CORRELATIONS IN *WW* EVENTS*

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A critical summary is given of the present status of the study of Bose–Einstein correlations in W-pair production at LEP 2. In particular, the evidence is reviewed for or against the existence of Bose–Einstein correlations between pions originating both from a different of the two W's. If present, such an inter-W interference would not only form a potential bias in the determination of the W mass, but also would provide a laboratory to measure the space-time development of the overlap. If absent, this would drastically change the conventional (Hanbury Brown and Twiss) picture of pion interferometry in high energy physics.

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1. Introduction

Correlations between pairs of identical particles (or, in the simplified experimental approach, pairs of like-sign particles) within a single hadronic system are a well known phenomenon, however the understanding of this effect is far from complete. Most often, it is considered to be an equivalent of the Hanbury Brown–Twiss effect in astronomy, reflecting the interference of identical bosons emitted incoherently from their source.

An alternative model, proposed by Andersson and collaborators [1], takes into account the full process of particle production in the fragmentation of the Lund string. The correlations appear as a coherent effect in the hadronization process, and they are fully predicted for a given set of final particles (ordered along the string).

We are therefore in the situation when the experimentally observed correlations can be interpreted in a rather different ways: in the "incoherent" approach, the shape of the correlation function reflects the shape of the

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source, and can be derived from the knowledge of the space-time density of the final particles regardless of the way they were produced; in the "coherent" picture, the correlations stem directly from the string area decay law, and depends on the history of the string breaking.

For a simple hadronic system like $q\bar{q}$ from a Z^0 decay, it may be impossible to decide between the two possibilities, since the incoherent approach leaves a freedom of the choice of the input particle density, which can be adjusted to reproduce the observed data (it should be noted, however, that the straightforward implementation of the "incoherent" formalism fails to describe the Z^0 data [2]).

The situation is different in the study of two close hadronic systems. In the incoherent scenario, the difference between correlations within a single hadronic system, and correlations between the two systems, should depend only on the overlap of the two systems (sources). In the coherent scenario, however, the correlations between the two systems may not exist at all, even for overlapping sources (as long as there is no interaction — colour flow — between them).

2. Measurements

In the light of the discussion above, the experimental measurement of correlations between two independent hadronic systems is of utmost interest, and LEP 2 provides a unique laboratory for such a measurement in the study of the decay of a pair of W^+W^- (Z^0Z^0, respectively,) bosons. The lifetime of these bosons is much shorter than the typical hadronization scale, and they decay on top of each other, overlapping (partially) in the momentum space.

The measurement of the size of the inter-$W(Z)$ correlations can be done in a different ways, and it is complicated by several factors, namely:

- the modelling of the effect is poor (none of models discussed in the introduction is fully implemented in MC generators); the most widely used model (LUBOEI/PYBOEI in Jetset [3]) consists in a simple reshuffling of momenta of final particles, leading to an artificial momentum transfer,
- the effect is defined with respect to a reference (uncorrelated) sample, which is arbitrary to a large extent, and different for each collaboration/measurement,
- detector effects can be important, and not easy to correct for because of model dependence of correction factors for 2-particle spectra.

The experimental methods used by the LEP collaborations for this measurement can be roughly classified according to the level of their model dependence.

The "model dependent" methods consist in tuning of a particular model at the Z^0/single W decay and in comparison of the prediction of the model with real WW/ZZ events. Such a method was used by ALEPH [5]. The correlations between the like-sign particles (after rejection of identified electrons and muons) are defined with respect to the unlike-sign particles sample, and the double ratio with the Monte Carlo sample is used to remove the effect of resonances as well as part of detector effects:

$$R^*(Q) = \frac{\left(\frac{N^{++,--}}{N^{+-}}\right)^{\text{data}}}{\left(\frac{N^{++,--}}{N^{+-}}\right)^{\text{MC}}_{\text{noBE}}} . \tag{2.1}$$

The tuning of PYBOEI routine is performed on the Z^0 sample enriched in light flavours and checked in the semileptonic W events. The residual discrepancies between data and simulation are corrected bin per bin and correction applied on MC predictions for fully hadronic events, in the scenario with and without correlation between the two boson systems (Fig. 1). The $q\bar{q}$ background is included in the MC prediction. The data disfavour the presence of the inter-W/Z correlations (for this particular tune of the model) by 2.7 σ.

Apart from a strong model dependence built in this measurement, one may worry also about the fact that due to the use of double ratios, the model may be actually quite far from the data in the direct comparison (not reproducing the Q distribution, itself).

A different method with lower model dependence was used by OPAL [4]. It is based on a simultaneous fit of correlation functions in Z^0/γ^*, $q\bar{q}l\nu$, and $q\bar{q}q\bar{q}$ events. The Z^0/WW content in these three samples is parameterised according to the selection efficiency obtained with the MC simulation. Correlation function, defined as the double ratio (2.1), is extracted for pairs of particles coming from Z^0/γ, single W, and from different W-s in a simultaneous fit. The result is shown in Fig. 2. Unfortunately, due to the large uncertainties, the method is far from being sensitive to the effect of inter-boson correlations (λ^{diff}), and no conclusions about the presence of these correlations can be made.

In the measurement proposed in [7] and published by L3 [8], the model dependence is largely removed due to the use of the reference sample constructed by mixing of the hadronic parts of the semileptonic W^+W^- events. Such a direct "data-to-data" comparison is experimentally robust and does not require a direct use of MC simulation (except for checking of the mixing method). The only residual model dependence is related to the subtraction of background events.

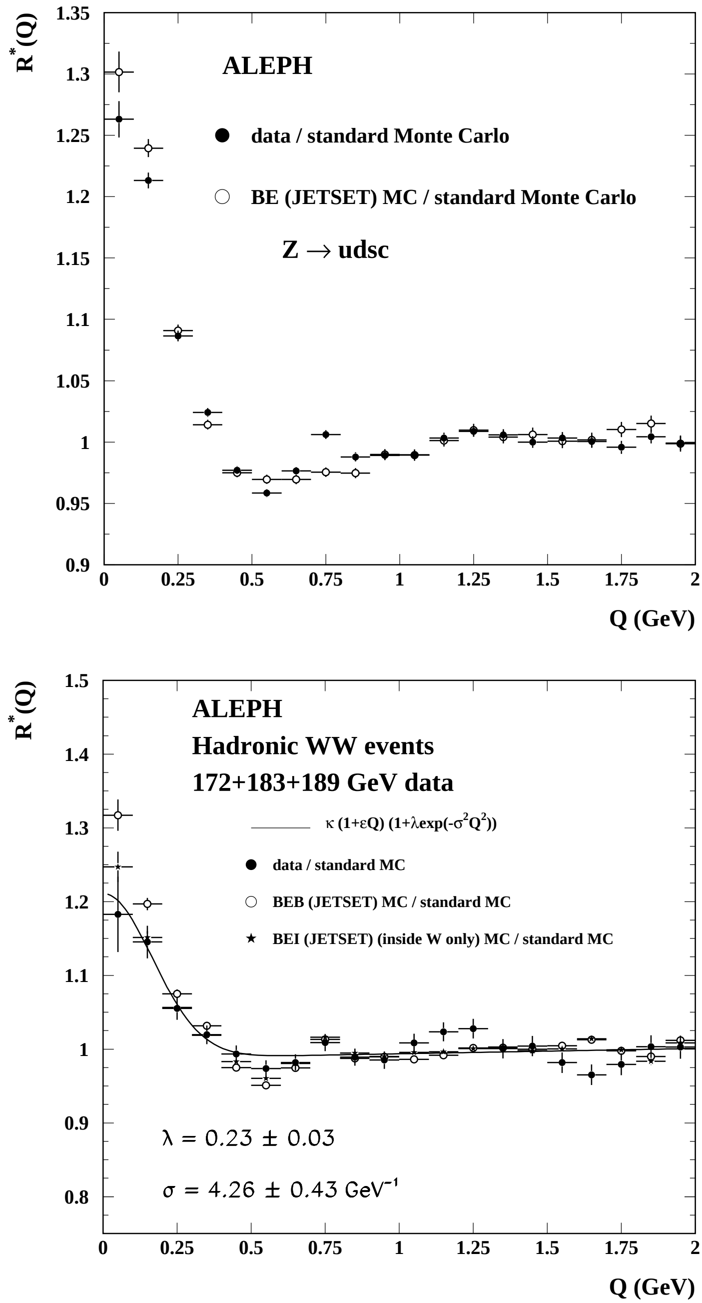
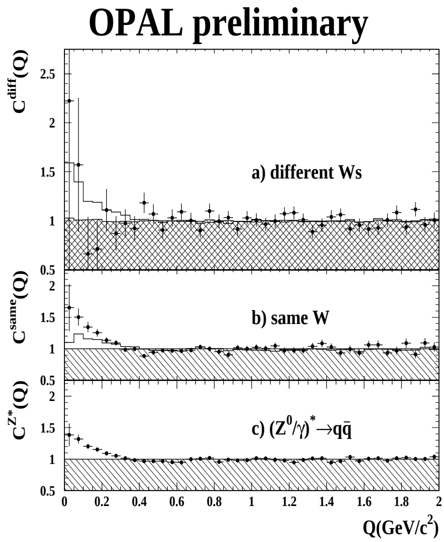


Fig. 1. The double ratios R^* measured in the Z^0 and in the fully hadronic W^+W^- sample, compared to the prediction of the model tuned at Z^0 (PYBOEI BE_3).



Results of the simultaneous fit:

$\lambda^{\text{diff}} = 0.05 \pm 0.67 \pm 0.35$
$R^{\text{diff}} = 1.51 \pm 0.05 \pm 0.09/\text{fm}$

$\lambda^{\text{same}} = 0.69 \pm 0.12 \pm 0.06$
$R^{\text{same}} = 1.07 \pm 0.07 \pm 0.12/\text{fm}$

$\lambda^{Z^*} = 0.43 \pm 0.06 \pm 0.0$
$R^{Z^*} = 1.01 \pm 0.08 \pm 0.14/\text{fm}$
(data at 172, 183 and 189 GeV)

Fig. 2. Correlation function for the unfolded classes. The data points show the experimental distributions. The open histogram shows (a) the result of the simulation including inter-W correlations, (b) the result of simulation including correlations within a single W. The cross-hatched histogram in (a) shows result of simulation with correlation only within a single W, while the hatched histograms in (b) and (c) correspond to a simulation without any BE correlations.

Fig. 3 shows the ratios of 2-particle densities obtained from the fully hadronic W^+W^- sample and from the mixed sample

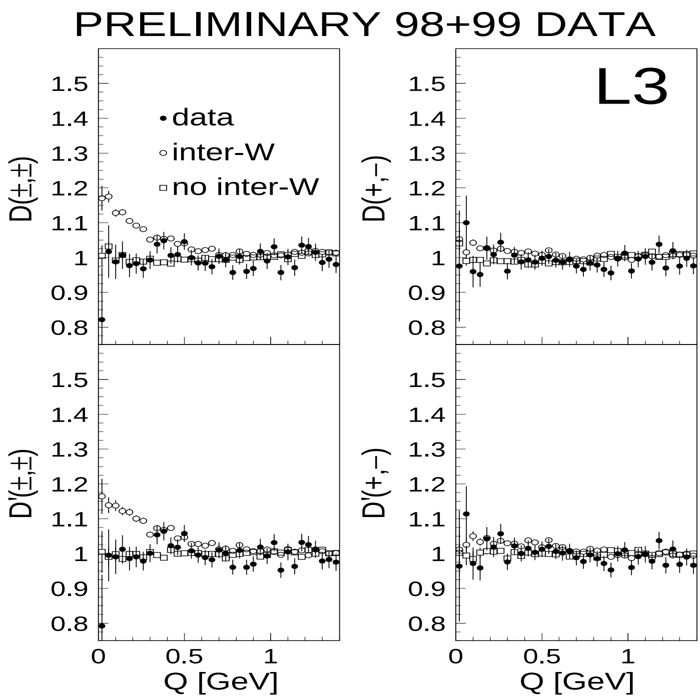
$$D(Q) = \frac{\rho_2^{\text{hadr.}WW}(Q)}{\rho_2^{\text{mixed }WW}(Q)}\,, \tag{2.2}$$

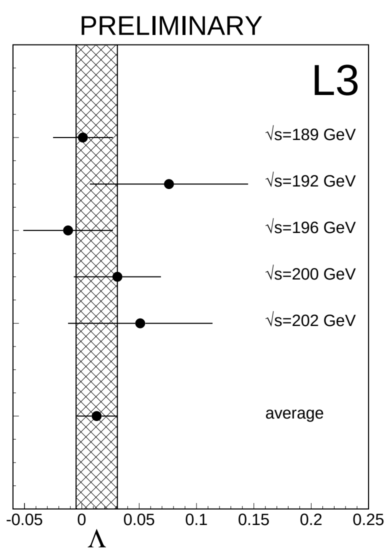
and the double ratio

$$D'(Q) = \frac{D^{\text{data}}(Q)}{D^{\text{MC,noBE}}(Q)}\,. \tag{2.3}$$

The L3 results do not show any evidence for the existence of inter-W correlations.

Since the model dependent measurements have only very limited impact, the advantages of the method used by L3 seem to be acknowledged by the other LEP experiments which are preparing similar measurements. Recently, ALEPH released preliminary results using the mixed reference sample [6]. The results cannot be quantified because of missing systematic errors, however the measurement seems to disfavour the presence of correlations, in agreement with L3 and with aforementioned ALEPH results.





Fit of the shape of $D'(\pm,\pm)$ with the function $(1+\varepsilon Q)(1+\Lambda \exp -k^2Q^2)$ gives the following result (combined 98+99 data): $\Lambda = 0.013 \pm 0.018 \pm 0.015$

Fig. 3. The results obtained by L3 using the mixing method, for like-sign and unlike-sign pairs in WW events, compared to the prediction of the tuned model (PYBOEI BE_{32}).

The DELPHI experiment, using similar analysis method, recently reported results compatible with the absence or strong suppression of inter-W correlations [9]. The measured $D(Q)$ (ratio of 2-particles densities) and $\Delta\rho(Q)$ (their difference) for pairs of like-sign particles are shown in Fig. 4. The data sample contains combined statistics from 3 years of LEP 2 running (1998–2000). The predictions of the PYBOEI model (BE32 scenario tuned at Z^0 data) with and without inter-W correlations are superposed for completeness.

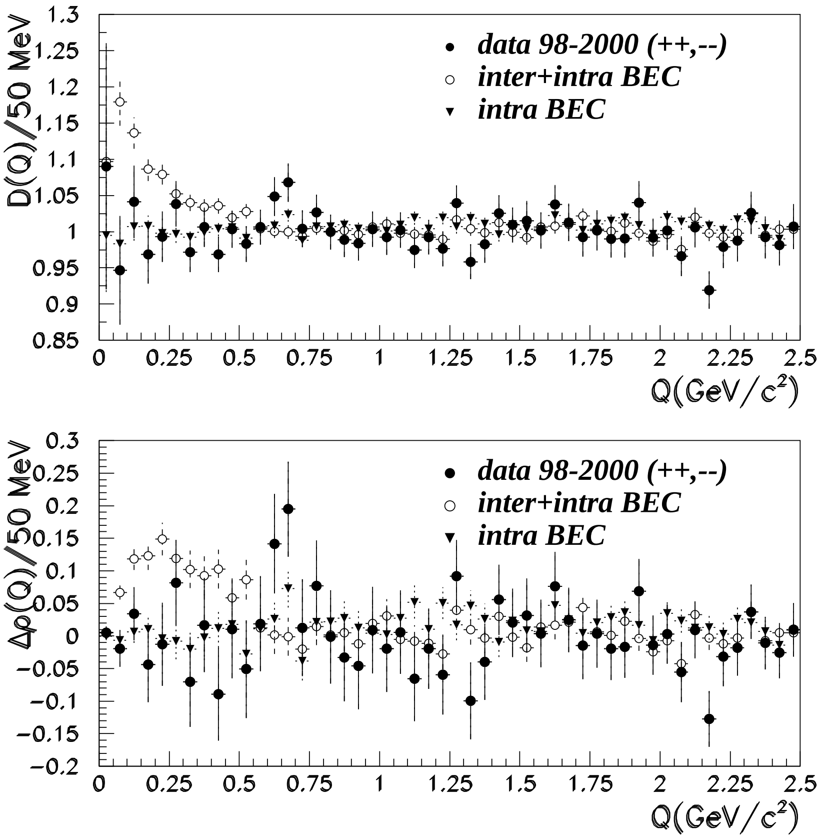


Fig. 4. The results obtained by DELPHI using the mixing method, for like-sign pairs in WW events, compared to the prediction of the tuned model (PYBOEI BE_{32}). The ratio (upper plot) and difference (lower plot) of 2-particle densities from fully hadronic and mixed WW events are shown. Z^0/γ^* background is subtracted from fully hadronic WW selection using the PYBOEI model.

Fit of the $D(Q)$ (Eq. (2.2)) by the function

$$N^*(1+\delta Q)\left(1+\lambda \exp\frac{-1.01\ Q}{\hbar}\right)\,,$$

yields (the parameter in the exponent is fixed to the value obtained when fitting model with inter-W correlations)

$$\lambda = -0.037 \pm 0.055(\mathrm{stat.}) \pm 0.055(\mathrm{syst.})\,.$$

The systematics of the measurement is largely dominated by the uncertainty related to the background subtraction.

3. Combination of LEP results

From the set of LEP 2 measurements reviewed in the previous section one can conclude that the correlations of particles belonging to different, though rather close hadronic systems, are strongly suppressed with respect to the amount of correlations measured within each system separately. Somewhat surprisingly, measurements are even consistent with the complete absence of such correlations. The observation contradicts the conventional perception of Bose–Einstein correlations in particle physics, however it is difficult to make quantitative statements in the absence of reliable theoretical models/calculations. On the other hand, the more profound understanding of the effect is highly desirable for LEP 2 community as the interplay of final states from WW decay may influence the direct reconstruction of the W mass.

In order to provide the best possible experimental upper limit as the input for further theoretical work, LEP collaborations plan to combine the measurements of inter-W correlations. The experiments converge to a single method *à la* L3, which provides the most direct, and less biased, access to the inter-W correlations. Because of differences in the event selection, but also due to the uncertainty related to the correction of detector effects, the combination may not be done at the level of 2-particle densities, but rather for $D(Q)$ and $\Delta\rho$. The uncertainty of the background subtraction, largely correlated between experiments, is likely to become the limiting factor for the precision of the combined measurement.

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