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Investigation of Colour Reconnection in WW Pairs Using Particle Flow

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Abstract

A possible colour flow connecting hadronically decaying W bosons pair-produced at LEP 2 has been investigated using data collected by DELPHI at centre-of-mass energies between 183 GeV and 208 GeV. The analysis is based on the study of the particle flow in WW 4-jet events and the results are preliminary.

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1 Introduction

The W production above the WW threshold at LEP is dominated by pair production. About 46% of the WW events are WW $\rightarrow$ $q_1\bar{q}_2q_3\bar{q}_4$ events (fully hadronic); about 44% are WW $\rightarrow$ $q_1\bar{q}_2\ell\bar{\nu}$, where ℓ is a lepton (semileptonic).

Interconnection between the hadronic products of the decay of different W bosons can be expected since the lifetime of the W ($\tau_W \simeq \hbar/\Gamma_W \simeq 0.1$ fm/c) is an order of magnitude smaller than the typical hadronisation times. The possible presence of colour flow between the two W bosons (this effect is called *colour reconnection* for historical reasons) is an important study item for LEP in phase 2, both in itself and for the possibly large systematics induced on the W mass measurement (see [1] for a recent review).

Colour reconnection has been previously investigated in DELPHI by comparing inclusive distributions of charged particles and the average W multiplicity into charged particles (unresolved) and identified (heavy) particles in fully hadronic WW events and in semileptonic WW events; the investigation did not show any effect and it was limited by statistics and systematics (see [2]).

In this paper we present an investigation of the colour reconnection between hadronically decaying W pairs using a technique pioneered by L3 [3] in which the particle flow between the jets in a 4-jet WW event is measured. The sensitivity in this method is increased due to the selection of events with particular topologies, chosen in order to define an intra-W region and an inter-W region.

The analysis uses data collected by DELPHI [4] at centre-of-mass energies $\sqrt{s}$ between 183 GeV and 208 GeV. The data collected in the year 2000, with centre-of-mass energies from 200 to 208 GeV and a luminosity weighted average centre-of-mass energy of 206 GeV, were analysed all together. The performance of the DELPHI detector is described in [5]. To compare with the expected results from processes in the Standard Model with and without colour reconnection included, simulation was used to generate events and simulate the DELPHI detector, event reconstruction and analysis procedure. At all energies, EXCALIBUR [6] was used to generate the 4-fermion final states (containing WW and ZZ contributions), after which the events were fragmented with JETSET Parton Shower development and fragmentation [7], tuned to DELPHI data at $\sqrt{s} = M_Z$ [8]. The background process $Z(\gamma)^* \rightarrow q\bar{q}(\gamma)$ was generated and fragmented using PYTHIA. In this analysis the double Z production and decay (ZZ) was also considered as a background process, and was generated and fragmented using PYTHIA. Its estimated contribution was subtracted both from the data and from the EXCALIBUR simulation samples. At 189 GeV, to compare with other experiments and with models with colour reconnection, samples with 100000 events generated with KoralW for the 4-fermion final states ("Crete samples") were also used. These samples have the same generated events and differ only in the parton shower evolution and fragmentation. The first "Crete sample" was obtained by applying to the generated events the JETSET Parton Shower development and fragmentation, tuned by ALEPH at $\sqrt{s} = M_Z$, with colour reconnection implemented by the model Sjöstrand-Khoze "Type 1" (SKI) [9] with 100% reconnection probability (CRCC); the second "Crete sample" was obtained by applying to the generated events the same JETSET without colour reconnection (CRJS); and the third "Crete sample" was obtained by applying to the generated events the HERWIG fragmentation tuned by ALEPH at $\sqrt{s} = M_Z$ without colour reconnection (CRHW).

All samples were passed through the normal DELPHI simulation and reconstruction programs [5], and through the analysis chains.

2 Event selection

Events with both Ws decaying into $q\bar{q}$ are characterised by high multiplicity, large visible energy, and tendency of the particles to be grouped in 4 jets. The background is dominated by $q\bar{q}(\gamma)$ events.

Charged particles were required to have momentum p greater than 100 MeV/c and below 1.5 times the beam energy, a relative error on the momentum measurement $\Delta p/p < 1$, polar angle θ with the beam axis between 20 and 160 degrees, distance of closest approach to the interaction point less than 4 cm, in the plane perpendicular to the beam axis, and less than $4/\sin\theta$ cm along the beam axis, and a reconstructed track length larger than 30 cm. Clusters in the electromagnetic or hadronic calorimeter with energy larger than 0.5 GeV and polar angle in the interval $10° < \theta < 170°$, not associated to charged particles were considered as neutral particles.

The events were pre-selected by requiring at least 12 charged particles, with a total transverse energy (charged plus neutral) above 20% of the centre-of-mass energy. To remove the radiative hadronic events, the effective centre-of-mass energy $\sqrt{s'}$, computed as described in [10], was required to be above 110 GeV.

The particles in the event were then clustered using the LUCLUS algorithm [7], for a separation value of $d_{join} = 6.5$ GeV/c, and the events were kept if there were 4 and only 4 jets and a multiplicity (charged plus neutral) in each jet larger than 3. The combination of these two cuts removed most of the semi-leptonic WW decays and the 2-jet and 3-jet events of the $q\bar{q}\gamma$ background.

For the study of the particle flow between jets, the initial quark configuration should be well reconstructed with a good quark-jet association. At 183 GeV and above, the W bosons produced have a significant boost, implying smaller angles between the jets into which the W decays, in the laboratory frame of reference, and this property tends to reduce the ambiguity in the definition of the inter-W and intra-W regions, in opposition to the situation in which the W decays at rest and the decay products are back-to-back.

The selection criteria are based on cuts in four of the six jet-jet angles. The two smallest jet-jet angles, spanning regions B and D in Figure 1, should be below 100° and not adjacent (not have a common jet). Two other jet-jet angles should be between 100° and 140° and not adjacent, spanning regions A and C in Figure 1. In case there are two different combinations of jets satisfying the above criteria for the angles A and C, the combination with the highest sum of angles (A+C) is chosen. This selection guarantees similar sharing of energy between the four primary partons with the two strings evolving back to back. In Figure 1, region B is the region corresponding to the smallest jet-jet angle, made by jets 2 and 3, region D corresponds to the second smallest jet-jet angle, made by jets 1 and 4, region A spans the angle between jets 1 and 2, the larger jet-jet angle of the chosen combination, and region C spans the angle between jets 3 and 4, the second larger angle of the chosen combination. In general, the regions are not in the same plane, as the decay planes of the W bosons do not coincide, and the large angles are not necessarily the largest jet-jet angles in the event.

The luminosity and the number of selected events for each energy, are summarized in Table 1. In the same table are listed the number of expected 4-jet WW events, the

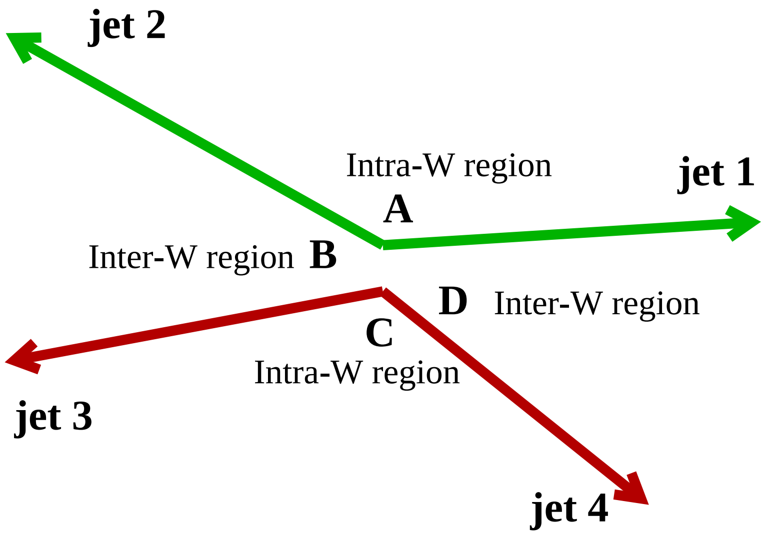

Figure 1: Schematic drawing of the angular selection.

$\sqrt{s}$	$\int Ldt$ (pb^{-1})	N_{sel}	#WW 4jets	#backgr.	Efficiency	Purity
183 GeV	52.7	83	56.9	14.2	14%	80%
189 GeV	157.6	203	175.0	36.9	15%	83%
192 GeV	25.9	32	29.2	5.9	14%	83%
196 GeV	77.3	97	66.2	19.4	10%	77%
200 GeV	83.4	117	84.6	19.4	12%	83%
202 GeV	40.6	37	38.7	7.7	11%	83%
206 GeV	163.9	190	130.1	37.7	9%	78%

Table 1: Luminosity and number of the selected events for each energy, number of expected events from 4-jet WW and background processes, purity and efficiency of the data samples

number of expected events from the total of the background processes, the purity of the selected data samples, and the efficiency to select 4-jet WW events. The expected numbers of events and the purities and efficiencies were estimated using simulation. The efficiency for correct pairing of jets to the same W boson, was estimated at 189 GeV, using simulation, to be equal to 76%.

The distribution of the reconstructed masses of the pairs making the large angles, candidates for the W bosons, after applying a (4C) kinematic fit requiring energy and momentum conservation, is shown in figure 2 for the selected events, and compared to the expected distribution from 4-jet WW signal without colour reconnection plus background processes, normalized to the luminosity of the data samples.

3 Analysis and results

The particle flow is defined by the number of charged particles in the intra-W and inter-W regions, after angular ordering of the jets, as in Figure 1. The selected events have two

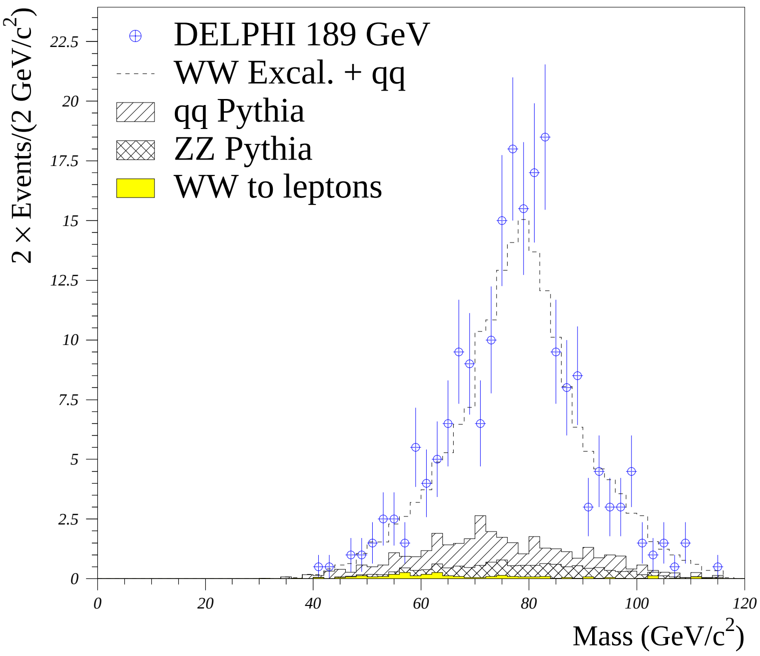

Figure 2: Reconstructed dijet masses (after a (4C) kinematic fit) for the selected pairs at 189 GeV, with 2 entries (of weight 0.5) per event (see text).

large jet-jet angles, which are assumed to be the intra-W regions, and two small angles, the smallest jet-jet angles in the event, which are assumed to be the inter-W regions, the regions between the different Ws. Following the definition of regions and jets from the previous section, jet 1 is the border between the regions A and D, jet 2 the border between regions A and B, jet 3 the border between regions B and C, and jet 4 the border between regions C and D, which corresponds to the ordering of 1234 in jets and of ABCD in regions.

In order to compare the particle production between the jets of the same and different W bosons, one has to take into account the fact that the W decay planes are not the same. So for each pair of adjacent jets (m,n), where (m,n) stands successively for (1,2), (2,3), (3,4), (4,1), the particle is projected onto the plane made by the jets m and n, and the angle of the projected momentum with the jet m is divided by the angle between the jets. If ϕ_i is the projected angle of particle i in the plane defined by jets m and n and ϕ_{mn} defines the angle between them, the rescaled angle is then defined as:

$$\phi^i_{resc} = \phi_i/\phi_{mn} \, .$$

Only the particles for which the projected angle in the plane of jets m and n was smaller than ϕ_{mn} were considered in the distribution relative to that plane. About 10% of the particles in the data and 10% in the Monte Carlo 4-jet WW signal were not included in any distribution. If for a particle there is more than one plane to which the projected angle is smaller than ϕ_{mn} then the particle is projected onto the plane to which it has the lowest transverse momentum. About 13.5% of the particles in the data and 14.7% in the Monte Carlo 4-jet WW signal could have been included in more than one distribution.

This leads to the particle flow distribution at 189 GeV shown in Figure 3, where one unity is added to the rescaled angle for each successive pair of jets (region A is plotted

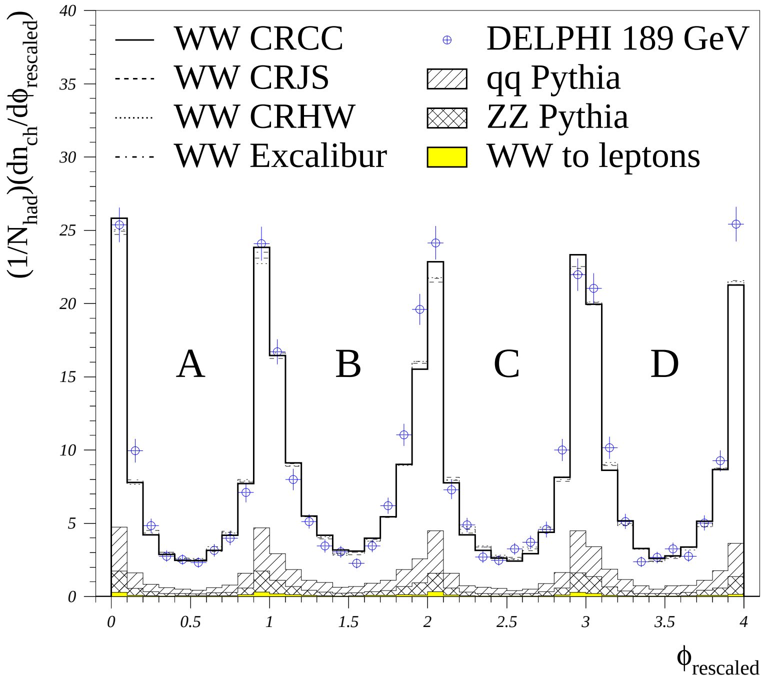

Figure 3: Average charged particle flow at 189 GeV. The lines (solid, dashed, dotted and dash-dotted) correspond to the sum of the simulated 4-jet WW signal with the background contributions, normalized to the total number of expected events.

from 0 to 1, region B from 1 to 2, region C from 2 to 3 and region D from 3 to 4). The statistical error on the bin contents (the average multiplicity per bin of ϕ^i_{resc}) was estimated, after performing 300 simulation experiments with the same number of events as in the data samples, to be the spread (r.m.s.) of the contents in that bin divided by the square root of the number of events. In this distribution the regions between the jets coming from the same W bosons (A and C), and from different W bosons (B and D), are very similar and can easily be compared.

In order to extract quantitative information about the different models, the following observable is defined as the ratio of the distributions, after summing the regions A and C, and the regions B and D, and integrating from 0.2 to 0.8:

$$R = \frac{\int_{0.2}^{0.8} dn/d\phi(A+C)d\phi}{\int_{0.2}^{0.8} dn/d\phi(B+D)d\phi}. \tag{1}$$

This region of integration was found to be the most sensitive region to colour reconnection. The statistical error on this ratio R was estimated as the spread (r.m.s.) of the values of R for 300 simulated experiments, each with a number of events equal to the size of the data samples.

The ratio can also be performed as a bin per bin ratio of distributions, leading to the ratio of distributions shown in Figure 4 for 189 GeV. The expected background was subtracted bin by bin from the observed distributions, which were then compared to the simulated samples.

The data points are compared to the full simulated samples with and without colour reconnection (the DELPHI tuned sample - EXCALIBUR - and the “Crete samples” CRCC,

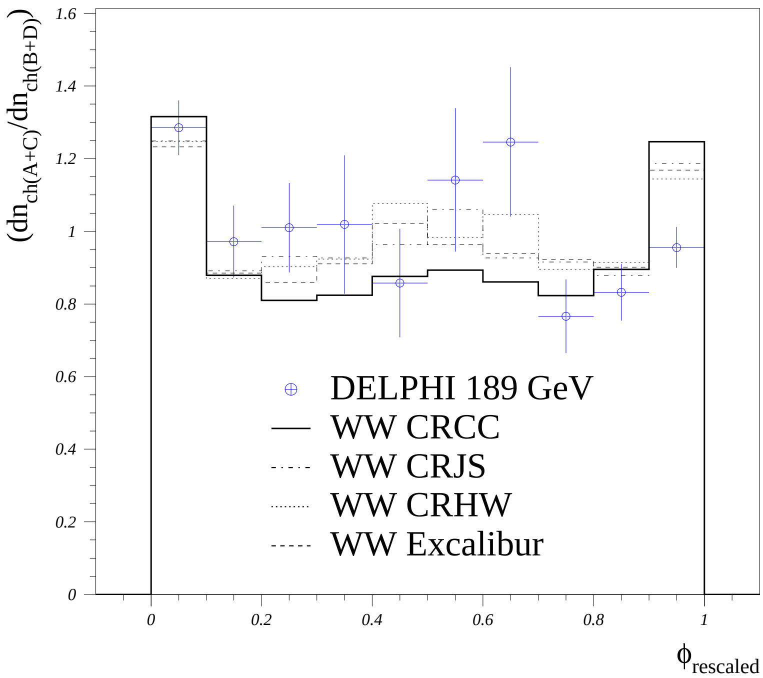

Figure 4: The ratio of the particle flow distributions (A+C)/(B+D), compared to different fragmentation models, with and without colour reconnection included.

CRJS and CRHW). Only the statistical errors are shown, and these were computed as the spread of the points for 300 simulated experiments with the same number of events as in the data samples.

The values for R obtained for the different centre-of-mass energies are shown in table 2, and compared to the expectations from Monte Carlo simulation without colour reconnection (EXCALIBUR samples at all energies). The changes in the value of R for the Monte Carlo samples are mainly due to the different values of the boost of the W systems.

The ratios at 189 GeV for the "Crete samples" were found to be $R_{SKI} = 0.841 \pm 0.010$ for the model of JETSET with full colour reconnection SKI model (CRCC), $R_{JS} = 0.945 \pm 0.013$ for the model of JETSET without colour reconnection (CRJS), and $R_{HW} =$

$\sqrt{s}$	# Events	R	Stat. error	Syst. error	MC
183 GeV	83	0.749	0.080	0.013	0.927±0.016
189 GeV	203	0.974	0.054	0.018	0.925±0.013
198 GeV	283	0.945	0.050	0.018	0.971±0.008
206 GeV	190	1.085	0.057	0.021	0.988±0.019

Table 2: Number of selected events and values of the ratio R for each energy (the first error is statistical, the second is systematic), and expected values with errors due to limited statistics of the simulation (see text). The values from 192 to 202 GeV were merged at a weighted centre-of-mass energy of 198 GeV, using as weights the number of selected events.

0.955 ± 0.014 for the model of HERWIG without colour reconnection (CRHW).

Systematic uncertainties in the ratios R take into account the following effects:

- Generators and Tuning
  At 189 GeV two different generators and tunings of the JETSET hadronisation model (EXCALIBUR and CRJS samples) were used to estimate the expected values of R without colour reconnection. Half of the difference of the values of R, 0.010, was taken as a systematic error on R. For the other energies a similar source was assumed with the same relative error.

- Fragmentation
  As the sample generated at 189 GeV with KoralW is common for the three "Crete samples", the underlying four fermion final states are identical for the different samples and the difference in the values of R for the samples fragmented with JETSET or with HERWIG, 0.010, can be considered as an uncertainty coming from fragmentation only, and was added in quadrature to the systematic error on R. For the other energies the same relative error was assumed.

- Bose Einstein correlations
  The difference in the observable R between a reference sample and a sample with BE correlations implemented in one W boson only (using JETSET model BE_3 [11] with λ input JETSET = 2.1 and radius input JETSET = 0.77 fm (PARJ(93)=0.26)), 0.004 at 189 GeV (and assuming the same relative error for the other energies), was added in quadrature to the systematic error.

- Background
  Uncertainties in the modelling of the background processes were estimated by half of the differences between the extreme values of R, 0.003 at 183 GeV, 0.007 at 189 GeV, 0.007 at 192-202 GeV, 0.010 at 206 GeV, after variation of the background by $\pm 10\%$. These values were added in quadrature to the systematic error.

  The fragmentation effects in the shape of the background were estimated by comparing the results in R when the subtracted $q\bar{q}$ sample was fragmented with ARIADNE 4.08 [12] tuned by DELPHI. The difference of the value in R at 189 GeV, 0.008, was added in quadrature to the systematic error. As the purities of the different samples are very similar, the same relative error was assumed for the other centre-of-mass energies.

The weighted average of the values obtained for R at the different centre-of-mass energies, using in the weights the statistical errors and taking correlations in the systematic errors between energies into account, at the luminosity weighted average centre-of-mass energy of 196 GeV, and after rescaling the R values at each energy to the value of R at this energy using simulation, was found to be:

$$\langle R_{rescaled} \rangle = 0.951 \pm 0.028 \pm 0.022 \tag{2}$$

The difference of this ratio, $\langle R_{rescaled} \rangle$, to the ratio obtained without rescaling the values before averaging, $\langle R \rangle = 0.964 \pm 0.029(stat) \pm 0.017(syst)$, was added in quadrature to the systematic error.

The average of the ratios at each energy between R measured for the data, and R expected from the model without colour reconnection, using as weights the statistical error on these ratios and taking correlations in the systematic errors between energies into account, was found to be:

$$\langle R_R \rangle = 1.009 \pm 0.030(stat.) \pm 0.019(syst.)\,, \qquad (3)$$

in which the uncertainties in the expected values of R, were taken into account in the systematic error.

4 Conclusions

The particle flow distributions were investigated using the DELPHI data at centre-of-mass energies from 183 to 208 GeV, for a total luminosity of 601.4 pb^{-1}.

The value of the ratio R of the integrals between 0.2 and 0.8 of the particle distribution in intra-W regions to the inter-W regions, at a luminosity weighted average centre-of-mass energy equal to 196 GeV and after rescaling the value at each energy to the value at 196 GeV, using simulation without colour reconnection, was found to be

$$\langle R_{rescaled} \rangle = 0.951 \pm 0.028(stat.) \pm 0.022(syst.)\,,$$

and compatible with models without colour reconnection.

The results on the ratio of ratios at 189 GeV reported recently by ALEPH [13], L3 [14] and the default analysis of OPAL [15], are smaller than the value found by DELPHI, whereas the similar analysis of OPAL [15] gives the same result as DELPHI.

These results are preliminary.

References

[1] P. de Jong, "Colour Reconnection in W Decays", hep-ex/0103018, to be published in the Proceedings of ICHEP 2000, July 2000, Osaka, Japan.

[2] DELPHI Collaboration, P. Abreu et al., Eur. Phys. J. **C18** (2000) 203.

[3] D. Duchesneau, Nucl. Phys. B Proc. Suppl. **96** (2001) 13.

[4] DELPHI Collaboration, P. Aarnio et al., Nucl. Instr. Meth. **A303** (1991) 233.

[5] DELPHI Collaboration, P. Abreu et al., Nucl. Instr. Meth. **A378** (1996) 57.

[6] F. A. Berends, R. Kleiss, R. Pittau, *"EXCALIBUR" in*, Physics at LEP2, eds. G. Altarelli, T. Sjöstrand and F. Zwirner, CERN 96-01 (1996) Vol. 2, 23.

[7] T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74.

[8] DELPHI Collaboration, P. Abreu et al., Z. Phys. **C77** (1996) 11.

[9] T. Sjöstrand and V. Khoze, Z. Phys. **C62** (1994) 281.

[10] P. Abreu et al., Nucl. Instrum. Meth. **A427** (1999) 487.

[11] L. Lönnblad and T. Sjöstrand, Eur. Phys. J. **C2** (1998) 165.

[12] L. Lönnblad, Comp. Phys. Comm. **71** (1992) 15.

[13] ALEPH Collaboration Note 2001-028 CONF 2001-022 (March 2001), submitted to the Winter 2001 Conferences.

[14] L3 Collaboration Note 2560 (March 2001), submitted to the Winter 2001 Conferences.

[15] OPAL Collaboration Physics Note PN448 (July 2000), submitted to ICHEP2000.