

Hadronic final state interactions at ALEPH and OPAL

V.M. Ghete ^a

^aInstitute for Experimental Physics, University of Innsbruck, A-6020, Innsbruck, Austria

The studies of Fermi–Dirac correlations of $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs in hadronic Z decays, Bose–Einstein correlations and colour reconnection in W-pairs decays performed by the ALEPH collaboration in e^+e^- annihilation at LEP are presented. The OPAL analysis of Bose–Einstein correlations in W-pair decays is also discussed.

1. Introduction

Bose–Einstein (BE) correlations between identical bosons and Fermi–Dirac (FD) correlations between identical fermions lead to an enhancement or a suppression, respectively, of the particle pairs produced close to each other in phase space. The effect is sensitive to the distribution of particle sources in space and time. The strength of the correlations can be expressed by the two-particle correlation function $C(p_1, p_2) = P(p_1, p_2)/P_0(p_1, p_2)$, 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 $P_0(p_1, p_2)$ is that of a reference sample, identical to the data sample in all aspects except the presence of FD or BE correlations. Usually $C(Q)$ is measured, where $Q^2 = -(p_1 - p_2)^2$.

For W-pairs from $e^+e^- \rightarrow W^+W^-$ at energies in the LEP2 range, the distance between W^+ and W^- vertices is less than 0.1 fm, i.e. less than the typical hadronic distance scale of 1 fm. Therefore the fragmentation of W^+ and W^- may not be independent. Two phenomena may appear: pions from different W's may exhibit BE correlations and pairs of quarks and antiquarks $q_1\bar{q}_4$ and $q_3\bar{q}_2$ from the decay of different W's can form colour strings (colour reconnection). Colour reconnection (CR) and BE correlations have opposite effects. They may influence the accuracy of the W mass measurement at LEP.

In this talk, three ALEPH analyses are presented: FD correlations of $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs in hadronic Z decays at LEP1 [1], colour reconnection [2] and BE correlations [3] in W-pairs decays at LEP2. The OPAL analysis of BE correlations

in W-pair decays [4] is also discussed here, due to the unavailability of the OPAL speaker.

2. Fermi-Dirac correlations in $(\Lambda\Lambda, \bar{\Lambda}\bar{\Lambda})$ system

The FD correlations in $(\Lambda\Lambda, \bar{\Lambda}\bar{\Lambda})$ system were studied using 3.9 million hadronic Z decays recorded by the ALEPH detector on and around the Z peak. A sample of 2133 pairs with $Q < 10$ GeV was obtained.

In the analysis, three reference samples were used: A) simulated pairs from JETSET MC without FD correlations, where $C(Q) = P(Q)_{\text{data}}/P(Q)_{\text{MC}}$; B) pairs obtained by event mixing, where $C(Q) = [P(Q)_{\text{data}}/P(Q)_{\text{data}}^{\text{mix}}]/[P(Q)_{\text{MC}}/P(Q)_{\text{MC}}^{\text{mix}}]$; C) reweighted sample of mixed pairs, where $C(Q) = P(Q)_{\text{data}}/P(Q)_{\text{data, mix}}^{\text{reweighted}}$.

The measured correlation functions are shown in Fig. 1, parametrised with

$$C(Q) = \mathcal{N}[1 + \beta \exp(-R^2Q^2)] \quad (1)$$

Consistent results are obtained for the three reference samples. The correlation function $C(Q)$ decreases for $Q < 2$ GeV; as Q tends to zero, it approaches the value of 0.5, as expected for a statistical spin mixture ensemble. If this is interpreted as a FD effect and the parametrisation of Eq. (1) is used, the resulting values for the source size R and for the suppression parameter β are

$$R = 0.11 \pm 0.02_{\text{stat}} \pm 0.01_{\text{sys}} \text{ fm}$$

$$\beta = -0.59 \pm 0.09_{\text{stat}} \pm 0.04_{\text{sys}}$$

An alternative method to study the $(\Lambda\Lambda, \bar{\Lambda}\bar{\Lambda})$ system is to measure the spin composition of the

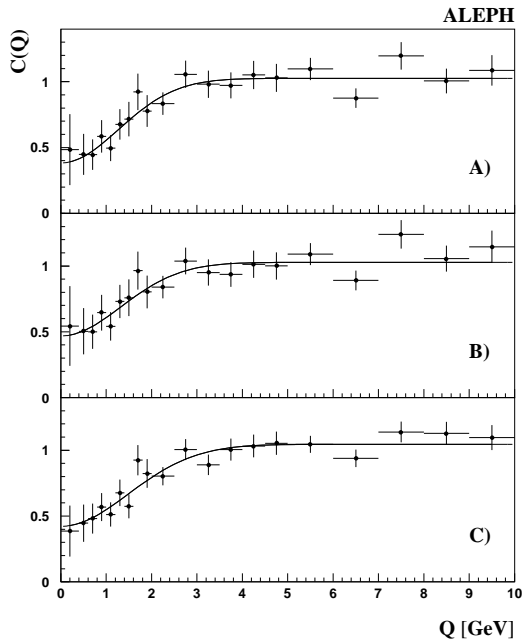


Figure 1. Correlation function for the $(\Lambda\Lambda, \bar{\Lambda}\bar{\Lambda})$ pairs using reference samples *A*, *B*, and *C*. The curves represent fits using the parametrisation given in Eq. (1).

system using the angular distribution dN/dy^* , with y^* the cosine of the angle between the two protons (antiprotons) in the di-hyperon centre-of-mass system. The measured dN/dy^* distribution has contributions from both $S = 1$ and $S = 0$ states:

$$\frac{dN}{dy^*} = (1 - \varepsilon) \left. \frac{dN}{dy^*} \right|_{S=0} + \varepsilon \left. \frac{dN}{dy^*} \right|_{S=1}$$

where ε is the fraction of $S = 1$ contribution. By fitting the dN/dy^* distribution in different Q ranges, the dependence $\varepsilon(Q)$ is obtained. But $\varepsilon(Q)$ can also be defined as $\varepsilon(Q) = C(Q)_{S=1} / [C(Q)_{S=0} + C(Q)_{S=1}]$, with $C(Q)_{S=1}$ and $C(Q)_{S=0}$ the contributions of $S = 1$ and $S = 0$ states to the correlation function $C(Q)$. Using the parametrisation given in Eq. (1), one obtains for a statistical spin mixture ensemble

$$\varepsilon(Q) = 0.75 \frac{1 - \gamma \exp(-R^2 Q^2)}{1 - 0.5\gamma \exp(-R^2 Q^2)} \quad (2)$$

with $\gamma = -2\beta$. The distribution $\varepsilon(Q)$ is shown in Fig. 2, fitted with the parametrisation given in

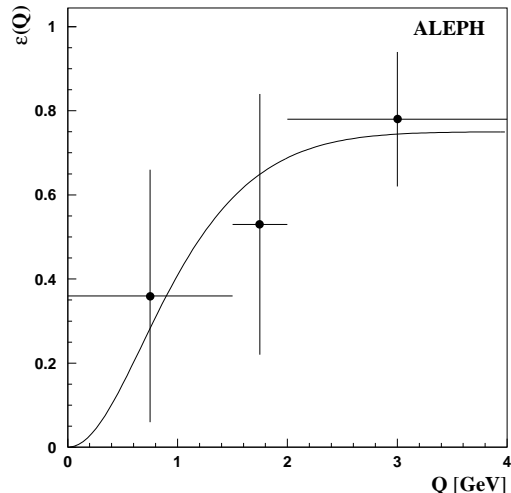


Figure 2. The fraction $\varepsilon(Q)$ of the $S = 1$ contribution for the $(\Lambda\Lambda, \bar{\Lambda}\bar{\Lambda})$ data. The curve represents a fit using the parametrisation given in Eq. (2).

Eq. (2) with γ fixed to one. The state $S = 1$ dominates for $Q > 2$ GeV, but it is suppressed for $Q < 2$ GeV. The value of the source size estimated from $\varepsilon(Q)$ is $R = 0.14 \pm 0.09_{\text{stat}} \pm 0.03_{\text{sys}}$ fm, in agreement with the value obtained from the correlation function. From comparison with results from $\pi^\pm \pi^\pm$ and $K^\pm K^\pm$ correlation measurements, one observes that the source dimension decreases with increasing mass of the emitted particle.

3. Colour reconnection in W-pair decays

The colour reconnection in $e^+e^- \rightarrow W^+W^-$ was studied in a data sample of 174.2 pb^{-1} at a centre-of-mass energy of $\sqrt{s} = 189$ GeV. Hadronic and semileptonic W-pair decays were selected and the experimental distribution $-\ln x_p$ of the charged particles was compared for each event type to the MC models KORALW and EXCALIBUR without CR and to EXCALIBUR with CR. Here $x_p = p/(\sqrt{s}/2)$ is the scaled momentum of a particle. KORALW and EXCALIBUR are used to generate W-pairs; both are coupled to JETSET for the hadronization part. Three CR models [2], denoted as *I*, *II* and *IIP* and implemented in JETSET, were compared to

data. The distribution obtained for the data and the MC models are shown in Fig. 3. The

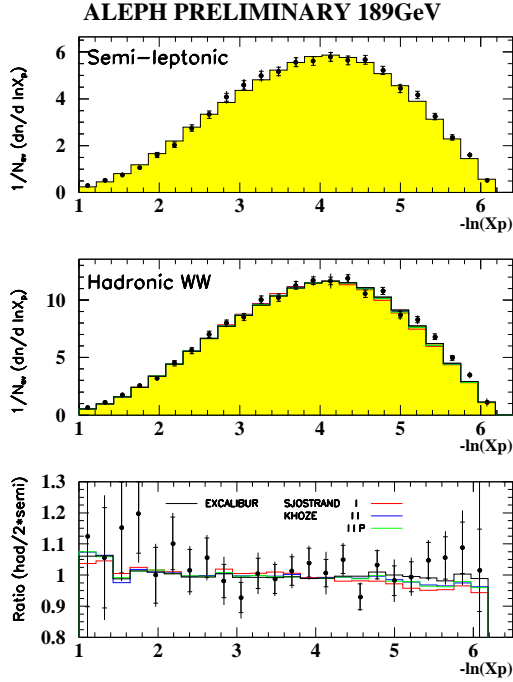


Figure 3. The $-\ln x_p$ distributions for semileptonic and hadronic W-pair decays for data and MC models with and without CR.

ratio of the multiplicity in fully-hadronic events to twice the multiplicity in semileptonic events is also shown. The multiplicities within the experimental acceptance for the semileptonic channel are $N_{ch}^{l\nu q\bar{q}} = 17.53 \pm 0.19 \pm 0.24$ for data and $N_{ch}^{l\nu q\bar{q}} = 17.41 \pm 0.04 \pm 0.29$ for MC (no CR), giving a difference between data and MC of 0.12 ± 0.42 . For the fully hadronic channel, the multiplicity is $N_{ch}^{q\bar{q}q\bar{q}} = 35.52 \pm 0.22 \pm 0.43$ for data and $N_{ch}^{q\bar{q}q\bar{q}} = 34.77 \pm 0.04 \pm 0.58$ for MC (no CR), which gives a difference of 0.75 ± 0.76 . The difference $N_{ch}^{q\bar{q}q\bar{q}} - 2N_{ch}^{l\nu q\bar{q}}$ is $0.47 \pm 0.44 \pm 0.26$ for data, -0.05 ± 0.09 for MC (no CR) and 0.52 ± 0.52 for the difference between data and MC. No colour reconnection was observed in the data, but at the current level of statistical precision both models with and without CR are compatible with the experimental results.

4. Bose–Einstein correlations in W-pair decays

The Bose–Einstein correlations in W-pair decays were studied using data recorded by the ALEPH detector at centre-of-mass energies of 172, 183 and 189 GeV. For the tuning of the MC models of BE correlations, Z data recorded at 91.2 GeV with the same detector configuration as for W^+W^- events were used. Pairs of unlike-sign pions were chosen as reference sample and the correlation function was defined as

$$R^*(Q) = \frac{\left(\frac{N_{\pi^{++},--}(Q)}{N_{\pi^{+-}}(Q)} \right)_{\text{data}}}{\left(\frac{N_{\pi^{++},--}(Q)}{N_{\pi^{+-}}(Q)} \right)_{\text{no BE}}^{\text{MC}}}. \quad (3)$$

The correlation function was parametrised with

$$R^*(Q) = \kappa(1 + \epsilon Q)(1 + \lambda e^{-\sigma^2 Q^2}) \quad (4)$$

where the term $1 + \lambda e^{-\sigma^2 Q^2}$ describes the BE effect. The two parameters λ and σ characterise the effective strength of the correlations and the source size, respectively. The term $1 + \epsilon Q$ takes into account some long range correlations due to the charge and the energy-momentum conservation, while κ is a normalisation factor.

The BE correlations were first measured in Z decays. A MC simulation of the BE effect with the JETSET BE₃ model [5] was then tuned on these data. The tuned parameters were $\lambda_{\text{input}} = 2.3$ and $R_{\text{input}} = 0.26$ GeV. As W bosons do not decay into b quarks, the BE effect was determined separately in an udsc sample and in a b sample. Two b samples of different purities were tagged [6] and the parameters λ_b and λ_{udsc} were determined. Using these parameters, the bb component was replaced by an udsc component. The agreement between the MC model and the udsc data is good; residual discrepancies between them are corrected bin by bin.

The prediction of the MC model tuned and corrected on Z data was then checked on semileptonic W-pairs decays. They were found to be in very good agreement. For the hadronic W-decays, two cases were considered in the MC

model: pions from different W 's may exhibit BE correlations (denoted as BEB) and only pions from the same W exhibit BE correlations (denoted as BEI). The comparison between these two MC models and data is shown in Fig. 4. The re-

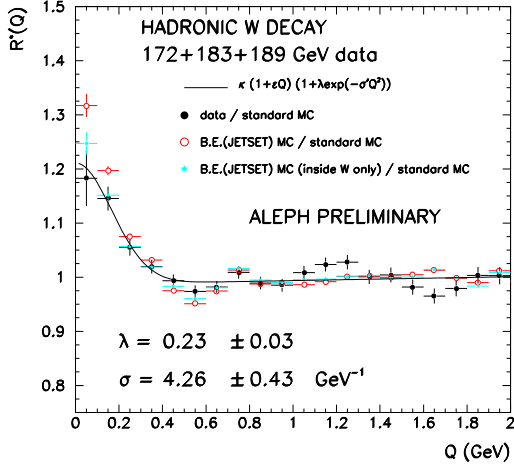


Figure 4. The correlation function $R^*(Q)$ for fully hadronic W -decays, compared to MC models of BE correlations.

sult of the fit with the parametrisation given in Eq. (4) is also shown. All four parameters κ , ϵ , λ and σ were free in this fit. The values of λ and σ were used to compute an integral of the BE signal $I_{BE} = \int_0^\infty \lambda e^{-\sigma^2 Q^2} dQ \propto \lambda/\sigma$ for data and MC. A second fit with κ , ϵ and σ fixed and λ free was also made to the first four bins only, where the effect is expected to be maximum. The differences between the data and the MC models for λ from the one-parameter fit are

$$\begin{aligned} \lambda^{\text{data}} - \lambda^{\text{MC BEB}} &= -0.088 \pm 0.026 \pm 0.020 \\ \lambda^{\text{data}} - \lambda^{\text{MC BEI}} &= -0.019 \pm 0.026 \pm 0.016 \end{aligned}$$

while for the I_{BE} quantity they are

$$\begin{aligned} I_{BE}^{\text{data}} - I_{BE}^{\text{MC BEB}} &= -0.0217 \pm 0.0062 \pm 0.0048 \\ I_{BE}^{\text{data}} - I_{BE}^{\text{MC BEI}} &= -0.0040 \pm 0.0062 \pm 0.0036 \end{aligned}$$

The first error is the statistical error, the second is the systematic one. A better agreement is obtained for the JETSET model with BE correlations present only for pions coming from the same

W boson. The JETSET model which allows for BE correlations between pions from different W 's is disfavoured by both λ and I_{BE} variables at 2.7σ level.

5. Bose–Einstein correlations in W -pair decays at OPAL

The OPAL collaboration has analysed data recorded at centre-of-mass energies of 172, 183 and 189 GeV. Three mutually exclusive event sample were selected: the fully hadronic event sample $W^+W^- \rightarrow q\bar{q}q\bar{q}$, the semileptonic event sample $W^+W^- \rightarrow l\nu q\bar{q}$ and the non-radiative $(Z^0/\gamma)^*$ event sample $(Z^0/\gamma)^* \rightarrow q\bar{q}$. The correlation function $C(Q)$ was defined according to Eq. (3). For each sample, the correlation function was written as a combination of contributions from the various pure pion classes, including the background. For hadronic event sample one has

$$\begin{aligned} C^{\text{had}}(Q) &= P_{\text{had}}^{\text{WW}}(Q)C^{\text{q}\bar{q}\text{q}\bar{q}}(Q) + \\ &[1 - P_{\text{had}}^{\text{WW}}(Q)]C_{bg}^{Z^*}(Q). \end{aligned}$$

Similar expressions were written for $C^{\text{semi}}(Q)$ and $C^{\text{non-rad}}(Q)$ correlation functions. The probabilities $P_{\text{had}}^{\text{WW}}(Q)$, etc. were taken from MC simulations without BE effect. Each correlation function $C^{\text{q}\bar{q}\text{q}\bar{q}}(Q)$, $C^{\text{q}\bar{q}}(Q)$ and $C^{Z^*}(Q)$ was parametrised by

$$C(Q) = N[1 + f_\pi(Q)\lambda \exp(-Q^2 R^2)] \quad (5)$$

where $f_\pi(Q)$ is the probability of the pair to be a pair of pions. A simultaneous fit was made to the experimental data, with the parameters N , λ and R free for each event class (nine free parameters). All three classes exhibit BE correlations with consistent R and λ parameters. BE correlations were then investigated separately for pions coming from the same W and from different W 's. The correlation function for the hadronic event sample was written as

$$\begin{aligned} C^{\text{had}}(Q) &= P_{\text{had}}^{\text{same}}(Q)C^{\text{same}}(Q) + P_{\text{had}}^{Z^*}(Q)C_{bg}^{Z^*}(Q) \\ &+ [1 - P_{\text{had}}^{\text{same}}(Q) - P_{\text{had}}^{Z^*}(Q)]C^{\text{diff}}(Q) \end{aligned}$$

where $C^{\text{same}}(Q)$, $C^{\text{diff}}(Q)$ and $C_{bg}^{Z^*}(Q)$ are the correlation functions for pions from the same

W, from different W's and from $(Z^0/\gamma)^* \rightarrow q\bar{q}$ events. Similar expressions were written for $C^{\text{semi}}(Q)$ and $C^{\text{non-rad}}(Q)$. The correlation functions $C^{\text{same}}(Q)$, $C^{\text{diff}}(Q)$ and $C^{Z^*}(Q)$ were unfolded from the data and are shown in Fig. 5. They were then parametrised by Eq. (5) and simultaneous fits to the experimental distributions were performed. Three different cases were considered: 1) the same source-size R for all event classes; 2) different R parameters for each class, and 3) R^{diff} is related to R^{same} using the theoretical prediction $(R^{\text{diff}})^2 = (R^{\text{same}})^2 + 4\beta^2\gamma^2c^2\tau^2$. The results obtained for the parameter λ for the third case are

$$\begin{aligned}\lambda^{\text{same}} &= 0.69 \pm 0.12 \pm 0.06 \\ \lambda^{\text{diff}} &= 0.05 \pm 0.67 \pm 0.35 \\ \lambda^{Z^*} &= 0.43 \pm 0.06 \pm 0.08\end{aligned}$$

At the current level of statistical precision it is not possible to determine if correlations between pions from different W's exist or not.

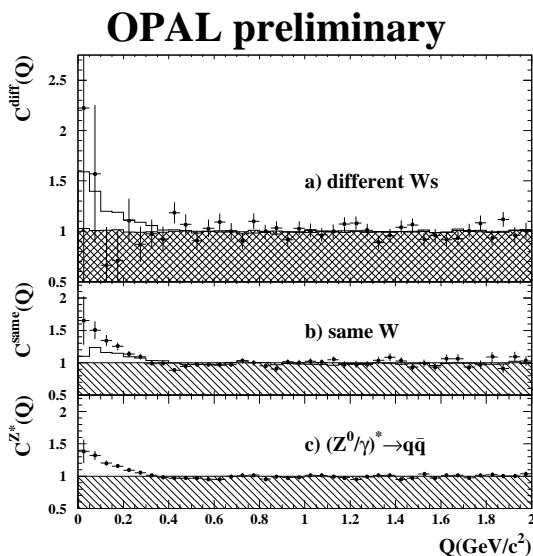


Figure 5. The correlation function for unfolded classes $C^{\text{same}}(Q)$, $C^{\text{diff}}(Q)$ and $C^{Z^*}(Q)$.

6. Conclusion

The ALEPH analyses of Fermi–Dirac correlations of $(\Lambda\Lambda, \bar{\Lambda}\bar{\Lambda})$ pairs in hadronic Z decays and of colour reconnection and Bose–Einstein correlations in W-pairs decays have been presented.

A depletion of events are observed for the region $Q < 2$ GeV in the $(\Lambda\Lambda, \bar{\Lambda}\bar{\Lambda})$ system. In the analysis of W-pair decays, no colour reconnection effects are observed, but models which predict such effects can not be excluded. The Bose–Einstein correlations measured in W-pair decays are reproduced by a Monte Carlo model with independent fragmentation of the two W's, while a variant of the same model with Bose–Einstein correlations between decay products of different W's is disfavoured at 2.7σ . The OPAL analysis of Bose–Einstein correlations in W-pair decays has also been presented. At the current level of statistical precision it was not possible to determine if correlations between pions from different W's exist or not.

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The experiments obviously use different methods to study BE correlations. It is technically possible to agree on one dataset and check the various methods on their systematics?

Answer: Each experiment has optimised the analysis on detector characteristics and on the aspects of BE correlations which were considered important to be studied with the available statistics. The methods are therefore different; this is a normal situation, there is no need to have coordinated analyses until each experiment obtains a set of “final results”. A too early coordination and convergence of the methods can reduce the quality of the analyses. Once the experiments obtains “final results”, an intercomparison is meaningful, followed by cross checks of the methods used by the other experiments (within the limits of statistics and... manpower). In fact, a LEP group was formed recently to understand the differences between the results of the four LEP experiments.