BLAST-WAVE SNAPSHOTS FROM RHIC

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I present fits with the so-called blast-wave model to single-particle spectra and HBT correlations from Au+Au collisions at a CMS energy of 130 AGeV. There is only little choice of freeze-out temperature and transverse flow velocity for which the model fits both the identified spectra and the correlation radii just well enough not to be excluded. The observed steep $M_\perp$ dependence of $R_{\rm side}$ leads to a temperature which it is problematic to interpret. The applicability of the model for the freeze-out description is thus questioned.

1 HBT interferometry in heavy-ion collisions

In heavy-ion collisions we study the collective behaviour of strongly interacting matter. HBT interferometry is a method that helps us to determine the final state of the fireball evolution, the so-called *freeze-out*. We thus obtain a snapshot of the result to which the collective evolution of the fireball leads.

A particularly interesting phenomenon at the freeze-out is the *transverse expansion*, as this is not a part of the initial conditions and is entirely generated by pressure of the QCD matter. Another interesting quantity is the *freeze-out temperature*, which characterizes the end of the collective system evolution. It has been argued [1] that both these quantities can be determined unambiguously from single-particle $p_\perp$ spectra and two-particle HBT correlations.

Here I report on such a project in the framework of the so-called *blast-wave model*. I analysed identified single-particle spectra [2] and HBT correlation radii [3,4] from central Au+Au collisions at a RHIC energy of $\sqrt{s} = 130\,A$GeV.

2 The (blast-wave) model

The main assumptions of this—now widely used—model, which are relevant to this study are:

1. Pions, nucleons and also kaons decouple all quite *suddenly* from the whole transverse profile of the fireball. For all of them the freeze-out happens at *the same proper time*, measured in a frame that co-moves longitudinally with the fluid element of the expanding fireball.

2. The radial density distribution at the freeze-out is *uniform*.

3. Longitudinal expansion is *boost-invariant*. Heavy-ion experts know this as Bjorken scenario, the rest of the world is familiar with the astrophysical analogue: the Hubble expansion.

4. In this study, the *transverse expansion* is parametrized through rapidity, which depends linearly on the radial coordinate.

Technically, these assumptions are expressed through the emission function[5], which is the Wigner density of the source normalized to the number of particles

$$\begin{aligned} S(x,p)\, d^4x &= \frac{1}{(2\pi)^3}\, m_\perp \cosh(y-\eta)\, \exp\left(-\frac{p_\mu u^\mu - \mu}{T}\right)\, \theta(R_B - r) \\ & \frac{1}{\sqrt{2\pi\Delta\tau^2}}\, \exp\left(-\frac{(\tau-\tau_0)^2}{2\Delta\tau^2}\right)\, \tau\, d\tau\, d\eta\, r\, dr\, d\phi\,, \qquad (1) \\ u^\mu &= (\cosh\eta_t\, \cosh\eta,\, \sinh\eta_t\, \cos\phi,\, \sinh\eta_t\, \sin\phi,\, \cosh\eta_t\, \sinh\eta)\,, \qquad (2) \\ \eta_t &= \sqrt{2}\, \eta_f\, \frac{r}{R_B}\,. \qquad (3) \end{aligned}$$

In this notation, space-time coordinates and the momentum in the so-called *out-side-long* system are parametrized as

$$\begin{aligned} x^\mu &= (\tau\, \cosh\eta,\, r\, \cos\phi,\, r\sin\phi,\, \tau\, \sinh\eta) \qquad (4) \\ p^\mu &= (m_\perp\, \cosh y,\, p_\perp,\, 0,\, m_\perp\, \sinh y)\,. \qquad (5) \end{aligned}$$

Model parameters are to be determined from a fit to data. These include: temperature T, scaled transverse flow gradient η_f, transverse geometric radius R_B, mean Bjorken lifetime τ_0, and mean proper emission duration $\Delta\tau$. The chemical potential μ is not being determined in this study. For the presentation of the results the average transverse velocity is used

$$\langle v_t \rangle = \frac{2}{R_B^2} \int_0^{R_B} r\, dr\, \tanh\eta_t(r)\,. \qquad (6)$$

For simplicity, Boltzmann distribution has been used in Eq. 1. Note that the model is formulated as thermal: it is assumed that particles decouple from a system in local thermal equilibrium with the temperature T. In the corresponding term, the particle momentum is coupled to the local flow velocity as $p_\mu u^\mu$ in order to obtain the energy in the rest frame of the fluid. The strength of this coupling is controlled by the temperature. The lower the temperature, the stronger the momentum of the particle corresponds to the fireball expansion velocity and the more pronounced the effects of the expansion in the observables are. In terms of HBT radii, the expansion is encoded in their $M_\perp$ dependence. A lower value of the temperature parameter thus leads to a stronger $M_\perp$ dependence.

Single-particle spectra were calculated via[1]

$$E_p \frac{dN}{d^3p} = \int d^4x\, S(x,p)\,. \qquad (7)$$

The HBT correlation radii were obtained from a numerical evaluation of the model-independent expressions[6], in which the second spatial moments of the emission function are used.

3 Fits to (low-momentum) single-particle $p_\perp$ spectra

With the blast-wave model, I fitted single-particle spectra of identified positive and negative pions, kaons and protons as measured by the PHENIX Collaboration[2]. Bose–Einstein statistics and resonance decays were assumed for pions. I assumed baryon chemical potential for the resonances as in an earlier paper[5], but no pion chemical potential was included.

An important issue in the analysis is that every spectrum was fitted individually. This allows for a check of the assumption that all particles freeze-out simultaneously. If so, fits to different spectra would lead to compatible results[a]. On the other hand, if the results do not agree, the assumption is wrong.

[a] The slope of the spectrum is determined by the temperature, the strength of the transverse expansion, and the mass of the particles.[7]

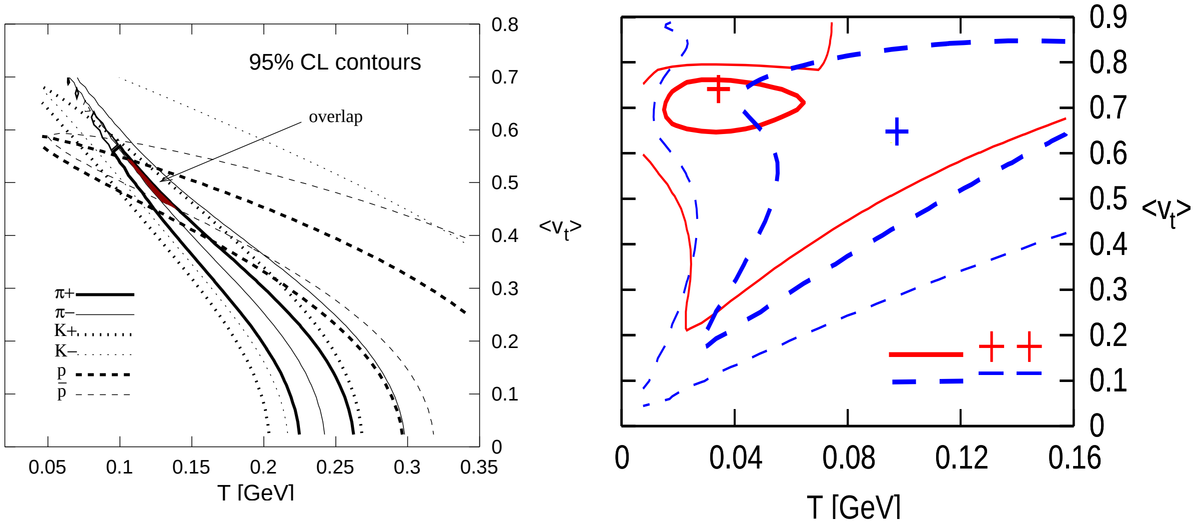

Figure 1: Left: The 95% confidence level contours in temperature and average transverse flow velocity resulting from fits to identified single-particle spectra. Right: The 1σ (thick lines) and 95% confidence level (thin lines) contours from fits to HBT radii from both STAR [4] and PHENIX [3]. Solid lines are for $\pi^+\pi^+$ correlations, dashed lines for $\pi^-\pi^-$ correlations. Crosses denote the position of the best fits.

There is no overlap between the fit results to different spectra at the 1σ level. Can the model be ruled out? In order to find out, I plot the contours corresponding to 95% confidence levels from the fits in Fig. 1. An overlap is found at this level, hence the model is not ruled out by the fits to spectra.

It remains to be checked whether the quality of the fits can be improved by fine-tuning the details of the model: changing the radial dependence of the transverse rapidity, introducing pion chemical potential, etc.

4 Fits to HBT correlation radii

The measurements of HBT radii by STAR and PHENIX cover different $M_\perp$ regions, with only one data point overlapping (Fig. 2). The PHENIX data show a steeper $M_\perp$ dependence of $R_{\rm side}$ than those of STAR. Such a steep $R_{\rm side}(M_\perp)$ would ask for a strong transverse flow and a low temperature.

Indeed, this is confirmed by the fits. At the 1σ level, some results from fitting data sets from the two collaborations do not agree. In order to have a robust statement about whether the model fails to reproduce the data, systematical errors quoted by the experiments were *added linearly* to the statistical ones. Under these circumstances one finds a large overlap at 95% confidence level from fitting all four data sets.

In order to improve statistics, data of the same charge from both collaborations were added together and fitted. Resulting χ^2 contour plots are displayed in Fig. 1. Note that there is only a tiny overlap between the 95% CL contour of $\pi^+\pi^+$ correlations with the result of fitting single-particle spectra. It is located at $T \approx 106\,\mathrm{MeV}$. Furthermore, the best fit to $\pi^+\pi^+$ correlations is obtained at $T = 33\,\mathrm{MeV}$ and $\langle v_t \rangle = 0.73$! This is not to be interpreted at the real physical freeze-out temperature! As seen from Fig. 2, these values of the model parameters are required in order to produce the observed steep $M_\perp$ dependence of $R_{\rm side}$. Thus T is merely to be interpreted as a parameter that controls the coupling of momentum to expansion velocity in the framework of the blast-wave model.

It is interesting to note that similar results appear from fitting the HBT data from the SPS program and the preliminary data from the RHIC run at full energy. This study is in progress.

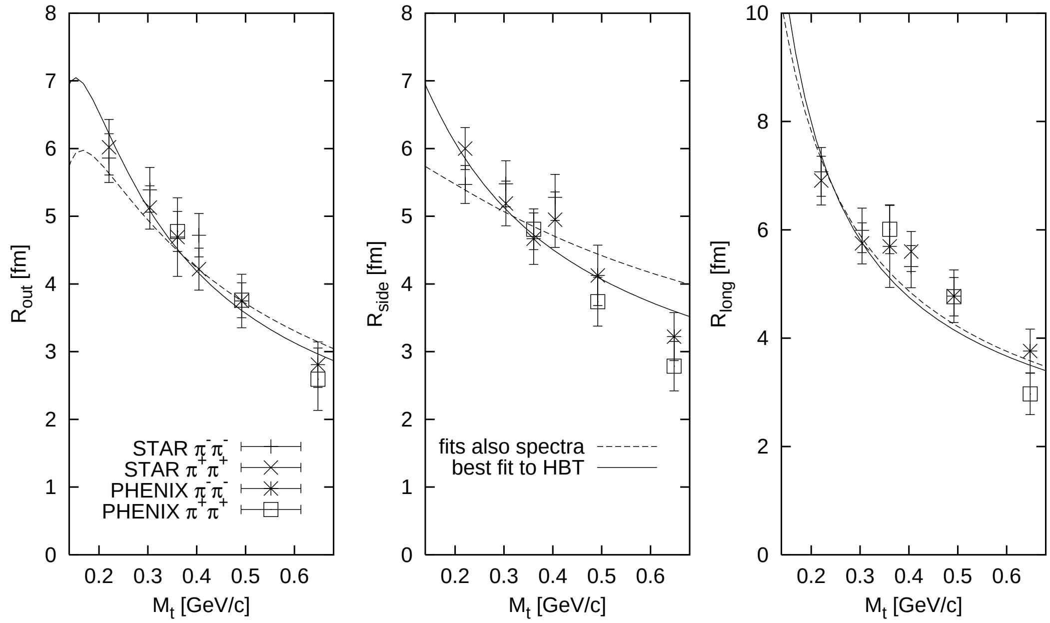

Figure 2: Example fits to HBT radii measured at RHIC. Dashed lines show the best model which fits both spectra and HBT: $T = 106\,\mathrm{MeV}$, $\langle v_t \rangle = 0.53$, $R_B = 12.36\,\mathrm{fm}$, $\tau_0 = 4.54\,\mathrm{fm}/c$, $\Delta\tau = 4.57\,\mathrm{fm}/c$. Solid lines correspond to the best fit to $\pi^+\pi^+$ correlations: $T = 33\,\mathrm{MeV}$, $\langle v_t \rangle = 0.73$, $R_B = 24.11\,\mathrm{fm}$, $\tau_0 = 21.32\,\mathrm{fm}/c$, $\Delta\tau = 1.09\,\mathrm{fm}/c$.

5 Conclusions

Summarizing the main observations: first, the blast-wave model can fit the spectra *and* the correlation radii only marginally. The resulting parameters are close to the 95% CL contour of both fits. Second, the best fit to HBT radii is achieved with model parameters that are hard to interpret phenomenologically. My conclusion is that the blast-wave model is probably *not a suitable description of the freeze-out.*

Note that we do have indications from cascade generators [8] and studies of pion scattering rate [9], which show that the freeze-out takes place continuously and there may even be ordering in the production of different species and transverse momenta. This feature is in contrast to the simple assumption of the blast-wave model, which says that all particles freeze out suddenly at the same time.

It will be crucial to formulate a good description of the freeze-out. This is because the momentum spectra are produced at freeze-out. If these spectra are to be searched for signatures of collective behaviour, it is important to understand the process in which they are produced.

References

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