COLOUR RECONNECTION IN W PAIRS AND MONTE CARLO TUNING AT LEP

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Colour reconnection effects are searched for in W pair production data. Several models are investigated and the HERWIG generator, with and without reconnection, is tuned to Z data.

1 Introduction

There is at present considerable interest in possible colour reconnection (CR) effects in the process $e^+e^- \rightarrow W^+W^- \rightarrow (q_1\bar{q}_2)(q_3\bar{q}_4)$ leading to a fully hadronic final state. Reconnection means that quarks from different W's form two colour singlets $(q_1\bar{q}_4)(q_3\bar{q}_2)$. The contribution from hard QCD has been shown to be small [1]. Since the distance of the W decay points is of order 0.1 fm, non-perturbative effects could be sizeable due to the overlap of the hadronisation regions which are of order 1 fm.

So far there is no experimental evidence for colour reconnection in data taken at LEP at energies above the W pair threshold.

The possible effects of colour reconnection which may systematically influence the W mass measurement from the 4q channel, can be studied in terms of QCD-inspired models. Several such models have been developed in the past and built into standard QCD event generators. These generators with or without inclusion of CR effects should be well tuned to describe $Z \rightarrow q\bar{q}$ data.

2 Models for colour reconnection

Several string-based models [1] for CR are implemented in PYTHIA [2]. Strings are viewed as extended flux tubes and the reconnection probability is related to the space-time overlap of the two strings (SK1). In a second model strings are viewed as thin vortex lines and reconnection occurs if they cross each other (SK2) and if in addition the total string length λ is reduced (SK2'). The (GH) model which does not work in space-time, chooses the recoupling that reduces λ most.

In ARIADNE [3], colour dipoles are allowed to reconnect [4] with probability $P_{reco} = 1/N_c^2$ if the total string length λ is reduced. Reconnections between W's are enabled only after all gluons with energies $E > \Gamma_W$ have been radiated (AR2).

HERWIG [5] generates a space-time picture of the parton shower. Pairs of clusters are then considered for rearrangement [6] with probability P_{reco} if the sum of cluster sizes is reduced. Setting $P_{reco} = 1$ (instead of the default value $1/N_c^2$) corresponds to a kind of non-singlet model [7]

Table 1: Fitted HERWIG5.9 parameters

PRECO	0.0	1/9	1.0
VMIN2		0.1	0.1
QCDLAM (GeV)	0.190 ± 0.001	0.187 ± 0.001	0.149 ± 0.001
M(gluon) (GeV)	0.77 ± 0.01	0.79 ± 0.01	0.69 ± 0.01
CLMAX (GeV)	3.39 ± 0.01	3.40 ± 0.01	3.72 ± 0.02
CLSMR(dusc)	0.59 ± 0.02	0.66 ± 0.03	1.96 ± 0.13
CLSMR(b)	0 (fixed)	0	0
PSPLT(dusc)	0.945 ± 0.009	0.886 ± 0.007	0.714 ± 0.005
PSPLT(b)	0.33	0.32	0.30
DECWT	0.71 ± 0.02	0.70 ± 0.02	0.47 ± 0.01
$\sum \chi^2$/ndf	2864/364	3085/364	4420/364

The CR models in ARIADNE and HERWIG allow reconnections to take place also inside single W and Z decays. Thus the hadronic final states are modified and retuning of fragmentation parameters is required. This has been done for the AR1 variant of ARIADNE and for HERWIG.

3 Tuning of HERWIG 5.9

HERWIG differs from the standard PYTHIA/JETSET generator in the hadronisation model and also in the realisation of the QCD cascade. The HERWIG reconnection model has not been studied so far in detail. The procedure of 'tuning' not only consisted of adjusting the free parameters but also of improving and correcting the program :

- Charge symmetry was violated in cluster decays due to missing isosinglet members of the higher spin $L = 2$ meson multiplets. The problem is avoided by simply removing these multiplets (array VTOCDK). This improved the overall χ^2.
- $\eta - \eta'$ mixing was corrected by adding 90° to the pseudoscalar mixing angle.
- The $b \rightarrow B$ fragmentation function was changed to better agree with data by allowing two parameters (CLSMR and PSPLT) to have different values in *b*- and *dusc* events.
- An error in the space-time code had the effect that no reconnections at all occured between the W's. This has been corrected.
- It was found [8] that VMIN2 (the minimum virtuality of quarks and gluons) is a sensitive parameter and its default value (10^{-4} GeV^2) produced unphysically large distances $d \approx$ 1000 fm ($d = M_g$/VMIN2 on average for final gluons). A more realistic value (0.1 GeV^2) gives $\approx$ 1.5 fm.

These corrections have been included into the new version 6.1. The most important QCD and fragmentation parameters of HERWIG have been tuned to ALEPH Z-peak data. The method (a true multi-parameter fit) and the set of distributions fitted are as described in [9]. In addition, the $x(B)$ [10] and $x_{ch}(b\bar{b})$ spectra (the latter from OPAL [11]) are used to fit the PSPLT(b) parameter. The fit results are given in Table 1 for three values of P_{reco}.

Globally, JETSET7.4 ($\chi^2 \approx 1900$) describes the data better than HERWIG, in particular the rates and spectra of identified hadrons. A remarkable exception is the $p_{T,out}$ distribution which is better described by HERWIG (Fig.1). HERWIG has problems in reproducing the rates of multi-strange versus non-strange baryons and thus the fit depends on which baryons are

Table 2: The shifts in average charged multiplicity and the reconstructed W mass in $WW \rightarrow 4q$ at 189 GeV at particle level, as predicted by the various reconnection models. Statistics is 300K events each.

model		parameter	ΔN_{ch}(CR–noCR) all	$p < 1$ GeV	ΔM_W(CR–noCR) $[MeV]$
PYTHIA 6.1	SK1	$k_1 = 0.6$	−0.19	−0.21	+40
	SK2		−0.14	−0.15	−11
	SK2'		−0.18	−0.19	−7
	GH	$P = 0.3$	−0.35	−0.32	+70
ARIADNE 4	AR2		−0.37	−0.35	+57
HERWIG 5.9	singlet	$P = 1/9$	+0.25	+0.17	+42
	'octet'	$P = 1$	+0.80	+0.54	+220

included (the $\Xi(1530)$ and Ω^- were omitted). As a result of the tuning, the average charged multiplicities in b- and *dusc* events are well reproduced and are constant with P_{reco}. This is important for W studies as the decay $W \rightarrow \bar{c}b$ is suppressed. The rising χ^2 suggests that at least the $P_{reco} = 1$ case is disfavoured by the data. The fit result for $P_{reco} = 1/9$ is stable in the range $(0.25)^2 <$ VMIN2 $< (0.40)^2$ GeV^2.

4 Properties of CR models

In $WW \rightarrow 4q$ events, the CR models predict a change in the average number of particles produced, mainly in the soft region[12], and a (small) systematic shift of the W mass reconstructed from 4 jets. Table 2 summarizes calculations done at $\sqrt{s} = 189$ GeV at particle level (no detector simulation) for the various models. For the 'noCR' mode, the variant AR1 was taken in case of ARIADNE and $2N_{ch}$ of single W decays was taken in case of HERWIG. The procedure to reconstruct the W mass is close to the experimental one : all final state particles are forced into 4 jets using the Durham cluster algorithm, the pairing is chosen which matches best the original quarks and a mass window 80.35 ± 10 GeV was applied to both jet-jet masses. ΔM_W is defined as the difference, with and without CR, between the averages of $(M_{W1} + M_{W2})/2$.

Compared to the overall $\langle N_{ch} \rangle \approx 38$ the change in multiplicity is less than 1 unit even for the extreme model and is of the order of 1% or less. The effect is concentrated in the soft region $0.1 < p < 1$ GeV. HERWIG predicts an increase of multiplicity when CR is switched on, contrary to the string-based models which predict a decrease. This increase arises from the increase of the cluster masses (before splitting). Despite this different behaviour, the W mass shifts are all positive except for SK2.

5 Search for colour reconnection

5.1 *Charged particle production*

The average charged multiplicities in WW fully hadronic and semi-leptonic events have been measured by the four LEP experiments [13,14,15,16] at $\sqrt{s} = 183$ and 189 GeV. The data were background subtracted and corrected for acceptance (ALEPH did not extrapolate into the region $p_t < 0.2$ GeV and did not correct for events lost by the selection criteria). The values of the differences $\langle N_{ch}(4q) \rangle - 2\langle N_{ch}(2q) \rangle$ are less than 1 unit and compatible with 0 within errors. The scaled momentum x or -ln(x) distributions have also been measured. No significant differences between the distributions from (4q) and 2(2q) events are seen at low momenta. The present statistical precision of a single experiment is not sufficient to distinguish the 'noCR' from the various CR scenarios. The results from the LEP run in 1999 at energies from 192 to 202 GeV were not available at the time of the conference.

5.2 Particle flow

A new method to study CR effects has been developed and applied to 189 GeV data by the L3 collaboration [15]. By employing a set of angular cuts specific 4-jet topologies are selected for which the angular regions belonging to the two W decays are well separated. This selects only 15% of the WW sample, or 209 events. Individual particles are assigned to one of the 4 adjacent planes belonging to the same W's (A,B) and different W's (C,D), and the distributions of rescaled angles are constructed. The ratio of distributions $(A + B)/(C + D)$ is shown in Figure 2. The result is promising though at the present level of statistics it is not possible to tell whether there is reconnection or not. In the GH model calculation shown in this figure 90% of the events are reconnected which can be considered unrealistic. Note that for the GH model result given in Table 2 a reduction factor of $P = 0.3$ was applied leading to a fraction of reconnected events similar to that of the SK2 model.

6 Conclusions

The hadronisation part of HERWIG has been improved and the main free parameters have been determined from a fit to Z data. This generator can now be used to estimate colour reconnection effects. In contrast to the string-based CR models, HERWIG predicts an increase of particle multiplicity when CR between two W's is included. Different CR models predict effects which are too small to be seen in present experimental data. A combination of data of the four experiments at the end of LEP-2 may show some sensitivity.

References

1. T.Sjostrand, V.A.Khoze, *Phys. Rev. Lett.* **72**, 28 (1994); *Z. Phys.* C **62**, 281 (1994).
2. PYTHIA program, version 6.1, T.Sjöstrand, *Comp. Phys. Comm.* **82**, 74 (1994).
3. ARIADNE program, version 4, L.Lönnblad, *Comp. Phys. Comm.* **71**, 15 (1992).
4. L.Lönnblad, *Z. Phys.* C **70**, 107 (1996).
5. HERWIG program, version 5.9, G.Marchesini et al., *Comp. Phys. Comm.* **67**, 465 (1992).
6. QCD event generators, in: *Physics at LEP2*, CERN 96-01, Vol.2, p.161, ed. G.Altarelli,T.Sjöstrand,F.Zwirner.
7. B.R.Webber, Talk at Phenomenology Workshop on LEP2 Physics, Oxford, April 1997.
8. B.R.Webber, private communication.
9. ALEPH collaboration, *Studies of QCD with the ALEPH detector, Phys. Rep.* **294**, 1 (1998).
10. ALEPH collaboration, *Phys. Lett.* B **357**, 699 (1995).
11. OPAL collaboration, *Eur. Phys. J. C* **5**, 369 (1999).
12. V.A.Khoze, T.Sjöstrand, preprint hep-ph/9804202.
13. ALEPH collaboration, CONF 99-020, contribution to the XXXIVth Rencontres des Moriond, 1999.
14. DELPHI collaboration, CONF 306, paper submitted to HEP99 conference, Tampere, Finland.
15. L3 collaboration, L3 Note 2503, paper submitted to this conference.
16. OPAL collaboration, OPAL Physics Note PN417, 1999.

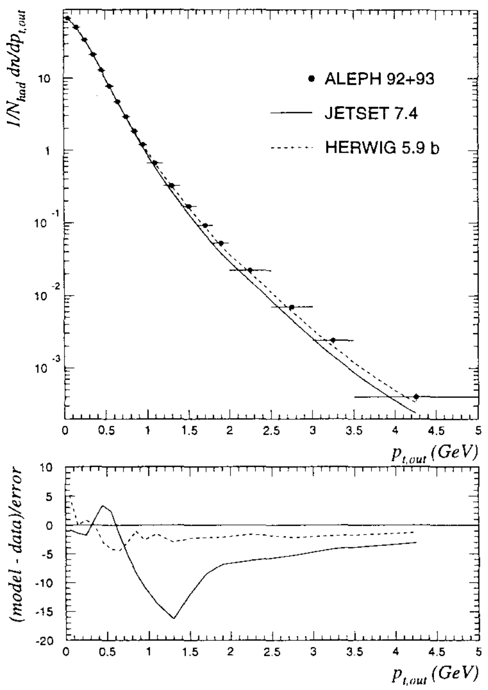

Figure 1: The $p_{T,tout}$ distribution of charged particles measured at the Z peak. $p_{T,tout}$ is the momentum component perpendicular to the event plane defined by the sphericity tensor

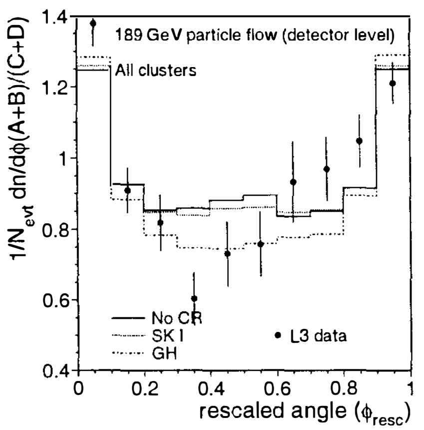

Figure 2: The ratio of particle flow versus the rescaled azimuthal angle measured in WW events by L3