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Bose-Einstein Correlations in WW Events

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Abstract

Bose-Einstein correlations in WW events where both W bosons decay hadronically may give rise to "cross-talk" between the two W bosons, leading to a systematic error in the reconstructed W mass. Phenomenological investigations now find values of this shift at the level of at most 20–30 MeV. Experimental investigations at LEP favour the absence of such correlations for identical pions coming from different W bosons. An indication is seen for a larger correlation strength in single hadronic W decays than in fully hadronic WW events.

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BOSE-EINSTEIN CORRELATIONS IN WW EVENTS

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Bose-Einstein correlations in WW events where both W bosons decay hadronically may give rise to "cross-talk" between the two W bosons, leading to a systematic error in the reconstructed W mass. Phenomenological investigations now find values of this shift at the level of at most 20–30 MeV. Experimental investigations at LEP favour the absence of such correlations for identical pions coming from different W bosons. An indication is seen for a larger correlation strength in single hadronic W decays than in fully hadronic WW events.

1 Introduction

In WW events at LEP2, the two W bosons typically decay at a distance much shorter than the hadronization scale of 0.5 – 1.0 fm. When both W bosons decay hadronically, there is therefore a possibility of interference due to colour reconnection, as discussed in the preceding talk,[1] and of Bose-Einstein correlations(BEC) [2] among identical bosons coming from *different* W bosons.

Such interference effects constitute a very interesting new potential source of information about hadron formation, but have also been recognized to give rise to some of the most worrisome systematic errors in the precision measurement of the W mass, as they may cause shifts in the reconstructed W mass which are quite hard to estimate.

The present talk reviews recent investigations of Bose-Einstein correlations in WW events at LEP2.[3,4,5,6]

Although the statistics collected at LEP2 is still limited, exploratory studies already show quite interesting results. Such studies are facilitated by the presence in the same detectors of WW events where one W decays hadronically and the other leptonically ("semileptonic" events), at about the same rate as fully hadronic events.

1.1 The correlation function

Bose-Einstein correlations are normally studied by means of the two particle correlation function

$$R(p_1, p_2) = \frac{P(p_1, p_2)}{P_0(p_1, p_2)}$$

where $P(p_1, p_2)$ is the two particle density for the identical bosons (e.g. $\pi^+\pi^+$ or $\pi^-\pi^-$) with momenta p_1 and p_2 and $P_0(p_1, p_2)$ is a corresponding reference distribution which ideally is identical in all respects to $P(p_1, p_2)$, except for the absence of BEC. These are then observed as an enhancement in R when the momentum difference is small.

It can be shown that for a given space-time distribution, $f(x)$, of uncorrelated sources, $R = 1 + \tilde{F}[f(x)]^2$, where $\tilde{F}[f(x)]$ is the Fourier transform of $f(x)$.

In e^+e^- collisions at lower energy, R is generally observed to be a function of the squared invariant momentum difference, $Q^2 = -(p_1 - p_2)^2$, and this is assumed in the analyses presented below. One also generally makes the assumption of a Gaussian source distribution, leading to

$$R(Q) = 1 + \lambda e^{-r^2 Q^2}$$

where r is a radius parameter and λ is a parameter introduced on phenomenological grounds to account for the fact, that the correlation for several reasons may not be seen at full strength. This assumption, while leading to a reasonable description of data from Z^0 decays, is not really well founded for WW events and should eventually be investigated further.

Typical values of r found in e^+e^- collisions are in the range 0.5 – 1.0 fm. The value of λ is very sensitive to the precise track selection, particle identification etc. In Z^0 events values consistent with 1 are found if only directly produced pions are considered (i.e. π mesons which originate from the decays of long lived resonances and heavy particles are discarded). If all pions are used, one finds $\lambda_\pi \approx 0.35$ and if all charged particles are treated as pions in the analysis, one finds $\lambda_{all} \approx 0.25$.[7]

1.2 Reference distribution

The choice of the reference distribution, $P_0(p_1, p_2)$, is one of the main problems in the data analysis. In most of the studies reported here pairs of particles of unlike sign from the data are used. This is not ideal, as the resonance content differ from that in like sign pairs, and as there may be possible residual BEC [8,13] in the $+-$ pairs. Any significant correlations in the low Q region will thus tend to distort the measured correlation function and if positive, as is indeed seen by DELPHI,[4] reduce its significance. Also the long range correlations are different, leading to a need for an additional Q-dependent factor, typically $(1 + \delta Q)$, in the fitted correlation function.

Such effects can be corrected for by using the *double ratio*

$$R^* = \frac{R}{R_{MC,noBE}} = \frac{P^{\pm\pm}}{P^{\pm}} / (\frac{P^{\pm\pm}}{P^{\pm}})_{MC,noBE}$$

where $(\frac{P^{\pm\pm}}{P^{\pm}})_{MC,noBE}$ is determined from Monte Carlo simulations without simulated BEC. The double ratio contains however a factor $(P^{\pm}/P^{\pm})_{MC,noBE}$ which mainly depends on the ability of the Monte Carlo program to describe correctly the $+-$ correlations, and which reduces the statistical sensitivity that can be obtained. In order to avoid this, DELPHI has therefore used Monte Carlo events without simulation of BEC directly to construct the reference distribution.

At lower energy, event mixing, i.e. taking pions from different events to form uncorrelated pairs, has been much used, but this is obviously quite difficult to construct in the case of WW events resulting in four or more jets. An attempt has been made to construct the correlation function for pions coming from differents Ws using mixed semileptonic WW events as a reference sample to fully hadronic events, and has been used in a cross check of the results reported by DELPHI.[4]

2 Estimating the W mass shift

The first estimates of the possible influence of BEC between pions from different Ws on the reconstructed W mass showed a shift, $\Delta(M_W)$, which was possibly larger than 100 MeV/c^2.[2] Since last year, the effect has been subject to a number of studies. The methods used fall in three classes:

- Imitation of BEC by shifting and readjusting particle momenta in simulated events.[9] This is the method used in the Lund routine LUBOEI, which forms part of JETSET.[10]
- Using global event weights to calculate statistically the effects of BEC on simulated samples of WW events.[11]
- A Monte Carlo adaptation [12] of the quantum mechanical approach to modelling of BEC based on proper symmetrization of the production amplitude of the bosons.[13]

From these studies, the shift in the reconstructed W mass is estimated to be at most 20–30 MeV/c^2, which is smaller than the statistical error that one hopes to achieve in the mass measurement.[14] A recent result from ALEPH [15] gives a somewhat larger negative value of the shift, however. Since on rather general grounds one expects the mass shift to be positive,[2] this needs further investigation.

3 Experimental results

The LEP collaborations have analysed data samples corresponding to about 55 pb^{-1} each at $\sqrt{s}$ = 183 GeV. ALEPH and OPAL have in addition each used 10 pb^{-1} at 172 GeV.

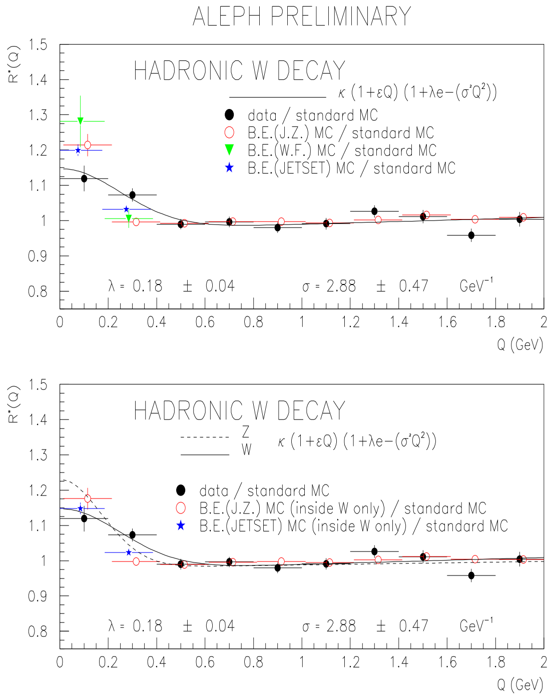

Figure 1: Correlation function for fully hadronic WW events in ALEPH.[3] Also shown is a fit, together with various model predictions. In the upper plot models include BEC among bosons from different Ws, in the lower plot only BEC inside each of the two Ws are included.

Figure 1 shows the measurement by ALEPH [3] of $R^*(Q)$ for hadronic W decays. All charged particles are used as pions in the analysis. In the upper plot the data are compared to a number of model calculations, which include BEC among all pions, and in the lower plot the data are shown again with the predictions of the same models including only BEC among the pions in each W system seperately. The model calculations agree reasonably with each other. Clearly the agreement between the predictions and the data is better in the lower plot, but the significance of this is not high, due to the limited statistics. The fit results are given in Table 1.

Figure 2 shows $R(Q)$ from DELPHI,[4] who uses Monte Carlo simulated events without BEC as reference distribution. One sees that $R(Q)$ in single Ws (semileptonic events) is larger at low Q than $R(Q)$ in fully hadronic WW events. This is intriguing and if taken at face value, results in a negative value of λ for particles coming from different Ws, which is not physically reasonable. If this result survives at higher statistics, it calls for an explanation, but at least one can say that

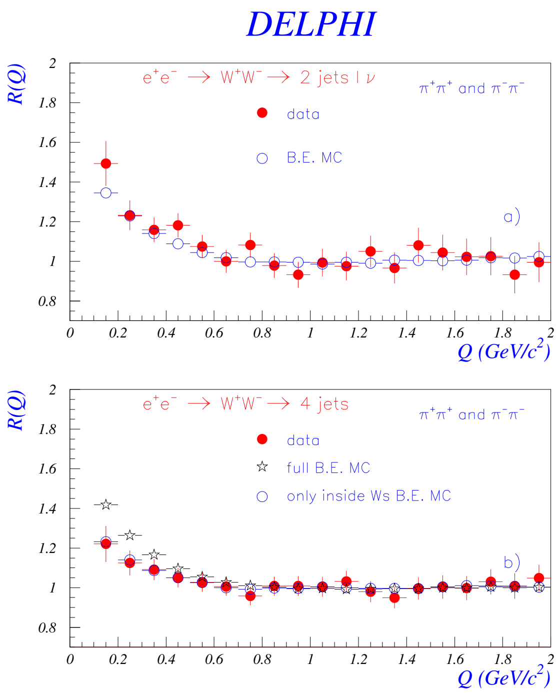

Figure 2: Correlation functions for 4 jet and semileptonic WW events in DELPHI.[4] Also shown are model predictions with full BEC and with BEC only inside each of the two Ws.

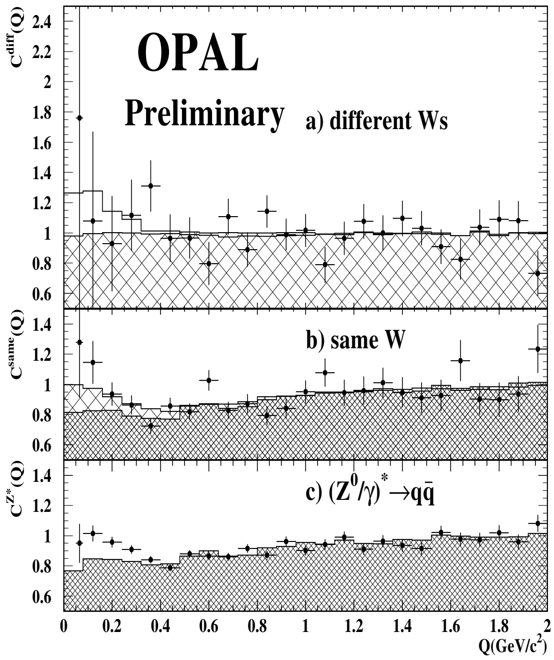

Figure 3: Correlation functions (here called C) for pions coming from different Ws, the same W and $(\mathrm{Z}^0/\gamma)^* \to q\bar{q}$ events in OPAL.[6] Also shown are model predictions described in the text.

the data do not support the presence of BEC for particles coming from different Ws. This is illustrated in the lower plot, where $R(Q)$ for fully hadronic events is shown together with predictions from Monte Carlo simulations, using JETSET and LUBOEI, that simulate BEC fully and inside seperate Ws only. As in the case of ALEPH, the latter gives the best description of the data, the difference being at the 2–3 σ level.

Similar conclusions are reached by L3 and OPAL. The L3 analysis uses the double ratio, R^*, and event by event assignment of the jets to Ws in order to measure R^* for particles coming from different Ws. The wrong assigments of jets to Ws are corrected for by Monte Carlo. From the L3 data and fit results (see Table 1), it is not possible to conclude whether inter-W correlations are present or not.

OPAL presents an analysis,[6] which uses a more stringent particle selection than the others, using also dE/dx to enhance the pion content in the selected tracks and a correction factor to account for the remaining fraction of non-pions. The reference sample is taken as $+-$ pairs, but the double ratio technique is not used. The correlation functions for pions from different Ws, same W and $(\mathrm{Z}^0/\gamma)^* \to q\bar{q}$ events are determined from a simultaneous 11 parameter fit to three selected samples of semileptonic, hadronic WW and non-radiative $q\bar{q}$ events. The radius parameter, r, is kept identical for all three classes of events. Figure 3 shows the result of unfolding the three correlation functions, together with predictions from model calculations without BEC, with BEC inside single Ws only, and with full BEC. As for the other experiments, the two first contributions are sufficient to describe the data, and there is no evidence seen for inter-W correlations, although they are not excluded either.

The results of fits to the data from the four collaborations are summarized in Table 1. Since the particle selections and analysis methods are different, one should be careful in comparing directly the values, in particular for the λ parameter. The fitted function is $N(1+\lambda e^{-r^2Q^2})$ for DELPHI, but includes an additional factor $(1+\delta Q)$ for ALEPH and L3, and $(1+\delta Q+\epsilon Q^2)$ for OPAL, necessary due to the use of $+-$ as reference distribution. DELPHI sees $\lambda^{2q} > \lambda^{4q} \approx \lambda^{\mathrm{Z}^0} \approx \lambda^{\mathrm{Z}^*}$, whereas the other experiments have $\lambda^{\mathrm{same}} \approx \lambda^{\mathrm{Z}^0}$, but the statistical errors are still large.

It has to be noted that colour reconnection could influence the results on λ for fully hadronic WW events and for the derived λ for inter-W correlations. Also final state interactions could influence the results more

Table 1: Fit results from the four LEP experiments. For comparison also results from fits to Z^0 data are shown.

		λ(all)	r(fm)	
	single W	$0.23 \pm 0.10 \pm 0.04$	$0.74 \pm 0.25 \pm 0.03$	
ALEPH	WW(all)	$0.18 \pm 0.04 \pm 0.04$	$0.57 \pm 0.09 \pm 0.03$	
172+	diff Ws	$0.15 \pm 0.18 \pm$ negl	$0.30 \pm 0.34 \pm$ negl	
183 GeV	Z^0	$0.26 \pm 0.01 \pm 0.04$	$0.812 \pm 0.016 \pm 0.030$	
	single W	$0.43 \pm 0.09 \pm 0.04$	$0.49 \pm 0.07 \pm 0.02$	
DELPHI	WW(all)	$0.24 \pm 0.08 \pm 0.04$	$0.57 \pm 0.12 \pm 0.06$	
183 GeV	Z^0(1997)	0.22 ± 0.01	0.61 ± 0.02	
	same jet	0.32 ± 0.17	0.80 ± 0.27	
L3	diff Ws	0.75 ± 1.80	1.03 ± 0.85	
183 GeV	Z^0	0.303 ± 0.006	0.935 ± 0.024	
		$\lambda(\pi\pi)$	r(fm)	N
	same W	$0.72 \pm 0.25 \pm 0.25$		$0.71 \pm 0.06 \pm 0.07$
OPAL	diff Ws	$0.40 \pm 0.50 \pm 0.39$	$0.94 \pm 0.09 \pm 0.13$	$1.00 \pm 0.02 \pm 0.01$
172+	$(Z/\gamma)^*$	$0.64 \pm 0.13 \pm 0.35$		$0.73 \pm 0.04 \pm 0.13$
183 GeV	Z^0	0.672 ± 0.027	0.955 ± 0.019	

than hitherto expected.[16] The absence of a detected signal for inter-W BEC is also in good agreement with calculations based on the quantum mechanical approach to BEC simulations.[12]

As the field is still in an exploratory phase, where there are large variations in the analyses, and hence also in the exact meaning of the fitted parameters, a more quantitative comparison, let alone combination of the results, is not yet meaningful.

DELPHI tried, in a cross check of their analysis, to predict $R(Q)$ in fully hadronic WW events from the observed $R^{2q}(Q)$ in single Ws in a linear model, assuming that the inter-W correlations have the same functional form as $R^{2q}(Q)$, except for λ, which as extreme cases is assumed to be either zero or one. The sensitivity to inter-W BEC is not large, as illustrated by Figure 4, where the upper plot shows the fraction of particle pairs coming from different Ws in the Monte Carlo reference sample of DELPHI. At low Q, where the enhancement in R is expected, this fraction is only about 25%. Hence, in the linear model the calculated $R(Q)$ in the two extreme cases do not differ very much. As seen in the plot, the data do also here agree best with the model calculation with no inter-W correlations, however.

In another cross check, DELPHI analysed the flavour dependence of BEC in Z^0 decays by comparing an unbiassed sample with a sample strongly depleted in b-quarks. The resulting λ value increased by almost 40% (for fixed r), indicating that flavour effects can be quite important, and should be taken into account when comparing results from WW events and Z^0 events.

4 Conclusions

In conclusion, Bose-Einstein correlations in W decays are clearly observed, with values of the radius parameter, r, in the 0.5–1.0 fm range, and λ values similar to the values obtained at the Z^0, but with rather large analysis dependent variations. DELPHI sees an indication that λ may be larger in W decays than in Z^0 decays, but this is not supported by the other collaborations.

There is so far no experimental evidence for Bose-Einstein correlations for pairs of same sign particles coming from different Ws. The sensitivity to see such correlations is not very high and the errors are still large compared with the expected signal.

Comparisons of the data with model predictions favour the absence of such inter-W correlations (at the 2σ level), while giving good agreement for the correlation function for same sign particles within a single W. Colour reconnection could influence these results and have not been taken into account in the analyses so far.

Phenomenological studies indicate that the shift in the W mass induced by BEC is at most 20–30 MeV/c^2, although a recent result from ALEPH gives a somewhat larger, negative value. Since these calculations assume a signal strength not supported by the data, the real value is likely to be smaller.

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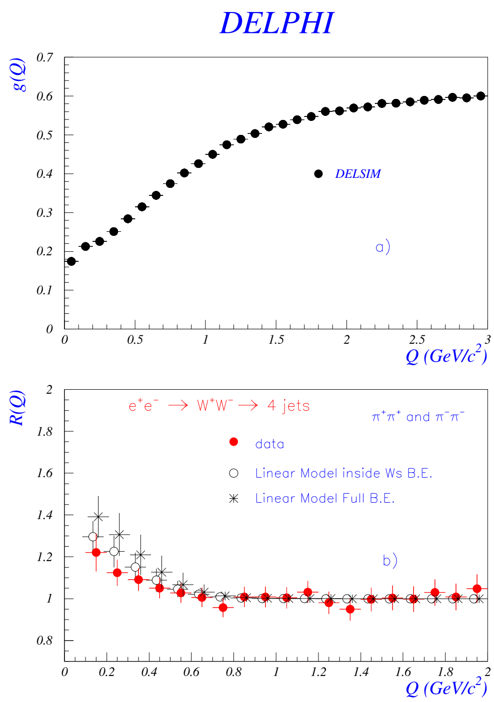

Figure 4: Fraction of pion pairs coming from different Ws in fully hadronic WW events in DELPHI.[4] Also shown is the result of a simple model calculation described in the text.

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