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Blast-wave fits with resonances to p_t spectra from Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

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We report results of our studies on how resonance decays influence freeze-out temperature and transverse flow profile obtained from fits to the single-hadron transverse-momentum spectra measured by the ALICE collaboration. We find that resonance contribution is nontrivial and cannot be easily neglected in the fits.

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1. Introduction

Hadron spectra produced in ultrarelativistic nuclear collisions are shaped by the dynamical state of the fireball at the moment of its breakup—the moment of kinetic freeze-out. It is useful to describe the freeze-out state of the fireball by hydrodynamically inspired parametrisations. They usually assume that freeze-out happens instantaneously along some hypersurface. The models include locally thermalized momentum distribution and some pattern of longitudinal and transverse expansion flow velocity. In our analysis we shall make use of the so-called blast-wave model [1]. The azimuthally integrated hadron p_t spectra are particularly characterised by the kinetic freeze-out temperature T and the transverse expansion velocity v_t.

An important part of final state hadrons does not originate directly from the fireball but comes from decays of unstable resonances which themselves were emitted from the fireball. They crucially influence the shape of the spectrum. In spite of this, the resonance contribution is often omitted in analyses due to its computational complexity. Calculations cannot be done analytically and one would have to resort to costly Monte Carlo simulations. We will show below that the effect of resonances cannot be accounted for by simple means like e.g. shifting the extracted temperature. Also, it cannot be eliminated by choosing a fiducial p_t interval for data fitting. It seems that some form of Monte Carlo is inevitable.

We have used the Monte Carlo (MC) event generator DRAGON [2] for the generation of theoretical spectra. It is a MC realisation of the blast wave model which was adapted to be identical to the one used by ALICE collaboration for data fitting [3]. Resonance production of hadrons is included. The theoretical spectra were compared with the data by ALICE collaboration on transverse momentum spectra of π, K, p [3], K^0 and Λ [4], Ξ and Ω [5], K^* and ϕ [6]. The fits to data allow us to deduce the values of kinetic freeze-out temperature and transverse expansion velocity more reliably than in fits with only direct thermal production included, e.g. [3].

In the next Section we summarize the relevant features of our package DRAGON. In Section 3 we study how resonance production of hadrons affects p_t spectra. Results of our fits are summarized in Section 4.

2. Model

The blast-wave model is characterised by its emission function, the Wigner phase-space density of the source of hadrons of type i

$$S(x,p)\,d^4x = g_i \frac{m_t \cosh(\eta - y)}{(2\pi)^3} \left(\exp\left(\frac{p_\mu u^\mu - \mu_i}{T} \right) + s_i \right)^{-1} \theta\left(1 - \frac{r}{R}\right)$$
$$\times r\,dr\,d\varphi\,\delta(\tau - \tau_0)\,\tau\,d\tau\,d\eta\,. \tag{2.1}$$

Because of the dominant expansion in the longitudinal direction one uses longitudinal proper time $\tau = \sqrt{t^2 - z^2}$ and space-time rapidity $\eta = \frac{1}{2}\ln((t+z)/(t-z))$. Polar coordinates r, φ are used in the transverse plane. We use proper quantum statistical distributions with $s_i = 1$ (-1) for fermions (bosons) and g_i is the spin degeneracy. Every isospin state is treated separately. This prescription assumes sharp freeze-out along the hypersurface $\tau = \tau_0$ and uniform density distribution within the

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radius R. This means that our freeze-out time does not depend on radial coordinate[1]. The expansion of the fireball is represented by the velocity field

$$u^\mu = (\cosh\eta_t \cosh\eta\,,\ \sinh\eta_t \cos\varphi, \sinh\eta_t \sin\varphi,\ \cosh\eta_t \sinh\eta\,) \tag{2.2}$$

where the transverse velocity is such that

$$v_t = \tanh\eta_t = \eta_f \left(\frac{r}{R}\right)^n . \tag{2.3}$$

In this relation η_f parametrises transverse flow gradient and n the profile of the transverse velocity. The mean transverse velocity is then

$$\langle v_t \rangle = \frac{2}{n+2}\eta_f\,. \tag{2.4}$$

The transverse size R and the freeze-out proper time τ_0 influence total normalizations of transverse momentum spectra. However, in this study we ignore those and hence we have no sensitivity to these geometric parameters.

From the emission function, spectrum of directly produced hadrons is obtained as

$$E\frac{d^3N}{dp^3} = \int_\Sigma S(x,p)\,d^4x\,, \tag{2.5}$$

where the integration runs over the whole freeze-out hypersurface.

Resonances are emitted as described by the emission function in eq. (2.1) and then decay exponentially in time according to their width. All matrix elements for the decays are assumed to be constant and thus the decay is determined by the phase-space only. In the end we look only at stable hadrons.

In our simulation we systematically vary the temperature T, transverse flow gradient η_f, and the power n. We construct histograms in p_t for some number of Monte Carlo events for each set of (T,η_f,n) parameters which are then compared with measured data and a value of χ^2 is obtained. This procedure is CPU and storage-demanding because the generation must be done separately for each set of parameters.

3. Resonance contribution to p_t spectra

We apply here the scenario of two freeze-outs: chemical freeze-out at a higher temperature is followed by further cooling and expansion which ends up in the thermal freeze-out. The abundances of all species including resonances are determined by chemical equilibrium at chemical freeze-out temperature of 152 MeV and baryochemical potential of 1 MeV [11] [2]. Our set-up actually implies that the kinetic freeze-out follows the chemical one so quickly that resonances decay only after the kinetic freeze-out [12][3].

[1]This is one of the differences between our model and the Cracow single freeze-out model [7] which was used in fits to p_t spectra measured by ALICE collaboration recently [8, 9, 10].

[2]Note that shifting these values slightly is not expected to cause a big change in the *shape* of the transverse momentum spectra.

[3]We shall reconsider it in the near future by accounting for decays and regeneration of short-lived resonances such as ρ between the two freeze-outs.

Table 1: Freeze-out parameters obtained from fits to pion, kaon and proton p_t spectra within fiducial intervals as defined in [3] for selected centrality classes.

centrality	ALICE [3]			DRAGON (no resonances)			DRAGON (with resonances)		
	T (MeV)	$\langle v_t \rangle$	n	T (MeV)	$\langle v_t \rangle$	n	T (MeV)	$\langle v_t \rangle$	n
0–5%	95	0.651	0.71	98	0.645	0.73	82	0.662	0.69
10–20%	99	0.639	0.74	102	0.637	0.73	90	0.649	0.71
30–40%	106	0.604	0.84	110	0.605	0.81	102	0.616	0.79
50–60%	118	0.535	1.10	122	0.527	1.15	126	0.541	1.03
70–80%	139	0.438	1.58	142	0.439	1.51	170	0.423	1.55

It is often argued that leaving out resonances is justified if the fit to p_t spectra is performed in a fiducial region where p_t is high enough so that the resonance contributions are not important and low enough so that hard processes play no role. However, assumption that resonance contribution is concentrated only at low p_t is wrong. To show that, we performed fits to fiducial p_t-intervals used in [3]. Results for selected centrality classes are summarised in Table 1. Our fit results with no resonances agree with those by ALICE [3]. The inclusion of resonances changes the results in a way which depends on centrality. While in central collisions the temperature drops by 10 MeV when resonances are included, in peripheral collisions it rises by 10 MeV.

To see the origin of the temperature shifts, we show in Fig. 1 contributions of individual resonance species to the resulting spectra for pions. This was calculated with our best fit parameters corresponding to the given centrality classes, as described below. In peripheral collisons we see that the resonance production populates mainly the low p_t region as might have been expected. This feature still survives in the 20-40% centrality class. In the most central collisions, however, the relative contribution from resonance decays grows with increasing p_t.

To see the reason for such a behaviour, we note that in central collisions the temperature is low and transverse flow strong. As shown in Fig. 1b, low p_t region in central collisions is populated by decays of η and ω. The former is light and the latter decays into three pions. Hence, there is not much energy left for the momentum of the pions. The higher-p_t tail is mainly populated by decays of ρ and heavier resonances. When they decay, much energy is available for the kinetic energy of the pions. Pions get a kick from decays of such resonances. Also, due to low temperature not many direct pions have high p_t and so the share of pions from heavy resonance decays grows. Strong transverse flow boosts also the heavy resonances and helps to pronounce the kick to high p_t. This changes when the temperature grows and the transverse expansion is weaker (peripheral collisions). There, directly produced pions can better populate also higher p_t and the share of resonance production at high p_t does not grow anymore.

Qualitatively similar results for resonance production, although not as pronounced as for pions, are obtained for protons. The resonance contribution to protons in the case of 0-5% central collisions is shown in Fig. 2 (left). The dominant contributor are Δ resonances. Figure 2 (right) depicts resonances contributing to Λ, with Σ and Σ^* as the main contributors.

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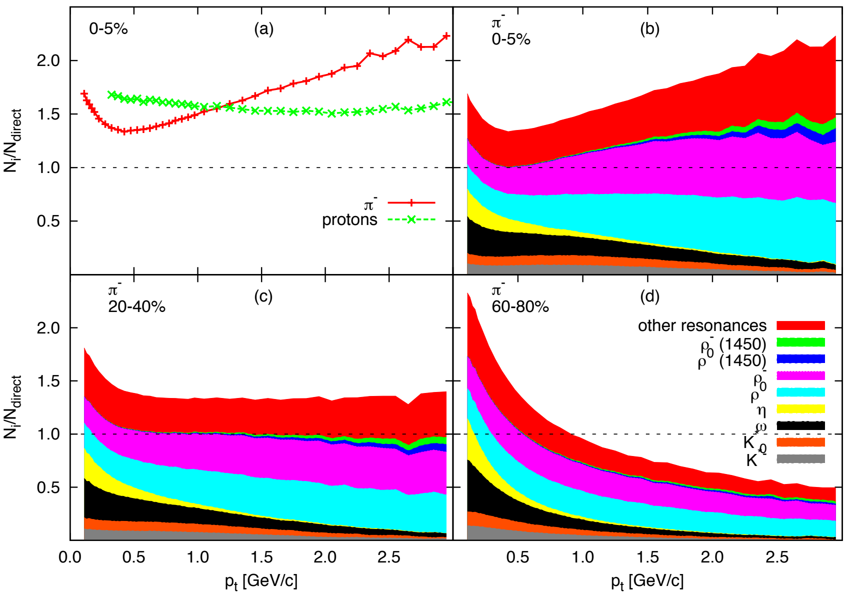

Figure 1: The ratio of hadrons from resonance decays to those produced directly as a function of p_t. (a) pions and protons in 0-5% central collisions; (b)-(d) the pion ratio is broken up into contributions from individual resonance species, different panels show different centralities. Simulations correspond to our best fits to the indicated centralities. The used values of T and $\langle v_t \rangle$ are indicated in Fig. 3.

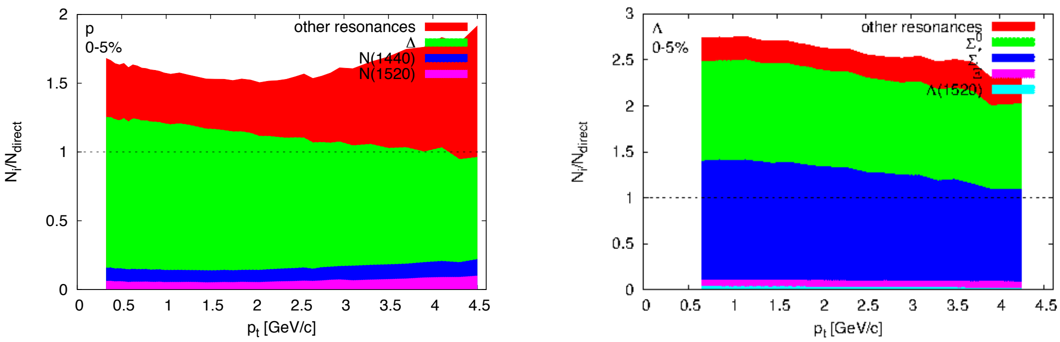

Figure 2: The ratio of hadrons from resonance decays to those produced directly as a function of p_t broken up into contributions from individual resonance species for 0-5% centrality class. Left: protons; right: Λ.

4. Fit summary

The obtained freeze-out temperature grows and the transverse expansion velocity decreases as we move from central collisions to more peripheral. The overview of results can be found in Fig. 3. With the model fitted to pions, kaons, nucleons, and Λ's we were able to reproduce also the K^* and ϕ spectra. However, the spectra of multistrange hadrons, Ξ and Ω, did not fall into this systematics. When we fitted them separately, the obtained temperatures were generally higher and transverse flows generally weaker than those of more abundant species. More detailed description of the procedure and results can be found in [13].

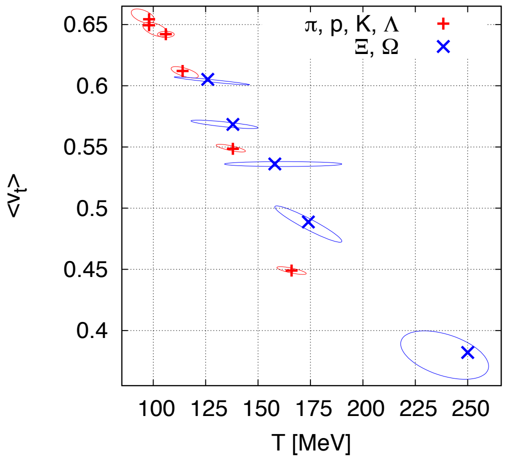

Figure 3: Best-fit values of T and $\langle v_t \rangle$ for transverse momentum spectra of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, K^0, and Λ are shown by red +'s. Results go from central (upper left) to peripheral (lower right) collisions, with centrality classes 0-10%, 10-20%,20-40%, 40-60%, 60-80%. Around each best fit value we estimate the 99% confidence-level region. By blue $\times$'s we show results of fits to spectra of multistrange species, with centralities 0-5%, 5-10%, 10-20%,20-40%, 40-60%, 60-80%. For multistrange species we estimate the 68% confidence-level regions.

5. Conclusions

We conclude that resonance decays have significant impact on hadron p_t spectra. There is no fiducial interval where resonance contribution can be ignored and no simple recipe stating that the inclusion of resonances will just shift the fit results by any fixed value.

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