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# Energy Dependence of Identified Hadron Fluctuations in p + p Interactions from NA61/SHINE

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The study of energy and system size dependence of fluctuations of identified hadrons is one of the key goals of NA61/SHINE at the CERN SPS. Results may allow to discover the critical point (CP) of strongly interacting matter as well as to uncover properties of the onset of deconfinement (OD). Measured fluctuations are affected by numerous other effects like volume fluctuations and conservation laws. NA49 seems to observe fluctuations possibly related to the CP in collisions of medium size nuclei at the top SPS energy. However, this result will remain inconclusive until systematic data on energy and system size dependence will be available. Moreover, fluctuations in p+p as well as in Pb+Pb interactions should be better understood. In this contribution new results on multiplicity fluctuations of identified hadrons in p+p interactions at the CERN SPS energies will be presented. The NA61 data will be compared with the corresponding results on central Pb+Pb collisions of NA49 in the common acceptance region of both experiments. Furthermore, predictions of models (EPOS, UrQMD and HSD) for p+p interactions will be tested.

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## 1. Introduction

The NA61/SHINE experiment [1] studies an important region of the phase diagram of strongly interacting matter. First, the Statistical Model of the Early Stage (SMES) of nucleus-nucleus collisions [2] predicted the energy threshold for deconfinement at the low SPS energies. Several structures in the excitation functions were expected within the SMES: a kink in the pion yield per participant nucleon, a sharp peak (horn) in the strangeness to entropy ratio, and a step in the inverse slope parameter of transverse mass spectra. Such signatures were observed in central Pb+Pb collisions by the NA49 experiment around $\sqrt{s_{NN}} = 7.6$ GeV [3]. Fluctuation analysis may provide additional evidence of the onset of deconfinement. Second, lattice QCD calculations suggest a critical point of strongly interacting matter which may be observable in the SPS energy range [4]. Fluctuations and correlations are basic tools to study this phenomenon. We expect enlarged fluctuations close to the critical point. In nucleus-nucleus collisions a maximum of fluctuations is expected when freeze-out happens near the CP.

## 2. NA61/SHINE identified hadron fluctuation studies

Multiplicity and chemical fluctuations of identified hadrons were measured in inelastic p+p interactions within the NA61/SHINE acceptance [5]. Obtained results are based on p+p interactions gathered in 2009 by NA61/SHINE at $\sqrt{s_{NN}} = 7.6,\ 8.7,\ 12.3,\ 17.3$ GeV. Fluctuations of charged pions ($\pi = \pi^+ + \pi^-$), kaons ($K = K^+ + K^-$) and protons + antiprotons as well as of positively charged hadrons were studied via first and second (pure and mixed) moments of identified particle multiplicity distributions. Second moments of identified hadron multiplicity distributions were obtained using the identity method [6, 7, 8] which allows to unfold the effect of imperfect identification. Particle identification is based on energy loss measurements in the relativistic rise region [9, 10]. Presented results include the statistical uncertainty and a first estimate of systematic uncertainty (still under studies are detector effects and influence of feed down).

Two quantities, the scaled variance $\omega_i$ of the multiplicity distribution and the two-particle measure $\Phi_{ij}$ [11, 13, 12], were chosen for the identified hadron fluctuation analysis. The scaled variance is defined as:

$$\omega_i = \frac{< N_i^2 > - < N_i >^2}{< N_i >}, \tag{2.1}$$

where $< N_i >$ and $< N_i^2 >$ are the mean multiplicity and the second moment of the multiplicity distribution of particles of type $i$, respectively. The scaled variance is an intensive measure [12], i.e. it is independent of the number of wounded nucleons in the Wounded Nucleon Model [14] or volume in the Grand Canonical Ensemble, but it depends on their fluctuations. The latter feature makes it difficult to compare results from p+p interactions with those from nucleus+nucleus collisions. For the Poisson distribution $\omega_i = 1$. Figure 1 shows the scaled variance of $\pi$, $K$ and $p+\bar{p}$ (left panel) as well as $\pi^+$, $K^+$ and $p$ (right panel) as a function of collision energy. The scaled variance for particles of both charges increases with collision energy for all considered particle types. The trend as well as the magnitude of the effect is well reproduced by the EPOS [15, 16], UrQMD [17, 18] and HSD [19, 20, 21, 22] models. Rich data on the charged particle multiplicity distribution in full phase space obey KNO scaling [23, 24]. From this scaling follows a linear increase of the scaled variance with mean multiplicity of charged particles visible as an increase of $\omega_\pi$ with collision energy (see bottom left panel of Fig. 1). The scaled variance of unidentified charged hadrons measured within the acceptance chosen for this analysis is shown in the same panel by purple diamonds. The increase with collision energy is weaker than that measured in full phase space, but



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agreement between $\omega_{N_{ch}}$ and $\omega_{\pi}$ indicates that KNO scaling may also apply to pion production. $\omega_{\pi^+}$ is approximately independent of energy and, moreover, it is below one. Such suppression

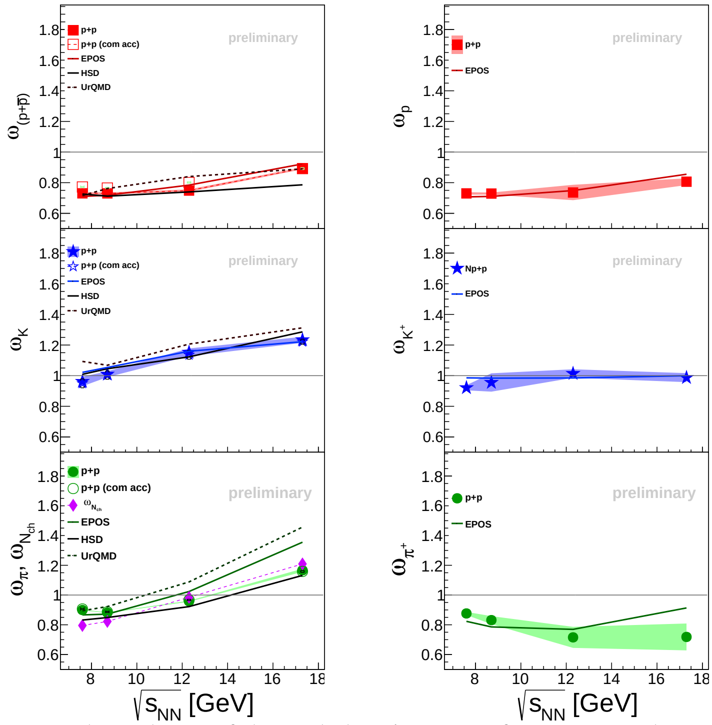


**Figure 1:** Left: Energy dependence of the scaled variance $\omega$ of $p+\bar{p}$, $K$ and $\pi$ multplicity distributions. Full symbols denote fluctuation results within the NA61 acceptance. Open symbols denote results within the common phase space region of NA61 and NA49. Model predictions are presented for the NA61/SHINE acceptance. Right: Energy dependence of $\omega_p$, $\omega_{K^+}$ and $\omega_{\pi^+}$.

is probably due to charge conservation [25]. Values of $\omega_K$ for all energies are close to or above one. This may be caused by strangeness conservation which leads to a correlation between the production of $K^+$ and $K^-$ mesons [13]. Again the effect is weakened by the limited acceptance. This interpretation is supported by the fact that $\omega_{K^+} < \omega_K$. For protons $\omega_p$ remains below one most likely due to baryon number conservation which seems to suppress proton multiplicity fluctuations. This is because the proton multiplicity is mostly given by the two initial protons as production of proton-antiproton pairs is strongly suppressed by their large masses.

In order to compare results for p+p and central Pb+Pb collisions, the strongly intensive measure $\Phi_{ij}$ defined for two hadron types, $i$ and $j$, was chosen. It is defined as:

$$\Phi_{ij} = \frac{\sqrt{<N_i><N_j>}}{<N_i+N_j>}[\sqrt{\Sigma^{ij}}-1] \,, \tag{2.2}$$

where $\Sigma^{ij} = [<N_i>\omega_j + <N_j>\omega_i - 2\cdot(<N_{ij}> - <N_i><N_j>)]/<N_i+N_j>$ [12]. As a strongly intensive measure, $\Phi_{ij}$ is not only independent of number of wounded nucleons or volume but also of their fluctuations. Figure 2 shows the energy dependence of $\Phi_{ij}$ for combinations of two hadron types: $\pi(p+\bar{p})$, $\pi K$ and $(p+\bar{p})K$ as well as for combinations of positively charged particles. Full symbols refer to the NA61 repsectively NA49 acceptance. Open symbols display results for the common phase-space region of NA49 and NA61. Differences between the individual

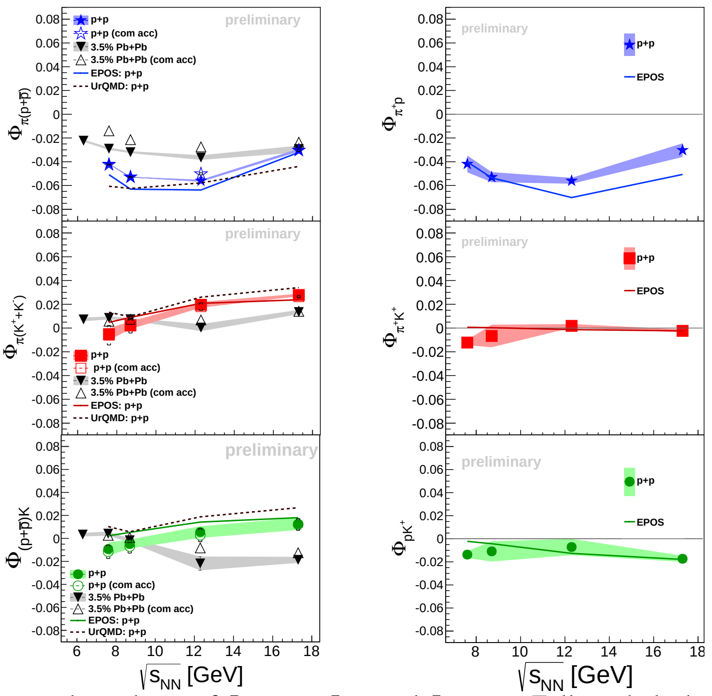


**Figure 2:** Left: Energy dependence of $\Phi_{(p+\bar{p})\pi}$, $\Phi_{\pi K}$ and $\Phi_{(p+\bar{p})K}$. Full symbols denote fluctuation results within the NA61 acceptance. Open symbols denote results within the common phase space region of NA61 and NA49. Right: Energy dependence of $\Phi_{p\pi^+}$, $\Phi_{\pi^+K^+}$ and $\Phi_{pK^+}$.

and common acceptance are small. When no inter-particle correlations are present $\Phi_{ij} = 0$. For $\pi K$ and $(p+\bar{p})K$ the value of $\Phi_{ij}$ increases with increasing energy. This increase if probably connected with associated production of $K^+$ and $K^-$ which is supported by the observation that $\Phi_{\pi^+K^+}$ and $\Phi_{pK^+}$ equal to 0. For $\pi(p+\bar{p})$ there is a minimum between 7.6 and 8.7 GeV. A similar but weaker effect is visible in Pb+Pb interactions. It also appears in the EPOS model. The energy dependence is similar for $\pi(p+\bar{p})$ and $\Phi_{\pi^+p}$. The increase of $\pi K$ for p+p interactions is not observed in Pb+Pb collisions. $\Phi_{pK}$ shows different behavior for p+p, where it increases, than in Pb+Pb where it decreases with increasing energy. $\Phi_{pK}$ crosses zero at similar energy $\sqrt{s_{NN}} \approx 8.7$ GeV for both systems.

## 3. Conclusion

The NA61/SHINE experiment successfully started the planned 2D energy-system size scan with p+p interactions. The results are needed as reference for the study of the onset of deconfinement and the search for the critical point. Multiplicity fluctuations of identified $\pi$, K and protons + antiprotons were measured in inelastic p+p interactions using the novel identity method. Results are well described by the EPOS, UrQMD and HSD models. Conservation laws seem to play an important role in fluctuations of hadron multiplicities. Comparison with data on central Pb+Pb collisions obtained by NA49 using the same procedure shows differences between p+p and Pb+Pb reactions which are most pronounced for $(p+\bar{p})K$ fluctuations (opposite energy dependence). Quantitative evaluation of the significance of the differences requires determination of final systematic uncertainties.

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