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Statistical model predictions for particle ratios at $\sqrt{s_{NN}} = 5.5$ TeV

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Particle production in central Pb-Pb collisions at the CERN Large Hadron Collider is discussed in the context of the statistical model. Predictions of various particle ratios are presented with the corresponding choice of model parameters made according to the systematics extracted from heavy-ion collisions at lower energies. The sensitivities of several ratios to the temperature and baryon chemical potential are studied in detail, and some of them, which are particularly appropriate to determining the chemical freeze-out point experimentally, are indicated. We show that the $\bar{p}/p$ ratio is most suitable for determining the baryon chemical potential, while the Ω^-/K^- and Ω^-/π^- ratios are best for determining the temperature at chemical freeze-out.

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I. INTRODUCTION

Particle production observed in heavy-ion collisions allows a systematic study of the thermal properties of the final state. In a wide energy range, from the energies of the GSI Schwerionen-Synchrotron (SIS) up to those of the BNL Relativistic Heavy Ion Collider (RHIC), the yields of produced particles have been shown to be consistent with the assumption that hadrons originate from a thermal source with a given temperature and a given baryon density. These properties have been quantified by comparing the measured particle ratios with statistical model calculations. By using only two thermal parameters, a successful description of particle ratios measured in heavy-ion collisions over a wide range of center-of-mass energies could be made [1]. The extracted chemical freeze-out parameters, temperature T, and baryon chemical potential μ_B can be characterized by a constant average energy per hadron $\langle E\rangle/\langle N\rangle$ of approximately 1 GeV [2]. The extrapolation of this freeze-out curve toward vanishing μ_B is bounded by the critical phase transition temperature as calculated in lattice gauge theory [3].

In view of the success of the statistical model, we discuss in this paper the expectations for particle ratios in central heavy-ion collisions at the energy of the CERN Large Hadron Collider (LHC). The calculations are performed at the chemical decoupling point extrapolated from the freeze-out systematics. The particle ratios are discussed with respect to their sensitivity to variations in the thermal parameters. Based on this analysis, we suggest observables that are best suited to extracting experimentally the freeze-out conditions in heavy-ion collisions at the LHC energy.

At LHC energies, because of the large number of produced particles, a novel type of data analysis is possible. In particular, the thermal origin and chemical decoupling conditions in heavy-ion collisions can be studied for various event classes and even within a single event. Consequently, the freeze-out conditions can be extracted event-wise, leading to distributions of the temperature and baryon chemical potential determined event-wise. Instead of a full analysis within the statistical model, the proposed particle ratios can be utilized to extract these values.

Furthermore, at these energies most particles might be produced via hard collisions, which could lead to particle ratios substantially different from those of the statistical model. Deviations from these predictions might lead to new insight into the hadronization mechanism.

II. STATISTICAL MODEL

The statistical model and its application to heavy-ion collisions has been summarized recently [1]. In the present calculations, we apply the statistical model with completely equilibrated flavor production. Because of the expected large multiplicity of strange particles in central Pb-Pb collisions at LHC energies, we use the grand-canonical formulation of strangeness conservation. Thus, strangeness, baryon number, and electric charge are determined by corresponding chemical potentials. Modeling particle yields in heavy-ion collisions within the statistical model usually requires an additional assumption that the thermal parameters are uniformly distributed in the phase space. An important issue in this context is whether to apply the model to data at midrapidity or to data integrated over the full phase space. While it is clear that full 4π yields should be used at low beam energies, this is no longer appropriate as soon as fragmentation and central regions can be distinguished [1]. In the latter case, the aim is to identify a boost-invariant region near midrapidity and to choose a slice in rapidity within that region. The analysis of particle production in nucleus-nucleus collisions at RHIC energies showed that an appropriate choice is a rapidity interval of width of one unit of rapidity centered at midrapidity [4]. In our study, the predictions of the model for particle yields at the LHC are restricted to the midrapidity interval which is accessible by the LHC experiments. We assume that conservation laws and the strangeness neutrality condition are valid not only in the whole phase space but also in a slice near midrapidity. This premise is supported by the agreement between RHIC data obtained at midrapidity and statistical model calculations [4]. It should be noted that for very peripheral heavy-ion collisions, the suppression of the strange-particle phase space due to canonical effects might occur even at LHC energies.

The charge chemical potential is constrained by the initial isospin asymmetry of the Pb nuclei, whereas the strange chemical potential μ_S, depending on both T and μ_B, is determined by strangeness neutrality. Thus, any particle ratio is uniquely determined by only two parameters, T and μ_B at chemical freeze-out.

To estimate particle ratios in Pb-Pb collisions at LHC, one needs to determine the expected range of thermal parameters. For this purpose, we apply the parametrized $\sqrt{s_{NN}}$-dependence of μ_B as it was recently extracted from the statistical model analysis of hadron multiplicities in heavy-ion collisions [5]. The baryon chemical potential μ_B, extrapolated to the LHC energy, is, according to this parametrization,

$$\mu_B(\sqrt{s_{NN}} = 5.5\ \text{TeV}) = 1\ \text{MeV}. \qquad (1)$$

Similar estimates of μ_B at the LHC energy have been obtained recently in [5–8].

Considering the variation of the chemical freeze-out temperature with collision energy in heavy-ion collisions, T is evidently an increasing function of $\sqrt{s_{NN}}$. However, from energies of the CERN Super Proton Synchroton (SPS) to those of RHIC, the change of the chemical freeze-out temperature is only moderate. Within the statistical and systematic errors, the temperature $T \approx 170$ MeV is consistent with the value derived at the top SPS and RHIC energies [1,9–12]. Lattice QCD results on the critical temperature, extrapolated to the chiral limit and at vanishing baryon density, concur within statistical error with this value [3]. Thus, we use this value as an estimate of the chemical freeze-out temperature at LHC. However, to account for possible uncertainties in the extrapolations of the chemical freeze-out parameters to the LHC energy, we consider a possible shift of T by ± 5 MeV and a variation of μ_B between 0 and 5 MeV.

From the sensitivity of different particle ratios on freeze-out parameters we deduce the reliability of the model predictions and the ability to determine the parameters experimentally. To identify the relevant particle ratios that can be used to constrain experimentally the chemical decoupling conditions in heavy-ion collisions at the LHC energy, we consider a broader range of parameters. The ratios are studied for $150 < T < 180$ MeV and for $0 < \mu_B < 30$ MeV.

III. PARTICLE RATIOS AT LHC

With the values of the thermal parameters expected at LHC and discussed in the previous section, we calculate a set of particle ratios using the THERMUS package [13]. The predicted particle ratios for Pb-Pb collisions at LHC are summarized in Tables I and II. The errors arise from variations of the temperature and the baryon chemical potential, as indicated. Additional systematic uncertainties, not included in the tables, are due to incomplete knowledge of decay modes of resonances into stable particles. We estimate that because of the uncertainty in branching ratios, the p/π^- and the Λ/p ratios might vary by up to 7%, whereas for the Ξ^-/Λ ratio, a change of 3% is possible. The other ratios are less sensitive to the resonance properties and affected by less than 1%. Within the considered range of thermal parameters, the antiparticle/particle ratios are insensitive to any variation in contributions from resonances, because the decay chains are equivalent for particles and antiparticles.

One of the expected features of particle production at LHC is that there should be a rather negligible difference between the yield of particles and their antiparticles. This is a direct consequence of the low net-baryon density expected in the collision fireball at LHC at chemical decoupling. With the range of the chemical potential $0 < \mu_B < 5$ MeV used in the actual calculations, the ratios of antiparticle to particle yields, called $\bar{h}/h$ hereafter, are indeed seen in Table I to be close to unity. Figure 1 illustrates the dependence of $\bar{h}/h$ ratios on T (left) and on μ_B (right). The calculations at $\mu_B \approx 27$ MeV serve as cross-checks with experimental data. At RHIC, at $\sqrt{s_{NN}} = 200$ GeV, several particle ratios were measured in Au-Au reactions by the BRAHMS [14], PHENIX [15], PHOBOS [16], and STAR [17] collaborations. Good agreement is observed for all ratios under study. As an example, the $\bar{p}/p$ ratio is indicated in Figure 1.

On the other hand, the ratios of particles with different masses and different quantum numbers are predominantly controlled by the freeze-out temperature and the particle masses (see Sec. IV below). The values of such yield ratios vary strongly with the particle mass difference, as seen in the right panel of Table I.

Some of the ratios are expected to change only slightly at LHC from their values measured at the SPS and RHIC. This can be seen from Fig. 2, showing little sensitivity of these ratios

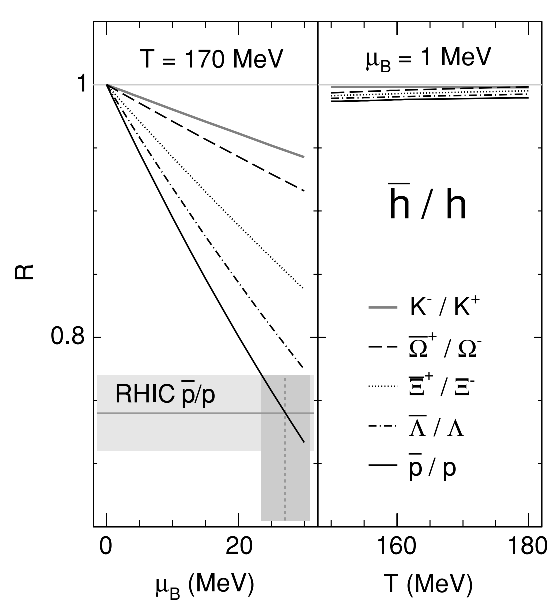

FIG. 1. Antiparticle/particle ratios R as a function of μ_B for $T = 170$ MeV (left) and as a function of T for $\mu_B = 1$ MeV (right). The horizontal line at 1 is meant to guide the eye. The $\bar{p}/p$ ratio (averaged over the data from the four RHIC experiments at $\sqrt{s_{NN}} = 200$ GeV) is displayed (gray horizontal line) together with its statistical error (gray band). As illustrated, $\mu_B \approx 27$ MeV (dashed line) can be read off the figure directly within the given accuracy (vertical gray band).

TABLE I. Particle ratios in central Pb-Pb collisions at freeze-out conditions expected at the LHC: $T = (170\pm5)$ MeV and $\mu_B = 1^{+4}_{-1}$ MeV. Errors correspond to variations in thermal parameters. Additional systematic uncertainties in the ratios of the right column arise from unknown decay modes. They are smaller than 1% in general, but reach 3% in the Ξ^-/Λ ratio and 7% in the p/π^- and the Λ/p ratios.

$\bar{h}/h$ ratio		Mixed ratio	
π^+/π^-	$0.9998^{+0.0002}_{-0.0010}$	K^+/π^+	$0.180^{+0.001}_{-0.001}$
K^+/K^-	$1.002^{+0.008}_{-0.002}$	K^-/π^-	$0.179^{+0.001}_{-0.001}$
$\bar{p}/p$	$0.989^{+0.011}_{-0.045}$	p/π^-	$0.091^{+0.009}_{-0.007}$
$\bar{\Lambda}/\Lambda$	$0.992^{+0.009}_{-0.036}$	Λ/p	$0.473^{+0.004}_{-0.006}$
$\bar{\Xi}^+/\Xi^-$	$0.994^{+0.006}_{-0.026}$	Ξ^-/Λ	$0.160^{+0.002}_{-0.003}$
$\bar{\Omega}^+/\Omega^-$	$0.997^{+0.003}_{-0.015}$	Ω^-/Ξ^-	$0.186^{+0.008}_{-0.009}$

with T and μ_B. A particular example are the K/π ratios which, within errors, are consistent with those measured at lower energies. Large deviations from SPS and RHIC measurements are seen for particle ratios built with baryons and antibaryons. This is a direct consequence of a substantial decrease in baryon stopping at LHC, which, in the statistical model, results in a decreasing baryon chemical potential.

Particle densities in central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV have been recently calculated within relativistic hydrodynamics [18]. Their results on ratios of pions, kaons, and protons are comparable to our findings given in Table I. However, the predictions of this hydrodynamic model depend strongly on the value of the decoupling temperature. A similar sensitivity to the decoupling temperature is found in both models.

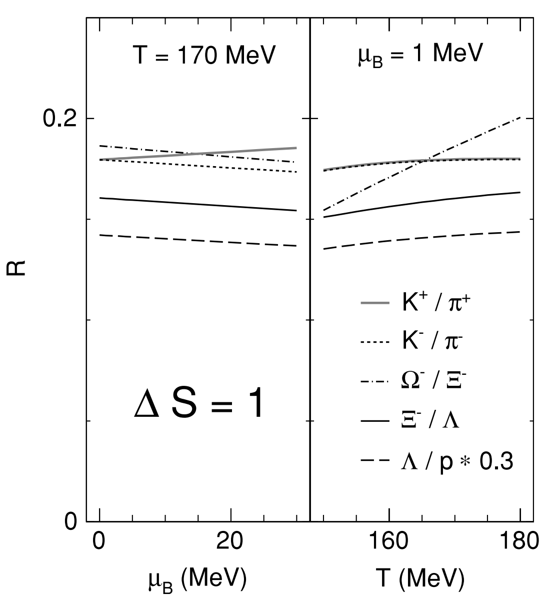

FIG. 2. Ratios R of particles with unequal strangeness content as a function of μ_B for $T = 170$ MeV (left) and as a function of T for $\mu_B = 1$ MeV (right).

TABLE II. Resonance/stable particle ratios in central Pb-Pb collisions at freeze-out conditions expected at the LHC: $T = (170\pm5)$ MeV and $\mu_B = 1^{+4}_{-1}$ MeV. Errors correspond to variations in thermal parameters. Additional systematic uncertainties arise from unknown decay modes. They are smaller than 1% in general, but reach 2% in the ϕ/K^- ratio and 3.5% in the $\rho^0(770)/\pi^-$ ratio. Resonance widths are from [23].

Ratio		Width(MeV)	
ϕ/K^-	$0.138^{+0.004}_{-0.004}$	ϕ	4.26 ± 0.05
$\Lambda(1520)/\Lambda$	$0.090^{+0.003}_{-0.003}$	$\Lambda(1520)$	15.6 ± 1.0
$K^*(892)^0/K^-$	$0.323^{+0.010}_{-0.009}$	$K^*(892)^0$	50.7 ± 0.6
$\rho^0(770)/\pi^-$	$0.127^{+0.001}_{-0.002}$	$\rho^0(770)$	150.3 ± 1.6

Resonance yields have been suggested as being a sensitive probe of the fireball expansion dynamics [19]. The resonances might be sensitive to collective effects and interactions with the surrounding medium. Such interactions can result in resonance broadening or mass shifts [20,21]. Assuming that resonances are produced according to a thermal distribution, their initial multiplicity can be calculated. Deviations from the thermal yields can be attributed to processes taking place in a later stage of the evolution after chemical freeze-out. In this late stage, the expansion dynamics might be driven mostly by elastic and pseudoelastic hadron scattering. Also, the reconstruction of short-lived resonances which decay in this stage will fail if at least one daughter particle undergoes an interaction with the medium. On the other hand, pseudoelastic processes might regenerate resonances [22] and consequently, the yield of resonances at thermal freeze-out can differ from the one calculated in the statistical model at chemical freeze-out. This has been observed in measurements of resonance yields in heavy-ion collisions at RHIC [22]. The observed yields of short-lived resonances such as ρ or K^* were found to differ from the model predictions even by a factor of 2 [1].

Benchmarks are essential to evaluating modifications in resonance yields. Therefore, resonance/stable particle ratios, as expected at chemical freeze-out, have been calculated by the statistical model without including dynamic effects in the final state. Similarly, for the width of the resonances, the values in vacuum were used; neither the mass nor the width was modified according to in-medium effects. The ratios are displayed in Table II together with the width of the resonances. Yields of shorter lived resonances, i.e., those with a large width, are expected to be affected more strongly [22].

IV. SENSITIVITY TO FREEZE-OUT PARAMETERS

In this section, we discuss the dependence of different particle ratios on the values of the thermal parameters. The main objective of this study is to identify observables that could serve as sensitive experimental probes for the chemical freeze-out conditions at the LHC energy. In this context, we consider the antiparticle to particle ratios as well as the ratios of strange and nonstrange particles of different masses and quantum numbers.

A. Antiparticle-to-particle ratios

Figure 1 shows the dependence of different antiparticle/particle ratios, $\bar{h}/h$, on μ_B (left) and T (right). For vanishing baryon chemical potentials, the density of particles is identical to that of antiparticles, thus $\bar{h}/h = 1$. For finite and increasing baryon chemical potentials, the $\bar{h}/h$ ratios are decreasing functions of μ_B. Such properties of antiparticle/particle ratios are qualitatively well understood in the statistical model. The mass terms in the particle and antiparticle partition functions are identical. Consequently, the leading dependence of the $\bar{h}/h$ ratios on μ_B is determined by

$$\bar{h}/h \propto \exp[-2(B\mu_B + S\mu_S)/T], \tag{2}$$

where B and S are the baryon and strangeness quantum numbers of the particle, respectively. In the expression above, feed-down contributions from resonance decays are ignored but they have been included in the model calculations. However, due to equivalent contributions of resonance decays to particles and antiparticles, Eq. (2) provides a good description of $\bar{h}/h$ ratios at the LHC energy. In the antibaryon/baryon ratios, the μ_B term dominates over the μ_S term because strangeness conservation implies that the baryon chemical potential is, in a strangeness neutral system and at a fixed temperature, always larger than the strangeness chemical potential. This, together with the opposite sign of the quantum numbers B and S of strange baryons, results in a weaker sensitivity to μ_B of $\bar{h}/h$ ratios for hadrons with increasing strangeness content. Consequently, as seen in Fig. 1, at a fixed value of μ_B, the antibaryon/baryon ratios are increasing with strangeness content of the hadrons.

The K^-/K^+ ratio shows qualitatively a similar dependence on the baryon chemical potential as the antibaryon/baryon ratios. This is because of the strangeness content of the kaons and the fact that μ_S is an increasing function of μ_B. The K^-/K^+ ratio has no explicit dependence on the baryon chemical potential and is therefore always larger than the antibaryon/baryon ratios at the same μ_B and T.

For small values of μ_B, as expected in heavy-ion collisions at the LHC energy, the $\bar{h}/h$ ratios are only weakly dependent on temperature, as seen in Fig. 1 (right). Thus, these ratios do not constrain the chemical freeze-out temperature in heavy-ion collisions. On the other hand, the high sensitivity of $\bar{h}/h$ on μ_B makes such ratios ideal observables for quantifying μ_B experimentally. As seen in Fig. 1, this is particularly the case for the $\bar{p}/p$ ratio, which exhibits the strongest dependence on the baryon chemical potential.

B. Mixed particle ratios

From the preceding section, one can conclude that ratios of particles with equal masses are not good thermometers of the medium. To extract the chemical freeze-out temperature in heavy-ion collisions, one should consider ratios that are composed of hadrons having different masses. The dependencies of such ratios on μ_B and T are illustrated in Fig. 2. Within the range of the freeze-out parameters considered in this figure, the ratios have a rather weak sensitivity to T and μ_B. In the case of the Ω^-/Ξ^- ratio, this can be seen analytically from the expression

$$\frac{\Omega^-}{\Xi^-} \propto \left(\frac{m_{\Omega^-}}{m_{\Xi^-}}\right)^{3/2} \exp\left[-\frac{m_{\Omega^-} - m_{\Xi^-}}{T}\right] \exp\left[-\frac{\mu_S}{T}\right], \tag{3}$$

where, in this simplified formula, feeding from resonance decays is ignored, with m_{Ω^-} and m_{Ξ^-} denoting the corresponding particle masses.

There is no explicit dependence on the baryon chemical potential in all ratios considered in Fig. 2, as also seen in Eq. (3). Changes in μ_B affect the ratios only indirectly through the μ_B dependence of the strangeness chemical potential. The values of μ_S are nearly proportional to μ_B in the range studied here. For all values of μ_B considered in Fig. 2, the strangeness chemical potential is always smaller than 8 MeV. Consequently, the dependence on the baryon chemical potential is comparatively weak.

The temperature dependence of the Ω^-/Ξ^- ratio is dominated by the mass term, since the difference $(m_{\Omega^-} - m_{\Xi^-}) \approx 350$ MeV is much larger than the strangeness chemical potential ($\mu_S < 1$ MeV for $\mu_B \approx 1$ MeV and for all considered values of T). However, to correctly quantify the temperature dependence of the ratios of particles with different masses, one needs to include contributions from resonance decays.

Figure 3 (upper and middle panels) displays particle densities from different sources. Particles called "primary" are directly produced from a thermal system with given temperature and chemical potentials. The second contribution, called "decay" in Fig. 3, originates from short-living resonances which feed the yield of stable hadrons. The sum of both contributions results in the "final" particle density.

There is no feeding to Ω^- hyperons from heavier resonances. In contrast, only about 50% of the Ξ^- hyperons are primary, while the other half originates from resonance decays. Since both contributions exhibit a similar temperature dependence, as demonstrated in Fig. 3, the sensitivity of the Ω^-/Ξ^- ratio to T can still be estimated from Eq. (3). The Ω^-/Ξ^- ratio increases by about 1% per 1 MeV temperature increase.

For light hadrons such as kaons and pions, the feed-down contributions exceed the thermally produced yield. As seen in Fig. 3 (lower panel) for the thermal conditions at LHC, approximately 75% of the pions are expected to be produced by resonance decays. Furthermore, the contributions from resonance decays feature a temperature dependence deviating from that of primarily created hadrons, as seen in Fig. 3; the former exhibit a steeper increase. Therefore, the temperature-driven increase in the heavy/light hadron ratios is progressively diluted when hadrons with lower masses are considered in the denominator. In the case of the K/π ratios, the contribution to the total pion yield from decays compensates fully for an increase in the kaon yield with increasing temperature. Consequently, the K/π ratios are almost independent of temperature.

This observation allows a stringent test of the model. If the experimental values for the K/π ratios deviate significantly from the predictions, they can hardly be reconciled with the statistical model. This would be an indication for a nonequilibrated system at chemical freeze-out.

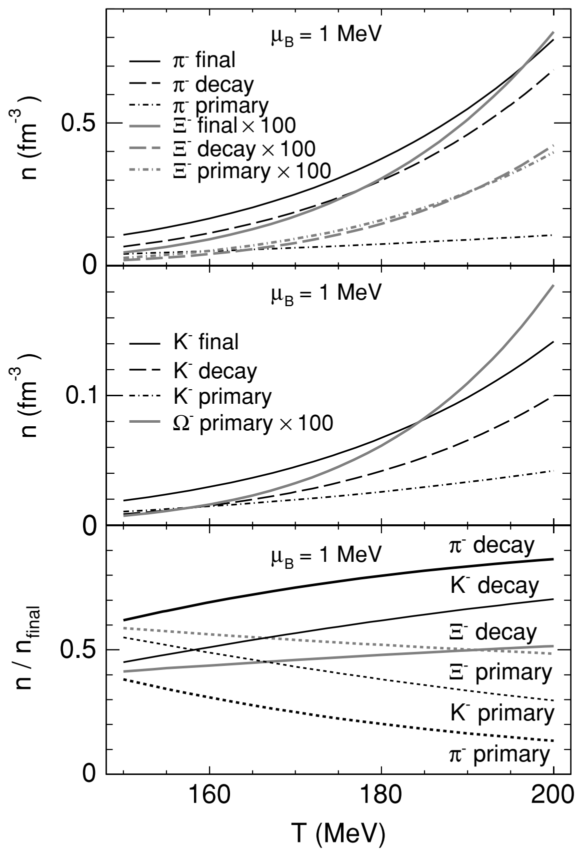

FIG. 3. Upper and middle panels: Particle densities of π^-, Ξ^-, K^-, and Ω^- hadrons as a function of T for $\mu_B = 1$ MeV. Different sources are indicated. The thermally produced, primary hadrons together with those from decays sum up to the finally observed densities. The primary and final density of Ω^- hyperons is identical, i.e., there is no contribution from resonances. Lower panel: Fractional amount of π^-, K^-, and Ξ^- hadrons from primary production and from decays of the final densities, shown as a function of T for $\mu_B =$ 1 MeV.

From the discussions above and in the previous section, it becomes clear that neither antiparticle/particle ratios nor ratios composed of hadrons with small mass differences are well suited to deducing the chemical freeze-out temperature. However, ratios with hyperons, in particular the hyperon/pion ratios, are excellent observables for extracting the chemical decoupling temperature in heavy-ion collisions. Figure 4 shows the temperature dependence of some particle ratios containing hyperons. The statistical model predictions of these ratios are shown up to $T = 200$ MeV.

In general, an upper limit for the chemical freeze-out temperature at LHC is given by the value of the QCD critical temperature at vanishing chemical potential. A recent lattice QCD finding [24] indicates that in $(2 + 1)$-flavor QCD, the critical temperature can be even as large as 185 MeV. This value is significantly larger than previously expected [3]. Figure 4 illustrates that the particle ratios are sensitive to temperature variations in the range that includes the above value of the critical temperature. However, at temperatures larger than 190 MeV, the statistical model results start to suffer

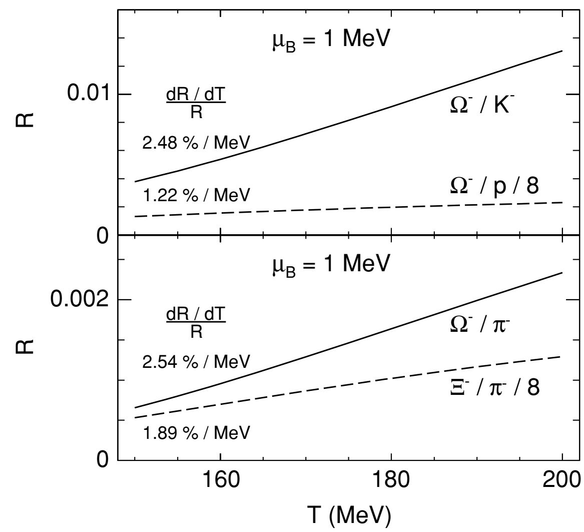

FIG. 4. Particle ratios R involving hyperons as a function of T for $\mu_B = 1$ MeV.

from an imprecise knowledge of high-mass resonances and their decay properties.

The sensitivity of different particle ratios on temperature is quantified in Fig. 4 by the variation of the ratio R per 1 MeV change in T relative to the value of R calculated at $T = 170$ MeV. The results given in this figure show that the temperature dependence is strongest for particle ratios with a large mass difference. This statement is also valid for ratios composed of antiparticles.

The largest (2.5%/MeV) sensitivity to temperature is exhibited by the Ω^-/π^- ratio. However, the variation is significantly smaller than that expected from only thermally produced particles. This is because at LHC, only about 25% of all pions are expected to be directly produced, while the remaining fraction originates from baryonic and, predominantly, from mesonic resonances [25]. The feed-down contribution to pions increases with temperature and reduces the sensitivity.

In view of the large decay contributions to the pion yield, the Ω^-/K^- ratio might be a better thermometer of the medium, since the feeding to kaons is noticeably smaller. Figure 4 demonstrates that the two ratios, Ω^-/π^- and Ω^-/K^-, are similarly sensitive to temperature variations. The combination of the larger kaon mass and smaller feeding compared to pions results in comparable temperature dependencies.

The Ξ^-/π^- ratio has a similar mass difference as the Ω^-/K^- ratio. However, the very large feeding of heavy resonances to pions destroys the expected similarity in the temperature dependence of these ratios. The sensitivity of the hyperon-to-proton ratio on temperature is rather weak because of the small mass difference of constituent particles.

From Fig. 4, it is obvious that the Ω^-/π^- and Ω^-/K^- ratios are best suited to determining the chemical freeze-out temperature. Experimentally, the latter might be more easily accessible and more precisely known, since the contributions from weakly decaying particles, which have to be obtained with high accuracy, are larger for π^- than for K^- mesons.

V. CONCLUSION AND SUMMARY

Predictions of the statistical model for different particle ratios for Pb-Pb collisions at the LHC energy are presented. The sensitivities of various ratios with respect to the temperature and the baryon chemical potential as well as the contribution of resonances are discussed and analyzed. We have shown that the $\bar{p}/p$ ratio is the best-suited observable for extracting the value of the baryon chemical potential at chemical freeze-out. The Ω^-/π^- and the Ω^-/K^- ratios are proposed as thermometers to extract experimentally the chemical freeze-out temperature in central Pb-Pb collisions at LHC.

Hard processes could dominate the particle production at LHC energies. From these interactions, very different particle ratios than those of a thermal source might be expected to be created. Deviations from the predictions given here will help us understand the dynamics and, possibly, the time scale of the hadronization procedure. Furthermore, in events selected, e.g., by high-energy jets, the resulting particle ratios might be different, perhaps indicating a higher freeze-out temperature or deviating completely from the thermal picture. Such selection criteria might make it possible to differentiate between early and late freeze-out. On the other hand, the frequent interactions between the constituents close to the phase boundary [26] could lead to a complete reshuffling, and a statistical distribution might be observed at the end, independent of the preceding history.

ACKNOWLEDGMENTS

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