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# QCD AT LEP 2 AND WW FINAL STATE INTERACTIONS [a]

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A short overview of the QCD program at LEP 2 is given. Studies of final state interactions in $e^+e^- \to W^+W^- \to q\bar{q}'q\bar{q}'$ decays are discussed.

[a] to be published in the proceedings of the $34^{th}$ Rencontres de Moriond, Les Arcs 1800, France, 13-20 March 1999

## 1 Introduction

After the studies of $e^+e^-$ collisions at a centre-of-mass energy of $\sqrt{s} = M_{Z^0}$ at LEP 1, the LEP 2 program has so far allowed the study of $e^+e^-$ collisions at $\sqrt{s} = 133$, 161, 172, 183 and 189 GeV. While at LEP 1, the collected data samples of typically 4 million $Z_0$ decays per experiment allow high precision QCD tests, one of the aims at LEP 2 is the study of the energy dependence of QCD quantities using non-radiative $e^+e^- \rightarrow q\bar{q}$ events. Typical data samples consist of several hundred events at lower LEP 2 energies going up to roughly 3000 events at $\sqrt{s} = 189$ GeV, the centre-of-mass energy for data collected in 1998.

Effects of the strong interaction are not only studied in $e^+e^- \rightarrow q\bar{q}$ events, but also in $e^+e^- \rightarrow W^+W^-$ events where both W bosons decay hadronically, $W \rightarrow q\bar{q}'$. The decay vertices of the two W bosons are on average less than 0.1 fm apart, which is small compared with the typical hadronic length scale of 1 fm. It is therefore possible that the decays of the two Ws are not independent but are affected by interactions between quarks from the decays of the two different W bosons via *colour reconnection* or by interactions between the hadrons produced in the hadronisation of the two W bosons via *Bose-Einstein correlations*. The study of these effects is interesting in its own right and is of special importance for the measurement of the W mass in fully hadronic W decays where the uncertainty due to possible WW final state interactions is currently the largest contribution to the systematic uncertainty [1]. The number of selected WW events per experiment is typically 400 for $\sqrt{s} = 183$ GeV and 1500 for $\sqrt{s} = 189$ GeV.

## 2 QCD at LEP 2

General features of hadronic events such as event shapes, jet rates or charged particle momentum spectra are studied by all LEP collaborations at all centre-of-mass energies. A very basic quantity is the mean charged particle multiplicity, for which results at the highest centre-of-mass energy of $\sqrt{s} = 189$ GeV are already available from three collaborations [2,3,4] as summarised in table 1. The energy evolution of this quantity is shown in fig. 1 and illustrates the remarkably good agreement between measurements and the predictions of parton shower models like JETSET, HERWIG and ARIADNE which include QCD coherence effects and which were tuned to describe the data at LEP 1. Parton shower models with no QCD coherence effects like COJETS or matrix element models as implemented in JETSET cannot explain the energy dependence. Good agreement between data and JETSET, HERWIG and ARIADNE predictions are also observed for various charged particle momentum distributions, jet rates and for event shapes like thrust.

Table 1: Mean charged multiplicity $\langle n_{ch} \rangle$ and $\alpha_s$ as determined from fits to the event shapes at a centre-of-mass energy of $\sqrt{s}$ =189 GeV. All numbers are preliminary.

| Experiment | $\langle n_{ch} \rangle$ | $\alpha_s$ |
|---|---|---|
| ALEPH | $27.37 \pm 0.20(\text{stat}) \pm 0.25(\text{syst})$ | $0.1119 \pm 0.0015(\text{stat}) \pm 0.0011(\text{exp}) \pm 0.0030(\text{theo})$ |
| L3 | $26.73 \pm 0.13(\text{stat}) \pm 0.18(\text{syst})$ | $0.1082 \pm 0.0028(\text{exp}) \pm 0.0052(\text{theo})$ |
| OPAL | $26.83 \pm 0.16(\text{stat}) \pm 0.30(\text{syst})$ | $0.107 \pm 0.001(\text{stat}) \pm 0.005(\text{syst})$ |

Event shapes are not only used to compare data and model predictions. Some event shape variables are predicted by $\mathcal{O}(\alpha_s^2)$ calculations combined with predictions of the next to leading log approximation (NLLA) of QCD. A fit of these $\mathcal{O}(\alpha_s^2)$+NLLA predictions to the measured event shapes allows the extraction of $\alpha_s$. Up to six different event shapes have been used, and the combined results for $\alpha_s$ at $\sqrt{s} = 189$ GeV are presented in table 1. In fig. 1, the energy dependence of these results is shown to be consistent with the expected energy evolution of $\alpha_s$. It is interesting to note that the uncertainty of the results at the highest energy points is no longer dominated by the statistical uncertainty and the total uncertainty is very similar to the total uncertainty of the $\alpha_s$ measurement at $\sqrt{s} = M_{Z^0}$.

The energy evolution of the mean value of some event shape distributions can be used to determine

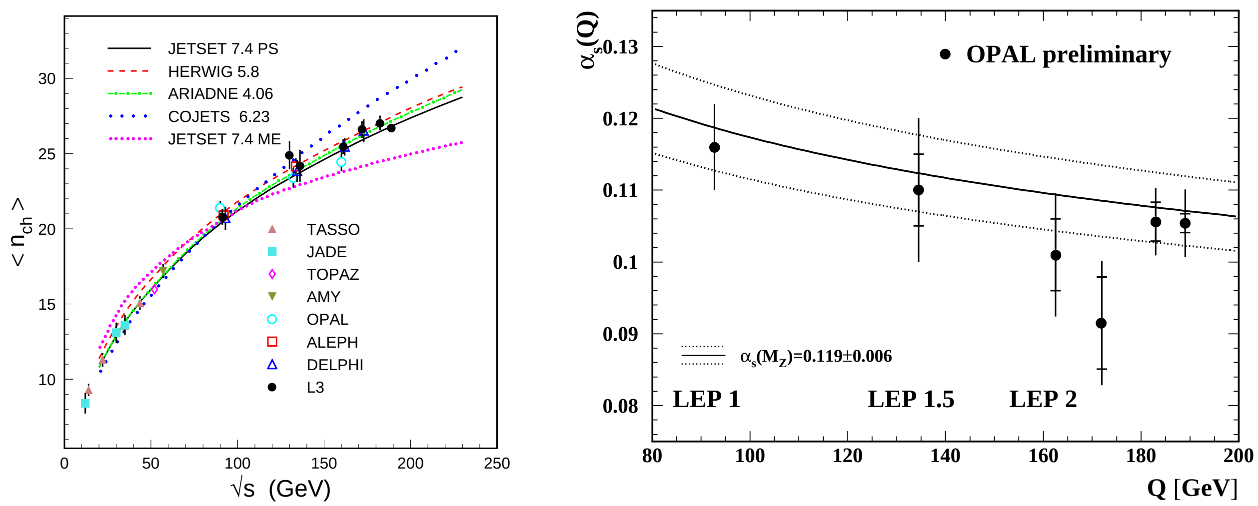


Figure 1: On the left: published measurements of the mean charged multiplicity at different centre-of-mass energies, together with preliminary L3 results and model predictions [3]. On the right: preliminary OPAL results for $\alpha_s$ at different centre-of-mass energies [4]. The error bars show the total errors, the extent of the statistical errors is indicated by small horizontal bars.

$\alpha_s$ using the power law ansatz of Dokshitzer and Webber [5]. In this ansatz non-perturbative effects depend only on the energy scale, $\alpha_s$ and a new universal parameter $\alpha_0$. ALEPH [6] and DELPHI [7] fitted the results for the main values of event shape variables to determine $\alpha_s$ and $\alpha_0$. Results for $\alpha_s$ are consistent with the world average and the numbers measured for $\alpha_0$ are consistent with a common value for all studied event shapes and with the values obtained from a study of re-analysed JADE data [8] and from lepton-proton scattering at H1 [9].

## 3 WW Final State Interactions

### *3.1 Colour Reconnection*

The decay products of the two W decays in $e^+e^- \rightarrow W^+W^-$ events may have a significant space-time overlap as the separation of their decay vertices is small compared to characteristic hadronic distance scales. In the fully hadronic channel this may lead to new types of final state interactions. Colour reconnection is the general name applied to the case where such final state interactions lead to colour flow between the decay products of the two W bosons. At present there is general consensus that observable effects of such interactions during the perturbative phase are expected to be small [10]. In contrast, significant interference in the hadronisation process is considered to be a real possibility. With the current knowledge of non-perturbative QCD, such interference can be estimated only in the context of specific models.

Studies of reconnection phenomena implemented with the ARIADNE, PYTHIA and HERWIG models show that these effects might lead to a reduction of the mean charged multiplicity by up to approximately 3% when compared to a situation in the absence of colour reconnection effects [10,11,12,13]. Studies using the Ellis-Geiger model predicted a reduction of the order of 10 % [14]. However, the Monte Carlo program VNI in which the Ellis-Geiger model is implemented does not describe the data [10,11]. Therefore, the present implementation of the VNI generator is not used to study effects of colour reconnection.

Some earlier estimates of the sensitivity to colour reconnection have been made within the context of given models, comparing "reconnection" to "no reconnection" scenarios for $W^+W^- \rightarrow q\bar{q}'q\bar{q}'$ events. In general, both the size and sign of any changes are dependent upon the model considered. At the expense of a reduction in statistical sensitivity, the dependence on the modelling of single hadronic W decays can be avoided by comparing directly with the properties of the hadronic part of $W^+W^- \rightarrow$

$q\bar{q}'\ell\bar{\nu}'$ events. All four LEP experiments compared the mean charged particle multiplicity in fully hadronic events $\langle n_{\rm ch}^{\rm 4q}\rangle$ and twice the charged particle multiplicity in semileptonic events $2\langle n_{\rm ch}^{\rm qq\ell\bar{\nu}}\rangle$ where the charged particles associated with the leptonically decaying W are excluded. Results of these comparisons are shown in table 2. Most results show no significant difference between $\langle n_{\rm ch}^{\rm 4q}\rangle$ and $2\langle n_{\rm ch}^{\rm qq\ell\nu}\rangle$, however, the uncertainty on the results are of the order of the effects predicted by the colour reconnection models implemented in PYTHIA, ARIADNE and HERWIG and only extreme models can be excluded so far. However, it is interesting to note that the DELPHI results for the ratio $\langle n_{\rm ch}^{\rm 4q}\rangle/2\langle n_{\rm ch}^{\rm qq\ell\bar{\nu}}\rangle$ differ from unity by one standard deviation for $\sqrt{s}$ = 189 GeV and two standard deviations for $\sqrt{s}$ =183 GeV. DELPHI have also measured this ratio for soft particles with momenta between 0.1 and 1 GeV where the effect is expected to be more pronounced. Preliminary results for this ratio in this restricted momentum range are $0.926 \pm 0.025 \pm 0.023$ for the $\sqrt{s}$ = 183 GeV data and $0.966 \pm 0.017 \pm 0.027$ for $\sqrt{s}$ = 189 GeV.

Table 2: Difference and ratio of the mean charged particle multiplicities for fully hadronic and semileptonic WW events. All results but those from OPAL are preliminary.

| Experiment | $\sqrt{s}$ | Studied Quantity | Result |
|---|---|---|---|
| ALEPH | 183 GeV | $\langle n_{\rm ch}^{\rm 4q}\rangle - 2\langle n_{\rm ch}^{\rm qq\ell\bar{\nu}}\rangle$ | 1.31±0.74±0.37 |
| ALEPH | 189 GeV | | 0.47±0.44±0.26 |
| L3 | 183 GeV | | -1.0± 0.8 ± 0.5 |
| OPAL | 183 GeV | | 0.7 ± 0.8 ± 0.6 |
| DELPHI | 183 GeV | $\langle n_{\rm ch}^{\rm 4q}\rangle/2\langle n_{\rm ch}^{\rm qq\ell\bar{\nu}}\rangle$ | 0.941±0.025±0.023 |
| DELPHI | 189 GeV | | 0.977±0.017±0.027 |

Not only has the mean value of the charged particle multiplicity been studied, but also its dispersion. Additionally the rapidity and $p_t$ distributions of charged tracks in fully hadronic events have been compared to those distributions in semileptonic events. DELPHI also studied the mean multiplicity of heavy hadrons in the low momentum region [15], where the effects of colour reconnection may be further enhanced. However, none of these results show clear evidence for colour reconnection effects.

### *3.2 Bose-Einstein Correlations*

Bose-Einstein correlations (BEC) between pairs of identical bosons, mainly the $\pi^\pm\pi^\pm$ system, have been extensively studied in a large variety of interactions and over a wide range of energies. Formally, they can be expressed by the correlation function

$$R(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)} \tag{1}$$

where $p_1, p_2$ are the four-momenta of the bosons, $\rho$ is the two-particle probability density and $\rho_0$ is the two-particle probability density that would occur in the absence of Bose-Einstein correlations. For the study of BEC in WW events ALEPH [16], L3 [17] and OPAL [18] used a reference distribution $\rho_0$ based on the observed two-particle probability density of particle pairs with opposite sign, while DELPHI [19] used the prediction for $\rho_0$ from Monte Carlo models that do not include Bose-Einstein effects. The correlation is large for small four-momentum differences, $Q = \sqrt{-(p_1 - p_2)^2}$, so that often Bose-Einstein correlations are parametrised in terms of this one-dimensional distance measure. A common parametrisation is

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

where $r$ estimates the size of the two-boson emitter which is taken to be of Gaussian shape and $\lambda$ is a measure of the strength of the Bose-Einstein effect.

The current studies of BEC in W events are motivated by the question of whether BEC for pions from different W bosons exist or not. An attempt to answer this question is to compare the measured correlation function for fully hadronic WW events with MC models that either include BEC among bosons from different Ws or include BEC only inside each of the two W systems. ALEPH as well as DELPHI have already analysed the $\sqrt{s} = 189$ GeV data sample and the results are shown in fig. 2. However, while ALEPH conclude from the comparison of data with carefully tuned JETSET model predictions that BEC between decay products of different W is disfavoured at a $2.7\sigma$ level, DELPHI now observe — in contrast to their previous results[20] — an indication of the presence of BEC between particles from different W bosons.

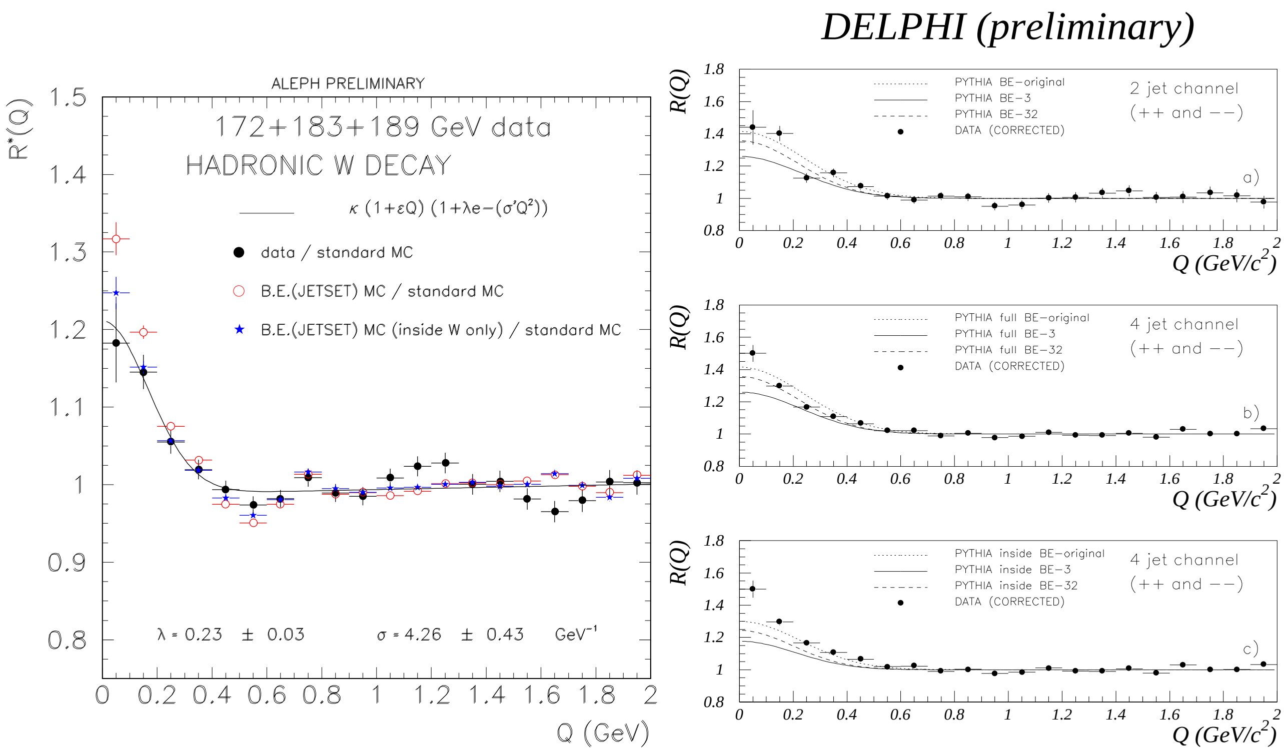


Figure 2: Results for the correlation function in fully hadronic events together with MC predictions from ALEPH (left) and correlation functions for semileptonic and fully hadronic WW events together with MC prediction from DELPHI (right).

All four LEP collaborations attempted to measure directly the strength of the BEC between particles from different W bosons. In an analysis of the $\sqrt{s} = 172$ data, DELPHI used the two particle densities in semileptonic WW events to subtract the contribution of particle pairs coming from the same W boson from the observed two-particle densities in fully hadronic events. The correlation strength of the remaining distribution is $\lambda^{\mathrm{diff\ W}} = -0.20 \pm 0.22 \pm 0.08$. ALEPH used a similar method and obtained for data with $\sqrt{s} = 172$ and 183 GeV a value of $\lambda^{\mathrm{diff\ W}} = 0.15 \pm 0.18(stat)$ with a negligible systematic error. L3 studied fully hadronic events at $\sqrt{s} = 183$ GeV and assigned jet pairs to the different W bosons, allowing a direct determination of the correlation strength of $\lambda^{\mathrm{diff\ W}} = 0.75 \pm 1.80$. OPAL performed a simultaneous fit to the correlation functions of fully hadronic WW events, semileptonic WW events and $e^+e^- \rightarrow q\bar{q}$ events. Based on the data collected at $\sqrt{s} = 172$ and 183 GeV, the value $\lambda^{\mathrm{diff\ W}} = 0.22 \pm 0.53 \pm 0.14$ was obtained. While all these published (DELPHI, OPAL) and preliminary (ALEPH, L3) results for $\lambda^{\mathrm{diff\ W}}$ are consistent with zero, i.e. compatible with the absence of BEC between particles from different W bosons, the most recent preliminary DELPHI results indicate evidence for BEC between particles from different Ws. The study is based on the data samples at $\sqrt{s} = 183$ and 189 GeV and uses a reference sample from "mixed events" which were constructed out of two semileptonic WW events. The result is $\lambda^{\mathrm{diff\ W}} = (0.073 \pm 0.025 \pm 0.018) \times f$ where $f$ is the fraction of like-sign particle pairs from different Ws in the fully hadronic WW channel at low Q, and was found to be 0.201 when calculated using PYTHIA MC events.

## 4 Conclusions

The QCD studies of the four LEP experiments in $e^+e^-$ collisions at a centre-of-mass energy of up to 189 GeV have resulted in measurements showing good agreement with model predictions. While extreme models for colour reconnection effects in fully hadronic $e^+e^- \to W^+W^-$ events can be excluded by the data there is as yet no conclusive answer to the question of whether or not there are Bose-Einstein correlations between particles from different W bosons.

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