Z. Phys. C – Particles and Fields 35, 227–230 (1987)

Zeitschrift für Physik C Particles and Fields

Analysis of the Semi-Inclusive p_T Distributions at the CERN $p\bar{p}$ Collider Based on the Two-Temperature Model

E.R. Nakamura [1], K. Kudo [2], T. Fukushima [2]

[1] Physics Department, Fukui Prefectural College, 97-Ohata, Fukui, 910 Japan
[2] Department of Applied Physics, Fukui University, Fukui, 910 Japan

Received 5 December 1986; in revised form 18 February 1987

Abstract. A two-temperature model is proposed for the semi-inclusive transverse momentum (p_T) distributions at the CERN $p\bar{p}$ collider. Our model accounts well characteristic multiplicity dependence of the p_T distributions. Energy dependence of the p_T distributions is investigated in comparison with the data at ISR energies. High temperature state becomes more important at high energy and multiplicity regions. The ratio between high and normal temperature is almost independent of energy and multiplicity.

Inspired by the measurements of the transverse momentum distributions of charged particles at the CERN $p\bar{p}$ collider [1, 2], several authors have proposed the respective theoretical ideas [3–5].

The p_T spectra measured in those experiments have the following characteristic properties:

(a) The invariant cross sections as a function of p_T show the steeply falling properties in the low p_T region. However, the slope of p_T spectrum becomes gentle in the intermediate p_T region, and has the well known large-p_T tail in the high p_T region.

(b) The slope of the p_T spectrum becomes more gentle as multiplicity (n) (or multiplicity per unit of rapidity) increasing. The overall cross sections increase with multiplicity. This spectrum becomes to be almost independent of n at high multiplicities.

(c) Compared with the inclusive p_T spectra at ISR energies [6], the slopes of those spectra are gentle in all regions.

(d) Data of the p_T spectra for pion, kaon, proton and lambda [2, 7] indicate that these spectra becomes gentle with the mass of observed particles.

It turns out from (b) that mean transverse momenta $\langle p_T\rangle_n$ increases with n and becomes flat at high multiplicities. If we assume the approximate energy-momentum conservation law for $\langle p_T\rangle_n$, we have $\langle p_T\rangle_n \sim n^{-1}$ as in the case of mean longitudinal momenta $\langle p_L\rangle_n$ affected by leading particles [8]. Therefore, the increasing property of $\langle p_T\rangle$ is considered to result from some dynamical effects.

The p_T spectra recently observed in $\alpha\alpha$, αp and pp collisions at ISR energies [9] also show the similar property with (b). Hence, it is necessary to analyse the p_T spectra at the CERN collider in more detail in comparison with the ISR data, whereas various theoretical investigations so far have been performed only to obtain the qualitative trends of $\langle p_T\rangle$ at collider energy. The purpose of this article is to investigate the p_T distributions for charged particles at the CERN collider on the basis of a thermodynamical model, by taking account of these distributions at ISR energies.

It is convenient for our understanding to consider the p_T distribution divided into three regions like (I) the low p_T region, (II) the intermediate p_T region and (III) the high p_T region. In the low p_T region, i.e. $p_T \leqq 1$ GeV/c, the p_T distributions are reproduced well by the exponentially decreasing function which is available over the wide energy regions including CERN collider energy both in semi-inclusive and inclusive reactions. This suggests that we can assume the exponentially falling thermal distribution in the low p_T region. On the other hand, in the high p_T region the hard collision model of quarks based on QCD is considered to be reliable. However, as for the intermediate p_T region, i.e. $1 \leqq p_T \leqq 4$ GeV/c ($\sim 10\,\langle p_T\rangle$), we do not have any definitely valid models. Recent experimental investigations have presented some characteristic features of the p_T distributions at this region with respect to multiplicity and energy dependences.

So-called QCD parametrization have been proposed [1, 2] in order to reproduce the data of the p_T spectra in a wide p_T region. Following the success of the hard-collision model which account the p_T^{-8} falloff of the invariant inclusive cross sections in the high p_T region, several authors have proposed their empirical parametrization

$$E d^3 \sigma / d p^3 = A(b + p_T)^{-a}. \tag{1}$$

Equation (1) yields p_T^{-a} behavior in the high p_T region because of $b \sim 1$ [1, 2]. Though (1) is introduced in an analogy with the hard-collison model for high-p_T processes, (1) is used up to low p_T region where soft interaction becomes dominant. Furthermore, in the especially low p_T region (1) deviates from the data which show the clear exponentially falling property.

Contrary to QCD parametrization, we will extend the thermodynamical model which is apparently reliable in the low p_T region.

Let us write the invariant cross sections for charged particles in terms of p_T, multiplicity per unit of rapidity ($n_y = n/\Delta y$) and square of c.m. energy (s) like

$$E d^3 \sigma_n / d p^3 = f(p_T, n_y, s). \tag{2}$$

The Bose-Einstein thermal distribution [5, 10] of secondary pions with mass m is given by

$$E d^3 \sigma_n / d p^3 = A[\exp(\alpha M_T) - 1]^{-1}, \tag{3}$$

where $M_T = (p_T^2 + m^2)^{1/2}$ is the transverse mass and $\alpha(n_y, s)$ can be written by already known ordinary temperature T as $\alpha = T^{-1}$.

It is well known that since (3) is the steeply falling distribution, (3) hardly contributes to the cross sections for relatively large p_T particles. Here we assume thermodynamical model to be valid up to the intermediate p_T region [11] where all data show the second exponentially falling slope which is one half or one third of the ordinary slope in the low p_T region. Hence, we assume production of hot thermal states* which contribute to production of these relatively large p_T particles. In our two-temperature model, adding to the ordinary thermal distribution (3) which dominates in the low p_T region, we assume the second component, i.e. the hot thermal distribution which is dominant in the intermediate (relatively high) p_T region. It is important to investigate the behaviour of this high thermal temperature. According to this

* It has been reported [12] that the multiplicity distributions at $\sqrt{s} = 200$ to 900 GeV show the different scaling curvatures between high p_T jet events and low p_T no-jet ones. We can speculate these characteristic events to come out from production of hot thermal states

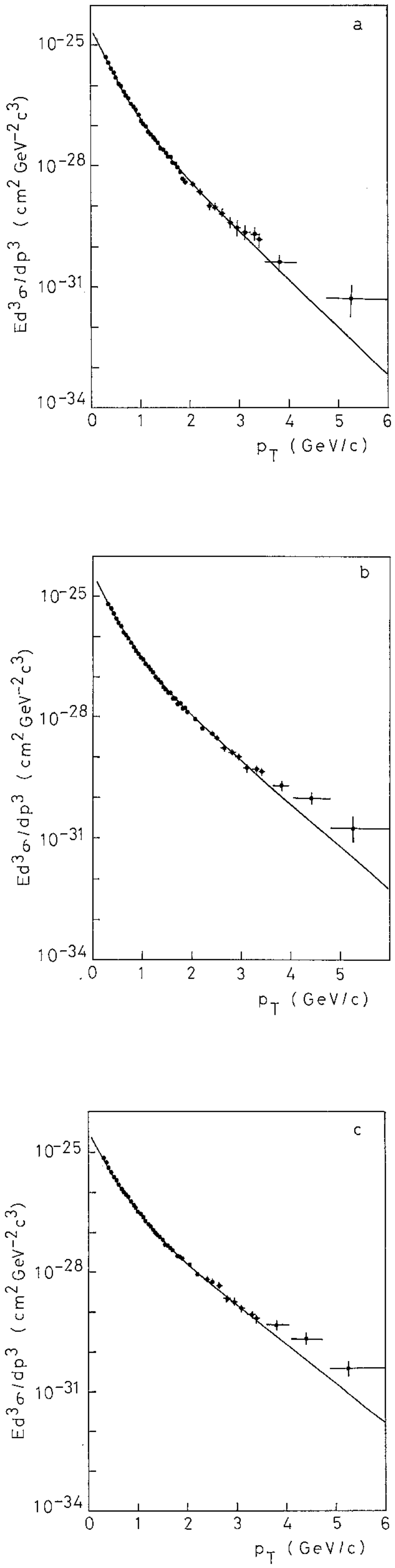

Fig. 1. The invariant cross sections as a function of p_T for charged hadrons ($\sqrt{s} = 540$ GeV) for **a** $\langle n_y \rangle = 2.4$, **b** $\langle n_y \rangle = 5.7$ and **c** $\langle n_y \rangle = 10.2$ in the interval $|y| < 2.5$ [1]. The solid lines are our calculation based on (4) (see Table 1)

Table 1. Fit parameters of $f(p_T, n_y, s) = A\{(1-R)[\exp(\alpha M_T)-1]^{-1} + R[\exp(\beta M_T)-1]^{-1}\}$ at $\sqrt{s}=540$ GeV for different multiplicities and at $\sqrt{s}=63$ GeV (at 90°). The fits were made for the region of $0<p_T<3.4$ GeV/c. The large value of χ^2 at $\sqrt{s}=63$ GeV results from uncertainty of original data

	A (10^{-25} cm^2 GeV^{-2} c^3)	R	α	β	γ	$\langle p_T \rangle$ (GeV/c)	χ^2	DoF
$\sqrt{s}=540$ GeV								
$\langle n/\Delta y \rangle$								
2.4	2.43 ± 0.05	0.040 ± 0.002	5.68 ± 0.05	2.76 ± 0.02	2.06	0.389	30	40
5.7	2.44 ± 0.04	0.053 ± 0.001	5.10 ± 0.04	2.46 ± 0.01	2.08	0.434	36	40
10.2	2.23 ± 0.04	0.060 ± 0.002	4.77 ± 0.04	2.26 ± 0.01	2.11	0.463	26	39
$\sqrt{s}=63$ GeV	2.88 ± 0.05	0.016 ± 0.002	7.47 ± 0.05	3.15 ± 0.02	2.37	0.38	207	12

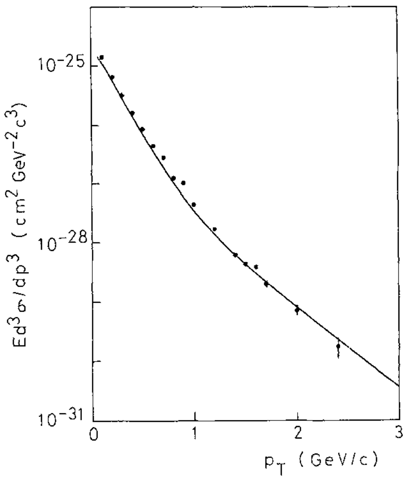

Fig. 2. The invariant cross sections as a function of p_T for charged hadrons ($\sqrt{s}=63$ GeV) at 90° [6]. The solid line is our calculation based on (4)

model, the invariant cross section (2) can be written by summation of those two components as follows;

$$f(p_T, n_y, s) = A\{(1-R)[\exp(\alpha M_T)-1]^{-1} + R[\exp(\beta M_T)-1]^{-1}\}, \qquad (4)$$

where $R = \sigma_H/(\sigma+\sigma_H)$, $\sigma(\sigma_H)$ is the cross section of ordinary (hot) thermal state production and $T_H = \beta(n_y, s)^{-1}$ indicates hot thermal state*. As shown in Figs. 1a–1c, our result gives a good agreement with the data of collider energy (see Table 1). In this analysis we introduced only two parameters (R and T_H), adding to well known ordinary T. Our model provides the satisfactory values of mean transverse momenta $\langle p_T \rangle_n$ which agree with the collider data [1]. Our analysis indicates R to be an increasing function of n and s. Therefore, we can state production of hot thermal states more clearly at higher multiplicities**. It should be noticed that both ordinary temperature and high temperature are the gradually increasing function of n and s, while the ratio of them $\gamma = T_H/T = \alpha/\beta$ is nearly constant. See, for comparison, Fig. 2 and Table 1. This indicates that hot thermal state, which is the origin of the p_T distribution at the intermediate p_T region, has always relatively high temperature compared with ordinary one independently of n and s. Therefore, if we can compare the KNO scaling distribution, which is independent of n and s, in the small p_T region with this distribution in the intermediate p_T region, we shall make certain of production of hot thermal state.

Even if those temperatures have same weak multiplicity and energy dependences, the increasing effect of the second component shall play an essential role for the rapid increase of mean transverse momenta $\langle p_T \rangle_n$. Our model yields

$$\begin{aligned}\langle p_T \rangle_n = &\sum_{j=1}^{\infty} [(1-R)(m^2 T/j) K_2(jm/T) \\ &+ R(\gamma m^2 T/j) K_2(jm/\gamma T)]/ \\ &\cdot \sum_{j=1}^{\infty} [(1-R)(2m^3 T/\pi j)^{1/2} K_{3/2}(jm/T) \\ &+ R(2\gamma m^3 T/\pi j)^{1/2} K_{3/2}(jm/\gamma T)], \qquad (5)\end{aligned}$$

where K_2 and $K_{3/2}$ are the modified Bessel function. The slight increase of the second component turns out the noticeable increasing property of $\langle p_T \rangle_n$ at collider energy because of $\gamma = 2 \sim 3$. If R increases with n quite slightly as in the case of the ISR data, $\langle p_T \rangle_n$

* Our high temperature is different from the high temperature [5, 13] which was proposed to explain large p_T phenomena

** According to the two-temperature model analysis for the semi-inclusive sphericity distribution [14], the p_T distribution of jets indicates that the hot thermal distribution becomes dominant at high multiplicities even at FNAL energy ought to show weak multiplicity dependence which comes only from the weak increasing property of two temperatures. It is expected in the future experiments at higher energies that production of hot thermal state becomes more apparent and we have more rapid increase of $\langle p_T \rangle_n$.

Acknowledgment. We are grateful to the members of the elementary particle group of Fukui University.

References

1. G. Arnison et al.: Phys. Lett. **118b**, 167 (1982)
2. M. Banner et al.: Phys. Lett. **122B**, 322 (1983)
3. L. Van Hove: Phys. Lett. **118B**, 138 (1982)
4. S. Barshay: Phys. Lett. **127B**, 129 (1983)
5. R. Hagedorn: Riv. Nuovo Cimento **6**, 1 (1983)
6. B. Alper et al.: Nucl. Phys. **B100**, 237 (1975)
7. K. Alpgard et al.: Phys. Lett. **115B**, 65 (1982); G.J. Alner et al.: Nucl. Phys. **B258**, 505 (1985)
8. K. Kudo, E.R. Nakamura: Phys. Rev. **D30**, 75 (1984)
9. W. Bell et al.: Z. Phys. C – Particles and Fields **27**, 191 (1985); A. Breakstone et al.: Phys. Lett. **183B**, 227 (1987)
10. A.T. Laasanen et al.: Phys. Rev. Lett. **38**, 1 (1977)
11. S. Kagiyama, T. Hirose: Prog. Theor. Phys. **69**, 1457 (1983)
12. F. Ceradini: CERN preprint, CERN-EP/85-196
13. C.K. Chew, Y.K. Lim, D.S. Narayan, K. K. Phua: Phys. Rev. **D30**, 1466 (1984)
14. S.P. Ratti, E.R. Nakamura, G. Introzzi: Z. Phys. C – Particles and Fields **24**, 171 (1984)