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New results on interference effects and correlations

E J Thomson

Physics Department, Imperial College of Science, Technology and Medicine,
Prince Consort Road, LONDON SW7 2AZ, UK

E-mail: evelyn.thomson@cern.ch

Abstract
New results on interference effects and correlations are reviewed, including Fermi-Dirac and Bose-Einstein correlations in hadronic Z^0 decays at LEP1.

1. Introduction

Studies of Bose-Einstein (BE) correlations of identical bosons and of Fermi-Dirac (FD) correlations of identical fermions produced in high energy collisions provide measurements of the distributions of particle sources in space and time. These correlations originate from the symmetrization or anti-symmetrization of the two-particle wave functions of identical particles and lead to an enhancement or a suppression of particle pairs produced close to each other in phase space. The strength of two-particle BE or FD correlation effects can be expressed in terms of a two-particle correlation function $C(p_1, p_2)$ defined as:

$$C(p_1, p_2) = P(p_1, p_2)/P_o(p_1, p_2)$$

where p_1 and p_2 are the four-momenta of the particles, $P(p_1, p_2)$ is the measured differential cross-section for the pairs and $P_o(p_1, p_2)$ is that of a reference sample, which is free of BE or FD correlations but otherwise identical in all aspects to the data sample. The main experimental difficulty is to define an appropriate reference sample $P_o(p_1, p_2)$ in order to determine that part of $P(p_1, p_2)$ which can be attributed to the BE or FD correlations. The correlation function C is usually measured as a function of the Lorentz invariant Q, with $Q^2 = -(p_1 - p_2)^2$. For $Q^2 = 0$, the effects of BE or FD correlations reach their extreme values.

Section 2 describes a new result on FD correlations in $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs. Section 3 discusses new results on multi-dimensional BE correlations in $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs. Section 4 summarises other new results and section 5 presents conclusions.

2. FD correlations in $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs

ALEPH have measured the two-particle correlation function of ($\Lambda\Lambda$,$\bar{\Lambda}\bar{\Lambda}$) pairs [1], using three different references as shown in figure 1. All three references rely to some extent on a proper description of the hadronization process by Monte Carlo. Reference A assumes the differential cross-section of simulated ($\Lambda\Lambda$,$\bar{\Lambda}\bar{\Lambda}$) in the JETSET Monte Carlo. References B and C are obtained by the technique of event mixing, where pairs of Λ's or $\bar{\Lambda}$'s are constructed by pairing each Λ or $\bar{\Lambda}$ with the Λ's or $\bar{\Lambda}$'s of all other events. However, this method removes not only possible FD or BE correlations, but it also affects all other correlations as can be seen from figure 2, where the cosine of the angle $\theta_{1,2}$ between the Λ or $\bar{\Lambda}$ momenta in the Z^0 rest frame is plotted. In

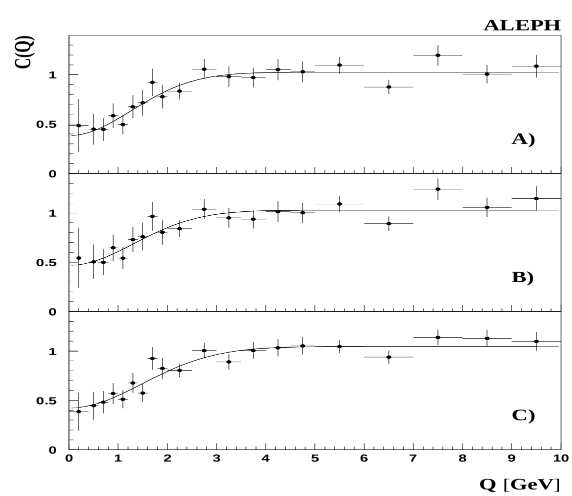

Figure 1. Correlation function $C(Q)$ for the ($\Lambda\Lambda$,$\bar{\Lambda}\bar{\Lambda}$) pairs using different reference samples: A) Monte Carlo, B) mixed event double ratio and C) mixed events with reweighted $\cos\theta_{1,2}$ distribution. The curves represent the results of fits using the Goldhaber parameterisation [1].

the unmixed events most pairs are produced back to back, whereas the distribution for the mixed sample is completely symmetric. This leads to a shift in the Q distribution for the mixed pairs towards lower values of Q. To overcome this problem, the double ratio of the cross sections is commonly used and this gives reference B:

$$C(Q) = \left(\frac{P(Q)_{\mathrm{data}}}{P(Q)_{\mathrm{data,mix}}}\right) \Big/ \left(\frac{P(Q)_{\mathrm{MC}}}{P(Q)_{\mathrm{MC,mix}}}\right)$$

Since the symmetrization of the $\cos\theta_{1,2}$ distribution is the main reason for the difference in the Q distributions of the mixed and original pairs, reference C is constructed from the mixed data sample, which is reweighted to reproduce the $\cos\theta_{1,2}$ distribution from the original pairs obtained from Monte Carlo.

Independent of the reference sample used, $C(Q)$ shows a decrease for $Q < 2$ GeV. If this is interpreted as a FD effect, the size of the source R estimated from $C(Q)$ with a Goldhaber parameterisation is:

$$R(\Lambda\Lambda, \bar{\Lambda}\bar{\Lambda}) \quad = \quad 0.11 \pm 0.02_{stat} \pm 0.01_{syst} \text{ fm}$$

This is consistent with the result of the less precise but less model dependent measurement of the spin composition [2] of the ($\Lambda\Lambda$,$\bar{\Lambda}\bar{\Lambda}$) system, which can have a total spin of 0 or 1. The spin 1 fraction, $\epsilon(Q)$, is expected to be 0.75 for a statistical spin mixture ensemble. Since the total wave function for the fermion pair must be antisymmetric, the symmetric spin 1 wave function must be paired with the antisymmetric space wave function, and thus $\epsilon(Q)$ is expected to decrease to 0 as Q goes to 0 due to FD statistics. ALEPH finds that $\epsilon < 0.75$ for $Q < 2$ GeV and $\epsilon \simeq 0.75$ for $Q > 2$ GeV, as shown in Table 1. The size of the source R estimated from $\epsilon(Q)$ is $R = 0.14 \pm 0.09_{stat} \pm 0.03_{syst}$ fm. For the $\Lambda\bar{\Lambda}$ system, which is free of FD correlations, the spin composition measurements are consistent with $\epsilon = 0.75$ in the entire Q range studied. ALEPH also proves that this spin composition technique, previously shown to hold approximately for low values of Q, is in fact valid for any value of Q. The results for $\epsilon(Q)$ are in agreement with previous measurements from OPAL [3] and DELPHI [4].

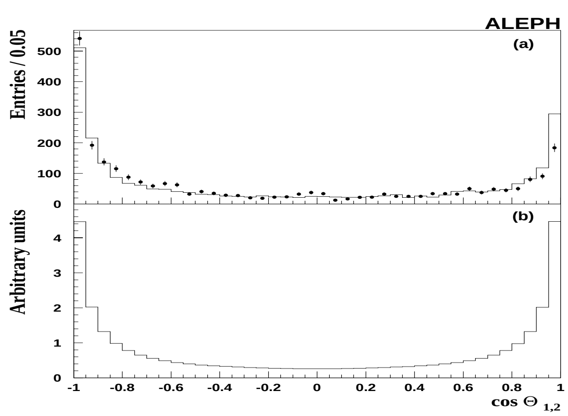

Figure 2. The histogram shows the $\cos\theta_{1,2}$ distribution for a) the original ($\Lambda\Lambda$,$\bar{\Lambda}\bar{\Lambda}$) pairs from the Monte Carlo and b) for the mixed pairs of the same sample. Points in a) show the $\cos\theta_{1,2}$ distribution of the data. The deviation of the Monte Carlo from data at large $\cos\theta_{1,2}$ is due to the FD effect.

A comparison of this result with the measured radii for identical charged pions [5] and kaons [6]:

$$\begin{aligned} R(\pi^\pm, \pi^\pm) &= 0.65 \pm 0.04_{stat} \pm 0.16_{syst} \text{ fm} \\ R(K^\pm, K^\pm) &= 0.48 \pm 0.04_{stat} \pm 0.07_{syst} \text{ fm} \end{aligned}$$

indicates that the dimension of the source decreases with the increasing mass of the emitted particles.

3. Multi-dimensional BE correlations

A recent model of BE correlations predicts that the longitudinal correlation length is different from the transverse one since momentum components longitudinal and transverse with respect to the string direction are generated by different mechanisms [7]. To verify this prediction, OPAL [8], DELPHI [9] and L3 [10] have all investigated multi-dimensional BE correlations in hadronic Z^0 decays in the so-called Longitudinally CoMoving System, which represents the local rest frame of the string.

OPAL use a sample of opposite sign particle pairs to define the reference for correlation function $C(Q)$ shown in figure 3(a). However, this reference

Table 1. The values of ϵ for the ($\Lambda\Lambda$,$\bar{\Lambda}\bar{\Lambda}$) and $\Lambda\bar{\Lambda}$ samples.

Q Range [GeV]	$\epsilon(\Lambda\Lambda,\bar{\Lambda}\bar{\Lambda})$	$\epsilon(\Lambda\bar{\Lambda})$
0.0 - 1.5	$0.36 \pm 0.30 \pm 0.08$	$0.61 \pm 0.13 \pm 0.07$
1.5 - 2.0	$0.52 \pm 0.31 \pm 0.10$	$0.77 \pm 0.07 \pm 0.03$
2.0 - 4.0	$0.78 \pm 0.16 \pm 0.09$	$0.51 \pm 0.11 \pm 0.12$

also contains pairs coming from resonance decays and from weakly decaying particles. In addition, the correlation function has to be normalised and suffers, at large four-momentum differences, from long-range correlations due to energy and momentum conservation. Therefore OPAL use a large sample of Monte Carlo to define a second correlation function $C'(Q) = C^{data}/C^{MC}$, shown in figure 3(b). This correlation function is more reliant on the Monte Carlo but is almost normalised with a reduced contamination from correlated unlike charge pairs. DELPHI and L3 both use event mixing techniques to define their references.

OPAL and DELPHI parameterise the two-pion correlation function in two dimensions, while L3 use three dimensions. OPAL also study a one-dimensional correlation function as a function of the angle between the two-pion momentum difference, in the rest frame of the $\pi\pi$ system, and the thrust direction. OPAL also check for any dependence on the two-jet nature of the events.

In all cases, a significant difference between the transverse, r_t, and longitudinal, r_l, dimensions is observed, indicating that the emitting source of pions has an elongated shape, with the longitudinal dimension about 1.3 times larger than the transverse dimension. For instance, the parameter values obtained by fitting an extended Goldhaber parameterisation to the correlation function $C'(Q)$ of OPAL are:

$$\begin{aligned} r_l &= 0.935 \pm 0.013_{stat} \pm 0.026_{syst} \text{ fm} \\ r_t &= 0.720 \pm 0.009_{stat} \pm 0.044_{syst} \text{ fm} \\ r_l/r_t &= 1.30 \pm 0.03_{stat} \pm 0.12_{syst} \end{aligned}$$

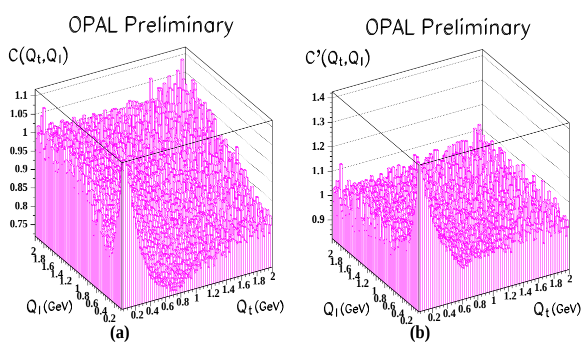

Figure 3. Two-dimensional BE correlation functions plotted versus the two components of the momentum difference, along the thrust axis, Q_l, and transverse to the same axis, Q_t.

4. Other results

OPAL measure BE correlations in $K^{\pm}K^{\pm}$ pairs [11], which confirms an earlier DELPHI result [12], and implies that there must also be such correlations in $K_s^0 K_s^0$ pairs, making it unlikely that previously observed threshold enhancements can be attributed entirely to $f_0(980)$ production. SLD study correlations in rapidity between identified charged hadrons and use the SLC electron beam polarisation to tag the quark hemisphere in each event, allowing the first study of rapidities signed such that the positive rapidity is along the quark direction, which provides new insights into the fragmentation process [13]. OPAL perform a multidimensional study of local multiplicity fluctuations and genuine multi-particle correlations in terms of factorial moments and, for the first time in e^+e^- annihilation, factorial cumulants, up to fifth order [14]. The Monte Carlo models JETSET 7.4 and HERWIG 5.9 are found to reproduce the trends but underestimate the magnitudes.

5. Summary and conclusions

FD correlations have been clearly observed in ($\Lambda\Lambda$,$\bar{\Lambda}\bar{\Lambda}$) pairs by ALEPH using two different techniques. A comparison of the source size measured in systems of identical pions, kaons and Λ's indicates that the source size decreases as the mass of the emitted particles increases. Several studies of multidimensional BE correlations by OPAL, DELPHI and L3 confirm a theoretical prediction that the emitting source of pions has an elongated shape, with a longitudinal dimension about 1.3 times larger than the transverse dimension. This indicates that models based on the assumption of a spherical source are too simple.

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