RAPIDITY AND MULTIPLICITY DEPENDENCE OF TRANSVERSE MOMENTUMSPECTRA IN pp COLLISIONS AT ISR ENERGIES

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ABSTRACT

In a high statistics experiment at the CERN-ISR we analyze the variation of the average transverse momentum in fixed rapidity intervals as a function of the multiplicity density of charged particles produced in proton-proton collisions at $\sqrt{s} = 31, 44$ and 62 GeV. The average transverse momentum depends on both rapidity y and charged multiplicity density, $\rho = \Delta n / \Delta y$. The dependence on ρ changes gradually from an increase at low y , constancy at intermediate y and decrease at large y .

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Experiments at the CERN proton-antiproton collider [1,2] at centre of mass energies between 200 and 900 GeV and at the ISR [3-5], $\sqrt{s} = 31-62$ GeV, have shown that there is an increase of the mean transverse momentum $\langle p_T \rangle$ with the density of charged particles $\rho = \Delta n / \Delta y$ produced in the central region of rapidity. A number of possible explanations of this increase have been proposed, such as thermodynamical models, geometric models, "mini-jets" and dual parton models [6-8].

In order to understand the source of this phenomenon it is important to determine precisely the shape of the $\langle p_T \rangle$ dependence on ρ and on the rapidity variable (or on any other longitudinal variable). Only experiments with very high statistics and large acceptance can answer these questions.

In previous papers [4,5], we studied the rise of $\langle p_T \rangle$ with ρ and its relation to the source size as determined through Bose-Einstein correlations. We also analyzed the energy dependence and the dependence on the type of colliding particles. Here we present an analysis of the dependence of $\langle p_T \rangle$ on charge particle density for different regions of rapidity. The data come from high statistics samples of minimum bias proton-proton events at centre of mass energies of 31, 44 and 62 GeV.

The experiment was performed at the CERN Intersecting Storage Rings (ISR) using the Split Field Magnet (SFM) detector. The magnetic volume of the detector was filled with multiwire proportional chambers and the momenta of charged particles were measured in nearly the full solid angle of 4π steradians [9]. We used a "minimum bias" trigger, which required the presence of at least one charged track in the detector. The events were reconstructed with a standard chain of computer programs. A good vertex fit, defined by a minimum of two charged tracks, was then required for each event. The interaction vertex was required to be in the overlap region of the two colliding beams. About 90% of the inelastic events were thus accepted.

In the subsequent analysis, a track was accepted if the relative precision in its momentum determination was $\Delta p/p < 0.8$. With this cut the number of badly measured tracks is substantially reduced and the remaining tracks have $\langle \Delta p/p \rangle \approx 18\%$, independent of multiplicity. Further details on

the experimental procedure can be found in references [3-5]. The present study is based on 880 000 events at $\sqrt{s} = 62$ GeV, 460 000 at 44 GeV and 1 400 000 at 31 GeV.

For each event we computed the mean value of the average transverse momentum for the $\Delta n'$ charged tracks in the rapidity interval $\Delta y'$

$$\bar{p}_T = \frac{1}{\Delta n'} \sum_{i=1}^{\Delta n'} p_{Ti} \quad (1)$$

and the mean value for all the N events having $\Delta n'$ tracks in $\Delta y'$

$$\langle p_T \rangle_{y,\rho} = \frac{1}{N} \sum_{j=1}^N \bar{p}_{Tj} \quad (2)$$

Unless otherwise stated we used the p_T range $0.15 < p_T < 2.5$ GeV/c. This method makes the best use of the statistics, but yields values of $\langle p_T \rangle$ slightly larger than the true values because of the low p_T cut. The method is nevertheless useful for the analysis of the variations of $\langle p_T \rangle$ on the charged particle density ρ and on the rapidity y (or pseudo-rapidity η). No correction for geometrical acceptance was applied. A number of checks were performed to ensure that the cuts at low and high p_T as well as other cuts did not affect the dependence of $\langle p_T \rangle$ on particle multiplicity and on rapidity [4,5].

In the analysis we shall use for each charged particle the absolute value of the c.m. rapidity variable

$$|y| = \left| \frac{1}{2} \ln \left(\frac{E + p_1}{E - p_1} \right) \right|, \quad (3)$$

where E and p_1 are the c.m. energy and longitudinal momentum of the produced charged particle. The use of the absolute value is appropriate, since the pp system is forward-backward symmetric. Since the SFM detector was not capable of identifying particles (except in a limited region), the pion mass was assumed for each track in order to compute y .

In order to compare with other data we shall also use the c.m. pseudo-rapidity, $|\eta| = |-\ln \tan \theta/2|$, where θ is the c.m. polar angle.

It was found convenient to also use the laboratory rapidity $y_{\text{lab}} = y_{\text{max}} - y$. It should be remembered that the rapidity variable is an additive variable when performing a Lorentz transformation.

We define the average multiplicity density, $\rho = \Delta n / \Delta y$, to be the number of charged particles in the whole phase space divided by the whole rapidity range (2×3.6 at $\sqrt{s} = 31$ GeV, 2×3.9 at 44 GeV, 2×4.2 at 62 GeV).

Fig. 1 shows the average transverse momentum $\langle p_T \rangle_{y,\rho}$ of the charged particles produced in specific rapidity bins plotted versus the average charged particle multiplicity density ρ in the whole rapidity range for pp collisions at $\sqrt{s} = 31, 44$ and 62 GeV. The main features of the spectra are the following:

- (a) In the central region, that is in the rapidity bins $0 - 0.5$ at 31 GeV, $0 - 1$ at 44 GeV and $0 - 1.5$ at 62 GeV, the average transverse momentum increases with multiplicity density. The rate of increase is larger at higher energy.
- (b) The average transverse momentum is essentially constant, independent of multiplicity density in the rapidity ranges $0.5 - 1.5$ at 31 GeV, $1 - 2$ at 44 GeV and $1.5 - 2.5$ at 62 GeV.
- (c) In the fragmentation region ($|y| > 2.5$), $\langle p_T \rangle_{y,\rho}$ decreases with increasing ρ , relatively slowly in $2.5 < y < 3$, and very fast in the next rapidity bins.

The same features are observed for positive and for negative tracks. As an example fig. 2 shows the distributions for negative tracks at $\sqrt{s} = 62$ GeV. A comparison of the main features of the data of fig. 1(c) (all charged tracks) with those of fig. 2 (negative tracks) shows that there are no major differences (but in the fragmentation region the $\langle p_T \rangle$ for all charged tracks is slightly larger than that for negative tracks). Negative tracks are mainly pions, with a small percentage of kaons and antiprotons. Positive tracks have a large proton content in the fragmentation region. A comparison of the data of fig. 1 in terms of the rapidity variable with those in terms of the pseudo-rapidity variable shows that identical features are observed when using the rapidity or the pseudo-rapidity variable.

We also checked that the same features apply to the dependence of $\langle p_T \rangle_{y,\rho}$, where the multiplicity density $\rho' = \Delta n'/\Delta y'$ is the multiplicity of particles inside the chosen $\Delta y'$ bin (fig. 3). Note that $\rho' > \rho$.

It was already pointed out in [3-5] that the increase of $\langle p_T \rangle$ with increasing ρ is enhanced when a low p_T cut is applied. We checked that the features shown in figs 1-2 remain the same, although the absolute values change, when the low p_T cut is raised.

The behaviour of $\langle p_T \rangle_{y,\rho}$ versus ρ in the fragmentation region at different energies suggests that it would be preferable to perform analyses using the laboratory rapidity variable, which is better suited to study the fragmentation region. Fig. 4 shows distributions of $\langle p_T \rangle_{y_{lab},\rho}$ versus ρ using y_{lab} as parameter. It is observed that in the lower y_{lab} bins the data at the three energies superimpose one another. The largest differences are at the largest y_{lab} , where the y_{lab} range changes with energy.

The average value of the transverse momentum in each rapidity bin may be computed from exponential fits of the invariant p_T distribution $E d^3\sigma/dp^3 = A \exp(-Bp_T)$ at fixed rapidity in the p_T range $0.25 < p_T < 0.65$ GeV/c ($\langle p_T \rangle_y = 2/B$). Using a sample of fully corrected data [10] we obtain the results shown in fig. 5. These average p_T have a relative large statistical error, but a considerably smaller systematic error [11]. The $\langle p_T \rangle$ for negative tracks is almost constant from $y = 0$ to $y = 2$ and becomes smaller for larger rapidity values. Positive particles yield a $\langle p_T \rangle$ distribution similar to the one for negative tracks for values of $|y| < 2$. At larger values of y the average p_T increases. It has to be remembered that at large y the proton contribution to positive tracks becomes dominant. The wrong assignment of the pion mass to protons and kaons shifts their rapidities to larger values.

We checked with a sample of data in a limited y -range that the shape of $\langle p_T \rangle$ versus ρ is the same when $\langle p_T \rangle$ is computed using formulae (1), (2) or as $2/B$.

In order to determine to what extent the dependence of $\langle p_T \rangle_{y,\rho}$ on $\rho = \Delta n/\Delta y$ may be explained by simple arguments (e.g. phase space alone), we

have compared our experimental distributions with a Monte-Carlo calculation based on longitudinal phase space (LPS). In the LPS Monte-Carlo the matrix element cuts off high transverse momenta in order to have $\langle p_T \rangle = 0.4$ GeV/c, and two protons are treated as leading particles with flat dn/dx distributions.

Fig. 6 shows our data and the prediction of longitudinal phase space at $\sqrt{s} = 62$ GeV in two rapidity bins ($|y| < 0.5$ and $3 < |y| < 3.5$). For $|y| < 0.5$ the LPS calculation predicts some increase of $\langle p_T \rangle_{y,\rho}$ with ρ ; however the measured increase is stronger than what is predicted by LPS and it extends to larger $\Delta n/\Delta y$. This may be interpreted by saying that the increase of $\langle p_T \rangle_{y,\rho}$ versus ρ is mainly of a dynamical origin.

For $3.0 < |y| < 3.5$ the measured decrease of $\langle p_T \rangle_{y,\rho}$ with increasing ρ is reproduced approximately by the longitudinal phase space calculation. This may suggest that part or most of the decrease is due to phase space limitations.

In conclusion, we have studied the dependence of $\langle p_T \rangle_{y,\rho}$ versus $\rho = \Delta n/\Delta y$ and $\rho' = \Delta n'/\Delta y'$ for proton-proton data at 31, 44 and 62 GeV, using different bins in c.m. rapidity and lab rapidity. The following features are found:

- (a) There is no factorization in (p_T, ρ) nor in (p_T, y) . The dependence of $\langle p_T \rangle$ on ρ changes gradually from an increase at low y , constancy at intermediate y , decrease at large y . The dependence of $\langle p_T \rangle$ on y is small at small y and larger at larger y .
- (b) In the central region, $|y| < 1.5$, the global increase of the average transverse momentum with $\Delta n/\Delta y$ is stronger the higher the c.m. energy.
- (c) In the fragmentation region, $y_{\text{lab}} < 1.5$, the average transverse momentum decreases with increasing $\Delta n/\Delta y$. Some or most of this decrease is connected to phase-space limitations.

We shall briefly comment on possible explanations of the above findings in the framework of the dual parton model [12-14]. In this model the multiplicity dependence of the average transverse momenta in very high energy collisions may be explained abandoning the purely soft multi-Pomeron

version and introducing a semi-hard component without changing the basic structure of particle production. Minimum bias physics is thus not purely soft, but the transition occurs gradually, without drastic changes. In this approach the initial partons may acquire a semi-hard transverse momentum, either via multiple-gluon emission or via semi-hard scattering, before hadronization. The increase of $\langle p_T \rangle$ with ρ in the central region arises because in high multiplicity events there are many strings, the additional strings being short, with the result that more particles will be produced close to the string ends and more particles will obtain a significant fraction of the momentum of the parton at the end of the string. No positive correlations are expected outside of the central region (populated by sea strings); negative correlations (decrease of $\langle p_T \rangle$ with increasing ρ) should arise there from the dominance of doubly diffractive events and because the $\langle p_T \rangle$ of the valence parton is shared by an increasing number of particles.

An alternative explanation comes from a multiperipheral model with a random walk effect in the various exchanges which can generate high transverse momentum particles, i.e. the products of an apparent hard scatter.

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FIGURE CAPTIONS

- Fig. 1 The average transverse momentum of charged particles produced in specific rapidity bins plotted versus average charged particle density, ρ , in pp collisions at: (a) $\sqrt{s} = 31$ GeV, (b) 44 GeV and (c) 62 GeV. Bin sizes are 0.5 absolute rapidity (a total of 1 in rapidity). The average transverse momentum is computed using the $0.15 < p_T < 2.5$ GeV/c range.
- Fig. 2 Distributions as in fig. 1(c), but for the production of negative particles. The multiplicity density is relative to charged tracks in the full phase space as in fig. 1.
- Fig. 3 The average transverse momentum of charged particles produced in specific rapidity bins versus the average charged particle density in the same bin, ρ' , for pp collisions at 62 GeV and for three rapidity bins.
- Fig. 4 Distributions as in fig. 1, but using the laboratory rapidity, y_{lab} .
- Fig. 5 Distribution in $\langle p_T \rangle_y$, the average transverse momentum, integrated over charged particle multiplicity, plotted versus y . It was computed from exponential fits of fully corrected p_T distributions. The systematic errors of these determinations are estimated to be $\sim 5\%$. For $y > 2$ the data points for positive particles are not exact (see text).
- Fig. 6 Distribution in $\langle p_T \rangle_{y,\rho}$ plotted versus ρ at $\sqrt{s} = 62$ GeV for the two rapidity bins $|y| < 0.5$ and $3 < |y| < 3.5$. Black points show the data; the solid and dashed lines are the predictions of the longitudinal phase space Monte-Carlo, for $0.15 < p_T < 2.5$ GeV and for all p_T values, respectively.

Fig. 1

Fig. 2

Fig. 3

dN/dy

Fig. 4

Fig. 5

Fig. 6