Soft Probes of the Quark-Gluon Plasma with ALICE at LHC

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Abstract. The Large Hadron Collider (LHC) should start its activity of data taking by the end of summer 2009, and will provide beams of p-p and Pb-Pb at colliding energies up to 14 TeV and 5.5 ATeV respectively. The Pb-Pb heavy-ion program aims at reaching the necessary conditions to create a deconfined state of partons, the Quark-Gluon Plasma (QGP), whose study is one of the most exciting physics topics to be explored thanks to the possibilities offered by this new-generation accelerator. In particular, the "soft" observables related to low and intermediate $p_T$ processes, will shed light on many fundamental properties of the system, such as thermodynamic parameters, chemical composition, expansion velocity etc. The p-p collisions will be of great interest as well, since they will serve as an essential reference for heavy ions. ALICE (A Large Ion Collider Experiment) is the LHC experiment dedicated to the study of the QGP. Its large acceptance and low magnetic field make it particularly suited for the study of soft phenomena. After having given an overview of this detector, I will present the main motivations and prospects for soft physics in both p-p and Pb-Pb collisions.

1. Introduction
More than 99% of the particles produced in heavy-ion collisions have a momentum lower than 2 GeV/c. Therefore the study of these “soft” particles and the physical processes involved in their production are of major interest for the comprehension of the Quark-Gluon Plasma (QGP) properties: they give access to the chemical composition of the system, its size, its temperature, and its dynamics. However, because of the large “jump” in energy, the abundance of hard processes at LHC will somehow modify our perception of soft physics: high-$p_T$ mechanisms, which have already left their fingerprints at RHIC, will certainly influence the medium in many respects. For this reason, it will be essential to measure all the observables relevant for heavy-ion data also in small systems such as p-p, first to get a hadronic reference for heavy-ion data interpretation, and second to understand the underlying pQCD processes at these energies.

At LHC, ALICE is the experiment best suited to study soft phenomena due to its low material budget, its low magnetic field and its main tracking device (the TPC), which provides a unique capability to identify many particles down to low momenta $\sim$ 100 MeV/c [1]. It is actually the only experiment at LHC almost fully dedicated to the study of the QGP, though having a substantial physics program for p-p to achieve. An overall description of this experiment can be found in ref. [2]. The following sections will give an overview of ALICE performance in the soft sector, showing results obtained for the following topics: event characterization, (strange-) particle production, flow, femtoscopy and event-by-event analyses.

2. Event characterization and particle production

All the heavy-ion collisions will be sorted as a function of the impact parameter between the two incident nuclei, used to describe the event “centrality”. This is of major importance to derive the involved number of participant nucleons and binary collisions, which are critical elements in this field. In ALICE the centrality is measured by combining the information from zero degree hadronic and electromagnetic calorimeters located near the beam axis. The distributions of their respective signals are described in refs. [1, 3]. The correlation of these two signals provide the number of spectators in the collision, from which one deduces the number of participants and the impact parameter, with estimated resolutions of 15 nucleons and 1 fm respectively [1].

Inclusive charged-particle multiplicity and pseudorapidity (\(dN_{ch}/d\eta\)) distributions supply additional event information: they relate to the initial energy density of the medium, and help in testing particle production models and understanding limiting fragmentation phenomena (see [4]). In ALICE these measurements are performed using the detectors ITS + TPC (central) and FMD (forward region) that allow a coverage of \(-3.4 < \eta < 5.1\) [5, 6]. The multiplicity and \(dN_{ch}/d\eta\) distributions will be the very first measurements ALICE will be able to achieve. The first run should take place in fall 2009 with proton beams, at \(\sqrt{s}\) equal to 0.9 and 10 TeV.

The amount of identified particles in ALICE will be sufficiently high to provide temperature and baryochemical potential event by event. This will give the possibility to place every event on the nuclear matter phase diagram \((T, \mu_B)\), which was not possible at lower energy heavy-ion accelerators. Experimentally, that will be done by comparing the relative abundances between the different particles species to the ones expected by the statistical models at equilibrium, which in turn furnishes the parameters \(T\) and \(\mu_B\) that best describe the data. These models have shown a good agreement with the data, for example at RHIC [7], which suggests that chemical equilibrium is reached. An inclusive measurement of all the particle species produced from LHC Pb-Pb collisions will give insight on the question of chemical equilibrium at an energy where hard processes are dominant. It will be interesting to compare them with the nonequilibrium scenario considered in ref [8] which involves substantial strangeness oversaturation.

A comparison to small “canonical” systems (p-p) will also be very important to detect volume effects in particle production. The measurement of unflavoured and especially strange species will strongly constrain these models.

Fig. 1 shows the range of transverse momentum that ALICE will cover with the expected statistics of the first year of Pb-Pb data taking, corresponding to \(10^7\) central events. At mid-rapidity, identification of charged particles is performed via their energy loss (ITS, TPC) and time of flight (TOF) up to momenta \(\sim 2\) GeV/c in a full azimuthal coverage. The TRD will in addition separate electrons from pions. At higher momentum the HMPID is used, extending the identification range of kaons and protons up to 5 GeV/c in a limited azimuthal coverage. In addition, identification of particle decays is done via invariant mass analysis (for resonances) plus topological methods for strange and charm secondary vertices. These methods improve substantially the accessible \(p_T\) range, up to more than 10 GeV/c.

3. Expansion and hadronization

As the fireball expands and cools down, the quarks hadronize and the system freezes-out. What happens during this expansion and hadronization phase can be inferred from the study of the dynamical properties of the resulting hadrons. In this respect, the study of elliptic flow brings interesting information (see [9].) The measurement of the reaction plane is one of the major issues in elliptic flow analysis. While the so-called “event plane” method is sensitive to “non-flow” effects, the “cumulant” method doesn’t give access to the reaction plane [10, 11]. A new possibility, based on both Lee-Yang Zeros and event-plane methods has been developed for ALICE; it provides the \(v_2\) factor with a precision of \(\sim 1%\) (statistic error only), getting rid of non-flow effects and auto-correlations, and the reaction plane with a resolution factor of about
Figure 1. Transverse momentum range of identification of mesons and baryons at mid-rapidity, expected for $10^7$ Pb-Pb central events at the energy $\sqrt{s_{NN}} = 5.5$ TeV. (Note: these ranges are sensitive to the models used in the simulations.)

0.8 $^{[12]}$ $^{[13]}$.

A good knowledge of the elliptic flow can supply substantial information on the hadronization mechanisms. RHIC data have shown a very good scaling of the $v_2$ factor with respect to the number of hadron constituent quarks (two or three) as a function of transverse mass. The coalescence models have been shown to provide one of the most accurate explanations of this behaviour, and that has been corroborated by baryon-over-meson ratio vs $p_T$ measurements $^{[14]}$. In this context, the identification of strange secondary vertices ($K^0_S$, $\Lambda$, $\Xi$ and $\Omega$) plays an important role: because their decay length is of several centimeters, their charged decay modes can be reconstructed with topological methods, in which single particle PID is not mandatory, and thus have no limitation other than statistics. As a result, the accessible $p_T$ range should go from 0.5 to at least 8-10 GeV/c in the first Pb-Pb run of ALICE (see fig. 1). This allows one to test the coalescence models and identify the $p_T$ region above which fragmentation dominates coalescence in hadron production. Light resonances ($\rho$, $K^*$, $\phi$...) will give complementary information on coalescence thanks to their range of identification in $p_T$, but will also help probe chiral symmetry restoration $^{[15]}$ and the time between chemical and kinetic freeze-outs $^{[16]}$. In that respect, the study of resonant-to-non-resonant particle ratios as a function of event multiplicity and $p_T$ will be interesting. It is expected that resonances can be identified up to 15 GeV/c in $p_T$, and recent studies show that PID is not mandatory either $^{[17]}$, be it in p-p or heavy-ion collisions.

The interferometry method applied to identical particles is also a powerful tool to probe the space-time evolution of the emitting source in heavy-ions collisions, which will help constrain the hydrodynamical models. The source radii observed at RHIC differ significantly from the model predictions, possibly due to an incomplete hydrodynamic evolution of the fireball. That measurement will therefore be fundamental at LHC. ALICE offers great opportunities to perform these femtoscopy analyses thanks to its identification performance at low $p_T$ and the expected high event multiplicities. In such conditions, source radii up to 15 fm should be measurable $^{[18]}$. 
4. Event-by-event physics

Fluctuations of thermodynamical quantities from event to event are fundamental to study the QCD phase transition and the order of this transition. As a matter of fact, thanks to the identified particle multiplicities expected in ALICE, various observables relative to the soft sector will be analysed on an event-by-event basis, as mentioned in section 2. For example, conserved quantities such as the net electrical charge may provide information on the degrees of freedom of the initial state of the collision, and thus directly on the phase transition; fluctuations in temperature (extracted from particle $p_T$ spectra) should indicate the universality (or not) of the freeze-out temperature.

Other interesting information will be obtained from the event-by-event analysis program of ALICE. Recent simulations using the Hijing particle generator show that the relative error on reconstructed $K/\pi$ and $p/\pi$ ratios, event by event, should not exceed a few percent; that will allow one to detect unexpected fluctuations due to QGP effects. In addition, the balance functions, whose width is directly related to the correlation range between particles, can probe the hadronization time. A new feature possible in ALICE will be the study of the balance function as function of $p_T$ for different rapidity gaps [19].

5. Conclusions

The ALICE experiment at LHC has a wide program dedicated to the soft phenomena. Both in p-p and Pb-Pb, the event multiplicity and particle pseudo rapidity distributions will be the first physics measurements ALICE will achieve. With the data collected in just a few hours of Pb-Pb beams, many questions related to the medium equilibrium, its equation of state, its expansion, and phase transition will be assessed. The expected large event multiplicities will give the possibility to address many observables on an event-by-event basis and thus allow a novel approach, hardly possible at lower-energy accelerators, to investigate the underlying physics. Obviously, all the soft physics results will have to be combined with results coming from hard probes (including heavy flavours and jets), in order to reach a broad vision of all the phenomena involved at these energies.

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