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MULTIPLICITY DEPENDENCE OF THE AVERAGE TRANSVERSE MOMENTUM AND OF THE
PARTICLE SOURCE SIZE IN p-p INTERACTIONS AT $\sqrt{s} = 62, 44$ AND 31 GeV

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ABSTRACT

The average transverse momentum and the size of the particle emitting source (measured via Bose-Einstein correlations) have been studied as functions of the charged particle density in the central region in p-p interactions at $\sqrt{s} = 62, 44$ and 31 GeV. Both the average transverse momentum and the source size increase with increasing density at all three energies. This effect, very weak at $\sqrt{s} = 31$ GeV, becomes stronger with increasing energy.

1. INTRODUCTION

Recent experiments at the CERN $\bar{p}p$ collider at various centre of mass energies, $\sqrt{s} = 540$ GeV [1], $\sqrt{s} = 200$ and 900 GeV [2] and at the highest ISR energy, $\sqrt{s} = 62$ GeV [3], have shown that there is an increase in the mean transverse momentum, $\langle p_T \rangle$, with the charged particle density in the central rapidity region, $\rho = \Delta n / \Delta y$. A number of possible explanations for this increase have been proposed. Among these are geometrical models [4], "mini-jets" production [5], and thermodynamical models [6].

An increase of the particle emitting source radius, r , with mean charged multiplicity which may be explained by a geometrical model [7], was measured in a study of Bose-Einstein (B-E) correlations in $\alpha\alpha$ interactions at $\sqrt{s} = 126$ GeV and in $\bar{p}p$ and pp interactions at $\sqrt{s} = 53$ and 62 GeV [8]. At $\sqrt{s} = 31$ GeV [3], no clear evidence of an increasing $\langle p_T \rangle$ with charged multiplicity was observed. Previous measurements of $\langle p_T \rangle$ and r at $\sqrt{s} = 19$ GeV [9] have also shown no dependence on the charged multiplicity.

It has been suggested recently [10] that in the framework of some thermodynamical models [6,11] one could find a correlation between the dependence on multiplicity of the pions' emitting volume and $\langle p_T \rangle$ which can be used to search for a possible phase transition from hadronic matter to quark-gluon plasma. In such models, the p_T distribution of secondaries reflects both the temperature and the evolution in the transverse direction of the hadronic system, while the central particle density provides a measure of the entropy. The radius, measured via Bose-Einstein correlations, gives information on the final volume of the particle emitting source after a possible expansion following the early stages of the interaction.

In this paper we present the results of a comparative analysis of the dependence of $\langle p_T \rangle$ and r on ρ (the charged particle density in the central region) in pp interactions at $\sqrt{s} = 62, 44$ and 31 GeV. Previous results on these subjects, with lower statistics, have been presented [3, 12, 13].

2. EXPERIMENT

The experiment was performed at the CERN Intersecting Storage Rings (ISR) using the Split Field Magnet (SFM) detector. The magnetic volume of the detector (with a maximum field strength of 1 Tesla) was filled with Multiwire Proportional Chambers. The momenta of the charged particles were measured over nearly the full solid angle. The performance of the detector is described in previous publications [14].

The experiment used two different triggers: (i) a "minimum bias" trigger, which required the presence of at least one charged track candidate in the detector, accepted about 95% of the inelastic cross section and (ii) an "electron trigger" which selected events with an electron candidate of positive or negative charge produced at a polar angle of 90° . A two-stage Cherenkov counter system was used to identify the electrons. The trigger particles covered a c.m.s. rapidity region $|y| < 0.35$ and an azimuthal angle region $|\phi| < 9^\circ$ [15]. Events were reconstructed with the standard chain of computer programs for the SFM detector. A good vertex fit, defined by a minimum of two charged tracks, was then required for each event. The present analysis is based on $\sim 880\,000$, $460\,000$ and $1\,400\,000$ "minimum bias" events at $\sqrt{s} = 62$, 44 and 31 GeV respectively and $\sim 350\,000$ "electron trigger" events at $\sqrt{s} = 62$ GeV.

3. ANALYSIS

A number of selection criteria were applied to the data:

- (a) The reconstructed interaction vertex was required to be in the overlap region of the two colliding beams.
- (b) Low multiplicity events (less than 5 charged particles), which may contain diffraction, were rejected.
- (c) In order to remove background from badly measured tracks at large p_T , only particles with $p_T < 3.0$ GeV/c were used.

- (d) Tracks were accepted if the estimated relative error in the measurement of their momenta, $\Delta p/p$, was less than 0.8. This cut substantially reduces the number of badly measured tracks and gives $\langle \Delta p/p \rangle \sim 0.18$, independent of multiplicity in the central region.

The charged multiplicity in the central region (defined as $\Delta y = -1.5 < y < 1.5$) was not corrected for acceptance losses. With the above cuts, these losses were estimated to be $\sim 20\%$ on average. After the above cuts were applied, we defined the charged particle density, $\rho = \Delta n/\Delta y$, to be the number of charged tracks per unit rapidity interval. All tracks were assumed to be pions.

3.1 Average transverse momentum determination

The average transverse momentum, $\langle p_T \rangle$, was estimated from the arithmetic mean

$$\langle p_T \rangle = \frac{1}{m} \sum_{i=1}^m (p_T)_i.$$

Only those tracks in a restricted range, $p_T \in [0.15, 2.5]$ GeV/c were used in this calculation in order to avoid acceptance problems at low p_T and to further suppress the contribution from badly measured tracks at large p_T . In terms of the charged particles density, $\rho = \Delta n/\Delta y$, for an event with Δn charged tracks in the rapidity range Δy only the subset of m tracks in the restricted p_T -range was used to estimate the average.

In order to check the validity of the average p_T determination, for some event subsamples a different method was used [12]. Specifically, the p_T distributions of the tracks in the range $0.3 < p_T < 0.8$ GeV/c were fitted to the exponential form $d\sigma/dp_T^2 = A \exp(-bp_T)$. The average transverse momentum was then computed from the fitted value of the slope, i.e. $\langle p_T \rangle = 2/b$. These checks lead to the conclusion that the $\langle p_T \rangle$ dependence on ρ has the same general shape when computed using either of the two methods.

Our reported values of $\langle p_T \rangle$ have not been corrected for acceptance losses. Acceptance corrections have been computed via Monte-Carlo simulation over limited phase-space regions covered by the apparatus. To

analyse the effects of the full acceptance, we then proceeded with following two steps:

- (a) First we computed the invariant inclusive cross section as a function of p_T and of y in the ranges $0.15 < p_T < 2.5$ GeV/c, $|y| < 1.5$, using only those regions of the apparatus in which the acceptance is well known and above 90%. This yields results in complete agreement with published data at the same energies.
- (b) Second, in the same regions used in (a), we computed the acceptance corrected values of p_T distributions. Comparing these corrected values with the uncorrected ones computed on the full apparatus, the differences found in the absolute values of the $\langle p_T \rangle$'s were at most around 20%, but the shape of the $\langle p_T \rangle$ dependence on ρ was essentially unchanged.

This procedure was repeated for different cuts in $\Delta p/p$, azimuthal angle ϕ and Δy , yielding the same conclusions. We present the results from the full apparatus.

3.2 Measurement of the particle source radius

We use Bose-Einstein correlations between like-charged pairs of particles to determine the size of the emitting regions. Results on Bose-Einstein correlations in pp and $\bar{p}p$ interactions at $\sqrt{s} = 62$ GeV and a detailed discussion on the non-interfering background have been published [13]. The following points should be noted:

- (a) Since all tracks were assumed to be pions in the analysis, the small contamination by kaons, protons and antiprotons results only in the observed interference effect appearing smaller than reality.
- (b) In addition to the cuts mentioned in the previous section, for each particle we required $\Delta p < 0.1$ GeV/c, where Δp is the estimated error in the momentum measurement of the track. This results in a relative error $\langle \Delta p/p \rangle \sim 0.08$ which was observed to be independent of particle density.
- (c) As for the average p_T computation, tracks with $p_T < 0.15$ GeV/c were rejected.

- (d) Events were kept in the analysis only if they contained at least two positive tracks and one negative track or vice versa in the interval $|y| < 1.5$.

Several parametrizations of the ratio between like and unlike pairs of charged particles, $R = N_L/N_U$, in terms of the variables constructed from the particle momenta were proposed [16]. In this work, R was analysed for different central rapidity densities as a function of the Lorentz invariant quantity for two particles $Q^2(12) = M^2(12) - (m_1 + m_2)^2$ as proposed in ref. [17].

The ratios, R , for different charged particle densities, ρ , were fitted to a function of the form

$$R(Q^2) = \gamma(1 + \alpha e^{-\beta Q^2})(1 + \delta \cdot Q), \quad (1)$$

where the parameter α , which is often called the chaoticity parameter, lies between zero (no Bose-Einstein effects) and one (maximum chaoticity and thus maximum interference). The parameter β is related to the emission radius, ($r = 0.197 \sqrt{\beta}$ fm), γ is a normalization factor and the term $(1 + \delta \cdot Q)$ accounts for the shape of R at large Q , ($Q \equiv \sqrt{Q^2}$). The parametrization (1) gives the space-time dimension of the particle emitting region and leads to values of r somewhat lower than different parametrization used in the literature [18]. All fits had values of χ^2/DOF close to unity.

4. RESULTS

4.1 Average p_T versus ρ for minimum bias data

The average transverse momenta of charged particles, computed in the previously mentioned p_T interval, as functions of the particle density in the central rapidity region, are shown in fig. 1. The plots refer to minimum bias events at $\sqrt{s} = 62$ GeV. In fig. 1(a) the $\langle p_T \rangle$'s for all charged particles are displayed, while figs 1(b) and 1(c) show the same quantities for negative and positive particles separately. The rise of $\langle p_T \rangle$ with the density is clearly seen. Taking the lower boundary of the p_T interval to be $p_T = 300$ MeV/c further enhances the rise of $\langle p_T \rangle$ with ρ , as was shown [3].

The same analysis of $\langle p_T \rangle$ as a function of ρ has been done for the minimum bias events at $\sqrt{s} = 44$ and 31 GeV. The results are shown in fig. 2(a) for $\sqrt{s} = 44$ and in fig. 2(b) for $\sqrt{s} = 31$ GeV. Comparing with the $\sqrt{s} = 62$ GeV data one can see that a similar dependence of the $\langle p_T \rangle$ on ρ is also present at 44 and 31 GeV but the $\langle p_T \rangle$ rise becomes weaker with decreasing $\sqrt{s}$. The weak rise of $\langle p_T \rangle$ at 31 GeV was not observed in our previous work [3, 12], in which the statistics were ~ 8 times smaller than available now and the $p_T > 0.15$ GeV/c cut was not applied.

4.2 Average p_T versus ρ for electron trigger data

The mean raw multiplicity in the electron sample, in the central region ($-1.5 < y < 1.5$), is about a factor of 2.5 larger than that of minimum bias events at the same energy. For these data, we analyzed the average p_T dependence on ρ separately for the trigger track and for all the other tracks.

Fig. 3(a) shows the $\langle p_T \rangle$ of the trigger particle, computed in the p_T range 0.4 - 1.0 GeV/c where the hadronic contamination to the trigger is estimated to be below 30% [15]. Only tracks with $\Delta p/p < 0.30$ have been used. With this cut the $\langle \Delta p/p \rangle$ of the tracks used in the analysis is 0.09.

The average p_T of all the secondary particles is shown in fig. 3(b). It is computed in the same way as in the minimum bias analysis.

Finally, in fig. 3(c) the average p_T as a function of ρ for non-trigger particles that lie in a ϕ interval of $\pm 40^\circ$ around the trigger track are shown. The $\langle p_T \rangle$ was computed considering all the tracks (apart from trigger) with $0.15 < p_T < 2.5$ GeV/c.

4.3 Average p_T versus local density

Since it is known [19] that the particle density reaches its highest values when $|y| \rightarrow 0$, we recompute the average p_T and all particle densities taking into account only those tracks in the rapidity interval $-0.5 < y < 0.5$. The results for the minimum bias data at $\sqrt{s} = 62$ GeV are shown in fig. 4(a). In fig. 4(b), we show the $\langle p_T \rangle$ of the trigger track in the electron trigger sample ($0.4 < p_T < 1.0$ GeV/c) as a

function of ρ , where in this case ρ is computed taking only those tracks lying in an interval $\Delta y = 1$ centred around the trigger particle rapidity.

4.4 Source dimensions

Figs 5(a), 5(c) and 5(d) show the radius r of the particle emitting region as a function of ρ at $\sqrt{s} = 62, 44$ and 31 GeV, respectively. A clear rise of r with increasing particle density is visible in the data at $\sqrt{s} = 62$ GeV, ranging from ~ 0.72 fm for $\rho < 2$ up to ~ 1.7 fm at $\rho \sim 6$. It was pointed out [18] that, due to the finite momentum resolution, the maximum measured value of r can only be an underestimate of the true maximum value. A very weak dependence of r on the particle density in the central region is observed at $\sqrt{s} = 31$ GeV (fig. 5(d)), while a rise of r with ρ is observed at 44 GeV in the ρ region between 1 and 4. The values of r as a function of ρ for electron trigger events are presented in fig. 5(b). They range from ~ 0.8 at ρ around 2 to about 1.3 at ρ around 6.

The values of the chaoticity parameter α , as shown in figs 6(a)-6(d), lie between 0.50 and 0.30, and decrease slowly with increasing multiplicity, at least up to ρ around 4, for all the three energies. The behaviour shown in figs 6(a)-6(c) is in agreement with previous results at ISR energies [8].

5. CONCLUSIONS

We have performed an analysis of the behaviour of the average transverse momentum and of the size of the particle emitting region as a function of the charged particle density variable, $\rho = \Delta n / \Delta y$, at $\sqrt{s} = 62, 44$ and 31 GeV using minimum bias trigger events. An additional sample of electron trigger events at $\sqrt{s} = 62$ GeV was also analyzed. The main results are:

- (i) The mean transverse momentum increases with increasing ρ at all energies. The rise of $\langle p_T \rangle$ becomes steeper when $\sqrt{s}$ increases from 31 to 62 GeV. In the electron trigger events an increase of the $\langle p_T \rangle$ of the trigger particle, as well as of the non-trigger particles, with increasing ρ is observed. Qualitatively the rise is approximatively linear in all cases, up to ρ around 4-5. In this region a flat distribution is visible which, when going to local density, is moved to values of ρ around 6-7.
- (ii) Also the particle source size increases with particle density. The rise, very weak at 31 GeV, becomes clear at $\sqrt{s} = 62$ GeV both in the minimum bias data and in the electron trigger data. The chaoticity parameter α slowly decreases with ρ at all energies at least for $\rho < 4$.

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FIGURE CAPTIONS

Fig. 1 (a) The average transverse momentum of charged particles, with $0.15 \leq p_T \leq 2.5$ GeV/c, produced in the central region of rapidity ($|y| \leq 1.5$) plotted versus charged particle density ρ , at $\sqrt{s} = 62$ GeV.

(b) Same as in (a) for negative particles only.

(c) Same as in (a) for positive particles only.

Fig. 2 The average transverse momentum of charged particles, with $0.15 \leq p_T \leq 2.5$ GeV/c, produced in the central region of rapidity ($|y| < 1.5$), plotted versus charged particle density, at (a) $\sqrt{s} = 44$ GeV and (b) $\sqrt{s} = 31$ GeV.

Fig. 3 Electron trigger data; $\sqrt{s} = 62$ GeV:

(a) The average transverse momentum of the triggering particle with $0.4 < p_T < 1$ GeV/c, as a function of $\rho = \Delta n / \Delta y$.

(b) The average transverse momentum of all the non-trigger particles having $0.15 \leq p_T \leq 2.5$ GeV/c as a function of ρ .

(c) The average transverse momentum for non-trigger particles, with $0.15 \leq p_T \leq 2.5$ GeV/c, lying in a ϕ interval of $\pm 40^\circ$ around the trigger track.

Fig. 4 (a) The average transverse momentum for tracks having $0.15 \leq p_T \leq 2.5$ GeV/c and $|y| < 0.5$ as a function of the particle density in the same y interval for minimum bias data at $\sqrt{s} = 63$ GeV.

(b) Electron trigger data. The average transverse momentum of the triggering track as a function of the particle density computed for the y interval ± 0.5 around the triggering track rapidity.

Fig. 5 Radius of the particle emitting source as a function of ρ :

(a) Minimum bias trigger at $\sqrt{s} = 62$ GeV.

(b) Electron trigger at $\sqrt{s} = 62$ GeV.

(c) Minimum bias trigger at $\sqrt{s} = 44$ GeV.

(d) Minimum bias trigger at $\sqrt{s} = 31$ GeV.

FIGURE CAPTIONS (Cont'd)

Fig. 6 Chaoticity parameter α as a function of ρ :

- (a) Minimum bias trigger at $\sqrt{s} = 62$ GeV.
- (b) Electron trigger at $\sqrt{s} = 62$ GeV.
- (c) Minimum bias trigger at $\sqrt{s} = 44$ GeV.
- (d) Minimum bias trigger at $\sqrt{s} = 31$ GeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6