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MANY-COMPONENT BEHAVIOUR OF MULTIPARTICLE PRODUCTION PROCESSES. DEPENDENCE OF MULTIPLICITIES ON THE TRANSVERSE MOMENTUM IN SEMI-INCLUSIVE PROCESSES

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Abstract: Some phenomenological features of the many-component description of the dependence of mean multiplicities on the transverse momentum in semi-inclusive processes are considered. The description is given in the framework of a model assuming the decomposition of secondaries into components, depending on the character of the correlations between the multiplicity n and the transverse momentum $p_\perp$ of a particle (trigger). Other specific features of the many-component description of inclusive and semi-inclusive processes are also investigated.

Introduction

An important property of inclusive processes in the region of large $p_\perp$ is the dependence of the mean associated multiplicity on the transverse momentum of a trigger (a particle detected in an inclusive reaction). The idea of many-component description of inclusive and semi-inclusive spectra is very useful for understanding the above regularity[1-10]. The many-component description of a multiple process implies that secondaries can be divided into groups with different mechanisms of their production (or regions of the phase space). Several attempts have been made to interpret the many-component structure of spectra and multiplicities[5-8]. In particular, it is convenient to classify the components (mechanisms) by the character of the correlations between the value $p_\perp$ of a trigger and the multiplicity of particles produced in association with the detected particle[5]. In this paper we consider the pecularities of this classification and try to show the physical meaning of some phenomena in the region of large transverse momenta.

1. The dependences we are interested in can be considered in terms of the characteristics of semi-inclusive processes:

$A + B \to C(p_\perp, x)$ (a particle with large $p_\perp$) + + (n-1) of charged particles + an arbitrary number of neutral ones. (1.1)

In this case, one of the secondaries (a charged secondary) is inclusively detected and receives a large transverse momentum ($C(p_\perp,x)$, i.e. it is the trigger particle in the interaction.

The average number of charged secondary particles (produced in association with a trigger) at the fixed transverse momentum $p_\perp$ of the $C(p_\perp,x)$ particle, i.e. the mean associated multiplicity of the reaction (1.1), is determined by

$$\langle n(p_\perp)\rangle = \sum_n (n-1)F(n,p_\perp)/ \sum_n F(n,p_\perp) \ . \qquad (1.2)$$

Here $F(n,p_\perp)$ is the differential single-particle distribution of a trigger for a given topology (the number of charged particles)[+)].

Following Ref.[5)], we assume that this distribution can be decomposed into components, in accordance with the correlation strength between the multiplicity (n) and the transverse momentum of a trigger ($p_\perp$):

$$F^{tot}(n,p_\perp) = F^{o}(n,p_\perp) + F'(n,p_\perp) \ . \qquad (1.3)$$

In this formula, the first term corresponding to the absence of correlations can be represented in the form[**)]

$$F^{o}(n,p\ ) = c(n)\cdot\phi(p_\perp) \ , \qquad (1.4)$$

and the second term corresponding to strong correlations between n and $p_\perp$ is parametrized in the automodel form[9)]

+) For more detailed definitions, see Ref.[10)].

**) Only the dependences on the arguments n, $p_\perp=\{p_x,p_y\}$ are given explicitly. For the sake of simplicity, the other variables are considered to be fixed.

$$F'(n,p_\perp) = a(p_\perp)\psi(n/f(p_\perp)) \quad . \tag{1.5}$$

Using the definition (1.2), we can easily show that the mean associated multiplicity in this case is

$$\langle n(p_\perp)\rangle^{tot} = \langle n^o\rangle + \langle n^1\rangle \quad . \tag{1.6}$$

Here $\langle n^o\rangle \sim$ const, i.e. it does not depend on $p_\perp$, which follows naturally from the distribution (1.4), and $\langle n^1\rangle \sim f(p_\perp)$ is the correlation term of the mean associated multiplicity generated by the distribution F'.

It should be noted that after we have constructed the normalized topological cross section using only the first term in formula (1.6), we pass to the well-known KNO scaling.

At the same time the correlation term of the mean associated multiplicity $\langle n^1\rangle$ and the corresponding distribution (1.5) lead to the <u>similarity law</u>***)

$$\langle n(p_\perp)\rangle \frac{d\sigma_n/dp_\perp}{\sum\limits_n d\sigma_n/dp_\perp} = \psi\left(\frac{n}{\langle n(p_\perp)\rangle}\right) \quad . \tag{1.7}$$

This law was proposed in Ref.[9] and is in agreement with experiments[9a].

Thus, from the viewpoint of $n \leftrightarrow p_\perp$ correlations, KNO scaling corresponds to zero (or negligible) correlations. In the case of <u>strong correlations</u>, relation (1.7) is expected to be valid.

***) This law follows, in particular, from the concepts of coherent nucleon excitation, which predict the dependence

$$\langle n(p_\perp,W)\rangle = a + bp_\perp^2 + c(W^2 - m^2) \quad ,$$

where W is the "missing" mass and m is the nucleon mass. The validity of (1.7) is preserved for a rather large class of correlations between $\langle n(p_\perp)\rangle$ and $p_\perp$.

However, note that such a separation of secondaries (with respect to the correlation strength between n and $p_\perp$) is not convenient for physical reasons. Moreover, the experimental possibilities for studying different components and their contributions to multiplicities (as it will be seen below) allos the investigation of other types of separation of secondaries. Later in this paper, analyzing different approaches to the many-component description of reactions of the type (1.1), we compare different ways of separation with the one given in this section.

2. Let us consider the structure of the phase space of a finite many-particle state of the reaction (1.1) and separate it into the following regions (components):

(i) $n_1 \equiv n_\pi$ is a set of soft ($x \sim 0$, $p_\perp \leq p_\perp^0$) particles distributed isotropically in the sphere of radius $p_\perp^0$ of the momentum space (in the centre-of-mass system of the initial particles A and B).

(ii) $n_2 \equiv n_j$, (n_{j_1} ($\phi=0^0$), n_{j_2} ($\phi=180^0$) is a set of particles with $p_\perp > p_\perp^0$ emitted in the cone along the motion of a particle (trigger) and in the opposite direction, respectively. (ϕ is the azimuthal angle from the direction of the detected particle C[****])).

Taking into account that all n particles produced in the finite state of the inclusive reaction (1.1) are defined

[****]) Note that the definition of the components n_j does not correspond to the multiplicities in the forward-backward hemispheres (see also Ref.[11])).

by the regions n_i (i=1,2), we have

$$(n-1) = n_\pi + n_{j_1}(0^\circ) + n_{j_2}(180^\circ) \ . \qquad (2.1)$$

We now determine the partial mean multiplicities of secondaries $\langle n_\pi\rangle$, $\langle n_j\rangle$ produced in association with the detected particle in the phase-space regions with the components n_i. The corresponding single-particle distributions F_n^i (i=1,2); $F_n^{tot}(p_\perp,x) = F_{n_\pi}^1 + F_{n_j}^2$ are determined in the regions $p_\perp < p_\perp^o$ and $p_\perp > p_\perp^o$. Then the total mean associated multiplicity will be expressed through the corresponding contributions F^i in the following way:

$$\langle n^{tot}(p_\perp,x)\rangle F^{tot} = \langle n_\pi(p_\perp,x)\rangle F^1 + \langle n_j(p_\perp,x)\rangle F^2 \ , \qquad (2.2)$$

or

$$\langle n(p_\perp)\rangle = \alpha\langle n_\pi\rangle + \beta\langle n_j\rangle \ , \qquad (2.3)$$

where $\alpha = F^1/F^{tot}$, $\beta = F^2/F^{tot}$; $F^{tot} = F^1+F^2$.

Assuming that to each component in the single-particle distribution $F_n^i(p_\perp,x)$ correspond strong correlations between the value of the transverse momentum $p_\perp$ of the particle C and the corresponding multiplicity n^i, the scale relation[9)] is obtained (see (1.7))

$$F_n^i(p_\perp) \to \psi(n/f^i(p_\perp)) = \psi(z^i) \ . \qquad (2.4)$$

The correlations can be correspondingly divided into two classes, depending on the components i=1,2. To this end, let us determine the so-called effective slope of the single-particle distribution

$$B(n,s) = \frac{d}{dp_\perp}\left[\ln \frac{d\sigma^{(n)}}{dp_\perp}\right]_{p_\perp \text{ fixed}} \tag{2.5}$$

Then the components $i=1,2$ may be compared with two regimes[5,9] of behaviour corresponding to the increasing and decreasing character of the effective slope of the distribution $F_n(p_\perp)$ with increasing multiplicity n [*****]:

$$\begin{aligned} B_1(n,s) &\simeq b_1 n && \text{the "narrowing of the slope,} \\ B_2(n,s) &\simeq b_2\, 1/n && \text{the "broadening" of the slope,} \end{aligned} \tag{2.6}$$

where the coefficients b_1 and b_2 may depend weakly on energy.

In terms of (2.6), the automodel argument of the semi-inclusive cross section (2.4) changes as follows:

$$z_i = B_i(n)/f^i(p_\perp) \ .$$

Thus, using the assumption of strong correlations of partial multiplicity and transverse momentum in both components, it is possible to obtain the observed dependence, in particular the growth of the total associated multiplicity $\langle n^{tot}(p_\perp)\rangle$ in the region of large transverse momenta[5].

Now, let us discuss the relation between the above assumptions on the structure of finite many-particle states and the production mechanism of these states in collisions of two hadrons. Assuming that hadrons A and B are sets of point components, it is convenient to classify different interaction mechanisms by the character of their longitudinal motion inside a hadron[12].

*****) Here we have restricted ourselves to the linear dependence on n; in a general case, the law B=B(n) is given by a more complicated formula.

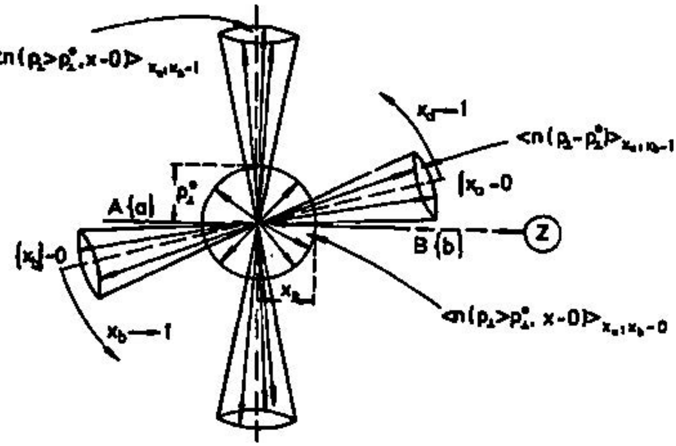

Fig. 1. Interaction of hadron constituents divided into two mechanisms.

The interaction of hadron constituents may be divided into two mechanisms, depending on whether the components are in "soft" ($x \sim 0$) or "hard" ($x \sim 1$) parts of the spectrum: the coherent interaction mechanisms responsible for the particle production in the forward-backward regions and the mechanism of production of particle "jets" with large transverse momenta (see Fig. 1).

Note that such a division is rather a rough approximation. In a general case, the values of the components x_i control the positions of the beam axes, and because the values of x_i run over the whole spectrum, the two approximations cannot be distinguished exactly. In particular, the inclusive spectra and associated multiplicities $\langle n(p_\perp)\rangle \sim \langle n(x,p_\perp,x_\perp)\rangle_{a(x_i);b(x_i)}$ depend strongly on x_a, x_b, x_c and thus define the contribution of the different mechanisms to the components.

We give the following illustrations of all possible mechanisms:

1. The region of the phase space of finite particles produced with small values of x and $p_\perp$ ($x \sim 0$, $p_\perp < p_\perp^0$). In this case we should take into account the mechanisms of independent emission of soft particles by statistical (and multiperipheral) contributions. The specific semi-inclusive distributions are[13,14]

$$\frac{d\sigma^{(n)}}{dx} \sim (1-x)^{n-1}\ , \qquad \frac{d\sigma^{(n)}}{dp_\perp} \sim e^{-np_\perp}\ ,$$

with decreasing associated moments[14]

$$\langle n(p_\perp)\rangle \sim [a + bp_\perp]^{-1},\quad a-|bp_\perp| \quad .$$

Note by the way that soft mesons produced in bremsstrahlung

(<n> $\sim$ ln $p_\perp$) also contribute to this region.

2. The region of intermediate values of $p_\perp$. In this region, the mechanisms of coherent interactions[15,17], composite systems, diffraction hadron excitation[18], multiple rescattering of components[19] and others play an important role. In particular, the eikonal regime of interaction of a fast particle with a composite system corresponds to a broadening of the slope of the semi-inclusive distribution (2.5), (2.6) and to a rapidly increasing associated multiplicity $\langle n(\Delta)\rangle \sim \Delta^2$ (Ref.[12]).

The same mechanism determines the finite interactions of particle jets produced in collisions of hard components ($x_a;x_b \sim 1$) in the region of large angles and transverse momenta ($p_\perp > p_\perp^0$).

In a number of experiments the mean associated multiplicites are determined from the following reactions:

$$\begin{aligned} &A + B \rightarrow C(p_\perp) + n_{cp}^{same} + x', \quad x' = x_0 + x_{opp}, \\ &A + B \rightarrow C(p_\perp) + n_{cp}^{opp} + x'', \quad x'' = x_0 + x_{same}, \\ &A + B \rightarrow C(p_\perp) + (n-1)_{cp}^{tot} + x_0 . \end{aligned} \tag{2.7}$$

If we restrict ourselves to the possible sources (components 1,2) of particle production (2.1) and take into account the isotropy of the (i=1) component, we can represent the multiplicities in the form

$$\begin{aligned} n^{same} &= \frac{n_\pi}{2} + n_j(0) , \\ n^{opp} &= \frac{n_\pi}{2} + n_j(180^o). \end{aligned} \tag{2.8}$$

The conditional mean multiplicities defined by (2.7) may indicate the presence of strong correlations $n_i \leftrightarrow p_\perp^c$ corresponding to the mechanism $i=1,2$ in the whole region of change of $p_\perp$ (including $p_\perp < p_\perp^o$).

Indeed, assuming that (2.8) are valid for the mean associated multiplicities, we compare the experimental data[20] on total and partial mean multiplicities. Fig. 2 shows that the observed increase and decrease with increasing $p_\perp$, which occur in the conditional distributions (e.g. $\langle n^s \rangle \sim -0.02 p_\perp$, $\langle n^{opp} \rangle \sim 0.1\, p_\perp$ at $\sqrt{s} \sim 23$ GeV), are compensated by the weak dependence $\langle n^{tot} \rangle \sim 0.008\, p_\perp$. Note that this regularity is conserved at all energies ISR ($\sqrt{s} \sim 23 \div 62$ GeV). Comparison with experimental data[21] at low energies ($\sqrt{s} \sim 6$ GeV) shows that such compensation occurs in the region of small $p_\perp$ ($p_\perp < 1.2$ GeV/c). Besides, a specific increase of $\langle n^{tot} \rangle$ at $p_\perp$ and decrease of $\langle n^s \rangle$ at $p_\perp$ indicate <u>the presence of strong correlations</u> in the competing mechanisms.

It should be noted that quantitative analysis of the corresponding distributions requires to take into account the weights of the cross sections of some components α, β (with unique normalization of experimental data).

Table 1 represents a general picture of the behaviour of the quantity $\langle n(p_\perp) \rangle$, obtained from the analysis of experimental data[20-25].

It should also be noted that the distributions of the quantities $\langle n^{tot}(p_\perp) \rangle$ and $\langle n^{opp}(p_\perp) \rangle$ are almost in-

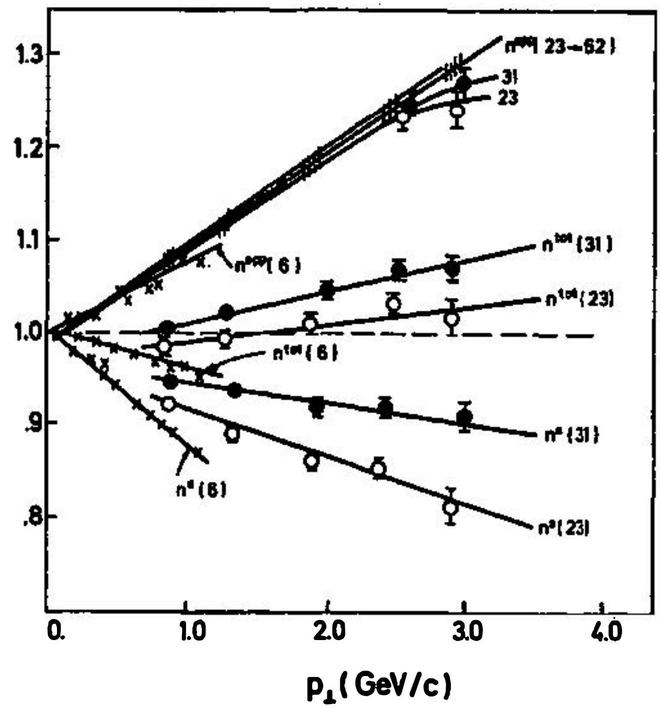

Fig. 2. The behaviour of the associated multiplicities $<n^{tot}>$, $<n^{s}>$, $<n^{opp}>$ as a function of $p_\perp$. The experimental data are taken from Refs.[20,21,24].

Table 1

Decrease of $\bar{n}(p_\perp)$ Narrowing of $F(n,p_\perp)$	$\bar{n}(p_\perp) \sim$ const $F(n,p_\perp) \simeq F^{(o)}(n)F(p_\perp)$	Increase of $\bar{n}(p_\perp)$ Broadening of $F(n,p_\perp)$
1. $\bar{n}^{tot}(p_\perp)$, $p_\perp<p_\perp^{(o)}$ $pp\to\pi,K$. $\sqrt{s}=6$ GeV[b]	1. $\bar{n}^{tot}(p_\perp)$, $p_\perp<p_\perp^{(o)}$ $pp\to p,\Lambda$, $\sqrt{s}=6$ GeV[b] $pp\to p(\pi)+MM$, $\sqrt{s}=$ $= 7.5$ GeV[d] $\pi^- p\to\pi$ $\sqrt{s}=9$ GeV[c]	1. $\bar{n}^{tot}(p_\perp)$, $p>p_\perp^{(o)}$ $pp\to\pi,K$. $\sqrt{s}=23\div62$ GeV[a] $pp\to p(\pi)+MM$, $\sqrt{s}=7.5$ GeV[d]
2. $\bar{n}^{s}(p_\perp)$, entire interval of $p_\perp$ $pp\to\pi^o,\pi^\pm,K$ $\sqrt{s}=23\div62$[a] $pp\to\pi^\pm$ $\sqrt{s}=12$ GeV[f] $pp\to\pi$ $s=6$ GeV[e]	2. $\bar{n}^{s}(p_\perp)$, entire interval of $p_\perp$ $pp\to\pi$, $\sqrt{s}=53$ GeV[a] $pp\to\pi,K,p,\bar{p}$ $\sqrt{s}=44$ GeV[g,h]	2. $\bar{n}^{s}(p_\perp)$, $p>p_\perp^{(o)}$ $pp\to\pi$, $\sqrt{s}\gtrsim62$ GeV[a]
3. $\bar{n}^{opp}(p_\perp)$, $p_\perp\sim p_{\perp max}$ $pp\to\pi,K$, $\sqrt{s}=23\div62$ GeV[a]	3. $\bar{n}^{opp}(p_\perp)$, $p_\perp<p_\perp^{(o)}$ $pp\to\pi$, $\sqrt{s}=12$[f]	3. $\bar{n}^{opp}(p_\perp)$, entire interval $p_\perp$ (except $p_{\perp max}$) $pp\to\pi,K,p,\bar{p}$ $\sqrt{s}=16,12$, 23-62 GeV[a,f-h]
4. $\bar{n}(x)$, entire interval $x(0,1)$ $pp\to\pi,K,p,\Lambda$, $\sqrt{s}=6$ GeV[b] $\pi^- p\to\pi$, $\sqrt{s}=9$ GeV[c]		4. $\bar{n}^{jet}(p_\perp)$, $p\geq p_\perp^{(o)}$ $pp\to$jet, $\sqrt{s}=23\div62$ GeV[g]

[a] Ref. 20
[b] Ref. 21
[c] Ref. 22
[d] Ref. 23
[e] Ref. 24
[f] Ref. 25
[g] Ref. 26
[h] Ref. 27

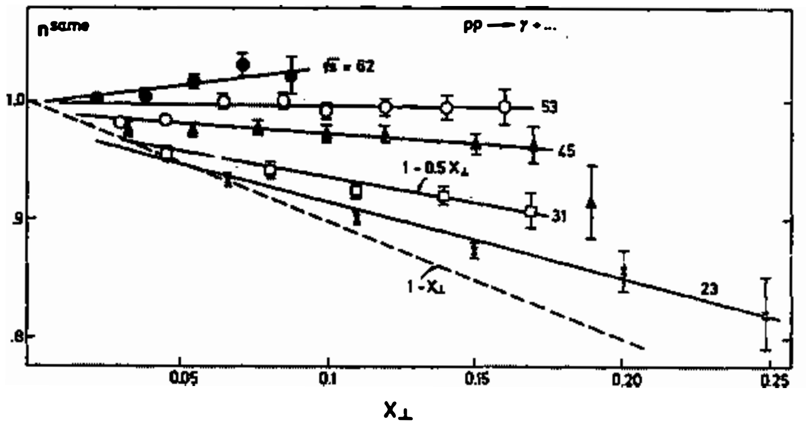

Fig. 3. The dependence of the quantity $\langle n^S(p_\perp, s)\rangle$ on the energy of the incident jet as a function of $x_\perp = 2p_\perp/\sqrt{s}$.

independent of the energy of the initial particles. The energy dependence of the quantities $\langle n^s(p_\perp)\rangle$ is obviously connected with the dominating contribution of the component $n_\pi(p_\perp,s)$ and may be parametrized as follows (see Fig. 3):

$$\langle n^s(p_\perp,s)\rangle \sim 1-kx_\perp, \quad x_\perp = 2p_\perp/\sqrt{s}\ . \tag{2.9}$$

It should be mentioned that in measuring the associated multiplicities at large values of $p_\perp$ we should take into account the presence of the background (particles with small $p_\perp$). With the appropriate choice of (2.7) the momenta can be cut off below the values of $p \sim p_\perp^o$. In this way it is possible to prevent the mixing of the components and to separate the two mechanisms (n_π, n_j) completely.

Since many experiments on particle production with large $p_\perp$ use nuclear targets, it is possible to study the influence of the value of transverse momenta on nuclear-scanning effects.

Analysis[28] of the data on the interaction of the proton jet with $p_\perp \sim 300$ GeV/c for three types of targets - Be, W and Ti - shows that scanning effects of single-particle cross sections for π-meson production decrease with increasing transverse momentum and disappear completely at $p_\perp \gtrsim 2$ GeV/c:

$$\frac{d\sigma^A}{d^3p/E} \equiv I(p_\perp,A) = I(p_\perp,1)A^{m(p_\perp)}\ , \tag{2.10}$$

$$m(p_\perp \lesssim 1\ \text{GeV/c}) = 0.8 \rightarrow m(p_\perp \gtrsim 2\ \text{GeV/c}) = 1.1\ .$$

Note that according to the relation of similarity[9] for

$$\psi(z) = \langle n(p_\perp)\rangle \frac{d\sigma_n/dp_\perp}{d\sigma/dp_\perp} ,$$
$$z = n/\langle n(p_\perp)\rangle , \qquad (2.11)$$

and taking into account the behaviour (2.10) of semi-inclusive single-particle distributions, we obtain the expression

$$\frac{d\sigma^A}{d^3p/E} \sim A^{\alpha(p_\perp)} \psi_{pp}\left(\frac{n}{\langle n(p_\perp)\rangle^A}\right) . \qquad (2.12)$$

Here the associated mean multiplicity depends on the mass number A in the following way:

$$\langle n(p_\perp)\rangle^A \sim A^{\beta(p_\perp)} \langle n(p_\perp)\rangle ,$$
$$\beta(p_\perp) = 0 \div 0.1, \quad p_\perp > p_\perp^0 . \qquad (2.13)$$

The phenomenological analysis performed in this paper shows that the many-component approach to inclusive and semi-inclusive processes enables one to investigate the role of mechanisms and their contributions to different regions of the phase space.

We want to stress that the behaviour of total associated multiplicities at large $p_\perp$ has not yet been cleared up. More detailed predictions in the framework of a many-component scheme can be made only if the contributions of the different components (especially $n_\dagger, n_j$) can be separated experimentally. In order to determine the strength of $\langle n(p_\perp)\rangle \leftrightarrow p_\perp$ correlations (total or partial), the semi-inclusive scaling law (1.7) should be checked experimentally in a wide region of s and t. However, the investigation of the behaviour of the different mechanisms is associated with considerable experimental difficulties. In this paper we try only outline, with the help of a simple model, the general principles of a many-component approach to semi-inclusive processes. However, as the structure of many-particle quantities is rather complicated, many-component phenomenology seems to be an adequate approach to the investigation of this problem.

We did not mention the problem of adequate theoretical descriptions of different mechanisms. A consideration of this type within the framework of quantum field theory is one of the basic problems of the theory of inclusive reactions (see Refs. 29-31, for example).

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VIŠEKOMPONENTNO PONAŠANJE PROCESA MNOGOČESTIČNE PRODUKCIJE. OVISNOST MULTIPLICITETA O TRANSVERZNOM IMPULSU U SEMI-INKLUZIVNIM PROCESIMA

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Sadržaj

Razmatrane su neke fenomenološke karakteristike višekomponentnog opisa ovisnosti srednjih multipliciteta o transverznom impulsu u semi-inkluzivnim procesima. Opis je dan u okviru modela koji pretpostavlja rastavljanje sekundarnih čestica u komponente, ovisno o karakteru korelacija izmedju multipliciteta (n) i transverznog impulsa $p_\perp$ detektirane čestice. Takodjer su istraživane druge specifične osobine višekomponentnog opisa inkluzivnih i semi-inkluzivnih procesa.