Interpretation of particle yields in pp interactions at $\sqrt{s}$ = 8.8, 12.3 and 17.3 GeV within statistical hadronization model

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Abstract. The statistical hadronization model ThermalFist was applied to numerous hadron yields measured in p+p collisions at $\sqrt{s}$ = 8.8, 12.3 and 17.3 GeV, including recently published yields of ϕ-mesons, measured by the NA61/SHINE Collaboration. We consistently used the energy-dependent widths of Breit-Wigner mass distributions of hadronic resonances, as this approach was generally found to provide better agreement with experimental data. The well-established experimental ϕ meson yields are consequently accounted for (although neglecting this particle was found to improve the fit quality). The canonical treatment of particles with open strangeness with the grand canonical approach for non-strange particles gave a moderately reasonable agreement with the measured yields, only when the volume of strange particles was allowed to vary freely. In all the studied cases this volume is found to be greater than the canonical one.

1 Introduction

For over three decades the predictions of the statistical hadronization model have been compared to the yields of hadrons emitted from heavy-ion (AA) collisions, leading to the very successful description of experimental results. A spectacular example is the precise description within the Grand Canonical Ensemble (GCE) of Pb+Pb collisions at the LHC [1], covering 9 orders of magnitude in multiplicity of produced particles. To some surprise, the statistical hadronization model also describes quite well elementary interactions like proton-proton collisions [2, 3]. With much lower particle multiplicities in p+p interactions compared to AA collisions, the conservation of the relevant physical quantities is an issue. In particular, strangeness is found to be rarely produced in the beam energy range from SIS18 up to SPS. Special treatment of strangeness is usually applied via: (i) reduction of yields of hadrons containing (anti-)strange quarks, parameterized by factor γ_S, (ii) different volume occupied by strangeness compared to the non-strange bulk, and (iii) strangeness-canonical approach (SC) combining the canonical treatment of strange hadrons and GCE for the rest of matter.

The recent experimental results by the NA61/SHINE collaboration [4] cover also the production of $K(892)^0$ mesons in p+p collisions at $\sqrt{s}$ = 8.8 and 12.3 GeV and encouraged us to expand the analysis performed at $\sqrt{s}$ = 17.3 GeV, where the volume occupied by strange particles was unexpectedly found to be larger than the bulk volume [3, 5].

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2 Analysis

The proton-proton collisions at $\sqrt{s}$ = 17.3 GeV were studied extensively by the NA49 and NA61/SHINE collaborations at the CERN SPS, providing (now) in total 17 yields of hadrons (up to double-strange Ξ). Several hadrons have been measured by two mentioned experiments and the adopted values are tabulated in [3]. Reasonable description of these yields within the statistical hadronization model was possible with $\gamma_s \sim 0.4$ (in agreement with the systematics [6]) and the volume occupied by strange particles was found larger than that of the bulk. This unexpected finding can not be ruled out as femtoscopy of kaon pairs (obtained at higher energies ($\sqrt{s} \in [27.4 - 900]$ GeV)) does not provide sufficient resolution. New yields of strange particles are available now from p+p collisions at $\sqrt{s}$ = 8.8 and 12.3 GeV, allowing to extend our initial observation towards lower energies. The hadron yields available for the statistical hadronization model calculations (see Table 1) show two distinct features of the measurements at $\sqrt{s}$ = 17.3 GeV: (i) the number of measured species is above that at RHIC energy of 200 GeV, and (ii) only here the neutron multiplicity is available, so the initial baryon number B = 2 is reconstructed as B = 1.92±0.11 [3]. One may expect that not yet available yields would be provided by the NA61/SHINE experiment, particularly the Λ baryon at lower beam energies.

Table 1. Summary of experimentally measured total particle yields in pp collisions. The lines separate the following particles: (i) light non-strange mesons, (ii) non-strange baryons (iii) hidden strangeness meson, (iv) open strangeness mesons, (v) $|S|$=1 baryons, (vi) $|S|$=2 baryons, (vii) $|S|$=3 baryons. The results are denoted: □=NA49, ■=NA61/SHINE, □ ⊕ ■=merged NA49 and NA61/SHINE ([3] and references therein), ★=STAR [7] (except π^0, which was measured by PHENIX [8]). Red color denotes recent experimental results

experiment	NA61				NA49&NA61	STAR
$\sqrt{s}$ (GeV)	6.3	7.7	8.8	12.3	17.3	200
π^0						▶◀
π^+	■	■	■	■	□ ⊕ ■	★
π^-	■	■	■	■	□ ⊕ ■	★
p	■	■	■	■	□ ⊕ ■	★
$\bar{p}$	■	■	■	■	□ ⊕ ■	★
n					□	
ϕ			■	■	□ ⊕ ■	★
K^0_S			■	■	■ (red)	
K^+	■	■	■	■	□ ⊕ ■	★
K^-	■	■	■	■	□ ⊕ ■	★
$K(892)^0$			■ (red)	■ (red)	□ ⊕ ■	
$\overline{K(892)}^0$					□	
Λ					■	★
$\bar{\Lambda}$						★
Λ(1520)					□	
Ξ^-					■	★
Ξ^+					■	★
$\Xi(1530)^0$					■	
$\overline{\Xi(1530)}^0$					■	
Ω						★
$\overline{\Omega}$						★

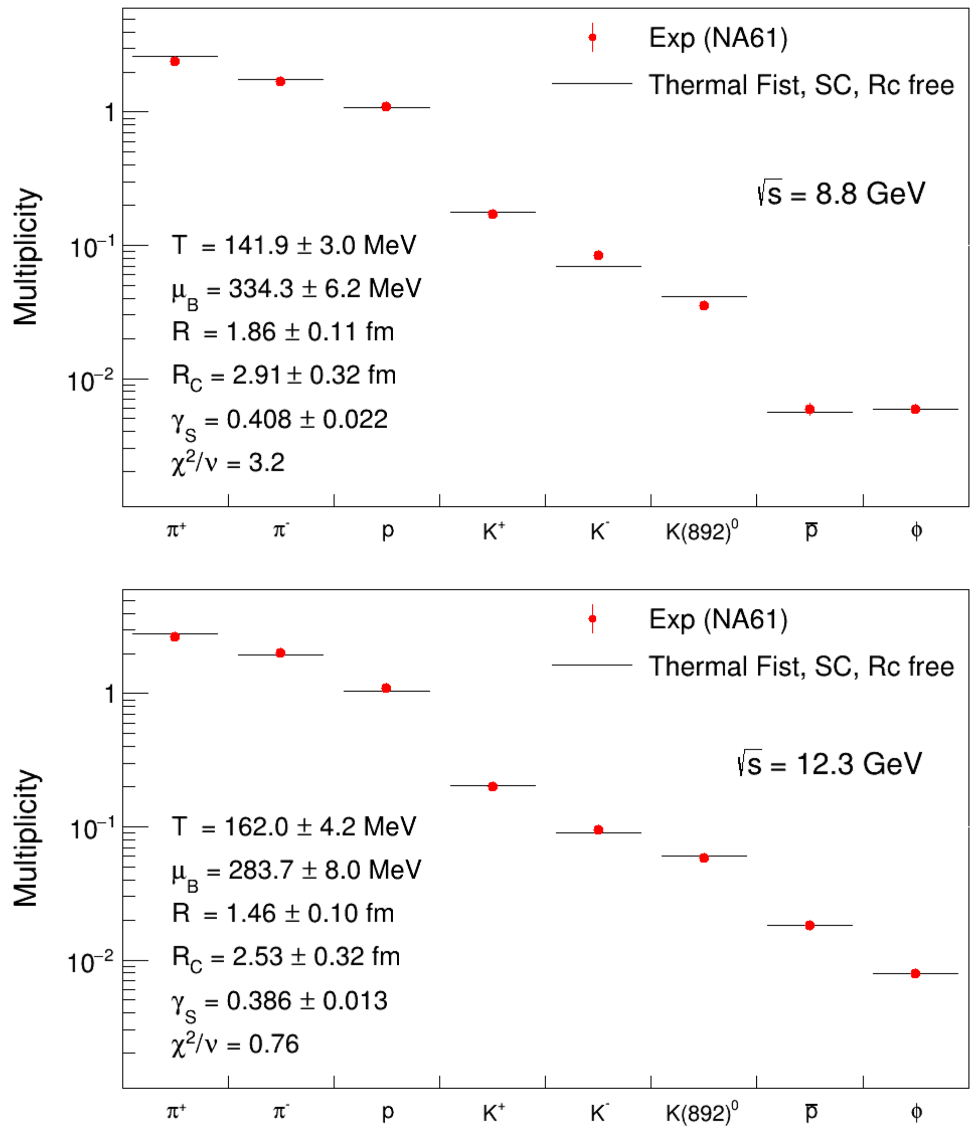

Figure 1. Results of statistical hadronization model fit (lines) to the experimental yields (full dots) of hadrons from p+p at $\sqrt{s} = 8.8$ GeV (upper panel) and 12.3 GeV (lower panel).

For the analysis we used the Thermal-FIST code [9] in the SC version, i.e the canonical treatment of hadrons with open strangeness and grand canonical for the rest of matter. We consequently include the yield of the ϕ-meson to the sample. The list of particles also included the light nuclei up to ^{4}He and their respective hypernuclei, but without charmed hadrons (negligible influence). We use the energy-dependent widths of Breit-Wigner distributions of masses of hadronic resonances which seems to be a more correct description of the mass distributions of hadronic resonances. The volumes are represented in terms of effective radii of spheres (R_C for the strangeness, and R for non-strange matter), which are both free parameters as well as the γ_S undersaturation factor. The resulting particle yields are well described by this version of the model, while the agreement without making R_c free is unsatisfactory. The parameters of the model are listed in Table 2.

Table 2. Values of best fits of SC statistical model to the experimental yields of hadrons from p+p collision at 3 collision energies (see text for details).

$\sqrt{s}$ (GeV)	T (MeV)	μ_B (MeV)	γ_S	R (fm)	R_C (fm)	χ^2/NDF
8.8	141.9±3.0	334.3±6.2	0.408±0.022	1.86±0.11	2.91±0.32	3.2
12.3	162.0±4.2	283.7±8.0	0.386±0.013	1.46±0.10	2.53±0.32	0.76
17.3	173.6±2.7	245.3±3.9	0.418±0.010	1.35±0.06	1.70±0.09	3.4

As in the case of the analysis of 17.3 GeV data [5], the volume of strange particles is found to be greater than of the bulk, and this difference seems to grow (although the accuracy is reduced). The comparison of measured and calculated multiplicities at $\sqrt{s}$ = 8.8 GeV and 12.3 GeV (Figure 1) shows good agreement also for the ϕ meson. Recently, much better agreement of statistical hadronization model with ALICE data was observed thanks to larger value of V_C than the canonical volume V_A [10]. Therefore, it seems that the size of strangeness canonical volume deserves more attention in statistical model calculations.

3 Summary and conclusions

The experimental particle yields in p+p collisions at $\sqrt{s}$ = 8.8 and 12.3 GeV, recently extended by the NA61/SHINE collaboration to include strange $K(892)^0$ mesons, were quite satisfactorily described within the Thermal-Fist hadron resonance gas model treating strange particles according to the canonical ensemble. This description was obtained only when the strangeness canonical volume was allowed to vary freely. As in $\sqrt{s}$ = 17.3 GeV case, this volume is found to be greater than that of the bulk. This effect is not excluded by femtoscopic analysis, because of lacking precision, and is considered also in recent model calculations of nucleus-nucleus collisions at LHC energies.

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