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Final state correlations at LEP 2

Bose-Einstein correlations and the W mass

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Abstract. Recent experimental results on Bose-Einstein correlations are presented. Emphasis will be put on the measurement of between-W correlations in WW events at LEP 2.

1 Introduction

The W mass and width measurements at LEP 2 rely on good Monte Carlo simulations of physics and detectors in the $e^+e^- \to$ WW process. Remaining sources of uncertainty are, among others, the simulation of fragmentation and hadronization, in particular colour interactions and correlations between partons and particles from the decay of different W's in WW $\to qqqq$ events. The four LEP experiments try to estimate these interconnections from the data, and this article will describe recent studies of Bose-Einstein correlations (BEC). The L3 results are final, the results from DELPHI, ALEPH and OPAL are still preliminary.

2 Bose-Einstein correlations

The observed enhancement of the production of identical bosons close in phase space is considered to be a result of the requirement of symmetrization of the production amplitude. We define a two-particle density function $\rho_2(Q)$ as $\rho_2(Q) = 1/N_{\text{ev}} dn_{\text{pairs}}/dQ$, where $Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M^2 - 4m^2}$ for pairs of identical bosons with 4-momenta p_1 and p_2 and mass m. The correlation function $R(Q)$ is then defined as $R(Q) = \rho_2(Q)/\rho_2^{\text{ref}}(Q)$, where $\rho_2^{\text{ref}}(Q)$ is derived from a reference sample with all properties of the sample under study, except Bose-Einstein correlations. Analyses have typically used reference samples of mixed events or unlike-sign particles, each of these have their disadvantages. It is known that for a spherical and Gaussian source with radius r, $R(Q)$ can be written as

$$R(Q) = N(1 + \delta Q)(1 + \lambda \exp(-(rQ)^2)), \qquad (1)$$

where N is a normalization, δ describes long-range (non-BEC) correlations, and λ is the correlation strength (or 'coherence' or 'chaoticity' parameter).

BEC between particles from the decay of a single W (inside-W-BEC) are identical to BEC in Z events, if corrected for the flavour difference. Studies of Z events and deep-inelastic scattering data have found that:

- correlations between more than two particles exist;
- $\pi^0\pi^0$ correlations exist, even though some 97% of the π^0's in these correlations originate from the decay of different hadrons [1];
- generalized BEC may exist in $\pi^\pm\pi^0$ or $\pi^+\pi^-$ pairs;
- the source is not spherical, but elongated [2].

3 Monte Carlo implementation

The implementation of BEC in Monte Carlo's can be categorized in three classes:

- PYTHIA (LUBOEI) [3];
- global reweighting methods [4];
- Lund string fragmentation inspired models [5].

At the time of analysis, only PYTHIA was available as a mature MC, and experiments compare their data to PYTHIA, with either only inside-W BEC, or both inside-W and between-W BEC ("full" PYTHIA). The PYTHIA parameters corresponding to λ and r are obtained by tuning the Monte Carlo to Z events (without Z $\to b\bar{b}$), and are also suited for inside-W BEC. In the analyses presented here, the parameters for between-W BEC simulations have been taken to be the same as for inside-W BEC. Variant BE_{32} is used.

Recently, the ALFS Monte Carlo has appeared as an implementation of BEC in the Lund model [5].

4 Between-W correlations measurement

4.1 Method

The method uses a reference sample consisting of mixed semi-hadronic WW events (WW $\to qq\ell\nu$). Mixed events

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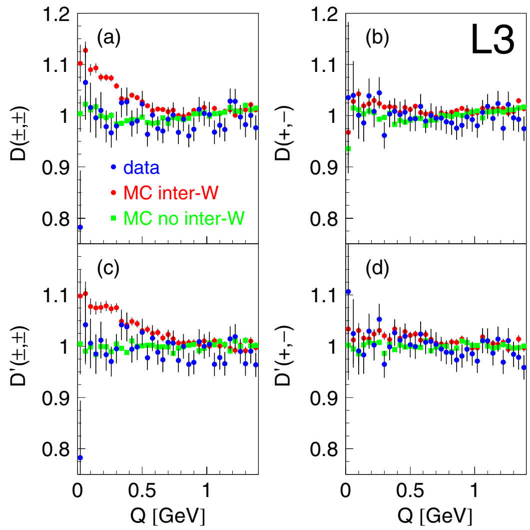

Fig. 1. The L3 $D(Q)$ and $D'(Q)$ distributions for like-sign and unlike-sign pairs in data and in PYTHIA

are constructed by taking two semi-hadronic WW events from a pool, removing the W-decay leptons from the events, and rotating and boosting the W's such that they are back-to-back. Care has to be taken in subtracting the non-WW four-jet background from the $qqqq$ sample. Mixed events have by construction no between-W BEC, and have the same inside-W BEC as real $qqqq$ events. The between-W BEC can now be extracted by comparing the real $qqqq$ to the mixed events [6]:

$$\Delta\rho(Q) = \rho_2^{WW}(Q) - 2\rho_2^{W}(Q) - 2\rho_{\text{mix}}^{WW}(Q),$$

$$D(Q) = \rho_2^{WW}(Q)/(2\rho_2^{W}(Q) + 2\rho_{\text{mix}}^{WW}(Q)),$$

where ρ_2^{WW} is the two-particle density function in $qqqq$ events, ρ_2^{W} is that function within single W's taken from $qq\ell\nu$ events, and ρ_{mix}^{WW} is that function for pairs of particles from different W's in mixed events. We also define $\Delta\rho'$ and D' as $\Delta\rho$ and D from data minus (c.q. divided by) PYTHIA without between-W BEC. If between-W BEC are absent, $\Delta\rho = 0$ and $D = 1$. Experiments apply a phenomenological fit to the $D(Q)$ distribution similar to Equation 1 (or like $\lambda\exp(-rQ)$) in order to quantify the between-W BEC strength. However, $D(Q)$ is not a correlation function like $R(Q)$, and parameters should be interpreted with care.

As an alternative, between-W BEC measurements are quantified by integration of the $\Delta\rho(Q)$ distribution, see the experimental papers for results.

4.2 L3 results

L3 [7] use 629 pb^{-1} of data between $\sqrt{s} = 189$ and 209 GeV, giving some 3800 $qq\ell\nu$ and 5100 $qqqq$ events. The $D(Q)$ and $D'(Q)$ distributions are shown in Fig. 1.

The L3 results are consistent with no between-W BEC, and disagree with full PYTHIA at the 3.8 σ level.

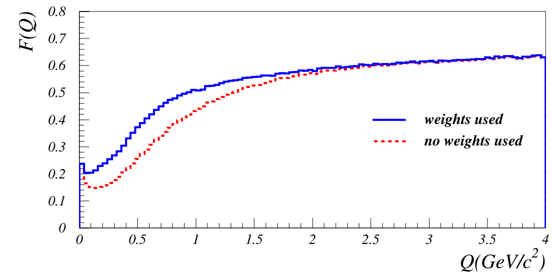

Fig. 2. The fraction $F(Q)$ of pion pairs where the two pions originate from different W's, as a function of Q, before and after reweighting (DELPHI)

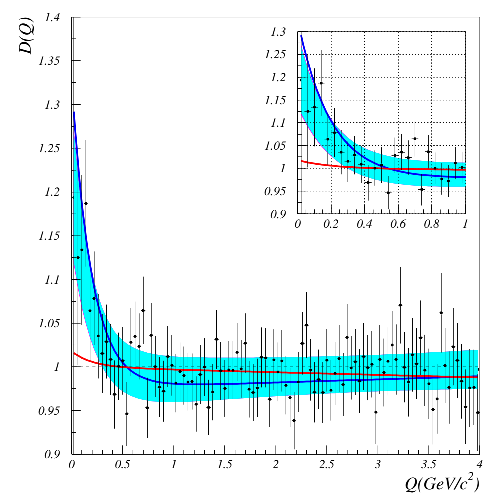

Fig. 3. The DELPHI $D(Q)$ distribution for like-sign pairs, and the fit to this distribution (band), compared to full PYTHIA (thick curve) and PYTHIA with inside-W BEC only

4.3 DELPHI results

DELPHI [8] observe that at low Q, the fraction $F(Q)$ of pion pairs where the two pions originate from different W's is very low, as shown in Fig. 2. In order to increase the sensitivity of the between-W correlations measurement, DELPHI reweight the pairs with their information content, obtained from three variables sensitive to the W parent.

For the analysis, DELPHI use 550 pb^{-1} of data between $\sqrt{s} = 189$ and 209 GeV, giving 2567 $qq\ell\nu$ and 3252 $qqqq$ events. The $D(Q)$ distribution is shown in Fig. 3.

DELPHI observe an indication for between-W BEC with a significance corresponding to 2.9 standard deviations. The magnitude of the effect is 2/3 of full PYTHIA. DELPHI also observe this in the unlike-sign pairs. The between-W BEC effect appears to be situated at smaller Q, or larger r, than in full PYTHIA.

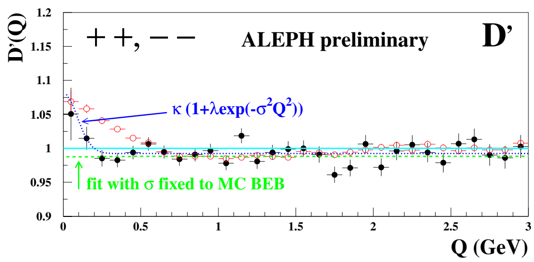

Fig. 4. The ALEPH $D'(Q)$ distribution for like-sign pairs and the fits with $\sigma = r$ left free or fixed to the full PYTHIA (= MC BEB) value. Open circles represent full PYTHIA MC

4.4 ALEPH results

ALEPH [9] use 685 pb^{-1} of data between $\sqrt{s} = 183$ and 209 GeV, giving 6154 $qqqq$ events, and 2406 constructed mixed events. The $D'(Q)$ distribution is shown in Fig. 4.

ALEPH observe no between-W BEC in the $\Delta\rho'$ and D' distributions if r is fixed to the full PYTHIA value, and disagree with full PYTHIA at the 3.7 standard deviation level. If r is left free in the fit to $D'(Q)$, a preference for larger r in between-W BEC is seen than in full PYTHIA.

4.5 OPAL results

OPAL [10] use 680 pb^{-1} of data between $\sqrt{s} = 183$ and 209 GeV, giving 4533 $qq\ell\nu$ and 4470 $qqqq$ events.

OPAL compare their data to both PYTHIA scenario's, and find that the results for $\Delta\rho$ prefer no between-W BEC, whereas the D analysis is consistent with either scenario.

4.6 LEP combination

Since the measurements are statistics-limited, it is interesting to combine them. The combination is shown in Fig. 5, where the measured between-W BEC strengths in each experiment are expressed as fraction of full PYTHIA. The arrows mark the results used in the combination. The combination has a χ^2 of 5.4 for 3 degrees of freedom; the probability for such a χ^2 (or higher) is 15%, which is acceptable. The largest deviation from the average (DELPHI) is less than two sigma.

The combination indicates that the LEP experiments measure a between-W correlation strength of 0.23 ± 0.13 times the one of full PYTHIA [1]. This would correspond, again in the PYTHIA framework, to a W mass shift in the $qqqq$ channel of 8 ± 5 MeV, and a W width shift of some 12 ± 8 MeV. The observation that r for between-W BEC seems larger than in full PYTHIA is interesting. Its effects remain to be further studied, but they again point to a W mass shift smaller than predicted by full PYTHIA.

[1] If the OPAL $D(Q)$ result had been used in the combination instead of the $\Delta\rho(Q)$ result, this number would have been only marginally different: 0.25 ± 0.14

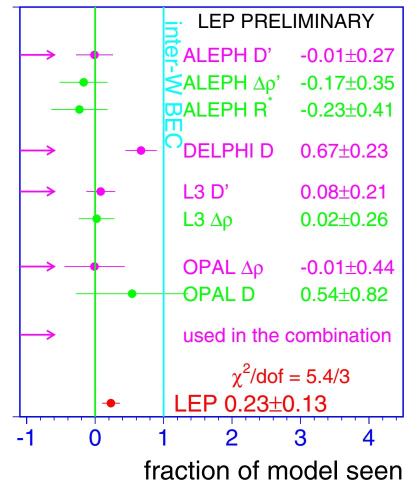

Fig. 5. LEP combination of the measured between-W BEC strengths expressed as fraction of full PYTHIA

5 Conclusions

The four LEP experiments measure in data a between-W BEC strength of 0.23 ± 0.13 times the implementation of full PYTHIA, which in the framework of that model corresponds to an upper limit on the W mass shift in the $qqqq$ channel of 13 MeV at 68% CL. Other MC models also predict shifts between 0 and 15 MeV [4,5]. There are indications that the small between-W BEC effect is located at smaller Q, or larger r, than BEC in single W or Z events. The data are consistent with the emerging theoretical picture that between-W BEC from incoherent W decays probably exist, but that the effects are much suppressed w.r.t. inside-W BEC (and thus full PYTHIA): there are two separated sources, and at low Q few pairs of pions originate from different W's. It thus appears that the influence of between-W BEC on the W mass is limited.

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