Lambda-to-Kaon Ratio Enhancement in Heavy Ion Collisions at Several TeV

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We introduced recently a new theoretical scheme which accounts for hydrodynamically expanding bulk matter, jets, and the interaction between the two. Important for the particle production at intermediate values of transverse momentum (p_t) are jet hadrons produced inside the fluid. They pick up quarks and antiquarks (or diquarks) from the thermal matter rather than creating them via the Schwinger mechanism—the usual mechanism of hadron production from string fragmentation. These hadrons carry plasma properties (flavor, flow) but also the large momentum of the transversely moving string segment connecting quark and antiquark (or diquark). They therefore show up at quite large values of p_t, not polluted by soft particle production. We will show that this mechanism leads to a pronounced peak in the Lambda-to-kaon ratio at intermediate p_t. The effect increases substantially with centrality, which reflects the increasing transverse size with centrality.

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Heavy ion collisions at relativistic energies are expected to lead to the formation of a quark gluon plasma, which strongly interacts and behaves as a fluid [1–4]. Nevertheless, it is difficult to directly observe the plasma properties since the fluid hadronizes, and the corresponding hadrons still interact among themselves before being detected. It is therefore desirable to find observables which keep information about the partonic system despite the hadronization procedure. In this Letter, we will discuss in which sense the transverse momentum dependence of the Lambda-to-kaon ratio is such an observable.

As already observed earlier in Au-Au scattering at 200 GeV [5], also in Pb-Pb collisions at 2.76 TeV there is an impressive increase of the Lambda yield compared to kaons, more and more pronounced with increasing centrality, as shown by the ALICE Collaboration [6]. This phenomenon concerns transverse momenta (p_t) in the range between 2 and 6 GeV$/c$. This so-called "intermediate p_t range" is the domain of coalescence models [7–11], where hadrons are produced by recombining quarks from the plasma, to be distinguished from "fragmentation" of partons. However, a detailed quantitative understanding of the intermediate p_t region is still missing, and as discussed in [12], it seems impossible to really separate an "intermediate p_t region" from the low and high transverse momentum domain.

In Ref. [12], we introduced a new theoretical scheme which accounts for hydrodynamically expanding bulk matter, jets and the interaction between the two. The whole transverse momentum range is covered, from very low to very high p_t. In [12], we show that the new approach can accommodate spectra of jets with p_t up to 200 GeV$/c$ in proton-proton (pp) scattering at 7 TeV, as well as particle yields and harmonic flows with p_t between 0 and 20 GeV$/c$ in Pb-Pb collisions at 2.76 TeV. Since our aim is a single model which is able to cover all phenomena, we will apply the approach of Ref. [12], with exactly the same parameters (EPOS2.17v3), to study Lambda and kaon production and try to understand the "Lambda-to-kaon ratio peak." In this Letter and in [12], we do ideal hydrodynamics, but we mimic viscous effects by using artificially large flux tubes to reduce initial fluctuations and to reduce elliptical flow, which would be otherwise 20%–30% too high.

Let us briefly recall the essential features of the new approach, which are relevant for the discussion of this paper. All the details can be found in [12]. The basis is multiple scatterings (even for pp), where a single scattering is a hard elementary scattering plus initial state radiation, the whole object being referred to as parton ladder. The corresponding final state partonic system amounts to (usually two) color flux tubes, being mainly longitudinal, 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.

Let us take the simple case of a single hard scattering producing two gluons, without initial state radiation. This leads to two flux tubes with one transversely moving piece each, corresponding to the hard gluons, as shown in Fig. 1.

These flux tubes do not only cover central rapidities, since they stretch from projectile to target remnant. Including initial state radiation (which is automatically included in all calculations) will add more transversely moving pieces, leading to complicated three-dimensional dynamics. But despite the complicated details, the flux tubes remain essentially longitudinal, with some transversely moving parts (kinks in the string language). The flux tubes (strings) will expand and at some stage break via the production of quark-antiquark or diquark-antidiquark pairs, as seen in Fig. 2.

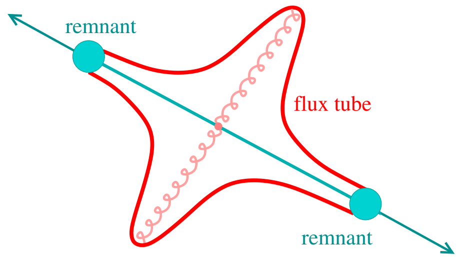

FIG. 1 (color online). A single hard scattering, leading to two flux tubes with transversely moving parts (kinky strings).

The string segments are identified with hadrons. Those close to the transversely moving pieces carry the large momentum coming from the partons of the hard scattering—they constitute the jets, indicated by the arrows in Fig. 2.

In heavy ion collisions and also in high multiplicity events in proton-proton scattering at very high energies, there are many elementary scatterings and therefore many flux tubes. Their density will be so high that they cannot decay independently as described above. Here, we have to modify the procedure as discussed in the following. The starting points are still the flux tubes (kinky strings) originating from elementary collisions, as discussed above. These flux tubes finally 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 is 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.

Three possibilities occur: (A) String segments which do not have sufficient energy to escape will constitute matter, they lose their character as individual strings. This matter will evolve hydrodynamically and finally hadronize ("soft hadrons"). (B) String segments having sufficient energy to escape and being formed outside the matter, constitute jets ("jet hadrons"). (C) There are finally also string segments 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").

The criterion for a string segment to leave the matter or not is based on energy loss, as discussed in [12]. We use a $\sqrt{T^3 E}$ dependence of the energy loss per unit length, as given in [13], with the temperature T being translated into string density. Technically, at some given initial proper time, we discretize strings and consider string segments, with all segments being well localized in space. This allows us to define a density ρ of segments per volume cell, after discretizing space. For each segment, we follow its trajectory through space and compute the integrated energy loss, where the energy loss per length depends on ρ (see [12]). All this is done initially, it is an initial estimate of energy loss, although the real physical process evolves in time. Having separated bulk and escaping segments, we compute the energy-momentum tensor from the bulk segments and use this as initial condition for hydrodynamics.

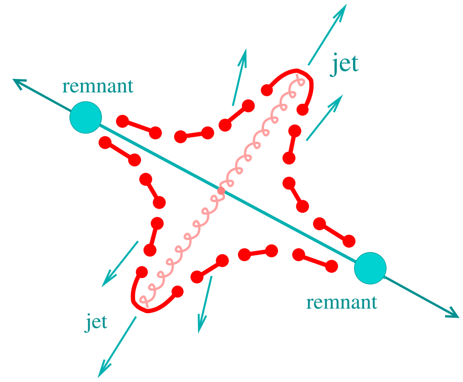

FIG. 2 (color online). Flux tube breaking via $q - \bar{q}$ production, which screens the color field (Schwinger mechanism).

Our initial conditions are somehow intermediate between the usual Glauber and Kharzeev-Levin-Nardi initial conditions, closer to the latter ones, as discussed in [14]. The system will then evolve hydrodynamically till freeze-out. The latter is defined by a constant temperature $T_H =$ 168 MeV (which is practically mandatory to get the baryon yields right), defining in this way a freeze-out hypersurface, representing the fluid boundary. Outside the fluid boundary, particles are still allowed to interact (via hadronic interactions). Having now all information about the space-time evolution of the fluid, we consider for a second time the trajectories of segments—the escaping ones. As in usual vacuum string fragmentation, string segments are considered to be hadrons after some time, and these formation times are assumed to be distributed as $\exp(-t/\gamma\tau_{\rm form})$, with a (crucial) parameter $\tau_{\rm form}$. Since the fluid surface is known, we can distinguish between hadrons produced inside or outside the fluid.

Concerning case B, high energy flux tube segments will leave the fluid, and they "materialize" (become hadrons) outside the fluid, providing jet hadrons via the usual Schwinger mechanism of flux-tube breaking caused by quark-antiquark or diquark-antidiquark production.

Case C is interesting. The jet hadrons are produced still inside matter or at the surface, but they escape. Here, we assume that the quark, antiquark, diquark, or antidiquark needed for the flux tube breaking is provided by the fluid with properties (momentum, flavor) determined by the fluid rather than the Schwinger mechanism, whereas the rest of the string dissolves in matter, see Fig. 3. 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 and explains azimuthal asymmetries up to quite large values of p_t, as discussed in much detail in [12].

Even more important for the present discussion are two other effects: the quark (antiquark) flavors are determined from Bose-Einstein statistics, with more strangeness

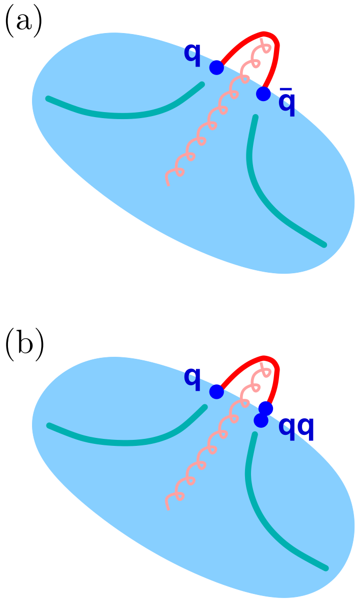

FIG. 3 (color online). Escaping string segment, getting its endpoint partons from the fluid. We show the case of a quark and an antiquark (a) and of a quark and a diquark (b). The rest of the string dissolves in matter.

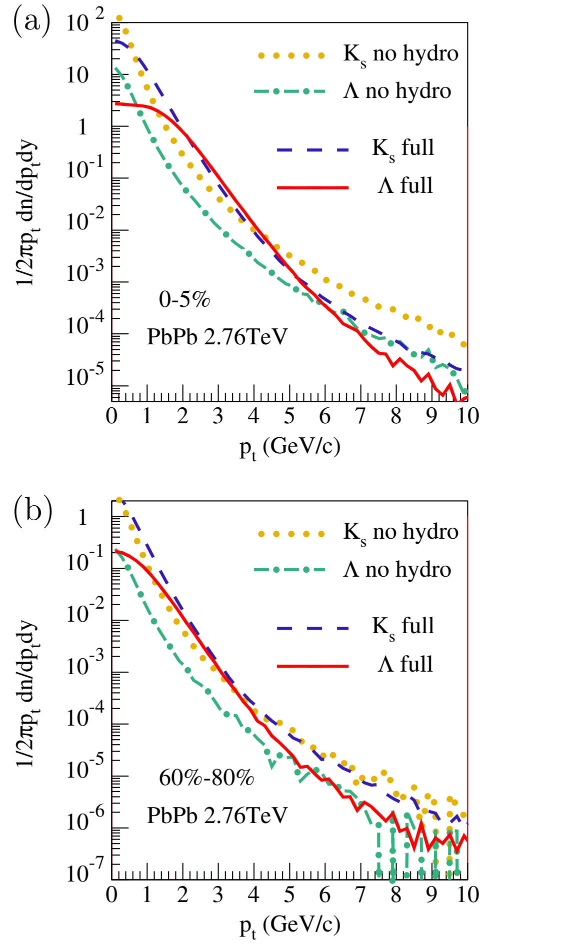

FIG. 4 (color online). Transverse momentum spectra for Lambda particles and kaons (K_s) for central rapidities in central (a) and peripheral (b) Pb-Pb collisions at 2.76 TeV. We show the full model calculations and also the ones without hydroevolution.

production compared to the Schwinger mechanism, and the probability $p_{\rm diq}$ to have a diquark rather than an antiquark will be bigger compared to a highly suppressed diquark-antidiquark breakup in the Schwinger picture.

Our procedure has few parameters: $\tau_{\rm form}$ ($= 1$ fm$/c$) and $p_{\rm diq}$ ($= 0.22$). In addition, in the energy loss formula,

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

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 η_s, dL is a length element, and $k_{\rm Eloss}$ and E_0 are parameters taken as $k_{\rm Eloss} = 0.042$, $E_0 = 6$GeV. We introduce an energy cutoff E_0 to have sufficient energy loss for slowly moving segments. Our procedure with four independent parameters allows us to cover in a single scheme the production of jets, of bulk, and the interaction between the two. The data used to fix these parameters are the transverse momentum dependencies of charged particle and identified proton yields and of v_2 in central Pb-Pb collisions at 2.76 TeV; see [12].

All the above-mentioned effects are important concerning Lambda and kaon production. In Fig. 4, we show transverse momentum spectra for Lambda particles and kaons for central rapidities in central and peripheral Pb-Pb collisions at 2.76 TeV. The spectra for the calculations without hydrodynamic evolution (pure string decay) are quite similar for Lambda particles and kaons, and they essentially differ by a factor, simply due to the fact that the relative probability of diquark-antidiquark to quark-antiquark breakup is small. However, the situation is completely different in case of the full calculation. Both Lambda particles and kaons increase at intermediate p_t but much more in the case of Lambda particles. This is first of all due to flow, which pushes the heavier Lambda particles more than the kaons.

The effect is magnified due to jet hadrons carrying fluid properties (process C): there is an additional momentum push from the fluid-jet interaction, which favors Lambda particles over kaons due to the higher number of quarks of the former ones. Also, the yield of Lambda particles is increased compared to kaons because diquarks compared to quarks are less suppressed when taken from the fluid as compared to the Schwinger mechanism.

The effects are similar in central and peripheral Pb-Pb collisions, but the preferred Lambda production compared to kaons is more pronounced in the central compared to the peripheral events: the Lambda curve crosses the kaon one in the case of central, but not in the case of peripheral,

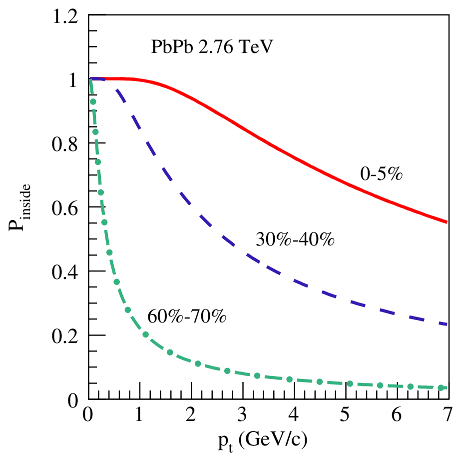

FIG. 5 (color online). The estimate P_{inside} of the probability to form (pre)hadrons inside the fluid (in the direction parallel to the impact parameter) as a function of p_t for Pb-Pb collisions at 2.76 TeV. We show the curves for the 0–5%, the 30%–40%, and the 60%–70% most central events.

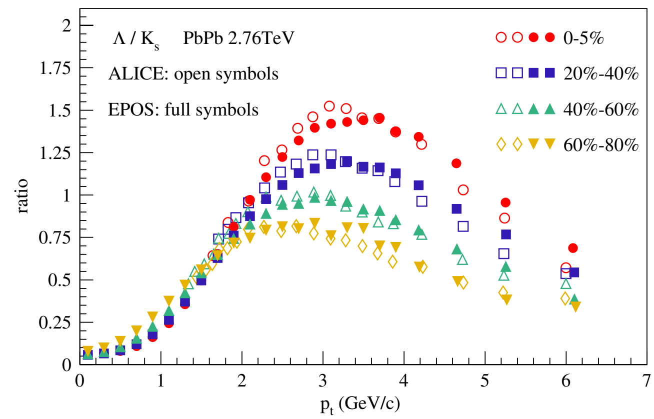

FIG. 6 (color online). Lambda-to-kaon ratio as a function of p_t in Pb-Pb collisions at different centralities. We show our theoretical results (full symbols) and preliminary data from ALICE [6] (open symbols), where the systematic errors of the order of 10% are not indicated.

collisions. The reason is that the number of jet hadrons carrying fluid properties depends on their formation times: these hadrons must have been formed inside the fluid. In Fig. 5, we plot the estimate P_{inside} of the probability to form (pre)hadrons inside the fluid as a function of p_t for different centralities (see [12]). This probability decreases strongly towards peripheral collisions because the transverse sizes get much smaller. So we get less Lambda enhancement at more peripheral collisions, and the enhancement is also shifted to smaller p_t.

In Fig. 6, we show the Lambda-to-kaon ratio as a function of p_t in Pb-Pb collisions at different centralities. Our calculations (full symbols) follow quite well the trend seen in the data (open symbols): going from peripheral towards central collisions, one observes a more and more pronounced peak, which also moves to higher p_t. The calculations would fit the data even better with a slightly smaller formation time, but we prefer to use the parameters of Ref. [12], which give quite good agreement with many other data sets.

To summarize, we introduced a new theoretical scheme which accounts for hydrodynamically expanding bulk matter, jets, and the interaction between the two. This approach covers the whole transverse momentum range, from very low to very high p_t. In this framework, we can reproduce the experimentally observed strong increase of the Lambda-to-kaon ratio at intermediate values of p_t. We understand this effect to be due to a communication between the fluid and jet hadrons: these hadrons are composed of a high p_t string segment (from the hard process) and (di)quarks from the fluid, carrying fluid properties. So the final hadrons are observed at relatively high p_t but, nevertheless, provide information about the fluid, whereas the soft hadrons from fluid freeze out carry only small p_t. The reason for the strong centrality dependence is the fact that the number of jet hadrons having suffered a fluid-jet interaction depends on the volume: the probability that such a jet hadron is produced inside the fluid is more likely for big volumes compared to small ones. The fact that the enhancement disappears for very peripheral collisions does not mean that there is no fluid. It means that the volume is too small for this particular effect to be seen.

The Lambda-to-kaon ratio enhancement in nuclear collisions has been considered since a long time to be a possible signal of a quark gluon plasma because, first of all, any observable showing a drastic change compared to proton-proton points to "new physics", and also coalescence of quarks from a plasma qualitatively should give a Lambda-to-kaon ratio peak. Here, we show for the first time a quantitative analysis, which explains the phenomenon, in an approach which explains in addition many other observations at intermediate p_t. Our explanation is based on the fluid-dynamical expansion of quark gluon matter. Both the flow and plasma properties are essential to explain the effect. The role of the jets is only to transport plasma properties to larger p_t and provide, therefore, an additional and clean tool to confirm the existence of the quark gluon plasma.

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