Bose-Einstein Correlations in $\bar{p}p$ interactions at $\sqrt{s} = 0.2$ to 0.9 TeV*UA1 Collaboration, CERN, Geneva, Switzerland*

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Abstract

Bose-Einstein correlations have been measured at the SPS collider at centre of mass energies from $\sqrt{s} = 0.2$ to 0.9 TeV. The size and the incoherence parameter of the particle emitting region have been determined as a function of charged particle density in pseudorapidity $\Delta n/\Delta\eta$, centre of mass energy and the direction of emission of the charged particles. For fixed values of $\Delta n/\Delta\eta$ the size of the interaction region and the incoherence parameter remain constant with rising $\sqrt{s}$. At fixed $\sqrt{s}$, the size of the interaction region increases with rising charged particle density while the incoherence parameter decreases.

Introduction

The first application of the use of Bose-Einstein correlations to determine the size of a particle source was made with the intensity interferometer developed by Hanbury-Brown and Twiss [1,2] who proposed to measure the size of distant stars by detecting correlations in the intensity of the light emitted by the stars. The method was first applied to particle physics by Goldhaber et al. in 1959 [3,4]. In the intervening years, the theoretical framework has been developed and the size of the interaction region has been measured by numerous experiments in high energy collisions between many different types of particles [see e.g. refs. 5 – 18].

Bose-Einstein correlations arise because the wave functions of identical bosons are symmetric with respect to particle exchange. If the dimensions of a boson emitting source are very small compared to the distance between the source and a detector, two identical bosons that arrive at the detector are indistinguishable with respect to their origin. The probability of finding them in the same element of phase-space is enhanced, compared to the probability of finding two non-identical particles. The interference pattern produced by incoherently emitted identical bosons can be related to the size of the source from which they were emitted.

This paper discusses the size of the interaction region in $\bar{p}p$ collisions at centre of mass energies from 0.2 to 0.9 TeV. It is not straightforward to compare the size of sources derived from the correlations observed by

different experiments at different values of $\sqrt{s}$. The selection of data and methods of analysis can introduce systematic errors that may have an impact on the determined radius. However, in 1985 the UA1 experiment at the SPS proton-antiproton collider collected data over a wide range of $\sqrt{s}$ during the so called ‘Ramping Run’, when the current of the machine magnets was cycled to produce centre of mass energies ranging from a flat bottom at $\sqrt{s} = 200$ GeV to a flat top at 900 GeV. Thus the correlations observed with the UA1 detector provide a single data set spanning this large range in centre of mass energies.

Analysis

The measurement of Bose-Einstein correlations requires the description of two particles in phase-space relative to each other. Kopylov [7] suggested as a set of variables q_0 , the energy difference between the two particles, and q_t , the projection of the three-momentum difference $\vec{p}_- = \vec{p}_1 - \vec{p}_2$ onto the plane perpendicular to the sum of the momenta $\vec{p}_+ = \vec{p}_1 + \vec{p}_2$. In the case of relativistic particles with small opening angles, q_0 can be approximated by q_l [11,13] which is defined as the projection of $\vec{p}_-$ onto $\vec{p}_+$.

The evaluation of these variables for all possible pairs of identical particles originating from the same event leads to a distribution $S(q_t, q_l)$ in q_t - q_l -space. Correlations may be observed by reference to a sample $D(q_t, q_l)$ that cannot contain correlated particles. In this experiment, we produce a reference sample by combining in pairs identical particles taken from different events. Dividing the two distributions yields a ratio C :

$$C(q_t, q_l) = S(q_t, q_l)/D(q_t, q_l) \quad (1)$$

In the case of no correlations, this ratio will be constant over all q_t, q_l . If there are Bose-Einstein correlations present, there will be deviations from this constant value when q_t and q_l are very small, i.e. when the two particles that form a pair are close in phase-space. The distribution of the ratio can be related to the Fourier transform of the distribution of the particle source. In collisions at high centre of mass energies, most emitted particles are pions. For identical pions, the ratio C will be enhanced compared to the uncorrelated case.

It is not known precisely how to parametrize the shape of the source of the emitted pions. The two most common assumptions for its shape are either a Gaussian distribution over some volume or a uniform distribution over the surface of a sphere, both of which seem to fit experimental data equally well.

The size of the source distribution, perpendicular to the direction of observation, can be evaluated by fitting the ratio $S(q_t, q_l)/D(q_t, q_l)$ as a function of q_t in a region of small q_l with a Gaussian or a Bessel function respectively, the Fourier transforms of the assumed distributions. The expressions used for the fits in this analysis are

a) Gaussian:

$$C_g = \gamma[1 + \lambda_g \exp(-\beta q_t^2)] \quad (2)$$

where γ is a normalization factor, λ can be interpreted as an ‘incoherence parameter’ which is equal to unity for a completely incoherent source and zero for a completely coherent source. Any inclusion of particles other than pions in the sample will also dilute the effect and decrease λ . The size of the Gaussian source distribution is reflected by the parameter β and $R_g = \hbar c \sqrt{\beta}$ gives the effective radius at which the source density is e^{-1} of its maximum value.

b) Bessel function:

$$C_b = \gamma[1 + 4\lambda_b J_1^2(q_t r)/(q_t r)^2] \quad (3)$$

where J_1 is the first order Bessel function and $R_b = r \hbar c$ is taken as the radius of the spherical source.

Data

The data for this analysis were taken with a so called ‘minimum bias’ trigger, requiring at least one charged particle in the pseudorapidity range of $1.5 < |\eta| < 5.6$ in each of the downstream arms of the detector. The data were collected during two runs of the CERN SPS collider, one at a fixed centre of mass energy of $\sqrt{s} = 630$ GeV and the other the Ramping Run. The energies of the Ramping Run between 200 and 900 GeV were divided into four intervals of 120 GeV width, from 200 to 680 GeV, and

one interval of 220 GeV width, from 680 to 900 GeV, in addition to the flat bottom and top values of 200 GeV and 900 GeV. The energies quoted in this paper are the mean values of these intervals. The numbers of events used in this analysis are given in table 1.

All information used for this analysis was obtained from reconstructed trajectories measured by the UA1 Central Detector [19] in a region of pseudorapidity of $|\eta| < 3$. It was assumed that all particles are pions. The azimuthal regions with $|\phi| \leq 15^\circ$ and $|\phi| \geq 165^\circ$ were excluded because of the high uncertainty of the momentum measurement in those regions. All tracks were required to have a good χ^2 , a good fit to the vertex and a minimum track length of at least 30cm. These requirements result in mean values of $\delta p/p$ of 0.6 % for 1 GeV/c tracks obtained at the fixed centre of mass energy of 630 GeV and 1.3 % for 1 GeV/c tracks taken during the Ramping Run. The reduced momentum resolution is due to the lower value of the magnetic field (0.21T instead of 0.7T) in the detector during the Ramping Run. Track pairs with an opening angle of less than 2.5° were removed to avoid problems with the two track resolution of the drift chamber. The pattern recognition sometimes splits one track into two. An algorithm was evolved which easily identifies this situation and only the first segment of the track is used. The influence of changes in the above-mentioned cuts on the final result are listed in table 2. The radius does not seem to be sensitive within the statistics to these changes. The incoherence parameter shows some sensitivity when a minimum momentum is required.

All events with tracks that satisfied the above conditions were analyzed for fixed intervals of charged particle multiplicities N_{ch} . These intervals range from 2-10, 10-20, 20-30 etc. The number of charged particles per event inside the range of η and ϕ given above was used to provide an approximate average value for the charged particle density $\langle \Delta n / \Delta \eta \rangle$. The value of $\langle \Delta n / \Delta \eta \rangle$ was corrected for the cut in the azimuthal angle ϕ . The variables q_t and q_l were evaluated for all possible combinations of like sign track pairs.

The uncorrelated reference sample $D(q_t, q_l)$ was chosen to consist of like sign track pairs mixed from two different events in the same N_{ch} range. All tracks of the reference sample have to satisfy the same conditions as the tracks of the correlated sample.

Results and Discussion

The ratio $C = S(q_t, q_l)/D(q_t, q_l)$ for all data was normalized to be equal to unity in the region $1.0 \leq q_t < 2.0$ GeV/c and $q_l < 1.0$ GeV/c where Bose Einstein correlations are negligible. The normalized data in the region of $q_l < 0.2$ GeV/c and $0.02 \leq q_t < 2.0$ GeV/c were fitted with the Gaussian expression. A typical fit is shown in fig 1. The χ^2 per degree of freedom of all fits is distributed around unity. For comparison, the data obtained at the fixed centre of mass energy of $\sqrt{s} = 630$ GeV were also fitted with the Bessel function over the same kinematic region. The values of R and λ of both fits are shown in figure 2. The Bessel function yields a size of the interaction region that is about two times larger than that obtained with the Gaussian. This can easily be explained by the fact that the shapes of the two functions are indistinguishable within the statistics of this measurement if the value for the radius R_b used in the Bessel function is put equal to $2R_g$, twice the value of the radius used in the Gaussian [20]. In both cases there is an increase in the effective source size with rising charged particle density $\Delta n/\Delta\eta$, while the incoherence parameter λ decreases. This result is in agreement with the results obtained at the ISR [13,16] in pp , $\bar{p}p$ and $\alpha\alpha$ collisions, where R seems to be a function of $\Delta n/\Delta\eta$ rather than particle type. Results on the radius of interaction at much higher values of $\Delta n/\Delta\eta$ have been obtained recently [21] in relativistic heavy ion collisions (Fig.3). A linear extrapolation of the present results passes close to the heavy ion points. It should be noted, however, that for the heavy ion collisions, the different values of $\Delta n/\Delta\eta$ are obtained by using different regions of η rather than selecting different event samples.

Figure 4a shows the dependence of the source size R_g on the centre of mass energy for four intervals of charged particle density $\Delta n/\Delta\eta$. There seems to be no significant dependence on $\sqrt{s}$, provided one fixes the charged particle density. The incoherence parameter (figure 4b) also appears to be independent of $\sqrt{s}$, at fixed $\Delta n/\Delta\eta$.

The source size was also measured as a function of the direction of emission of the particle pairs for the run at $\sqrt{s} = 630$ GeV. Assuming azimuthal independence, the momentum sum vector $\vec{p}_+$ of a particle pair was required to be inside one of the three pseudorapidity-intervals of $|\eta| = 0-1, 1-2$ or $2-3$. Combining the four lowest intervals of charged particle

density to improve statistics yields source sizes as shown in figure 5. There is no significant dependence of the source size on the angle of emission of the pair. It should be stressed that the source size measured in this study is an average over all directions normal to $\vec{p}_+$. The directional dependence observed by Akesson et al. [20] is in the difference vector $\vec{p}_-$.

The result of increasing source size with rising values of $\Delta n/\Delta\eta$, also seen in other experiments [13,16,21], is expected in thermodynamical models [22,23,24]. Landau suggested that an appropriate equation of state for particle production might be

$$\frac{S}{VT^3} = \text{const.} \quad (4)$$

He showed that the entropy S is proportional to $\Delta n/\Delta\eta$. The thermodynamical analogy can be completed if one relates the temperature T of the system to the average value of transverse momentum $\langle p_t \rangle$ of the emitted charged particle and determines the volume V of the particle emitting region from the radius R . We recall that UA1 [25] previously established a correlation between the charged particle density $\Delta n/\Delta\eta$ and the average transverse momentum $\langle p_t \rangle$. Although the observed behaviour is not inconsistent with such a thermodynamical picture [26], hard scattering effects [27] may also play a significant role, making it difficult to draw a simple overall conclusion.

Conclusions

The measured radius R of the particle emitting region and the incoherence parameter λ seem to be independent of the centre of mass energy of the colliding hadrons over a range of 200 to 900 GeV, provided a constant value of charged particle density in pseudorapidity is selected. While the radius rises with increasing $\Delta n/\Delta\eta$, the value of the incoherence parameter decreases. The observed dependence of R on $\Delta n/\Delta\eta$ seems to be common to a wide variety of reactions and energies.

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Table 1

The quoted energies for the ramping run between 260 and 790 GeV describe average values, as the energy ramp was divided into four segments with width of 120 GeV and one segment of 220 GeV.

Energy	Events
Minimum Bias Run	
$\sqrt{s} = 630$ GeV	117427
Ramping Run	
$\sqrt{s} = 200$ GeV	28180
$\langle \sqrt{s} \rangle = 260$ GeV	9378
$\langle \sqrt{s} \rangle = 380$ GeV	10638
$\langle \sqrt{s} \rangle = 500$ GeV	12702
$\langle \sqrt{s} \rangle = 620$ GeV	15339
$\langle \sqrt{s} \rangle = 790$ GeV	33657
$\sqrt{s} = 900$ GeV	59456

Table 2

Results for R_g and λ_g (Gaussian fit) after modified cuts on data taken at $\sqrt{s} = 630$ GeV and $10 < N_{ch} \leq 20$. Only one cut was changed at a time.

Cut	Radius	λ
Track length > 60 cm	$0.709 +0.031 -0.028$	0.237 ± 0.010
$30^\circ < \phi < 150^\circ$	$0.778 +0.039 -0.036$	0.276 ± 0.013
$ \eta < 2.5$	$0.751 +0.034 -0.031$	0.272 ± 0.012
opening angle $> 4^\circ$	$0.709 +0.031 -0.029$	0.243 ± 0.010
momentum > 0.25 GeV	$0.740 +0.031 -0.029$	0.350 ± 0.017
unmodified	$0.728 +0.031 -0.029$	0.252 ± 0.010

Figures

Figure 1. C_g distribution versus q_t for a q_t -interval of $0 \leq q_t < 0.2$ GeV with a Gaussian fit. The distribution has been obtained at $\sqrt{s} = 630$ GeV for $10 < N_{ch} \leq 20$ which corresponds to $\langle \Delta n / \Delta \eta \rangle \simeq 2.9$.

Figure 2a. Radius of the pion emitting source as a function of charged particle density $\Delta n / \Delta \eta$ for data obtained at $\sqrt{s} = 630$ GeV. The dots represent the fits with the Gaussian function, the open circles are the results of the fits using the Bessel function.

Figure 2b. Incoherence parameter λ_g as a function of charged particle density $\Delta n / \Delta \eta$ for data obtained at $\sqrt{s} = 630$ GeV. The results shown were obtained using the Gaussian fit; the results for λ_b using the Bessel function are the same within the given errors.

Figure 3. Comparison of the radius R_g of the pion emitting source, obtained from the Gaussian fit, as a function of charged particle density $\Delta n / \Delta \eta$ with the results of relativistic heavy collisions (NA35). In the lat-

ter case, we have divided the radius by $\sqrt{2}$ to allow for a difference of definition between the two experiments. The values of $\Delta n/\Delta\eta$ plotted for heavy ions are twice those for negative tracks.

Figure 4a. Radius R_g of the pion emitting source obtained from the Gaussian fit as a function of the centre of mass energy $\sqrt{s}$ for 4 different intervals of charged particle density. The horizontal lines represent the weighted means of the distributions.

- (a) $2 \leq N_{ch} \leq 10$ corresponding to $\langle \Delta n/\Delta\eta \rangle \simeq 1.5$
- (b) $10 \leq N_{ch} \leq 20$ corresponding to $\langle \Delta n/\Delta\eta \rangle \simeq 2.9$
- (c) $20 \leq N_{ch} \leq 30$ corresponding to $\langle \Delta n/\Delta\eta \rangle \simeq 4.9$
- (d) $30 \leq N_{ch} \leq 40$ corresponding to $\langle \Delta n/\Delta\eta \rangle \simeq 6.9$

Figure 4b. Incoherence parameter λ_g of the pion emitting source obtained from the Gaussian fit as a function of the centre of mass energy $\sqrt{s}$ for 4 intervals of charged particle density (see fig 4a). The horizontal lines represent the weighted means of the distributions.

Figure 5. Radius R_g of the pion emitting region as a function of the direction of $\vec{p}_+$ in pseudorapidity η .

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$q_t \text{ [GeV/c]}$

FIG. 1

FIG. 2a

FIG. 2b

FIG. 3