1 Motivation

Hadronic data in $e^+e^-$ collisions can be characterised by event shape distributions and inclusive observables such as charged particle multiplicities and momentum spectra. In addition to tests of Monte Carlo models, measurement of the properties of the hadronic sector of $W^+W^-$ decays allows the question of ‘colour reconnection’ to be addressed experimentally. The decay products of the two W decays may have a significant space-time overlap as the separation of their decay vertices at LEP2 energies is small compared to characteristic hadronic distance scales. In the fully hadronic channel this may lead to final state interactions. Colour reconnection is the general name applied to the case where such final state interactions lead to a rearrangement of the colour flow between the two W bosons. At present there is general consensus that observable effects of interactions between the colour singlets during the perturbative phase are expected to be small. 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. One should be aware that other final state effects such as Bose-Einstein correlations between identical bosons may also influence the observed event properties. The combined action of these two effects may be either to reduce or enhance possible characteristic signatures of their presence.

2 Event Properties

The results shown are based on $\sim 55$ pb$^{-1}$ data per LEP collaboration. Simple observables such as the inclusive charged multiplicity are obvious candidates for study. There have been predictions that the effects of colour reconnection may be $\sim 10\%$ on $\langle n_{ch}^{qq} \rangle$, the mean charged multiplicity in $W^+W^-\rightarrow qq\ell\nu$ events. The reference sample against which such changes are gauged is typically taken to be twice the multiplicity of the hadronically decaying W in $W^+W^-\rightarrow q\bar{q}\ell\nu$ events, $\langle n_{ch}^{qq\ell\nu} \rangle$.

Recent measurements of the properties of $W^+W^-$ events produced in $e^+e^-$ collisions at $\sqrt{s} \sim 183$ GeV at LEP are reviewed. The data are used to investigate the predicted effects of final state interactions, specifically “colour reconnection”.

**Figure 1:** Observed track multiplicity, $W^+W^-\rightarrow q\bar{q}\ell\nu$, events.

 Charged particles associated with the leptonic component of such events are excluded. The difference is defined $\Delta \langle n_{ch} \rangle = \langle n_{ch}^{qq\ell\nu} \rangle - 2\langle n_{ch}^{qq\ell\nu} \rangle$. This reduces the dependence on the modelling of single W decays at the expense of a lower statistical significance of the test performed. The observed (uncorrected) track multiplicities for selected $W^+W^-\rightarrow q\bar{q}\ell\nu$ candidates are shown in Figure 1 by OPAL, together with the predictions from a variety of colour reconnection models. The mean charged particle multiplicities, $\langle n_{ch}^{qq\ell\nu} \rangle$ and $\langle n_{ch}^{qq\ell\nu} \rangle$, may be extracted from such data, after subtraction of the predicted background, by employing a matrix-based unfolding procedure. This uses the event-by-event correlation, taken from Monte Carlo, between the charged multiplicity at hadron level and that observed in the detector after all analysis cuts have been applied. A subsequent correction for the effects of initial state photon radiation and to full acceptance is applied. Alternative methods for measuring $\langle n_{ch}^{qq} \rangle$ and...
Changes in \( \langle n_{ch}^{4q} \rangle \) predicted vary with the colour reconnection model used, and the extent to which it may have been retuned. Representative shifts, defined as \( \langle n_{ch}^{4q \text{ connection}} \rangle - \langle n_{ch}^{4q \text{ normal}} \rangle \) for each model, are:

- Sjöstrand-Khoze (SK) I \( \sim -0.3 \)
- SK II, SK II’ \( \sim -0.2 \)
- ARIADNE 2 \( \sim -0.1 \)
- ARIADNE 3 (AR 3) \( \sim -1.0 \)

As unfolding the data may introduce a bias towards the model used, the procedure is repeated using a variety of models to estimate any associated systematic effect. L3 and OPAL also unfold their data using several colour reconnection models as part of such studies. ALEPH correct their data for experimental effects, such as finite detector resolution, but not for losses due to tracking inefficiency in the low momentum region \( p_T < 200 \text{ MeV} \), or phase space and topological biases invariably present in experimental event selections. By using only a partial unfolding, their data should be less affected by model biases but cannot be compared directly with other experimental results, or to model predictions without passing through their detector simulation and analysis cuts.

The mean multiplicities, \( \langle n_{ch}^{4q} \rangle, \langle n_{ch}^{qq\ell}\ell \rangle \), and \( \Delta \langle n_{ch} \rangle \) measured by the LEP collaborations are shown in Table 1. Although the ALEPH mean multiplicities should not be compared directly with other data, the associated difference may be more meaningfully compared. The LEP average multiplicity difference obtained is:

\[
\text{LEP } \Delta \langle n_{ch} \rangle = +0.20 \pm 0.50(\text{stat. } \pm \text{syst.}),
\]

This is consistent with there being no change in the \( \langle n_{ch}^{4q} \rangle \) due to colour reconnection effects. As the systematics considered and the dominant source varied between the collaborations, this average assumes all systematics were uncorrelated. If, instead, the smallest over-

| Expt.   | \( \langle n_{ch}^{4q} \rangle \) | \( \langle n_{ch}^{qq\ell}\ell \rangle \) | \( \Delta \langle n_{ch} \rangle \) |
|---------|---------------------------------|---------------------------------|---------------------------------|
| ALEPH†  | 35.33 ± 0.73                    | 17.01 ± 0.37                    | +1.31 ± 0.83                    |
| DELPHI | 37.36 ± 1.00                    | 19.48 ± 0.73                    | -1.6 ± 1.5                      |
| L3      | 36.3 ± 0.9                      | 18.6 ± 0.6                      | -1.0 ± 0.9                      |
| OPAL    | 39.4 ± 1.0                      | 19.3 ± 0.4                      | +0.7 ± 1.0                      |

Table 1: Mean charged particle multiplicities, errors are sum of statistical and systematic components. †: only partially unfolded.

Table 2: Dispersions of charged particle multiplicities, errors are sum of statistical and systematic components

| Expt.   | \( \langle n_{ch}^{4q} \rangle \) | \( \langle n_{ch}^{qq\ell}\ell \rangle \) | \( \Delta \langle n_{ch} \rangle \) |
|---------|---------------------------------|---------------------------------|---------------------------------|
| DELPHI | 8.24 ± 0.51                     | 5.76 ± 0.49                     | +0.09 ± 0.84                    |
| OPAL    | 8.8 ± 0.7                       | 6.1 ± 0.5                       | +0.2 ± 0.6                      |

all systematic estimated by any collaboration is considered as fully correlated, the average value obtained is \( \Delta \langle n_{ch} \rangle = +0.15 \pm 0.80(\text{stat. } \pm \text{syst.}) \). Performing the average while excluding the ALEPH results leads to the same conclusions.

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2.1 Ellis-Geiger Model

The Ellis-Geiger model, implemented in the Monte Carlo program VNI, has been studied by the LEP collaborations. ALEPH and OPAL illustrate this by quoting some predictions from VNI. It is noted that the Ellis-Geiger model as implemented within VNI has not been tuned recently to describe Z boson production. For these reasons, the collaborations do not use the Ellis-Geiger model as currently implemented in VNI to estimate possible systematic effects on the W boson mass.
2.2 Thrust

The thrust, $T$, distribution shown in Figure 2 from L3 illustrates how $W^+W^-\rightarrow q\bar{q}q\bar{q}$ events are more spherical than the $Z^0/\gamma\rightarrow q\bar{q}$ background, which is dominated by two-jet events. Qualitatively, colour reconnection effects are expected to be enhanced in $W^+W^-$ events where the hadronic cascades from two W bosons overlap, but this is precisely the background dominated, two-jet like region generally excluded by the experimental event selections.

It is interesting to compare the hadron level predictions of a standard $W^+W^-$ event generator such as KORALW with the VNI generator in its colour blind scenario. The distribution of $1-T$ is shown in Figure 3 for these two models. It can be seen that VNI predicts $W^+W^-$ events to be more spherical than other models. While this might influence the efficiency with which such events are selected, they are topologically more distinct from the background than predicted by most models, so should fall well within the acceptance of the detectors.

2.3 Model Tuning

In general each model must be retuned to data after fixing reconnection related strength parameters or probabilities. The Sjöstrand-Khoze models do not require such retuning once the JETSET hadronisation model has been tuned. HERWIG, ARIADNE and the Ellis-Geiger model all require retuning. OPAL use a tuning of ARIADNE summarised in while ALEPH describe in detail their tuning of HERWIG. The mean charged multiplicities in HERWIG for $Z^0/\gamma$, $W^+W^-\rightarrow q\bar{q}q\bar{q}$ and $W^+W^-\rightarrow q\bar{q}\ell\nu$ events as a function of the reconnection probability, PRECO, are shown in Figure 4 by ALEPH. The effect of retuning at each PRECO, and its necessity, is clear. A good description of the $W^+W^-$ events may be achieved after suitable
2.4 Alternative Observables

The effects of colour reconnection are generally predicted to be enhanced in the soft particle region, therefore studies of fragmentation functions are interesting. Figure 5 shows the ratio of the corrected, scaled momentum distributions for $W^+W^-\rightarrow q\bar{q}q\ell\nu\ell$ and $W^+W^-\rightarrow q\bar{q}q\ell\nu\ell$ events, together with predictions of $W^+W^-$ event generators and the colour reconnection model in which they found the largest effects, AR 3. Although this latter predicts differences which are as large as 5% in the lowest momentum interval, it is still consistent with data. OPAL also measure a variety of mean event shape variables, all of which are consistent with model predictions (neglecting $V_{ni}$):

$$\langle x_p^{4q} \rangle = (3.16 \pm 0.05 \pm 0.04) \times 10^{-2}$$
$$\langle x_p^{\ell\ell} \rangle = (3.25 \pm 0.07 \pm 0.04) \times 10^{-2}$$
$$\Delta \langle x_p \rangle = (-0.09 \pm 0.09 \pm 0.06) \times 10^{-2}$$
$$\langle (1 - T)^{4q} \rangle = 0.240 \pm 0.015 \pm 0.009$$
$$\langle |y^{4q}| \rangle = 1.017 \pm 0.016 \pm 0.016$$

DELPHI show in Figure 6 the transverse momentum distributions relative to the thrust axes for $W^+W^-\rightarrow q\bar{q}q\ell\nu\ell$ and $W^+W^-\rightarrow q\bar{q}q\ell\nu\ell$ events, and their ratio. In the semileptonic events the thrust axis is calculated taking the momentum imbalance in each event to be the neutrino momentum. There is no significant difference found between the data in the two channels.

3 Heavy Hadrons

It was recently predicted that the effects of colour reconnection may be further enhanced by restricting analyses to heavier hadrons such as charged kaons and protons in the low momentum region, $0.2 < p < 1.2$ GeV.
Numerically this increases the relative size of the effect, but taking into account the branching fractions to such species as well as experimental effects such as finite particle detection efficiency, background and modelling, it is not clear this will lead to an improved significance in the analyses. DELPHI use their TPC, RICH and vertex detector for particle identification, attaining tagging efficiencies for kaons and protons of order 90–50%, with purities in the range 90–75%. They observe 181 heavy hadrons in $W^+W^- \rightarrow q\bar{q}q\bar{q}$ events, 88 in $W^+W^- \rightarrow q\bar{q}q\ell$. After unfolding for tagging effects this gives:

\[
\langle q\bar{q}q\ell/(2q\bar{q}\ell) \rangle = 1.03 \pm 0.15 \text{(stat.)}.
\]

The statistical uncertainty on this measurement seems unlikely to be less than 5% even with the nominal LEP2 integrated luminosity of 500 pb\(^{-1}\). To reduce the statistical uncertainty on these studies, they also use $Z^0$ calibration data as a reference sample. Pairs of $Z^0$ events, after boosting, are used to emulate $W^+W^- \rightarrow q\bar{q}q\ell$ events, and a direct comparison is made with genuine $W^+W^- \rightarrow q\bar{q}q\ell$ data. The two data samples and the corresponding Monte Carlo predictions are shown in Figure 7. The qualitative agreement is reasonable, although there may be differences between $W^+W^-$ data and predictions for $p > 0.6$ GeV. The final result of their analysis is the ratio:

\[
\langle n^{\text{heavy}} \rangle_{W^+W^-/Z^0} = 0.870 \pm 0.090 \text{(stat.)} \pm 0.044 \text{(syst.)}.
\]

### Table 3: Model dependent, colour reconnection bias estimates for $M_W$ determination in $W^+W^- \rightarrow q\bar{q}q\bar{q}$ channel (statistical uncertainties). †: fast detector simulation, ‡: modified version of model.

| Exp. | ALEPH | DELPHI† | OPAL  |
|------|-------|---------|-------|
| SK I | $+25 \pm 21$† | $+40 \pm 12$ ‡ | $+50 \pm 17$ |
| SK II | $+5 \pm 15$ | $-$ | $+17 \pm 17$ |
| SK II§ | $+17 \pm 15$‡ | $+3 \pm 10$ | $+18 \pm 17$ |
| GH | $-$ | $+13 \pm 18$ | $-$ |
| HW | $-31 \pm 25$ | $-$ | $+$ |
| AR 2 | $-$ | $-$ | $+73 \pm 18$ |
| AR 3 | $-$ | $-$ | $+146 \pm 18$ |

4 W Mass Biases

Updated bias estimates for the effects of colour reconnection on the W mass measurement were presented by ALEPH, DELPHI and OPAL, as summarised in Table 3. It is noted that ALEPH and OPAL estimates are using their respective default $M_W$ analyses, while the DELPHI results are a variant on their main $M_W$ analysis. The bias estimates from HERWIG and ARIADNE are made after these models have been tuned to describe $Z^0$ data at $\sqrt{s} = 91$ GeV. As a cautionary note, there are non-negligible statistical uncertainties on all of these bias estimates which must be reduced for future analyses. No bias estimates are presented for the Ellis-Geiger model for reasons discussed earlier.

5 Summary

Studies of colour reconnection are maturing, in particular the area of Monte Carlo tuning is being addressed. There is no significant difference observed in the charged particle multiplicity of a single W boson produced in either a $W^+W^- \rightarrow q\bar{q}q\ell$ or a $W^+W^- \rightarrow q\bar{q}q\ell$ event. Most models are consistent with data based on an integrated luminosity of $\sim 55$ pb\(^{-1}\) per collaboration. Identified particle studies in progress pose an interesting experimental challenge. The Ellis-Geiger model, as currently implemented and tuned, is not used for $M_W$ bias estimates as it does not describe the data. Finally, the 1998 data should allow some models to be excluded leading to better control of the colour reconnection systematic on $M_W$ measurements.

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