BOSE-EINSTEIN CORRELATIONS IN pp AND $p\bar{p}$ INTERACTIONS AT $\sqrt{s} = 63$ GeV

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ABSTRACT

Bose-Einstein correlations between two equal charge pions were measured in pp and $\bar{p}p$ collisions at $\sqrt{s} = 63$ GeV. The data were recorded at the CERN-ISR with the Split Field Magnet detector (SFM) using minimum bias triggers. The second order interference is used to determine the size and the degree of coherence of the pion source in pp and $\bar{p}p$ collisions. They are found to be equal within errors.

The size of the region from where pions originate in high energy collisions may be determined from the study of second order (intensity) interference effects between identical pions (Bose-Einstein correlations). The method is similar to that used by Hanbury-Brown and Twiss to determine angular stellar sizes of distant stars from two-photon correlations [1]. The application of this method for the determination of the space time structure of hadronic production was first developed by Kopylov and Podgoretsky [2] and by Cocconi [3]. The interference originates from the ambiguity in the paths of the two pions. The amplitude arising from the pion produced by source a (b) hitting detector A (B) interferes with the amplitude arising from the pion produced by source b (a) hitting detector A (B). The interference depends on the dimensions of the source and on the detector position. It is constructive for identical pions and is zero for non identical pions.

Following the prescriptions of refs 2 and 3, we consider a pair of pions with momenta $\vec{P}_1$ and $\vec{P}_2$ and energies E_1 and E_2 in the pp ($\bar{p}p$) c.m.s., and we define the two vectors $\vec{P} = \vec{P}_1 + \vec{P}_2$ and $\vec{Q} = \vec{P}_1 - \vec{P}_2$. The variable

$$q_t = |\vec{Q} \times \vec{P}| / |\vec{P}| \quad (1)$$

represents the relative transverse momentum of the two pions, with respect to the direction $\vec{P}/|\vec{P}|$. We define $I(q_t) dq_t$ to be the probability to observe the value q_t , within dq_t , when $E_1 \approx E_2$ ($q_0 = |E_1 - E_2|$). For pairs of pions of equal electric charge the second-order interference enhances this probability at small q_t . For a source of radius R , which emits pions with an intensity decreasing with the distance from the centre as $\exp(-(r/R)^2)$, one expects [2,3]

$$I(q_t) = (1 + a \cdot e^{-b q_t^2}) I_0(q_t), \quad (2)$$

where $I_0(q_t) dq_t$ would be the probability to observe q_t if there were no second-order interference effects. The coefficient a describes the degree of incoherence of the two pions, whereas the parameter b measures the size of the source ($R \sim \sqrt{b}$).

The enhancement of the probability to observe two identical particles when they are close in phase space was first observed by G. Goldhaber et al. for charged pions emitted in low energy $\bar{p}p$ annihilation [4]. Subsequently, similar results were obtained by several experiments in

hadron-hadron [5-19] and hadron-nuclei [20] collisions. An extensive review is given in ref. [20].

In this letter, experimental results are presented on Bose-Einstein correlations for charged pions produced in proton-proton and antiproton-proton collisions at $\sqrt{s} = 63$ GeV. The data were recorded with the Split Field Magnet detector (SFM) [21] at the CERN Intersecting Storage Rings (ISR). For pp collisions the detector was used with a minimum bias trigger, which required at least one charged track candidate in the spectrometer. This trigger accepted about 95% of the inelastic cross section, and about 90% of the triggers were good events (beam-beam interactions). For $\bar{p}p$ collisions the detector was used with a minimum bias trigger as well as with a trigger which required at least two charged tracks in the detector, one in each of the forward and backward hemispheres (quasi-minimum bias trigger). Only about 4% of the $\bar{p}p$ minimum bias triggers were good events; the remaining triggers were due to beam-gas interactions, which were mainly due to the low luminosities [22]. Most of the beam-gas background events were eliminated after event reconstruction by requiring that the interaction vertex lies inside the known overlap region of the beams. The quasi minimum bias trigger accepted about 67% of the inelastic cross section, and more than 75% of the triggers were good events.

The events were analyzed with the standard SFM off-line program chain. We required a "good" vertex fit originating from at least two charged tracks. After this requirement, the differences between the event samples from minimum bias and quasi-minimum bias triggers were reduced to only the lowest multiplicities, i.e. $n_{ch} < 6$.

The sample from pp interactions contained ~ 268.000 events and the samples from $\bar{p}p$ interactions contains ~ 15.000 events from the minimum bias trigger and ~ 68.000 from the quasi minimum bias trigger. Table 1 gives a summary of the available data.

The analysis of the Bose-Einstein correlations requires the study of the ratio $I(q_t)/I_0(q_t)$ as a function of q_t for a given range of $q_0 = |E_1 - E_2|$. $I(q_t)$ is the q_t -distribution for equal pions, while $I_0(q_t)$ is the ideal uncorrelated distribution.

The distribution $I(q_t)$ may be approximated from the data by plotting the q_t distribution for particles of the same charge ($I_l(q_t)$ for "like" pairs). The following cuts and conditions were applied to the data in order to obtain a clean sample.

- (a) Only events with charged multiplicities $n_{ch} \geq 6$ were accepted. This condition removes diffractive events and beam-gas events with vertices in the overlap region of the two beams. This cut also makes the remaining sample of events from the quasi-minimum bias trigger to appear identical to that from the minimum bias trigger.
- (b) Since two identical pions can interfere only when their energies do not differ too much, only pairs with $q_0 = |E_1 - E_2| < 0.2$ GeV were used. The analysis of events in the regions $0.2 < q_0 < 0.4$ GeV, $0.4 < q_0 < 0.6$ GeV and $q_0 > 0.6$ GeV shows correlation signals which decrease with increasing q_0 .
- (c) We required the c.m.s. angle of a pair of identical pions to be smaller than 90° ($\cos \theta_{ll} > 0$).
- (d) All tracks were assumed to be pions. The small contamination by kaons, protons and antiprotons should give only a decrease in the observed interference, more important for positive pairs than for negative ones.
- (e) For each track we required:
 - (e.1) $|x_F| < 0.5$ (x_F is the Feynman variable, $x_F = 2p_L/\sqrt{s}$). This cut removes leading baryons.
 - (e.2) $0.1 < p_t < 2$ GeV/c. This cut removes some acceptance problems at low p_t and also some background from mismeasured events at large p_t .
 - (e.3) $\Delta p < 0.1$ GeV/c, where Δp is the measurement error on each track momentum. This cut on the absolute uncertainty, which removes badly measured tracks, was found to be important for a proper study of the correlations. The data with a cut at $\Delta p < 0.2$ GeV/c show correlations, but with a slightly smaller magnitude.

- (f) A number of technical tests were performed in order to remove badly reconstructed tracks. In particular a study of tracks erroneously reconstructed as two tracks leads to the conclusion that there are none for $q_t > 0.04$ GeV/c.
- (g) After the above cuts on the tracks, an event was kept if it contained at least two positive and two negative tracks.

The resulting data sample contained 110.850 pp and 45.970 $\bar{p}p$ events, respectively.

An approximation of the ideal uncorrelated distribution $I_o(q_t)$ is given by the distribution $I_u(q_t)$ of charged particles of opposite charge (unlike pairs). This distribution is obviously free from Bose-Einstein correlation effects, but it is different from the ideal uncorrelated distribution for the following reasons.

- (a) The decays of resonances produce more unlike than like pairs, thus contributing mainly to $I_u(q_t)$. This contribution decreases with increasing charged multiplicities and is minimized by the applied cut, $n_{ch} \geq 6$. Moreover, because of the relatively large resonance masses, the effect does not give any appreciable contribution for q_t smaller than 0.6 GeV/c.
- (b) The inclusive single particle distributions for negative and positive particles are different, in particular in the forward direction. This yields a difference between I_u and I_o . The applied cuts, especially $|x_F| < 0.5$ and $n_{ch} \geq 6$, minimize the difference in the spectra, which then appear essentially identical.
- (c) The detector had slightly different acceptances for positive and negative particles. This may affect the ratio of like to unlike pairs, N_l/N_u . Studies of the ratios $(--)/(++)$ and $(++)/(-+)$ and of the acceptances indicated that this effect does not give a contribution larger than the present statistical errors. Also the effects arising from the relatively large beam crossing regions and their difference between pp and $\bar{p}p$ collisions have been checked and found to yield negligible corrections.

Because of the uncertainties in the $I_u(q_t)$ distribution determined from $\pi^+\pi^-$ pairs, it has become customary to try other approximations of I_o [18,20]. In particular we tried a form obtained with positive and negative tracks from different events (mixed events, I_{me}). We also studied I_l/I_u using only tracks from part of the apparatus. The signal for Bose-Einstein correlations was present in all these tests. However, the magnitude of the signal varied by only 20% in the extreme case.

In fig. 1 the ratio of the q_t distributions for like pairs to that for unlike-charge pairs is plotted for the pp and $\bar{p}p$ samples. Pairs with $q_t < 0.04$ GeV/c have been excluded from the plot. The data shown in fig. 1 exhibit the expected behaviour, with a Gaussian-like maximum at small values of q_t , superimposed on a background linear in q_t . The data were fitted to the function

$$\frac{N_l}{N_u} = \gamma(1+\delta q_t)(1 + \alpha e^{-\beta q_t^2}) \quad (3)$$

where γ is a normalization constant and δ is expected to be close to zero. The parameter α , which may be called the chaoticity parameter, should lie between zero (no Bose-Einstein effects) and unity (maximum chaoticity and thus maximum interference). The parameter β is related to the emission radius through $R = 0.197 \sqrt{\beta}$ (R in fermi, q_t in GeV/c and β in $(\text{GeV}/c)^{-2}$).

Table 2 gives the results of the fits to the data with eq. (3). The fits have reasonable χ^2/DoF and yield values of δ consistent with zero. This indicates that for large q_t like and unlike pairs have a similar q_t dependence. We also performed fits to the data with the simpler function

$$\frac{N_l}{N_u} = \gamma' (1 + \alpha' e^{-\beta' q_t^2}) \quad (4)$$

The results of the fits to the data with eq. (4) are also given in table 2. The fits have acceptable χ^2/DoF and yield values for the chaoticity parameter and for the emission radius which are, within errors, equal for pp and $\bar{p}p$ interactions ($\alpha \approx 0.44$, $R \approx 1.1$ fermi).

A better test of the equality of the Bose-Einstein correlations in pp and $\bar{p}p$ interactions is obtained by plotting the ratio of like pairs in pp and $\bar{p}p$ interactions ($A = N_{\ell}^{\text{pp}}/N_{\ell}^{\bar{p}p}$) as a function of q_t . In this way all problems connected with the choice of I_0 and some of the problems connected with the detector acceptances cancel.

A possible difference in acceptance between pp and $\bar{p}p$ could be connected with the different location of the region where the two beams cross. In order to study this, we analysed the ratio N_{ℓ}^{pp} (with vertices in the pp crossing region) divided by $N_{\ell}^{\bar{p}p}$ (with vertices in the $\bar{p}p$ crossing region). No effect was observed. Further checks were made on effects which could arise from the different initial charge configuration (zero charge for $\bar{p}p$, charge +2 for pp). In particular, we studied the charge (--) configuration in the hemisphere of the outgoing proton. These checks yielded results which, within errors, were equal to those obtained with the global sample.

The ratio A is shown in fig. 2 for the same pp and $\bar{p}p$ samples used for the previous analyses, and using the same cuts. The ratio is clearly unity within experimental errors, which in this case are only statistical. A fit with a linear dependence on q_t , $A = a + b \cdot q_t$, yields $a = 1.00 \pm 0.01$ and $b = 0.00 \pm 0.01$, indicating no q_t dependence. The average value of the ratio for $0.04 < q_t < 0.5$ GeV/c is $\langle A \rangle = 1.01 \pm 0.02$.

A similar analysis on the ratio of unlike pairs in pp and $\bar{p}p$ interactions ($A' = N_u^{\text{pp}}/N_u^{\bar{p}p}$) yields $\langle A' \rangle = 1.01 \pm 0.02$.

The values for the radius of the pion source in pp and $\bar{p}p$ interactions in the present experiment are about 1.1 fermi. This value is somewhat larger than values obtained in e^+e^- interactions ($r \sim 0.9$ f) and is somewhat smaller than the radii obtained in lower energy hadron-hadron measurements (which gave radii of 1.4 - 1.8 fermi [18,20] but using expressions different from eqs (3), (4)). The differences from e^+e^-

results are probably significant, though part of the differences may be of a technical nature, such as momentum resolutions of the particles, proton and kaon contaminations, acceptances and choice of uncorrelated distributions. The method yields only the size of the volume in which pions with similar momenta are emitted. Moreover we find that the longitudinal and transverse sizes are different.

In conclusion, our data show the existence of Bose-Einstein interference effects in pp and $\bar{p}p$ interactions at ISR energies. The interference is only partial, in the sense that the chaoticity parameter α is about 0.44 (and not unity). The radius of the pion emitting region is about 1.1 fermi, which is somewhat smaller than the values found at lower energies. We find that the chaoticity parameter and the radius of the pion source are equal in pp and $\bar{p}p$ interactions.

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TABLE 1

Summary of the event samples before and after cuts
and of the numbers of ++, --, +- pairs after applying
the cuts itemized in the text.

Collisions	Number of events		Number of pairs		
	raw	after cuts	++	--	+-
pp	268.270	110.850	96.246	85.006	210.572
$\bar{p}p$	83.000	45.970	35.991	29.908	76.252

TABLE 2

Values of the parameters obtained from the fits of the experimental distributions to eqs. 3 and 4.

From the fit to eq. 4 one has $r_{pp} = 0.197/\beta' = 1.13 \pm 0.04$ and $r_{\bar{p}p} = 1.03 \pm 0.07$ fermi. Only statistical errors are considered. One should add a systematic uncertainty arising from the choice of I_u as I_o , which could yield an uncertainty of 2-3 times the statistical uncertainty.

Collisions	γ	δ (GeV/c) ⁻¹	β (GeV/c) ⁻²	α	χ^2/Dof	γ'	β' (GeV/c) ⁻²	α'	χ^2/Dof
pp	0.914±0.018	0.029±0.036	30.9±3.2	0.445±0.026	1.3	0.928±0.005	32.7±2.6	0.432±0.021	1.3
$\bar{p}p$	0.927±0.033	-0.020±0.061	28.3±5.0	0.430±0.045	1.0	0.916±0.008	27.2±3.6	0.440±0.033	1.0

FIGURE CAPTIONS

Fig. 1 The $N_l(q_t)$ distributions for like pairs divided by unlike pairs $N_u(q_t)$ for the pp and $\bar{p}p$ samples. The lines represent the results of the fits to eq. 4.

Fig. 2 The ratio $N_l^{pp}/N_l^{\bar{p}p}$ for like pairs of the pp sample relative to the $\bar{p}p$ sample plotted versus q_t .

Fig. 1

Fig. 2