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Soft probes of the Quark-Gluon Plasma measured by ALICE

Marek Chojnacki for the ALICE Collaboration

University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark

Abstract

In these proceedings an overview of the main ALICE results on soft probes of the Quark-Gluon Plasma (QGP) in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV is presented. It comprises measurements of light flavour hadron production, azimuthal flow, and system size. All of the results are compared to hydrodynamical calculations to extract global properties of the QGP. In addition, particle production is also compared to results from statistical models. In order to show the evolution of soft probes with system size, some of the measurements from pp and p–Pb collisions are compared to those from Pb–Pb collisions.

Keywords:
LHC, ALICE, QGP

1. Introduction

The main goal of the heavy-ion program at the Large Hadron Collider (LHC) is to study properties of the Quark-Gluon Plasma (QGP), a state of deconfined quarks and gluons. The evolution of the system created during ultrarelativistic heavy-ion collisions can be understood as divided into a few phases. In our current understanding, a preequlibrium phase [1], which eventually reaches an approximate local thermalization, exists. This stage is followed by an expansion in a common velocity field [2, 3]. During the expansion, the system behaves very much like a perfect liquid and cools down until it forms hadrons as a result of chemical freeze-out at the temperature $T_{\rm ch}$ [4]. The formed hadron gas cools down further until it reaches the kinetic freeze-out temperature ($T_{\rm kin}$) after which the collective expansion stops [5].
The initial shape and energy density of the system are given by the overlapping region of the two Lorentz contracted colliding nuclei. This results in an initial spatial anisotropy which is transformed during the evolution into an anisotropy in the momentum distribution of the produced particles. This effect is called anisotropic flow and it can be characterized by the coefficients of the Fourier expansion of the $\mathrm{d}N/\mathrm{d}\phi$ distribution of produced particles. The Fourier coefficients $v_{\rm n}$ are sensitive to the properties of the system created in the collisions such as the ratio of shear viscosity to the entropy (η/s). The particle type dependence of anisotropic flow can also probe the system freeze-out conditions and the hadronization mechanism.
In summary, particle species dependent studies of soft particle production, transverse momentum ($p_{\rm T}$) and correlations between the particles provide methods to characterize the dynamical evolution of the system created in ultrarelativistic heavy-ion collisions.
In the highest multiplicity class of p–Pb collisions at the LHC, the pseudorapidity density of produced particles is comparable to peripheral heavy-ion collisions. This opens up the possibility to have collective phenomena developing in p–Pb collisions, which could have similar signatures as in heavy-ion collisions. This hypothesis was also checked using LHC data.

Email address: Marek.Chojnacki@cern.ch (Marek Chojnacki for the ALICE Collaboration)

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2. ALICE detector

The combination of multiple particle identification systems along with precise tracking (p_T resolution lower than 2% for p_T below 5 GeV/c) makes ALICE (A Large Ion Collider Experiment) an effective tool for studying the soft probes of the QGP. The results presented here are obtained using data from the pp collision from 2010 and Pb–Pb collisions from 2010 and 2011, and p–Pb collisions from early 2013. During those periods the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) were the main detectors used for reconstructing of charged particle tracks and measuring their momenta in the pseudorapidity range $|\eta| < 0.9$. The ITS was also used for triggering and reconstructing the interaction point. Particle identification was performed using the ITS, TPC and the Time-of-Flight (TOF) detectors. The V0 detector, composed of two scintillator arrays measuring particles in range $-3.7 < \eta < -1.7$ (V0-C) and $2.8 < \eta < 5.1$ (V0-A), was used for the centrality determination and triggering. The full performance of ALICE during the first LHC run is reported in [6].

3. p_T-spectra of identified hadrons

The collective behaviour of the system created during ultrarelativistic, heavy-ion collision can be described by hydrodynamical models. The identified hadron production at low p_T is a major constraining factor for those models. Figure 1 presents the p_T spectra for pions, kaons and protons measured by ALICE for the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [7, 8]. For comparison RHIC results from Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [9, 10] and calculations from hydrodynamical models are also presented. Since the spectra for positive and negative particles were found to be compatible within uncertainties, the combined measurement is presented. The spectra exhibit higher mean p_T than at RHIC, which can be attributed to stronger radial flow at LHC energies. From the comparison with hydrodynamical models, we see that VISH2+1 [11] describes well the pion and kaon spectra when $p_T < 1.5$ GeV/c, but it does not describe the proton spectra. The VISHNU model [12] that couples the hydrodynamical evolution of the system to a hadronic cascade model seems to better describe the spectra. The hadronic phase is also implemented in the HKM Model [13] which agrees better with the data than VISH2+1. The Kraków model [14], which also shows good agreement with data, uses non-equilibrium corrections due to the bulk viscosity which changes the effective T_{ch}. The EPOS [15] model uses

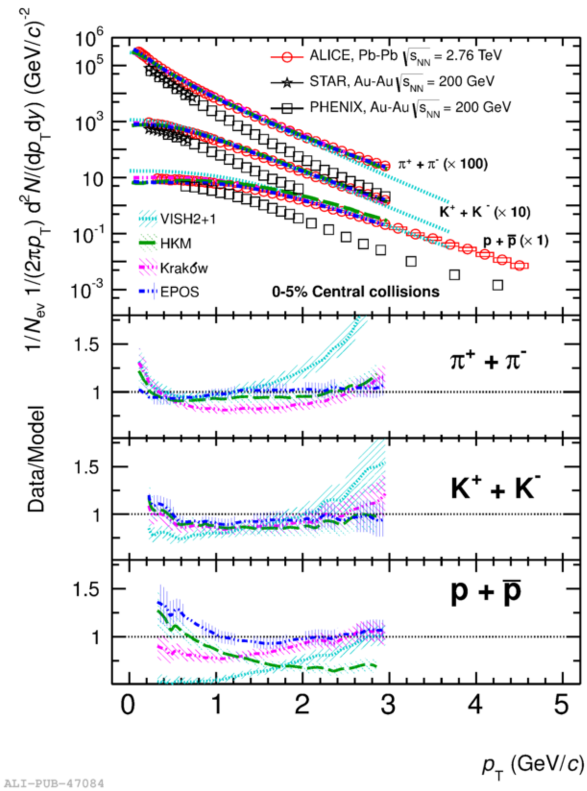

Figure 1: Measured pion, kaon and proton p_T spectra for the most central (0-5%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, compared to results from lower energies and model predictions.

an approach including the breakup of flux tubes created during initial hard scatterings to describe the spectral shapes over a wide p_T range.

Figure 2 shows the p_T spectra of pions, kaons, protons, K^0_S and Λ measured by ALICE [16] in high multiplicity p–Pb collisions. The results are compared to hydrodynamical models (Kraków [17], EPOS LHC [18], blast-wave [19]) and to the QCD-inspired DPMJET event generator [20]. For $p_T < 2$ GeV/c the hydrodynamical models describe the ALICE measurements reasonably well. In the same p_T range, DPMJET fails to describe the spectra but it correctly describes the pseudorapidity distribution of charged particles, as shown in [21]. The fact that p–Pb spectra from high multiplicity collisions can be described by hydrodynamical models might indicate the existence of collective phenomena in the system created during p–Pb collisions at the LHC.

The particle spectra for both p–Pb and Pb–Pb were fitted with the blast-wave function [19], which assumes a thermalized medium and collective expansion with a common velocity field ended with a one common freeze-out. The results of the fits (i.e. the radial flow velocity $\langle\beta_T\rangle$

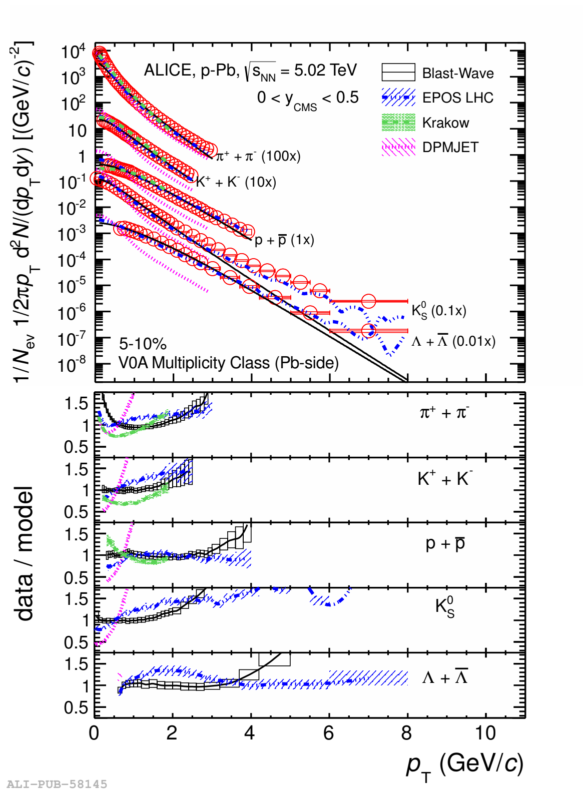

Figure 2: Identified hadron p_T spectra in high multiplicity p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to model predictions.

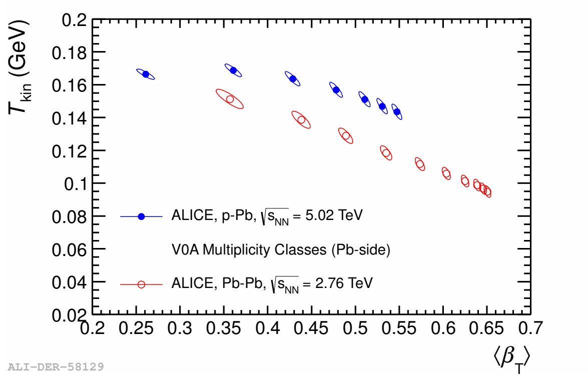

Figure 3: The results of the blast-wave fit to the ALICE results from the Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The $\langle\beta_T\rangle$ stands for the radial flow velocity T_{kin} is the temperature when kinetic freeze-out occurs. The centrality for the Pb–Pb collisions and multiplicity for p–Pb collisions increase with $\langle\beta_T\rangle$.

and the temperature of kinetic freeze-out T_{kin}) are summarized in Figure 3. The results for p–Pb collisions follow the same trend as those for Pb–Pb collisions: T_{kin} decreases with increasing $\langle\beta_T\rangle$ and multiplicity.

4. Total particle production

To estimate the chemical freeze-out temperature (T_{ch}), the production yields for different particle species at mid-rapidity measured by ALICE were fitted (see Figure 4) with three thermal models (GSI [22], THERMUS [23] and SHARE [24]). During the fitting procedure the baryochemical potential (μ_B) was set to 1 MeV since the measured yields of antiparticles and particles are equal within uncertainties. All three models gave a temperature, T_{ch}, around 155 $\sim$ 156 MeV. The thermal models reproduce many of the ALICE particle yield results, but fail to reproduce the proton and antiproton production yields. Possible reasons for this are: baryon annihilation after chemical freeze-out [25], a non-equilibrium statistical hadronization [24] (implemented in SHARE but not used in the fit), flavour hierarchy in the QCD phase transition from QGP to hadrons [26], missing higher mass resonance states in the equilibrium thermal model, and the existence of a pion condensate [27]. The inability to reproduce the proton and antiproton production by statistical models is one of the most puzzling observations of the first LHC heavy-ion data. The interpretation of this effect is still not clear and needs further investigation.

5. Elliptic flow

Figure 5 presents the second Fourier coefficient v_2 as a function of p_T for different particles species measured by ALICE [28] in the 10-20% (upper plot) and 40-50% (lower plot) centrality intervals in Pb–Pb collisions For p_T below 2 GeV/c, a mass ordering (where higher mass corresponds to lower v_2 for a fixed p_T) is seen. This is an effect of the interplay between elliptic and radial flow. For p_T larger than 3 GeV/c, the v_2 values tend to divide into two groups, one for mesons and one for baryons. There is one exception, the v_2 of the ϕ-meson, which follows the baryons for central collisions and moves progressively to the meson band for peripheral collisions.

The ALICE v_2 measurements were compared to hydrodynamical calculations coupled to a hadronic cascade model [12] (VISHNU). This comparison for the 10-20% centrality bin is presented in Figure 6. The VISHNU model can describe the main characteristics of v_2 for p_T lower than 2 GeV/c qualitatively. The mass ordering observed in the data is not reproduced by the model where the Λ and ϕ v_2 is larger than the proton

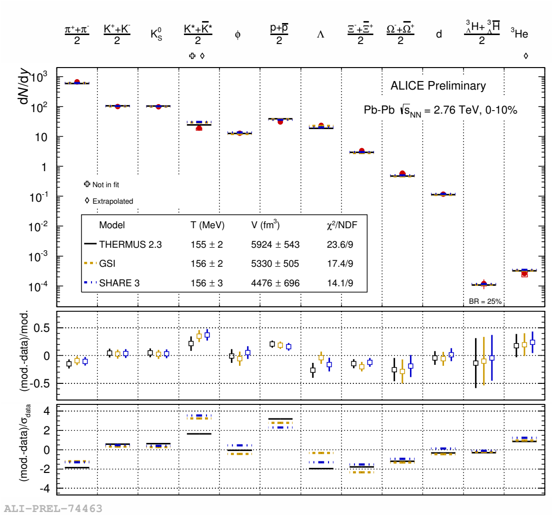

Figure 4: The production yields at mid-rapidity measured by ALICE fitted to three different statistical models.

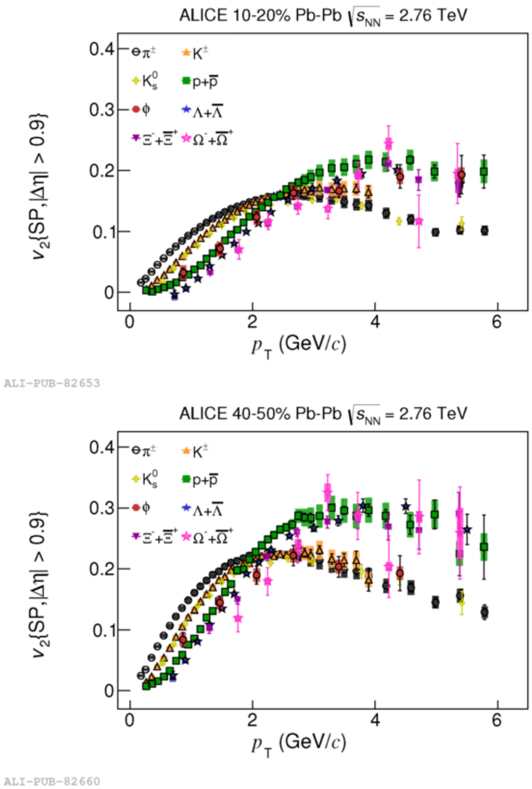

Figure 5: v_2 as a function of p_T for identified particles for two centrality classes 10-20% (top) and 40-50% (bottom) in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV measured by ALICE.

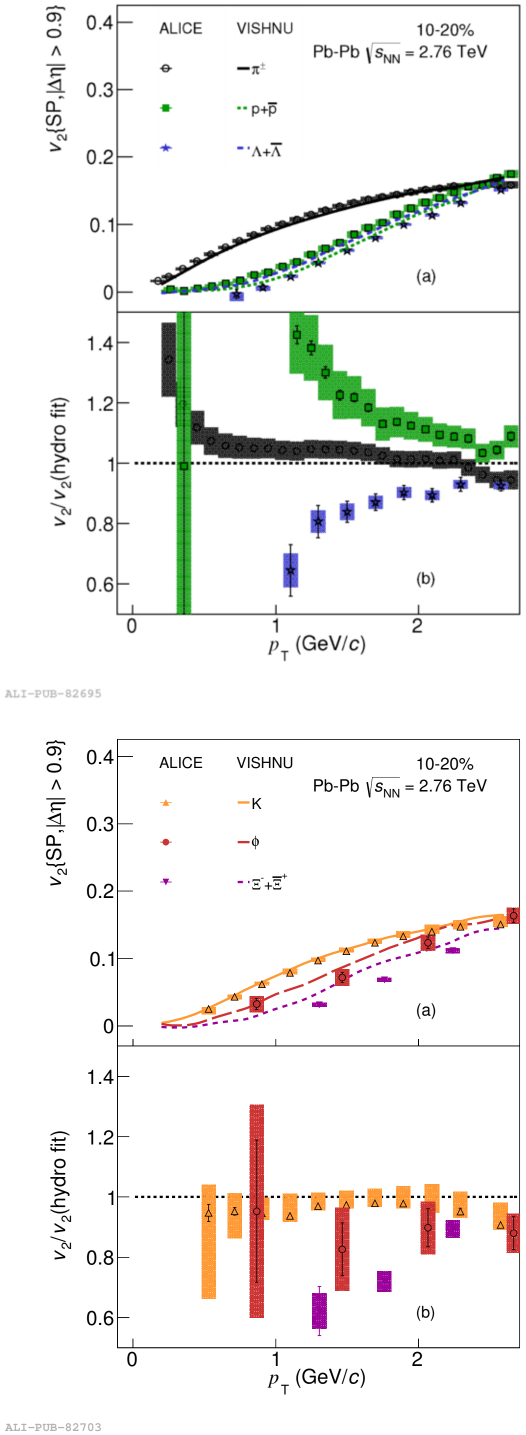

Figure 6: v_2 as a function of p_T for the 10-20% centrality range in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV compared to the VISHNU model. Top panel shows results for pions, protons and Λ and bottom kaons, ϕ and Ξ.

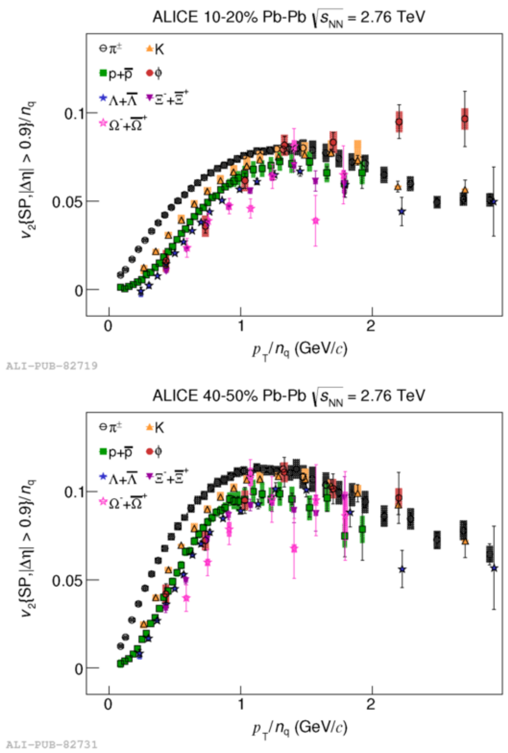

Figure 7: The p_T/n_q dependence of v_2/n_q for identified particles for two centrality classes: 10-20% (top) and 40-50% (bottom).

and antiproton v_2. This suggests that the hadronic cascade phase and the hadronic cross-sections in the model require further tuning.
The ALICE v_2 measurements were also used to test the number of constituent quarks (NCQ) scaling. The results of this test for two centrality bins are shown in Figure 7, where v_2/n_q as function of p_T/n_q is plotted. The NCQ scaling should be present for p_T/n_q higher than 1 GeV/c where coalescence is claimed to be dominant. In this region, the scaling is only approximate since deviations of ±20% are observed in both centrality bins.

6. Source size

The size of the particle production region was measured by ALICE based on correlation measurements of identical bosons at low relative momentum. Figure 8 presents the ALICE results [29] of the source size obtained using 2-pion correlations in pp collisions at $\sqrt{s}$ = 7 TeV, p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. Those results are compared to GLASMA calculations with and without a hydrodynamical expansion stage [30]. All GLASMA calculations are scaled to match the ALICE pp data. The

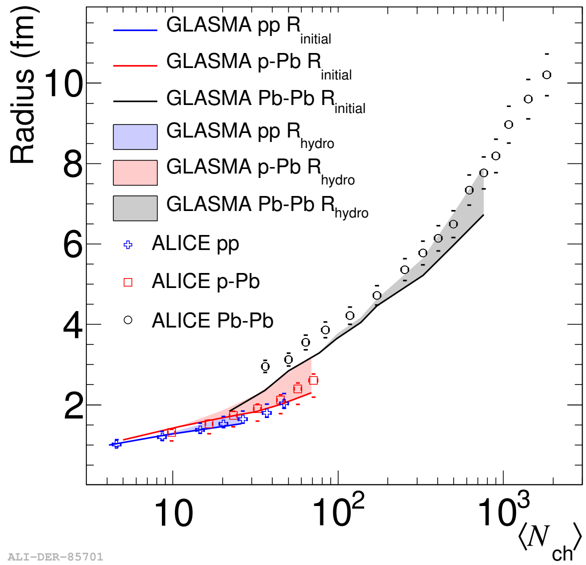

Figure 8: The 1D radii of the particle production region obtained by Bose-Einstein correlation measurements by ALICE in pp, p–Pb, and Pb–Pb collisions as a function of the number of charge particles compared to GLASMA calculations with and without a hydrodynamical stage of expansion.

shaded regions in Figure 8 represent the effect of the hydrodynamical expansion. The results in Pb–Pb collisions clearly indicate the existence of a hydrodynamical phase. The results for pp and p–Pb collisions are not conclusive and within the uncertainties, can be described by both scenarios: with and without the hydrodynamical phase.

7. Conclusions

The ALICE collaboration has characterized the QGP in the new energy regime using the data from the first LHC run. The results on soft probes show that the system created during the heavy-ion collisions undergoes a hydrodynamical evolution. The measured radial flow is larger than that for collisions at lower energies. Particle production is described by statistical thermodynamics although some deviations for the proton yield are observed. The possible explanation for that deviation is still unknown and many scenarios are being investigated. Some indications of hydrodynamical expansion were also seen in p–Pb collisions, its origin is still unclear and require further measurements using the second LHC run.

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