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The reconstructed Big Bang from RHIC data

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ABSTRACT: The final state of $Au + Au$ collisions at $\sqrt{s} = 130$ AGeV at RHIC has been reconstructed within the framework of the Buda-Lund hydro model, by performing a simultaneous fit to preliminary PHENIX and STAR data on two-particle Bose-Einstein correlations and identified single particle spectra, and the Hubble constant is determined to be $H = \langle u_t \rangle = 0.77 \pm 0.09$.

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1. Introduction

The reconstruction of hadronic final state from the measured single particle spectra and two-particle correlation functions is of great current research interest in high energy heavy ion collisions, in order to identify one or more new phases of hot and dense hadronic matter in the collisions of the biggest available nuclei at the highest available bombarding energies. It has been expected [1, 2], that for a Bjorken type of initial condition [3] and for a long-lived, soft, transient Quark Gluon Plasma phase, pions are evaporated from a predominantly longitudinally expanding, transversely almost expansionless fireball during a long period of time and this signature of the QGP phase can be observed experimentally from the analysis of two-pion Bose-Einstein correlation functions.

An alternative approach is to reconstruct the hadronic final state from the measureable single-particle spectra and two-particle correlation functions. From this reconstructed final state and the knowledge of the equation of state of hot and dense hadronic matter (e.g. from lattice QCD calculations) one can, in principle, reconstruct the initial state of the reaction by running the (relativistic) hydrodynamical equations backwards in time, and determine if this initial state had been in the QGP phase or not. Here we report on such a reconstruction within the framework of the Buda-Lund hydro model.

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2. Buda-Lund hydrodynamic model

The Buda-Lund hydro parameterization (BL-H) has been developed in refs. [4, 5] to describe particle correlations and spectra in central heavy ion collisions at CERN SPS.

We assume that high energy heavy ion collisions can be interpreted within the core-halo picture [6] where the center of the interactions is the core which is surrounded by the decay products of long lived resonances, corresponding to the halo. The Buda-Lund hydro parameterization describes the core of the particle emitting region as a cylindrically symmetric, finite hydrodynamically expanding system [4, 5], with emission function

$$S_c(x,p)\,d^4x = \frac{g}{(2\pi)^3}\,\frac{p^\mu d^4\Sigma_\mu(x)}{\exp\left(\dfrac{u^\mu(x)p_\mu}{T(x)} - \dfrac{\mu(x)}{T(x)}\right) + s}, \tag{2.1}$$

where the subscript $_c$ refers to the core of collision (surrounded by a halo of long lived resonances). The degeneracy factor is denoted by g, the four-velocity field is denoted by $u^\mu(x)$, the temperature field is denoted by $T(x)$, the chemical potential distribution by $\mu(x)$ and $s = 0$, -1 or 1 for Boltzmann, Bose–Einstein or Fermi–Dirac statistics.

The particle flux over the freeze-out layers is given by a generalized Cooper–Frye factor, assuming that the freeze-out hypersurface depends parametrically on the freeze-out time τ and that the probability to freeze-out at a certain value is proportional to $H(\tau)$,

$$p^\mu d^4\Sigma_\mu(x) = m_t \cosh[\eta - y] H(\tau) d\tau\, \tau_0 d\eta\, dr_x\, dr_y, \tag{2.2}$$

$$H(\tau) = (2\pi\Delta\tau^2)^{-1/2} \exp\left[-(\tau-\tau_0)^2/(2\Delta\tau^2)\right], \tag{2.3}$$

where we keep only the mean and the variance of the effective proper-time distribution $H(\tau)$. The transverse mass and coordinate are $m_t = \sqrt{m^2 + p_x^2 + p_y^2}$ and $r_t = \sqrt{r_x^2 + r_y^2}$, the rapidity y and the space-time rapidity η are defined as $y = 0.5 \log\left[(E+p_z)/(E-p_z)\right]$ and $\eta = 0.5\log\left[(t+z)/(t-z)\right]$.

The distributions of $1/T(x)$ and $\mu(x)/T(x)$ are parameterized within BL-H as

$$\frac{\mu(x)}{T(x)} = \frac{\mu_0}{T_0} - \frac{r_x^2 + r_y^2}{2R_G^2} - \frac{(\eta - y_0)^2}{2\Delta\eta^2}, \tag{2.4}$$

$$\frac{1}{T(x)} = \frac{1}{T_0}\left(1 + \left\langle\frac{\Delta T}{T}\right\rangle_r \frac{r_t^2}{2R_G^2}\right)\left(1 + \left\langle\frac{\Delta T}{T}\right\rangle_t \frac{(\tau-\tau_0)^2}{2\Delta\tau^2}\right). \tag{2.5}$$

The central temperature and chemical potential at the mean freeze-out time are denoted by $T_0 = T(r_x = r_y = 0; \tau = \tau_0)$ and $\mu_0 = \mu(r_x = r_y = 0; \tau = \tau_0)$. With the surface temperature $T_r = T(r_x = r_y = R_G, \tau = \tau_0)$ and the temperature after freeze-out, $T_t = T(r_x = r_y = 0; \tau = \tau_0 + \sqrt{2}\Delta\tau)$, the relative transverse and temporal temperature decrease are introduced, see refs. [7, 5, 4, 8] for further details. The variation of the chemical potential in coordinate space is related to the finiteness of the density profile in the core.

The four-velocity $u^\mu(x)$ of the expanding matter is assumed to have the form[4, 12, 13]:

$$\begin{aligned} u^\mu(x) &= \left(\cosh[\eta]\cosh[\eta_t],\, \sinh[\eta_t]\frac{r_x}{r_t},\, \sinh[\eta_t]\frac{r_y}{r_t},\, \sinh[\eta]\cosh[\eta_t]\right), \\ \sinh[\eta_t] &= \langle u_t\rangle r_t/R_G, \end{aligned} \tag{2.6}$$

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where R_G stands for the transverse geometrical radius of the source. Such a flow profile, with a time-dependent radius parameter R_G, was recently shown to be an exact solution of relativistic hydrodynamics of a perfect fluid at a vanishing speed of sound [14]. It turned out [15, 16], that the flow field is a generalized Hubble flow and the average transverse flow at the geometrical radius is formally similar to Hubble's constant that characterizes the rate of expansion in our Universe, $\langle u_t \rangle = \dot{R}_G = H$. This emphasizes the similarity between the Big Bang of our Universe and the Little Bangs of heavy ion collisions.

2.1 Single particle spectra and two particle correlations

The invariant single particle spectrum is obtained [4, 8] as

$$N_1(\mathbf{k}) = \frac{d^2 n}{2\pi m_t dm_t \, dy} = \frac{g}{(2\pi)^3}\, \overline{E}\, \overline{V}\, \overline{C} \frac{1}{\exp\left(\frac{u^\mu(\overline{x}) k_\mu}{T(\overline{x})} - \frac{\mu(\overline{x})}{T(\overline{x})}\right) + s}. \tag{2.7}$$

The correlation function is found in the binary source formalism [9, 8] as:

$$C_2(\mathbf{k}_1, \mathbf{k}_2) = 1 + \lambda_* \, \Omega(Q_\parallel) \;\; \exp\left(-Q_\parallel^2 \overline{R}_\parallel^2 - Q_=^2 \overline{R}_=^2 - Q_\perp^2 \overline{R}_\perp^2\right). \tag{2.8}$$

The pre-factor $\Omega(Q_\parallel)$ of the BECF induces oscillations within the Gaussian envelope as a function of $Q_\parallel$. This oscillating pre-factor satisfies $0 \le \Omega(Q_\parallel) \le 1$ and $\Omega(0) = 1$. In practice, the period of oscillations is larger than the corresponding Gaussian radius, so the oscillations are difficult to resolve. The above invariant BL-H form of the two-particle correlation function can be equivalently expressed in the frequently used but not invariant Bertsch-Pratt (BP) form in the LCMS frame [17], within the $\Omega = 1$ approximation:

$$C_2(\mathbf{k}_1, \mathbf{k}_2) = 1 + \lambda_* \exp\left[-R_s^2 Q_s^2 - R_o^2 Q_o^2 - R_l^2 Q_l^2 - 2R_{ol}^2 Q_o Q_l\right], \tag{2.9}$$

where the dependence of the fit parameters on the value of the mean momentum of the pair is suppressed. The above formulas for the BECF and IMD, as were used in the fits, have been introduced in refs. [4, 5, 7, 18], and summarized recently in ref. [8]. We recommend this latter review paper for the formulas that relate the BL-H model parameters to the above forms for the spectra and correlation functions, in particular, eqs. (84-105), (115-118) and (129-140) of ref. [8].

3. Fitting preliminary STAR and PHENIX data on Au + Au at RHIC

Here, we reconstruct the space-time picture of particle emission in Au + Au collisions at RHIC within the BL-H framework, by fitting simultaneously the PHENIX and STAR preliminary data on two-particle correlations and single-particle spectra as presented at the Quark Matter 2001 conference, refs. [19, 20, 21, 22]. For a proper core-halo correction $\propto 1/\sqrt{\lambda_*}$ the experimental values of the intercept parameter $\lambda_*(y, m_t)$ have to be taken from the measurements. In the lack of these $\lambda_*(y, m_t)$ values in ref. [20], we have utilized their average λ_* for a core-halo correction when fitting the PHENIX spectra. In particular,

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the following average values were used for the various particle types: $\overline{\lambda}_*(\pi) = 0.39 \pm 0.14$, $\overline{\lambda}_*(K) = 0.80$ (estimated from the NA44 data on kaon-kaon correlations at CERN SPS [23], $\overline{\lambda}_*(\overline{p}) = 1$ (the fraction of long lived resonances that decay to anti-protons is neglected). In case of the STAR data, we have utilized the same values for $\overline{\lambda}_*(K)$ and $\overline{\lambda}_*(\overline{p})$ however, for pions we have utilized the $\lambda_*(m_t)$ values of ref. [22]. Note also that we have performed the data analysis within the $\Omega = 1$ approximation. Here we improve on our earlier results [25] by taking into account an m_t dependent core-halo correction for the STAR spectra and correlations, and by fitting the absolute normalization of the single particle spectra in both experiments, properly utilizing the fugacity and quantum statistical factors. This allows us to extract the chemical potencial in the center of the fireball, in contrast to our earlier fits [25] where the absolute normalization of the particle spectra and the central value of the chemical potential distribution were not yet determined. Unique minima are found and a good χ^2/NDF is obtained for both data sets. Within errors, all the fit parameters remained the same as in ref. [25], but χ^2/NDF decreased slightly. See Figs. 1 and 2 for an illustation. The hypothesis that pions, kaons and protons are emitted from the same hydrodynamical source is in a good agreement with all the fitted data.

4. Conclusions

We find that the PHENIX and STAR data on single particle spectra of identified π^-, K^- and $\overline{p}$ as well as detailed m_t dependent HBT radius parameters are consistent with the Buda-Lund hydro model as well as with one another. The final state of central Au + Au collisions at RHIC corresponds to a cylindrically symmetric, large ($R_G = 7.3 \pm 0.7$ fm) and homogenous ($T_0 = 142 \pm 4$ MeV) fireball. A large mean freeze-out time, $\tau_0 = 8.4 \pm 0.5$ is found with a short duration of particle emission and small inhomogeneities of

BL-Hydro parameters	STAR preliminary	PHENIX preliminary	Au+Au $\langle RHIC \rangle$	Pb+Pb $\langle SPS \rangle$	h+p SPS
T_0 [MeV]	144 ± 5	139 ± 5	142 ± 4	139 ± 6	140 ± 3
$\langle u_t \rangle$	0.86 ± 0.10	0.68 ± 0.3	0.77 ± 0.09	0.55 ± 0.06	0.20 ± 0.07
R_G [fm]	8.0 ± 0.5	6.6 ± 0.3	7.3 ± 0.7	7.1 ± 0.2	0.88 ± 0.13
τ_0 [fm/c]	8.9 ± 0.5	7.9 ± 0.3	8.4 ± 0.4	5.9 ± 0.6	1.4 ± 0.1
$\Delta\tau$ [fm/c]	0.5 ± 1.0	0.6 ± 1.2	0.5 ± 1.1	1.6 ± 1.5	$\geq$ 1.3 ± 0.3
$\Delta\eta$	1.0 ± 0.1	1.5 ± 0.1	1.2 ± 0.3	2.1 ± 0.4	1.36 ± 0.02
$\langle \frac{\Delta T}{T} \rangle_r$	0.09 ± 0.01	0.04 ± 0.01	0.06 ± 0.03	0.06 ± 0.05	0.71 ± 0.14
$\langle \frac{\Delta T}{T} \rangle_t$	1.6 ± 0.4	0.86 ± 0.09	1.2 ± 0.4	0.59 ± 0.38	-
$\mu_0^{\pi^-}$ [MeV]	0 (fixed)	0 (fixed)	0 (fixed)	-	-
$\mu_0^{K^-}$ [MeV]	46 ± 11	-	-	-	-
$\mu_0^{\overline{p}}$ [MeV]	300 ± 18	376 ± 38	338 ± 28	-	-
χ^2/NDF	32/54 = 0.59	46/58 = 0.79	0.69	1.20	0.94

Table 1: Preliminary source parameters from simultaneous fittings of preliminary RHIC data of PHENIX and STAR on particle spectra and HBT radius parameters with the Buda-Lund hydrodynamical model. The third column indicates their average. The (average) fit parameters are shown for Pb+Pb collisions at CERN SPS [24] and for h+p collisions at CERN SPS [18].

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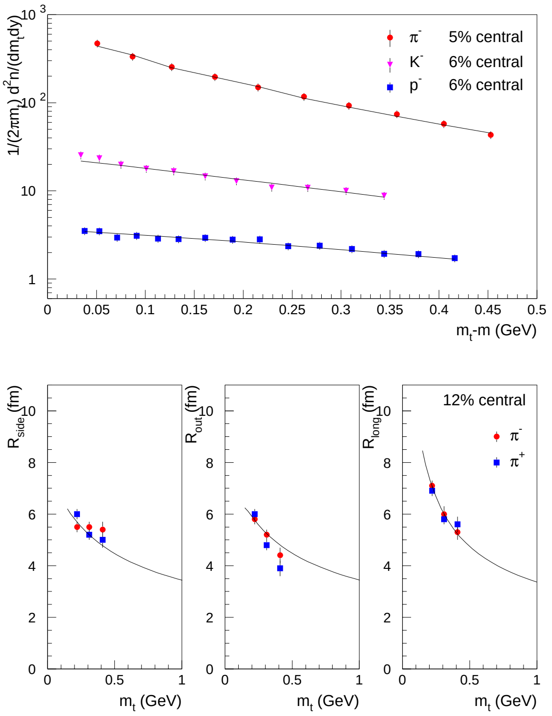

Figure 1: Simultaneous fits to STAR particle spectra and HBT radius parameters.

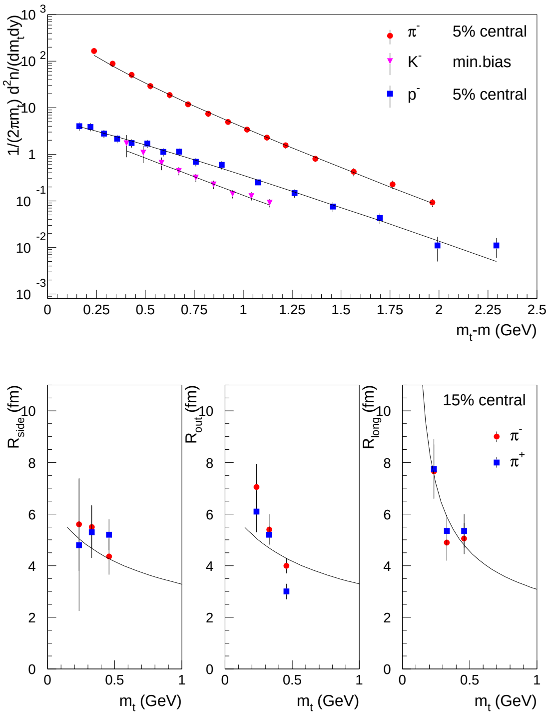

Figure 2: Simultaneous fits to PHENIX particle spectra and HBT radius parameters.

the temperature profile during the particle emission process. At the reconstructed final state, the hadronic fireball expands three-dimensionally with a strong transverse flow, characterized by the Hubble constant $H = \langle u_t \rangle = 0.77 \pm 0.09$. The major difference between the final state of heavy ion collisions at RHIC and at CERN SPS seems to be an increased freeze-out time and an increased transverse flow or Hubble constant at RHIC. Within the presently large errors we do not find a significant increase in the reconstructed geometrical source size when increasing the energy from SPS to RHIC. This and other questions are being addressed by an attempt to include the pseudo-rapidity distribution at RHIC into the fitted data sets, and by repeating the analysis using final, published PHENIX and STAR data.

We have found a non-vanishing chemical potential for kaons and anti-protons in the center of the fireball from the absolutely normalized single-particle spectra, while the pion data were well described in all cases with a vanishing pion chemical potential in the center of the fireball. These values together with the inhomogeneous chemical potential distribution of eq. (2.4) indicate a clear deviation from chemical equilibrium in the reconstructed hadronic final state.

The similarities and the differences between an effective Quark Matter (QM) stage and a Quark Gluon Plasma (QGP) phase have been summarized recently in ref. [26]. The observed short duration of particle emission and the large transverse flow at RHIC contradicts to the picture of a soft, long-lived, evaporative Quark Gluon Plasma phase, that would consist of massless quarks and gluons. However, the final state does not exclude a

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transient, explosive, suddenly hadronizing Quark Matter phase, that could be characterized by massive valence quarks, the lack of gluons as effective degrees of freedom, and a hard equation of state.

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