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Flow, spectra and HBT radii in heavy-ion collisions

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The expansion of the fireball created in relativistic heavy ion collisions is described using the $3+1$D hydrodynamical model. Experimentally observed transverse momentum spectra at different rapdities, elliptic flow and HBT correlations of produced particles can be reproduced. We give estimates of shear viscosity corrections at freeze-out, which we find important only for the elliptic flow coefficient.

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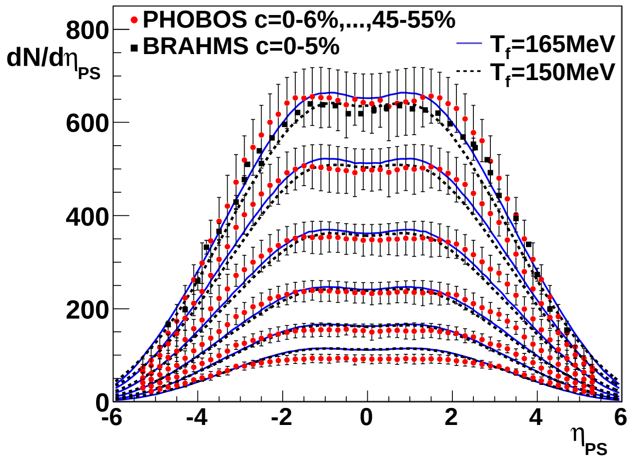

Figure 1: Distribution of charged particles in pseudorapidity $\eta_{PS} = \frac{1}{2}\ln\left(p+p_{\|}\right)/(p-p_{\|}))$ in different centrality bins c, calculated from the 3+1D hydrodynamic model [2], compared to experimental data of BRAHMS and PHOBOS Collaborations [3].

The expansion of the dense and hot fireball created in relativistic heavy-ion collisions can be described using relativistic hydrodynamics [1]. We perform $3+1$D hydrodynamic simulations of Au-Au collisions at the highest RHIC energy $\sqrt{s_{NN}} = 200$GeV [2]. Compared to existing calculations [4], we use a very short initial time 0.25fm/c and a realistic equation of state of dense matter [5]. The absence of a soft point in the equation of state leads to a rapid expansion of the system, resulting in a strong build up of the transverse flow. The initial energy density profile in the transverse plane is taken from the Glauber Model, and the initial distribution in space-time rapidity is adjusted to reproduce the measured charged particle distributions (Fig. 1).

Hydrodynamic equations of a perfect fluid $\partial_\mu T^{\mu\nu} = 0$ are solved for each impact parameter. The shape of the constant temperature ($T_F = 150$MeV) freeze-out hypersurfaces, as well as the final collective velocities of the fluid are exported to a statistical emission and resonance decay code THERMINATOR [6]. The THERMINATOR code generates complete events including statistically emitted particles from the fireball. Calculated transverse momentum spectra of produced particles follow very well the experimental results [2]. It is true for particles emitted at central rapidities for different collision centralities, up to 50%; also the agreement with the data at forward/backward rapidities is striking (solid lines in the left panel of Fig. 2) and proves that the hydrodynamic expansion model of the fireball combined with statistical emission applies in a broad range of rapidities. Microscopically it means that approximate local equilibrium is reached and maintained during a sizable time-span of the collective expansion. HBT correlation radii [9] calculated from the model are within 10% from the measured values (right panel of Fig. 2) [2]. A short initial time of the evolution requires a narrow initial distribution in space-time rapidity, this results in a strong suppression of elliptic flow when approaching the fragmentation regions (Fig 3).

We estimate the effects of viscous corrections on particle emission. Using the velocity flow obtained in a $3+1$D perfect fluid dynamics we calculate nonequilibrium corrections to the Cooper-Frye formula from shear viscosity [10]. Modified momentum distributions are implemented in

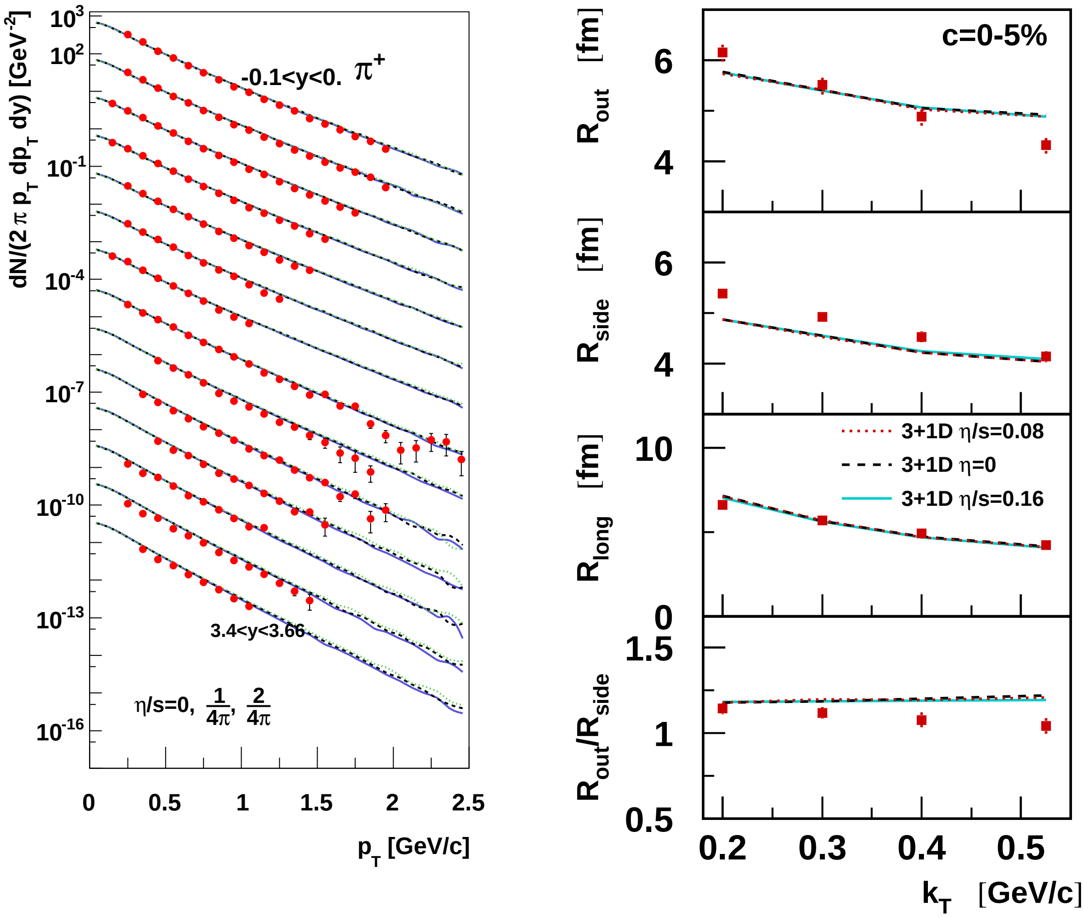

Figure 2: (Left panel) Transverse momentum spectra of π^+ at different rapidities for three different shear viscosity coefficients at freeze-out ($\eta/s = 0, \frac{1}{4\pi}, \frac{1}{2\pi}$, solid, dashed, and dotted lines) compared to BRAHMS Collaboration data [7]. (Right panel) HBT correlation radii for different strengths of shear viscosity corrections at freeze-out, STAR Collaboration data [8].

the statistical emission code. Results range from, no appreciable modifications of the transverse momentum spectra for $p_T < 1.5$GeV/c and central rapidities, up to a 30% increase at rapidity $y = 3.5$ and $p_T = 3$GeV/c for $\eta/s = 0.16$. The HBT radii are not sensitive at all to the shear corrections at freeze-out if the flow remains unchanged (Right panel in Fig. 2).

A significant reduction of the elliptic flow is induced by stress corrections (Fig. 3). The reduction is 20% at central rapidity and goes up to 60% at pseudorapidity 4 for $\eta/s = 0.16$. This observation agrees with the results of Ref. [12], where dissipation from hadronic rescattering was found to be important at large rapidities. This effect modifies strongly the dependence of the elliptic flow of charged particles on pseudorapidity. From the ratio $\frac{-\sigma^{33}}{\partial_\alpha u^\alpha} = \frac{-2\nabla^3 u^3 + 2/3\ \Delta^{33}\partial_\alpha u^\alpha}{\partial_\alpha u^\alpha}$ presented in the right panel of Fig. 3 we expect large shear viscosity corrections at large rapidities, whereas at central rapidities correction from bulk viscosity (proportional to $\partial_\alpha u^\alpha$) could also be important. The approximate agreement of perfect fluid calculations with the data on elliptic flow is accidental. Moreover shear viscosity modifies also the longitudinal acceleration of matter [13] changing the

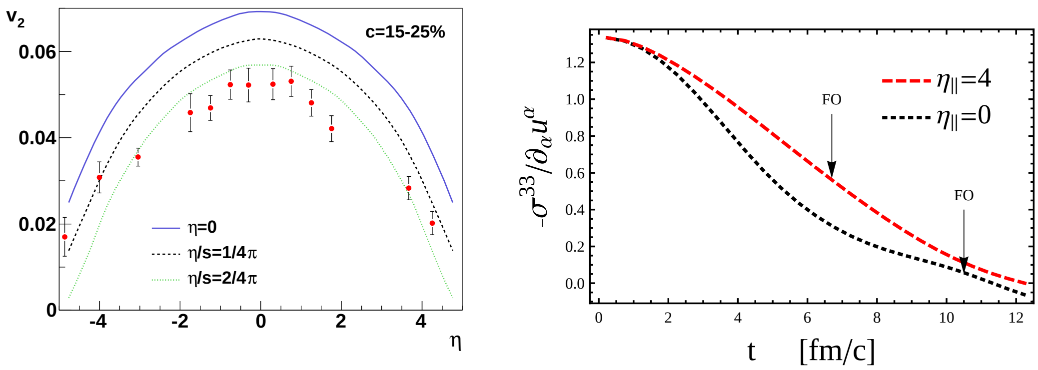

Figure 3: (Left panel) Elliptic flow coefficient for charged particles as function of pseudorapidity for three different viscosity coefficients at freeze-out, compared to PHOBOS Collaboration data [11]. (Right panel) Ratio of the stress velocity gradient to the overall expansion rate as function of time at two space-time rapidities. The arrows indicate the time of the freeze-out.

distributions in Figs. 1 and 3.

Summarizing, we find good agreement of the results of $3+1$D perfect fluid hydrodynamics with the measured transverse momentum spectra, HBT radii and elliptic flow. Estimates of shear viscosity effects show that the last observable is not robust and a reliable estimate thereof requires the use of a fluid expansion model including shear and bulk viscosity.

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