FINAL STATE INTERACTIONS IN HADRONIC WW DECAY AT LEP

MARK DIERCKXSENS
NIKHEF, PO Box 41882, 1009 DB Amsterdam, The Netherlands

An overview is given of the study of final state interactions in hadronically decaying W pairs produced in e^+e^--collisions as it is performed by the four LEP experiments. Bose-Einstein correlations are investigated by comparing like- with unlike-signed pairs of pions and/or using the mixed event analysis technique. Colour reconnection is examined with a method that compares the particle flow distributions in inter-jet regions.

1 Introduction

The second phase of the LEP programme was devoted to run at centre-of-mass energies above the W pair threshold. When such a pair is produced, the W bosons will immediately decay due to their very short lifetime ($\tau_W \sim 0.1$ fm/c). In 46% of the cases this will give rise to a final state with four quarks, the so-called hadronic channel. Considering the full integrated luminosity delivered by the LEP machine, each experiment has collected roughly 5000 such events. The produced quarks will hadronise after typical scales of about 1 fm, resulting in jets of particles measured with the detector. Due to the large space-time overlap, correlations between the particles coming from different W's might occur. The possible effects studied at LEP are Bose-Einstein correlations (BEC) between identical bosons in the jets, and colour reconnection (CR) between the quarks themselves.

When an exchange of particles or energy and momenta between the two W bosons is inadequately described by the Monte Carlo programs, this will cause a bias in the measurement of the W mass. The statistical uncertainty on the W mass is 30 GeV/c^2 when combining the results from all the LEP experiments using the hadronic channel only [1]. Various models exist to describe the Final State Interactions (FSI) and a number of them predict biases several times larger than this statistical error. Besides the measurement on itself, these results are therefore also important for the determination of the W mass.

Table 1: The energy ranges and corresponding integrated luminosities used by the four LEP experiments for the studies of Bose-Einstein correlations and colour reconnection.

Experiment	BEC		CR	
	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]
ALEPH	$183-209$	683	$189-209$	628
DELPHI	$189-209$	531	$183-209$	601
L3	$189-209$	627	$189-209$	627
OPAL	$172-189$	250	189	183

2 Bose-Einstein Correlations

Since the bosons produced in the hadronisation process obey Bose-Einstein statistics, an enhancement in the number of identical bosons created close in phase space is expected due to amplitude symmetrisation. This effect has been observed in e.g. $Z \to q\bar{q}$ at LEP1, thus between particles coming from the same boson. Now that boson pair production is possible at LEP2 energies, the question which arises is whether BEC also exist between particles coming from different W's (inter-W BEC). The energy ranges and luminosities used by the four LEP experiments for this measurement [2] can be found in table 1.

BEC are typically studied by looking at the two-particle density in momentum space

$$\rho(Q) = \frac{1}{N_{ev}} \frac{\mathrm{d}n_{pairs}}{\mathrm{d}Q}, \tag{1}$$

where n_{pairs} is the number of pairs in N_{ev} selected events and Q is the 4-momentum difference $\sqrt{-(p_1-p_2)^2}$, with p_1 and p_2 the momenta of the two particles. The presence of BEC will give rise to an enhancement of like-signed particle pairs at low Q. The two-particle density is often parametrised as $\rho \simeq (1 + \Lambda \exp(-R^2Q^2))$ and interpreted as a Gaussian source of radius R and strength Λ.

The BE_{32} algorithm from the LUBOEI model [3] is used to generate Monte Carlo samples containing BEC inside and between the W bosons. This model just reshuffles the momenta of identical bosons and is tuned to the hadronic Z decay data to describe BEC in these events.

2.1 Unlike-sign Pair Analysis

In this method, the ratio between the number of like-signed pairs and unlike-signed pairs obtained from data is compared with a Monte Carlo sample generated without inter-W BEC and studied as a function of Q.

OPAL extracts these values for three event classes: hadronic and semi-leptonic WW decays and non-radiative $Z^* \to q\bar{q}$ events. The double ratios are then deconvoluted to obtain the contributions of pions coming from different W's, same W and hadronic Z decays. The result is shown in figure 1. A fit to these distributions results in a strength parameter $\Lambda = 0.69 \pm 0.12 \pm 0.06$ for pairs coming from the same W, again proving the existence of BEC inside the W. The fit to the distribution for pions from different W's gives $\Lambda = 0.05 \pm 0.67 \pm 0.35$, being compatible with both inter-W and no inter-W BEC due to the small statistical sample used.

The double ratio from the ALEPH data up to 202 GeV shown in the right plot of figure 1, is fitted with a similar function as described above and the integral over Q of this function is calculated. The same procedure is followed for a MC sample using the JETSET model with inter-W BEC. When compared to the data, this model is disfavoured at the level of 2.2σ.

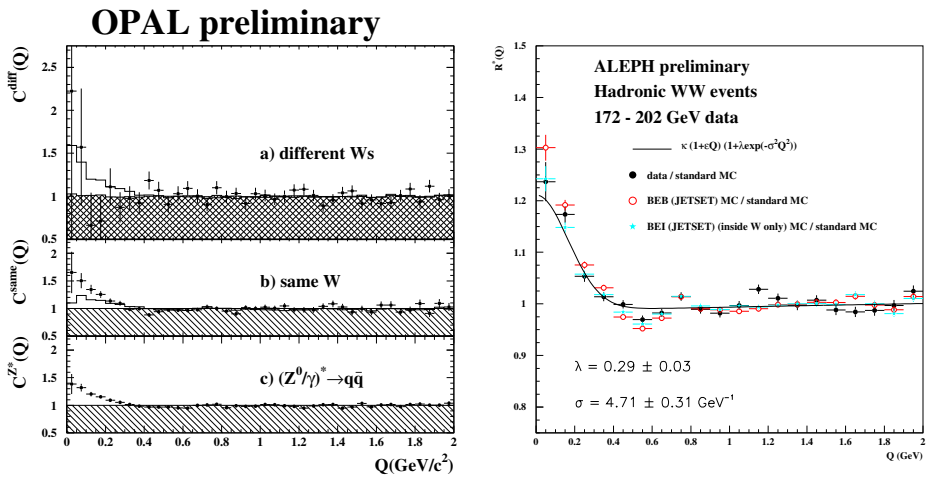

Figure 1: The double ratio distributions as a function of Q from OPAL (left), deconvoluted to different contributions, and ALEPH (right), where the fit to the data is indicated as a solid line.

2.2 Mixed Event Analysis

Inter-W BEC can be accessed directly from data, without relying on a certain model, by comparing the hadronic decays with events constructed from the hadronic part of two different semi-leptonic events [4]. This analysis has been preformed by ALEPH, DELPHI and L3.

If the two W bosons in a hadronic event decay independently, the two-particle density can be written as

$$\rho^{WW\to 4q} = 2\rho^{W\to 2q} + 2\rho^{WW}_{mix}\,, \tag{2}$$

where the first term on the right hand side is taken from semi-leptonic events, and the second term is obtained by mixing the hadronic part of two different semi-leptonic events. Then the sensitive distributions are the difference or the ratio between left and right hand side:

$$\Delta\rho = \rho^{WW\to 4q} - 2\rho^{W\to 2q} - 2\rho^{WW}_{mix}\,, \qquad D = \frac{\rho^{WW\to 4q}}{2\rho^{W\to 2q} + 2\rho^{WW}_{mix}}. \tag{3}$$

When BEC between particles coming from different W bosons do not exist, $\Delta\rho = 0$ and $D = 1$.

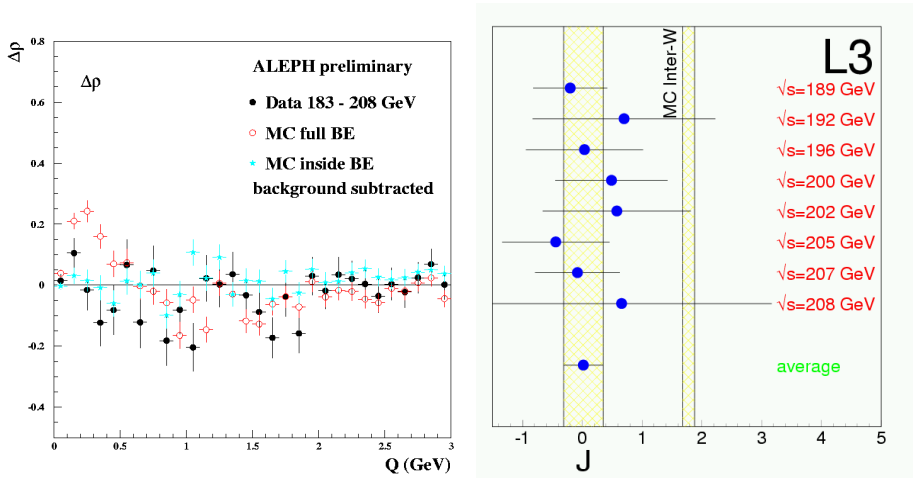

Figure 2: The $\Delta\rho$ distribution as a function of Q from ALEPH (left) and the integral $J \equiv \int_0^{Q_{max}} \Delta\rho(Q)\mathrm{d}Q$ at different centre-of-mass energies from L3 (right).

Figure 2 shows the $\Delta\rho$ distribution for the ALEPH data, which is in good agreement with the prediction from a MC containing only intra-W BEC. The same conclusions can be drawn when looking at these distributions from DELPHI and L3. Another way to look at the data is to calculate the integral $J \equiv \int_0^{Q_{max}} \Delta\rho(Q)\mathrm{d}Q$. As can be seen in the right plot of figure 2, the value obtained from a MC with inter-W BEC clearly does not agree with the data.

Comparing the strength parameter Λ from the fit to the distribution of the ratio D from the DELPHI experiment (fig. 3), the MC containing inter-W BEC is excluded on the level of 3.2σ. L3 looks at the ratio between the D distribution from data and this distribution from a MC with only intra-W BEC in order to eliminate some possible systematic errors. Comparing the strength parameter from the fit to this double ratio using the data with the one obtained when a MC with inter-W BEC is used, the latter one can be excluded by 4.7 standard deviations.

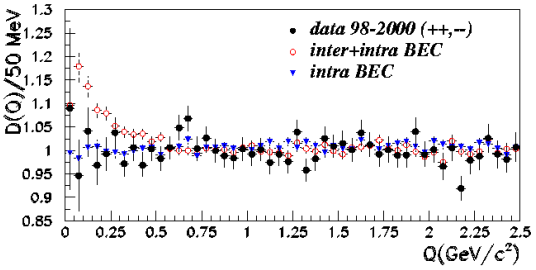

Figure 3: The D distribution as a function of Q from the DELPHI experiment

3 Colour Reconnection

In the string picture, the hadronisation particles come from the decay of the colour string stretched between the quarks coming from the same W. When the colour flow pattern is modified, referred to as colour reconnection, strings might span between two quarks from different W bosons and sebsequently decaying particles cannot be uniquely assigned to either W.

Different phonomenological models exist to describe CR. In the model of Sjöstrand-Khoze [6], as it is implemented in PYTHIA, CR might occur when strings overlap. In the type I model (SKI), the strings are associated to colour flux tubes and the reconnection probability, P_{reco}, is related to the volume of the overlap, $f(\sqrt{s})$, by the following relation:

$$P_{reco} = 1 - e^{-f(\sqrt{s})\cdot k_I}, \tag{4}$$

where k_I is a free parameter that can be varied to obtain samples with different reconnection probabilities. Also the predictions from other models like SKII, ARIADNE, HERWIG and Rathsman are tested against the LEP data.

3.1 Particle Flow Method

This method compares the particle rates between jets from same and different W bosons, since CR will result in a depletion or enhancement in inter-jet regions. This approach, pioneered by L3 [7], is much more sensitive to CR effects than previous methods and is now adopted by the other experiments. The data samples used by the different LEP experiments for this analysis [5] are indicated in table 1.

In order to study the particle flow, the momenta of the particles are projected onto the plane spanned by the most energetic jet and the jet most likely coming from the same W. Since the W decay planes are not planar, the momentum of a particle i is further projected on the planes spanned by the 2 adjacent jets k and j. In order to be able to compare the different inter-jet regions, the angle ϕ_i between the projected momentum and the most energetic jet, is rescaled by the angle ϕ_{kj} between the nearest jets.

DELPHI and L3 perform a topological selection with tight cuts on the angles of the jets in order to obtain a high purity sample with almost planar jets, but with a low selection efficiency.

ALEPH and OPAL use a selection based on there standard W mass selection, which has a larger efficiency but the jet topology is less trivial and the background contamination is higher.

An example of the particle flow distribution is shown in figure 4. Due to the definition of the rescaled angle, the direction of the jets are pointing to integer values. The two regions inside a W (indicated with A and C on the plot) are now combined, as well as the two regions between the W's (B and D). These two particle flow distributions are then compared to each other by taking the ratio, R, which can be seen in the left plot of figure 5. In order to quantify the CR effects of the different models, the particle flow inside and between the W's is integrated over ϕ_{resc} between 0.2 and 0.8, the region most sensitive to CR. Then the ratio between the two integrals is called R_N and shown in figure 5.

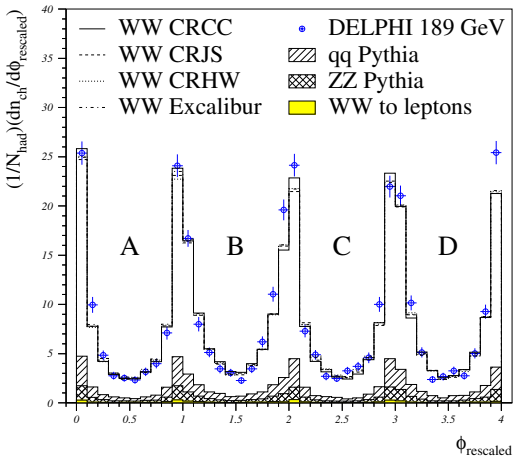

Figure 4: The particle flow distribution as a function of the rescaled angle from DELPHI.

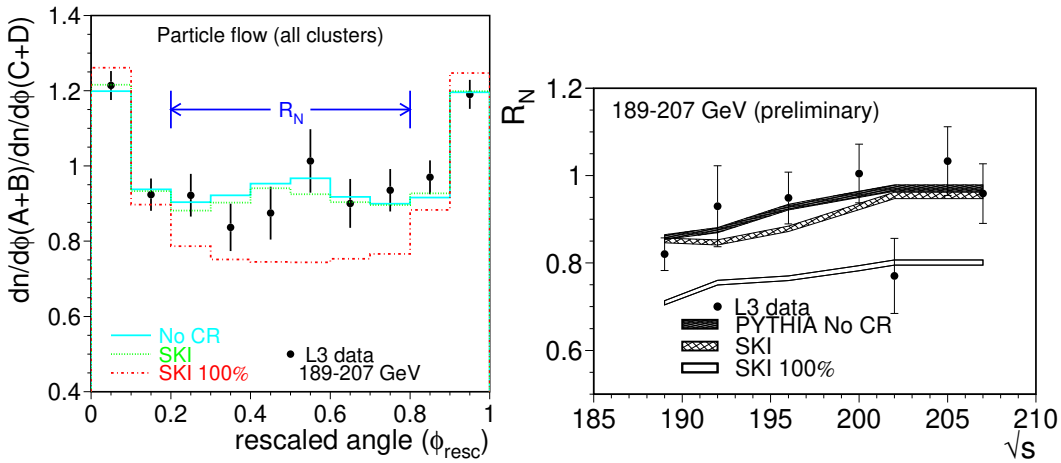

Figure 5: The ratio R between the particle flows inside and between the W's (left) and the ratio R_N between the integrals over the particle flows as function of centre-of-mass energy (right).

In order to compare the different experiments, the ratios between the R_N value from data and a MC without and with CR (SKI with 100% reconnection probability) have been calculated[8] and are shown in table 2. A deviation from unity is a measure of the disagreement between data and the model used. The measurements of DELPHI and L3 show clearly a preference for no CR, while ALEPH prefers a model inbetween no and 100% CR. The OPAL experiment comes to the same conclusion when using the W mass selection. They also applied the topological selection as a cross check analysis and then found a preference for no CR. This is actually under study in all LEP experiments to see whether this is due to the type of selection, the background or other possible sources.

The results can now be interpreted in terms of the free parameter k_I in the SKI model, see equation (4), by calculating a χ^2 from the comparison of R_N between data and MC samples evaluated at different values of k_I. L3 obtains a limit of $k_I < 1.55$ at 68% C.L., while ALEPH prefers a value of $\langle k_I \rangle = 3.55$ (a reconnection probability at $\sqrt{s} = 189$ GeV of about 50% and 80% respectively).

Table 2: The ratios between the R_N variables from data and a MC sample, one without CR and one with CR using the SKI model with 100% reconnection probability. The values between brackets indicate the deviation from unity.

	$\langle R_R \rangle$ Data/no CR		$\langle R_R \rangle$ Data/CR	
ALEPH	$0.961 \pm 0.012 \pm 0.007$	(-2.8σ)	$1.041 \pm 0.013 \pm 0.008$	$(+2.7\sigma)$
DELPHI	$1.009 \pm 0.030 \pm 0.019$	$(+0.3\sigma)$	$1.110 \pm 0.033 \pm 0.029$	$(+2.5\sigma)$
L3	$0.990 \pm 0.025 \pm 0.023$	(-0.3σ)	$1.194 \pm 0.039 \pm 0.029$	$(+4.7\sigma)$
OPAL	$0.906 \pm 0.033 \pm 0.011$	(-2.7σ)	$1.050 \pm 0.038 \pm 0.013$	$(+1.2\sigma)$
	$0.996 \pm 0.051 \pm 0.011$	(-0.1σ)	$1.193 \pm 0.061 \pm 0.014$	$(+3.1\sigma)$

4 Conclusions

A large part of the data samples collected by the four LEP experiments has been analysed to study possible final state interactions in hadronically decaying W pair events. None of the experiments observe any indication for the existence of Bose-Einstein correlation between particles coming from different W bosons. The LUBOEI model used to simulate such an effect is strongly disfavoured. The results from the different colour reconnection analyses are inconsistent. DELPHI and L3 prefer no CR, while ALEPH prefers a large value for the reconnection probability. OPAL gets different results depending on the selection used. All experiments are presently investigating the possible causes. When the foreseen combination of the results from the four collaborations will be performed, the contribution to the systematic error on the W mass from the effects described here will be reduced significantly.

References

1. The LEP Collaborations ALEPH, DELPHI, L3, OPAL; LEPEWWG/MASSW/2001-02; http://www.cern.ch/LEPEWWG/wmass/
2. ALEPH Collaboration, Note 2001-064 CONF 2001-044 (July 10, 2001);
   DELPHI Collaboration, Note 2001-107 CONF 534 (May 15, 2001);
   L3 Collaboration, Note 2674 (June 25, 2001);
   OPAL Collaboration, Physics Note PN393 (June 30, 1999).
3. L. Lönnblad and T. Sjöstrand, E. Phys. J. **C 2** (1998) 165.
4. S.V. Chekanov, E.A. De Wolf and W. Kittel, E. Phys. J. **C 6** (1999) 403.
5. ALEPH Collaboration, Note 2001-047 PHYS 2001-019 (July 11, 2001);
   DELPHI Collaboration, Note 2001-061 CONF 489 (July 2, 2001);
   L3 Collaboration, Note 2683 (June 27, 2001);
   OPAL Collaboration, Physics Note PN448 (June 21, 2000).
6. T. Sjöstrand and V. Khoze, Z. Phys. **C 62** (1994) 281; Phys. Rev. Lett. **72** (1994) 28; V. Khoze and T. Sjöstrand, Eur. Phys. J. **C 6** (1999) 271.
7. D. Duchesneau, "New method based on energy- and particle-flow in $e^+e^- \rightarrow W^+W^- \rightarrow hadrons$ events for colour reconnection studies", preprint LAPP-EXP 2000-02; Nucl. Phys. B (proc. Suppl.) **96** (2001) 13.
8. P. Abreu, "Colour Reconnection at LEP2", hep-ph/0111395, to be published in the Proceedings of ISMD 2001, September 2001, Datong, China.