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# Light flavour measurements with ALICE at the LHC: Elliptic flow and particle spectra

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**Summary.** — The study of the properties of the Quark Gluon Plasma (QGP) produced in heavy ion collisions at the LHC at unprecedented energies is the main purpose of the ALICE Collaboration. Light flavour measurements give the possibility to study the parton energy loss in the hot and dense medium, the collective expansion of the fireball and the hadronization mechanism. In this talk results on elliptic flow and transverse momentum spectra of identified light flavour particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ will be reported.

PACS 25.75.Ag – Global features in relativistic heavy ion collisions.
PACS 25.75.Dw – Particle and resonance production.
PACS 25.75.Ld – Collective flow.
PACS 25.75.Nq – Quark deconfinement, quark-gluon plasma production, and phase transitions.

## 1. – Introduction

In high energy Pb-Pb collisions, after the hard scattering between partons during which heavy quarks, jets and direct photons are produced, a termalized deconfined medium dominated by soft interactions is created, the QGP, that expands and cools down [1]. When the temperature becomes lower than the critical one, hadrons are produced (hadronization phase). When the chemical freezout temperature $T_{ch}$ is reached, the inelastic collisions stop and the relative particle abundances are fixed. Finally, as soon as the temperature decreases below the kinetic freezout one $T_{kin}$, also the elastic collisions stop and the transverse momentum spectra $p_T$ of all the particle species are fixed.

To quantify the QGP properties, not only nucleus-nucleus but also pp and p-nucleus collisions have to be studied. They provide a reference for nucleus-nucleus data, give the

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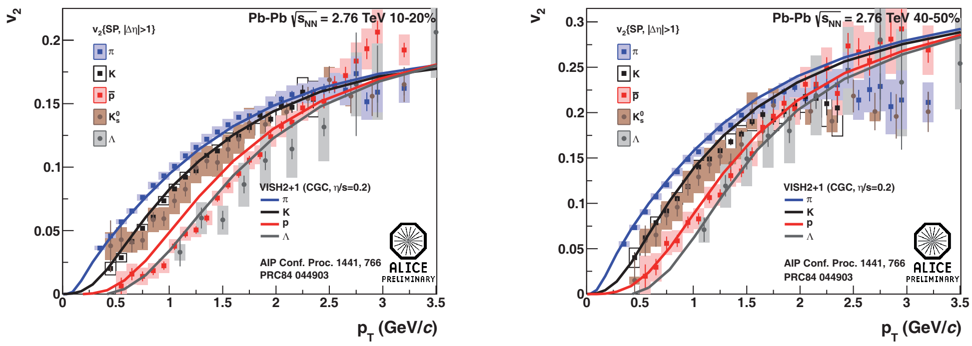


Fig. 1. – $v_2$ as a function of $p_T$ for $\pi$, $K$, $p$, $K^0_s$ and $\Lambda$ for 10-20% (left) and 40-50% (right) centrality classes. Predictions from viscous hydrodinamic models are superimposed to the data.

possibility to decouple initial and final state effects and are fundamental to test QCD inspired Monte Carlo models.

In the following sections, results on elliptic flow and spectra of light flavour identified particles measured by ALICE [2] in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ will be reported.

## 2. – Elliptic flow

In non central nucleus-nucleus collisions, the initial spatial azimuthal anisotropy in the overlap region of the colliding nuclei is converted, via multiple interactions, into anisotropy in the momentum space [3]. The azimuthal dependence of the particle yield can be written in the form of a Fourier series:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_T\mathrm{d}p_T\mathrm{d}y}\left(1+\sum 2v_n\cos[n(\varphi-\Psi_n)]\right), \tag{1}$$

where $E$ is the particle energy, $\varphi$ the azimuthal angle, $y$ the rapidity and $\Psi_n$ the $n$-th harmonic symmetry plane angle. The coefficients $v_n = \langle\cos[n(\varphi-\Psi_n)]\rangle$ are called differential flow: $v_1$ is the direct flow, $v_2$ is the elliptic flow, $v_3$ the triangular flow, etc.

The anisotropic flow gives the possibility to characterize the properties and the evolution of the system created in nucleus-nucleus collisions and to study the collective effects among produced particles. The higher harmonics are sensitive to the initial shape fluctuations while $v_2$ is sensitive to the hydrodynamic radial expansion of the medium. Studying anisotropic flow provide information also on the $\eta/s$ (shear viscosity over entropy density) of the medium.

In fig. 1 $v_2$ is reported as a function of $p_T$ for $\pi$, $K$, $p$, $K^0_s$ and $\Lambda$ for 10-20% and 40-50% centrality classes. It can be noticed that there is a centrality dependence and a mass ordering for all the species up to $p_T \sim 2.5\,\text{GeV/c}$ (the lighter is the particle, the higher is $v_2$). In fig. 1, the comparison with viscous hydrodynamic model predictions is also reported. VISH2+1 ($\eta/s = 0.2$) [4] shows a good agreement at low $p_T$ in peripheral collisions while it can not describe heavier particles especially in more central collisions. The agreement improves if an hadronic rescattering (UrQMD) after the hydro stage is added to the model [5].

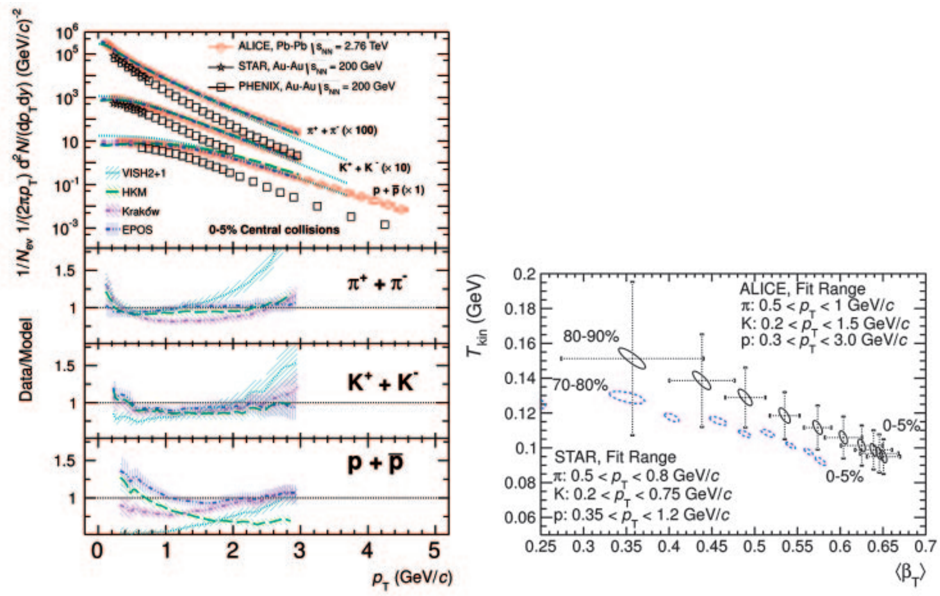


Fig. 2. – Left: $p_T$ spectra of primary pions, kaons and protons measured by ALICE (red) and RHIC (black) in central collisions. Hydrodynamic models predictions are superimposed to the data. Right: $T_{kin}$ as a function of $\langle \beta_T \rangle$ for events with increasing centrality measured by ALICE (black) and STAR (blue).

## 3. – Light flavour low $p_T$ spectra and particle abundances

Light flavour low $p_T$ spectra and particle abundances are fundamental to study the collective and thermal properties of the QGP. These studies allow to constrain the transport properties of the medium and are important since the signals produced in the QGP phase have to be folded with the space-time evolution of the whole system. The low $p_T$ spectra can be described by hydrodynamic models from which it is possible to get information on the collective transverse expansion of the system (radial flow) and the kinetic freezout temperature $T_{kin}$. The particle abundances can be described by thermal models that reflect the properties of a medium in thermal and chemical equilibrium providing information on the baryochemical potential $\mu_B$ (net baryon content) and the chemical freezout temperature $T_{ch}$.

In fig. 2 (left) $p_T$ spectra of primary pions, kaons and protons measured for 0-5% centrality class by ALICE [6] in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ and by STAR [7] and PHENIX [8] in Au-Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ are reported. We define as primary all the prompt particles including decay products except those from weak decay of strange particles. It can be seen that the spectra at LHC energy are harder than the ones at RHIC energy. This can be attributed to a stronger radial flow. Superimposed to the data a fit with a Blast-Wave function [9] is reported. It provides a transverse expansion velocity $\beta_T = 0.65 \pm 0.02$, 10% higher than RHIC results (consistent with the increasing of $\langle p_T \rangle$ with the collision energy) and $T_{kin} = 95 \pm 10\,\text{MeV}$ comparable with that estimated at RHIC.

In fig. 2 (left) the spectra are also compared to hydrodynamic models: VISH2+1 [10], HKM [11] and Krakow [12]. VISH2+1 is a viscous hydrodynamic model. HKM is

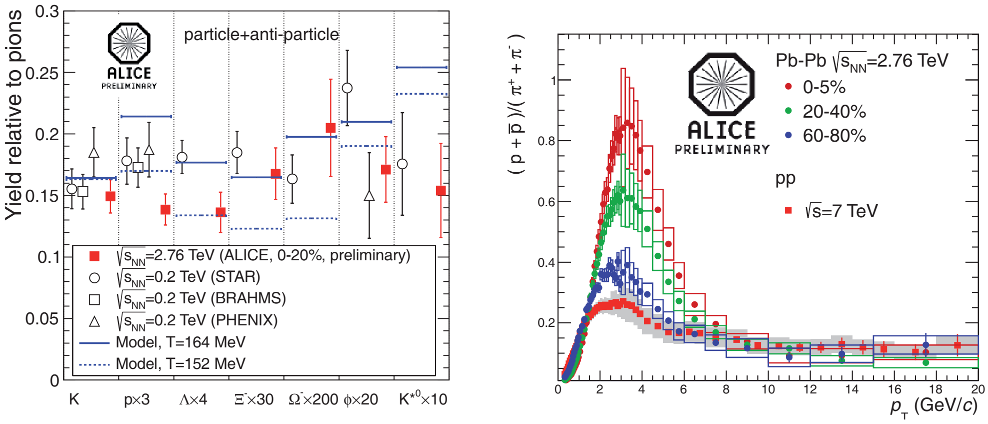


Fig. 3. – Left: Yields of $K$, $p$, $\Lambda$, $\Xi$, $\Omega$, $\phi$ and $K^{*0}$ relative to the yield of pions measured by ALICE (red points) in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ and by RHIC (black points) in Au-Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$. Right: $p/\pi$ as a function of $p_T$ for 0-5%, 20-40% and 60-80% centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$. The comparison with the same ratio measured in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ is also shown.

a hydrodynamic model combined with UrQMD description of the hadronic phase that builds additional radial flow (due to elastic interactions) and affects the particle ratios (due to inelastic interactions). Krakow introduces non equilibrium corrections due to viscosity at the transition from the hydrodynamic description to particles which change the effective $T_{ch}$. The last two models give a better description of the data suggesting that at LHC energies a pure hydrodynamic model is not able to describe the data.

In fig. 2 (right) the blast-wave fits parameters $T_{kin}$ and $\langle\beta_T\rangle$ for collisions with different centrality classes measured by ALICE [13] and RICH [14] are reported. It can be noticed that while $\langle\beta_T\rangle$ increases with centrality, $T_{kin}$ decreases. This could be an indication of a more rapid expansion with increasing centrality consistent with the expectation of a shorter lived fireball with stronger radial gradients in peripheral collisions.

In fig. 3 (left) yields of $K$, $p$, $\Lambda$, $\Xi$, $\Omega$, $\phi$ and $K^{*0}$ relative to the yield of pions measured by ALICE (red points) in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ [15] and by RHIC experiments (black markers) in Au-Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ are reported. The ratios at the two energies are compatible except for $p/\pi$ and $\Lambda/\pi$. The data are compared with a thermal model prediction [16], which assumes thermal and chemical equilibrium, and successfully described particle ratios at lower energy. It can be seen that if the temperature is set to the value extrapolated from lower energies ($T = 164\,\text{MeV}$), $p/\pi$ and $\Lambda/\pi$ are not reproduced. A fit of the measured yields to the same model brings to a lower temperature ($T = 152\,\text{MeV}$), but some tensions between the model and the data are seen, especially for protons and multistrange baryons. Different mechanism have been suggested to solve this discrepancy, such as non equilibrium Statistical Hadronization Model [17], hadronic final state interactions (in particular antibaryon-baryon annihilation) [18] or pre-hadronic bound states above the critical temperature [19].

In fig. 3 (right) the $p/\pi$ ratio is reported as a function of $p_T$ for 0-5%, 20-40% and 60-80% centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$. The comparison with the same ratio measured in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ is also shown. At intermediate transverse momentum ($2 < p_T < 7\,\mathrm{GeV/c}$), the ratio is enhanced as compared to pp collisions. This enhancement becomes more pronounced for more central collisions. The rise of the ratio is due to the transverse flow while the maximum and the decrease can be explained by the coalescence of partons from the deconfined medium [20]. At high momentum, $p_T > 10\,\mathrm{GeV/c}$, the ratio is similar for both Pb-Pb and pp collisions: the explanation is that in this $p_T$ region the parton fragmentation is not modified by the medium. The shape of the ratio can be interpreted as an interplay between the transverse flow, the jet fragmentation and the coalescence.

## 4. – Conclusions

Some of the results produced by the ALICE Collaboration, based on Pb-Pb data collected in 2010 and 2011, have been summarized in this contribution. In particular, transverse momentum spectra and elliptic flow measurements provide a way to investigate the properties of the parton energy loss in the hot and dense medium, the collective expansion of the fireball and the hadronization mechanism.

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