THREE-PARTICLE RAPIDITY CORRELATIONS
IN PROTON-PROTON INTERACTIONS AT ISR ENERGIES

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ABSTRACT

Measurements are presented of short range three-particle rapidity correlations in pp interactions at c.m. energies $\sqrt{s} = 31, 44$ and 62 GeV. The data were obtained at the CERN Intersecting Storage Rings (ISR) using the Split Field Magnet Detector (SFM) with a minimum bias trigger. Three-particle short range rapidity correlations are observed for the $(-+-)$ and $(+--)$ combinations; no short-range rapidity correlation is observed for the $(---)$ and $(+++)$ configurations. The rapidity range of the three-particle correlations is approximately the same as for the two-particle correlations.

Short-range rapidity correlations are one of the main features of multiparticle production in high energy interactions at low p_T . Two-particle rapidity correlations have been extensively studied at the CERN ISR [1-9] and elsewhere. There are only few measurements of three-particle rapidity correlations, mainly using the rapidity gap method [5-8]. Large statistics and large solid angle coverage are required to study three-particle correlations.

In this letter we present the measurements of three-particle rapidity correlations in pp interactions at c.m. energies $\sqrt{s} = 31, 44$ and 62 GeV. We find short-range rapidity correlations in the $(-+-)$ and $(+--)$ charge combinations, but not in the $(---)$ and $(+++)$ combinations.

The experiment was performed at the CERN ISR using the Split Field Magnet (SFM) Detector [10]. The magnetic volume of the detector (with a maximum field strength of 1 Tesla) was filled with multiwire proportional chambers. The momenta of charged particles were measured in nearly the full solid angle.

This experiment used a "minimum bias" trigger, which essentially required the presence of at least one candidate track in the detector. This trigger accepted $\sim 95\%$ of the inelastic cross section. The events were reconstructed with the standard SFM chain of computer programs. A successful vertex fit, defined by a minimum of two tracks, was required for each event. This reduced the acceptance to $\sim 90\%$ of the inelastic cross section.

The available raw data include 1.4 million triggers at $\sqrt{s} = 31$ GeV, 0.5 million at 44 GeV and 0.82 million at 62 GeV. Note that the statistics are almost an order of magnitude larger than in our previous analyses of two-particle and multiparticle rapidity correlations [3-5].

A number of selection criteria were applied to the data:

- (a) For the present analysis, each selected event was required to have a number of charged tracks ≥ 8 .
- (b) Charged tracks were accepted if the relative precision in the measurement of their momenta was $\Delta p/p < 1$ in order to reduce the number of badly measured tracks and ensure the correct charge determination of the track.

- (c) The Feynman-x for each track was required to be smaller than 0.2, $|x_F| < 0.2$. This cut reduces the contribution from diffractive events.

The contamination of electrons from π^0 and γ conversions was estimated to be $\sim 2\%$ and was neglected. No other corrections, such as for acceptance were made. We point out that acceptance corrections cancel out in the correlation functions defined below (if the two and three-track acceptances are equal to the product of the one-track acceptances, see below). As for most detectors, the SFM detector was not able to identify charged particles in the whole region of phase space; thus, the pion mass has been assigned to all particles when computing rapidities.

Consider the inclusive reactions

$$p + p \rightarrow h_1 + h_2 + X, \quad (1)$$

$$p + p \rightarrow h_1 + h_2 + h_3 + Y, \quad (2)$$

where h_1, h_2, h_3 are charged hadrons. In analogy with previous studies we define the single-particle rapidity density $\rho_1(y) = \sigma_{in}^{-1} d\sigma/dy$, the two-particle density $\rho_2(y_1, y_2) = \sigma_{in}^{-1} d^2\sigma/dy_1 dy_2$ and the three-particle density $\rho_3(y_1, y_2, y_3) = \sigma_{in}^{-1} d^3\sigma/dy_1 dy_2 dy_3$. The normalized two and three-particle correlation functions [11] are then written as

$$\begin{aligned} R_2(y_1, y_2) &= \rho_2(y_1, y_2) / \rho_1(y_1) \rho_1(y_2) - 1 \\ &= \sigma_{in} (d^2\sigma/dy_1 dy_2) / [(d\sigma/dy_1)(d\sigma/dy_2)] - 1, \end{aligned} \quad (3)$$

and

$$\begin{aligned} R_3(y_1, y_2, y_3) &= [\rho_3(y_1, y_2, y_3) + 2\rho_1(y_1) \rho_1(y_2) \rho_1(y_3) \\ &- \rho_2(y_1, y_2) \rho_1(y_3) - \rho_2(y_2, y_3) \rho_1(y_1) - \rho_2(y_3, y_1) \rho_1(y_2)] \\ &\times \{\rho_1(y_1) \rho_1(y_2) \rho_1(y_3)\}^{-1}. \end{aligned} \quad (4)$$

A peak in R_2 indicates the existence of short-range correlations between charged hadrons h_1 and h_2 in reaction (1). Similarly, a peak in R_3 indicates the existence of correlations between hadrons h_1, h_2 and h_3 in

reaction (2); these true three-particle correlations do not depend on the presence of two-body correlations, which are removed in the definition (4). The two-body correlations however would be present in the quantity

$$R'_3(y_1, y_2, y_3) = \frac{\rho_3(y_1, y_2, y_3) - \rho_1(y_1) \rho_1(y_2) \rho_1(y_3)}{\rho_1(y_1) \rho_1(y_2) \rho_1(y_3)}. \quad (5)$$

In practice, for the two-track correlation function we used the quantity

$$R_2(y_1, y_2) = N N_2(y_1, y_2) / [N_1(y_1) N_1(y_2)] - 1, \quad (6)$$

where, in a sample of N events, $N_1(y_1)$ tracks are observed within Δy_1 at rapidity y_1 and $N_2(y_1, y_2)$ pairs are observed within Δy_1 and Δy_2 at rapidities y_1 and y_2 respectively.

For the three-particle correlation function we fix the rapidities of h_1 and h_2 at equal values, $y_1 = y_2$, with the same bin size $\Delta y = \Delta y_1 = \Delta y_2$, and vary the rapidity y_3 of h_3 (again with the same bin size $\Delta y_3 = \Delta y$).

The ability of the SFM Detector to measure the momentum and charge of the produced charged particle allows us to study the correlations R_2^{+-} , R_2^{++} , R_2^{--} , R_3^{+-} , R_3^{++} , R_3^{--} , R_3^{+++} .

Fig. 1 shows the normalized three-particle rapidity correlation functions for the configurations $(-+-)$, $(+--)$, $(---)$ and $(+++)$, plotted versus the rapidity of particle 3, where the first two particles are kept fixed at rapidities $y_1 = y_2 = 0$, within bins $\Delta y_1 = \Delta y_2 = 0.5$. For R_3^{--} , particle 1 is negative, particle 2 is positive and particle 3 is negative; for R_3^{++} , particles 1 and 3 are positive and particle 2 is negative. For clarity only few errors are shown; the fluctuations of the points give an estimate of the statistical errors. It is observed that the correlation functions R_3^{+-} and R_3^{++} are within errors equal and that they exhibit a peak at $y_3 = 0$. The heights of the peaks seem to be largest at $\sqrt{s} = 62$ GeV and smallest at $\sqrt{s} = 31$ GeV. Fig. 1 also indicates that there is no clear three-particle short-range rapidity correlation in R_3^{--} and in R_3^{+++} . However, the positive values (with a mean value of ~ 0.05) suggest the presence of some longer range correlation, as discussed in ref. [5].

Fig. 2 shows the correlation function $R_3'^{-+-}$ as defined in (5): it has a large peak at $y = 0$, whose main contribution must come from two-body correlations, as already discussed.

At 62 GeV, we checked that when particle 1 is in a Δy_1 bin at $y_1 = -0.5$ and particle 2 is in a Δy_2 bin at $y_2 = +0.5$, $R_3'^{-+-}$ has a peak as for $R_3'^{-+-}$ for the case $y_1 = y_2 = 0$, but in this case the height is smaller and the width is larger.

Fig. 3 shows the three-particle correlation functions $R_3'^{-+-}$ and $R_3'^{++-}$ for fixed rapidities $y_1 = y_2 = 1$ of particles h_1 and h_2 . In this case, one observes a peaking of the correlation functions around $y_3 = +1$ at 62 GeV; at lower energies the correlations are smaller. The fact that the peak at $\sqrt{s} = 62$ GeV moves in y_3 , when y_1 and y_2 are changed, is a clear indication of the existence of correlations. For $y_1 = y_2 = -1$ there is a situation very similar to that illustrated in fig. 3, with a peak at $y_3 = -1$. For $y_1 = y_2 = +2$ and -2 , no clear correlation is observed within present statistical uncertainties.

Fig. 4 shows the two-particle correlation functions $R_2'^{+-}$ and $R_2'^{--}$ at the three energies of $\sqrt{s} = 31, 44$ and 62 GeV. Particle 1 is kept fixed at $y_1 = 0$ with $\Delta y_1 = 0.5$. One observes peaks at $y_2 = 0$ for both $R_2'^{+-}$ and $R_2'^{--}$, the peak for $R_2'^{+-}$ being larger. We checked that $R_2'^{++}$ is within errors equal to $R_2'^{--}$. The peaks in $R_2'^{+-}$ and $R_2'^{--}$ seem to increase with increasing c.m. energy.

The three-particle correlations have about the same ranges of the two-particle correlations, both about two units of rapidity. The two-particle rapidity correlations are strongly dependent on the event multiplicity, which affects the shape of the distributions and the heights of the peaks [6].

The two-particle rapidity correlation data in the central region were usually described in the framework of models which incorporate independent emission of (charged) clusters, which subsequently decay [12]. Fits to these models suggested that one cluster with an average mass of 1.3 GeV was produced per one unit of rapidity and that, on the average, each

cluster decayed into 1.8 charged particles [6-8]. The data of ref. [5] were consistent with the presence of two types of clusters: one type of large, wide clusters; the other type of small, narrow ones.

In the present analysis we found that three-particle short range rapidity correlations exist for the $(-+-)$ and $(+--)$ combinations, while $(---)$ and $(+++)$ combinations do not reveal any appreciable correlation. Moreover, the widths of the three-particle correlations are similar to those of the two-particle correlations. These features agree with the cluster model interpretation.

The multiplicity distributions of charged particles produced in high energy pp and $\bar{p}p$ collisions are well described by negative binomial functions [13-15]. This may be interpreted in terms of a cascade process, where N "ancestors" are originally produced; subsequently each of these ancestors gives rise to n_c^i particles which are said to belong to a "clan" [14].

The cascade model with ancestors and clans could resemble the old cluster model. But while the clusters are small, energy independent and can mainly be interpreted as resonances, the clans needed to explain the multiplicity data seem to be quite different. With increasing c.m. energy the average number of clans grows very slowly, while the average number of particles per clan grows substantially with energy. If this is correct one would expect an increase with energy of real three-particle correlations.

It was found [15] that over the ISR energy range the number of clans is ~ 6.6 and that the mean number of charged particles per clan is about 1.7, with only a minor energy dependence. These values are about equal to what was found for the mean number of clusters and for the number of particles per cluster. Thus, the two models do not show sizeable differences in terms of rapidity correlations at ISR energies, but become quite different at higher energies.

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FIGURE CAPTIONS

Fig. 1 Three-particle rapidity correlations for (+++), (---), (-+-) and (+-+) triplets. The correlation function R_3 is plotted versus the rapidity of particle 3, y_3 , keeping fixed the rapidities of particles 1 and 2 at $y_1 = y_2 = 0$ for bins $\Delta y_1 = \Delta y_2 = \Delta y_3 = 0.5$. The data are for pp collisions at $\sqrt{s} = 31, 44$ and 62 GeV with the (a), (b) and (c) cuts discussed in the text. For clarity, error bars are included only for a few representative points.

Fig. 2 Correlation function R'_3 as defined in (5) for the +- combinations at $\sqrt{s} = 62$ GeV, keeping, as in fig. 1, the rapidities of particles 1 and 2 at $y_1 = y_2 = 0$. R'_3 contains contributions from two-body correlations, which are instead removed in the R_3 correlation function.

Fig. 3 Three-particle correlation functions R_3^{-+-} and R_3^{++-} when the rapidities of particles 1 and 2 have been kept fixed at $y_1 = y_2 = +1$.

Fig. 4 Two-particle rapidity correlations for (+-) and (--) pairs in pp collisions at $\sqrt{s} = 31, 44$ and 62 GeV. The rapidity of particle 1 is kept fixed at $y_1 = 0$, within a bin $\Delta y_1 = 0.5$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4