Jet Fragmentation due to a Quark/Diquark Pick-up in High Energy Heavy Ion Collisions

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(March 25, 2022)

We propose a model aimed at explaining jet quenching, large azimuthal asymmetry and baryon/meson ratio at large transverse momenta $p_t = 2 - 10 \, \text{GeV}/c$ observed at RHIC. Its main point is that a QCD string can be cut by matter quarks and/or diquarks before its natural breaking. We model the early quark/diquark production via QCD sphalerons.

1. Observations. The field of heavy ion collisions entered the new era with first experiments at Relativistic Heavy Ion Collider (RHIC), which revealed a number of new phenomena. While the totality of data for most secondaries, with $p_t < 2 \, \text{GeV}/c$, agree with a picture of strong collective explosion of matter close to equilibrium, and is well described by relativistic hydrodynamics [1], for $p_t > 2 \, \text{GeV}/c$ the regime changes. Based on pp data it has been anticipated that this region can be described perturbatively, by a standard parton model, with modest modifications due to initial and final state interaction. (Such ideology was implemented e.g. in popular event generator HIJING.) Instead, RHIC experiments at $p_t = 2 - 10 \, \text{GeV}/c$ have found that: (i) hadron yields, relative to pp or parton model, are smaller by the “jet quenching factor” $Q < 1/3$; (ii) the azimuthal asymmetry is unexpectedly large, with $v_2 = \cos(2\phi) \sim 0.1$ for mid-peripheral collisions; (iii) the baryon/meson ratio is unexpectedly large, $\sim 1$, well above that in the usual jet fragmentation; (iv) a clear link between the two last points is seen from the fact that $v_2$ for baryons ($p, \Lambda$) is larger than for mesons ($\pi, K$). In this paper we propose a mechanism which may account for all these observations.

2. Recent literature. A simple theoretical argument made by one of us [2] is that in any model of jet quenching by absorption is limited by the regime of surface emission. Its consequence is the geometrical limit: $v_2(b) < v_2^s(b)$ where the r.h.s. is uniquely related to the shape of the almond-shaped nuclear overlap region at impact parameter $b$. However, as emphasized in [2], STAR data seem to exceed the geometric limit [3], which rules out all purely absorptive models.

It was suggested by Lin and Ko [4] and Voloshin and Molnar [5] that quark coalescence into hadrons enhances $v_2$, and $v_{\text{baryon}}/v_{\text{meson}} \approx 3/2$. The coalescence has been further discussed in Refs [6,7]. It is concluded that the coalescence of 2 or 3 hard partons is very improbable. The coalescence of soft thermalized partons produces thermal-like distribution of hadrons in the rest frame of each matter cell, reproducing basically the Cooper-Frie formula used in all hydro papers. How many partons participates in coalescence seem to be nearly irrelevant. A coalescence of hard-soft kind may enhance the baryon/meson ratio. However, due to jet quenching the hard partons only contribute to hadronic spectra if they are produced at the surface and move outward. The soft ones, to be lifted by flow, have to wait a significant time of $\sim 10 \, \text{fm}/c$, at which point hard ones are too far away. Our model to be introduced below includes a hard-soft coalescence at very early time, $< 1.5 \, \text{fm}/c$. Hard and soft partons are not at the same place, but are connected by a string.

3. The model. Unlike models mentioned above, we focus on the matter-induced modification of the jet fragmentation process. Our first new point is that although the outgoing hard quark (or gluon) leaves the system promptly, the QCD string (or 2 strings) is still extended behind and is crossing the excited matter. The string helps to explain the timing problem mentioned above, among other ones. The second new point is that the QCD sphalerons can provide prompt quarks or diquarks, conveniently concentrated on thin and expanding spheres [8].

New mechanism of string breaking must act before (in the jet center of mass frame) than both (i) the usual spontaneous string-breaking, as described by the Lund-model [9]; and (ii) the perturbative gluon radiation from a parton. (Due to strongly falling $p_t$ spectra, even modest energy loss makes the contribution irrelevant.) An approximate expression for the time of both phenomena (i) and (ii) combined [10] can be written as a condition

$$\tau < \tau_{\text{string breaking}} \approx \frac{p_t}{\sigma + p_t^2/45}$$

where $\sigma = (0.44 \, \text{GeV}/c)^2$ is the usual string tension.

The “string cutting” is the main idea of the model, while the sphalerons used as a description of matter at early time is admittedly an extreme one, and can possibly be later combined/replaced by another one. It was chosen due to its simple geometrical rules, and also to maximize both (i) the radiative jet quenching and (ii) quark and diquark pick-up rate. We hope the reader will find it reasonable to go to the extreme in the first exploratory study, since so many other models we and others tried have failed.

Theory of the QCD sphalerons is discussed in detail in [8]. In brief, they are unstable classical soliton-like objects with masses $\sim 3 \, \text{GeV}/c$, excited from the part of the vacuum wave function under the topological barrier by high energy collisions.

For discussion of their production in hadronic collisions in experiments see e.g. [11] and references therein.
Like jets, sphalerons are produced in (semi-)hard $qq$ collisions and thus have the same distribution of the origination points in the transverse plane. Once produced, they evolve into expanding spheres, also moving with a speed of light. The radiative energy loss in a single crossing of a parton through the sphaleron was calculated in [12]. Using its results we estimated that this generate quenching of a parton by about an order of magnitude, provided the time is shorter than $\tau < \tau_{sp}$. After that time we stop the model.

The rules of the model thus are as follows: (i) If a jet goes through the sphaleron sphere, it is eliminated; (ii) If a jet escapes all the sphalerons but its string is crossed by a sphere of one of them, the string is cut by $q$ pickup. (iii) With a probability $P_{qq}$ a diquark instead of a quark is picked up. The parameters we will use below are (i) the sphaleron density $dN_{sp}/dy = 200$ in central AuAu; (ii) $P_{qq} = 1$; (iii) the lifetime of the process $\tau_{sp} = 1.5 \text{ fm}/c$.

Further evolution of a $\bar{q} -\text{ string} - q$ ($q -\text{ string} - qq$) systems is done following the Lund model. As they are produced earlier compared with the creation of pairs in the usual fragmentation, those have relatively small invariant masses.

4. Fragmentation in the Lund model (e.g., in PYTHIA [13,14] event generator) describe a gluon jet as a pair of strings that stretches from it to the forward-backward-moving quarks [9]. The usual treatment only fulfills the Lund Area Law on average which is inadequate for small masses dominated by the few-body decays. Fragmentation of the low energy quark jets has been studied only recently [15] in this framework, passing the tests provided by the BES collaboration [16].

Unfortunately, the corresponding fragmentation of low mass gluon strings have not yet been studied. Since the production of relevant particles at RHIC is dominated by gluon jets, we have to address the issue. Additionally, we found that the issue of the shape of the gluon string is very important. It in turn is related to string-string attraction, first introduced by Montvay [17]. If the tension of the double string is less than twice that of a single one, $\sigma_{gl}/(2\sigma_q) \equiv r < 2$, the minimal energy configuration of a $qq\bar{q}$ jet system have shapes shown in Fig. 1. The value of $r$ is not yet fixed from data. T. Sjostrand [18] concluded only that the this ratio should be $r > 1.5$ in order to describe the 3-jet data, we use a value $r = 1.8$ [19].

The junction moves according to the forces produced by strings along the direction of the gluon, with the velocity $v = r/2 \approx 0.9$, and the whole fragmentation is simplified in its rest frame. In this frame, if no breaking occurs, the partons will oscillate in the direction of the strings in a yo-yo motion. The turning time of the gluon (in this frame) is $t_c = E_g/\sigma_q$ where $E_g$ is the energy in the junction rest frame.

The string configuration just described can interact with quarks located at sphaleron spheres. If a string can interact with several sphalerons, we assume that the fragmentation is determined by the one that cuts the $q$-strings closest to the junction, in its rest frame. (As the gluonic piece of a string is very short and extended outwards, the cutting happens predominantly in the quark part as shown in Fig 1 by the horizontal dashed lines.)

Once the pick up happens, one is left with a system with low invariant mass $M$. For example, hadrons of $p_t = 3-4 \text{ GeV}/c$ come from jet subsystems with $M \sim 3 \text{ GeV}$, which is precisely where few-body fragmentation starts to be important. One may work out the complete exclusive fragmentation distribution for the low energy gluons, which we have not yet done.

At this energy, quark jet fragmentation is dominated by three and four body decays [15]. However, if in the interaction with the sphaleron the string picks up a diquark, a two body decay or a single string breaking shown in Fig 1 would be enough. So, whenever a baryon is produced, the fragmentation is described by a combination of a two body decay plus the standard fragmentation described by standard fragmentation functions. In the former case, the energy-momentum conservation together with the linear potential of the string determine uniquely the four momentum of the two particles produced. The kinematics alone ensure that the effect disappears with the increasing $p_t$ of the gluon.

In our simulation, with $r = 1.8$, the 2-body fragmentations die out around $p_t \sim 8 \text{ GeV}/c$, which corresponds to the length of the gluonic string of 1 $\text{ fm}$ in the junction rest frame: longer strings should break by the usual mechanism [20]. The typical time and position of pick up is such that in the junction rest frame the turning time of the gluon defined above is smaller than the pick up time. This means that the string works as a slingshot, allowing the gluon to give all its energy to the baryon or pion. By requiring that the invariant masses of the two subsystems after the spontaneous breaking correspond to a nucleon and a $\pi$, we obtain two possible four momenta (corresponding to the two possible cuts). Surprisingly the previous remark makes the hadron that absorbs the gluon string to move in opposite direction to the initial one because in the moment of the pick up the gluon is moving back-wards. This characteristic is maintained when we translate to the original frame. The outcome is that we obtain a very energetic particle (the one that does not absorb the gluon string) with fraction of the three momentum of the gluon close to one. In fact, as the second hadron moves in the opposite direction, this fraction can be even slightly bigger than one.

FIG. 1. String configuration of a $qq\bar{q}$ event. The pick up from the sphaleron produces a $q$ and a diquark. The two permitted spontaneous breakings are shown.
The two possible ways of breaking correspond to boosting either the meson or the nucleon produced. The requirement of producing physical masses is more easily fulfilled when the $\pi$ does not absorb the gluon string (as it is expected, given its small mass). So, in many cases only one fragmentation is possible. When both are possible, we have assumed that the two cuts happen with equal probability. In principle this does not have to be true and phase space and dynamical (area law suppression) considerations should be taken into account. We have also assumed that only $\pi$’s or nucleons are produced. A more realistic model should also consider other channels.

Summarizing this point: a gluon fragmentation function at moderate $p_t$ contains a part in which only two hadrons are generated. Those are harder than the usual ones because one of the particles takes almost all the momentum of the initial gluon. Due to string dynamics, it can even happen that the three momentum of one of the particles is even bigger than the momentum of the gluon.

5. The results follow from numerical simulation of non-central AuAu collisions at mid-rapidity, in which we produce quark and gluon jets according to standard nuclear shapes and the structure functions of the parton model, reproducing pp data. All trajectories are traced, some jets are quenched by sphalerons; from those that escape some have their strings cut off, with remnants fragmenting as described above.

The pion quenching factor is a combination of absorption due to quenching and enhancement due to modified fragmentation. The results shown in Fig 2 are in agreement with the data from PHENIX [21] for $p_t = 3 - 7 \text{ GeV/c}$. The pick up mechanism disappears for $p_t > 8 \text{ GeV/c}$ where we are only left with the strong absorption produced by the sphalerons.

The baryon/meson ratio close to 1 is not trivial to obtain: even though the only process we consider always generates one nucleon and one $\pi$, the boosts that these particles obtain are different. In general it is easier to generate high energy $\pi$’s than protons. These $\pi$’s come from the string piece that does not include the gluon string; so it will be easier to generate a particle with small mass from this cut. The other cut is suppressed by kinematic reasons. So, if we fix the $p_t$ of the gluons we will always obtain more $\pi$ than protons. However, we observe that when the nucleon is boosted, it carries a bigger fraction of the momentum. Finally, when we convolute yields with the cross section we obtain the ratio shown in Fig.3. We found that the value decreases with $p_t$ as it is expected, although slowly.

We have set the probability of picking up diquarks $P_{qq} = 1$. As the mechanism of production of particles links the nucleon and $\pi$ production, the ratio of those particles coming from this mechanism will be independent of $P_{qq}$. $P_{qq}$ determines, however, the strength of the effect. If we reduce it, the pick up of quarks (that we have not included in the version reported here, for simplicity) would start to play a role.

As already explained, the production of only two $\pi$ would not be dominant because the invariant mass is too big. Other channels could be important, for example the production of $\rho$ instead of $\pi$. The introduction of $\rho$ does not lead directly to the reduction of the $p/\pi$ ratio. We have assumed in the simulation that all strings produce a $\pi$, but this is not necessarily true. So by introducing any other channel we will reduce the number of $\pi$ even though all of them will generate high energy nucleons.

Azimuthal asymmetry follows from underlying geometry in a non-trivial way. The absorption reduces the contribution of jets produced in the center of the almond, pushing the production of particles that escape toward the surface halo of the nuclei (see Fig.3(b)). This is precisely the problem of all absorptive models.

However, the density of sphalerons is smaller in the halo and the (di)quark pick up (which boosts the fragmentation) is more effective for more central jets. The outcome of both processes is that the emission is dominated by a relatively thin layer, see Fig.3(a). As it is shaped approximately as the surface of the overlap region of two hard spheres, the model produces values of $v_2$ close to the geometric limit.
The experimental values at the same impact parameter \(b = 6 \, \text{fm}\) for charged \(\sqrt{s}\) values are found to be approximately independent of \(v_\pi\). The contribution from the halo reduces the value of \(p_t\) along the \(x\) axis from pure absorption models. Further work is needed to tune the parameters better and make the model more realistic, hopefully bringing it in even better agreement with the experimental data.

6. Conclusions. We have presented a model in which the medium interacts not only with the partons produced in the collision, but also with the strings (color fields) that the partons stretch. This interaction modifies the whole process of fragmentation and leads to fragmentation functions that are harder than the vacuum ones. We have presented a very simplified model in which we have assumed that in the relevant energy the fragmentation process is dominated by two body decay, and we have given an explanation for large \(p/\pi\) ratio and small quenching factor. We have also significantly improved the value of \(v_\pi\) from pure absorption models. Further work is needed to tune the parameters better and make the model more realistic, hopefully bringing it in even better agreement with the experimental data.

Acknowledgements

This work is partly supported by the US DOE grant. We thank B. Kopeliovich, C. M. Ko, R. J. Fries and T. Sjöstrand for helpful comments.