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A Search for Anomalous ZWW Couplings

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Abstract

A search for the decay $Z \to W^*W^*$ is described where W^* is an off mass shell W boson. This process is sensitive to anomalous ZWW couplings. A limit on the branching ratio is set at 1.7×10^{-5} (95% CL) from which limits on the strength of anomalous ZWW couplings are derived.

Introduction

The standard model of electroweak interactions has been extremely successful in describing a wide range of experimental observations. However, these observations up to now have only been sensitive directly to the couplings of bosons and fermion pairs. The standard model can equally well be used to predict the strength of the ZWW couplings and, conversely, a measurement of the strength of such couplings can be used as a test of the model. A decay mode sensitive to these couplings is $Z \to W^*W^*$ where W^* is an off mass shell $W^{\pm}$ boson. In the standard model the branching ratio for this process is expected to be 5×10^{-7}[1] which is currently beyond the limit of the sensitivity of the LEP experiments. However, if there exist anomalous non-abelian couplings in the model this branching ratio becomes large enough to measure even when such couplings are quite small. The observation of the decay $Z \to W^*W^*$ at LEP would then indicate new physics beyond the standard model.

Previous searches for anomalous couplings have been made by looking for the decay of a Z° to one real $W^\pm$[2, 3]. Barger and Han[1] showed that the sensitivity to such couplings is increased by a factor ~ 5 if the $W^\pm$ are both allowed to be off mass shell.

In this paper we describe a search for the decay $Z \to W^*W^*$ based on data taken between 1991 and 1993 using the ALEPH detector, corresponding to a total luminosity of 71 pb^{-1}. The decay modes searched for have either one or both virtual W bosons decaying to a lepton which, in consequence, will be well isolated from all the other particles. Thus events were looked for which contained electrons or muons which were well separated from all other tracks in the event in order to isolate the decay mode $Z \to W^*W^*$.

Data Analysis

Search for the decay $Z^0 \to (W^* \to \ell\nu) + W^*(\to q\bar{q})$

Events with candidate leptons (either μ or e) with momentum greater than 6 GeV/c which were isolated by an angle of greater than 30° from all neighbouring tracks and photons were selected as preliminary candidates for the decay $Z \to W^*W^*$. This is sensitive to the Z decays in which one W^* undergoes leptonic decay and the other decays to $q\bar{q}$ which form jets. Furthermore, the multiplicity of good charged tracks was demanded to be at least 4 in order to avoid large numbers of events from Z decays to $\tau^+\tau^-$ pairs. Here a good charged track was defined to be one with a momentum greater than 0.15 GeV, with at least 4 hits in the TPC and to have passed within 0.3 cms transversly and 5.0 cms longitudinally of the interaction point.

Good electrons were defined by the KEIDIP(ICHT) flag in ALPHA and good muons from the ALPHA routine QMUIDO. Additional constraints were imposed on the muons, demanding at least five of the last 10 planes of HCAL to have fired and to have no more than 2 extra expected hits in HCAL than observed. This preselection already eliminates most of the backgrounds from $\gamma\gamma$ interactions, Bhabha, $\mu^+\mu^-$ pairs, $\tau^+\tau^-$ pairs and $Z \to q\bar{q}$ decays. However, some residual background still remains. This is shown in the second and third rows of table I where the initial and final numbers of events surviving the preselection from each process as computed from the Monte Carlos are given, together with those from the data and and the $Z \to W^*W^*$ Monte Carlo. In the latter simulation events were generated distributed according to the matrix elements calculated by Barger and Han[1] using Standard model couplings. The generated off shell W^* were fed into the PYTHIA programme to produce the decay products which were then passed through GALEPH to simulate detection in ALEPH. All decay modes of the W^* were allowed, so the acceptances include the leptonic branching ratios of the W^*.

It can be seen from Table I that, whilst the preselection is effective in reducing background, the data can be roughly explained by the simulated conventional sources and further steps must be taken to eliminate the residual events from such sources.

Elimination of Backgrounds from Bhabha events and $\mu^+\mu^-$ pairs

Backgrounds from this source arise because radiated photons can convert to give events of sufficient track multiplicity to be candidates from $Z \to W^*W^*$.

These events were eliminated by demanding that no pair of tracks was a candidate converted photon for events with track multiplicities of less than 6. Here candidate pairs were identified using the ALPHA routine QPAIRF. A candidate pair was defined to be a pair of oppositely charged tracks in which $XMA < .05$ GeV, $|DXY| < 5.0$ cms and $DZ2 < 8.0$. Here XMA is the invariant mass of the two tracks of the candidate pair, DXY is the distance in the xy plane between the two tracks at the closest approach to the materialisation point and $DZ2$ is the Z separation at this point. Fig. 1 shows the distribution of the pair conversion coordinates for candidate pairs in the preselected events. The outline of the various walls in ALEPH can be seen. Further reduction of this background was achieved by requiring that the total summed electromagnetic energy (GAMPEC photons plus identified electrons) be less than 55 GeV and that events with track multiplicity ≤ 6 should have one and only one identified lepton.

Row 4 in table I shows that these cuts eliminate the background from Bhabha events and $\mu^+\mu^-$ pairs.

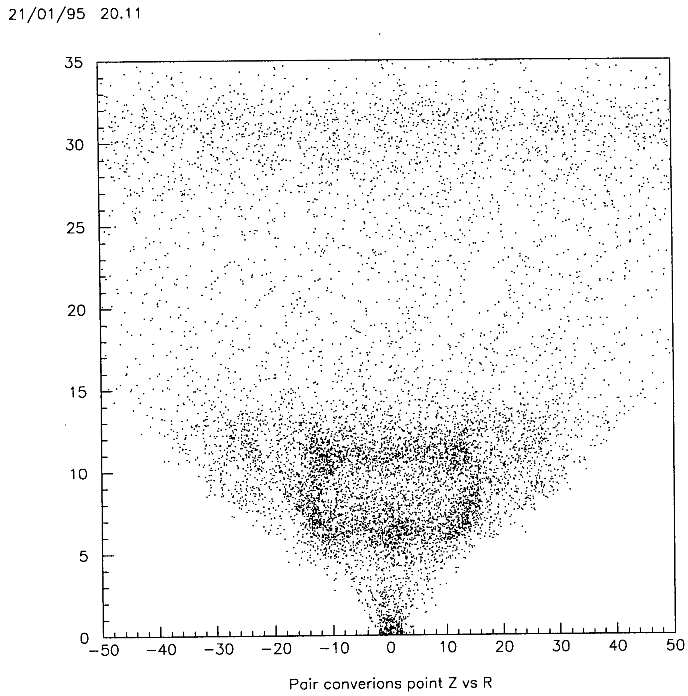

Fig. 1a - Pair candidate conversion points in preselected data.

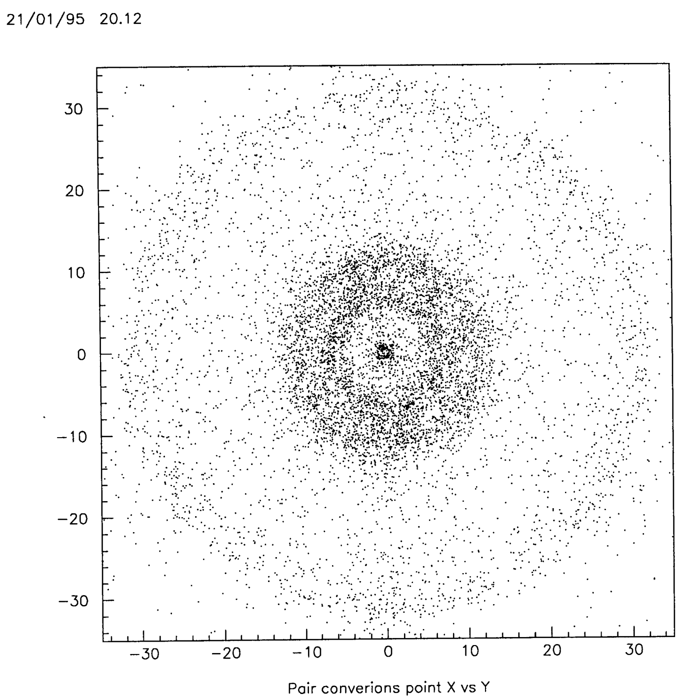

Fig. 1b - Pair candidate conversion points in preselected data.

Elimination of $Z \to \tau^+\tau^-$ Backgrounds

The cuts designed to eliminate the background from $ee \to \tau^+\tau^-$ depend on;

(a) The mass of the hadronic system opposite the isolated lepton should be greater than the τ mass. Hence it was required that this mass be greater than 2.0 GeV.

(b) The momentum vectors of the lepton and the hadronic system tend to be almost colinear in $Z \to \tau^+\tau^-$ events. Hence we demand that the angle between these two vectors has a cosine greater than -0.98.

Table I (row 5) shows that these cuts almost eliminate the $\tau\tau$ background. The small residue is decreased significantly by the remaining cuts (described below) designed to eliminate the remaining background from $Z \to q\bar{q}$ decays and $\gamma\gamma$ interactions. However, there is little loss in sensitivity to the decay $Z \to W^*W^*$.

Elimination of Backgrounds from $Z \to q\bar{q}$ Decays

To eliminate this background events were first rejected if they had hadron multiplicity greater than 28. This value was derived from fig. 2 which shows the hadron multiplicity for $Z \to q\bar{q}$ events and from $Z \to W^*W^*$ production Monte Carlo simulations.

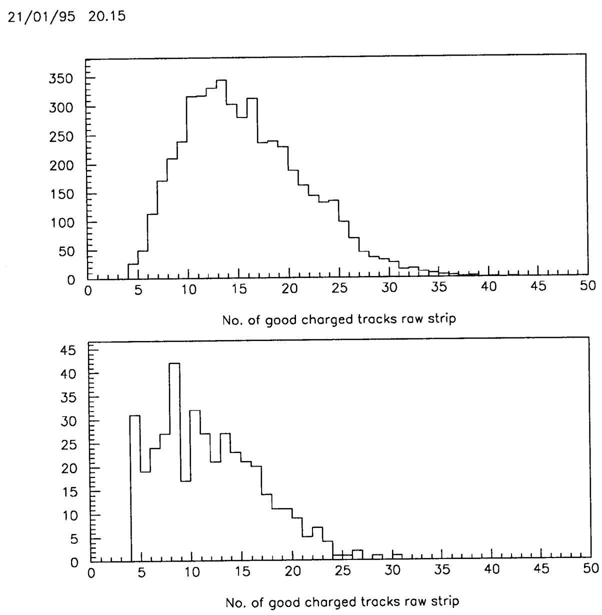

Fig. 2 - Track multiplicity for $ee \to q\bar{q}$ Monte Carlo (upper) and $Z \to W^*W^*$ Monte Carlo (lower).

The transverse mass is defined[1] by

$$M_T^2 = (E_\ell + \not{E}_T)^2 - (\vec{P}_\ell + \not{P}_T)^2$$

where (E_ℓ, P_ℓ) is the energy-momentum of the isolated lepton and $\not{E}_T$ and $\not{P}_T$ are missing transverse energy and momenta. Fig. 3 shows the distribution of M_T for $Z \to q\bar{q}$ and $Z \to W^*W^*$ decays before the cuts. Demanding $M_T > 10$ GeV is an effective way of reducing the $Z \to q\bar{q}$ background and this cut was imposed.

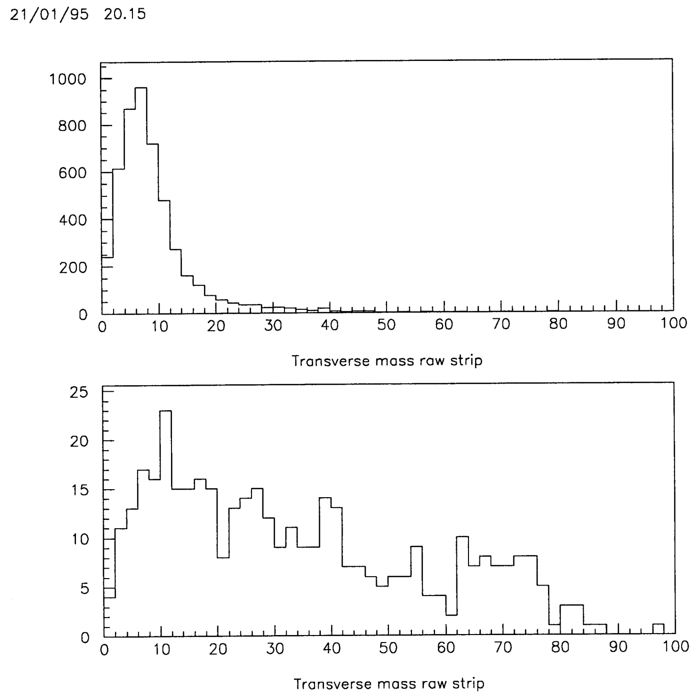

Fig. 3 - Transverse Mass distributions for $ee \to q\bar{q}$ Monte Carlo (upper) and $Z \to W^*W^*$ Monte Carlo (lower).

To reduce further this background, the events were divided into two hemispheres about a plane perpendicular to the thrust axis and the momentum sum formed of all energy flow objects in each hemisphere (excluding the isolated lepton). Fig. 4 shows the cosine of the angle between the jets in each hemisphere as a function of the momentum asymmetry of the events $A = \frac{|\vec{P}_1|-|\vec{P}_2|}{|\vec{P}_1|+|\vec{P}_2|}$, for $Z \to q\bar{q}$ and $Z \to W^*W^*$ events. There is a clear trend for $Z \to q\bar{q}$ to produce nearly back to back and symmetric jets. Accordingly, events were eliminated if $\cos\delta < -0.95$ with $|A| > 0.5$ or $\cos\delta < -.92$ with $|A| < 0.25$.

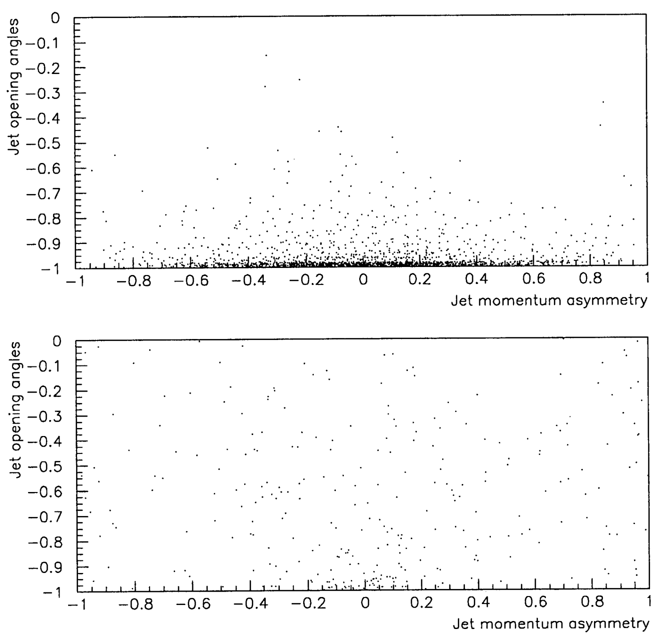

Fig. 4 - Jet momentum asymmetry versus cosine of jet opening angles for $ee \to q\bar{q}$ Monte Carlo (upper) and $Z \to W^*W^*$ Monte Carlo (lower).

Row 6 of Table I shows the residual numbers of events from each sample after these cuts. The number of events in the data and that predicted from the Monte

Carlo agree reasonably well and the majority of the residual background comes from $\gamma\gamma$ interactions.

Cuts to Eliminate $\gamma\gamma$ Events

These were based on the observed total P_T and on the summed longitudinal momentum in an event. For $\gamma\gamma$ interactions the summed P_T tends to be small whilst the summed longitudinal momentum is large corresponding to large missing longitudinal momentum. The normalised longitudinal momentum balance[4] was defined to be

$$N = \frac{\sum_i P_z^i \cos\theta_{isol}}{E_{beam}|\cos\theta_{isol}|}$$

where the longitudinal momentum sum is performed over all energy flow objects and θ_{isol} is the angle of the isolated track relative to the beam axis.

Fig. 5 shows N as a function of P_T for Monte Carlo samples of $Z \to q\bar{q}, Z \to W^*W^*$, $\gamma\gamma$ interactions and the data which illustrate the difference in populations of this plot coming from the different event samples.

Events were only accepted into the final sample if the summed P_T was more than 10 GeV and if the value of N lay below ~ 0.7

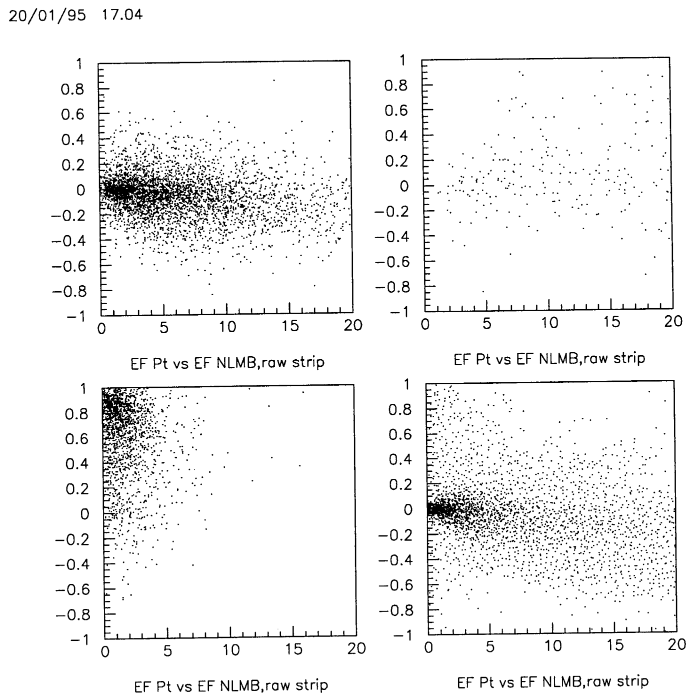

Fig. 5 - Summed P_T in an event versus Normalised Longitudinal Momentum Balance (see text) for $Z \to q\bar{q}$ Monte Carlo (top left), $Z \to W^*W^*$ Monte Carlo (top right) $\gamma\gamma \to q\bar{q}$ Monte Carlo (bottom left) and preselected data (bottom right).

The numbers of events expected was computed from the Monte Carlo at each stage of the cuts using the luminosities given and is shown in the final column (column 10) of table I. Comparing columns 9 and 10 shows that the agreement between Monte Carlo and data, whilst not perfect, is fair. This shows that even in the tails of the distributions, where all the surviving events lie, the Monte Carlo simulations give a reasonable representation of the data, leaving little room for a large anomalous signals.

The Final Sample

These are shown in the final row of Table I. A single event survives in the data with an expected background of 1.84 ± 0.66 events.

We conclude that the process $Z \to W^*W^*$ is not observed in ALEPH and an upper limit at 95% CL of 4.4 events can be set on the signal. The acceptance was determined to be $8.8 \pm 0.7\%$ (column 8 of Table I) (note that this acceptance includes the branching ratios for $W^* \to \ell\nu$). The data from 1991-1993 corresponded to a luminosity of 71 pb^{-1} which yielded 1.59 $\times 10^6$ hadronic Z decays ie a total of 2.28 $\times 10^6$ Z° decays. From these data the upper limit on the branching ratio for $Z \to W^*W^*$ at 95% confidence level is 2.4 $\times 10^{-5}$.

The residual data event (event number 7981, run number 15581) was examined and found to have 7 good tracks of which 3 were identified as electrons and there were two candidate pair conversions. Visual examination of the event does not show it as resembling the topology of a $Z \to W^*W^*$. The large number of electrons and converted pairs in the event together with rather large total seen electromagnetic energy (50 GeV compared to the cut at 55 GeV) indicate that it is most probably a radiative Bhabha with showering photons. The fact that no similar event appeared in the Bhabha Monte Carlo is probably due to the difficulty in simulating the tails of the distributions.

We assume that it is a radiated Bhabha event and make an extra cut to eliminate such events, in addition to the other cuts to remove Bhabha events, demanding that there should be no more than a single pair candidate for events with 8 or fewer tracks (previously this cut was only applied for 6 or fewer track events). Table II shows the results when this cut is applied. The background remains unchanged, the signal from the single event disappears and the acceptance becomes $8.5 \pm 0.7\%$. These data yield a 95% confidence level upper limit on the branching ratio for the decay $Z \to W^*W^*$ of 1.7×10^{-5}.

The limit could be improved by ~20% by looking for non-linear lepton pairs such as those looked for in the Higgs search[3]. This sample, which is sensitive to $Z \to HZ^*$ with either the H or the Z^* decaying to lepton pairs, has an identical topology to $Z \to W^*W^*$ with each W^* decaying to a lepton plus neutrino. We could therefore use the results of the Higgs search directly to improve our sensitivity to the decay $Z \to W^*W^*$.

The Significance of the Limit

The effective lagrangian describing the decay $Z \to W^*W^*$ is given in [1]. Six coupling constants appear in the lagrangian of which three are prohibited from deviating from their standard model values by gauge invariance. In the standard model, the three remaining coupling constants should have values $\kappa = 1, \tilde{\lambda} = 0, \lambda = 0$ and anomalous couplings would imply different values.

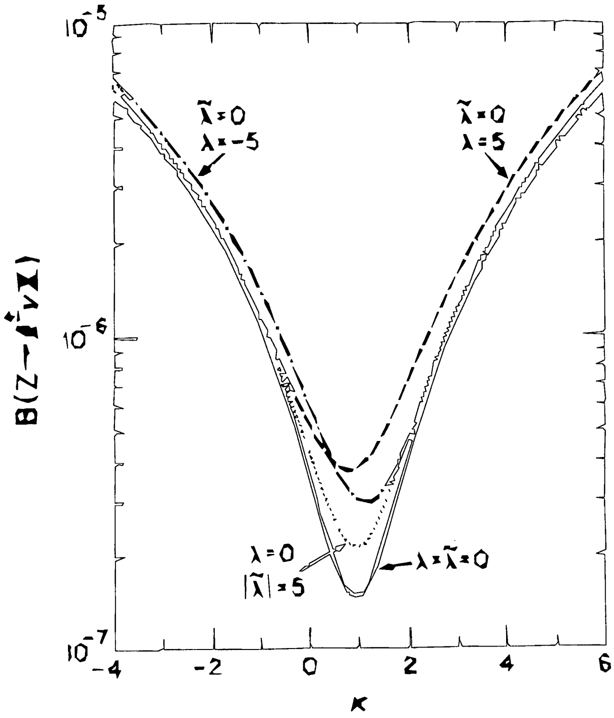

Fig. 6 - The calculated branching ratio for $Z \to W^*W^*$ reproduced from [1], with one W^* decay to e, μ and neutrino, as a function of the coupling κ for different values of the couplings and $\lambda\tilde{\lambda}$.

The branching ratio limits given above can be converted to limits or measurements of these couplings using fig. 6 which is reproduced from [1]. The 95% confidence level limit for $Z \to W^*W^*$ of 1.7×10^{-5} implies that the 95% confidence level limit on the process of $Z \to l\nu W^*$ (where l is a μ or e) is 5.4×10^{-6}. From fig. 6, it can be seen that this implies that $-3.5 < \kappa < 5.5$ at 95% confidence level with little sensitivity to λ or $\tilde{\lambda}$.

Alternatively, the data could be used as a measurement of the branching ratio of $0 \pm 2.0 \times 10^{-6}$ where the quoted error is the 1 σ (68% confidence level) limit. From fig. 6, this implies that $\kappa = 1 \pm 2.6$, again with little sensitivity to λ or $\tilde{\lambda}$.

It is likely that in the future better sensitivity to these anomalous couplings will become available from studies of inclusive $W\gamma$ production at the Tevatron, from measurements of $b \to s\gamma$ [5] and from LEP2. However, it is still useful to search directly for the decay $Z \to W^*W^*$ since there could still be new physics at an energy scale > 1 TeV to which neither $W\gamma$ or $b \to s\gamma$ would be sensitive. Such new physics, such as the blind directions proposed in[6] could show up in the decay mode studied here. The limits presented on the branching ratio $Z \to W^*W^*$ can then be used to restrict the couplings in such theories.

Conclusions

The decay mode $Z \to W^*W^*$ has been searched for in the ALEPH data from 1991-1993. No signal was seen and a 95% confidence level upper limit on the branching ratio of this decay mode is set at 1.7×10^{-5}. This limit allows either a measurement of the W-W-boson coupling of $\kappa = 1 \pm 2.6$ or the coupling to be bounded at 95% confidence level at $-3.5 < \kappa < 5.5$.

References

[1] V Barger and T Han, *Phys. Lett.* **241B** (1990) 127.

[2] Lee West, PhD Thesis, Royal Holloway (1992).

[3] ALEPH, *Phys. Reports* **216** (1992) 253.

[4] JADE, *Z. Phys.* *C***24** (1984) 231.

[5] T Rizzo, ANL-HEP-PR-93-19.

[6] A de Rujula, M Gavela, P Hernandez and E Masso, *Nucl. Phys.* **B384** (1992) 3.

Table I - Numbers of surviving events at each stage of the cuts for all M-C and data samples

Process	Bhabha	$\mu^+\mu^-$ pair	$ee \to \tau\tau$	$ee \to q\bar{q}^t$		$\gamma\gamma \to q\bar{q}$	$\gamma\gamma \to \tau\tau$	$Z \to W^*W^*$	Data	Expected†
				Muons	Electrons					
1. Luminosity	107.6 pb^{-1}	181.6 pb^{-1}	198.5 pb^{-1}	40 pb^{-1}	71 pb^{-1}	930 pb^{-1}	926 pb^{-1}	-	71 pb^{-1}	
2. Events Generated	346000	263000	298000	1.12 $\times 10^6$	2.01 $\times 10^6$	6677 (tagged)	3000 (tagged)	2000 (all decay modes)	1991-93	
3. Preselection	183	147	308	150	251	1048	168	312	1197	898
4. Bhabha & $\mu^+\mu^-$ cuts	0	0	135	147	233	938	93	302	774	620 ± 27
5. Cuts against $\tau\tau$	0	0	33	48	84	891	84	269	324	255 ± 16
6. Cuts against $Z \to q\bar{q}$	0	0	11	2	6	478	56	222	78	54 ± 4.1
7. Cuts against $\gamma\gamma$ interactions	0	0	3	0	0	4	6	175	1	1.84 ± 0.66

t By error the muons were not reconstructed for one sample of the Monte Carlo.

† Expected here means the rate calculated from the normalised sum of the different background channels simulated by Monte- Carlo (columns 2-8)

Table II - as Table I with the extra cut against Bhabhas (see text)

Process	Bhabha	$\mu^+\mu^-$ pair	$ee \to \tau\tau$	$ee \to q\bar{q}^t$		$\gamma\gamma \to q\bar{q}$	$\gamma\gamma \to \tau\tau$	$Z \to W^*W^*$	Data	Expected[†]
				Muons	Electrons					
1. Luminosity	107.6 pb^{-1}	181.6 pb^{-1}	198.5 pb^{-1}	40 pb^{-1}	71 pb^{-1}	930 pb^{-1}	926 pb^{-1}	-	71 pb^{-1}	
2. Events Generated	346000	263000	298000	1.12 $\times 10^6$	2.01 $\times 10^6$	6677 (tagged)	3000 (tagged)	2000 (all decay modes)	1991-93	
3. Preselection	183	147	308	150	251	1048	168	312	1197	898
4. Bhabha & $\mu^+\mu^-$ cuts	0	0	128	147	233	929	90	294	764	617 ± 27
5. Cuts against $\tau\tau$	0	0	30	48	84	882	81	261	322	253 ± 16
6. Cuts against $Z \to q\bar{q}$	0	0	10	2	6	471	55	215	76	54 ± 4.1
7. Cuts against $\gamma\gamma$ events	0	0	3	0	0	4	6	169	0	1.84 ± 0.66

t By error the muons were not reconstructed for one sample of the Monte Carlo.

[†] Expected here means the rate calculated from the normalised sum of the different background channels simulated by Monte- Carlo (columns 2-8)