Separating jets from bulk matter in heavy ion collisions at the LHC

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Abstract. We discuss a theoretical scheme that accounts for bulk matter, jets, and the interaction between the two. The physical picture of our approach is the following: Initial hard scatterings result in mainly longitudinal flux tubes, with transversely moving pieces carrying the $p_t$ of the partons from hard scatterings. These flux tubes constitute eventually both bulk matter (which thermalizes, flows, and finally hadronizes) and jets, according to some criteria based on partonic energy loss. High energy flux tube segments will leave the fluid, providing jet hadrons via the usual Schwinger mechanism of flux-tube breaking caused by quark-antiquark production. But the jets may also be produced at the freeze-out surface. Here we assume that the quark-antiquark needed for the flux tube breaking is provided by the fluid, with properties (momentum, flavor) determined by the fluid rather than the Schwinger mechanism. Considering transverse fluid velocities up to 0.7c, and thermal parton momentum distributions, one may get a “push” of a couple of GeV to be added to the transverse momentum of the string segment. This will be a crucial effect for intermediate $p_t$ jet hadrons.

The starting point is a multiple scattering approach corresponding to a marriage of Gribov-Regge theory and perturbative QCD (pQCD). An elementary scattering corresponds to a parton ladder, containing a hard scattering calculable based on pQCD, including initial and final state radiation (for details see [1]). These ladders are identified with flux tubes, which are mainly longitudinal objects, with transversely moving parts, carrying the transverse momenta of the hard scatterings. These objects are also referred to as kinky strings. One should note that here multiple scattering does not mean just a rescattering of hard partons, it rather means a multiple exchange of complete parton ladders, leading to many flux tubes. In this case, the energy sharing between the different scatterings will be very important, to be discussed later.

The consistent quantum mechanical treatment of the multiple scattering is quite involved, it is based on cutting rule techniques to obtain partial cross sections, which are then simulated with the help of Markov chain techniques [2].

As said before, the final state partonic system corresponding to elementary parton ladders are identified with flux tubes. The relativistic string picture [3, 4, 5] is very attractive, because its dynamics is essentially derived from general principles as covariance and gauge invariance. The simplest possible string is a surface $X(\alpha, \beta)$ in 3+1 dimensional space-time, with piecewise constant initial velocities $\partial X/\partial \beta$. These velocities are identified with parton velocities, which
provides a one to one mapping from partons to strings. For details see [2, 1]. The high transverse momentum ($p_t$) partons will show up as transversely moving string pieces. Despite the fact that in the TeV energy range most processes are hard, and despite the theoretical importance of very high $p_t$ partons, it should not be forgotten that the latter processes are rare, most kinks carry only few GeV of transverse momentum, and the energy is nevertheless essentially longitudinal. In case of elementary reactions, the strings will break via the production of quark-antiquark pairs according to the so-called area law [6, 7, 2, 1]. The string segments are identified with final hadrons and resonances. This picture has been very successful to describe particle production in electron-positron annihilation or in proton-proton scattering at very high energies.

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In heavy ion collisions and also in high multiplicity events in proton-proton scattering at very high energies, the density of strings will be so high that the strings cannot decay independently as described above. Here we have to modify the procedure as discussed in the following (see ref. [8]). The starting point are still the flux tubes (kinky strings) originating from elementary collisions. These flux tubes will constitute both, bulk matter which thermalizes and expands collectively, and jets. The criterion which decides whether a string piece ends up as bulk or jet, will be based on energy loss. In the following we consider a flux tube in matter, where “matter” first means the presence of a high density of other flux tubes, which then thermalize. A more quantitative discussion will follow.

Three possibilities should occur, referred to as A, B, C, see Fig. 1(a,b):

A String segments far from the surface and/or being slow will simply constitute matter, they lose their character as individual strings. This matter will evolve hydrodynamically and finally hadronize (“soft hadrons”).

B Some string pieces (like those close to transversely moving kinks) will be formed outside the matter, they will escape and constitute jets (“jet hadrons”).

C There are finally also string pieces produced inside matter or at the surface, but having enough energy to escape and show up as jets (“jet hadrons”). They are affected by the flowing matter (“fluid-jet interaction”).

Let us discuss how the above ideas are realized. In principle the formation and expansion of matter and the interaction of partons with matter is a dynamical process. However, the initial distribution of energy density and the knowledge of the initial momenta of partons (or string segments) allows already an estimate about the fate of the string segments. By “initial time” we mean some early proper time $\tau_0$ which is a parameter of the model. Strictly speaking, energy loss concerns partons, modifying eventually the kink momenta in our picture, and the momenta of the string segments after breaking will be reduced. We will therefore base our discussion on energy loss on string segments.

We estimate the energy loss $\Delta E$ of string segments along their trajectory to be

$$\Delta E = k_{\text{Eloss}} E_0 \int (\rho V_0)^{3/8} \max(1, \sqrt{E/E_0}) dL/L_0,$$

inspired by [9], where $\rho$ is the density of string segments at initial proper time $\tau_0$, $V_0$ is an elementary volume cell size (technical parameter, taken to be 0.147 fm$^3$), $L_0$ is a (technical) length scale (taken to be 1 fm), $E$ the energy of the segment in the “Bjorken frame” moving with a rapidity $y$ equal to the space-time rapidity $\eta_s$, $dL$ is a length element, and $k_{\text{Eloss}}$ and $E_0$ are parameters. We introduce an energy cutoff $E_0$ to have sufficient energy loss for slowly moving segments.

A string segment will contribute to the bulk (type A segment), when its energy loss is bigger than its energy, i.e.

$$\Delta E \geq E.$$
All the other segments are allowed to leave the bulk (type B or C segments). Only the bulk segments are used to determine the initial conditions for hydrodynamics, following the same procedure as explained in [1, 8]. Starting from this initial condition, the bulk matter will evolve according to the equations of ideal hydrodynamics till “hadronization”, which occurs at some “hadronization temperature” $T_H$ [1]. Hadronization means that we change from matter description to particle description, but hadrons still interact among each other, realized via a hadronic cascade procedure [10], already discussed in [1].

After having performed the hydrodynamic expansion, we have to come back to the string segments which escape the bulk because their energy is bigger than the energy loss. We employ a formation time: the string segments are formed at times $t$ distributed as $\exp(-t/\gamma \tau_{\text{form}})$, with some parameter $\tau_{\text{form}}$ which is taken to be $1\text{fm}/c$. If the formation time is such that the segment is produced outside the “hadronization surface” defined by $T_H$, the segment will escape as it is (type B segment).

Most interesting are the segments which are formed inside but still escape, because they have $E > \Delta E$. These are type C segments. They escape, but their properties change. Actually such a segment leaves “matter” at the hadronization surface at a particular space-time point $x$, which is characterized by some collective flow velocity $\vec{u}(x)$. We assume that the string breaking in this case is modified such that the quark and antiquark (or diquark) necessary for the string breaking are taken from the flowing fluid rather than being produced via the Schwinger mechanism. So the new string segment is composed of a quark and antiquark (diquark) carrying the flow velocity, and the string piece in between, which has not been changed. This string piece may or may not carry large momentum, depending on whether it is close to a kink or not, the former possibility shown in Fig. 1(c).

In any case, due to the fluid-jet interaction, the properties of this segment change drastically compared to the normal fragmentation:

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** (Color online) Flux tube in matter (from other flux tubes, blue colored area). One distinguishes three types of behavior for string segments, noted as A, B, C (see text). The highest $p_t$ string segment may be of type B (a) or of type C (b). A type C segment picks up quark and antiquark from the fluid, carrying momenta and flavor according to the fluid properties (c).
The quark and antiquark (or diquark) from the fluid provide a push in the direction of the moving fluid.

- The quark (antiquark) flavors are determined from Bose-Einstein statistics, with more strangeness production compared to the Schwinger mechanism.
- The probability $p_{\text{diq}}$ to have a diquark rather than an antiquark will be bigger compared to a highly suppressed diquark-antidiquark breakup in the Schwinger picture ($p_{\text{diq}}$ is a parameter).

Our procedure has 4 parameters: $k_{\text{Eloss}}(=0.042)$, $E_0 (=6\text{ GeV})$, $\tau_{\text{form}} (=1\text{ fm/c})$, $p_{\text{diq}} (=0.22)$. It allows to cover in a single scheme the production of jets, of bulk, and the interaction between the two.

A crucial ingredient to the mechanism of fluid-jet interaction is the formation time of jet hadrons (the hadrons which leave the fluid). An estimate of the probability distribution of the formation times $t$ of jet hadrons with gamma factors $\gamma$ is given as [8]

$$P_{\text{inside}} = 1 - \exp \left( - \frac{(r_{\text{PB}} - b/2) m}{p_t \tau_{\text{form}}} \right).$$

In Fig. 2, we show the result for the 0-5% and the 20-30% most central events in Pb-Pb collisions at 2.76 TeV, using $c\tau_{\text{form}} = 1\text{ fm}$, $mc^2 = 1\text{ GeV}$, $r_{\text{PB}} = 6.5\text{ fm}$, and for the average impact parameters $b = 1.8\text{ fm (0-5\%)}$ and $b = 7.8\text{ fm (20-30\%)}$.

By construction, the probability $P_{\text{fluid-jet}}$ of having a fluid-jet interaction is equal to the probability of forming (pre)hadrons inside the fluid, so its estimate is given by $P_{\text{inside}}$. From Fig. 2, we see that the probability is quite large for intermediate values of $p_t$, but even large values (50 GeV/c) are significantly affected. Whether the effect of the interaction can be seen in some observable is a different question and will be discussed later.

The bulk matter extracted as described above provides the initial condition for a hydrodynamic evolution. As explained in [1], we compute the energy momentum tensor and the flavor flow vector at some position $x$ (at $\tau = \tau_0$) from the four-momenta of the bulk string segments. The time $\tau = \tau_0$ is as well taken to be the initial time for the hydrodynamic evolution. We employ three-dimensional ideal hydrodynamics as described in [8]. We try to mimic viscous effects by taking artificially large values of the flux tube radii (we take 1 fm), in order to get smoother initial conditions. This has the effect of reducing the elliptical flow by 20-30%, as needed.

**Figure 2.** (Color online) The estimate $P_{\text{inside}}$ to form (pre)hadrons inside the fluid, as a function of $p_t$, for Pb-Pb collisions at 2.76 TeV. We show the curves for the 0-5% and the 20-30% most central events.

- The quark and antiquark (or diquark) from the fluid provide a push in the direction of the moving fluid.
- The quark (antiquark) flavors are determined from Bose-Einstein statistics, with more strangeness production compared to the Schwinger mechanism.
- The probability $p_{\text{diq}}$ to have a diquark rather than an antiquark will be bigger compared to a highly suppressed diquark-antidiquark breakup in the Schwinger picture ($p_{\text{diq}}$ is a parameter).
Our prescription for bulk-jet separation and interaction should strongly affect dihadron correlations, which provide much more information than simple spectra. With all parameters \((k_{\text{Eloss}}, E_0, \tau_{\text{seg}}, p_{\text{diq}})\) being fixed from the considerations in the last section, we now compute dihadron correlation functions defined as
\[
R(\Delta \eta, \Delta \phi) = \frac{M}{S} \times \frac{S(\Delta \eta, \Delta \phi)}{M(\Delta \eta, \Delta \phi)},
\]
where \(S\) is the number of pairs in real events, and \(M\) the number of pairs for mixed events.

In Fig. 3, we show a correlation function for \(p_T^{\text{trigg}}\) in the interval 5.5-8.0 GeV/c and \(p_T^{\text{assoc}}\) in the range 2-2.5 GeV/c, in the 0–10% most central Pb-Pb collisions at 2.76 TeV. Although the trigger \(p_T\) is too large to originate from freeze-out (from the flowing fluid), one observes a ridge structure, which is due to the fluid-jet interaction. Let us consider the situation of an initial azimuthal anisotropy in the energy density which is transported into a corresponding anisotropy in the flow. We sketch in Fig. 4 the (somewhat exaggerated) situation of a triangular transverse flow pattern with maximal flow around \(\phi = 0^\circ, 120^\circ, 240^\circ\) (with respect to the \(y\)-axis). The flow maxima are indicated by blue arrows. Again it is very important that this flow pattern is (not necessarily in magnitude, but in shape) very similar at different longitudinal positions – in the figure indicated by the two transverse planes \(P\) and \(P'\), corresponding to two different space-time rapidities \(\eta_s\) and \(\eta'_s\). A soft hadron (\(S\)) produced at \(\eta_s\) at the fluid surface close to the position of maximal flow (for example at \(\phi = 0^\circ\)), will be boosted by the latter one and therefore carry information about this flow. A jet hadron (\(J\)) produced at \(\eta'_s\) at the same angle \((\phi = 0^\circ)\) close to the surface, will pick up a quark and an antiquark, both carrying flow, which adds the corresponding transverse momentum to the \(p_T\) of the string segment (red element in the figure). It is the same flow which affects the jet hadron at \(\eta'_s\) and the soft hadron at \(\eta_s\), which creates the dihadron correlation at \(\Delta \phi = 0\), the “ridge”. The correlation remains visible, even when the flow contribution to the jet hadron is only 10%, this is why the correlation is still present even for trigger transverse momenta beyond 10 GeV/c.

In semi-peripheral Pb-Pb collisions at 2.76 GeV/c, one observes for example for \(p_T^{\text{trigg}}\) in the interval 5.5-8.0 GeV/c and \(p_T^{\text{assoc}}\) in the range 2-2.5 GeV/c a clear elliptical flow structure, again due to the mechanism of fig. 4.
The correlation functions are essentially flat as a function of $\Delta \eta$, for large $\Delta \eta$. One therefore gets complete information about the long range correlations by integrating over $\Delta \eta$,

$$R(\Delta \phi) = \frac{1}{2(B - A)} \int_{A<|\Delta \eta|<B} R(\Delta \eta, \Delta \phi) d\Delta \eta,$$

where we use $A = 0.8$ and the maximum $B = 2$. This function agrees perfectly with its Fourier decomposition,

$$R(\Delta \phi) = 1 + \sum_{n=1}^{5} 2V_{n\Delta} \cos(n\Delta \phi),$$

using the first five terms. This is very convenient, because it allows to discuss the features of the correlation functions for different options for $p_t^{\text{trigg}}$ and $p_t^{\text{assoc}}$ by simply considering the Fourier coefficients.

In fig. 5, we plot some coefficients $V_{n\Delta}$ as a function of $p_t^{\text{trigg}}$. We compare our simulation (stars) with the results from ALICE [11] (circles). We see clearly the dominance of elliptical flow: the $n = 2$ coefficients are by far the largest. Nevertheless, also the higher harmonics contribute. We see in all cases an increase of the coefficients with $p_t^{\text{assoc}}$ and with $p_t^{\text{trigg}}$ up to values of around 2-3 GeV/c. At the latter values the hydrodynamic flow contributes the most to the correlation between soft hadrons from the fluid. For higher transverse momenta, the coefficients get smaller, because the correlation between soft particles dies out. But $V_{2\Delta}$ does not at all drop to zero at high $p_t$ because here the correlations between soft and jet particles come into play – the jet particles which suffered a push by the fluid, as discussed earlier (fluid-jet interaction). The fluid transfers at maximum few GeV/c of transverse momentum to the jet, but this is easily visible in the correlation (even at 20 GeV/c).

Whereas dihadron correlations provide the most complete information about particle production – in particular concerning the role of the “flowing” fluid, one may get the essential information by considering the elliptical flow coefficient $v_2$ of single particle production. Here we consider a definition where the reference plane is given by the event plane angle $\phi^{\text{backward}}$ ($\phi^{\text{forward}}$), obtained from counting all particles in the opposite hemisphere [12]. In Fig. 6, we plot $v_2$ as a function of the transverse momentum for different centralities in Pb-Pb collisions at 2.76 TeV. The magnitude of the elliptical flow coefficients increase at low $p_t$ to reach a maximum around 2-3.5 GeV/c and then drop slowly at large $p_t$. 

**Figure 4.** (Color online) Sketch of two cuts of the fluid volume corresponding to the space-time rapidities $\eta_s$ and $\eta'_s$, the two corresponding transverse planes being $P$ and $P'$. We show the example of a triangular flow pattern – the same at $\eta_s$ and $\eta'_s$. 

The correlation functions are essentially flat as a function of $\Delta \eta$, for large $\Delta \eta$. One therefore gets complete information about the long range correlations by integrating over $\Delta \eta$,
The behavior at high $p_t$ is the most interesting aspect: even at 10 GeV/c, there is a significant amount of elliptical flow, due to the fluid-jet interaction, which pushes jet particles in the direction of the collective flow at the freeze-out surface (and this effect will continue up to even higher $p_t$, but we are simply running out of statistics). The high $p_t$ behavior is closely related to the formation time discussion we had earlier. The non-vanishing $v_2$ at high $p_t$ is mainly due to fluid-jet interactions, and the values follow indeed the estimated probability $P_{\text{inside}}$ to form the jet hadron inside the fluid, see ref. [8].

To summarize: We presented a theoretical scheme which accounts for bulk matter, jets, and the interaction between the two. The criterion for bulk-jet separation is based on parton energy loss. But in addition to the latter mechanism, there are very important new phenomena which have not been discussed so far: The interaction between jet hadrons and soft ones (from fluid freeze-out), and the interaction between the fluid and jet hadrons at the moment of the creation of the latter ones. Particle production between zero and (at least) 20 GeV/c is affected. We understand quantitatively azimuthal anisotropies in single particle production and dihadron (long range) correlations at large values of $p_t$.

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Figure 6. (Color online) $p_t$ dependence of elliptical flow (defined with respect to the opposite hemisphere sub-event plane) for different centralities in Pb-Pb collisions at 2.76 TeV. We compare the ATLAS data [12] (circles) with calculations (red lines).

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