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Inclusive hadron and lepton production at large angles in a statistical model for violent collisions*

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The observed s dependence of inclusive single-pion spectra at $\theta_{c.m.} = 90°$ ($x = 0$) and *low* transverse momenta can be understood in terms of a statistical model that reproduces the main features of large-transverse-momentum phenomena. A simple physical picture for multiparticle production processes is proposed. This picture is compared with recent inclusive experiments on hadron and lepton production.

It has been proposed in an earlier paper[1] that processes in which particles with large transverse momentum ($p_\perp > 2$ GeV/c, say) and/or particles associated with large multiplicities (i.e. also those in high-multiplicity events which only consist of low-$p_\perp$ particles)[2] are produced can be described by a statistical model. The spirit of the model is similar to that of Fermi's,[3] although they are entirely different in the following essential points: Firstly, Fermi's model is proposed for *all* production processes, while the present one is designed *only* for the processes mentioned above, which we shall, following Chao and Yang,[4] call *violent collisions*. That is to say, it does *not* account for fragmentation[5] which is *gentle* in the sense that only an infinitesimal energy transfer, an infinitesimal longitudinal-momentum transfer, and a finite transverse-momentum transfer are required. Secondly, according to Fermi, the conglomerate formed by the two colliding highly energetic particles remains in a "frozen" state until it decays. But in the present model the conglomerate first expands and then decays when a certain *critical volume* is reached. The critical volume of the conglomerate in its rest system is assumed[6] to be *independent of the total energy* ($\sqrt{s}$) *of the system*. From this (and standard thermodynamics) we obtain that the temperature (T) of the system has the behavior

$$T \propto s^{1/8}, \tag{1}$$

and the inclusive cross section of a single pion (we consider pions because of the existing data; generalization is trivial) can be written as

$$\frac{d^3\sigma}{d^3p}(p_\perp, \theta; s) = \frac{a}{\exp(bEs^{-1/8}) - 1}, \tag{2}$$

where $E = (p^2 + m^2)^{1/2} - m$, $p = |\vec{p}|$, and m are the kinetic energy, the momentum [in the center-of-mass system (c.m.s.)] and the mass of the observed pion, respectively. a and b are positive real constants.[7]

For the case in which particles with large transverse momentum ($p_\perp \gg m$) are detected at the c.m.s. production angle $\theta = 90°$, we have

$$\frac{d^3\sigma}{d^3p}(p_\perp, 90°; s) = a\exp(-bp_\perp s^{-1/8}). \tag{3}$$

Comparison[1,8] with the large-$p_\perp$ data[9-13] shows that the main features of the single-particle spectra (e.g. its s dependence and its increase in s dependence with increasing $p_\perp$) can indeed be described by this extremely simple formula, but a more refined version of this oversimplified model is needed to obtain a better qualitative agreement between experiment and theory. In particular, it is clear that all effects related to correlation cannot be explained as long as the interactions between the particles are completely neglected. Although there are many ways to introduce such interactions in the model (e.g. one can consider that the independently emitted objects are clusters which decay into the observed particles, or that the conglomerate is a system of real gas, etc.), we were not sure whether we should push this particular statistical model to such an extent before we have seen more experimental evidence for the relevance of this approach.

In the present note we shall discuss the results of some very recent experiments, all of which seem to suggest this approach indeed deserves further investigation.

The first experiment which we would like to discuss is the striking result obtained by Bøggild *et al.*[14] They found that at $\theta = 90°$ and $50 \leq p_\perp \leq 350$ MeV/c, the inclusive single-pion spectra *increase* *with* s about 40% when $\sqrt{s}$ is increased from 23 to 63 GeV. Furthermore, the above-mentioned increase is found to be almost *independent of the transverse momenta* in this kinematical region.

Now, since particles with large transverse momenta as well as those with small transverse momenta can be produced in a violent collision, which we describe with the present model,[2] a natural question to ask is, "What does this model say about the s and the $p_\perp$ dependence of the ratio

$$R(p_\perp; s, s_0) = \frac{d^3\sigma/d^3p\,(p_\perp, \theta=90°; s)}{d^3\sigma/d^3p\,(p_\perp, \theta=90°; s_0)}, \tag{4}$$

for which Bøggild *et al.* have provided the above-mentioned results?"

From Eq. (2) we immediately obtain for the case $E \ll b^{-1}s^{1/8}$

$$R(p_\perp; s, s_0) = \left(\frac{s}{s_0}\right)^{1/8}. \tag{5}$$

It is interesting to see that this simple, *parameter-free* expression indeed shows the characteristic features (the rather rapid increase with s and the independence of $p_\perp$) of R which have been found experimentally. A detailed comparison with the data[14] is given in Fig. 1.

Although we are aware of the fact that this oversimplified version is not capable of explaining the phenomena related to correlation effects among the produced particles, we think the amazing agreement of the main features between experiment and theory in both large- *and* small-$p_\perp$ regions[15] suggests the following: (a) In the central region, particles with large and small $p_\perp$ are produced by the *same* mechanism. (b) In the first-order approximation, this mechanism can be decribed by the present model.

Hence, it seems that the gross features of high-energy collision processes can, in the first-order approximation, be understood in terms of the following picture[16]: The two colliding particles *either* go through each other (elastic scattering, fragmentation) *or* arrest each other, forming a conglomerate that expands and then decays when a critical volume (which in its rest system is independent of the total energy) is reached (violent collision). While the fragmentation products are predominantly to be found in the forward and the backward hemispheres, the products of violent processes (the distribution of which is *not* confined to the forward and the backward c.m.s. angles only) will dominate in the central region.

As further support for this simple naive picture, we now discuss the very recent ISR results ob-

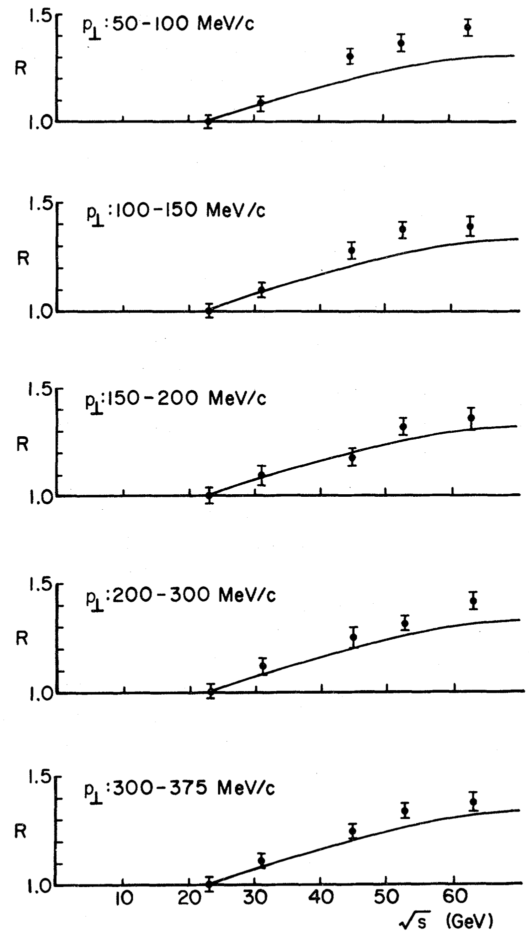

FIG. 1. Data for

$$R(p_\perp; s, (23\text{ GeV})^2) = \frac{\text{number of events/luminosity } (\sqrt{s})}{\text{number of events/luminosity (23 GeV)}}$$

are taken from Ref. 14 (preliminary result). The curve is calculated from Eq. (5) with $\sqrt{s_0} = 23$ GeV.

tained by the CCHK[17] and ACHM[18] groups: Della Negra *et al.*,[17] investigating the fragmentation regions at $\sqrt{s} = 52.5$ GeV by triggering positively charged particles in a c.m.s. angular range $9° \leq \theta \leq 21°$, have found that the forward-diffraction peak is strongly depressed when a particle with large $p_\perp$ (>1 GeV/c) in the triggering device placed at the opposite hemisphere is detected. The agreement between this result and the proposed "*either* fragmentation *or* violent collision" picture is obvious. Eggert *et al.*,[18] studying two-particle rapidity correlations among charged particles at $\sqrt{s} = 53$ GeV, have found by triggering on a large-$p_\perp$ π^0 at $\theta = 90°$ that the correlation functions *with* high-transverse-momentum production are the same as those *without*. This indicates in particular that in the central region particles with large and small $p_\perp$ are indeed produced by the *same* mechanism.[19]

Finally, we shall briefly discuss the experimental results on direct lepton production[20-23] and their possible relation to the picture mentioned above.

It is clear that on accepting the proposed model for the production of large-$p_\perp$ hadrons, an immediate question would be whether large-$p_\perp$ leptons are produced by the same mechanism. An examination of the spirit as well as the structure of the model leads us to the conclusion that there is, *a priori, no* reason why leptons *cannot* be produced in a similar fashion. Suppose that leptons (in general, in the form of clusters) indeed exist in the conglomerate; let us now discuss what kind of consequences we have to face. First of all, we note that in this model the main differences between a hadron and a lepton are their masses and their interactions with the other particles in the conglomerate. But, as we have seen in the hadron case, for the description of large-$p_\perp$ particles produced in the central region, masses as well as interactions can be neglected. Hence we expect that large-$p_\perp$ leptons observed at $\theta = 90°$ should share many of the features of large-$p_\perp$ hadrons detected under the same conditions.[24] To be more specific, for $p_\perp > 1$ GeV/c, say, in the $\log d^3\sigma/d^3p$ $(p_\perp, 90°; s)$ vs $p_\perp$ plot, the data set for leptons and that for hadrons taken at a given total energy $\sqrt{s}$ should, in the first-order approximation, be on straight lines with roughly the same slope; furthermore, in the $s^{1/8} \log d^3\sigma/d^3p$ $(p_\perp, 90°; s)$ vs $p_\perp$ plot, also the lepton data taken at different s values should be parallel to each other. It is interesting to see that the above-mentioned $p_\perp$ and s dependences have indeed been observed experimentally.

In closing, we would like to make the following remarks:

(a) An attempt has been made in this paper to understand the results of several recent experiments, which might be considered unrelated to one another,[25] in terms of a simple physical picture. The result of the analysis seems encouraging.

(b) Since the main purpose of this study is to check the basic ideas underlying the proposed picture (e.g., the observed s dependence of $d^3\sigma/d^3p$ in the central region at large and that at small $p_\perp$ are due to the same kind of production processes—violent collisions) with experiment; second-order effects due to the detailed properties of interactions between the produced particles are neglected in our discussion.

(c) In deriving Eq. (5), we made use of the fact that the pion is a boson. In the first-order approximation this result is also expected to be true if the observed pions are decay products of clusters which obey Bose-Einstein statistics. The agreement between experiment and the result given in Eq. (5) strongly supports the idea that the *dominating* part of the observed pions are produced in the above-mentioned manner. What shall we see in the production of heavy particles such as protons, antiprotons, and kaons? Since it seems rather unlikely (because of their large masses) that such particles can be produced via clusters which obey statistics different from that of their own (e.g. protons via a boson cluster), we expect that heavy fermions and heavy bosons will have completely different s dependence at low $p_\perp$ and high incident energies [such that $bE^{-1/8} \ll 1$ is valid, cf. Eq. (2)]. To be more precise, under the condition mentioned above, Eq. (5) should be valid also for kaons and antikaons, but

$$R(p_\perp; s, s_0) \approx 1 \tag{6}$$

for protons, antiprotons, Λ particle, etc. (unless these baryons are produced via superheavy boson clusters).

(d) The important role of angular momentum conservation in noncentral collision processes has already been pointed out by Fermi[3] (statistical model for multiparticle production) and Yang[26] (geometrical description of hadron structure in elastic and inelastic processes). In the framework of this model, the effect of angular momentum conservation, which has been neglected in deriving Eq. (2), can be taken into account in a straightforward manner.[27,30] A natural consequence of the conservation of angular momentum in noncentral violent collisions is that the particles produced in each event should have the tendency of becoming coplanar and tend to show peaklike structures in the angular distribution (within this plane). Recent experiments[28] indicate that such plane and jet (or fan) structure indeed exists in violent collision processes.

(e) The simple picture proposed in this note can be applied to hadron-nucleus processes. Taken together with the usual assumption[29] that multibody final states in high-energy hadron-hadron collisions are *not* produced instantaneously, it is observed that the main features of the existing hadron-nucleus multiple-production data,[29] including the nuclear-size dependence of inclusive cross sections at large transverse momenta,[13,21,22] can be readily understood in this framework. Details of this investigation are presented elsewhere.[30]

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[1]Meng Ta-chung, Phys. Rev. D 9, 3062 (1974).

[2]See in this connection the discussion in Sec. I and Sec. IV of Ref. 1.

[3]E. Fermi, Prog. Theor. Phys. 5, 570 (1950); Phys. Rev. 81, 683 (1951).

[4]Alexander Wu Chao and Chen Ning Yang, Phys. Rev. D 9, 2505 (1974).

[5]J. Benecke, T. T. Chou, C. N. Yang, and E. Yen, Phys. Rev. 188, 2159 (1969); T. T. Chou and Chen Ning Yang, Phys. Rev. D 7, 2005 (1971).

[6]This simple and in fact rather natural assumption must be considered as *ad hoc* because we do not have a strong theoretical argument why this should be preferred to e.g. the usual hypothesis that the conglomerate decays at an s-independent critical temperature. It is, however, our intention that detailed dynamical assumptions (for the production process in general and for the expansion mechanism of the conglomerate in particular) be avoided and only the simple ansatz with direct, experimentally feasible consequences be used in our attempt to understand the grossest features of high-energy collisions.

[7]That is, numbers independent of $p_\perp$, θ, and s. Here we have neglected the observed very weak s dependence of the total cross section.

[8]S. D. Ellis, in *Proceedings of the XVII International Conference on High Energy Physics, London, 1974*, edited by J. R. Smith (Rutherford Laboratory, Chilton, Didcot, Berkshire, England, 1974), p. V-23; P. V. Landshoff, *ibid.*, p. V-57.

[9]B. Alper *et al.*, Phys. Lett. 44B, 521 (1973); see also Nucl. Phys. B87, 19 (1975).

[10]M. Banner *et al.*, Phys. Lett. 44B, 537 (1973).

[11]F. W. Büsser *et al.*, Phys. Lett. 46B, 471 (1973).

[12]D. C. Carey *et al.*, Phys. Rev. Lett. 32, 24 (1974).

[13]J. W. Cronin *et al.*, Phys. Rev. Lett. 31 1426 (1973); see also Phys. Rev. D 11, 3105 (1975).

[14]H. Bøggild *et al.*, paper presented by B. G. Duff, in Proceedings of the International Conference on High Energy Physics, Palermo, 1975, edited by A. Zichichi (CERN, Geneva, to be published).

[15]The answer to the question "How about other $p_\perp$ values values?" is as follows: with $b \approx 10$, $a \approx 3.2 \times 10^{-26}$ (s, $p_\perp$, and $d^3\sigma/d^3p$ are given in GeV^2, GeV/c, and cm^2c^{-3} GeV^{-3}, respectively). Equation (2) gives a reasonable fit to the $p_\perp$-distribution data in the entire $p_\perp$ region. Details on this point and especially in connection with noncentral collisions as well as with correlation problems will be discussed elsewhere. In connection with the above-mentioned question, see also the paper by Charles B. Chiu and Kuo-Hsiang Wang, Phys. Rev. D 12, 2725 (1975).

[16]The idea that two different kinds of inelastic processes exist in high-energy hadron collisions has already been extensively discussed in the literature; see, for example L. Van Hove, Phys. Lett. 43B, 65 (1973), and the papers cited therein. The point which we emphasize in this connection is the following: Large-$p_\perp$ events and large-multiplicity events (with *or* without large-$p_\perp$ particles) are caused by the *same* mechanism. Such events which dominate the central region can be approximately described by the statistical model of Ref. 1.

[17]M. Della Negra *et al.*, Phys. Lett. 59B, 401 (1975).

[18]K. Eggert *et al.*, Nucl. Phys. B98, 73 (1975).

[19]We recall that according to the present picture a process is either a fragmentation or a violent collision. The latter can, but does not necessarily produce large-$p_\perp$ particles in the central region.

[20]F. W. Büsser *et al.*, Phys. Lett. 48B, 371 (1974); CCRS group, in Proceedings of the International *Conference* on High Energy Physics, Palermo, 1974, edited by A. Zichichi (CERN, Geneva, to be published).

[21]J. P. Boymond *et al.*, Phys. Rev. Lett. 33, 112 (1974).

[22]J. W. Cronin, lecture given at the International School of Subnuclear Physics, Erice, 1975 (unpublished), and papers cited therein.

[23]L. M. Lederman, in Proceedings of the 1975 *International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, 1976), p. 265, and papers cited therein.

[24]Because of the complete neglect of all interactions between the particles and the consequent lack of detailed descriptions of possible cluster production, we are not in a position to calculate particle ratios in this oversimplified version of the model. In order to make more quantitive statements on this and other related points, especially in the low-$p_\perp$ region, detailed dynamical assumptions will be necessary. See, in this connection, the model proposed by L. M. Lederman and S. White, [Phys. Rev. Lett. 35, 1543 (1975)].

[25]We understand e.g. that in the conventional way of thinking small- and large-$p_\perp$ hadrons observed in the central region are due to entirely different mechanisms; leptons and hadrons with large $p_\perp$ should be described by completely different models or theories.

[26]C. N. Yang, in Proceedings of the International Symposium on High-Energy Physics, Tokyo, 1973, edited by Y. Hara *et al.* (Institute for Nuclear Study, University of Tokyo, 1973), p. 629.

[27]E. Moeller, thesis, Freien Universität Berlin, 1976 (unpublished).

[28]M. Jacob, summary of the ISR Discussion Meeting Between Experimentalists and Theorists, 1975 (unpublished), and the papers cited therein.

[29]See e.g., W. Busza, in *Proceedings of the Sixth International Conference on High-Energy Physics and Nuclear Structure*, Sante Fe and Los Alamos, 1975, edited by D. E. Nagele *et al.* (A.I.P., New York, 1975), p. 211.

[30]Meng Ta-Chung, in Proceedings of Topical Meeting on Multiparticle Production on Nuclei at Very High Energy, Trieste, Italy, 1976, edited by G. Bellini and L. Bertocchi (CERN, Geneva, to be published).