

Self-similarity of strangeness production in pp collisions at RHIC

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Abstract. New experimental data on transverse momentum spectra of strange particles ($K_S^0, K^-, K^*, \phi, \dots$) produced in pp collisions at $\sqrt{s} = 200$ GeV obtained by the STAR and PHENIX collaborations at RHIC are analysed in the framework of z -scaling approach. Scaling properties of the data z -presentation are illustrated. Self-similarity of strange particle production is discussed. A microscopic scenario of constituent interactions developed within the z -scaling approach is used to study constituent energy loss, proton momentum fraction and recoil mass in dependence on the transverse momentum, strangeness, and mass of the inclusive particle. The obtained results can be useful for understanding strangeness origin, for searching for new physics with strange probes and can serve as a benchmark for complex analyses of self-similar features of strange production in heavy ion collisions.

1. Introduction

The production of particles with high transverse momenta from the collisions of hadrons and nuclei at high energies has relevance to constituent interactions at small scales. One of the leading principles governing these interactions is self-similarity. This principle reflects hadron structure at different scales, interaction of hadron constituents and processes of fragmentation into colorless particles. Strange particles as well as other probes (direct photons, jets, lepton pairs) play an important role to study fundamental features of the produced matter in hadron and nuclear interactions and provide information about its transition into observed particles.

The scaling behavior of particle production related to self-similarity of hadron interactions at constituent level is manifested by the z -scaling [1, 2]. The concept of this scaling was used for analysis of inclusive spectra obtained at the accelerators U70, SppS, SPS, ISR, Tevatron and RHIC [3]-[9]. The experimental spectra reveal striking similarity over a wide range of kinematic variables when expressed by the variable z . The z -scaling is treated as a manifestation of the self-similarity of the structure of the colliding objects, interaction mechanism of their constituents, and processes of fragmentation into real hadrons. The approach can be a suitable tool to search for phase transitions and the critical point in hadron and nuclear matter. The parameters of the z -scaling, c, δ and ϵ , have physical interpretation as the heat capacity of the produced matter, the fractal dimension of the structure of hadrons or nuclei and the fractal dimension of the fragmentation process, respectively. Universality of the scaling is given by its flavour



independence. It means that spectra of particles with different flavour content can be described by a universal function $\Psi(z)$ when using the scale transformation $z \rightarrow \alpha_F z$, $\Psi \rightarrow \alpha_F^{-1} \Psi$.

In this contribution we illustrate properties of the z -presentation of the transverse momentum distributions of strange particles produced in pp collisions. We present results of new analysis of data on inclusive cross sections obtained by the STAR and PHENIX collaborations at RHIC. The dependence of the momentum fractions and recoil mass on the collision energy, transverse momentum and mass of the inclusive particle is used to estimate the constituent energy loss.

2. z -Scaling

The z -scaling has been suggested to express general regularities found in the inclusive hadron production in high energy proton-(anti)proton and nucleus-nucleus collisions. It manifests itself in the fact that the inclusive spectra of various types of particles can be described with a universal scaling function. The function $\Psi(z)$ depends on a single variable z in a wide range of the transverse momentum, registration angles, collision energies and centralities. The scaling variable is expressed by the formula:

$$z = z_0 \cdot \Omega^{-1}. \quad (1)$$

Here z_0 and Ω are functions of kinematic variables:

$$z_0 = \frac{\sqrt{s_\perp}}{(dN_{ch}/d\eta|_0)^c m_N} \quad (2)$$

$$\Omega = (1 - x_1)^{\delta_1} (1 - x_2)^{\delta_2} (1 - y_a)^{\epsilon_a} (1 - y_b)^{\epsilon_b}. \quad (3)$$

The variable z is proportional to the transverse kinetic energy of the selected binary constituent sub-process required for production of the inclusive particle with mass m and its partner (antiparticle). The multiplicity density $dN_{ch}/d\eta|_0$ of charged particles in the central region, the nucleon mass m_N and the parameter c completely determine the dimensionless quantity z_0 . The parameter c has meaning of the "specific heat" of the medium produced in the collisions.

The quantity Ω is proportional to the relative number of the constituent configurations which include the binary sub-processes corresponding to the momentum fractions x_1 and x_2 of colliding hadrons (nuclei) and to the momentum fractions y_a and y_b of the secondary objects produced in these sub-processes. The parameters δ_1 and δ_2 are fractal dimensions of the colliding objects, and ϵ_a and ϵ_b stand for the fractal dimensions of the fragmentation process in the scattered and recoil direction, respectively. For unpolarized processes we assume the later to have the same value $\epsilon_a = \epsilon_b = \epsilon_F$ which depends on the type of the inclusive particle. The selected binary sub-process, which results in production of the inclusive particle and its recoil partner (antiparticle), is defined by the maximum of $\Omega(x_1, x_2, y_a, y_b)$ with the kinematic constraint

$$(x_1 P_1 + x_2 P_2 - p/y_a)^2 = M_X^2. \quad (4)$$

Here $M_X = x_1 M_1 + x_2 M_2 + m/y_b$ is the mass of the recoil system in the sub-process. The 4-momenta of the colliding objects and the inclusive particle are P_1, P_2 and p , respectively. The microscopic scenario of constituent interactions developed in the framework of z -scaling is based on dependencies of the momentum fractions on the collision energy, transverse momentum and centrality. The scaling variable z has property of a fractal measure. It grows in a power-like manner with the increasing resolution Ω^{-1} defined with respect to the constituent sub-processes which satisfy (4). The scaling function $\Psi(z)$ is expressed in terms of the inclusive cross section $Ed^3\sigma/dp^3$, multiplicity density $dN/d\eta$, and total inelastic cross section σ_{in} . All these quantities are measurable for the inclusive reaction $P_1 + P_2 \rightarrow p + X$. The function $\Psi(z)$ is determined by the expression:

$$\Psi(z) = -\frac{\pi}{(dN/d\eta)\sigma_{in}} J^{-1} E \frac{d^3\sigma}{dp^3}. \quad (5)$$

Here J is Jacobian of the transformation from the variables $\{p_T^2, y\}$ to $\{z, \eta\}$. The function $\Psi(z)$ is normalized as follows:

$$\int_0^\infty \Psi(z) dz = 1. \quad (6)$$

Equation (6) allows us to interpret $\Psi(z)$ as probability density of the production of the inclusive particle with the corresponding value of the variable z .

3. Scaling properties of strangeness production

The self-similarity of production of different hadron species in pp collisions provides the basis for analysing scaling properties of the hadron spectra for more complicated systems. The hadrons with strange quarks constitute a special interest as they are the lightest particles with quantum numbers which are absent in the net amount in the initial state.

Figure 1(a) shows z -presentation of the transverse momentum spectra of strange mesons and baryons measured in pp collisions in the central rapidity region at RHIC. The symbols representing data on differential cross sections include baryons which consist of one, two and three strange valence quarks. The open circles and diamonds correspond to the respective spectra of K_s^0 and K^- mesons measured by the STAR collaboration [10, 11]. The data on the neutral short-lived $K^*(892)$ resonance obtained by the STAR [12] and PHENIX [13] collaborations are depicted by the triangles down and triangles up, respectively. The open squares correspond to the PHENIX data on ϕ -meson production [14] detected in the K^+K^- and e^+e^- decay channels. The z -presentation of spectra of strange baryons shown in the figure is based on data collected by the STAR collaboration [10]. The distributions of Λ , Ξ^- and Ω baryons are depicted by stars, black circles and black squares, respectively. The spectra of strange baryon resonances $\Sigma^*(1385)$ (full triangles up) and $\Lambda^*(1520)$ (full triangles down) were taken from [15].

The solid line represents the scaling curve obtained from analysis of pion production in $pp/\bar{p}p$ collisions ($\epsilon_\pi = 0.2$, $\alpha_\pi = 1$) over a wide range of kinematic variables. The curve is consistent with the energy, angular and multiplicity independence of the scaling function for different hadrons. One can see that the corresponding fragmentation dimension ϵ_F for strange mesons is larger than for pions, suggesting larger energy loss by production of mesons with strangeness content. The fragmentation dimension for strange baryons grows with the number of the strange valence quarks. This is connected with the increase of energy losses.

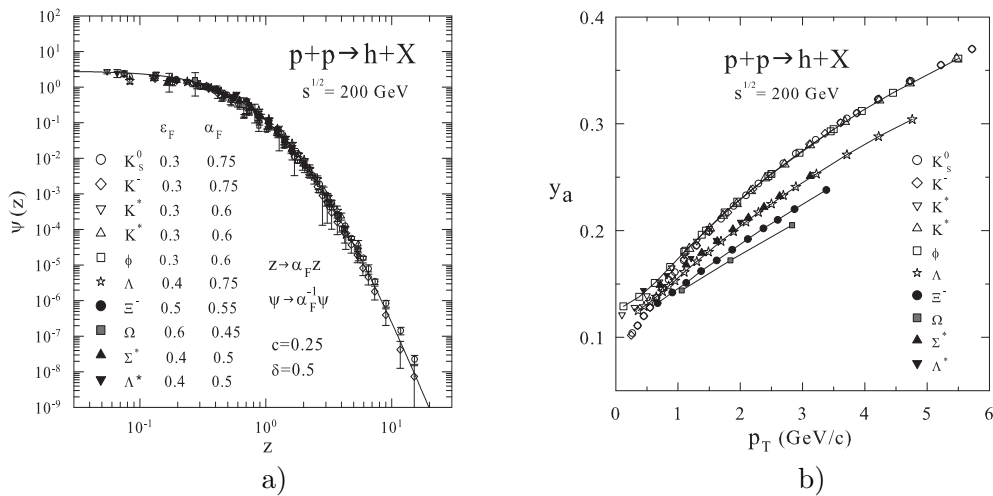


Figure 1. (a) Inclusive transverse momentum spectra of strange particle production in pp collisions in z -presentation. (b) Relative energy loss $\Delta E/E = (1 - y_a)$ in dependence on p_T .

The p_T -dependence of the energy loss by production of strange hadrons is shown in Fig.1(b). The relative energy loss $\Delta E/E = (1 - y_a)$ depends on value of the fragmentation dimension ϵ_F . As one can see, the relative energy loss decreases with increasing transverse momentum for all particles. For particles with a given $p_T > 1$ GeV/c, the energy loss is larger for strange baryons than for strange mesons. The growth indicates increasing tendency with larger number of strange valence quarks inside the strange baryon. Such a tendency corresponds to the z -scaling universality (Fig.1(a)) for hadron production including strange mesons and baryons.

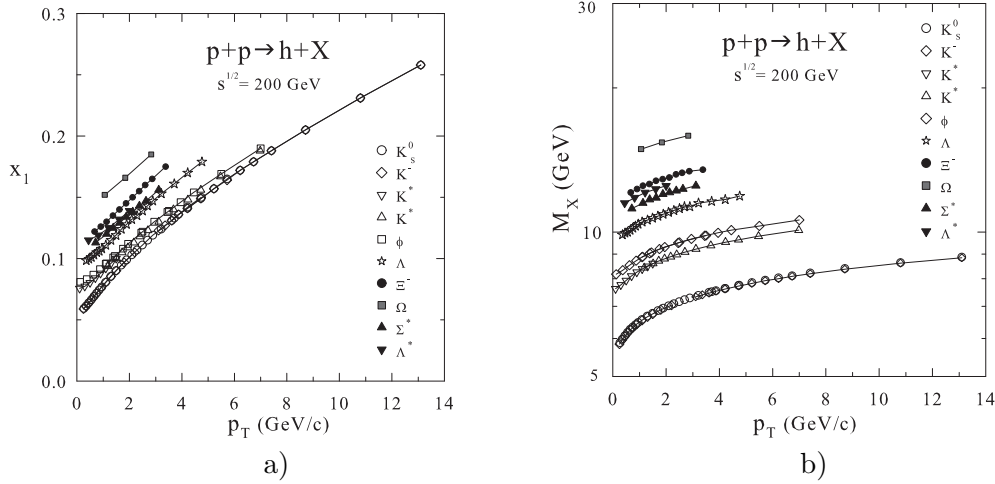


Figure 2. The p_T -dependence of the momentum fraction x_1 (a) of the colliding proton and the recoil mass M_X (b) for production of strange hadrons.

Figure 2(a) shows p_T -dependence of the momentum fraction x_1 for production of different hadrons. The fraction x_1 characterizes amount of energy (momentum) of the incoming proton carried by the interacting constituent which underlies production of the inclusive particle with momentum p_T . One can see that, for given strangeness and p_T , the value of x_1 increases with the mass of the strange meson. The same tendency is observed for the recoil mass M_X (Fig.2(b)).

In summary, we have analysed new transverse momentum spectra of strange particles measured by the STAR and PHENIX collaborations in pp collisions at $\sqrt{s}=200$ GeV using data z -representation. The analysis confirmed flavor independence of the scaling function $\Psi(z)$. The universality of description of the spectra is consistent with a hierarchy of the energy loss in dependence on hadron strangeness and for a given strangeness with the increasing tendency of the recoil mass M_X and the constituent energy with the mass of the strange hadron.

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