Spectra, flow and HBT in Pb-Pb collisions at the LHC

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Abstract. The transverse momentum spectra, elliptic flow and interferometry radii for Pb-Pb collisions at the LHC are calculated in relativistic viscous hydrodynamics. For Glauber model initial conditions, we find that the data can be described using a small value of shear viscosity $\eta/s = 0.08$. The viscosities and the equation of state are the same as used for RHIC energies.

The experiments with Pb-Pb collisions at $\sqrt{s} = 2.76$GeV at the LHC opened further possibilities for the studies of the properties of the hot and dense matter. Compared to the highest RHIC energies the multiplicity of charged particles in central collisions increased by a factor $\simeq 2.4$ [1]. The fireball has a higher energy density and lives longer than the one created in Au-Au collisions at $\sqrt{s} = 200$GeV. At RHIC, the production of particles with soft momenta can be described using the relativistic hydrodynamic model. A satisfactory description of the measured Hanbury Brown-Twiss (HBT) radii requires the use of an equation of state without a soft point at the transition from the quark-gluon plasma to the hadronic phase [2]. This observation is consistent with lattice QCD calculations of the equation of state showing a crossover transition [3]. Studies of the elliptic flow at different centralities of the collisions lead to the estimate of the ratio of the shear viscosity to entropy $\eta/s = 0.08 - 0.2$ [4], depending on the assumed initial eccentricity of the source.

We apply $2+1$ dimensional relativistic viscous hydrodynamics with shear and bulk viscosities to model the collision dynamics at $\sqrt{s} = 2.76$GeV. The shear viscosity is fixed to the AdS/CFT value $\eta/s = 0.08$, while the bulk viscosity is set to $\zeta/s = 0.04$, in the hadronic phase. Second order viscous hydrodynamic equations [7] are solved and hadrons are emitted at the freeze-out. The deviations from the equilibrium momentum distributions at freeze-out are implemented using a quadratic and an asymptotically linear ansatz in momentum for the shear and bulk viscosity corrections respectively [8]. An exponential ansatz for the bulk viscosity corrections leads to similar results as the linear one. The initial entropy density profile of the fireball is proportional to a mixture of participant and binary collisions densities

$$s(x,y) \propto (1-\alpha)\rho_{part}(x,y,b) + 2\alpha\rho_{bin}(x,y,b) \ ,$$

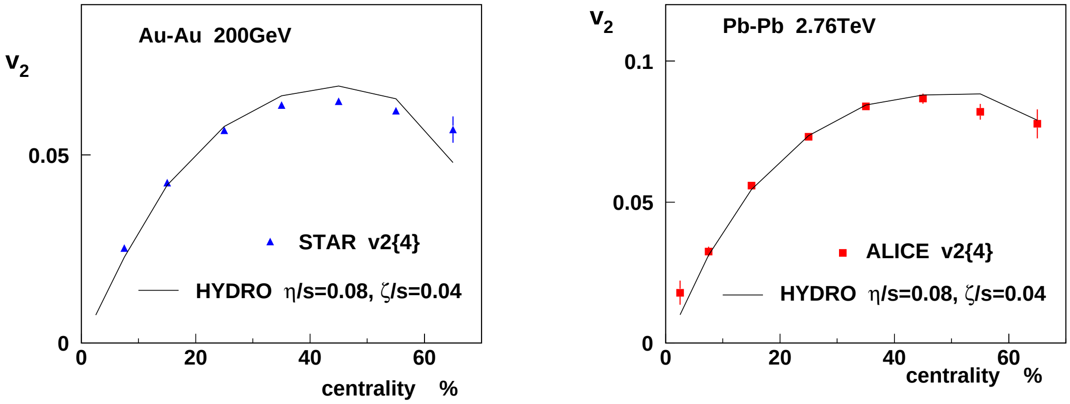

Figure 1. (left panel) Elliptic flow coefficient in Au-Au collisions at $\sqrt{s} = 200\text{GeV}$, as function of centrality, STAR Collaboration data [5]. (right panel) same for Pb-Pb collisions at 2.76TeV, ALICE Collaboration data [6].

with $\alpha = 0.15$, fixed to reproduce the measured centrality dependence of the charged particle multiplicity [9].

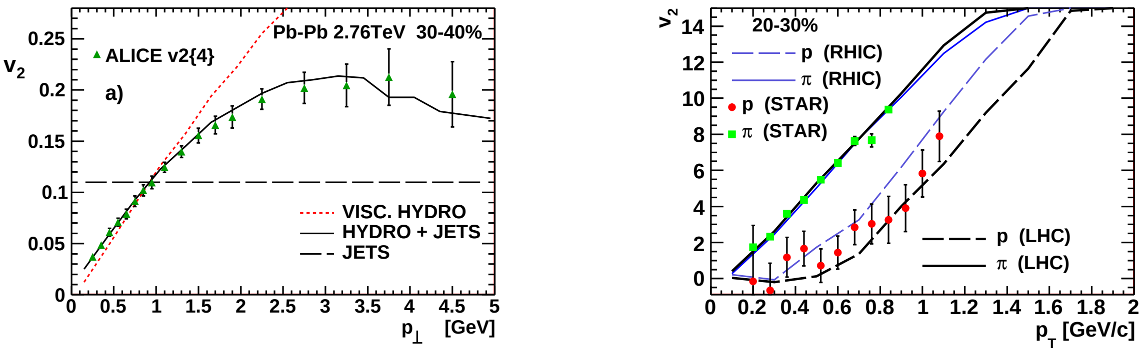

Figure 2. (left panel) Elliptic flow of charged particles as function of transverse momentum, ALICE Collaboration data [6] compared to the results of relativistic hydrodynamics (dotted line) and to a schematic model including also a contribution from jets (solid line). (right panel) The elliptic flow of identified particles at RHIC and at the LHC in relativistic viscous hydrodynamics, STAR Collaboration data [5].

The elliptic flow coefficient of charged particles v_2 is calculated for collisions at different centralities. It is significant that the elliptic flow at such very different collision energies can be described in a satisfactory way using the same viscosity coefficients and the same equation of state (Fig 1). Assuming Glauber model initial conditions, the shear viscosity coefficient that describes the data is small, $\eta/s \simeq 0.08$. Other studies of the elliptic flow in heavy ion collisions at the LHC show that the fluid has a small viscosity [10]$\eta/s = 0.08 - 0.2$. The elliptic flow created in central and semi-central collisions is well described within viscious hydrodynamics with a constant value of η/s, there is no sign of a change of the shear viscosity to entropy ratio for higher temperatures reached at the LHC.

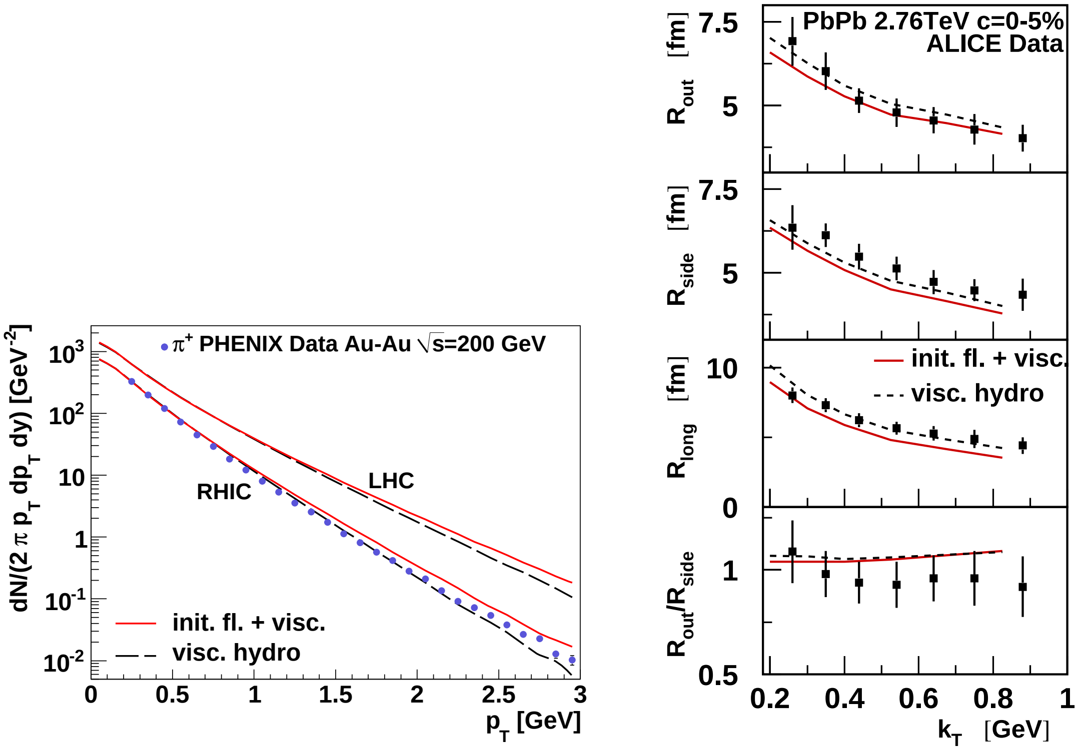

Figure 3. (left panel) Transverse momentum spectra of pions at RHIC and the LHC, PHENIX Collaboration data [11]. (right panel) The interferometry radii for pions emitted in Pb-Pb Collisions at $\sqrt{s} = 2.76$GeV. The hydrodynamic model results are denoted by the dashed lines for zero initial flow and by the solid lines when the initial pre-equilibrium flow is included [12], ALICE Collaboration data [13].

The measured elliptic flow as function of the transverse momentum shows systematic deviations from the predictions of the hydrodynamic model (Fig. 2, left panel). At high transverse momenta, such deviations are expected, as the majority of particles emitted at few GeV's originate from jets. However, the data points at low momenta deviate from the hydrodynamic calculation as well. If this effect is not a systematic experimental bias, it could mean that a substantial contribution from non-thermalized remnants of jets is present; the elliptic flow from jets is of a geometrical origin and could be larger than the one from the collective hydrodynamic flow at low momenta [9]. The elliptic flow of identified particles shows a stronger mass splitting at the highest energy. It is due to a stronger flow, which makes the corrections from bulk viscosity more important. We note that in order to get the mass splitting correctly in a model without a hadronic cascade after-burner a realistic non-zero bulk viscosity in the hadronic stage must be taken [8].

The strong transverse flow generated in the expansion of the hot fireball leads to flatter transverse momentum spectra at the LHC than at RHIC (Fig. 3, left panel) [12]. The inclusion of the pre-equilibrium flow [14] makes the spectra harder, especially at RHIC energies. The HBT radii can be described to within $10 - 15\%$. The effect of the pre-equilibrium flow is small at $\sqrt{s} = 2.76$TeV, but improves slightly the agreement with the data at $\sqrt{s} = 200$GeV [12]. A similar quality in the data description is achieved in some earlier calculations using ideal fluid hydrodynamics [15], especially when using modified profiles of the fireball or initial flow. For collisions at the LHC, the hydrodynamic stage in the expansion dominates and the pre-equilibrium flow (if present) is relatively less important. We note that the preliminary transverse momentum spectra of pions, kaons and protons presented by the ALICE Collaboration at this conference can be described by the calculation without initial flow.

We present the results of a viscous hydrodynamic model for Pb-Pb collisions at $\sqrt{s} = 2.76$TeV. A simultaneous description of the transverse momentum spectra, elliptic flow and HBT radii is achieved. It shows that relativistic hydrodynamics is a reasonable model of the expansion of the fireball and of the production of the bulk of the particles. The parameters of the model: the equation of state, the viscosity coefficients, the initial time and the freeze-out temperature are the same as deduced from the analysis of RHIC data. In particular, for Glauber model initial densities it means that $\eta/s = 0.08$; an almost perfect fluid is produced in heavy-ion collisions at the LHC.

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