PARTICLE CORRELATIONS IN Z AND WW EVENTS

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Important information about the dynamics of hadron production can be obtained by the study of particle correlations. More than 16 million hadronic Z\(^0\) decays and several thousand W\(^+\)W\(^-\) events have been recorded from the four LEP collaborations between 1989 and 2000. Recently, in Z\(^0\) decays, new results of Bose–Einstein correlations in pairs of pions and Fermi–Dirac correlations for antiproton pairs were reported. In fully–hadronic W\(^+\)W\(^-\) decays particle correlations were used to study whether the two W bosons decay independently.

1 Introduction

From 1989 until 1995 the LEP collider operated at centre–of–mass energies around 91 GeV which allowed each of the four experiments to record more than four million hadronic Z\(^0\) decays. After the collider energy had been increased above the WW threshold, each experiment recorded about ten thousand W\(^+\)W\(^-\) events until the end of LEP in 2000. 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 π\(^0\) mesons, but also, to a lesser extent, to kaons, protons and Λ–hyperons, which allows to study particle correlations in detail and thus to get important information about the hadron production mechanism.

Bose–Einstein correlations (BEC) between identical bosons are well established in high energy physics experiments and are often considered to be equivalent to the Hanbury Brown & Twiss\(^5\) (HBT) effect in astronomy, describing the interference of photons emitted incoherently. An alternative approach was proposed by Andersson et al.\(^2\), 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 pairs of identical bosons with a small four–momentum difference Q\(^2\) = –(p\(_1\)^\mu – p\(_2\)^\mu)^2. Traditionally, BEC are studied using a two–particle correlation function C(p\(_1\),p\(_2\)) = ρ\(_2\)(p\(_1\),p\(_2\))/ρ\(_2\)(p\(_1\),p\(_2\)). where ρ\(_2\) and ρ\(_2\) are the two–particle densities with and without BEC, respectively. For the construction of the reference sample ρ\(_2\) frequently a MC model without BEC is used. Following the pioneering analysis of Goldhaber, Goldhaber, Lee and Pais\(^3\) (GGLP), a correlation function of type C(Q) = 1 + λ exp(–Q\(^2\)R\(^2\)) is often used to yield a value for R, which is interpreted as the emitter radius. The factor λ measures the strength of the BEC effect but sometimes absorbs also experimental inpurities.

2 Particle Correlations in Z\(^0\) Decays
2.1 Bose–Einstein Correlations in Pairs of Pions

Fig. 1 shows recent L3 measurements 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 visible. Using a GGLP type of parametrisation, the obtained source radius R for neutral pions is tending to be smaller than for charged pions, as qualitatively expected in the Lund string model.

2.2 Fermi–Dirac Correlations in Pairs of Antiprotons

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 Q → 0.

As a preliminary result, the OPAL collaboration reported a depletion of anti–proton pairs at low Q, as shown on the left–hand side of Fig. 2.
2.3 Dependence of the Emitter Radius on the Hadron Mass

Together with results for the emission radius for pion, kaon and Λ pair correlations, compiled by Alexander et al. [8], the radius R for pairs of antiprotons is shown as a function of the hadron mass on the right-hand side of Fig. 2. The observed hierarchy \( R_π > R_K > R_{\bar{p},\Lambda} \) can be explained qualitatively by a model based on the Heisenberg uncertainty principles and an approach taking into account the strong correlation between space/time \( x^\mu \) and momentum/energy \( p^\mu \) of the particle in the hadron production process.

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 have in general 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 by Chekanov et al. [11]. If the \( W^- \) and \( W^+ \) decay independently, then \( \Delta \rho(Q) = 0 \) for all Q with the test distribution \( \Delta \rho \) defined as:

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

with the two–particle densities \( \rho_{WW \rightarrow 4q}^W \) determined by the \( W^+W^- \rightarrow q\bar{q}q\bar{q} \) sample, \( \rho_{W \rightarrow 2q}^W \) by the hadronic part of semileptonic \( W^+W^- \rightarrow q\bar{q}l\nu \) events and \( \rho_{WW \text{ mix}}^W \) from events build from two independent semileptonic events without the leptonic parts and combining only particles originating from different W’s.

![Figure 3: Preliminary \( \Delta \rho \) distributions from L3 (left) and DELPHI (right) compared with MC models.](image)

In Fig. 3, the L3 collaboration [12] compares the \( \Delta \rho \) distribution obtained from the data with two scenarios of the PYTHIA/PYBOEI [13] Monte Carlo model with BEC. The inter–WW BEC in the Monte Carlo model can be seen as an enhancement of like–sign pairs in the low Q region. 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 (i.e. same \( R, \lambda \)) as the correlations within the same W, is strongly disfavoured. The same is true for similar results from DELPHI [14], as shown on the right–hand side of Fig. 3. Both results are preliminary.

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, 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. 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

Bose–Einstein correlations in high energy physics have been studied extensively for more than 40 years. It seems that we have now come to a better understanding of the effect 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, the study of particle correlations provides us with details complementary to those obtained from global event properties and single–particle distributions.

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