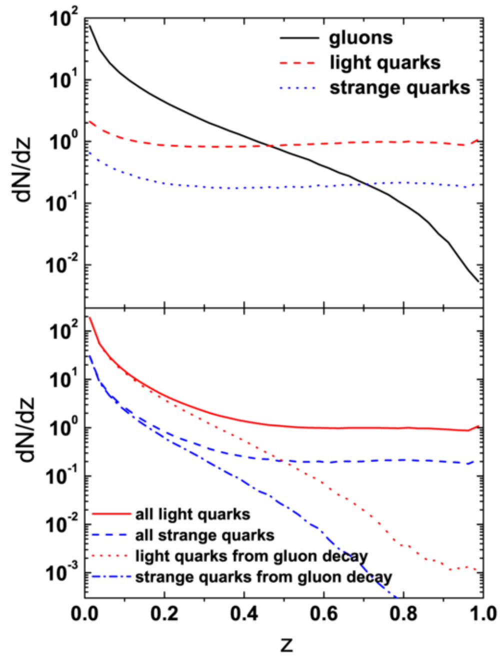

Figure 1: Distribution dN/dz of partons in 100 GeV PYTHIA quark showers before (top panel) and after (bottom panel) decay of gluons.

of quark-antiquark pairs in 100 GeV PYTHIA showers (after gluon decays) as a function of distances Δr and Δk 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 ω is well known to be [11]

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

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