MEASUREMENTS OF FOUR-FERMION PRODUCTION VIA NEUTRAL ELECTROWEAK CURRENTS AT LEP *

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representing the four LEP collaborations

Four-fermion production via electroweak neutral currents has been measured by all four LEP collaborations at center-of-mass energies near the Z resonance and for the first time also at energies well above the Z peak. Essentially all possible final states have been covered in four different topologies.

1 Introduction

The study of four-fermion production via neutral electroweak currents at LEP is one of the basic tests of higher order processes in the electroweak Standard Model. Theoretically this process is well understood within the Standard Model, and experimentally four-fermion events have a clear signature. Neutral current four-fermion production also constitutes an important background for particle searches, so that specialized analyses, like searches for Higgs or SUSY particles, try to suppress it. A dedicated study of neutral current four-fermion production thus represents a complementary search for new physics, that could manifest itself in sizable deviations of rates or kinematic distributions from the expectations. *

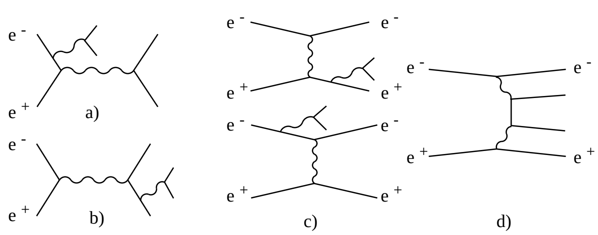

Figure 1: Feynman diagrams for four-fermion final states involving only neutral gauge boson exchange, represented by wiggly lines. The solid lines not labelled as $e^{\pm}$ may be quarks, charged leptons, or neutrinos in case of Z exchange: a) "conversion", b) "annihilation", c) "bremsstrahlung", and d) multiperipheral production.

In the following we review results from all LEP collaborations obtained for the final states $\ell\ell'\ell'$, $\ell\ell$qq, $\nu\nu\ell\ell$, and $\nu\nu$qq, (ℓ = e, μ, τ) at center-of-mass energies, $\sqrt{s}$, near the Z resonance (LEP-1), at $\sqrt{s}$ = 130–136 GeV (LEP 1.5), and from the ongoing LEP-2 run at $\sqrt{s}$ = 161 GeV. The above channels cover all experimentally accessible four-fermion final states that proceed via neutral gauge boson exchange according to the diagrams in Fig. 1. The only exception is the qqqq final state that is difficult to distinguish from higher order QCD corrections to $e^+e^-\to q\overline{q}$. The relative contributions from the various diagrams vary strongly with $\sqrt{s}$, and are especially large if one of the intermediate bosons is close to its mass shell. At the highest center-of-mass energies, above the W^+W^- threshold, there are irreducible contributions from charged current diagrams, notably to the $\nu\nu\ell\ell$ final state.

*Invited talk given at the 28th International Conference on High Energy Physics, ICHEP96, 25-31 July, 1996, Warsaw, Poland; to be published in the proceedings.

2 Event selection

In the following we describe the main features of the event selections that are largely in common for all four experiments. In detail, the signal acceptances and background contaminations can still be rather different amongst the experiments, as will be obvious from the results in Section 3.

Cuts on two quantities separate four different event classes, which will be dicussed in the following subsections. First, cuts on missing momentum separate channels with and without neutrinos. These are then further subdivided by cuts the charged particle multiplicity. The $\ell\ell'\ell'$ and $\nu\nu\ell\ell$ channels feed the low multiplicity classes, while the $\ell\ell$qq and $\nu\nu$qq channels contribute to both high and low multiplicity final states, depending on the invariant qq mass available for fragmentation.

2.1 Low multiplicity and large missing momentum: $\nu\nu V$

With a multiplicity requirement of two, this class contains mainly $\nu\nu$ee and $\nu\nu\mu\mu$ events. To optimize the efficiency, not all experiments perform a detailed lepton identification. These selections then also accept $\nu\nu\tau\tau$ events as well as $\nu\nu$qq channels where the quarks fragment to two charged hadrons, mainly via intermediate vector resonances like ρ, ω, and ϕ. The (usually low mass) lepton or hadron pair is denoted as V in the following. Further kinematical cuts are applied to reduce the main background sources, namely lepton pairs from two-photon processes, and $\gamma\nu\nu$ events with a converted photon.

2.2 High multiplicity and large missing momentum: $\nu\nu qq$

This class is composed of $\nu\nu$qq states with a charged multiplicity of 4 or more. Again kinematical cuts, like on the missing transverse momentum, reject the two-photon background, whereas $e^+e^- \to q\bar{q}$ background is reduced by requiring a large missing mass. Events where the missing momentum is carried by the decay products of a heavy particle, like the Z^0 in the Standard Model "conversion" process (Fig. 1a), or by (new) invisible heavy particles, will therefore pass this selection.

2.3 Low multiplicity and small missing momentum: $\ell\ell V$

This channel covers the multiplicities four and six, to allow for $\tau\tau$V contributions with one 3-prong τ decay, where again V stands for a lepton or hadron pair. While for the LEP-1 data, the various two-pair combinations contributing to this class are further subdivided into electron, muon, tau, and hadron pairs by means of lepton identification, this is usually not the case for the low-statistics measurements at $\sqrt{s}$ well above the Z resonance. A rejection of photon conversions is performed to reduce the background from γff events to the eeff channel, and 3-prong mass cuts are applied to suppress the $\tau\tau$ background.

2.4 High multiplicity and small missing momentum: $\ell\ell qq$

In this channel $e^+e^- \to q\bar{q}$ and, above the W^+W^- threshold, also the $\ell\nu$qq semileptonic W-pair decays are the main backgrounds. Therefore an explicit lepton identification is necessary in order to avoid, that split-off tracks from quark jets are taken as lepton candidates. Results are therefore given separately for the eeqq and $\mu\mu$qq channel. The Standard Model $\tau\tau$qq expectation is very small. Minimum lepton momentum requirements and especially the isolation of the lepton pair from the quark jets (Fig. 2) are the most powerful variables to reject the background.

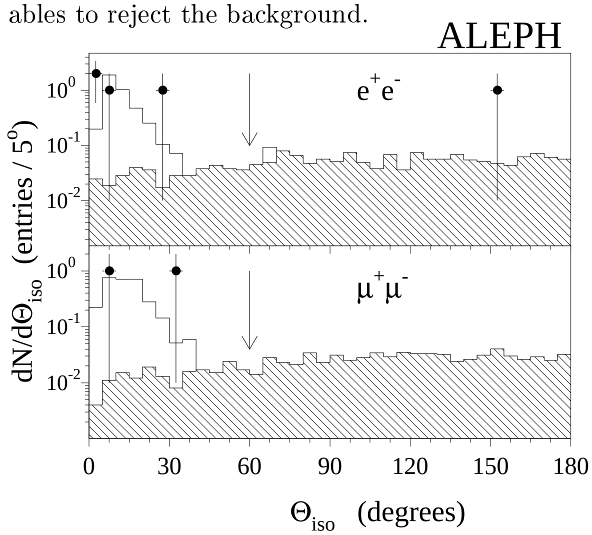

Figure 2: The sum, $\Theta_{\rm iso}$, of the individual lepton isolation angles as measured by ALEPH for eeqq and $\mu\mu$qq candidate events at $\sqrt{s}$ = 130–136 GeV. All cuts, except isolation, have been applied. The hatched histograms show the signal expectation, the solid one the background, data are the points, and the arrow indicates the cut value.

3 Results

The selected number of events in the data, and their kinematical distributions have been compared with the expectations for signal and background events. In the following we will tabularize the number of expected and observed events for the different classes at the various values of $\sqrt{s}$. For better readability of the tables, the errors on these numbers have been omitted. All results for LEP-1 are final, while for LEP-1.5 only the OPAL collaboration (for eeqq and $\mu\mu$qq) and the ALEPH collaboration have published their results. All other results at LEP-1.5 and LEP-2 are preliminary.

The signal predictions are mostly derived from the `FERMISV`[1] generator, usually after corrections for dominant higher order effects (e.g. running α and vector resonances, typically amounting to 10–15%) have been applied. Residual experimental and theoretical uncertainties of the signal predictions are of the order of 10%. Expected backgrounds are usually small but, especially above the Z resonance, the precision of the background prediction suffers from low statistics and the modelling of rare phase space regions and can in some cases reach uncertainties of a factor of two.

Table 1: LEP-1 results for four-fermion analyses. The upper line gives the numbers of events expected for Standard Model signal + background, the lower line the experimental observations. See the text for typical errors of the signal and background expectations. A background of 0 means, that the expectation is below 0.5 events. The entry $\nu\nu$ff is the sum over $\nu\nu$V (1 event observed) and $\nu\nu$qq (2 events observed).

$\sqrt{s}\approx m_Z$	$\int \mathcal{L}$dt	$\nu\nu$ff	$\ell\ell$V	eeqq	$\mu\mu$qq	sum
ALEPH [2]	79 pb^{-1}	3 + 0	232 + < 2	14 + 1	13 + 0	262 + < 3
		3	229	10	19	261
DELPHI [3]	16 pb^{-1}	− + −	23 + 3	− + −	− + −	23 + 3
		−	27	−	−	27
L3 [4]	36 pb^{-1}	− + −	45 + 4	15 + 1	5 + 0	65 + 5
		−	43	18	6	67
OPAL [5,6]	132 pb^{-1} ($\ell\ell$V: 19 pb^{-1})	− + −	44 + 13	19 + 1	20 + 8	83 + 22
		−	50	25	28	103

3.1 Results at $\sqrt{s} \approx m_Z$ (LEP-1)

At $\sqrt{s}$ near the Z resonance the dominant four-fermion process is the final state radiation of a fermion pair from one of the decay products of the intermediate Z (Fig. 1b), i.e. from a lepton in $\ell\ell$V events and (preferrably) a quark in $\ell\ell$qq events. Initial state fermion pair radiation for a *on-shell* intermediate Z (Fig 1a) is suppressed by the available phase space. This leads to a suppression of the $\nu\nu$ff topology, since here Fig. 1a is the only neutral current diagram contributing.

The four LEP experiments, based on different amounts of integrated luminosity $\int \mathcal{L}$dt, have covered a large variety of channels, as detailed in Table 1. No deviations from expected cross-sections have been found with a statistics of typically 3 $\nu\nu$ff, 20-50 $\ell\ell$qq, and 30-230 $\ell\ell$V events for each experiment. An early excess of $\tau\tau$V events observed by ALEPH [7] was not confirmed with larger statistics. Likewise all kinematical distributions agree with the expectations. One exception is a slightly unlikely mass and transverse momentum configuration of the three ALEPH $\nu\nu$ff events, which becomes less significant after taking into account also contributions from charged current exchanges [8].

3.2 Results at $\sqrt{s}$ = 130–136 GeV (LEP-1.5)

At center-of-mass energies well above the Z resonance the dominant four-fermion process, apart from the t-channel "bremsstrahlung" diagram for the eeff final state, is the initial state emission of a fermion pair with an energy appropriate for a "return" to the Z resonance. This leads to a clear separation of the two fermion pairs and increases the selection efficiency, especially for the $\ell\ell$qq channels, resulting in a visible cross-section comparable to that on the Z resonance.

The results of the four LEP experiments at $\sqrt{s}$=130–136 GeV are summarized in Table 2. Generally, the observed numbers of events agree well with the expectations. The only exception is the $\mu\mu$qq channel, where the OPAL collaboration observes 5 events for 0.55 signal and 0.06 background events expected [6]. This excess is not seen by the three other collaborations, that together observe 2 events in this channel, where 2.2 are expected. Apart from their abundance, all other features of the OPAL $\mu\mu$qq events are consistent with the Standard Model expectation, as is illustrated for the invariant mass distributions in Fig. 3.

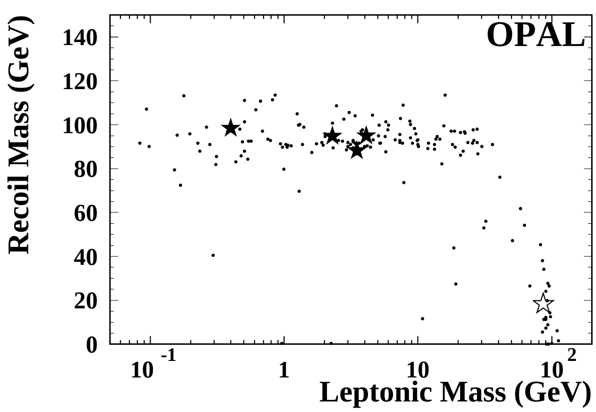

Figure 3: Scatter plot of the mass of the lepton pair and its recoil mass for the $\mu\mu$qq channel at 130-136 GeV, as observed by OPAL. The small points is the FERMISV expectation for the signal distribution. The four data events with large recoil mass are indicated by filled stars, whereas the open star represents a low recoil mass event.

Summing all final states from all collabora-

Table 2: LEP-1.5 results for four-fermion analyses. The upper line gives the numbers of events expected for Standard Model signal + background, the lower line the experimental observations. See the text for typical errors of the signal and background expectations. A background of 0.0 means, that the expectation is below 0.05 events.

$\sqrt{s}\approx$133 GeV	$\int \mathcal{L}$dt	$\nu\nu$V	$\nu\nu$qq	$\ell\ell$V	eeqq	$\mu\mu$qq	sum
ALEPH [9]	5.8 pb^{-1}	1.8 + 0.0 2	0.5 + 0.0 1	1.9 + 0.0 1	1.7 + 0.1 1	0.9 + 0.0 0	6.7 + 0.2 5
DELPHI [10]	5.9 pb^{-1}	0.3 + 0.0 1	0.3 + 0.3 0	0.2 + 0.0 0	0.9 + 0.3 0	0.7 + 0.1 2	2.4 + 0.7 3
L3 [11]	5.0 pb^{-1}	– + – –	– + – –	– + – –	1.4 + 0.7 2	0.5 + 0.0 0	1.9 + 0.7 2
OPAL [6,12]	5.2 pb^{-1}	– + – –	– + – –	1.3 + 0.1 2	0.6 + 0.1 1	0.5 + 0.1 5	2.5 + 0.3 8
LEP-1.5	21.9 pb^{-1}	2.0 + 0.1 3	0.8 + 0.3 1	3.4 + 0.2 3	4.7 + 1.2 4	2.6 + 0.2 7	13.5 + 1.9 18

tions at LEP-1.5 we observe 18 neutral current four-fermion candidate events in a total of 22 pb^{-1} data luminosity. Since 13.5 signal and 1.9 background events are predicted, there is no indication of an additional strong source for these final states within or beyond the Standard Model.

3.3 Results at $\sqrt{s}$ = 161 GeV (LEP-2)

The analysis of the same channels as at LEP-1.5 has been repeated by the four LEP collaborations with similar cuts also for the ongoing run at $\sqrt{s}$ = 161 GeV, that has started two weeks before the start of this conference. In the first 10 days of running a sum of about 11 pb^{-1} integrated luminosity has been collected by the four experiments together. Three four-fermion events have been observed (1 eeqq by OPAL, 1 $\mu\mu$qq by DELPHI, and 1 $\nu\nu$qq by DELPHI), compared to an expectation of 3.9 signal and 0.8 background events[10,13,14,15], summed over all channels and experiments apart from the three DELPHI channels without observed events.

4 Conclusions

Four-fermion production via electroweak neutral currents has been measured by all four LEP collaborations at center-of-mass energies near the Z resonance and for the first time also at energies well above the Z peak where different diagrams dominate. Deviations from the Standard Model predictions in single channels by single experiments are consistent with statistical fluctuations. At none of the center-of-mass energies there is evidence for a yet unknown extra source of four-fermion events.

Acknowledgments

I would like to thank S. Gonzales and Ch. Hoffmann (ALEPH), A. Lipniacka and J. Marco (DELPHI), and F. Di Lodovico (L3) for supplying me with the most recent results and plots from the ongoing 161 GeV run, and for helpful discussions.

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