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Prospects for Strangeness Production in $p - p$ Collisions at LHC

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Abstract.

Prospects for strangeness production in $p - p$ collisions at the Large Hadron Collider (LHC) are discussed within the statistical model. Firstly, the system size and the energy dependence of the model parameters are extracted from existing data and extrapolated to LHC energy. Particular attention is paid to demonstrate that the chemical decoupling temperature is independent of the system size. In the energy regime investigated so far, strangeness production in $p - p$ interactions is strongly influenced by the canonical suppression effects. At LHC energies, this influence might be reduced. Particle ratios with particular sensitivity to canonical effects are indicated.

Secondly, the relation between the strangeness production and the charged-particle multiplicity in $p - p$ interactions is investigated. In this context the multiplicity dependence studied at Tevatron is of particular interest. There, the trend in relative strangeness production known from centrality dependent heavy-ion collisions is not seen in multiplicity selected $p - p$ interactions. However, the conclusion from the Tevatron measurements is based on rather limited data samples with low statistics and number of observables. We argue, that there is an absolute need at LHC to measure strangeness production in events with different multiplicities to possibly disentangle relations and differences between particle production in $p - p$ and heavy-ion collisions.

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Keywords: Statistical model, Strangeness undersaturation, Particle production

1. Introduction

For more than half a century the statistical model has been used to describe particle production in high-energy collisions [1]. In the past 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 have been described in a very systematic and appealing way unmatched by any other model [2]. The statistical model has also provided a very useful framework for the centrality and system-size dependence of particle production [3, 4]. The applicability of the model in small systems like $p - p$ and $e^+ - e^-$ annihilation has been the subject of several recent publications [5, 6]. In the following, we present predictions of the statistical model for particle productions at the LHC energy. Any deviation of data from our predictions allows to disentangle a new physics phenomena in high energy $p - p$ collisions.

The thermal parameters of central heavy-ion collisions, given by the temperature T and the baryon chemical potential μ_B , appear to fall on a common chemical freeze-out curve in the $T-\mu_B$ plane. This observation allows to extrapolate the model parameters to the LHC energy regime and to predict particle ratios in heavy-ion collisions. To verify the validity of this method for $p - p$ interactions we investigate the system-size dependence of the model parameters. In Section 2 we focus on differences emerging in the chemical freeze-out temperatures in Refs. [3] and [4] as recently studied in Ref. [7].

The canonical suppression of the strange particle phase-space in $p - p$ collisions was found to be essential to quantify the SPS and RHIC data. Its evolution to LHC energy is necessary to correctly describe the strangeness sector. The energy dependence of the canonical effect is discussed in detail in Section 3. Here, we propose to distinguish between early and late strangeness production from experimental data based on the strength of the canonical suppression.

As a first step towards higher collision energies, we consider Tevatron data in Section 4. We argue that, the strangeness production and in particular its multiplicity dependence might suggest that the production is established at an early stage. However, as we discuss in the Outlook, this observation is based on a rather weak ground and only experiments at LHC energies might provide definite conclusions.

2. System size and centrality dependence

The trends of temperature and baryon chemical potential when varying the number of participating nucleons from central heavy ion to $p - p$ collisions were studied at SPS [3, 4] and RHIC [8]. The same value of μ_B is found in phase-space integrated data, while mid-rapidity data show a decreasing number of net baryons as the multiplicity decreases. This, together with smaller μ_B at higher energy, can be explained by weaker stopping due to higher transparency. On the other hand, the chemical freeze-out temperature was found to be multiplicity-independent at RHIC and also in our analysis at SPS [3]. These results are in contrast with findings from Ref. [4] where the temperature was

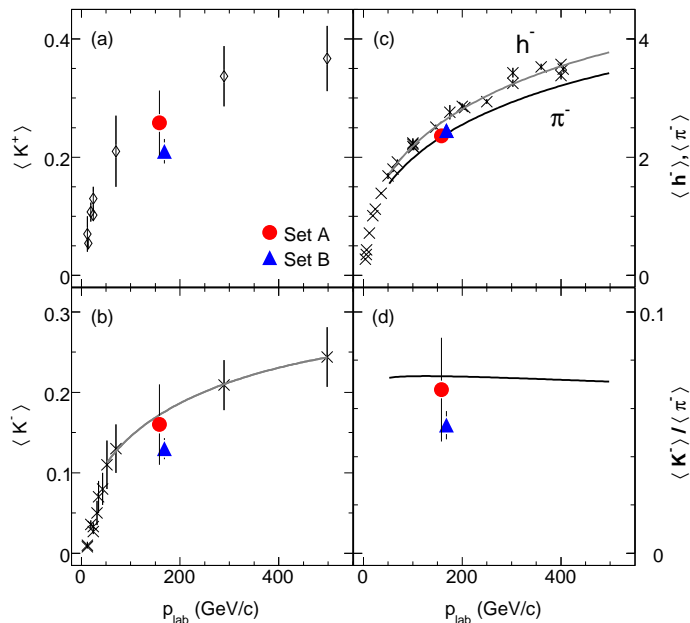


Figure 1. Charged kaon yields (left panels), negatively charged hadron h^- and pions π^- (c), and K^-/π^- ratios (d) in $p - p$ collisions as a function of laboratory momentum. The charged kaon yields, K^+ (diamonds) and K^- (crosses), are from Ref. [12]. The lines are fits to data. The SPS yields from Ref. [10] (circle) and from Ref. [11] (triangle) are also shown. The negatively charged hadrons are from Ref. [13].

shown to be higher in smaller systems. Such behavior has dramatic consequences, e.g., it indicates that one can probe in $p - p$ interactions QCD matter beyond the freeze-out line established in heavy-ion collisions [9]. Below we discuss what is the origin of such different predictions.

The largest difference in extracted model parameters from Refs. [3] and [4] appears in $p - p$ collisions. The main reason is that the above analyses are based on different data sets and in some cases also on different numerical values for particle yields. The largest differences are observed in the charged kaon yields as illustrated in Fig. 1. Some data appear below the line which has been obtained from an interpolation between different lab momenta. The use of those data in the statistical model fit imply a stronger suppression of the strange-particle phase-space (smaller γ_S). This has to be compensated by higher T in order to describe various strange-particle yields like e.g. hyperons and K_S^0 mesons. This is illustrated in Fig. 2 where the left panel shows the fit to the data set of Ref. [5] while in the right panel the charged kaon yields are replaced by values used in Ref. [4]. The charged kaons in Fig. 2(a) are taken from the parametrisation proposed in Ref. [10]. Figure 3(a) shows that these data are consistent with preliminary data obtained for yields of multi-strange baryons [14].

The analysis in Ref. [4] includes the ϕ meson. Based on measured data we have shown in Ref. [3] that the ϕ meson behaves like particle with strangeness between 1 and 2 in its multiplicity dependence. Therefore, this particle cannot be correctly treated in the statistical-model analysis. When including the ϕ meson in the analysis, we are unable to find a set of parameters that describes all particle yields simultaneously. In addition, the fit results in large χ^2 along with the values of thermal parameters that leave a reasonable range as demonstrated in Fig. 3(b). Only fits that contain the ϕ

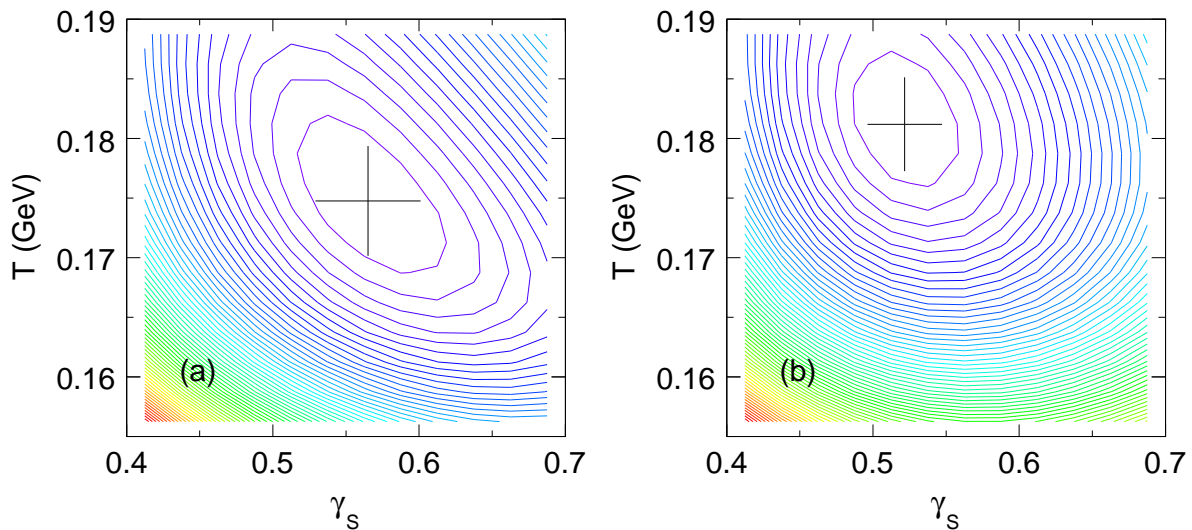


Figure 2. The χ^2 scan in the $(T-\gamma_s)$ -plane. Starting from its minimum, χ^2 increases by 2 for each contour line. Fit to (a) data set of Ref. [5] (data set A1 in [7]) and (b) same data set but charged kaons as used in Ref. [4] (data set A4 in [7]), in the canonical model. The minima are indicated by the crosses.

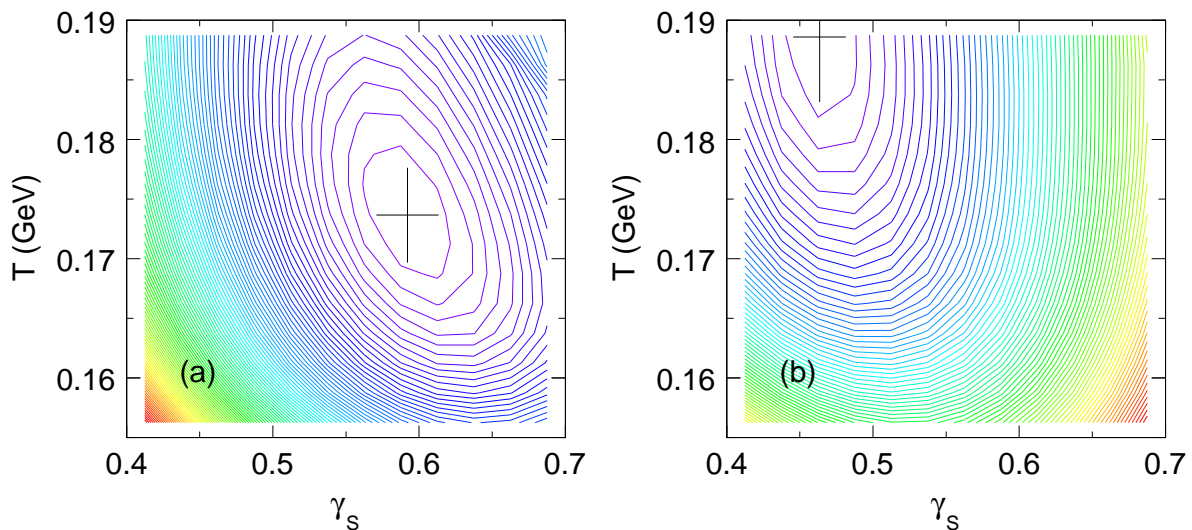


Figure 3. Same data set as in Fig. 2(a) but (a) extended by Ξ and Ω baryons [14] and (b) by the ϕ meson, respectively.

meson result in a very high temperature that exceeds that obtained in central heavy-ion collisions at the corresponding energy.

From the above we conclude, that at a given energy the chemical freeze-out temperature is system-size independent both at RHIC and at the SPS. In addition, the magnitude and the centrality dependence of the ϕ meson is obviously inconsistent with the statistical model systematics. Consequently, including this particle in the fit can lead to misleading conclusions on the model parameters and their qualitative properties.

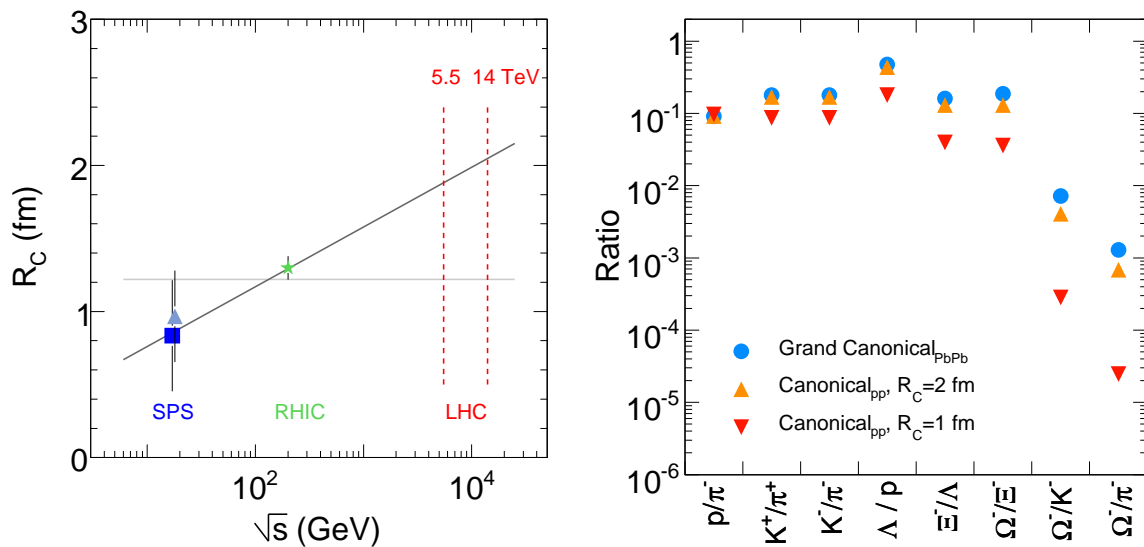


Figure 4. Left panel: The cluster radius R_C as a function of energy, extracted from the analysis of SPS data (triangle, square) and RHIC data (star) [5]. The lines illustrate possible evolutions toward LHC energies as discussed in the text. Right panel: Predictions for various particle ratios using different values of R_C [5].

3. Extrapolation to LHC

Based on the discussion above, we assume that the multiplicity-independence of the temperature found at SPS and RHIC is also valid at LHC. In addition, to extrapolate T and μ_B to $p - p$ interactions at the LHC we use the same parametrisation of their energy dependence as it was found in the systematics of heavy-ion collisions. The baryon chemical potential at midrapidity decreases towards smaller systems, however, at the LHC μ_B is so small that any variation with system size can be neglected.

The canonical suppression is implemented in the following way. Strangeness production is assumed to be correlated inside chemically equilibrated clusters that may be smaller than the fireball. The size of these subvolumes (clusters) quantifies the strength of the canonical suppression. The correlation length R_C extracted from SPS and RHIC data, as illustrated in Fig. 4 left, does not allow to quantify its energy dependence. We consider two extreme scenarios: (i) Small subvolumes independent of the incident energy which can be interpreted as being driven by the initial size of the proton or the range of strong interactions. Thus strangeness production would be determined at an early stage of the reaction. (ii) Subvolumes that increase with energy. In this case the strangeness production in $p - p$ collisions per charged particle would be multiplicity dependent, reflecting a late determination of the strangeness content. In such a scenario, at a given energy, one expects less strangeness suppression in high multiplicity events. Consequently, high-multiplicity events in $p - p$ interactions could appear like heavy-ion collisions in respect to the observed particle ratios.

As seen in Fig. 4 left, our actual knowledge from the SPS and RHIC energies does

not allow for a definite extrapolation of the correlation volume towards the LHC energy. The radius R_C of the canonical correlation volume can appear in the range between 1 and 2 fm. Figure 4 (right) shows the sensitivity of different particle ratios to the value of the correlation radius. From this figure it is clear, that measurements of the Ω/π and Ω/K ratios are best be used to extract the strangeness correlation radius that quantifies canonical suppression effects and the production dynamics of strange particles.

4. Strangeness production at Tevatron

Before LHC results become available, Tevatron data provide already some insight into strangeness production at higher energies. There, mainly kaons and Λ hyperons were measured as strangeness carriers. The kaon and pion yields were found to increase smoothly and similarly with energy. Thus, the K/π ratio seems to saturate with energy [15]. This hints towards saturating correlation length since the temperature is almost unchanged with collision energy beyond the SPS. When studying the multiplicity dependence at fixed energy, we can rule out a possible counterbalance between T and R_C . Indeed, in $p - \bar{p}$ interactions the p/π and K/π ratios were found to be independent of the charged-particle multiplicities. These data indicate, that neither the temperature nor the cluster size exhibits variations with multiplicity. This interpretation is also supported by the multiplicity-dependent Λ/p ratio measured by the E735 and the CDF collaborations [15, 16].

After the above qualitative discussion, we show in Fig. 5 a quantitative comparison of Tevatron data to the statistical model. The measured K/π ratio points to significant canonical suppression. The cluster size is small with none or weak energy dependence when comparing to RHIC and SPS results. This supports the interpretation that strangeness production is determined at an early stage and is quantified by the size of the colliding proton or the range of strong interactions. Consequently, we expect strange/non-strange particle ratios to saturate towards LHC energies with only small variations due to decreasing μ_B . Due to the large errors the Λ/p ratio contributes weakly to constrain the strength of the canonical suppression.

5. Summary and Outlook

We have shown that the statistical model results are indeed very sensitive to the data selection. We have traced back the apparent variation of the chemical freeze-out temperature at SPS to kaon yields that are not in line with earlier measurements at lower and higher beam momenta. We conclude that the chemical freeze-out temperature exhibits no system-size nor multiplicity dependence in the energy range under study. Thus, we confirm a similar observation made at RHIC.

The strangeness correlation length describes the strength of the canonical suppression. Its energy and multiplicity dependence can give insight into the question whether the relative strangeness production is defined at an early or late stage of the

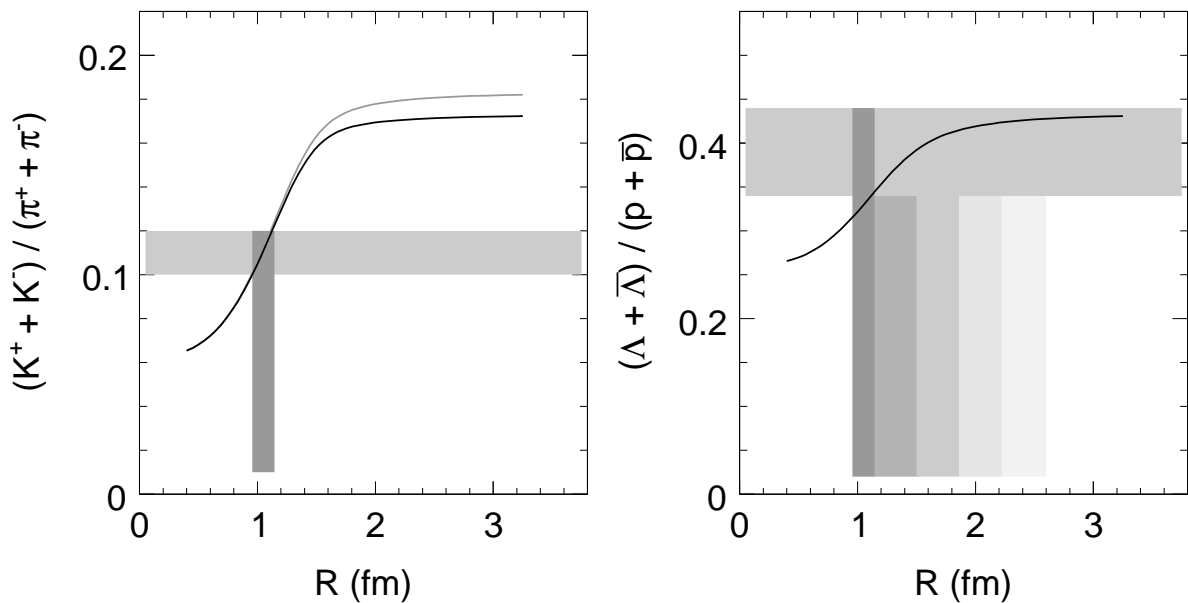


Figure 5. The statistical model results for the K/π (left panel) and the Λ/p (right panel) ratio obtained with the chemical freeze-out parameters expected at Tevatron ($T = 170$ MeV and the initial quantum numbers $B = S = Q = 0$) as a function of the radius R of a spherical volume. Experimental results from Ref. [15] are indicated by horizontal bands. Derived ranges of the correlation length are displayed by vertical bands; for the Λ/p ratio only a lower limit can be extracted (large values that correspond to vanishing canonical suppression are consistent with the Λ/p data, too), the dark vertical band shows the range extracted from the K/π ratio. The gray curve in the left panel indicates the uncertainties due to a mismatch between feed-down corrections in data and model calculations.

reaction. At present, the extrapolation of the correlation length extracted from SPS and RHIC data towards LHC energies is not unique due to rather large uncertainties. The results from the Tevatron point towards small clusters and an early stage of strangeness production. However, this conclusion is based on a rather incomplete and low-statistics data.

To quantify strangeness production and its energy dependence data with much better statistics are needed to reduce errors. Also there is a lack of multi-strange baryons, and the multiplicity dependence of strangeness production at fixed energy in $p - p$ collisions requires more complete data. Further, the E735 and CDF data cover a charged particle densities up to 25 and 35, respectively. This compares to very peripheral heavy-ion interactions, e.g. it corresponds to Cu-Cu collisions at RHIC where the 40% most central events were left out.

At LHC we expect to have soon good statistics of events with a charged-particle density up to 100 or more in $p - p$ interactions corresponding to semi-central Cu-Cu collisions. It is clear that after a long period of successful running with $p - p$ at the LHC we will be able to investigate the similarities between $p - p$ and heavy-ion

interactions. Such comparison requires data with high statistics on many particle species and particularly on multi-strange baryons. We are convinced that the LHC will provide a very deep insight into strangeness production dynamics in $p - p$ and in heavy-ion collisions and it will allow us to verify or strengthen our conclusions drawn from the existing data.

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