PHYSICAL REVIEW C **81**, 024903 (2010)

Particle production in p-p collisions at $\sqrt{s} = 17$ GeV within a statistical model

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(Received 16 October 2009; published 4 February 2010)

A thermal-model analysis of particle production of p-p collisions at $\sqrt{s} = 17$ GeV using the latest available data is presented. The sensitivity of model parameters on data selections and model assumptions is studied. The system-size dependence of thermal parameters and recent differences in the statistical model analysis of p-p collisions at the super proton synchrotron are discussed. It is shown that the chemical freeze-out temperature and strangeness undersaturation factor depend strongly on kaon yields, which, at present, are still not well known experimentally. Excluding the ϕ meson and using data that are in agreement with the overall trend, it is rather unlikely that the chemical decoupling temperature in p-p collisions exceeds significantly that extracted from central heavy-ion collisions.

DOI: 10.1103/PhysRevC.81.024903 PACS number(s): 12.40.Ee, 24.10.Pa, 25.40.Ve, 25.75.Dw

I. INTRODUCTION

The statistical model has been used to describe particle production in high-energy collisions for more than half a century [1]. In this period, it has evolved into a very useful and successful model describing a large variety of data; in particular, hadron yields in central heavy-ion collisions [2,3] have been described in a very systematic and appealing way unmatched by any other model. It has also provided a very useful framework for the centrality [4] and system-size dependence [5,6] of particle production. The applicability of the model in small systems like p-p [7] and e^+-e^- annihilation [8] has been the subject of several recent publications [9–11].

The statistical-model analysis of elementary particle interactions can be summarized by the statement that the thermal parameters show almost no energy dependence in the range of $\sqrt{s} = 14$–900 GeV, with the chemical freeze-out temperature being about 165 MeV and the strangeness undersaturation factor γ_S being in the range between 0.5 and 0.7.

In the context of the system-size dependence of particle production, the collisions at $\sqrt{s} = 17$ GeV have been analyzed in detail recently. On the basis of similar data sets, the extracted parameters in different publications deviated significantly from each other: In a previous analysis (Refs. [5,11]), we derived for p-p interactions $T = 164 \pm 9$ MeV and $\gamma_S = 0.67 \pm 0.07$, with $\chi^2/n = 1.7/3$, while the authors of Ref. [6] obtained $T = 178 \pm 6$ MeV, $\gamma_S = 0.45 \pm 0.02$, with $\chi^2/n = 11/7$. These findings motivated different conclusions: In Ref. [5], no system-size dependence of the thermal parameters was found, except for γ_S, which tends to increase when more nucleons participate in the collisions, but this rise is weaker than the errors on the strangeness suppression parameter. In Ref. [5], it was therefore concluded that the hadron gas produced in central collisions at $\sqrt{s} = 17$ GeV reaches its limiting temperature. On the basis of Ref. [6], on the other hand, it was argued in Ref. [12] that decreasing γ_S and, in particular, increasing freeze-out temperature toward smaller systems allows for probing QCD matter beyond the freeze-out curve established in Pb-Pb and Au-Au collisions [13,14].

The goal of this article is to understand the origin of these rather different thermal-model results obtained in the analysis of p-p data. We use an up-to-date complete set of data and discuss the sensitivity of the thermal model parameters on their values. We present systematic studies of data used as inputs and the methods applied in their thermal model analysis.

The article is organized as follows. In Sec. II, we discuss the experimental data on which different analyses are based. In Sec. III, we summarize the main features of the statistical model and present the analysis of the super proton synchrotron (SPS) data obtained in p-p collisions. In the final section, we present our conclusions and summarize our results.

II. DATA

The data used throughout this article for hadron yields in p-p collisions at $\sqrt{s} = 17.3$ GeV are summarized in Table I. Data in column set A were exploited in our previous analysis [11], and the corresponding references are given in the table. If the numerical values deviate in the analysis of Ref. [6], they are listed in column set B. The relative differences between the particle yields from sets A and B are also indicated in Table I. The commonly used data in the statistical model description of particle production in p-p collisions at the SPS are displayed in the bottom half of Table I.

In Table II, the experimental data are grouped into sets, which are used in Sec. III to perform the statistical-model analysis. In the following, we motivate the particular choice of data in these sets and discuss how they can influence the model predictions on thermal conditions in p-p collisions.

Data set A1 is most restricted. First, the production yields of Ξ and Ω are not included because their numerical values

TABLE I. Particle yields (4π integrated) in minimum-bias p-p collisions at $\sqrt{s} = 17.3$ GeV. Numerical values of set A are from Ref. [11]. For set B and common values (data below the horizontal line), the references are given in the last column.

Particle	Set A	Set B	Δ_{yield} (%)	Δ_{err} (%)	Ref.
π^+	3.02 ± 0.15	3.15 ± 0.16	4.4	10.5	[15]
π^-	2.36 ± 0.11	2.45 ± 0.12	3.8	5.9	[15]
K^+	0.258 ± 0.055				[16]
K^-	0.160 ± 0.050				[16]
K^+		0.210 ± 0.021	19	62	[17]
K^-		0.130 ± 0.013	19	74	[17]
Λ	0.116 ± 0.011	0.115 ± 0.012	0.9	9.1	[18]
$\bar{\Lambda}$	0.0137 ± 0.0007	0.0148 ± 0.0019	8.0	171	[18]
K_S^0	0.18 ± 0.04				[17]
$\bar{p}$	0.0400 ± 0.0068				[17]
Λ^*	0.012 ± 0.003				[19]
ϕ	0.0120 ± 0.0015				[20]
Ξ^- [a]	0.0031 ± 0.0003				
$\bar{\Xi}^+$ [a]	0.00092 ± 0.00009				
Ω^- [a]	0.00026 ± 0.00013				
$\bar{\Omega}^+$ [a]	0.00016 ± 0.00009				

[a]Production yields included for cross checks only (in sets A2 and B2) because these numbers were taken from a compilation of NA49 data available online (http://na49info.web.cern.ch/na49info/na49/). They are preliminary, unpublished data taken from a PhD thesis. For a detailed discussion, see Sec. II.

are only preliminary. Second, the Λ^* resonance is also not included so as to restrict the analysis to stable hadrons. Finally, the ϕ meson is omitted in set A1 because this particle is difficult to address in the statistical model because of its hidden strangeness, as discussed in Ref. [5].

The lower yields of charged kaons in set B of Table I are taken from results published in conference proceedings [17]. Such kaon yields are in disagreement with trends from data measured at lower and higher energies, as seen in Fig. 1.

Figures 1(a) and 1(b) show the charged kaon multiplicities from p-p interactions at lower and higher beam momenta [21], together with data from Table I. The lines in this figure are simple parametrizations interpolating to SPS energies. The K^- yield from Ref. [16] is seen to be 7% below the expected value from the preceding parametrization; however, it agrees within errors. The K^- abundance from Ref. [17] is 24% lower, and its error is only 10%. As we discuss later, such a low value for the multiplicity of charged kaons influences the statistical model fit in an essential way.

Figure 1(c) shows negatively charged hadrons from p-p interactions at several beam momenta from Ref. [22]. As indicated in Ref. [22], K^-, $\bar{p}$, and Σ^- supplement the π^- yield. In this case, the ratio π^-/h^- amounts to 91%. Including more sources of feed-down, the π^-/h^- ratio stays at the same level as long as Λ and K_S^0 can be separated. Consequently, to calculate the negatively charged pions from h^- yields, one can use the preceding 91% scaling factor. Figure 1(c) shows the fit to h^- yields as a function of beam momenta and then by rescaling the expected result for the p_{lab} dependence of the negatively charged pions. The yields of π^- at SPS from Table I agree quite well with the yields expected from an interpolation line shown in Fig. 1. They are only slightly higher, by 1%, for yields taken from Ref. [15], and they are higher by 5% for yields used in Ref. [6].

TABLE II. Different sets of particle yields used in the thermal model fits. The type A sets contain numerical values from the left (and common) columns of Table I. The type B sets contain data from set B and common columns of Table I.

Set	Particles	Comment
A1	$\pi^\pm$, K$^\pm$, Λ, $\bar{\Lambda}$, K$_S^0$, $\bar{p}$	Set of Ref. [11]
A2	$\pi^\pm$, K$^\pm$, Λ, $\bar{\Lambda}$, K$_S^0$, $\bar{p}$, Λ^*, Ξ^-, $\bar{\Xi}^+$, Ω^-, $\bar{\Omega}^+$	
A3	$\pi^\pm$, K$^\pm$, Λ, $\bar{\Lambda}$, K$_S^0$, $\bar{p}$, Λ^*, ϕ	
A4	$\pi^\pm$, K$^\pm$, Λ, $\bar{\Lambda}$, K$_S^0$, $\bar{p}$	K$^\pm$ from Ref. [17]
B1	$\pi^\pm$, K$^\pm$, Λ, $\bar{\Lambda}$, K$_S^0$, $\bar{p}$, Λ^*	Λ^* contribution
B2	$\pi^\pm$, K$^\pm$, Λ, $\bar{\Lambda}$, K$_S^0$, $\bar{p}$, Λ^*, Ξ^-, $\bar{\Xi}^+$, Ω^-, $\bar{\Omega}^+$	Fit A of Ref. [6]
B3	$\pi^\pm$, K$^\pm$, Λ, $\bar{\Lambda}$, K$_S^0$, $\bar{p}$, Λ^*, ϕ	Fit B of Ref. [6]
B4	$\pi^\pm$, K$^\pm$, Λ, $\bar{\Lambda}$, K$_S^0$, $\bar{p}$	Set B1 without Λ^*

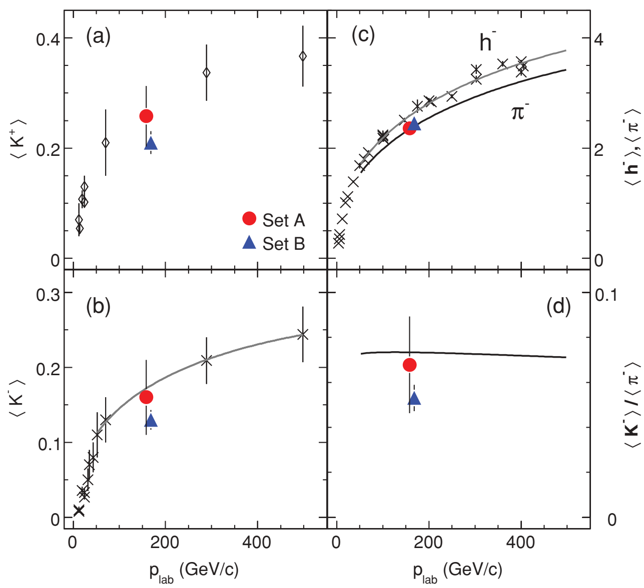

FIG. 1. (Color online) (a, b) Charged kaon yields, (c) negatively charged hadron h^- and pions π^-, and (d) K^-/π^- ratios in p-p collisions as a function of laboratory momentum. The charged kaon yields, K^+ (diamonds) and K^- (crosses), are from Ref. [21]. The lines are fits to data. The SPS yields from Ref. [16] (circles) and from Ref. [17] (triangles) are also shown. The negatively charged hadrons are from Ref. [22].

Figure 1(d) shows the K^-/π^- ratio at SPS compared to the interpolated data from other beam momenta. The mean value of the K^-/π^- used in Ref. [11] is 8% below the interpolated line but agrees within errors, while the corresponding value used in Ref. [6] is 28% smaller and exhibits an error of only 11%. Clearly the preceding differences in the K^-/π^- ratios influence the thermal model fits.

In general, a smaller kaon yield implies a stronger suppression of the strange-particle phase space, resulting in a smaller value for the strangeness undersaturation factor γ_S. If other strange particles are included, then the strong suppression caused by γ_S has to be compensated by a higher temperature. This might be one of the origins for the different thermal fit parameters obtained in Refs. [11] and [6]. To quantify this, we have selected a data set A4, which is equivalent to set A1, but with the kaon yields of Ref. [16] being replaced by the values from Ref. [17].

Set B1 is (besides the Λ^*) equivalent to set A1, but with numerical values for particle yields from the set B column in Table I. Set B4 is used to demonstrate the influence of the Λ^* resonance on thermal fit parameters. Sets A3, B3 and A2, B2 are chosen to study the influence of the ϕ meson and the multistrange hyperons on thermal fit parameters.

III. STATISTICAL MODEL ANALYSIS

The usual form of the statistical model formulated in the grand-canonical ensemble cannot be used when either the temperature or the volume, or both, is small. As a rule of thumb, one needs $VT^3 > 1$ for a grand-canonical description to hold [23,24]. Furthermore, even if this condition is matched, but the abundance of a subset of particles carrying a conserved charge is small, the canonical suppression still appears, even though the grand-canonical description is valid for the bulk of the produced hadrons. There exists a vast literature on the subject of canonical suppression, and we refer the reader to several articles (see, e.g., Refs. [3,25,26]).

The effect of canonical suppression in p-p collisions at ultrarelativistic energies is relevant for hadrons carrying strangeness. The larger the strangeness content of the particle, the stronger is the suppression of the hadron yield. This has been discussed in great detail in Ref. [27].

In line with the previous statistical model studies of heavy-ion scattering at lower energies, the collisions of small ions at SPS revealed [5] that the experimental data show stronger suppression of strange-particle yields than what was expected in the canonical model [5,28,29]. Consequently, an additional suppression effect had to be included to quantify the observed yields. Here we introduce the off-equilibrium factor $\gamma_S \leqslant 1$, which reduces densities n_s of hadrons carrying strangeness s by $n_s \rightarrow n_s \cdot \gamma_S^{|s|}$ [24].

We investigate whether all quantum numbers have to be conserved exactly in p-p collisions within a canonical approach by comparing data with two model settings:

(i) Canonical (C) model: All conserved charges, that is, strangeness, electric charge, and baryon number, are conserved exactly within a canonical ensemble

(ii) Strangeness canonical (SC) model: Only strangeness is conserved exactly, whereas the baryon number and electric charge are conserved on the average, and their densities are controlled by the corresponding chemical potentials.

The parameters of these models are listed in Table III. In the following, we compare predictions of the preceding statistical models with p-p data summarized in the different sets discussed earlier.

TABLE III. A list of parameters needed to quantify particle yields in the SC and C statistical models (see text). The symbols S, Q, and B are the strangeness, electric charge, and baryon number, respectively, with μ_i for $i = (S, Q, B)$ being chemical potentials related with conservation of these quantum numbers. Variable γ_S is the strangeness undersaturation factor, T is the chemical freeze-out temperature, and R is the radius describing the spherical volume of the collision zone.

	SC model		C model	
Fit parameter	μ_B: R		S, Q, R	
Constrained parameter	μ_Q: $B/2Q = 0.5$			
Fixed parameter			$B = 2$	
Fit/scan parameter	T, γ_S		T, γ_S	
No. of parameters	5		6	
	Fit	χ^2 scan	Fit	χ^2 scan
No. of free parameters	4	2	5	3
No. of fixed parameters	1	3	1	3

TABLE IV. Thermal parameters extracted within the SC and C models (see text) from fits to 4π-integrated data in p-p collisions at $\sqrt{s} = 17.3$ GeV. In the SC model analysis for data set B1, a fit does not converge, and the minimum of the χ^2 scan is displayed. The fits to data sets A3 and B3 do not exhibit a χ^2 minimum in the parameter range considered, and thus only the tentative parameters of a possible minimum are indicated.

Set	T (MeV)	γ_S	R (fm)	μ_B (MeV)	χ^2/n
		SC model results			
A1	163 ± 5	0.68 ± 0.05	1.50 ± 0.11	208 ± 14	1.7/4
A2	168 ± 1	0.66 ± 0.02	1.37 ± 0.03	221 ± 8	8.6/9
A3	>190	≈ 0.5	<1.1	>250	
A4	177 ± 5	0.59 ± 0.03	1.23 ± 0.10	233 ± 16	5.1/4
B1	176	0.56	1.24 ± 0.01	240 ± 12	7.7/7
B2	179 ± 5	0.61 ± 0.02	1.19 ± 0.09	242 ± 18	16/9
B3	>190	≈ 0.5	<1.1	>250	
		C model results			
A1	175 ± 5	0.57 ± 0.04	1.33 ± 0.09		0.5/3
A2	174 ± 4	0.59 ± 0.02	1.34 ± 0.08		6.6/8
A3	189 ± 5	0.46 ± 0.02	1.12 ± 0.09		23/5
A4	181 ± 4	0.52 ± 0.03	1.22 ± 0.07		3.5/3
B1	177 ± 5	0.51 ± 0.03	1.30 ± 0.09		6.8/4
B2	180 ± 4	0.56 ± 0.02	1.23 ± 0.08		18/8
B3	178 ± 5	0.45 ± 0.02	1.30 ± 0.10		19/5
B4	177 ± 5	0.50 ± 0.03	1.31 ± 0.09		4.8/3

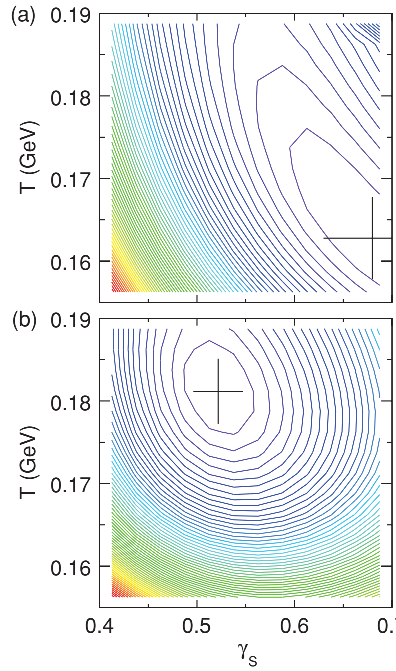

FIG. 2. (Color online) The χ^2 scan in the $(T - \gamma_S)$ plane. Starting from its minimum, χ^2 increases by 2 for each contour line. (a) Fit to data set A1 in the model, where only strangeness is conserved exactly (SC). (b) Fit to data set A4 in the C model. The minima are indicated by the crosses.

A. Comparative study of p-p data at SPS

We start from the analysis of data set A1 and modify it stepwise to find out in which way one matches the conclusion of larger temperature in p-p than in central A-A collisions at SPS, as indicated in Ref. [6]. All numerical values of model parameters are listed in Table IV. A detailed discussion on their choice and correlations is presented in the appendix, based on the χ^2/n systematics.

The fit to data set A1 in the SC model complies with our previous analysis from Ref. [11] [see also Fig. 2(a)]. The SC model fit to these data does not change when including Λ^* hyperons, resulting in the same values of thermal parameters and their errors, as summarized in Table IV.

The most striking effect on thermal parameters is expected when replacing the kaon yields in set A1 [Fig. 3(a)] by those from Ref. [17], set A4 [Fig. 2(b)]. Indeed, smaller kaon yields cause an increase of temperature and a decrease of γ_S. These changes come along with a reduced volume and, in the case of the SC fit, with an increase of the baryon chemical potential. The kaons from Ref. [17] dominate the fit because their errors are 10%, while the uncertainties of the K^+ and K^- yields, taken from Ref. [16], are 21% and 31%, respectively. Consequently, the smaller errors dominate the statistical model fit.

In the next step, we add Λ^*, Ξ, and Ω hyperons, resulting in set A2 [see Fig. 3(b)]. The measured hyperon multiplicities coincide with the model results obtained before, thus within errors the statistical model parameters remain unchanged. We focus on set A3 and add the ϕ meson [Fig. 3(c)]. In this case, the temperature is indeed much higher. In the SC model, the thermal parameters obtained from sets A3 and B3 appear to be meaningless and unphysical because of the ϕ meson contribution.

Additionally to different kaon data in sets A and B, there are also slightly different values for pions and Λ yields (see Table I). Compared to results obtained from data set A4, in the fit of set B1, the higher pion yield reduces the strange to nonstrange particle ratios, resulting in a slightly smaller value of γ_S. The fit obtained with set B4 yields similar results as that obtained from set B1, indicating that the Λ^* resonance does not affect the model parameters.

In the C model analysis, sets A1 and A2 tend toward a slightly higher temperature and smaller γ_S than that obtained in the SC analysis. The situation is different for sets A3 and B3, which include the ϕ meson. Here, in the SC model, the temperature is very high, and $\gamma_S \simeq 0.5$. In the C model, the temperature decreases, and γ_S drops below 0.5. We can conclude that in the case in which the ϕ meson is included in the fit, one needs to apply the C analysis to get lower temperatures, however, with very small values of γ_S and a large χ^2/n. For set B3, the numerical results for T and γ_s summarized in Table IV coincide with those obtained in Ref. [6], however, with a larger χ^2/n.[1]

[1]We compare our results to fit B from Ref. [6].

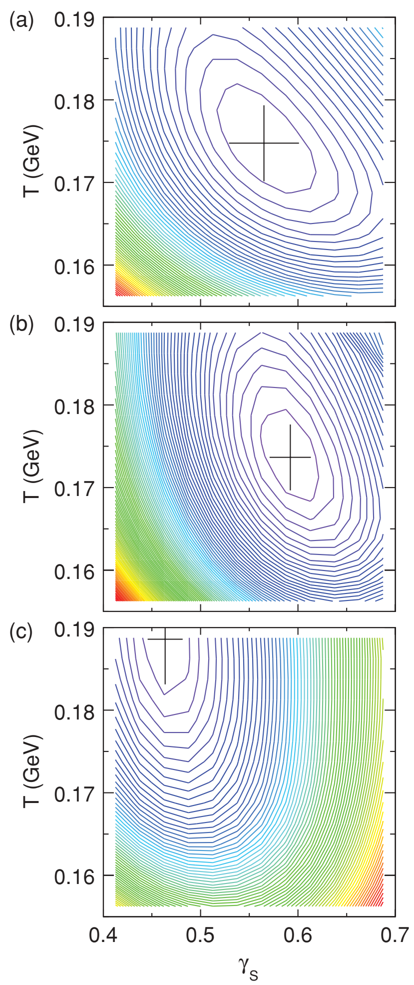

FIG. 3. (Color online) As in Fig. 2, but for data sets (a) A1, (b) A2, and (c) A3. Canonical ensemble.

IV. DISCUSSION AND SUMMARY

The statistical-model analyses of hadron yields for p-p collisions at $\sqrt{s} = 17$ GeV from Refs. [5] and [6] yield different results and lead to different conclusions on the system-size dependence of thermal parameters [5,12]. In this article, we have reanalyzed the p-p data and studied the sensitivity of the thermal fit to data selection and on model assumptions. We have shown that different conclusions from Refs. [5] and [6] are mostly due to differences in data selection.

Slightly different numerical values for charged pions and Λ hyperons used in Refs. [5] and [6] as well as the contribution of the Λ^* resonance altered thermal parameters only within errors. However, the used charged-kaon yields in both approaches differ substantially. We have argued that data of kaon yields in Ref. [6] deviate from trends seen in data at different energies, resulting in a higher chemical freeze-out temperature.

We have shown that higher kaon yields expected from the systematics in the energy dependence in p-p collisions are in line with data on multistrange baryons. Unlike the hyperons, when adding the ϕ meson, the thermal model fit leaves a reasonable range of parameters, resulting in a very high temperature exceeding 190 MeV and large χ^2/n. Therefore it is not possible to describe the full data set (i.e., including the ϕ meson and the hyperons) simultaneously. We have quantified the modifications of these results when including an exact conservation of all quantum numbers in the C statistical model. We have shown that in the absence of the ϕ meson, the thermal fits are rather weakly influenced by canonical effects because of an exact conservation of the baryon number and an electric charge, leading, in some cases, to a systematic increase of the freeze-out temperature. Fits including the ϕ meson are sensitive to an exact conservation of all quantum numbers, resulting in lower temperatures. However, the thermal-model analysis of data sets with hidden strangeness has the largest χ^2/n, indicating that this particle cannot be addressed properly in this model.

On the basis of particle ratios following the overall trend observed as a function of incident momentum, the extracted chemical freeze-out temperature in p-p collisions at SPS is in agreement with the one obtained for central Pb-Pb collisions. Including the ϕ meson in the analysis, which is not easily describable within the statistical model, causes a small γ_s and, consequently, a higher temperature and, also, a large χ^2 value.

ACKNOWLEDGMENTS

K.R. acknowledges stimulating discussions with P. Braun-Munzinger and the support of DFG, the Polish Ministry of Science MEN, and the Alexander von Humboldt Foundation. The financial support of the BMBF, the DFG-NRF, and the South Africa-Poland scientific collaborations is also gratefully acknowledged.

APPENDIX: THE χ^2 CONTOURS OF THERMAL FITS

In this appendix, we quantify the choice of thermal parameters within the statistical model through χ^2 contours in the parameter space. Because the chemical freeze-out temperature T and γ_S are of particular interest here, the quality of the fits is shown in Figs. 2 and 3 in the $(T-\gamma_S)$ plane. In these figures, for a fixed (T, γ_S) pair, the remaining model parameters were fitted, and the corresponding χ^2 was calculated.

Figure 2(a) shows the analysis of the data set A1 within the SC model. The analysis in the model with canonical treatment of all conserved charges (C model) is shown in Fig. 3 for all data sets besides set A4, which is presented in Fig. 2(b).

In the C model description of data set A1, there is a large region of a very low χ^2, which manifests the expected anticorrelation of T and γ_S. Reasonable fits are possible over a large range of parameters. For the set A2, the minimum is located at the same temperature and a slightly higher γ_S. The contributions of Ξ and Ω baryons disfavor small values of γ_S.

The ϕ meson, as seen in Fig. 3, directs fits toward very high chemical decoupling temperatures and very strong strangeness suppression. Also, the pattern of $(T$-$\gamma_S)$ anticorrelations shows decreasing χ^2 with increasing temperature at fixed γ_S.

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