PARTICLE CORRELATIONS AT LEP

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Particle correlations are extensively studied to obtain information about the dynamics of hadron production. From 1989 to 2000 the four LEP collaborations recorded more than 16 million hadronic $Z^0$ decays and several thousand $W^+W^-$ events. In $Z^0$ decays, two–particle correlations were analysed in detail to study Bose–Einstein and Fermi–Dirac correlations for various particle species. In fully–hadronic $W^+W^-$ decays, particle correlations were used to study whether the two $W$ bosons decay independently. A review of selected results is presented.

1 Introduction

The analysis of particle correlations in high energy interactions gives important information about the hadron production mechanism, complementary to studies of global event properties and single–particle distributions.

The LEP $e^+e^-$ collider provides an ideal environment for such studies. From 1989 until 1995, LEP operated at centre–of–mass energies around 91 GeV which allowed each of the four experiments, ALEPH, DELPHI, L3 and OPAL, to record more than four million hadronic $Z^0$ decays. From 1996, after the collider energy had been increased above the WW threshold, until the end of LEP four years later, each experiment recorded about ten thousand $W^+W^-$ events. A hadronic decay of a $Z$ or $W$ boson leads to some dozen particles in the final state, mostly charged pions and photons from the decay of the $\pi^0$ mesons, but also, to a lesser extent, to kaons, protons and lambda hyperons, which allows to study particle correlations in detail.

Bose–Einstein correlations (BEC) between identical bosons are a well–established phenomenon in high energy physics experiments and are often considered to be an equivalent of the Hanbury Brown & Twiss (HBT) effect in astronomy describing the interference of photons emitted incoherently. An alternative approach was proposed by Andersson et. al. taking into account the dynamics of hadron formation in a coherent production process within the framework of the Lund string model related to the symmetrisation of the quantum–mechanical amplitude.

Bose–Einstein correlations lead to an enhanced production of identical boson pairs with a small four–momentum difference $Q^2 = -(p_1^2 - p_2^2)^2$. Traditionally it is studied using a two–particle correlation function $C(p_1,p_2) = \rho_2(p_1,p_2)/\hat{\rho}_2(p_1,p_2)$, where $\rho_2$ and $\hat{\rho}_2$ are the two–particle densi-
ties with and without BEC, respectively. For the construction of the reference sample \( \tilde{\rho} \), frequently a MC model without BEC is used. Following the pioneering analysis of Goldhaber, Goldhaber, Lee and Pais (GGLP), a correlation function of type \( \mathcal{C}(Q) = 1 + \lambda \exp(-Q^2r^2) \) is often used to yield a value for \( r \), which is interpreted to be the emitter radius. The factor \( \lambda \) measures the strength of the BEC effect but sometimes absorbs experimental impurities. Extra terms in the parametrisation are occasionally used to account for imperfections in the description of other correlations in the reference sample.

2 Particle Correlations in \( Z^0 \) Decays

2.1 Bose–Einstein Correlations in Pion Pairs

![Figure 1. Correlation function \( \mathcal{C}(Q) \) for pairs of charged and neutral pions.](image)

Fig. 1 shows recent L3 measurements\(^a\) of the correlation function for charged (left) and neutral (right) pion pairs using a MC without BEC as the reference samples. For both the charged and neutral pion pairs an enhancement at low \( Q \) is clearly visible. Using a parametrisation à la GGLP, the obtained source radius for neutral pions is tending to be smaller than \( r \) for charged pions, as qualitatively expected in the Lund string model\(^b\).

2.2 Elongation of the Pion Source

A difference in the Bose–Einstein correlation length longitudinally and transversely with respect to the jet axis in \( e^+e^- \) annihilation, arises naturally in a model for Bose–Einstein correlations based on the Lund string model.\(^b\)
In the Longitudinal Centre–of–Mass System, which is defined for each pair of particles as the system in which the sum of the two particles’ momenta is perpendicular to the thrust axis of the process, the three–momentum difference $\vec{Q}$ is decomposed in three components as illustrated in Fig. 2. An analysis with a GGPL parametrisation, separately for the components $Q_{\text{long}}, Q_{\text{t,side}}$, and $Q_{\text{t,out}}$, gives access to the transverse and longitudinal emitter radius. In spite of different methods for the construction of the reference sample, the results of DELPHI, L3 and OPAL consistently demonstrate that the particle emission source is elongated along the direction of motion with a ratio of transverse to longitudinal radius in the range 0.6—0.8.

2.3 Bose–Einstein Correlations in Kaon Pairs

Bose–Einstein correlations have also been established in charged and neutral kaon pairs at LEP. The left–hand side of Fig. 3 shows the correlation function of selected pairs of charged kaons obtained by OPAL. The kaons were identified using information of the specific ionisation energy loss (dE/dx) in the large volume jet chamber. For neutral kaons an enhanced production at low $Q$ is expected if the C parity of the system is +1 as for two $K_S$ mesons. On the right–hand side of Fig. 3 the correlation function for pairs of $K_S$ is shown as obtained by ALEPH. The $K_S$ mesons were identified by using the $M_{\pi^+\pi^-}$ invariant mass spectrum for candidates with a secondary vertex.
2.4 Fermi–Dirac Correlations

Recently it has been proposed to extract an emitter dimension for pairs of equal baryons by utilising the Fermi–Dirac exclusion principle. The correlation function can be parametrised by an equation similar to the GGLP parametrisation with the plus sign replaced by a minus sign. Antisymmetrising the total wave function yields four states, three of which are antisymmetric in space and symmetric in spin. Thus, for an incoherent source, $C(Q)$ should decrease to a value $1/2$ in the limit as $Q \to 0$. The left–hand side of Fig. 4 shows the ALEPH results for the correlation function from lambda and anti–lambda pairs. The hyperons were identified with a similar method as described for the $K_S$ mesons. Using three different methods for the construction of the reference sample (A, B, C), a depletion at low $Q$ is observed in all cases. As shown on the right–hand side of Fig. 4, a depletion for baryons at low $Q$ is confirmed by preliminary results from the OPAL collaboration using pairs of anti–protons, identified by $dE/dx$ information.

2.5 Mass Dependence of the Emitter Radius

On the left–hand side of Fig. 5, the measured source radii for pairs of pions (averaged by Alexander et. al), kaons, lambda hyperons and (anti–)protons are plotted as a function of the hadron mass. A mass hierarchy $r_\pi > r_K > r_p,A$ is visible, although the statement is only justified because of the baryon measurements. The Lund string model in its basic form expects $r(m)$ to increase...
with m, thus the very small value obtained for $r_\Lambda$ and $r_p$ poses a challenge to this model. It has been shown that by applying the Heisenberg uncertainty principles one can derive an expression for $r(m)$ that decreases with the hadron mass $m$, namely $r(m) = c\sqrt{\frac{\hbar}{\Delta t}}/\sqrt{m}$. In Fig. 5 the prediction is shown with $\Delta t$ set to (0.5/1.0/1.5) $\cdot 10^{-24}$ sec (lower dashed/solid/upper dashed line), to represent a typical scale for strong interactions. The prediction is able to qualitatively describe the data. As pointed out by Alexander, an enormous energy density of the order of 10–100 GeV/fm$^3$ arises for the baryons if the measured $r$ in fact represents the emitter radius. Another interpretation of the data in the framework of the inside–outside cascade model avoids the potential problem with the extrem energy density. A proportionality between the four–momentum of a produced particle and the four–vector describing its space–time position at the freeze–out is commonly accepted in the description of high–energy collisions. Provided that all particles are emitted from a tube of $\approx 1$ fm in diameter at a constant proper time of $\approx 1.5$ fm, the model can explain the data as shown in the right–hand side of Fig. 5. In this approach the measured $r(m)$ dependence is solely a consequence of the strong correlation between $x^\mu$ and $p^\mu$. 

Figure 4. Correlation function for $\Lambda^0$, $\bar{\Lambda}^0$ (left) and anti–proton (right) pairs.
3 Inter–WW Bose–Einstein Correlations

In $W^+W^- \rightarrow q\bar{q}q\bar{q}$ events at LEP, the products of the W decays in general have a significant space–time overlap as the separation of the their decay vertices is small compared to characteristic hadronic distance scales. The W boson mass, a fundamental parameter in the Standard Model, is determined from the corresponding jet masses and could potentially be biased if Bose–Einstein correlations between the decay products of the two W bosons exist.

A robust framework to test the presence of such inter–WW BEC was proposed in. If the $W^-$ and $W^+$ decay independently, then $\Delta \rho(Q) \equiv 0$ for all Q with the test distribution $\Delta \rho$ defined as:

$$\Delta \rho = \rho_{W^+W^- \rightarrow 4q} - 2 \cdot \rho_{W \rightarrow 2q} - \rho_{WW^{\text{mix}}},$$

with the two–particle densities $\rho_{W^+W^- \rightarrow 4q}$ determined by the $W^+W^- \rightarrow q\bar{q}q\bar{q}$ sample, $\rho_{W \rightarrow 2q}$ by the hadronic part of semileptonic $W^+W^- \rightarrow q\bar{q}l\bar{\nu}$ events and $\rho_{WW^{\text{mix}}}$ from events build from two independent semileptonic events without the leptonic parts and combining only particles originating from different W’s. In Fig. 6, the L3 collaboration compares the $\Delta \rho$ distribution obtained from the data with two scenarios of the PYTHIA/PYBOEI$^{19}$ Monte Carlo model with BEC. In the upper plot the inter–WW BEC in the Monte Carlo model can be seen as an enhancement of like–sign pairs in the low Q region. Unlike–sign pairs (lower plot) are artificially effected by the technical implementation of the inter–WW BEC in PYBOEI. The data are consistent with
no inter–WW correlations and the Monte Carlo which describes BEC between particles from different W bosons in the same way as the correlations within the same W is strongly disfavoured. The same is true for similar results from DELPHI as shown on the right–hand side of Fig. 6. Both results are preliminary.

Figure 6. Preliminary $\Delta \rho$ distributions from L3 (left) and DELPHI (right) compared to MC models with and without inter–WW BEC.

In the Lund model, Bose–Einstein correlations arise when identical bosons are produced close to each other within the same string. Because of the strong correlation of production space–time and momentum of the hadron in the inside–outside cascade, the measured $r$ is interpreted as the distance in the string where the momentum spectra of the particles still overlap. In the absence of colour reconnection effects, particles from different W bosons are not produced in the same string. However, in addition to the coherent correlations inside a string a second correlation effect of an incoherent HBT type could be present. An analysis of the hadron formation within the Lund model shows that the space–time distance of the production vertices for pairs of particles from different strings is of the order of several fm as illustrated in Fig. 6. For such large distances any remaining inter–WW BEC effect would manifest itself only at very low $Q$ values which are hard to exploit with the limited statistics of WW events at LEP.
4 Summary

More than 40 years after BEC entered the high energy physics stage, we now have come to a better understanding of the effect. It has become clear that one has to go beyond a naive HBT interpretation by taking into account the dynamics of hadron production. Since no firm theory exists to describe the hadronisation phase, we rely on phenomenological models. To test such models, particle correlations provide us with details complementary to those obtained from global event properties and single–particle distributions.

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